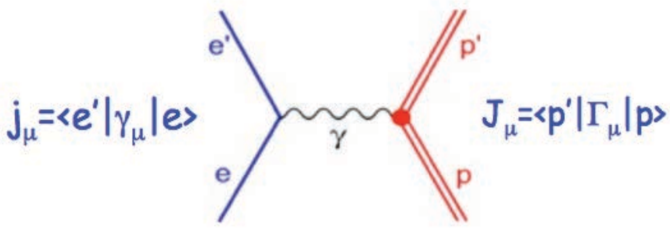
The SuperBigbite Program at JLab
from Form Factors to SIDIS and TDIS

G.B. Franklin
Carnegie Mellon

- Barriers to higher Q^2
- The SuperBigbite Spectrometer (SBS)
  - Wide aperture dipole
  - Flexible high-rate detector packages
- The SBS Suite of Experiments
- Further into the Future

Nucleon Form Factor Measurements

Transition matrix: $M \propto \frac{j_\mu J^\mu}{Q^2}$



Electron current: $j_\mu = e\bar{u}(k')\gamma_\mu u(k)$

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

Form Factors:

$F_1(Q^2) = \text{Dirac FF (chirality non-flip)}$

$F_2(Q^2) = \text{Pauli FF (chirality flip)}$

Sachs Form Factors:

$G_E(Q^2) = F_1(Q^2) - \kappa\tau F_2(Q^2)$

$G_M(Q^2) = F_1(Q^2) + \kappa F_2(Q^2)$

Nucleon Form Factor Measurements

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{d\sigma}{d\Omega}(E,\theta)_{\mathrm{M}} \frac{E'}{E}\left[\frac{G_E^2+\tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right]$$

Allows "Rosenbluth Separation" of G_E and G_M

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

$$E' = E/(1+2\frac{E}{M} sin^2\frac{\theta}{2})$$

$$Q^2 = 4EE' sin^2\frac{\theta}{2}$$

$$\tau = \frac{Q^2}{4M^2}$$

Road to higher Q^2

Q^2 =few $(GeV/c)^2$ → $Q^2 > 10\ (GeV/c)^2$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = 4\alpha^2 \frac{E'^2}{Q^4} \propto \frac{E^2}{Q^4}$$

$$\text{Form Factors} \propto \frac{1}{Q^8}$$

$$\text{Cross Section} \propto \frac{E^2}{(Q^2)^6}$$

Doubling electron energy, E, helps, but…

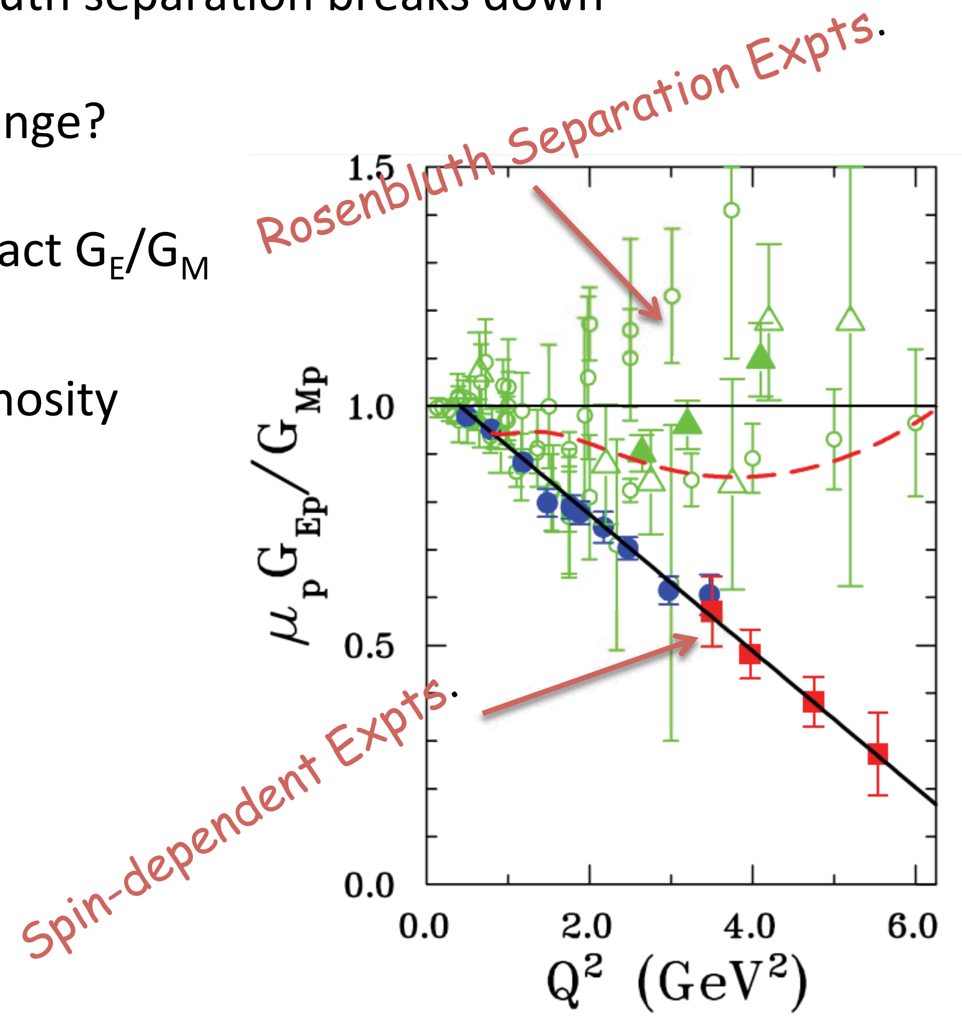
Cross section decreases by factor of 16 when doubling Q^2 and E

Need to maximize luminosity and acceptance

Road to higher Q^2

Q^2 =few $(GeV/c)^2$ → Q^2> 10 $(GeV/c)^2$

- Separation of G_M and G_E via Rosenbluth separation breaks down
- Complications from 2 photon-exchange?
- Spin-dependent measurements extract G_E/G_M
- But polarized targets may limit luminosity



Road to higher Q^2

The Jefferson Lab Energy Upgrade

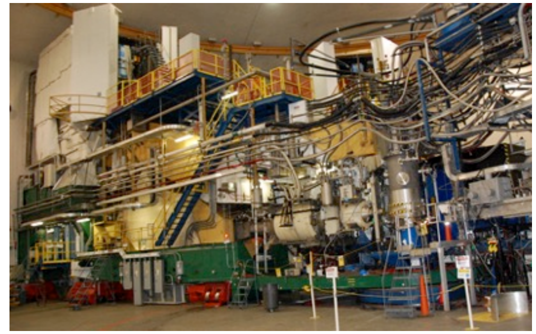
6 GeV → 11 GeV

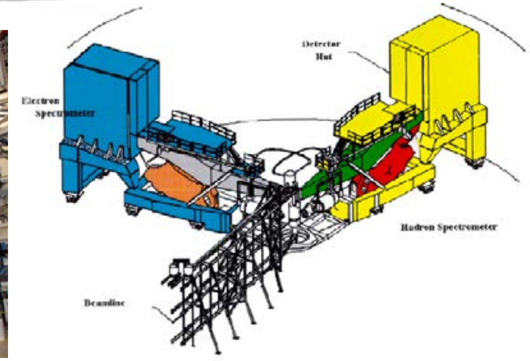
- Increase # RF modules
- Upgrade existing RF modules
- Upgrade arc magnets
- Extra ½ turn for Hall D gives 12 GeV

High Resolution, Small $\Delta\Omega$ → Large $\Delta\Omega$, open geometry

Twin High Resolution Spectrometers

- $\Delta\Omega$: ~6 msr
- P range: ±4.5%
- σ_p/p: ~1 x 10^{-4}
- Detectors highly shielded





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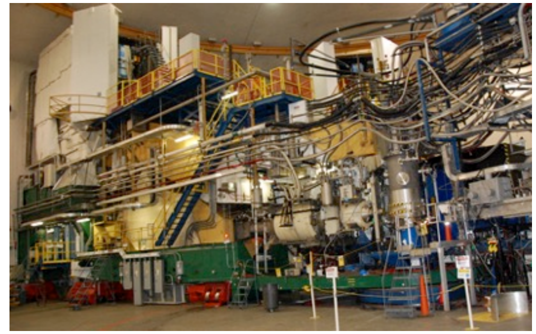
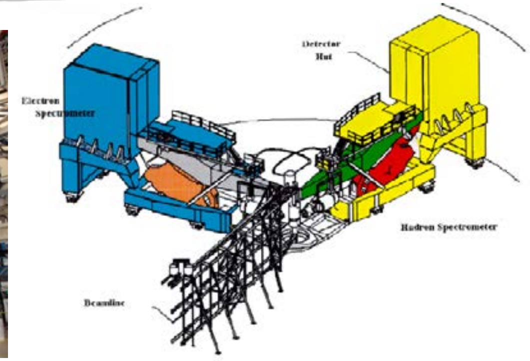
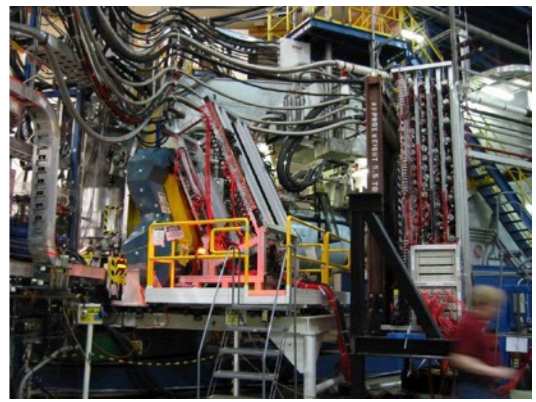
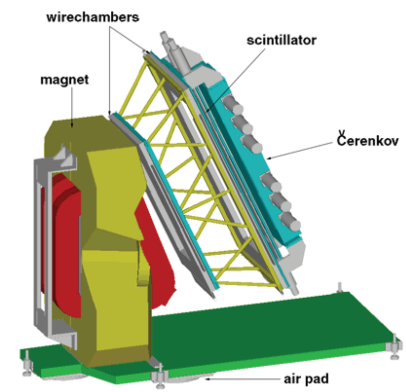




BigBite Spectrometer

- $\Delta\Omega$: ~76 msr
- p range: 0.6 to 1.8 GeV
- σ_p/p: ~1 x 10^{-2}
- Open geometry, tracking depends on redundant chambers





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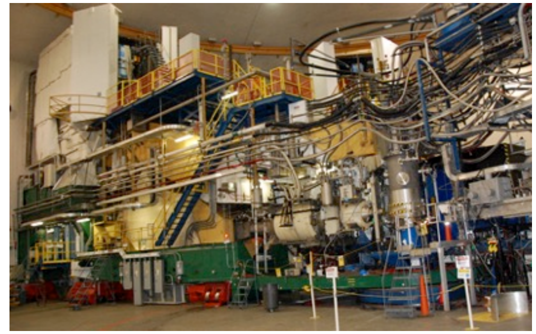

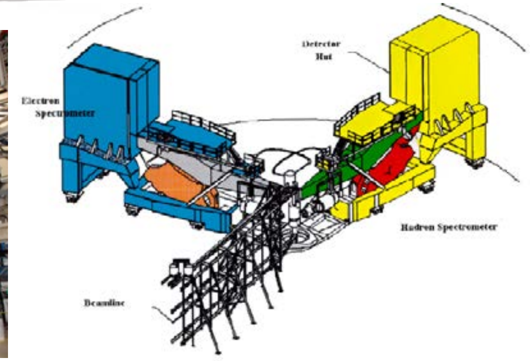

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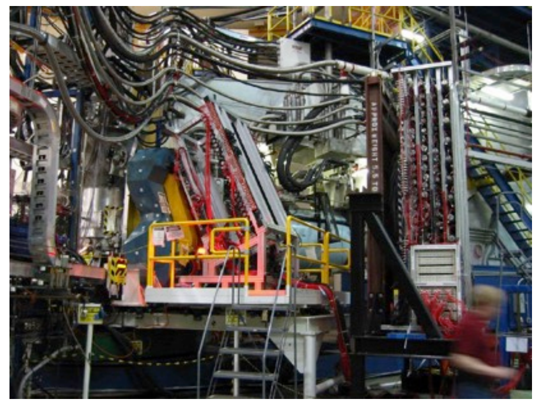
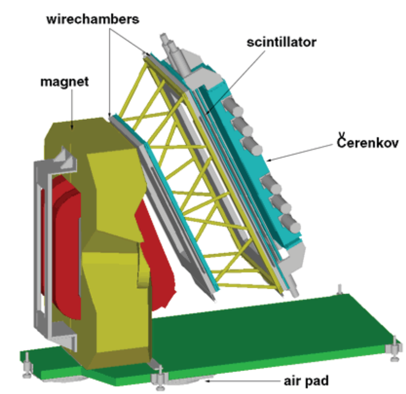
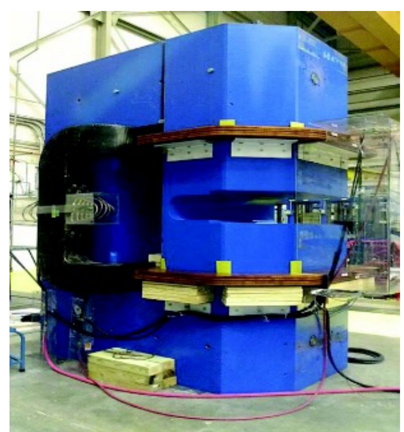
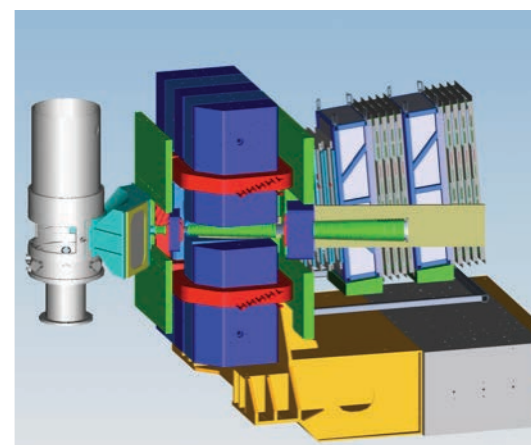




Super Bigbite Spectrometer (SBS)

- Under construction
- $\Delta\Omega$: 76 msr @ 30°
  5 msr @ 3.5°
- Δp: 2 to 10 GeV
- σ_p/p: ~1 x 10^{-3} p [GeV]
- Highly segmented, configurable detector packages

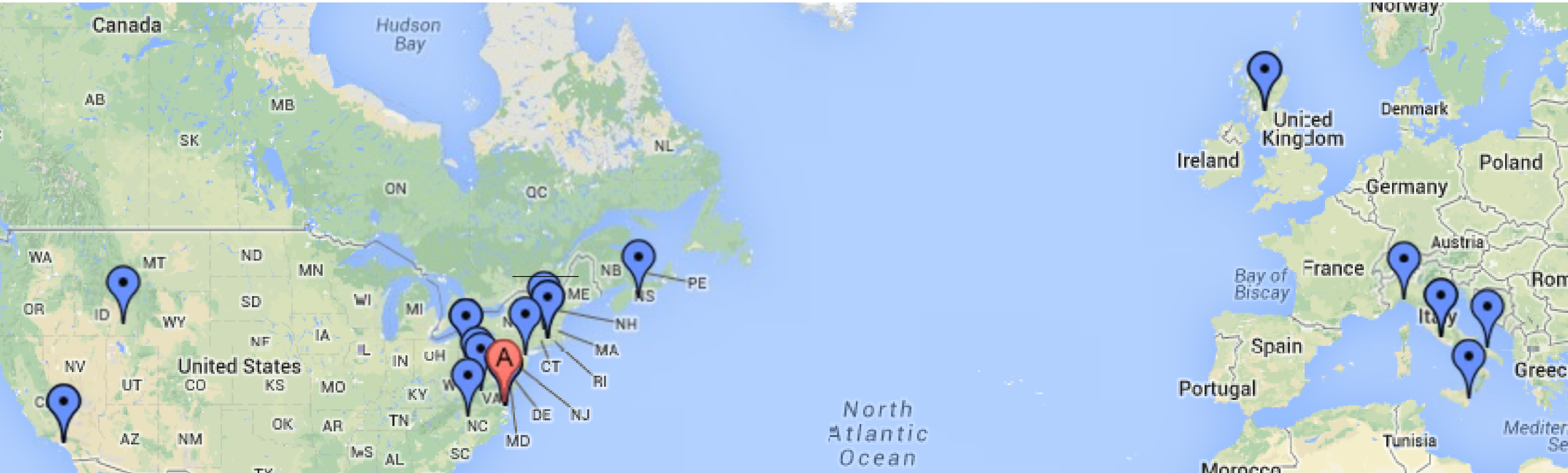




The SuperBigbite Spectrometer Project

- Spectrometer based on open-geometry magnet
- Accommodates small-angle hadrons
- Suite of *configurable* detector packages
- Suite of approved experiments with multiple configurations

Jefferson Lab
California State, L.A.
Carnegie Mellon Univ.
Christopher Newport Univ.
Univ. of Connecticut
Univ. of Glasgow
Norfolk State Univ.
James Madison Univ.
Idaho State Univ.
INFN / (Rome, Catania, Bari, Genoa)
St. Mary's Univ.
Univ. of Massachusetts
North Carolina A&T
Rutgers
Univ. of Virginia
College of William and Mary
Yerevan Physics Inst



The SuperBigbite Spectrometer Project

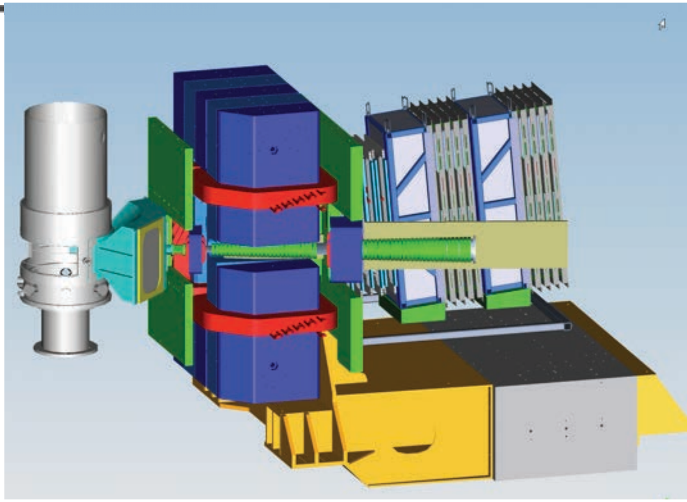
First suite of SBS experiments

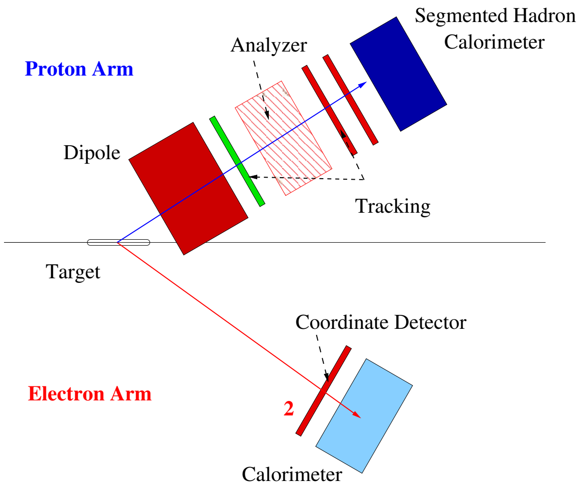
	Max Q^2 (GeV^2/c^2)	Reaction	JLab Exp
G_E^p	14.5	Proton Electric FF $p(\vec{e}, e'\vec{p})$	E12-07-109
G_E^n	10.5	Neutron Electric FF $\vec{n}(\vec{e}, e'n)pn$	E12-09-106
G_M^n	13.5	Neutron Magnetic FF $d(e, e'n)p$ and $d(e, e'p)n$	E12-09-019
SIDIS	9.0	Semi-Inclusive single-spin asymmetry $\vec{n}(\vec{e}, e'x)$ where $x=\pi^+, \pi^-, K^+, K^-$	E12-09-018
A_1^n	8.0	Neutron Spin A_{1n} in valence region $\vec{n}(\vec{e}, e)X$	E12-06-122
TDIS	3	Tagged Deep Inelastic Scattering Meson component of the nucleon $p(e, e'n)X$ and $d(e, e'pp)X$	E12-15-006

The SuperBigbite Spectrometer Project

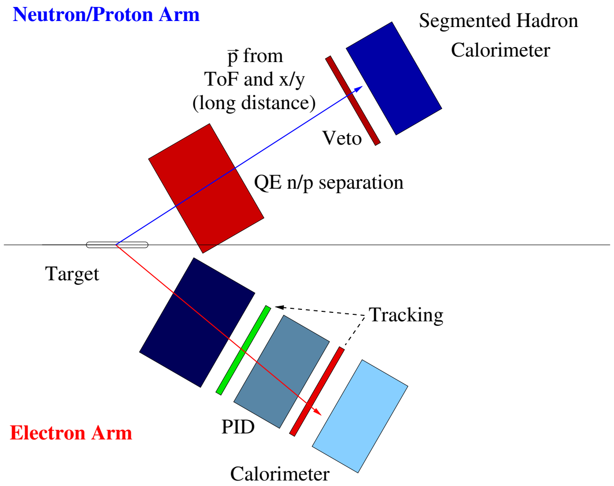
Configurable Detectors

- Open-geometry magnet
- GEM Tracking Detectors
- Hadron Calorimeter
- Electron Calorimeter
- Polarimeter





G_{Ep} Configuration

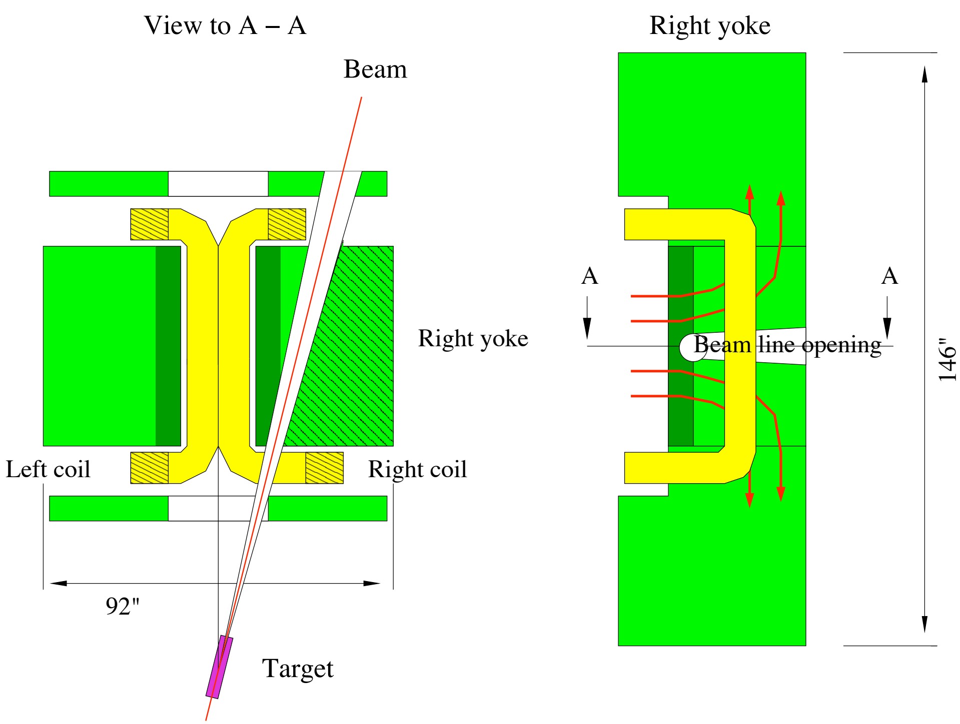


G_{En} Configuration

The Dipole

Small aperture, high resolution → Wide aperture

- Magnet: 48D48 - 46 cm gap, 2.5 Tesla*m
- Solid angle is 70 msr at angle 15 deg.
- Momentum acceptance is 2 to 10 GeV



The SuperBigbite Spectrometer Project

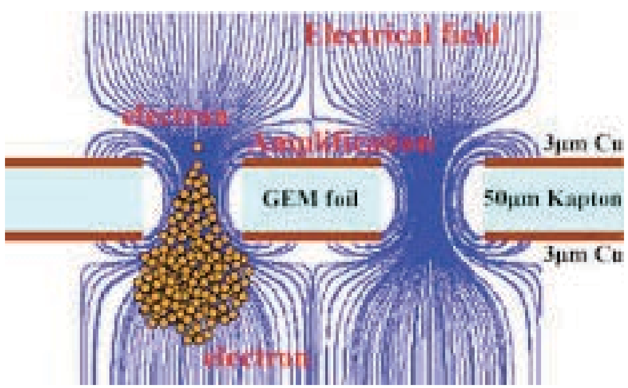
Drift Chambers → GEM Tracking Chambers

Used in Hadron Arm (Tracking and Polarimeter) and Electron Arm

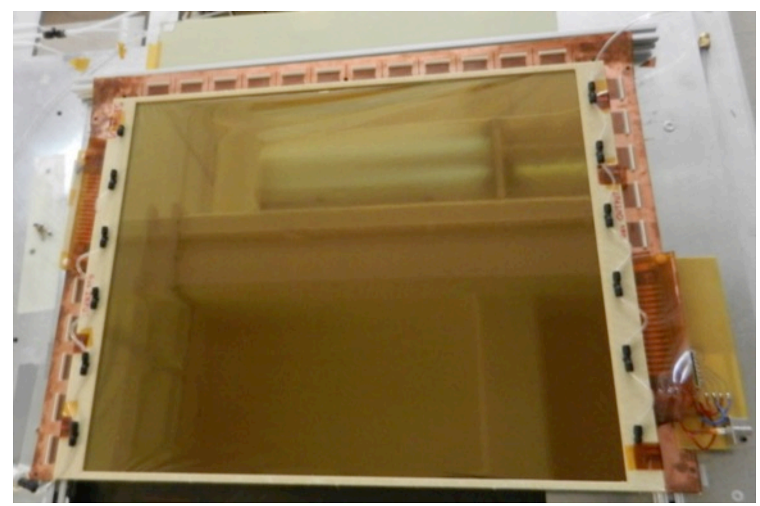
INFN/Rome-Catania-Genoa-Bari, U.Virginia

Tracking Chamber Rate Limitations

	Drift Chambers	GEMs
Ion drift:	~ 3mm	50μm
Intrinsic limit:	10-50 kHz/cm^2	> 10 MHz/cm^2
JLab BigBite:	10 kHz/cm^2 →	
SBS Electronics:		~ 500 kHz /cm^2



Gas Electron Multiplier
1997 Fabio Sauli

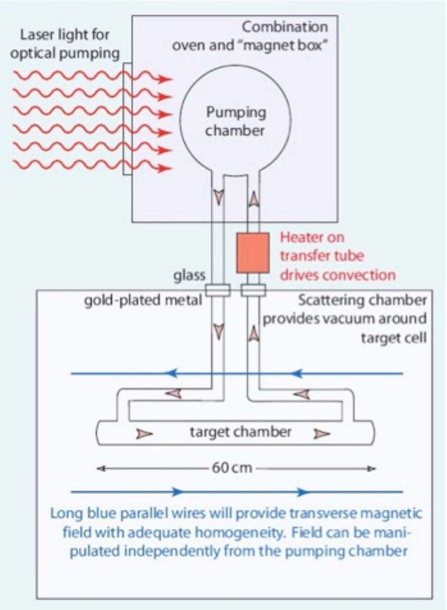


The SuperBigbite Spectrometer Project

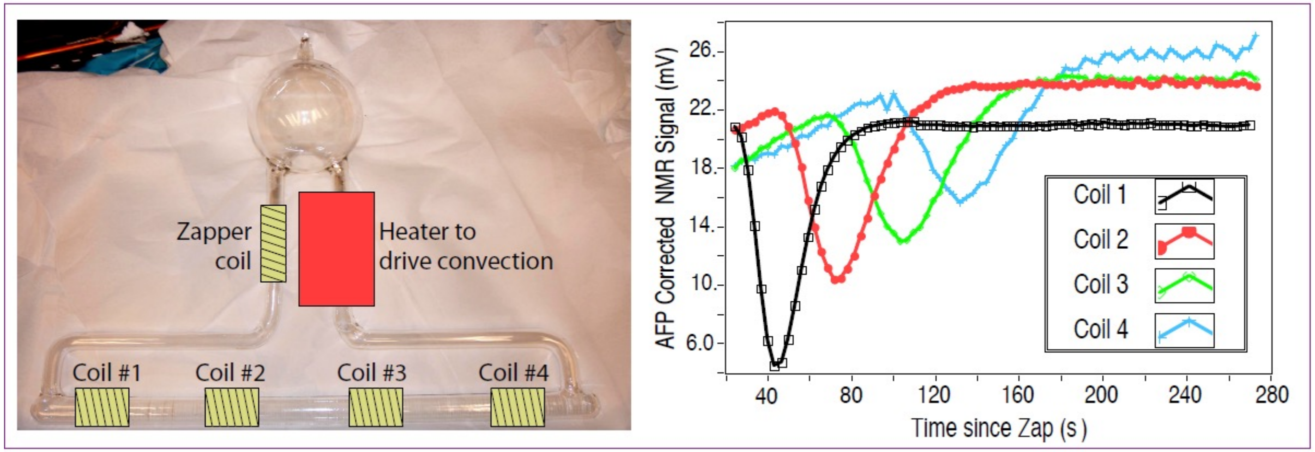
Diffusion Polarized ^{3}He Target → Convection-based Polarization

Polarized 3He Target used for polarized neutrons
U.Virginia

	Old Design	New Design
Max current:	8 μA	60 μA
Length:	40 cm	55 cm

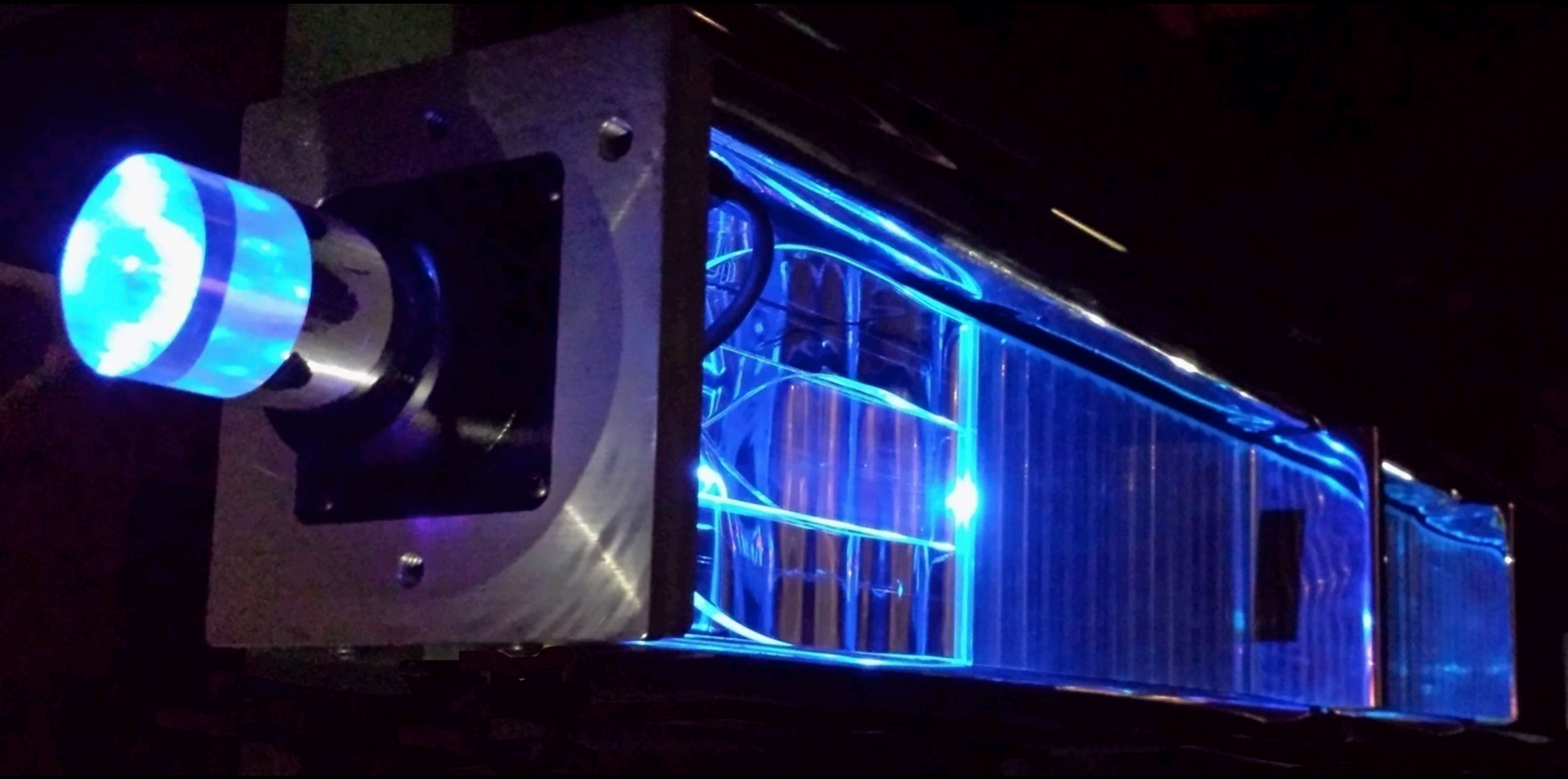


Convection + metal cell ends allow for sustained polarization of ~60% with 60μA beam



The SuperBigbite Spectrometer Project

Additional Detector Packages



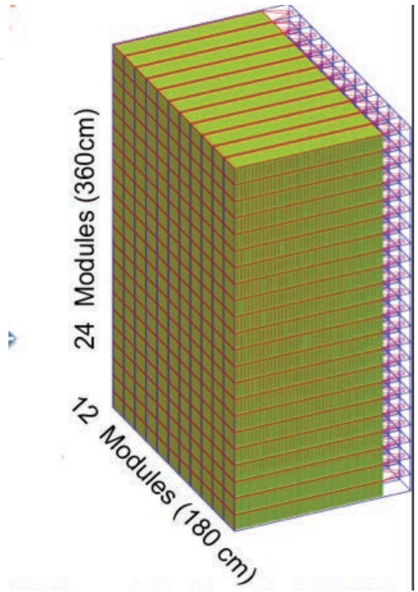
Hadron Calorimeter Module *

* Had to use this picture somewhere

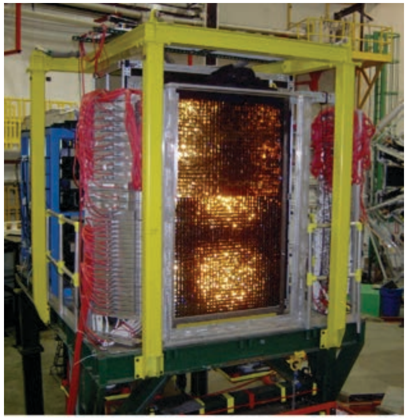
The SuperBigbite Spectrometer Project

Additional Detector Packages:

HCAL-J 40 Ton Hadron Calorimeter for Hadron Arm
288 modules
700 ps ToF resolution, 95% efficiency
Carnegie Mellon, JLab, INFN/Catania



ECal Electron Calorimeter for Electron Arm (G_E^p)
Must survive 0.5 kRad/h
JLab, SUNY



The SuperBigbite Spectrometer Project

Additional Detector Packages:

CDET Coordinate Detector
Electron arm (G_E^p)
Hadron arm
Idaho State, St. Mary's, Jlab

GRINCH Threshold Cerenkov
Bigbite PID, 510 PMT array
William & Mary, North Carol.,
A&T, Glasgow

RICH Ring-Imaging Cerenkov
π/K separation for SIDIS experiment
UConn, JLab

The SuperBigbite Spectrometer Project

First suite of SBS experiments

The Form Factor Measurements

	Max Q^2 (GeV^2/c^2)	Reaction
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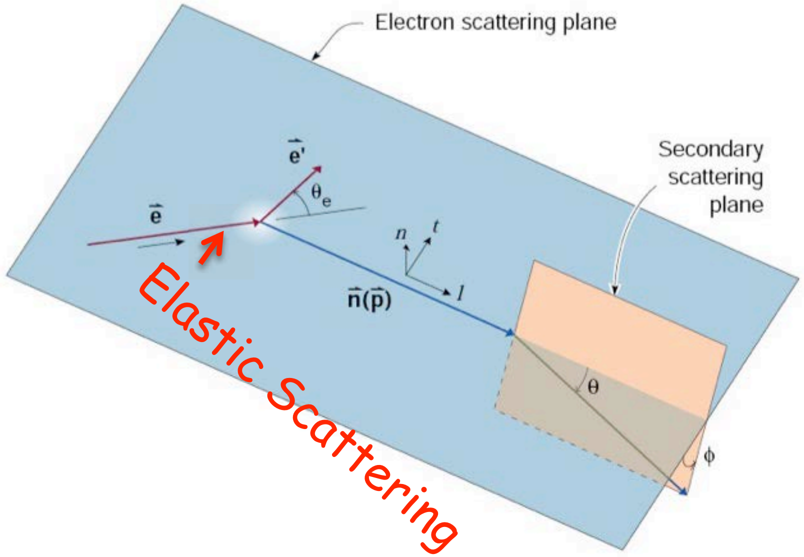
TDIS	3	Tagged Deep Inelastic Scattering Meson component of the nucleon $p(e, e'n)X$ and $d(e, e'pp)X$

G_E^p: Electric FF of the Proton $p(\vec{e}, e'\vec{p})$

Measures $G_E(Q^2)/G_M(Q^2)$ for proton

- Spin-transfer determines $G_E(Q^2)/G_M(Q^2)$
- Uses Two Recoil Polarimeters
- 70μA beam on 40 cm LH2 Target
- Q^2 up to 12 GeV^2



Spin Transfer in Elastic Scattering

Interaction includes spin-spin terms: $\vec{S}_e \cdot \vec{S}_p$

Define coordinate axes for scattered proton

$$\begin{array}{llll} longitudinal: & \hat{\ell} = \vec{p}/|\vec{p}| & & along\ protron\ momentum \\ normal: & \hat{n} = (\vec{k}_e \times \vec{k}'_e)/|\vec{k}_e \times \vec{k}'_e| & & normal\ to\ scattering\ plane \\ transverse: & \hat{t} = \hat{n} \times \hat{\ell} & & \end{array}$$

G_{Ep} uses a *longitudinally* polarized beam, $\vec{P}_e = hP_e\hat{k}_e,\ h = \pm 1$

$$\begin{aligned} P_n &= 0 \\ P_t &\neq 0 \\ P_\ell &\neq 0 \end{aligned}$$

$G_E{}^p$: Electric FF of the Proton

Calculate $d\sigma/d\Omega$ using spin-projection operators $\mathcal{P}$

$$\frac{d\sigma}{d\Omega}(E_e, \theta_e, \pm, \pm\hat{\ell}) = \sum_{spins} |M|^2 \mathcal{P}_{(\vec{S}_e = \pm\frac{1}{2}\hat{k}_e)} \mathcal{P}_{(\vec{S}_p = \pm\frac{1}{2}\hat{\ell})}$$

For a 100% polarization electron beam, proton polarization in longitudinal direction $\hat{\ell}$ becomes

$$P_t = [\tfrac{d\sigma}{d\Omega}(E_e, \theta_e, +, +\hat{t}) - \tfrac{d\sigma}{d\Omega}(E, \theta, +, -\hat{t}]/[''sum'']$$

$$= [\tfrac{d\sigma}{d\Omega}(E_e, \theta_e, +, +\hat{t}) - \tfrac{d\sigma}{d\Omega}(E, \theta, -, +\hat{t}]/[''sum'']$$

$$= -2\sqrt{\tau(1+\tau)} G_E G_M tan\tfrac{\theta}{2} / I_0$$

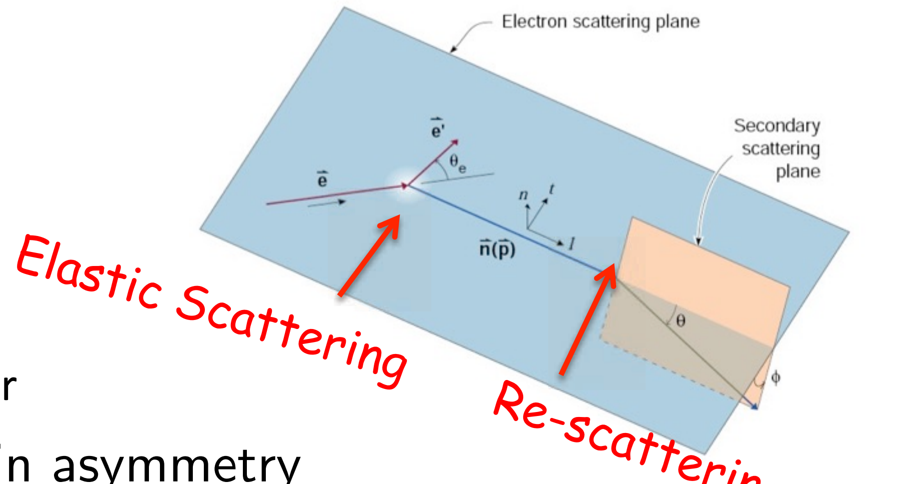
where $I_0 = G_E^2 + \frac{\tau}{E} GM^2.$

Similarly $P_\ell = \frac{E_e + E_e'}{M}\sqrt{\tau(1+\tau)} G_M^2 tan^2\frac{\theta}{2} / I_0$

thus $\frac{G_E}{G_M} = -\frac{P_t}{P_l}\frac{E_e + E_e'}{M} tan\frac{\theta}{2}$

G_E^p: Electric FF of the Proton

Recoil Polarimeter

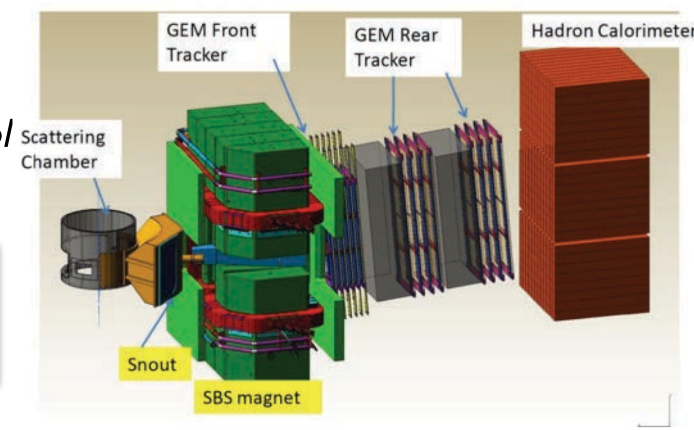


Protons re-scatter in CH_2 at back spectrometer

Analyzing power comes from single-spin asymmetry

$$
\begin{aligned}
\text{Let} \quad \vec{n}' &= \vec{p} \times \vec{p}' / |\vec{p} \times \vec{p}'| \text{ (normal to re-scattering plane)} \\
\text{and} \quad \vec{P}^{pol} &= \text{ proton polarization at the polarimeter} \\
\text{Then} \quad \vec{P}_p^{pol} \cdot \hat{n}' &= (P_t^{pol} \hat{t} + P_n^{pol} \vec{n}) \cdot \hat{n}' \\
&= P_t^{pol} sin\phi - P_n^{pol} cos\phi
\end{aligned}
$$

Helicity-dependent asymmetry determines P_t^{pol} and P_n^{pol}



$$
A(\theta, \phi) = P_e A_n(\theta)(P_t^{pol} sin\phi - P_n^{pol} cos\phi)
$$

G_E^p: Electric FF of the Proton

Polarimeter measures P_t^{pol} and P_n^{pol}

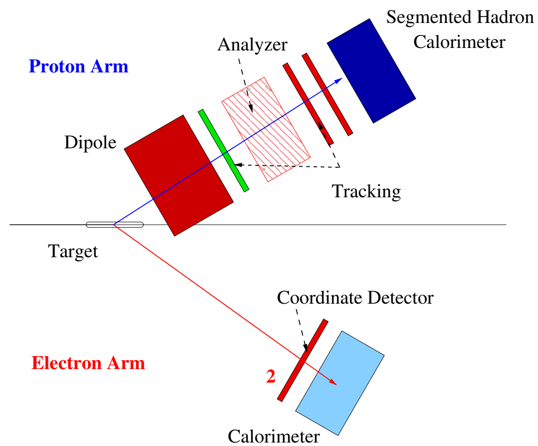
We need P_t and P_ℓ

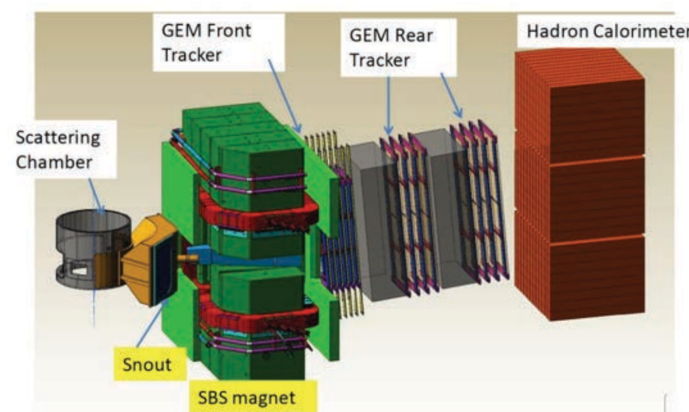
Spectrometer field precesses spin about B

Spin precession

$$\frac{P_t}{P_\ell} = \frac{P_t^{pol}}{P_n^{pol}} sin(\gamma_p(\mu_p - 1)\Delta\theta) + \gamma_p(\mu_p - 1)\Delta\phi$$

$$\frac{G_E}{G_M} = -\frac{E_e + E'_e}{M} tan^2\frac{\theta}{2}\left(\frac{P_t^{pol}}{P_n^{pol}} sin(\gamma_p(\mu_p - 1)\Delta\theta) + \gamma_p(\mu_p - 1)\Delta\phi\right)$$





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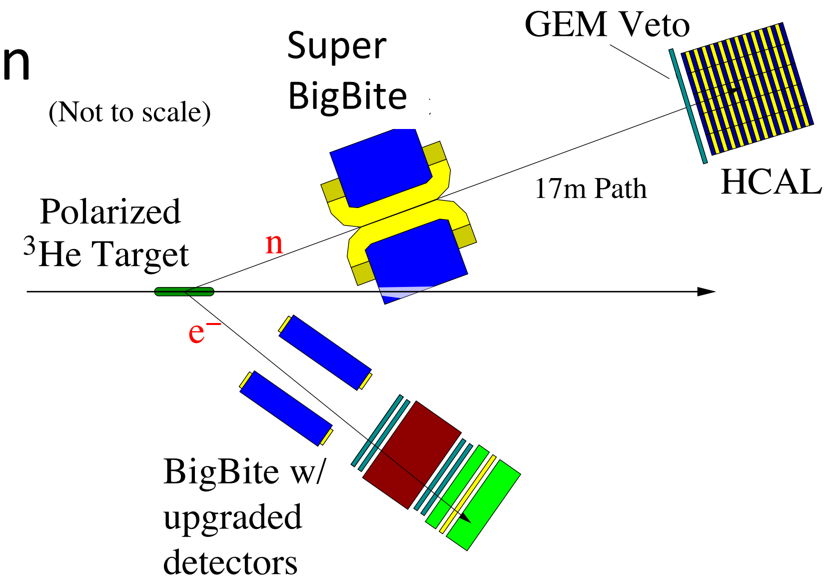
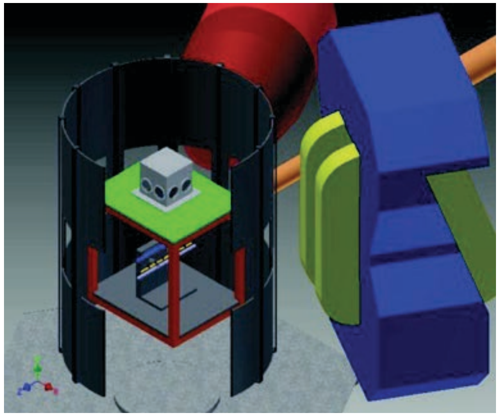
G_E^n: Electric FF of the Neutron $\vec{n}(\vec{e}, e'n)pn$

Measures $G_E(Q^2)/G_M(Q^2)$ for neutron

- Q^2 up to 10.5 GeV^2
- Polarized ^3He target
- SBS serves as p/n separator
- Upgraded BigBite with improved π^- rejection





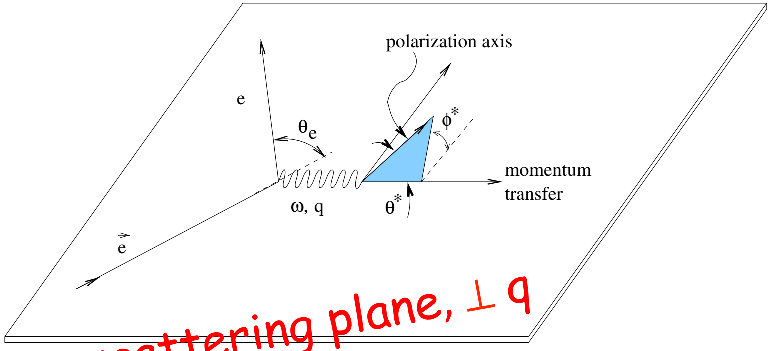
G_E^n: Electric FF of the Neutron

$\vec{n}(\vec{e},e'n)pn$

For target polarization $\vec{P}$, beam helicity asymmetry is:

$$A = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E G_M}{(G_E)^2+(G_M)^2(\tau+2\tau(1+\tau)\tan^2(\theta/2))}\vec{P}\cdot\hat{t} -$$

$$\frac{2\tau\sqrt{1+\tau+(1+\tau)^2 tan^2(\theta/2)}tan(\theta/2)(G_M^n)^2}{(G_E)^2+(G_M)^2(\tau+2\tau(1+\tau)\tan^2(\theta/2))}\vec{P}\cdot\hat{q}$$



With target polarization P along $\hat{t}$ ← In scattering plane, ⊥ q

$$A_\perp = -\frac{2\sqrt{\tau(\tau+1)}\tan(\theta/2)G_E/G_M}{(G_E/G_M)^2+(\tau+2\tau(1+\tau)\tan^2(\theta/2))} P$$

The SuperBigbite Spectrometer Project

First suite of SBS experiments

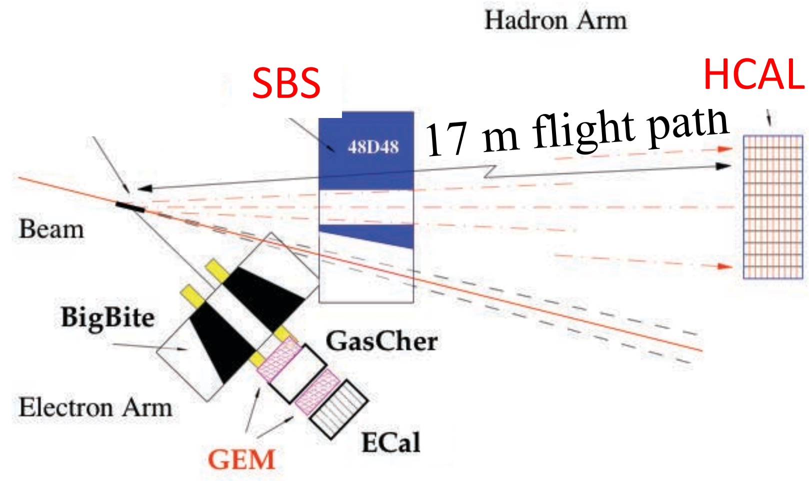
The Form Factor Measurements

	Max Q^2 (GeV^2/c^2)	Reaction
G_E^p	14.5	Proton Electric FF $p(\vec{e}, e'\vec{p})$
G_E^n	10.5	Neutron Electric FF $\vec{n}(\vec{e}, e'n)pn$
G_M^n	13.5	Neutron Magnetic FF $d(e, e'n)p$ and $d(e, e'p)n$
SIDIS	9.0	Semi-Inclusive single-spin asymmetry $\vec{n}(\vec{e}, e'x)$ where $x=\pi^+, \pi^-, K^+, K^-$
A_1^n	8.0	Neutron Spin A_{1n} in valence region $\vec{n}(\vec{e}, e)X$
TDIS	3	Tagged Deep Inelastic Scattering Meson component of the nucleon $p(e, e'n)X$ and $d(e, e'pp)X$

G_M^n: Magnetic FF of the Neutron $d(e,e'n)p$ and $d(e,e'p)n$

Measures $G_{M\text{-neutron}}(Q^2)/G_{M\text{-proton}}(Q^2)$

- Q^2 up to 13.5 GeV^2
- Deuteron target
- SBS serves as p/n separator



$$R'' = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'n)}}{\left(\frac{d\sigma}{d\Omega}\right)_{d(e,e'p)}} \xrightarrow[\text{corr.}]{\text{nucl.}} \frac{\left(\frac{d\sigma}{d\Omega}\right)_{n(e,e')}}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}} \xrightarrow[1\gamma]{} \frac{\eta\frac{\sigma_{\text{Mott}}}{1+\tau}\left(\left(G_E^n\right)^2+\frac{\tau}{\varepsilon}\left(G_M^n\right)^2\right)}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}$$

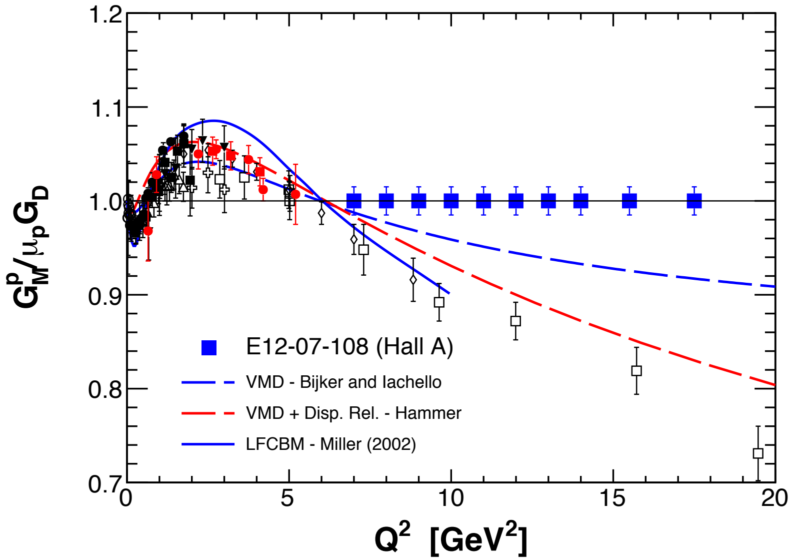
$$\xrightarrow[\text{Electric}]{\text{neutron}} \quad \boxed{R = \frac{\eta\sigma_{\text{Mott}}\frac{\tau/\varepsilon}{1+\tau}\left(G_M^n\right)^2}{\left(\frac{d\sigma}{d\Omega}\right)_{p(e,e')}}}$$

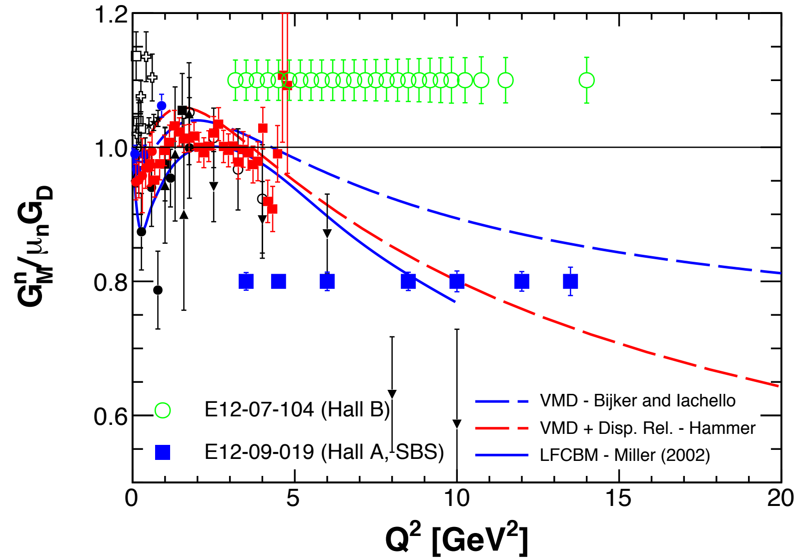
The 4 Form Factor Measurements

Proton

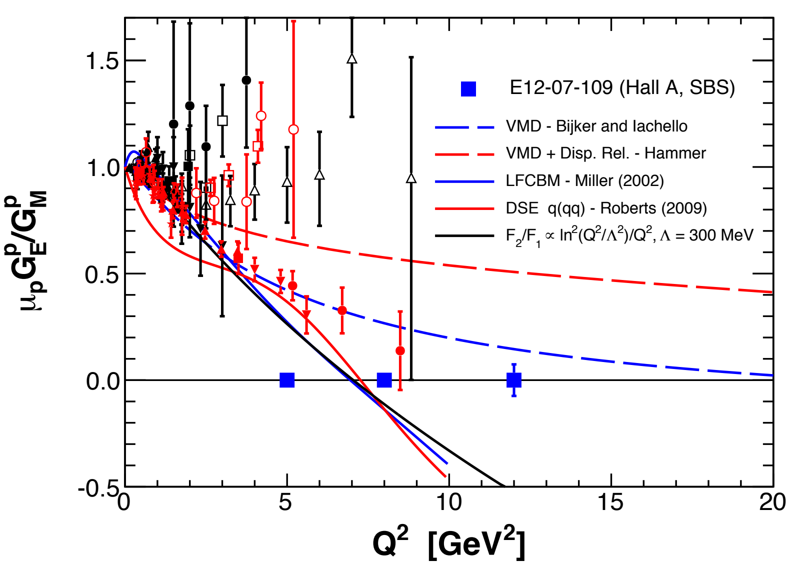
Neutron

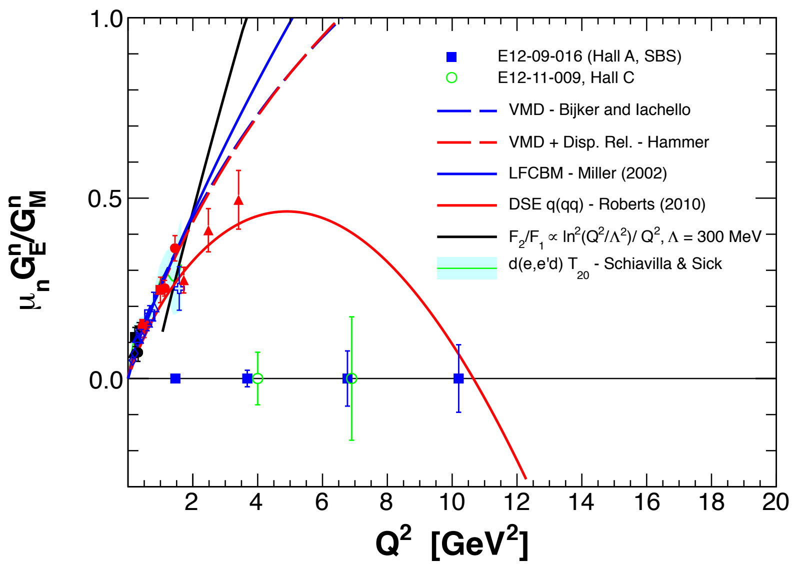
G_M





G_E





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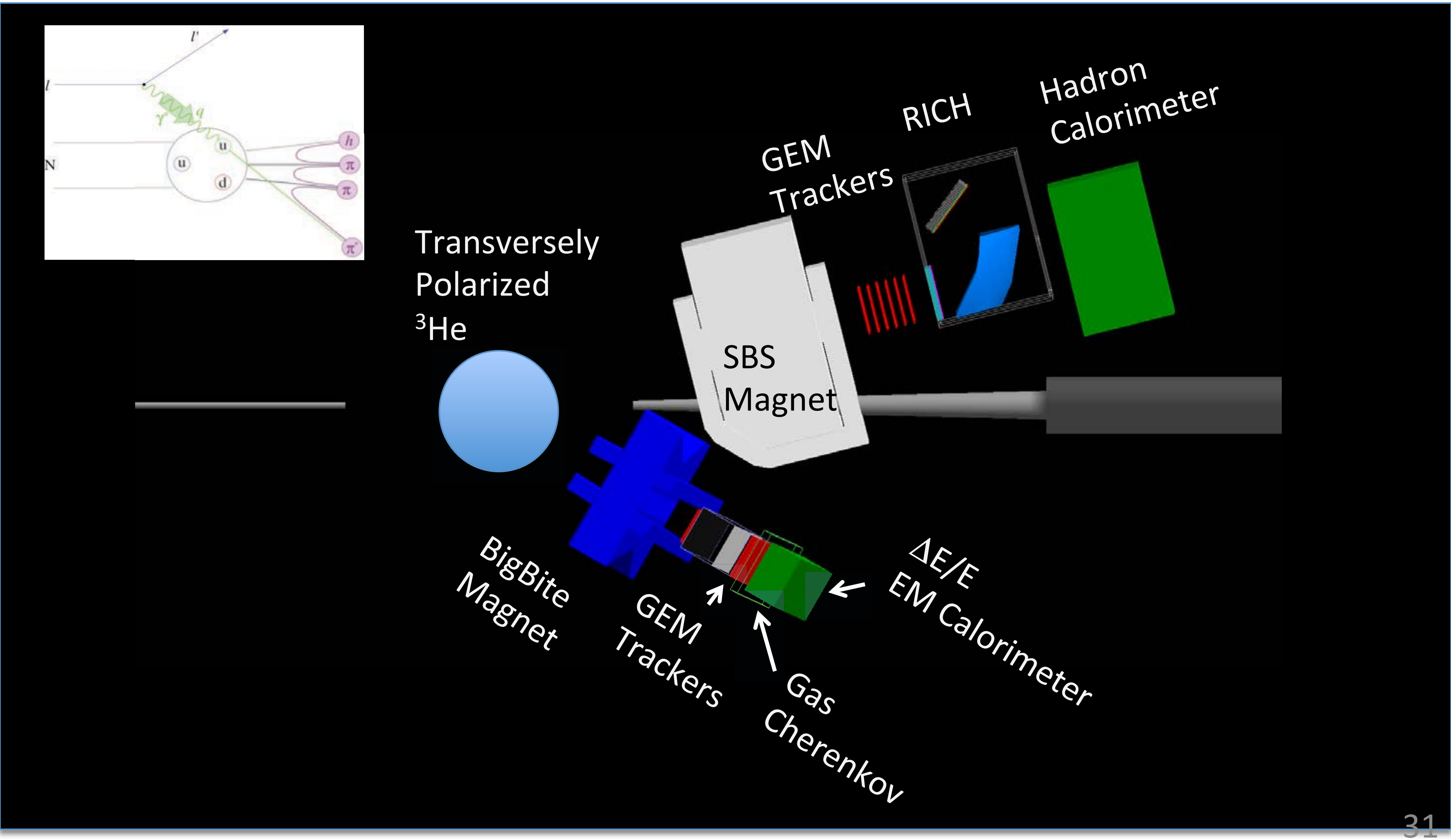
The Deep Inelastic Measurements

SIDIS: Semi-Inclusive Deep Inelastic Scattering

Single-spin Asymmetries *
*mostly

$\vec{n}(\vec{e}, e'x)$ where x=π^+, π^-, K^+, K^-



SIDIS: Transverse Momentum Distributions (TMDs)

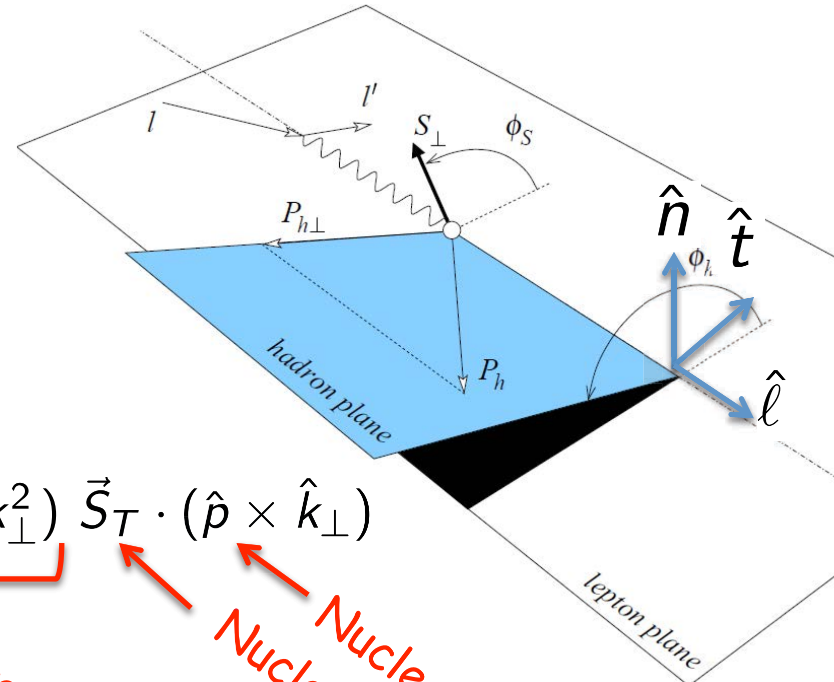
Sivers Distribution

$\vec{k}_\perp$: Struck quark transverse momentum

$f_{q/p}(x, \vec{k}_\perp)$: Transverse Momentum Distribution (TMD)

Can $f_{q/p}(x, \vec{k}_\perp)$ depend on $\vec{k}_\perp$ direction?

Yes, if nucleon is polarized



$$f_{q/p\uparrow}(x, \vec{k}_\perp) = f_{q/p}(x, k_\perp^2) + \frac{1}{2} \triangle^N_{f_{q/S_T}}(x, k_\perp^2)\ \vec{S}_T \cdot (\hat{p} \times \hat{k}_\perp)$$

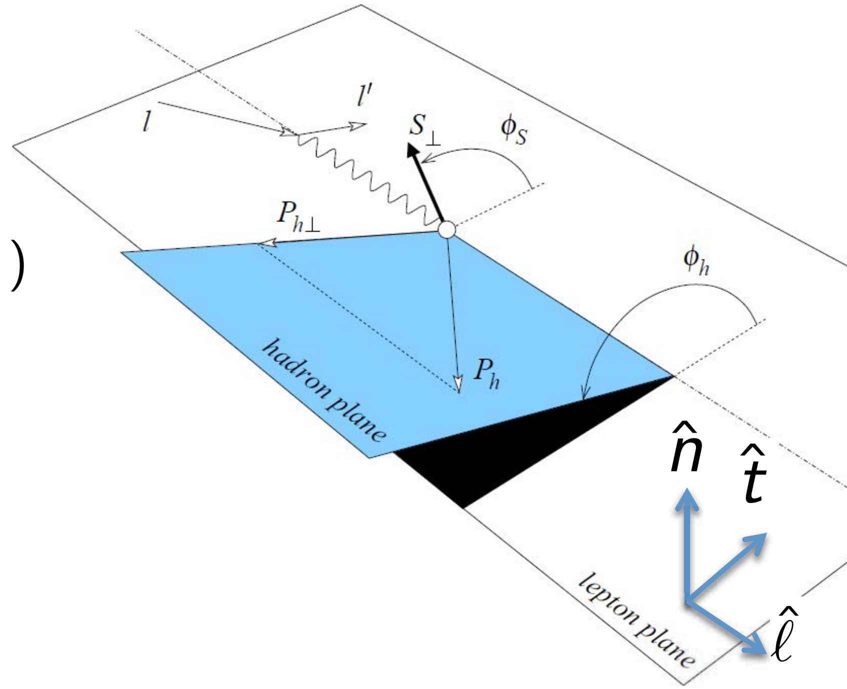
Unpolarized TMD

Sivers Distribution Function

Nucleon trans. spin direction

Nucleon momentum

SIDIS: TMDs and Sivers Effect



$$\hat{p} = -\hat{\ell} = \text{proton momentum direction}$$
$$\hat{S_T} = \text{Target Polarization Direction } (\perp \text{ to } \vec{p}\ )$$
$$\hat{k_\perp} = \text{Struck quark } \perp \text{ momentum direction}$$

asimuthal angles

ϕ_S	:	target polarization
ϕ_h	:	detected hadron
ϕ	:	struck quark

$$\hat{S}_T \cdot (\hat{p} \times \hat{k_\perp}) = (cos\phi_S \hat{t} + sin\phi_S \hat{n}) \cdot (-\hat{\ell} \times (cos\phi \hat{t} + sin\phi \hat{n})$$
$$= sin\phi_h cos\phi_S - cos\phi sin\phi_s$$
$$= sin(\phi - \phi_S)$$

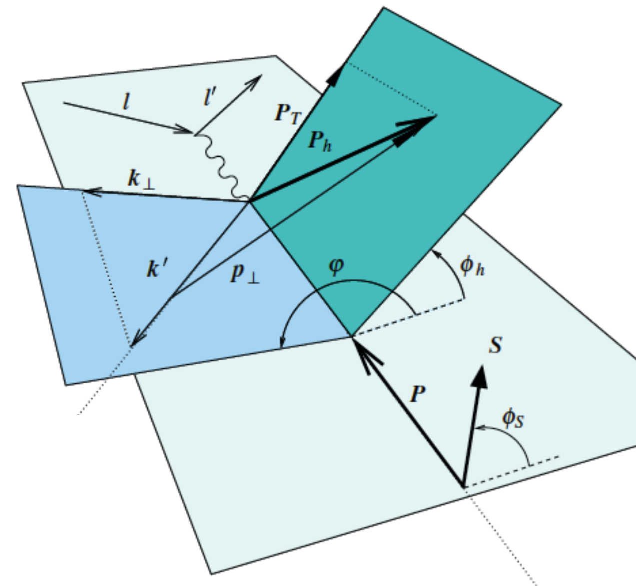
SIDIS: TDMs and Sivers Effect

Integrate over $\int \vec{k}_\perp^2$

$\hat{S}_T \cdot (\hat{p} \times \hat{k}_\perp) = sin(\phi - \phi_S) \rightarrow$ 0 ?

But ϕ symmetry broken if hadron detected

Target polarization asymmetry related to:



$$\triangle_{Sivers}(\phi_S, \phi_h) = d\sigma_{Sivers}(\vec{S}_T, \phi_h) - d\sigma_{Sivers}(-\vec{S}_T, \phi_h)$$
$$= \sum_q \int d^2\vec{k}_\perp \triangle^N_{f_{q/S_T}}(x, k_\perp^2) \sin(\phi - \phi_S) \frac{d\hat{\sigma}}{dQ^2} D^h_q(z, \vec{p}_\perp)$$

Sivers Function

Electron-q scattering

Fragmentation Function

Detected hadron wrt fragmenting quark

$\vec{p}_\perp = \vec{P}_T - z\vec{k}_\perp$

SIDIS Sivers Effect

$$\Sigma(\phi_S,\phi_h) = d\sigma(\vec{S}_T,\phi_h) + d\sigma(-\vec{S}_T,\phi_h)$$
$$= 2\sum_q \int d^2\vec{k}_\perp f_{q/p}(x,\vec{k}_\perp)\frac{d\hat{\sigma}}{dQ^2}D_q^h(z,\vec{p}_\perp)$$

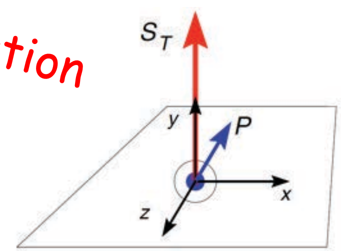
Sivers Asymmetry

$$A_{UT}^{sin(\phi_h-\phi_S)} = 2\frac{\int d\phi_S d\phi_h sin(\phi_h-\phi_S)\triangle(\phi_S,\phi_h)}{\int d\phi_S d\phi_h \Sigma(\phi_S,\phi_h)}$$

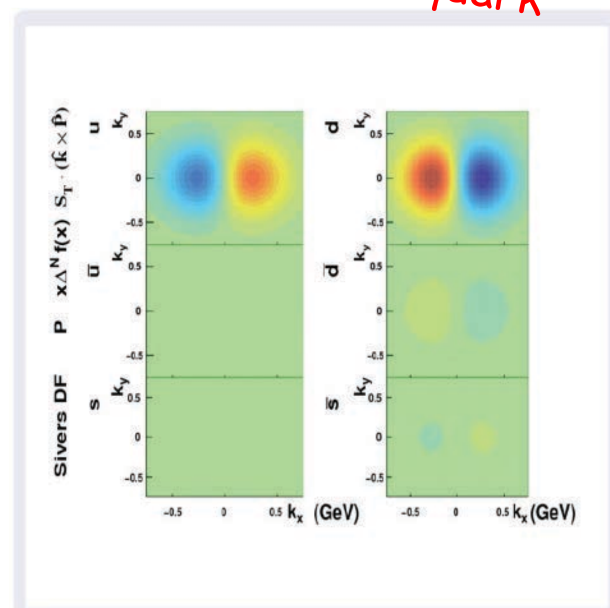
Extracts $\triangle^N_{f_{q/S_T}}(x,k_\perp^2)\otimes D_q^h(z,\vec{p}_\perp)$

Sivers Correlation between (unpolarized} quark transverse momentum and nucleon spin direction

Fragmentation correlation between detected hadron and struck quark momentum



A. Prokudin

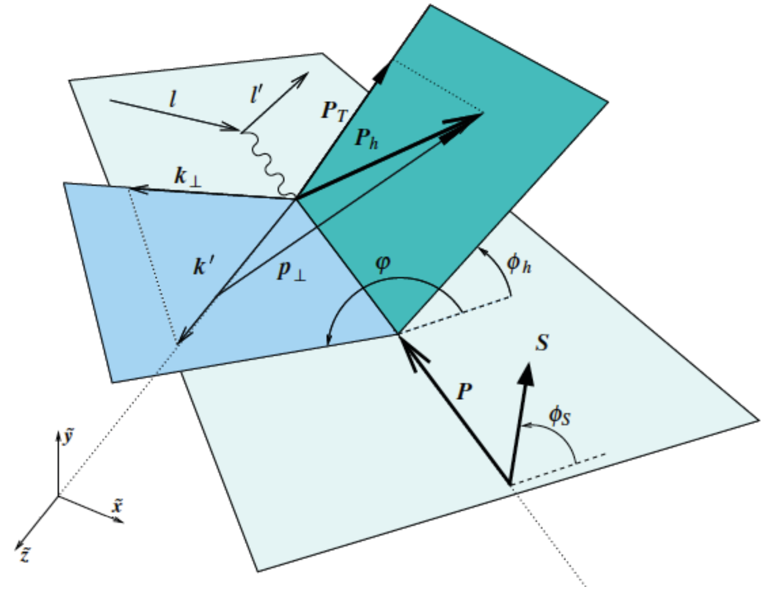


• Sivers effect: a left-right asymmetry in the transverse momentum distribution of unpolarized quarks in a transversely polarized nucleon

SIDIS: Collins Effect

Fragmentation Function
correlation with quark spin:

$$\vec{S}_q \cdot (\vec{k'} \times \vec{p}_\perp)$$



$\vec{S}_q$: spin of fragmenting quark
$\vec{k'}$: momentum of fragmenting quark
$\vec{p}_\perp$: $\perp$ component of $\vec{P}_{hadron}$ wrt fragmenting quark

Anseimino, et al.
Phys. Rev D75 (2007)

$$\begin{aligned}\triangle_{Col}(\phi_S,\phi_h) &= d\sigma_{Col}(\vec{S}_T,\phi_h) - d\sigma_{Col}(-\vec{S}_T,\phi_h)\\ &= \sum_q e_q^2 \int d^2\vec{k}_\perp \triangle_{qT}(x,k_\perp^2) sin(\phi+\phi_S+\phi_q^h)\frac{d\Delta\hat{\sigma}}{dQ^2}\\ &\quad \cdot \triangle^N_{D_{h/q\uparrow}}(z,\vec{p}_\perp)\end{aligned}$$

SIDIS: Collins Effect

$$A_{UT}^{sin(\phi_h+\phi_S)} = 2\frac{\int d\phi_S d\phi_h sin(\phi_h+\phi_S) \triangle (\phi_S,\phi_h)}{\int d\phi_S d\phi_h \Sigma(\phi_S,\phi_h)}$$

Extracts $\triangle_{qT}(x,k_\perp^2) \otimes \triangle^N_{D_{h/q\uparrow}}(z,\vec{p}_\perp)$

$\triangle_{qT}(x,k_\perp^2)$ Is related to the *transversity* distribution

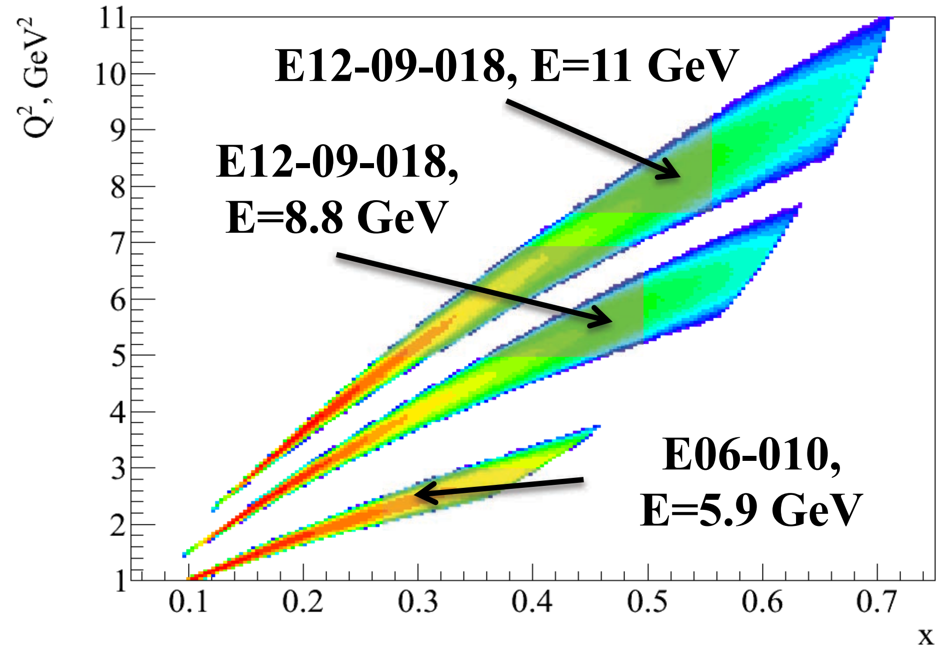
$$h(x) = \int d^2\vec{k}_\perp \triangle_{qT}(x,k_\perp^2)$$

SIDIS: Kinematic Coverage

E12-09-018

- 4×10^{36} cm^{-2}s^{-1} luminosity
- 60% ^{3}He target polarization
- ~85% electron polarization

- 40 days E_{beam} = 11 GeV
- 20 days E_{beam} = 8.8 GeV
- 4 days calibrations, etc.



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The Deep Inelastic Measurements

A_1^n $\vec{n}(\vec{e}, e)X$

- Double-Spin Asymmetry
- Longitudinally polarized target and beam
- Measures contribution of quark-spin to neutron's spin

$$A_1(x,Q^2) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} \approx \frac{g_1(x,Q^2)}{F_1(x,Q^2)} \quad \text{at high } Q^2$$

For longitudinally polarized virtual photons to be absorbed on quark, quark and "photon" spins must be anti-parallel.

A_1^n $\vec{n}(\vec{e}, e)X$

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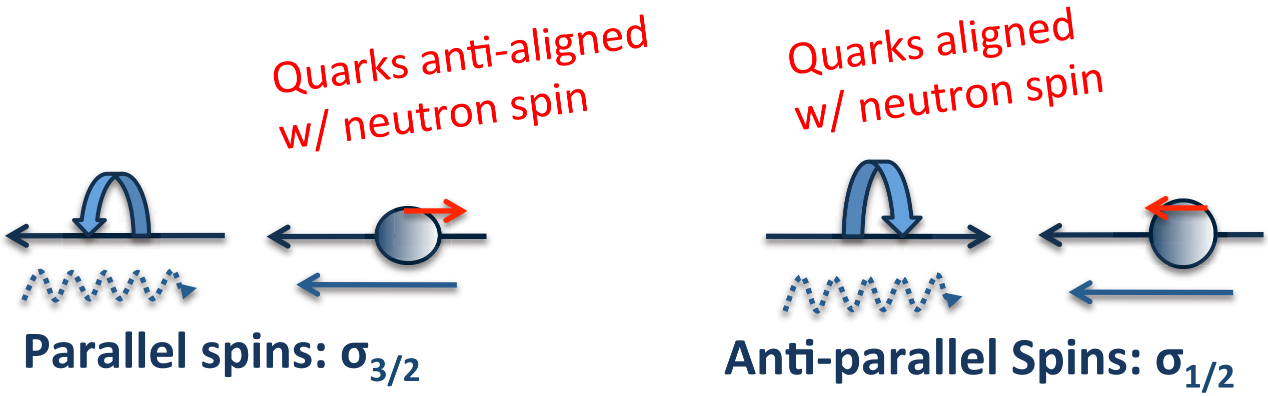

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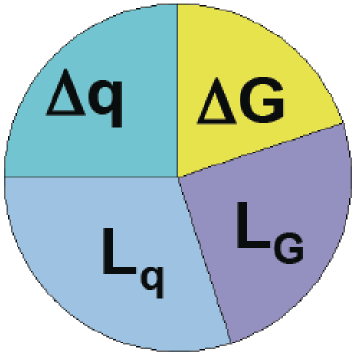
For longitudinally polarized virtual photons to be absorbed on quark, quark and "photon" spins must be anti-parallel.

Proton Spin Crisis/Puzzle

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



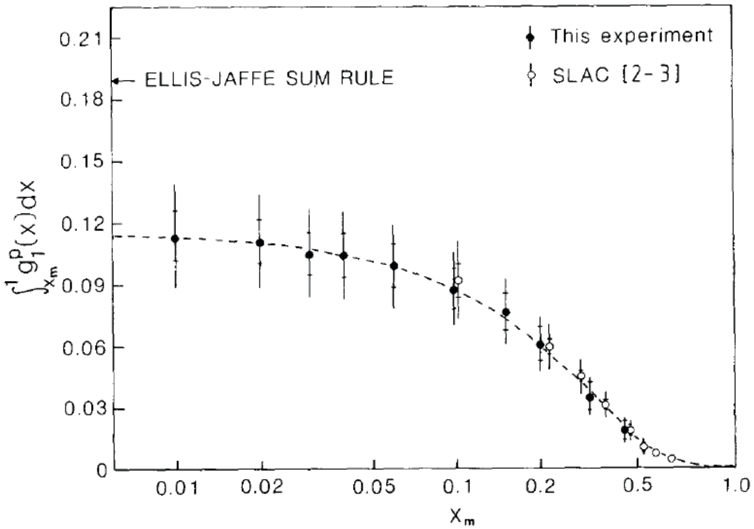


Fig. 13. The convergence of the integral $\int_{x_m}^1 g_1^p\,dx$ as a function of x_m, where x_m is the value of x at the low edge of each bin.

$$\begin{aligned}\Delta\Sigma &= \int_0^1 dx\left[\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right] \\ &= +0.12 \pm 0.094 \pm 0.138 \text{ (EMC)}\end{aligned}$$

“Crisis”: EMC collaboration, NPB 328, 1 (1989)

A_1^n

More precisely…

- The theory:

$$A_1^n(x, Q^2) = \frac{g_1(x, Q^2) - (Q^2/\nu^2)g_2(x, Q^2)}{F_1(x, Q^2)} \rightarrow \frac{g_1(x, Q^2)}{F_1(x, Q^2)}$$

- The measurement:
  - We have longitudinally polarized *electrons*, not virtual *photons*
  - Need two measurements to subtract out contribution of transverse component, ε.

$$A_1^n(x, Q^2) = \frac{1}{D(1+\eta\xi)} A_{=} - \frac{1}{d(1+\eta\xi)} A_{\perp}$$

Extracted A_1^n

Longitudinally polarize target data

Transversely polarize target data

where

$$\epsilon = 1/[1 + 2(1 + Q^2/\nu^2)tan^2(\theta/2)]$$

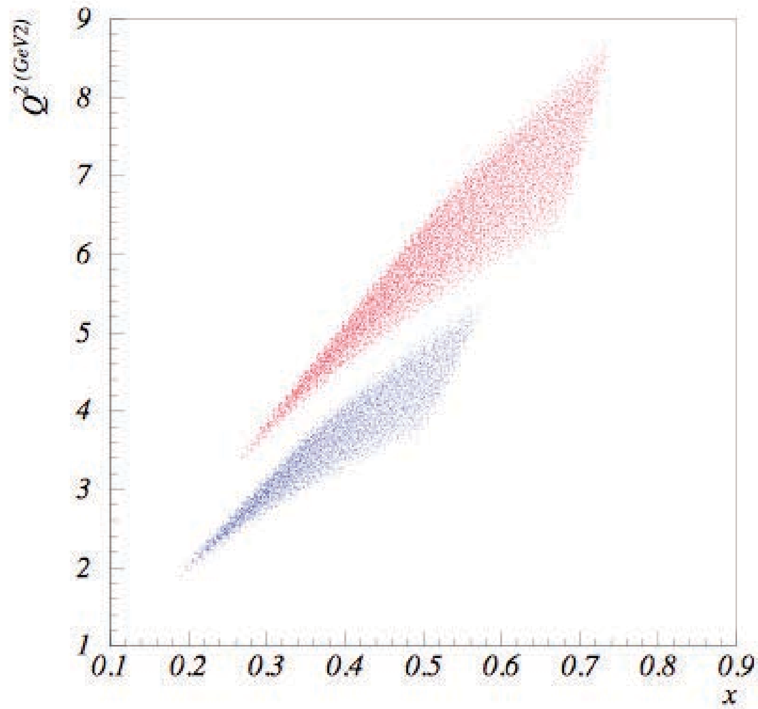
D, d *and* η kinematic variables

R also a function of F_1/F_2

A_1^n

Kinematic coverage for approved A_1^n

(BigBite spectrometer)



8.8 GeV and 6.6 GeV running
(W^2>4 GeV^2 cut applied)

Updated SBS-based proposal under development

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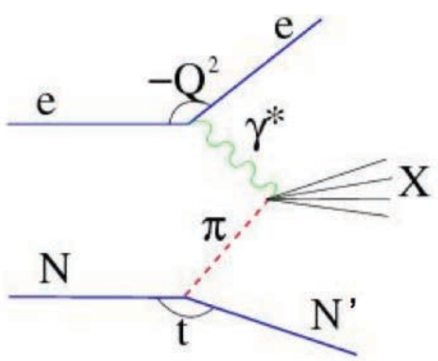
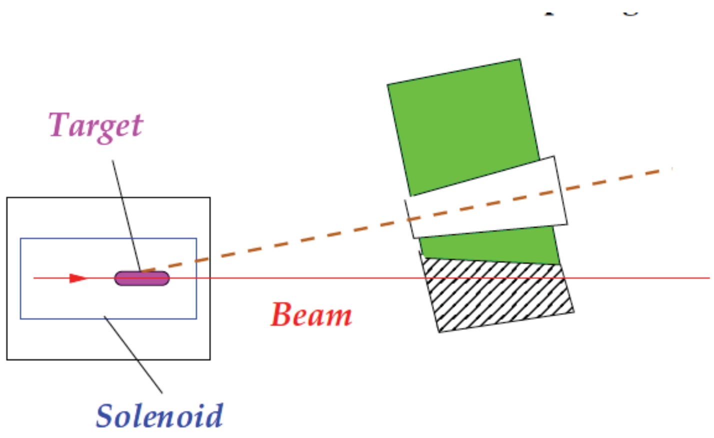
The Deep Inelastic Measurements

TIDIS. Tagged Deep Inelastic Scattering

$p(e,e'n)X$ and $d(e,e'pp)X$

π Structure Function via Sullivan Process



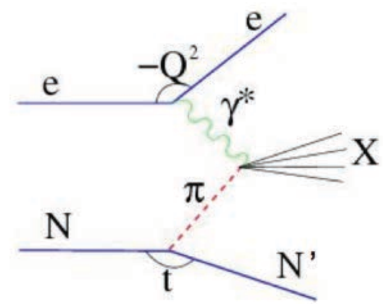


$$
\begin{aligned}
k_\perp &: \text{ transverse momentum of } \pi \\
z &: \text{ fraction of nucleon momentum carried by } \pi \\
x' &: \text{ fraction of } \pi \text{ momentum carried by parton} \\
x &= zx' \\
F_{\pi N}(x, z, k_\perp) &= f_{\pi/N}(z, k_\perp) F_{2\pi}\left(\frac{x}{z}\right)
\end{aligned}
$$

TIDIS. Tagged Deep Inelastic Scattering

$$p(e, e'n)X \text{ and } d(e, e'pp)X$$

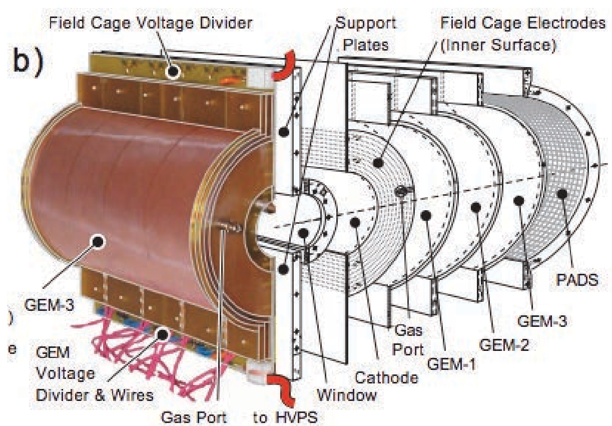
Soft nucleons detected in RTPC
Tags "pions"

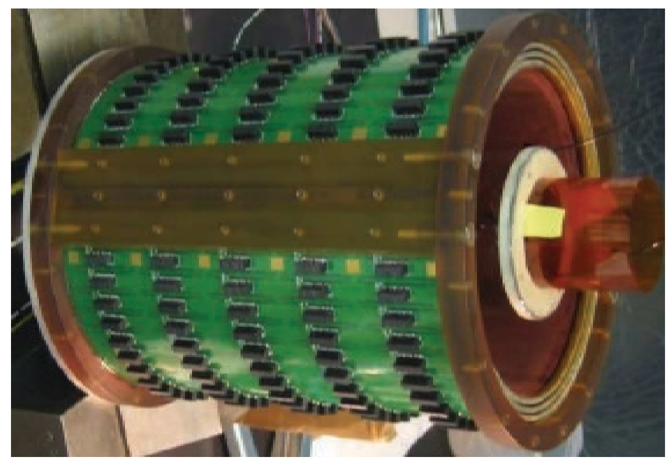


$8 < W^2 < 18$ GeV^2

$1 < Q^2 < 3$ GeV^2

$0.5 < x < 0.2$





BONUS Radial Time Projection Chamber

SBS Further into the Future

- Double DVCS
- Double Polarized Wide Angle Compton Scattering
- A_1^n /d_2^n
- A_1^p /d_2^p
- D(e,e'd)
- Parity-violating DIS
- J/Psi as gluon probe of QCD
- J/Psi production
- T/^{3}He(e,e')
- RCS

Conclusion

- SBS Project Completion July 2017
- SBS Program Starts 2018 ?

- Backup

Nucleon Form Factor Measurements

Kinematics Example: θ= 40°

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{d\sigma}{d\Omega}(E,\theta)_{\mathrm{M}} \frac{E'}{E}\frac{1}{1+\tau}\left[G_E^2 + G_M^2[0.31\frac{Q^2}{M^2} + 0.016\frac{Q^4}{M^4}]\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2}{4E^2 sin^4\theta/2} cos^2\frac{\theta}{2} = 16\frac{\alpha^2}{E^2}$$

$$E' = E/(1+2\frac{E}{M}sin^2\frac{\theta}{2}) = E/(1+0.23\frac{E}{M})$$

Recoil Energy significant at E=10 GeV

$$Q^2 = 4EE' sin^2\frac{\theta}{2} = 0.48E^2/(1+0.23\frac{E}{M})$$