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Form Factor Results from BLAST *

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Introduction

Bates Large Acceptance Spectrometer Toroid

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Bates Large Acceptance Spectrometer Toroid

- Symmetric, large acceptance, general purpose detector
  Detection of $e^{\pm}$, $\pi^{\pm}$, p, d, n

- Longitudinally polarized electrons in storage ring (SHR)
  850 MeV, 200 mA, P_e = 65% (longitudinal)

- Highly polarized internal gas target of pure H and D (ABS)
  6×10^{13} atoms/cm^2, $L = 6 \times 10^{31}/(cm^2 s)$, $P_{H/D}$ = 80%

Overview

- Motivation:
  Electromagnetic structure of nucleons and light nuclei
  with **spin-dependent electron scattering**
  from internal polarized targets **at low Q^2**

- Experimental Setup:
  The **BLAST** experiment at **MIT-Bates**

- Preliminary Results:
  Nucleon: Elastic form factors of the proton and neutron
  Deuteron: Charge, quadrupole, and magnetic form factors

BLAST physics program

- Polarized **Hydrogen**

  $\vec{p}(\vec{e},e')x$ $\vec{p}(\vec{e},e'p)$ $\vec{p}(\vec{e},e'p)\gamma,\pi^0$ $\vec{p}(\vec{e},e'\pi^+)n$ $\vec{p}(\vec{\gamma},\pi^+n)$

  Inclusive G^p_E/G^p_M N-Δ: C2/M1 photoprod.

- Vector and Tensor Polarized **Deuterium**

  $\vec{d}(\vec{e},e')$ $\vec{d}(\vec{e},e'd)$ $\vec{d}(\vec{e},e'p)n$ $\vec{d}(\vec{e},e'n)p$ $\vec{d}(\vec{e},e'\pi^{\pm,0})$

  G^n_M T^e_{11}: G^d_M A^V_{ed}: L=2 G^n_E N-Δ

  $\overleftrightarrow{d}(e,e'd)$ $\overleftrightarrow{d}(e,e'p)n$, $\overleftrightarrow{d}(e,e'n)p$ $\overleftrightarrow{d}(\gamma,pn)$

  T_{20}: G^d_Q A^T_d: L=2 photodisint.

BLAST physics program

- Polarized **Hydrogen**

$\vec{p}(\vec{e},e')x$	$\vec{p}(\vec{e},e'p)$	$\vec{p}(\vec{e},e'p)\gamma,\pi^0$	$\vec{p}(\vec{e},e'\pi^+)n$	$\vec{p}(\vec{\gamma},\pi^+n)$
Inclusive	G^p_E/G^p_M	N-Δ: C2/M1		photoprod.

- Vector and Tensor Polarized **Deuterium**

$\vec{d}(\vec{e},e')$	$\vec{d}(\vec{e},e'd)$	$\vec{d}(\vec{e},e'p)n$	$\vec{d}(\vec{e},e'n)p$	$\vec{d}(\vec{e},e'\pi^{\pm,0})$
G^n_M	T^e_{11}: G^d_M	A^V_{ed}: L=2	G^n_E	N-Δ
	$\overleftrightarrow{d}(e,e'd)$	$\overleftrightarrow{d}(e,e'p)n$, $\overleftrightarrow{d}(e,e'n)p$		$\overleftrightarrow{d}(\gamma,pn)$
	T_{20}: G^d_Q	A^T_d: L=2		photodisint.

BLAST physics program

- Polarized **Hydrogen**

$\vec{p}(\vec{e},e')x$	$\vec{p}(\vec{e},e'p)$	$\vec{p}(\vec{e},e'p)\gamma,\pi^0$	$\vec{p}(\vec{e},e'\pi^+)n$	$\vec{p}(\vec{\gamma},\pi^+n)$
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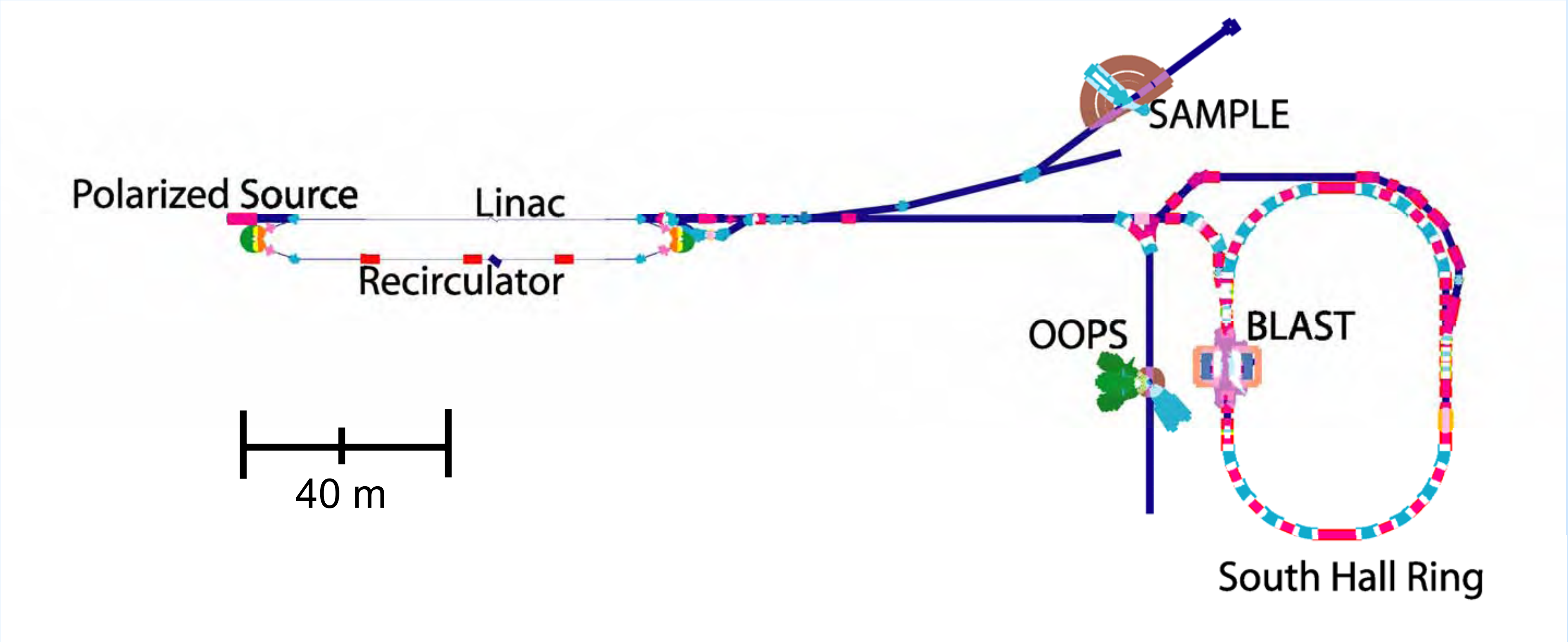
- Vector and Tensor Polarized **Deuterium**

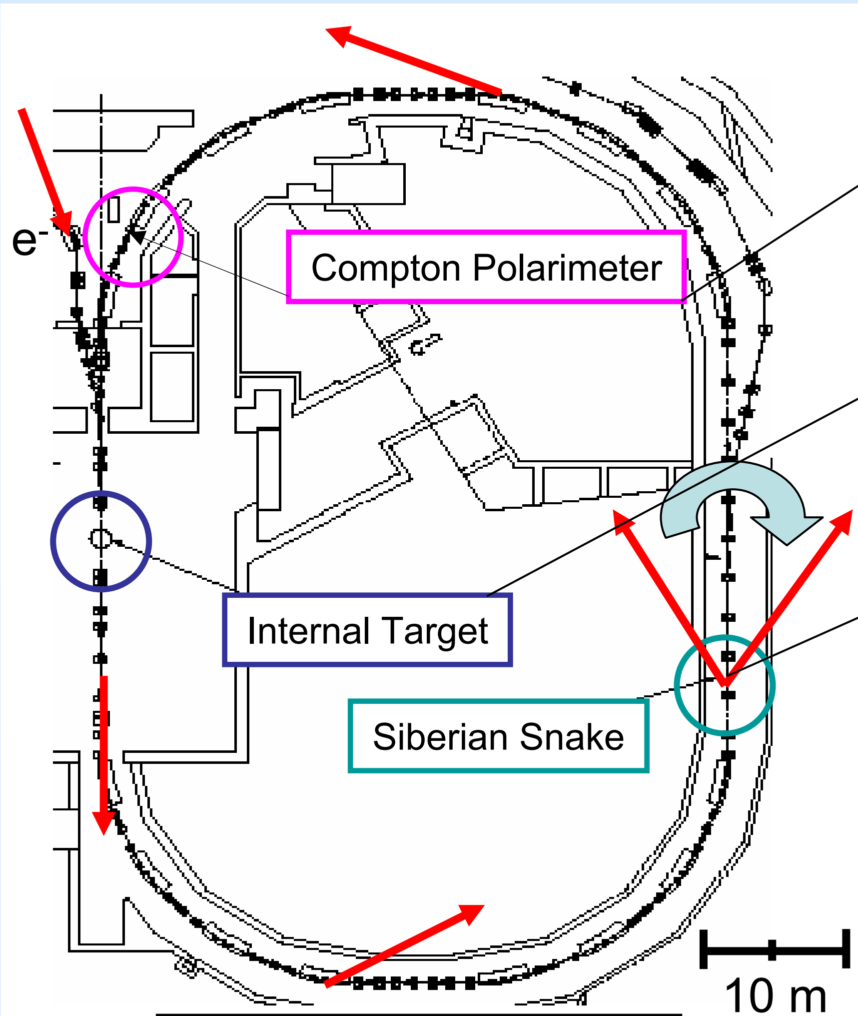
$\vec{d}(\vec{e},e')$	$\vec{d}(\vec{e},e'd)$	$\vec{d}(\vec{e},e'p)n$	$\vec{d}(\vec{e},e'n)p$	$\vec{d}(\vec{e},e'\pi^{\pm,0})$
G^n_M	T^e_{11}: G^d_M	A^V_{ed}: L=2	G^n_E	N-Δ
	$\overleftrightarrow{d}(e,e'd)$	$\overleftrightarrow{d}(e,e'p)n$, $\overleftrightarrow{d}(e,e'n)p$		$\overleftrightarrow{d}(\gamma,pn)$
	T_{20}: G^d_Q	A^T_d: L=2		photodisint.

MIT-Bates Linear Accel. Center



- **Beam:** Stored (SHR) 850 MeV, 200 mA, P_e = 65%
- **Detector:** **B**ates **L**arge **A**cceptance **S**pectrometer **T**oroid
- **Target:** Internal (ABS) $6 \times 10^{31}/(\mathrm{cm}^2\mathrm{s})$, $P_{H/D}$ = 80%

MIT-Bates South Hall Ring

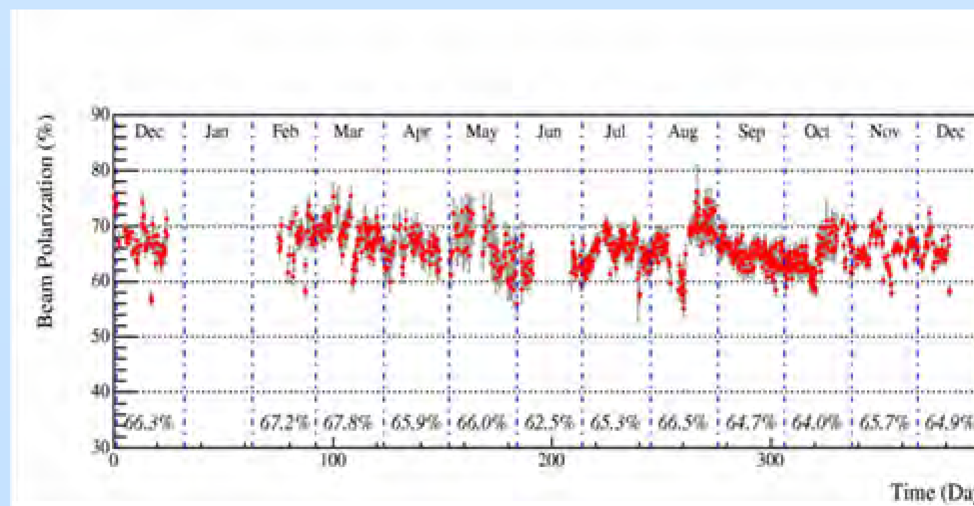


In-plane spin transport

Monitoring of electron beam polarization

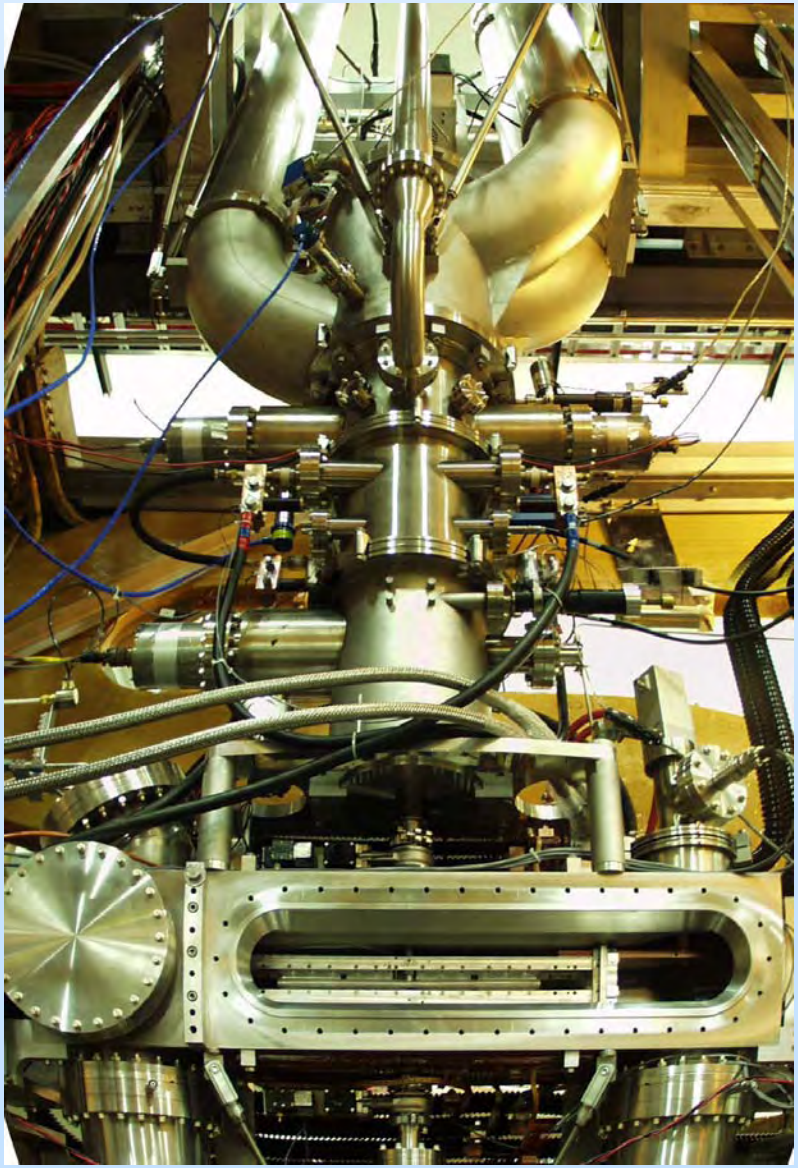
Injection with longitudinal spin at internal target

Siberian snake to restore longitudinal polarization

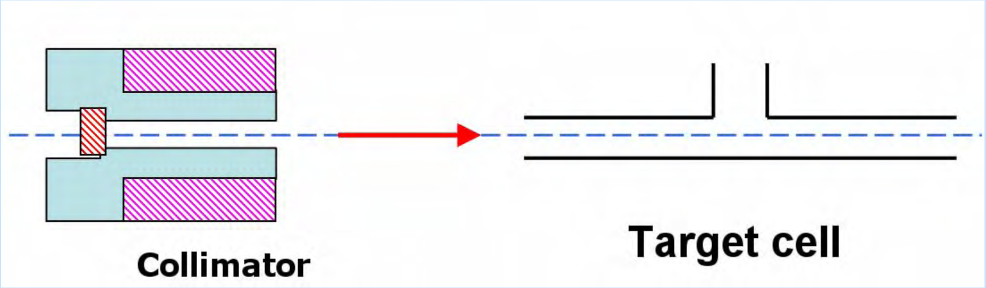


$P_e = 0.65 \pm 0.04$

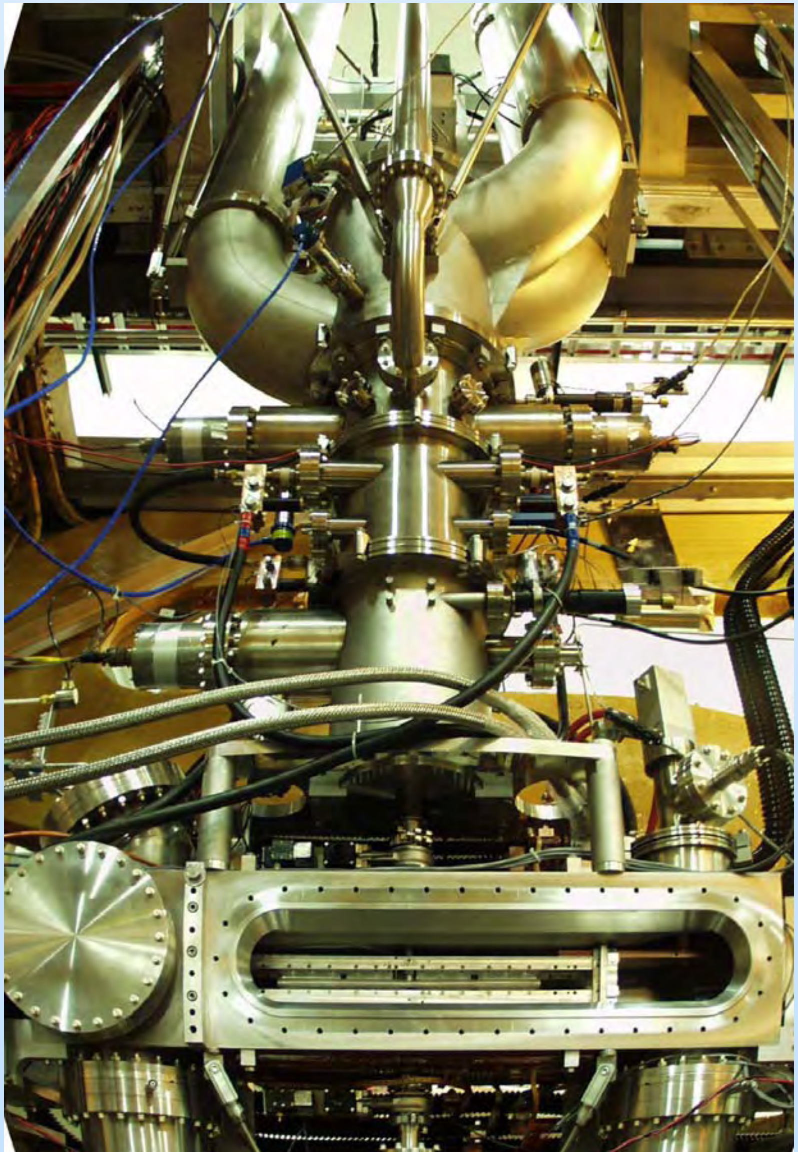
Atomic Beam Source (ABS)

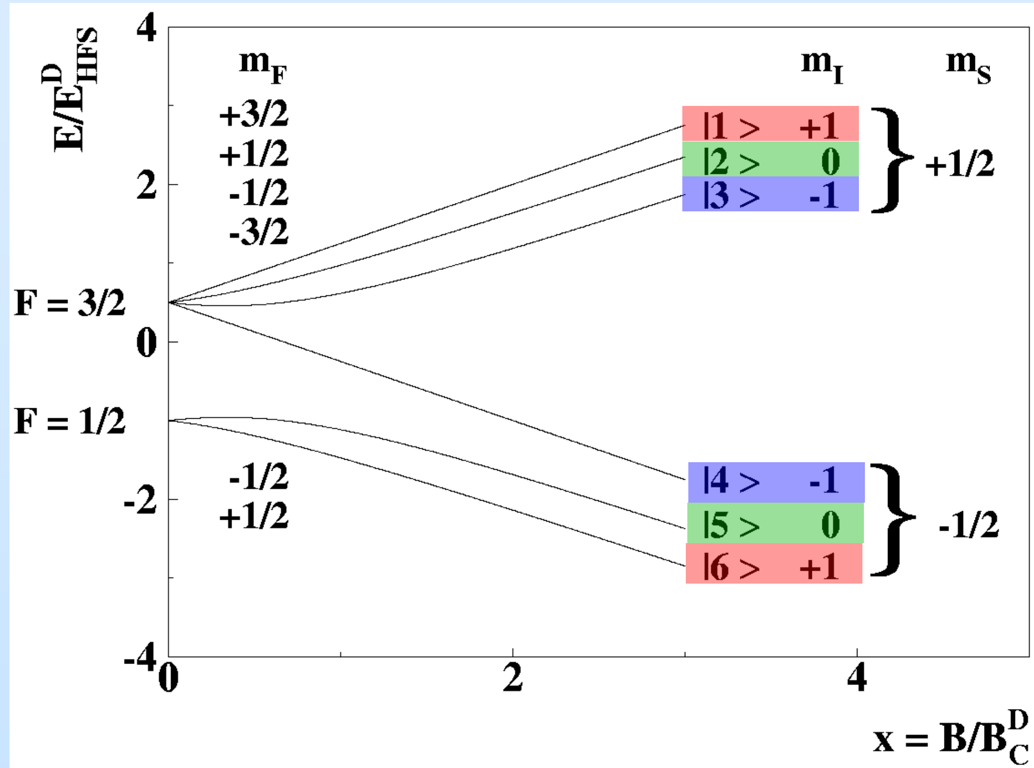


- Isotopically pure H or D atoms
  (Vector-) polarized H
  Vector- and tensor-polarized D
- Target thickness / luminosity
  Flow 2.2×10^{16} atoms/s
  Density 6×10^{13} atoms/cm^2
  Luminosity 6×10^{31} cm^{-2}s^{-1}
- Target polarization 70-80%
  P_z, P_{zz} from low Q^2 analysis



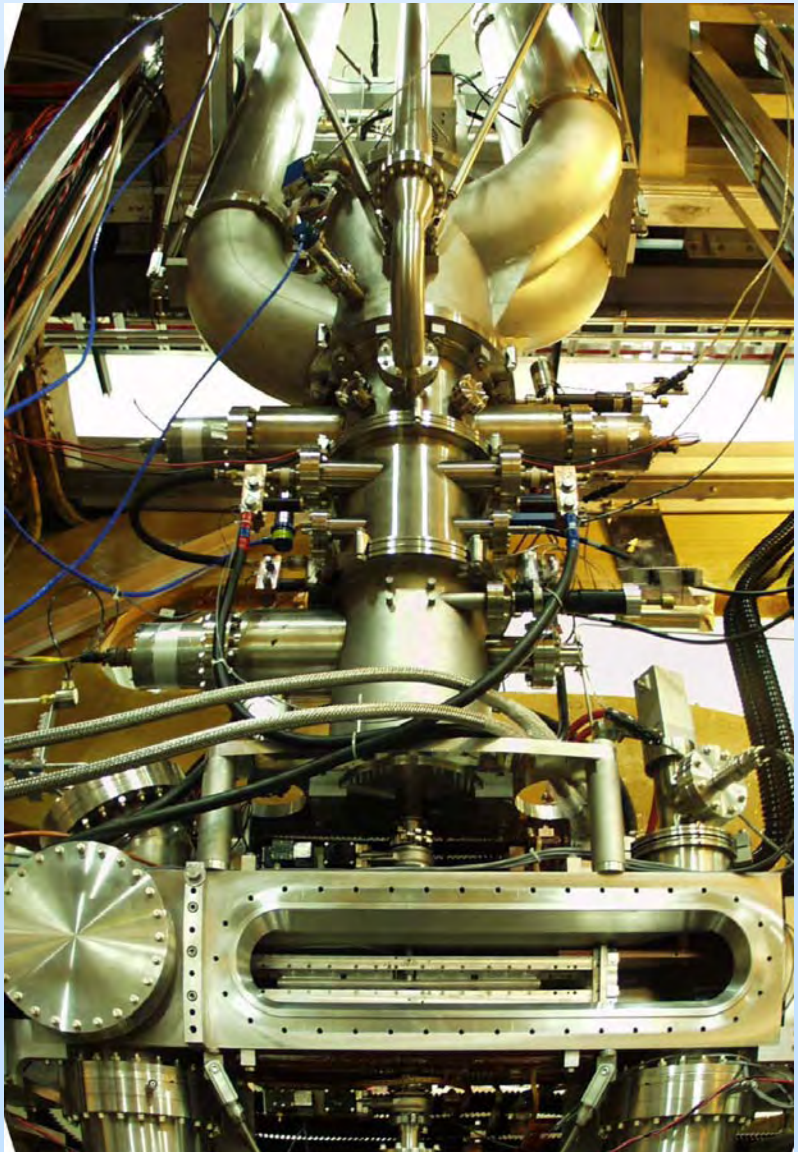
Atomic Beam Source (ABS)





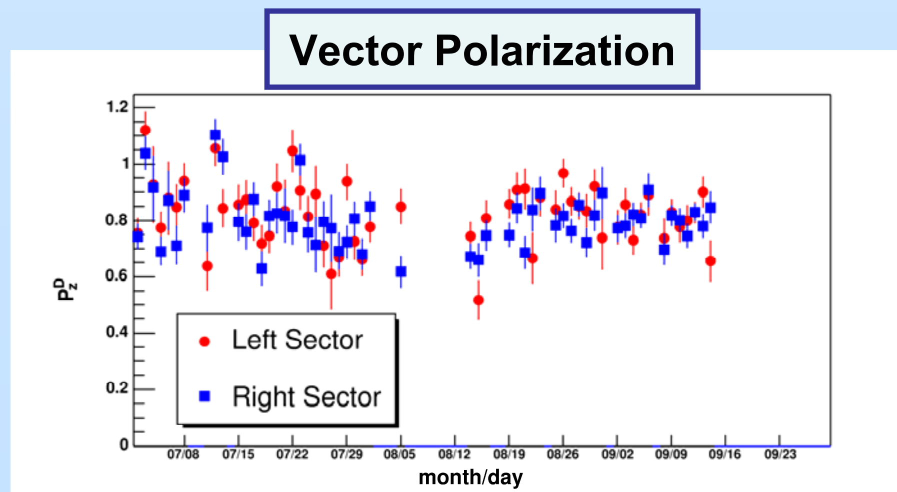
- Separately prepare m_I = **+1**, **0**, **-1** with sextupoles and RF transitions
- Switch between states every 5 minutes

Target Polarization (ABS)



Vector Polarimetry

- Quasielastic $^{2}\vec{H}(\vec{e},e'p)$, elastic $^{1}\vec{H}(\vec{e},e'p)$
- Beam-target vector asymmetry A^{V}_{ed}
- $A^{V}_{ed}(exp) = hP_z\, A^{V}_{ed}$
- $\langle hP_z \rangle$ = **0.558 ± 0.009**
  $\langle h \rangle$ = 0.65 ± 0.4
  $\rightarrow \langle P_z \rangle$ = **0.86 ± 0.05**

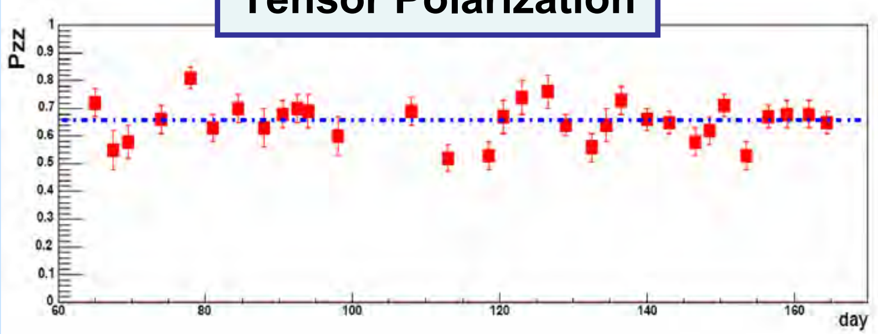


Target Polarization (ABS)

Tensor Polarimetry

- Elastic $^2\overleftrightarrow{H}(e,e'd)$
- Target tensor asymmetry A^T_d
- $A^T_d(exp) = P_{zz}\, A^T_d(th)$
- $\langle P_{zz} \rangle$ = **0.678 ± 0.014**
- However: theory error 5-10%

Tensor Polarization



Vector Polarimetry

- Quasielastic $^2\vec{H}(\vec{e},e'p)$, elastic $^1H(e,e'p)$
- Beam-target vector asymmetry A^V_{ed}
- $A^V_{ed}(exp) = hP_z\, A^V_{ed}(th)$
- $\langle hP_z \rangle$ = **0.558 ± 0.009**
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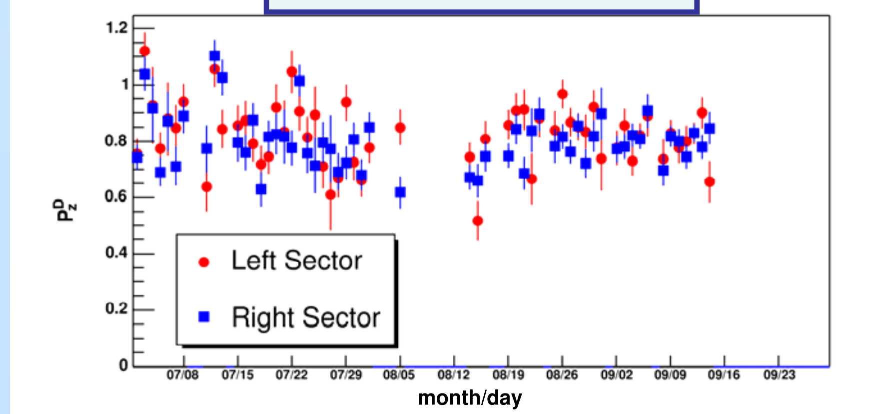
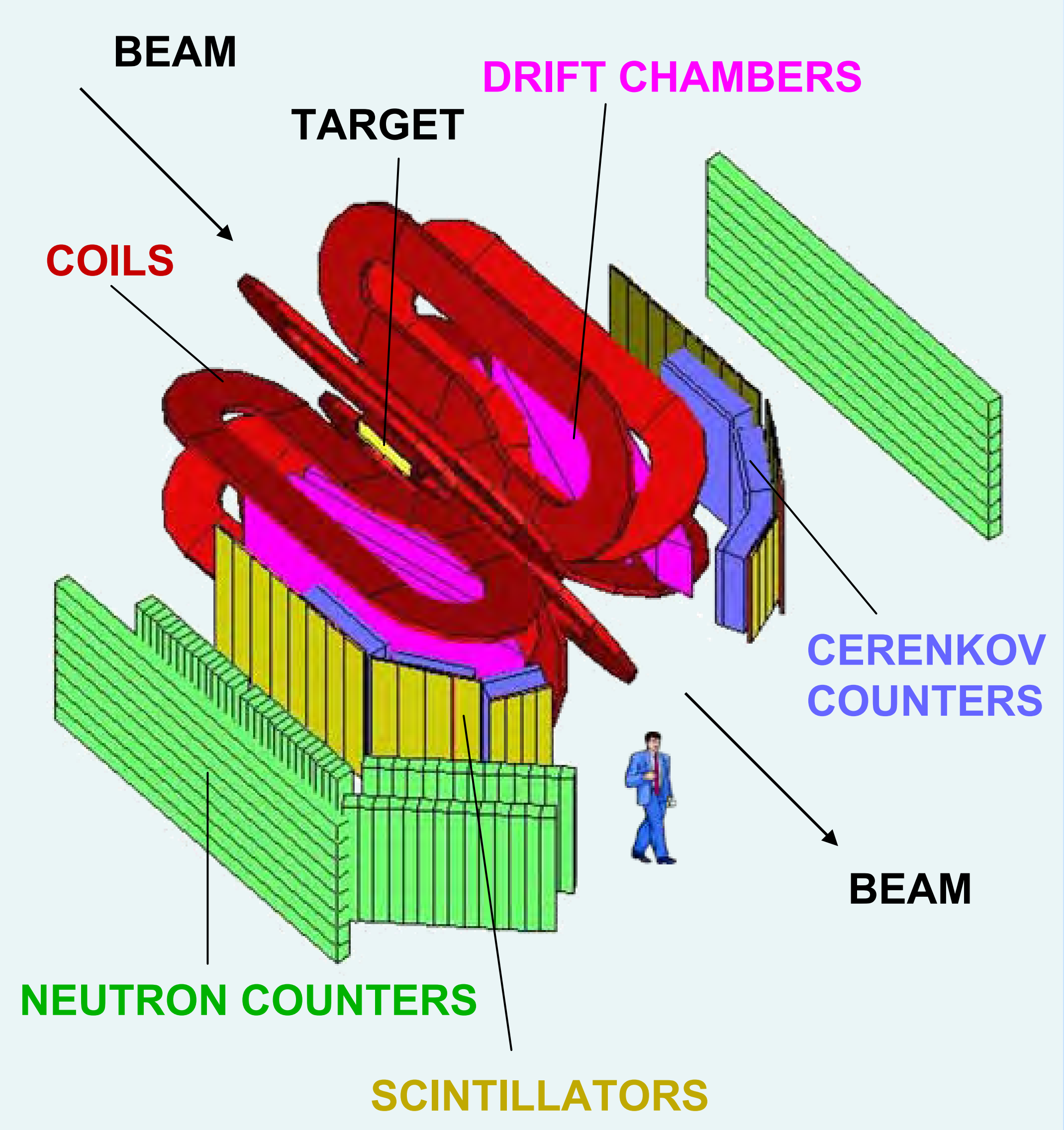
Vector Polarization

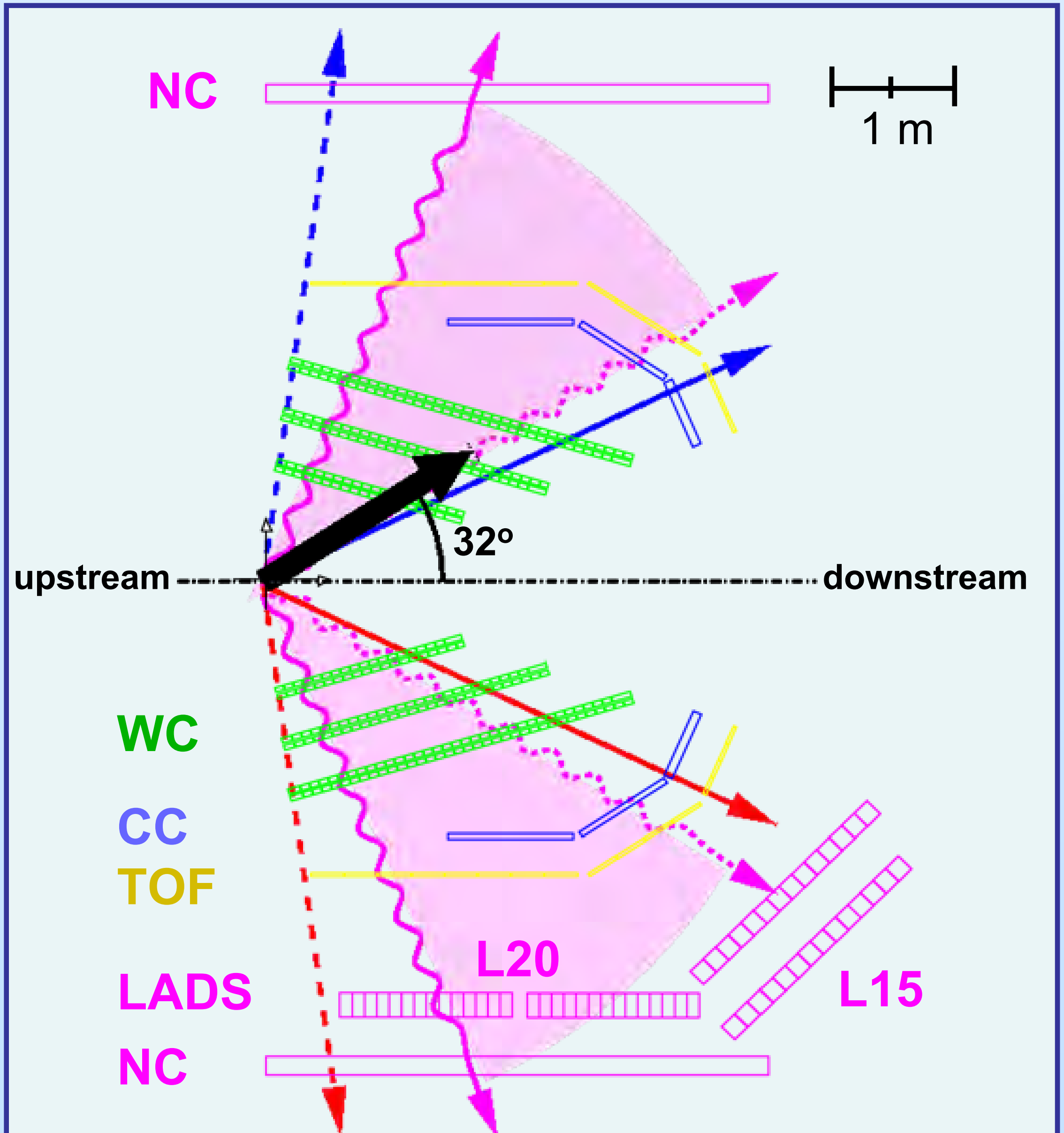


The BLAST Detector

- **Left-right symmetric**
- **Large acceptance:**
  $0.1 < Q^2/(GeV/c)^2 < 0.8$
  $20^o < \theta < 80^o, -15^o < \phi < 15^o$
- **COILS** $B_{max} = 3.8$ kG
- **DRIFT CHAMBERS**
  Tracking, PID (charge)
  $\delta p/p = 3\%$, $\delta\theta = 0.5^o$
- **CERENKOV COUNTERS**
  e/π separation
- **SCINTILLATORS**
  Trigger, ToF, PID (π/p)
- **NEUTRON COUNTERS**
  Neutron tracking (ToF)



Target Spin Orientation



Freedom of in-plane spin angle

32° (2004) / 47° (2005)

e- left → $\theta^* \approx 90^o$

"spin-perpendicular"

e- right → $\theta^* \approx 0^o$

"spin-parallel"

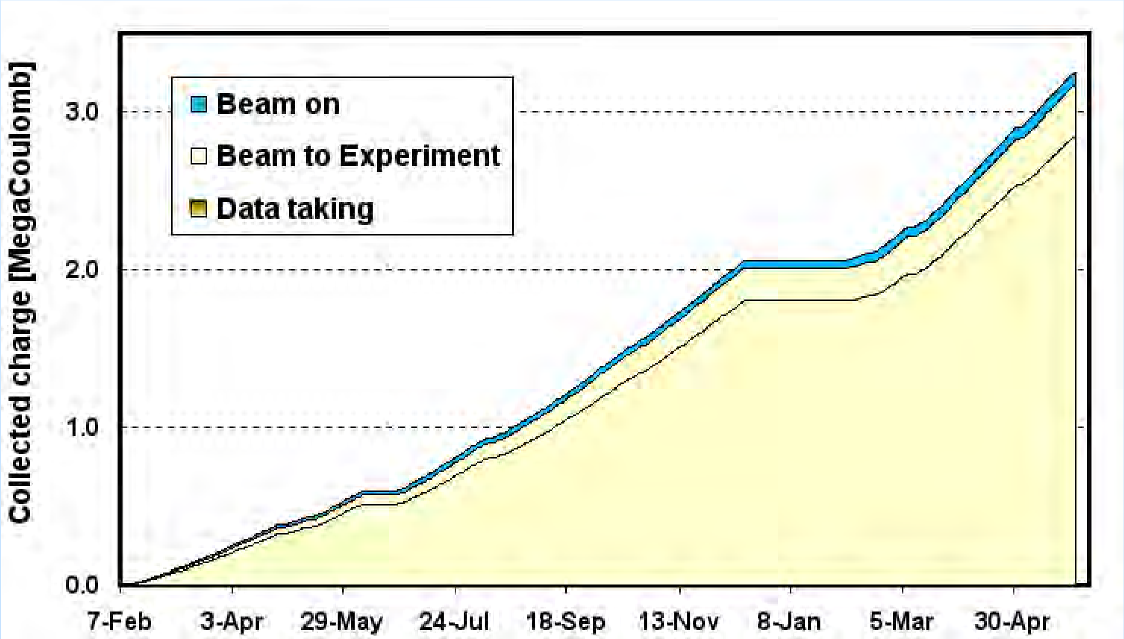
BLAST Data Collection

- **> 3 MC** accumulated charge for **Hydrogen** and **Deuterium** 2004/05

- **Hydrogen 2004**
  θ_d = 47°, 290 kC (**90 pb^{-1}**)
  P_z = 82%

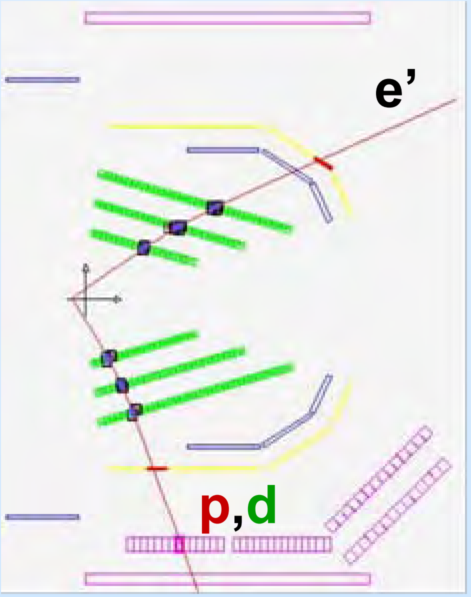
- **Deuterium 2004**
  θ_d = 32°, 450 kC (**169 pb^{-1}**)
  P_z = 86%, P_{zz} = 68%

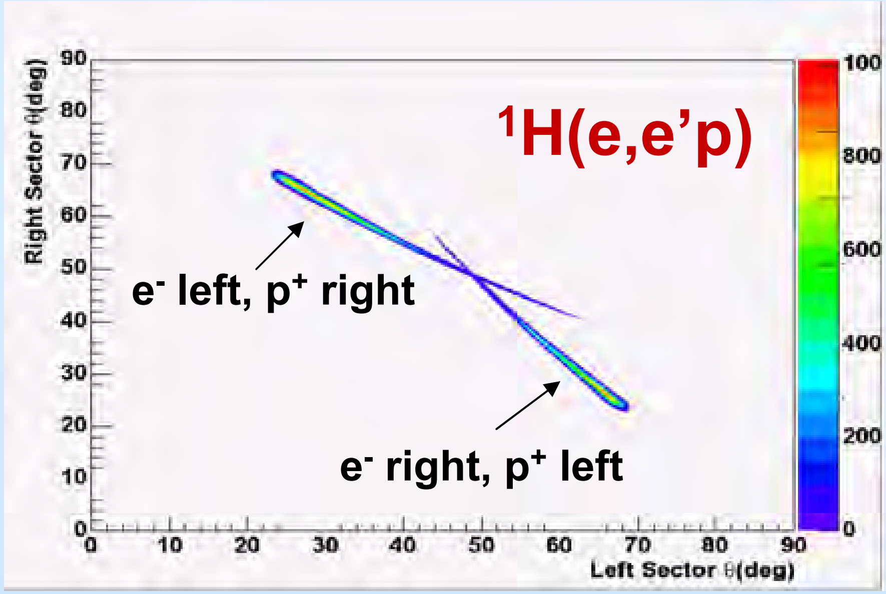
- **Deuterium 2005**
  θ_d = 47°, 550 kC (**150 pb^{-1}**)
  P_z = 73%, P_{zz} = 56%

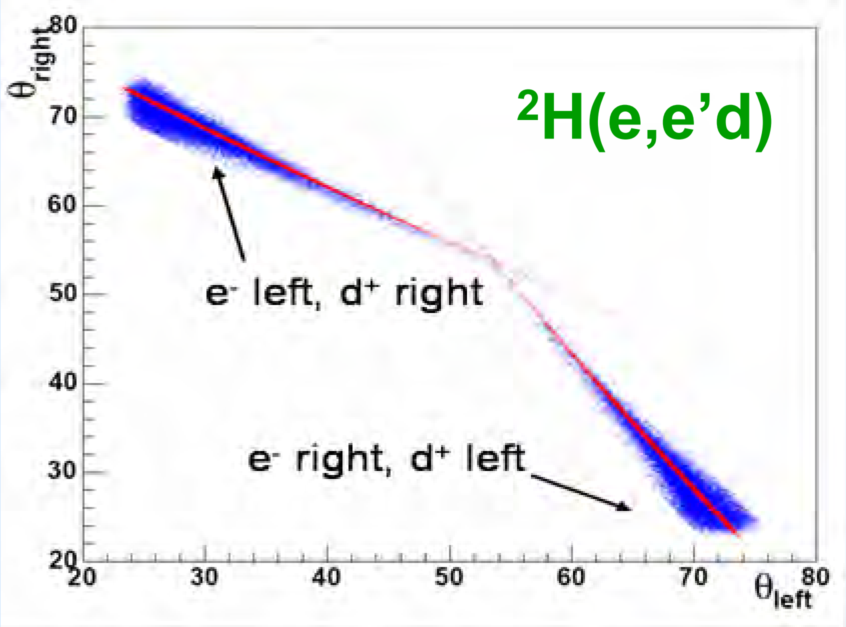


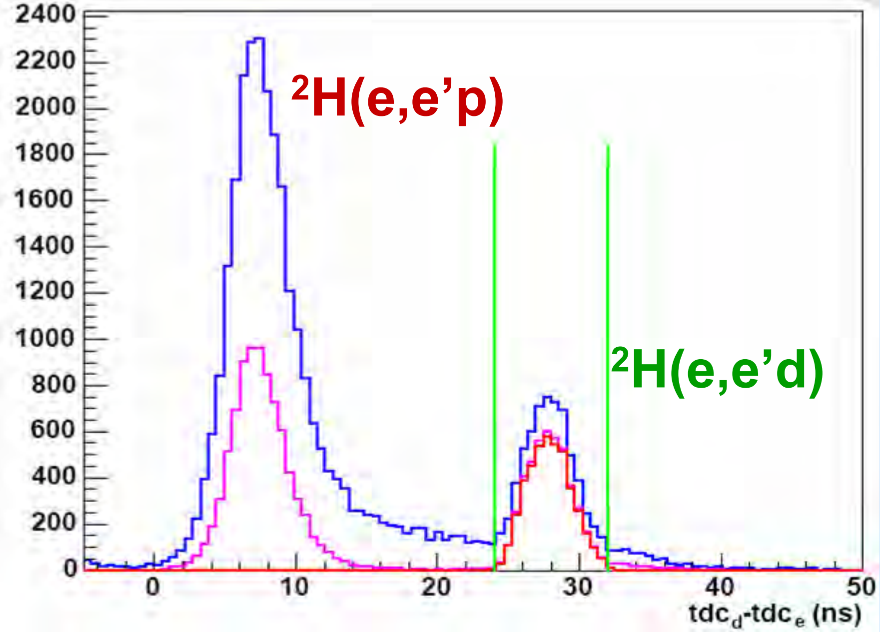
Identification of Elastic Events

- Charge +/-
- Coplanarity
- Kinematics
- Timing



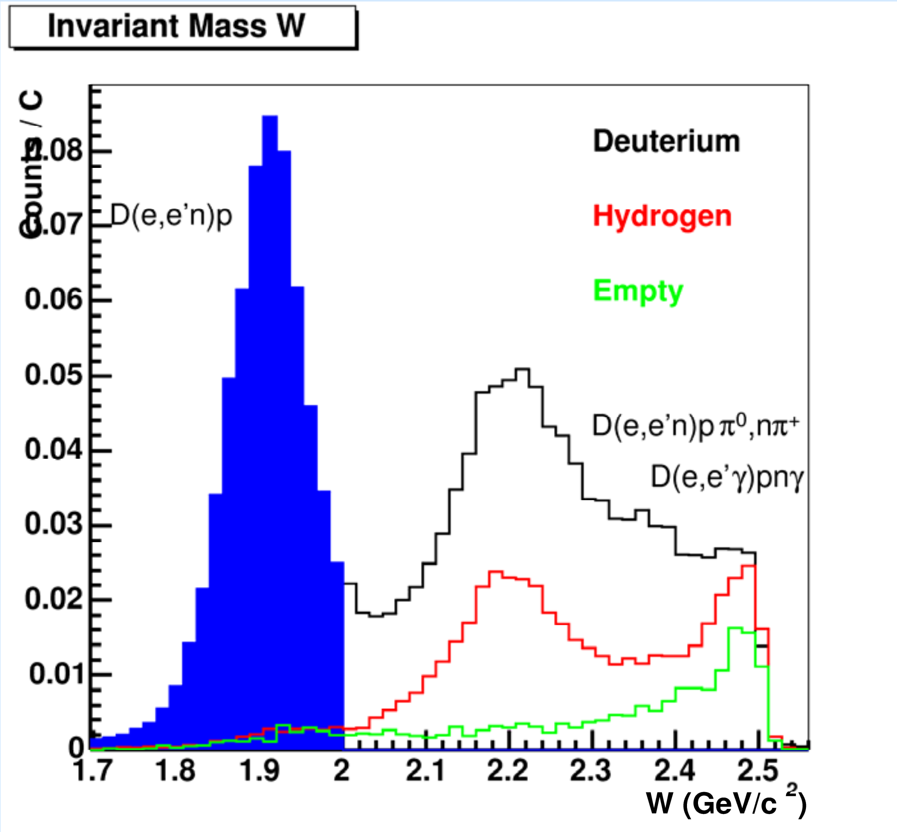


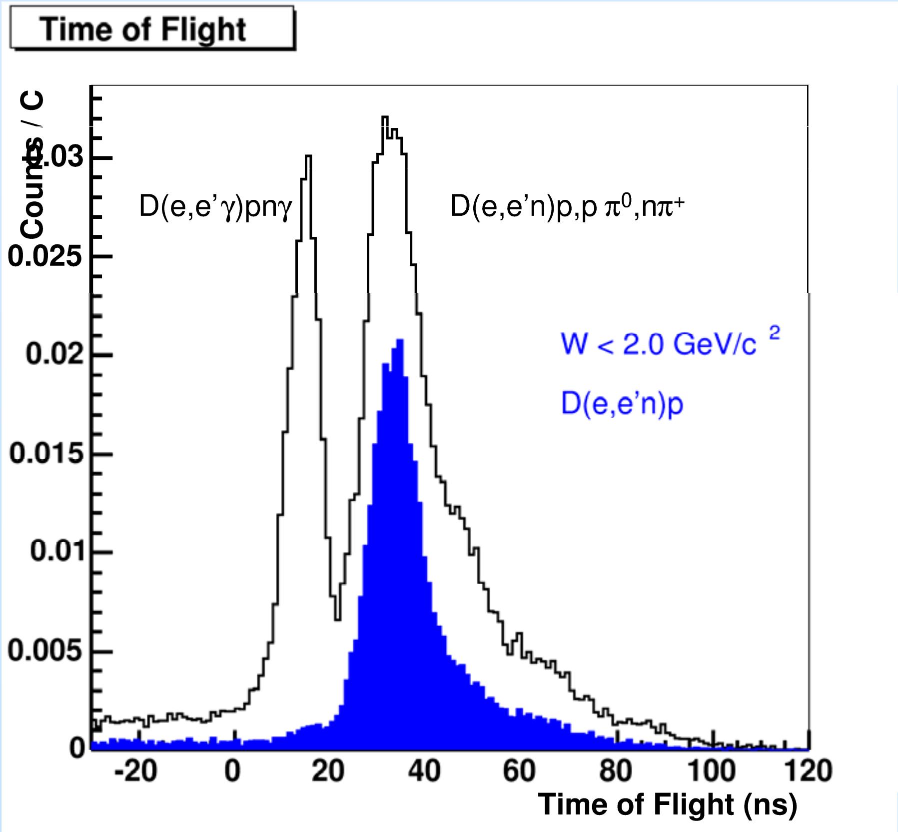




Identification of Neutron Events

- Very clean quasielastic ^{2}**H(e,e'n)** spectra
- Highly efficient **proton veto** (drift chambers + TOF)





Nucleon Elastic Form Factors

- General definition of the nucleon form factor

$$\langle N(P')|J^{\mu}_{\mathrm{EM}}(0)|N(P)\rangle =$$
$$\bar{u}(P')\left[\gamma^{\mu}F_1^N(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2^N(Q^2)\right]u(P)$$

- Sachs Form Factors $G_E = F_1 - \tau F_2; \quad G_M = F_1 + F_2, \quad \tau = \frac{Q^2}{4M^2}$

- In One-photon exchange approximation above form factors are observables of **elastic electron-nucleon** scattering

$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = \frac{\sigma}{\sigma_0} = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

Nucleon Elastic Form Factors

- Double polarization in elastic ep scattering:
  Recoil polarization or polarized target
  $^{1}H(\vec{e},e'\vec{p})$, $^{1}\vec{H}(\vec{e},e'p)$

- Polarized cross section
  $$\sigma = \sigma_0 \left(1 + P_e P_t \, A\right)$$

- Double spin asymmetry
  $$-\sigma_0 \cdot A = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \tilde{P}_x + \tau\sqrt{1-\epsilon^2} G_M{}^2 \tilde{P}_z$$

- Asymmetry ratio ("Super ratio") $\frac{A_\perp}{A_\parallel} \propto \frac{G_E}{G_M}$

  independent of polarization or analyzing power

Form Factor Parameterizations

- $G(Q^2) \overset{\text{Fourier}}{\longleftrightarrow} \rho(r)$ charge and magnetization density

- Dipole form factor $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \quad \leftrightarrow \quad \rho_D(r) = \rho_0\, \mathrm{e}^{-\sqrt{0.71}r}$

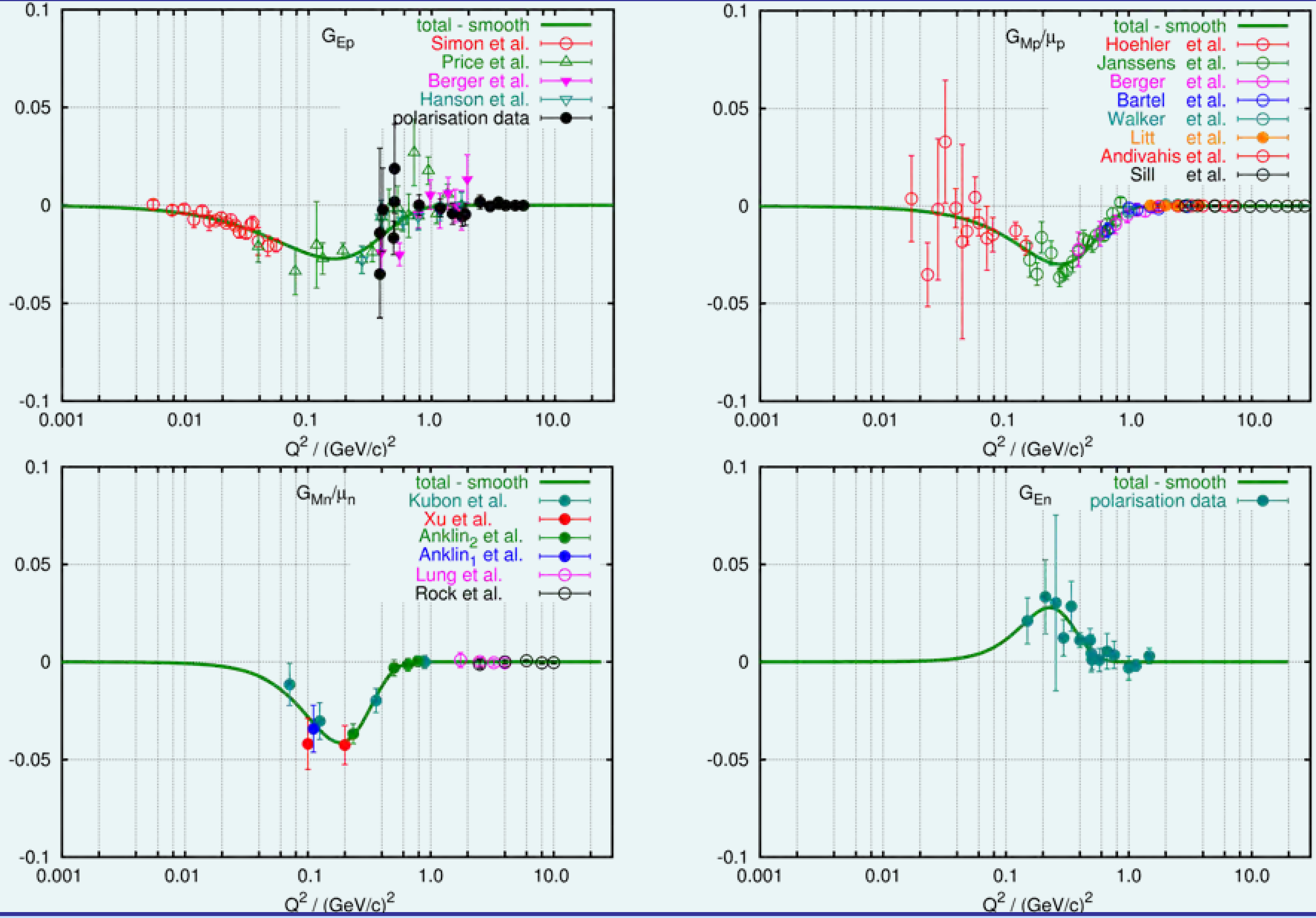
  $G_E^p \approx G_M^p/\mu_p \approx G_M^n/\mu_n \approx G_D$ within 5% for $Q^2 < 1.0$ $(\mathrm{GeV/c})^2$

- Deviations from dipole at low $Q^2 \rightarrow$ effects of meson cloud
  e.g. Friedrich-Walcher parameterization:

$$G_{FW} = \frac{a_{10}}{(1+Q^2/a_{11})^2} + \frac{a_{20}}{(1+Q^2/a_{21})^2} + a_b\, Q^2 \left(\mathrm{e}^{-\frac{1}{2}\left(\frac{Q-Q_b}{\sigma_b}\right)^2} + \mathrm{e}^{-\frac{1}{2}\left(\frac{Q+Q_b}{\sigma_b}\right)^2} \right)$$

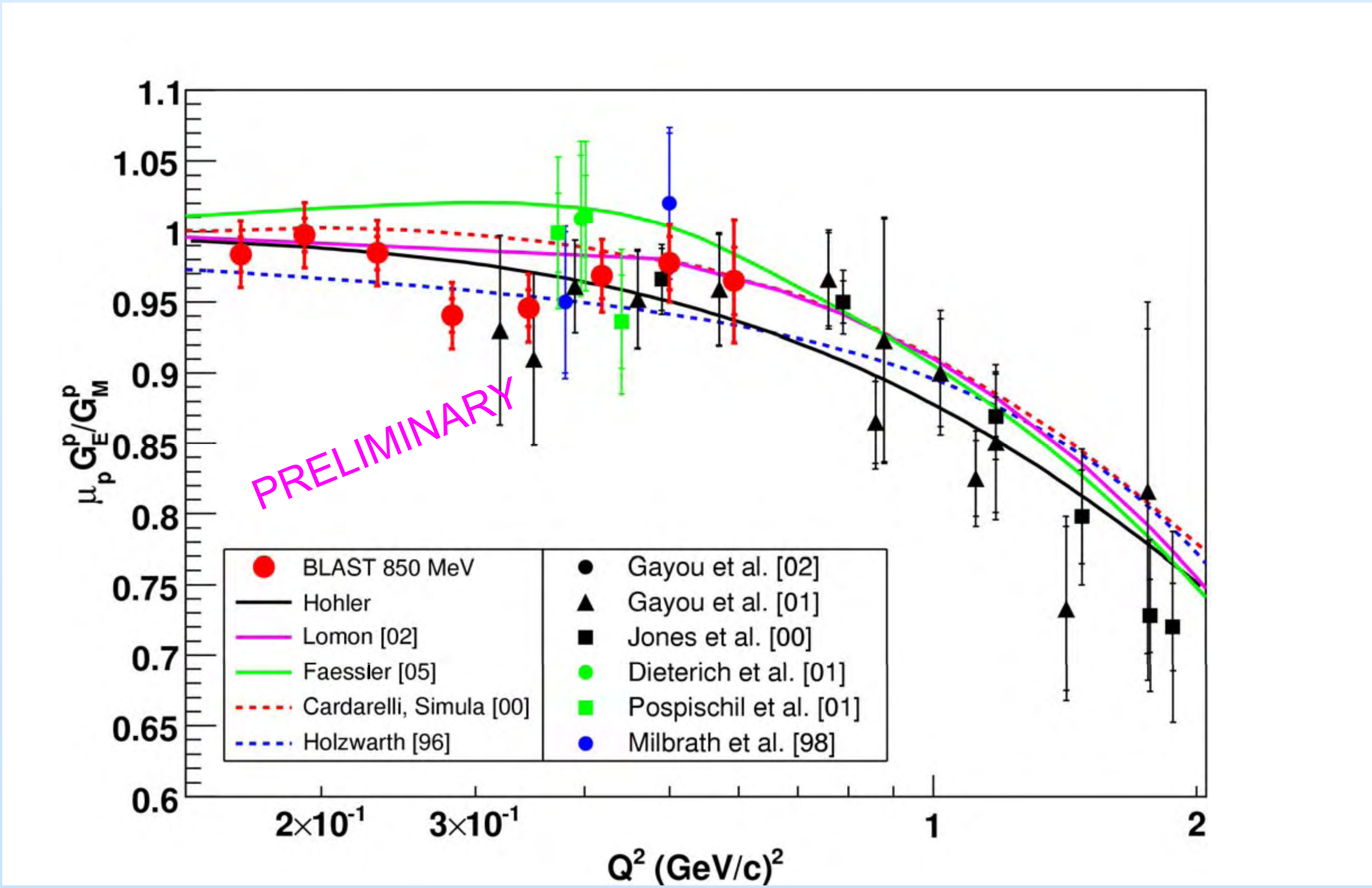
"smooth part" "bump part"

Nucleon Form Factors at Low Q^2



Proton

Proton Form Factor Ratio $\mu_p G^p_E/G^p_M$*

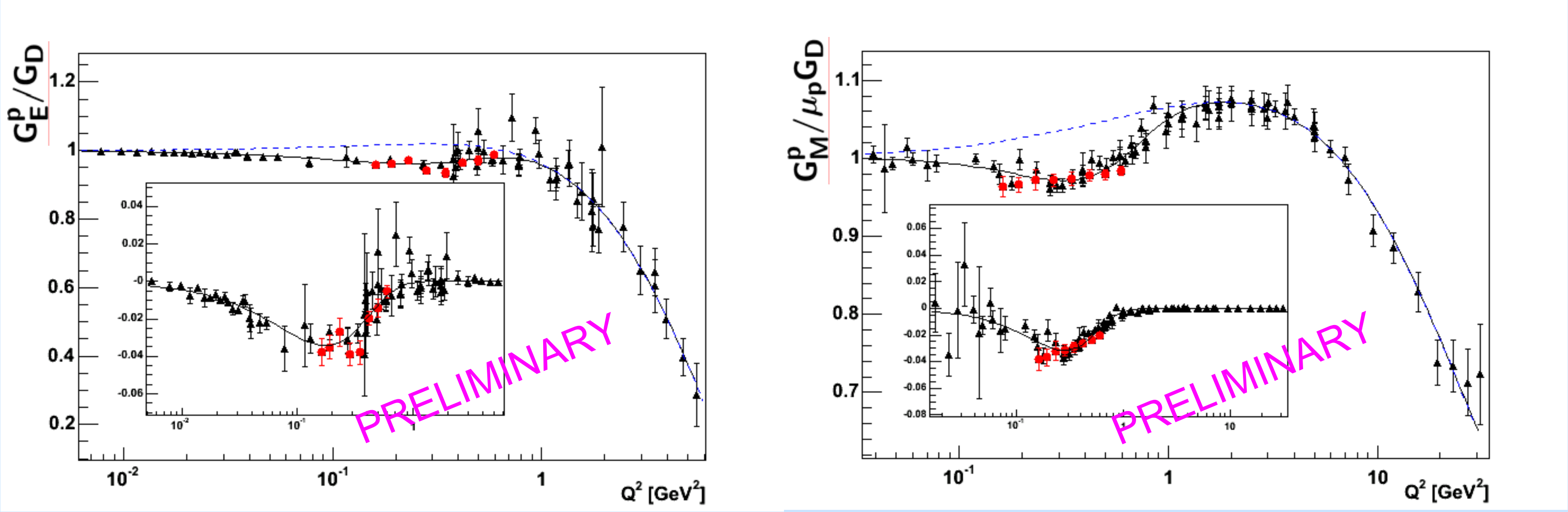


$\mu_p G^p_E/G^p_M$ with BLAST (polarized target) / from recoil polarization (colored) versus unpolarized (grey)

*Ph.D. work of C. Crawford (MIT) and A. Sindile (UNH)

Separate Form Factors G^p_E and G^p_M*

World data (Rosenbluth $Q^2 < 1.0$ GeV^2/c^2) + $\mu_p G^p_E/G^p_M$ **+ BLAST**



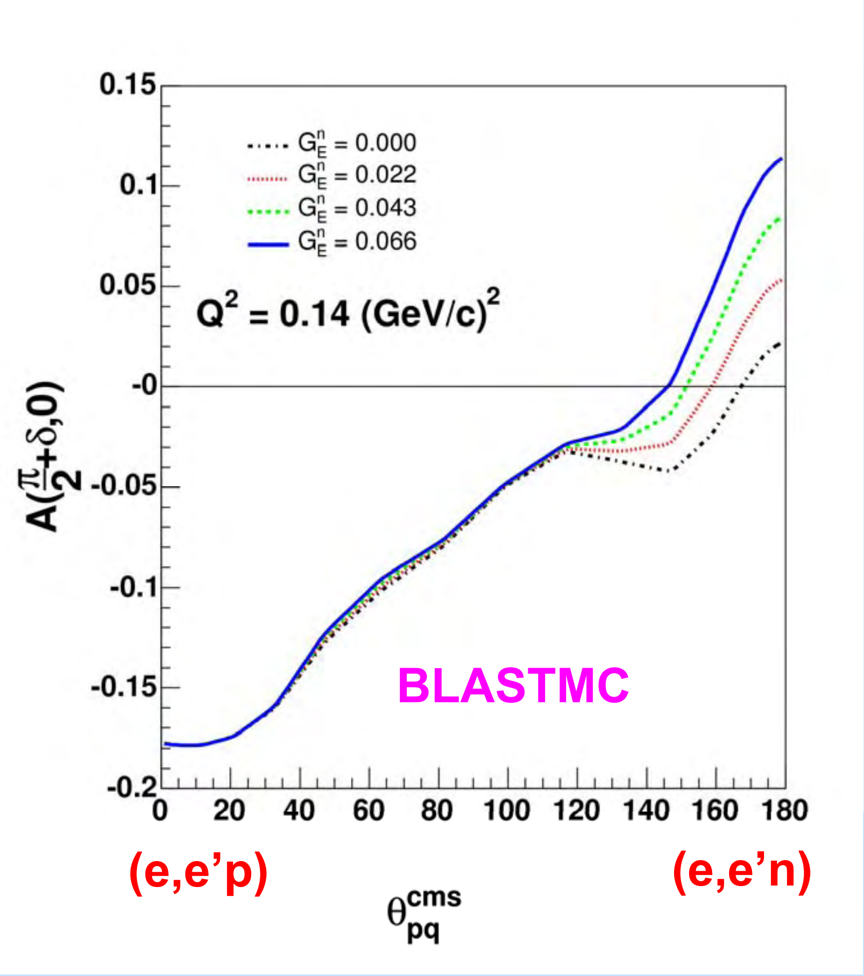
*Ph.D. work of C. Crawford (MIT) and A. Sindile (UNH)

Neutron

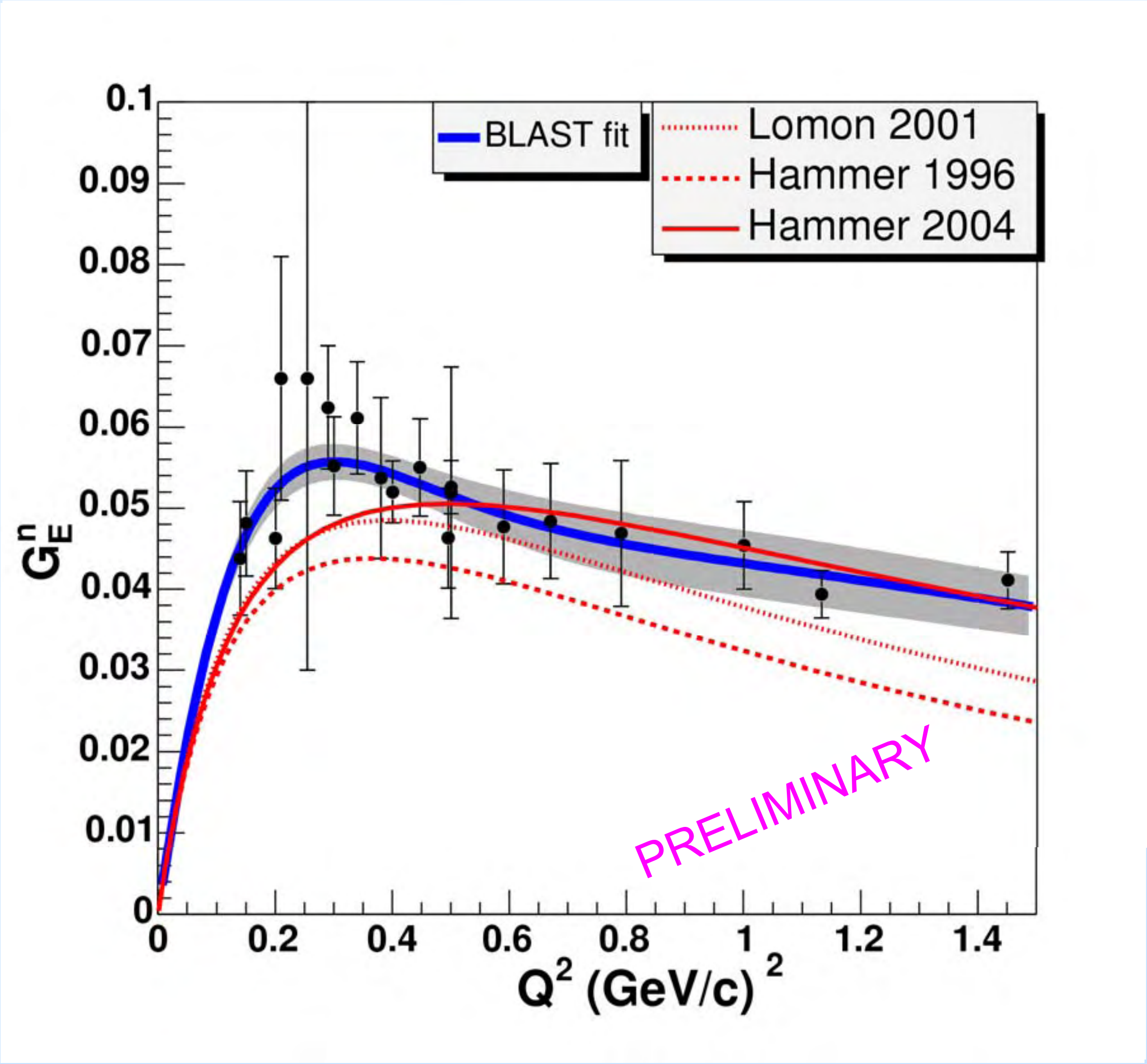
Extraction of G^n_E

$$A^V_{ed} = \frac{a\, {G^n_M}^2 \cos\theta^* + b\, G^n_E G^n_M \sin\theta^* \cos\phi^*}{c\, {G^n_E}^2 + {G^n_M}^2} \approx a\cos\theta^* + b\,\frac{G^n_E}{G^n_M}\sin\theta^* \cos\phi^*$$

- Quasielastic $^2H(e,e'n)$
- Full Montecarlo simulation of the BLAST experiment
- Deuteron electrodisintegration by H. Arenhövel
- Accounted for FSI,MEC,RC,IC
- Spin-perpendicular beam-target vector asymmetry A^V_{ed} shows high sensitivity to G^n_E
- Compare measured A^V_{ed} with BLASTMC, vary G^n_E



Neutron Electric Form Factor G^n_E*

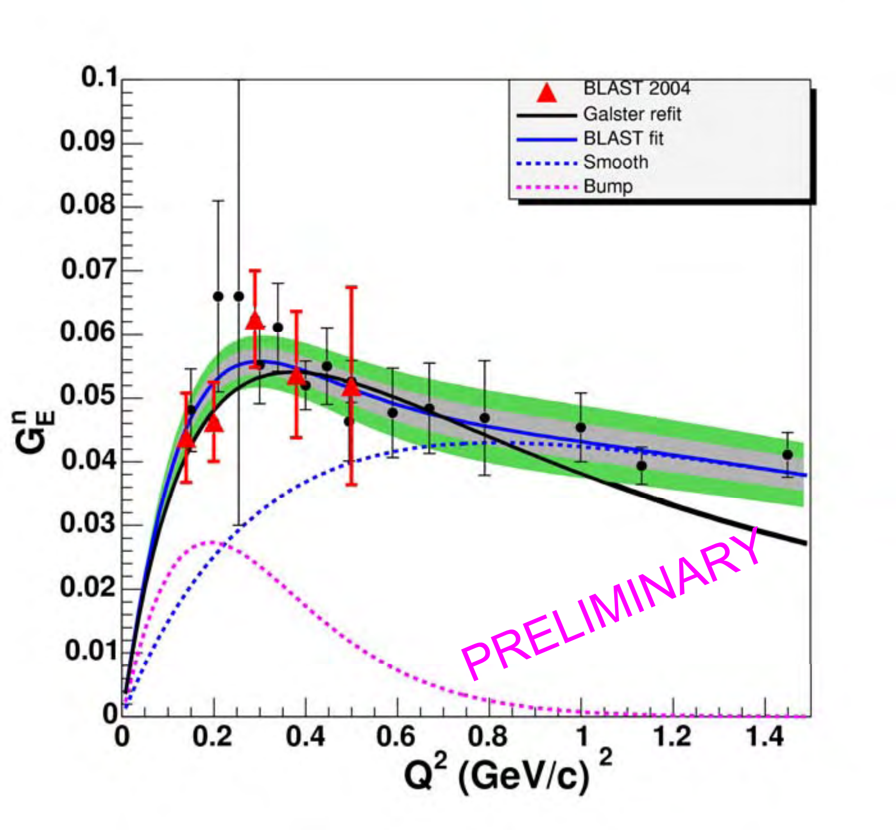


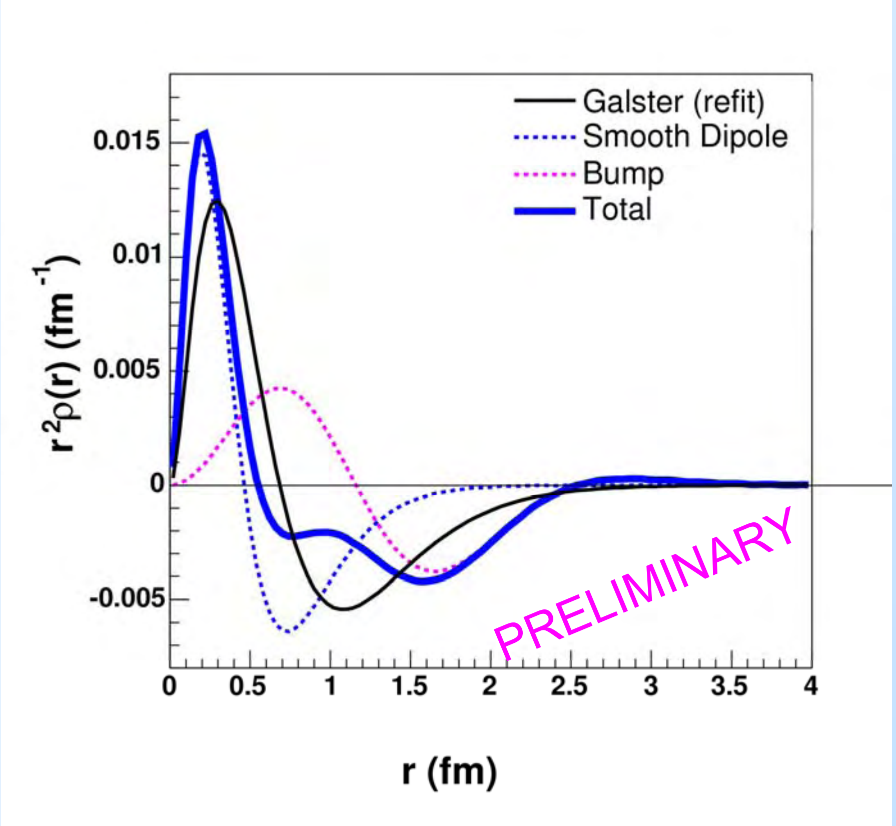
- G^n_E world data from double pol. Experiments
- **Including BLAST 2004**
- **BLAST fit**
  $\langle r^2_n \rangle = -0.115\ fm^2$
  → Pion cloud effect?
- Theoretical models
- Dispersion theory

*Ph.D. work of V. Ziskin (MIT) and E. Geis (ASU)

Neutron Electric Form Factor G^n_E*

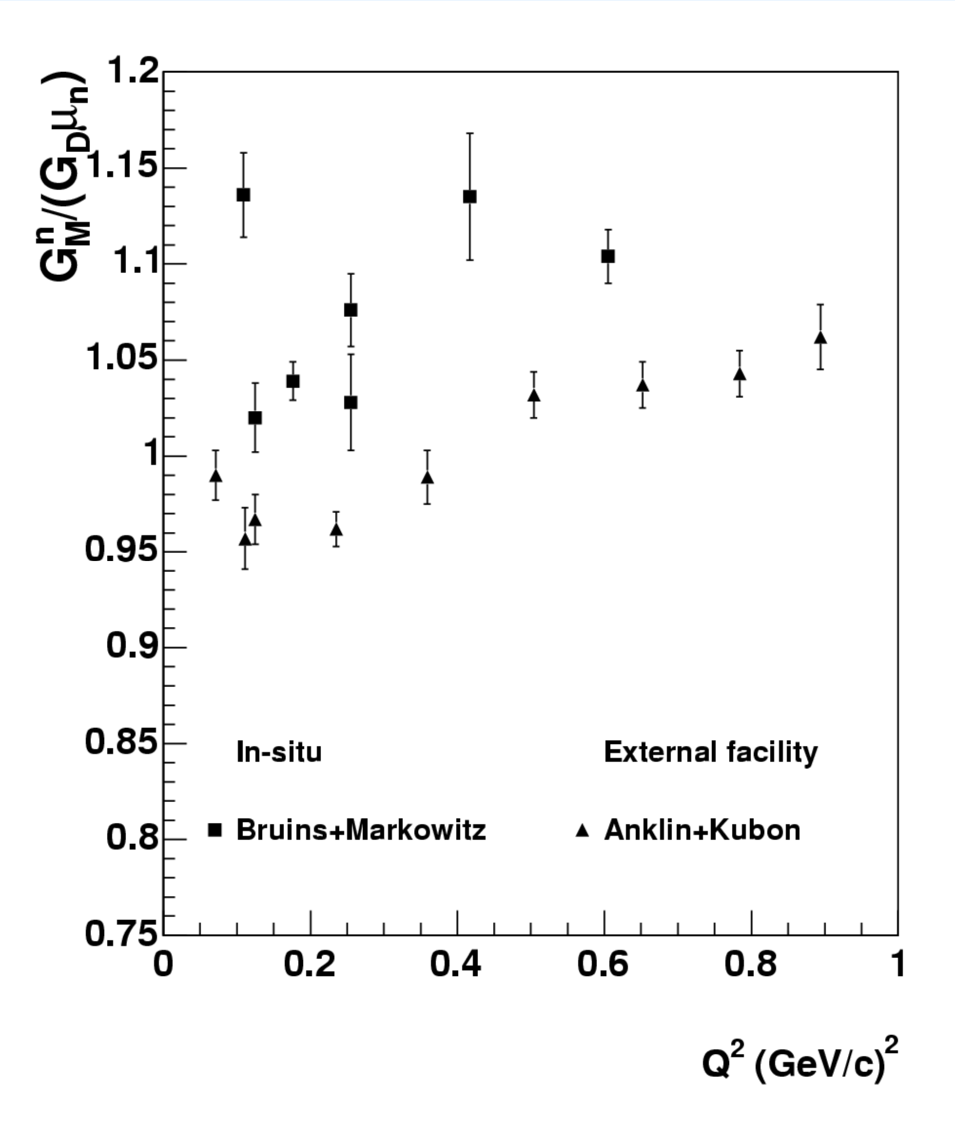
Charge form factor ↔ Charge Distribution





*Ph.D. work of V. Ziskin (MIT) and E. Geis (ASU)

Neutron Magnetic Form Factor G^n_M



- **Pre-polarization era**
- G^n_M world data from unpolarized experiments
- Cross section ratio

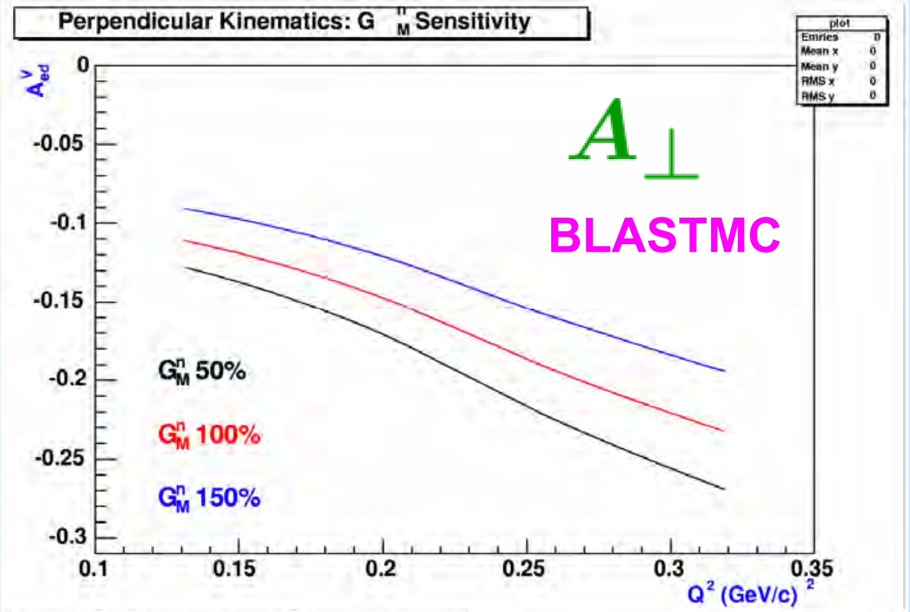
quasielastic $\dfrac{d(e,e'n)}{d(e,e'p)}$

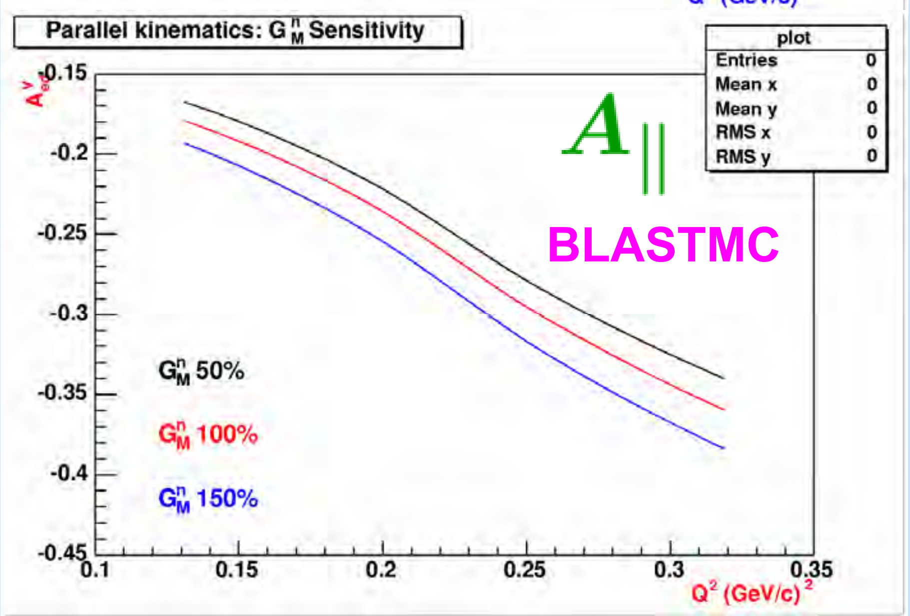
Extraction of G^n_M

- Quasielastic ^{2}H(e,e') inclusive
- Full Montecarlo simulation of the BLAST experiment
- Deuteron electrodisintegration by H. Arenhövel
- Accounted for FSI,MEC,RC,IC
- Beam-target vector asymmetry A^V_{ed} spin-parallel + perpendicular show sensitivity to G^n_M
- PWIA:

$$A_\perp \approx \frac{c\,(G^p_E/G^p_M)}{a + b\left(1 + (G^n_M/G^p_M)^2\right)}$$

$$A_\parallel \approx \frac{d\left(1 + (G^n_M/G^p_M)^2\right)}{a + b\left(1 + (G^n_M/G^p_M)^2\right)}$$



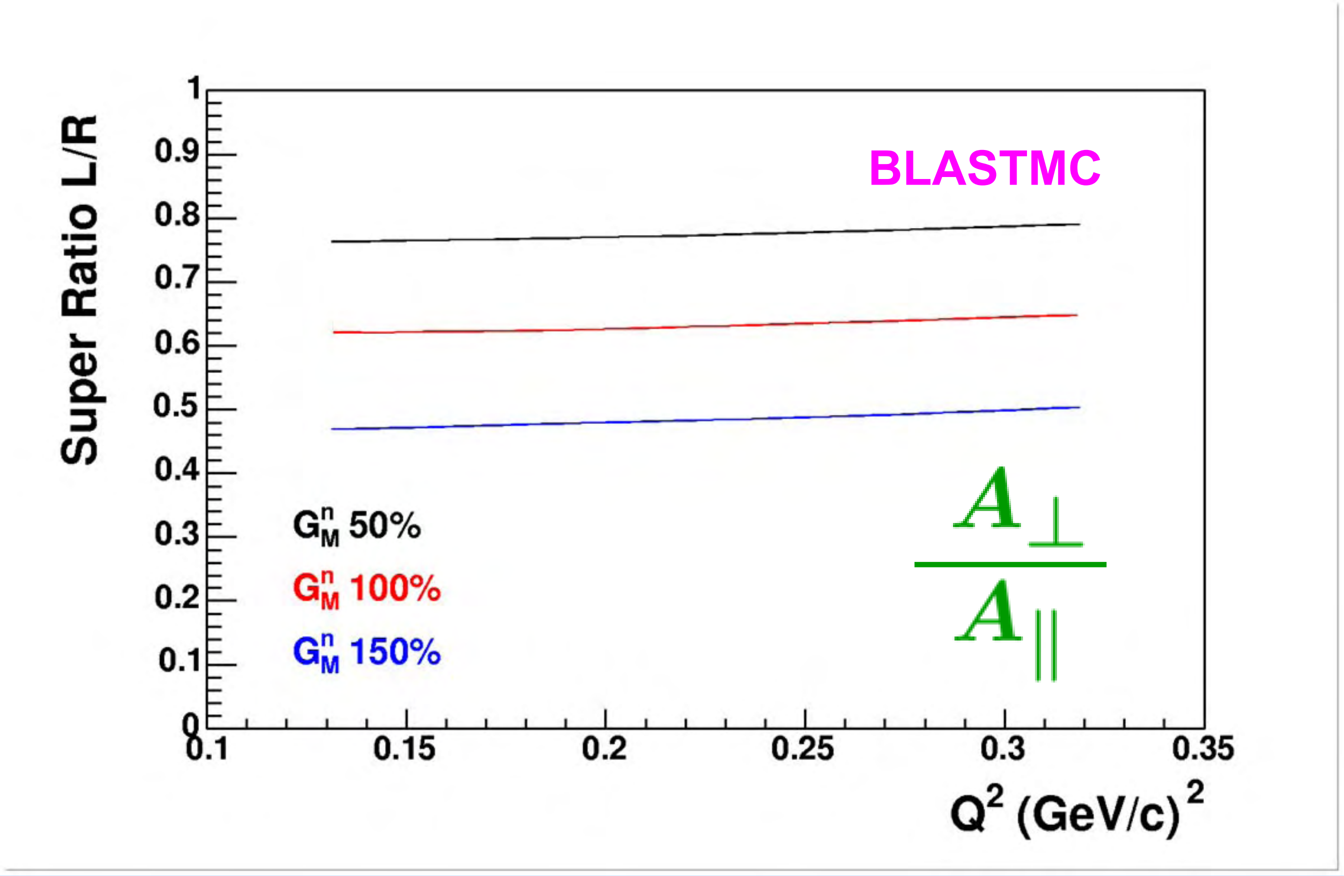


Extraction of G^n_M

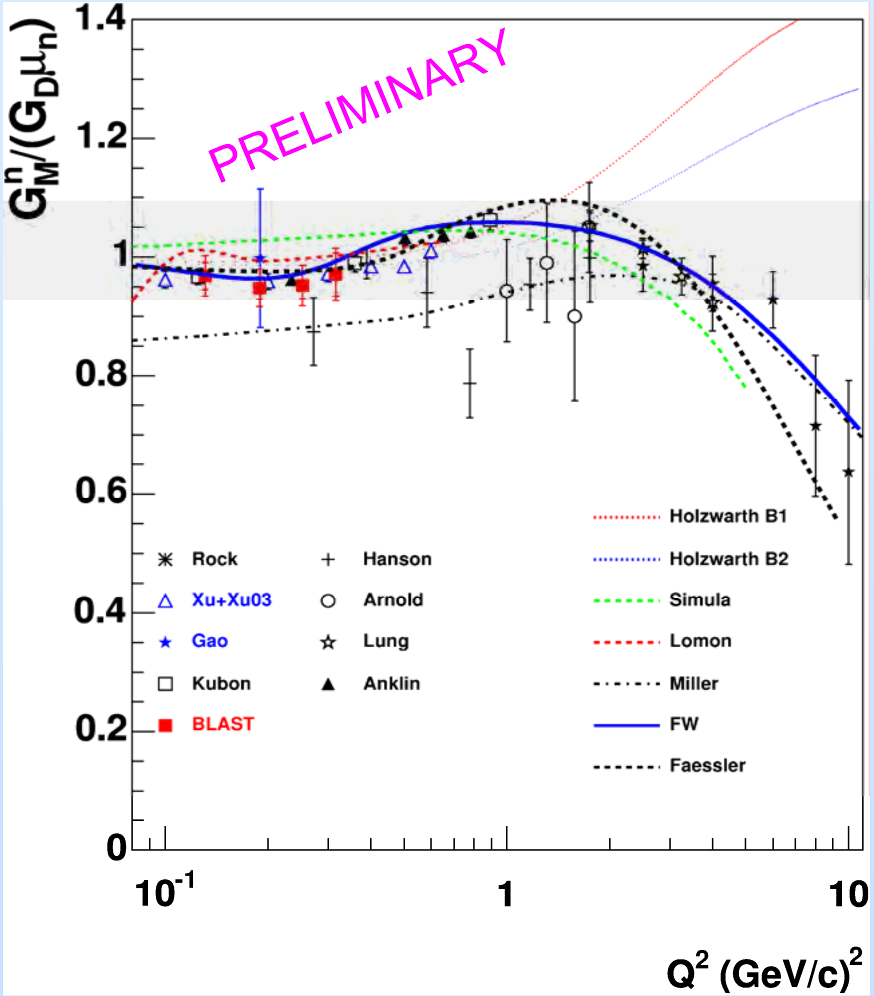
$$\frac{A_\perp}{A_\parallel} \approx \frac{\kappa \frac{G_E^p}{G_M^p}}{1 + \left(\frac{G_M^n}{G_M^p}\right)^2}$$

Enhanced sensitivity in super ratio

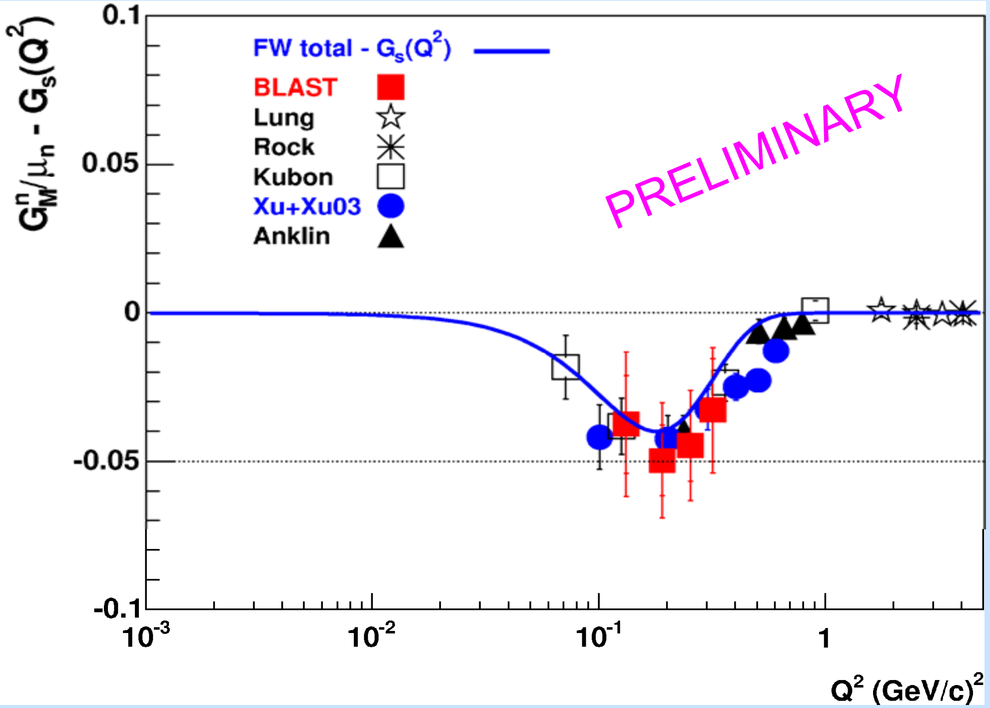
Independent of polarization



Neutron Magnetic Form Factor G^{n}_{M}*



G^n_M world data + ^{3}He + BLAST

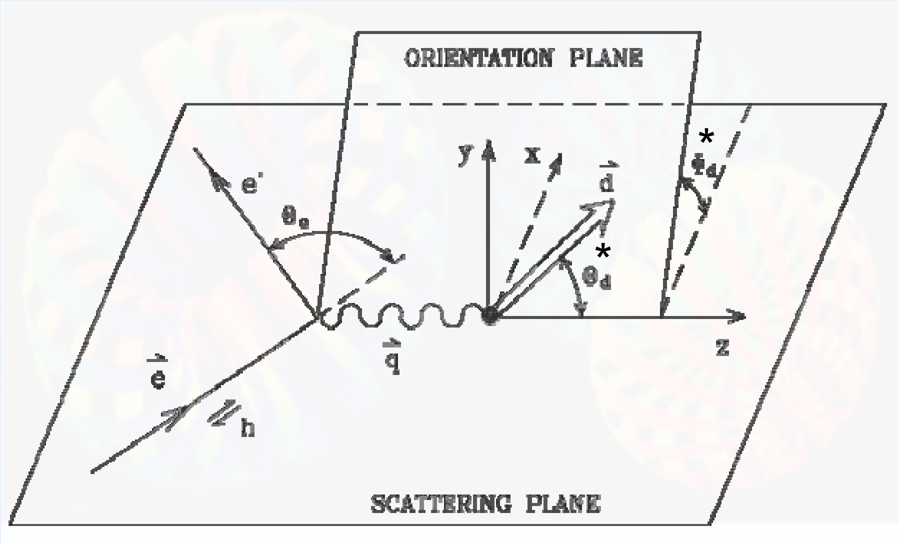


*Ph.D. work of N. Meitanis (MIT)

Deuteron

Elastic Electron-Deuteron Scattering

- Spin 1 ↔ three elastic form factors
  G^d_C, G^d_Q, G^d_M
- Quadrupole moment
  $Q_d = G^d_Q(0) = 25.83$
- G^d_Q ↔ Tensor force, D-wave



- Unpolarized cross section

$$\sigma_0 = \sigma_{\text{Mott}} \left(A + B \tan^2(\theta_e/2)\right) := \sigma_{\text{Mott}} S_0$$

$$A(Q^2) = {G^d_C}^2 + \frac{8}{9}\eta^2 {G^d_Q}^2 + \frac{2}{3}\eta(1+\eta){G^d_M}^2$$

$$B(Q^2) = \frac{4}{3}\eta(1+\eta)^2 {G^d_M}^2; \quad \eta = Q^2/(4M_D^2)$$

- Polarized cross section

$$\sigma = \sigma_0 \left(1 + P_{zz} A^T_d + h P_z A^V_{ed}\right)$$

Tensor-pol. Elastic ed Scattering

- Tensor asymmetry and tensor analyzing powers

$$A_d^T = \frac{3}{2}\left(\cos^2\theta_d - 1\right) T_{20} - \sqrt{\frac{3}{2}} \sin 2\theta_d \cos\phi_d T_{21} + \sqrt{\frac{3}{2}} \sin^2\theta_d \cos 2\phi_d T_{22}$$

$$T_{20}(Q^2,\theta_e) = \frac{1}{\sqrt{2}S_0}\left[\frac{8}{3}\eta\, G_C^d G_Q^d + \frac{8}{9}\eta^2 {G_Q^d}^2 + \frac{1}{3}\eta\left(1 + 2\left(1+\eta\right)\tan^2\frac{\theta_e}{2}\right) {G_M^d}^2\right]$$

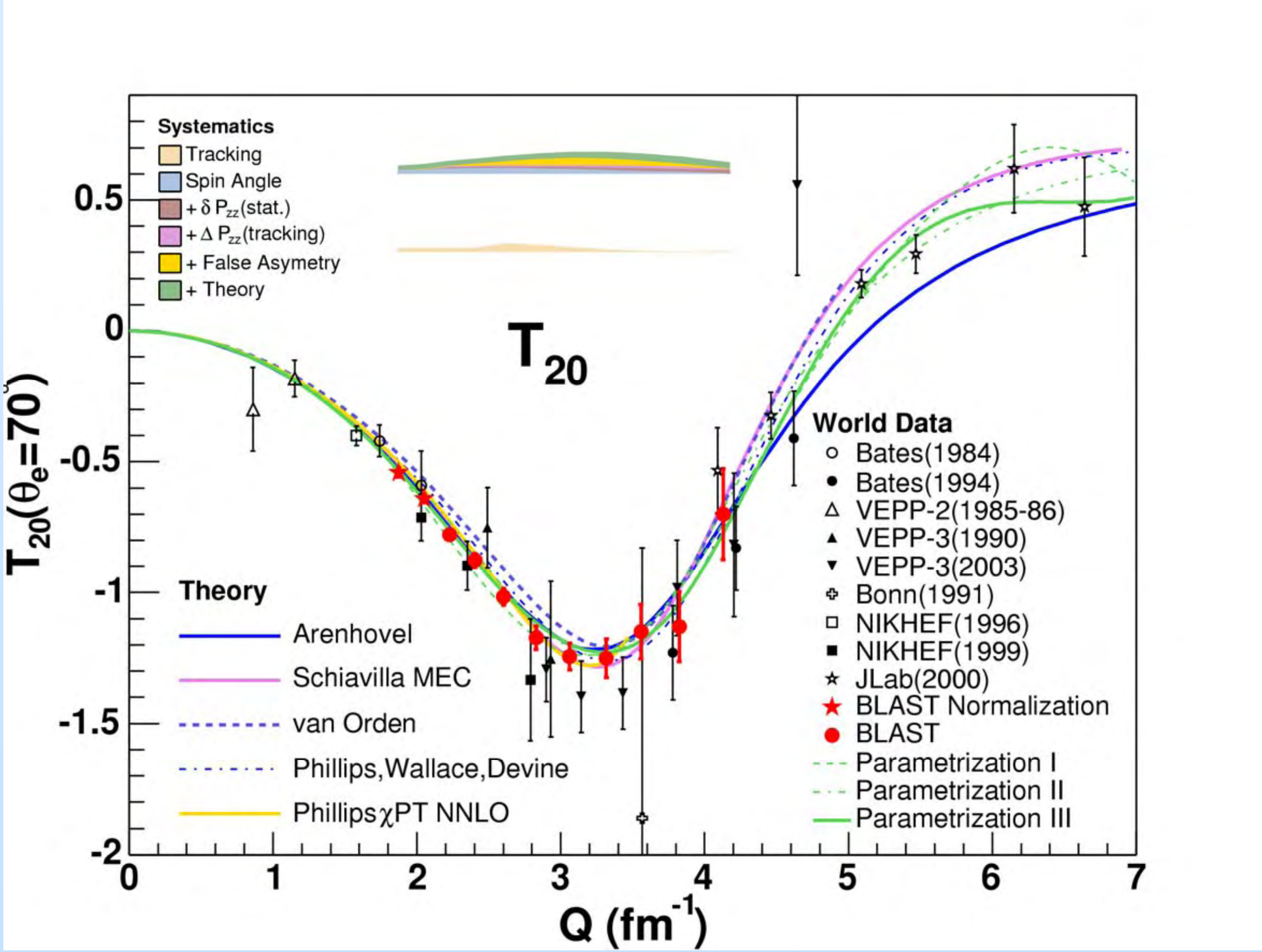
$$T_{21}(Q^2,\theta_e) = \frac{1}{\sqrt{3}S_0} 2\eta\sqrt{\eta + \eta^2 \sin^2\frac{\theta_e}{2}} \sec\frac{\theta_e}{2}\, G_M^d G_Q^d$$

$$T_{22}(Q^2,\theta_e) = -\frac{1}{2\sqrt{3}S_0}\eta\, {G_M^d}^2$$

- T_{20} dominant, T_{21} significant, T_{22} small

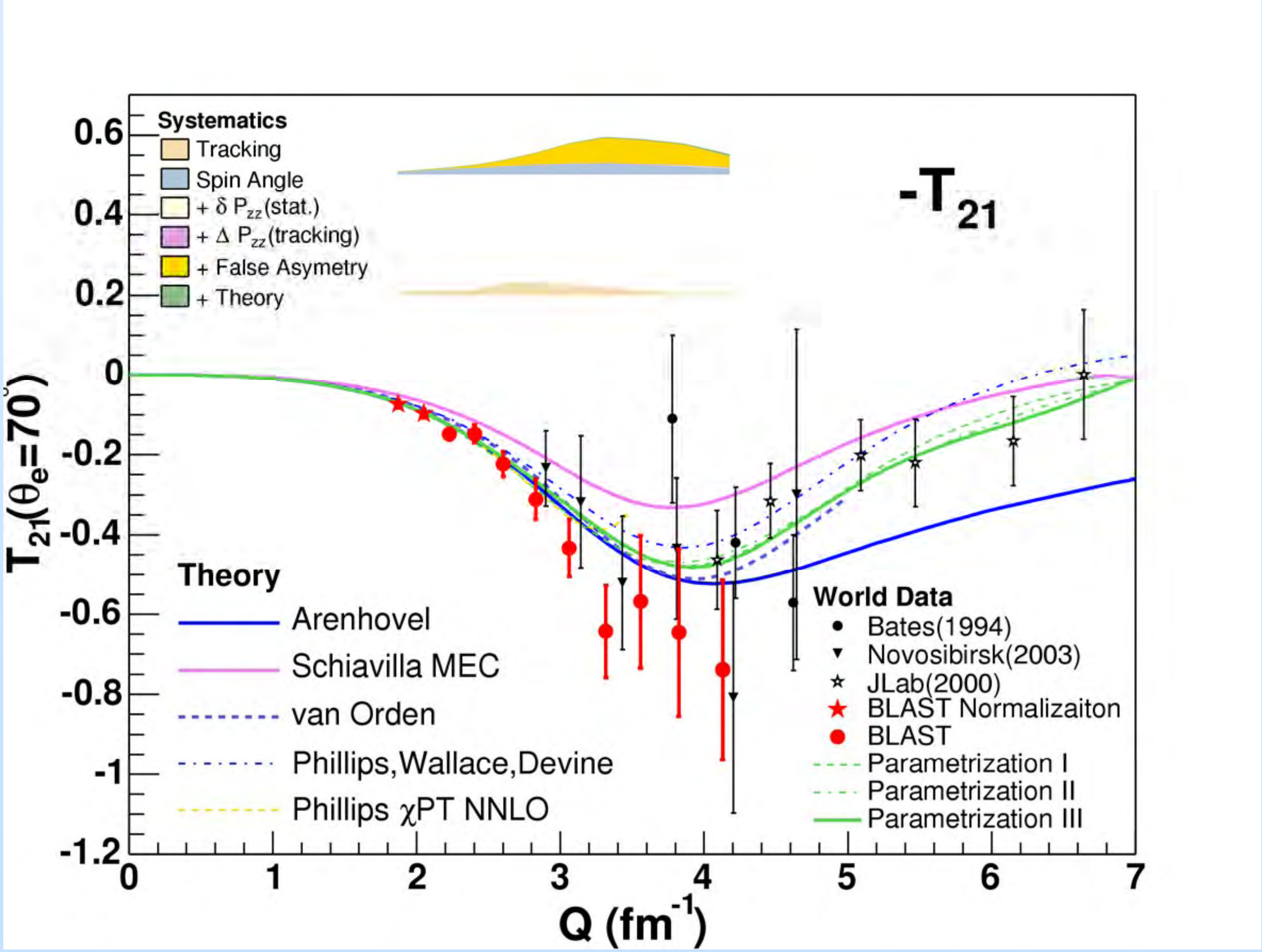
- Global fit analysis to determine G^d_C, G^d_Q and G^d_M from world data + BLAST

Tensor Analyzing Power T_{20}*



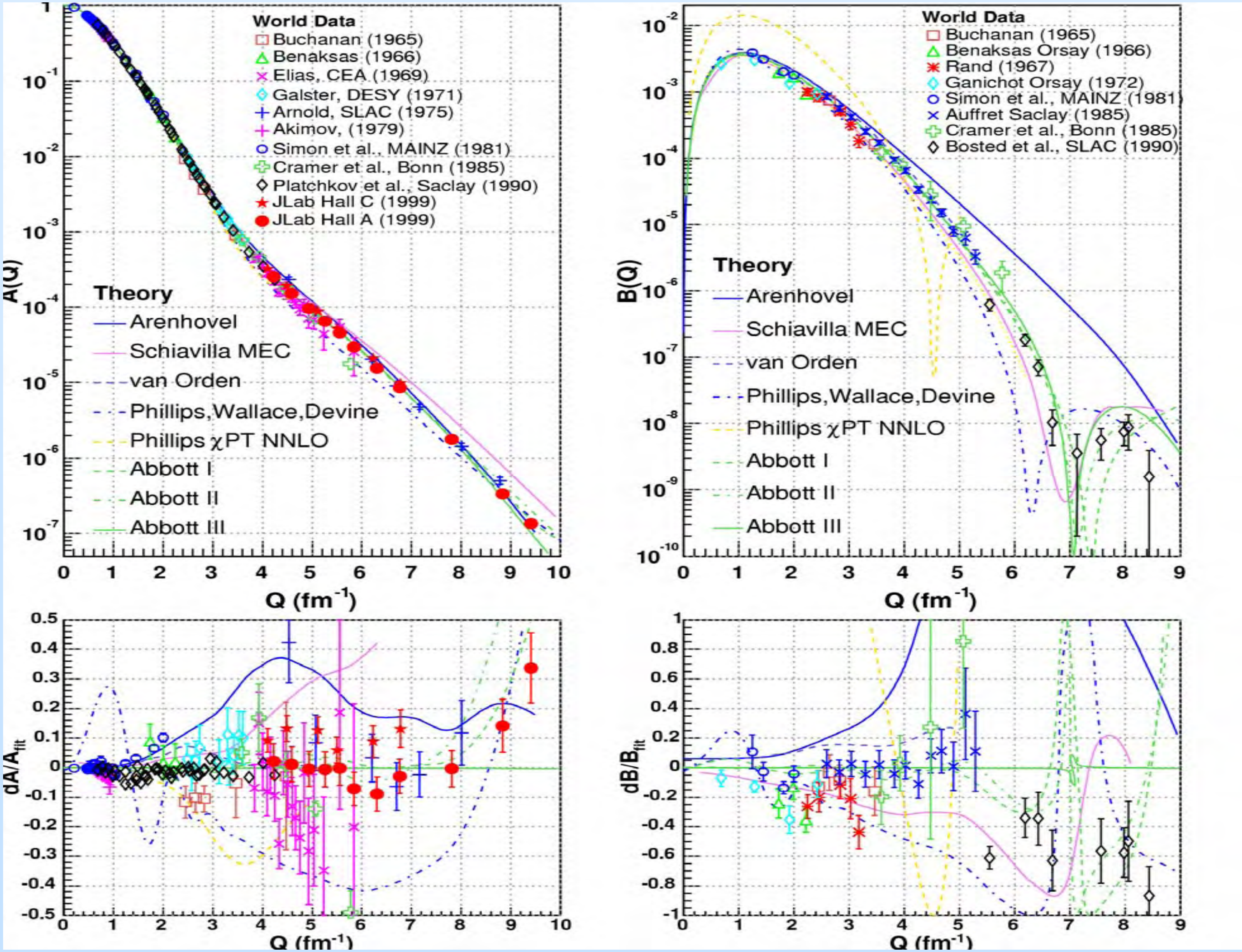
*Ph.D. work of C. Zhang (MIT)

Tensor Analyzing Power T_{21}*

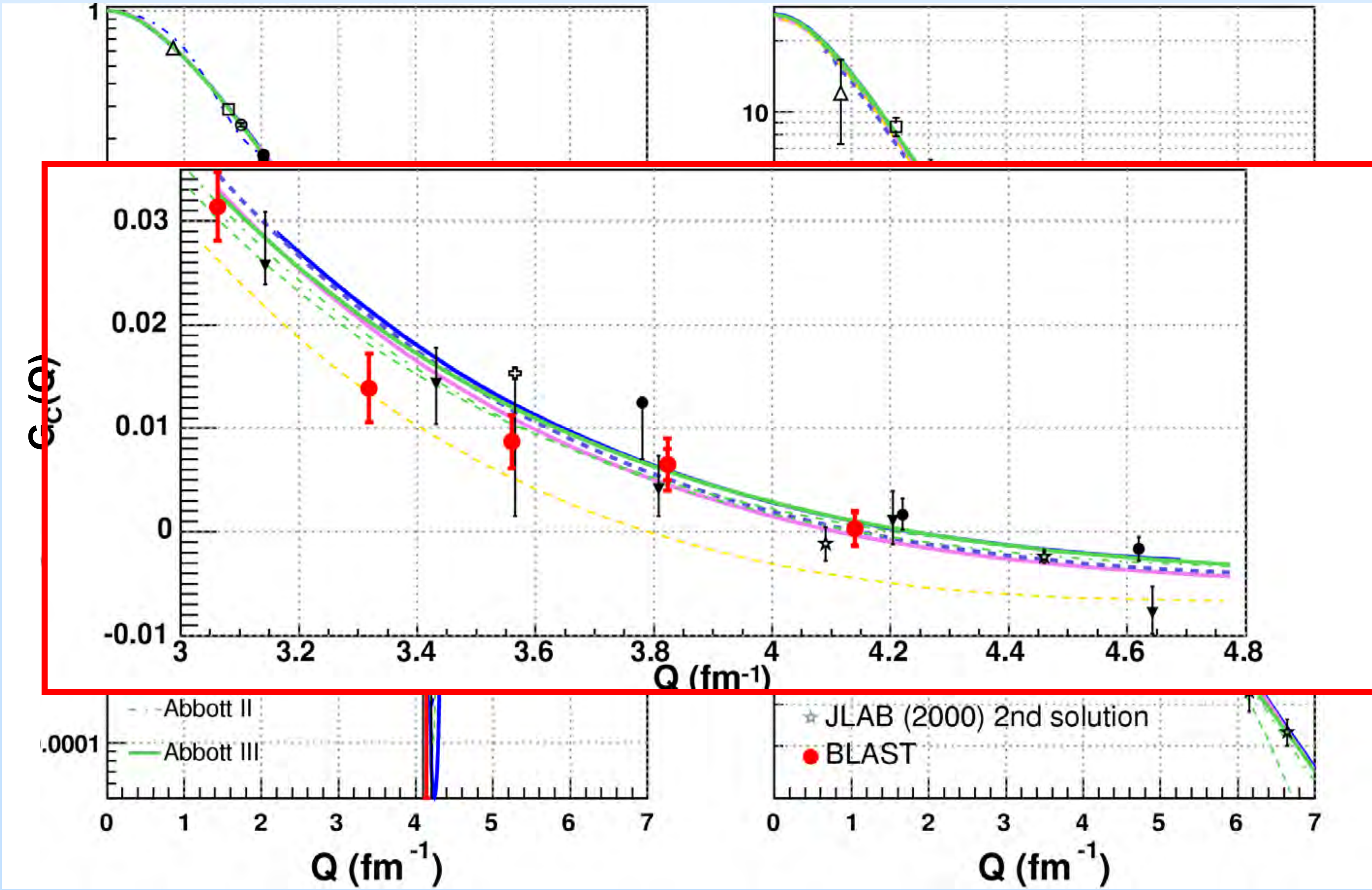


*Ph.D. work of C. Zhang (MIT)

A and B


World Data
Buchanan (1965)
Benaksas (1966)
Elias, CEA (1969)
Galster, DESY (1971)
Arnold, SLAC (1975)
Akimov, (1979)
Simon et al., MAINZ (1981)
Cramer et al., Bonn (1985)
Platchkov et al., Saclay (1990)
JLab Hall C (1999)
JLab Hall A (1999)
Theory
Arenhovel
Schiavilla MEC
van Orden
Phillips,Wallace,Devine
Phillips χPT NNLO
Abbott I
Abbott II
Abbott III
A(Q)
Q (fm^{-1})
World Data
Buchanan (1965)
Benaksas Orsay (1966)
Rand (1967)
Ganichot Orsay (1972)
Simon et al., MAINZ (1981)
Auffret Saclay (1985)
Cramer et al., Bonn (1985)
Bosted et al., SLAC (1990)
B(Q)
dA/A$_{fit}$
dB/B$_{fit}$

G_C and G_Q*



*Ph.D. work of C. Zhang (MIT)

Vector-pol. Elastic ed Scattering

- Beam-target vector asymmetry and vector analyzing powers

$$A_{ed}^{V} = \sqrt{3}\left(\frac{1}{\sqrt{2}}\cos\theta_d\, T_{10}^{e} - \sin\theta_d \cos\phi_d\, T_{11}^{e}\right)$$

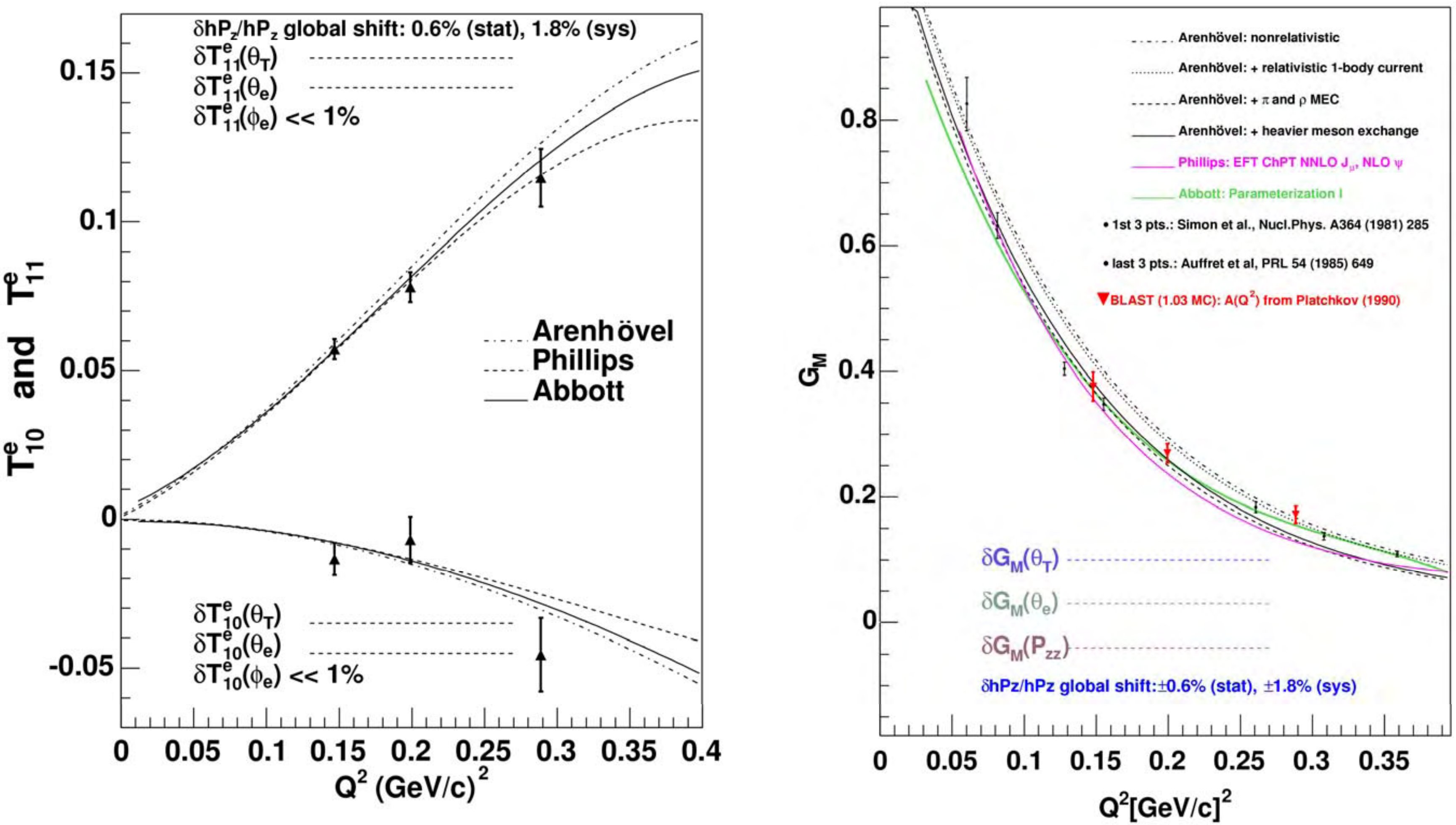
$$T_{10}^{e}(Q^2,\theta_e) = -\frac{\sqrt{2}}{\sqrt{3}S_0}\eta\sqrt{(1+\eta)\left(1+\eta\sin^2\frac{\theta_e}{2}\right)}\sec\frac{\theta_e}{2}\tan\frac{\theta_e}{2}\, {G_M^d}^2$$

$$T_{11}^{e}(Q^2,\theta_e) = \frac{2}{\sqrt{3}S_0}\sqrt{\eta\,(1+\eta)}\tan\frac{\theta_e}{2}\, G_M^d\left(G_C^d + \frac{1}{3}\eta G_Q^d\right)$$

- T^e_{10} small, T^e_{11} dominant
- Determine G^d_M at low Q^2 from T^e_{11}, T_{20} and world data on $A(Q^2)$

$$G_M^d = \frac{\sqrt{3}S_0\, T_{11}^{e}}{2\sqrt{\eta\,(1+\eta)}\tan\frac{\theta_e}{2}\left(G_C^d + \frac{1}{3}\eta\, G_Q^d\right)}$$

Vect. Anal. Powers T^e_{10}, T^e_{11}, and $G^{d\,*}_M$



*Ph.D. work of P. Karpius (UNH)

Summary

- **Proton, neutron**, and **deuteron** spin observables with **BLAST**
- High precision, low systematics
- **Nucleon structure:**
  - Consistent and precise determination of elastic **nucleon form factors** at low momentum transfer → Evidence for **structure at low Q2**
- **Deuteron structure:**
  - Precision measurement of T_{20} allows to separate G^d_C and G^d_Q
  - First measurement of T^e_{11} allows to determine G^d_M at low Q^2
- More reaction channels being analyzed (quasielastic, inelastic)
- Expect first publications soon