Polarized light ion physics with EIC, Ghent, Belgium, Feb. 5-9, 2018

BLAST Deuteron Tensor Asymmetry Results

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BLAST: B-LAST

History

- **1989: BLAST first conceived**
- **1998: Funding starts**
- **2004-2005 Production data**

Publications:

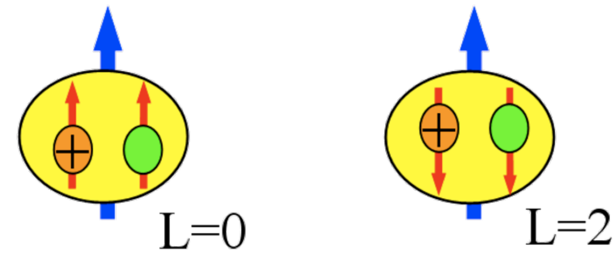
1. C.B. Crawford *et al.*, PRL 98, 052301 (2007) [GEp/GMp]
2. E. Geis *et al.*, PRL 101, 042501 (2008) [GEn/GMn]
3. D. Hasell *et al.*, Nucl. Instr. and Methods in Physics Research 603, 247 (2009) [BLAST]
4. D. Hasell *et al.*, Annu. Rev. Nucl. Part. Sci. 61, 409 (2011) [Review]
5. C. Zhang *et al.*, PRL 107, 0252501 (2011) [T20, T21]
6. A. DeGrush *et al.*, PRL 119, 182501 (2017) [QE ep]

11 PhD Theses:

1. Vitaly Ziskin (MIT, April 2005)
2. Chris Crawford (MIT, May 2005)
3. Aaron Maschinot (MIT, September 2005)
4. Peter Karpius (University of NH, Dec. 2005)
5. Nikolas Meitanis (MIT, March 2006)
6. Chi Zhang (MIT, May 2006)
7. Adrian Sindile (University of NH, May 2006)
8. Octavian Filoti (University of NH, April 2007)
9. Eugene Geis (Arizona State, May 2007)
10. Yuan Xiao (MIT, 2009)
11. Adam DeGrush (MIT, 2010)

Outline

- Deuteron Properties
  NN interaction
  Deuteron Structure



- The BLAST Experiment:
  Polarization Observables in
  Electron-Deuteron Scattering

- Summary

Deuteron Properties

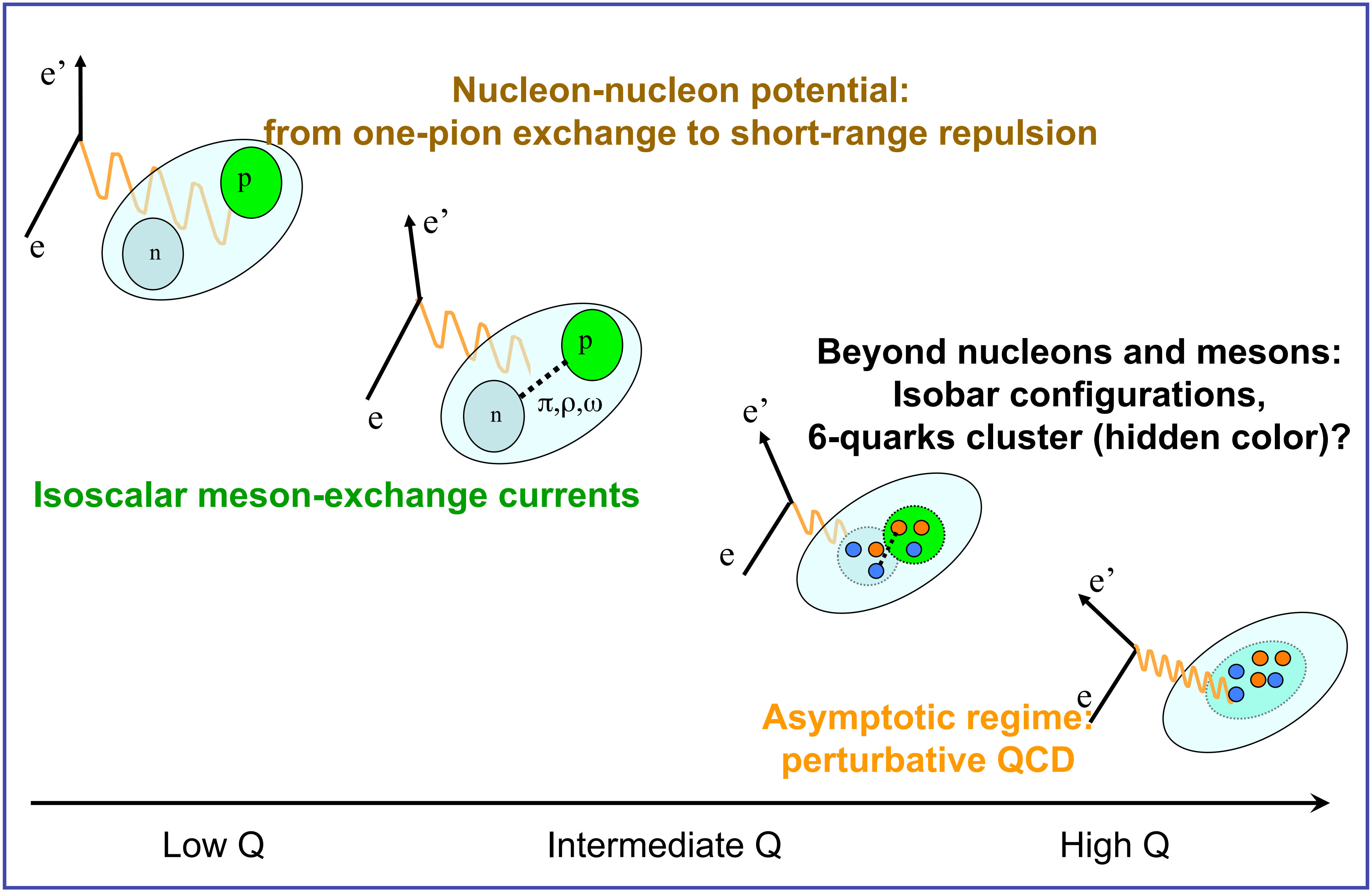
- Deuteron not a nucleus? ⟶ Bound NN system
  NN interaction, T=0 isoscalar, no 3N force

- Charge Radius, size ~2 fm (large!)
  Binding Energy ~1.1 MeV/nucleon (small!)
  Deuteron = **Neutron target**
- Base system to build nuclei ("H-atom of nuclear physics")

- Spin-triplet S=1 → **can be polarized!**
- Magnetic Moment μ_d ~0.86 μ_N ($< \mu_p+\mu_n$)
- Quadrupole moment ~0.2859 fm^2 (sizable)

→ Evidence for non-central (tensor) force

Deuteron Degrees of Freedom

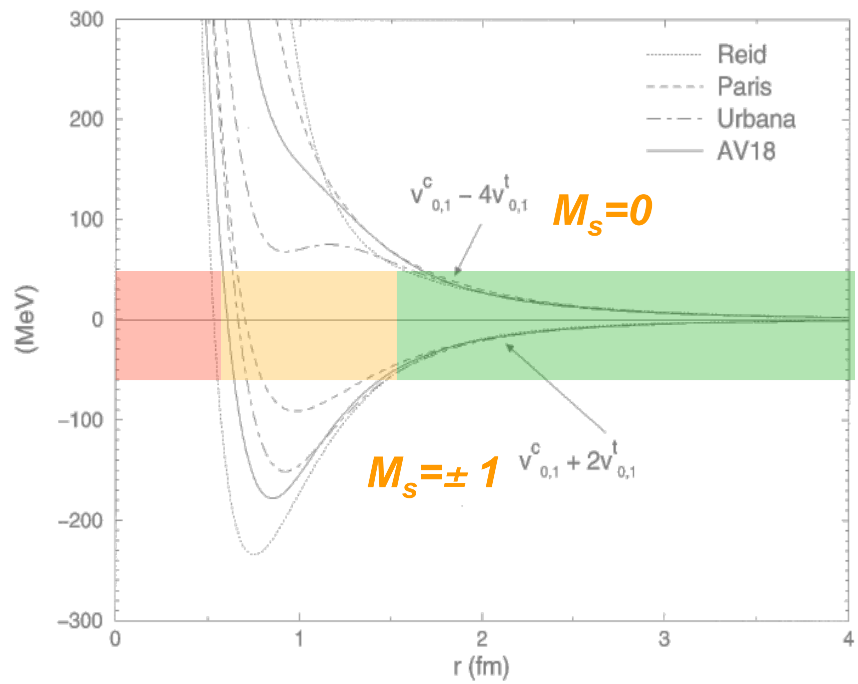


NN Interaction Potential

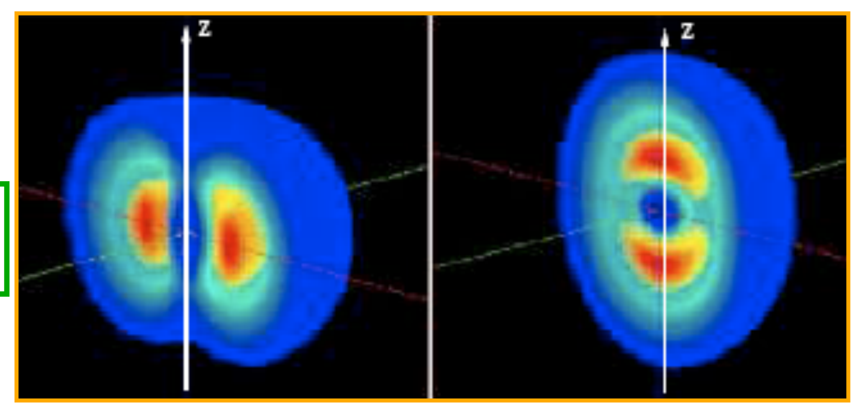
Structure ↔ Interaction

- Phenomenological NN potentials:
  OPE + 2-body + …
  P_D=4-6% ↔ tensor force
- Bound state (**structure**) generated by **interaction** potential minimum
- Repulsive core
- Q_d problem / πNN coupling

Interaction generating Structure



Tensor force generates bound deuteron state



EM Studies with Polarized Deuterium

- NN interaction: deuteron only bound state
  Spin-1 system $S = 1$; $M_S = 0, \pm 1$
  Tensor force ⟹ $L = 0, 2$ admixture

- Spin observables in elastic scattering and quasielastic electrodisintegration
  → Deuteron form factors G_C, G_Q, G_M
  → Spin-dependent momentum distributions $\rho_0(p), \rho_{\pm 1}(p)$
  probed by vector and tensor asymmetries

- Simultaneous study of
  Nuclear theory → NN potential and tensor force
  Reaction mechanism → FSI, MEC, IC, RC
  Nucleon properties → $G^p_{E/M}, G^n_{E/M}$

EM Studies with Polarized Deuterium

- Elastic ed: d(e,e'd)
- Quasielastic ed: d(e,e'p)n
- Pion electroprod.: d(e,e'π^+)nn, d(e,e'π^-)pp

BLAST: Longitudinally polarized electron beam
Vector and tensor polarized deuterium target
Large acceptance detector

→ Simultaneous measurements

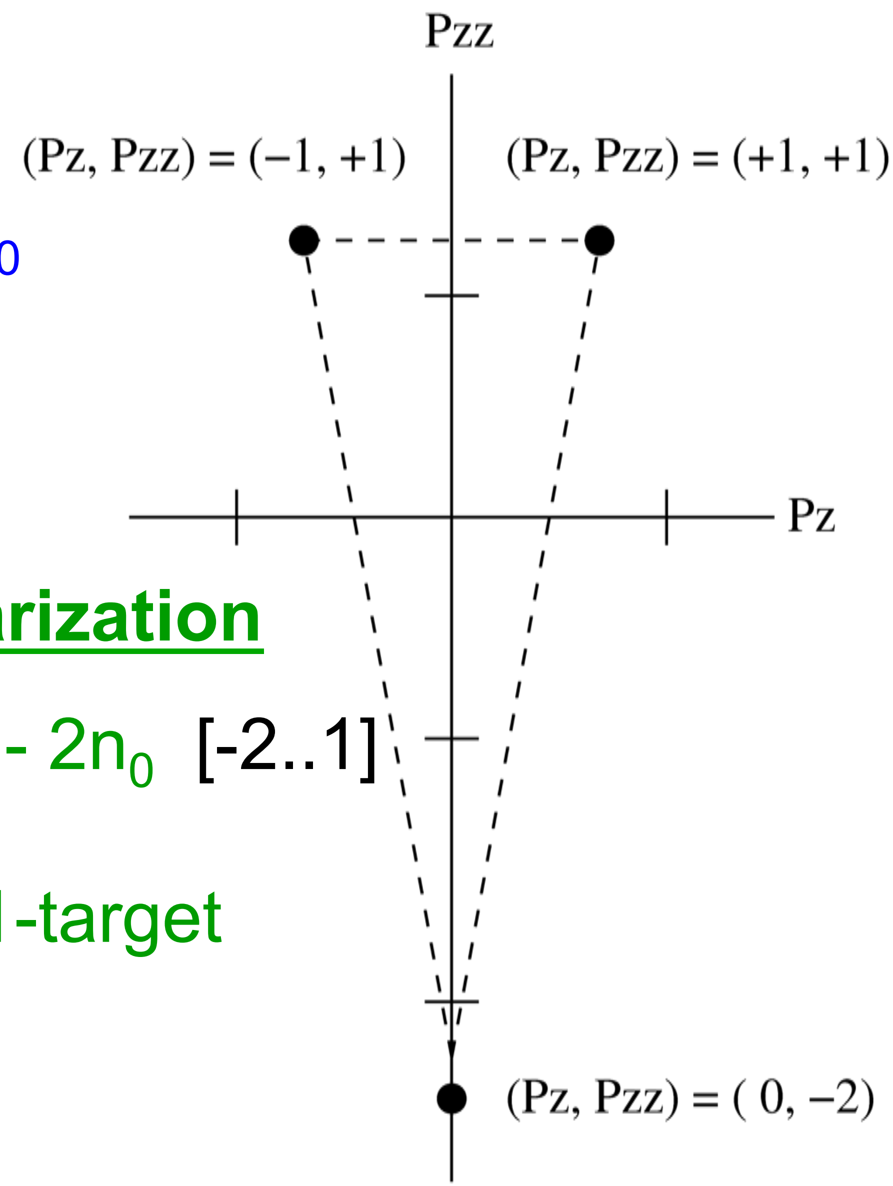
EM Studies with Polarized Deuterium

- Exploit **single and double polarization observables** to keep **systematic errors low**
- Exploit **internal target in storage ring** to provide **highly polarized, isotopically pure (background free) target**
- Exploit **large angular and energy acceptance** to provide **simultaneous measurement of all reaction channels** over complete Q^2 range
- Exploit **field free region at target** to allow orientation of **target polarization in any direction** → Toroid

→ **Bates Large Acceptance Spectrometer Toroid**

Polarized deuterium

- *$S=1$, $M_s= \pm 1, 0$*
- Population numbers $N = N_+ + N_- + N_0$
  $n_+ = N_+/N$, $n_- = N_-/N$, $n_0 = N_0/N$



Vector Polarization

$P_z = n_+ - n_-$ [-1…1]

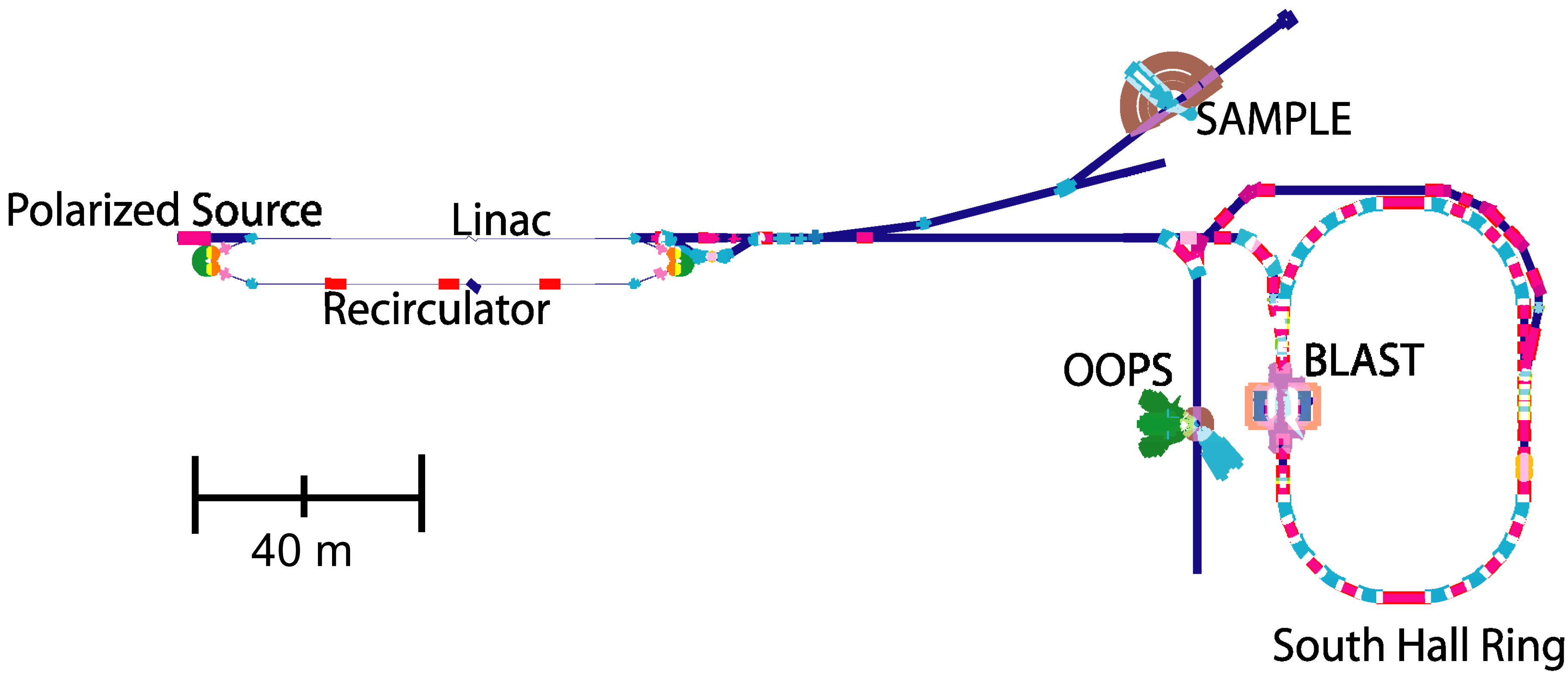
S-State: $\vec{N}$-target

Tensor Polarization

$P_{zz} = n_+ + n_- - 2n_0$ [-2..1]

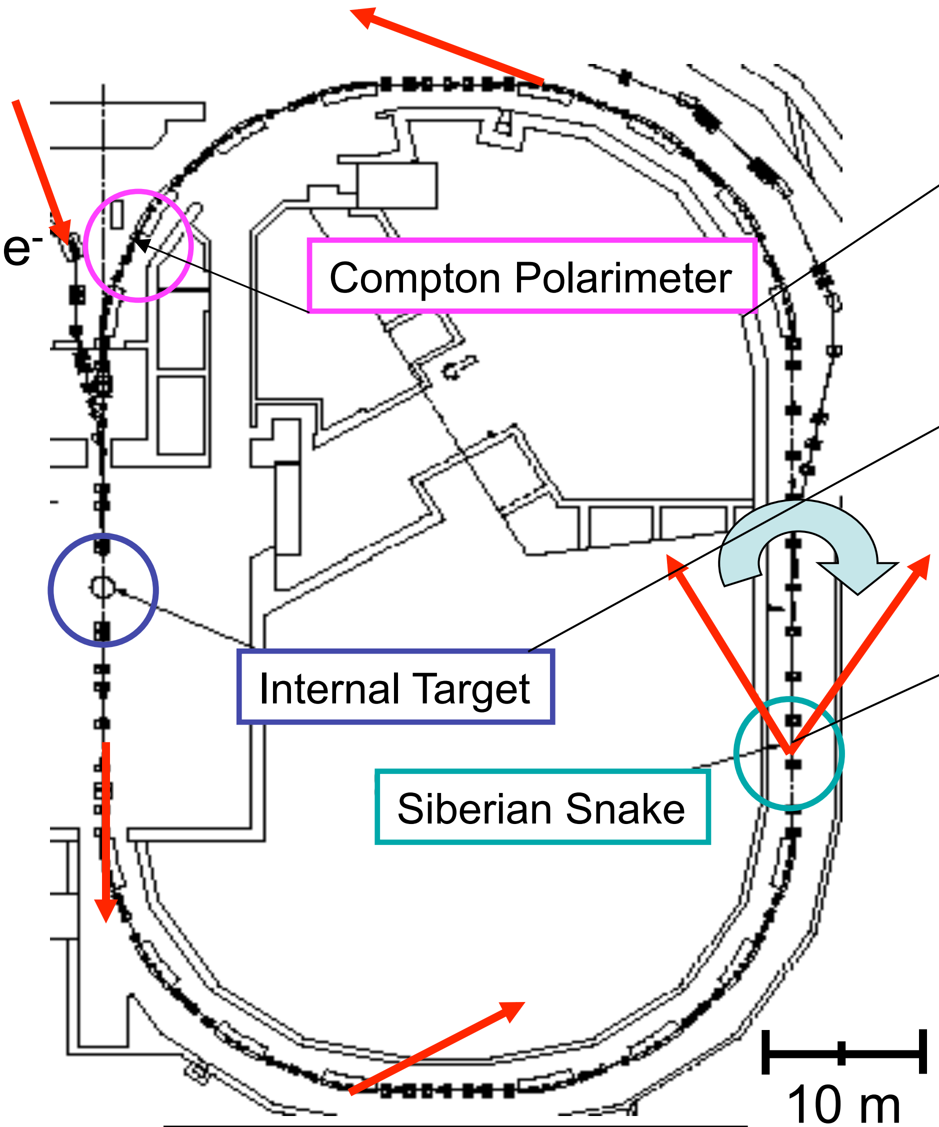
D-State: S=1-target

MIT-Bates Linear Accelerator Center



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

MIT-Bates South Hall Ring



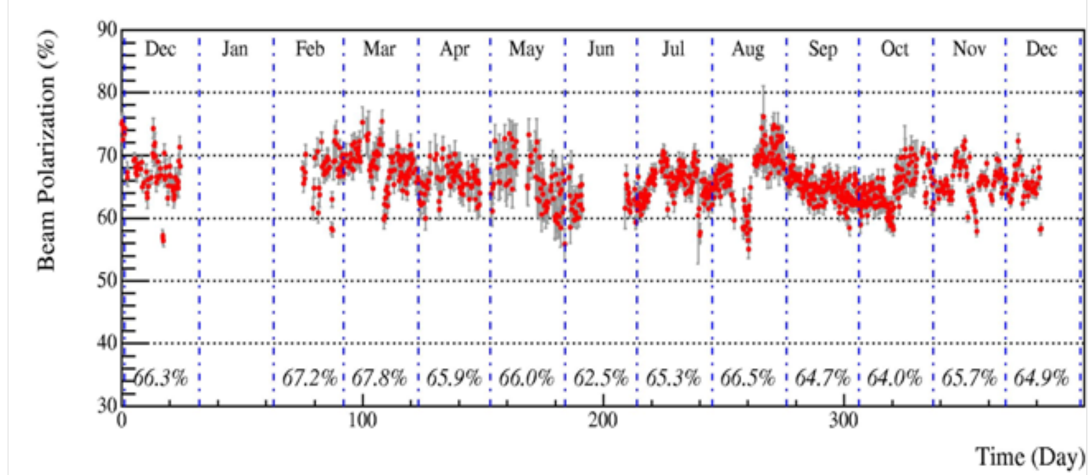
Monitoring of electron beam polarization

Injection with longitudinal spin at internal target

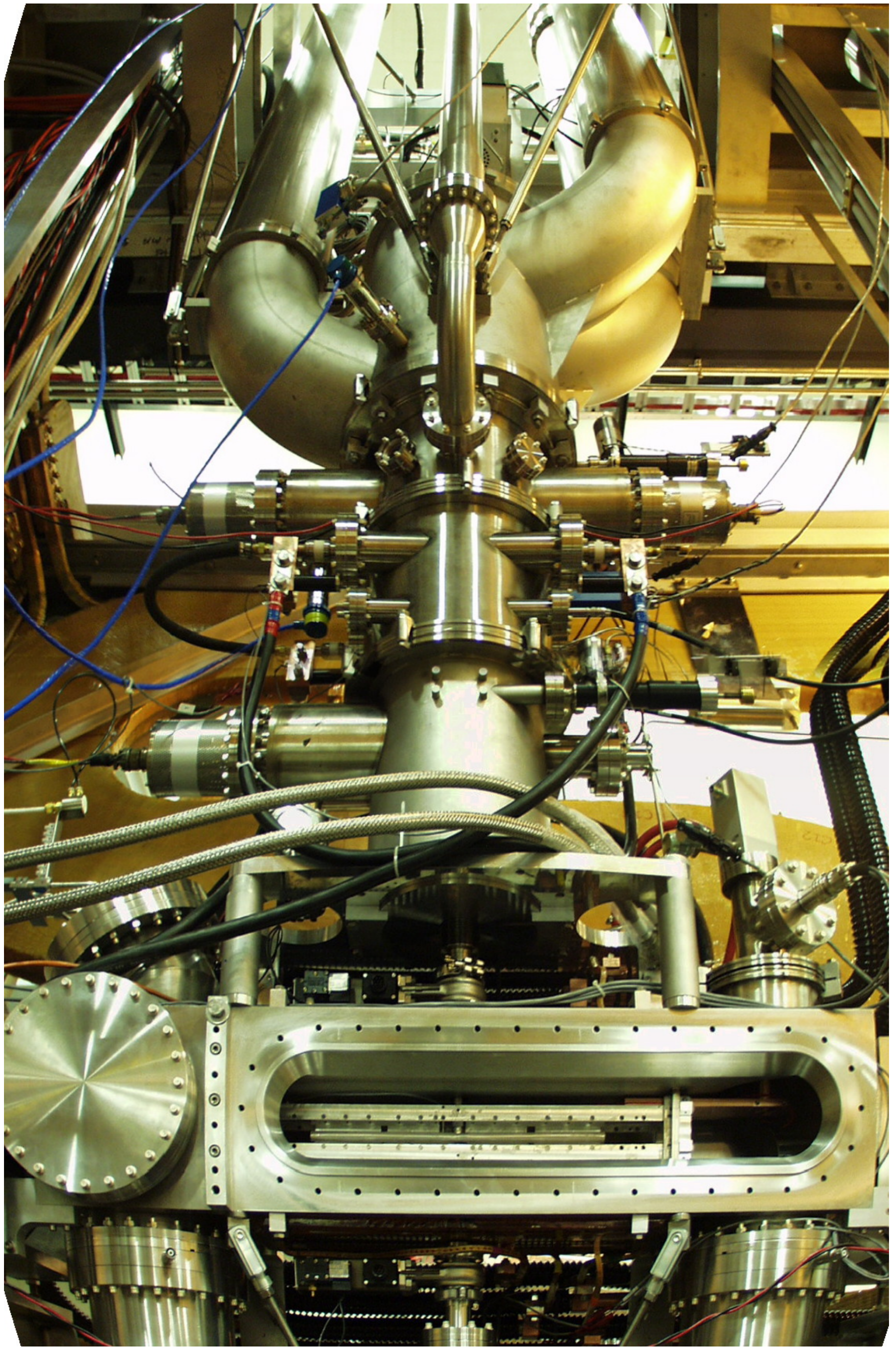
Siberian snake to restore longitudinal polarization

In-plane spin transport

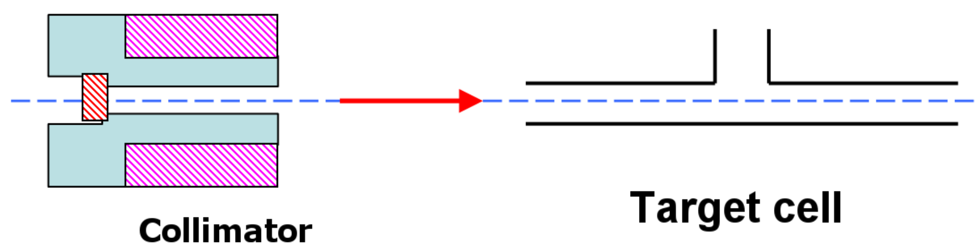
$P_e = 0.65 \pm 0.04$



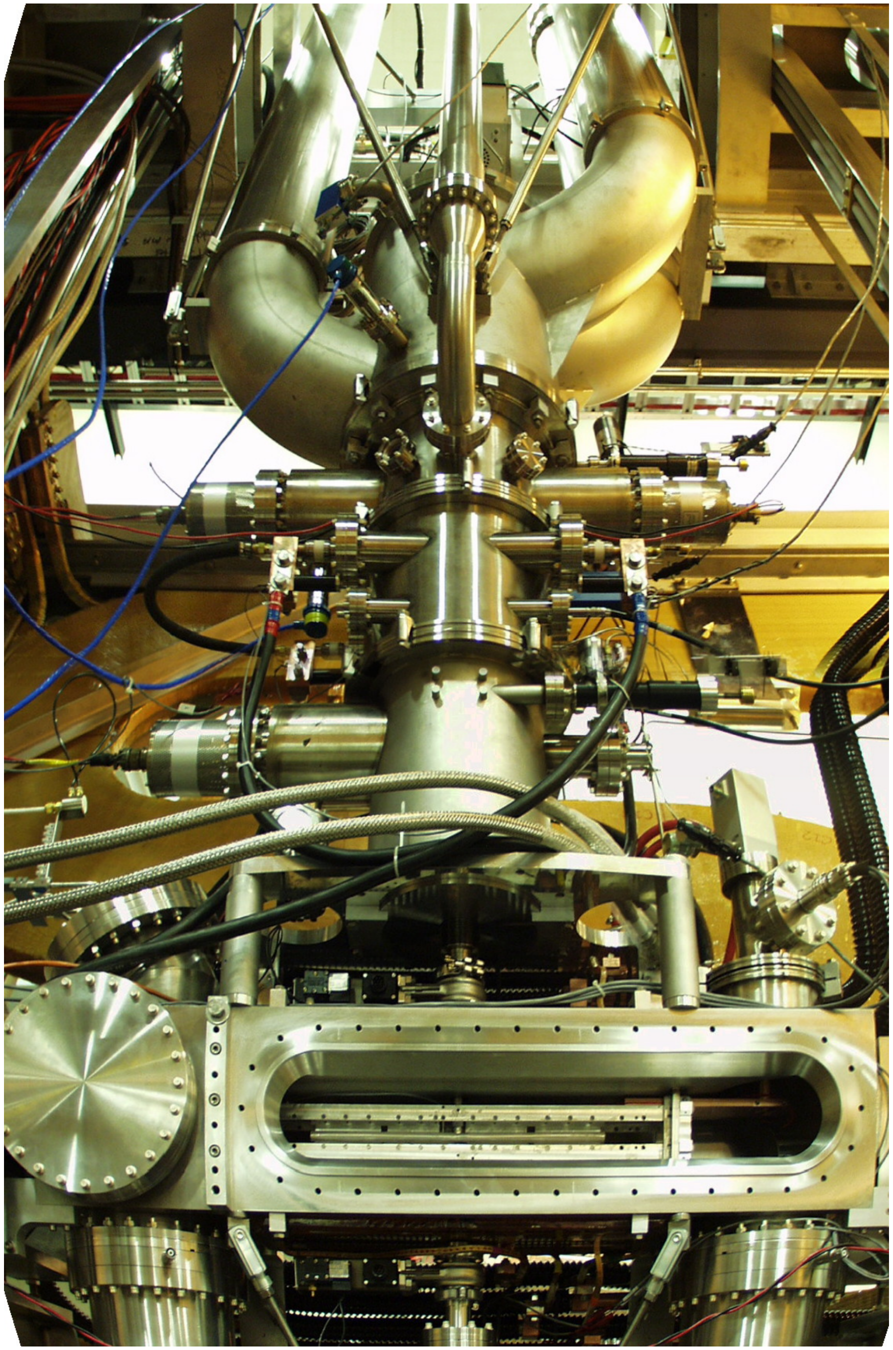
Atomic Beam Source (ABS)

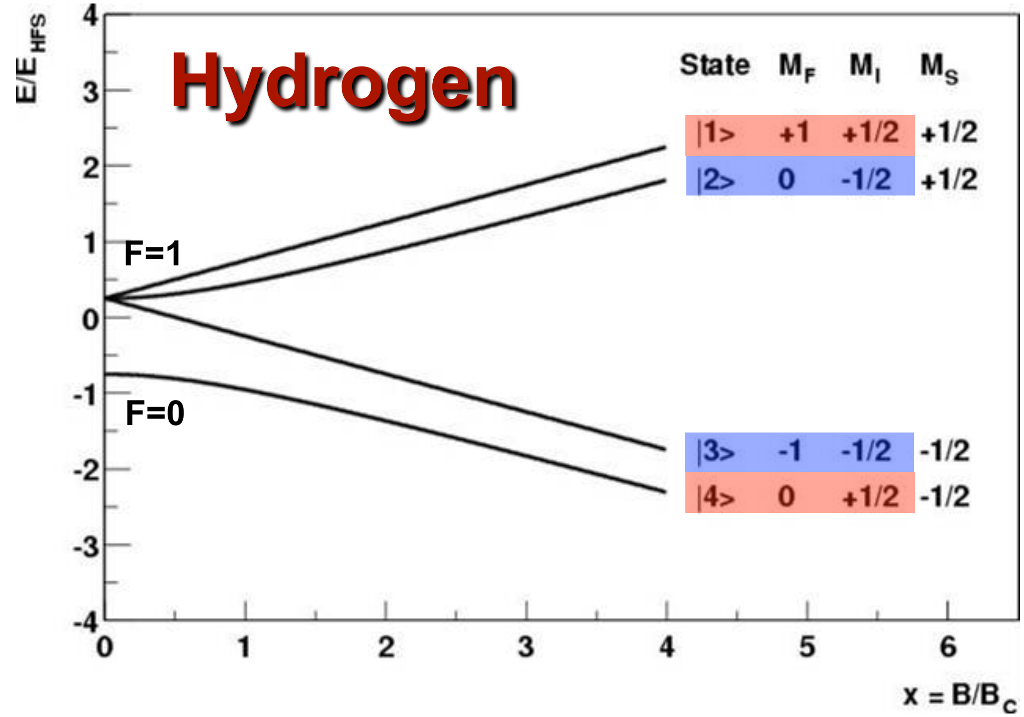


- **Isotopically pure H or D atoms**
  (Vector-) polarized H
  Vector- and tensor-polarized D
- **Target thickness / luminosity**
  $\rho=6x10^{13}$ at/cm^2, $L=6x10^{31}/(cm^2s)$
- **Operated within BLAST B-field**
  B_{max} = 3.8 kG
- **Target polarization 70-80%**
  P_z, P_{zz} from low Q^2 analysis



Atomic Beam Source (ABS)

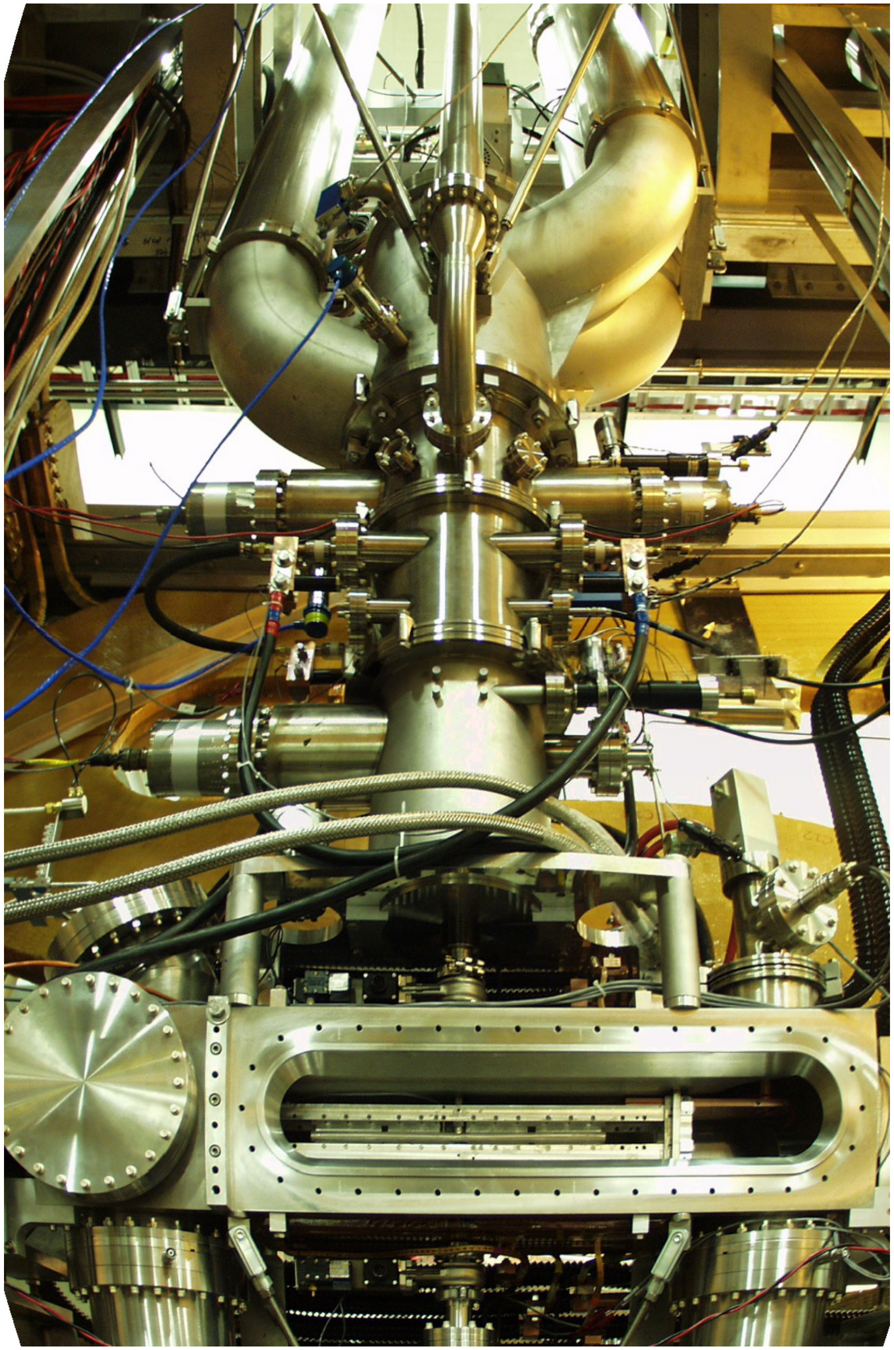




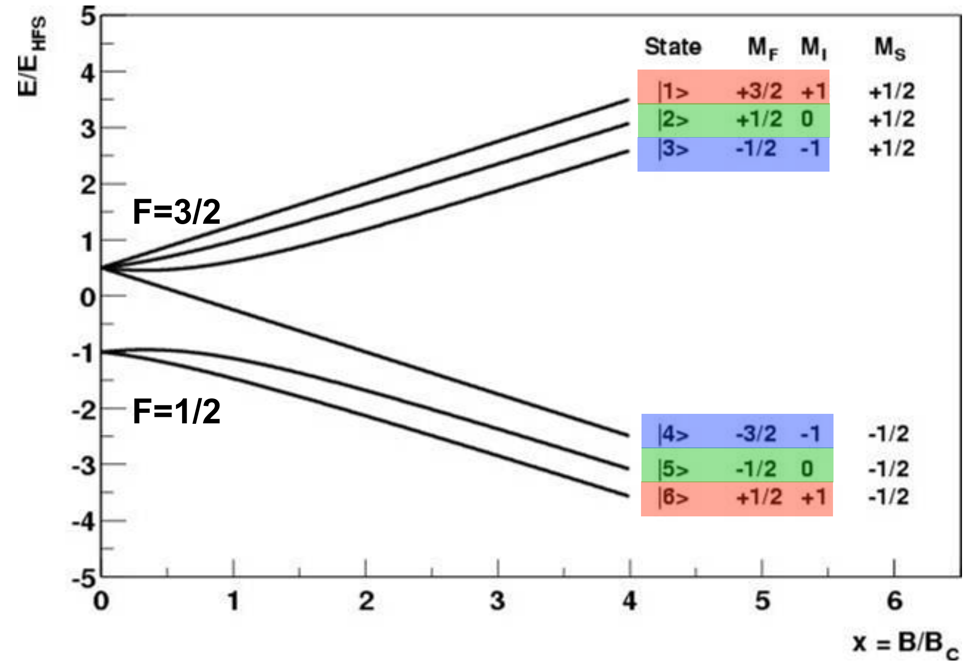
- Separately prepare m_I = **+½**, **-½** (**hydrogen**) and

  with sextupoles and RF transitions
- Switch between states every 5 minutes

Atomic Beam Source (ABS)



Deuterium



- Separately prepare m_I = **+½**, **-½** (**hydrogen**) and m_I = **+1**, **0**, **-1** (**deuterium**) with sextupoles and RF transitions
- Switch between states every 5 minutes

ABS transition sequences

V+: M = +1

$$\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \end{pmatrix} \xrightarrow{6-pole} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ 0 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{MFT} \begin{pmatrix} n_1 \\ n_2 \\ 0 \\ n_4 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{6-pole} \begin{pmatrix} n_1 \\ n_2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{SFT} \begin{pmatrix} n_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ n_6 \end{pmatrix}$$

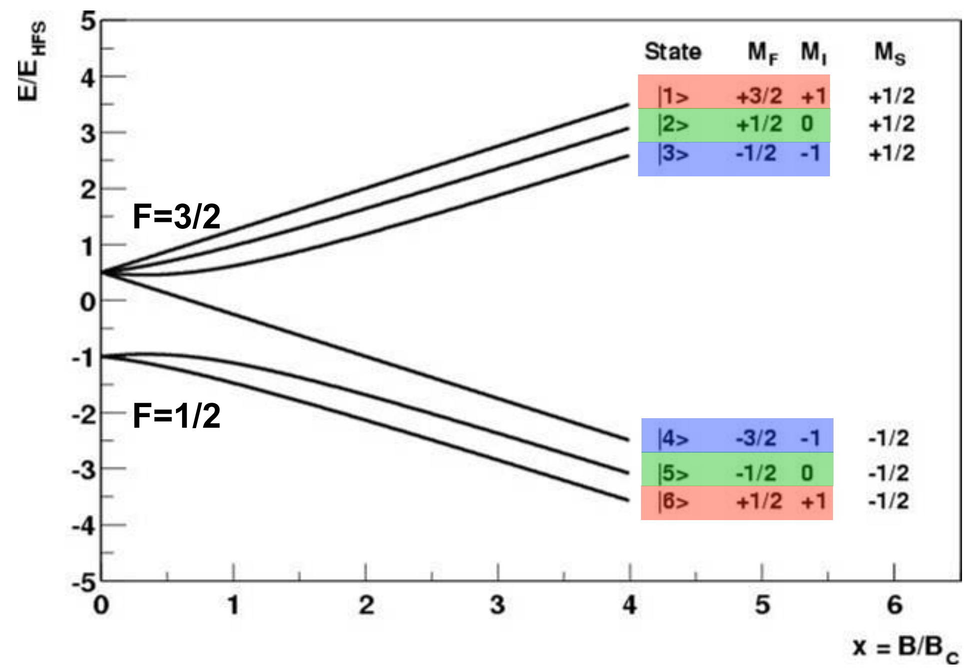
V-: M = -1

$$\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \end{pmatrix} \xrightarrow{6-pole} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ 0 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{MFT} \begin{pmatrix} n_1 \\ n_2 \\ 0 \\ n_4 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{6-pole} \begin{pmatrix} n_1 \\ n_2 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{WFT} \begin{pmatrix} 0 \\ 0 \\ n_3 \\ n_4 \\ 0 \\ 0 \end{pmatrix}$$

T-: M = 0

$$\begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ n_4 \\ n_5 \\ n_6 \end{pmatrix} \xrightarrow{6-pole} \begin{pmatrix} n_1 \\ n_2 \\ n_3 \\ 0 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{MFT} \begin{pmatrix} 0 \\ n_2 \\ n_3 \\ n_4 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{6-pole} \begin{pmatrix} 0 \\ n_2 \\ n_3 \\ 0 \\ 0 \\ 0 \end{pmatrix} \xrightarrow{SFT} \begin{pmatrix} 0 \\ n_2 \\ 0 \\ 0 \\ n_5 \\ 0 \end{pmatrix}$$

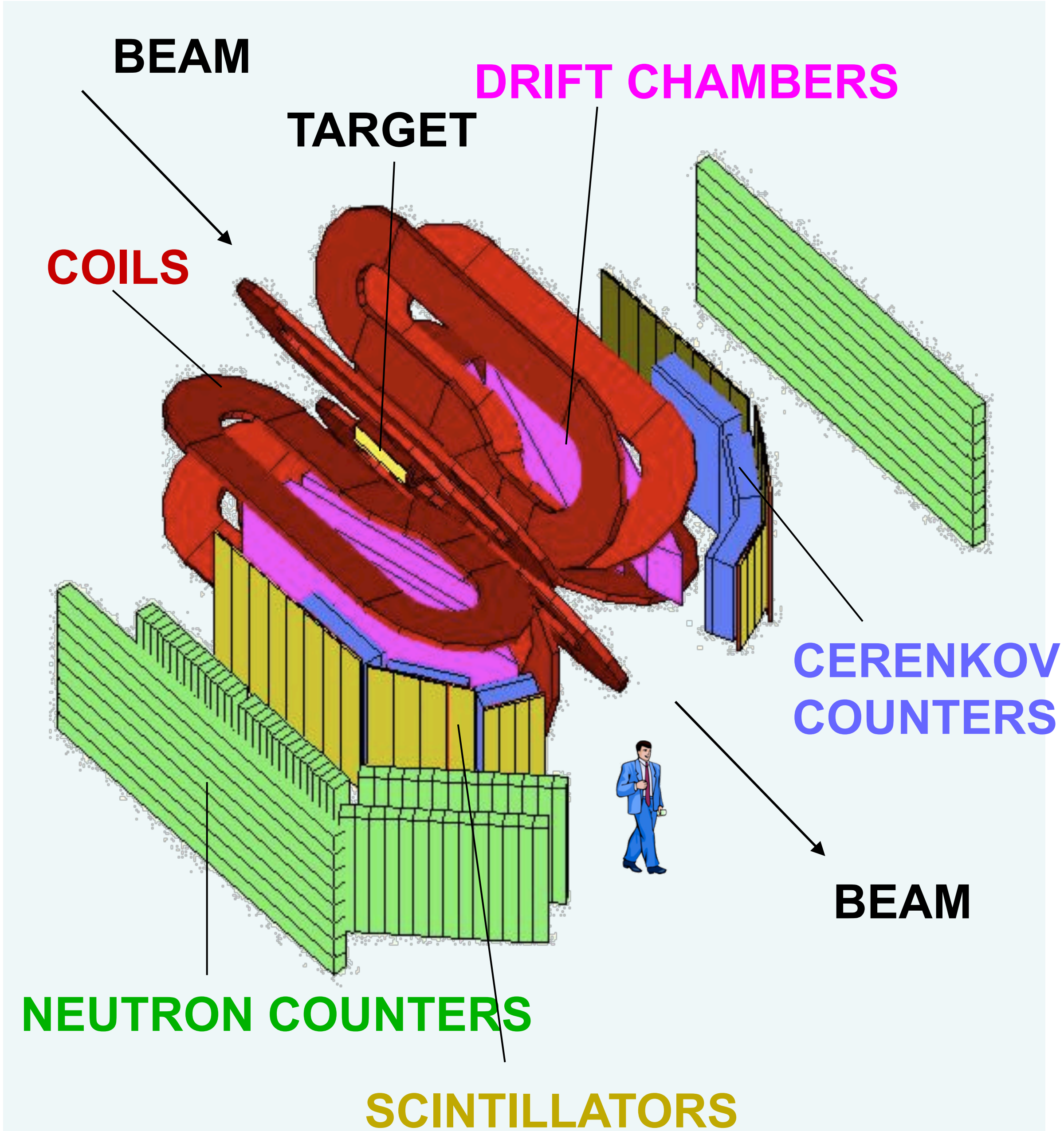
Deuterium



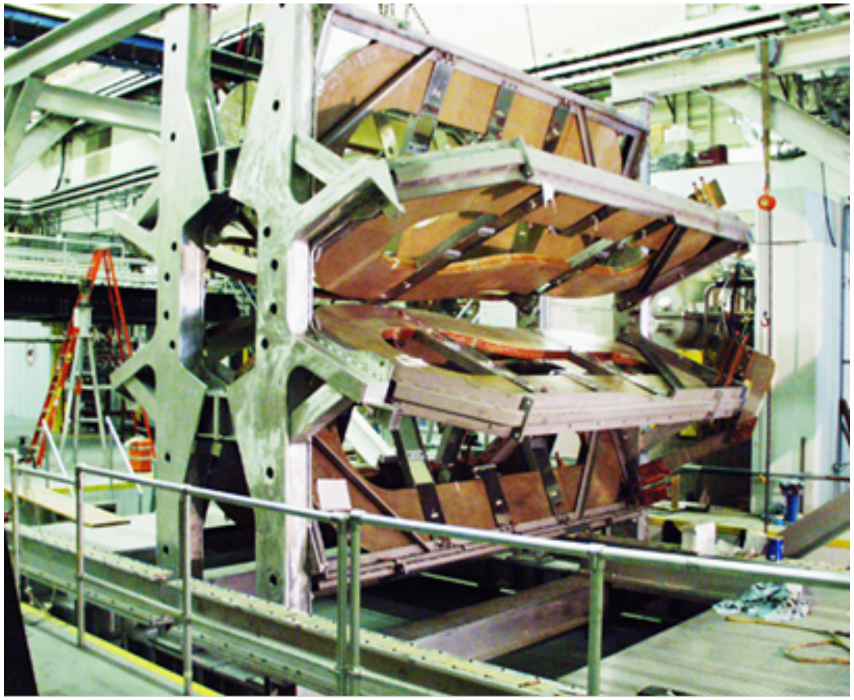
- Separately prepare m_I = **+½, -½** (**hydrogen**) and m_I = **+1, 0, -1** (**deuterium**) with sextupoles and RF transitions
- Switch between states every 5 minutes

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)

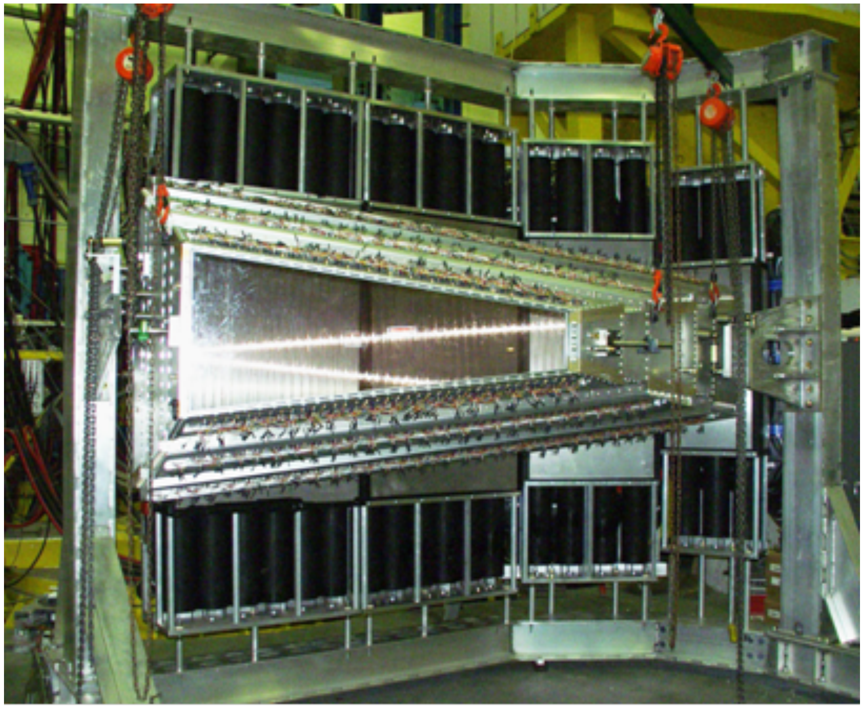


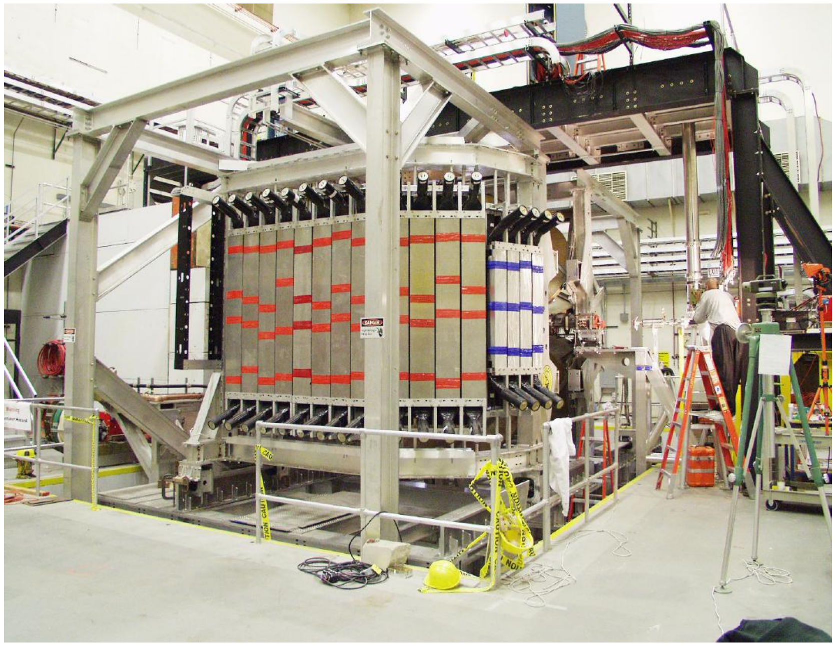
The BLAST Detector



Bates

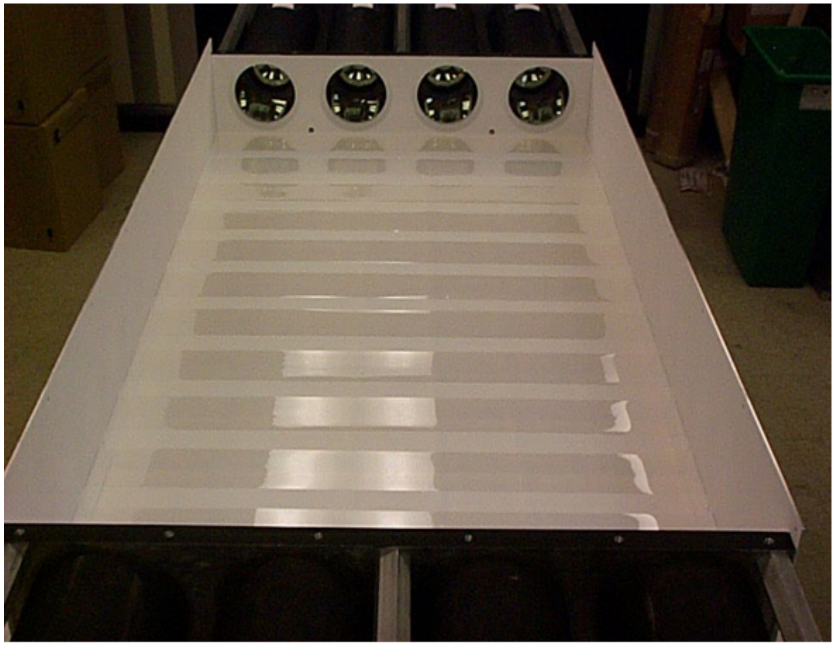
MIT





UNH

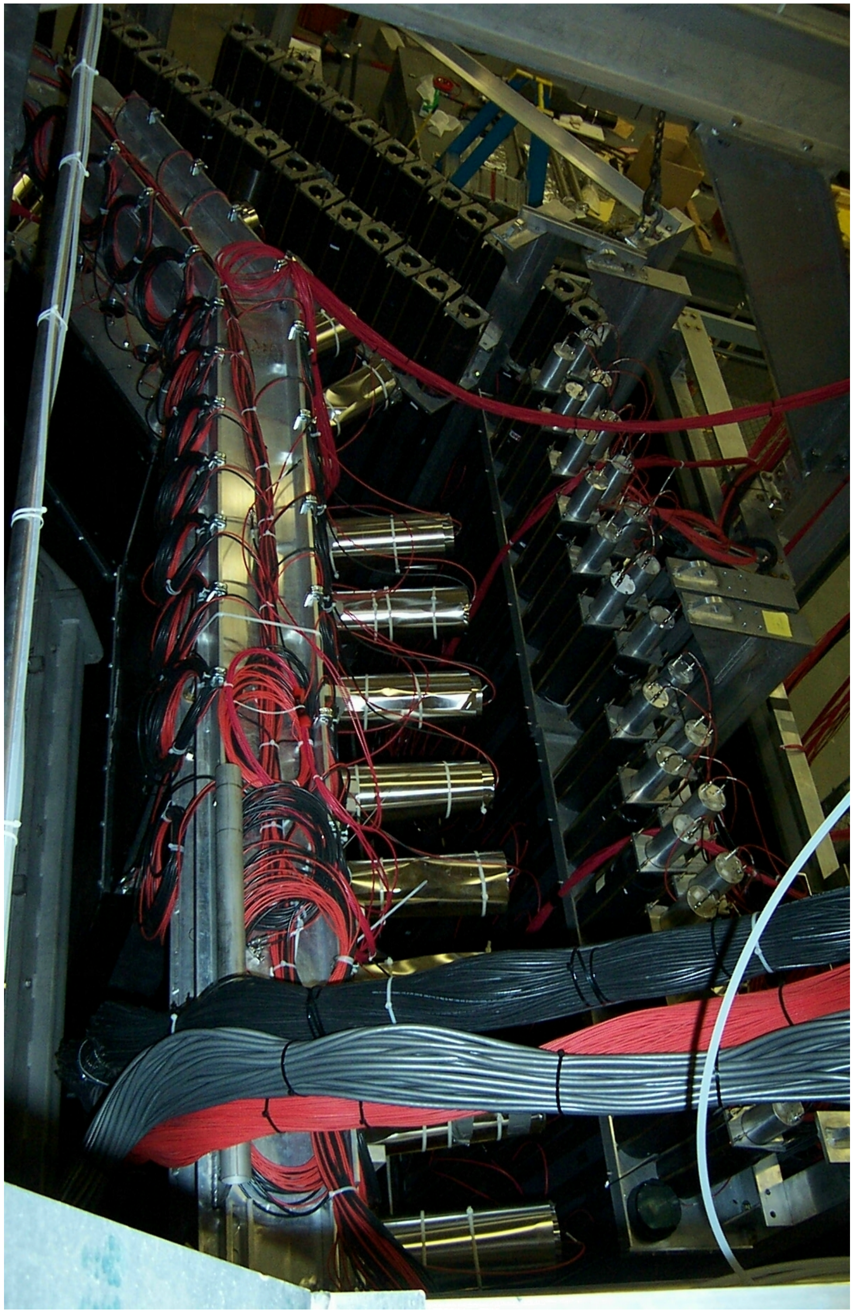
ASU



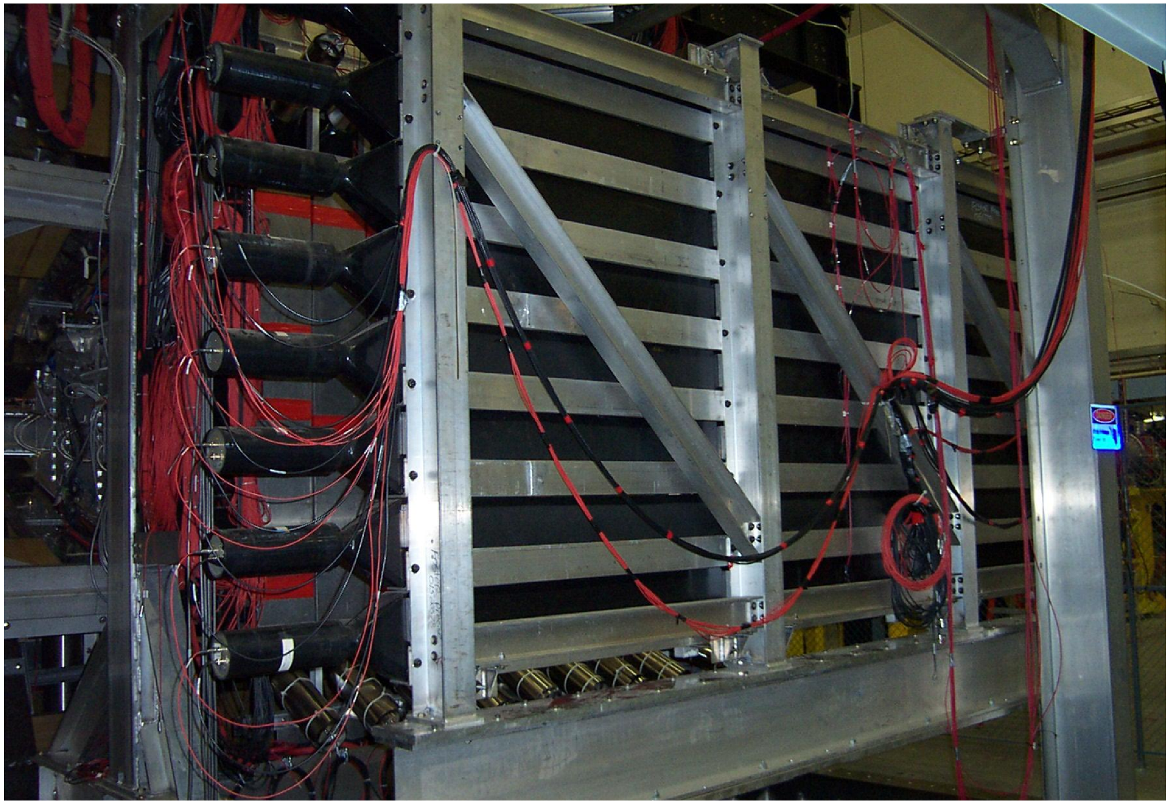
The BLAST Detector

Neutron Detectors

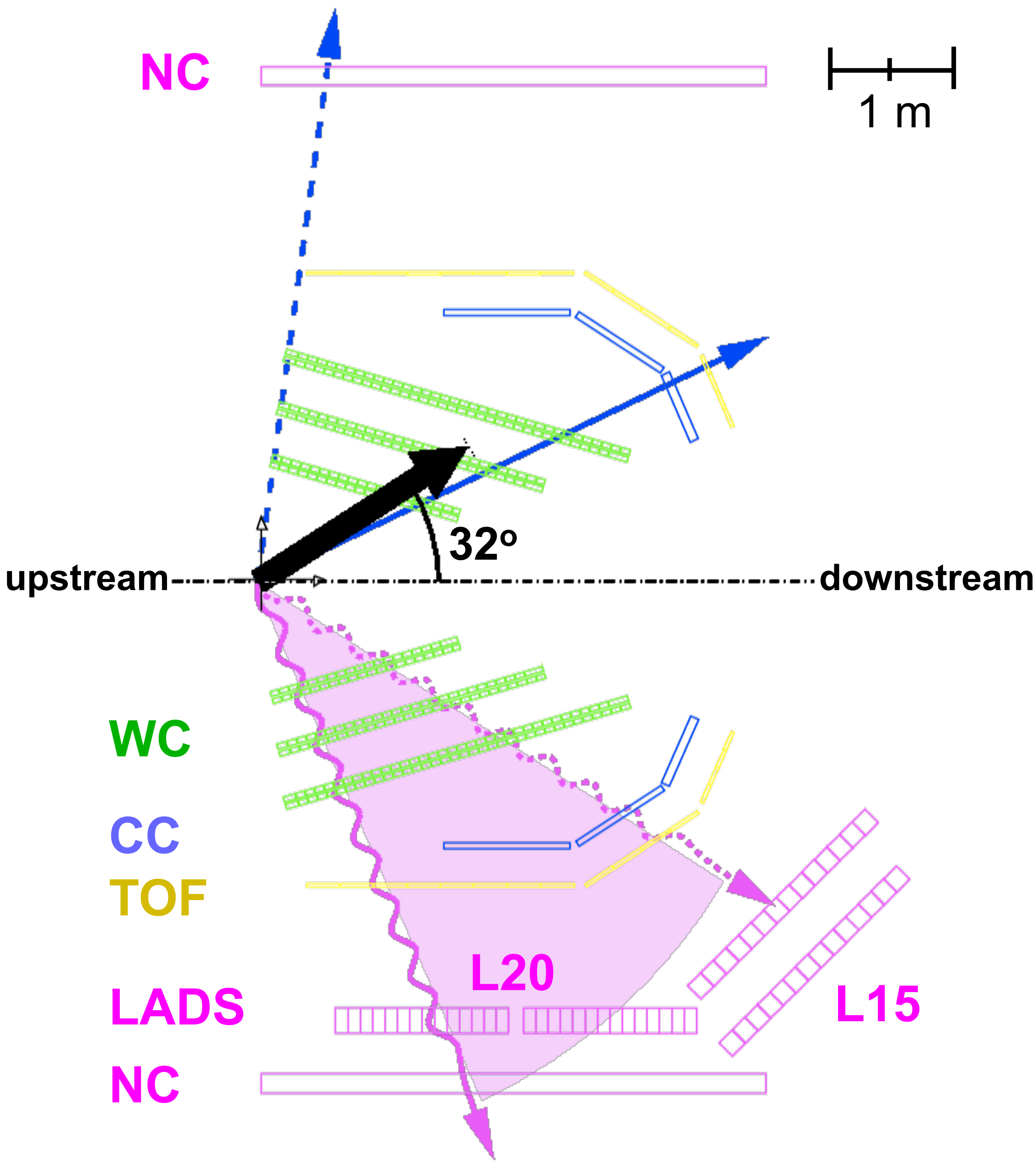
Bates



Ohio University



Target Spin Orientation



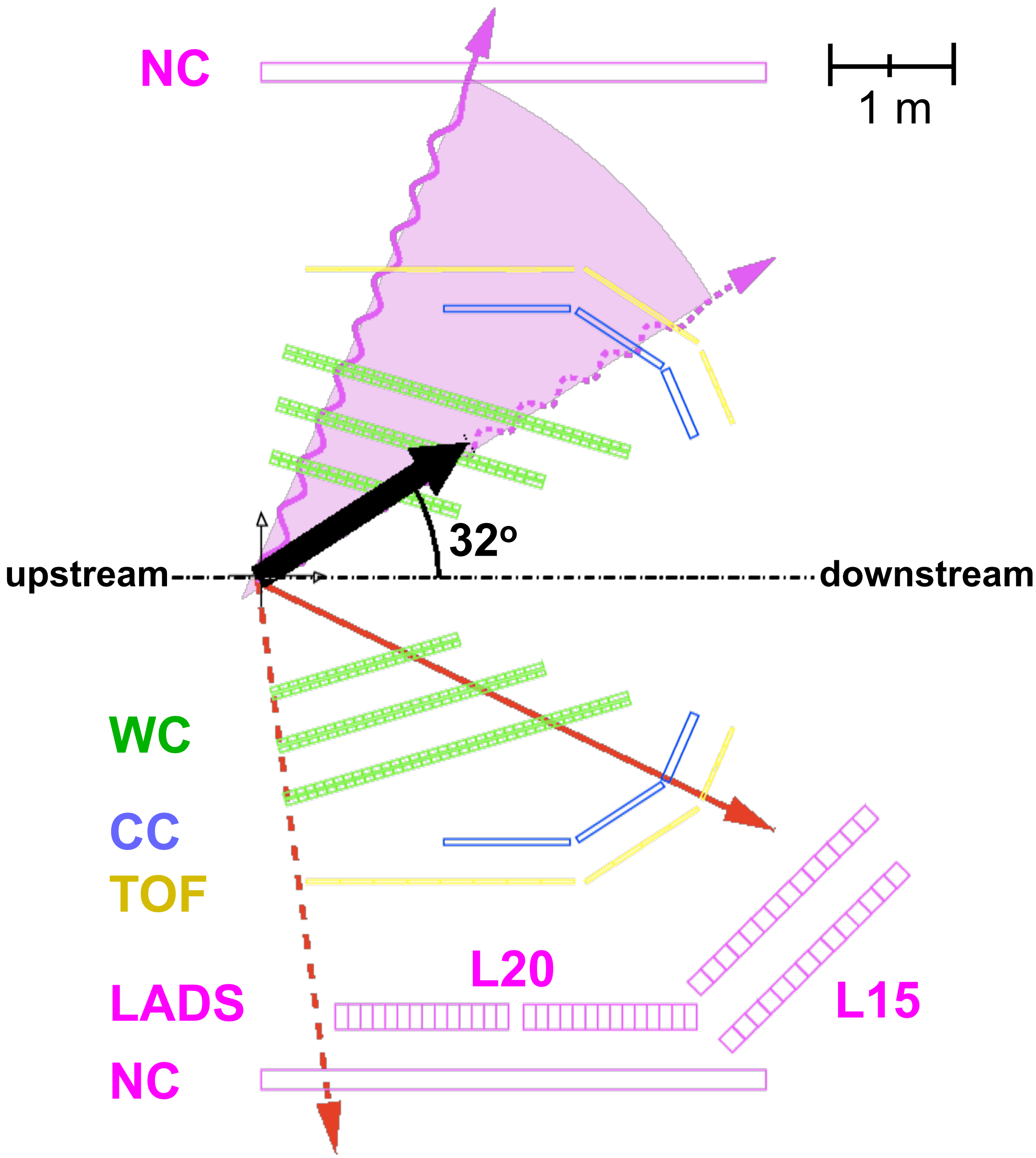
Freedom of in-plane spin angle

32^{o} (2004) / 47^{o} (2005)

e- left → θ* ≈ 90^{o}

"spin-perpendicular"

Target Spin Orientation



Freedom of in-plane spin angle
32° (2004) / 47° (2005)

e- left → $\theta^* \approx 90°$
"spin-perpendicular"

e- right → $\theta^* \approx 0°$
"spin-parallel"

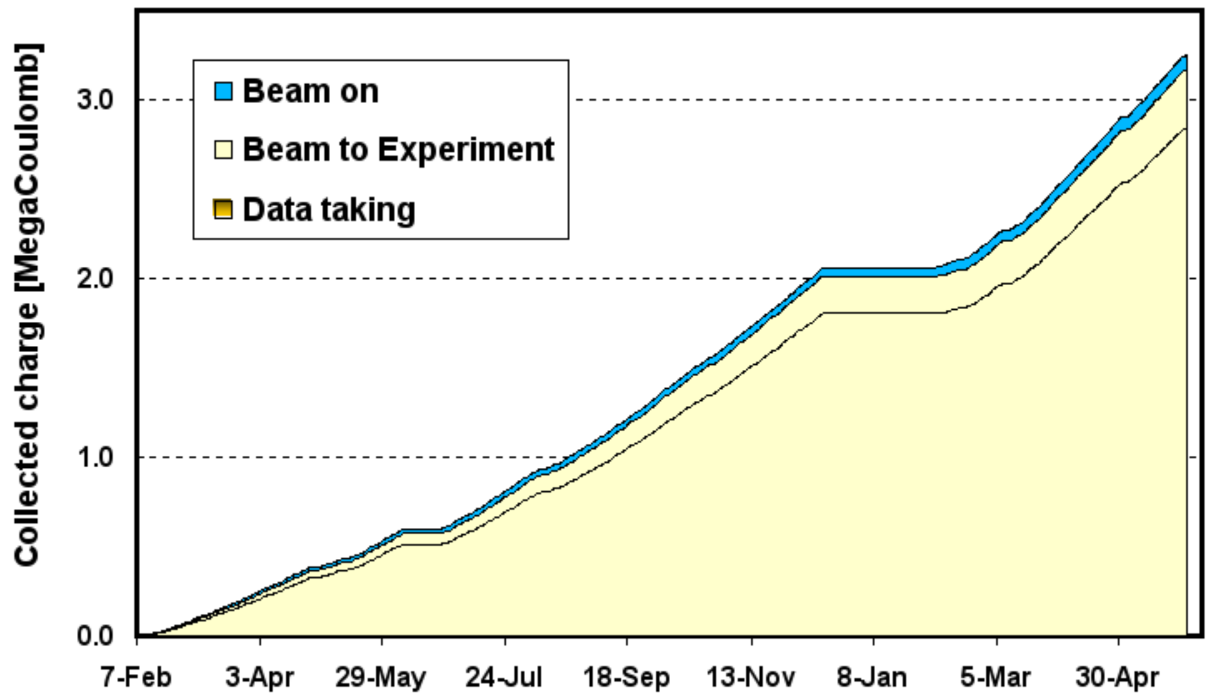
BLAST Data Collection

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

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

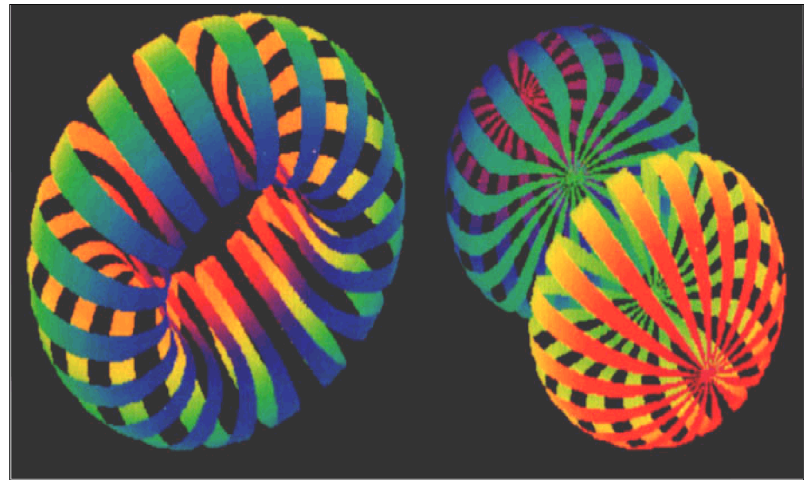
- **Deuterium 2004**
  θ_d = 32°, 450 kC (**169 pb^{-1}**)
  P_z = 86%, P_{zz} = 68%

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



Elastic Electron-Deuteron Scattering

- Spin 1 ↔ three elastic form factors
  G^d_C, G^d_Q, G^d_M
- Quadrupole moment
  $M^2_d Q_d = G^d_Q(0) = 25.83$
- G^d_Q ↔ Tensor force, D-wave



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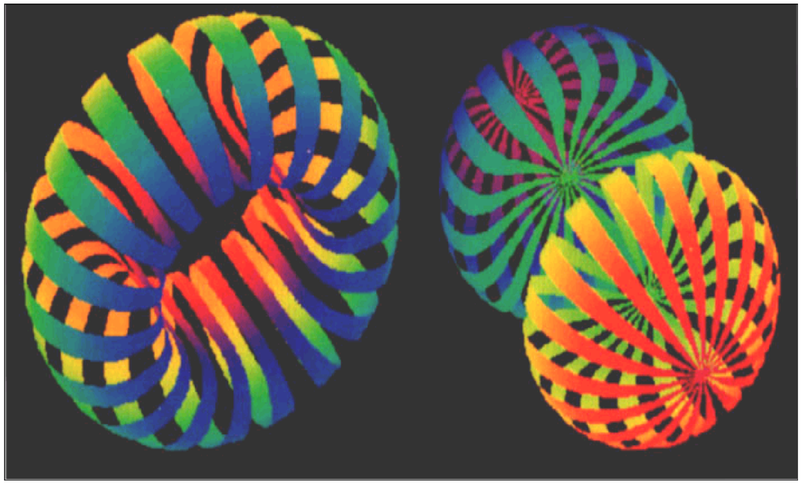

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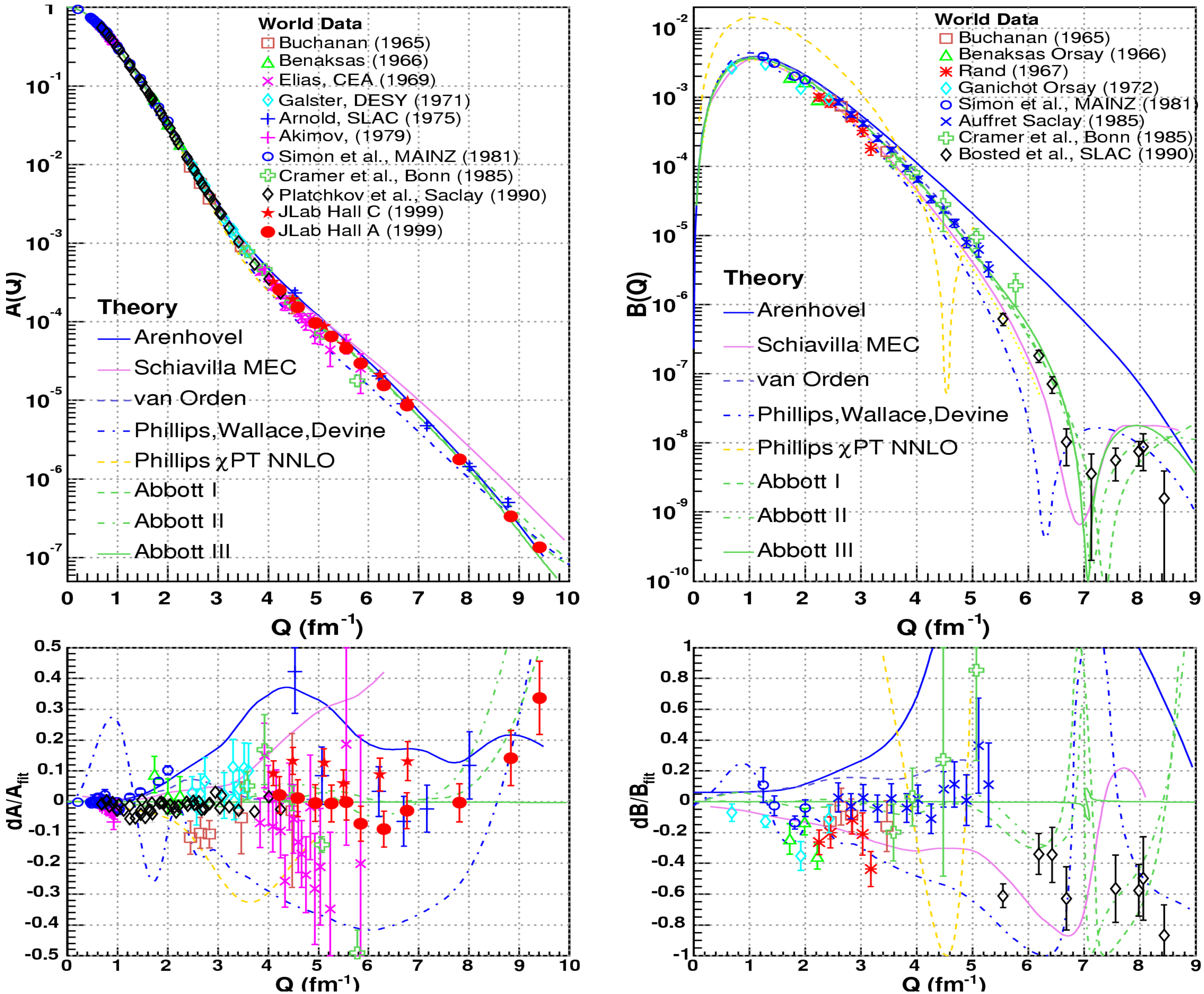
- Quadrupole moment
  $M^2_d Q_d = G^d_Q(0) = 25.83$
- G^d_Q ↔ Tensor force, D-wave
- Unpolarized elastic cross section

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

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

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

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)
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Cramer et al., Bonn (1985)
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Theory
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Abbott III
B(Q)
Q (fm⁻¹)
dA/A_fit
Q (fm⁻¹)
dB/B_fit
Q (fm⁻¹)

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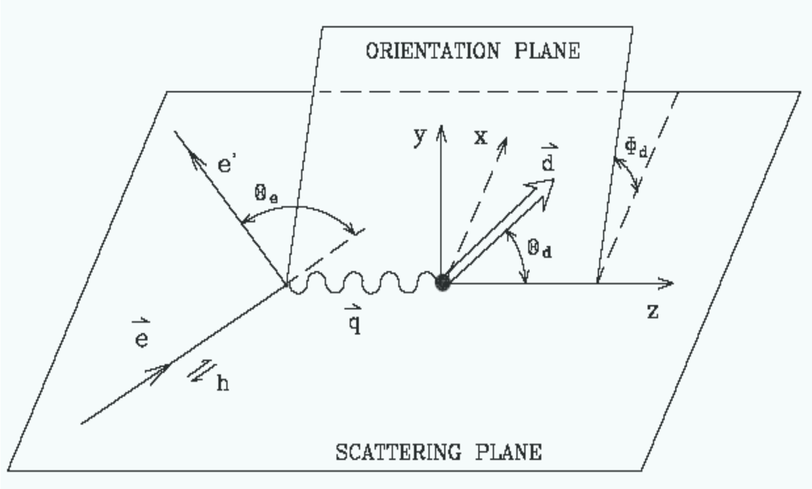

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$$B(Q^2) = \frac{4}{3}\eta(1+\eta){G^d_M}^2; \quad \eta = Q^2/(4M_D^2)$$

- Polarized cross section

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

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

Tensor-pol. Elastic ed Scattering

- Tensor asymmetry and tensor analyzing powers

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

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

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

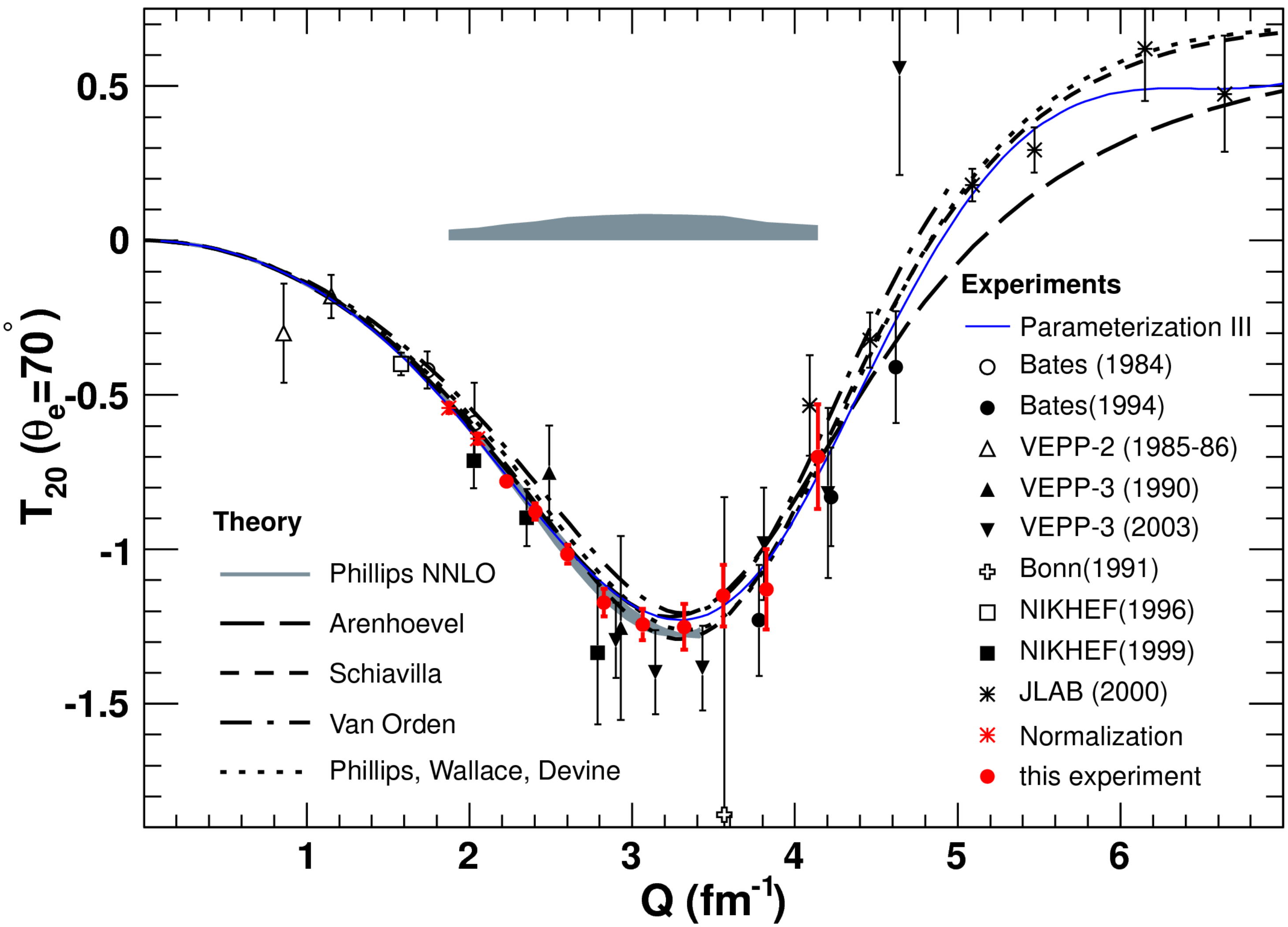
$$T_{22}(Q^2,\theta_e) = -\frac{1}{2\sqrt{3}S_0}\eta\, {G_M^d}^2$$

- 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}*

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



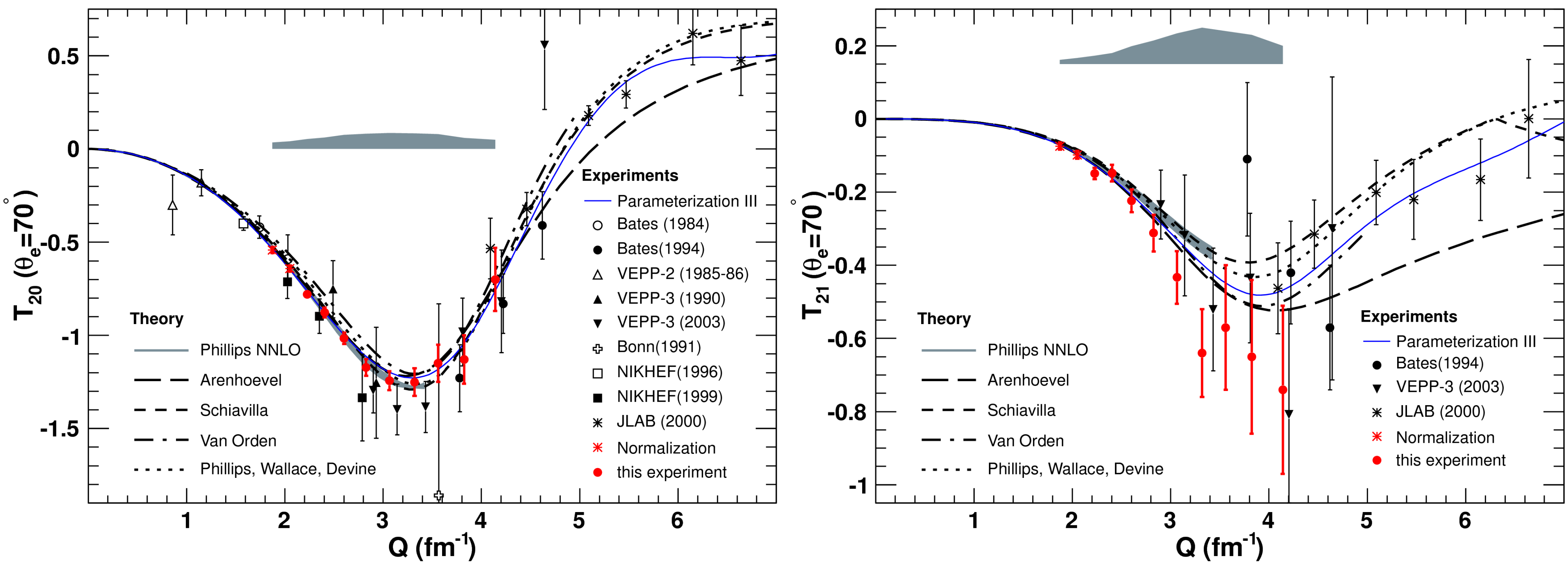
*Ph.D. work of C. Zhang (MIT)

C. Zhang, M.K. et al., PRL107, 0252501 (2011)

Tensor analyzing powers T_{20}, T_{21}*

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

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



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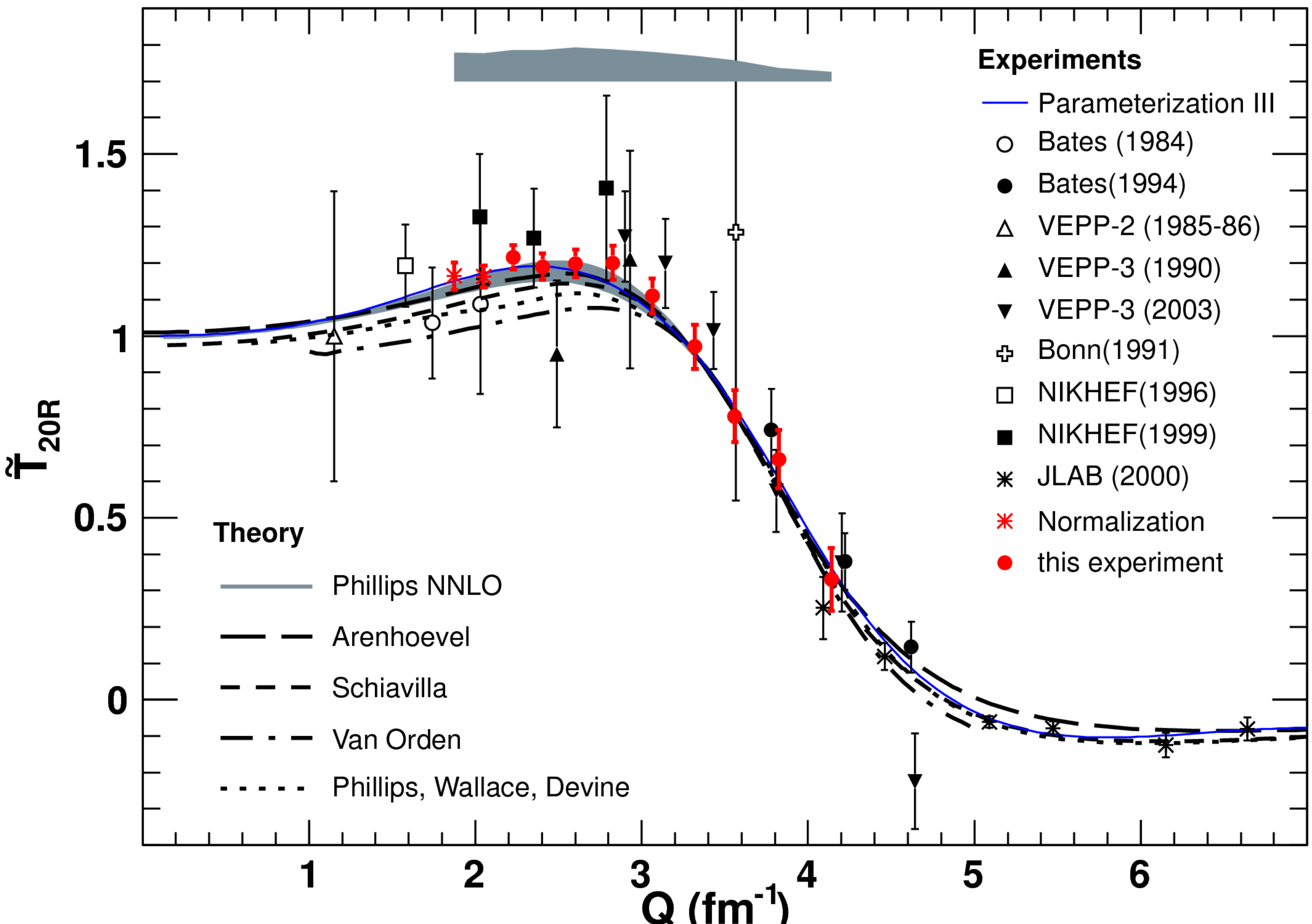
Reduced Tensor Analyzing Power T_{20R}*

$$\tilde{T}_{20R} = -\frac{3}{\sqrt{2}Q_d Q^2}\tilde{T}_{20}$$

The Q_d problem

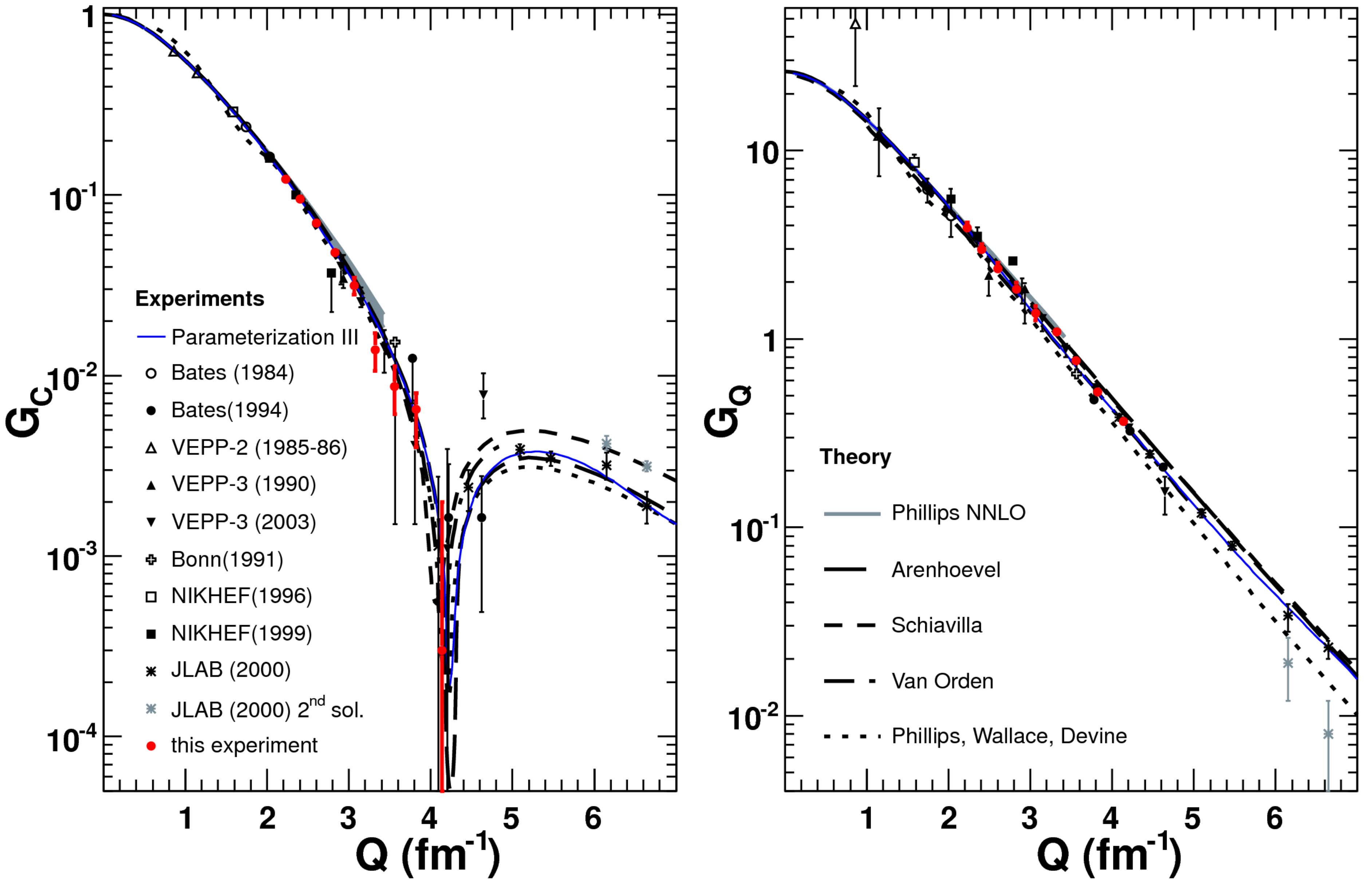
D. Phillips, J. Phys. G 34, 365 (2007)



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

C. Zhang, M.K. et al., PRL107, 0252501 (2011)

G_C and G_Q *



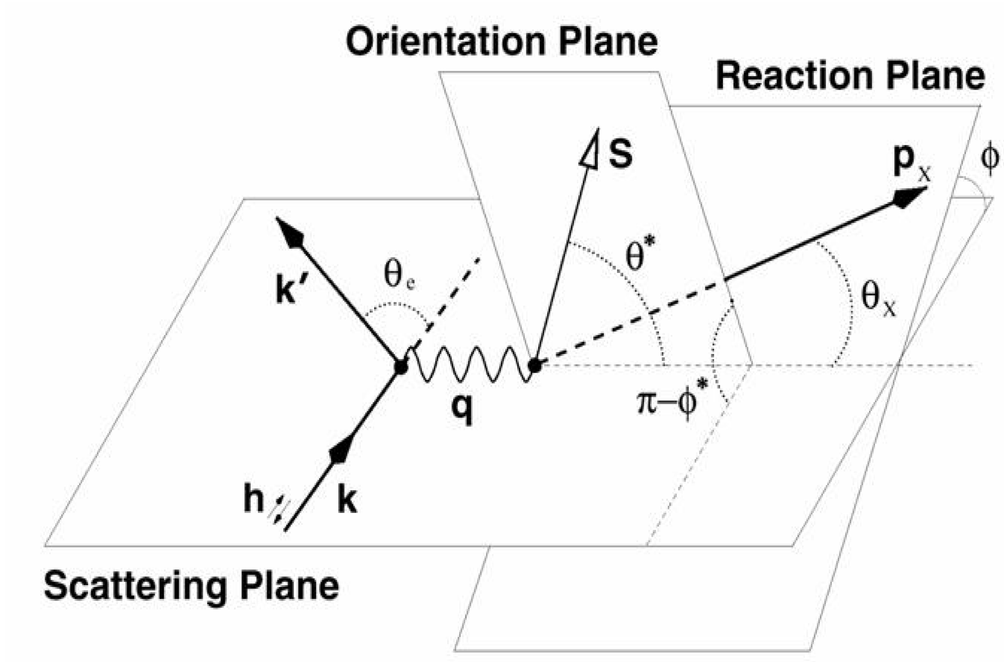
Node of charge form factor confirmed at 4.19(5) fm^{-1}

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

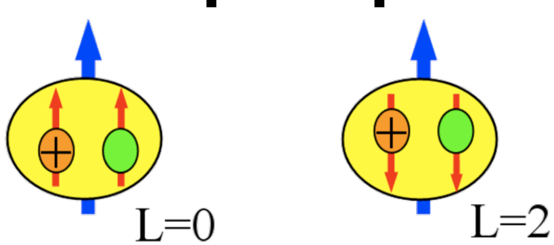
C. Zhang, M.K. et al., PRL107, 0252501 (2011)

Deuteron Electrodisintegration

- **Quasielastic breakup**
  e + d $\rightarrow$ e' + p + n
- **D(e,e'p), PWIA:**
  $\vec{p}_m = \vec{q} - \vec{p}_p = -\vec{p}_{p,l}$
- $$\frac{\sigma}{\sigma_0} = (1 + P_{zz} A_d^T + h P_z A_{ed}^V)$$

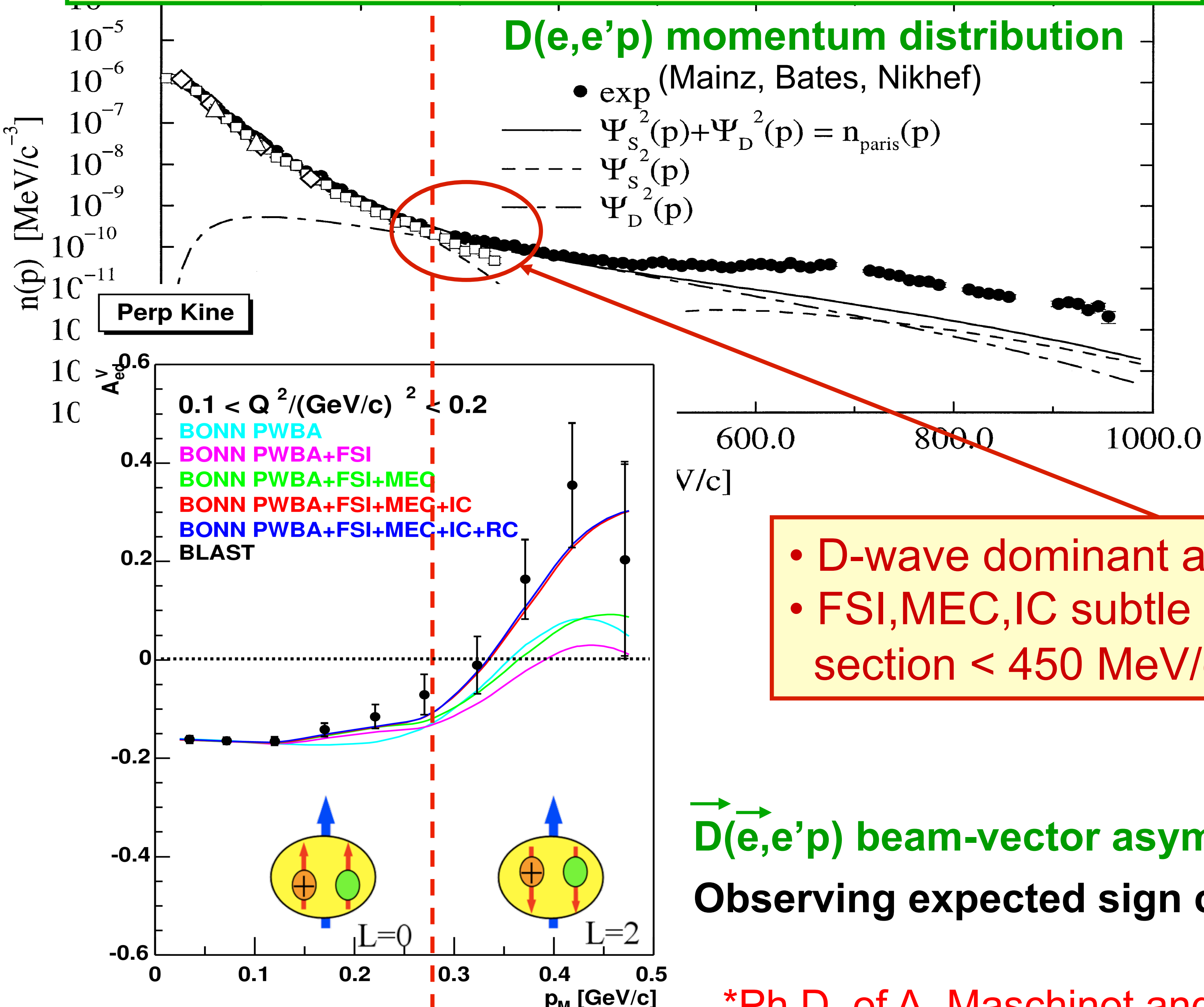


- **Beam-vector asymmetry (PWIA):**
  $$A_{ed}^V(p,n) = \frac{a \cos\theta^* + b\left(G_E^{p,n}/G_M^{p,n}\right)\sin\theta^*\cos\phi^*}{1 + c\left(G_E^{p,n}/G_M^{p,n}\right)^2}$$
- **Nucleon spins parallel** $\rightarrow A_{ed}^V\,(p_{miss})$ **changes sign**



Deuteron Electrodisintegration *

A. DeGrush, A. Maschinot et al., PRL 119, 182501 (2017)



- D-wave dominant at p_m>300 MeV/c
- FSI,MEC,IC subtle effects in cross section < 450 MeV/c

D(e,e'p) beam-vector asymmetry

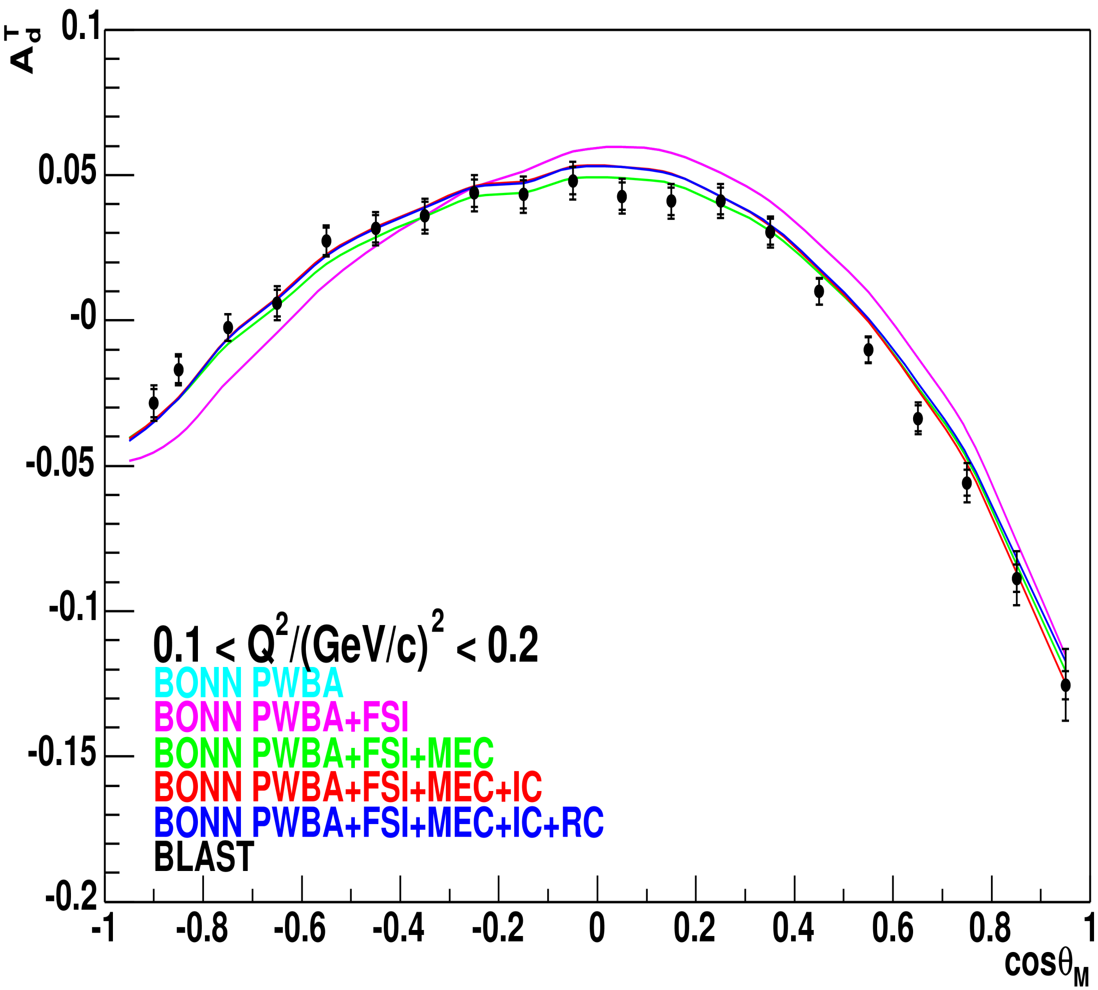
Observing expected sign change!

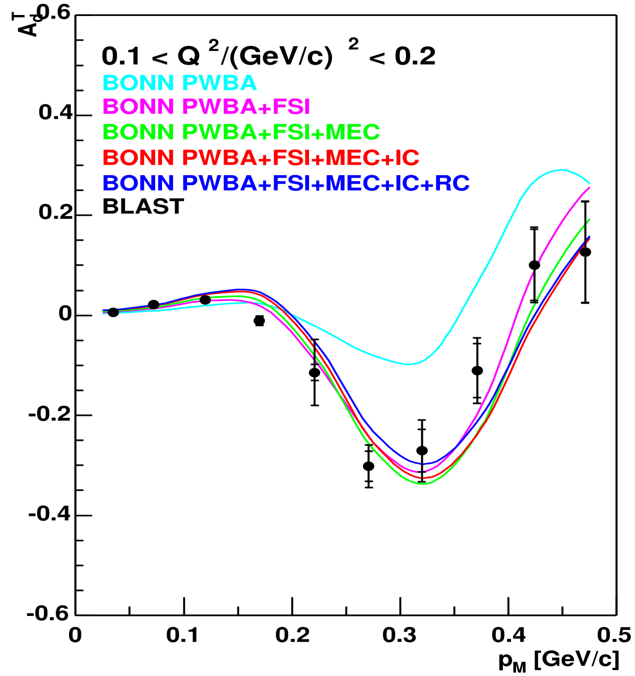
*Ph.D. of A. Maschinot and A. DeGrush (MIT)

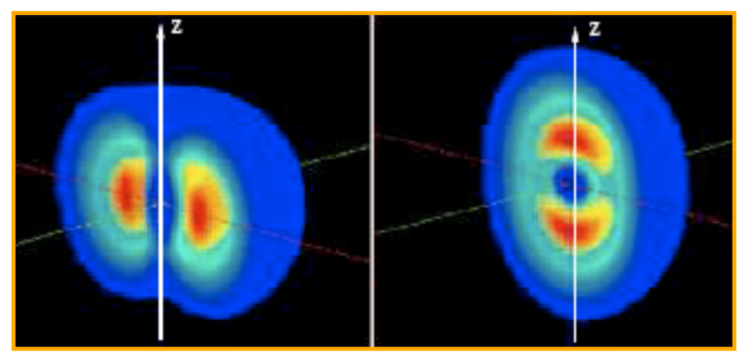
Quasielastic Tensor Asymmetry*

A. DeGrush, A. Maschinot et al., PRL 119, 182501 (2017)

$$A_d^T = \frac{\frac{1}{2}\left(\rho^+ + \rho^-\right) - \rho^0}{\rho^+ + \rho^- + \rho^0} = \frac{C_2}{C_0} P_2(\cos\theta) = \frac{R_2(p)\left(\sqrt{2}R_0(p) - \frac{1}{2}R_2(p)\right)}{R_0(p)^2 + R_2(p)^2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$







M=0 M=±1

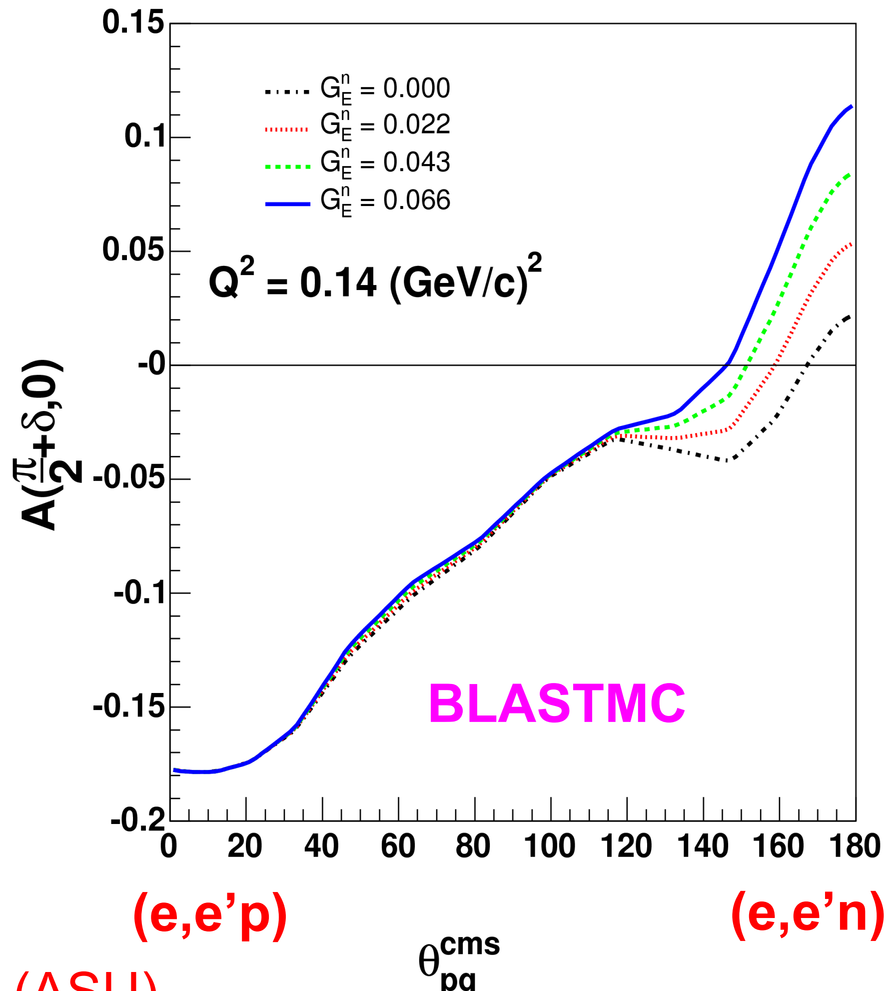
*Ph.D. work of A. Maschinot and A. DeGrush (MIT)

Extraction of G^n_E *

E. Geis, M.K., V. Ziskin et al., PRL 101, 042501 (2008)

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

- Quasielastic $^2\vec{H}(\vec{e},e'n)$
- 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



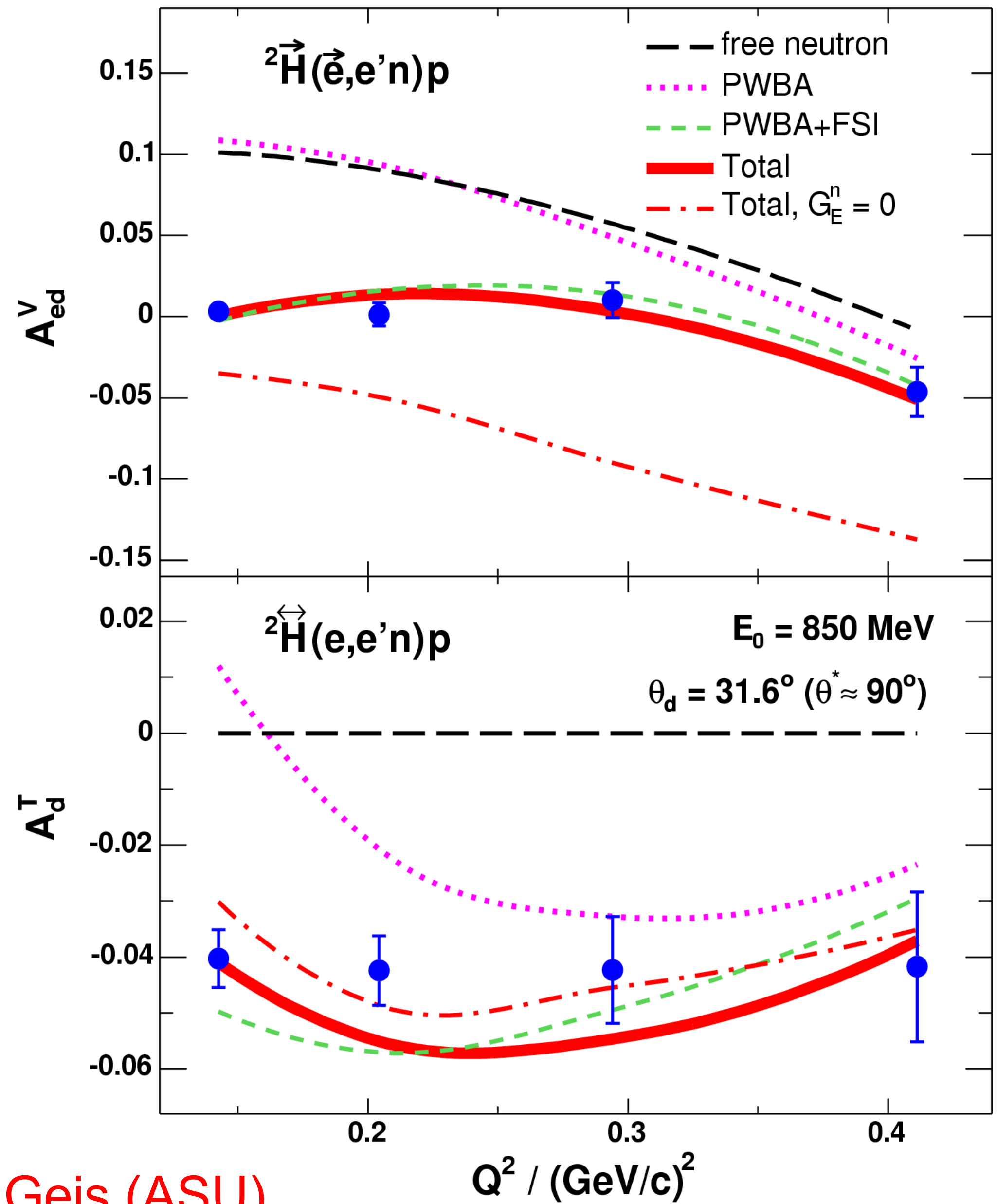
*Ph.D. work of V. Ziskin (MIT) and E. Geis (ASU)

How well is the FSI effect known?

E. Geis, M.K., V. Ziskin et al., PRL 101, 042501 (2008)

- Quasielastic $^2\vec{H}(\vec{e},e'n)$
- 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

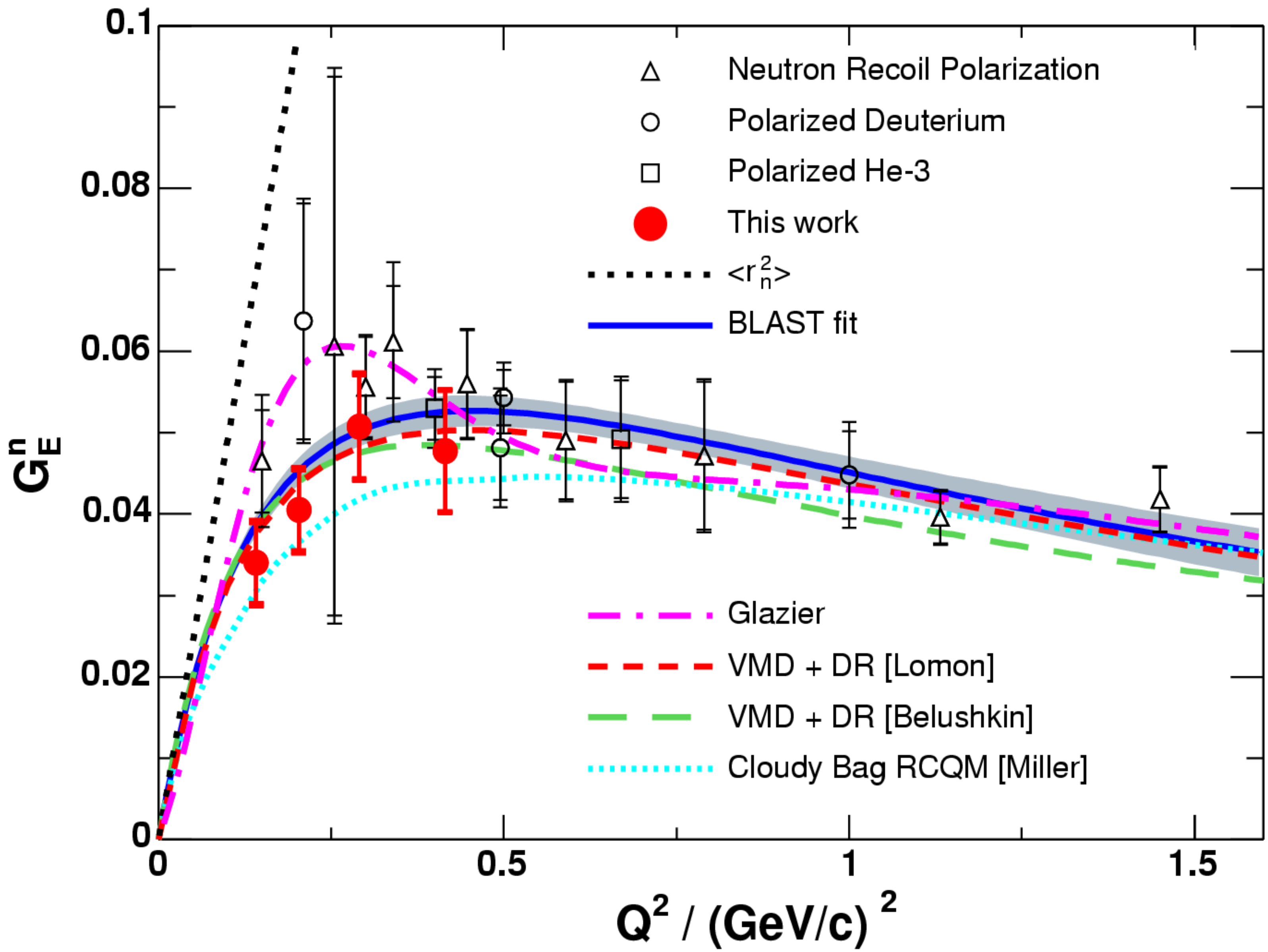
- **Use tensor asymmetry to control FSI**



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

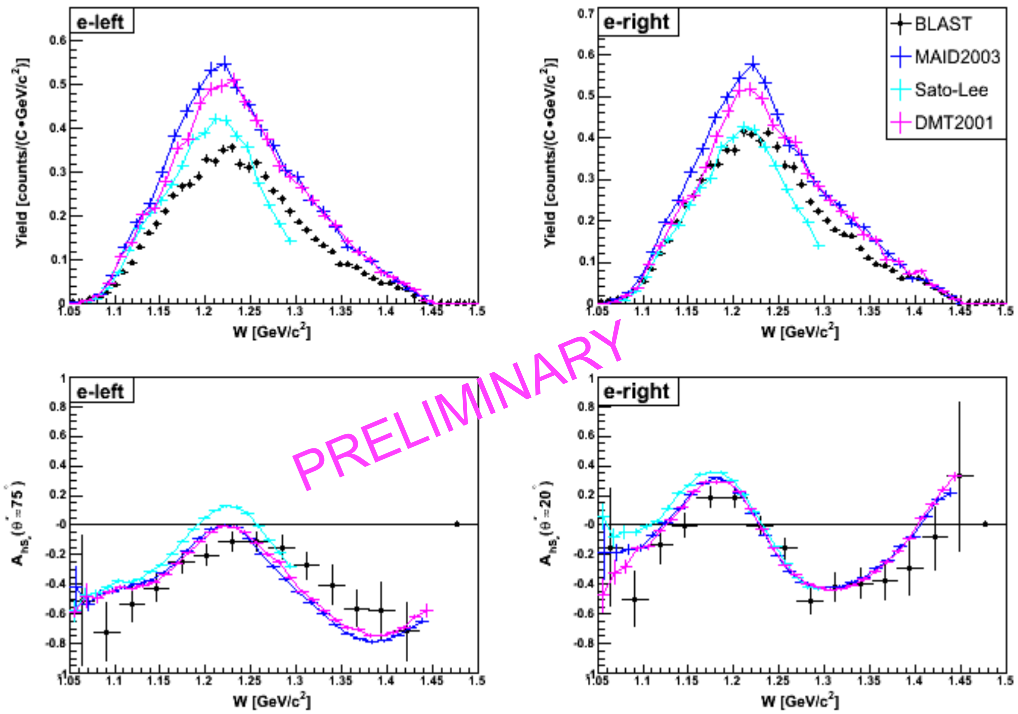
Neutron Electric Form Factor G^n_E *

E. Geis, M.K., V. Ziskin et al., PRL 101, 042501 (2008)



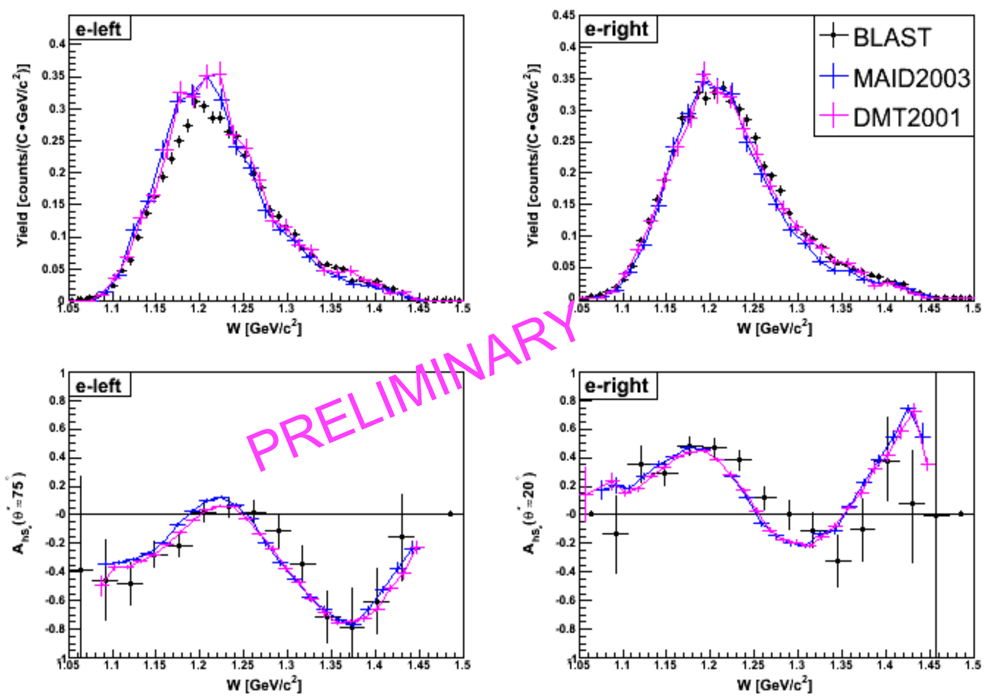
*Ph.D. work of V. Ziskin (MIT) and E. Geis (ASU)

$\vec{D}(\vec{e},e'\pi^{\pm})nn,pp$ Beam-Vector Asym.*



$D(e,e'\pi^{+})$ channel

Models: π^{+} from free p



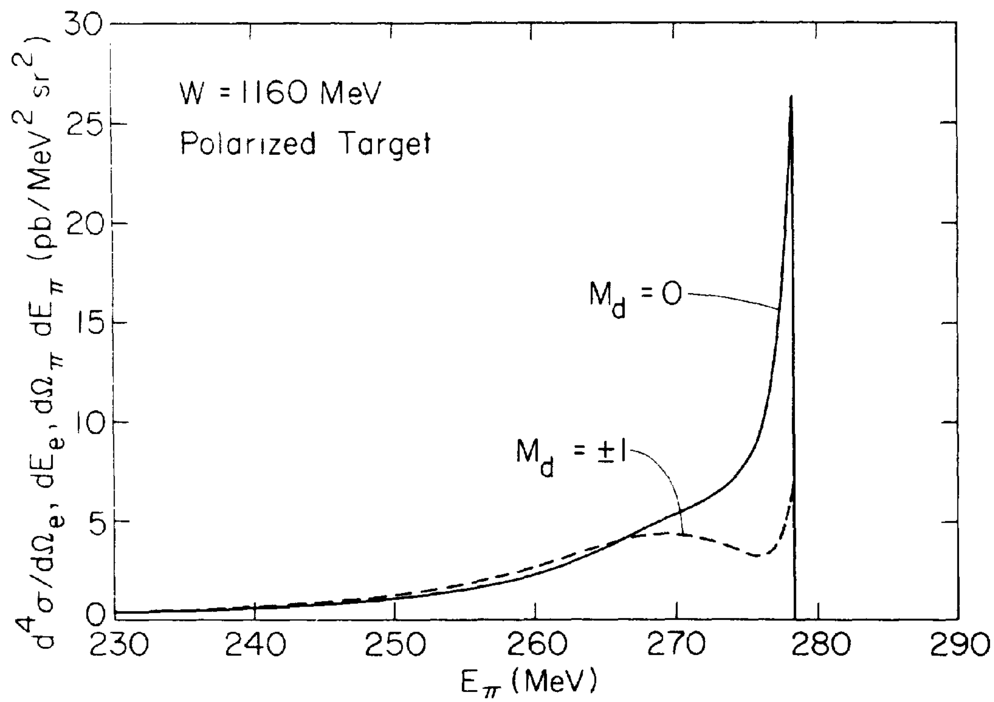
$D(e,e'\pi^{-})$ channel

Models: π^{-} from free n

*Analysis by A. Shinozaki (MIT)

Pion Electroproduction from Deuterium

R.J. Loucks, V.R. Pandharipande, R. Schiavilla, PRC49 (1994) 342



Strong FSI effect to explain quenching of ~80% in ratio of $d(e,e'\pi^+)nn$ / $p(e,e'\pi^+)n$ observed at Saclay

R. Gilman et al., PRL64 (1989) 622

Large tensor asymmetry (<0) predicted for scattering into quasibound singlet 2N state

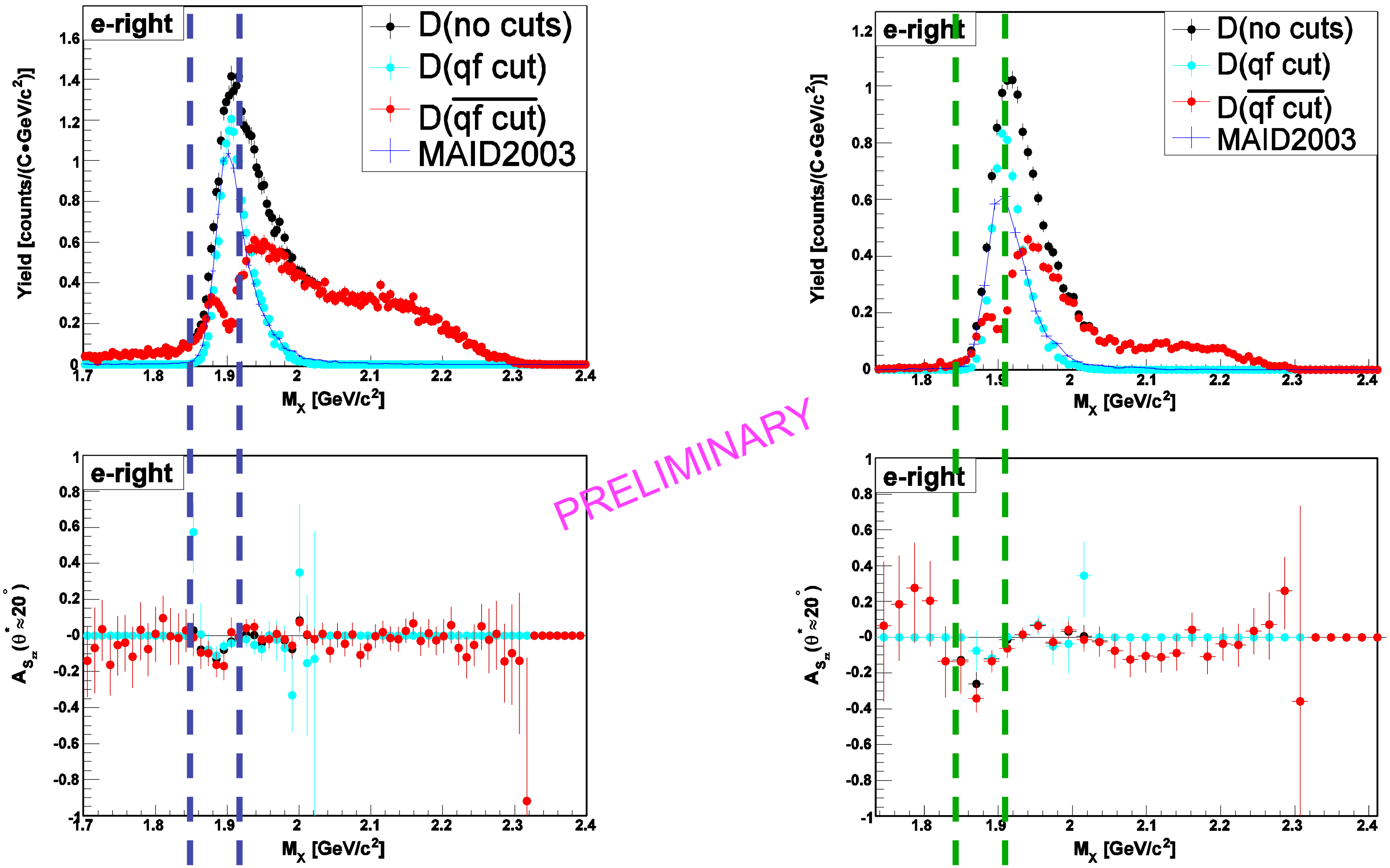
Two-nucleon term scheme:

pp — pn — nn **|T=1,S=0>**

d **|T=0,S=1>**

$D(e,e'\pi^{\pm})nn,pp$ Tensor Asymmetries *

$d(e,e'\pi^{+})nn$ $d(e,e'\pi^{-})pp$



*Analysis by A. Shinozaki (MIT)

Summary

- BLAST WAS A GREAT SUCCESS!!!
- First class single and double polarization data on H and D in elastic, quasielastic and Delta region
- Produced 11 Ph.D.'s and 3 Junior Faculty in the US
- BLAST detector re-used for OLYMPUS @ DESY

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