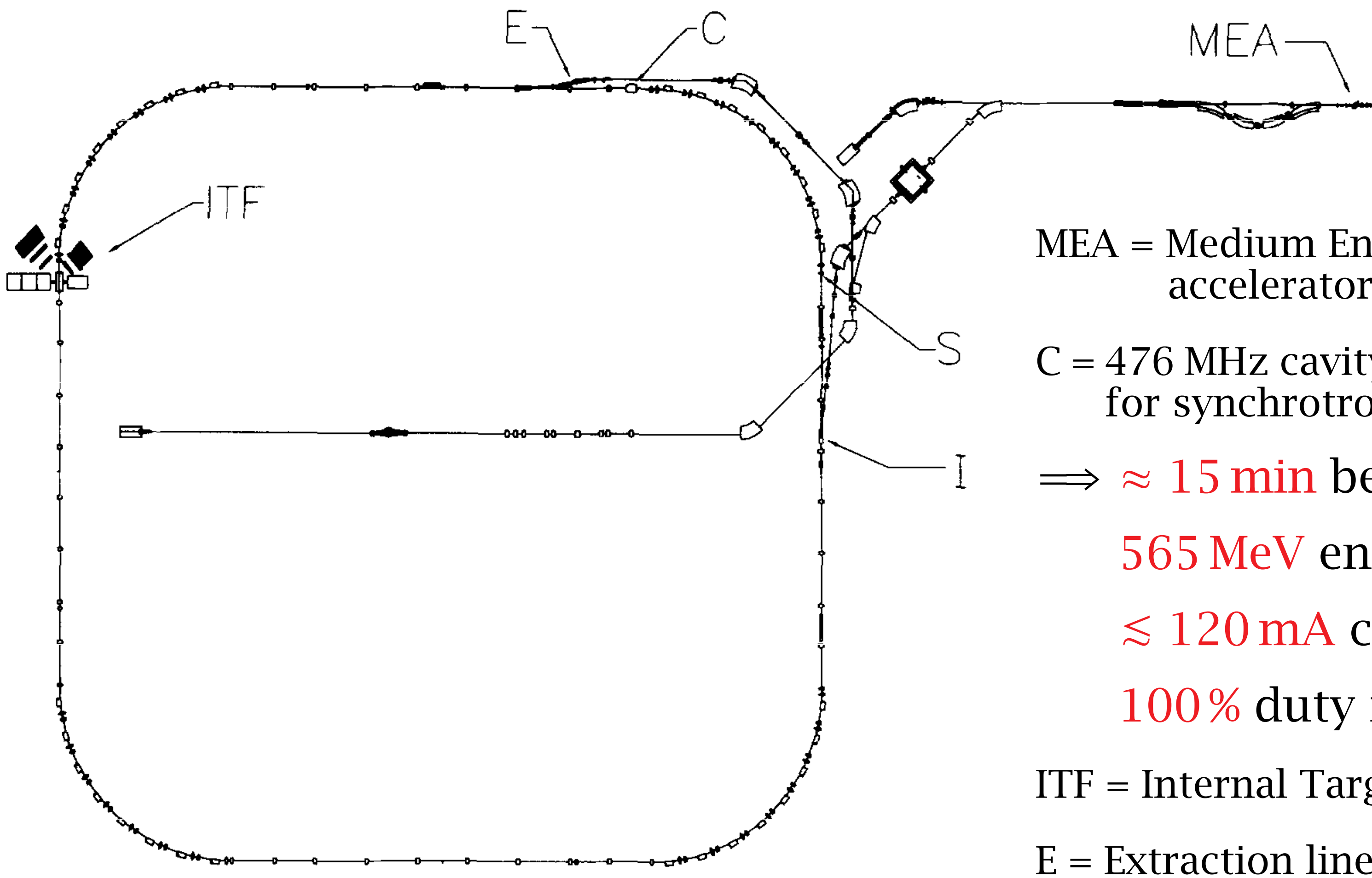
Vector- and tensor-deuteron legacy of NIKHEF and MIT-Bates

S. Širca, U of Ljubljana, Slovenia Trento, July 12, 2023

AmPS at NIKHEF



MEA = Medium Energy electron accelerator (up to 700 MeV)

C = 476 MHz cavity to compensate for synchrotron radiation loss

$\Longrightarrow$ ≈ 15 min beam lifetimes

565 MeV energy

≲ 120 mA currents

100 % duty factor

ITF = Internal Target Facility

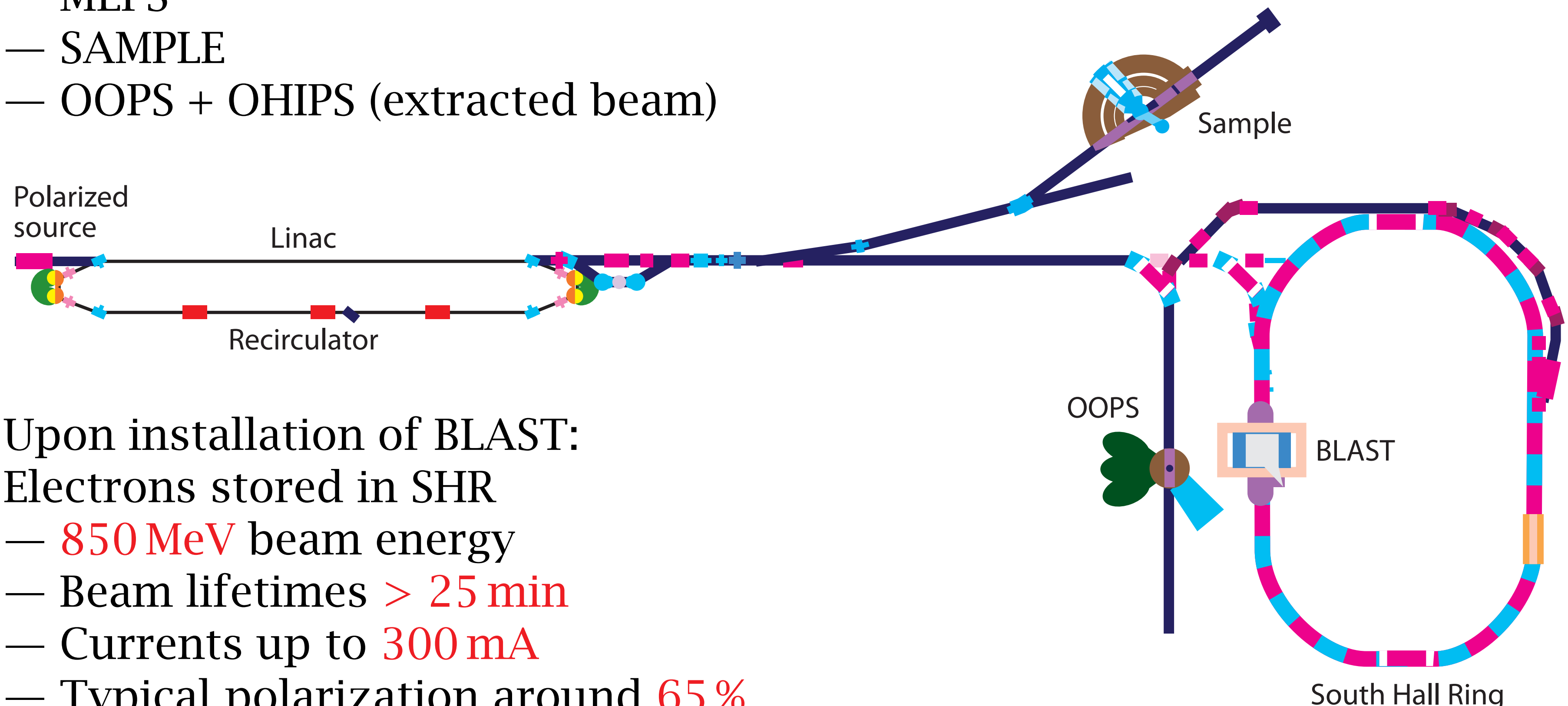
E = Extraction line (for EMIN)

polarized beam after mid-1990s

Zhou++, NIMA **378**, 40 (1996)

Accelerator / Experiment Layout at MIT-Bates

Pre-BLAST era:
— Elssy
— MEPS
— SAMPLE
— OOPS + OHIPS (extracted beam)



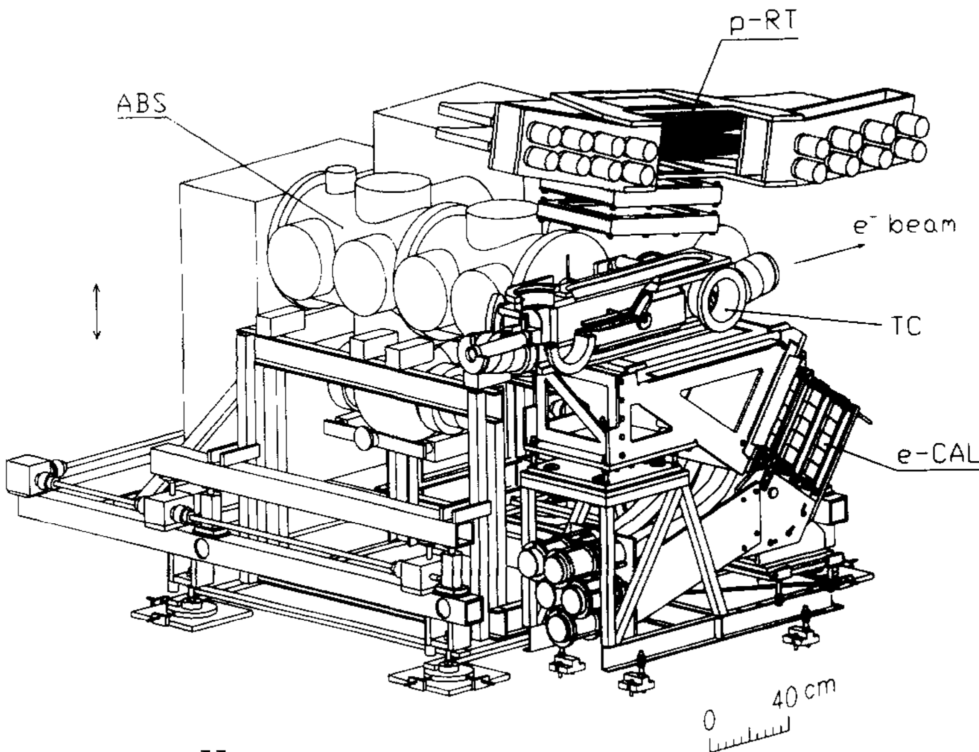
Upon installation of BLAST:
Electrons stored in SHR
— 850 MeV beam energy
— Beam lifetimes > 25 min
— Currents up to 300 mA
— Typical polarization around 65 %

Longitudinal orientation at target maintained by "Siberian snake"

Polarization monitored by Compton polarimeter

Hasell++, NIMA **603**, 247 (2009)
Morozov++, PRSTAB **4**, 104002 (2001)

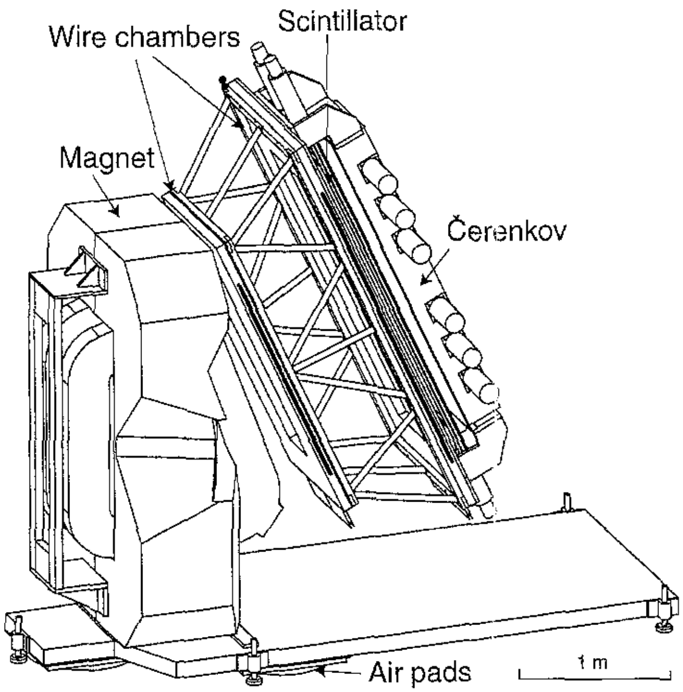
First detector setup in ITF @ NIKHEF

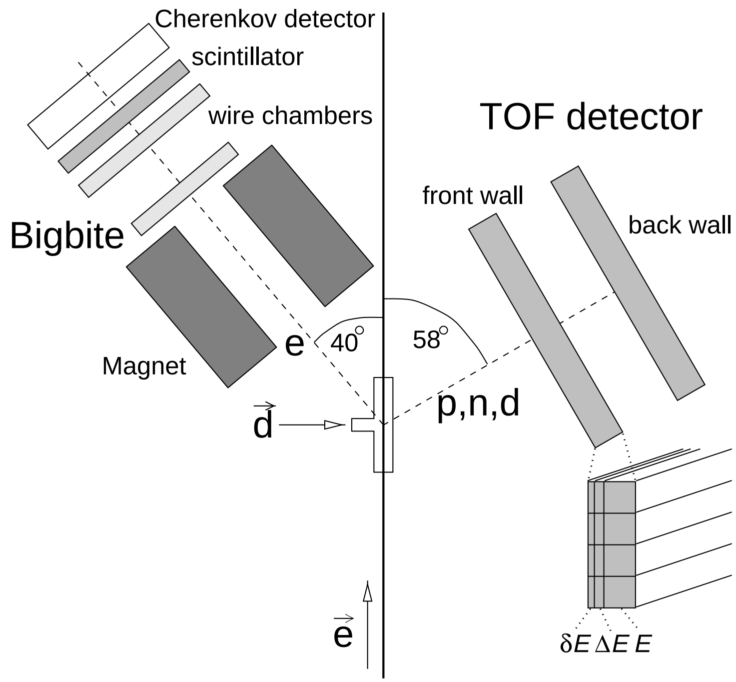


Zhou++, NIMA **378**, 40 (1996)

- ABS mounted horizontally
- Electrons: EM calorimeter = 6 layers of CsI(Tl) blocks, +2 plastic scintillators for triggering, $\Delta\Omega = 180\,\mathrm{msr}$, $\delta E \approx 22\,\mathrm{MeV}$
- Hadrons: range telescope = 1×2 mm + 15×1 cm plastic scintillator +2 sets of VDCs for tracking, $\Delta\Omega \approx 300\,\mathrm{msr}$, $E^{d}_{\mathrm{thr}} = 19\,\mathrm{MeV}$
- Used for T_{20} in elastic $^{2}\overleftrightarrow{\mathrm{H}}(\mathrm{e},\mathrm{e}')$ and $A^{\mathrm{T}}_{\mathrm{d}}$ in QE $^{2}\overleftrightarrow{\mathrm{H}}(\mathrm{e},\mathrm{e}'\mathrm{p})$

NIKHEF setup with BigBite



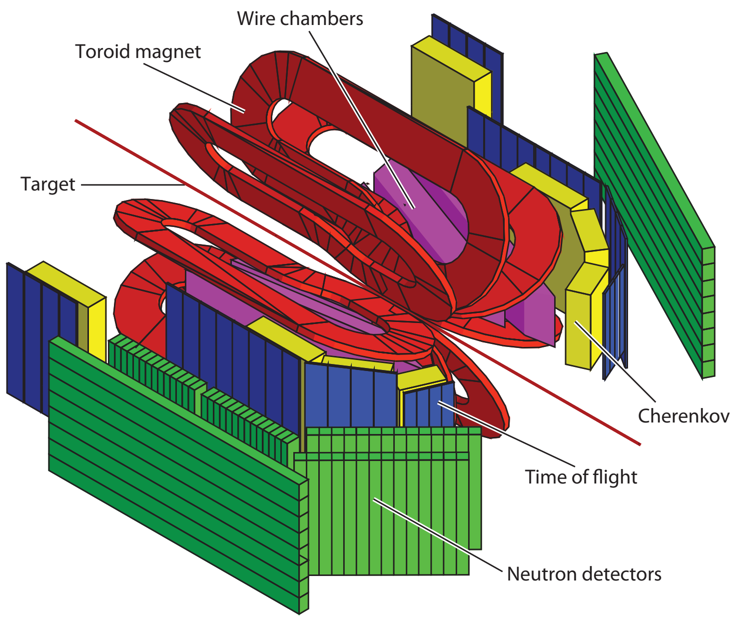


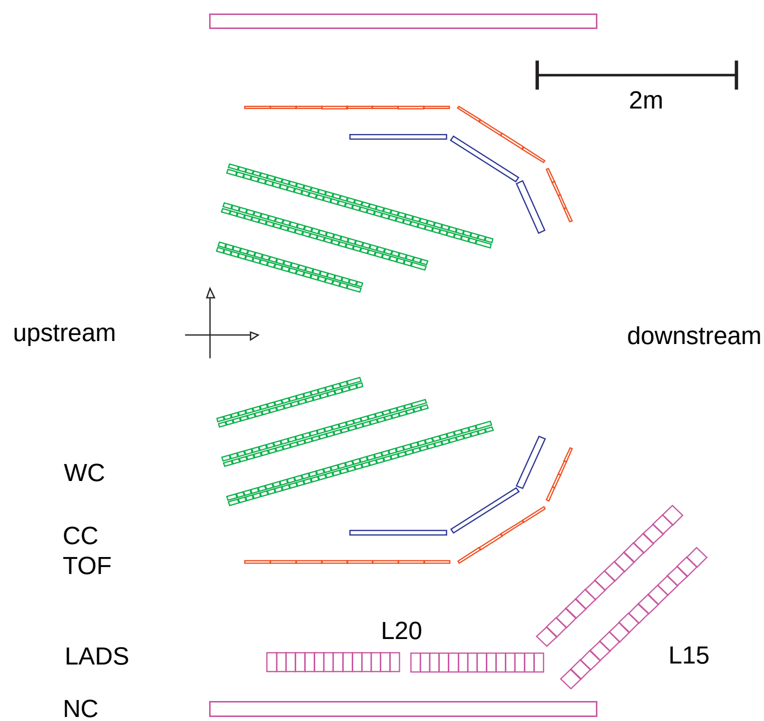
de Lange++, NIMA **406**, 182 (1998); NIMA **412**, 254 (1998)
Higinbotham, NIMA **414**, 332 (1998)

- Electrons: NIKHEF incarnation of BigBite: $\Delta\Omega = 96\,\mathrm{msr}$, $250 \le p \le 720\,\mathrm{MeV}/c$
- Hadrons: ToF system = 2 arrays of segmented (20 cm) plastic scintillators: "δE"/3 mm + "ΔE"/10 mm (veto) + "E"/20 cm
- Used for $A_{\mathrm{ed}}^{\mathrm{V}}$ in QE $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{n}) \Longrightarrow G_{\mathrm{E}}^{\mathrm{n}}$
  and $A_{\mathrm{ed}}^{\mathrm{V}}$ in QE $^2\vec{\mathrm{H}}(\vec{\mathrm{e}},\mathrm{e}'\mathrm{p})$

The BLAST Detector @ MIT-Bates

- Toroidal field, 8 normal conducting coils, max. 3.8 kGauss
- Only 1/6 azimuth instrumented
  - ▷ VDCs: $\pm 15^\circ$ in ϕ, L and R, 20°–80° in θ
  - ▷ Aerogel Cherenkov detectors for e|π: $n = 1.020, 1.030$; $\varepsilon \approx 90\,\%$
  - ▷ ToF scintillators: BC-408
  - ▷ Neutron detectors (“Ohio walls”, LADS15, LADS20 in variable configuration): BC-408





Hasell++, NIMA **603**, 247 (2009)

The heart of both setups: the ABS = Atomic Beam Source

- Exploits hyperfine states of deuterium atoms
- Interaction Hamiltonian of coupled nuclear ($\vec{I}$) and electron ($\vec{J}$) spins:

$$H_{\text{int}} = \mu_{\text{B}} \left(g_I \vec{I} + g_J \vec{J} \right) \cdot \vec{B} + \frac{2h\nu_0}{3} \vec{I} \cdot \vec{J}$$

$$\begin{aligned} g_I &= -0.00047 \\ g_J &= 2.0023 \\ h\nu_0 &= \mu_{\text{B}}(g_J - g_I) B_{\text{c}} \\ B_{\text{c}} &= 11.7\,\text{mT} \\ \nu_0 &= 327.4\,\text{MHz} \end{aligned}$$

- Energy eigenstates = linear combinations of spin eigenstates:

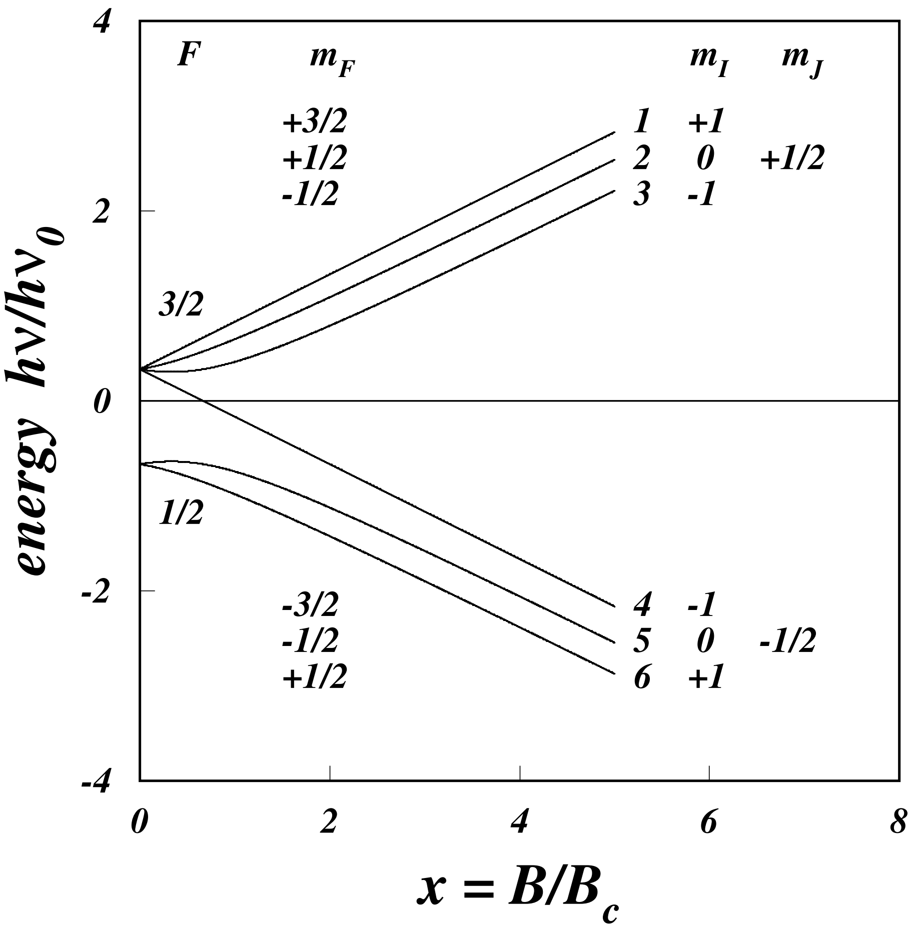
$$\begin{aligned} |1\rangle &= |1, \tfrac{1}{2}\rangle \\ |2\rangle &= \alpha_{-+}|1, -\tfrac{1}{2}\rangle + \alpha_{++}|0, \tfrac{1}{2}\rangle \\ |3\rangle &= \alpha_{--}|0, -\tfrac{1}{2}\rangle + \alpha_{+-}|-1, \tfrac{1}{2}\rangle \\ |4\rangle &= |-1, -\tfrac{1}{2}\rangle \\ |5\rangle &= \alpha_{+-}|0, -\tfrac{1}{2}\rangle - \alpha_{--}|-1, \tfrac{1}{2}\rangle \\ |6\rangle &= \alpha_{++}|1, -\tfrac{1}{2}\rangle - \alpha_{-+}|0, \tfrac{1}{2}\rangle \end{aligned}$$

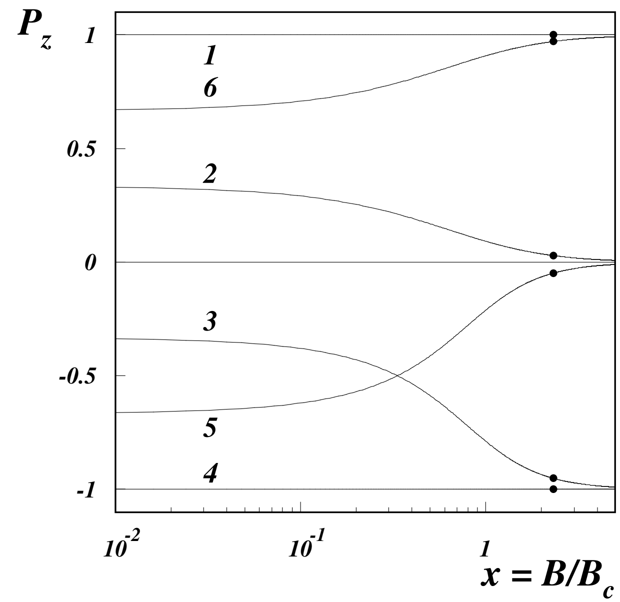
$$\begin{aligned} \alpha_{+\pm} &= \sqrt{\tfrac{1}{2}(1 + a_\pm)} \\ \alpha_{-\pm} &= \sqrt{\tfrac{1}{2}(1 - a_\pm)} \\ a_\pm &= (x \pm \tfrac{1}{3}) / \sqrt{1 \pm \tfrac{2}{3}x + x^2} \\ x &= B/B_{\text{c}} \end{aligned}$$

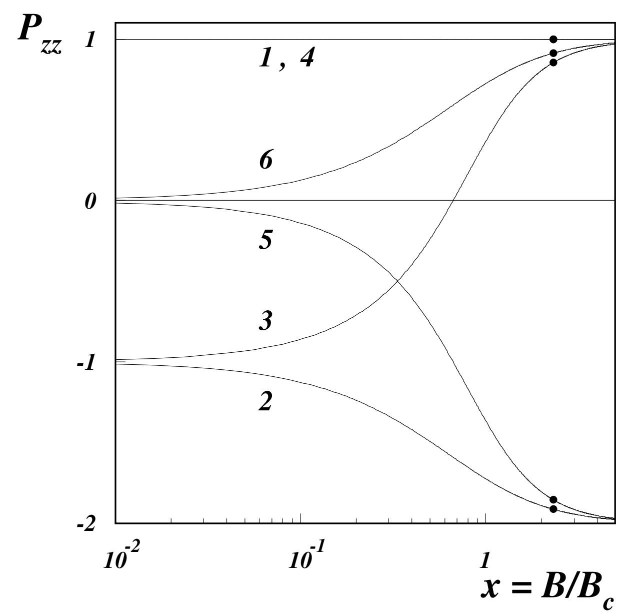
- Vector/tensor polarizations (ensemble averages):

$$\begin{aligned} \boldsymbol{P_z} &= \langle I_z \rangle = n_1 + \alpha_{-+}^2 n_2 - \alpha_{+-}^2 n_3 - \alpha_{--}^2 n_5 + \alpha_{++}^2 n_6 = \boldsymbol{n_+ - n_-} \\ \boldsymbol{P_{zz}} &= \langle 3I_z^2 - 2 \rangle = 1 - 3\left(\alpha_{++}^2 n_2 + \alpha_{--}^2 n_3 + \alpha_{+-}^2 n_5 + \alpha_{-+}^2 n_6 \right) = \boldsymbol{1 - 3n_0} \end{aligned}$$

Hyperfine transitions in deuterium, P_z and P_{zz}

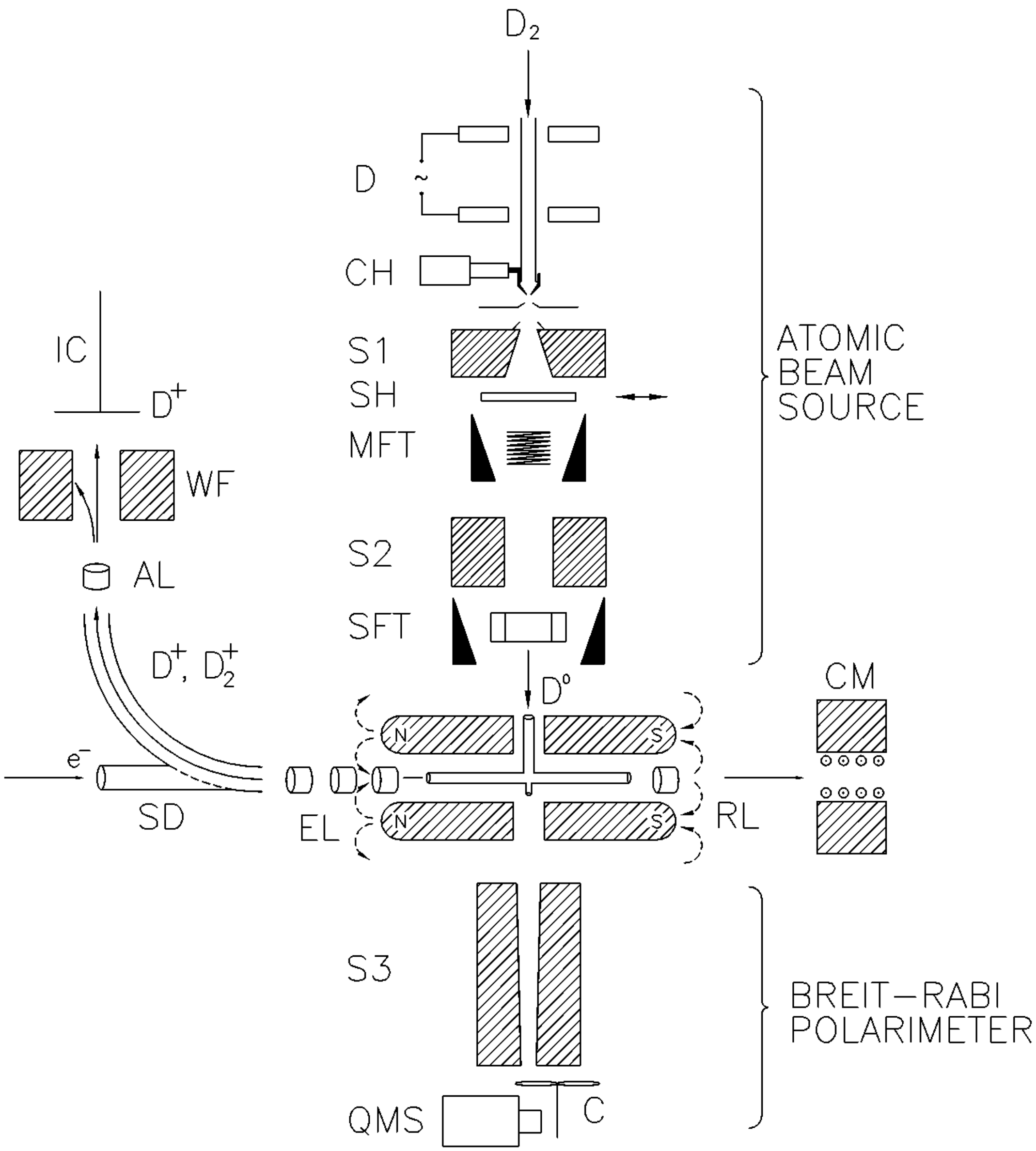


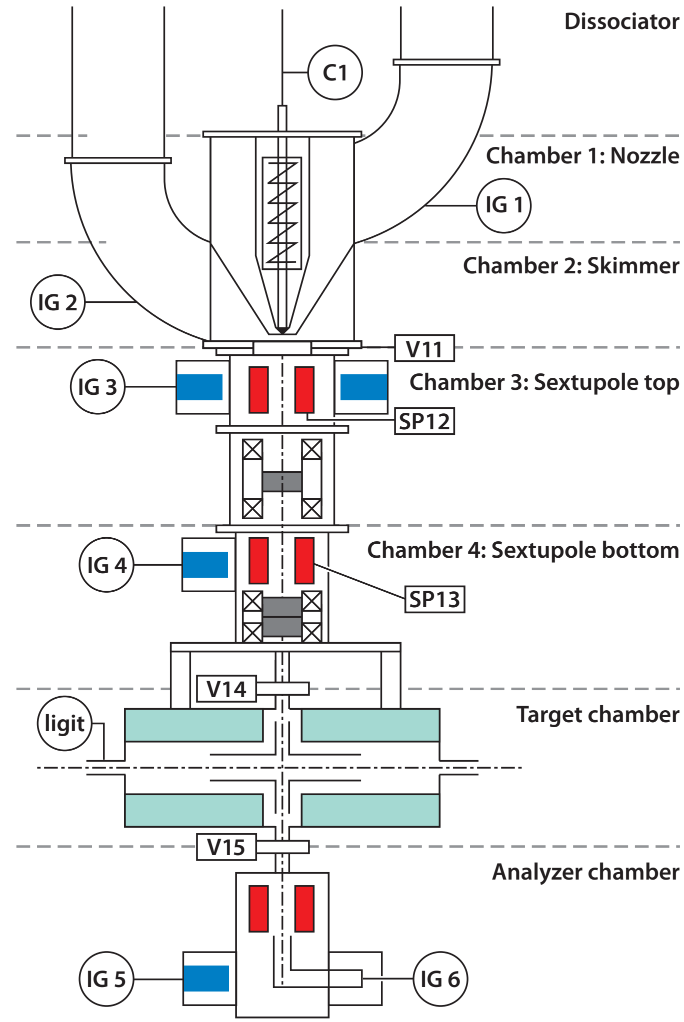




$$\vec{F} = \vec{I} + \vec{J}$$

ABS setup at NIKHEF and MIT-Bates



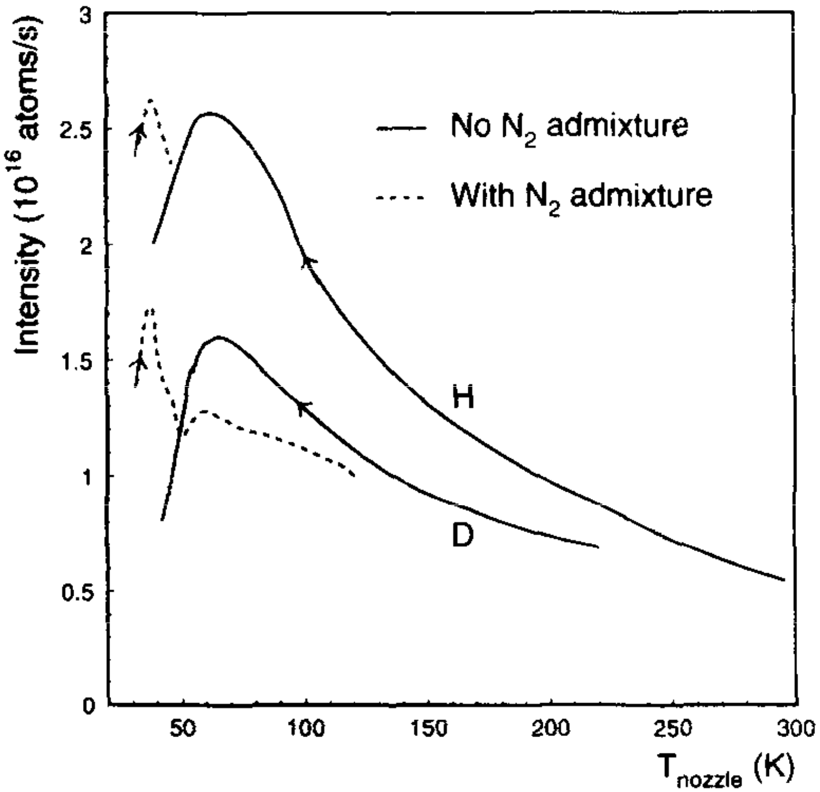


ABS — the RF transition schemes

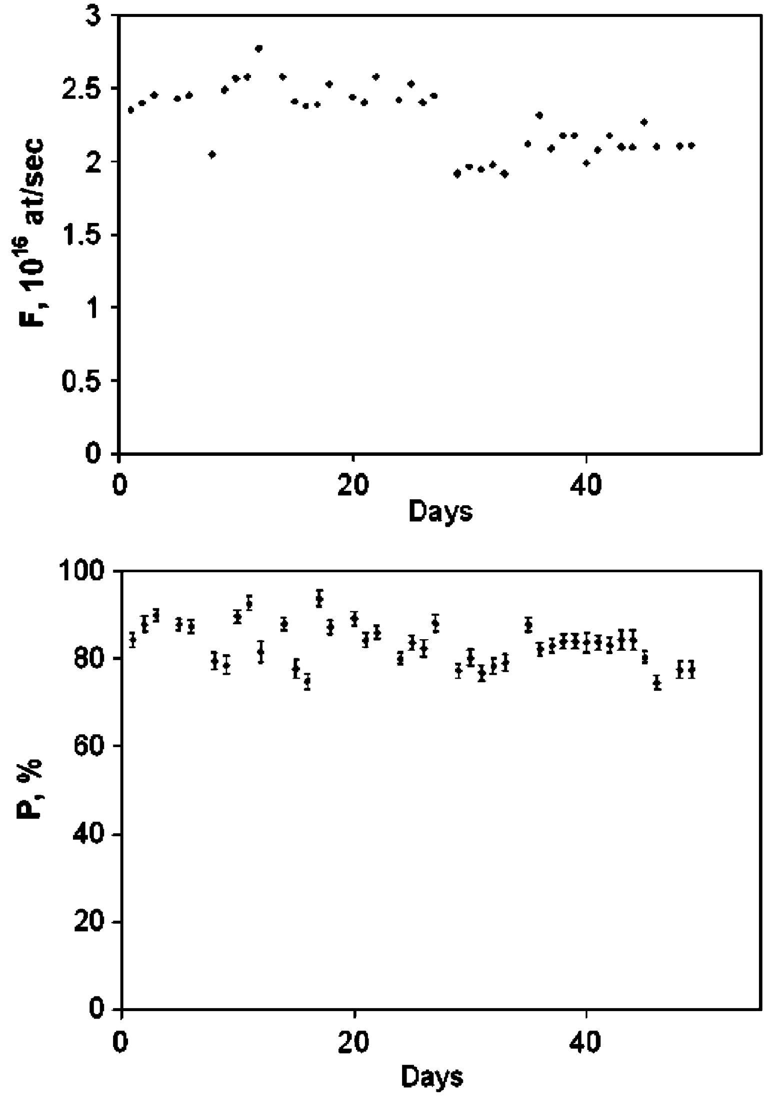
	Tensor ($B_t \gg 11.7$ mT) +	Tensor ($B_t \gg 11.7$ mT) −	Vector ($B_t \gg 11.7$ mT) +	Vector ($B_t \gg 11.7$ mT) −	Vector ($B_t \ll 11.7$ mT) +	Vector ($B_t \ll 11.7$ mT) −
States after 1^{st} sext.	1 , 2 , 3		1 , 2 , 3		1 , 2 , 3	
MFT	$1 \leftrightarrow 4$		$3 \leftrightarrow 4$		$3 \leftrightarrow 4$	
States after MFT	2 , 3 , 4		1 , 2 , 4		1 , 2 , 4	
States after 2^{nd} sext.	2 , 3		1 , 2		1 , 2	
SFT	$2 \leftrightarrow 6$	$3 \leftrightarrow 5$	$2 \leftrightarrow 6$	off	$2 \leftrightarrow 6$	
States after SFT	3 , 6	2 , 5	1 , 6	1 , 2	1 , 6	
WFT	off		off	$1,2 \leftrightarrow 3,4$	off	$1,6 \leftrightarrow 5,4$
States after WFT	3 , 6	2 , 5	1 , 6	3 , 4	1 , 6	4 , 5
Tensor Polariz. P_{zz}	+1	−2	+1	+1	+1/2	+1/2
Vector Polariz. P_z	0	0	+1	−1	+5/6	−5/6
Figure of merit	18		8		5.6	

Typical performance of ABS

NIKHEF



MIT-Bates



Cheever++, NIMA **556**, 410 (2006)

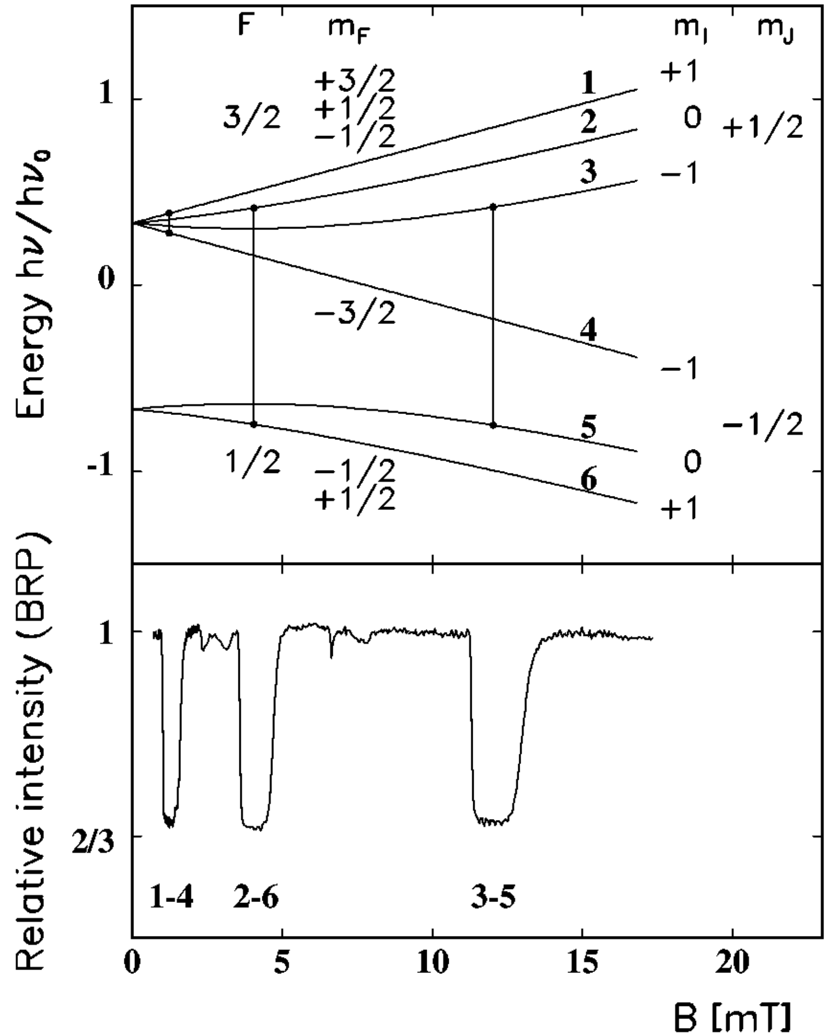
Target polarimetry #1

Breit-Rabi electron polarimeter

- ▷ The 1–4, 2–6 and 3–5 RF transitions involve a *collective* electron and nuclear spin flip
  $\Longrightarrow$ a measurement of electronic polarization allows one to measure the efficiencies of the MFT and SFT, and control the injected polarization states

- ▷ Typical efficiencies:
  $\varepsilon(1 \leftrightarrow 4) = 0.97 \pm 0.01$
  $\varepsilon(2 \leftrightarrow 6) = 1.02 \pm 0.02$
  $\varepsilon(3 \leftrightarrow 5) = 0.99 \pm 0.02$

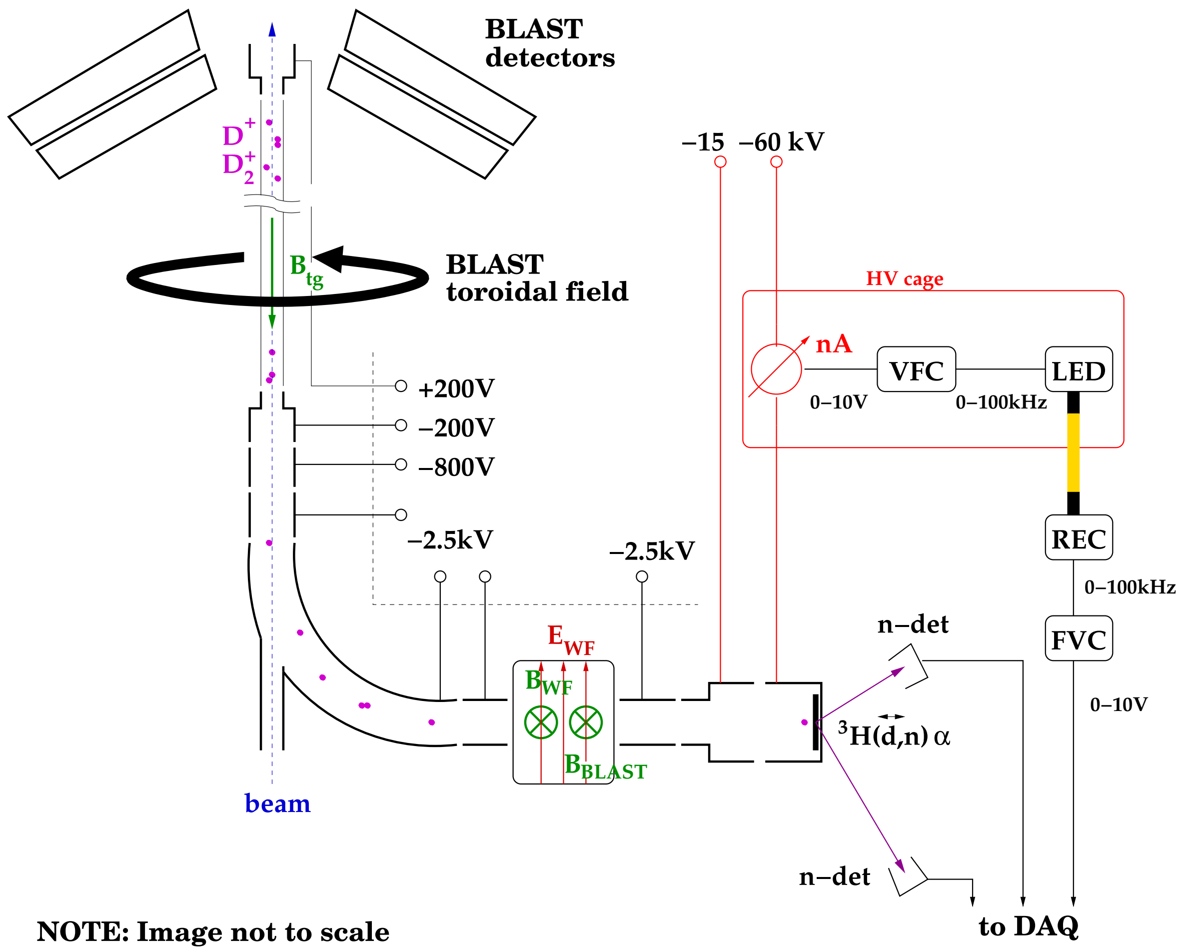
  Ferro-Luzzi++, NIMA **364**, 44 (1995)



Target polarimetry #2

Ion extraction polarimetry for direct measurement of P_{zz}

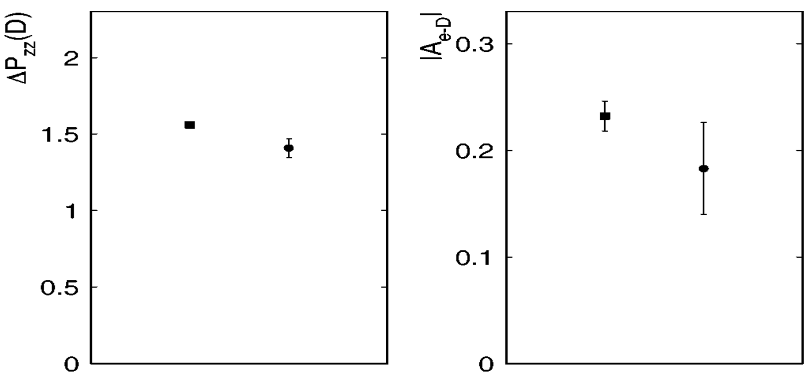
- Done at NIKHEF and should have been done at MIT-Bates: exploits angular asymmetry of the ^{3}H-$\overleftrightarrow{d}$ fusion process, $n(\theta) \propto 1 - \frac{1}{4} f(E_d) P_{zz}(3\cos^2\theta - 1)$, with $f \approx 0.959$ at $E_d = 51\,\text{keV}$ // Zhou++, NIMA **379**, 212 (1996)

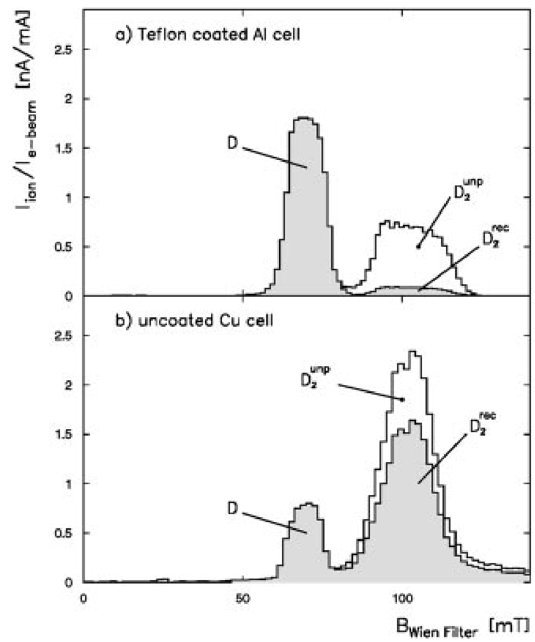


Evidence of nuclear tensor polarization in deuterium molecules

$$P_{zz}^{\mathrm{tot}} = \frac{n_{\mathrm{D}} P_{zz}(\mathrm{D}) + 2n_{\mathrm{D}_2^{\mathrm{rec}}} P_{zz}(\mathrm{D}_2^{\mathrm{rec}})}{n_{\mathrm{D}} + 2n_{\mathrm{D}_2^{\mathrm{rec}}} + 2n_{\mathrm{D}_2^{\mathrm{unp}}}} = \xi\, P_{zz}(\mathrm{D}) + \zeta\, P_{zz}(\mathrm{D}_2^{\mathrm{rec}})$$

- Measured $P_{zz}(\mathrm{D})$ extracted from Teflon-coated Al cell vs. uncoated Cu cell by ion polarimetry: $P_{zz}^{+}(\mathrm{D}) = +0.523 \pm 0.005$ / $P_{zz}^{-}(\mathrm{D}) = -1.037 \pm 0.007$ vs. $P_{zz}^{+}(\mathrm{D}) = +0.434 \pm 0.027$ / $P_{zz}^{-}(\mathrm{D}) = -0.974 \pm 0.035$
- Determined $P_{zz}(\mathrm{D_2})$ from asymmetry for electron–deuteron elastic scattering: $A_{\mathrm{ed}} = -0.232 \pm 0.014$ vs. $A_{\mathrm{ed}} = -0.183 \pm 0.043$





$\Longrightarrow$ $\Delta P_{zz}(\mathrm{D}_2^{\mathrm{rec}}) = (0.81 \pm 0.32)\Delta P_{zz}(\mathrm{D})$

$\Longrightarrow$ May allow one to develop a robust polarized H_2/D_2 target insensitive to beam-induced depolarizations, polarization losses due to spin-exchange collisions, and radiation damage to cell surface

van den Brand++, PRL **78**, 1235 (1997)

The ABC of e–d elastic scattering

- Spin(deuteron) = 1 $\Longrightarrow$ three form-factors $G_{\rm C}(Q^2)$, $G_{\rm Q}(Q^2)$ and $G_{\rm M}(Q^2)$
- The unpolarized XS, $\sigma_0 = \sigma_{\rm Mott} f_{\rm rec}^{-1} S$, where $S = A(Q^2) + B(Q^2)\tan^2\theta_{\rm e}/2$, allows for separation of two linear combinations of form-factors:

$$A(Q^2) = G_{\rm C}^2 + \tfrac{8}{9}\eta^2 G_{\rm Q}^2 + \tfrac{2}{3}\eta G_{\rm M}^2 \,, \quad B(Q^2) = \tfrac{4}{3}\eta(1+\eta) G_{\rm M}^2 \,, \quad \eta = Q^2/4M^2$$

$\Longrightarrow$ A polarized measurement is needed to disentangle $G_{\rm C}$ from $G_{\rm Q}$

$$\sigma = \sigma_0 \left[1 + \frac{P_{zz} A_{\rm d}^{\rm T}}{\sqrt{2}} \right] \,, \quad A_{\rm d}^{\rm T} = \sum_{i=0}^{2} d_{2i} T_{2i}$$

$$d_{20} = \frac{3\cos^2\theta^* - 1}{2} \,, \quad d_{21} = -\sqrt{\frac{3}{2}} \sin 2\theta^* \cos\phi^* \,, \quad d_{22} = \sqrt{\frac{3}{2}} \sin^2\theta^* \cos 2\phi^*$$

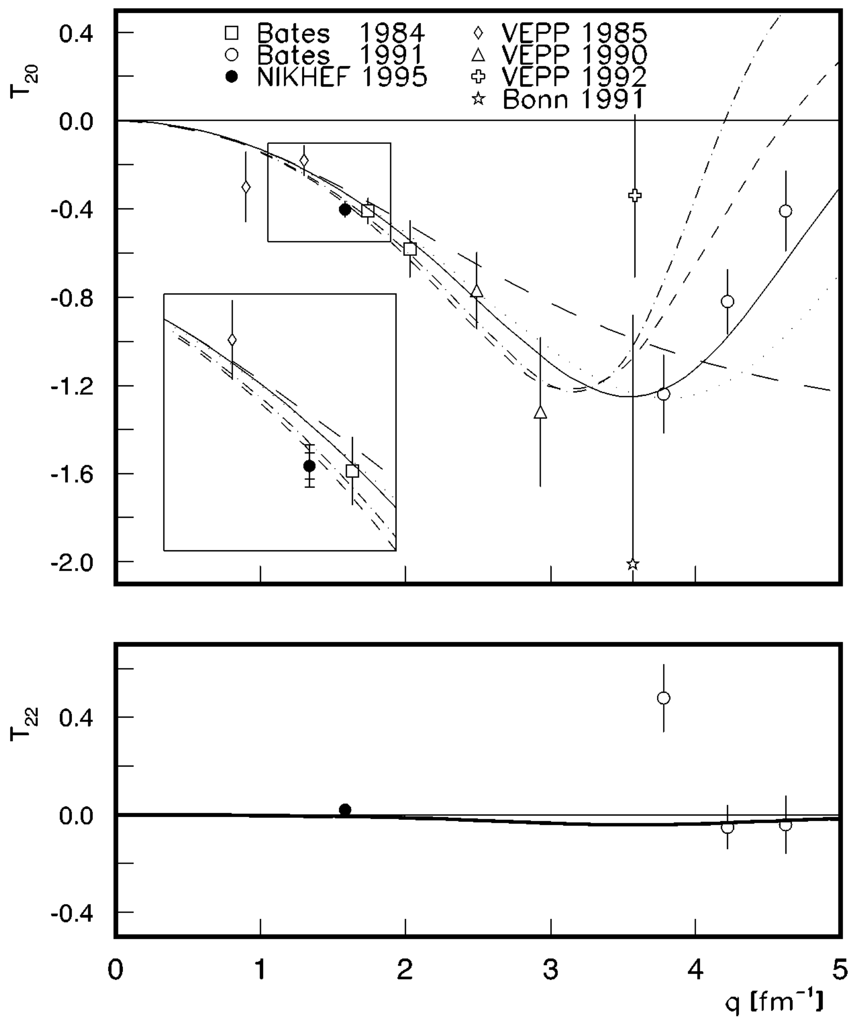
- Tensor analyzing powers (access controlled by spin angles (θ^*, ϕ^*)):

$$\begin{aligned}
T_{20} &= -\frac{1}{\sqrt{2}S} \left[\frac{8}{3}\eta \underline{G_{\rm C} G_{\rm Q}} + \frac{8}{9}\eta^2 G_{\rm Q}^2 + \frac{1}{3}\eta \left(1 + 2(1+\eta)\tan^2\frac{\theta_{\rm e}}{2} \right) G_{\rm M}^2 \right] \\
T_{21} &= -\frac{2}{\sqrt{3}S} \sqrt{\eta^3 \left(1 + \eta \sin^2\frac{\theta_{\rm e}}{2} \right)} G_{\rm Q} G_{\rm M} \sec\frac{\theta_{\rm e}}{2} \\
T_{22} &= -\frac{2}{2\sqrt{3}S} \eta G_{\rm M}^2
\end{aligned}$$

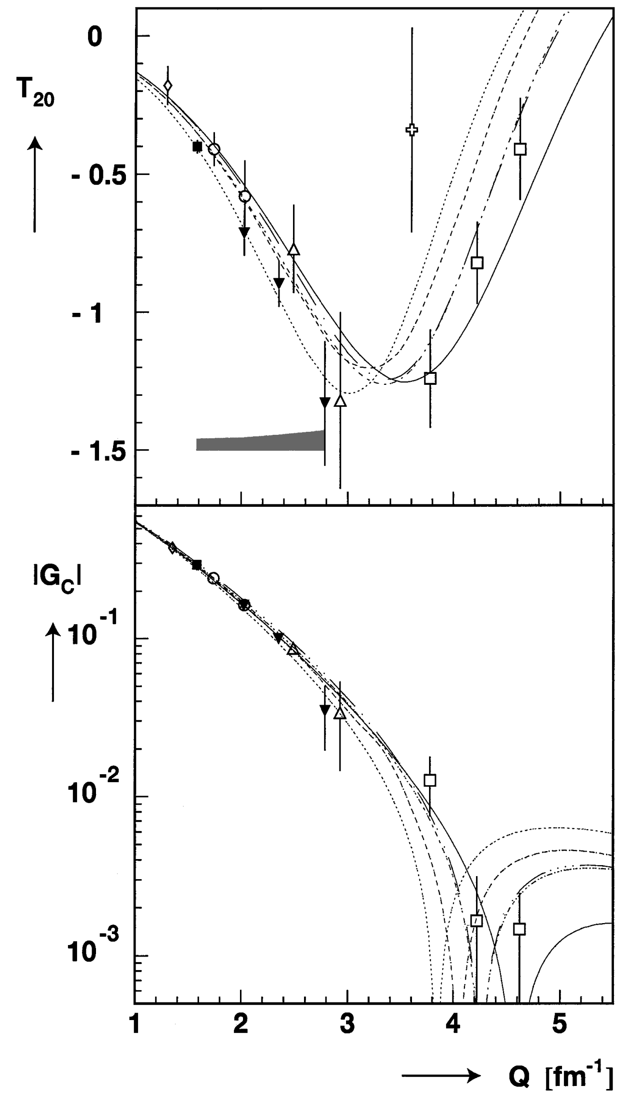
The $T_{20}(70°)$ results from NIKHEF

1996: a single point in T_{20} and T_{22}, small contribution from T_{21} estimated from existing data on $G_Q(Q^2)$ and $B(Q^2)$

1999: three new points, with absolute polarimetry



Ferro-Luzzi++, PRL **77**, 2630 (1996)



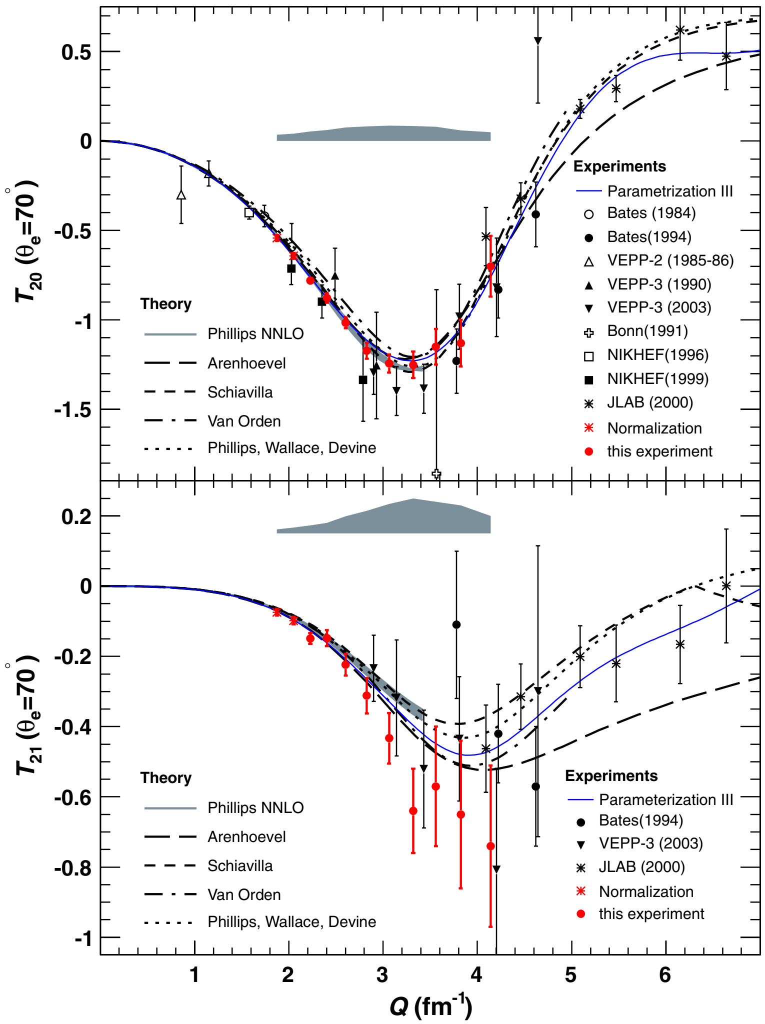
Bouwhuis++, PRL **82**, 3755 (1999)

The $T_{20}(70°)$ results from MIT-Bates

- The 1984 and 1991/1994 MIT-Bates experiments yielded deuteron tensor polarizations t_{20} via $\mathrm{d}(\mathrm{e},\mathrm{e}'\overleftrightarrow{\mathrm{d}})$ by using recoil polarimetry

  Schulze++, PRL **52**, 597 (1984)
  The++, PRL **67**, 173 (1991)
  Garçon++, PRC **49**, 2516 (1994)

- The 2004/2005 experiments at BLAST (using ABS) extracted T_{20} and T_{21} like at NIKHEF
  - ▷ Small T_{22} contribution subtracted by using a parameterization of previous low-Q data
  - ▷ In absence of absolute polarimetry, polarization and spin angle calibrated by the two lowest-Q points

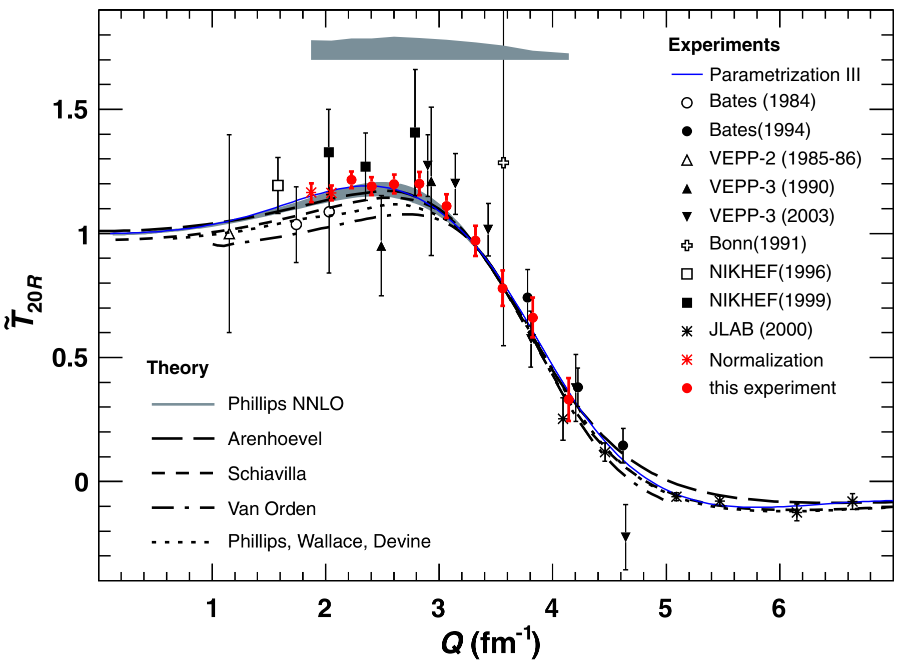


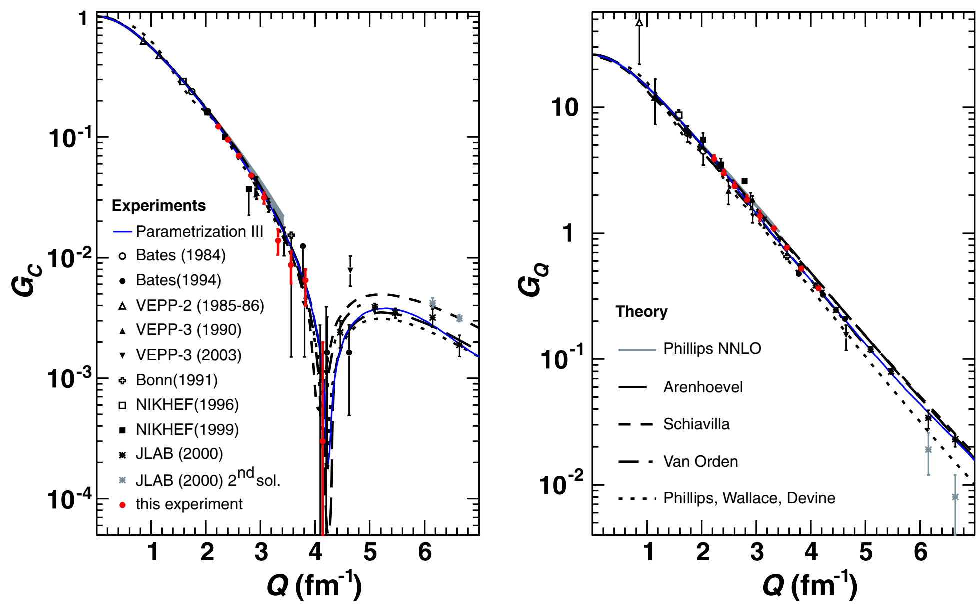
Zhang++, PRL **107**, 252501 (2011)

$\tilde{T}_{20R}$ from BLAST

Eliminate the dependence on θ_e and G_M; in addition, divide out the leading Q^2-dependence ("reduced T_{20}"):

$$\tilde{T}_{20} = -\frac{\frac{8}{3}\eta G_C G_Q + \frac{8}{9}\eta^2 G_Q^2}{\sqrt{2}\left(G_C^2 + \frac{8}{9}\eta^2 G_Q^2\right)}, \qquad \tilde{T}_{20R}(Q^2) = -\frac{3}{\sqrt{2}\,Q_d Q^2}\tilde{T}_{20}(Q^2)$$





Zhang++, PRL **107**, 252501 (2011)

- Precise data covering the minimum of T_{20} and the first node of G_C
- Strong constraint on models

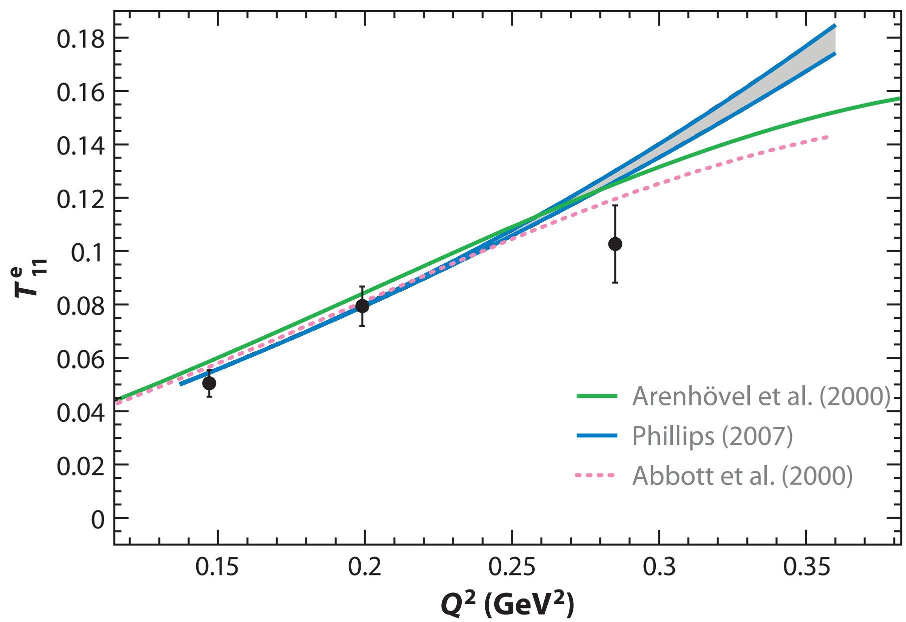
T_{11}^{e} from BLAST (e–d elastic)

With polarized beam and vector-polarized target, $A_{\mathrm{ed}}^{\mathrm{V}}$ becomes accessible:

$$\sigma = \sigma_0 \left[1 + \sqrt{\frac{1}{2}} P_{zz} A_{\mathrm{d}}^{\mathrm{T}} + \sqrt{\frac{3}{2}} P_{\mathrm{e}} P_z A_{\mathrm{ed}}^{\mathrm{V}} \right]$$

$$A_{\mathrm{ed}}^{\mathrm{V}} = \sqrt{3} \left(\frac{1}{\sqrt{2}} \cos\theta^* T_{10}^{\mathrm{e}}(Q^2, \theta_{\mathrm{e}}) - \sin\theta^* \cos\phi^* T_{11}^{\mathrm{e}}(Q^2, \theta_{\mathrm{e}}) \right)$$

$$T_{11}^{\mathrm{e}} \propto G_{\mathrm{M}} \left(G_{\mathrm{C}} + \frac{\eta}{3} G_{\mathrm{Q}} \right)$$ – measured for the first time :

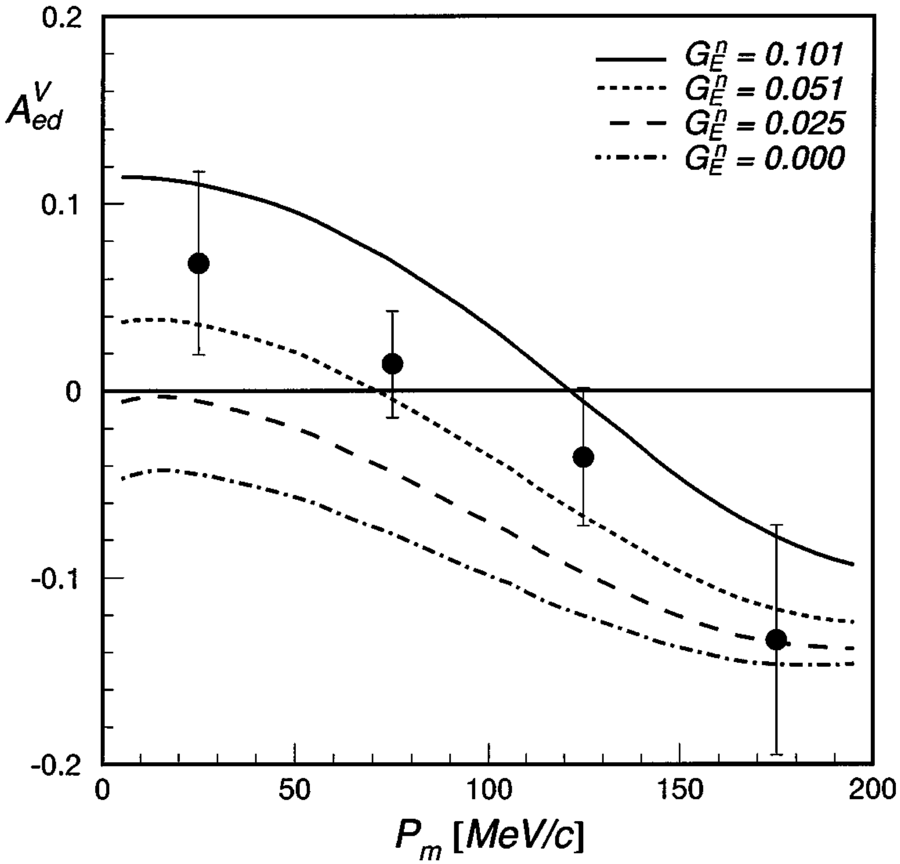


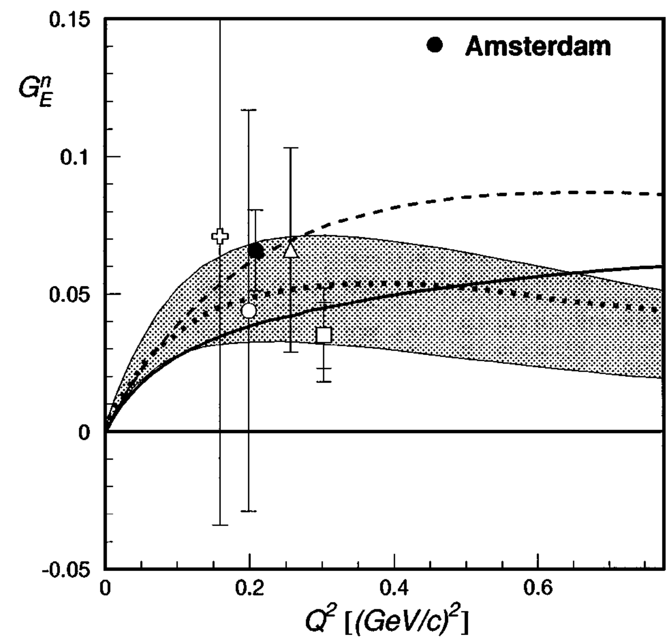
Hasell++, Annu. Rev. Nucl. Part. Sci. **61**, 409 (2011)

$A_{\mathrm{ed}}^{\mathrm{V}}(\theta^* = 90°, \phi^* = 0°)$ in quasi-elastic $^2\vec{\mathrm{H}}(\vec{\mathrm{e}}, \mathrm{e}'\mathrm{n})$ — NIKHEF

$$\sigma = \sigma_0 \left[1 + P_1^{\mathrm{d}} A_{\mathrm{d}}^{\mathrm{V}} + P_2^{\mathrm{d}} A_{\mathrm{d}}^{\mathrm{T}} + h P_{\mathrm{e}} \left(A_{\mathrm{e}} + P_1^{\mathrm{d}} A_{\mathrm{ed}}^{\mathrm{V}} + P_2^{\mathrm{d}} A_{\mathrm{ed}}^{\mathrm{T}} \right) \right]$$

$$P_1^{\mathrm{d}} = \sqrt{\tfrac{3}{2}} (n_+ - n_-)$$



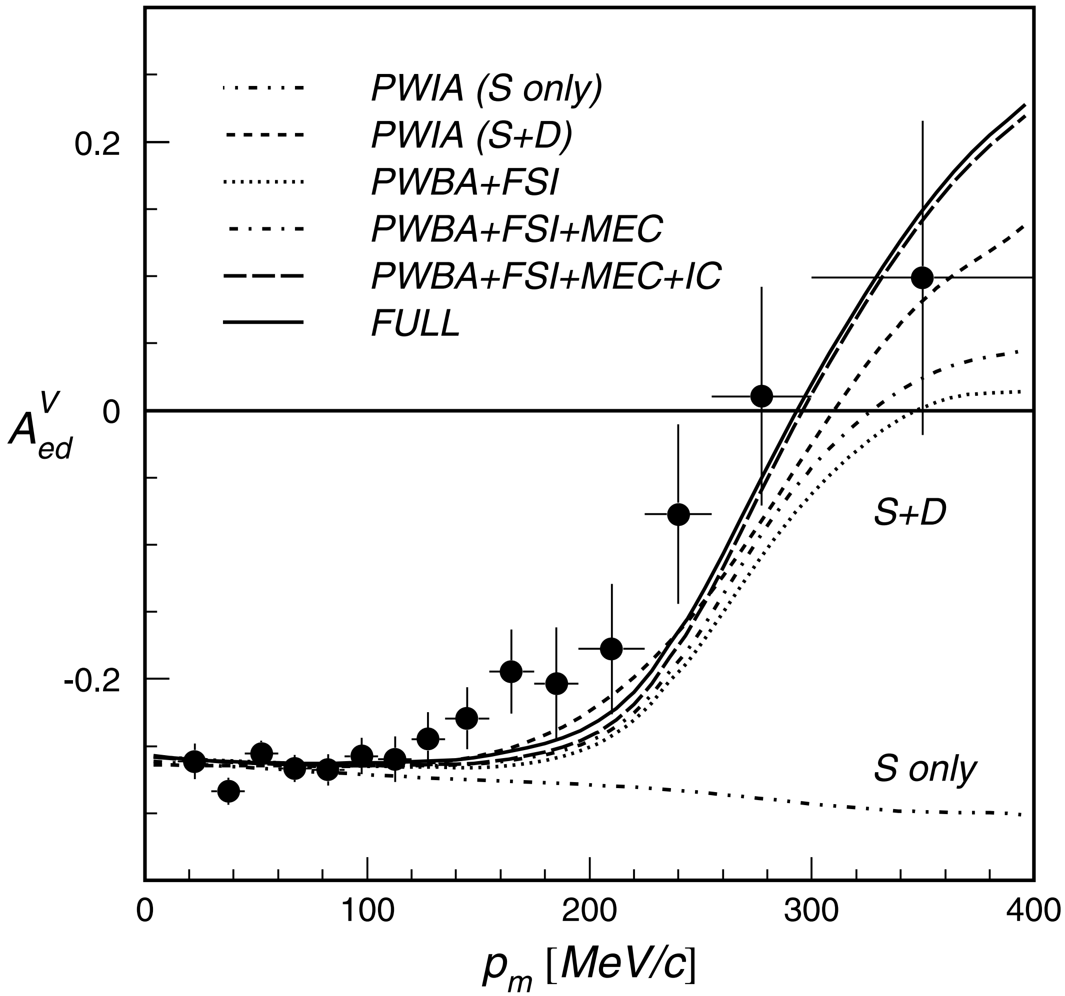


$$A_{\mathrm{ed}}^{\mathrm{V}} \approx a \cos\theta^* + b \frac{G_{\mathrm{E}}^{\mathrm{n}}}{G_{\mathrm{M}}^{\mathrm{n}}} \sin\theta^* \cos\phi^*$$

... from the days when each Q^2-point was precious ... Passchier++, PRL **82**, 4988 (1999)

$A_{\rm ed}^{\rm V}(\theta^* = 90°, \phi^* = 0°)$ in quasi-elastic $^2\vec{\rm H}(\vec{\rm e}, {\rm e'p})$ — NIKHEF

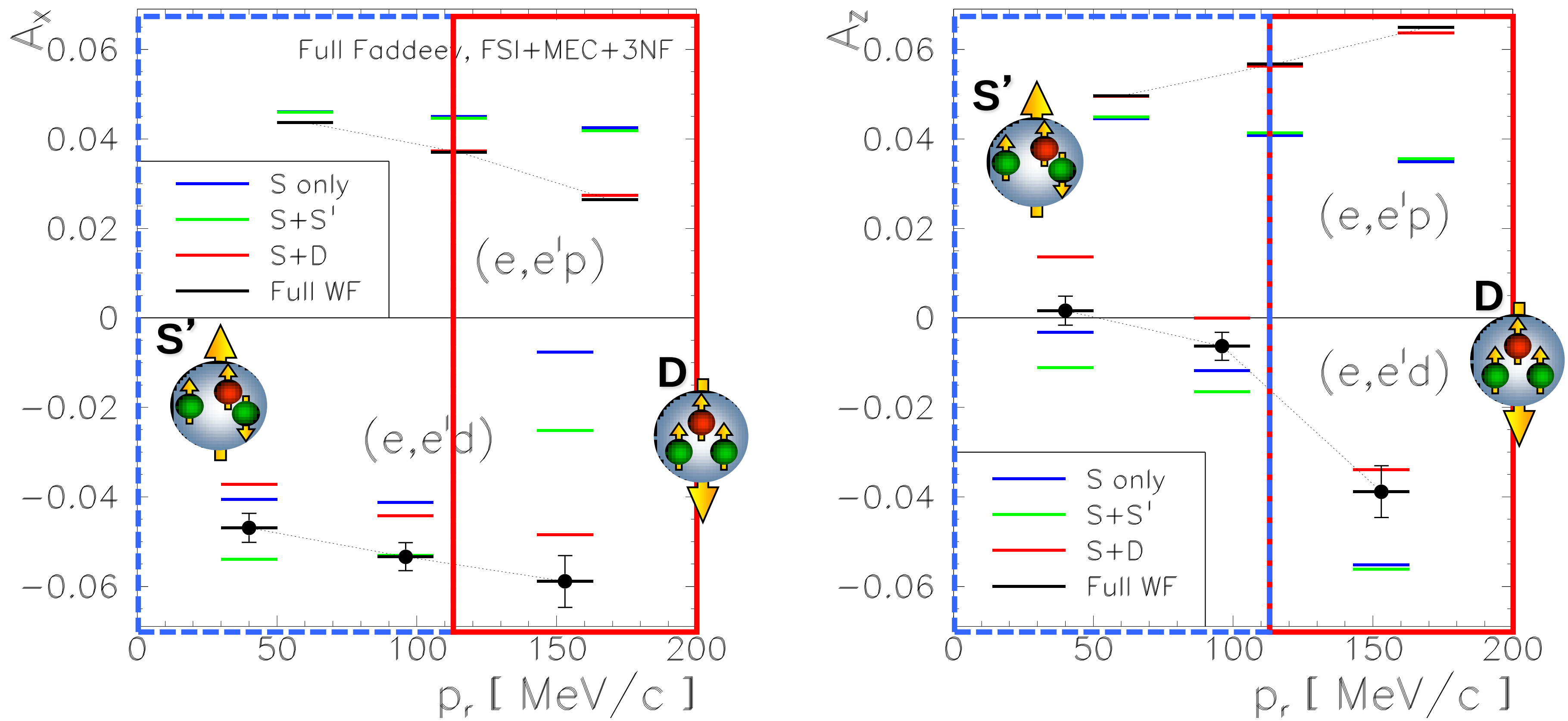
Very nice: $p_{\rm miss}$ dependence of $A_{\rm ed}^{\rm V}(\theta^* = 90°, \phi^* = 0°)$ at $Q^2 = 0.21\ ({\rm GeV}/c)^2$:



Passchier++, PRL **88**, 102303 (2002)

Sidetrack: $^3\vec{\mathrm{He}}(\vec{e}, e'd)$ & $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ KRAKOW/BOCHUM CALC.

Motivation behind the 2009 BigFamily of polarized-^{3}He experiments in Hall A — incidentally, using BigBite (!)



- S' state relevant at small p_r ($= p_\mathrm{miss}$)?
- D state governs variation of A_z at large p_r?

For answers, see Mihovilovič++, PRL **113**, 232505 (2014) and PLB **788**, 117 (2019)

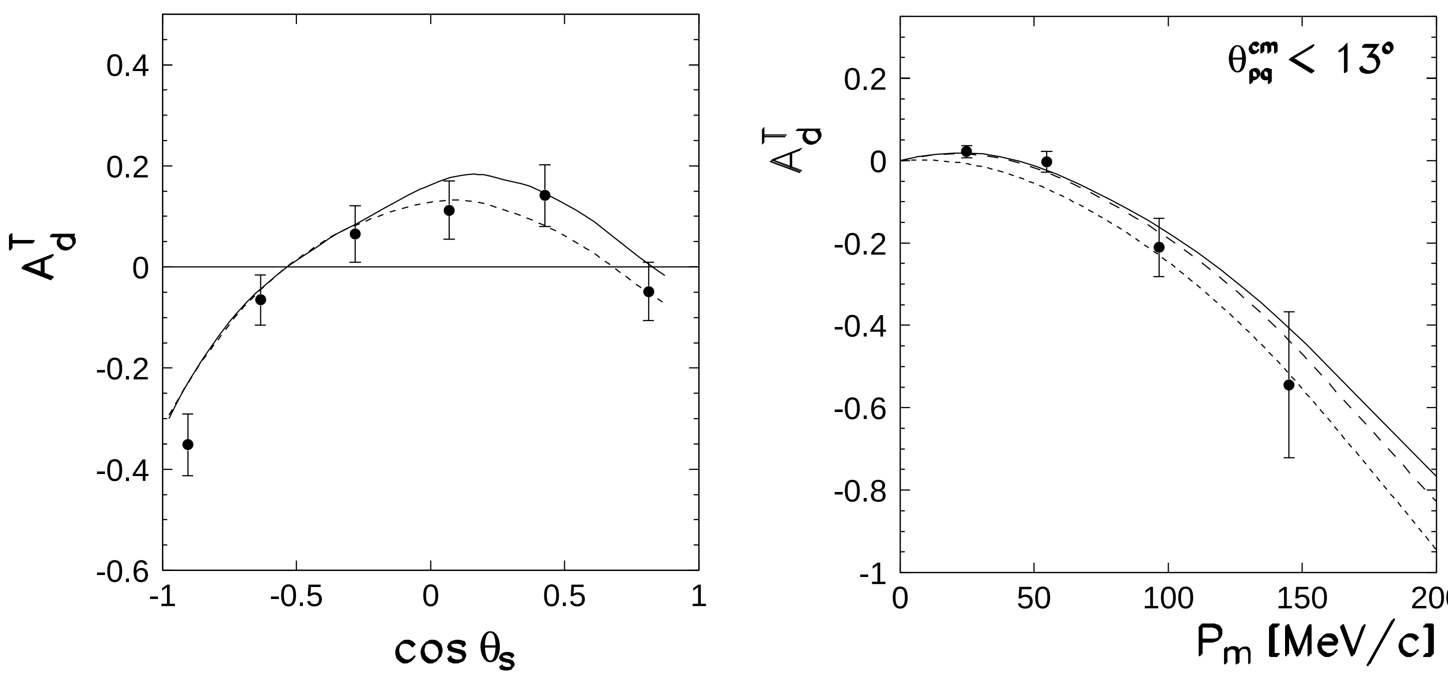
A_d^T in quasi-elastic $^2\overleftrightarrow{H}(e, e'p)$ — NIKHEF

Probes spin-dependent momentum densities ρ_{m_z}:

$$\rho_0(\boldsymbol{p}) \propto \left[R_0 + \sqrt{2}R_2 d^2_{0,0}(\theta)\right]^2 + 3\left[R_2 d^2_{1,0}(\theta)\right]^2$$

$$\rho_{\pm1}(\boldsymbol{p}) \propto \left[R_0 - \tfrac{1}{\sqrt{2}}R_2 d^2_{0,0}(\theta)\right]^2 + \tfrac{9}{8}R_2^2(1-\cos^4\theta)$$

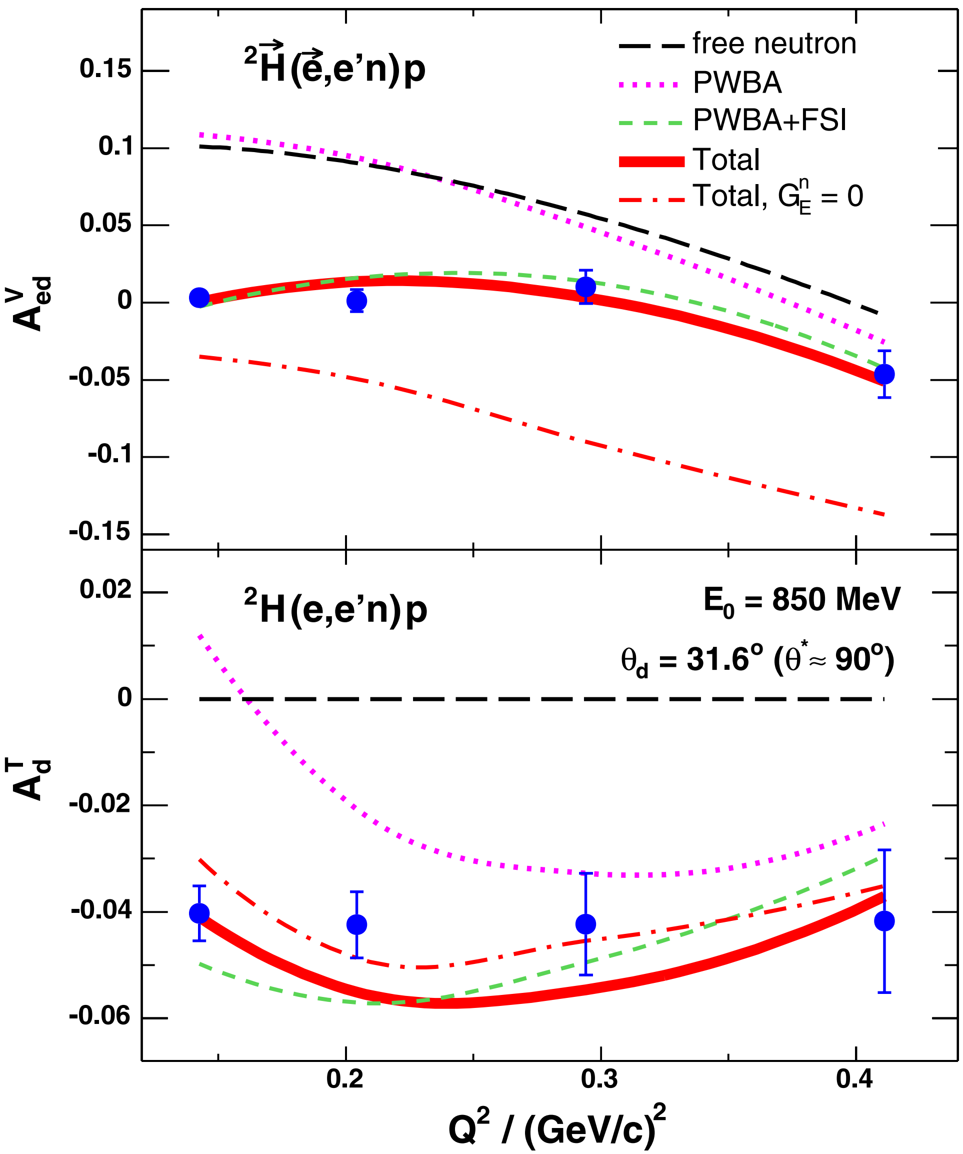
$$A_d^T = \sqrt{\frac{1}{2}}\frac{\sigma_+(p_m)+\sigma_-(p_m)-2\sigma_0(p_m)}{\sigma_+(p_m)+\sigma_-(p_m)+\sigma_0(p_m)} \overset{\text{PWIA}}{=} -\frac{2R_0(p)R_2(p)+\sqrt{\frac{1}{2}}R_2^2(p)}{R_0^2(p)+R_2^2(p)} d^2_{0,0}(\theta)$$

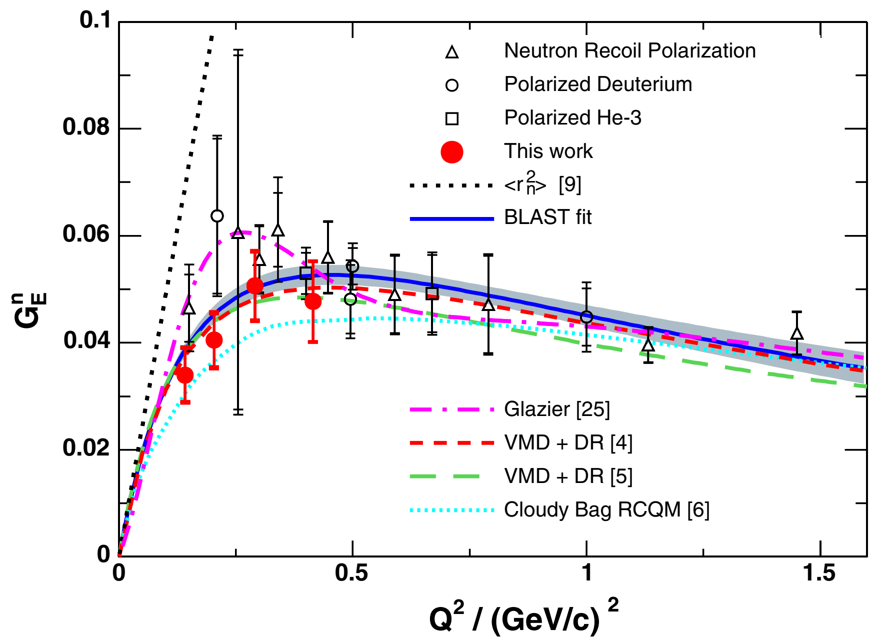


- One of the many statements that FSI, MEC & RC are needed

Zhou++, PRL **82**, 687 (1999)

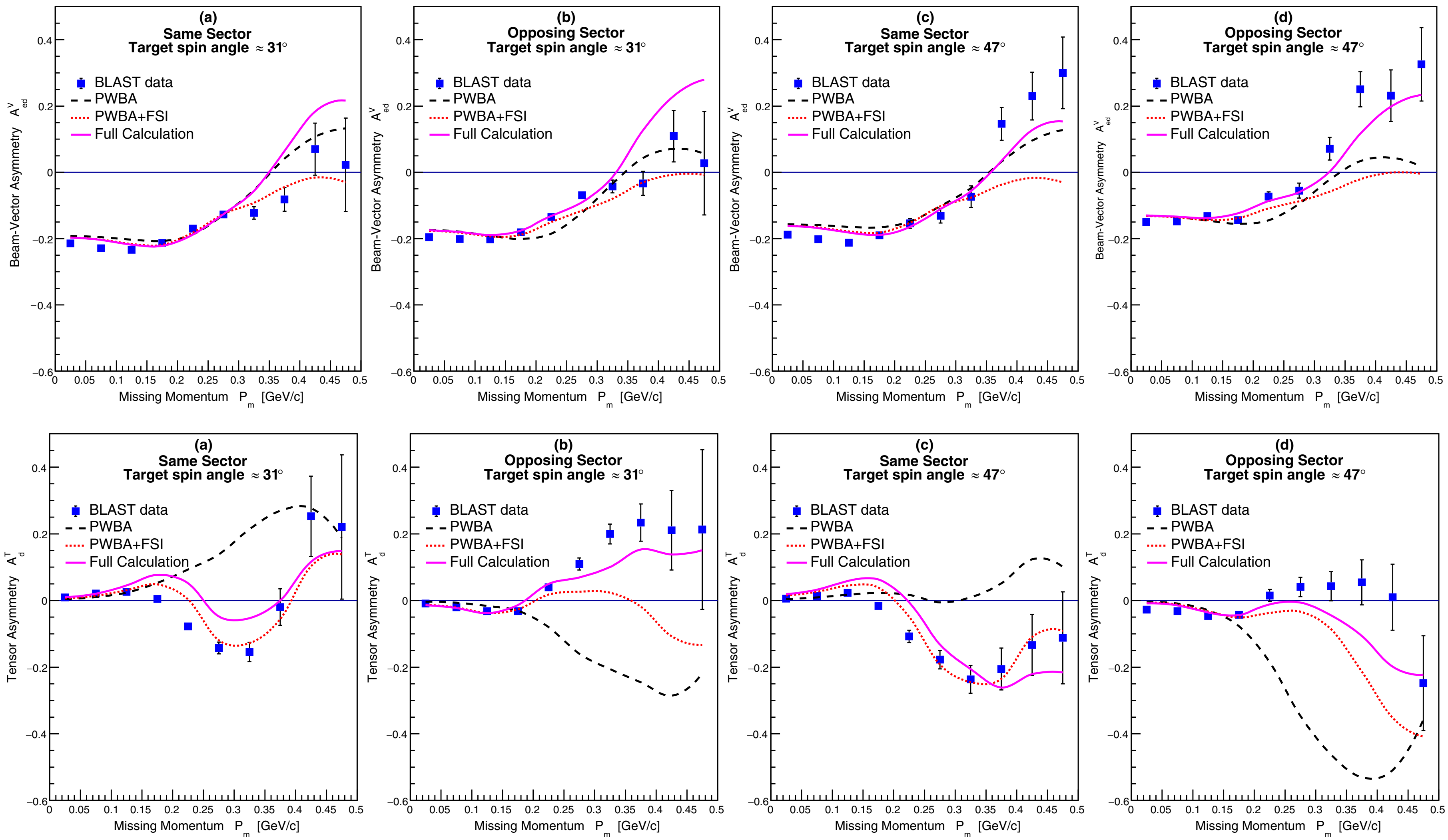
A_{ed}^{V} / A_{d}^{T} in QE $^{2}\vec{\mathrm{H}}(\vec{\mathrm{e}}, \mathrm{e}'\mathrm{n})$ / $^{2}\overleftrightarrow{\mathrm{H}}(\mathrm{e}, \mathrm{e}'\mathrm{n})$ — BLAST





Geis++, PRL **101**, 042501 (2008)

A^{V}_{ed} / A^{T}_{d} in QE $^{2}\vec{H}(\vec{e}, e'p)$ / $^{2}\overleftrightarrow{H}(e, e'p)$ — BLAST



DeGrush++, PRL **119**, 182501 (2017)

Conclusions

- *O wondrous ABS!*
- Groundbreaking vector/tensor deuteron work at NIKHEF ...
- ... which was inherited by & bore more fruit at MIT-Bates
- BLAST: lots of stuff on tape & not analyzed
- Good polarimetry is essential