A New Limit on Time-Reversal-Invariance Violation in Beta Decay: Results of the emiT-II Experiment

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NEW RESULT: $D=[-0.96\pm1.89(\text{STAT})\pm1.01(\text{SYS})]\text{x}10^{-4}$

$$\varphi_{AV} = 180.013 \pm 0.028 \qquad \frac{g_A}{g_V} = |\lambda| e^{i\varphi_{AV}}$$

Work supported in part by NIST and grants from the DOE and NSF

Polarized neutron decay

1957: In the wake of the Parity Revolution (Le, Yang, Ambler, Wu)
Jackson, Treiman, Wyld:

$$H_{\text{int}} = \sum_{i=V,A,S,P,T} (\overline{\psi}_p \mathrm{O}_i \psi_n)(C_i \overline{\psi}_e \mathrm{O}_i \psi_\nu + C_i' \overline{\psi}_e \gamma_5 \mathrm{O}_i \psi_\nu)$$

SM: $C_V' = C_V$ and $C_A' = C_A$

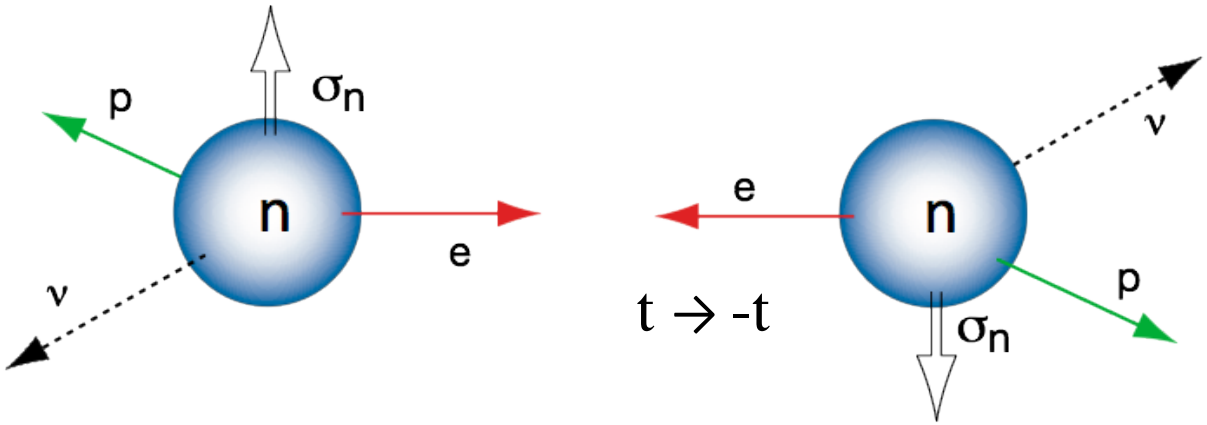
C_i real if T-symmetry

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \mathbf{P}\cdot\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}\right)\right)$$

a: -0.103(4) b: * A: -0.1187(8) B: 0.9807(30) D: **-0.0001(2)**

*Fierz interference (S, T) unmeasured for neutron

Time (motion) Reversal



$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \mathbf{P}\cdot\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}\right)\right)$$

T-odd, P-even

Motion reversal, initial and final states *not* exchanged but phase shifts lead to final state interactions: $|D_{f.s.}| \sim 2 \times 10^{-5}$

Note *R* coefficient - $\boldsymbol{\sigma}_n \cdot (\boldsymbol{\sigma}_e \times \mathbf{p}_e)$ (T-odd, P-odd):

$R_{8Li} = [0.9 \pm 2.2] \times 10^{-3}$ (Sromicki *et al.* Phys Rev. Lett. 82 57: 1999)

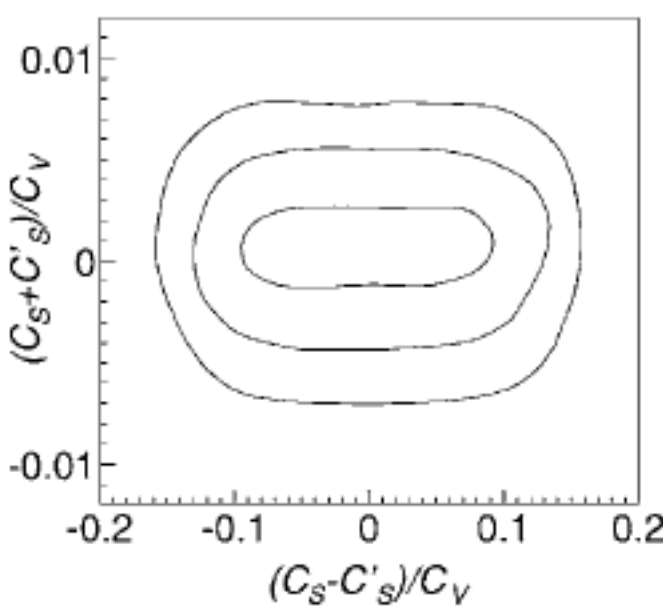
$R_n = [8 \pm 15(\text{stat}) \pm 5(\text{sys})] \times 10^{-3}$ (Kozela *et al.* Phys. Rev. Lett. 102 17230: 2009)

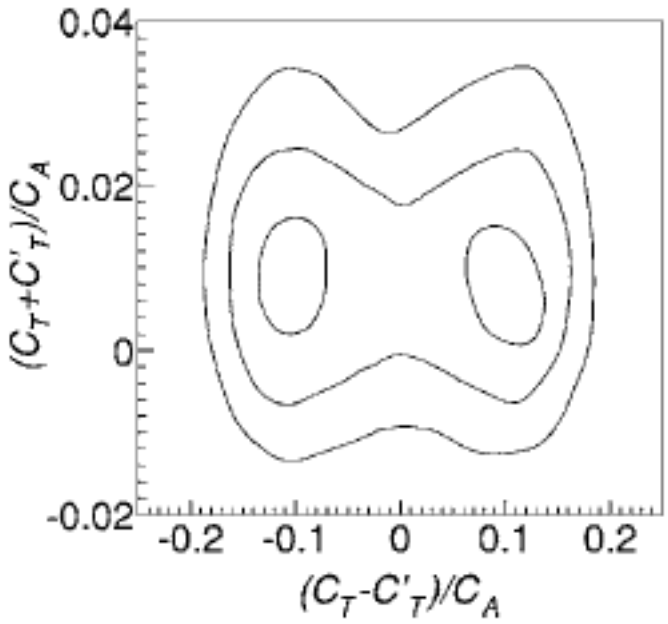
Beyond SM Physics

$$D_T \approx \frac{1}{1+3|\lambda|^2}\left\{-2\frac{\mathrm{Im}(C_V C_A^*)}{|C_V{}^2|} + \frac{\mathrm{Im}(C_S C_T^* + C'_S C_T^*)}{|C_V{}^2|} + \frac{\alpha m}{p_e}\left(\lambda^* \frac{\mathrm{Re}(C_T + C'_T)}{C_A^*} + \lambda^* \frac{\mathrm{Re}(C_S + C'S)}{C_V^*}\right)\right\}$$

$$2\frac{\mathrm{Im}(\lambda)}{1+3|\lambda|^2}$$

$$\frac{C_A}{C_V} = |\lambda| e^{i\varphi_{AV}}$$





|CS/CV|<0.067 and |CT/CA|<0.081 (95% c.l.)

N. Severijns et al. RMP, **78** p991 (2006)

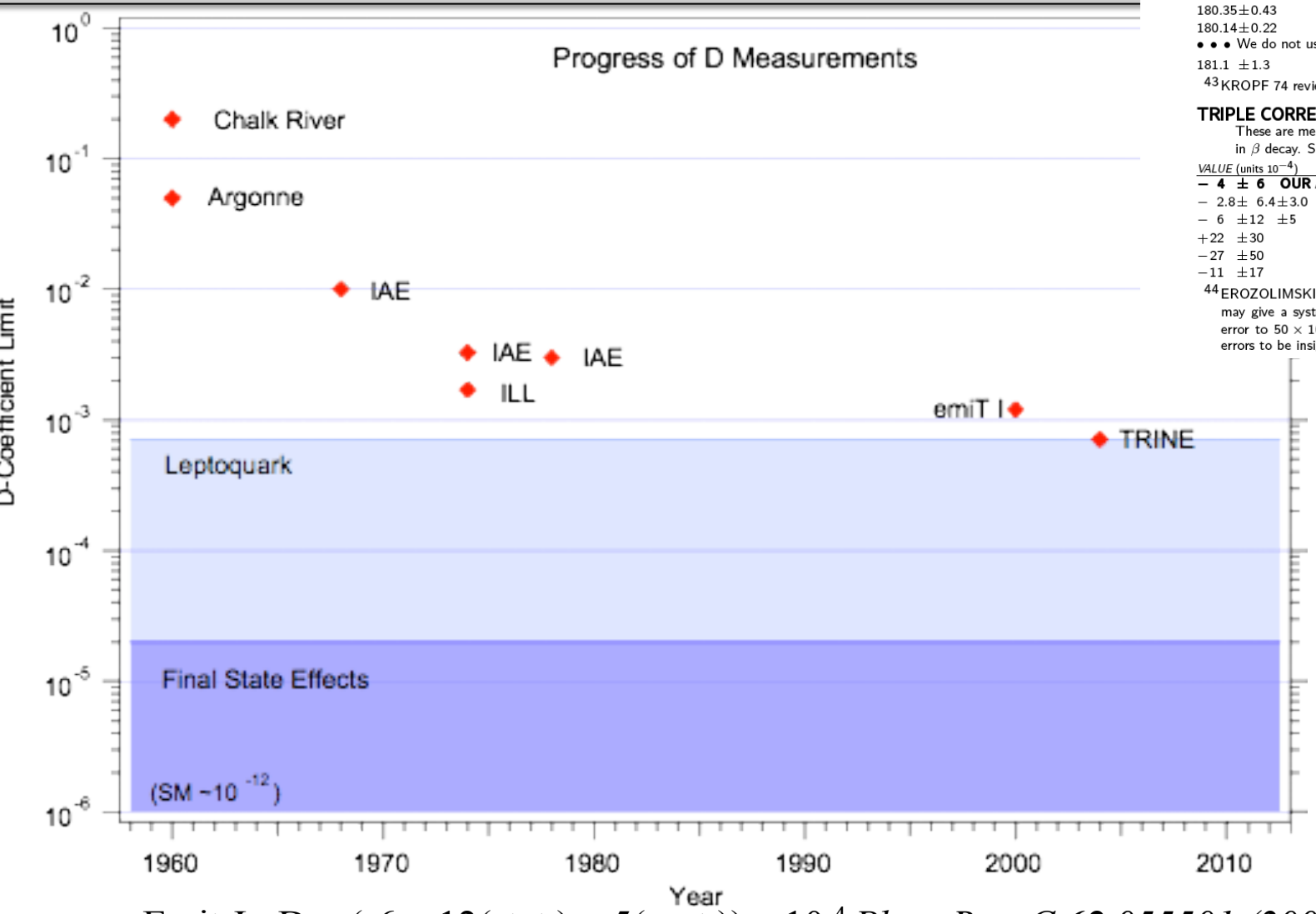
Models

Model	Contribution to D	Constrained by
CKM Phase	10^{-12}	K-meson/b-meson
θ_{QCD}	2×10^{-15}	EDMs (n, ^{199}Hg)
Left-right symmetry	10^{-7}-10^{-5}	W_L limits (B)+EDMs
Non-SM Fermions	10^{-7}-10^{-5}	Direct production+EDMs
Charged Higgs SUSY	10^{-7}-10^{-6}	
Leptoquark	4.5×10^{-4}	This experiment

Our limit: $|D_T|<4.5\times10^{-4}$ (95% c.l.)

$D_{FSI}\sim2\times10^{-5}$

History



ϕ_{AV}, PHASE OF g_A RELATIVE TO g_V

Time reversal invariance requires this to be 0 or 180°. This is related to D given in the next data block and $\lambda \equiv g_A/g_V$ by $\sin(\phi_{AV}) = D(1+3\lambda^2)/2\lambda$; this assumes that g_A and g_V are real.

VALUE (°)	DOCUMENT ID		TECN	COMMENT
180.06±0.07 OUR AVERAGE				
180.04±0.09	SOLDNER	04	CNTR	Cold n, polarized
180.08±0.13	LISING	00	CNTR	Polarized >93%
179.71±0.39	EROZOLIM...	78	CNTR	Cold n, polarized
180.35±0.43	EROZOLIM...	74	CNTR	Cold n, polarized
180.14±0.22	STEINBERG	74	CNTR	Cold n, polarized
• • • We do not use the following data for averages, fits, limits, etc. • • •				
181.1 ±1.3	[43] KROPF	74	RVUE	n decay

[43] KROPF 74 reviews all data through 1972.

TRIPLE CORRELATION COEFFICIENT D

These are measurements of the component of n spin perpendicular to the decay plane in β decay. Should be zero if T invariance is not violated.

VALUE (units 10^{-4})	DOCUMENT ID		TECN	COMMENT
− 4 ± 6 OUR AVERAGE				
− 2.8± 6.4±3.0	SOLDNER	04	CNTR	Cold n, polarized
− 6 ±12 ±5	LISING	00	CNTR	Polarized >93%
+22 ±30	EROZOLIM...	78	CNTR	Cold n, polarized
−27 ±50	[44] EROZOLIM...	74	CNTR	Cold n, polarized
−11 ±17	STEINBERG	74	CNTR	Cold n, polarized

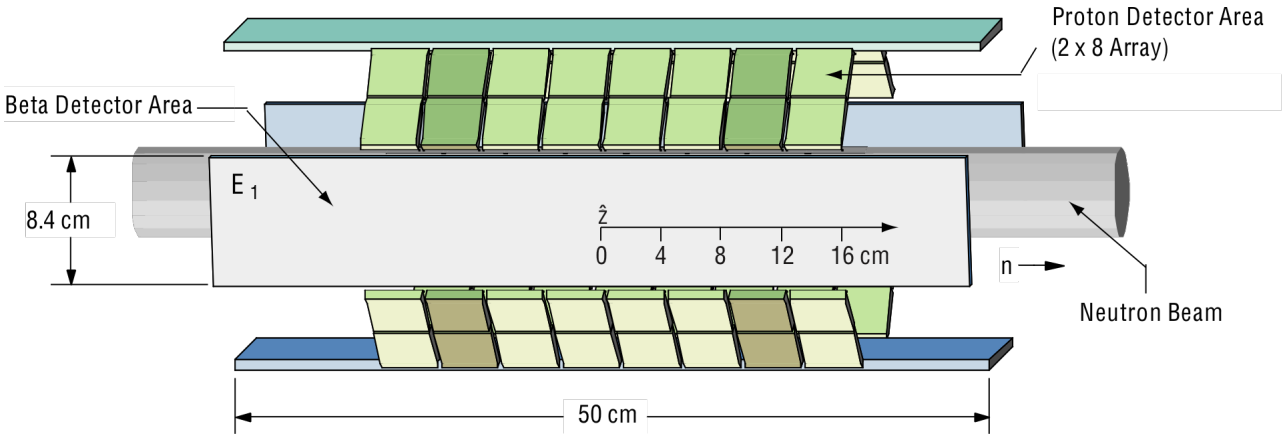
[44] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to 30×10^{-4}, thus increasing the EROZOLIMSKII 74 error to 50×10^{-4}. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

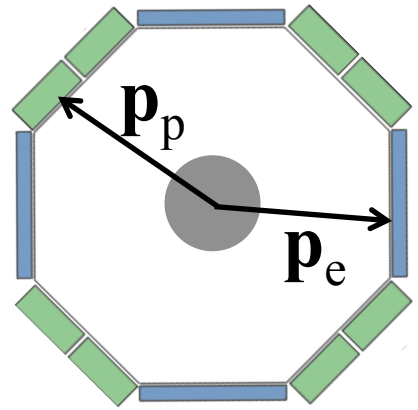
Emit-I: $D = (-6 \pm 12(\text{stat.}) \pm 5(\text{syst.})) \times 10^{-4}$ *Phys. Rev. C* ***62*** *055501 (2000)*

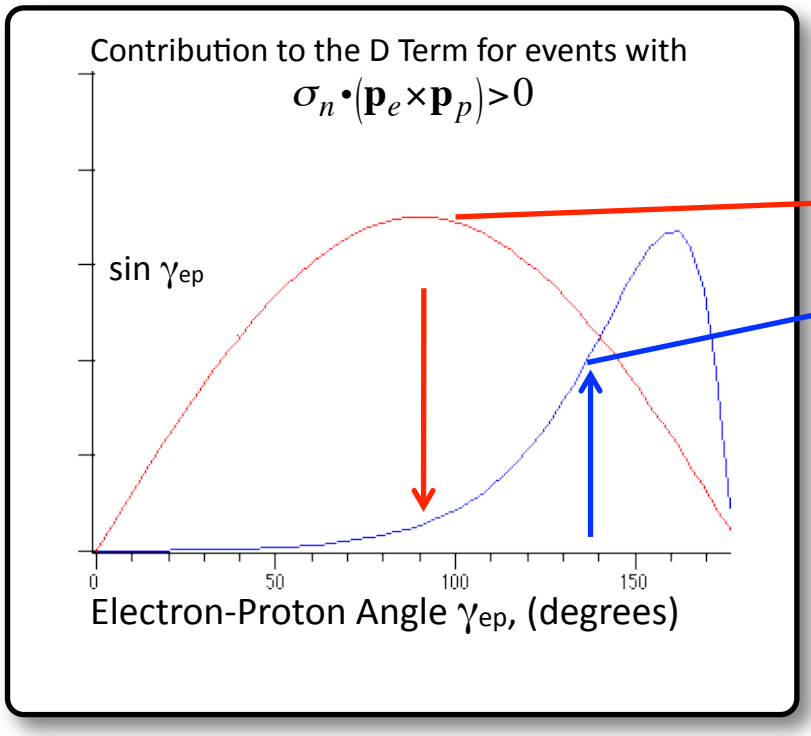
TRINE: $D = (-2.8 \pm 7.1) \times 10^{-4}$ T. Soldner et al. *Phys. Lett.* **B** 581 (2004)

^{19}Ne: $D = (1 \pm 6) \times 10^{-4}$ F. Calaprice, in Hyperfine Interactions (1985)

emiT: 8-fold symmetry - 64 proton SBDs/4 β scintillators

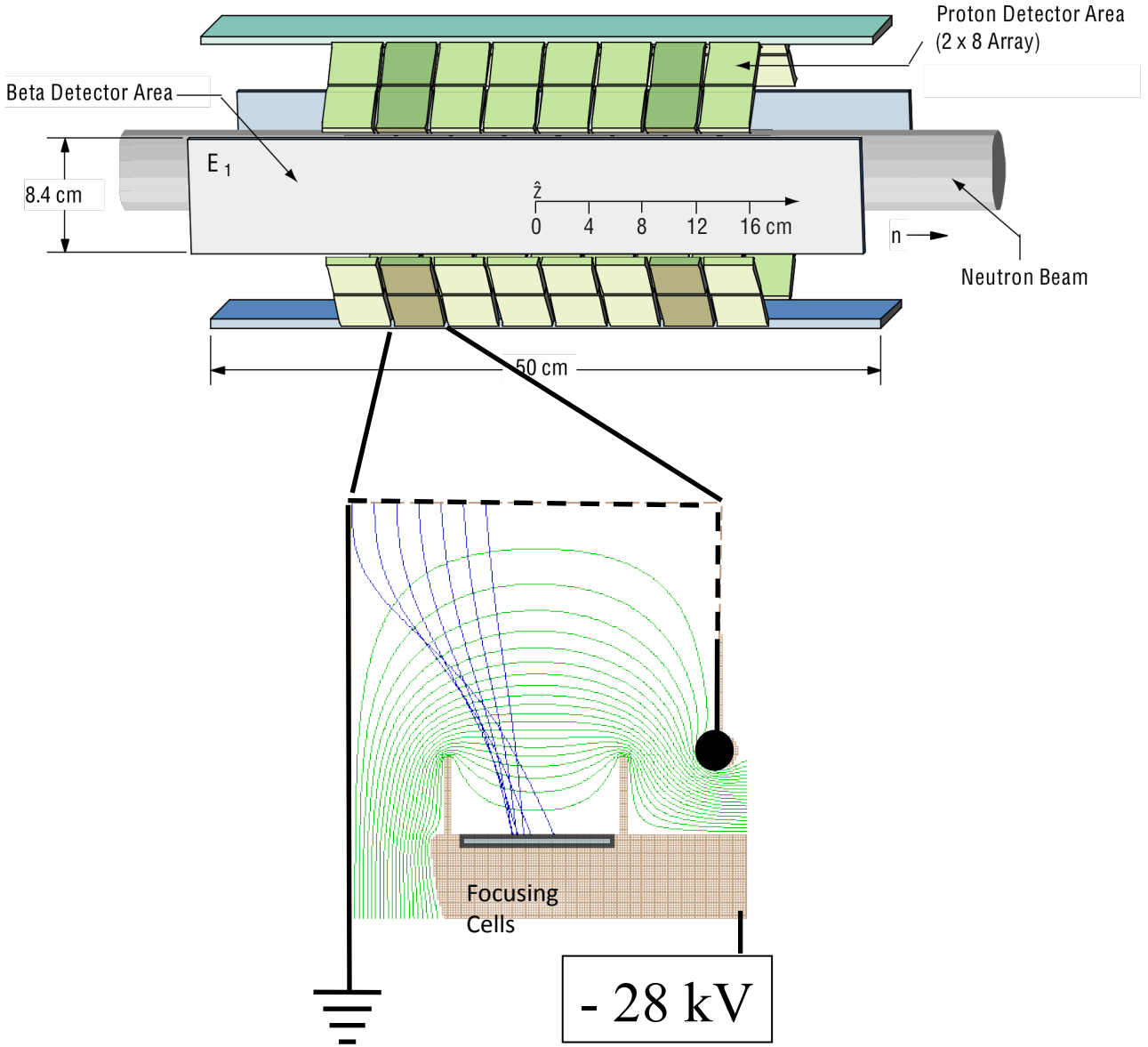




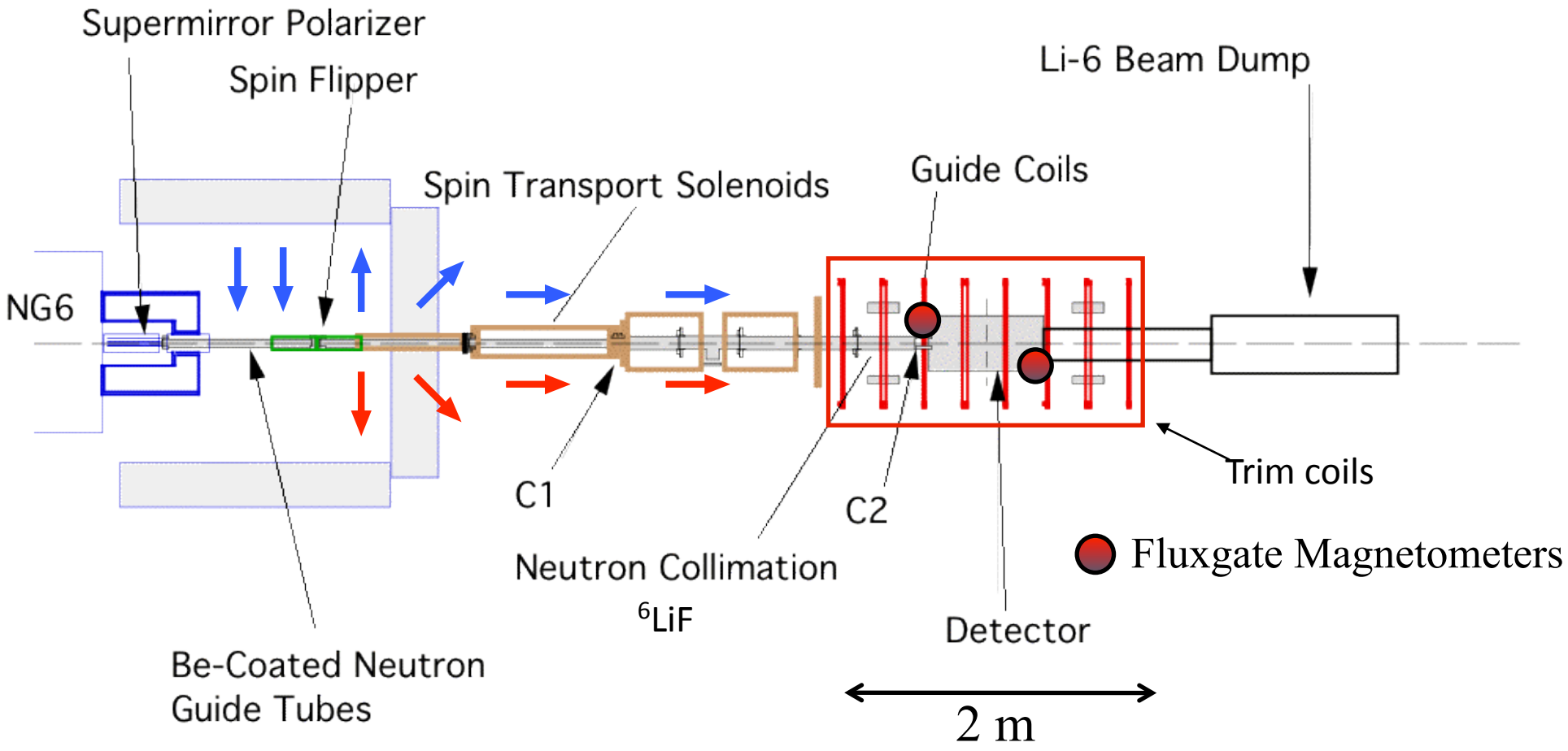


- Proton-electron momenta anticorrelated
  - Coincidence rate favors 180°
  - $\sin\theta_{ep}$ favors 90°
  - FOM ($1/\sigma^2$) 9x improved at 135°
- Symmetrical, segmented detector:
  - Minimize sensitivity to *A* and *B*
  - Investigate nonuniformities
  - Study systematic effects

emiT proton detection

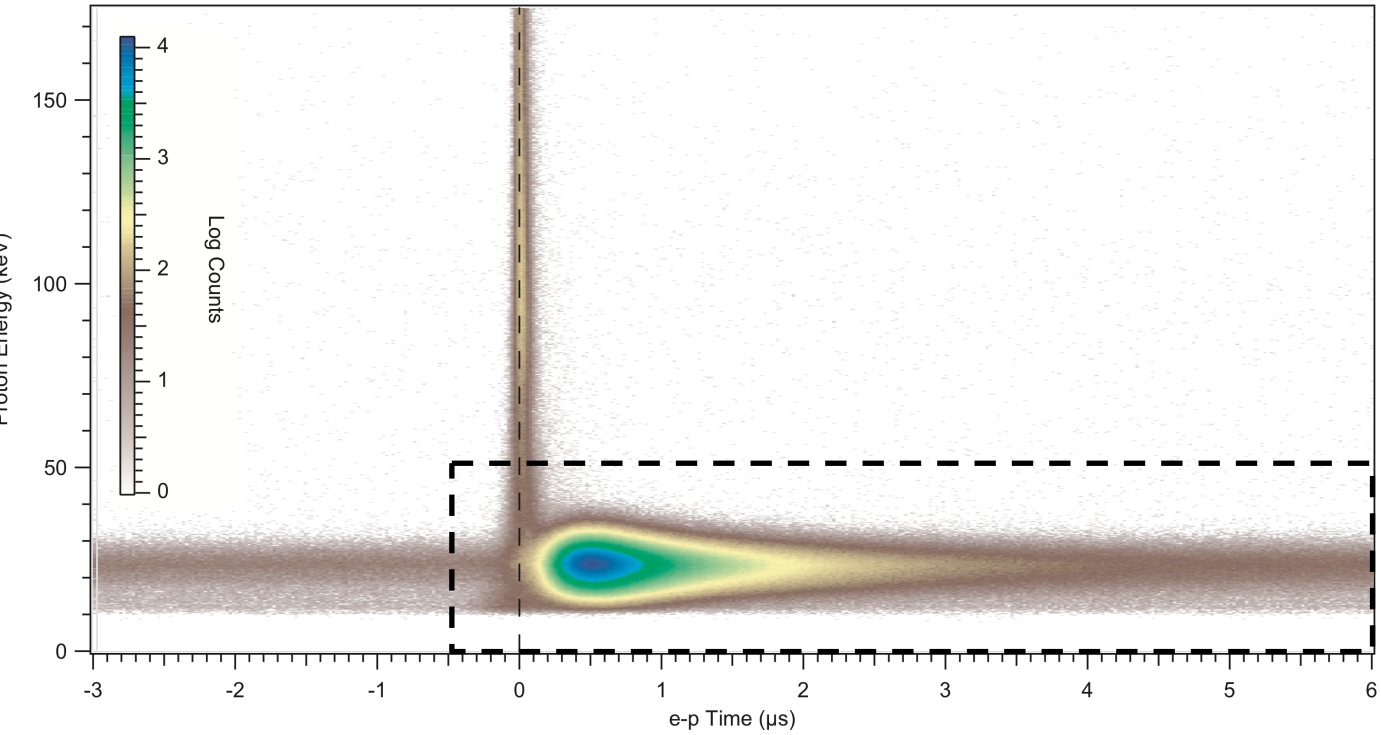


Neutron Beam and Spin transport



- High neutron flux (1.7 x 10^8 cm^{-2} s^{-1} at "C2") (fission chamber)
- 560 μT guide field, monitored during run
- Beam profile measured at 3 positions via Dysprosium foil activation
- Polarization measured with supermirror analyzer flipping ratio measurement

Data and cuts



Rates

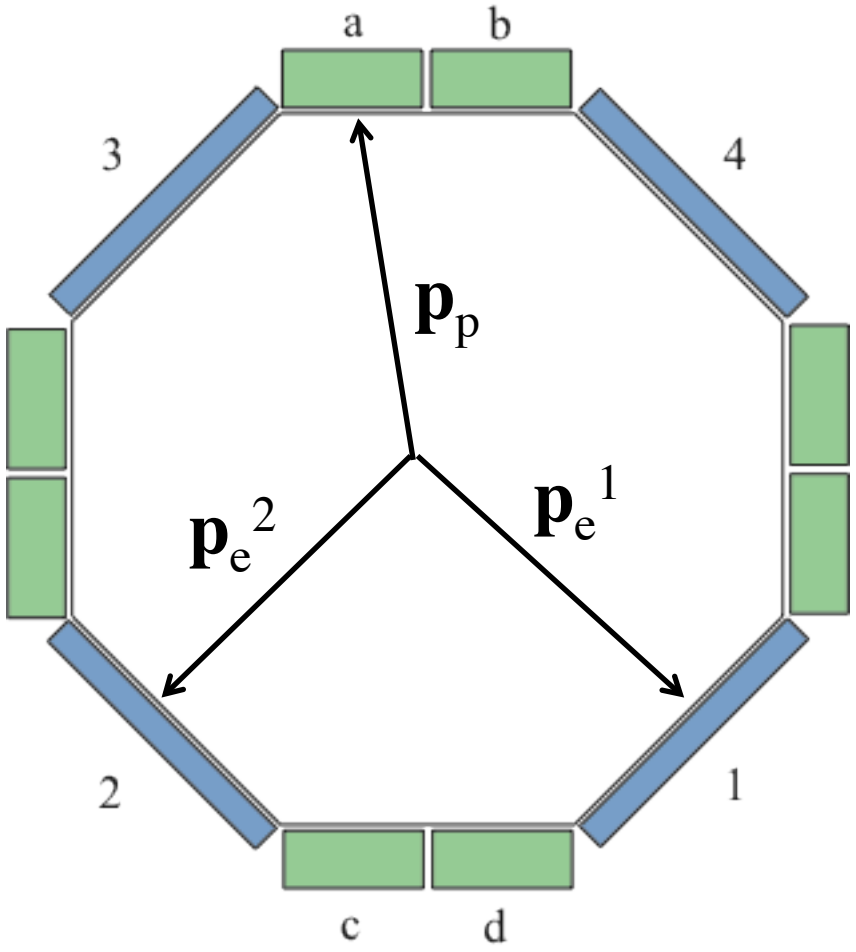
- 3 Hz singles per proton surface barrier detectors
- 100 Hz singles per beta plastic scintillators
- 25 Hz average total coincidence rate
- BR determined by pre-prompt events: S/B = 30/1

Filtering

- Data collected with acceptable operational parameters (magnetic fields, currents, spin state, ...) : 12% removed
- β-energy threshold set to 90 keV, to minimize detection efficiency drifts arising from PMT gain drifts : 14% removed
- Require single β detector in coincidence with single proton event : 7% removed

Final data set ~ 300 million accepted coincidence events.

Measurement Principle



Proton Detector

Electron Detector

Spin-flip asymmetry

$$w^{p_i e_j} = \frac{N_+^{p_i e_j} - N_-^{p_i e_j}}{N_+^{p_i e_j} + N_-^{p_i e_j}}$$

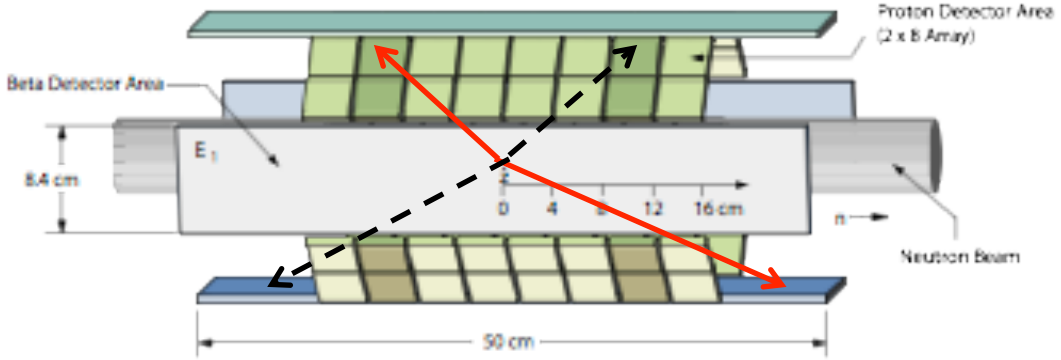
For a single proton cell:

$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A\tilde{\mathbf{K}}_A^{p_i e_j} + B\tilde{\mathbf{K}}_B^{p_i e_j} + D\tilde{\mathbf{K}}_D^{p_i e_j} \right)$$

Combine w's

$$v^{p_i} = \frac{1}{2}\left(w^{p_i R} - w^{p_i L}\right) \propto \int \frac{(\vec{p}_p \times \vec{p}_e)}{E_e E_\nu} dE_e d\Omega_e d.$$

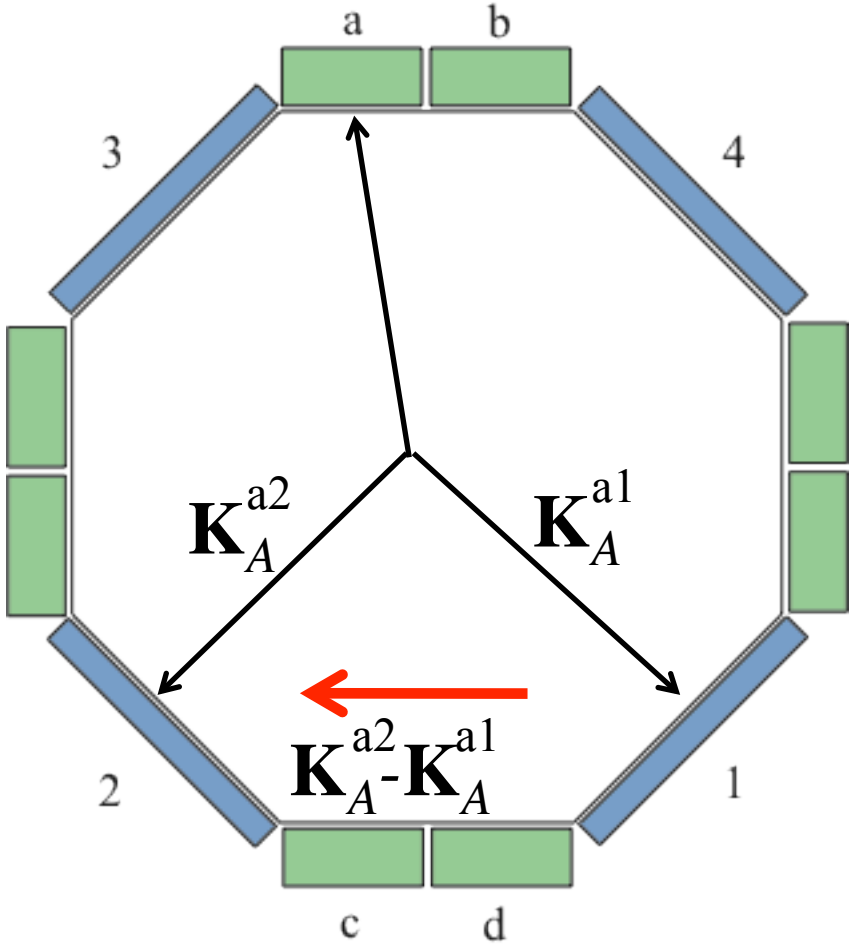
$$v^{p_i} = PD\hat{z} \cdot \left(\tilde{\mathbf{K}}_D^{p_i e_R} - \tilde{\mathbf{K}}_D^{p_i e_L} \right) + A\hat{z} \cdot \Delta \frac{\vec{p}_e}{E_e}$$



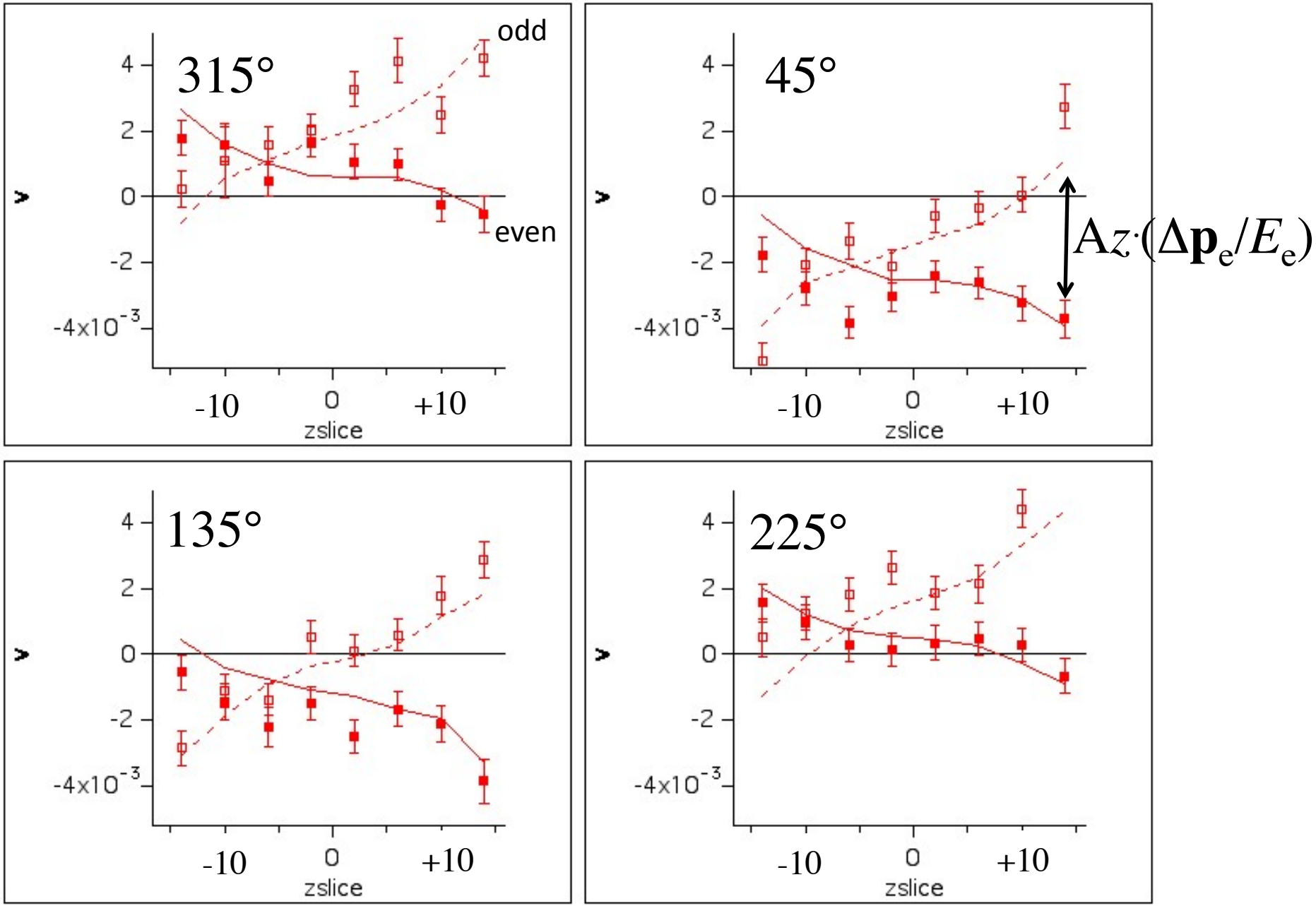
Transverse Polarization (5 mR guide field misalignment)

$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A\tilde{\mathbf{K}}_A^{p_i e_j} + B\tilde{\mathbf{K}}_B^{p_i e_j} + D\tilde{\mathbf{K}}_D^{p_i e_j} \right)$$

$$v^{p_i} = \frac{1}{2}(w^{p_i R} - w^{p_i L})$$



Transverse polarization, **B** and beam expansion



emiT II Result

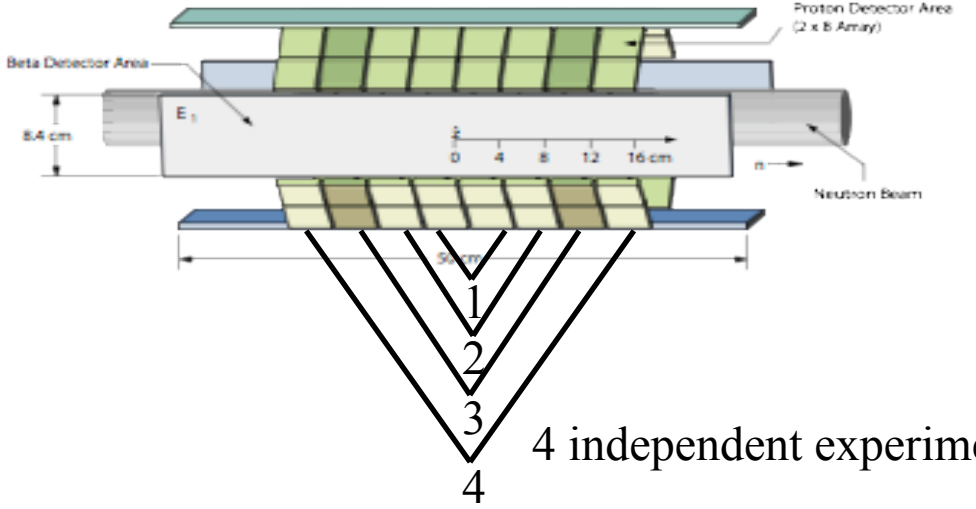
Blind analysis: $w^{p_i e_j} = \frac{N_+^{p_i e_j} - N_-^{p_i e_j}}{N_+^{p_i e_j} + N_-^{p_i e_j}} + \mathcal{B}\hat{z} \cdot \tilde{\mathbf{K}}_D^{p_i e_j}$

hidden offset

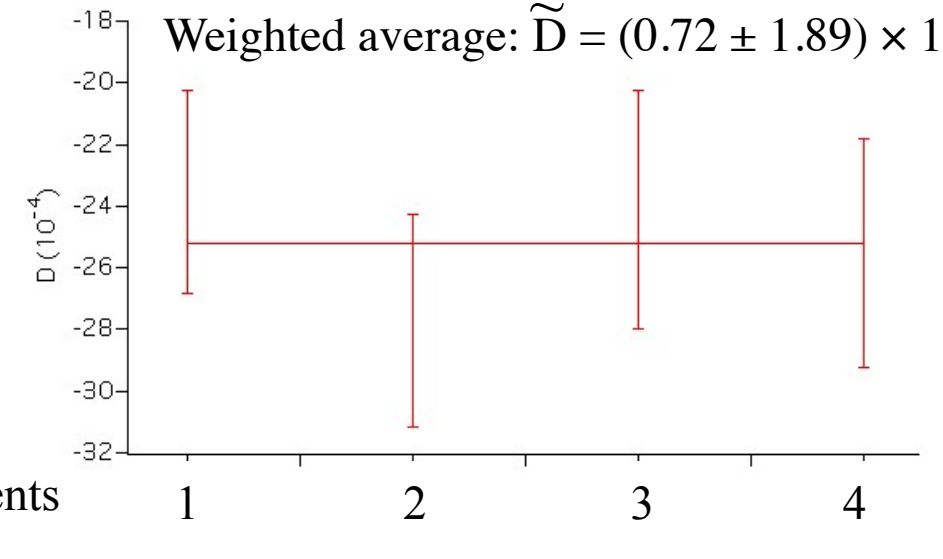
$$v^{p_i} = \frac{1}{2}(w^{p_i R} - w^{p_i L})$$

$$\bar{v} \approx \bar{K}_D P \tilde{D} \rightarrow D \quad \text{(with corrections)}$$

$$\bar{K}_D = 0.378 = \hat{z} \bullet \left(\tilde{\mathbf{K}}_D^{p_i e_R} - \tilde{\mathbf{K}}_D^{p_i e_L} \right)$$



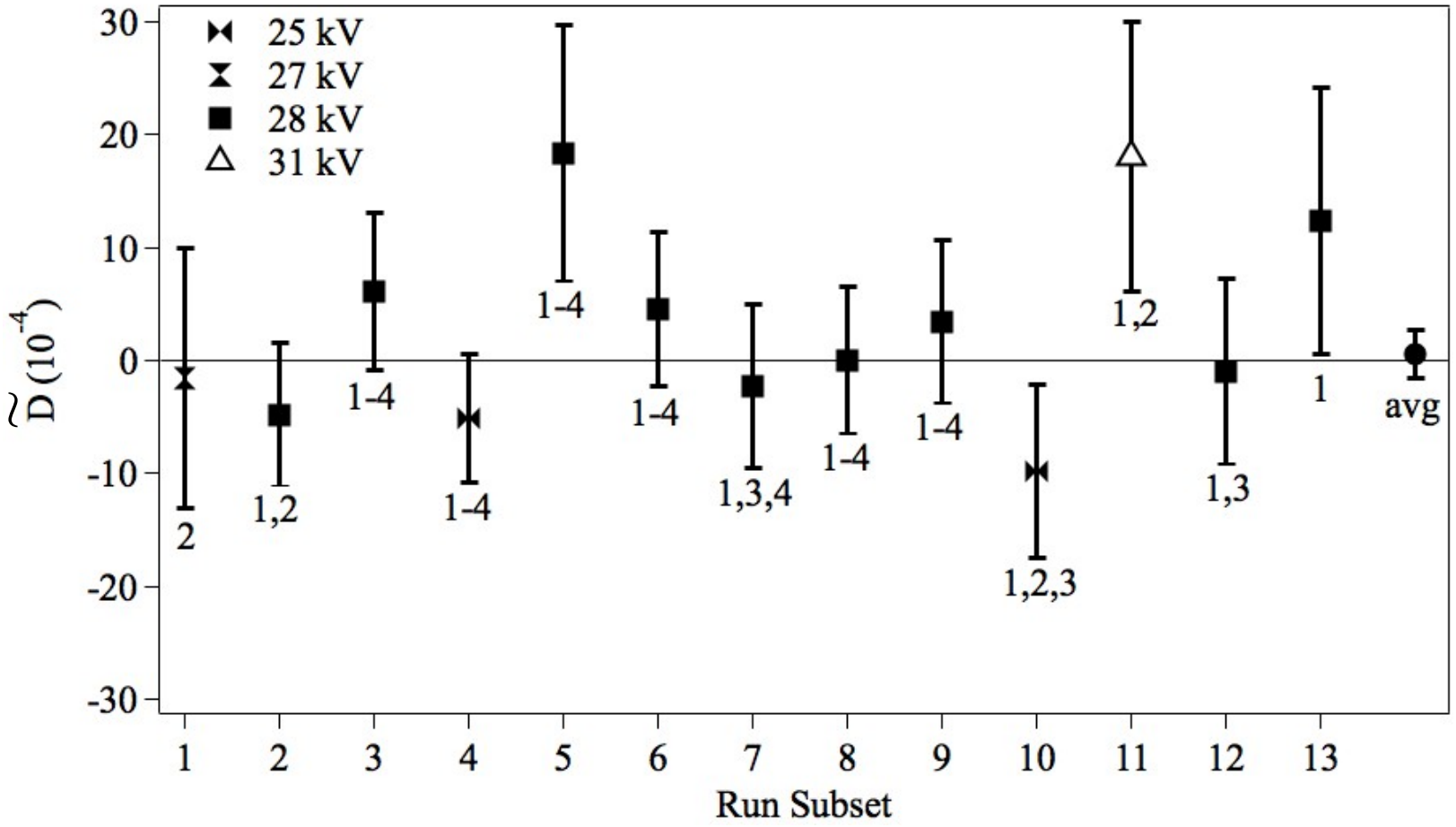
4 independent experiments



$$D = (-0.96 \pm 1.89(\text{stat}) \pm 1.01(\text{sys})) \times 10^{-4}$$

Cuts suggest proton HV dependence

Results for ~D by run subset



No correlation (constant D): chi2=10.4/12 df.

Correlation with HV: chi2=5.6/11 df (2.1 sigma)

- Conclude it's accidental correlation

Corrections (10^{-4})

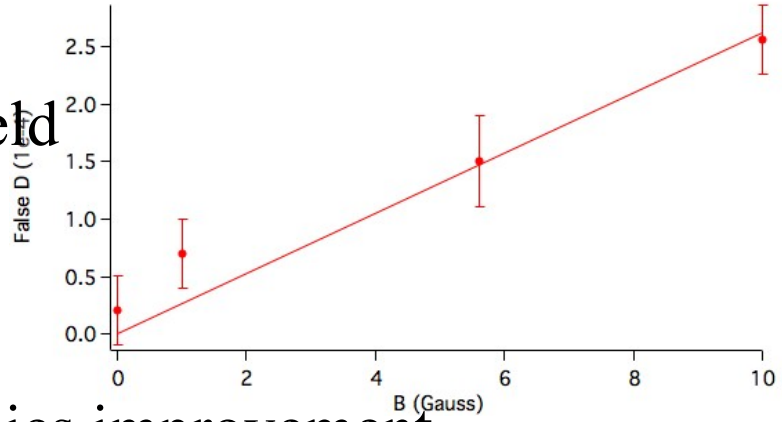
All studies completed while data were still "blind"

Source	Correction	Uncertainty
BR asymmetry	upper limit	0.30
BR subtraction	0.03	0.00
Electron Backscattering	0.11	0.03
Proton Backscattering	upper limit	0.03
Beta threshhold uniformity	0.04	0.10
Proton threshhold effect	-0.29	0.41
Beam Expansion/**B**-field	-1.50	0.40
Pol uniformity	upper limit	0.10
Asymmetric-beam/Trans. Pol (ATP)	-0.07	0.72
ATP twist	upper limit	0.24
Spin correlated flux	<1e-6	0.00
Spin correlated polarization[a]	<1e-6	0.00
Polarization (95±5%)	Included in $\widetilde{D}$	0.04
K_D (0.378±0.019)	Included in $\widetilde{D}$	0.05
Total	-1.68	1.01

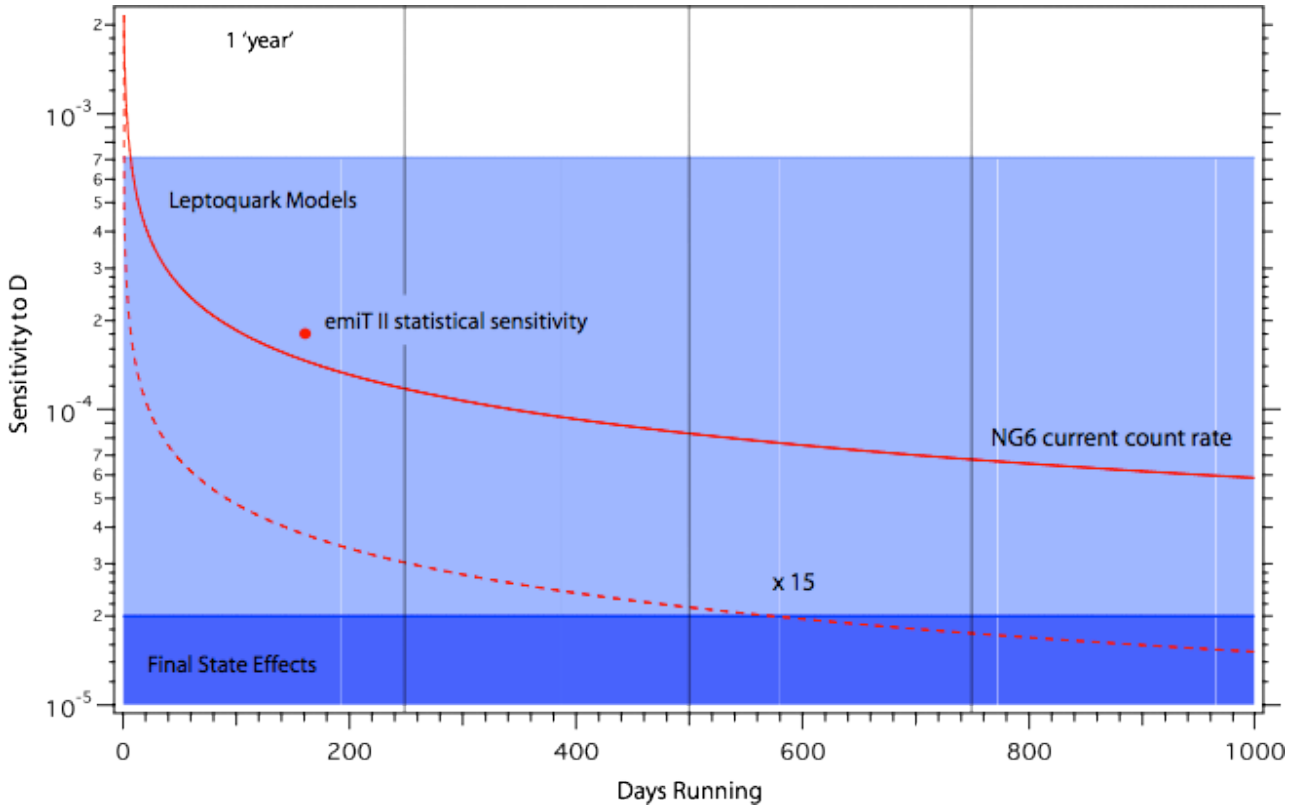
[a] Includes spin-flip time, cycle asymmetry, and flux variation.

Improvements

- Major systematics
  - Beam expansion/magnetic field: reduce field
  - ATP error also limited by beam shape
    - AFP spin flipper
    - ^{3}He Polarizer ★★★
  - Proton threshold requires detector/electronics improvement

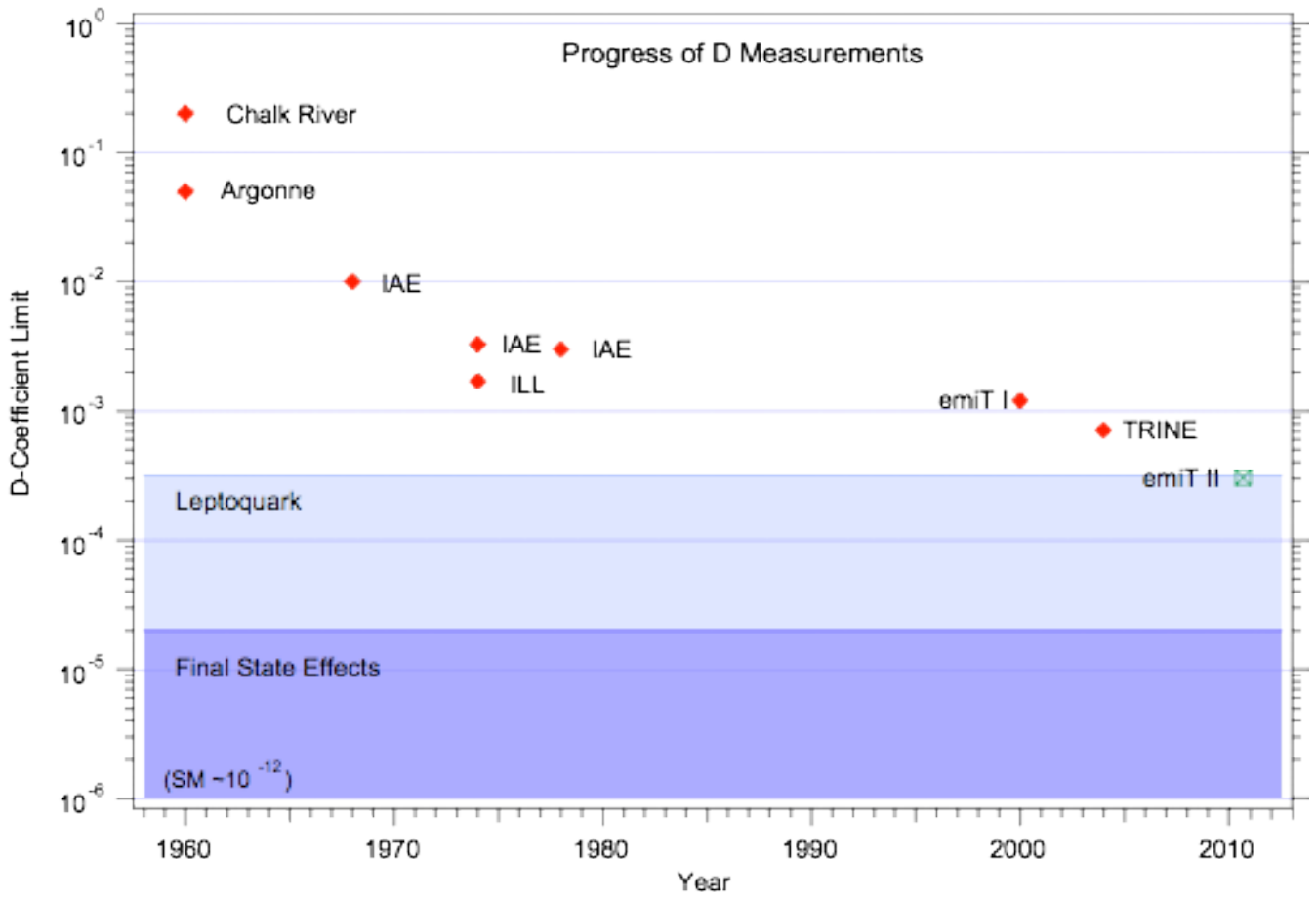


- NIST-NGC beam line could provide factor 10 increase in neutron decay rate



Summary: $D=(-0.96\pm1.89\ (stat)\pm1.10(sys))\times10^{-4}$

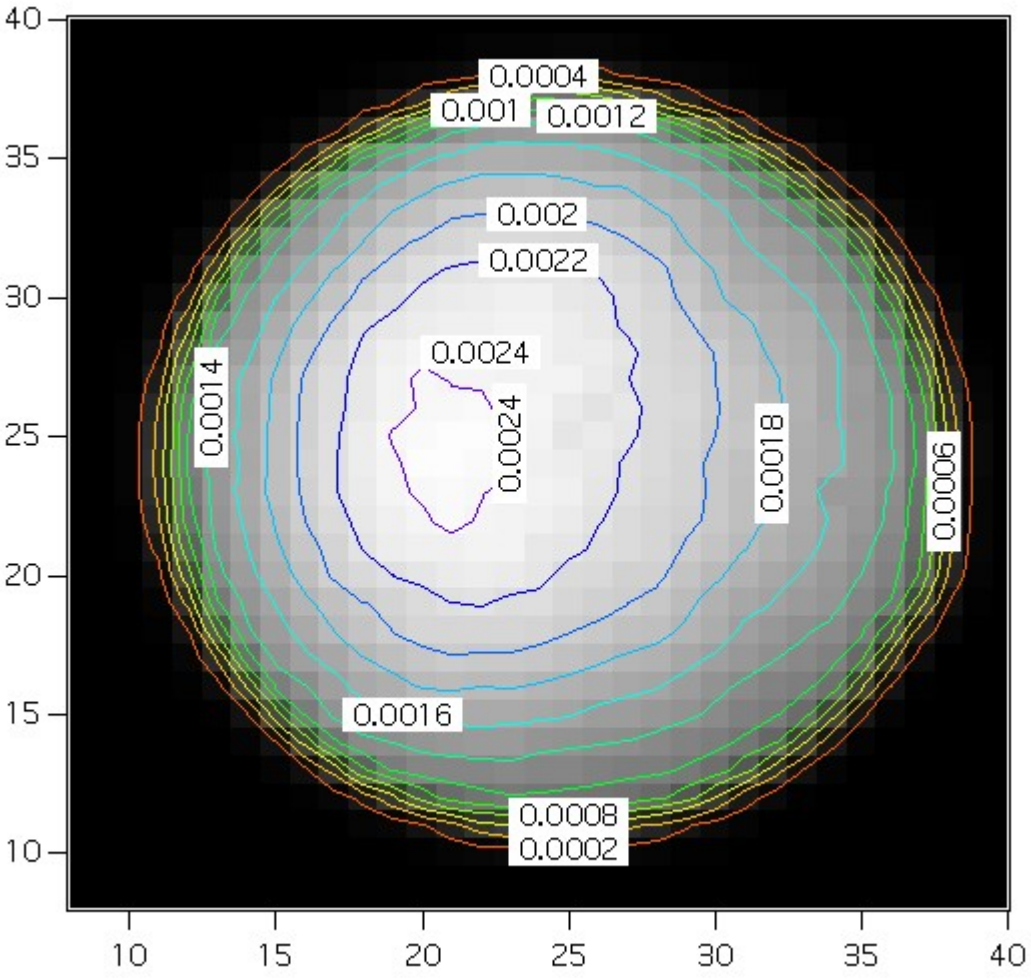
$\phi_{AV} = 180.013° \pm 0.028°$



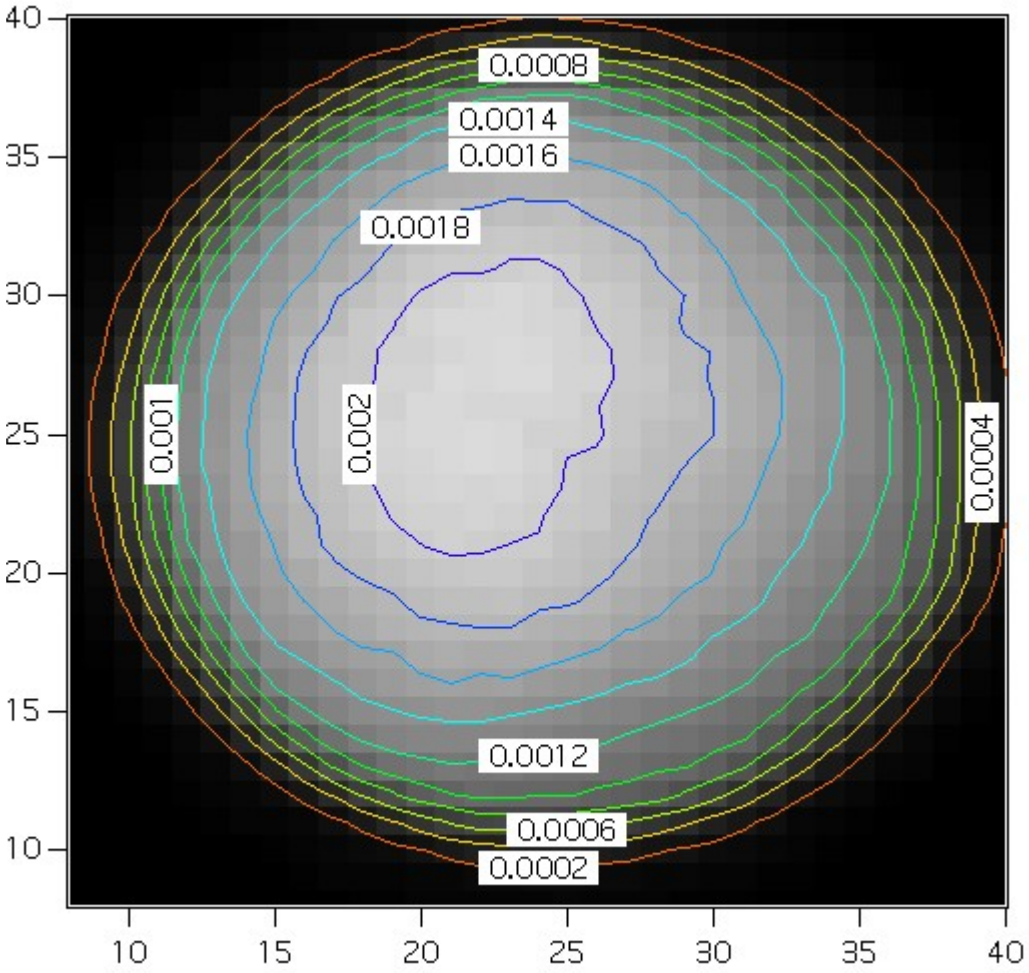
Thank You!

Extra Slides

Beam profiles

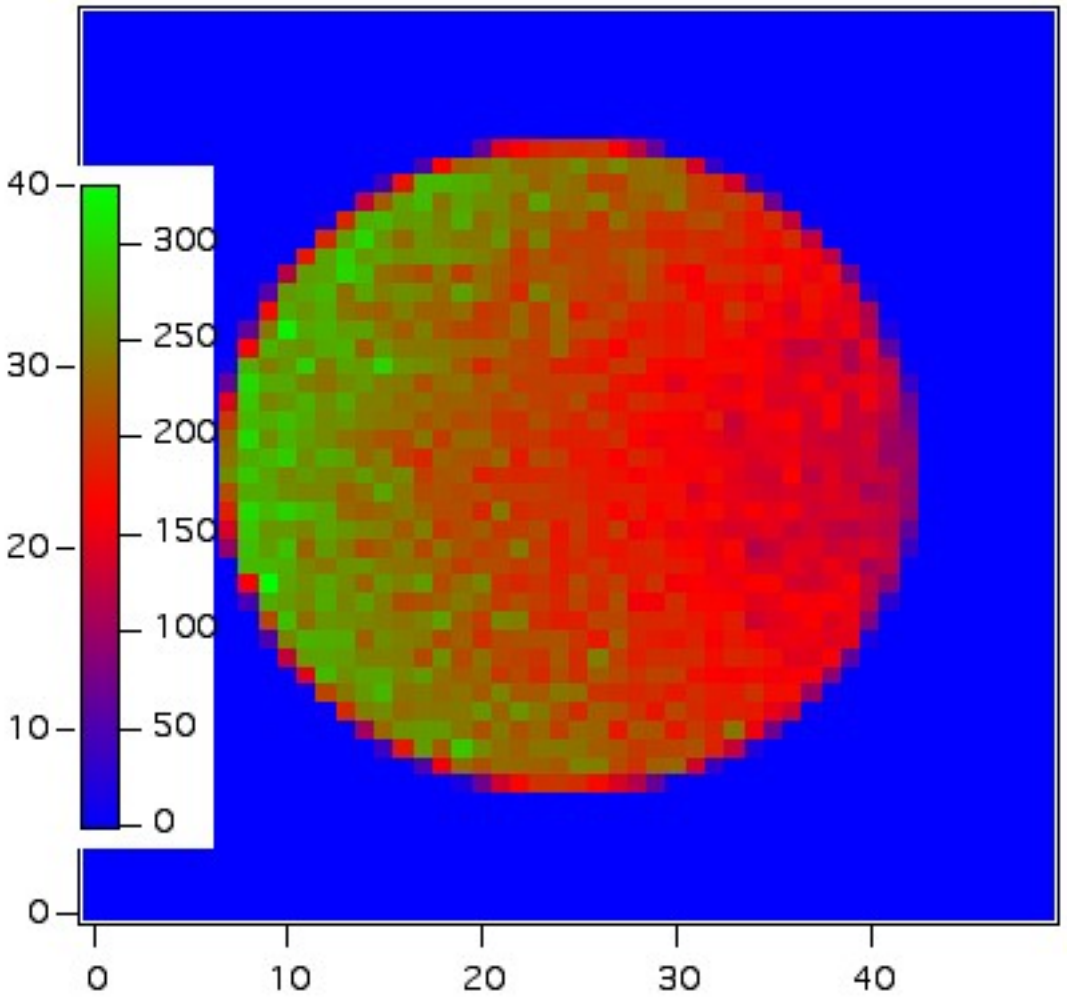


Upstream



Downstream

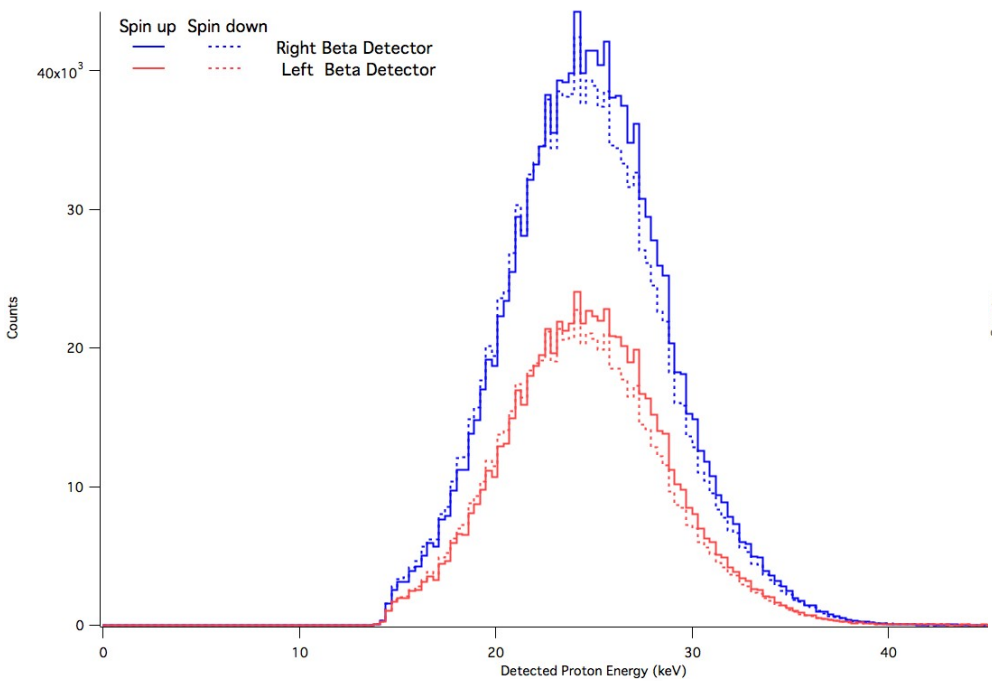
Polarization map (flipping ratio: P*f*A)

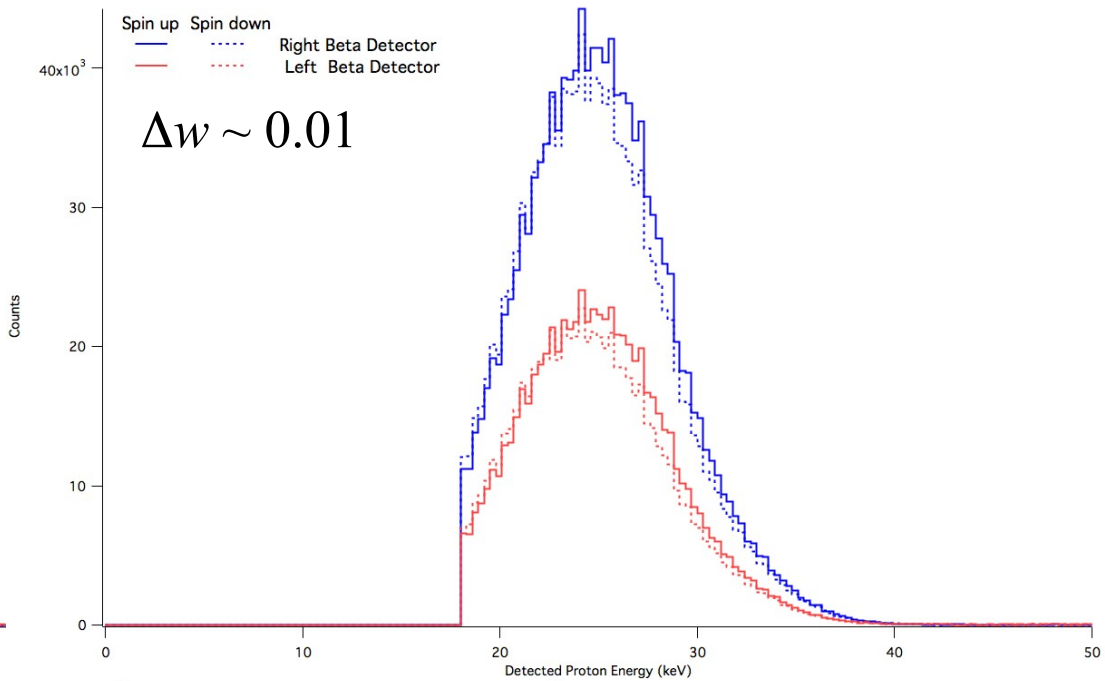


P>91% (for *f*=1, P=A) (95% c.l.)

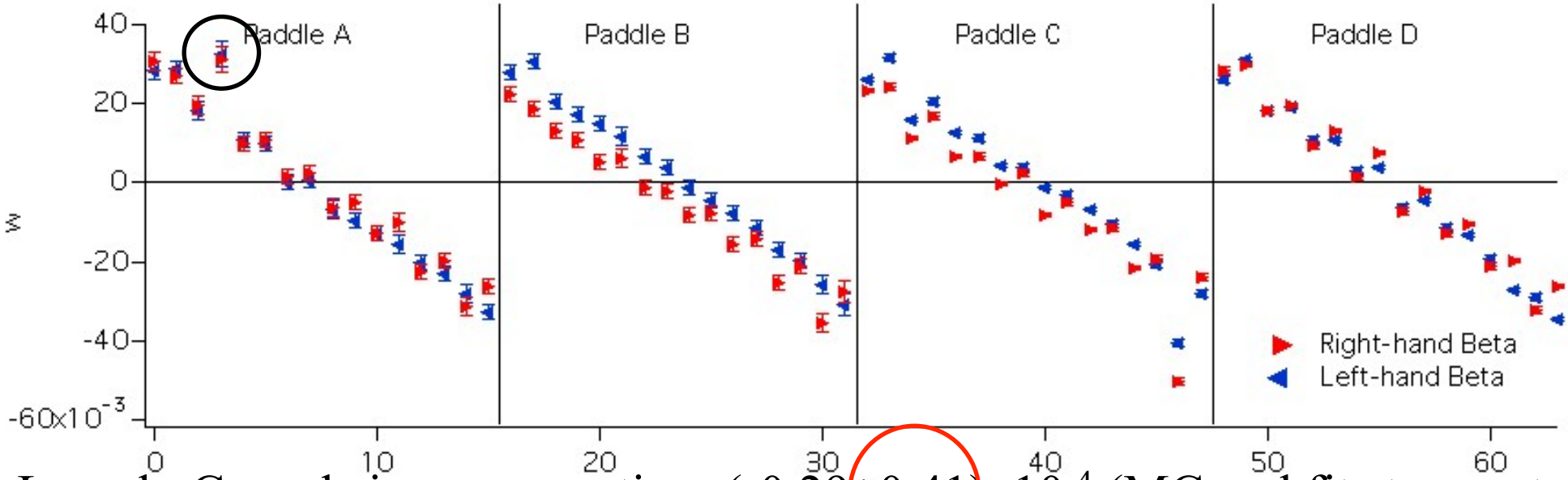
f=95±5% (calculated)

Proton threshold effect





$\Delta w \sim 0.01$



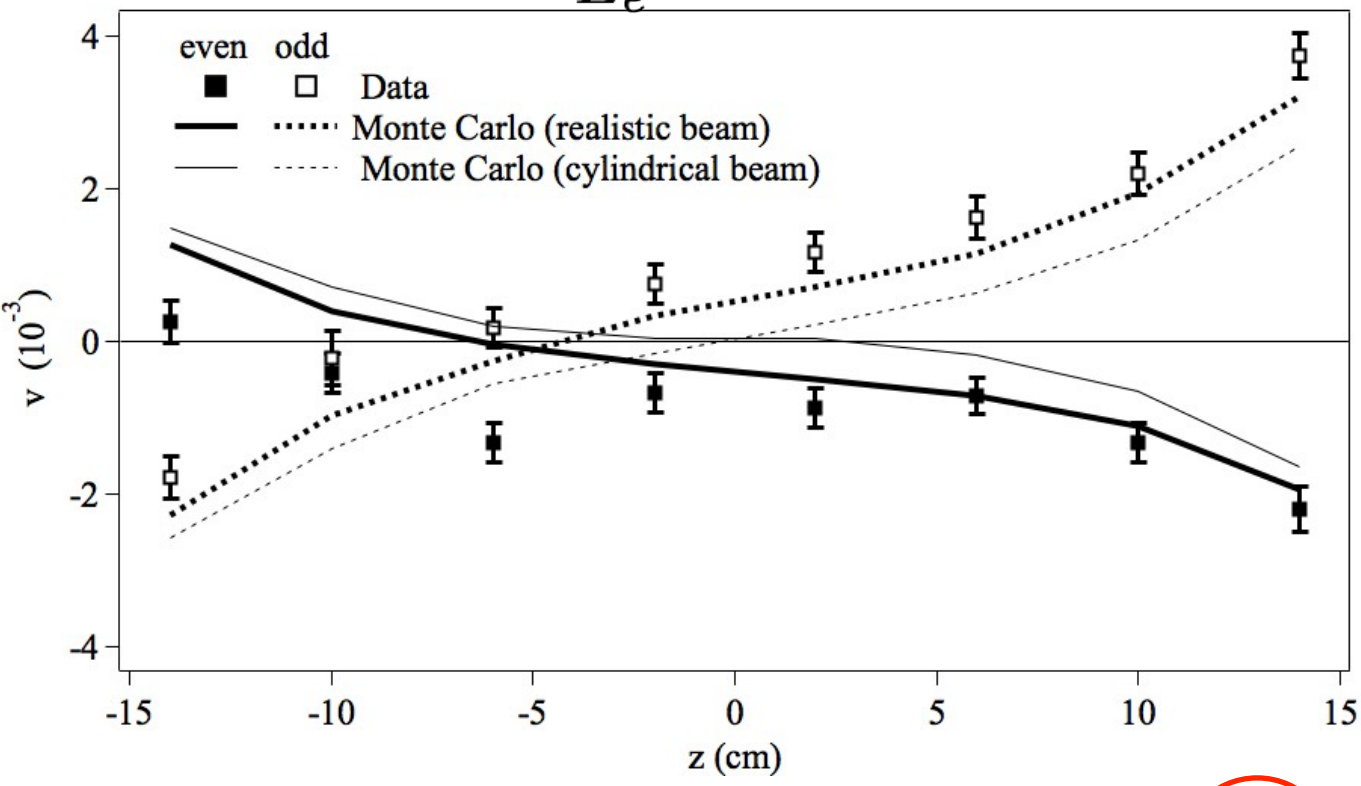
Largely Cancels in v - correction: $(-0.29 \pm 0.41) \times 10^{-4}$ (MC and fits to spectra)

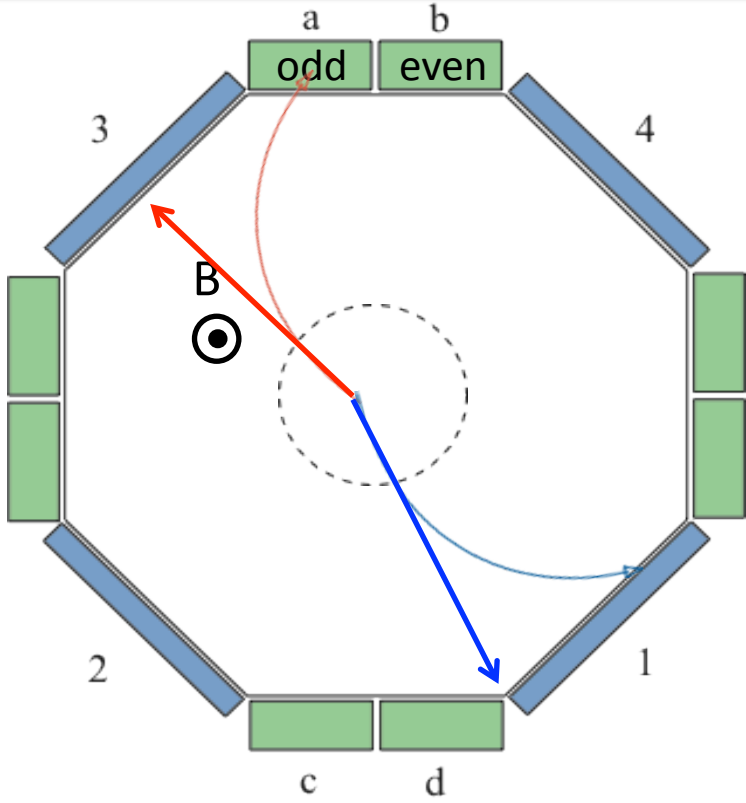
threshold variations, etc.

Beam Expansion Effect

Magnetic field changes e-p angular acceptance. Expansion changes average.

$$A\sigma_n \cdot \frac{p_e}{E_e}$$





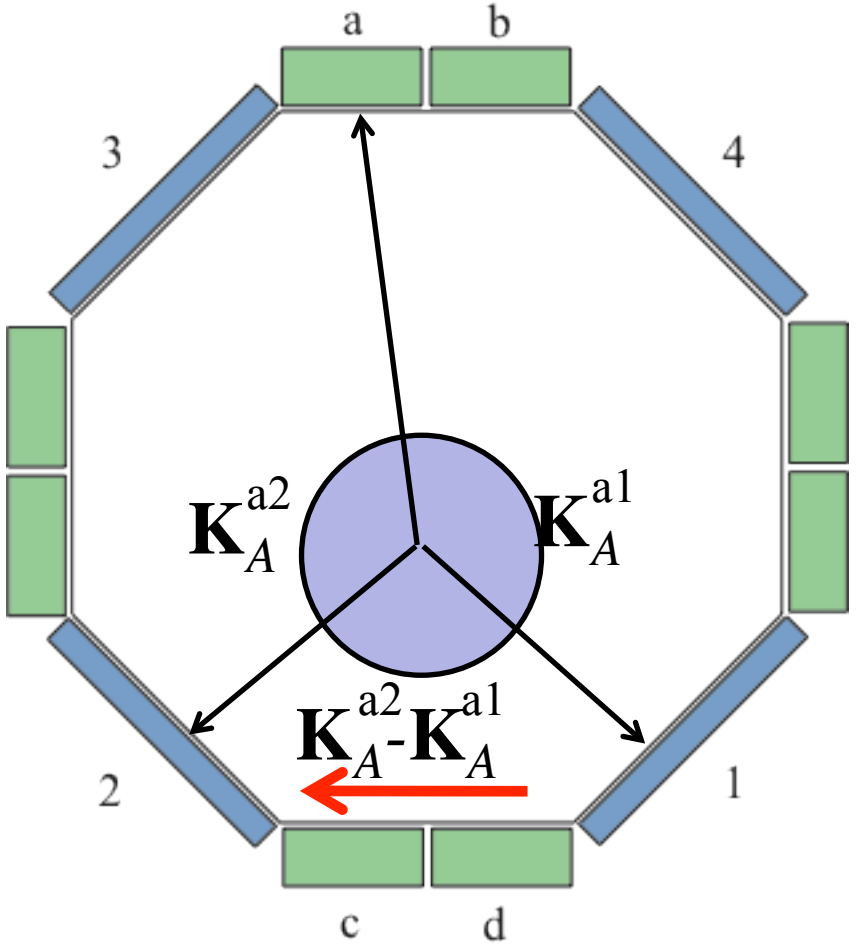
Correction from Monte Carlo: $(-1.5 \pm 0.4) \times 10^{-4}$

uncertain beam shape, etc.

Asymmetry beam/Transverse Polarization (ATP)

$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A\tilde{\mathbf{K}}_A^{p_i e_j} + B\tilde{\mathbf{K}}_B^{p_i e_j} + D\tilde{\mathbf{K}}_D^{p_i e_j} \right)$$

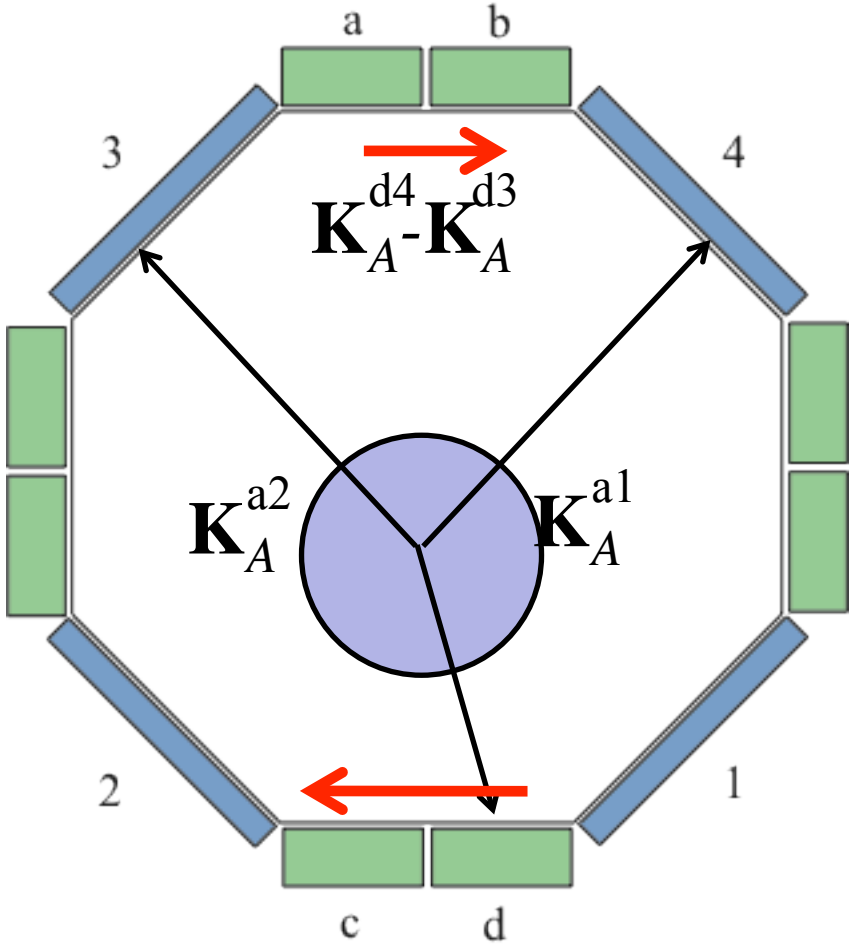
$$v^{p_i} = \frac{1}{2}(w^{p_i R} - w^{p_i L})$$



Asymmetry beam/Transverse Polarization (ATP)

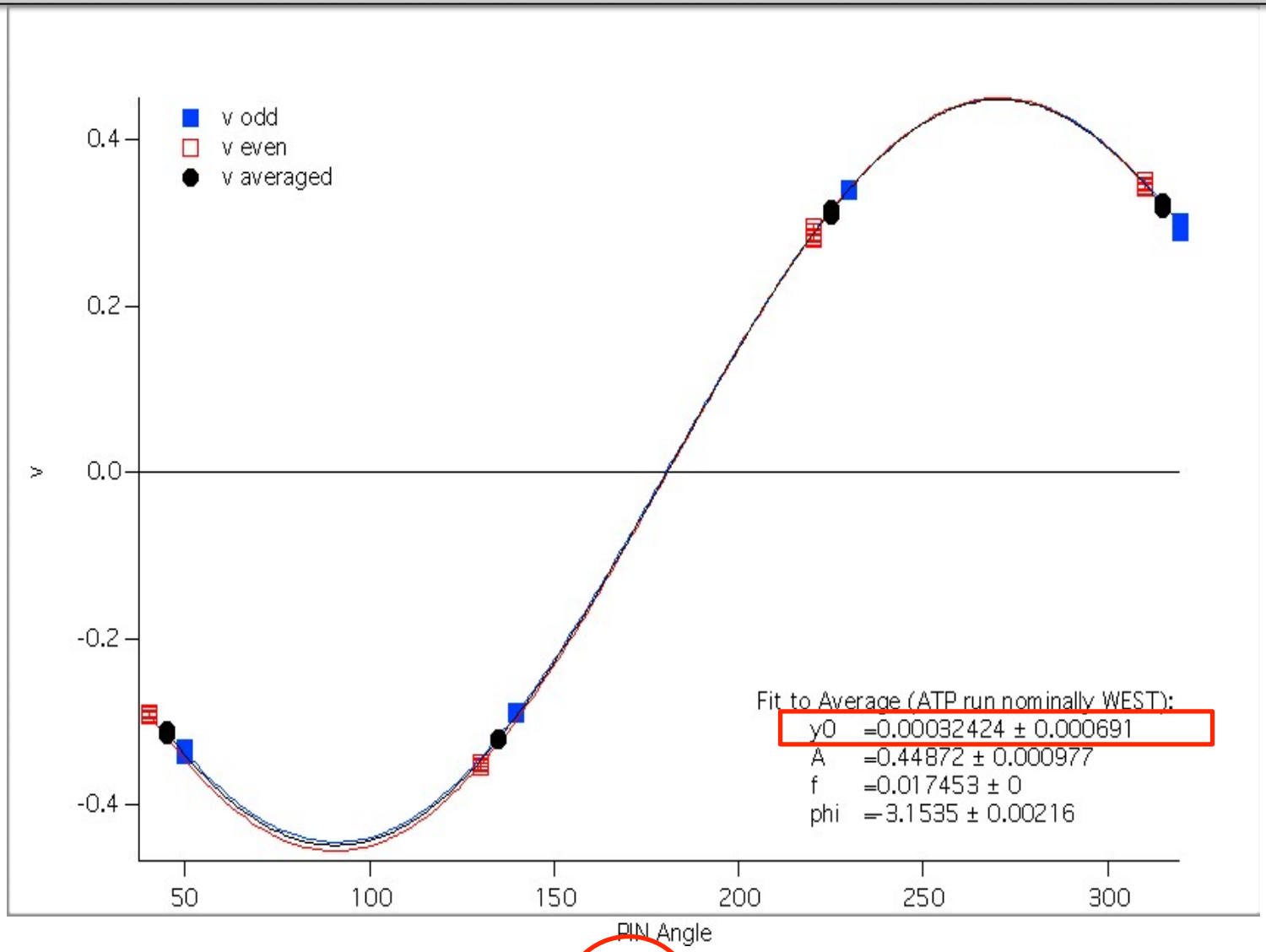
$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A\tilde{\mathbf{K}}_A^{p_i e_j} + B\tilde{\mathbf{K}}_B^{p_i e_j} + D\tilde{\mathbf{K}}_D^{p_i e_j} \right)$$

$$v^{p_i} = \frac{1}{2}(w^{p_i R} - w^{p_i L})$$



ATP correction from calibration runs

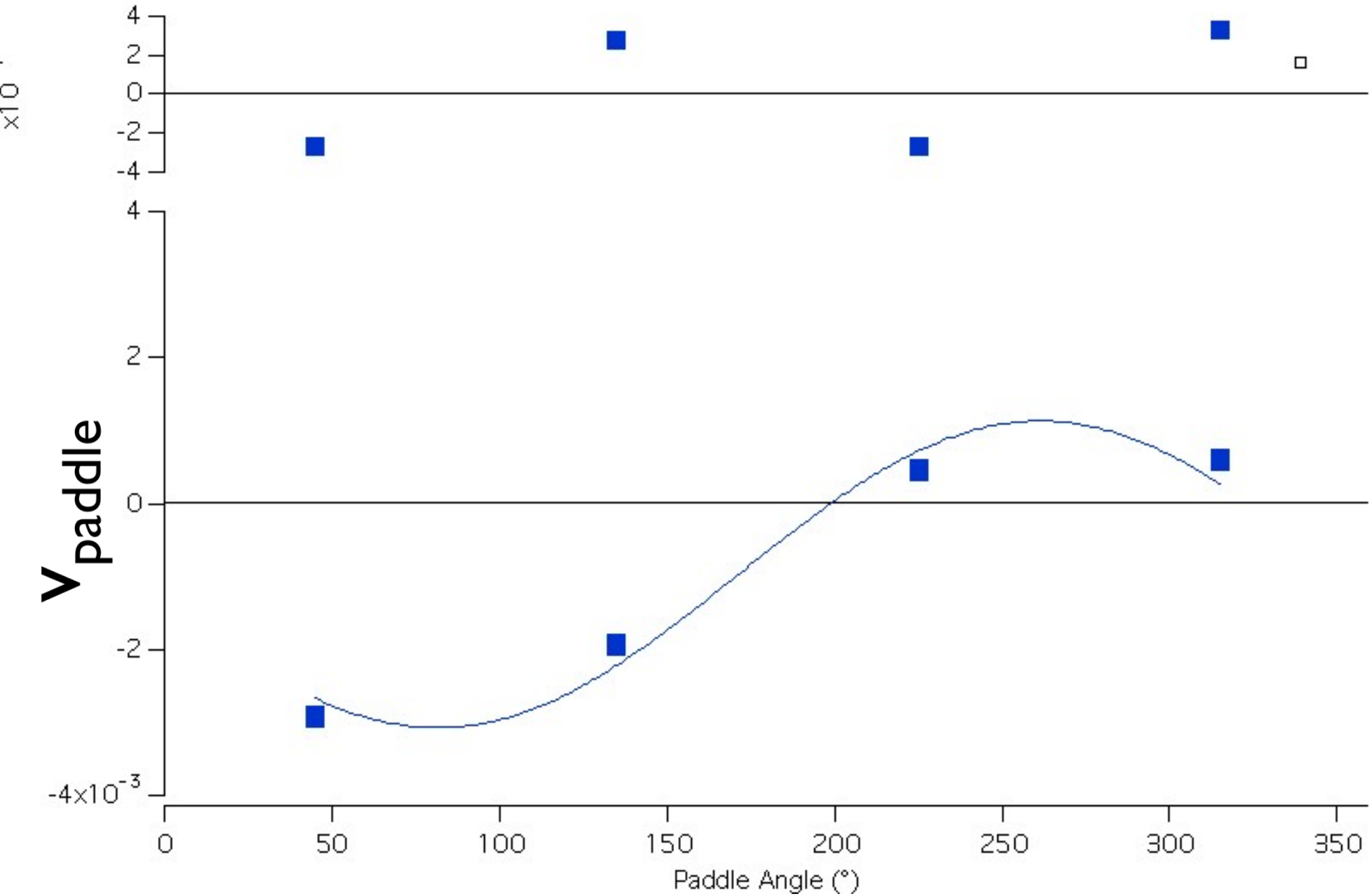
Asymmetry beam/Transverse Polarization (ATP)



ATP correction: $(-0.07 \pm 0.72) \times 10^{-4}$ ($\theta_P \sim 5$ mrad)

Polarization direction uncertainty

Transverse Polarization



Current Status

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \mathbf{P}\cdot\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + D\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu}\right)\right)$$

		% error	Ref	SM (tree level)	$\frac{1}{\alpha}\lvert\partial\alpha/\partial\lambda\rvert$
λ	-1.2694±0.0028	0.2	PDG		
a	-0.103±0.004	3.9	PDG	$\frac{1-\lvert\lambda\rvert^2}{1+3\lvert\lambda\rvert^2}$	2.8
A	−0.1187 ± 0.0008	0.7	W.A.	$-2\frac{\lvert\lambda\rvert^2+\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	3.2
B	0.9807 ± 0.0030	0.3	PDG	$+2\frac{\lvert\lambda\rvert^2-\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	0.08
C	−0.2377 ± 0.0036	1.1	PERKEOII-B	$C = 4\frac{\mathrm{Re}(\lambda)}{1+3\lvert\lambda\rvert^2}$	0.52
D	(-0.96±2.14)x10^{-4}	-	our result	$2\frac{\mathrm{Im}(\lambda)}{1+3\lvert\lambda\rvert^2}$	
ϕ_{AV}	180.013±0.0028	-	our result		

k=0.27484 for $0 \le E_p \le 750$ eV

C/k=-0.8649±0.0095

A+*B*=0.8619±0.0031

k(*A*+*B*)=0.2369±0.0009

$$\frac{1}{(1+3\,|\,\lambda\,|^2)} = \tau_n G_F^2 |V_{ud}|^2 \frac{m_e^5}{c^5}(1+\delta_R)$$