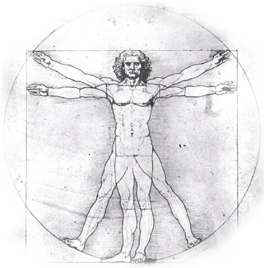
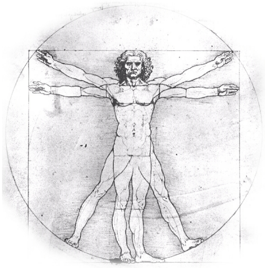

“Time-reversal and the neutron”

Tim Chupp
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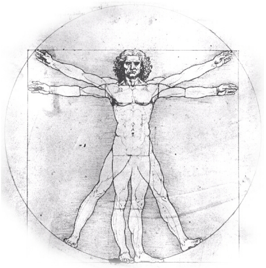
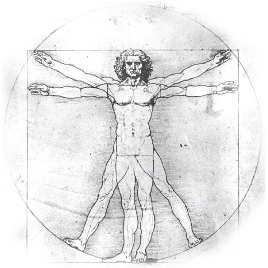
chupp@umich.edu

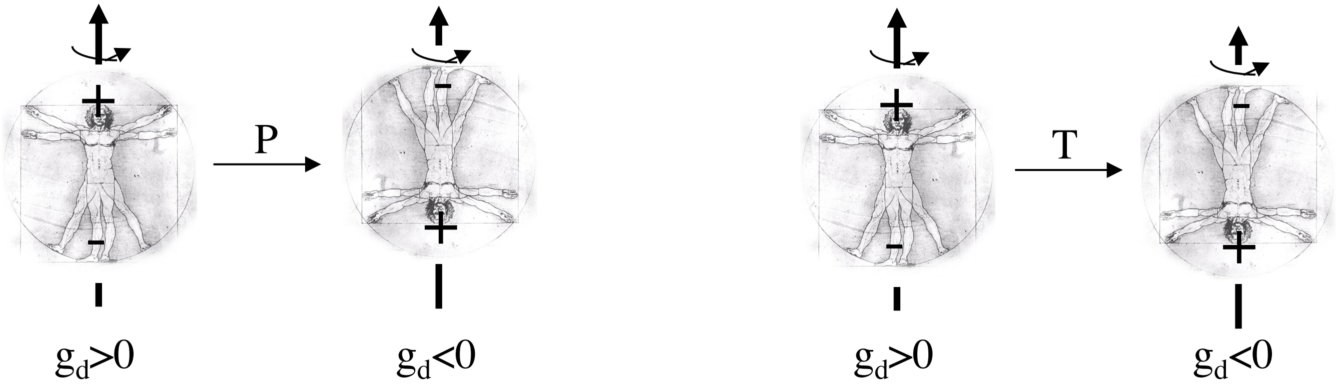
Motivations/observables
Neutron decay: the D coefficient
Relation to neutron EDM
emiT-II Results

Observables – T-violating

EDMs

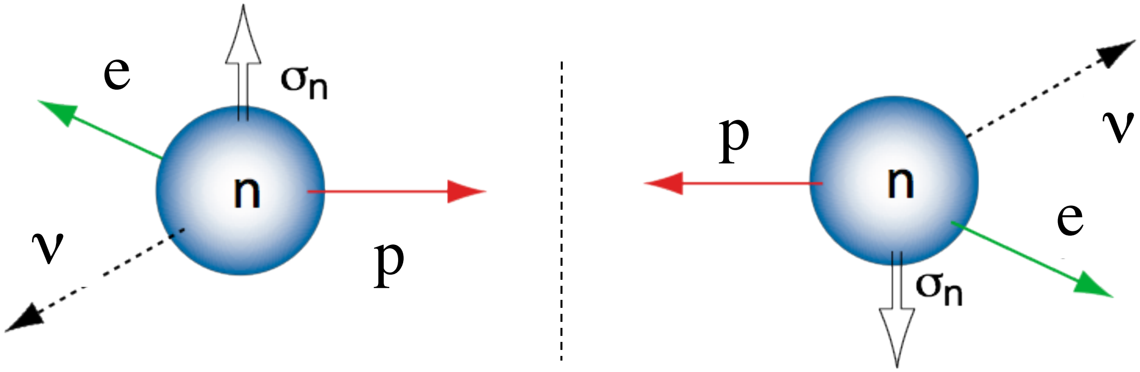
$\not{P}\not{T}$



Decay correlations $D\vec{J}_n \cdot (\vec{p}_p \times \vec{p}_e)$

$n \rightarrow p e \bar{\nu}$

$P\not{T}$



TIME

EMIT

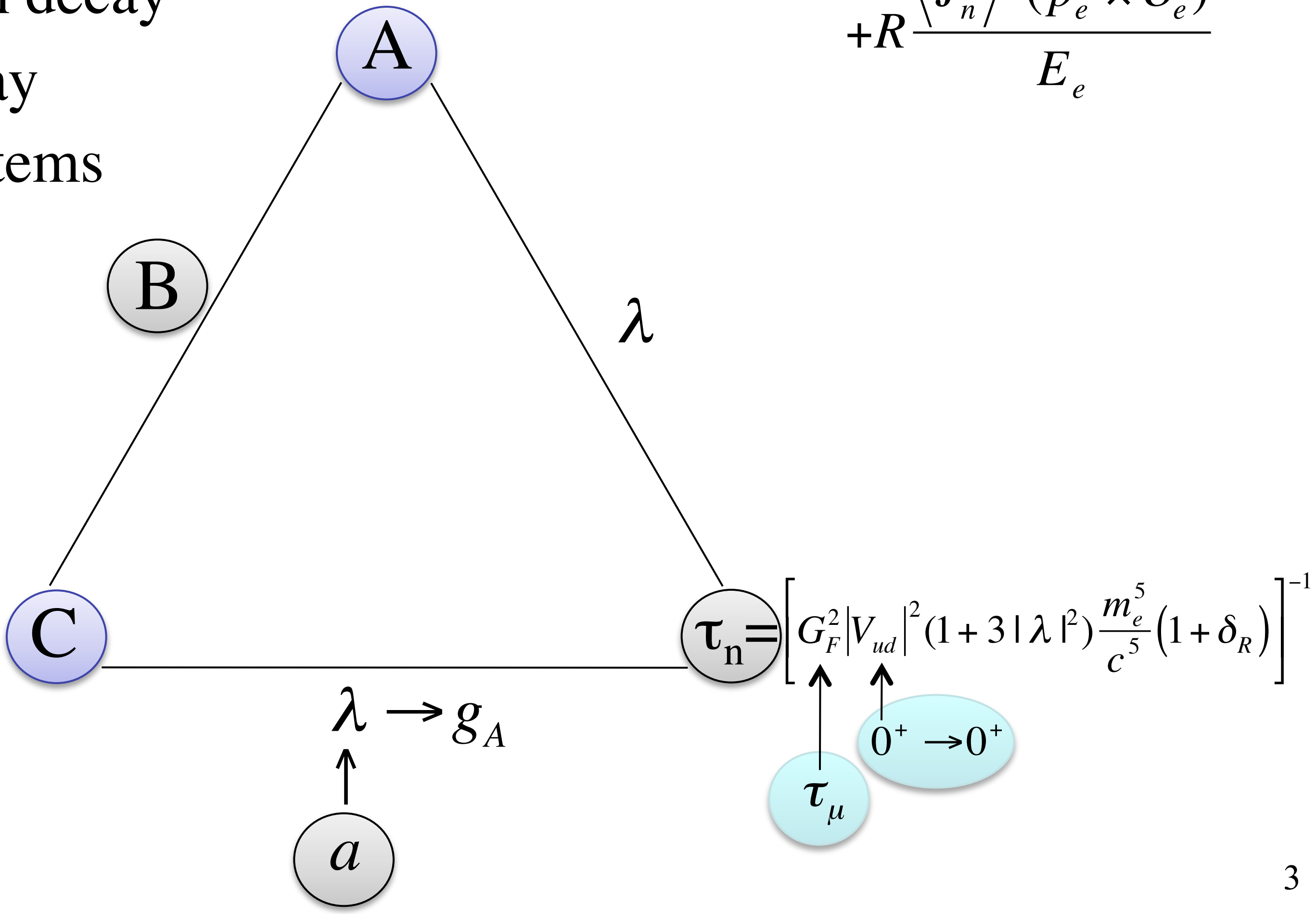
Neutron Decay

Two parameters but many observables

$$\frac{d^5\Gamma}{dE_e\,d\Omega_e\,d\Omega_\nu} = G(E_e)\left(1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + A\frac{\langle\vec{J}_n\rangle\cdot\vec{p}_e}{E_e} + B\frac{\langle\vec{J}_n\rangle\cdot\vec{p}_\nu}{E_\nu} + D\frac{\langle\vec{J}_n\rangle\cdot(\vec{p}_e\times\vec{p}_\nu)}{E_eE_\nu}\right)$$

$$+R\frac{\langle\vec{J}_n\rangle\cdot(\vec{p}_e\times\vec{\sigma}_e)}{E_e}$$

- Polarized neutron decay
- Unpolarized decay
- Input – other systems



$$\tau_n = \left[G_F^2|V_{ud}|^2(1+3|\lambda|^2)\frac{m_e^5}{c^5}(1+\delta_R)\right]^{-1}$$

Correlation coefficients in neutron decay

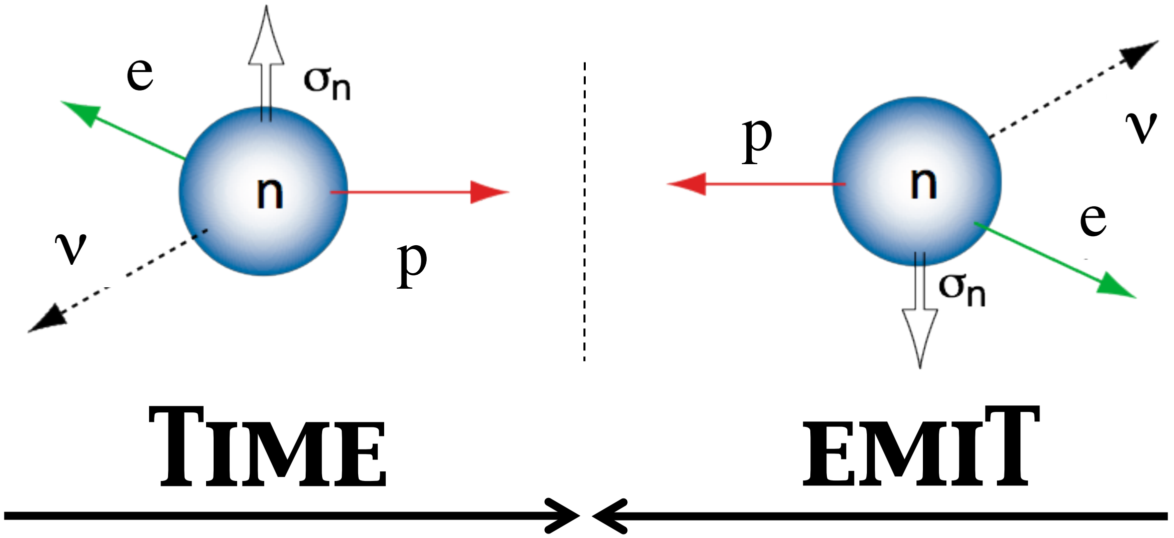
$$\frac{d^5\Gamma}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{m_e}{E_e} + A\frac{\langle\vec{J}_n\rangle\cdot\vec{p}_e}{E_e} + B\frac{\langle\vec{J}_n\rangle\cdot\vec{p}_\nu}{E_\nu} \boxed{+ D\frac{\langle\vec{J}_n\rangle\cdot\left(\vec{p}_e\times\vec{p}_\nu\right)}{E_eE_\nu}}\right)$$

		% 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	TBA	-	emiT-II	$2\frac{\mathrm{Im}(\lambda)}{1+3\lvert\lambda\rvert^2}$	

Time reversal vs motion reversal

Experiment does not reverse time, but observable $D\vec{J}_n \cdot (\vec{p}_p \times \vec{p}_e)$ includes $\not{T}$ and Final State Interactions: $D = D_{\not{T}} + D_{FSI}$

$D_{\mathrm{FSI}} \sim 2\mathrm{x}10^{-5}$

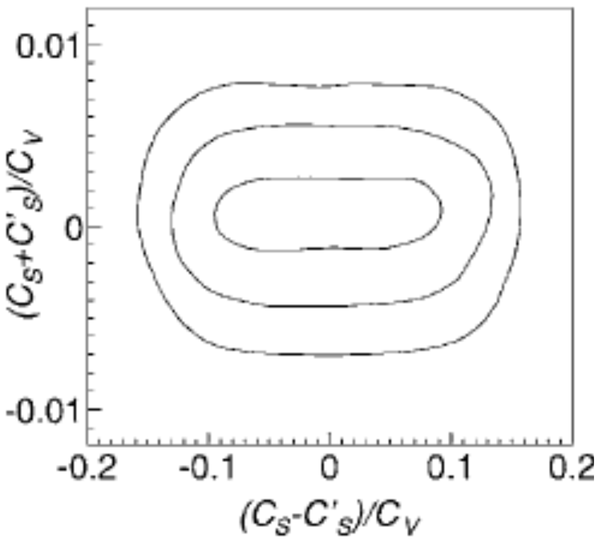


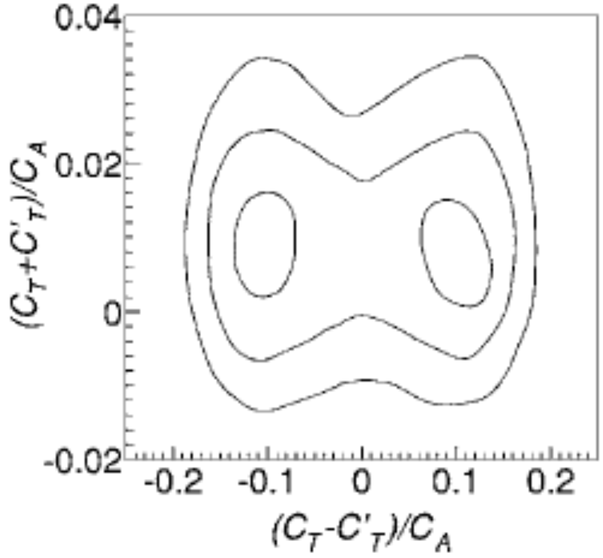
Beyond SM Physics

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

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

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





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

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

Models: $D_{\not T} = \sum_{sources} D_{source}$

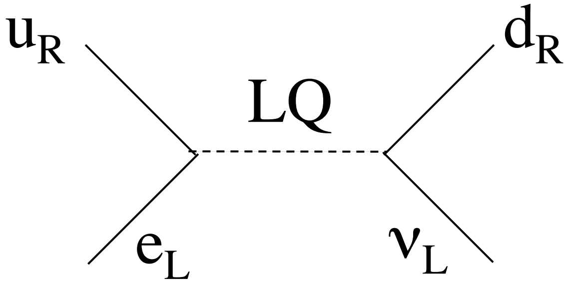
$$\Gamma \propto \left| A_{\not P T} + A_{P \not T} + \underset{\text{EDM}}{A_{\not P \not T}} \right|^2 \sim \Gamma_{\not P T} + \frac{A_{P \not T}}{A_{\not P T}} \sin \varphi_{P \not T} + \frac{A_{\not P \not T}}{A_{\not P T}} \sin \varphi_{\not P \not T} + \ldots$$

Model	**Contribution to D**	**Constrained by**
CKM	10^{-12}	Mixing
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}	
4-fermion/leptoquark	$<10^{-4}$	Ng/Tulin (nEDM)

$D_{FSI} \sim 2 \times 10^{-5}$

Relationship to EDM (4 quark operator)

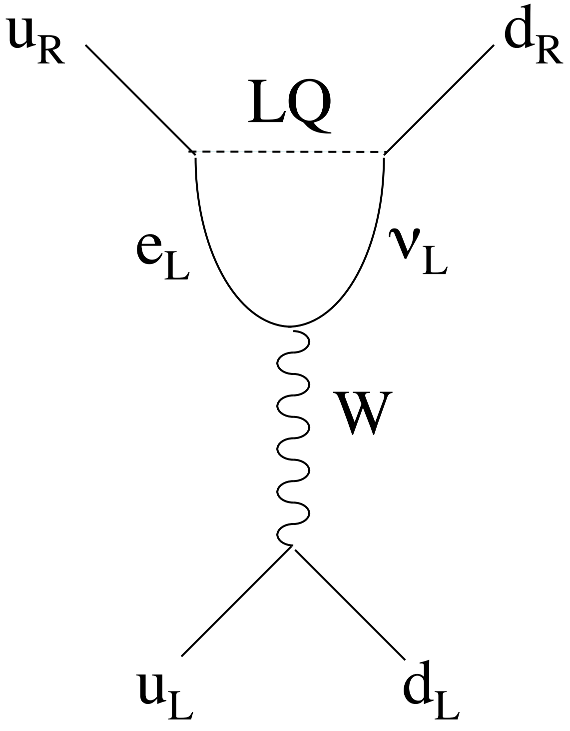
(Ng & Tulin: PRD **85** 033001 ‘12)



nDecay

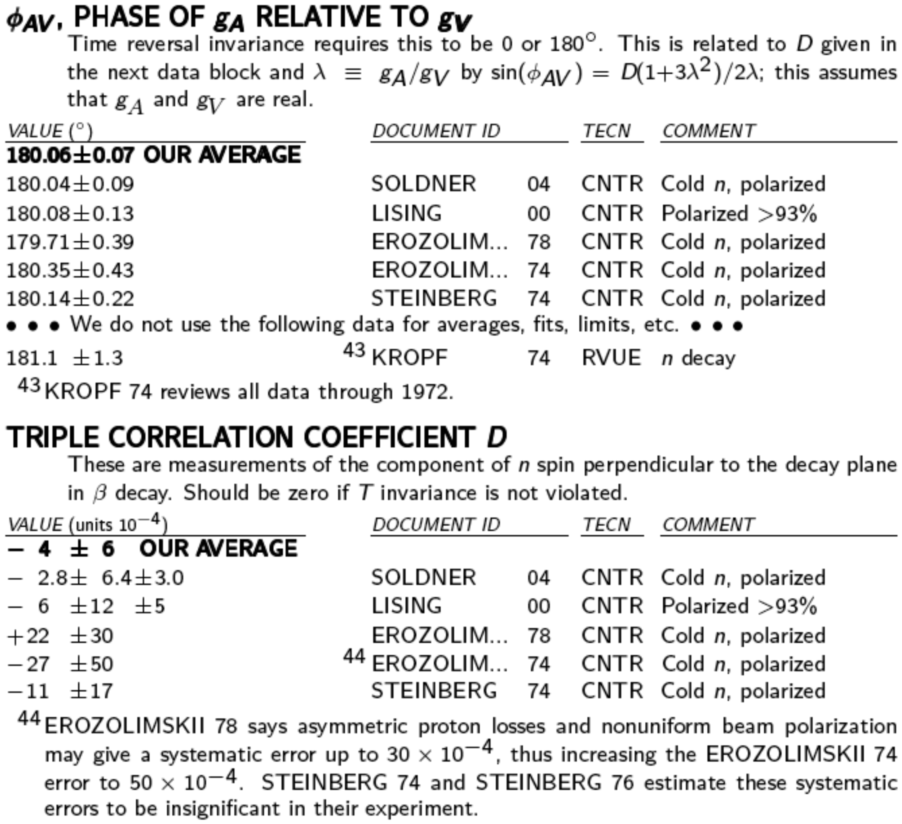
Relationship to EDM (4 quark operator)

(Ng & Tulin: PRD **85** 033001 ‘12)



EDM

History of *D* measurements



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 ± 12(stat.) ± 5(syst.)) x 10^{-4} *Phys. Rev. C* ***62*** *055501 (2000)*

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

^{19}Ne: D = (1 ± 6) × 10^{-4} F. Calaprice, in Hyperfine Interactions (1985)

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

T.E. Chupp, K.P. Coulter & R.L. Cooper
University of Michigan

S.J. Freedman & B.K. Fujikawa
University of California - Berkeley/
Lawrence Berkeley National Laboratory

G.L. Jones
Hamilton College

A. Garcia
University of Washington

H.P. Mumm, J.S. Nico, & A.K. Thompson
National Institute of Standards and Technology

C. Trull & F.E. Wietfeldt
Tulane University

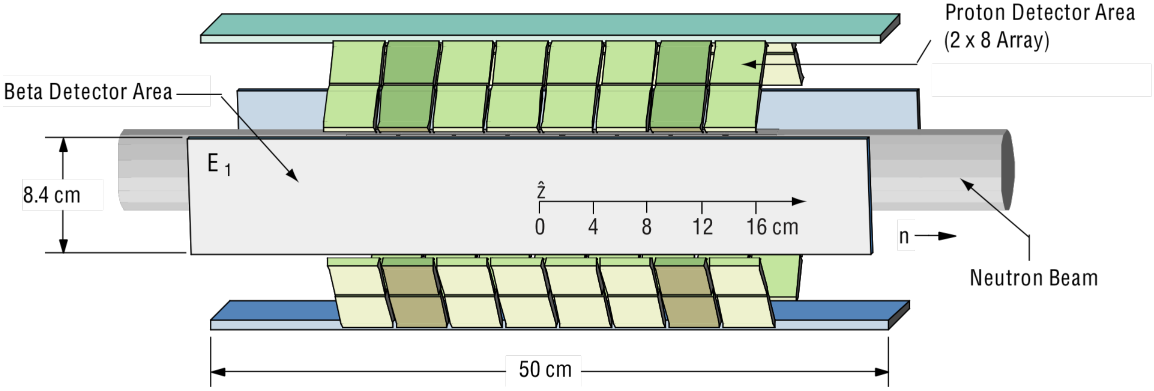
J.F. Wilkerson
University of North Carolina

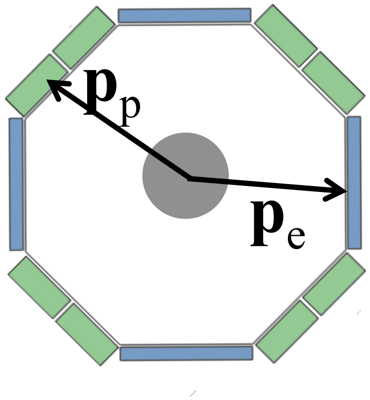
NEW RESULT: $D=[-0.94\pm1.89(\mathrm{STAT})\pm0.97(\mathrm{SYS})]\mathrm{x}10^{-4}$ (arXiv:1205.6588)

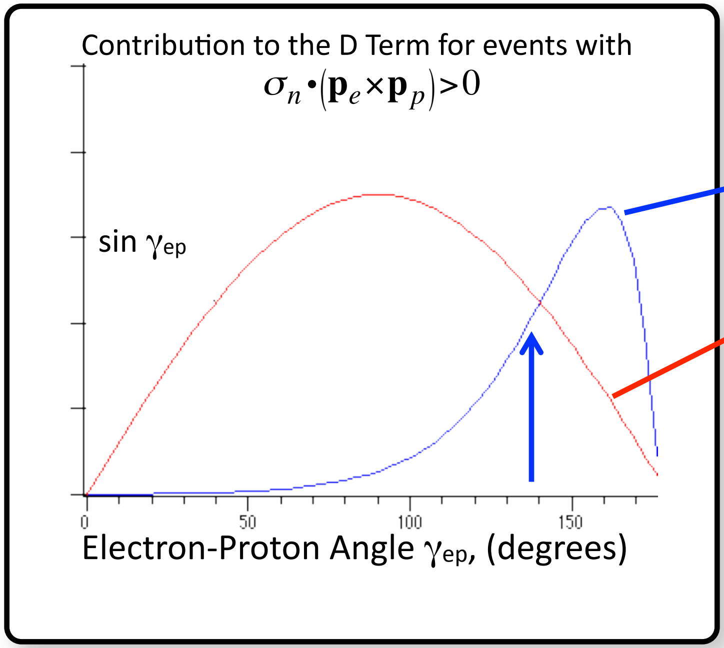
$$\varphi_{AV} = 180.012 \pm 0.028 \qquad \frac{g_A}{g_V} = |\lambda| e^{i\varphi_{AV}}$$

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

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



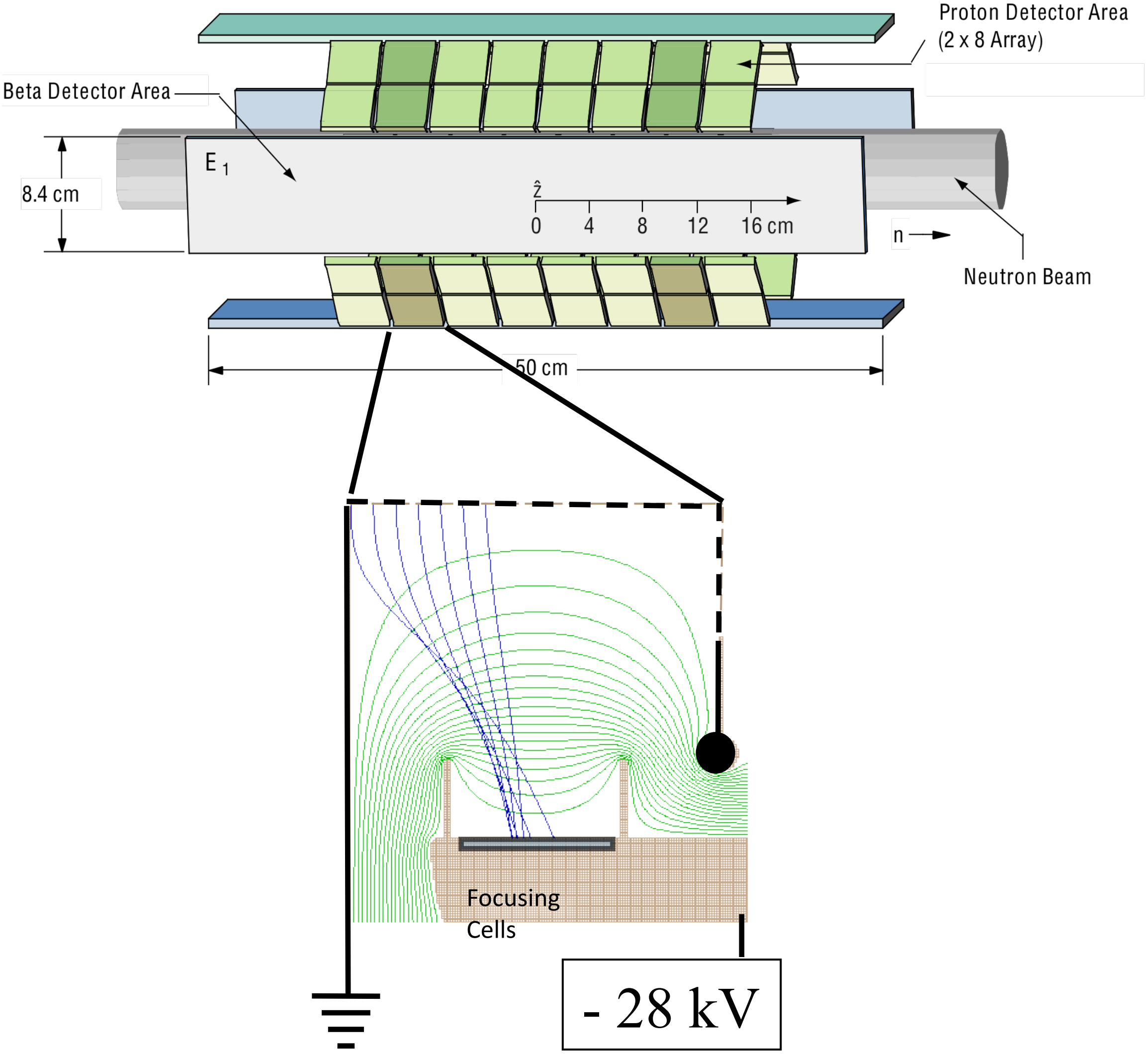




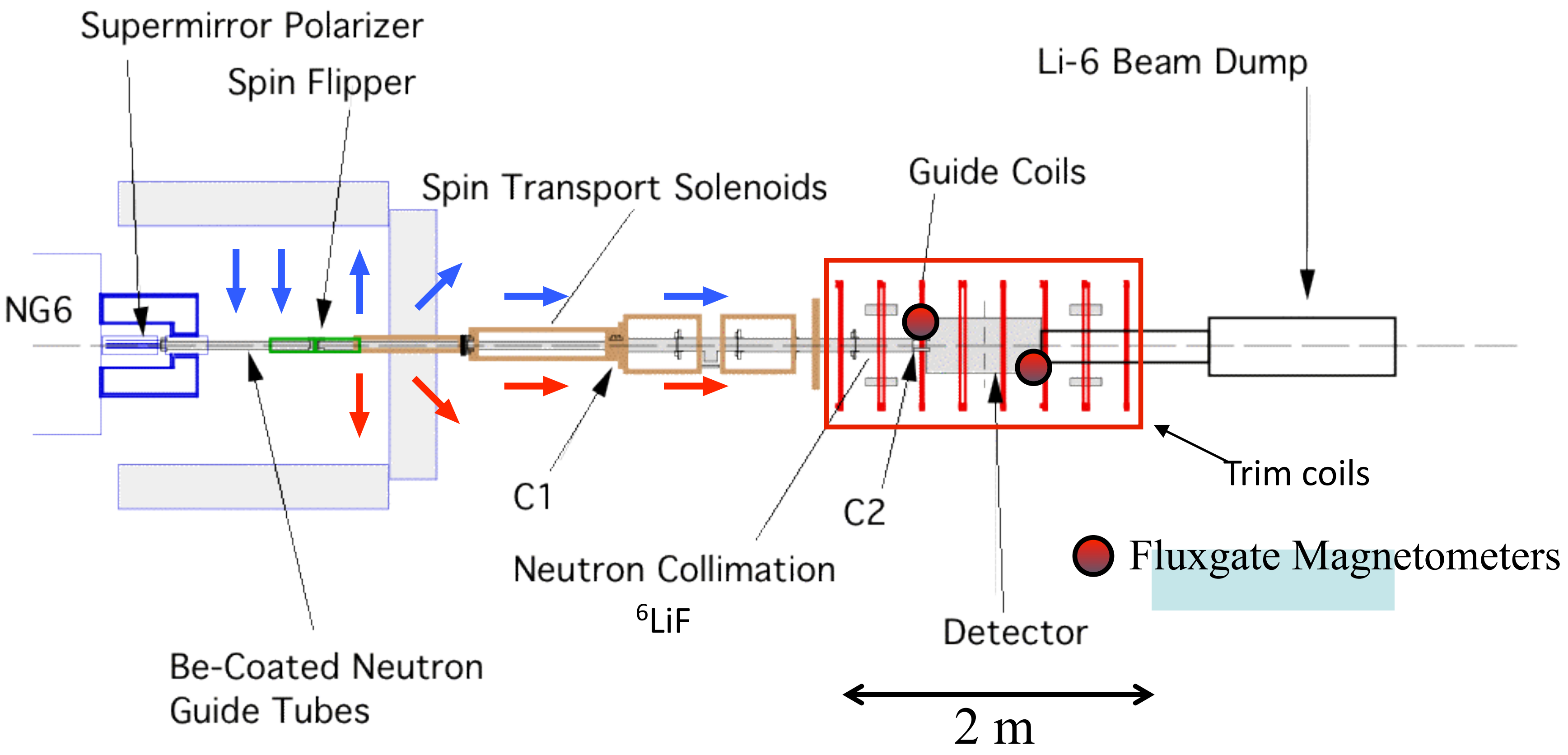
$$D\vec{J}_n \cdot (\vec{p}_p \times \vec{p}_e)$$

- 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

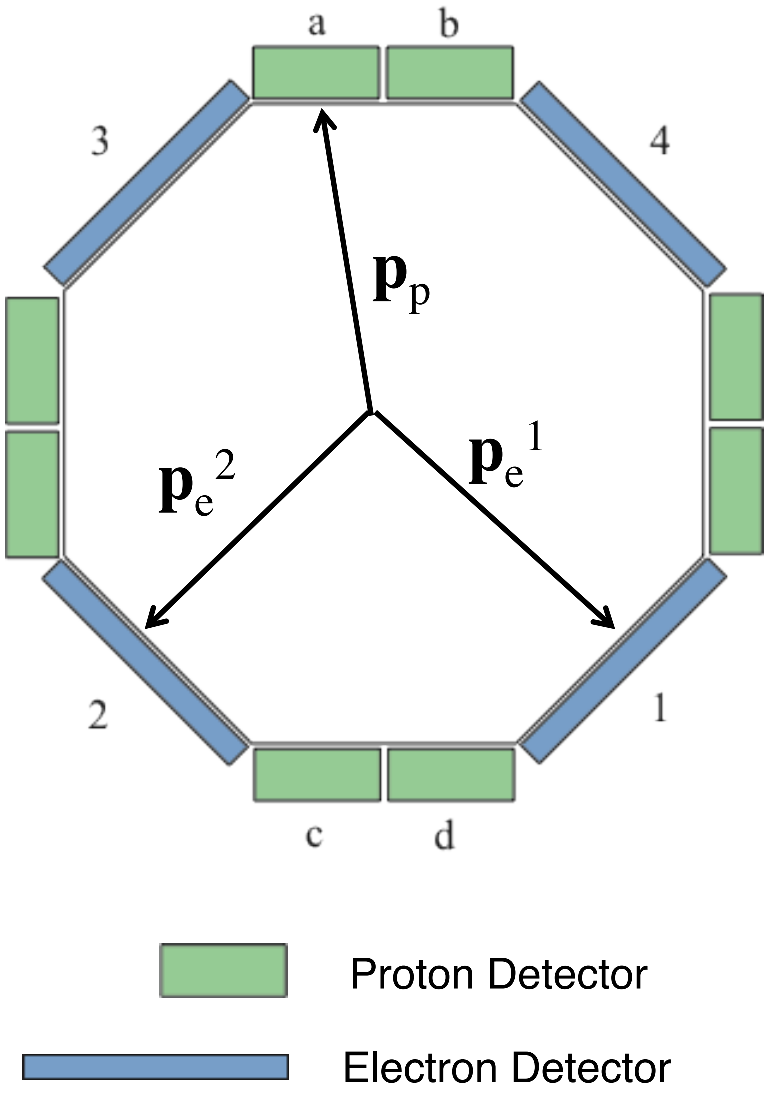


Neutron Beam and Spin transport



- 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 determined with supermirror-analyzer
  P>91% (for $f=1$, $P=A$) (95%) f=95±5% (calcualted)

Measurement Principle



Spin-flip asymmetry

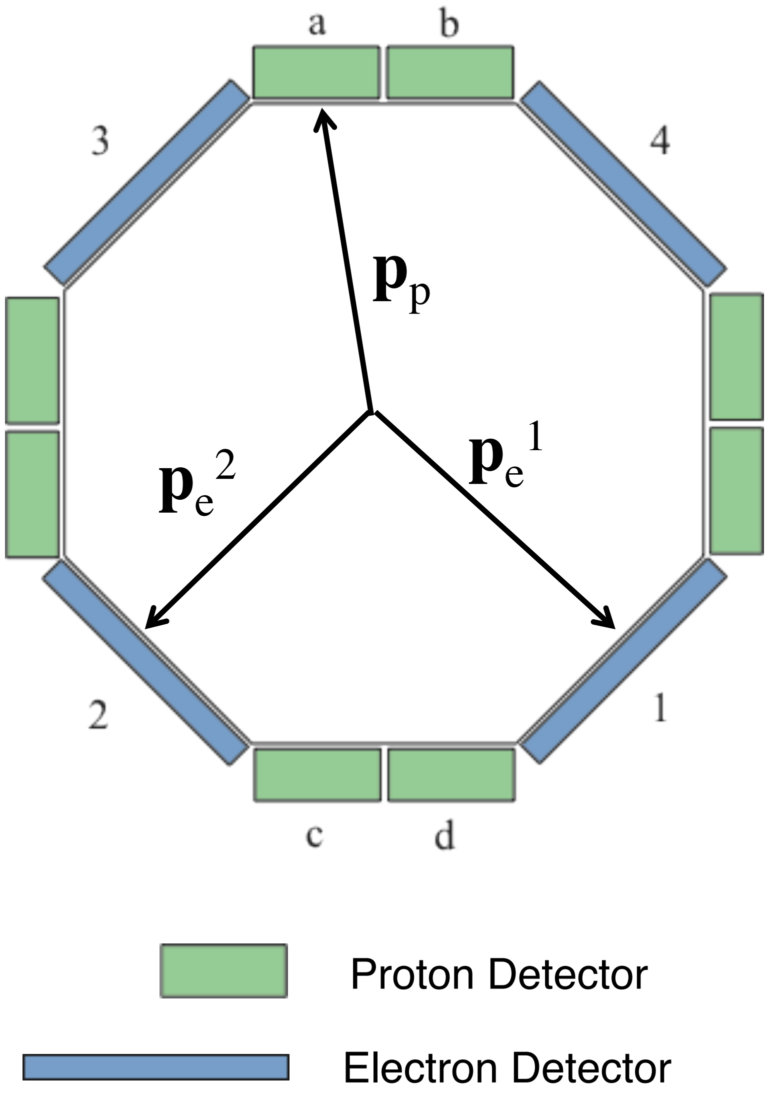
$$w^{p_i e_j} = \frac{N_+^{p_i e_j} - N_-^{p_i e_j}}{N_+^{p_i e_j} + N_-^{p_i e_j}}$$

Combine *w*'s

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

$$v^{p_i} = PD\hat{z} \cdot \left(\tilde{\mathbf{K}}_D^{p_i e_R} - \tilde{\mathbf{K}}_D^{p_i e_L}\right)$$

Measurement Principle



Spin-flip asymmetry

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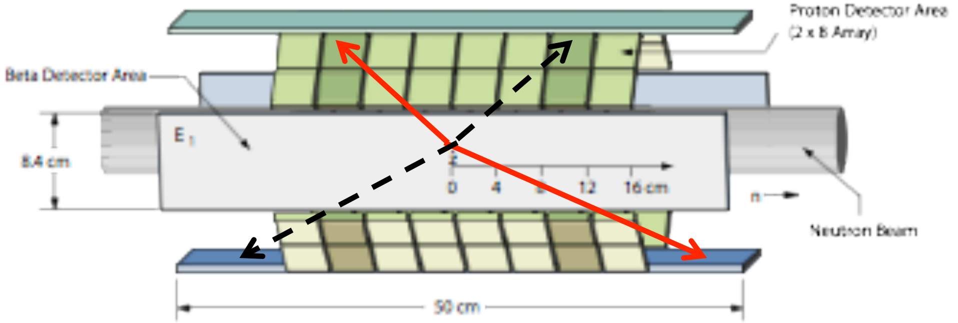
Combine *w*'s

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

$$v^{p_i} = PD\hat{z}\cdot\left(\tilde{\mathbf{K}}_D^{p_i e_R} - \tilde{\mathbf{K}}_D^{p_i e_L}\right)$$

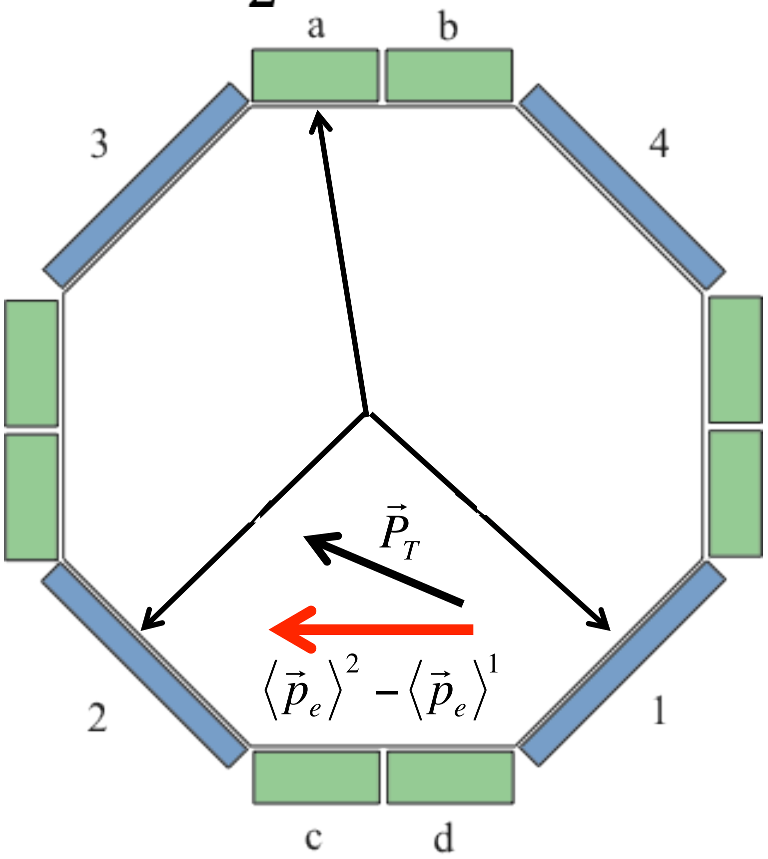
$$+A\hat{z}\cdot\Delta\frac{\vec{p}_e}{E_e} + B\hat{z}\cdot\Delta\frac{\vec{p}_\nu}{E_e}$$



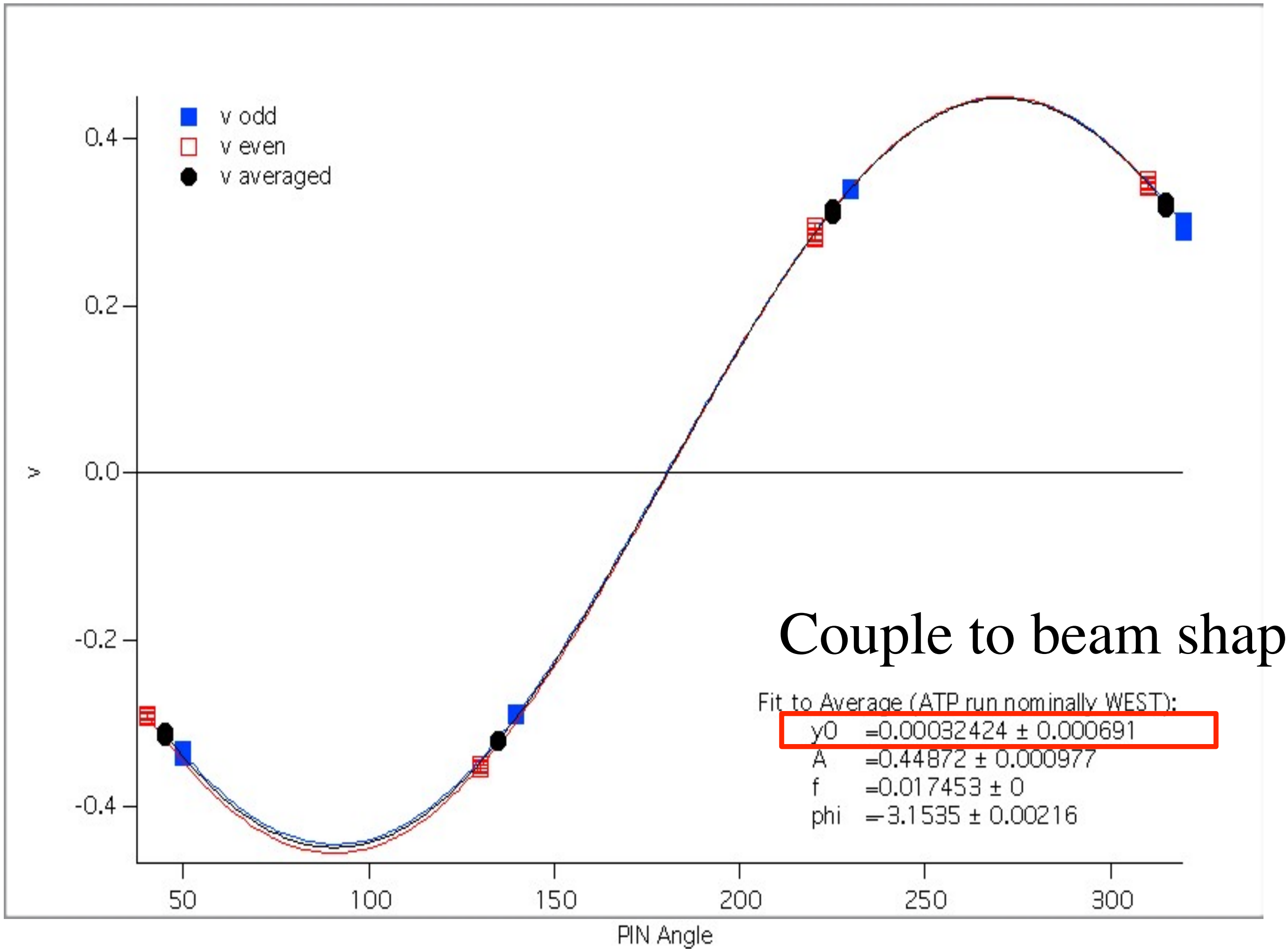
Transverse Polarization (5 mR guide field misalignment)

$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A \int \frac{\vec{p}_e}{E_e} + B \int \frac{\vec{p}_{\nu j}}{E_e} + D \int \frac{(\vec{p}_p \times \vec{p}_e)}{E_e E_\nu} \right)$$

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



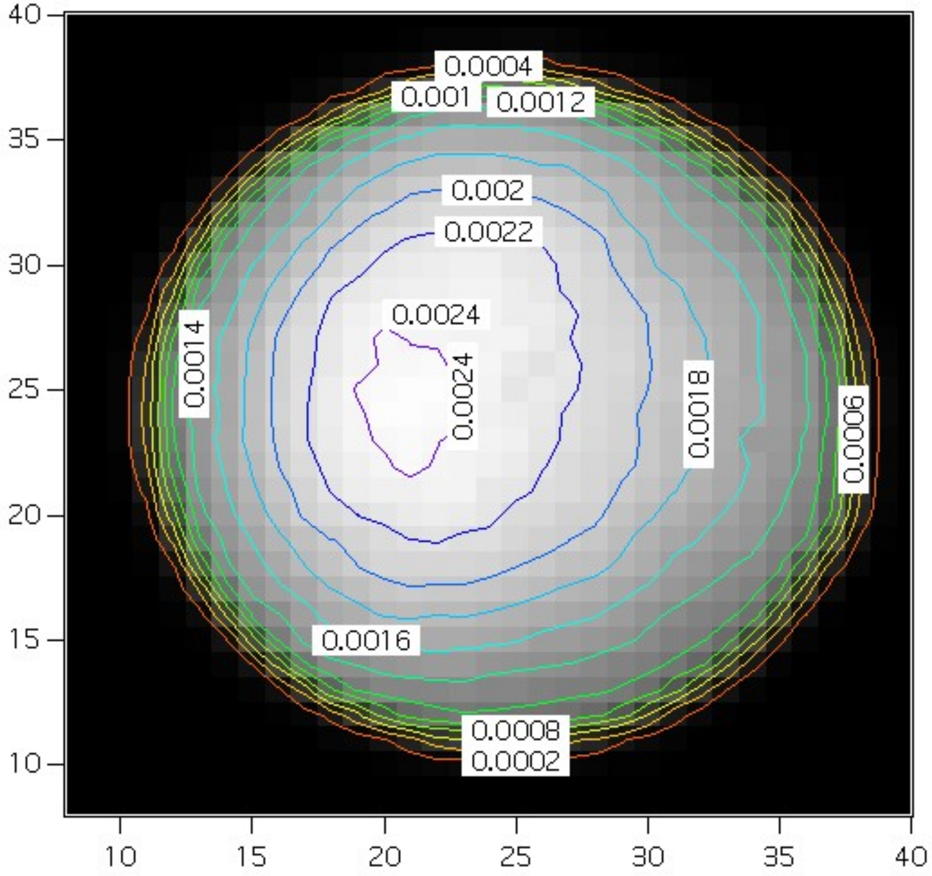
Transverse Polarization Calibration Run



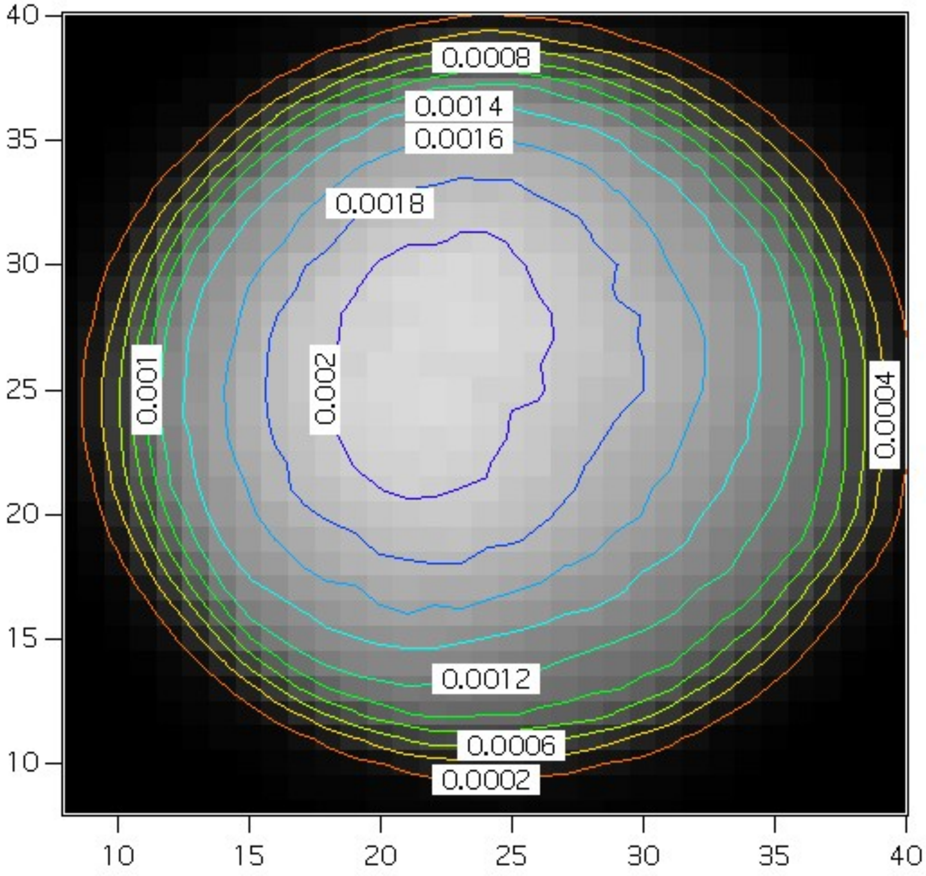
Couple to beam shape (ATP)

Fit to Average (ATP run nominally WEST):
y0 =0.00032424 ± 0.000691
A =0.44872 ± 0.000977
f =0.017453 ± 0
phi =-3.1535 ± 0.00216

Beam profiles

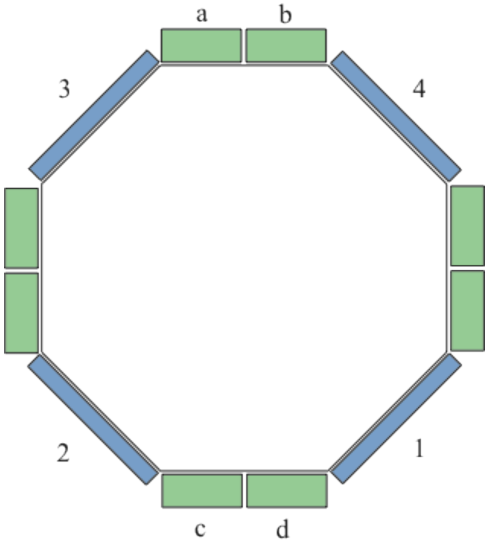


Upstream



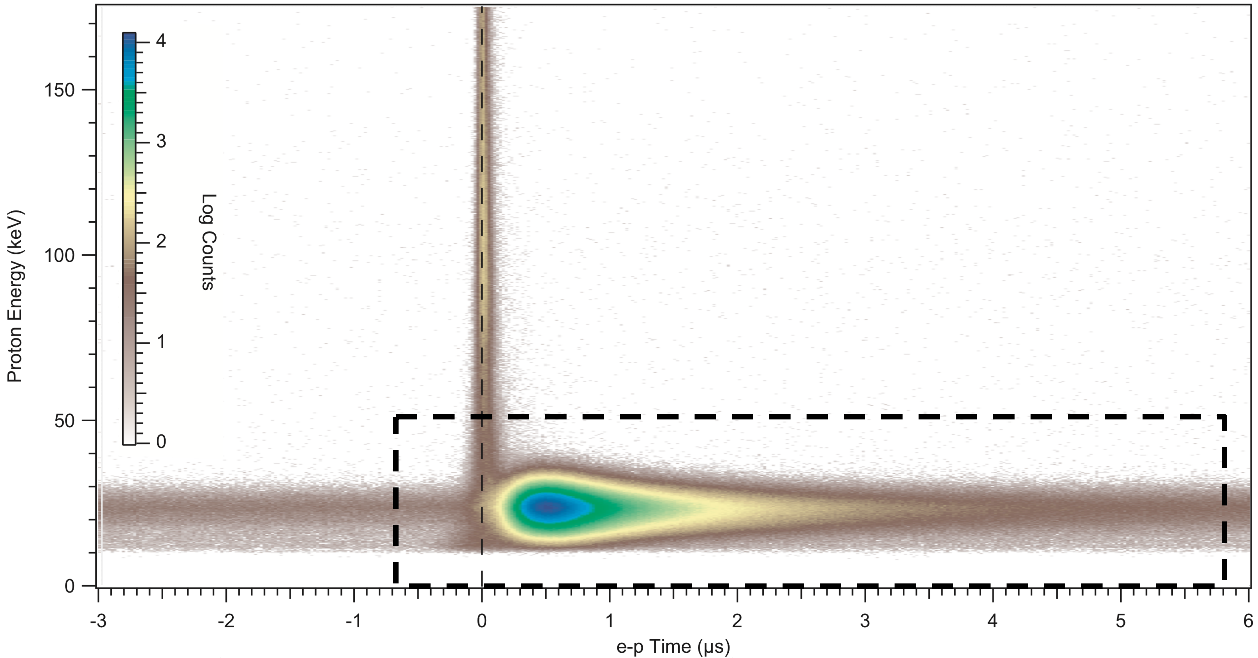
Downstream

Proton-electron coincidences



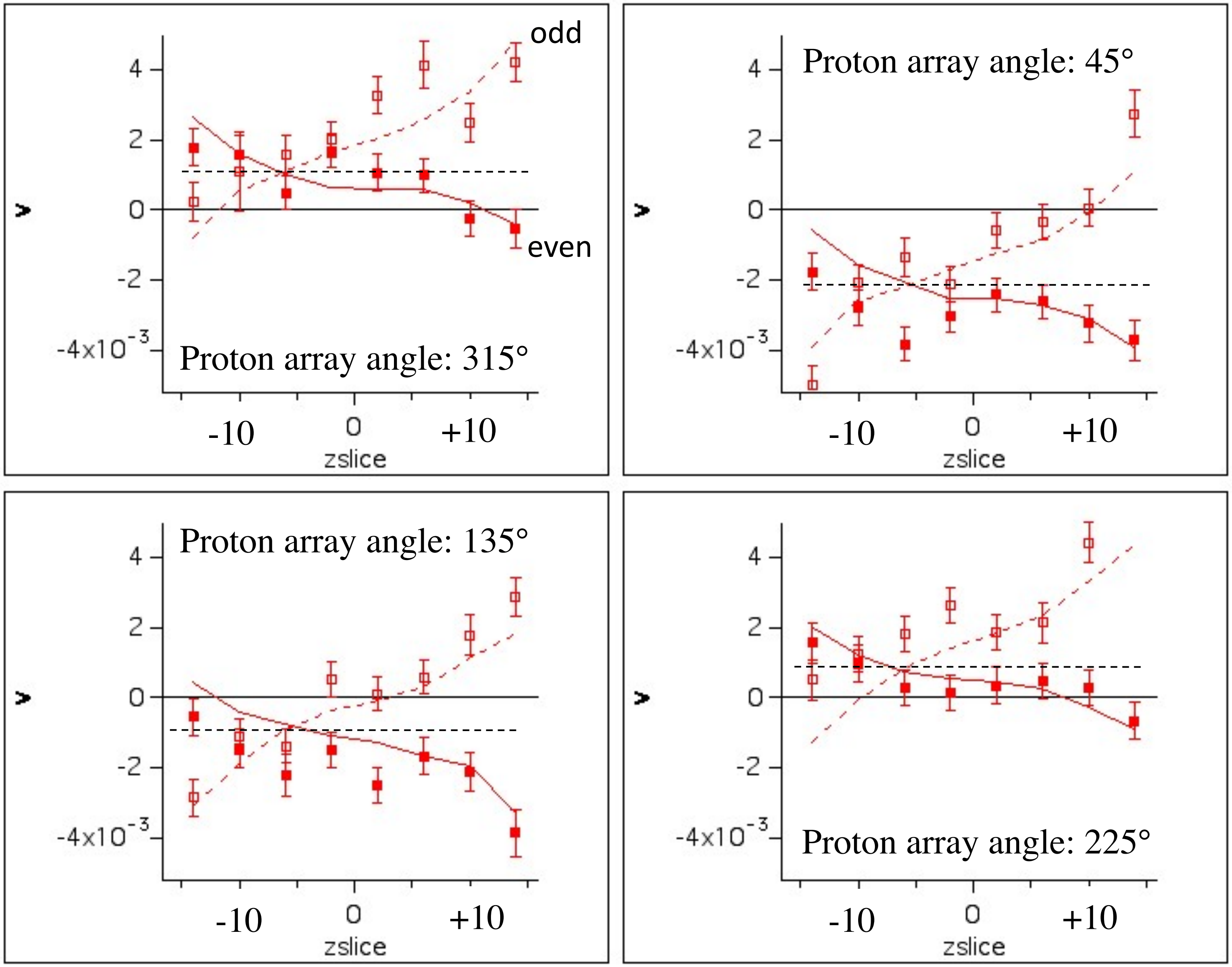
Rates

- 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

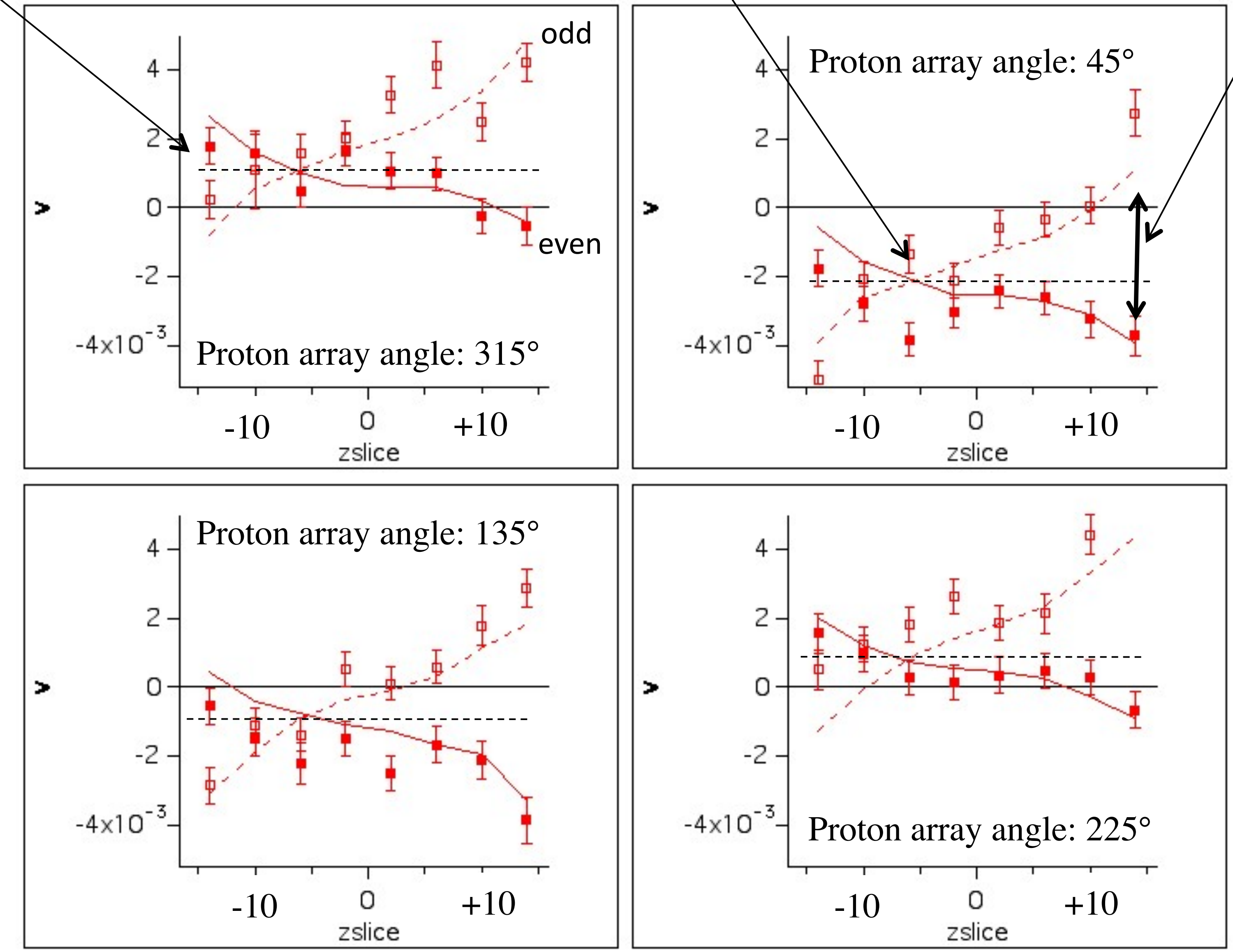


Final data set ~ 300 million accepted coincidence events.

$$v^{p_i} = \frac{1}{2}(w^{p_i R} - w^{p_i L}) \approx A\hat{z}\cdot\left(\left\langle \frac{\vec{p}_e}{E_e}\right\rangle^{R} - \left\langle \frac{\vec{p}_e}{E_e}\right\rangle^{L}\right)$$ For D=0



Transverse polarization, beam expansion, and **B**



Corrections (10^{-4})

All studies completed while data were still “blind”

Source	Correction	Uncertainty
BR asymmetry	-0.07	0.070
BR subtraction	0.03	0.09
Electron Backscattering	0.20	0.08
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 $\tilde{D}$	0.04
K_D (0.378±0.019)	Included in $\tilde{D}$	0.05
Total	-1.66	0.097

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

emiT II Result

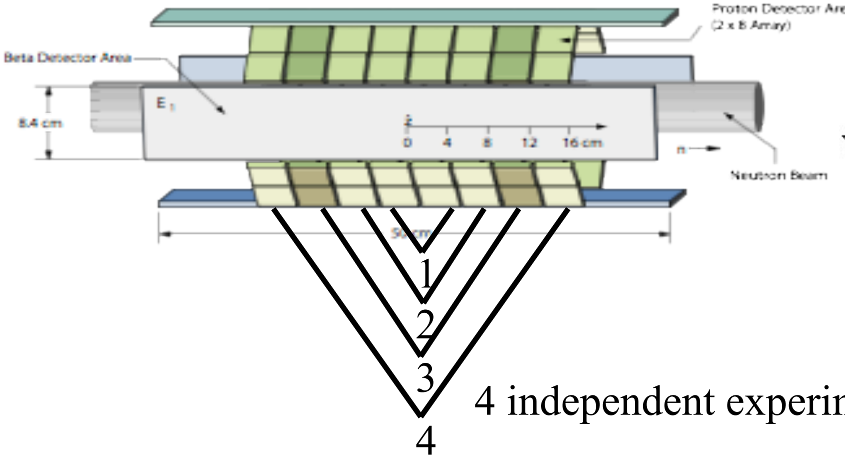
Blind analysis: $$w^{p_i e_j} = \frac{N_+^{p_i e_j} - N_-^{p_i e_j}}{N_+^{p_i e_j} + N_-^{p_i e_j}} + \mathcal{B}\hat{z}\cdot\tilde{\mathbf{K}}_D^{p_i e_j}$$

hidden offset

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

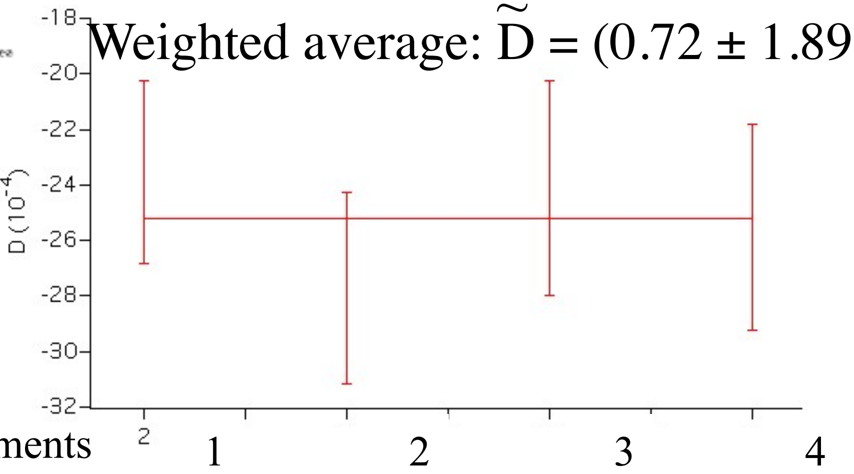
$$\bar{v} \approx \bar{K}_D P\tilde{D} \rightarrow D \quad \text{(with corrections)}$$

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



4 independent experiments

Weighted average: $\tilde{D} = (0.72 \pm 1.89) \times 10^{-4}$

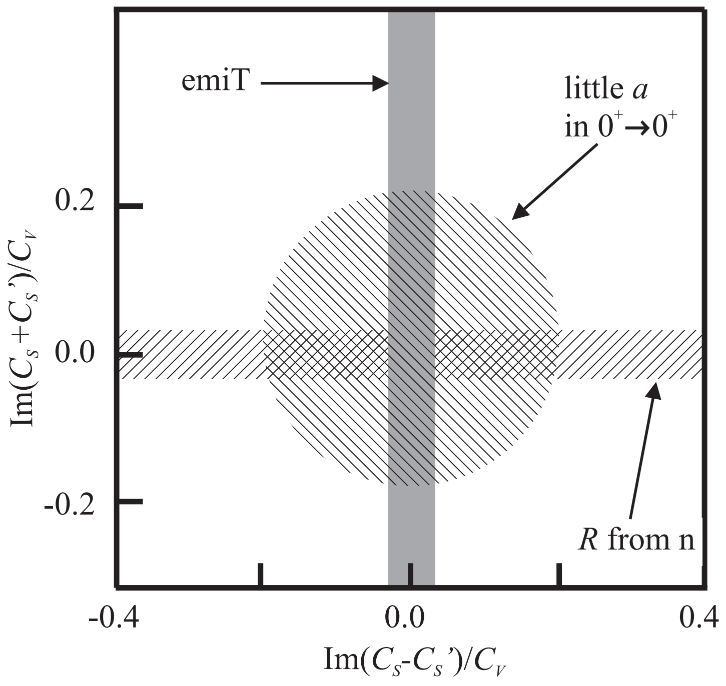


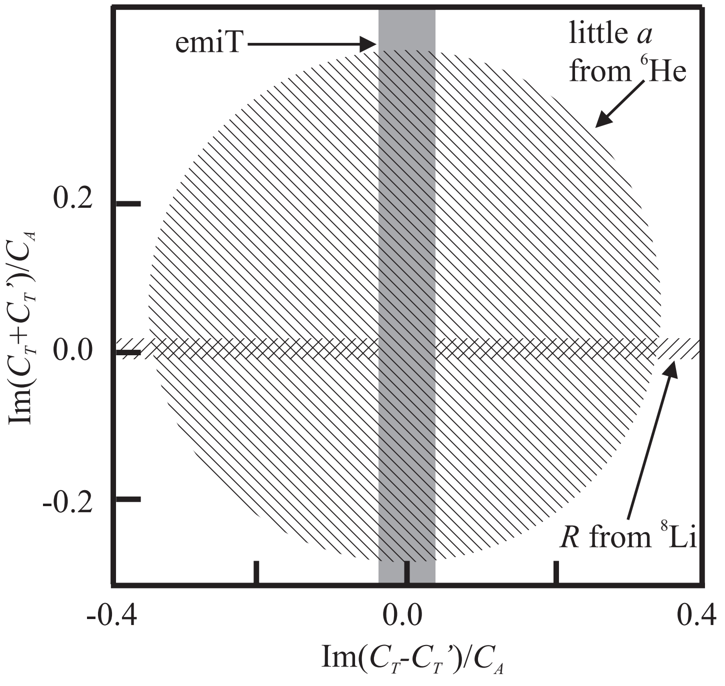
$$\boxed{D = (-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})) \times 10^{-4}}$$

Final Result

$$D=(-0.94\pm1.89\ (\mathrm{stat})\pm0.97(\mathrm{sys}))\times10^{-4}$$

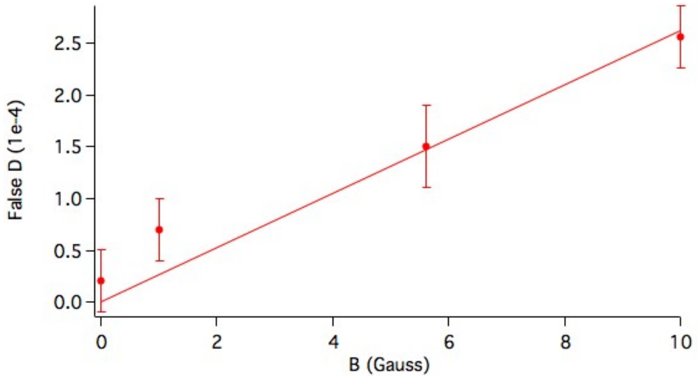
$$\phi_{AV} = 180.012^\circ \pm 0.028^\circ$$





Improvements

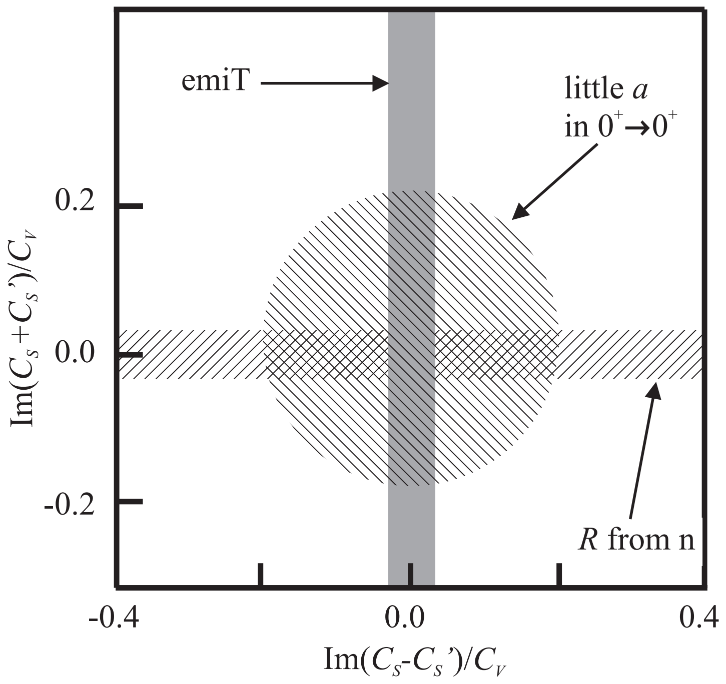
- Major systematics
  - Beam expansion/magnetic field: reduce field
  - ATP error also limited by beam shape
    - AFP spin flipper
    - ^{3}He Polarizer ★★★
  - Proton threshold requires detector/electronics
- NIST-NGC beam line could provide factor 10 increase in neutron decay rate

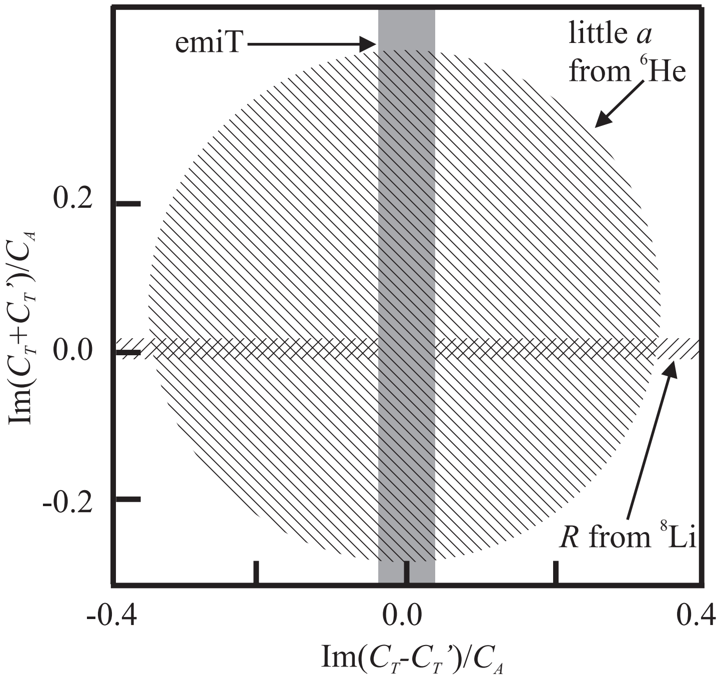


Final Result

$$D=(-0.94\pm1.89\ (\text{stat})\pm0.97(\text{sys}))\times10^{-4}$$

$$\phi_{AV} = 180.012° \pm 0.028°$$



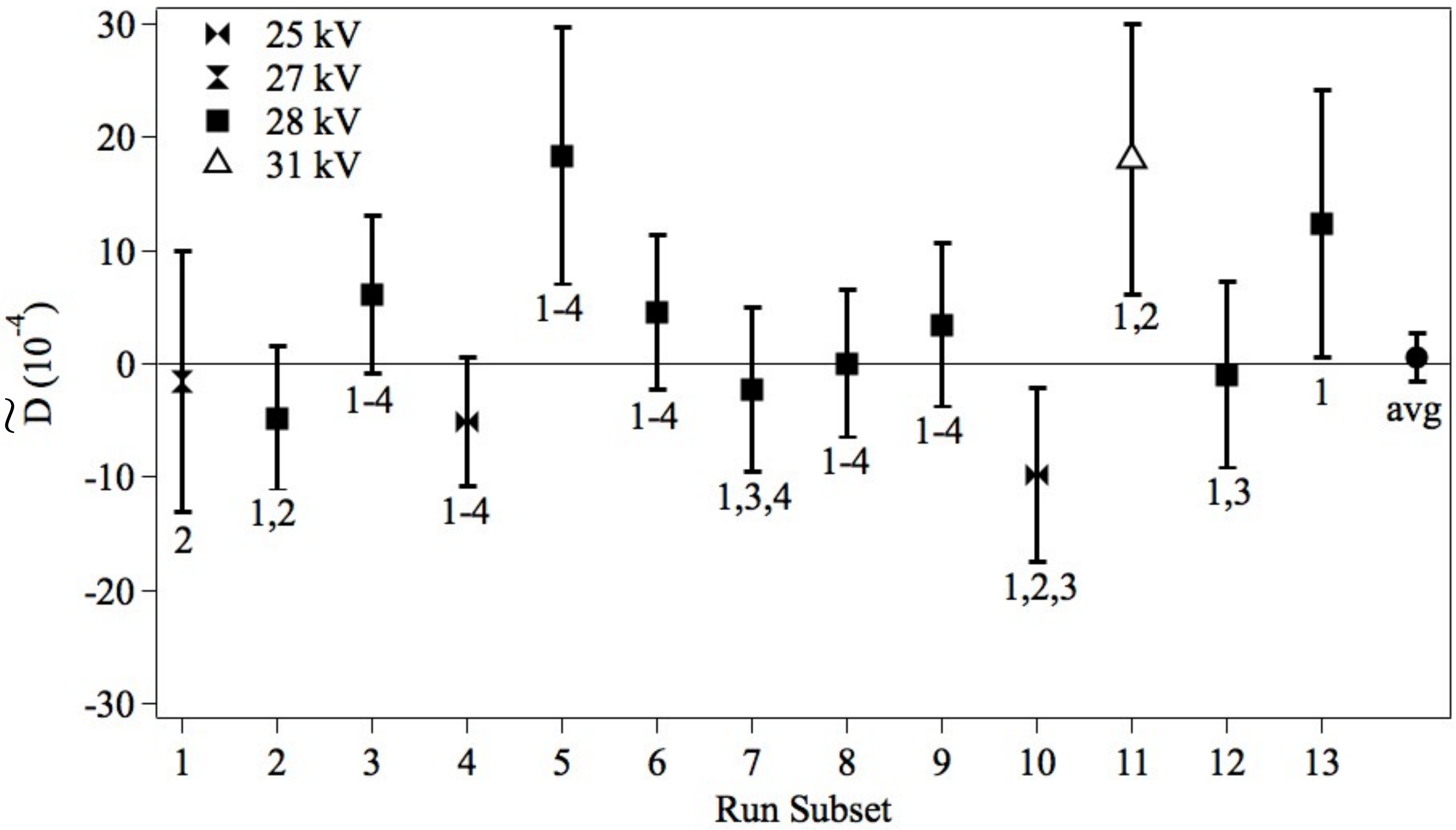


THANK YOU!

Extra Slides

Cuts suggest proton HV dependence

Results for ~D by run subset



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

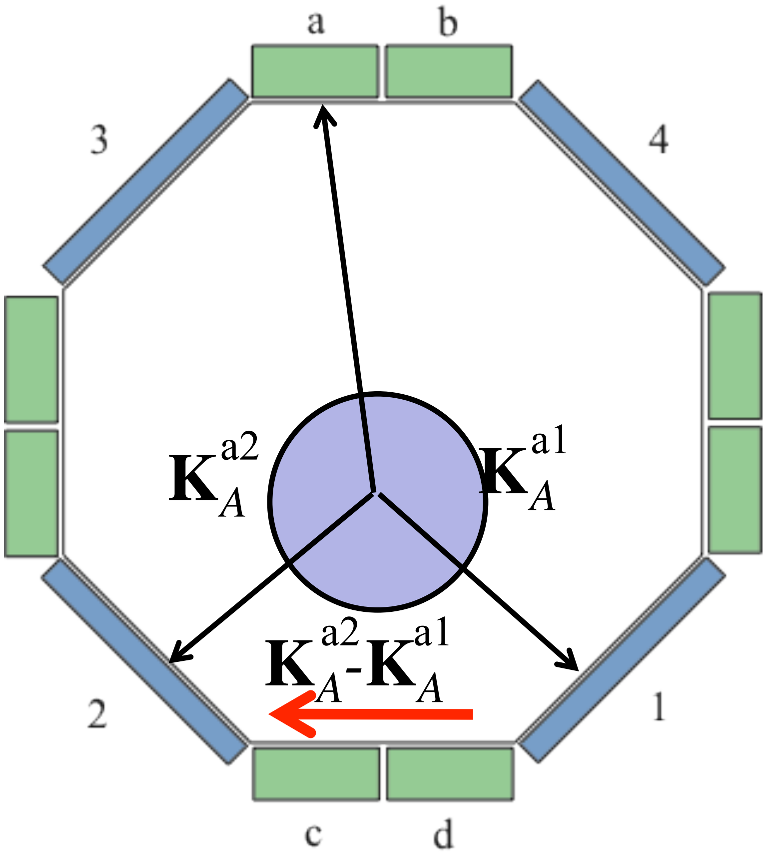
Correlation with HV: chi2=5.6/11 df (2.1 sigma)

- Conclude it's accidental correlation

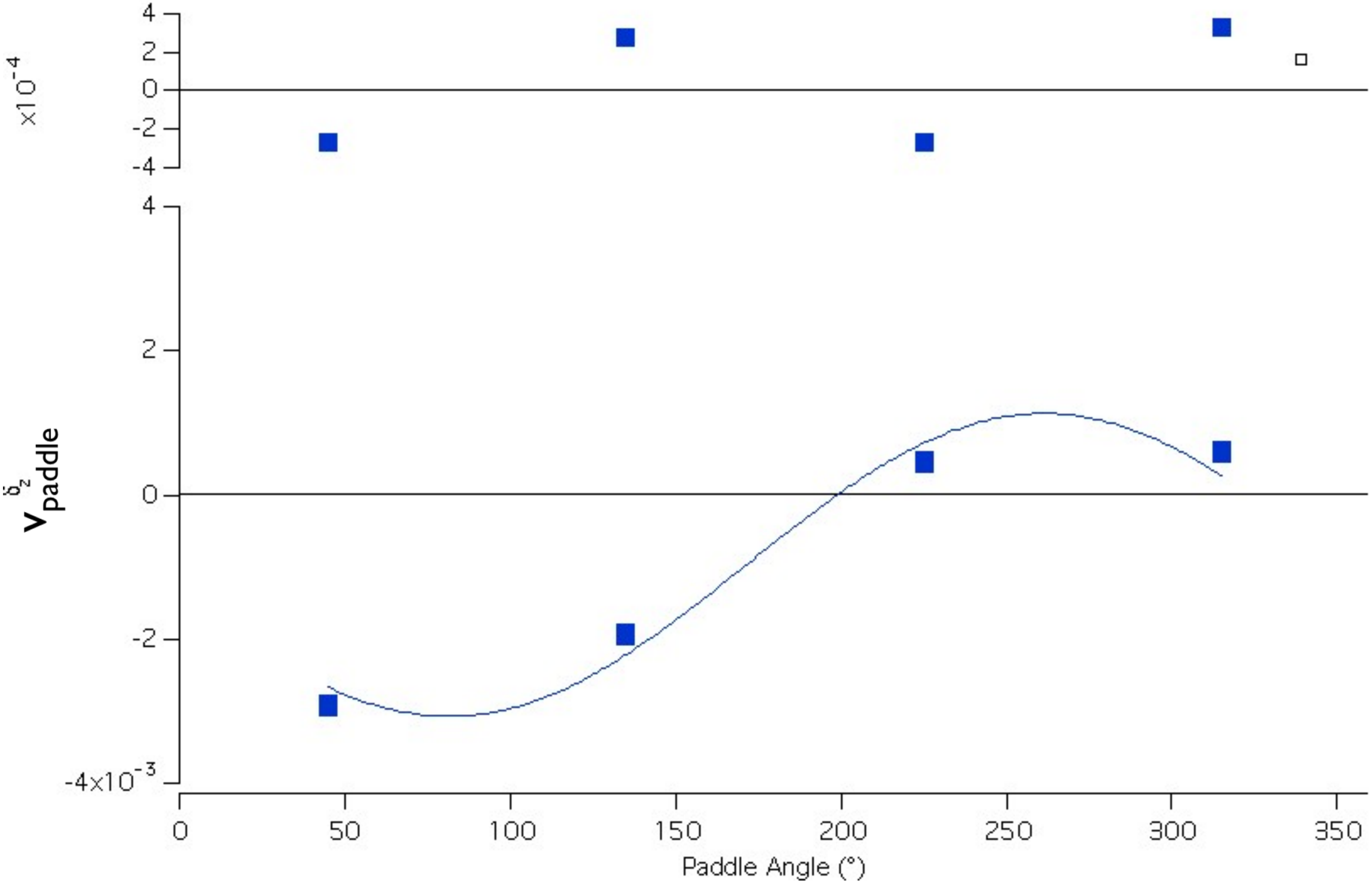
Asymmetry beam/Transverse Polarization (ATP)

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

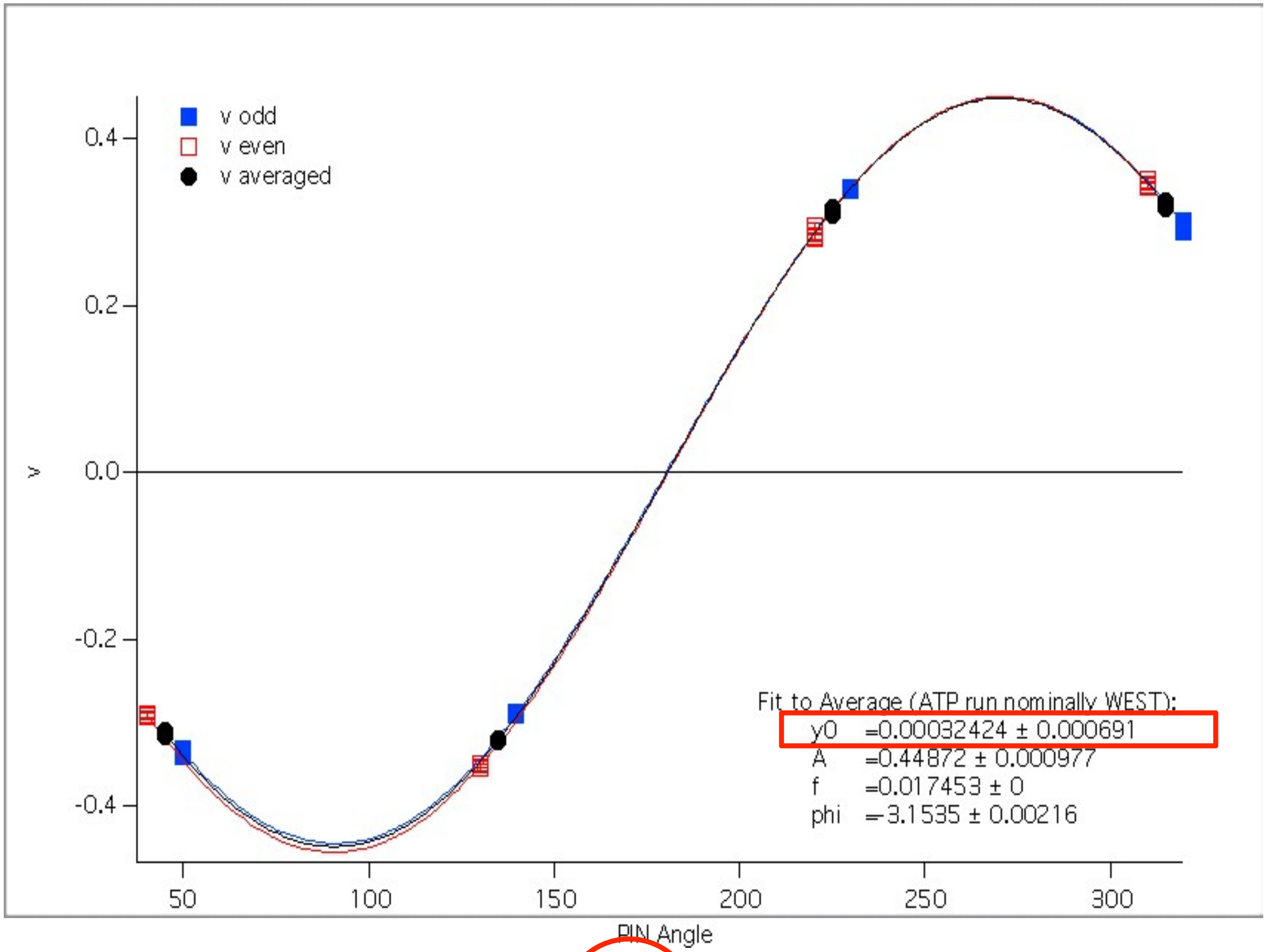
$$v^{p_i} = \frac{1}{2}(w^{p_i R} - w^{p_i L})$$



Transverse Polarization



Asymmetry beam/Transverse Polarization (ATP)



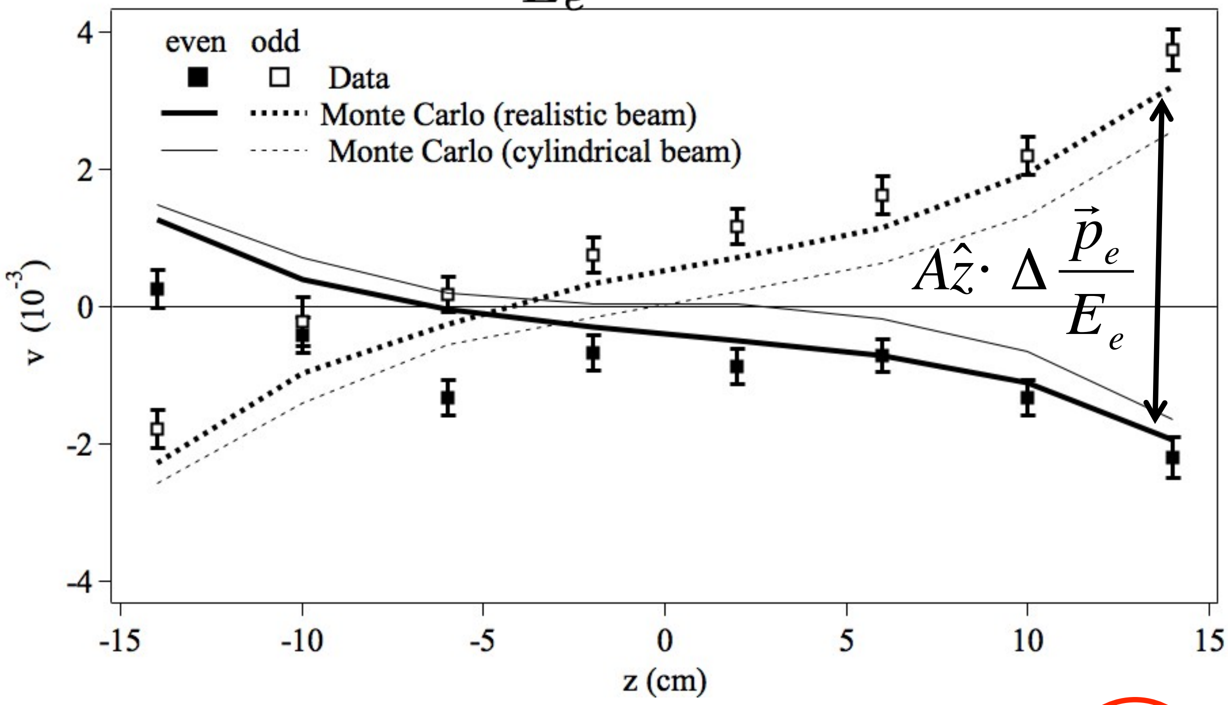
ATP correction: $(-0.07\pm0.72)\mathrm{x}10^{-4}$ ($\theta_P \sim 5$ mrad)

Polarization direction uncertainty

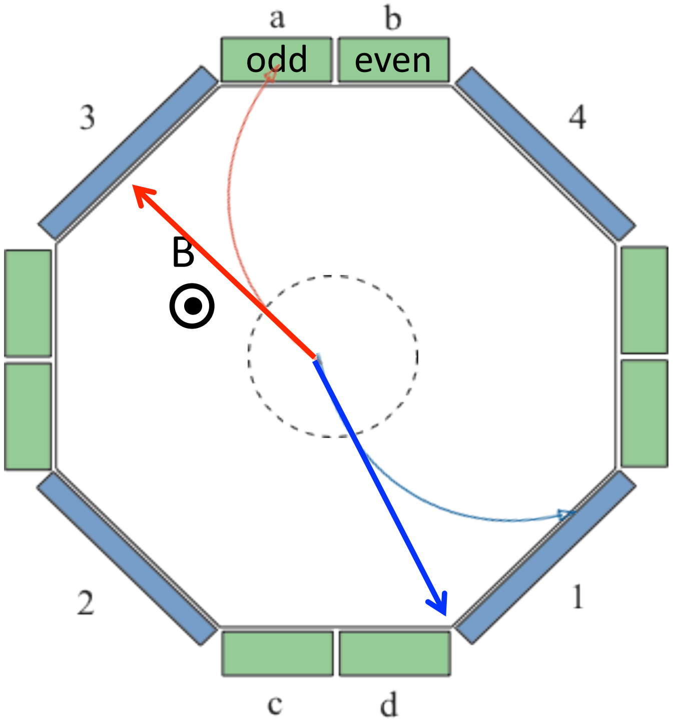
Beam Expansion Effect

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

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



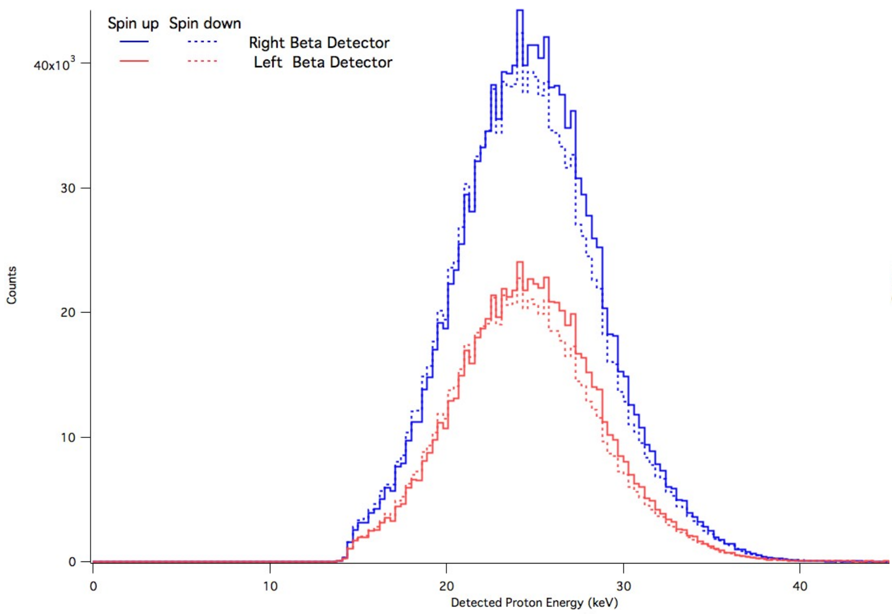
$$A\hat{z}\cdot \Delta \frac{\vec{p}_e}{E_e}$$

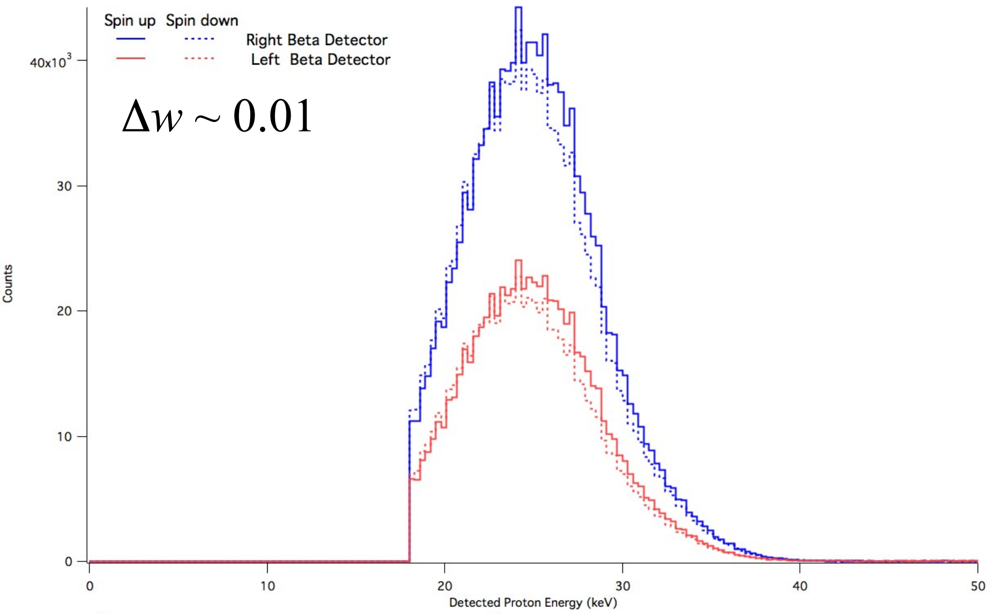


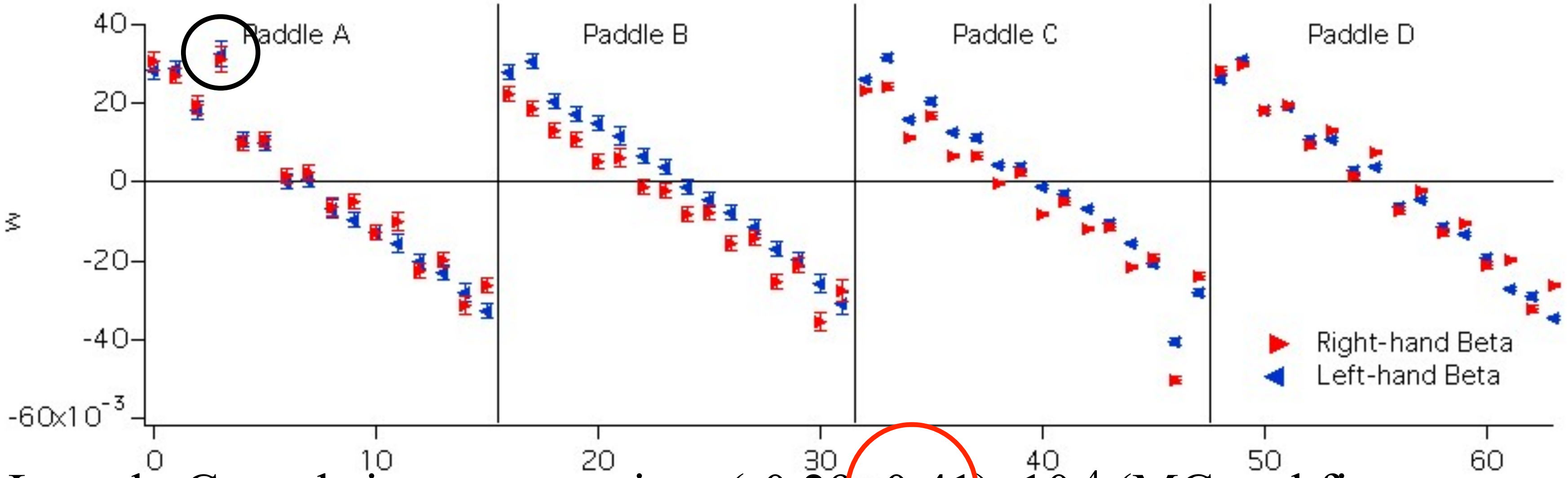
Correction from Monte Carlo: $(-1.5\pm 0.4)\times 10^{-4}$

uncertain beam shape, etc.

Proton threshold effect



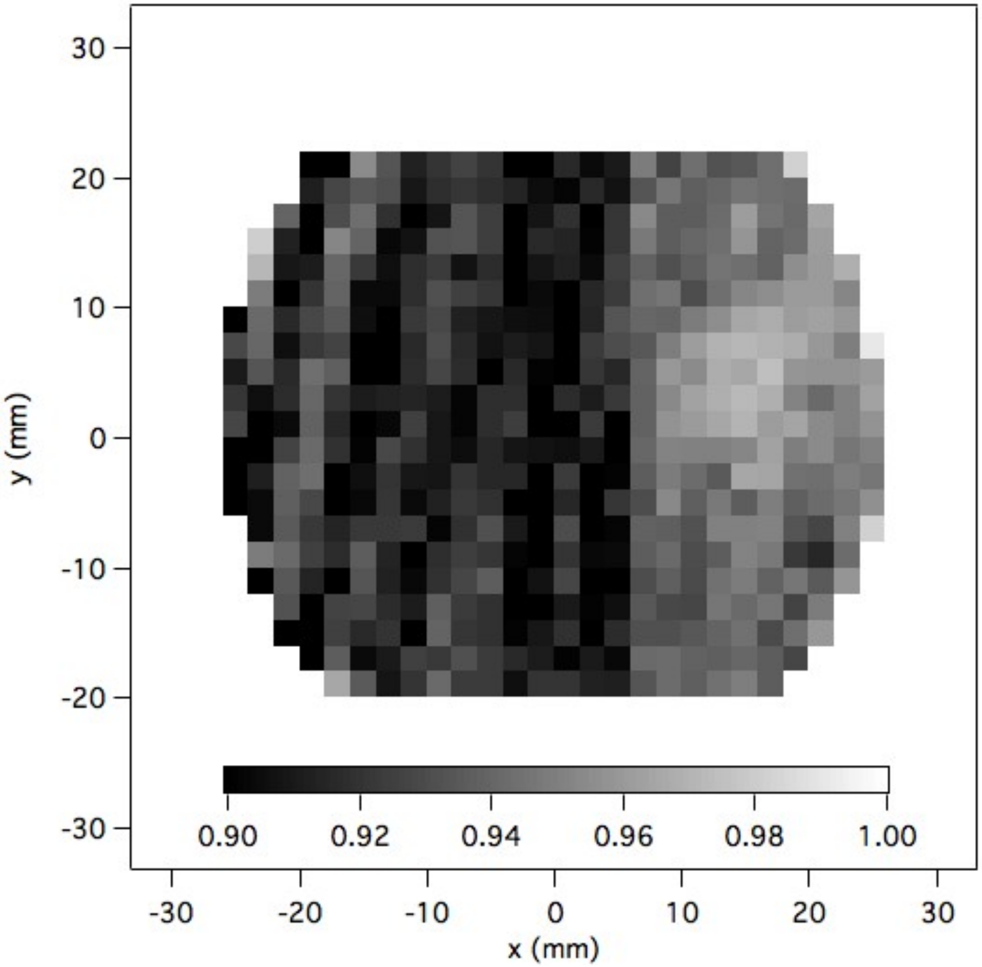

$\Delta w \sim 0.01$



Largely Cancels in *v* - correction: (-0.29±0.41)x10^{-4} (MC and fits to spectra)

threshold variations, etc.

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



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

f=95±5% (calculated)