Part 3

Nuclear Scattering Polarimetry

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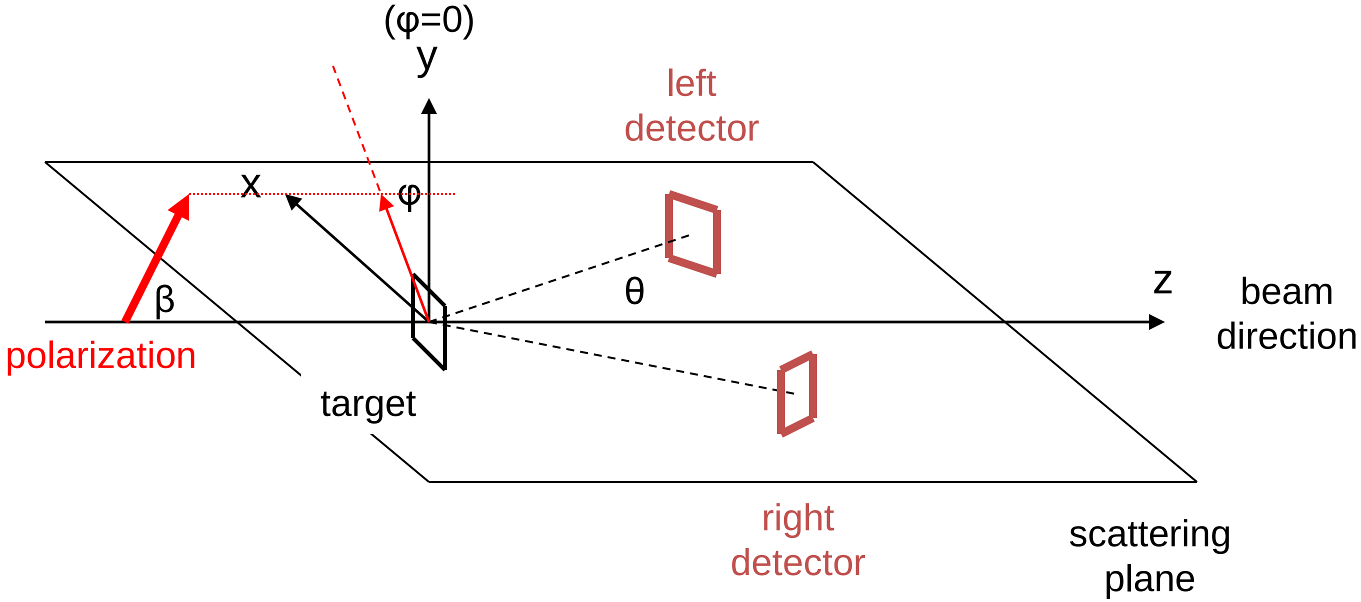
A typical experimental layout contains:



A polarization of the beam (p) causes a difference in the rates for scattering to the left and right according to:

$$\sigma(\theta,\beta,\varphi) = \sigma_{unp}(\theta)\left(1 + pA(\theta)\sin\beta\cos\varphi\right) \qquad p = f_+ - f_-$$

unpolarized cross section (determined by nuclear effects in scattering) governs efficiency

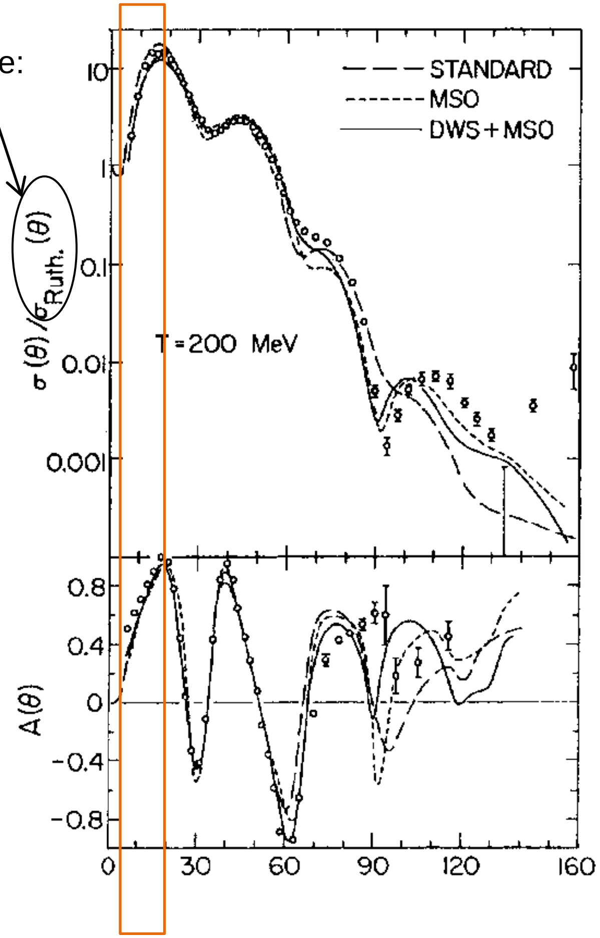
analyzing power (determined by nuclear effects in scattering) governs spin sensitivity

in the ion source magnetic field

Example for proton scattering on carbon

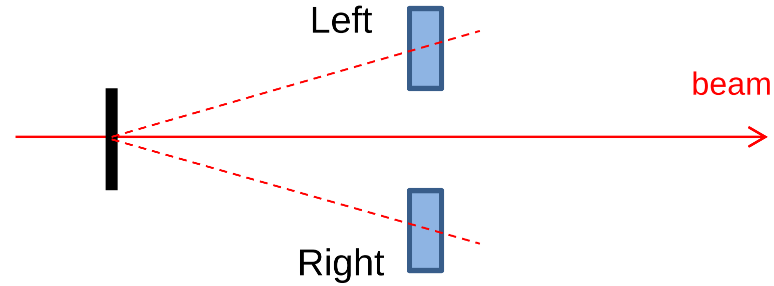
H.O. Meyer *et al.*, Phys. Rev. C **27**, 459 (1983)

Note:



Region most used for polarimetry (6° - 20°)

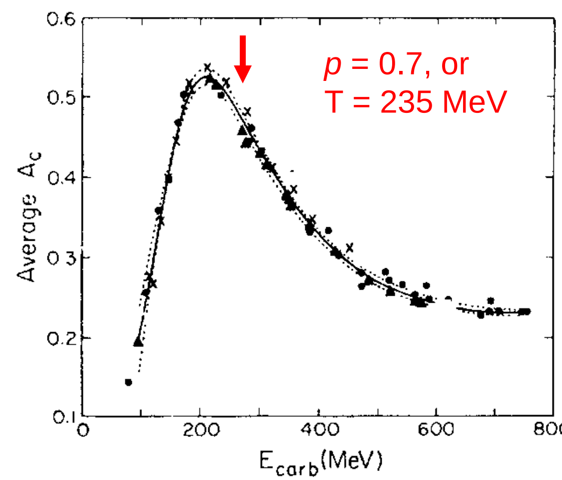
There is a long history of L/R systems.



$$pA = \frac{L-R}{L+R}$$

independent of cross section

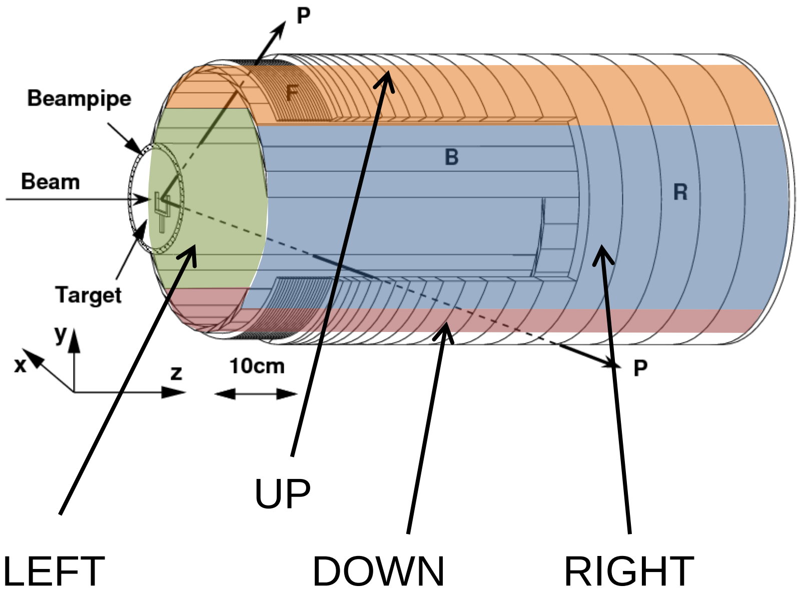
Using plastic scintillator passing detectors, a number of polarimeters were built and operated for nuclear structure work.



We are lucky to have landed near this peak.

This leads directly to a scheme for picking out the EDM signal.

EDDA detector



Azimuthal angles yield two asymmetries:

$$\varepsilon_{EDM} = \frac{L-R}{L+R} \qquad \varepsilon_{g-2} = \frac{D-U}{D+U}$$

This asymmetry is EDM sensitive.

In order to maintain "frozen spin", or longitudinal polarization, for 1000 s, ending with a 20° error at the end means holding machine conditions to 4×10^{-11}. This requires continuous feedback on the error in the polarization direction.

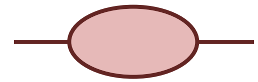
Measure this continuously.

If a vertical asymmetry appears, immediately correct the machine (frequency or field).

This puts a premium on statistics, and polarimeter efficiency.

For deuterons, there are three magnetic spin projections.
Polarized ion sources (good quantization axis) produce two polarizations.

Vector: $p_V = f_1 - f_{-1}$ Tensor: $p_T = 1 - 3 f_0$



Polarizations:

$$it_{11} = \frac{\sqrt{3}}{2} p_V \sin\beta \cos\varphi$$

$$t_{20} = \frac{1}{\sqrt{8}} p_T (3\cos^2\beta - 1)$$

$$t_{21} = \frac{\sqrt{3}}{2} p_T \sin\beta \cos\beta \sin\varphi$$

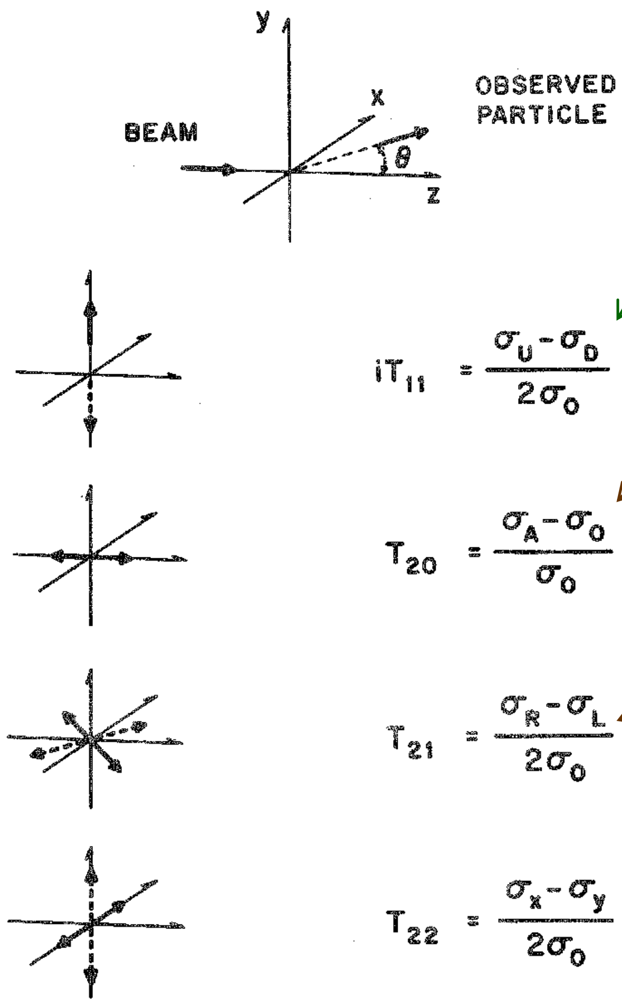
$$t_{22} = \frac{\sqrt{3}}{4} p_T \sin^2\beta \cos 2\varphi$$

spin-1 analyzing power

$$\sigma(\theta,\beta,\varphi) = \sigma_{UNP}(\theta)[1 + 2it_{11}iT_{11}(\theta) + t_{20}T_{20}(\theta) + 2t_{21}T_{21}(\theta) + 2t_{22}T_{22}(\theta)]$$

Spherical Tensor notation (another scheme is Cartesian)

Scheme for measuring the various deuteron polarizations or analyzing powers with a single detector.



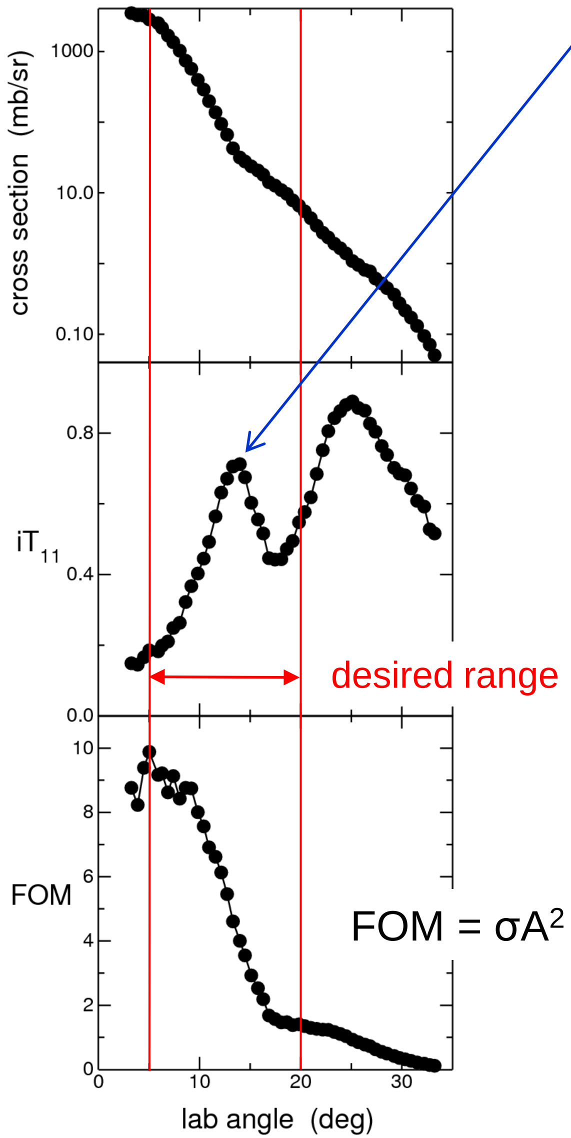
Like the proton, the vector asymmetry carries the EDM signal. Here a comparison of polarization up and down rates replaces left-right scattering.

If you choose maximal polarization for both vector and tensor ($p_V = p_T = 1$, all f_1) then a T_{20} measurement directly gives the longitudinal polarization.

One problem with this scheme is that any small rotation of the polarization away from the forward direction also produces a left-right asymmetry through T_{21}, an analyzing power that is commonly small. But it comes with a down-up asymmetry (used to monitor the polarization direction), so should be distinguishable.

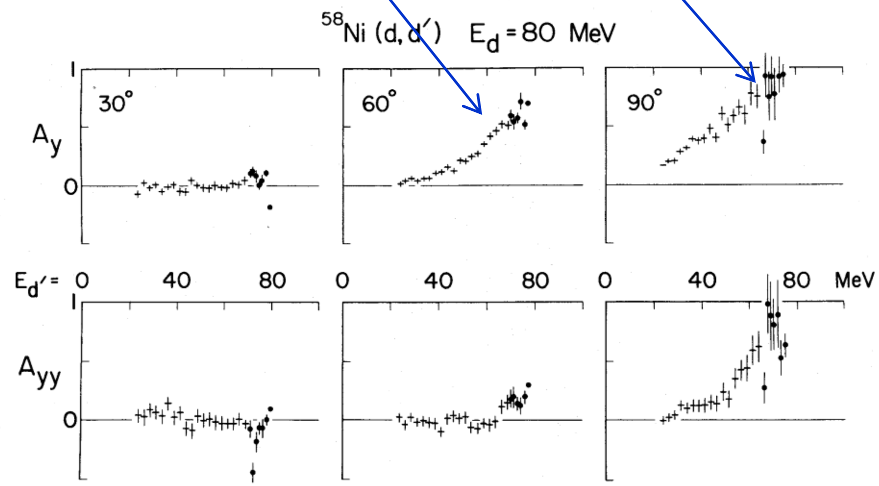
d+C elastic, 270 MeV

Deuteron-carbon analyzing powers are large at forward angles (optical model spin-orbit force).



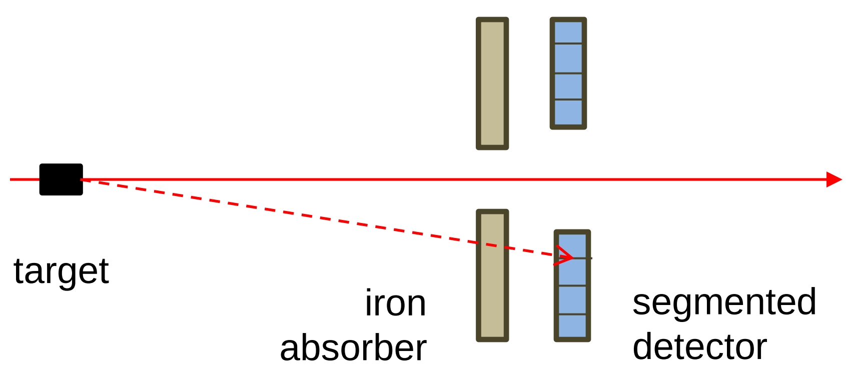
Y. Satou, PL B **549**, 307 (2002)

Inelastic and (d,p) are similar, and should be included.



Breakup has no analyzing power, so avoid it.

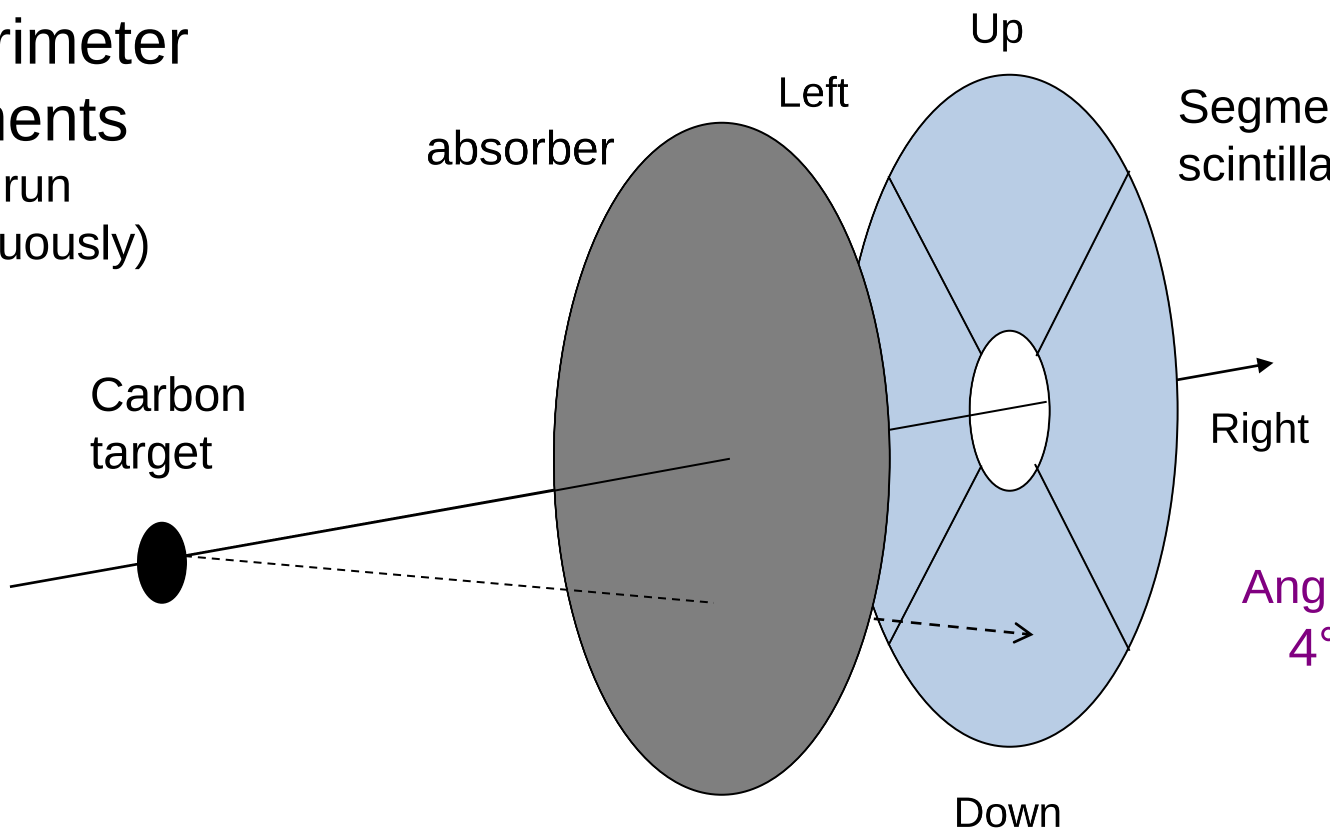
Simplest polarimeter is absorber/detector:



SUMMARY

Functional polarimeter elements

(must run continuously)



Angle range: 4° - 20°

$$\varepsilon_{LR} = \frac{L-R}{L+R}$$

Left-right asymmetry carries EDM information.

$$\varepsilon_{DU} = \frac{D-U}{D+U}$$

Down-up asymmetry carries information on g-2 precession.

Part 4

Polarimeter Efficiency

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High statistics are important for:

1. getting sensitivity to EDM
2. having feedback to tune machine

Solution is thick targets:

every event has maximum change for nuclear scatter

spectrometers have used several cm to get 1-4%

Limit on thickness is:

changes in cross section/analyzing power angular distribution

beam multiple scattering, spreading into sensitive region

energy straggling at the detector

Cleanly detecting simple reaction channel gets lost.

Polarimeter becomes “black box” with good properties.

Build for reproducibility, then calibrate.

Use elastic scattering on carbon, 4° - 20°.

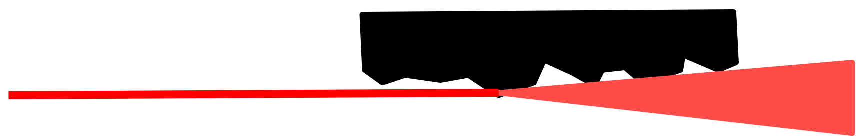
In COSY work, limits of 1.5 cm and > 9° cost more than a factor of 10.

How does it work?

1 Put thick target near beam, move beam into target.
Use position ramp or white noise applied to electric field plates.

Motion is << μm/turn

2 Beam particle hits ridge on target, multiple scatters (Coulomb).

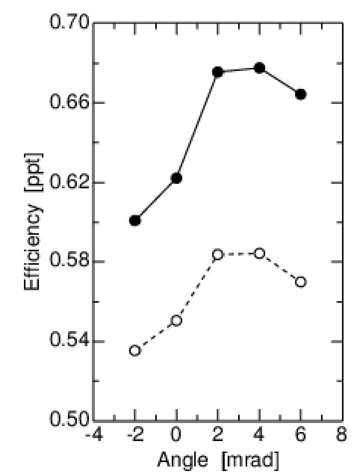


Some particles penetrate target and scatter.

3 Betatron motion on next turns brings particles into target face.

Typical depth = 0.2 mm.

Typical depth comes from efficiency changes when beam tilts.



Values agree with simulations.
Efficiencies of 1% are possible.

Part 5

Polarimeter Systematic Errors

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How to manage systematic errors:

(measuring left-right asymmetry)

Usual tricks: Locate detectors on both sides of the beam (L and R).
Repeat experiment with up and down polarization.
Cancel effects in formula for asymmetry (cross-ratio).

From experiments with large induced errors and a model of those errors:

$$pA = \varepsilon = \frac{r-1}{r+1} \qquad r^2 = \frac{L(+)R(-)}{L(-)R(+)}$$

But this fails at second order in the errors.

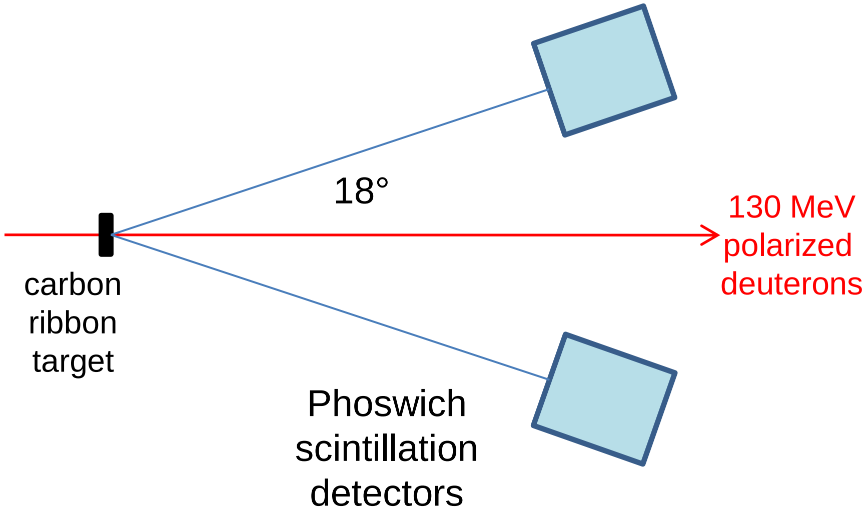
Using the data itself, devise parameters: $\phi = \frac{s-1}{s+1} \quad s^2 = \frac{L(+)L(-)}{R(+)R(-)}$, and rate $W = L + R$

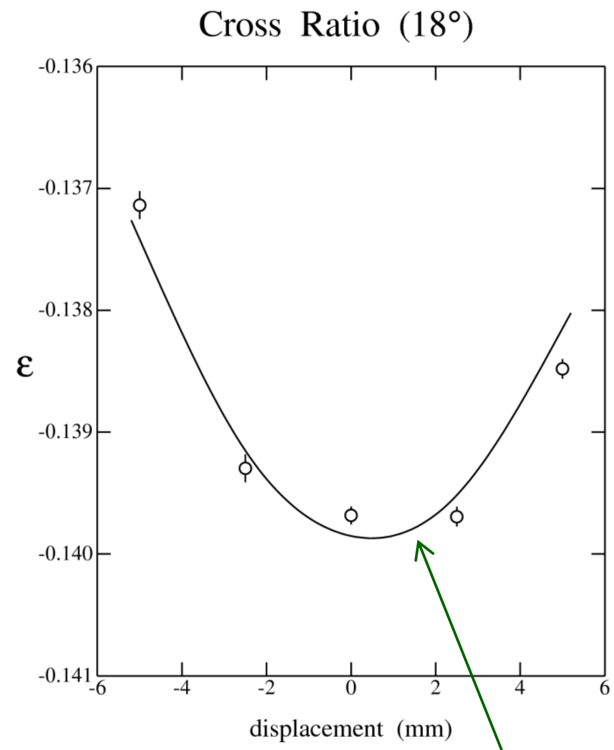
Calibrate polarimeter derivatives and correct (real time):

$$\varepsilon_{CR,corr} = \frac{r-1}{r+1} - \left(\frac{\partial \varepsilon_{CR}}{\partial \phi}(\phi)\right)_{MODEL} \Delta\phi - \left(\frac{\partial \varepsilon_{CR}}{\partial W}(W)\right)_{MODEL} \Delta W$$

geometry data rate

Tests made at the KVI (2007)





Calculation based on deuteron elastic scattering data at 130 MeV and measured beam polarizations.

Best method: "cross ratio", "square root" method

$$\varepsilon = \frac{3}{2} pA = \frac{r-1}{r+1} \qquad \text{where} \qquad r^2 = \frac{L(+)R(-)}{L(-)R(+)}$$

This method fails at second order in errors.

$$\varepsilon(\exp) = \varepsilon + \frac{1}{1-\varepsilon^2}\left\{ \varepsilon^3 u^2 + 2\varepsilon^2 \left(\frac{1}{A}\frac{\partial A}{\partial x}\right) ux + \varepsilon \left[\left(\frac{1}{A}\frac{\partial^2 A}{\partial x^2}\right)(1-\varepsilon^2) - \left(\frac{1}{A}\frac{\partial A}{\partial x}\right)^2 \varepsilon^2 \right] x^2 \right\}$$

"true" asymmetry

observed asymmetry

$$u = p(+) - p(-),\ p(-) < 0$$

Changes to beam position/angle produced effects that calibrate the polarimeter for errors.

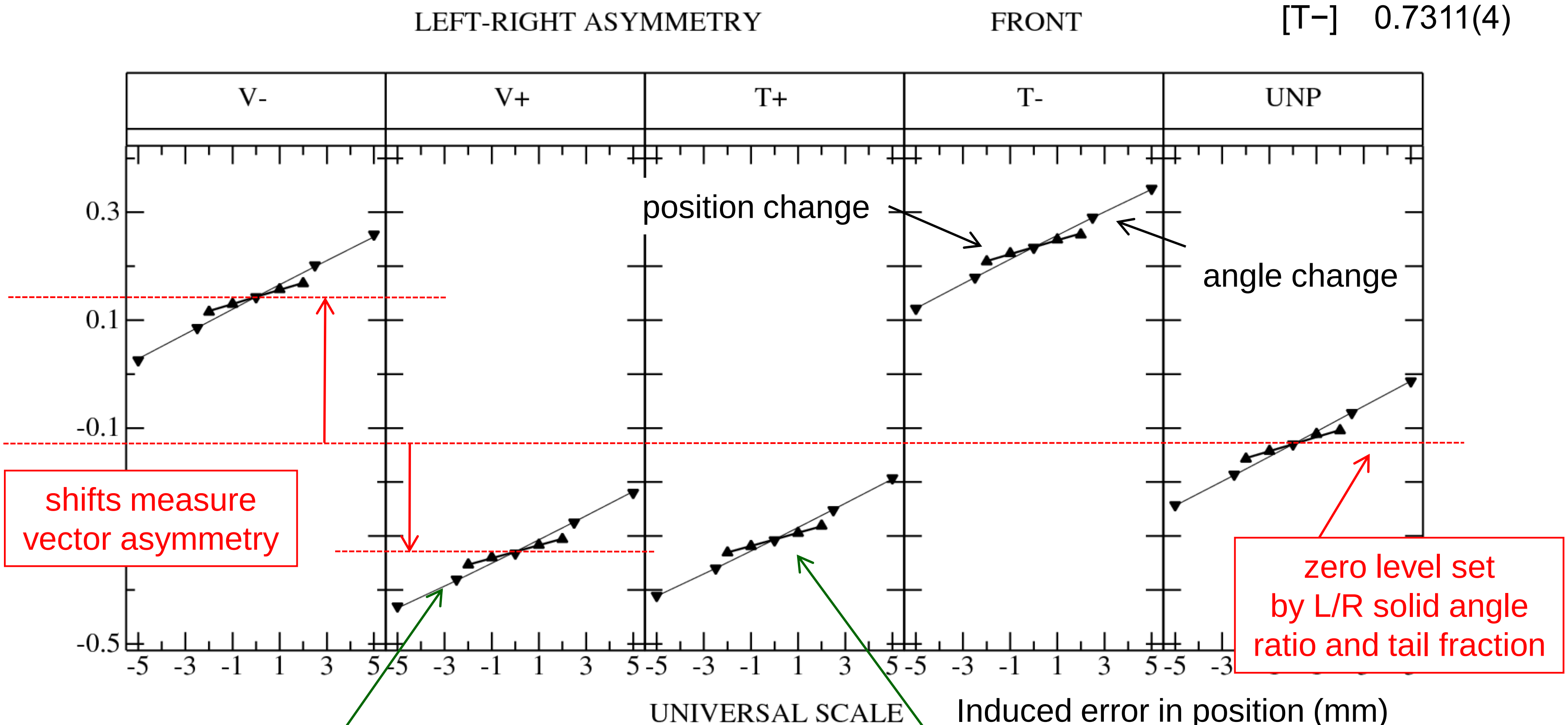
Group 5

Vector Analyzing Power

$A_y = 0.349(6)$

Vector Polarization p_y

[V−]	0.5370(4)
[V+]	−0.3954(4)
[T+]	−0.3399(4)
[T−]	0.7311(4)



Induced error in position (mm) or angle (mrad)

slopes given by $\left(\frac{\sigma'}{\sigma}+\frac{A'}{A}\right)\varepsilon^2-\frac{\sigma'}{\sigma}$

$\frac{\sigma'}{\sigma}=-0.02562(9) \quad \frac{A'}{A}=0.0055(3) \quad \frac{1}{rad}$

X/θ = 52.4(8) cm

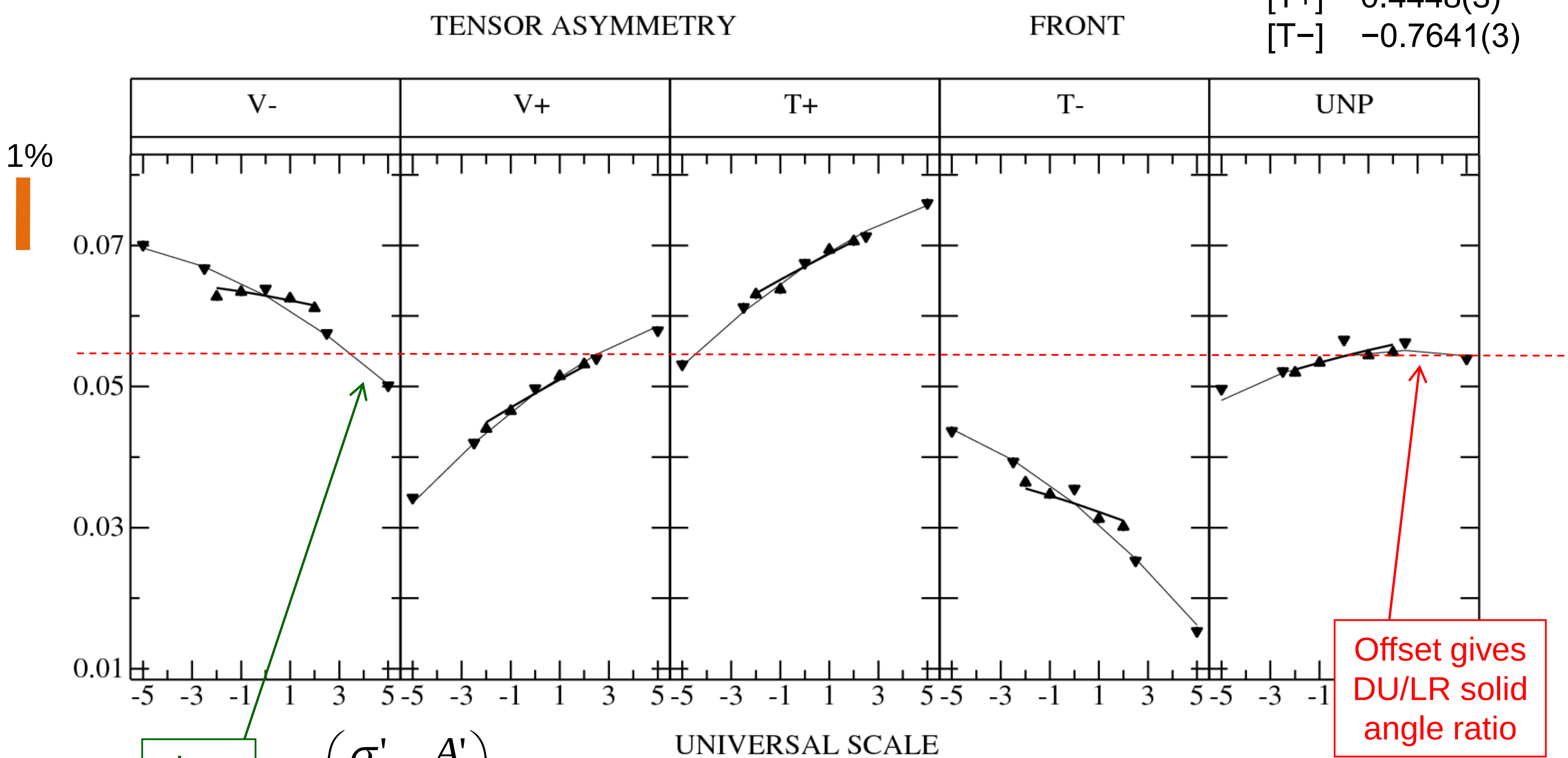
$$\varepsilon = \frac{D+U-L-R}{D+U+L+R} = \frac{\sqrt{6}\,p_T T_{22}}{\sqrt{8}-p_T T_{20}} \cong \frac{1}{2}\,p_T A_T$$

Group 5

Tensor Analyzing Power
$A_T = 0.0721(2)$

Tensor Polarization p_T

[V−]	0.1580(3)
[V+]	−0.0841(3)
[T+]	0.4448(3)
[T−]	−0.7641(3)



slope gives $\varepsilon_V\left(\frac{\sigma'}{\sigma}+\frac{A'}{A}\right)$

curvature gives $-\frac{\sigma''}{\sigma}$

0.00029(1) 1/rad^2

Offset gives DU/LR solid angle ratio

1.3048(2)

difference from one compensates for tail fraction

Geometry model

Parameters we know we need to include:

EDDA Analyzing power: A_y and $A_T = \frac{\sqrt{6}T_{22}}{\sqrt{8} - p_T T_{20}}$

Polarizations: p_V and p_T for the states V+, V−, T+, T−

There is some information available from the COSY Low Energy Polarimeter.

Logarithmic derivatives: $\frac{\sigma'}{\sigma}, \frac{\sigma''}{\sigma}, \frac{A_y'}{A_y}, \frac{A_y''}{A_y}, \frac{A_T'}{A_T}, \frac{A_T''}{A_T}$

Solid angle ratios: L/R D/U (D+U)/(L+R)

Total so far: 19 parameters

Parameters we found we needed:

Rotation of Down/Up detector (sensitive to vertical polarization): θ_{rot}

X – Y and θ_X – θ_Y coupling (makes D/U sensitive to horizontal errors): C_X, C_θ

Ratio of position and angle effects (effective distance to the detector):

$X/\theta = R$

Tail fraction: multiple-scattered, spin-independent, lower-momentum flux that is recorded only by the “right” detector (to inside of ring)

F = fraction F_X, F_θ sensitivities to position and angle shifts

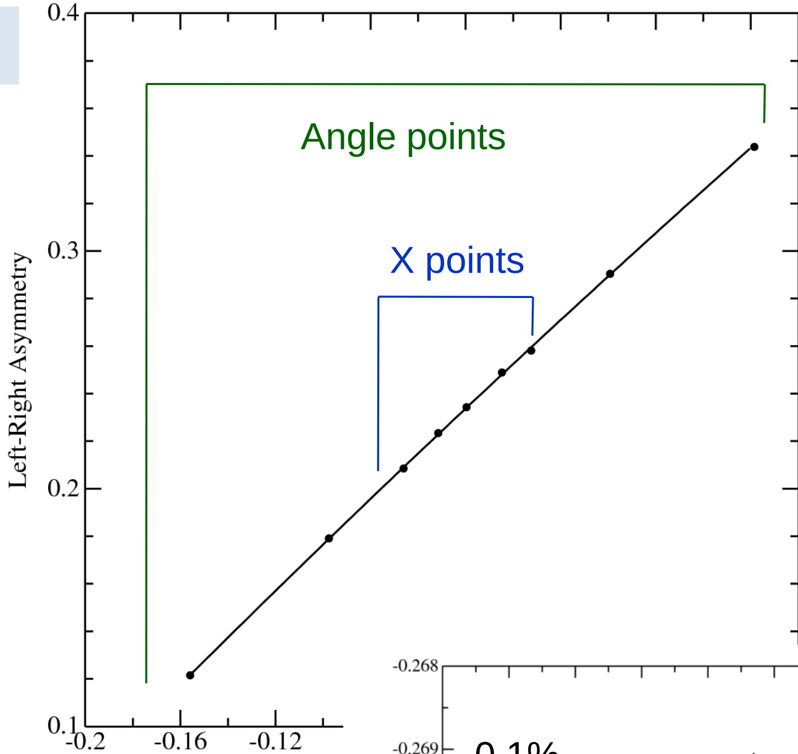
Total parameters: 26

Fitting revealed one continuous ambiguity involving L/R and (D+U)/(L+R) solid angle ratios, the tail fraction, effective detector distance, and all polarizations.

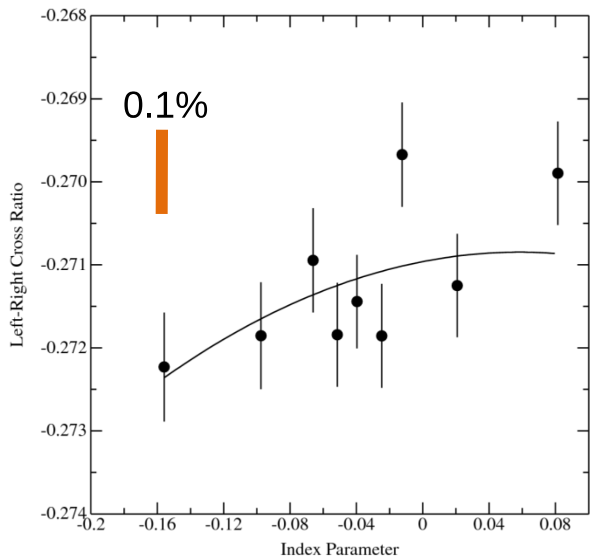
Choice was to freeze L/R solid angle ratio for front rings at <u>one</u>.

Conclusions

1



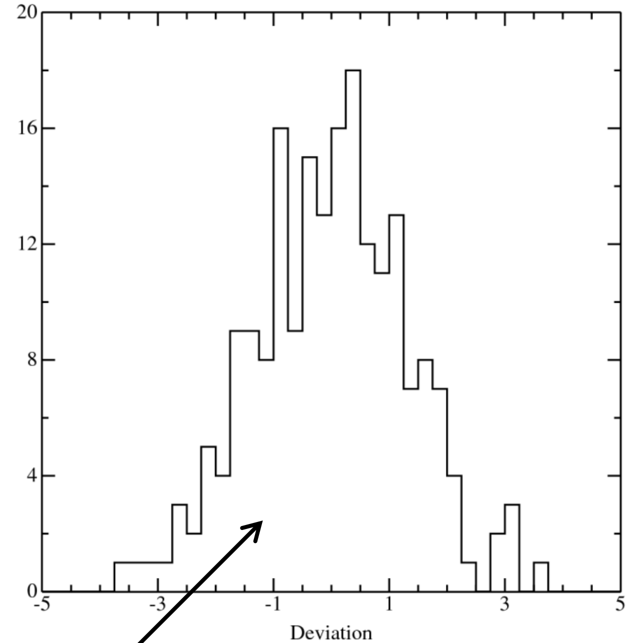
10%



Corrections for A and θ match.
One index can be used for both.

2

Chi square distribution for geometry fit

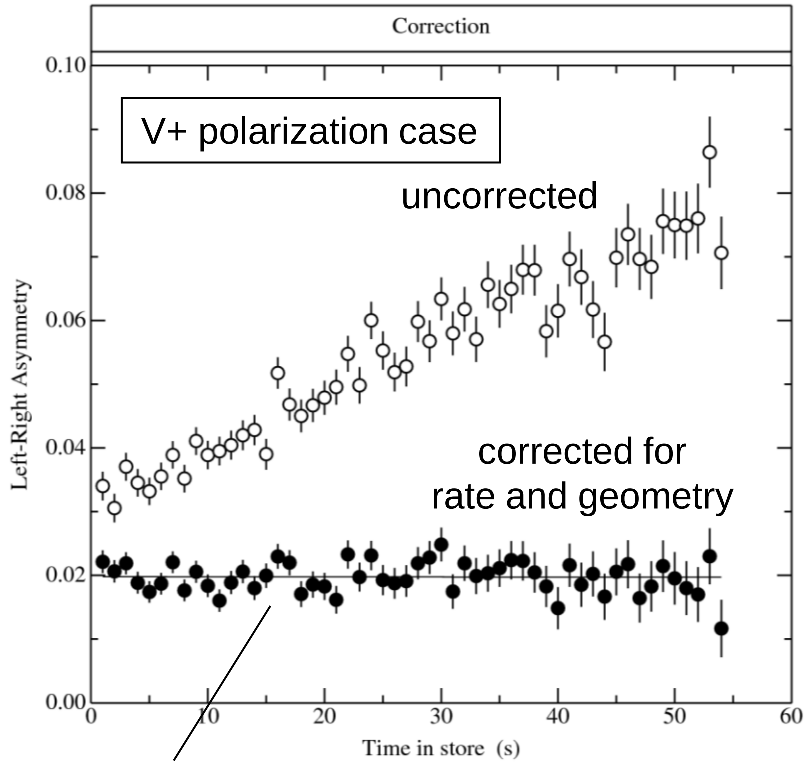


Reduced chi square is 1.7

Reproduction of data by model is good; there are no unexplained features.

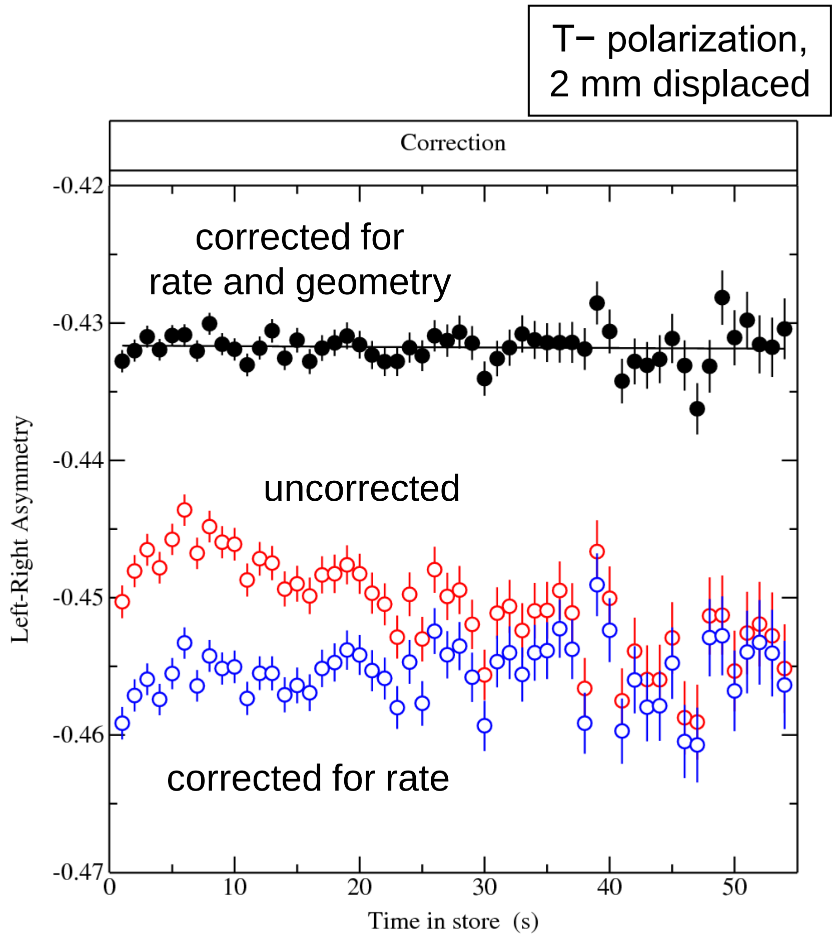
3

Tests were made with the beam shifting by 4 mm during the store.



slope: $-1.4 \pm 28 \times 10^{-6}$ /s

Tests were made with high rate and displaced beam.



Since asymmetry depends only on count rates and calibration coefficients, we get results in real time.

Corrections work.