R & D Activities for the Storage Ring EDM Search at the Cooler Synchrotron (COSY)

Polarimeter Systematic Errors
Future Polarimeter Development Plans
Polarization Lifetime (Spin Coherence)

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C-AD Review
March 14, 2011

Why COSY?

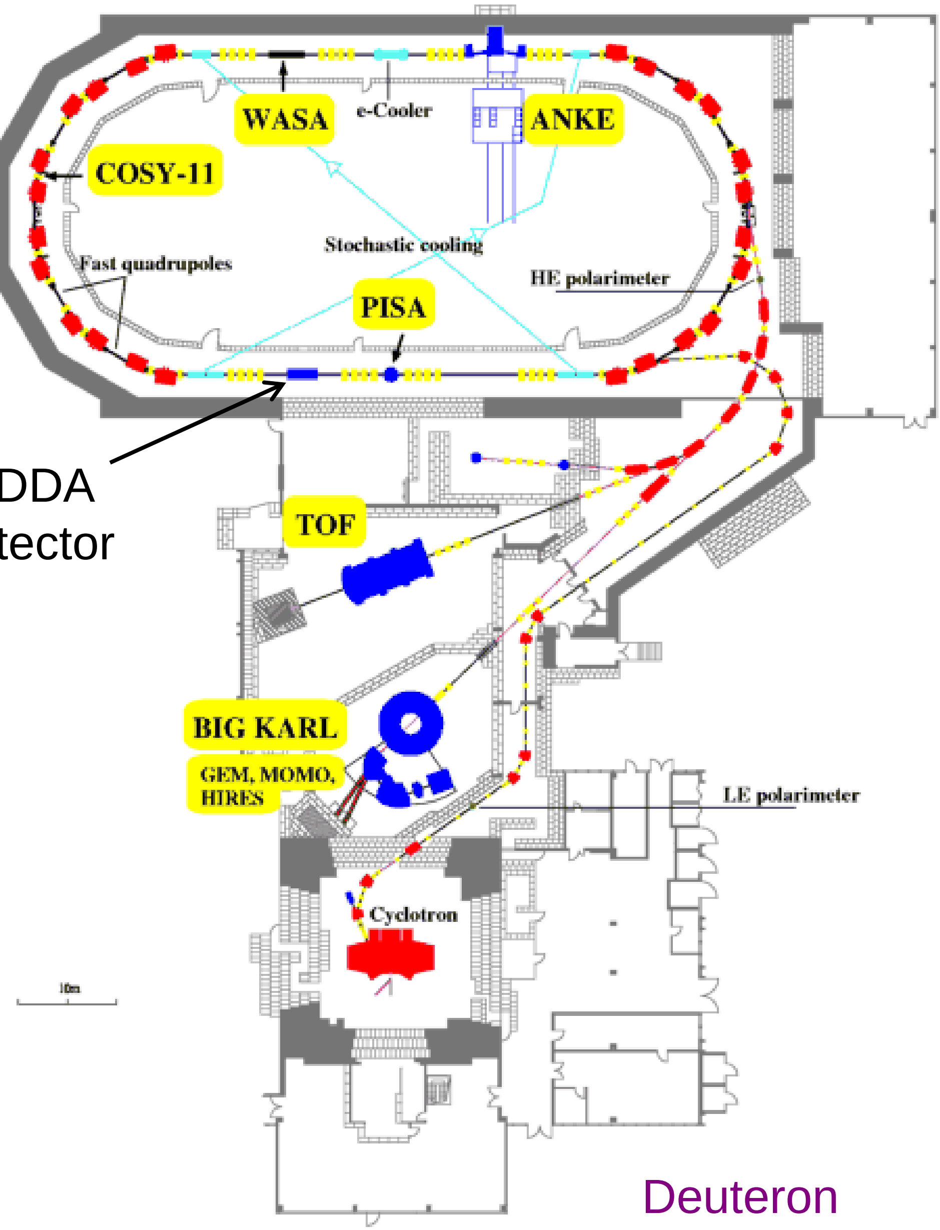
- Scale like EDM ring
- Polarized P/D beams
- Electron cooling
- Outside user program
- Available equipment

History

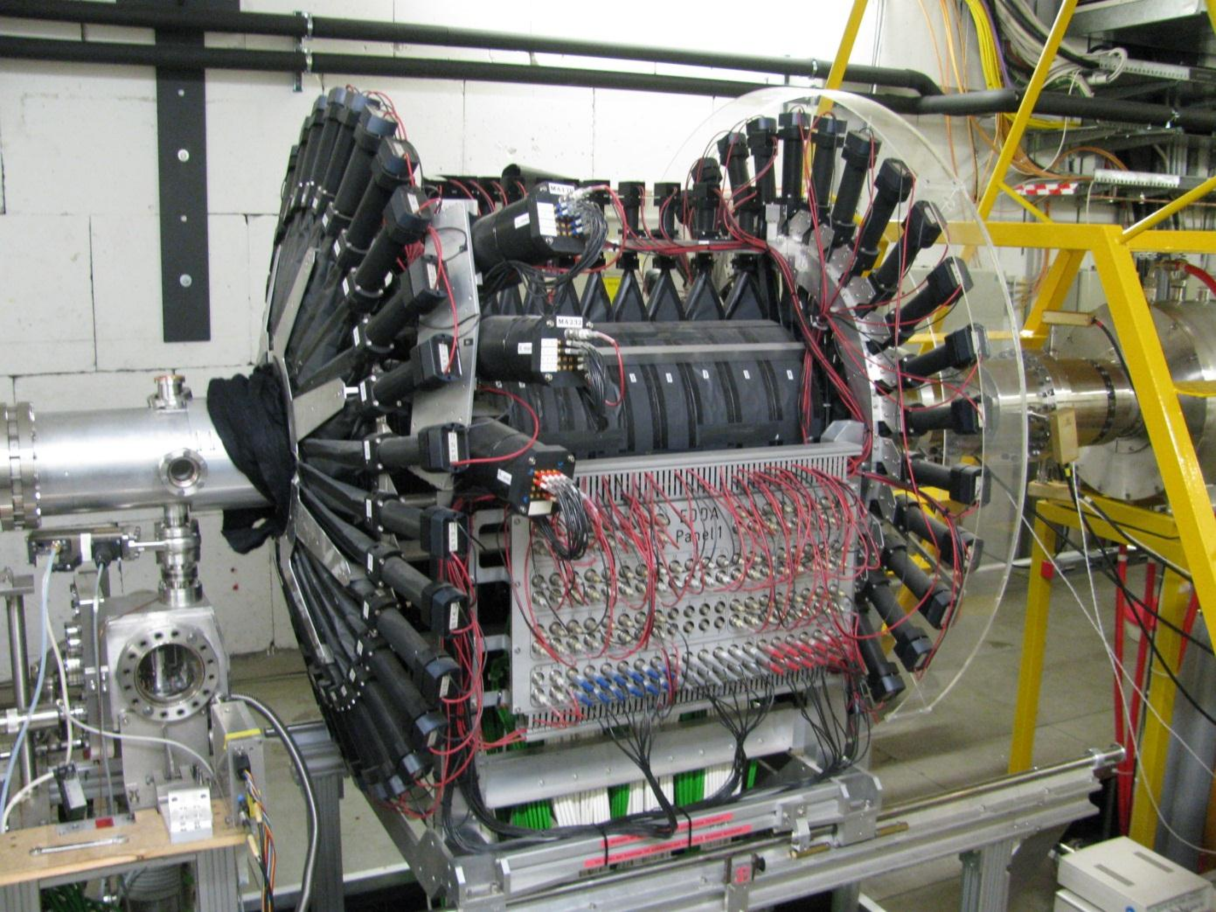
- Proposal in 2007
- Visit SPIN@COSY run
- Three polarimeter runs:
  - June 2008 – initial tests
  - September 2008 – trial data
  - June 2009 – final long run (paper in preparation)
- Polarization lifetime runs:
  - January 2011 – initial tests

Prior work at KVI, Groningen
- d=C data, 2004 + 2005
- Systematic errors, 2007

EDDA detector



Deuteron beam

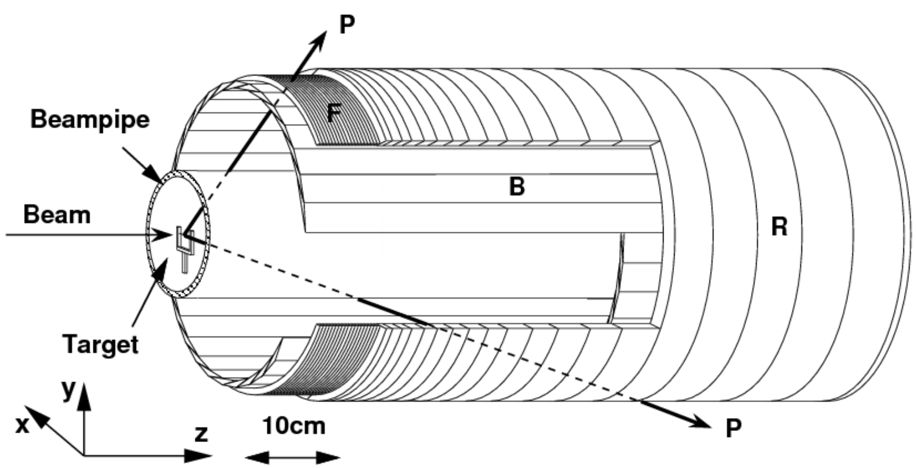


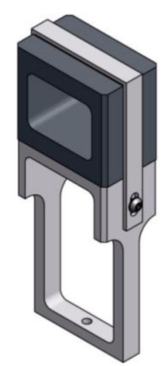
EDDA detector

32 bars measure azimuthal angle

rings measure scattering angle

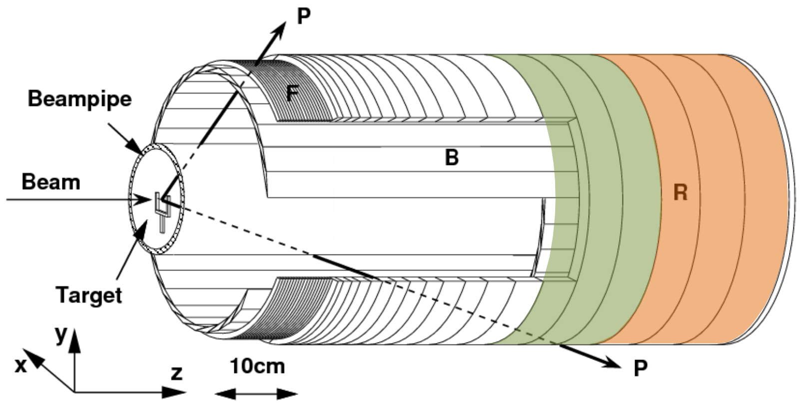
Operate as stopping detector for deuterons, sets beam momentum to be p = 0.97 GeV/c





Thick carbon target used for continuous extraction and high efficiency

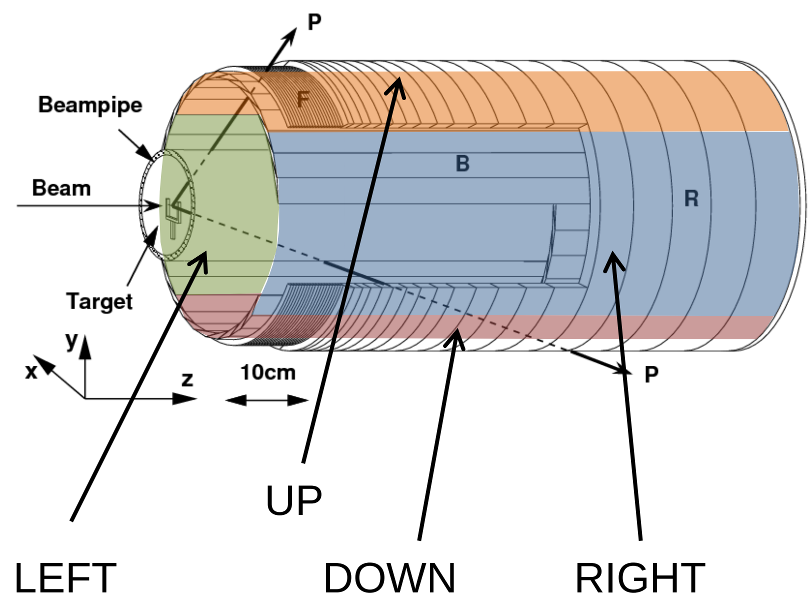
Rings and bars to determine angles.



Operated with two sets of scattering angle bars to make two "polarimeters".

Azimuthal angles yield two asymmetries:

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



Polarimeter Operation

General Goal:	Confine *charged,* polarized particles with a large electric field Watch for change of polarization direction perpendicular to **E** as signature for Electric Dipole Moment (EDM) Candidates: proton, deuteron, (^{3}He)…can polarize, analyze
Sensitivity:	For ~ 10^{-29} e·cm expect 10^{-6} rad in ~ 1000 s
Polarimeter Requirements: ~ 250 MeV	High efficiency (useful events / particles lost from beam) Large analyzing power Control of systematic errors as beam conditions change

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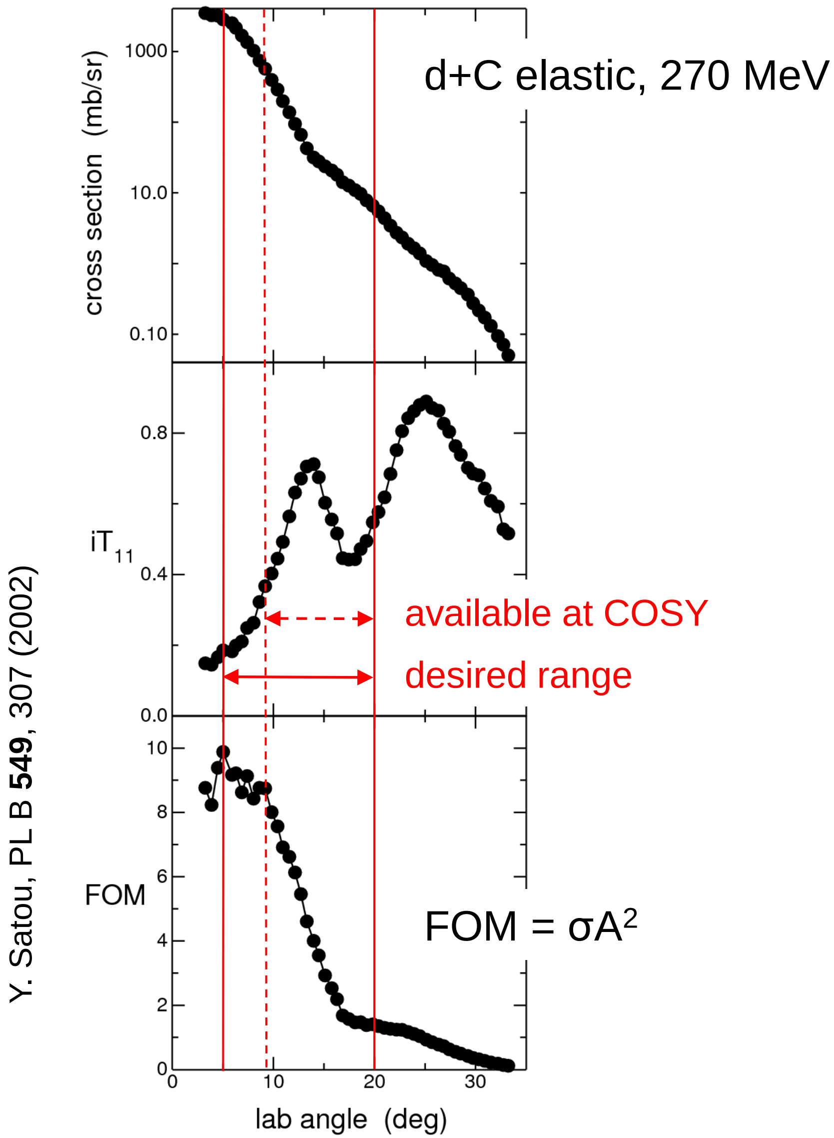
Effective goal: 0.5

Forward angle elastic scattering (large spin-orbit distortions)
Carbon target
Include low Q-value reactions (similar analyzing power)

Deuteron case

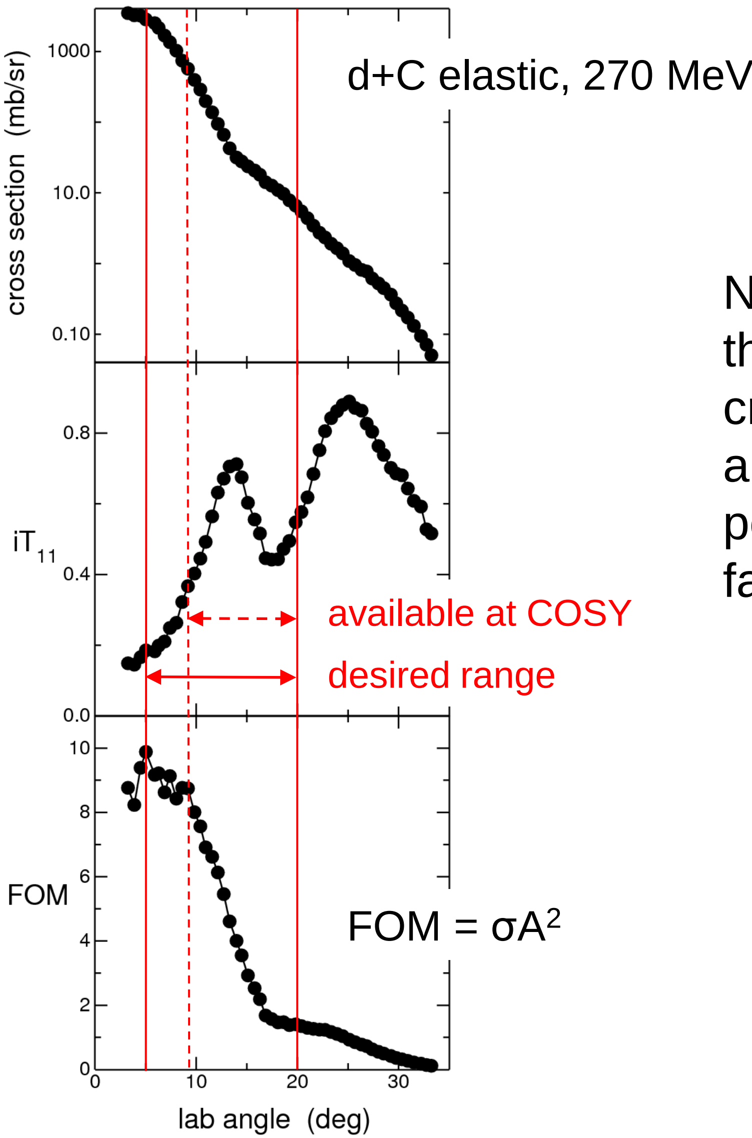


Deuteron case

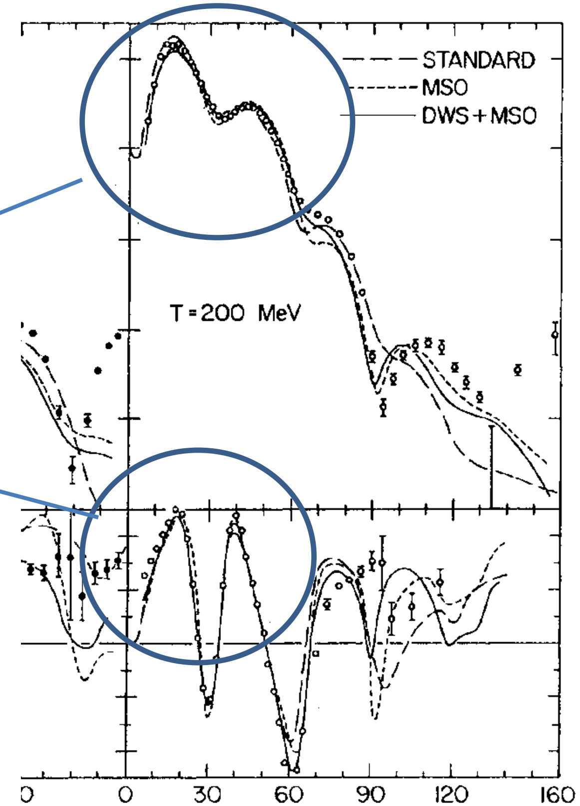
Proton case

Similarity to deuteron case means results apply to both.

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



Near 230 MeV the forward cross section and analyzing power are favorable.



We can expect:

efficiency ~ 1.1 % (over 2π)
analyzing power ~ 0.6

with some selection on elastics

Errors

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).

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

But this fails at second order in the errors.

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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.

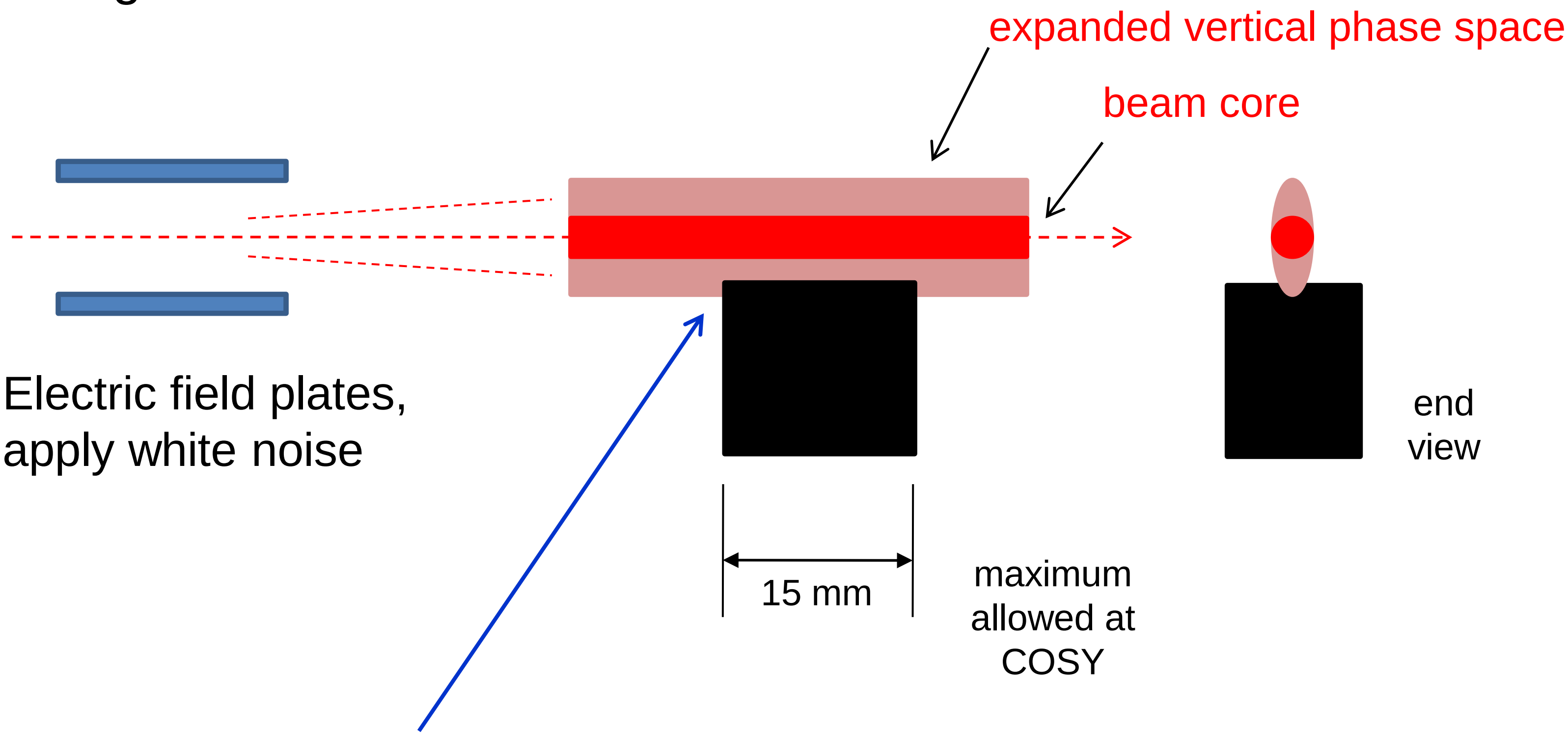
Using the data itself, devise parameters: $\phi = \frac{s-1}{s+1} \quad s^2 = \frac{L(+)L(-)}{R(+)R(-)}$, and rate $W = L + R$

Calibrate polarimeter derivatives and correct (real time):

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

Will this work? for both X and θ?

Target solution found at COSY:



Do enough particles penetrate far enough into the front face to travel most of the way through the target?

This requires a comparison of the efficiency with model values.

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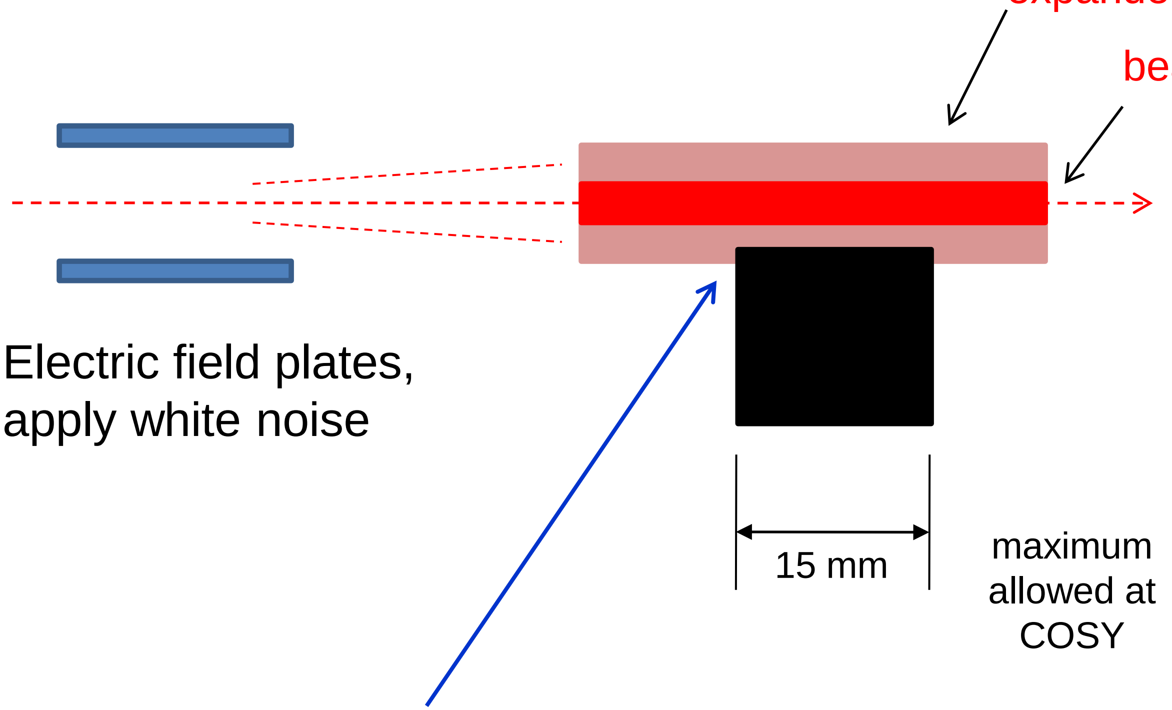


Yes,

	front	back
model	5.7	4.7
data	6.8	5.9

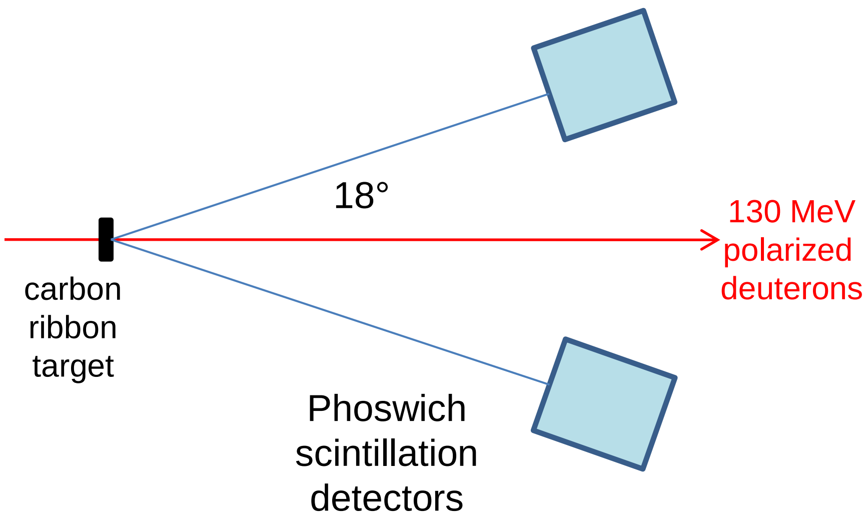
$\times 10^{-4}$

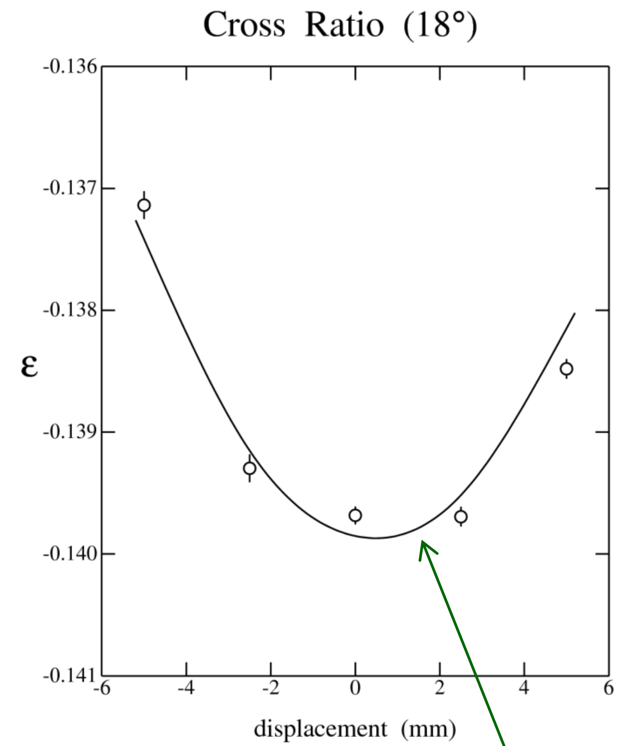
Values well below ~ 1% because of thin target and loss of small angles.

Do enough particles penetrate far enough into the front face to travel most of the way through the target?

This requires a comparison of the efficiency with model values.

Tests made at the KVI (2007)





Best method: “cross ratio”, “square root” method

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

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

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

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

Experimental approach at COSY:

Work in one plane:

Change beam position (Δx) or angle ($\Delta\theta$).

Watch vertical as well as horizontal effects, also tensor.

Change rate during measurement.

Cycle through all “error” points:

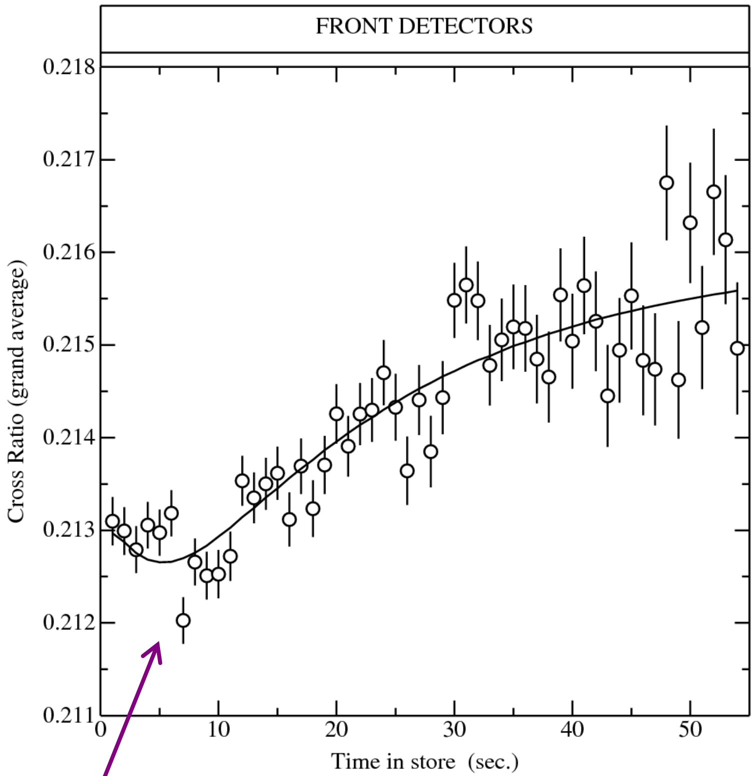
$\Delta x = -2, -1, 0, 1$, and 2 mm

$\Delta\theta = -5.0, -2.5, 0, 2.5, 5.0$ mrad

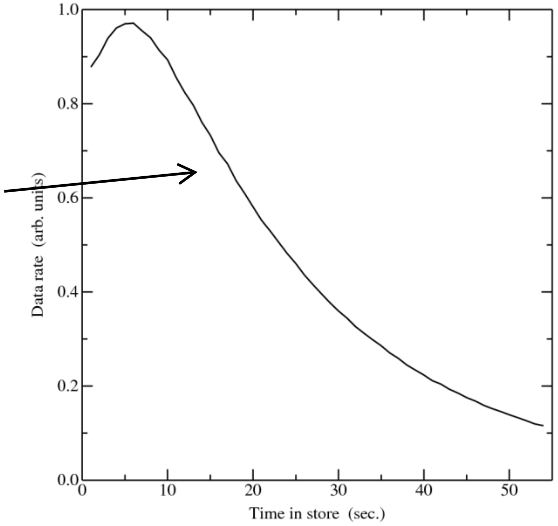
Cycle through 5 polarization states: Unp, V+, V−, T+, T−

Record data as a function of time during the store.

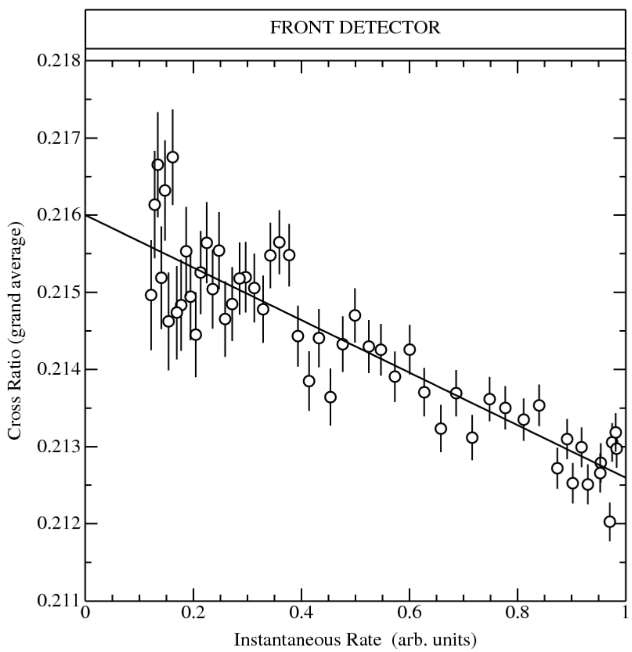
Data from the higher-rate initial running



The curve has the same shape as the count rate distribution shown here.



Linearity of effect against rate led to model curve.



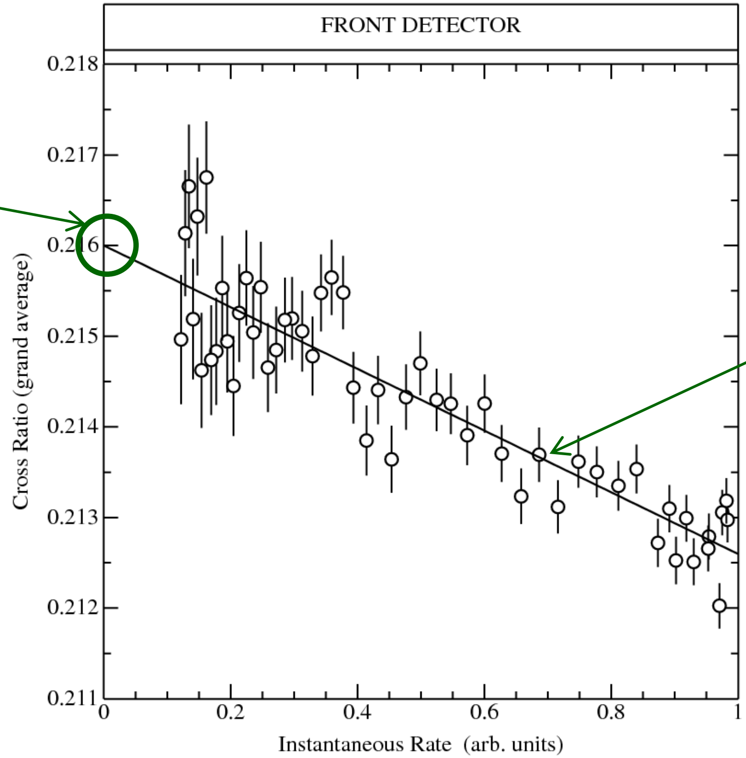
The cross ratio result changes from early to late in the store !

<u>Build a model framework of parametrized effects to investigate issues</u>

Include only what you need…

First, separate rate and geometry effects.

Make a linear fit to the data from the stores. Assume the zero rate point is independent of rate and can be used for the analysis of <u>geometry</u> effects.



Use the slope for the study of <u>rate</u> effects.

Each point is a specific observable that depends on polarization and ΔX or Δθ.

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 $\theta_X - \theta_Y$ 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 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>.

Quality of the fit

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

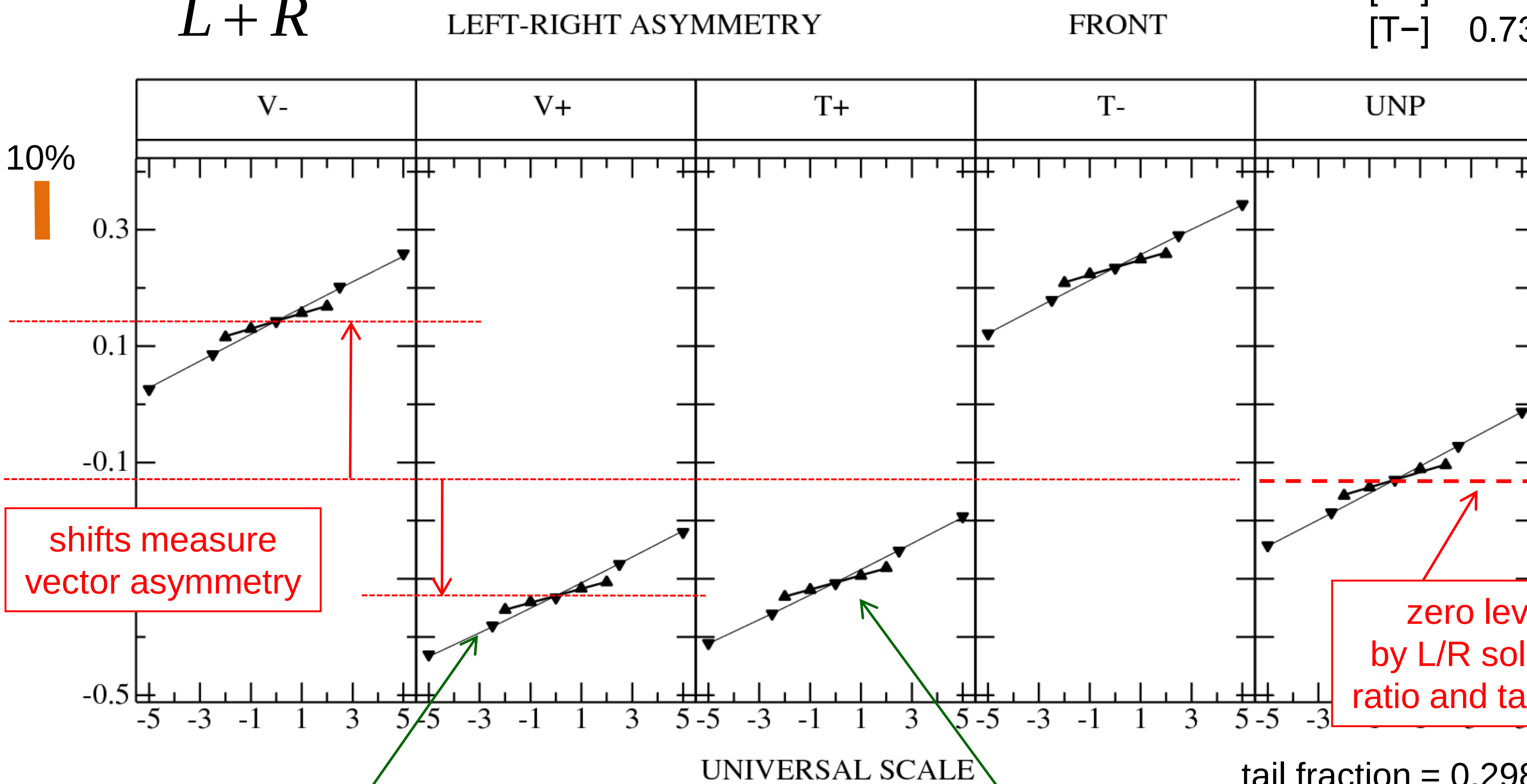
Group 5

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)



shifts measure vector asymmetry

zero level set by L/R solid angle ratio and tail fraction

tail fraction = 0.2985(2) with L/R solid angle ratio = 1

slopes given by

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

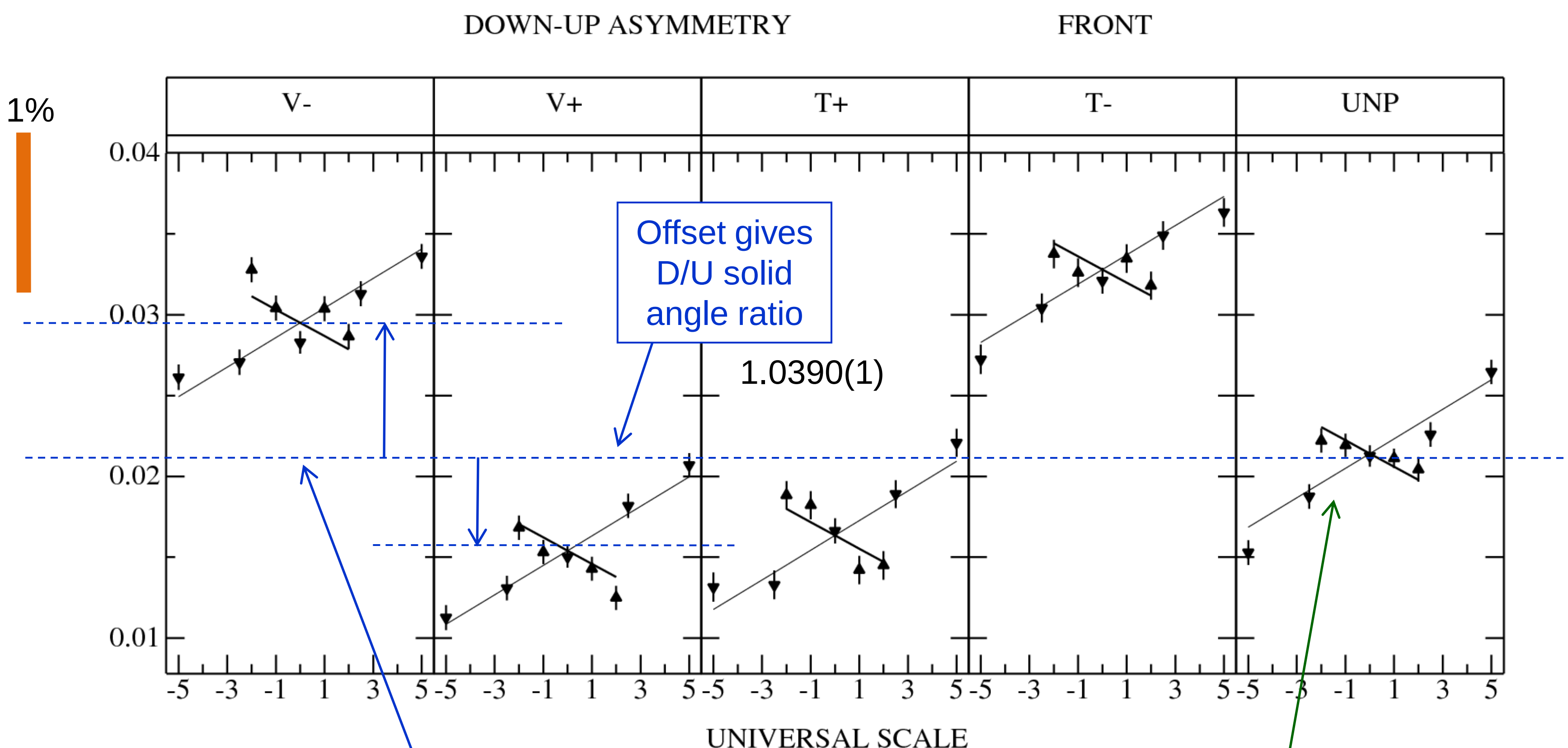
$$\frac{\sigma'}{\sigma} = -0.02562(9) \quad \frac{A'}{A} = 0.0055(3) \quad \frac{1}{rad}$$

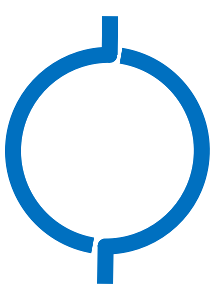
slope difference measures “effective” distance to detector

X/θ = 52.4(8) cm

$$\varepsilon = \frac{D-U}{D+U}$$

Group 5





Broken symmetry of ring detectors creates false rotation in vertical asymmetry and sensitivity to polarization.

rot = 0.0278(5) rad

Beam X – Y and $\theta_X - \theta_Y$ coupling connects to horizontal beam motion

X coupling = −0.031(5)
θ coupling = 0.036(2)

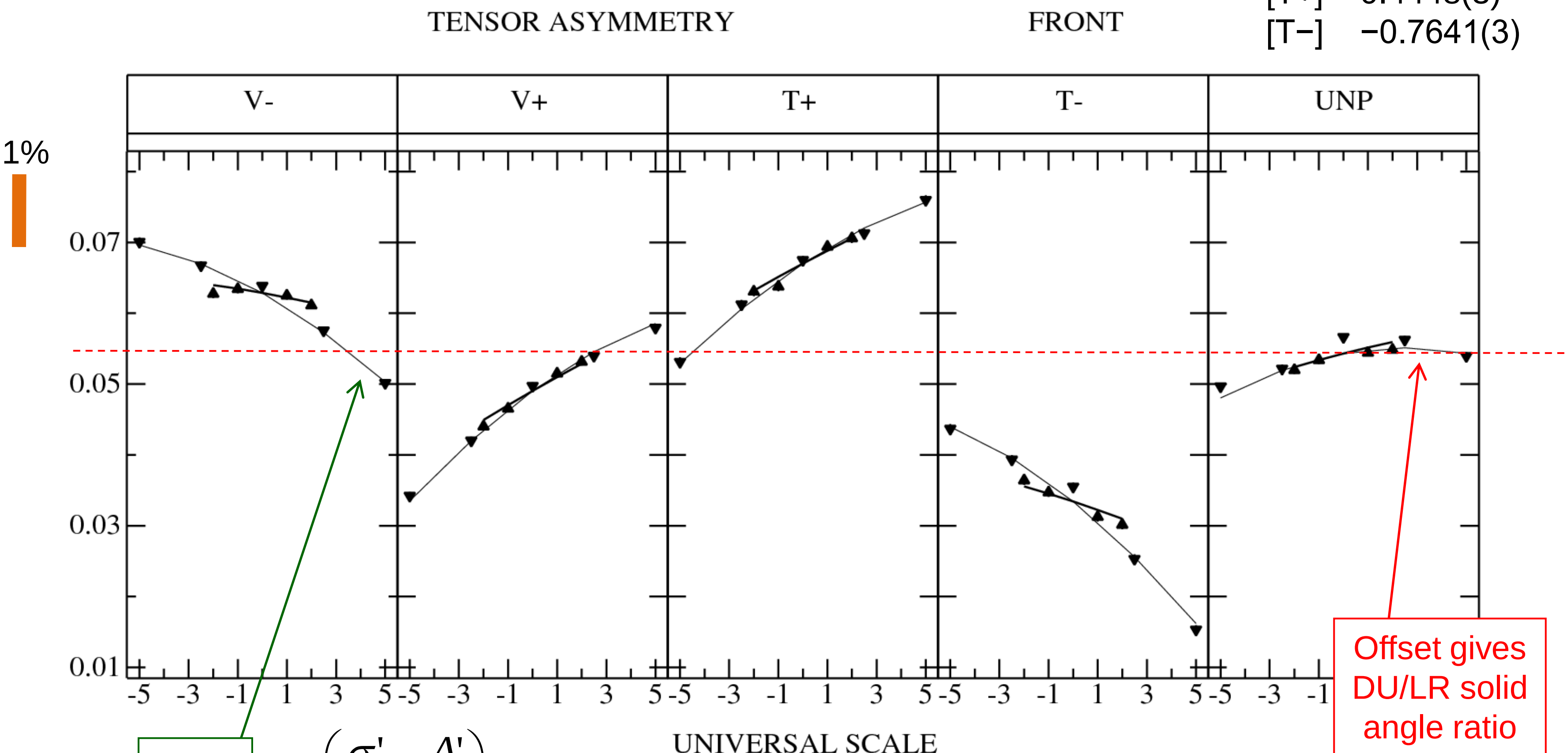
$$\varepsilon = \frac{D+U-L-R}{D+U+L+R} = \frac{\sqrt{6}\,p_T T_{22}}{\sqrt{8}-p_T T_{20}} \cong \frac{1}{2}\,p_T A_T$$

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) $1/\mathrm{rad}^2$

1.3048(2)

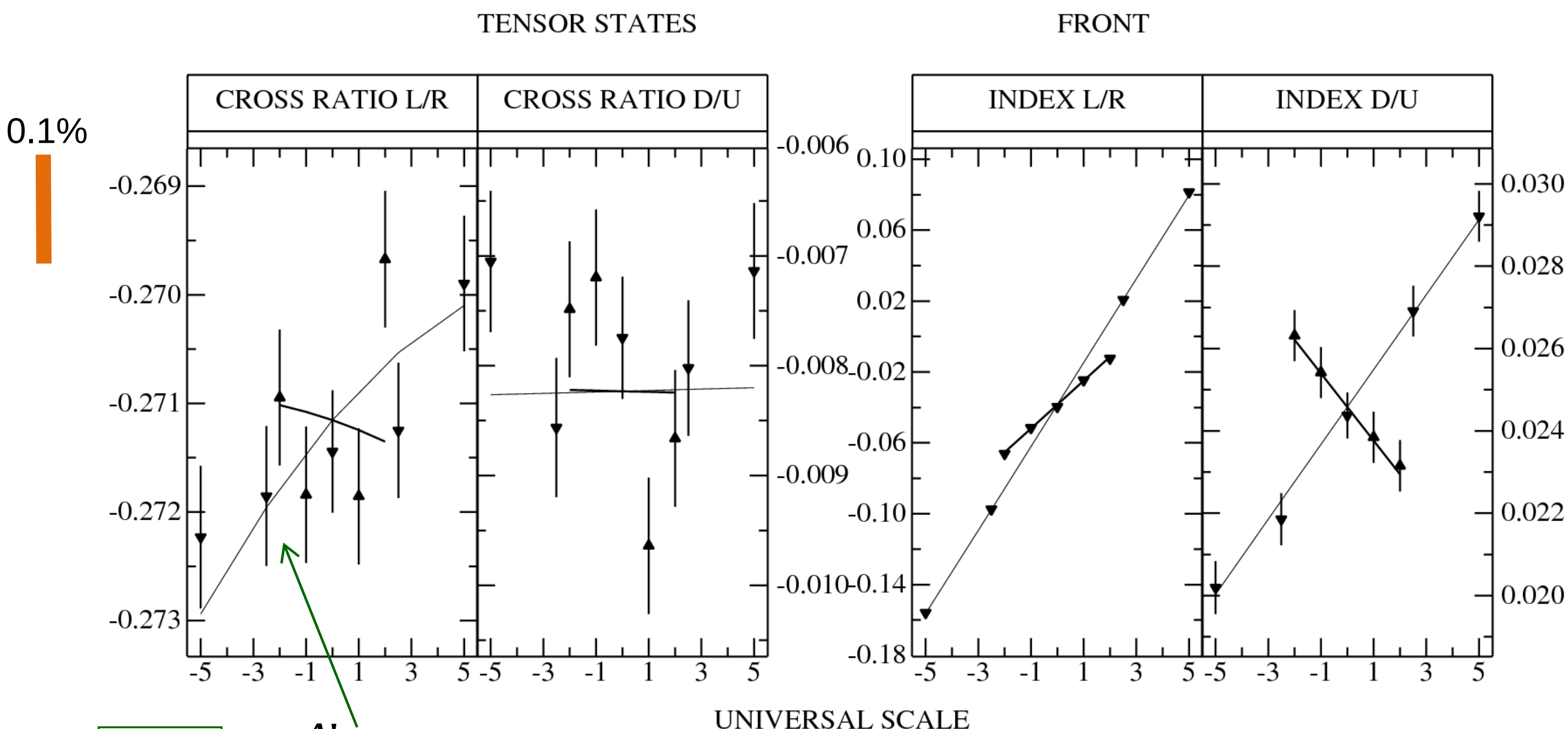
difference from one compensates for tail fraction

$$\varepsilon_{CR} = \frac{\sqrt{L_+R_-} - \sqrt{L_-R_+}}{\sqrt{L_+R_-} + \sqrt{L_-R_+}}$$

removes first order effects

Group 5

$$\phi = \frac{\sqrt{L_+L_-} - \sqrt{R_+R_-}}{\sqrt{L_+L_-} + \sqrt{R_+R_-}}$$



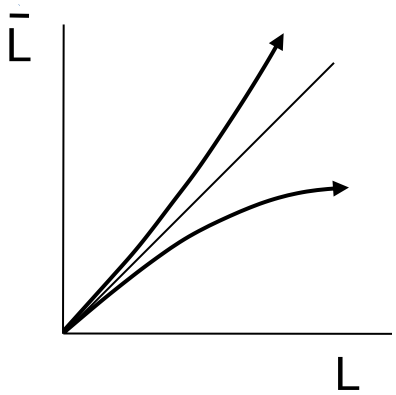
slope gives $\varepsilon_V^2 \frac{A'}{A}(p_+ + p_-)$

curvature gives $\varepsilon_V \left(\frac{A''}{A} - \left(\frac{A'}{A} \right)^2 \varepsilon_V^2 \right)$

A''/A = 0.00007(6) 1/rad^2

slopes depend on earlier first-order terms

Rate Model:



Rate effects require a non-linear response to input rate.

Detector rate $L = C(1 + \varepsilon)$, C = unpolarized rate

Rate effects can be $\bar{L} = L + hL^2 \ldots$

For a simple asymmetry: $\varepsilon_{exp} = \varepsilon\,[1 + hC(1 - \varepsilon^2)\ldots]$

rate dependence

For $h > 0$, there are excess events
(pileup, more events crossing threshold…)

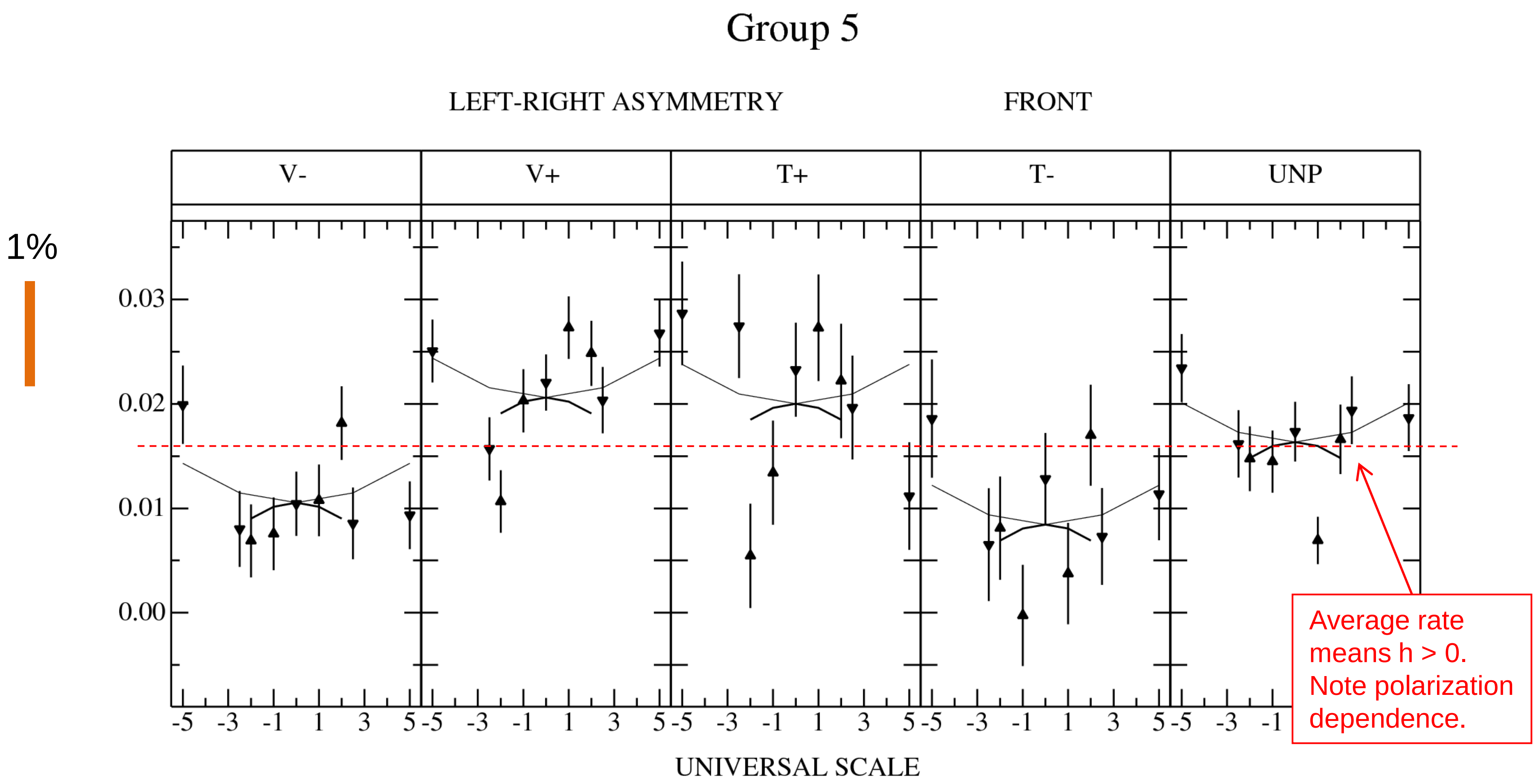
For $h < 0$, there are lost events
(PMT gain sag…)

This represents our case.

Higher order effects introduce polarization dependence.

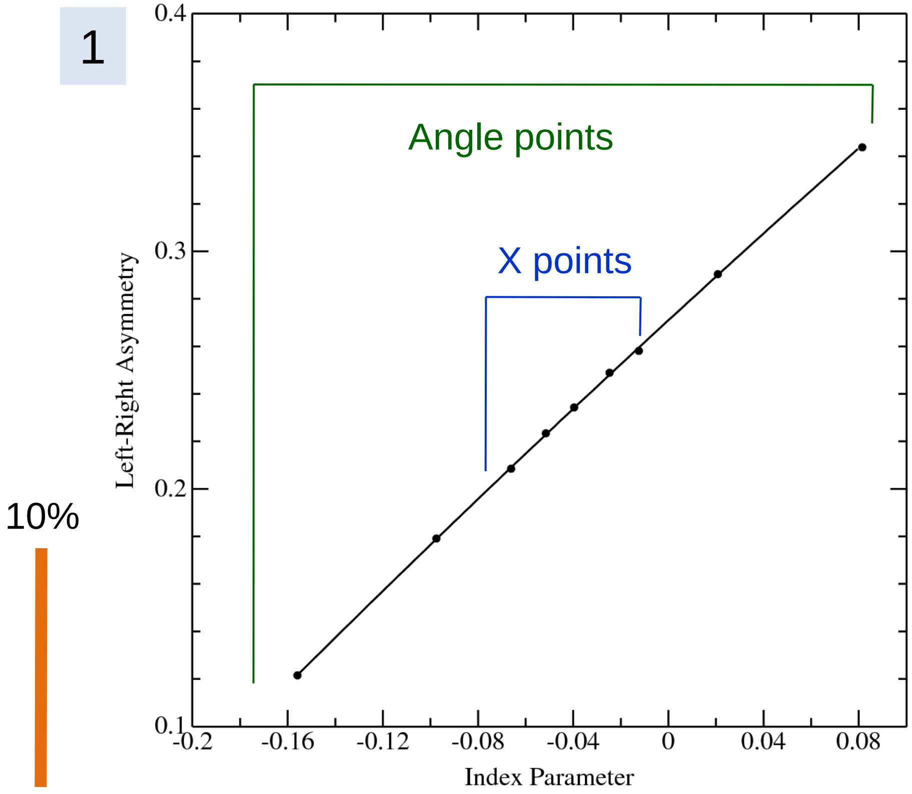
There is some evidence for quadratic X and θ dependence.
Polarization dependence not needed for cross ratio rate dependence.

Rate dependence results



Conclusions

1



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

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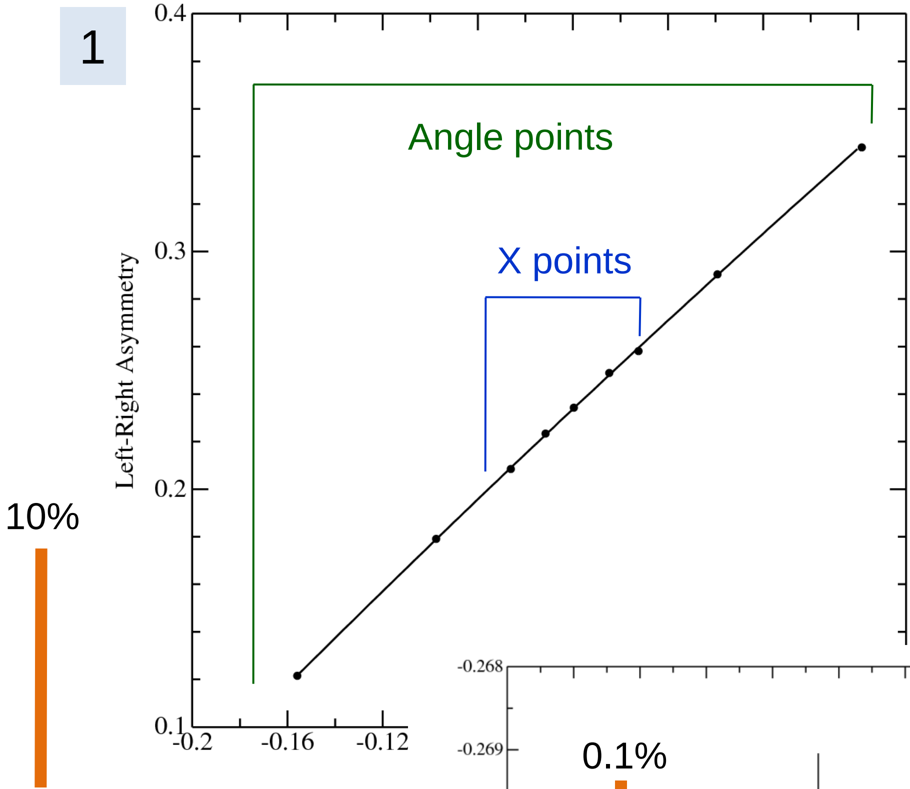

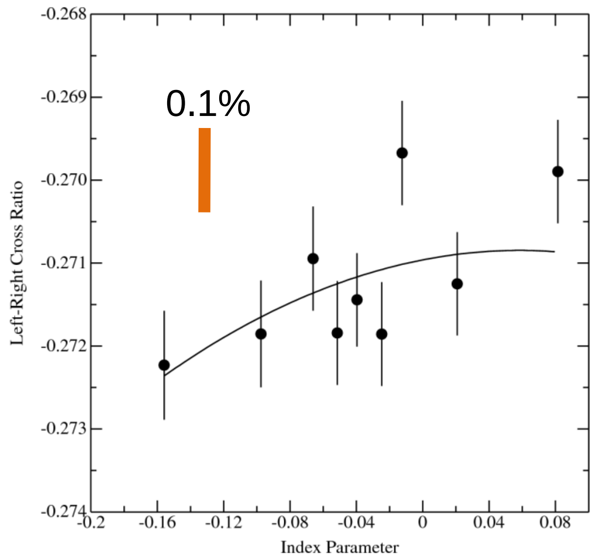

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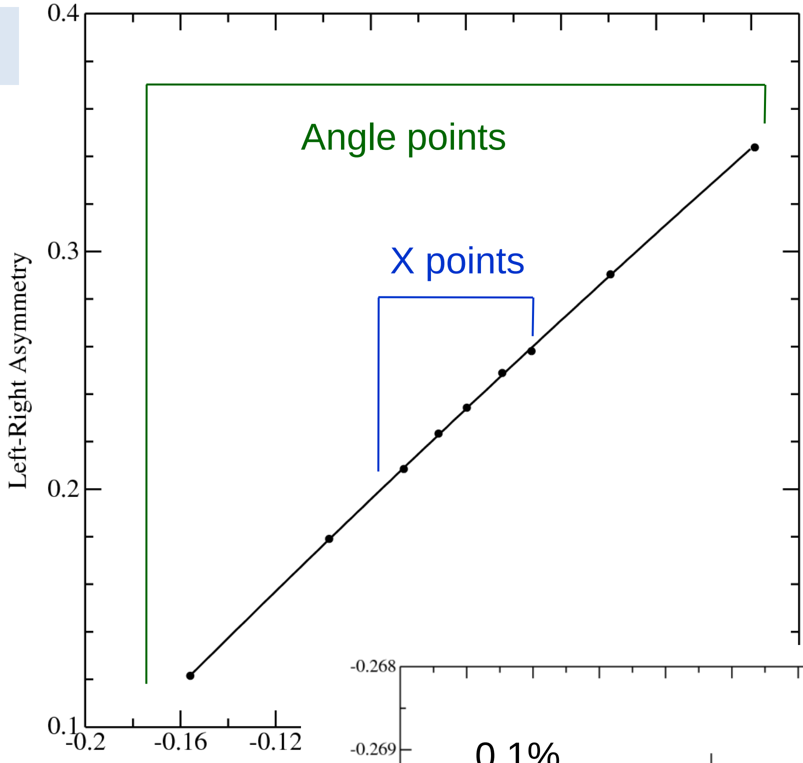
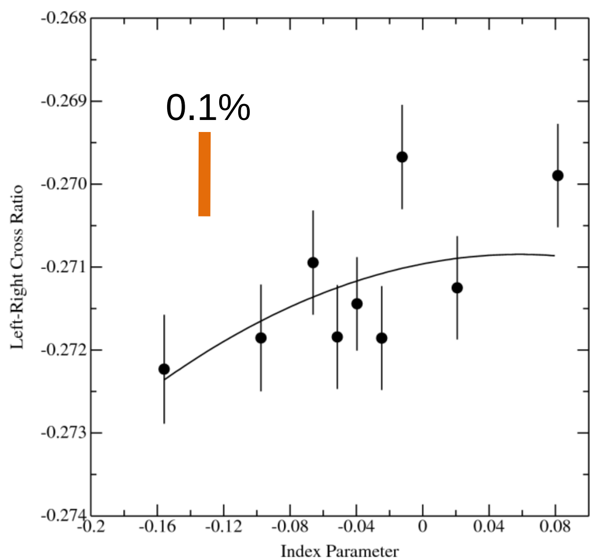


10%



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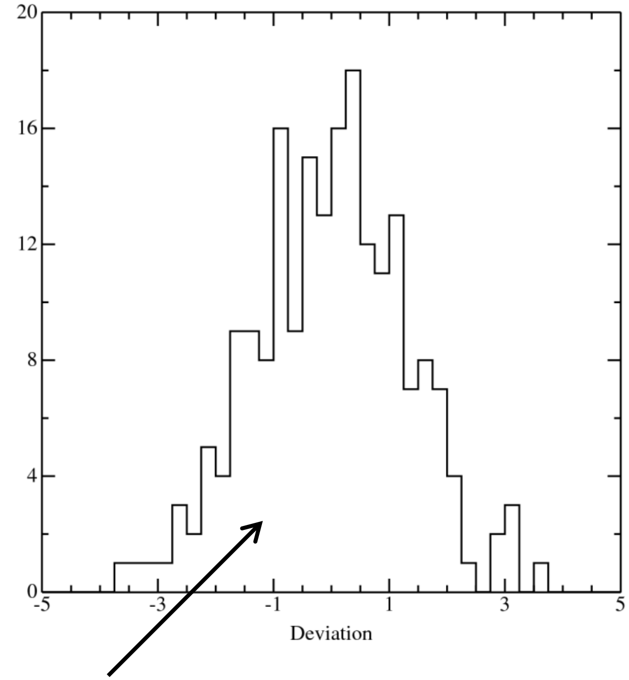
2

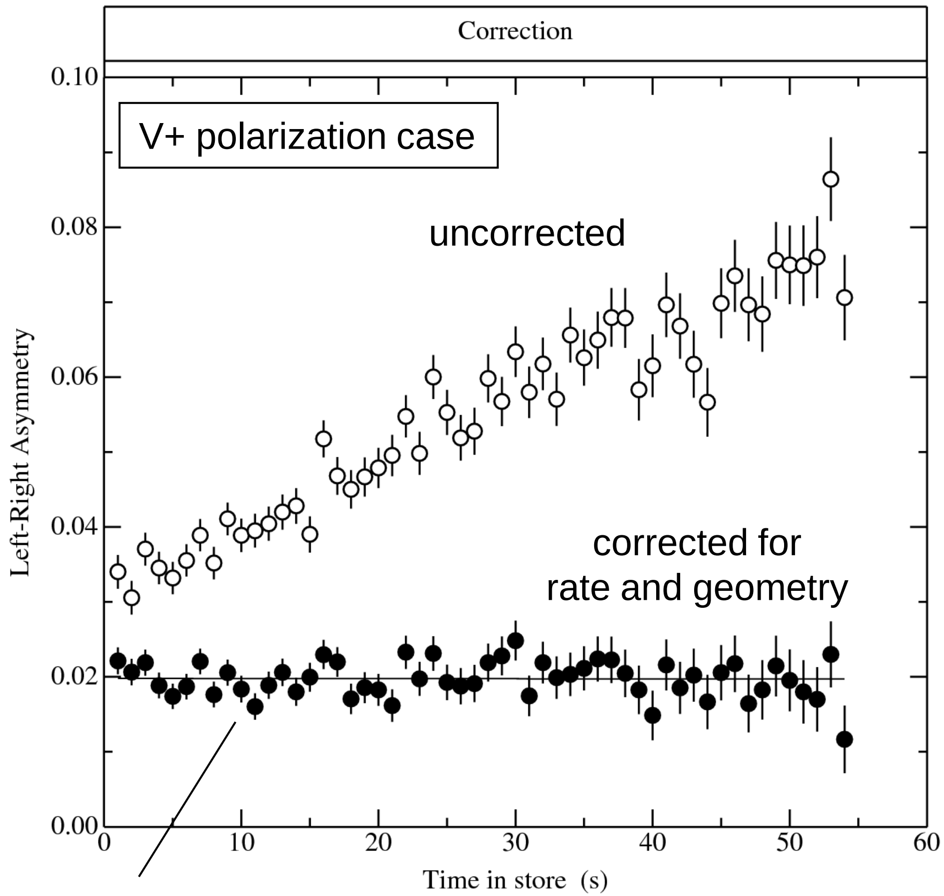
Chi square distribution
for geometry fit



Reduced chi square is 1.7

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

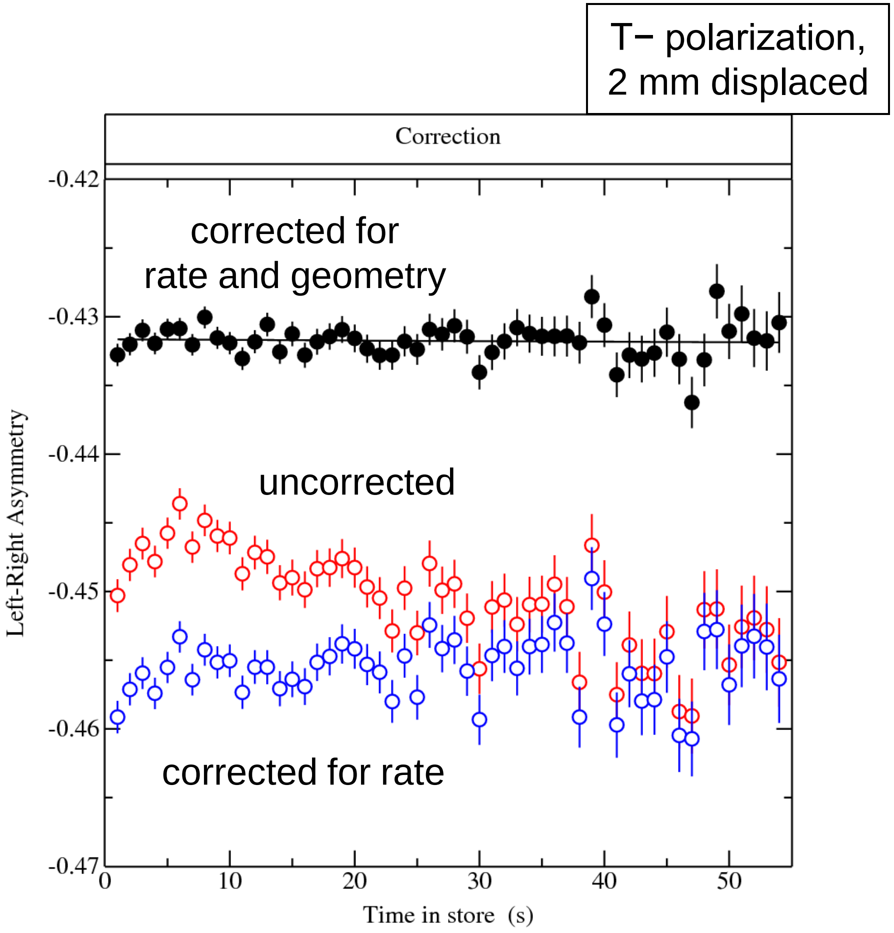
Tests were made with the beam shifting by 4 mm during the store.



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

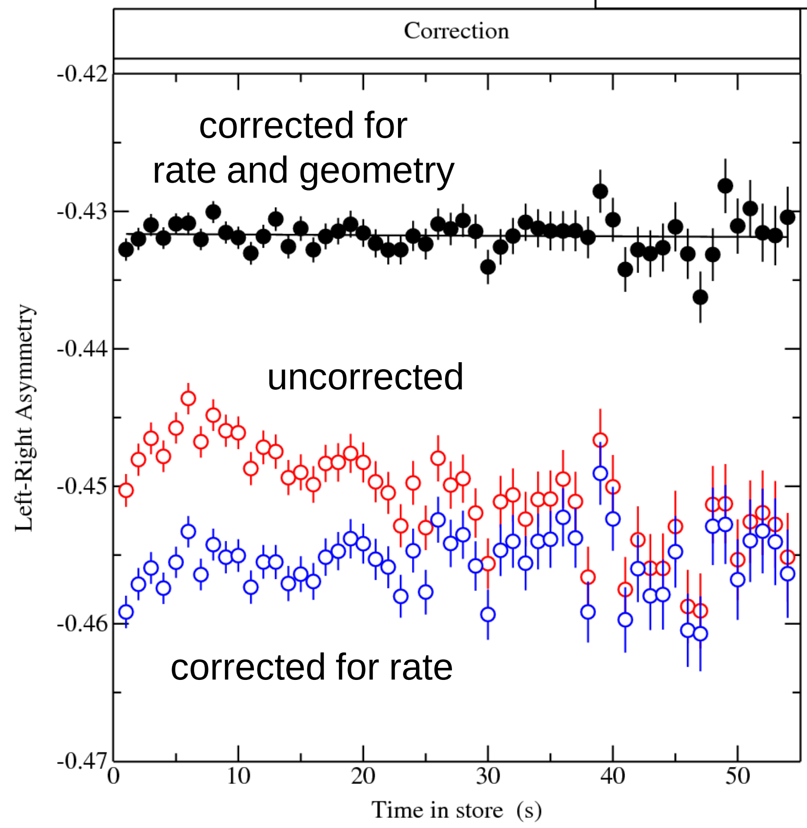
Corrections work.

Tests were made with high rate and displaced beam.



Tests were made with high rate and displaced beam.

T− polarization, 2 mm displaced



Corrections work.

Scaling down:

For deuteron EDM ring:
  position changes < 10 μm
  initial vertical $\varepsilon < 0.01$
gives control of systematics to < 30 ppb, well under requirement.

cross ratio:
$A'/A = 0.0055$
$\varepsilon = 0.01$
$\Delta p = 0.05$
use $(A'/A)\varepsilon^2\Delta p$

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

Polarimeter
Summary

It is possible to design a (deuteron) polarimeter with the efficiency and analyzing powers needed for the EDM ring.

Thick target extraction keeps the efficiency high.

Systematic errors may be corrected (in real time) using information contained within the left-right data set (assuming up and down polarization).

A prior calibration of the sensitivity of the polarimeter to error terms involving geometry and rate changes is required.

For the EDM search, a measurement of a small rotation should be possible with a systematic error after correction of less than one part per million.

Polarimeter Developments (What's next?)

1 Database for d+C and p+C

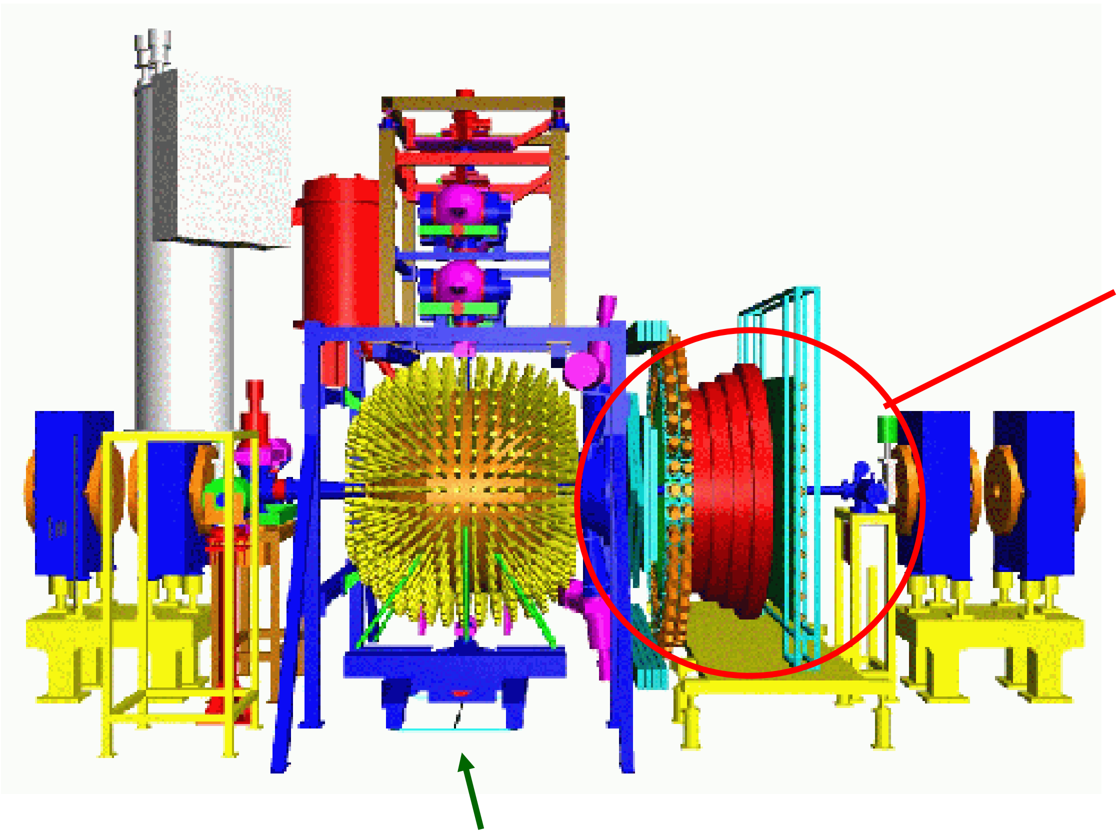
2 Detector choice

3 Polarimeter Monte Carlo

4 Design, construction, calibration

5 Alternative: polarized target

Gather data for polarimeter design



WASA detector will
need new holder
for solid fiber targets.

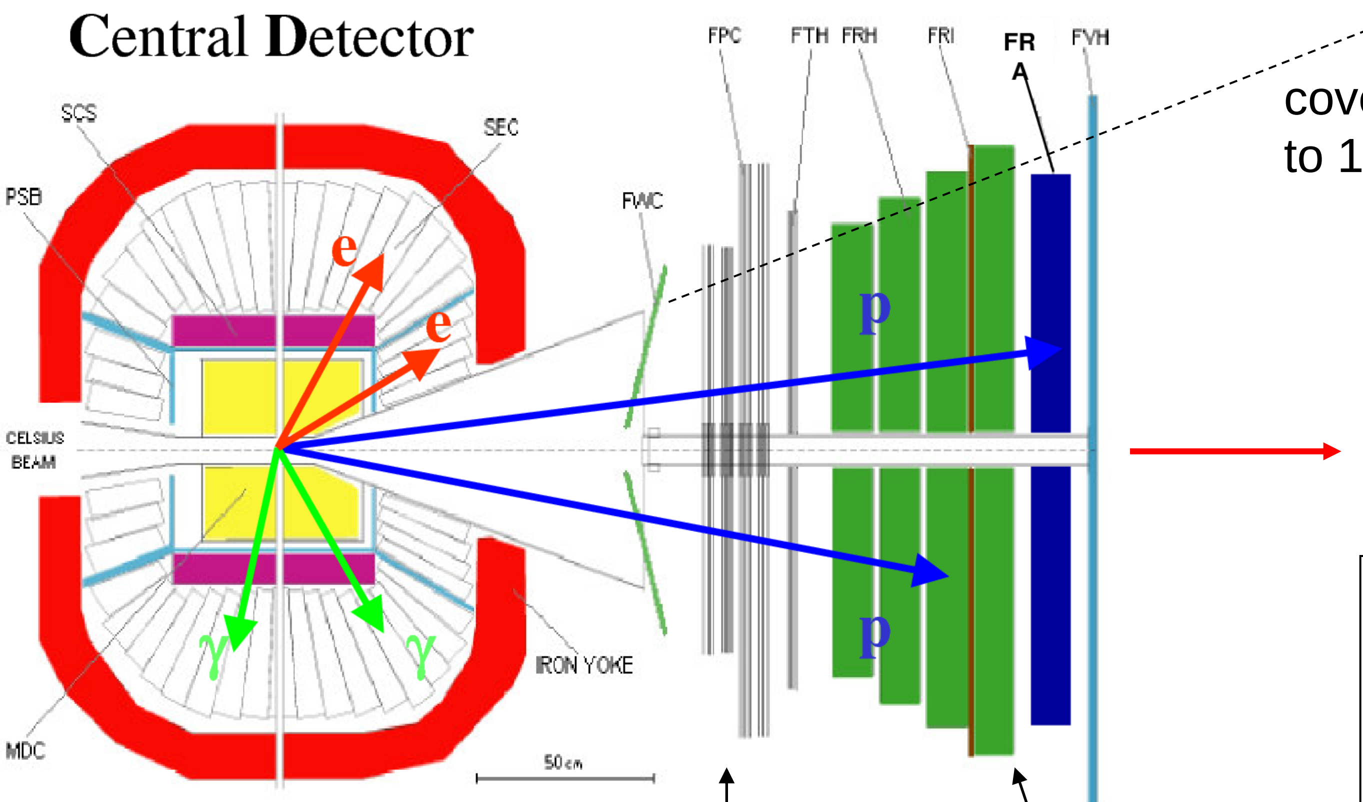
Measure cross section
and analyzing power
angular distributions for
deuteron-induced reactions
near 1.0 GeV/c
using the WASA forward
tracking detector.

The EDM polarimeter must
separate elastic scattering
and low Q-value reactions
(useful for polarization
measurement) from breakup
protons (no spin dependence).
Data will go into polarimeter
Monte Carlo simulation.

The COSY project

d+C data

The best option with an existing detector appears to be WASA.



coverage to 17°

Full azimuth

beam

Particle identification with energy loss

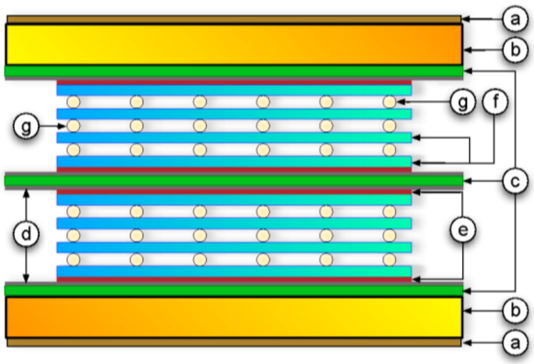
wire chambers for tracking

scintillator arrays that (mostly) stop deuterons

Detector systems: alternatives to scintillators

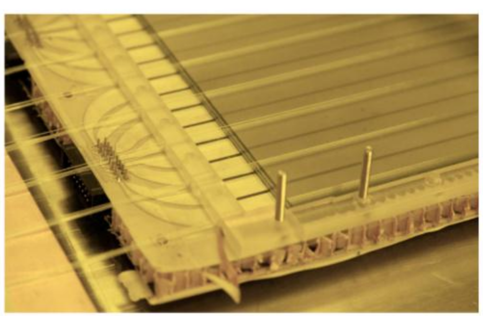
A

Multi-resistive plate chambers(Italy)



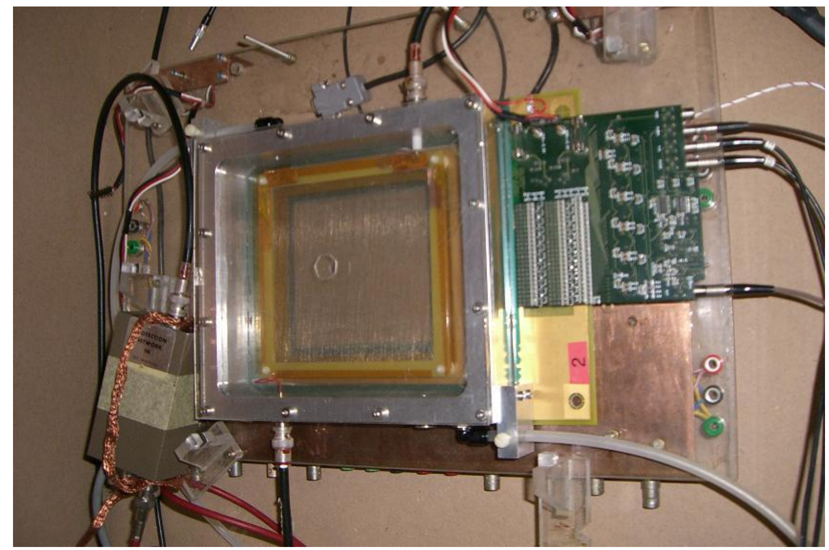
pickup electrodes (green)
also shown in photograph

The 20cm x 50cm prototype



B

Micro-megas avalanche detection system Greece)



C

Gas electron multiplier (GEM) system

In-beam tests are needed (COSY) to provide sample data sets.

NEW PROJECT

Polarization Lifetime (Spin Coherence)

A useful EDM signal needs long accumulation times (~15 minutes).
The polarization must stay longitudinal (w/ feedback) and large (unstable).

Various mechanisms spread momentum, gamma, spin tune.
First-order Δp/p remover (on average) by beam bunching.
Second-order terms: $(\Delta p/p)^2$, θ_X^2, θ_Y^2

Goal: Show that second-order may be canceled by sextupole fields.
(COSY has 18 sextupole magnets.)

RUN PLAN

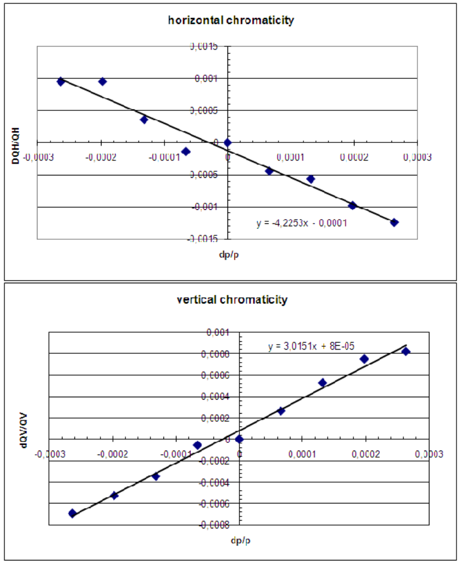
A Benchmark ring properties for detailed spin tracking studies.
Use RF solenoid at depolarizing resonance to start characterization.

B Measure horizontal polarization directly; measure second-order terms.

C Using spin-tracking strategy, lengthen polarization lifetime using sextupoles.

Preliminary Results from January, 2011, Run

Chromaticity

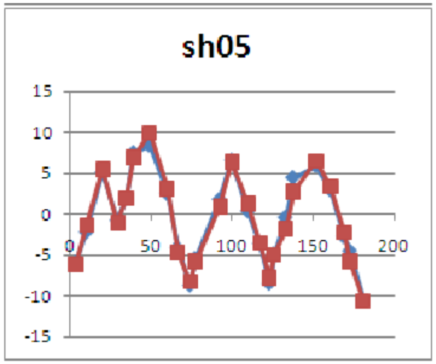


ΔQ/Q

Δp/p

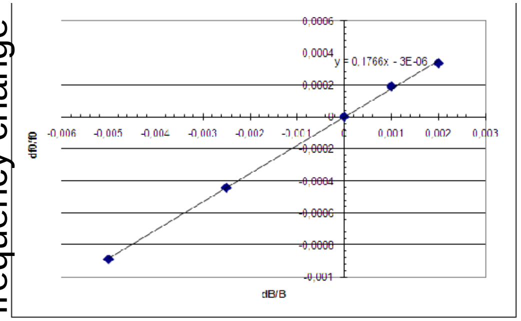
Response (blue) to steerer change, matrix reproduction in red.

beam motion (mm)



ring position (m)

cyclotron frequency change

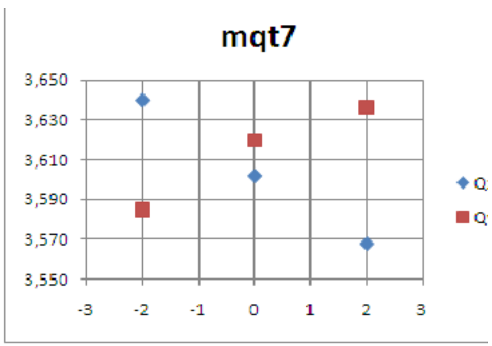


magnetic field change

Frequency slip factor

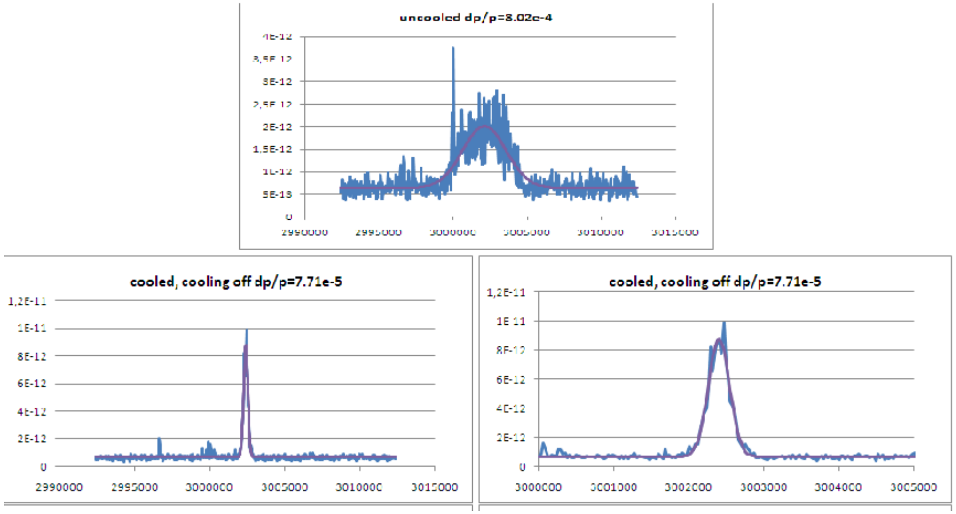
Tune change for quadrupole adjustment

tune



percentage change

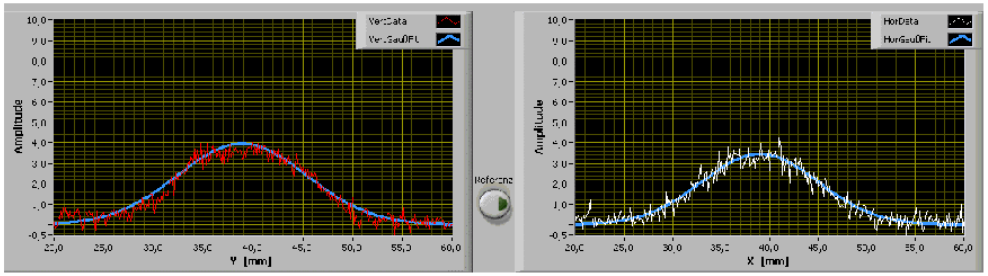
Schottky measurements of momentum spread



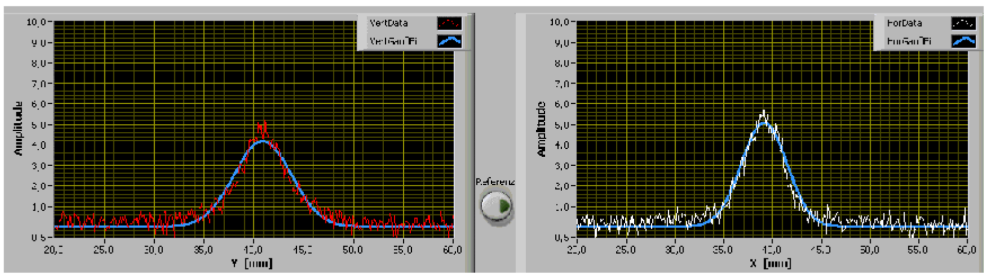
frequency (4th harmonic) (Hz)

Emittance measurements

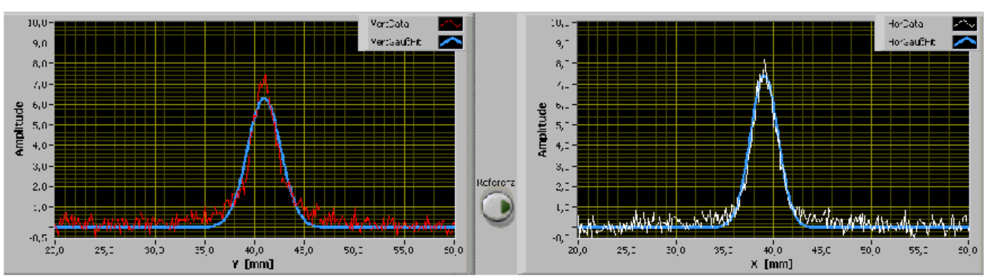
fixed time



Vertical (left) and horizontal (right) beam profiles for the uncooled beam and Gaussian fits.



Vertical (left) and horizontal (right) beam profiles for 30 sec cooling and 30 sec cooling off and Gaussian fits.

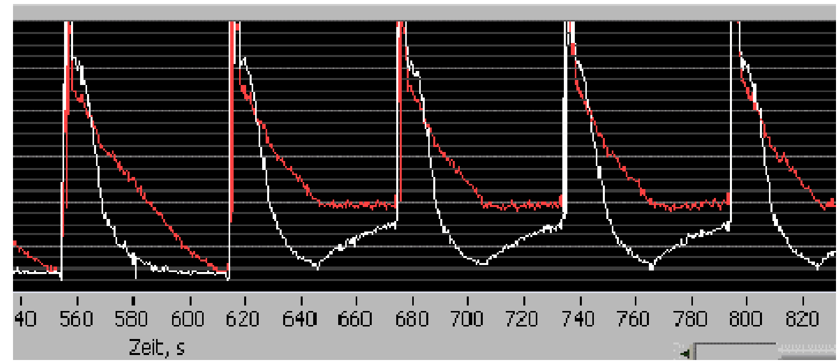


Vertical (left) and horizontal (right) beam profiles for 60 sec cooling.

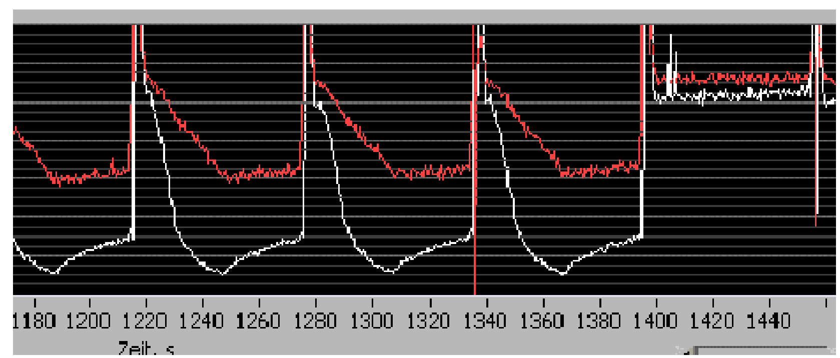
during cycle

cooling on

cooling on (30 s), then off

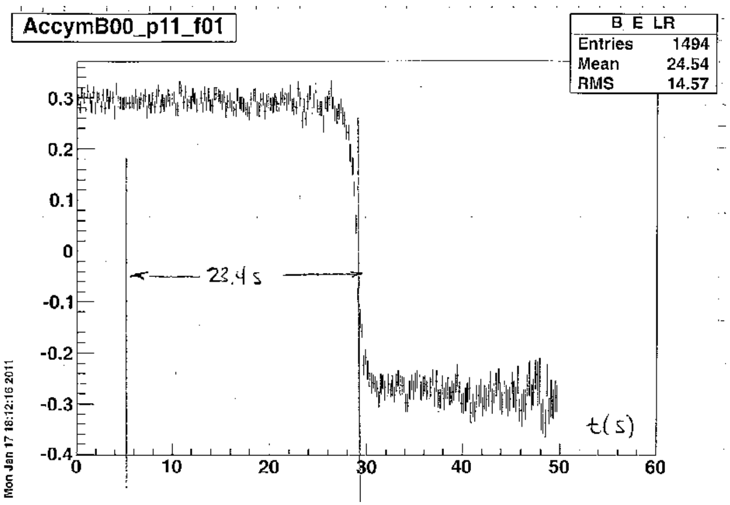


no cooling



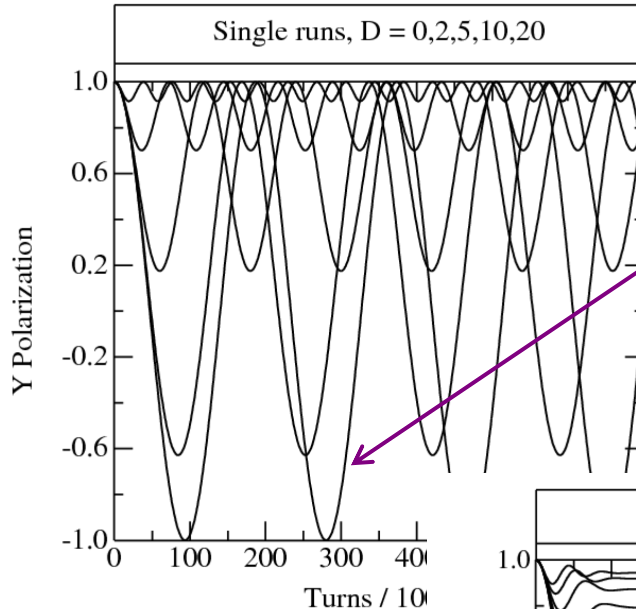
Data from RF solenoid

Compared to previous experiments, we now have continuous polarimetry !

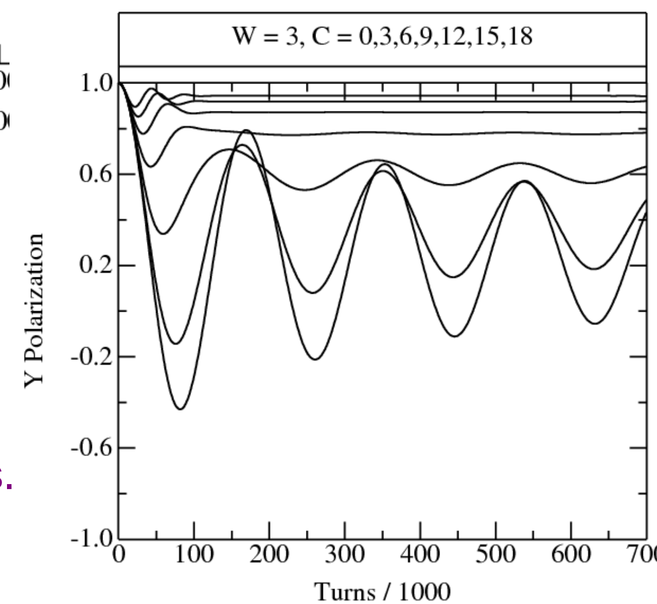


Froissart-Stora scan

What to expect for tune spread and fixed frequency measurements…



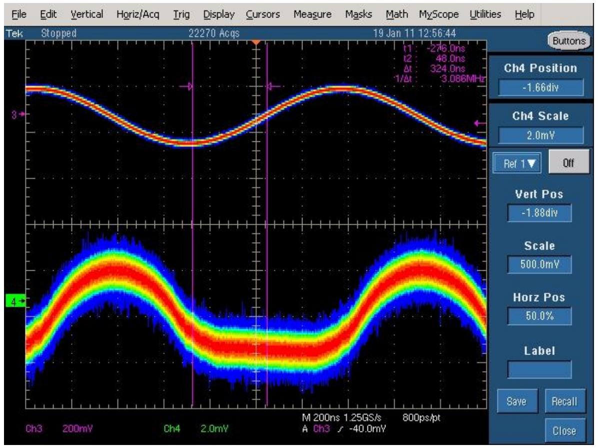
All curves are off resonance, except this one.

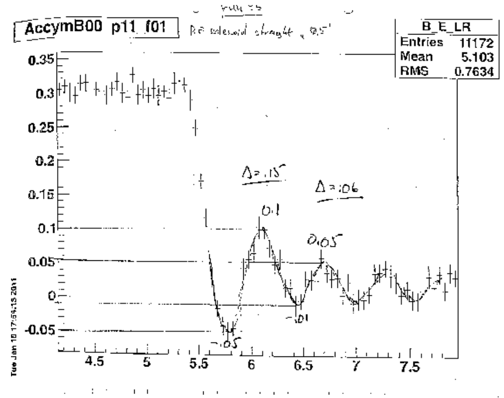


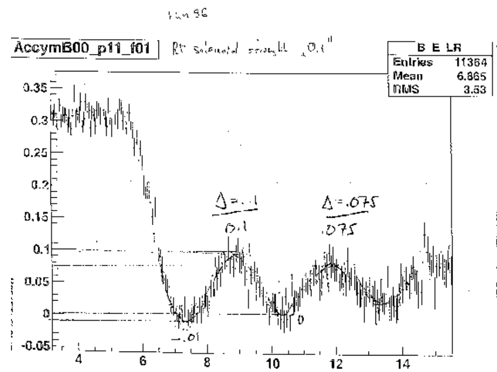
In a beam with a finite tune spread, you get positive, damped oscillations.

What we got was different…

For electron cooling OFF

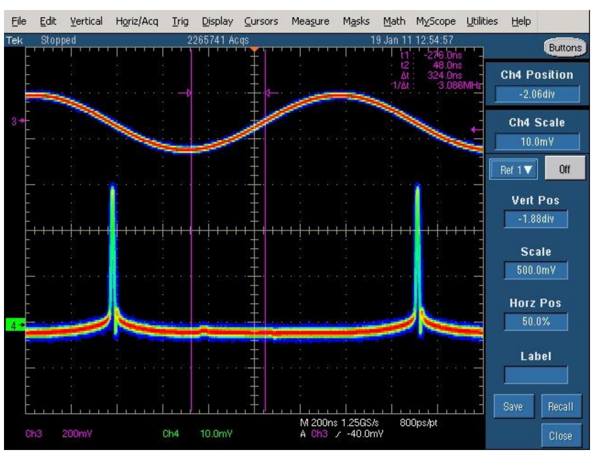




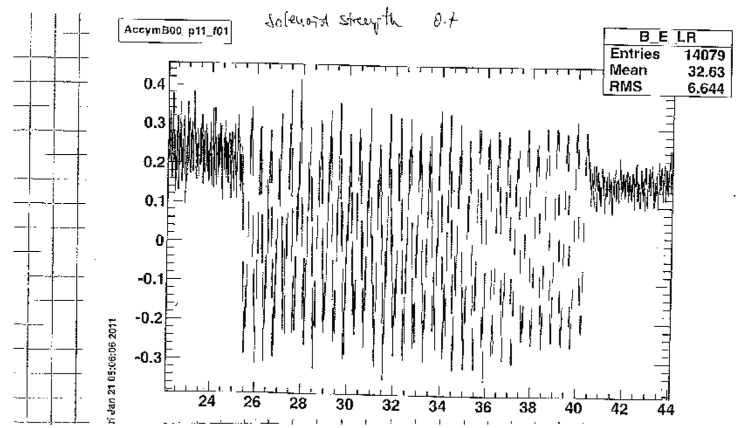


quick drop in oscillation amplitude, then slow decline with oscillation center close to zero

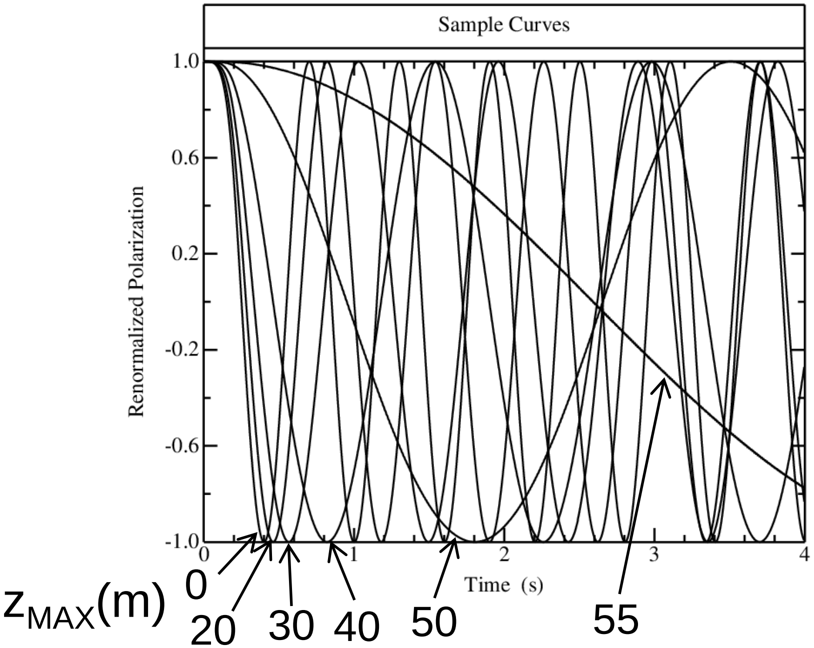
ON

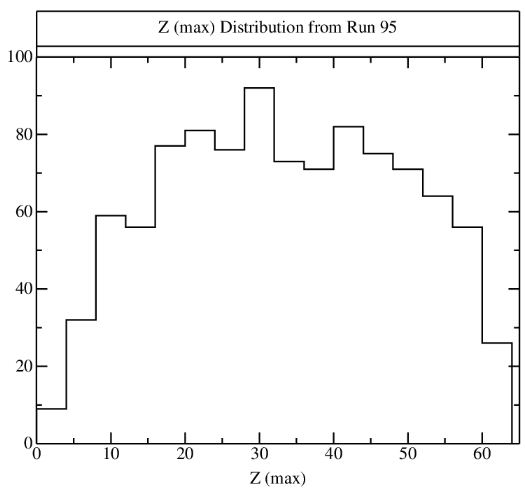


long-lived oscillation pattern, later seen with small decline (1/e time = 520 s)

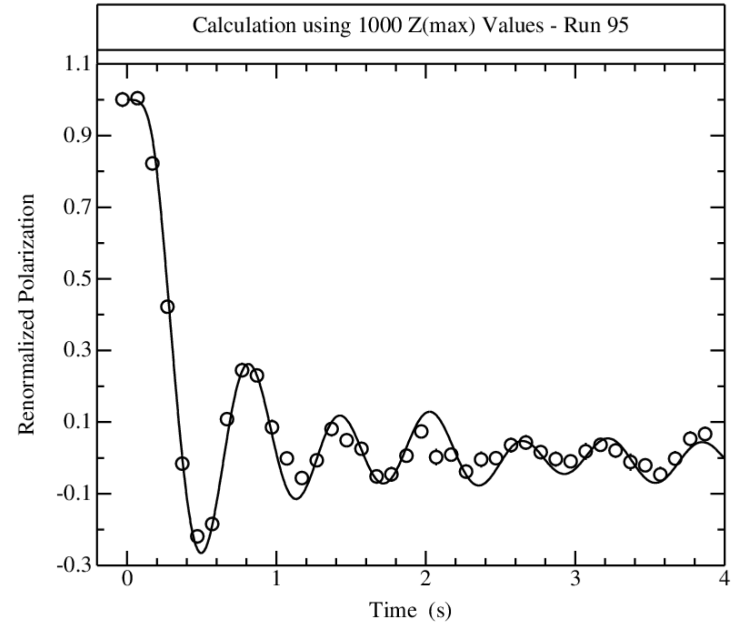


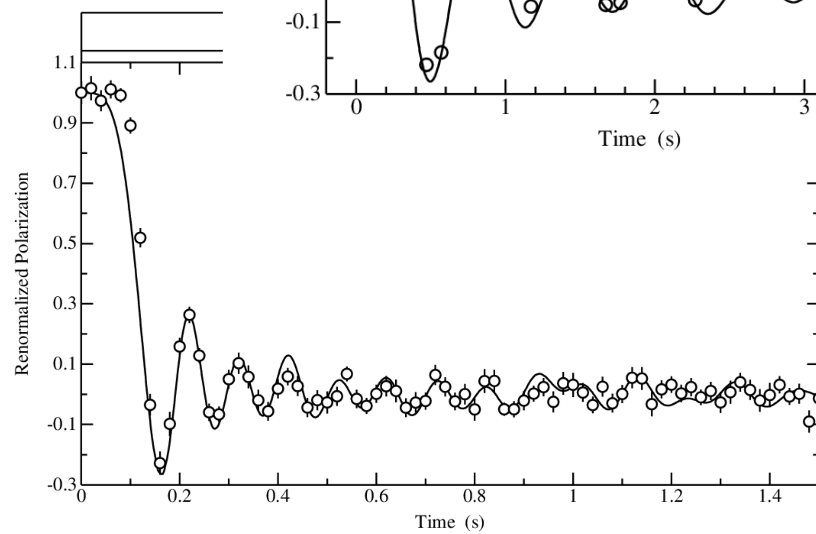
If instead you model synchrotron oscillations…
you get this set of curves:





Starting with this distribution



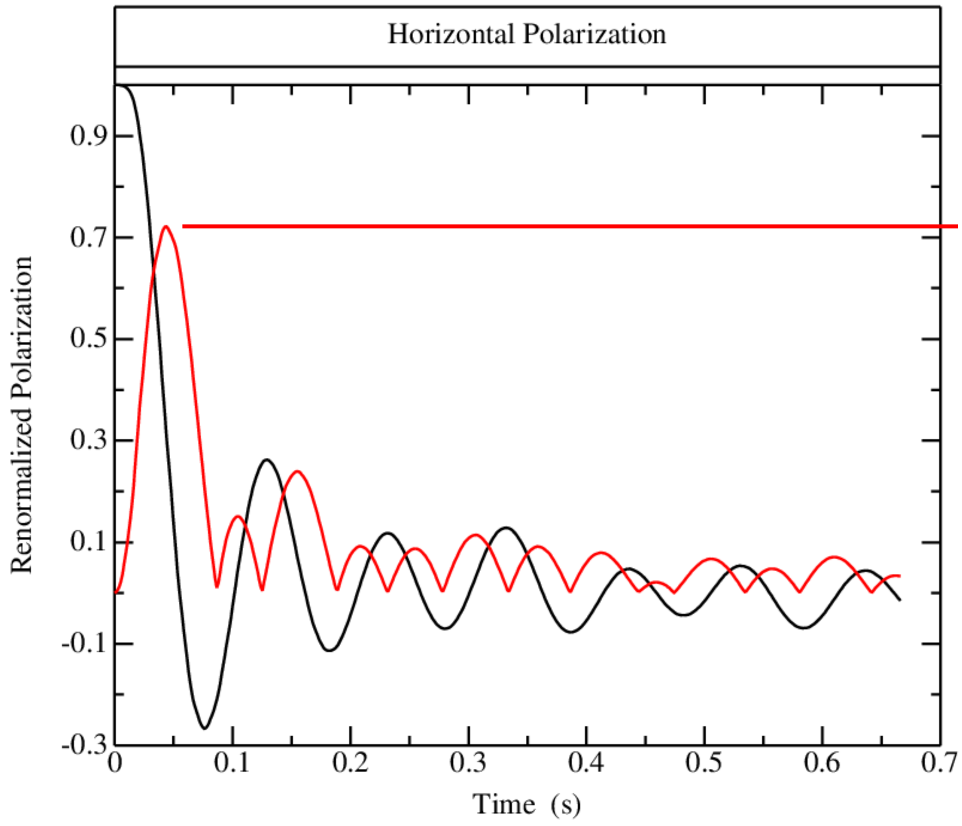


The main effect comes when particles away from the bunch center pass the RF solenoid out of phase, making it less effective on average.

No clear second-order effects seen so far in data.

Next beam time request due shortly.

transverse polarization magnitude



Large horizontal polarization possible based on synchrotron oscillation model. It is possible to turn off RF solenoid at this peak time.