# Part 6

## Spin Coherence Time

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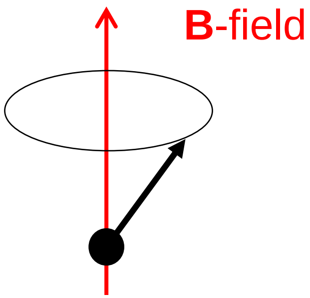
There is a requirement that the initial polarization remain parallel to the particle velocity for times up to 1000 s. This is an unstable situation, so some action is required.

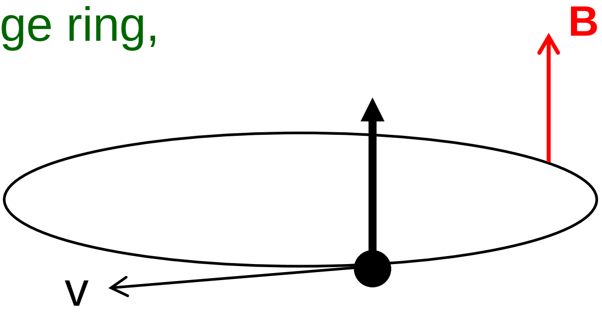
In general:



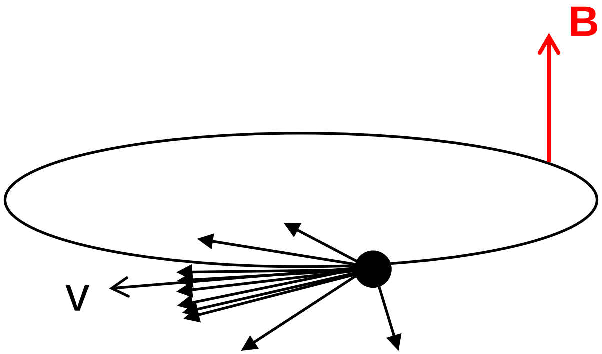
spin precesses
around **B**-field

NOTE: To preserve the
EDM signal, the experiment
will move the polarization
into a stable condition.

In a storage ring,



polarization parallel to the ring field remains.



Because of small variations in the
precession rate, spin directions in
the ring plane will spread out.

# Decoherence, where does it arise?

The simplest explanation rests on small momentum changes from one particle to another.

Typically $\dfrac{\Delta p}{p} = 10^{-3} - 10^{-4}$

Changes in momentum make changes in γ.

$$\theta_{PREC} = (\mu - 1)\gamma\theta_{BEAM}$$

anomalous moment

Define spin tune: $(\mu - 1)\gamma = G\gamma = \nu_S$

If $\Delta p / p = 10^{-4}$

$$\Delta\nu_S / \nu_S = \Delta\gamma / \gamma = \beta^2\,\Delta p / p = 2.1 \times 10^{-5}$$

As an example, use (COSY) deuterons with $p$ = 0.97 GeV/c

From $f_{CYC}$ = 750602.5 Hz
$f_{RES}$ = 871434.5 Hz
$G$ = –0.1429875
$\gamma$ = 1.125832
$\beta$ = 0.459396
$T$ = 236.01292 MeV
*Circum.* = 183.484 m

“Depolarization” lifetime comes when a typical spin vector is 1 rad off the velocity.

$$\tau_{POL} = \frac{1}{2\pi G\gamma\, f_{CYC}\,\Delta\nu_S / \nu_S} = 63\, ms$$

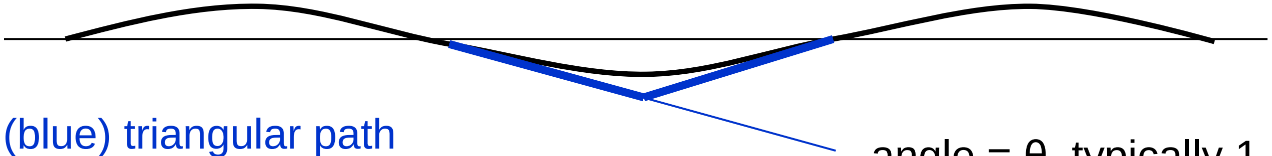
This is much less than 1000 s, we have to do something !

## TRICK NUMBER 1 Bunch the beam.

This forces all particles to travel together. Small momentum differences disappear on average.

Particles will oscillate from the front to the back of the bunch, making ± Δ*p*/*p*.

The next difficulty is betatron (position) oscillations:
Bunching forces a longer path in the same time, so speed goes up.
What is the change?



angle = θ, typically 1 mrad

The (blue) triangular path is longer by

$$\frac{\Delta L}{L} = \sqrt{1+\theta_X^2+\theta_Y^2} - 1$$

$$\cong \frac{1}{2}\left(\theta_X^2+\theta_Y^2\right)$$

The curved path is half of that.

$$\boxed{\frac{\Delta L}{L} = \frac{1}{4}\left(\theta_X^2+\theta_Y^2\right)}$$

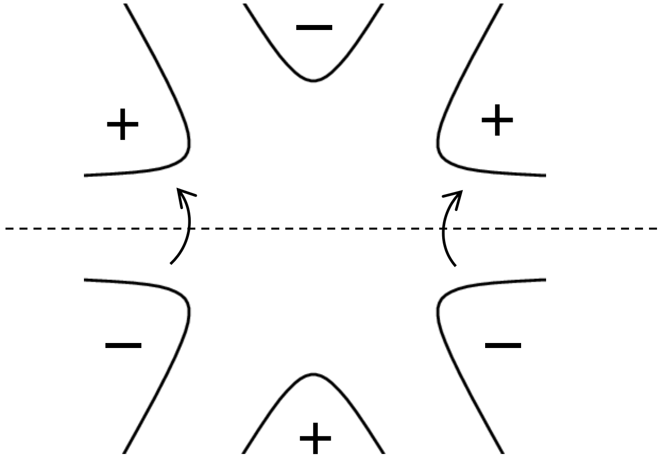
$$\frac{\Delta \nu_S}{\nu_S} = \gamma^2\beta^2\frac{\Delta v}{v} = \gamma^2\beta^2\; 0.5\times 10^{-6}$$

$$\tau_{POL} = 9.9\; s$$

Not good enough !

# TRICK NUMBER 2 Can higher order fields help?

A sextupole has the right symmetry.

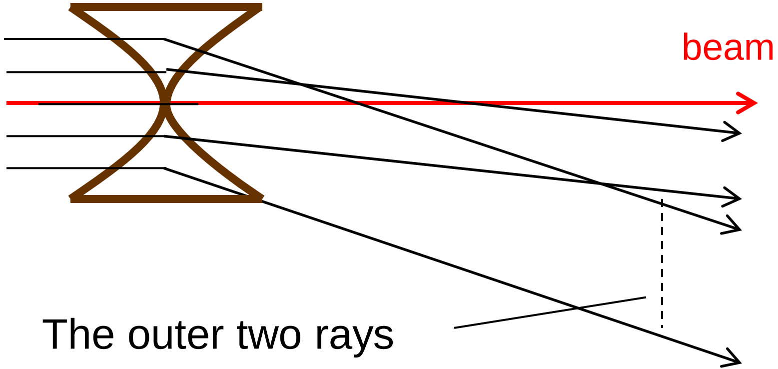


And the field varies quadratically with X.

This means that the field will rise as the path length, since X follows θ.

This needs to be tested at COSY.
But first…

In a simple model, imagine that the sextupole is like a dipole with expanding pole faces. Then follow rays:



The outer two rays bend 4 times more than the inner two rays.

If such bending can be arranged to shorten the path length (such as in an arc of the ring), then compensation for path lengthening is possible.

# We need two more things before a test at COSY:

1 There is no “frozen spin”. In fact, the polarization in the horizontal plane rotates at 120832 Hz.

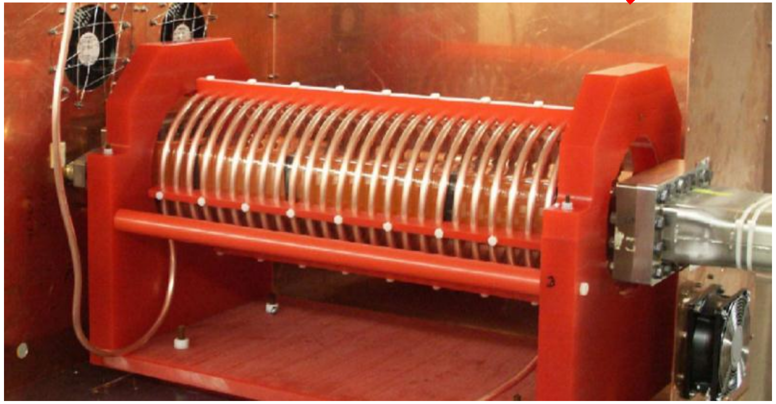
If you know this frequency well enough, then you know which way the polarization points at any time. Can polarimeter events be sorted by “direction” and a polarization calculated? We could only see the oscillation of the sideways component.

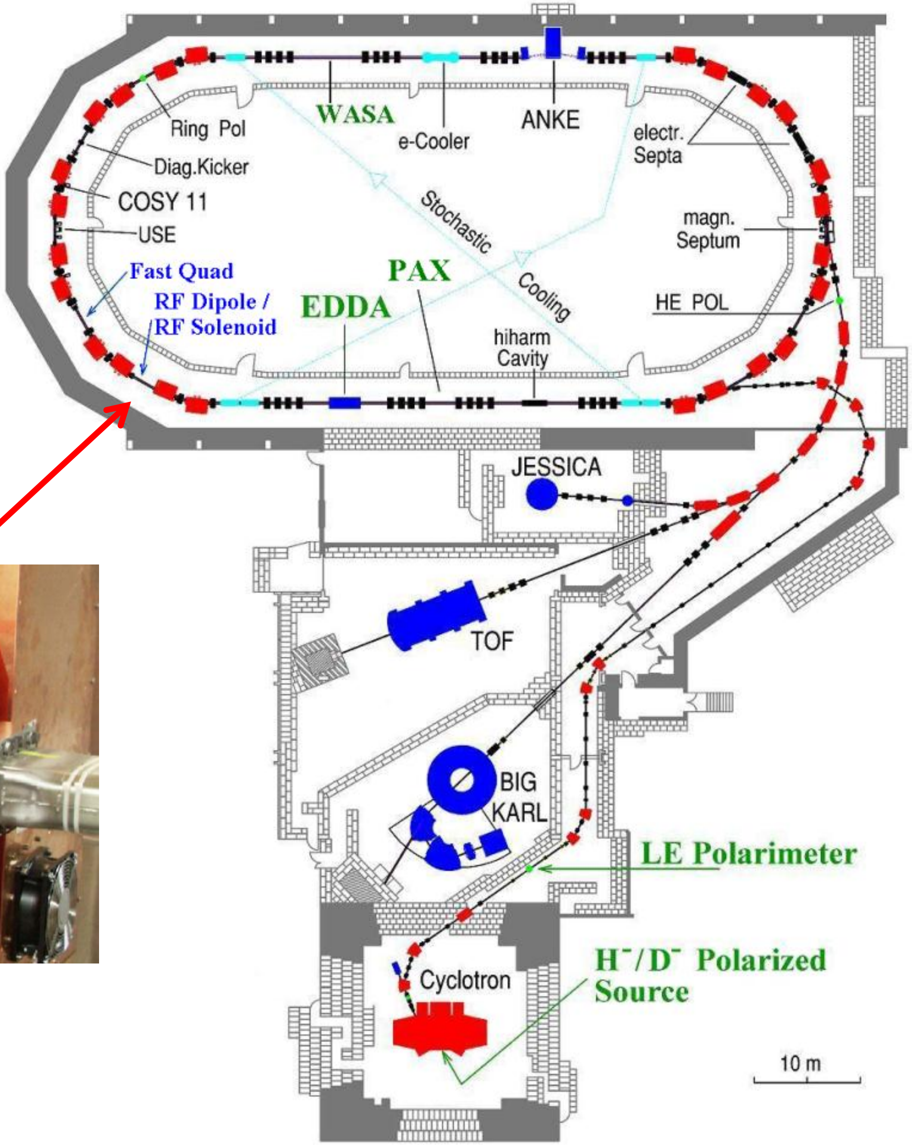
2 You have to inject and ramp the beam with the polarization up, or else it depolarized from ring-plane rotations. There needs to be a way to get it into the horizontal plane.

The missing piece of equipment is an RF-solenoid. It provides regular kicks, if the solenoid polarity changes at the same rate that the polarization rotates (or a harmonic of it).

So let’s explore these two systems…

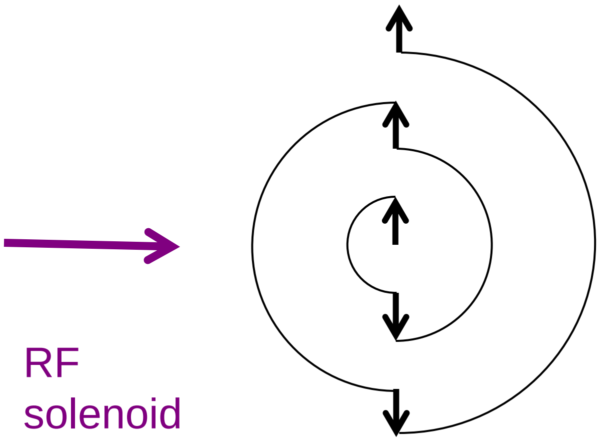
An RF solenoid is located on the COSY beam line.





Make a series of kicks in opposite directions as the polarization precesses about the vertical.

Process seen from above.

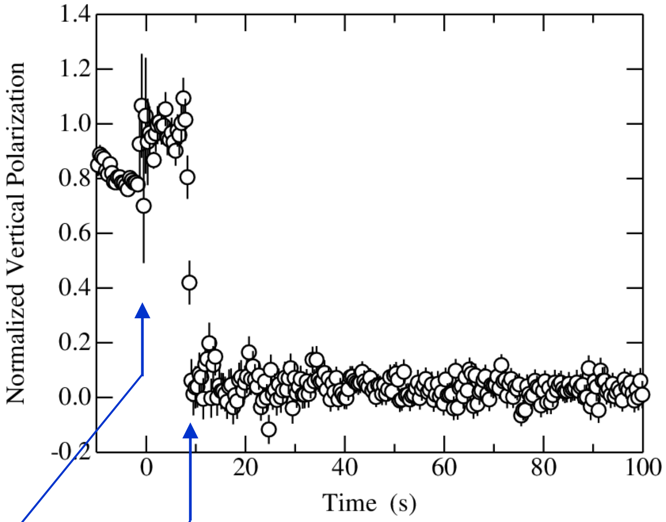


RF
solenoid
field direction

Kicks are small, about $10^{-5}$ rev. Precession into the horizontal plane takes a fraction of a second.

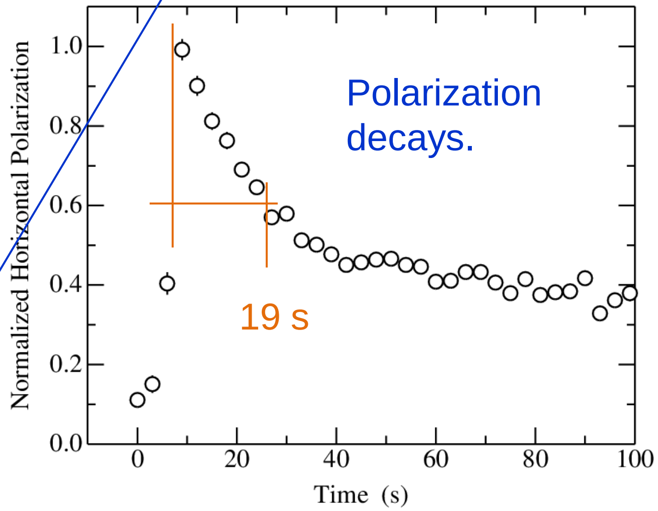
## Sample data.

(Data rescaled to begin at one.)



Extraction is ready and data taking “starts”.

RF solenoid runs for about one second.



# New data acquisition procedure – time stamp every event

Count turn number (bunched beam) → distribution of turn number fraction yields beam distribution

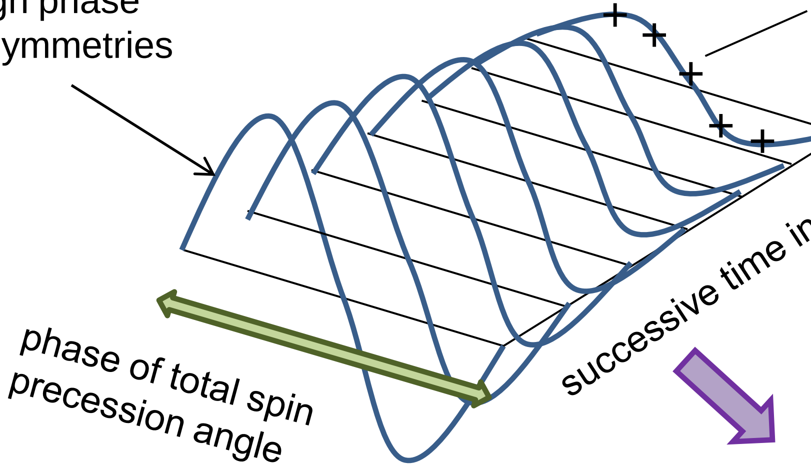
Compute total spin precession angle → based on integral part of turn number

Bin by phase around the circle

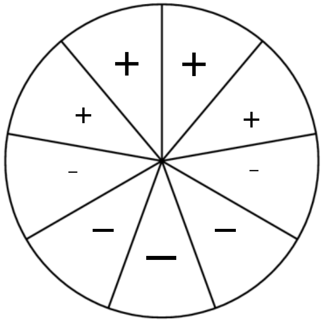
Compute asymmetry in each bin

smooth curves through phase bin asymmetries

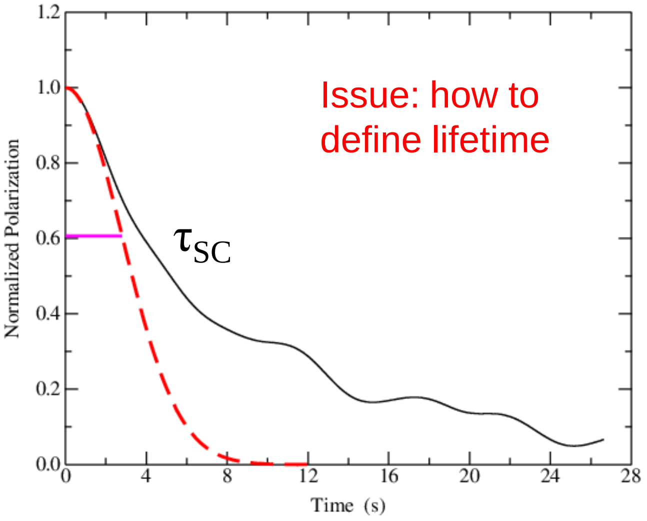
these curves determined by asymmetry measurements for 9 angle bins



correcting phase slip from one bin to the next adjusts the spin tune

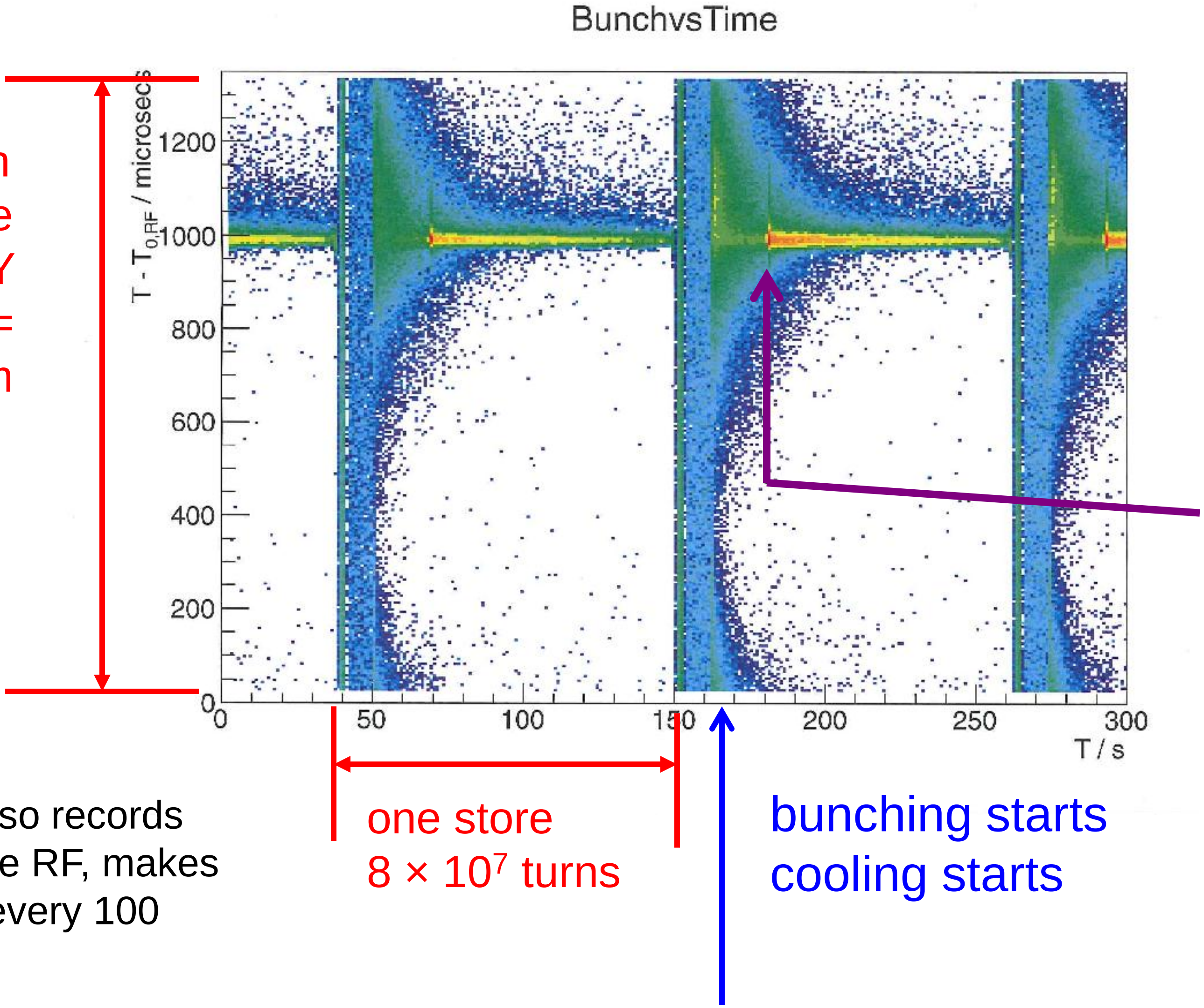


As the polarization rotates the down-up asymmetry reflects the sideways projection of the polarization.



Issue: how to define lifetime

# First Milestone: Counting turn number



length of one COSY orbit = 183 m

full extraction starts

one store
$8 \times 10^7$ turns

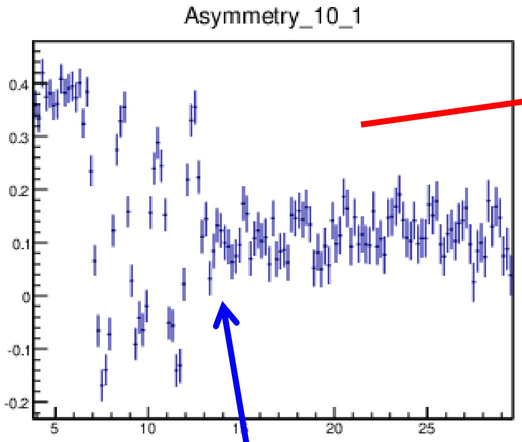
bunching starts
cooling starts

DAQ also records machine RF, makes check every 100 turns.

# Second Milestone: Asymmetry by phase of total spin precession angle

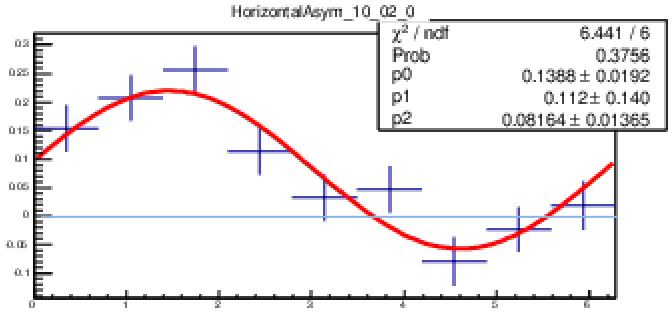
starting point, vertical polarization

sideways asymmetry in a one second time bin

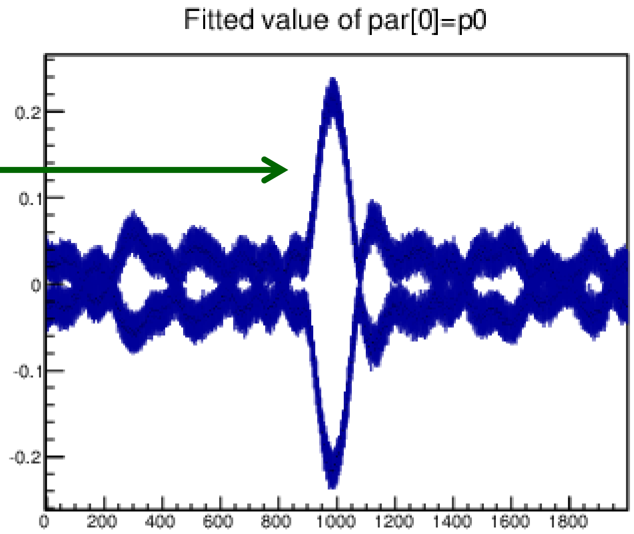


RF-solenoid on Py oscillates

stop at Py = 0, cooled beam is horizontally polarized



match of the calculated spin tune to the sine wave amplitude



spin tune = 0.16096 0.16099

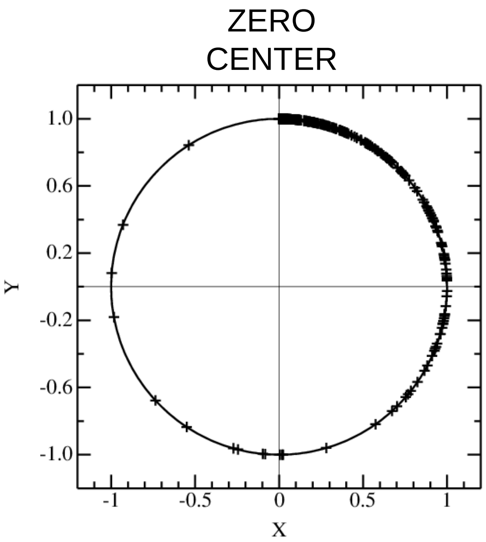
FWHM = 1.8 × $10^{-6}$. (11 ppm)

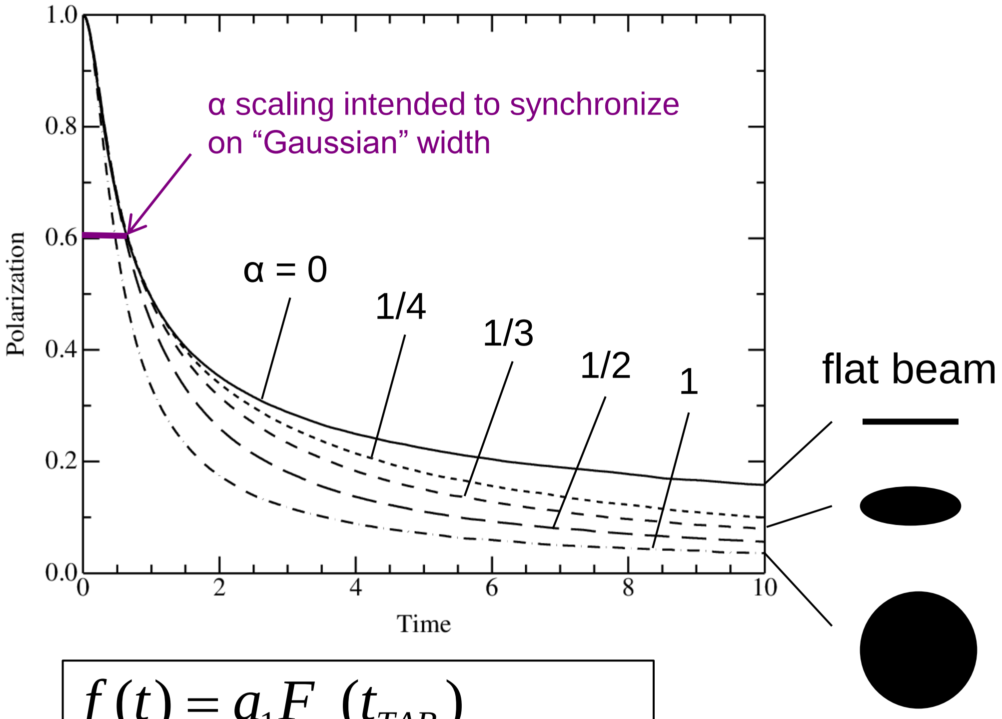
# Function (F) to describe the time evolution of the polarization

Main contribution is path lengthening due to betatron oscillations.
With bunched beam, this goes as $\theta_X^2 + \theta_Y^2$
The maximum angles follow Gaussian distributions with $\sigma_X$, $\sigma_Y$

Generally X is larger than Y distribution, so $\alpha = \dfrac{\sigma_Y}{\sigma_X} < 1$

Distribute points on circle
in horizontal plane





α scaling intended to synchronize on “Gaussian” width

Point distributions expands with time.
Calculate X and Y polarization,
combine for magnitude.

$$f(t) = a_1 F_\alpha(t_{TAB})$$

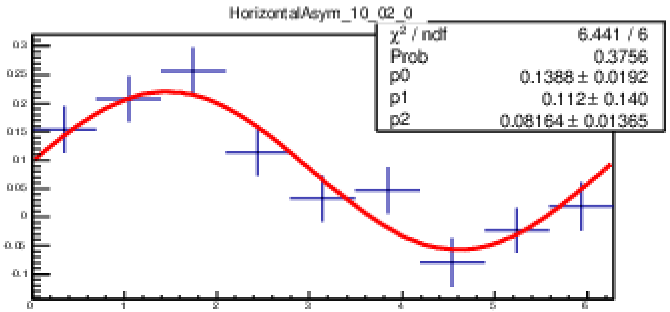
$$t_{EXP} = a_2\sqrt{1+\alpha^2}\, t_{TAB} + a_3$$

round beam

# “POSITIVITY” PROBLEM:

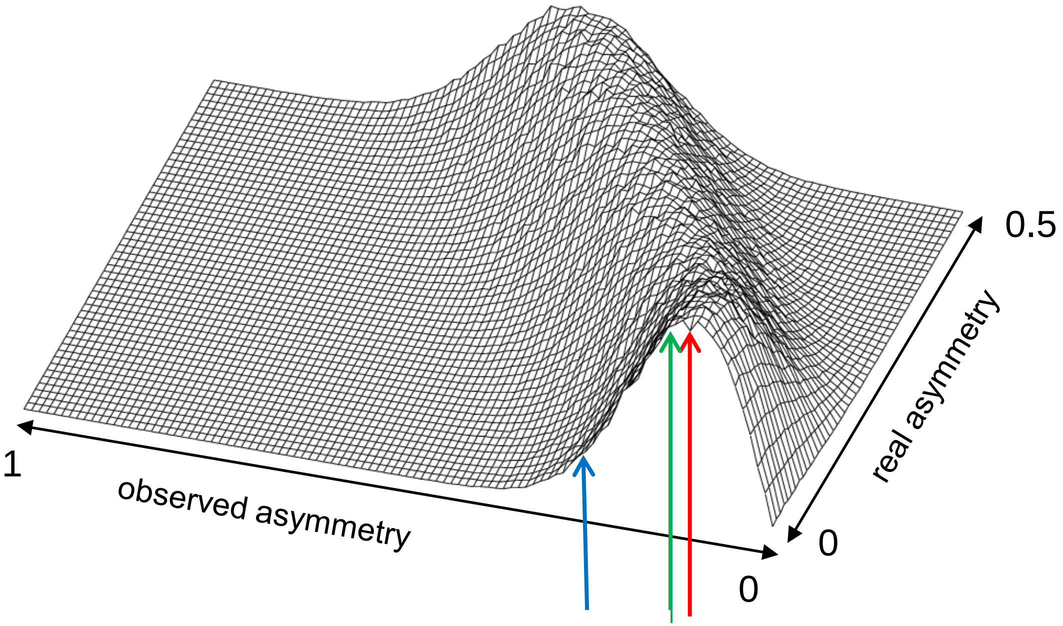
Any random distribution of points fit to a sine wave with adjustable phase and offset will yield a non-zero amplitude.

SAMPLE OF A GOOD DISTRIBUTION



You can model this (MC) by picking a typical error for the asymmetry at each point and adding (or not) some real signal to that.

For illustration, pick a case where the error is about the size of the typical signal.



At ε = 0:

mean = 0.14

most probable = 0.11

error = 0.25

(10 point circle average)

PLAN: Add this effect to template.

# As you adjust $a_1$ and $a_2$, include positivity correction.

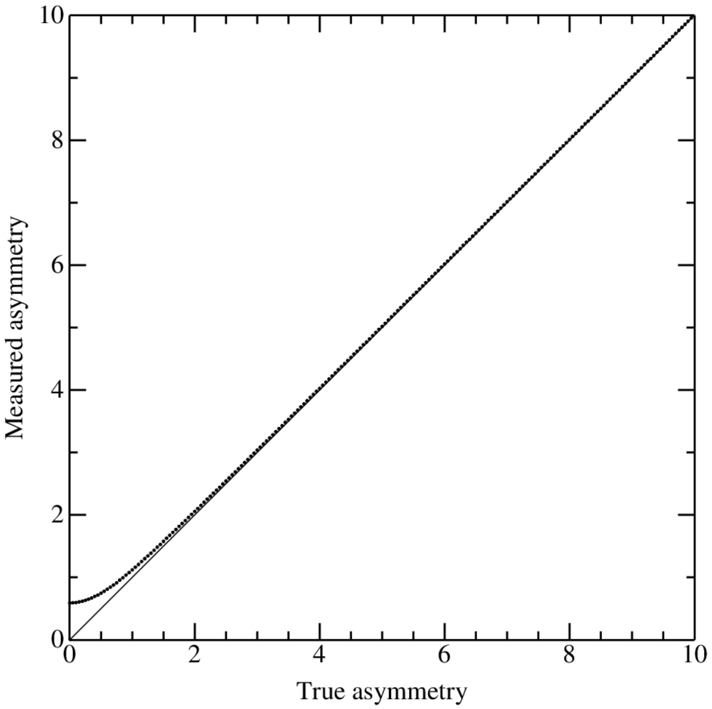
## Template:

Calculated with σ = 1.

100,000 points used for each average.
(difference less than 1:1000 at ε = 0)

200 point table.

Values used from cubic spline fit.



Non-linear regression based on CURFIT
from P.R. Bevington with numerical derivatives.

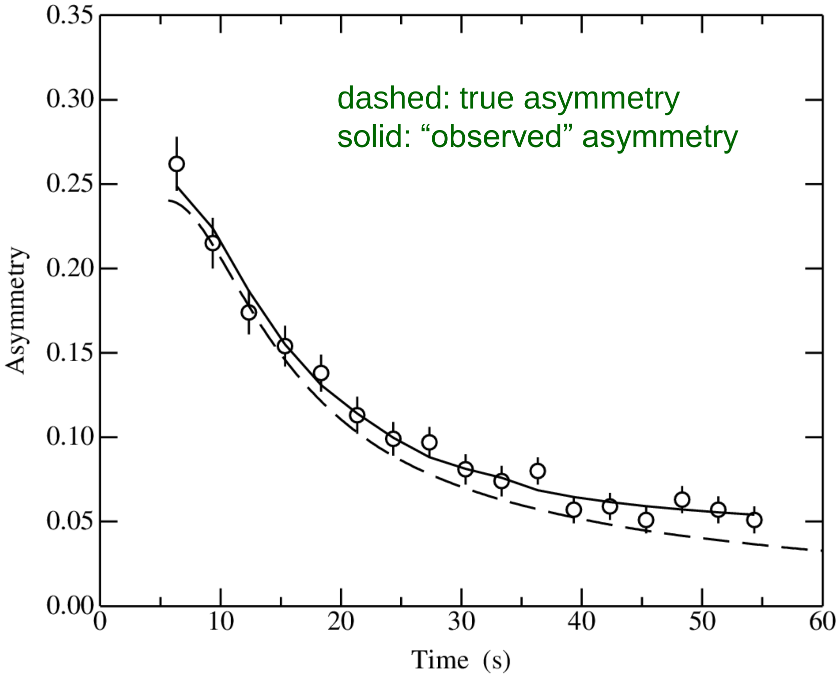
## Run 1143:

Shape value interpolated at each data point.

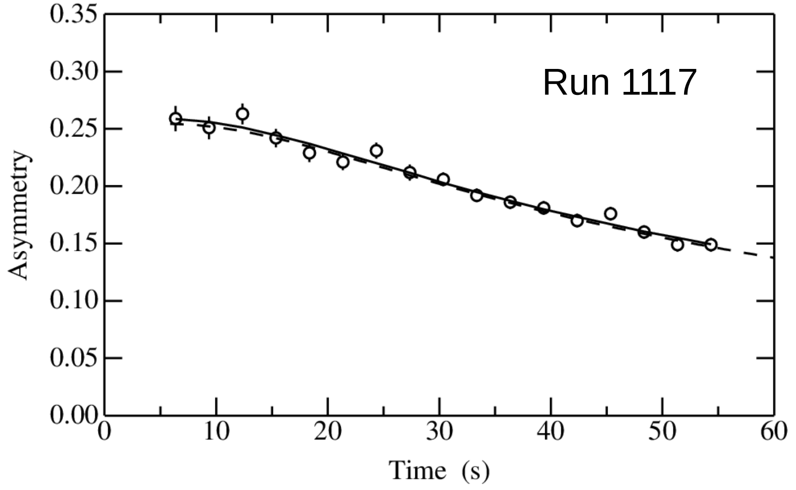
Correction calculated based on σ (cycle error)
deduced from individual error in average (δ).

$$\sigma = \sqrt{\frac{N_{slices} N_{cycles}}{2}}\,\delta$$

Fit made using corrected values (changed at each iteration).

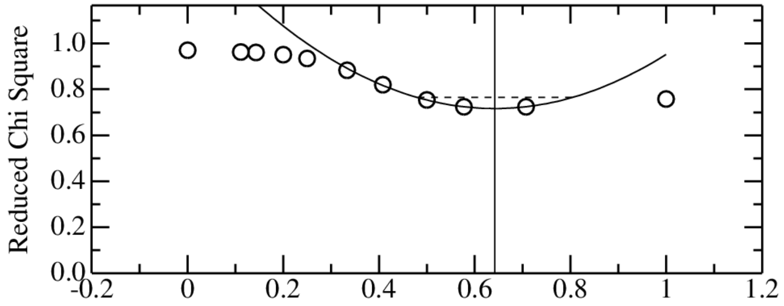


# Some sample data (higher statistics runs)

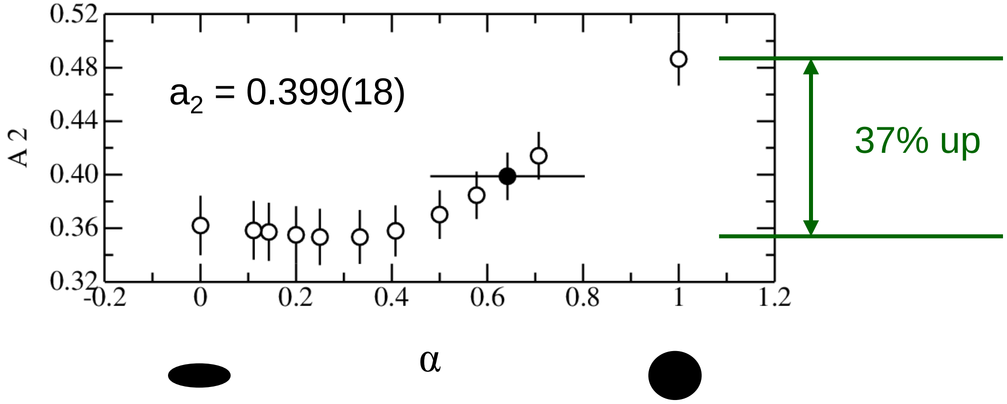


"Best" shape, from chi square minimum

Solid: corrected calculation
Dashed: true asymmetry

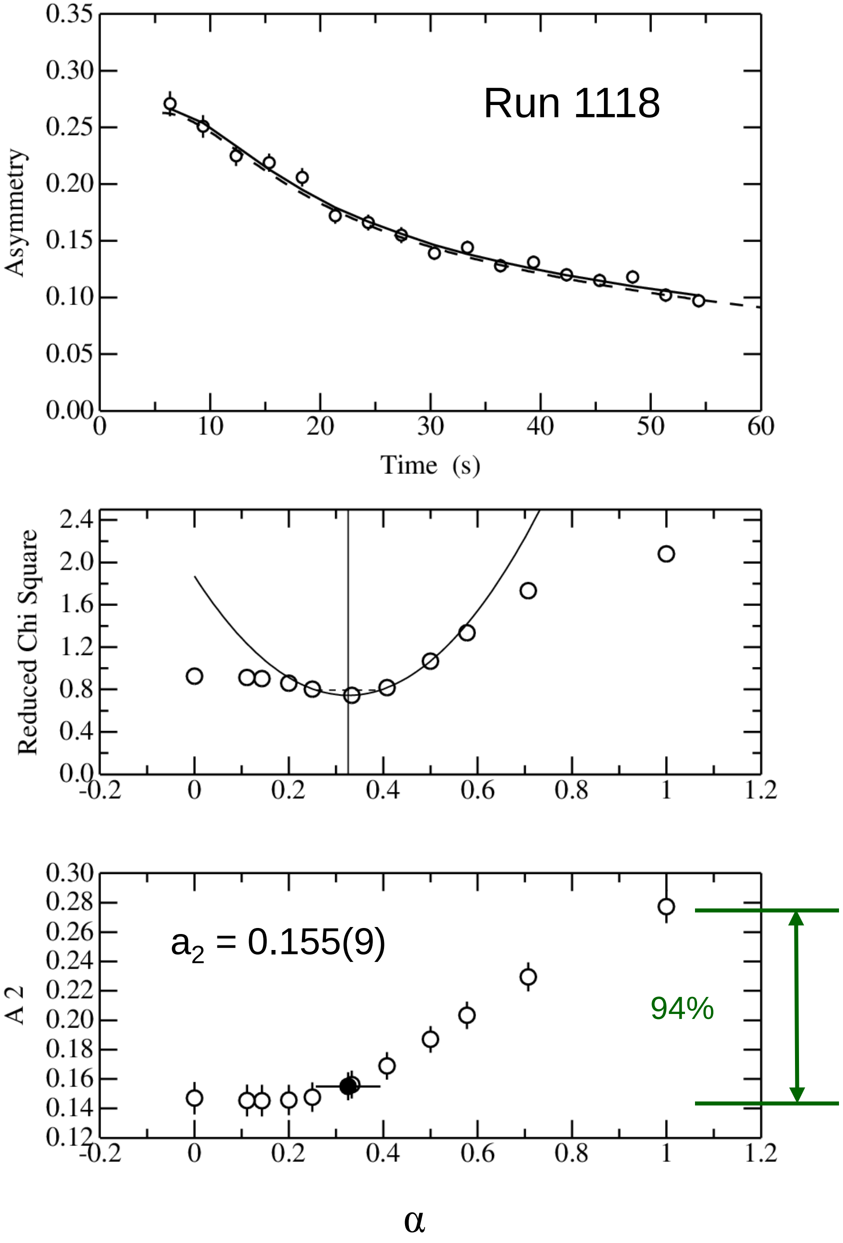


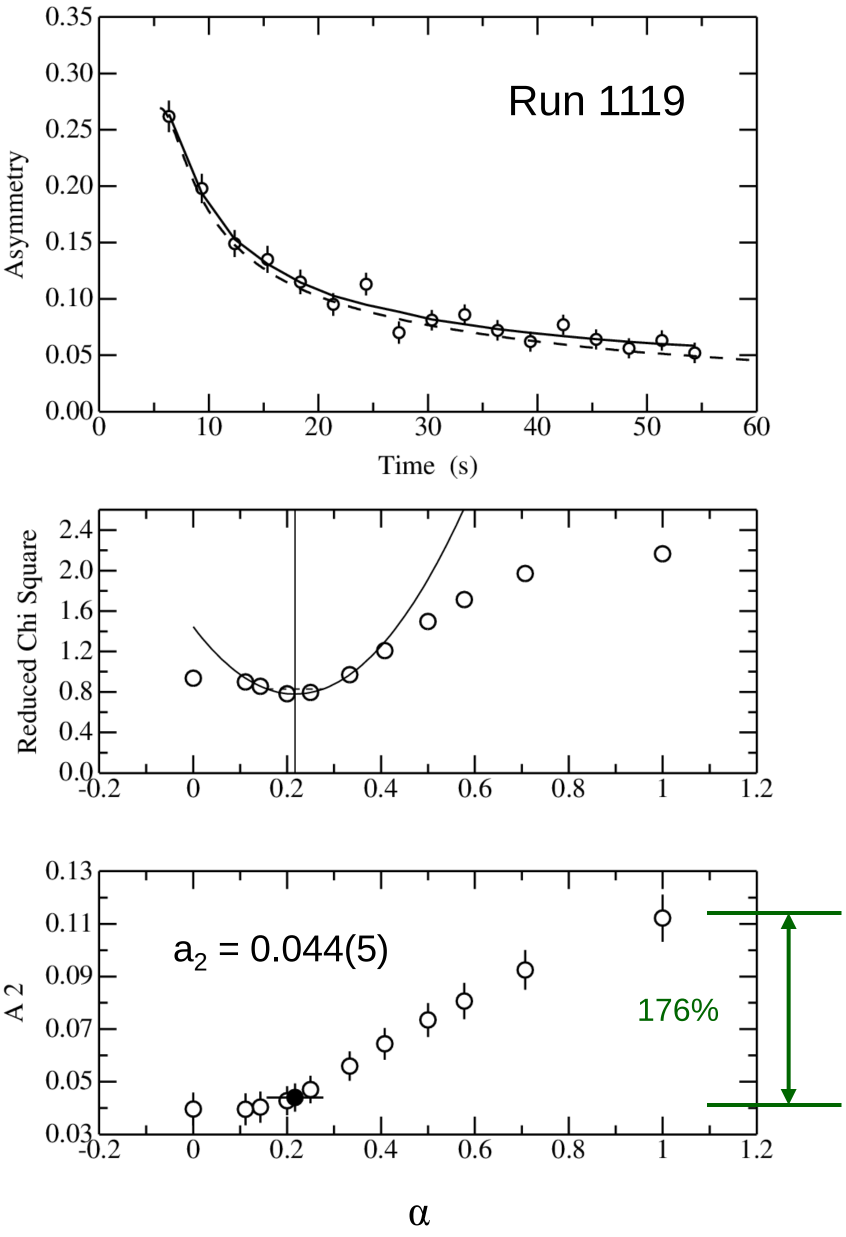
Curve is quadratic fit to reduced chi square.
Vertical line is center, best value of α.
Dashed line is standard deviation width
for this chi square curve. This width is
marked below.



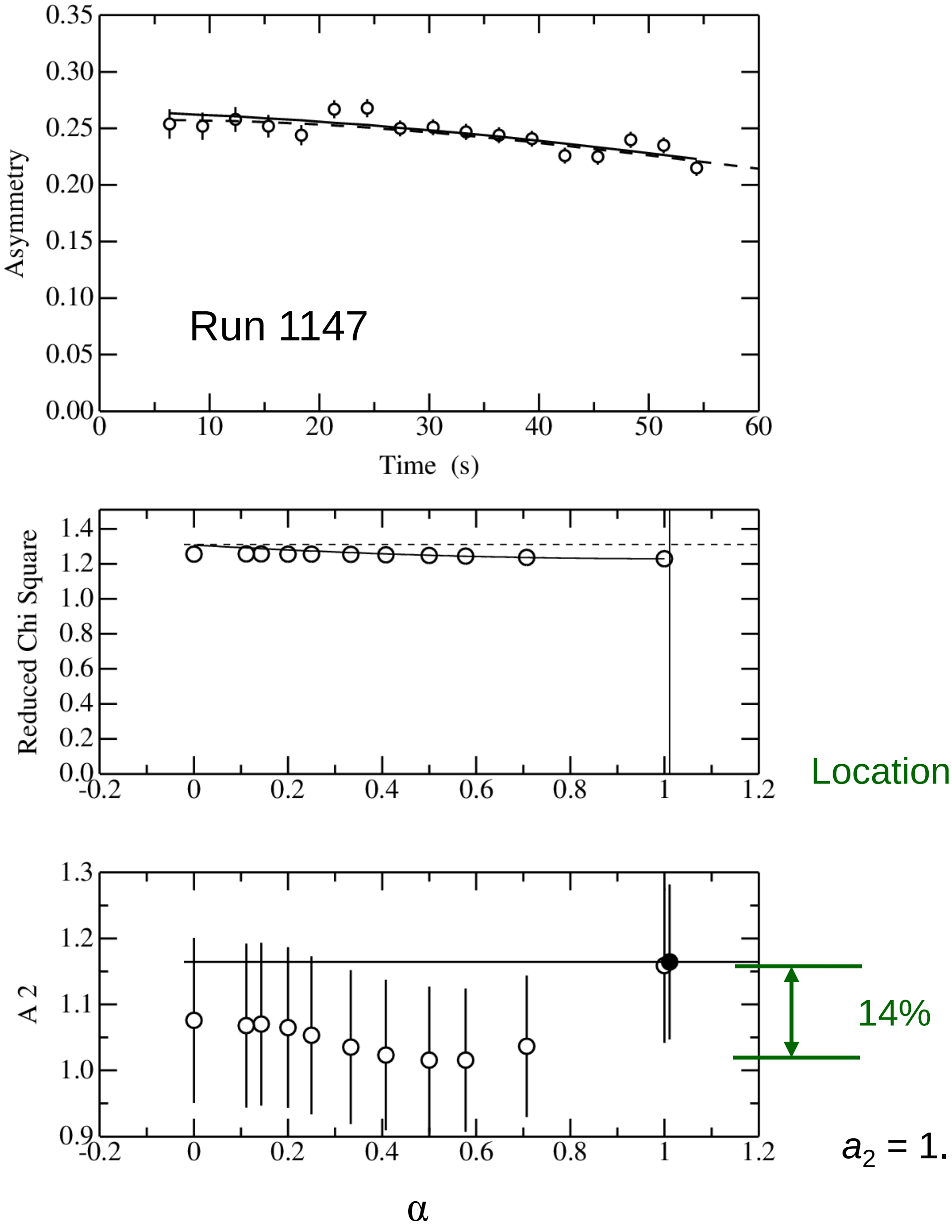
Variation of *a*2 with α.
Solid point is "best".

shorter SCT = wider beam





# Long lifetime sample

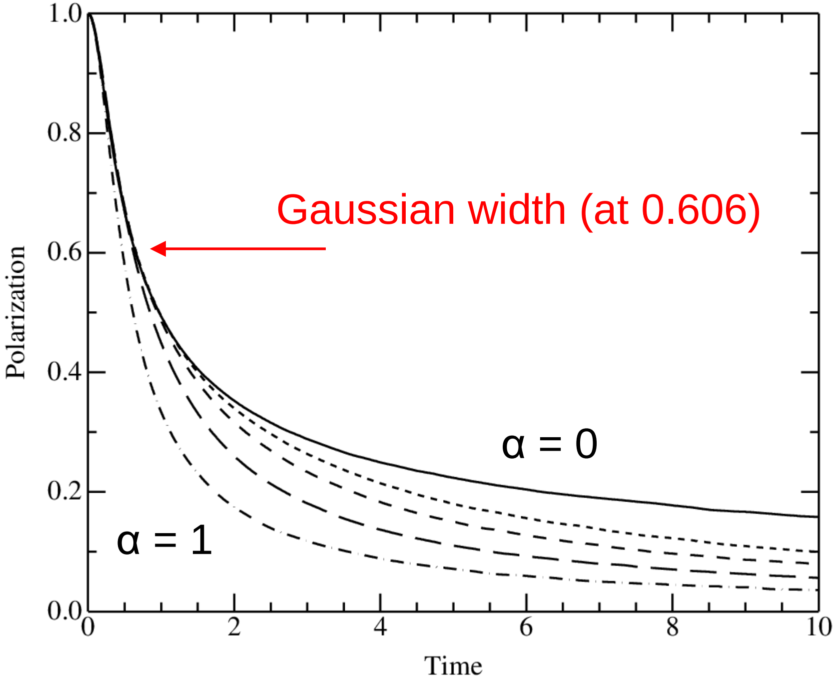


Location of best fit is not determined.

For the longest lifetime cases, the determination of $a_2$ is nearly shape independent.

$a_2 = 1.165(118)$

# Definition of spin coherence time (unit conversion):

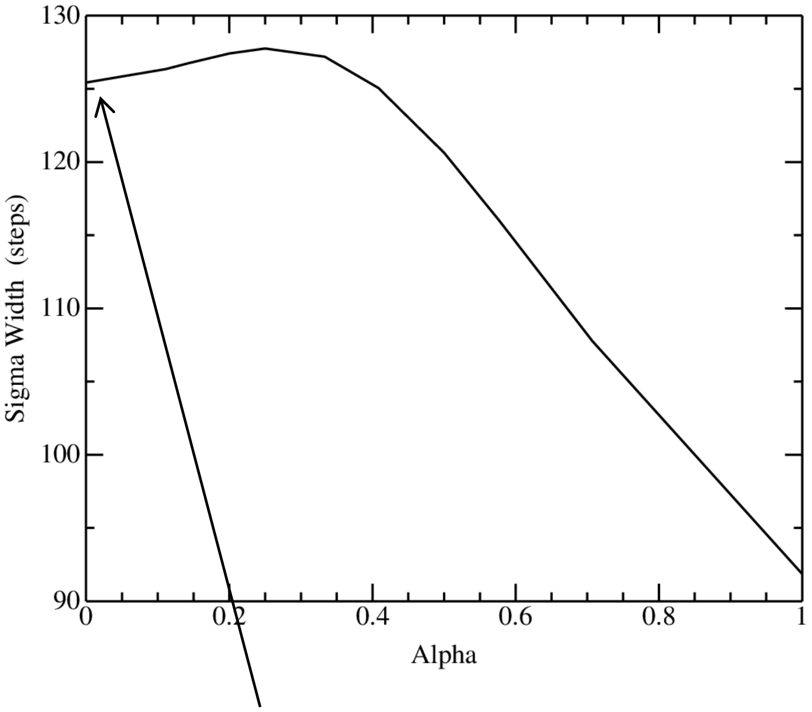


Gaussian width (at 0.606)

α = 0

α = 1

At a polarization of 0.606…, the conversion from $a_2$ to time in seconds varies with shape.



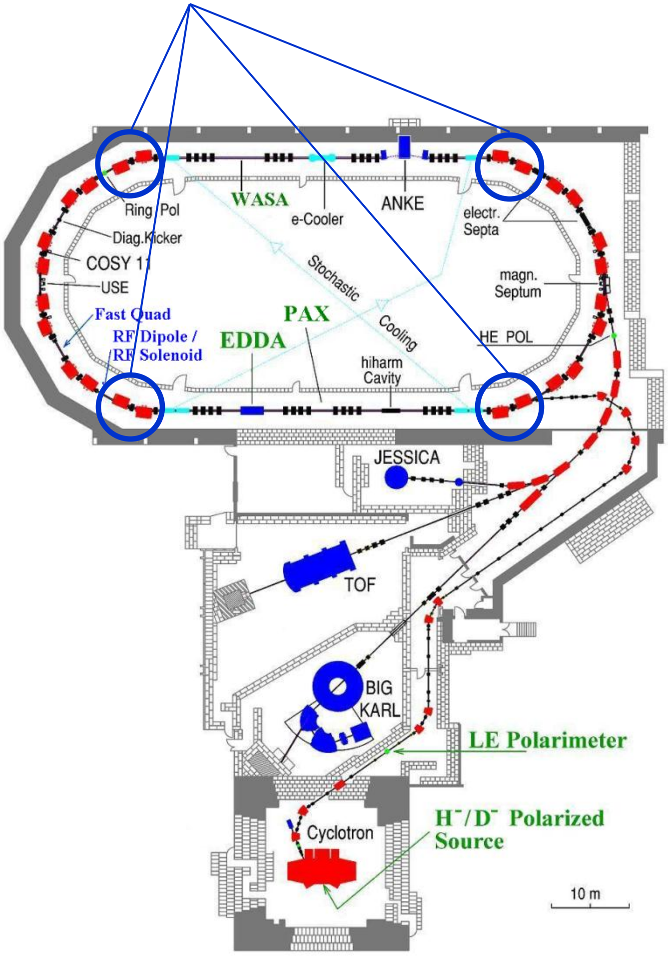
time (s) = 125.43 $a_2$

The ambiguity is (at least) to use the Gaussian width point or to assume that the similarity at very small times means choosing one value. -- Finally, it makes little difference.

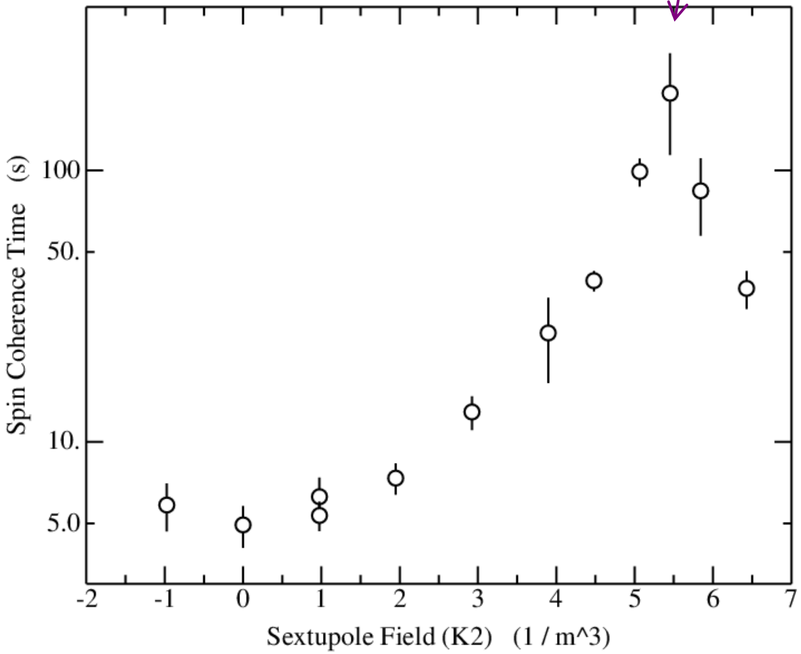
# Can we lengthen in spin coherence time by changing the ring sextupole fields?

Only horizontal width of beam was adjustable.
Choose a wide beam with short SCT, then fix it.

Use MXS sextupole family (large $\beta_X$)



Results



Much better !

Does the lifetime follow this dependence?

$$\frac{1}{\tau_{SC}} = \left|\underbrace{A - a_1 S} - a_2 L\right| X^2_{RMS} + \left|B - b_1 S - b_2 L\right| Y^2_{RMS}$$

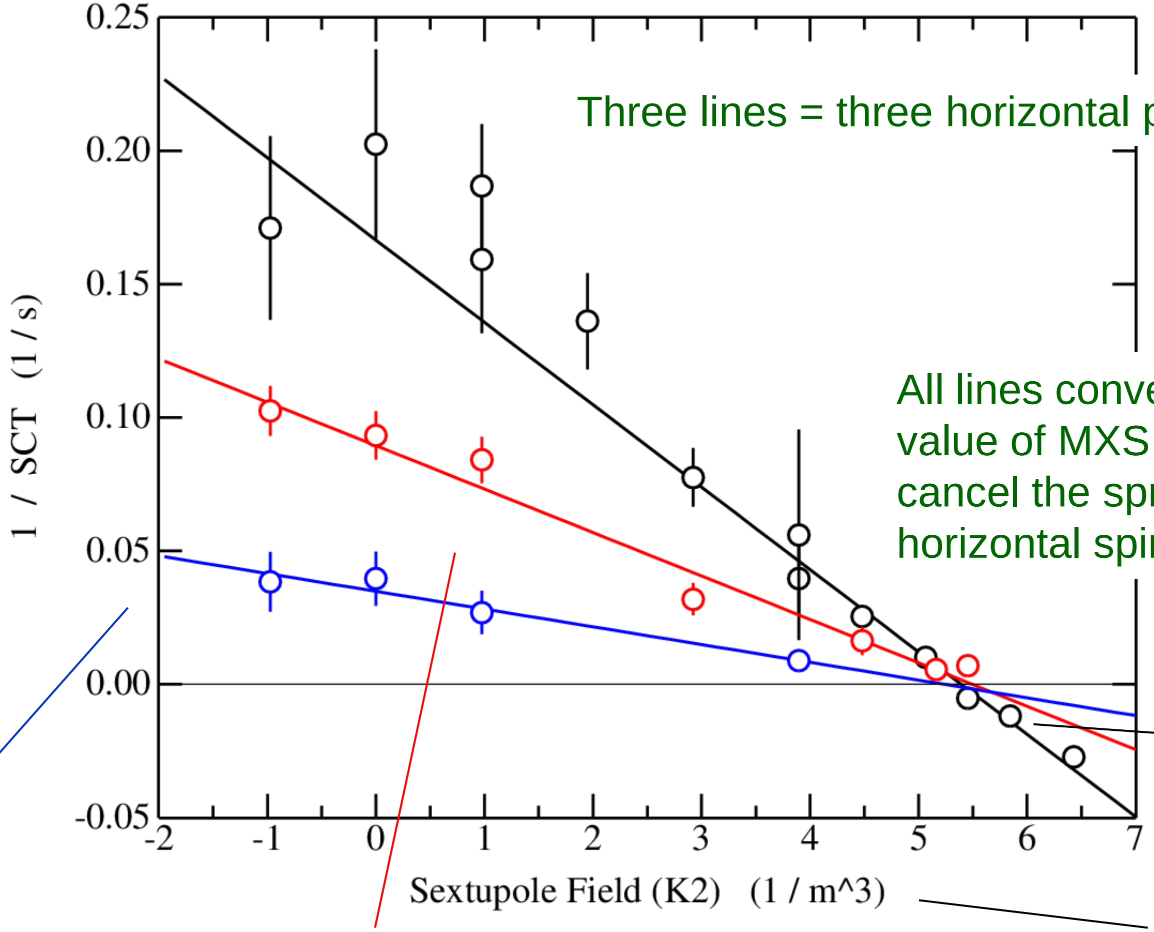
Run only tested this.

No correlations with alpha, quality of fit.

heat = 0.35

= 0.2

= 0.2



Three lines = three horizontal profile widths

Polarization state 10

All lines converge to same value of MXS strength to cancel the spread in the horizontal spin tune.

Sign changed for these three points to maintain linearity.

Early runs:
1126, 1133, 1142, 1152

Late runs:
1202, 1203, 1206, 1217, 1220, 1221, 1222

$$K_2 = \frac{1}{B\rho}\frac{\partial^2 B}{\partial x^2}$$

# This remains a work in progress…

Recently:

Another test shows that best spin coherence time comes when chromaticity is zero.

$$\xi_{X,Y} = \frac{(\Delta\nu/\nu)_{X,Y}}{\Delta p/p}$$

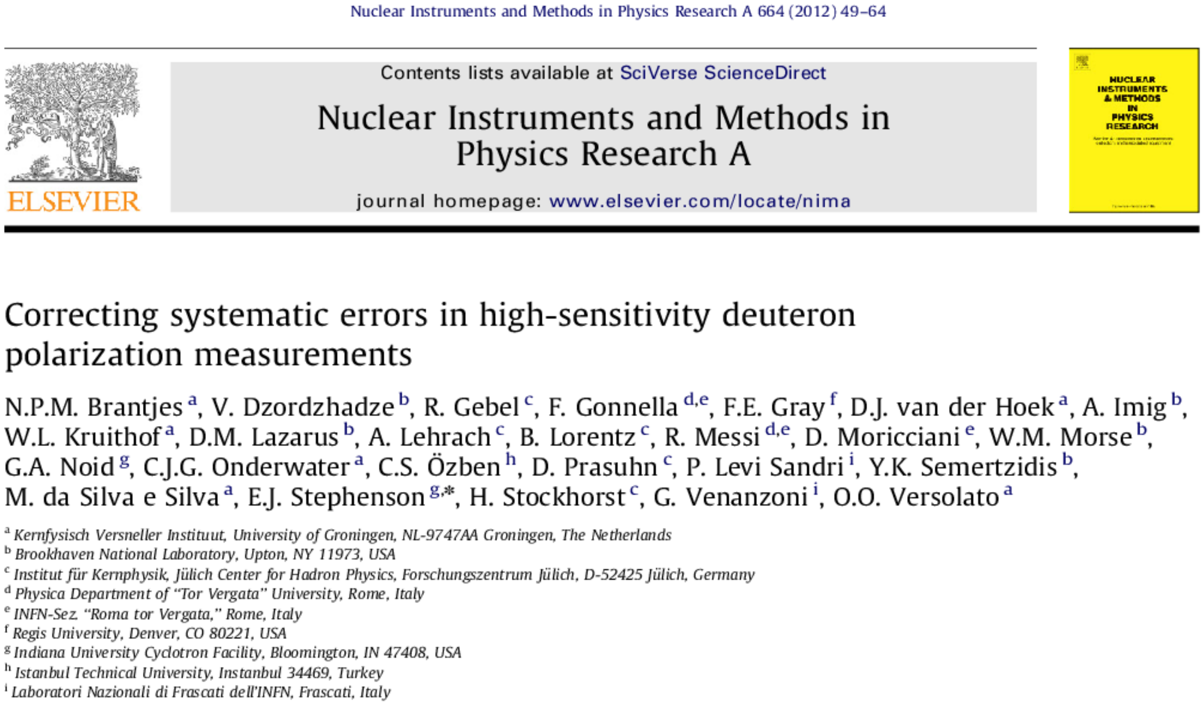
Planned:

Further studies that characterize Y as well as X.

Is zero chromaticity a requirement?

Are there $\Delta p/p$ contributions beyond emittance?

Does beam mixing extend spin coherence time?



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## Correcting systematic errors in high-sensitivity deuteron polarization measurements

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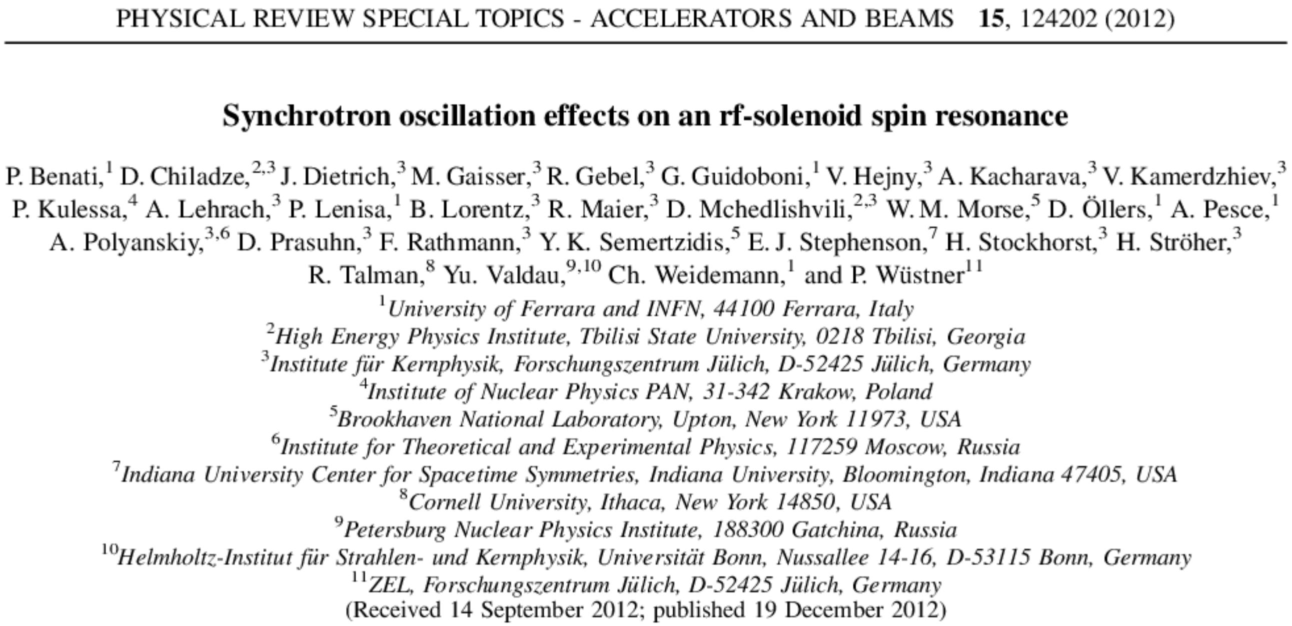

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## Synchrotron oscillation effects on an rf-solenoid spin resonance

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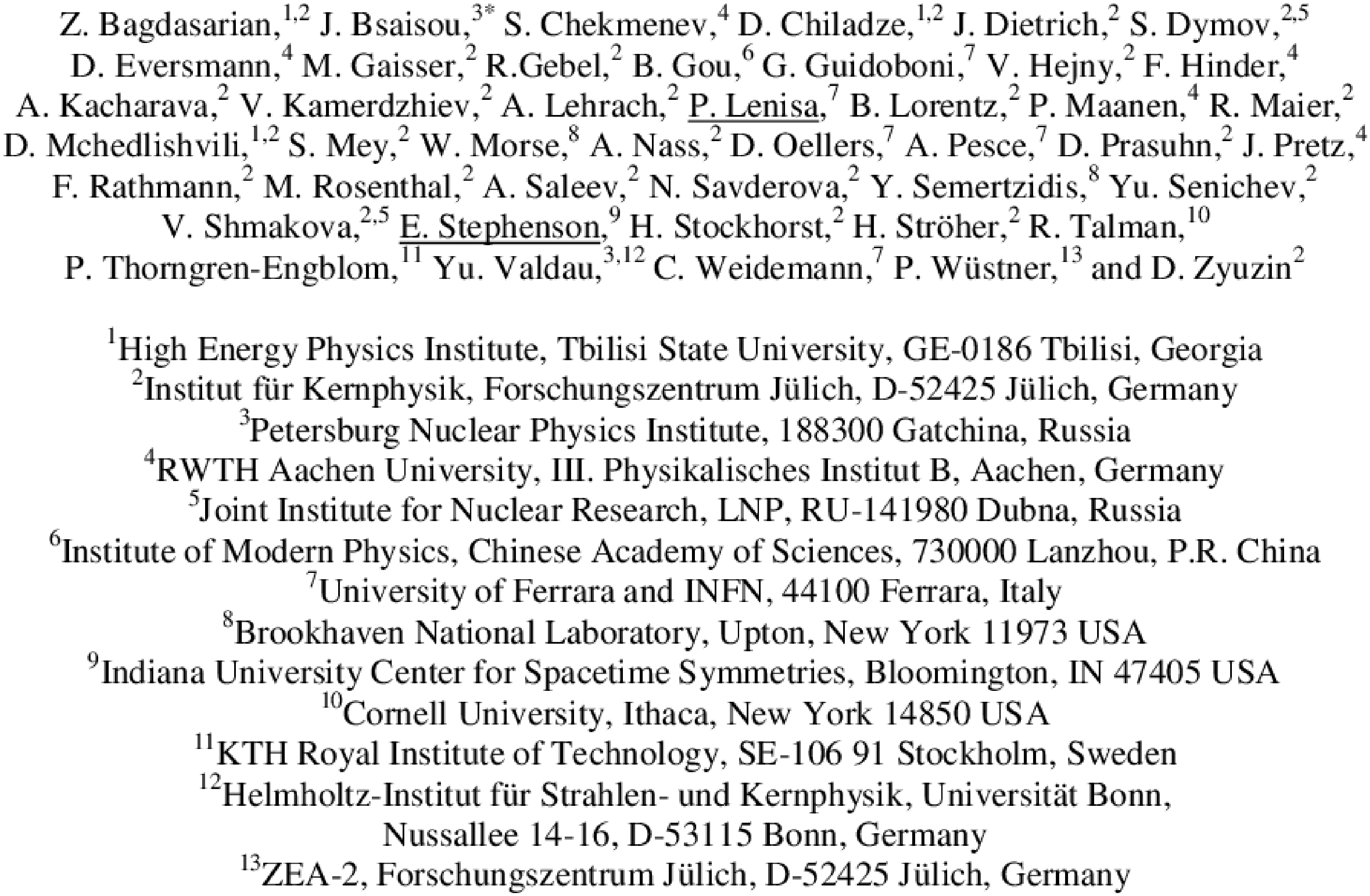
# Collaboration List (2013)



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