Spin Tune Determination at COSY Storage Ring

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JEDI-Collaboration

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Baryon Asymmetry and CP violation

- One precondition for Baryon asymmetry: CP violation
- Standard Model prediction: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-18}$
- WMAP and COBE (2012): $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$

Electric Dipole Moments (EDMs) of non degenerate particles violate P and T

polar / axial vector

Assuming CPT

$$\mathcal{H} = -\, d\, \frac{\vec{S}}{S} \cdot \vec{E}$$

P: $\mathcal{H} = +\, d\, \frac{\vec{S}}{S} \cdot \vec{E}$

T: $\mathcal{H} = +\, d\, \frac{\vec{S}}{S} \cdot \vec{E}$

→ **EDM** is probe of CP violation in the early universe

Jülich Electric Dipole moment Investigation

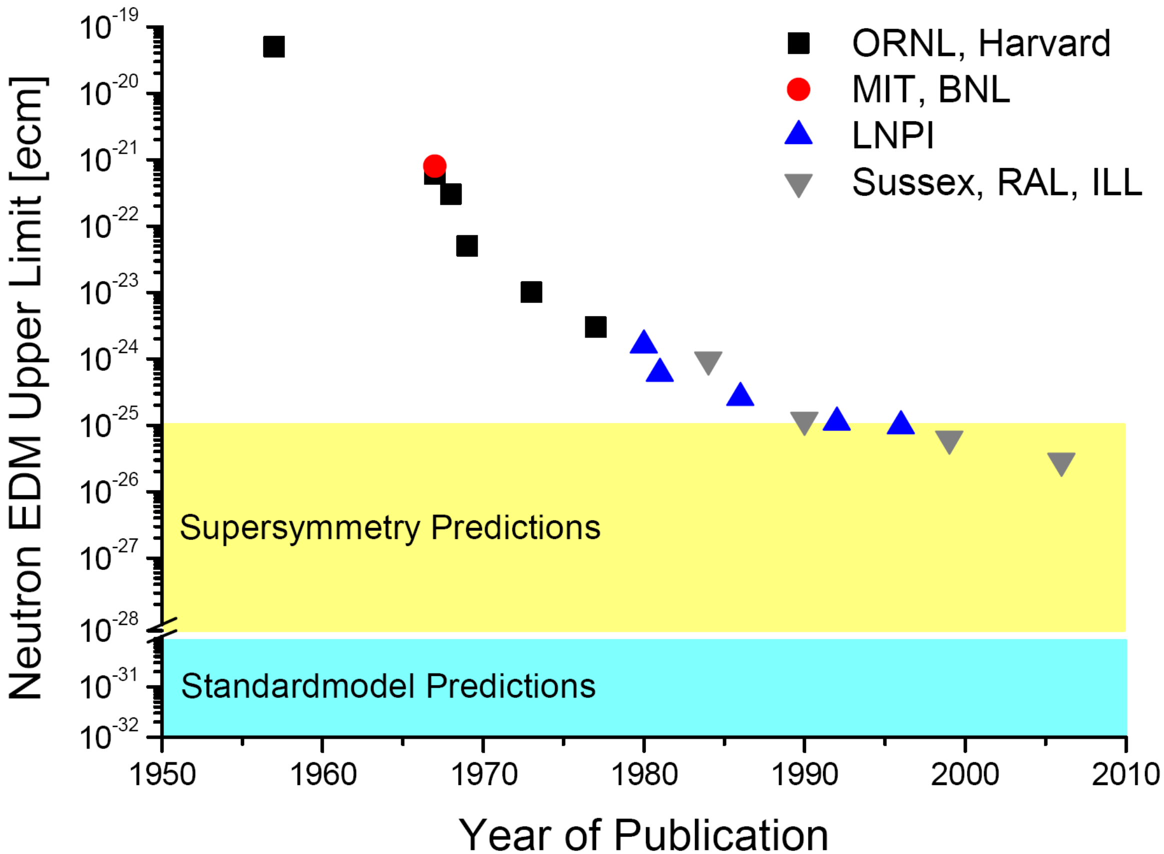
- Feasibility studies of a charged hadron EDM experiment in a storage ring (COSY) and first measurement of a deuteron EDM limit of

$$\sigma_d < 10^{-24}\,\mathrm{e}\cdot\mathrm{cm}$$

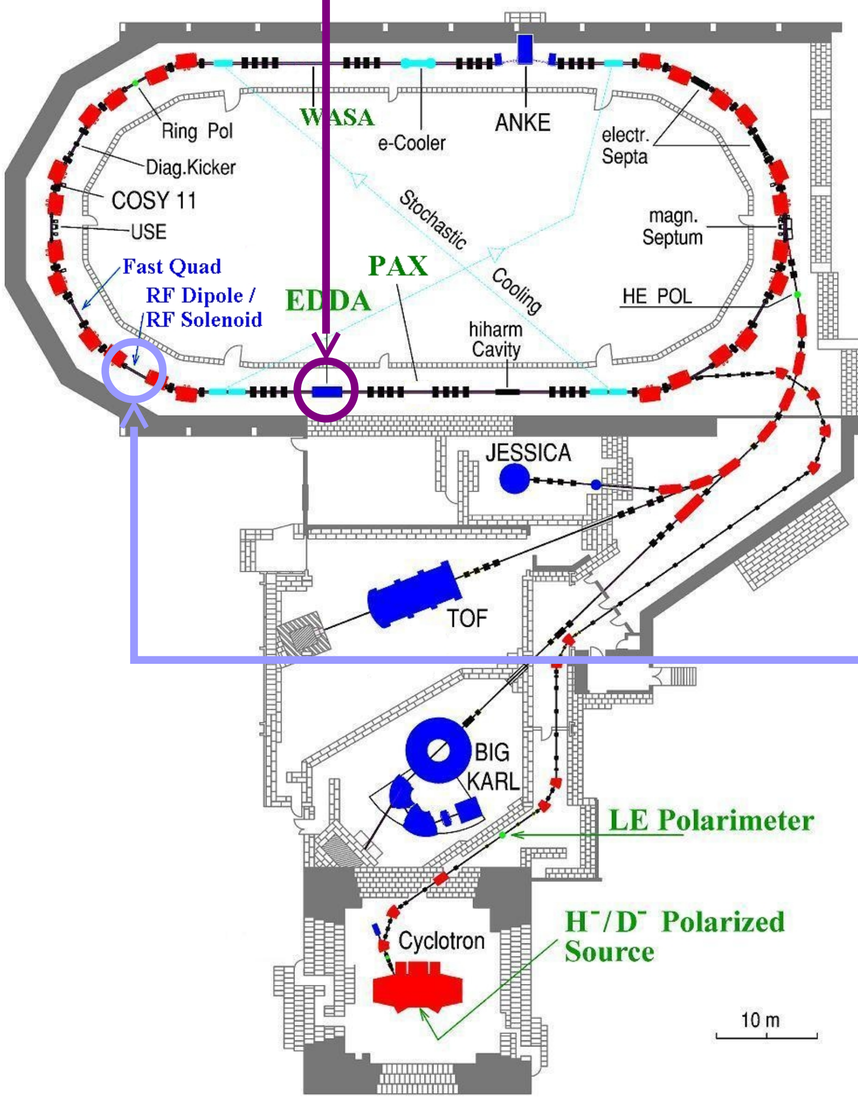
- Dedicated ring to measure first direct proton EDM limit and improve deuteron limit to

$$\sigma_d < 10^{-29}\,\mathrm{e}\cdot\mathrm{cm}$$

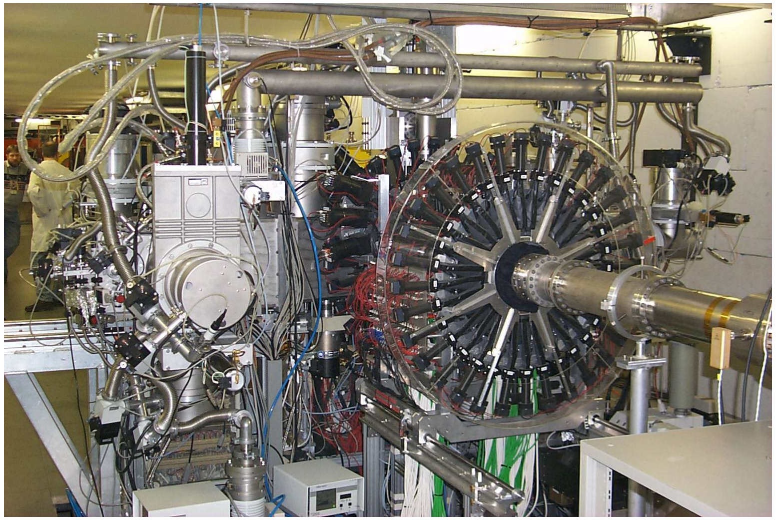
- Sensitive to SUSY models



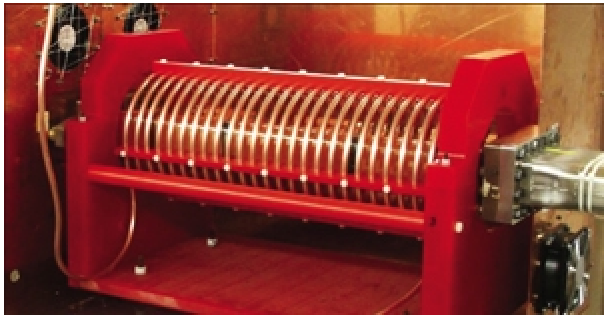
Circumference: 184m
Polarized proton and deuteron beam



EDDA Detector



Solenoid



Thomas BMT Equation and Spin Tune

The **spin precession** in **electric** and **magnetic** fields affected by an **electric dipole moment (EDM)**

$$\frac{d\vec{S}}{dt} = \vec{\Omega}_s \times \vec{S} \quad \text{with} \quad \vec{\Omega}_s = \frac{q}{m}\left\{ G\vec{B} + \left(\frac{1}{\gamma^2-1} - G\right)\left(\frac{\vec{\beta}\times\vec{E}}{c}\right) + d\,\frac{mc}{q\hbar S}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

In a pure magnetic ring (COSY) and no **EDM d=0**

$$\frac{d\vec{S}}{dt} = \left(\underbrace{\frac{q\vec{B}}{\gamma m}}_{} G\gamma\right)\times\vec{S}$$

$$\frac{d\vec{S}}{dt} = G\gamma\,\vec{\omega}_{cyc}\times\vec{S}$$

Spin tune: Spin rotations per particle turn in the ring

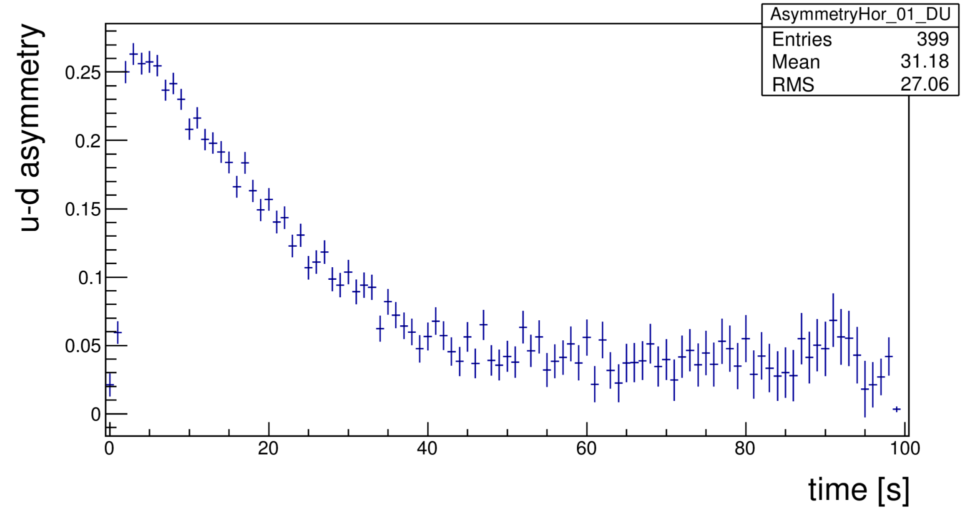
$$\nu_s = \frac{\text{spin rotations}}{\text{particle revolutions}} = \frac{|\vec{\Omega}_s|}{|\vec{\omega}_{cyc}|} = \gamma G_d \approx -0.1609$$

$$G_d \approx -0.143$$

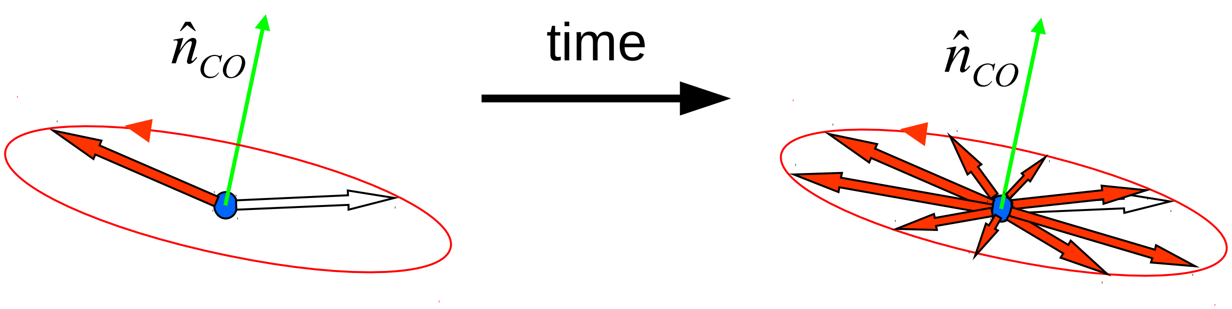
$$\gamma \approx 1.126$$

Beamtime August/September 2013

- Bunched deuteron beam with $p_D \approx 0.97 \frac{\mathrm{GeV}}{\mathrm{c}}$ and $\sim 10^9$ particles per fill
- 3 polarization states (2 vector, 1 tensor)
- Beam is extracted by elastic scattering onto a carbon target



- Two extraction methods:
  1. White noise E-field extraction
  2. Bumped extraction
- Spin is tilted into the horizontal plane by a RF-solenoid
- Polarization loss due to spin decoherence → sextupole magnets are used

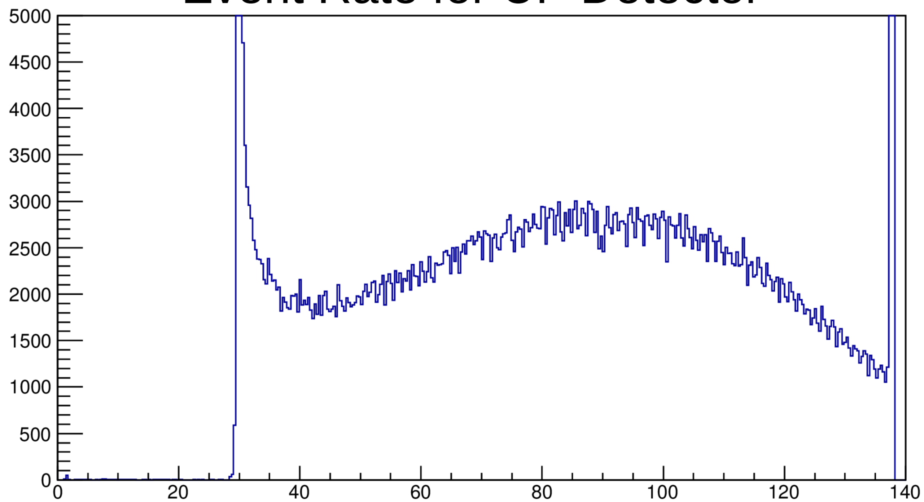


Compare counting rates of two opposite detector areas

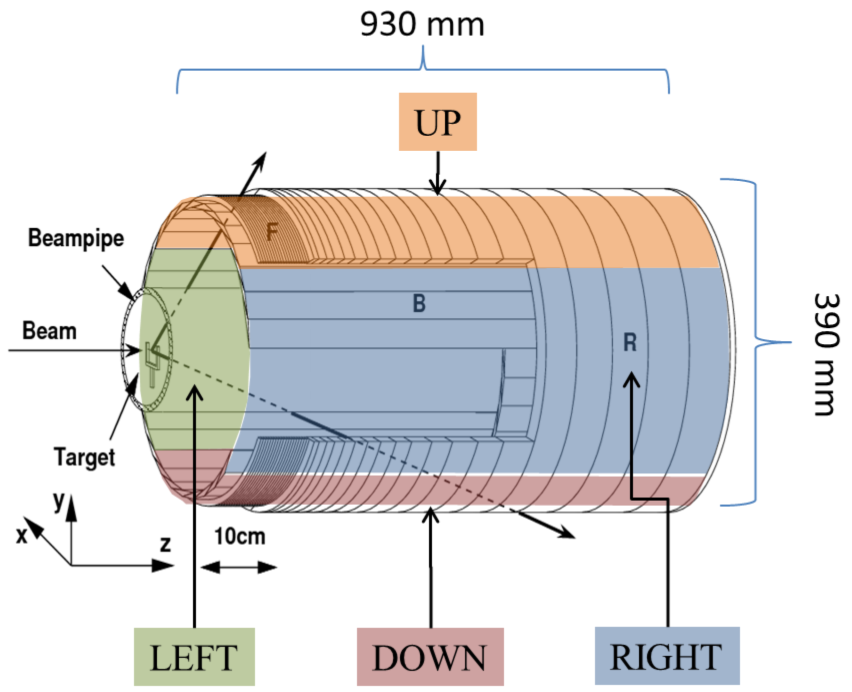
Horizontal polarization measurement

$$\mathcal{A}(t)=\frac{N_{up}(t)-N_{down}(t)}{N_{up}(t)+N_{down}(t)} \sim \sin\left(\left|\vec{\Omega}_s\right| t+\varphi_0\right)$$

Event Rate for UP Detector



EDDA Polarimeter



Challenge:

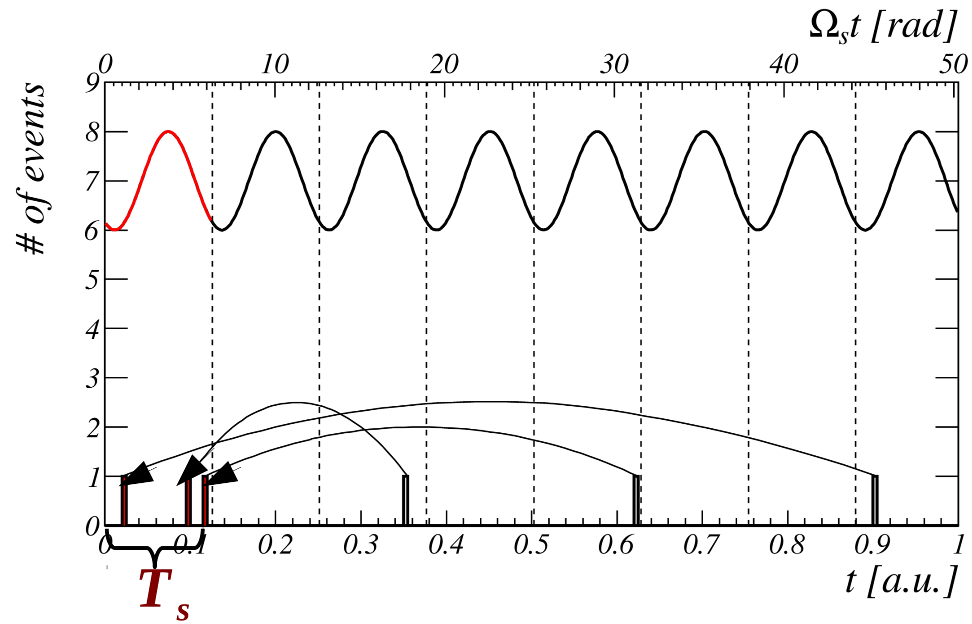
spin precession: $\gamma G_d \omega_{cyc} \approx 120\,\mathrm{kHz} \gg 2-3\,\mathrm{kHz}$ event rate

→ no **direct fit possible**

Horizontal Polarization

I. Take modulo of event time t with a assumed **spin precession period**

$$T_s = \frac{2\pi}{|\vec{\Omega}_s|} = \frac{1}{\nu_s f_{rev}}$$

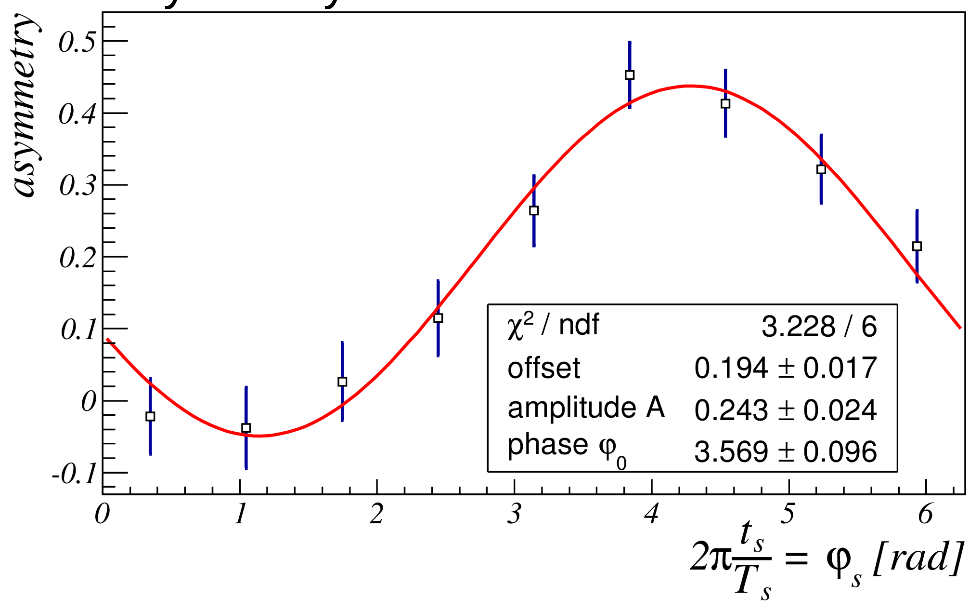


II. Calculate asymmetry during a one second interval and fit a sine

$$\mathcal{A}_{fit}(\varphi_s) = \boldsymbol{A}\sin(\varphi_s + \boldsymbol{\varphi_0}) + offset$$

Amplitude

Spin phase at $t = k \cdot T_s$
$\Leftrightarrow \varphi_s = k \cdot 2\pi$



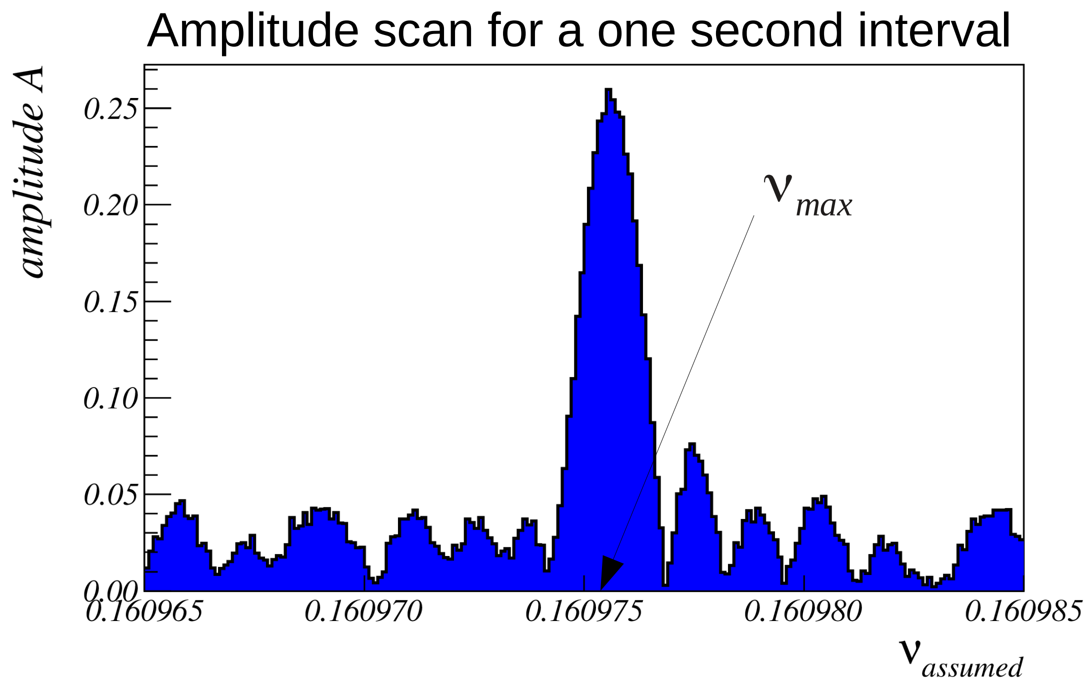
III. Vary the spin tune and find the maximum amplitude

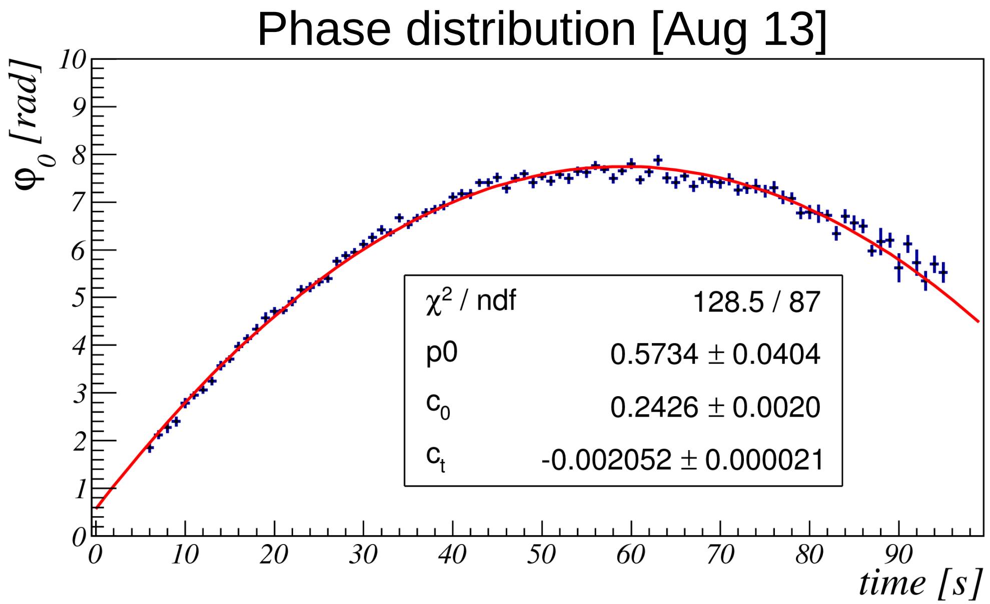
→ Spin precision of 10^{-6} for a 1s intervall

IV. Fix the spin tune for a whole cycle and monitor the phase

$$\nu_s(t) = \nu_{max} + \frac{1}{\omega_{\text{rev}}} \frac{\partial \varphi_0(t)}{\partial t}$$

$$= \nu_{max} + 2.71 \cdot 10^{-7} \frac{1}{\text{s}} \left(c_0 + 2c_t \cdot t \right)$$

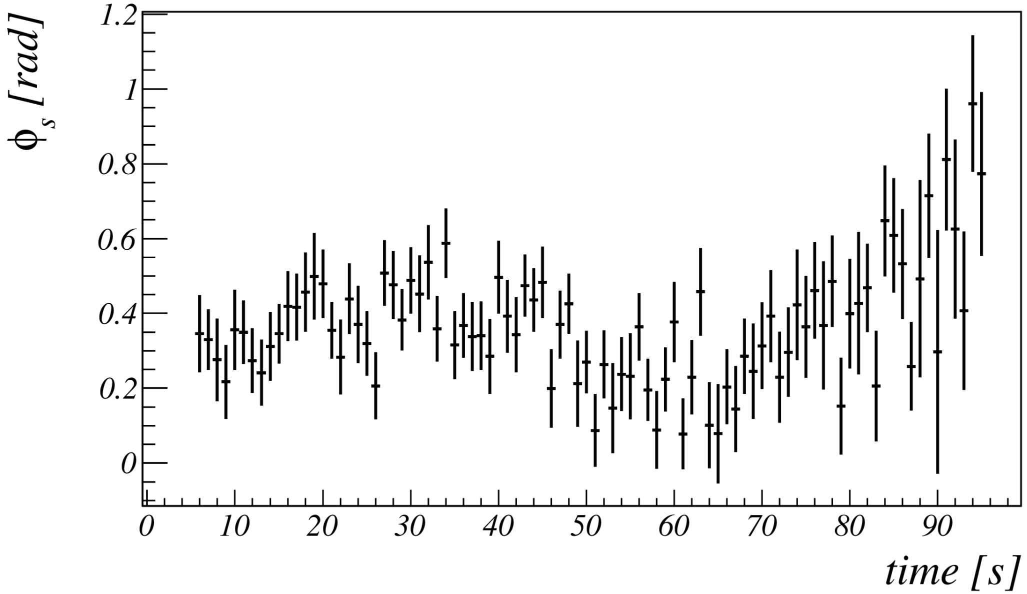




V. Use time depending spin tune for the analysis

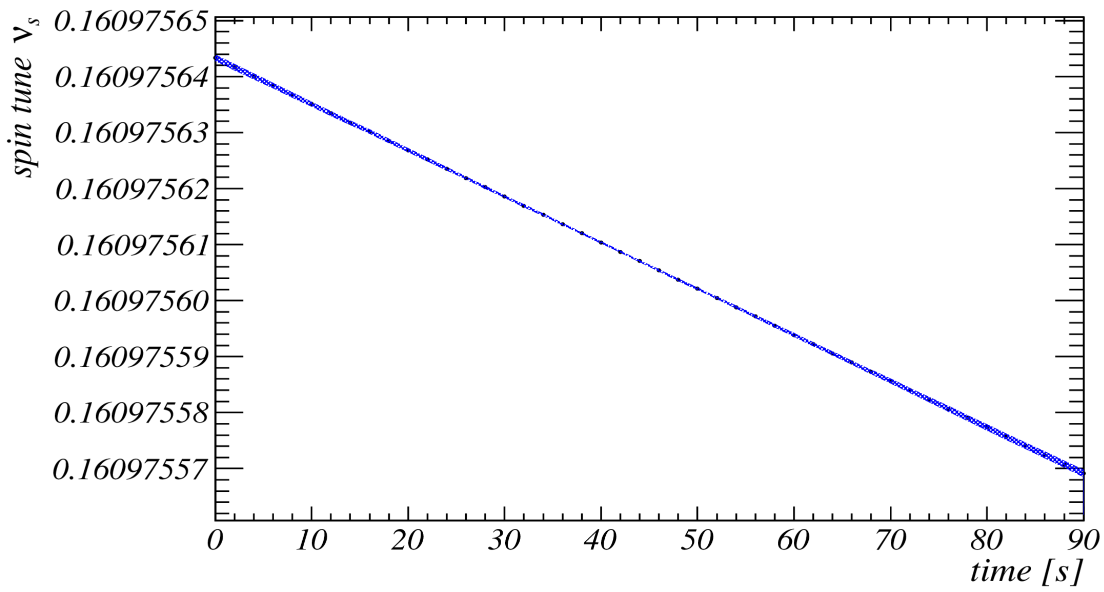
$$\nu_s(t) = \nu_{max} + \frac{1}{\omega_{rev}} \frac{\partial \varphi_0(t)}{\partial t}$$

Quadratic phase change implies linear spin tune change



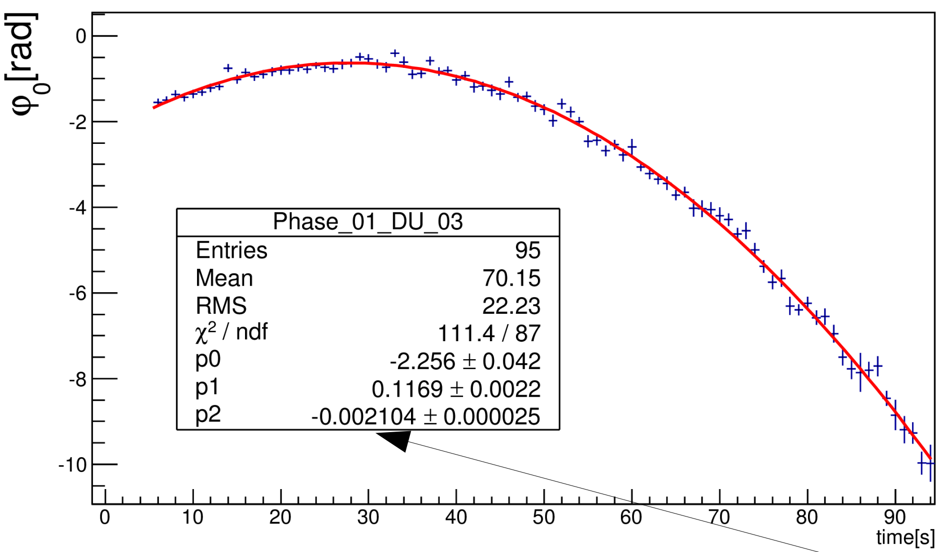
VI. Interpolation of the spin tune for a whole cycle

→ Spin precision of 10^{-10} during a 100 s intervall

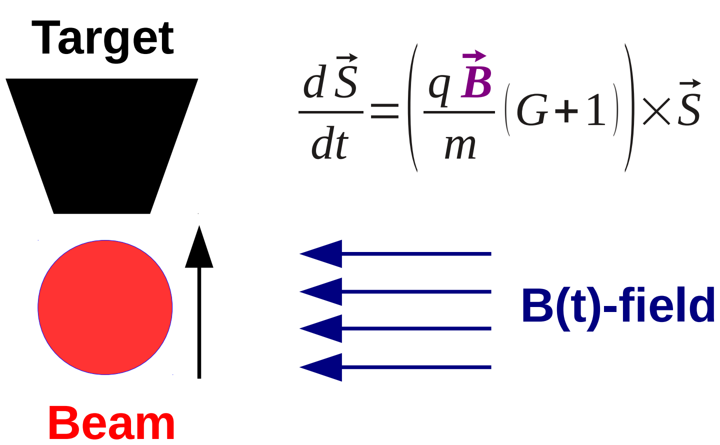


Extraction Methods

Bumped extraction (vertical)

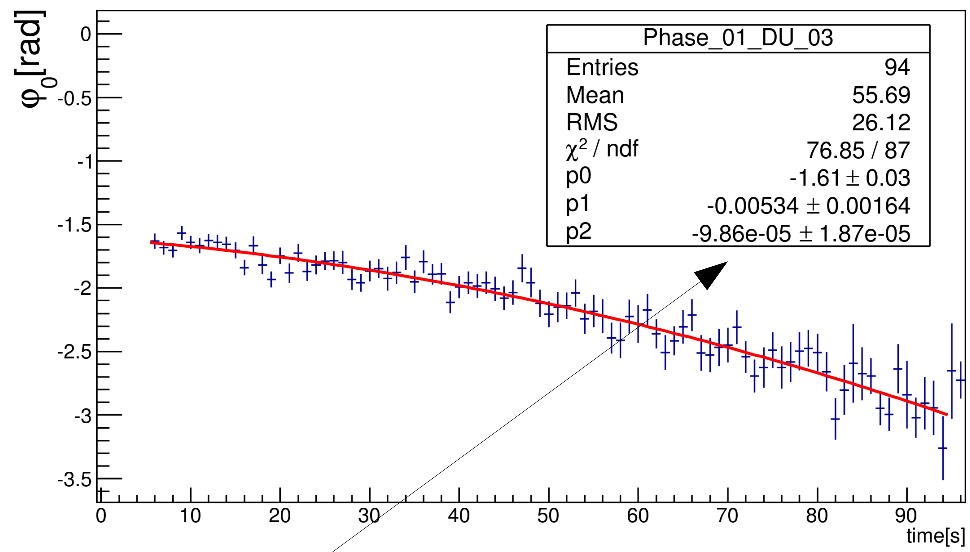


Non perfectly aligned time depending B-field manipulates spin



$$\frac{d\vec{S}}{dt}=\left(\frac{q\vec{B}}{m}(G+1)\right)\times\vec{S}$$

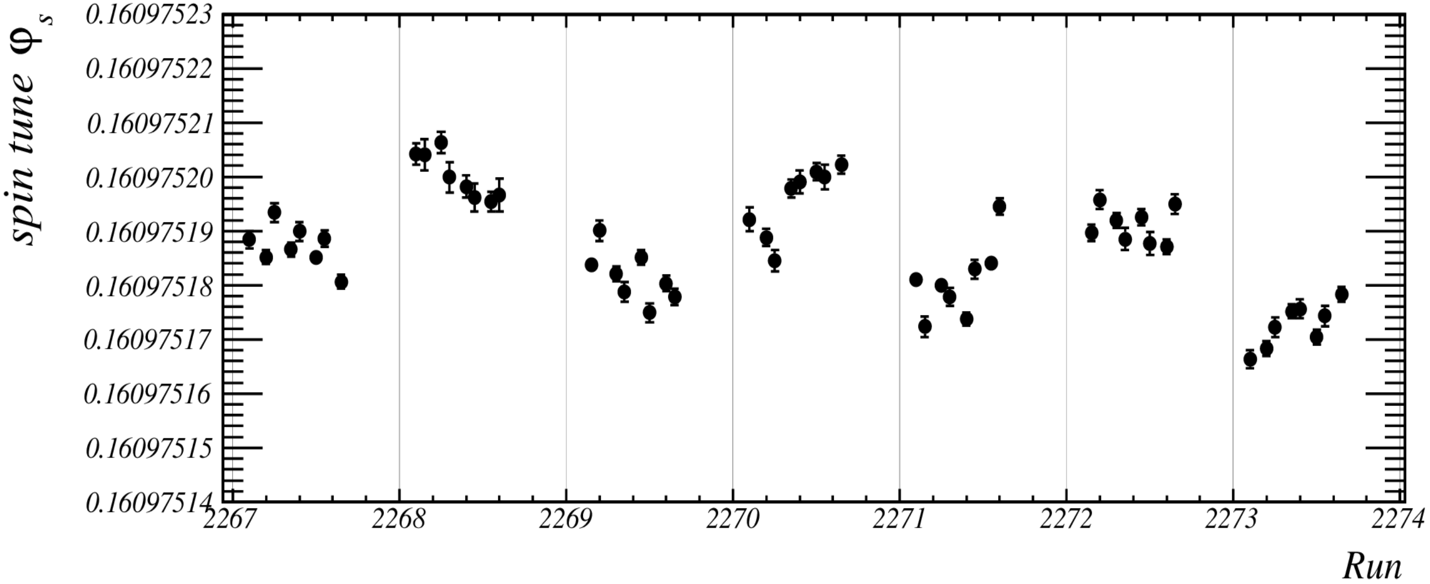
White noise extraction



Spin tune change is one order of magnitude less

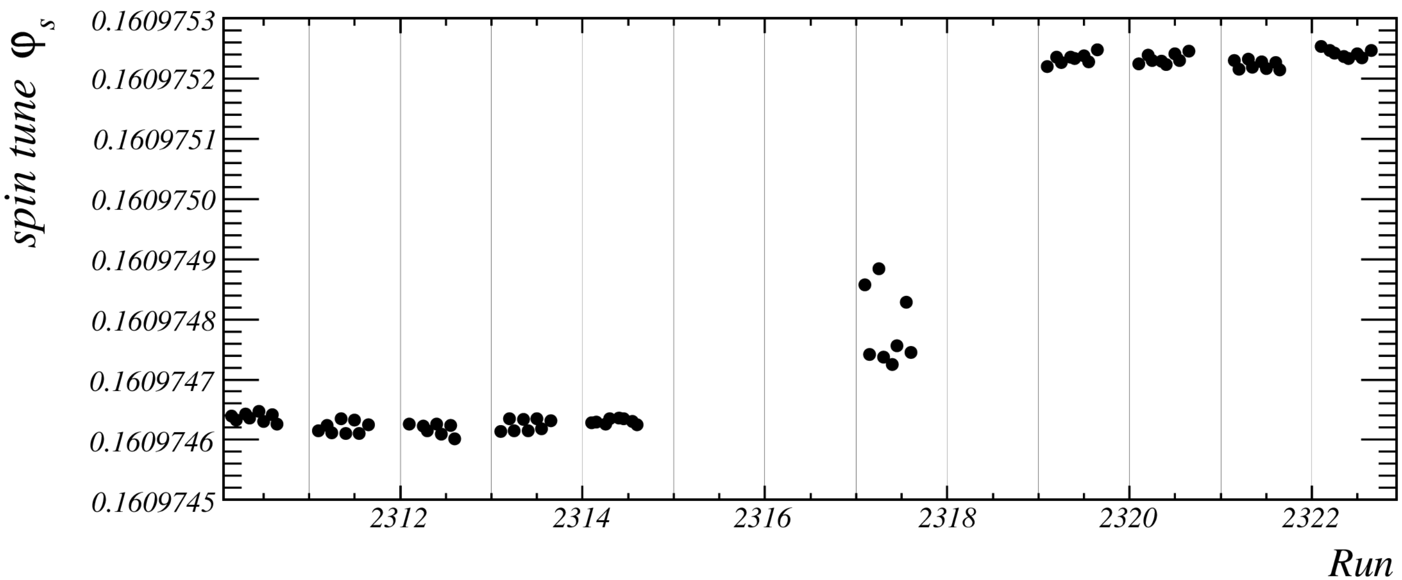
Beam is heated by white noise E-field
↔ random particle extraction
→ in average no spin tune change

Spin tune change



Spin tune jump due to change of sextupoles

$$\Delta \nu_s \sim 10^{-8}$$



Spin tune jump due to change of quadrupoles

$$\Delta \nu_s \sim 10^{-6}$$

Conclusion

Extraction Method	Horizontally	Vertically	White noise
Spintune change $\frac{\Delta \nu_s}{\Delta t}$	$2 \cdot 10^{-9} \frac{1}{s}$	$-0.5 \cdot 10^{-9} \frac{1}{s}$	$-0.1 \cdot 10^{-9} \frac{1}{s}$

PRECISION EXPERIMENT

We are sensitive to a spin tune change of $\mathbf{10^{-10}}$

→ one tool to reach upper EDM limit in the order of $\sigma_d \sim 10^{-24}\, \mathrm{e} \cdot \mathrm{cm}$

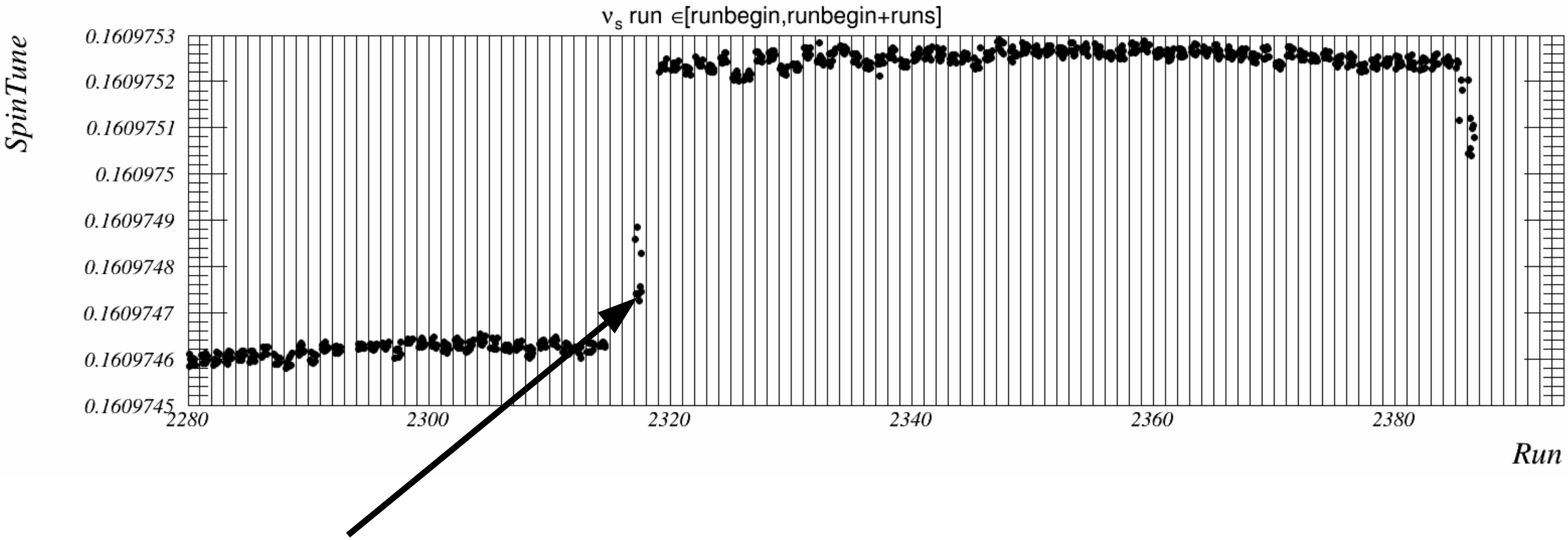
Questions?

Thank you!

Questions?

Spin tune change from cycle to cycle

White noise extraction

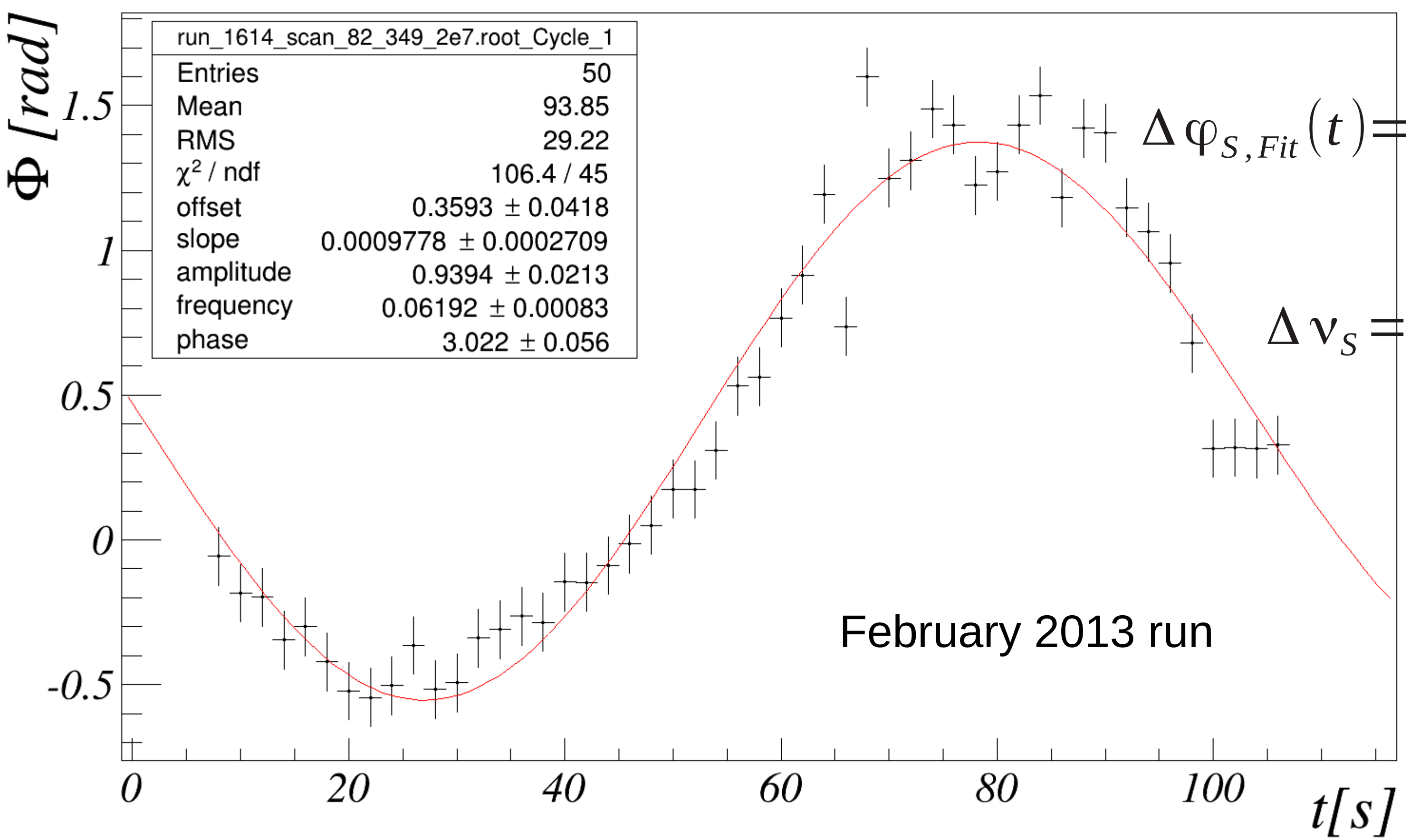


The huge jump is due to the change of the quadrupole magnets.

This was done to move the tune away from potential 3rd order spin resonances

- Time distribution of the asymmetry phase
- The phase distribution of the asymmetry fit describes the spin tune change in one cycle:

$$\Delta\nu_S(t)=\frac{\Delta f_S(t)}{f_{COSY}}=\frac{\Delta\omega_S(t)}{\omega_{COSY}}=\frac{\partial\Delta\varphi_S(t)}{\partial t}\frac{1}{\omega_{COSY}}$$



Is minimized by hitting right spin tune

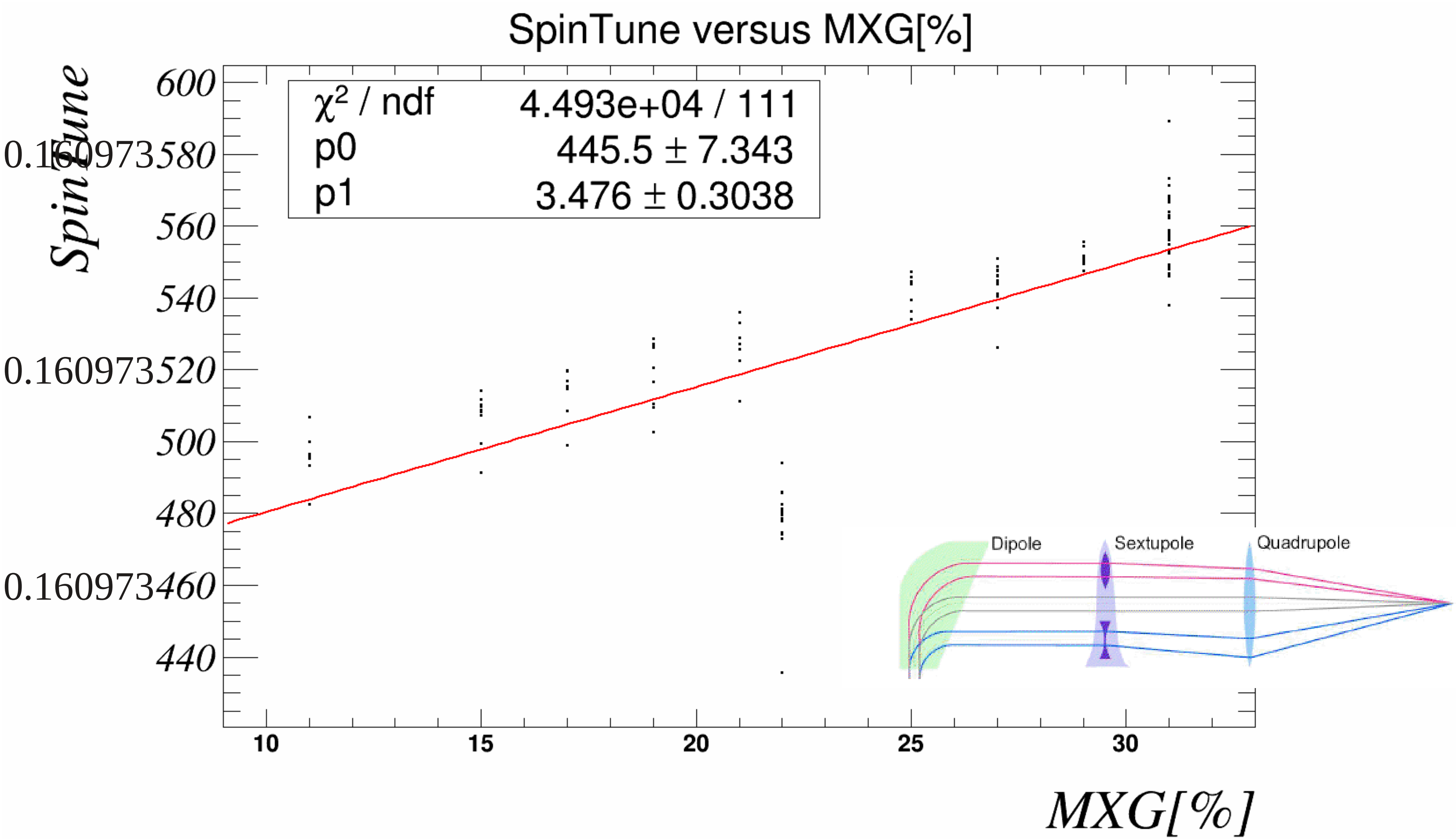
$$\Delta\varphi_{S,Fit}(t)=a+b\cdot t+A_{\varphi_S}\cdot\sin(\omega_{\varphi_S}\cdot t+\varphi)$$

$$\Delta\nu_S=\frac{\partial\Delta\varphi_S(t)}{\partial t}\frac{1}{\omega_{COSY}}=\frac{A_{\varphi_S}\cdot\omega_{\varphi_S}}{\omega_{COSY}}$$

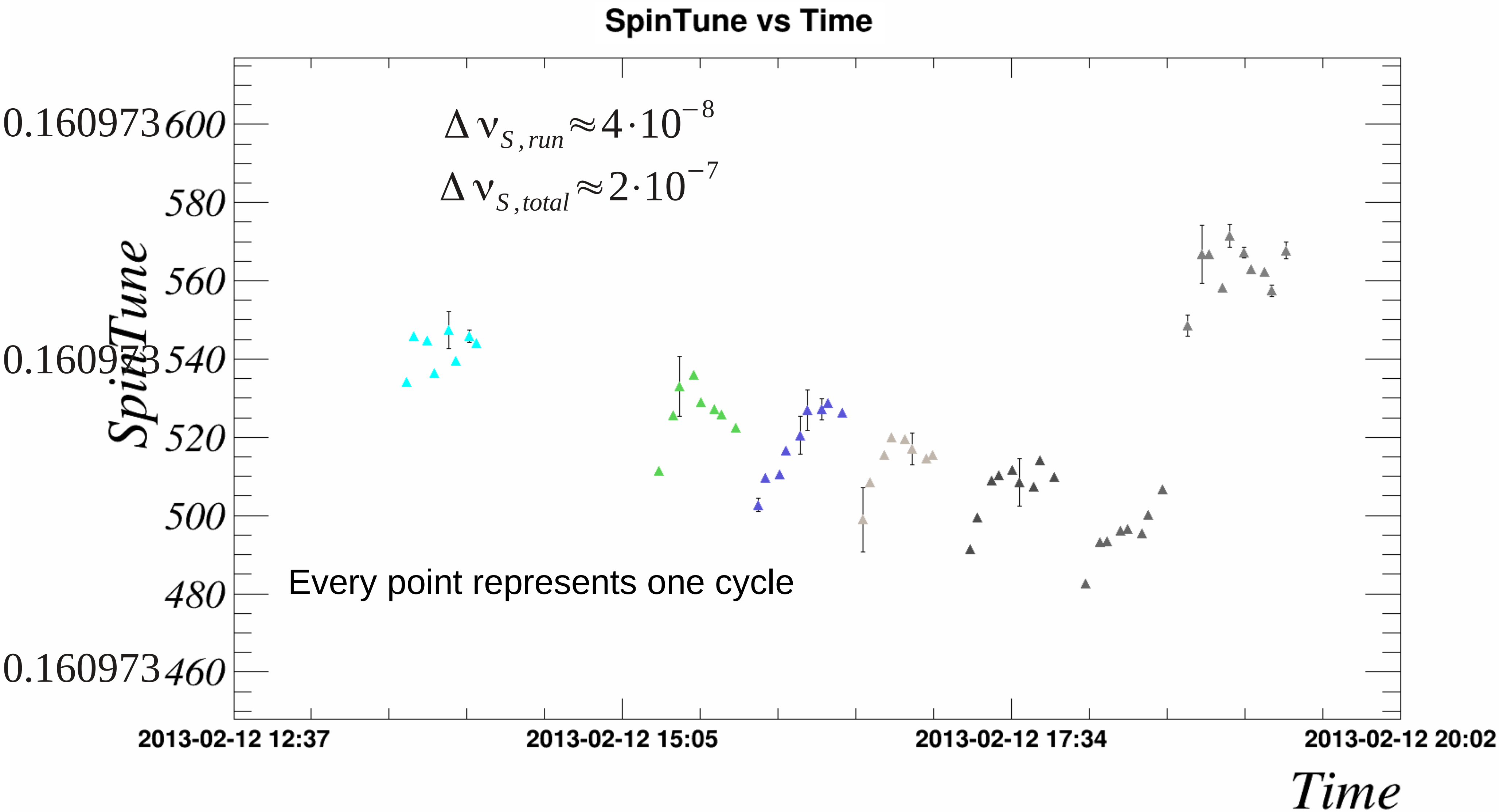
$$\Delta\nu_S=1.08\cdot10^{-8}$$

Spin Tune against Sextupole

A one percent change of the MXG sextupole magnets induces a change of the spin tune of $3.5\cdot 10^{-9} \rightarrow \Delta E = 0.46\ \text{keV}$



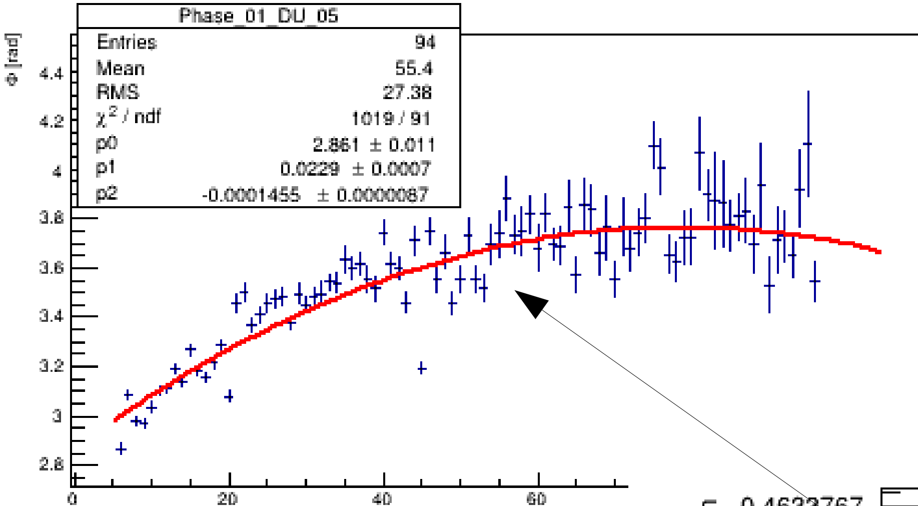
Spin tune distribution for different runs



Spin tune increases at the beginning of each run to get more stable later

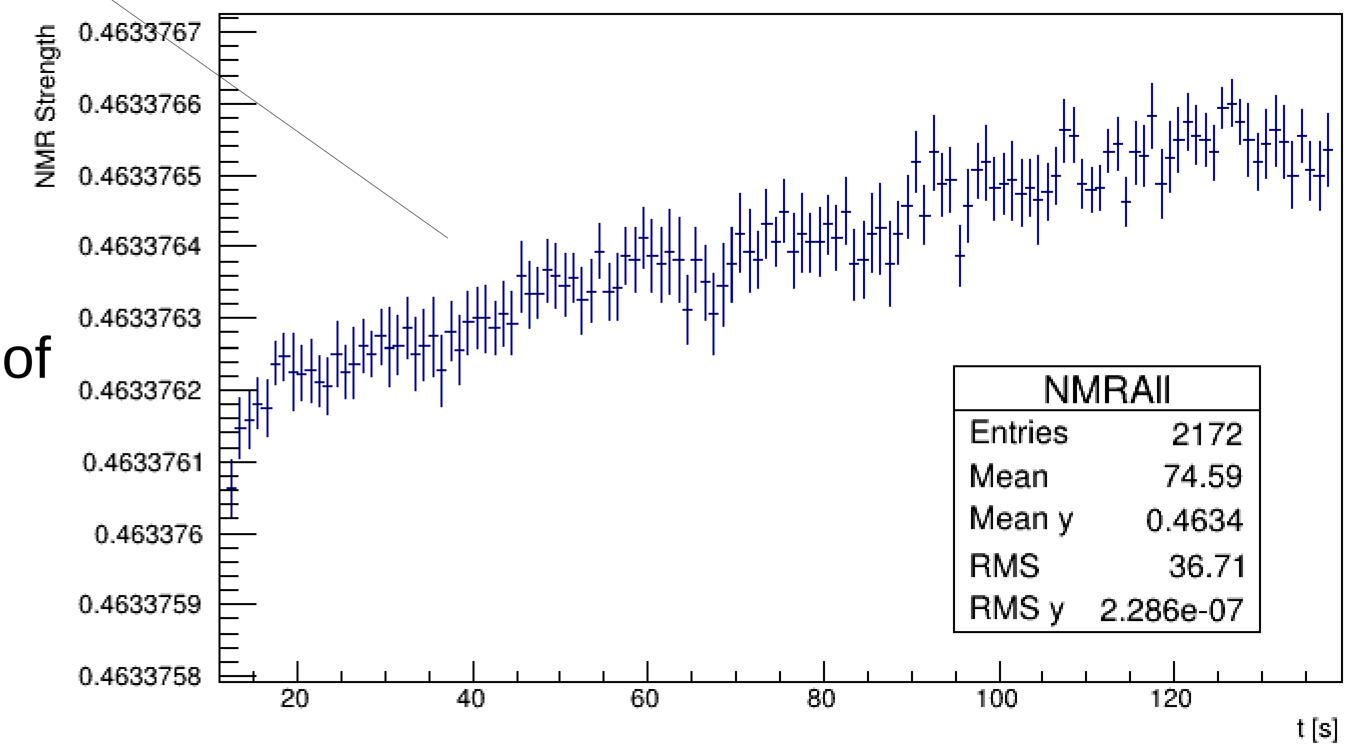
Sep13 Beam Time

EDM Run Sep13 (vertical extraction)



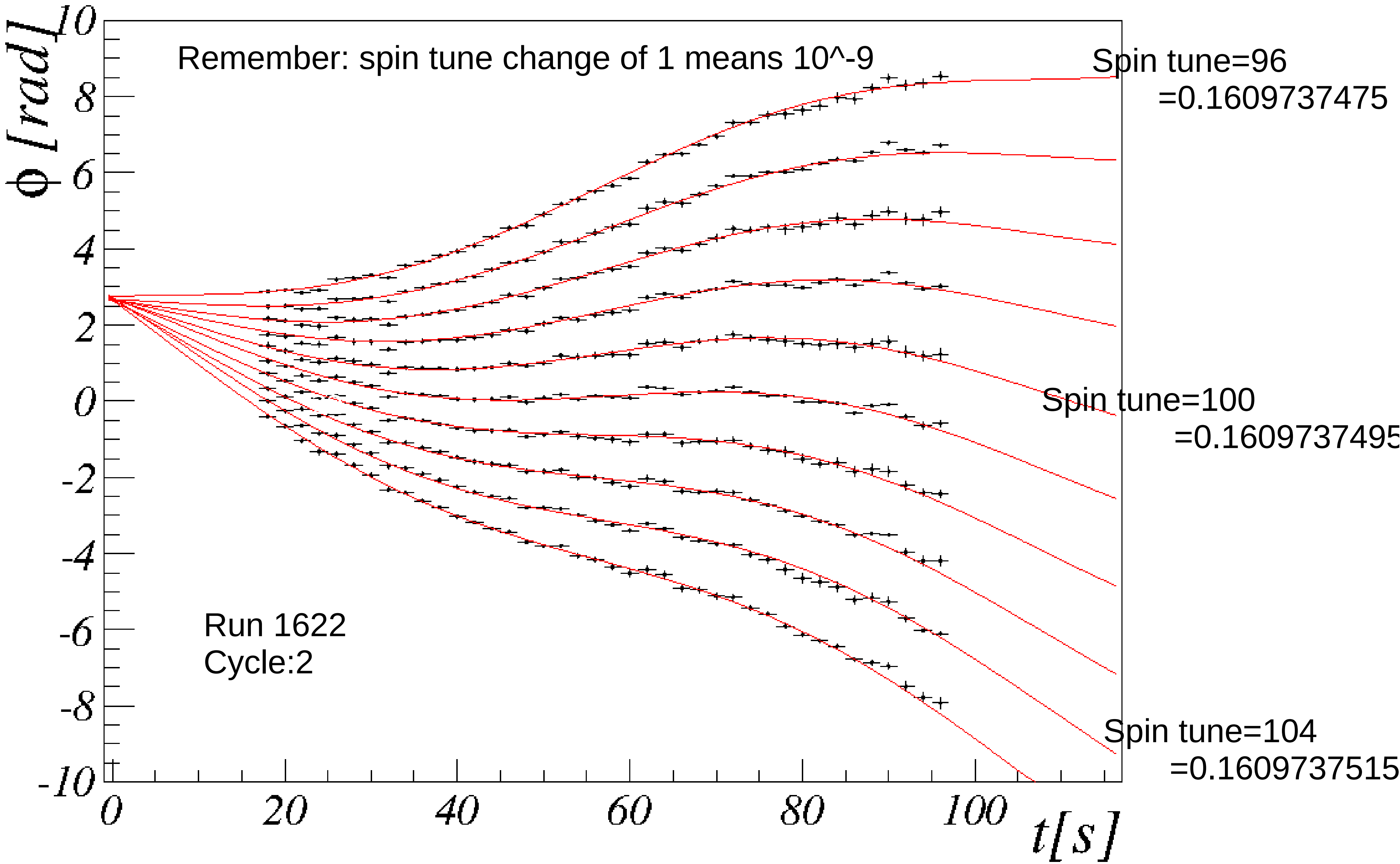
Dipole field increases linearly with time
→ Quadratic phase behavior

One has to investigate the order of magnitude of this effect



Spares

Phase distribution of the asymmetry fit for different spin tunes



- Up-down asymmetry proportional to horizontal polarization

$$A_{UD}=\frac{D-U}{D+U}=P_x A_y$$

- No real time analysis possible due to event rate < $f_{\nu_s}=\nu_S f_{COSY}\approx 120\,kHz$
- Find period of one spin precession ΔT_{ν_s} & sort all events in one ΔT_{ν_s}-intervall
- Precise measurement of the COSY f_{COSY} and solenoid f_{sol} frequencies
- Possibility to calculate spin tune, when solenoid is on resonance

$f_{COSY}\approx 750\,kHz$

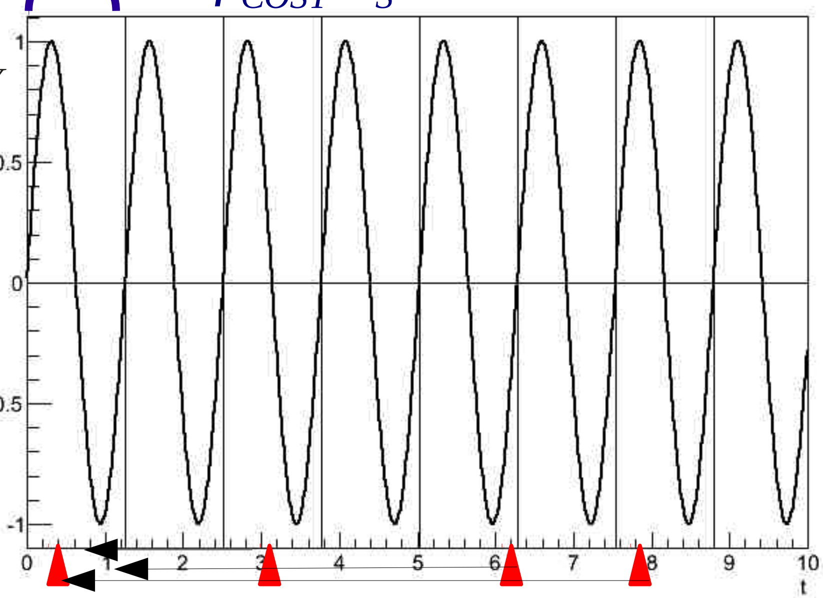
$f_{sol}\approx 871\,kHz$

$\nu_S\approx -0.161$ 1st harmonic

$$f_{sol}=(k\pm\gamma G)f_{COSY}$$

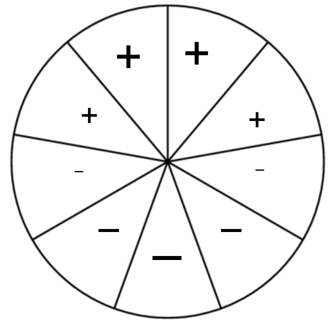
$$\boxed{\rightarrow -\nu_S=-\gamma G=\frac{f_{sol}}{f_{COSY}}-1}$$

$$\underbrace{\Delta T_{\nu_s}}=\frac{2\pi}{f_{COSY}\,\nu_S}\approx 10^{-6}\,s$$



:Sorting events in one 2π -interval

Spares



- 2π divided into 9 bins (phase interval of 40 degrees)
- Absolute angle of the spin precession

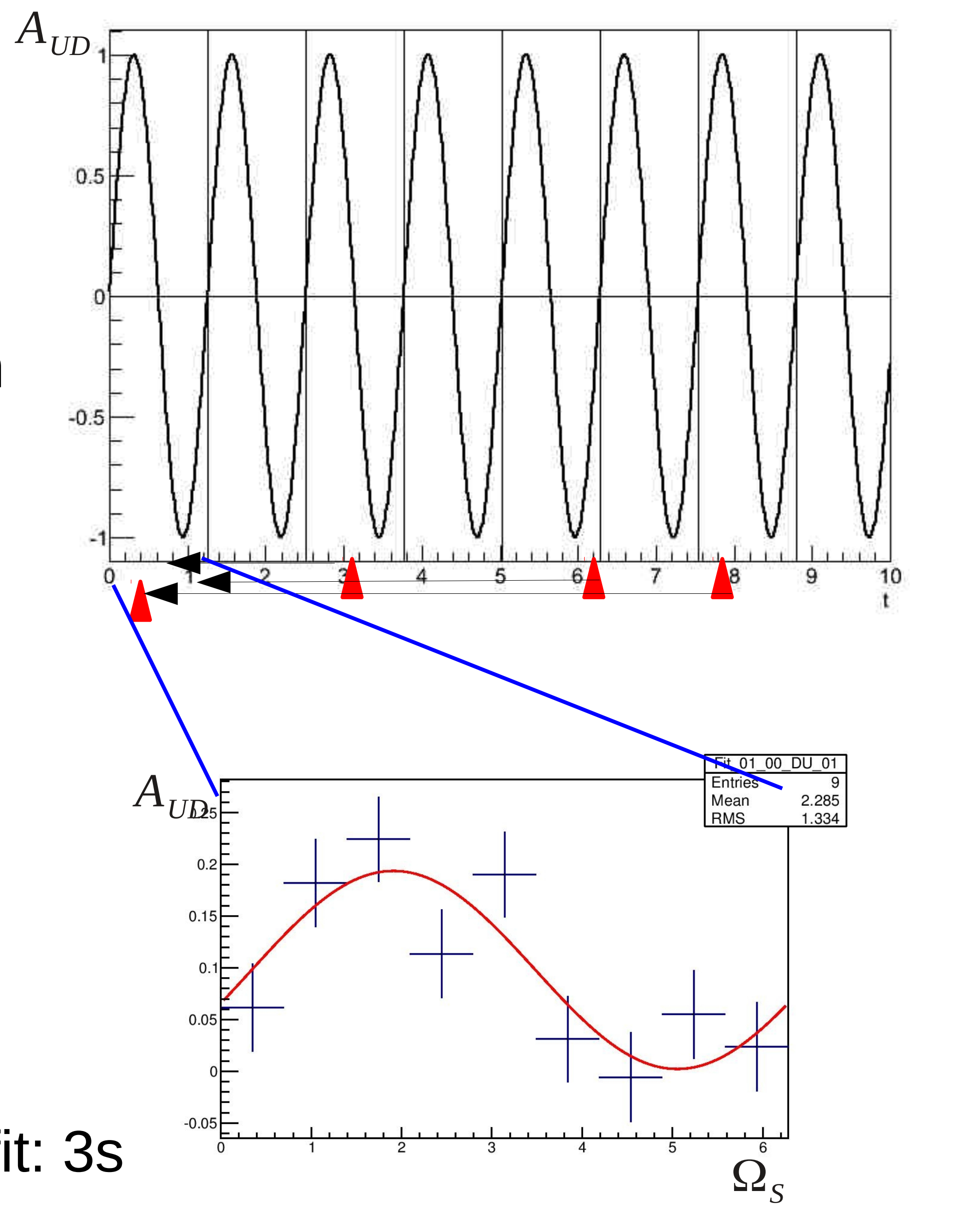
$$\Omega_{S,tot} = 2\pi\,\nu_S\,N_{turn}$$

- Relative phase of the spin: (spin direction) $\Omega_S = \Omega_{S,tot}\; mod\; 2\pi$
- Fit function:

$$f_{A_{UD}}(\Omega_S) = a\sin(\Omega_S + \varphi) + b$$

Free parameters: Amplitude, phase and Offset

- Total time interval of one asymmetry fit: 3s



Energy of the Particle

- Energy of the beam:

$$E=\gamma m c^2=\frac{\nu_S}{G} m c^2=2111.5445 \pm 1\cdot 10^{-4}\ \mathrm{MeV}$$

$$G=-0.14298727$$

$$m=1875.612793\,\frac{MeV}{c^2}$$

$$\nu_s=-0.16097352$$

- Momentum of the beam:

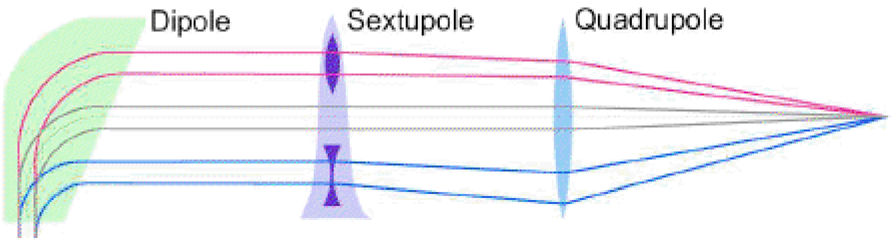
$$p=\sqrt{E^2-m^2}=969.8952\pm 4\cdot 10^{-4}\ \frac{\mathrm{MeV}}{\mathrm{c}}$$

- Energy shift of the beam during one cycle:

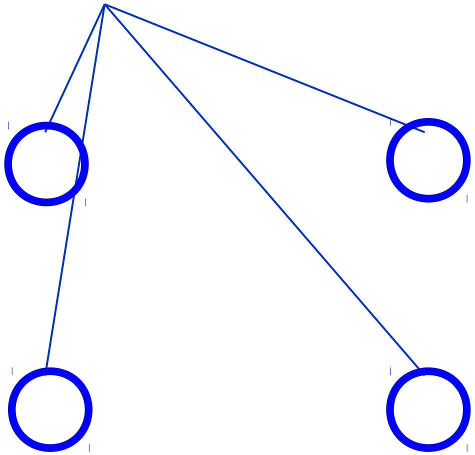
$$\Delta E=\Delta\gamma m c^2=\frac{\Delta\nu_S}{G} m c^2=1.3\ \mathrm{keV}$$

Sextupole Magnets

Correction of Chromaticity

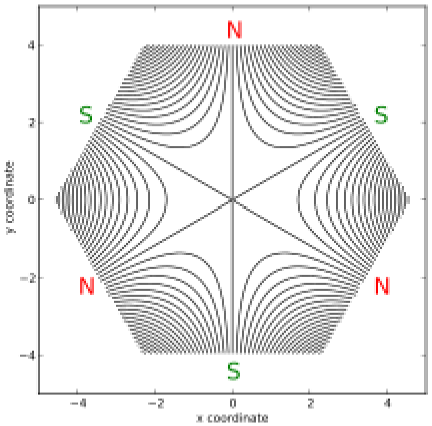


Sextupole magnets at high β_x



Magnetic fields:

$$B_y = \frac{1}{2}\frac{\partial^2 B_y}{\partial x2}(x^2 - y^2) \qquad B_x = \frac{1}{2}\frac{\partial^2 B_y}{\partial x2} xy$$



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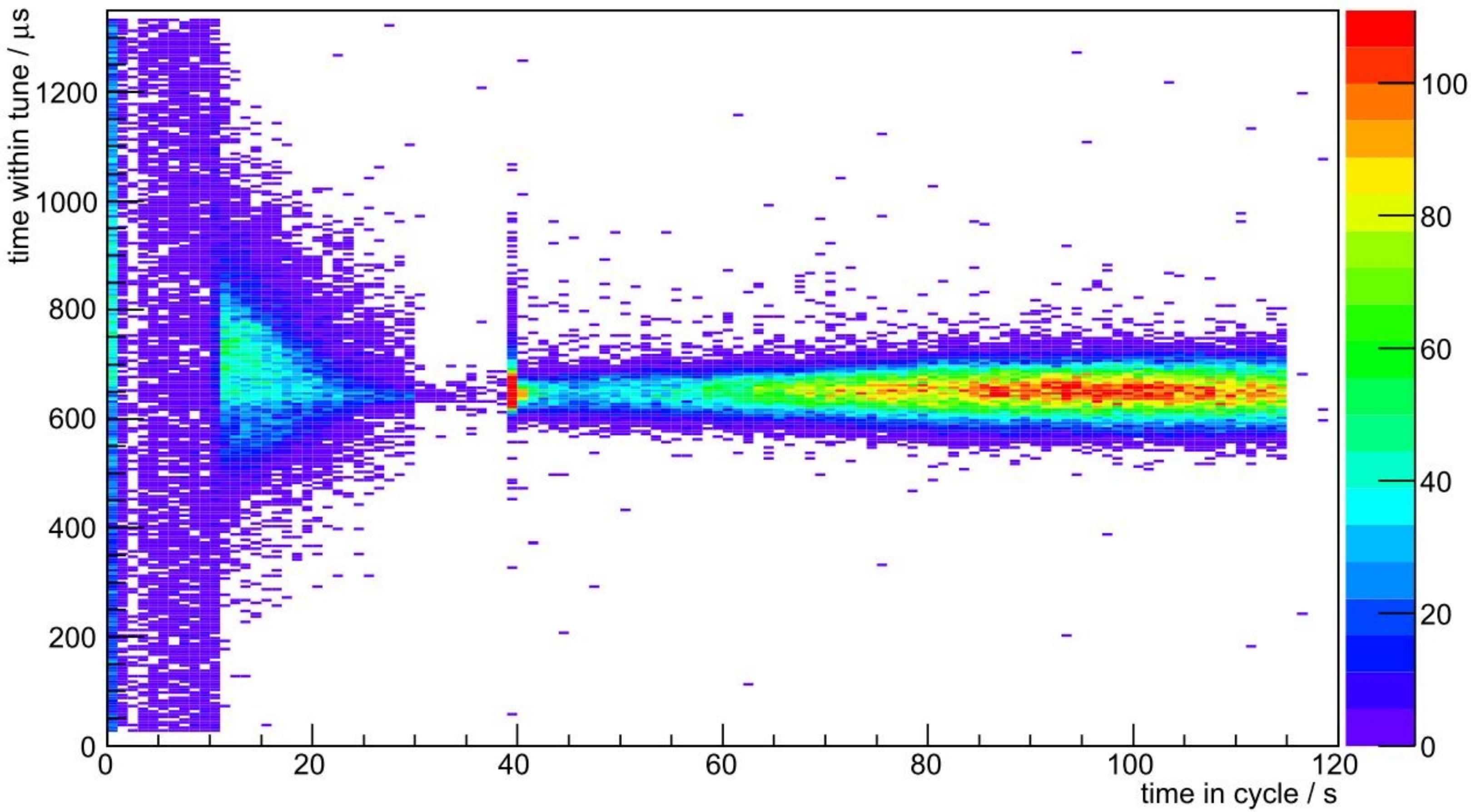

time within tune / µs
time in cycle / s
0
200
400
600
800
1000
1200
20
40
60
80
100
120