Studies of systematic limitations in the EDM searches at COSY

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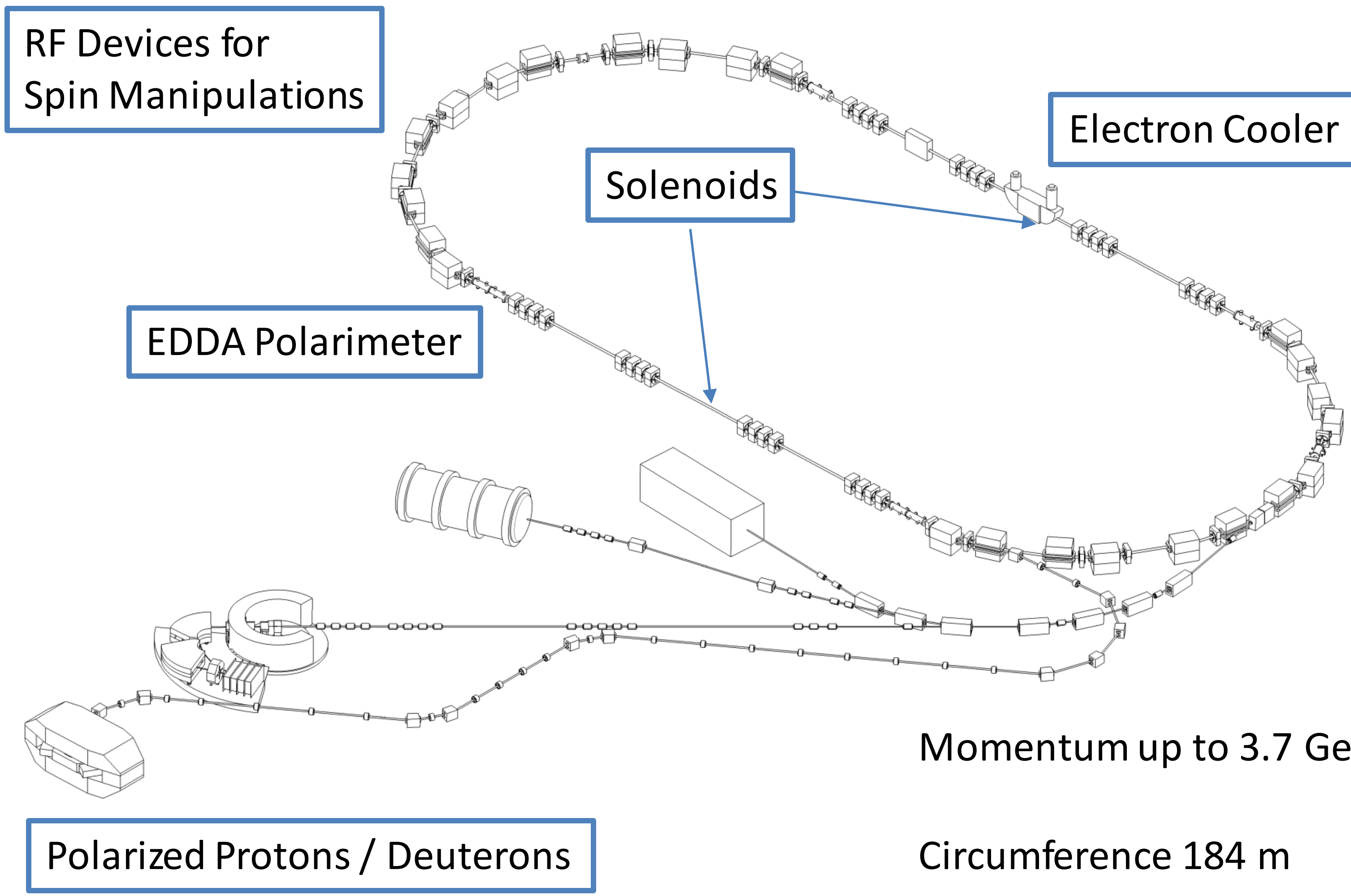
Outline

- Exploring the COSY ring for Electric Dipole Moment (EDM) studies (JEDI - Jülich Electric Dipole moment Investigations)
- Imperfection background to EDM spin precession
- Mapping the spin tune with static solenoids
- Summary

Cooler Synchrotron COSY in Jülich



Momentum up to 3.7 GeV/c,

Circumference 184 m

Spin Motion in Storage Ring

- *Thomas BMT eqn. for the Magnetic Dipole Moment (MDM)*

$$\frac{d\vec{S}}{dt} = \vec{S} \times \vec{\Omega}_{MDM}$$

$$\vec{\Omega}_{MDM} = \frac{q}{m}\left(G\vec{B} - \left(G - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c} - \frac{G\gamma}{\gamma + 1}\vec{\beta}(\vec{\beta} \cdot \vec{B}) \right)$$

Spintune ≔ Number of spin turns relative to particle turns, for the ideal pure magnetic ring like COSY:

$$\nu_s := \frac{\left|\vec{\Omega}_{MDM}\right|}{\omega_{rev}} = \frac{\frac{q}{m}GB}{\frac{q}{m\gamma}B} = \gamma G$$

Spin Precession by EDM in Pure Magnetic Ring

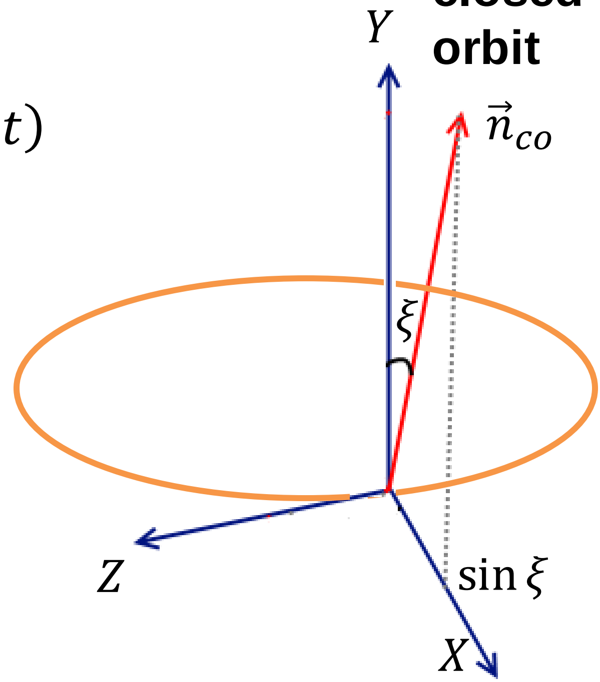
- If particle has $d \neq 0$, T-BMT equation takes form

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

- Interaction of the EDM with the motional E-field tilts the stable spin axis (or "spin closed orbit"):

$$\vec{n}_{co} = \left(\vec{e}_x \sin\xi + \vec{e}_y \cos\xi\right)$$

$$\tan\xi = -\frac{\eta}{G}\beta \qquad \eta = d\frac{m}{q}$$



- Observable spin evolution:

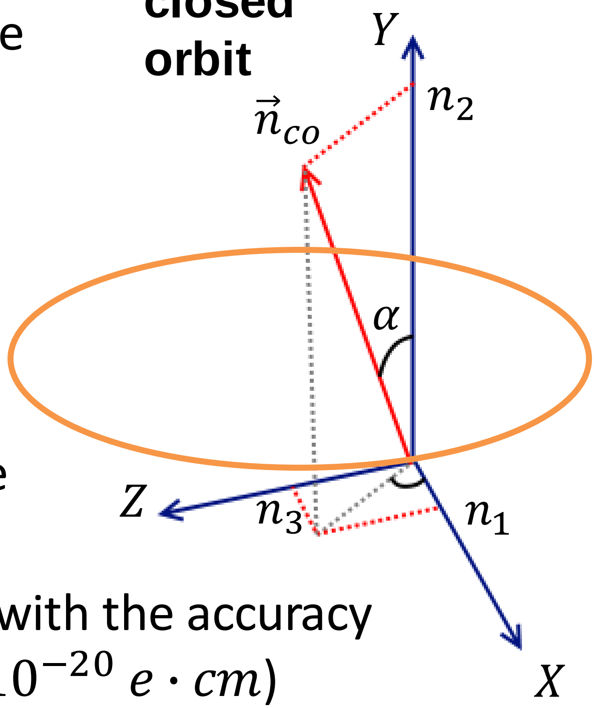
$$\vec{S}(t) = \hat{R}(\vec{n}_{co}, \nu_s)\,\vec{S}(0)$$

- The JEDI Collaboration aims at a first direct measurement of the deuteron and proton Electric Dipole Moment (EDM) at COSY

Imperfection In-plane Fields

- A current task for JEDI: exploring the EDM dynamics and systematic limitations of the EDM searches at all magnetic rings

Spin closed orbit



- Misalignment of any magnetic elements produces the in-plane imperfection magnetic fields
- Imperfection spin kicks perturb $\vec{n}_{co}$ and ν_s:

$$\vec{n}_{co} = \left(\vec{e}_x n_1 + \vec{e}_y n_2 + \vec{e}_z n_3\right)$$
$$\nu_s = G\gamma + O(a^2)$$

- The nonvanishing n_1 and n_3 generate a background to the EDM-signal of the ideal imperfection-free case

$$n_1 = \sin\xi\,, \qquad n_3 = 0$$

- The challenge is to control background (for example with the accuracy $n_1 \sim 10^{-6}\, rad$ would amount to sensitivity for $d = 10^{-20}\, e\cdot cm$)

Mitglied der Helmholtz-Gemeinschaft

EDDA Polarimeter

- ***Left-Right*** asymmetry

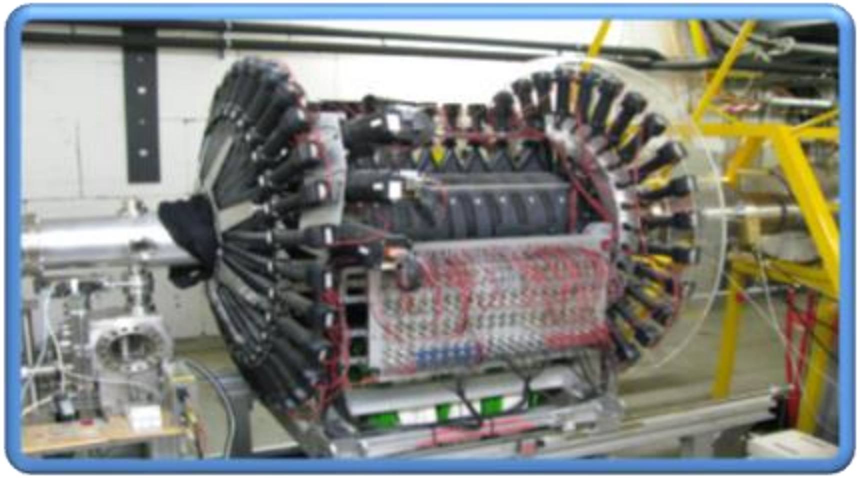
  ⇒ ***vertical*** polarization

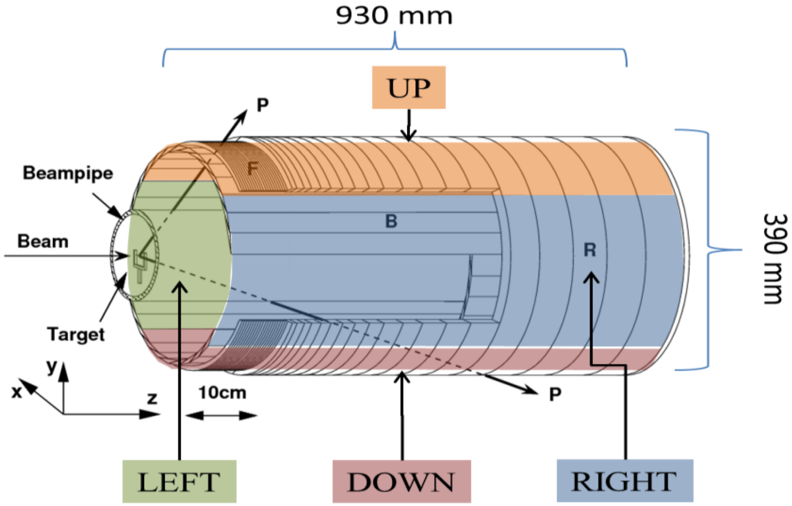
$$P_V \propto \epsilon_{ver} = \frac{N_l - N_r}{N_l + N_r}$$

- ***Up-Down*** asymmetry

  ⇒ ***horizontal*** polarization

$$P_H \propto \epsilon_{hor} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}}$$





Spin Tune Measurement

- Spin vector precesses with $f_{\text{Spin}} = \nu_s f_{rev}$ in the horizontal plane around spin closed orbit $\vec{n}_{co}$

- Asymmetry is given by:

$$\epsilon_{hor}(t) = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} \approx AP(t)\sin(2\pi\nu_s f_{rev} t + \phi)$$

- What do we expect? (Deuterons, $p = 0.97$ GeV/c)

$$\nu_s \approx 0.16, \qquad f_{rev} = 750\ \text{kHz}$$

- Spin precession frequency: $\nu_s \cdot f_{rev} \approx 120\ \text{kHz}$

- Special spin tune analysis software resolves ν_s with an accuracy 10^{-8} in 1-second interval

Spin Tune Response to the Artificial Imperfections

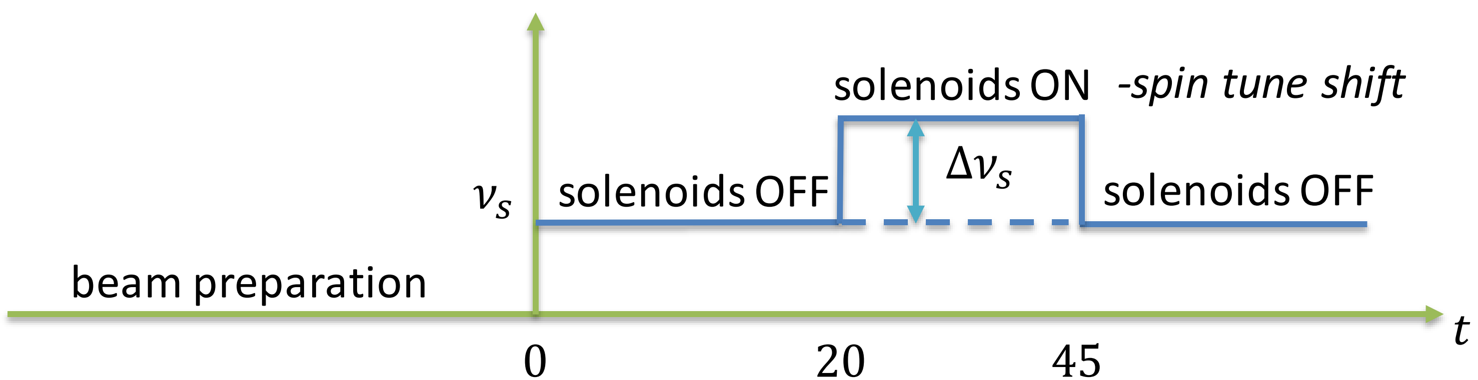
- The spin tune is perturbed by spin kicks in the ring imperfection fields:

$$\nu_s = G\gamma + O(n_1^2, n_3^2)$$

- The idea is to probe the in-plane imperfection fields by introducing well-known *artificial imperfections.*
- Artificial imperfections: spin kicks χ_1 and χ_2 by compensation solenoids from e-coolers in straight sections

$$\nu_s + \Delta\nu_s = G\gamma + O(n_1^2, n_3^2, \chi_1^2, \chi_2^2)$$

- Perform the measurement:



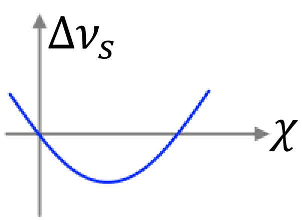
Probing the ring imperfections

- Parabolic dependency of spin tune w.r.t. artificial imperfection spin kick χ, depends on the ring $\vec{n}_{co}$ at the point of the applied kick

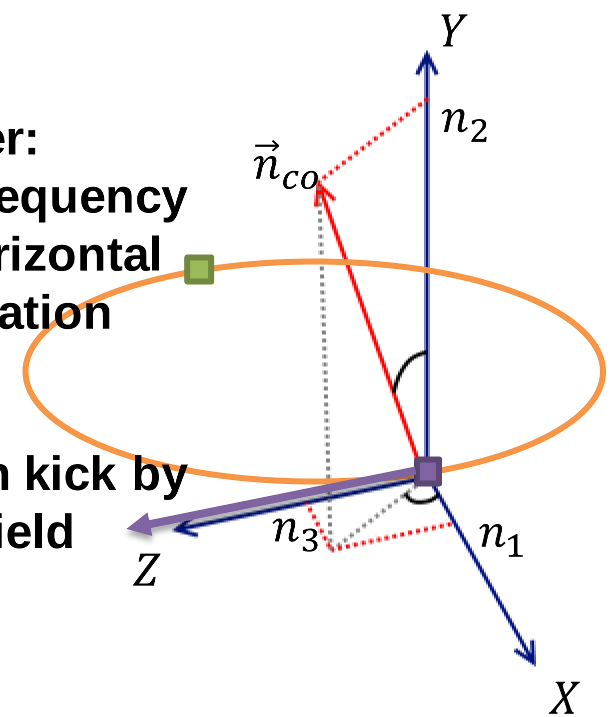
- If spin kick is from pure solenoid field, then:

$$\cos\pi(\nu_s + \Delta\nu_s) = \cos\pi\nu_s \cos\frac{\chi}{2} + n_3 \sin\pi\nu_s \sin\frac{\chi}{2}$$

- where $\Delta\nu_s$ is spin tune shift:



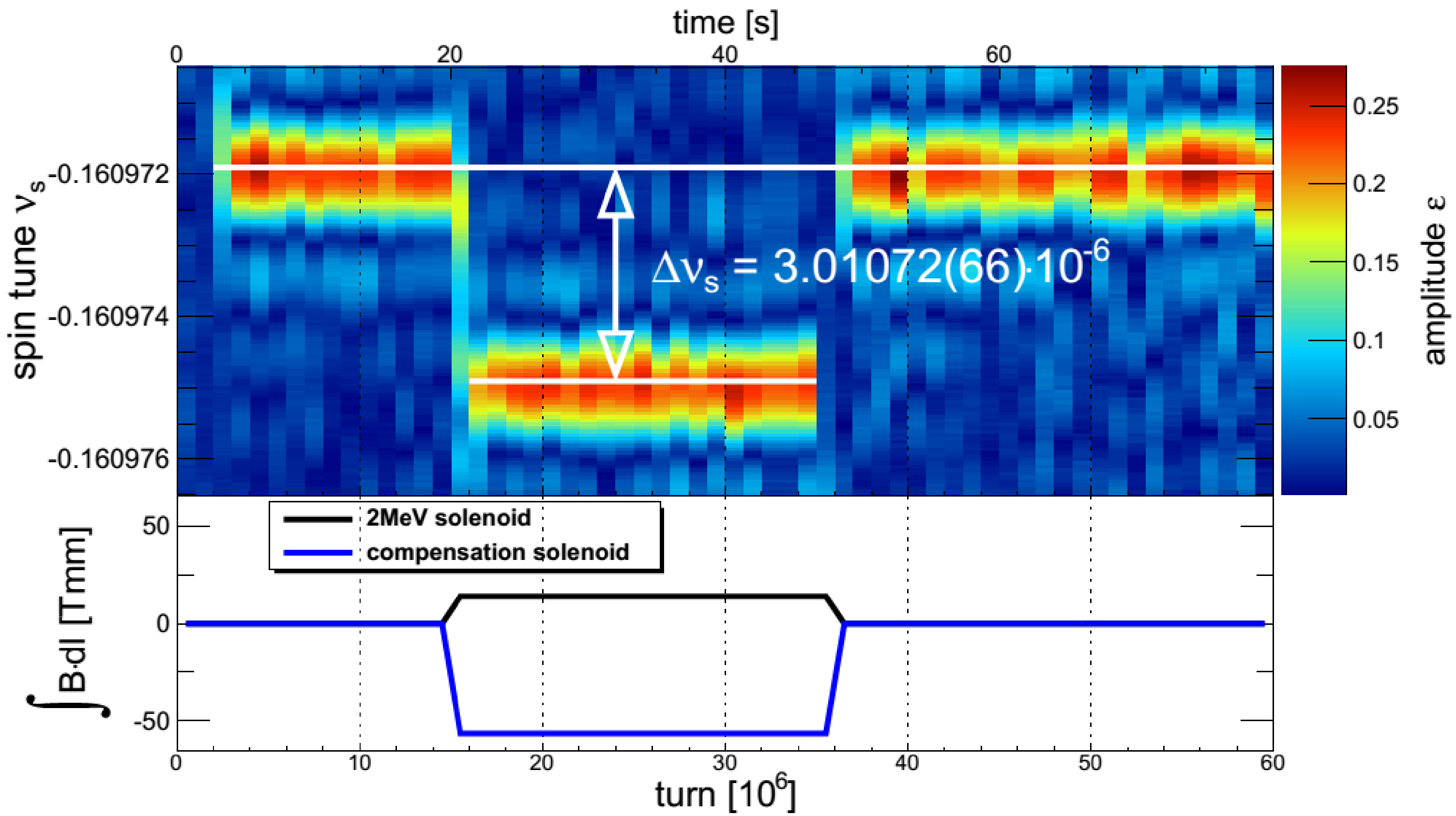
Polarimeter: observe frequency shift in horizontal spin oscillation



Apply spin kick by solenoid field

Measurement of Spin Tune Shift

- Spin tune shift registered in the data analysis:



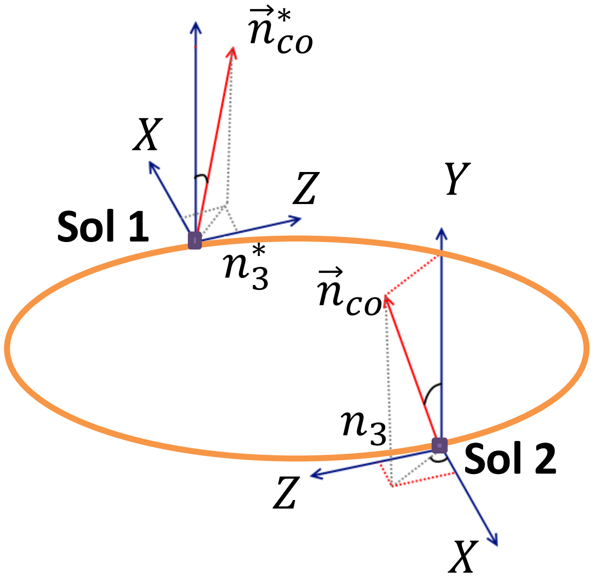
- The spin tune shift was observed at $t = [20, 45]\ s$

Two solenoids probe $\vec{n}_{co}$ at 2 points of the ring

- When 2 solenoids turned on simultaneously:

$$\cos\pi(\nu_s + \Delta\nu_s) = \cos\pi\nu_s \cos\frac{\chi_1}{2}\cos\frac{\chi_2}{2} - \sin\pi\nu_s\, n_3^* \sin\frac{\chi_1}{2}\cos\frac{\chi_2}{2}$$
$$-E\sin\frac{\chi_1}{2}\sin\frac{\chi_2}{2} - \sin\pi\nu_s\, n_3 \sin\frac{\chi_2}{2}\cos\frac{\chi_1}{2}$$

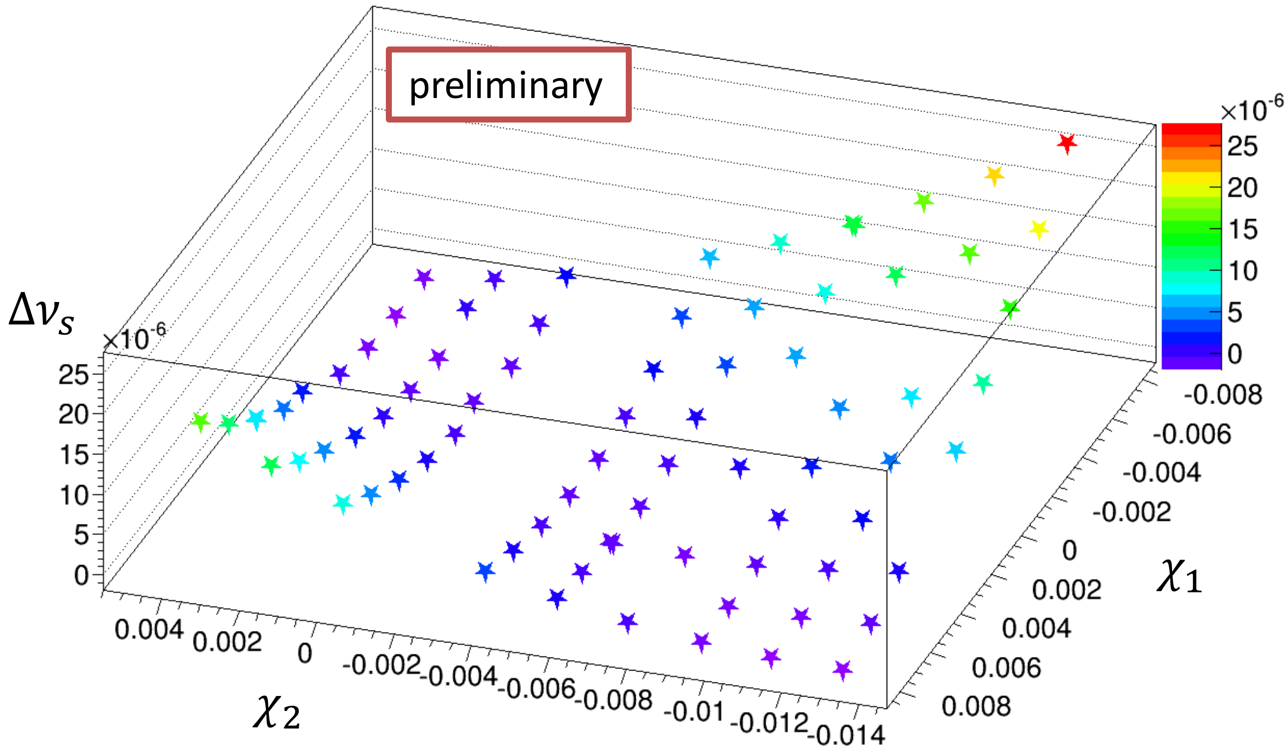
- ν_s - base spin tune
- $\Delta\nu_s$ - a spin tune shift
- $E \approx 1$



- Any deviation from $\Delta\nu_s(\chi_1, \chi_2)$-dependence is related to field errors and orbit perturbation

The Spin Tune Mapping

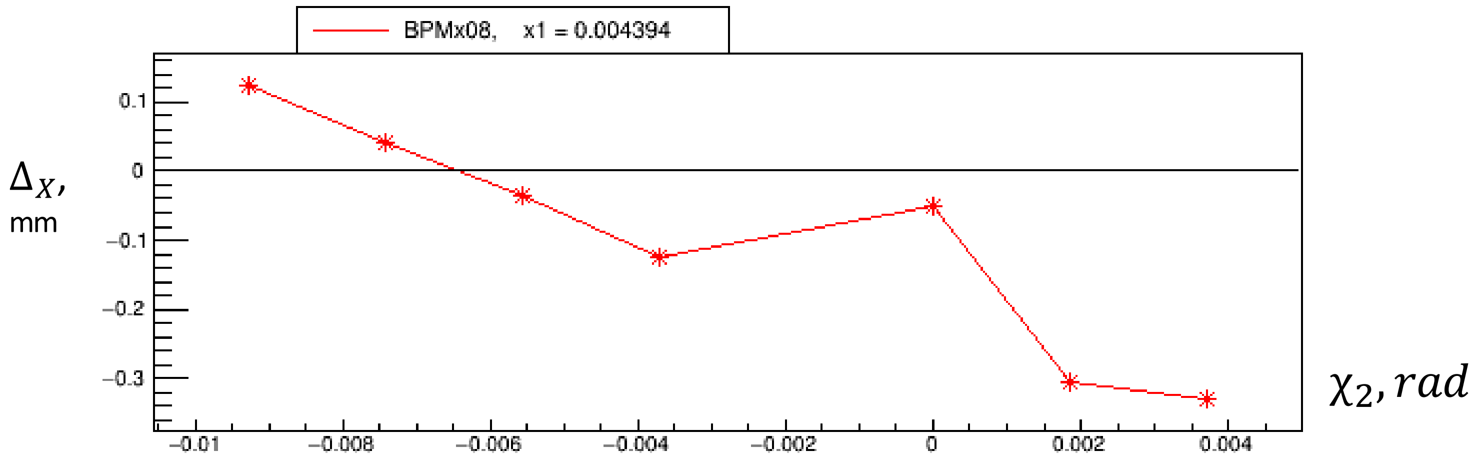
Take multiple measurements with different χ_1 , χ_2 and build a spin tune map $\Delta\nu_s(\chi_1, \chi_2)$:

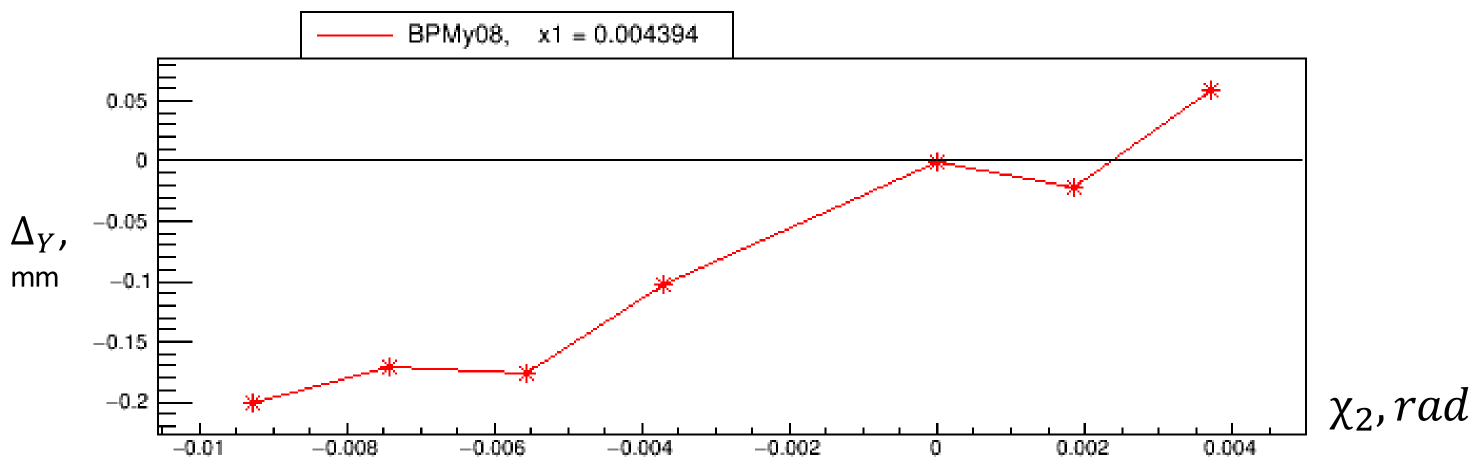


- Spin tune shift w.r.t. the solenoid spin kicks, $\Delta\nu_s \sim \chi_1^2$, $\Delta\nu_s \sim \chi_2^2$

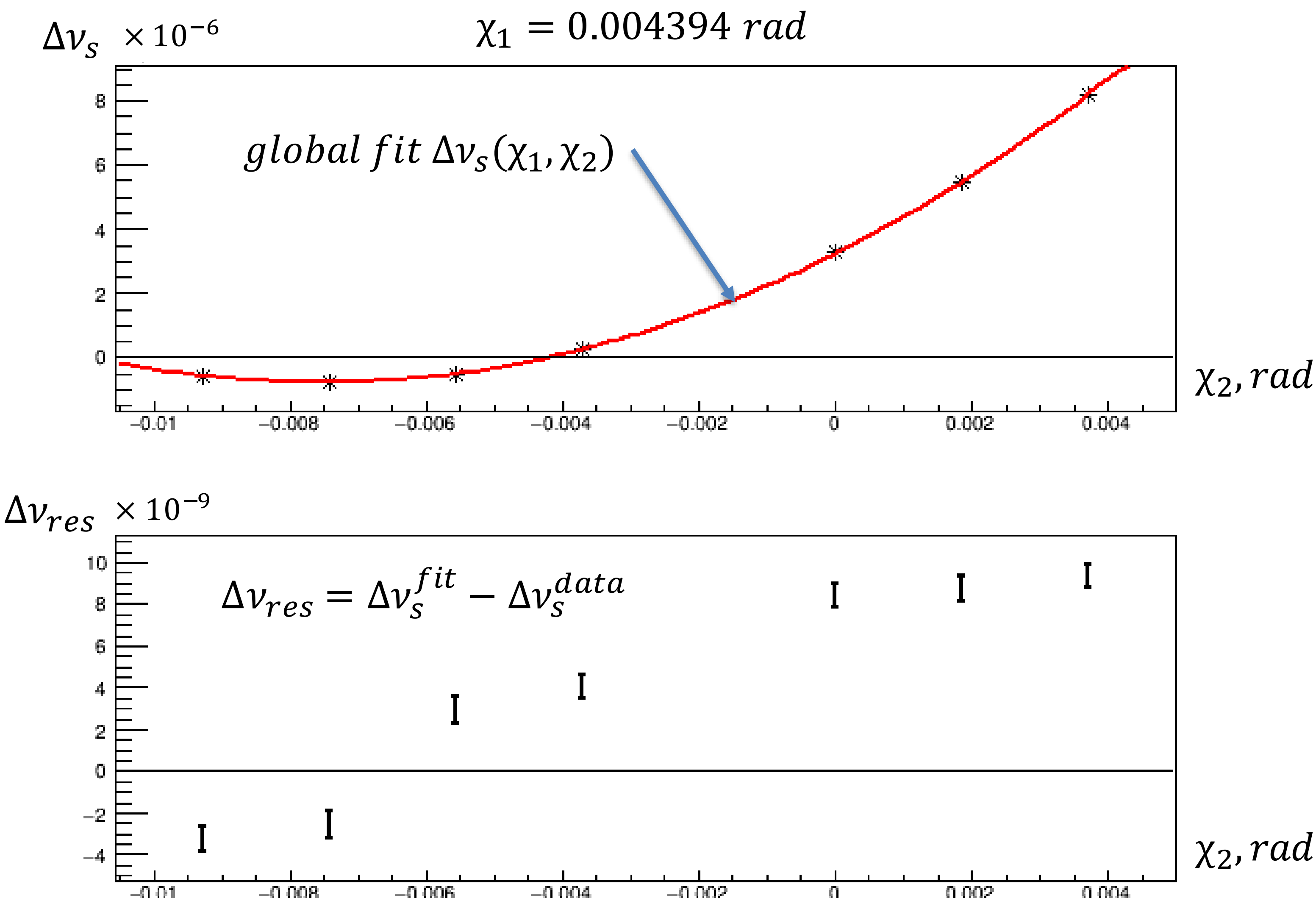
The orbit perturbation by solenoid

- Relative orbit shift measured by one of the BPMs when solenoids are turned on:





The spin tune perturbation by solenoid



The Spin Tune Mapping

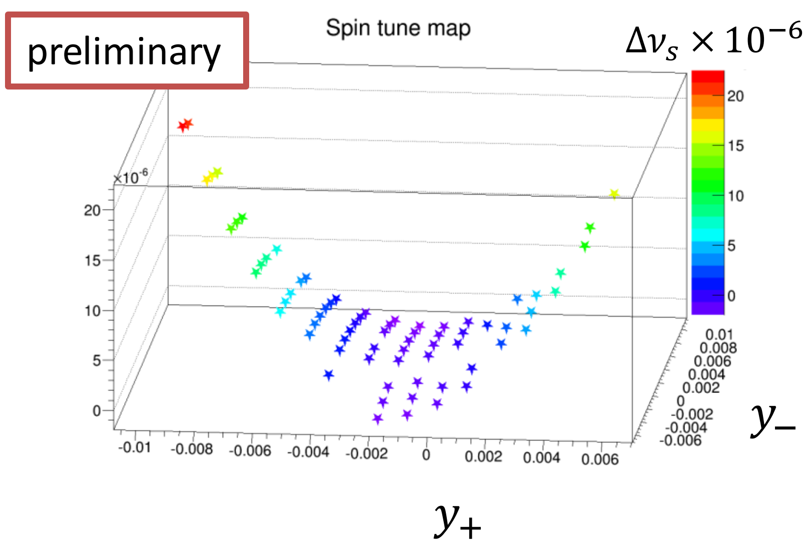
- If the kicks are translated to:

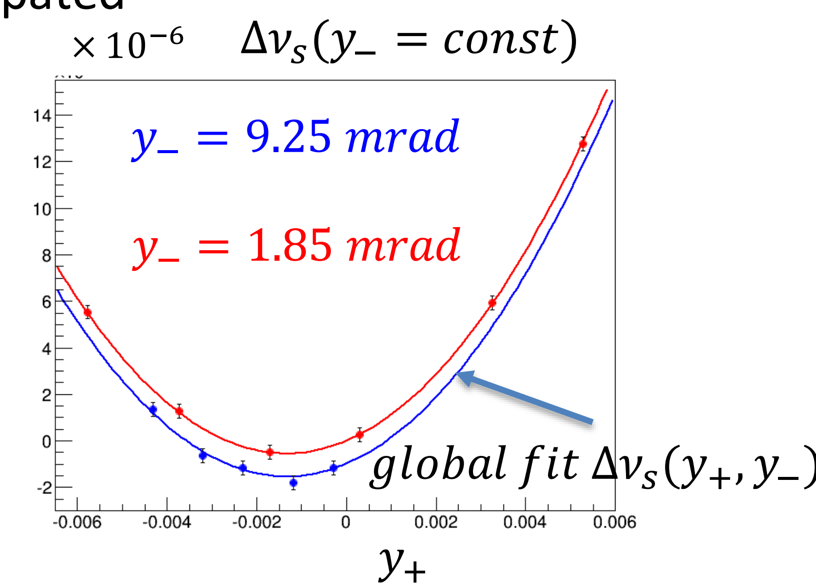
$$y_+ = \frac{1}{2}(\chi_1 + \chi_2) \qquad y_- = \frac{1}{2}(\chi_1 - \chi_2)$$

- then

$$\Delta\nu_s \propto -(y_- - a_-)^2, \qquad \Delta\nu_s \propto (y_+ - a_+)^2$$

- The distributions of the data points in $y_\pm$ dimension share common parabolic features : equal curvature and extremum $a_\pm$
- It is a sign that the solenoids work as anticipated





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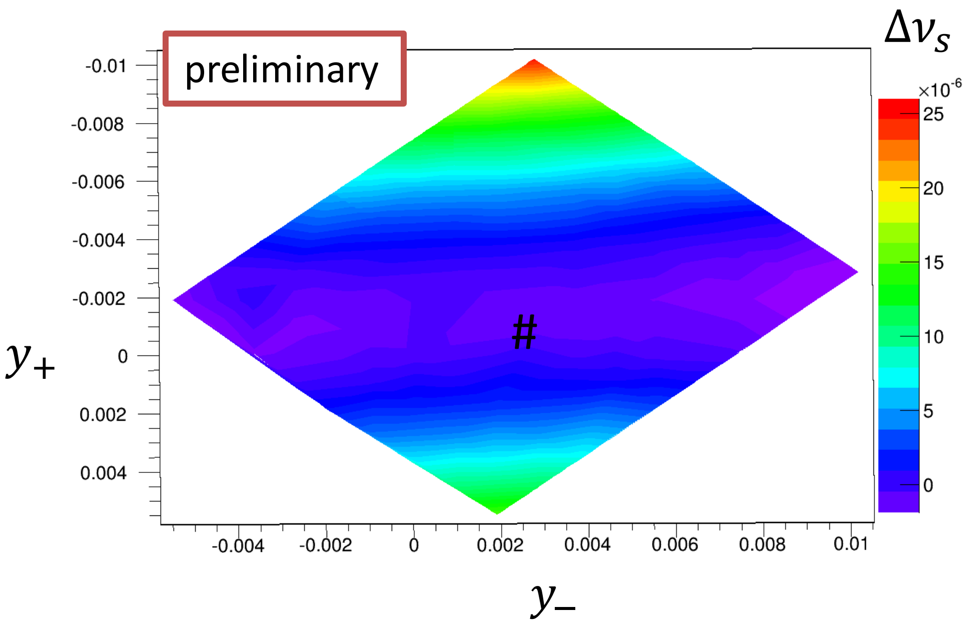
Imperfection Strength



The fitted saddle point at #:

$$a_+ = -0.00111077 \pm 6.1 * 10^{-8} \text{ rad}$$

$$a_- = 0.00244326 \pm 2.1 * 10^{-7} \text{ rad}$$

$$n_3 = -0.00299124 \pm 1.8 * 10^{-7}$$

$$n_3^* = -0.00163653 \pm 7.1 * 10^{-8}$$

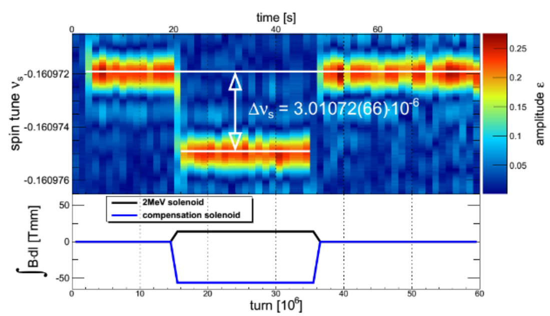
- Position of the saddle point measures projections of SCO, n_3 and n_3^*
- Strength of imperfection fields in the ring is at the level of $\approx 3\ Tmm$

- For an ideal ring, the saddle point would be at $a_\pm = 0$

Summary

- The technique of spin tune measurement appears as a precision tool for the systematic analysis of the ring imperfections

- First high precision measurement of the imperfection fields at COSY



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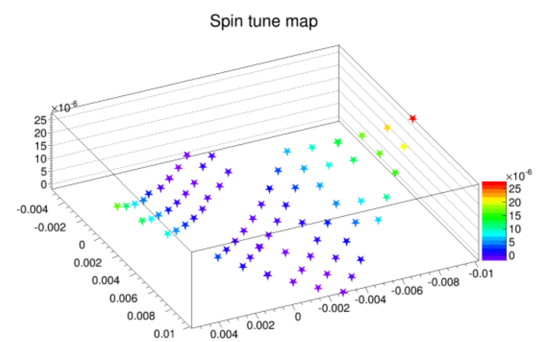


❖ The ultimate goal of the JEDI: to understand the EDM dynamics in storage rings as a prerequsite to the construction of the dedicated storage ring for the EDM searches

More Details About Spin Tune Analysis

Sorting the Events

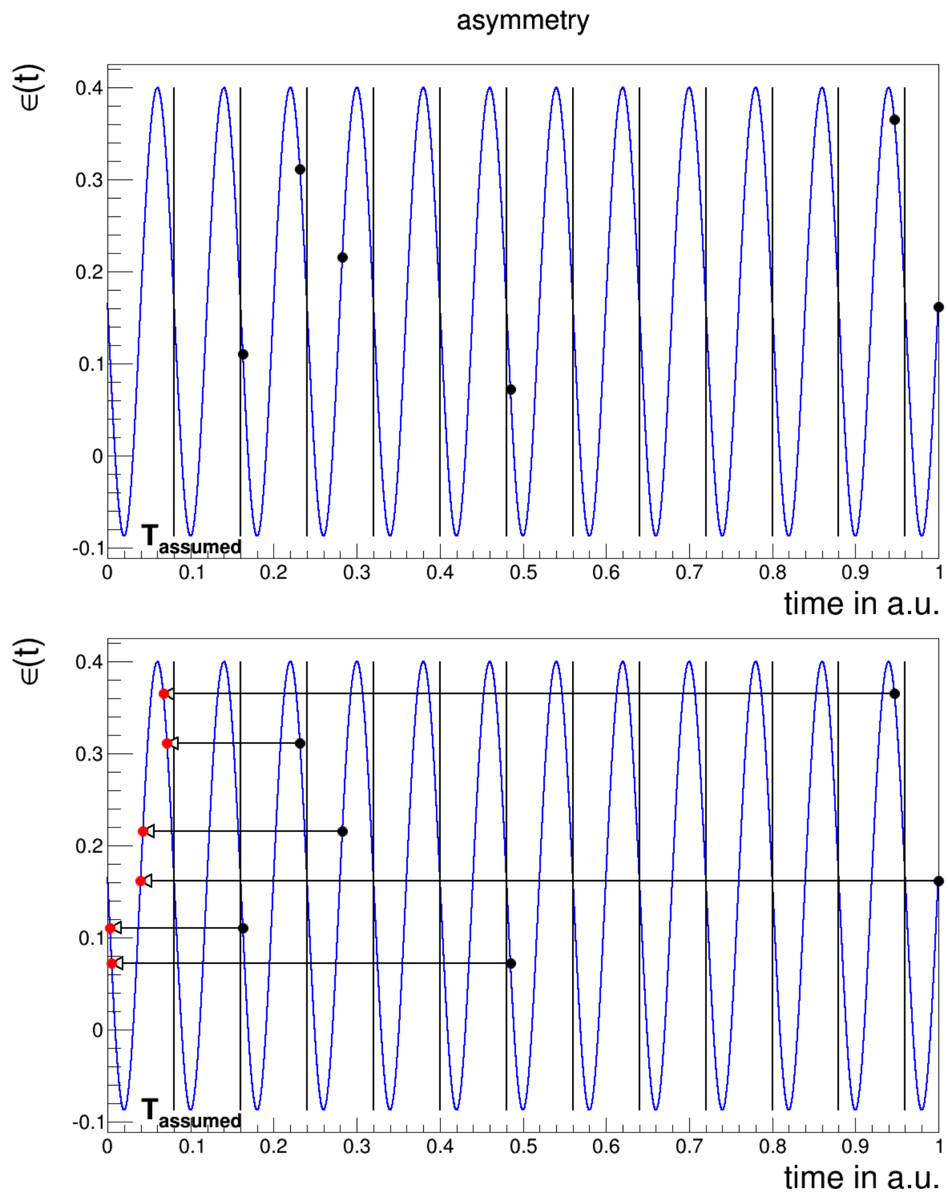
1. Assume Spin Tune $\nu_{assumed}$

$$T_{assumed} = \frac{2\pi}{\nu_{assumed} f_{rev}}$$

2. Map all events of a macroscopic time interval (2s) in first period:

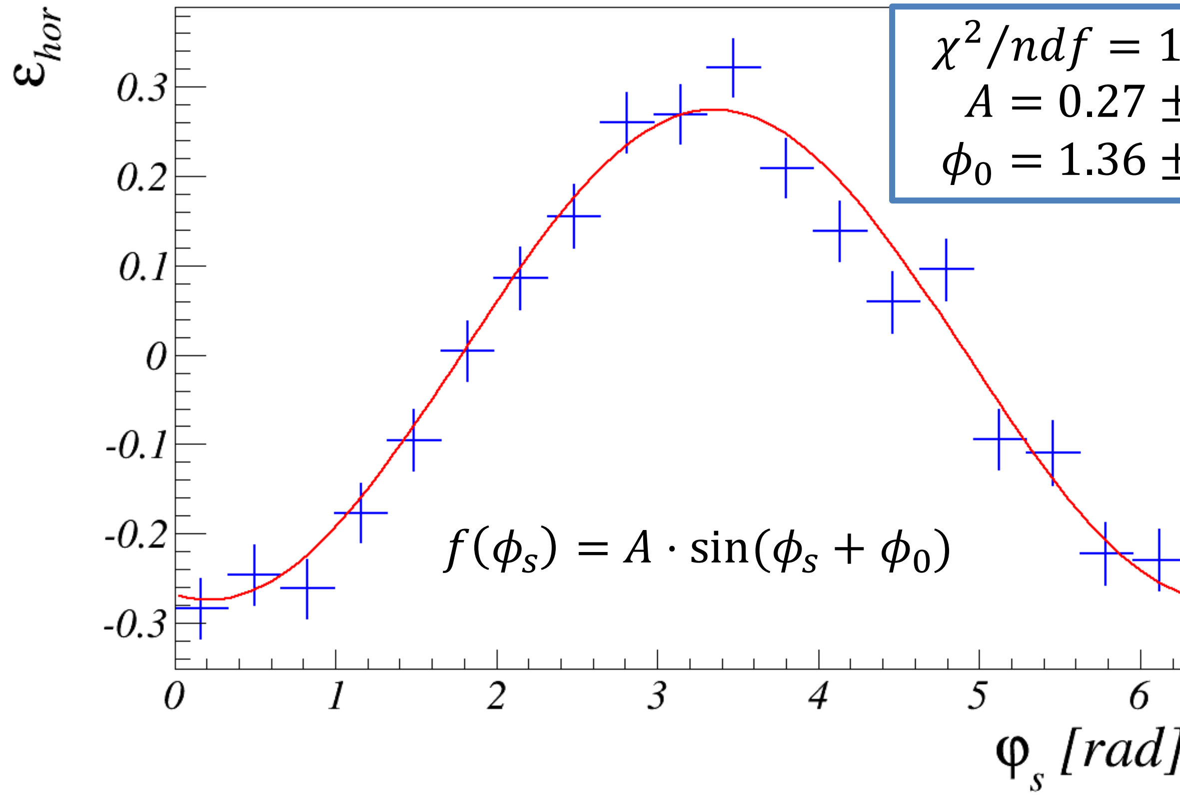
$$t' = mod(t, T_{assumed})$$

3. Fit asymmetry to first period



Fit Asymmetry to First Period

1. $T_{assumed}$
2. Mapping events
3. Fit asymmetry to first period



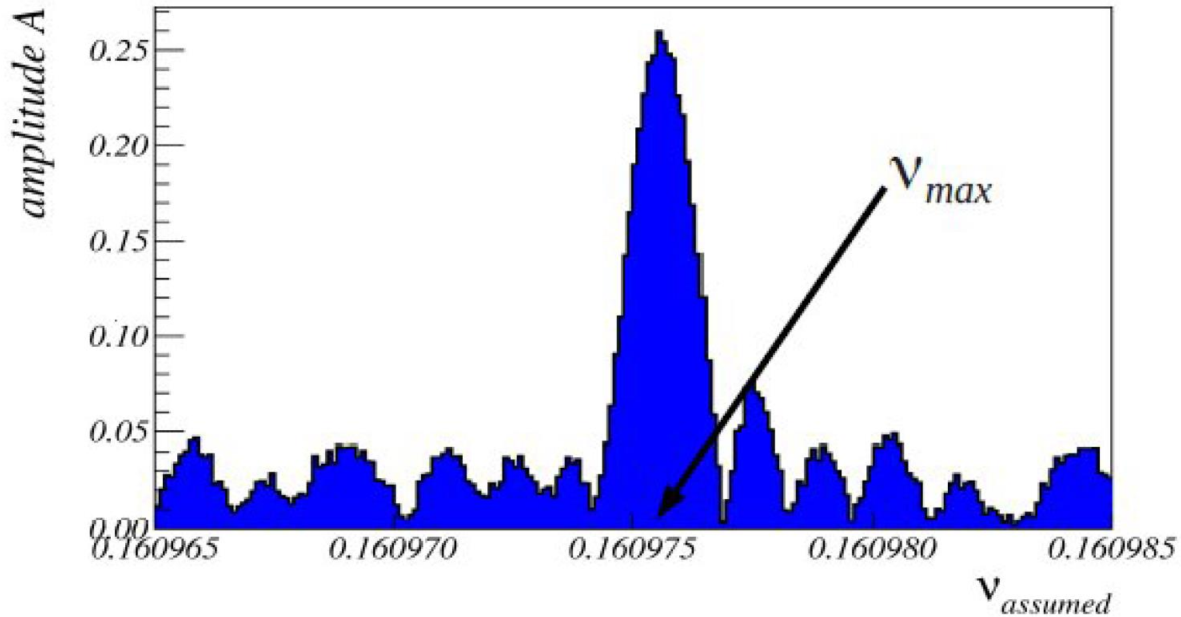
$\chi^2/ndf = 18.4/17$
$A = 0.27 \pm 0.01$
$\phi_0 = 1.36 \pm 0.04$

Extract amplitude $A \propto Polarisation$

Find Correct Spin Tune

1. $T_{assumed}$
2. Sorting events
3. Fit asymmetry to first period

- Vary $T_{assumed}$ and repeat steps 1 to 3
- Plot extracted parameter A vs $\nu_{assumed}$



- ν_{max} is correct spine tune in macroscopic time interval $(2\ s)$
- $\nu_{max} = 0.160975 \pm 10^{-6}$