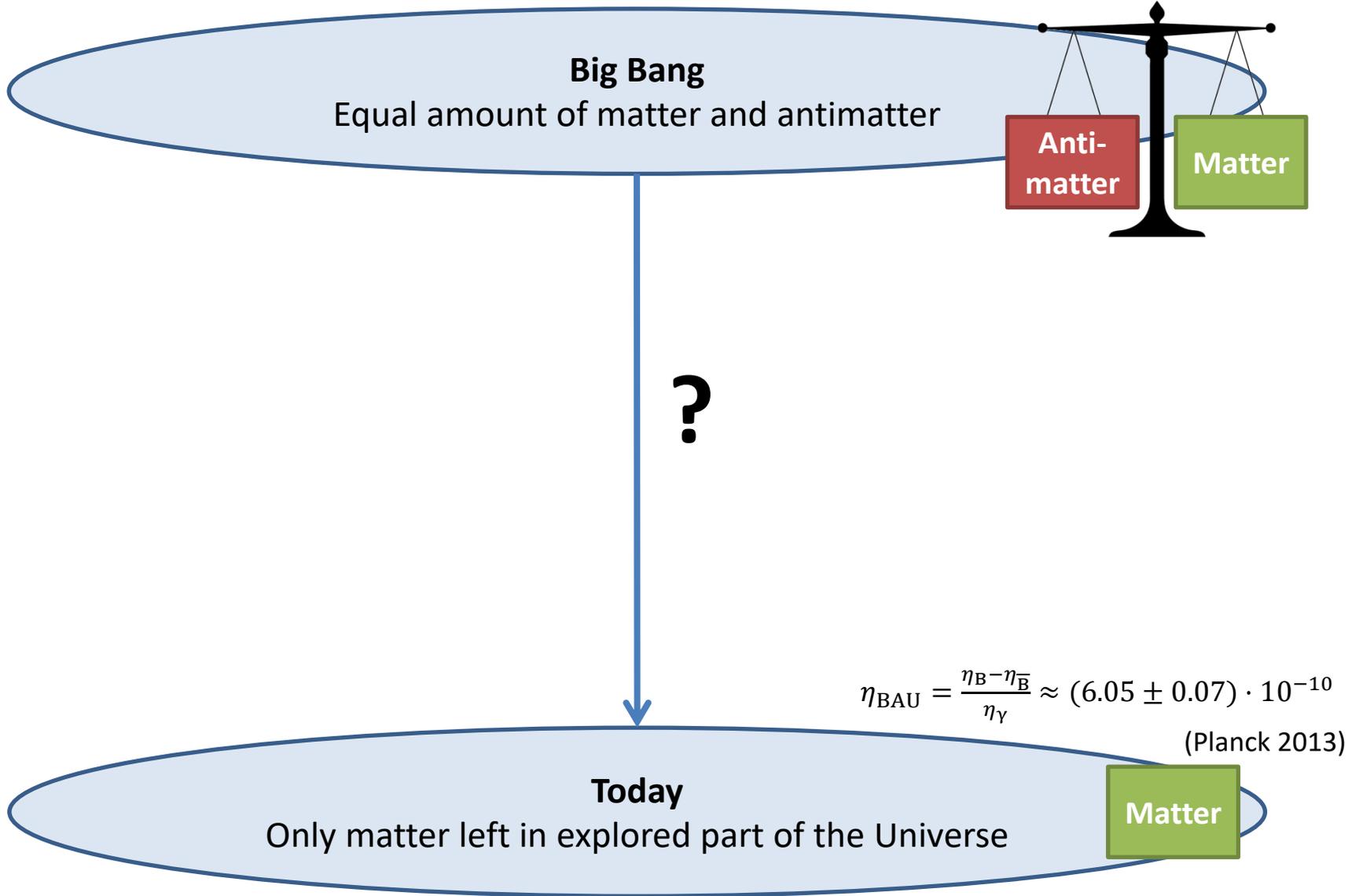


RF Wien Filter Method for EDM Search with CW/CCW Beams

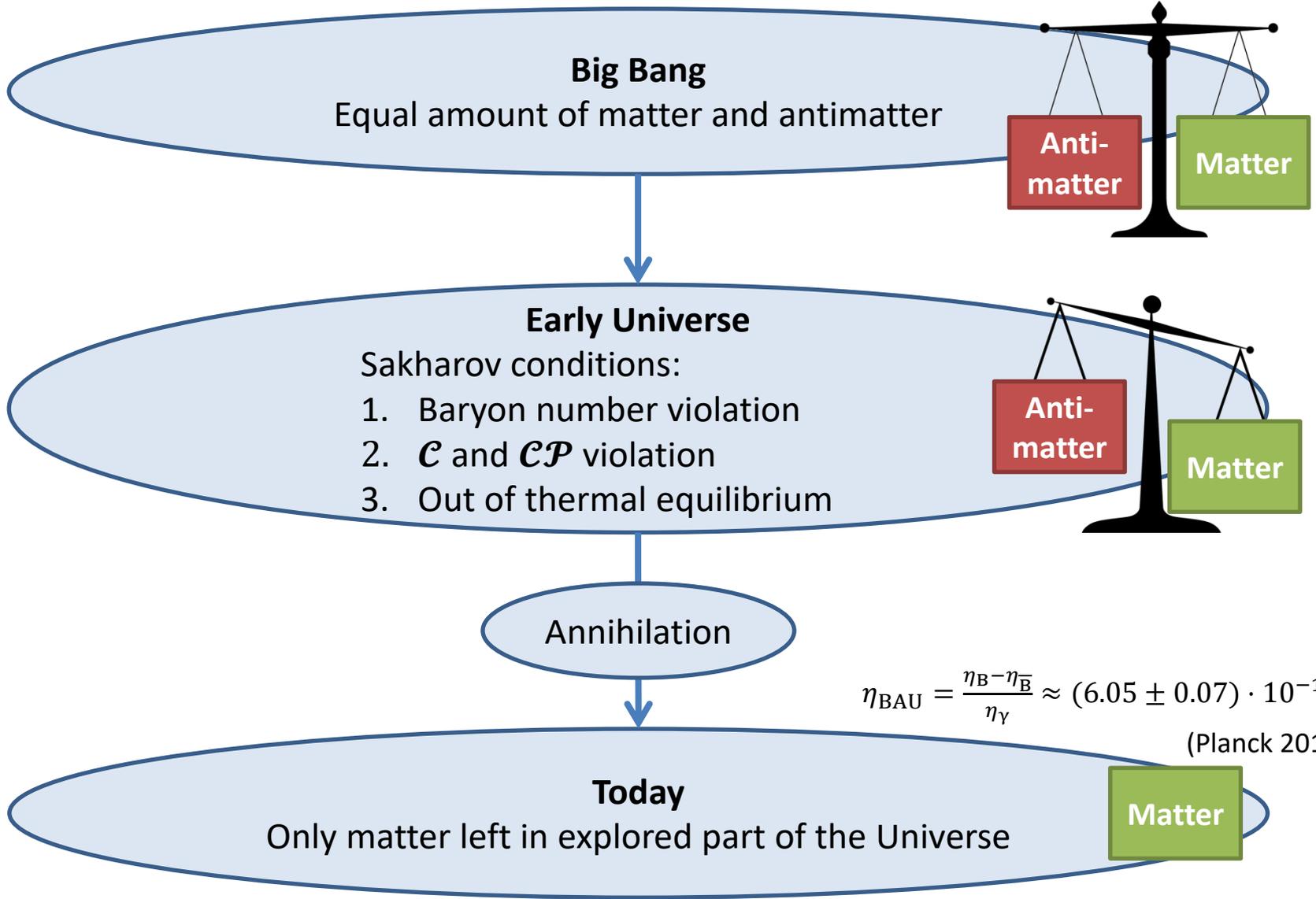
Marcel Rosenthal on behalf of the JEDI Collaboration

Tuesday, 27th September 2016, 22nd International Spin Symposium, Champaign, USA

Matter-antimatter asymmetry



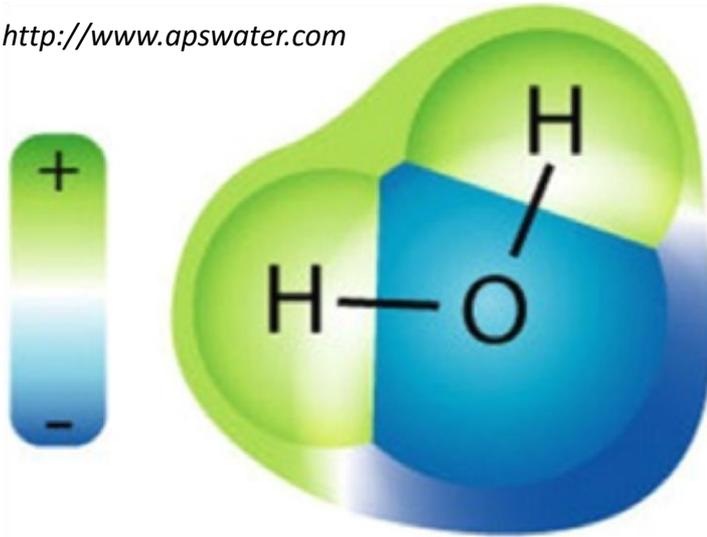
Matter-antimatter asymmetry



$$\eta_{\text{BAU}} = \frac{\eta_{\text{B}} - \eta_{\bar{\text{B}}}}{\eta_{\gamma}} \approx (6.05 \pm 0.07) \cdot 10^{-10}$$

(Planck 2013)

Source: <http://www.apswater.com>

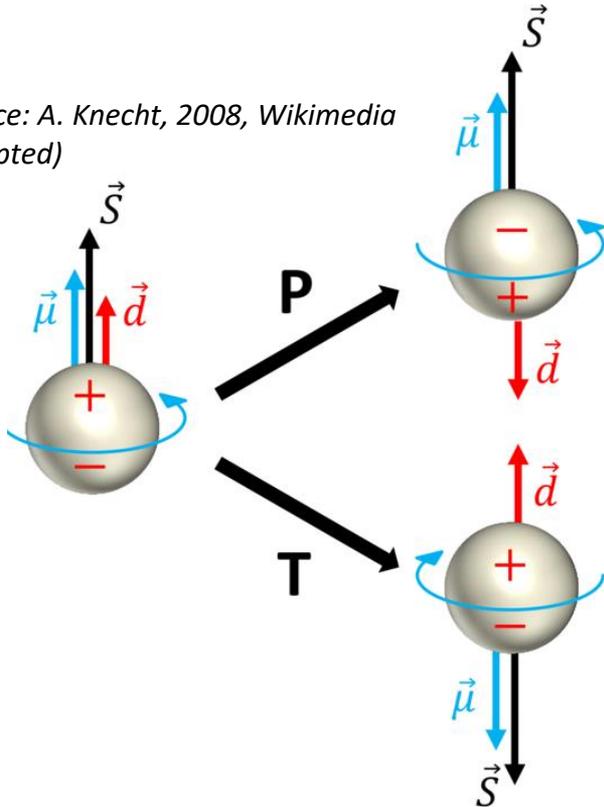


- Electric Dipole Moments:
 - Classical: $\vec{d} = \sum_i q_i \cdot \vec{r}_i$

- Example:
 - Water molecule (H_2O):
 $d \sim 4 \cdot 10^{-9} \text{ e cm}$

Electric Dipole Moments (EDMs)

Source: A. Knecht, 2008, Wikimedia
(adapted)



➤ Electric Dipole Moments:

➤ Classical: $\vec{d} = \sum_i q_i \cdot \vec{r}_i$

➤ For elementary particles defined along spin direction:

$$\vec{\mu} = g \cdot \frac{e}{2m} \vec{S} \quad \vec{d} = \eta \cdot \frac{e}{2mc} \vec{S}$$

➤ Examples:

➤ Neutron:

$$d < 3 \cdot 10^{-26} \text{ e cm}$$

➤ Muon:

$$d < 2 \cdot 10^{-19} \text{ e cm}$$

➤ Permanent EDMs of elementary particles violate \mathcal{P} and \mathcal{T} symmetries

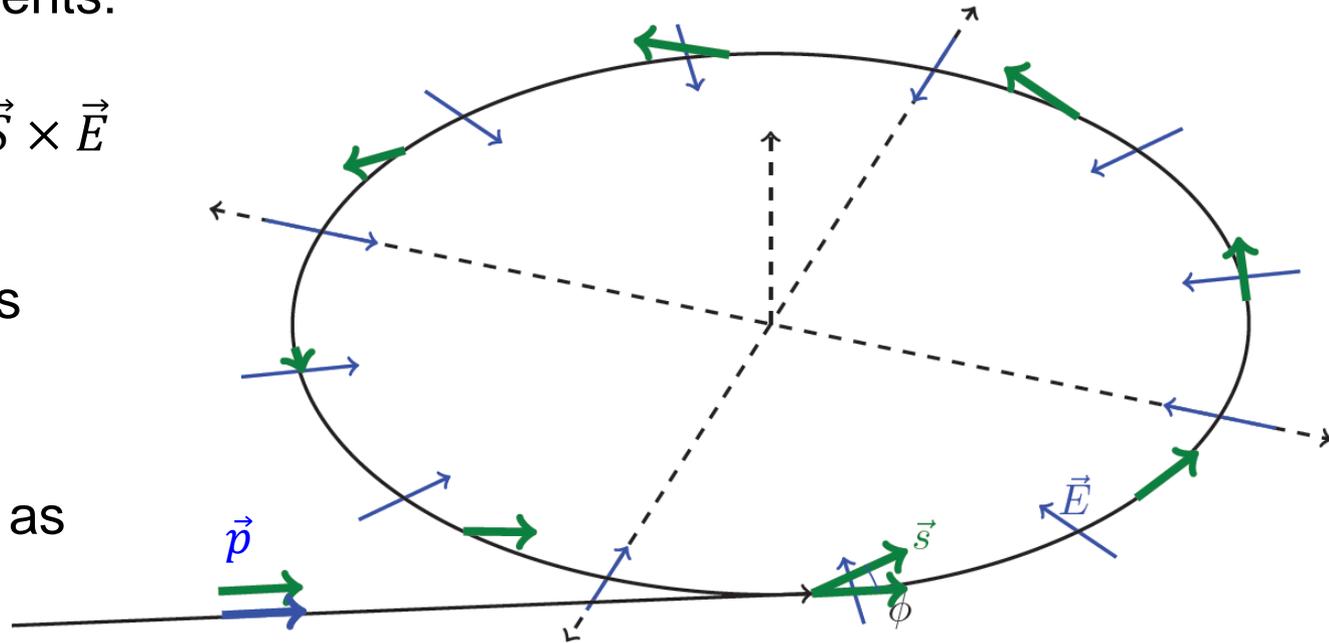
➤ $\mathcal{T} \Leftrightarrow \mathcal{EP}$ (\mathcal{CPT} theorem)

- All EDM experiments:

$$\frac{d\vec{S}}{dt} \propto \vec{d} \times \vec{E} \propto \vec{S} \times \vec{E}$$

- Charged particles
→ Lorentz force

- Use storage ring as particle trap



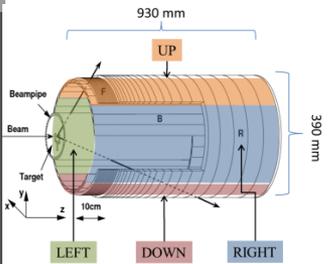
- Basic principle:
 - Inject polarized particles with spin parallel to momentum vector
 - $\vec{d} \neq 0$: EDM couples to electric bending fields → slow signal buildup

The Cooler Synchrotron COSY



Radiofrequency Solenoid

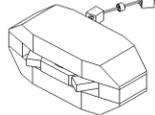
Cooled beams
(e-cooling, stochastic cooling)



Polarimetry



**Currently running test experiments:
Polarized deuterons, $p = 970 \text{ MeV}/c$**



Polarized protons & deuterons



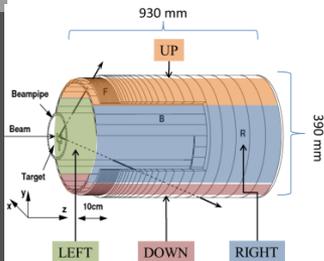
The Cooler Synchrotron COSY



Radiofrequency Solenoid



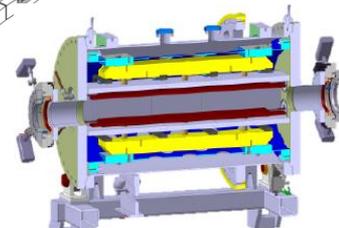
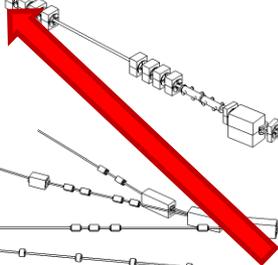
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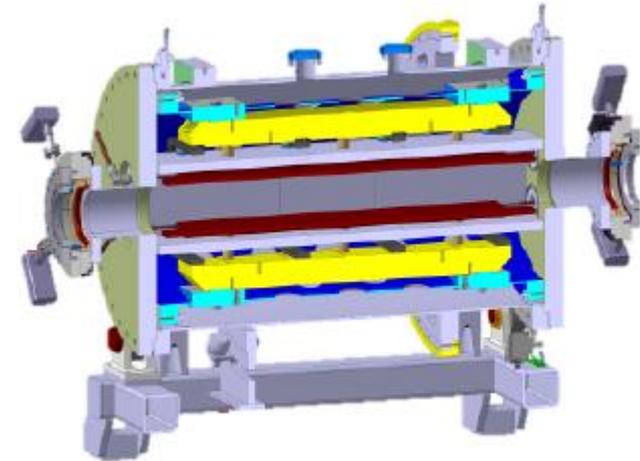
Polarized protons & deuterons



- Insert Radiofrequency Wien filter
- Generate EDM related signal

The Radiofrequency Wien filter

- Superposition of
 - Radial electric field $E_x \sim \cos(\omega t + \phi)$
 - Vertical magnetic field $B_y \sim \cos(\omega t + \phi)$
- Ratio adjusted to minimize Lorentz force contribution



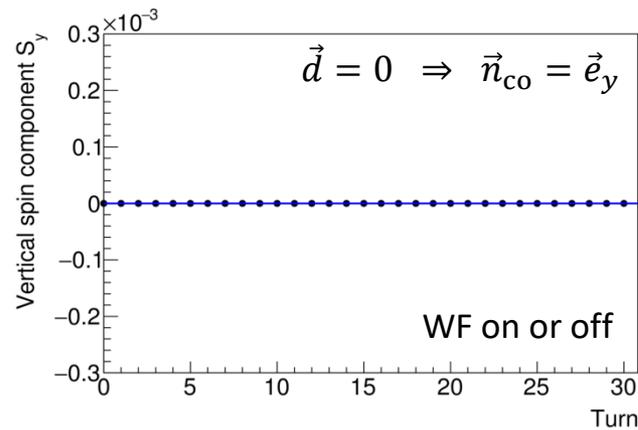
Source: Nucl. Instrum. Methods Phys. Res. A 828, 116 (2016)

$$\frac{d\vec{S}}{dt} = \vec{\Omega}_{\text{MDM}} \times \vec{S} + \vec{\Omega}_{\text{EDM}} \times \vec{S}$$
$$\vec{\Omega}_{\text{MDM}} \parallel \vec{e}_y \quad \vec{\Omega}_{\text{EDM}} \propto \left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right] = 0$$

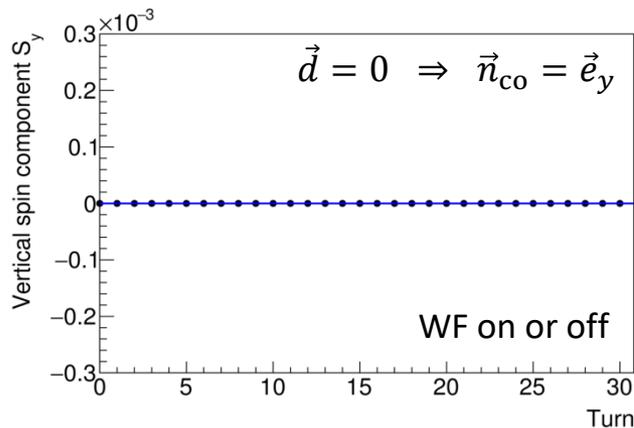
Wien filter rotates spin about vertical axis

- System of two rotations/oscillations:
 - Permanent rotation of spin about spin closed orbit \vec{n}_{CO} with spin tune ν_s
 - Oscillating fields of RF Wien filter, which act locally
 - **Frequency** locked to spin rotation frequency in storage ring (resonance condition)
 - **Phase** dependency between spin rotation and WF oscillating fields is free parameter

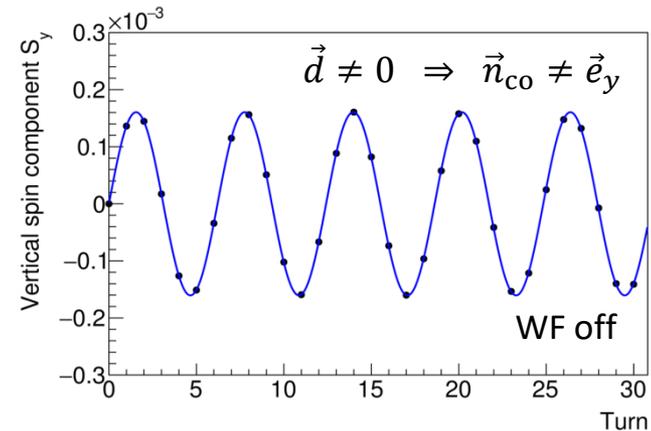
- Spin precessing perpendicular to spin closed orbit \vec{n}_{co}



- Spin precessing perpendicular to spin closed orbit \vec{n}_{co}



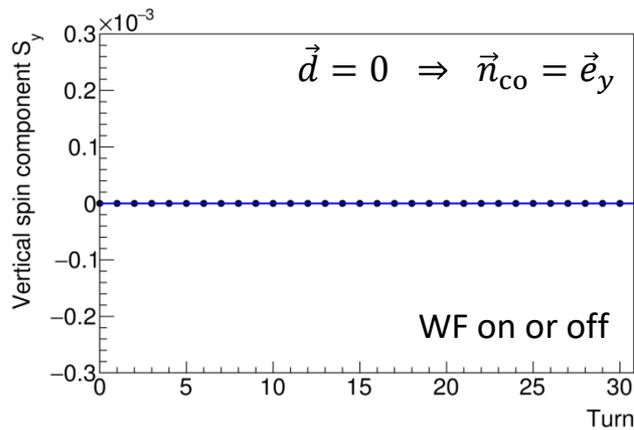
EDM $\neq 0$
WF off



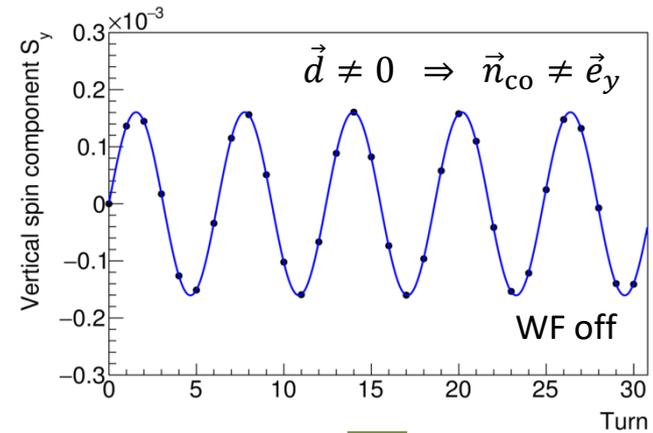
$\nu_s \approx G\gamma \approx -0.16$
→ 6 turns per spin oscillation

Amplitude proportional to EDM
→ used for muon EDM limit in
g-2 experiment

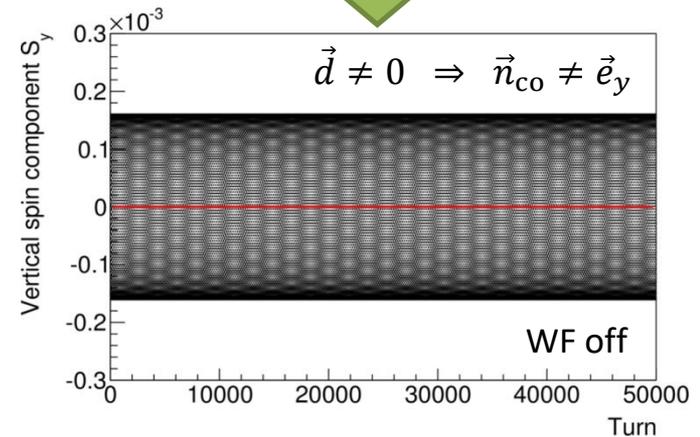
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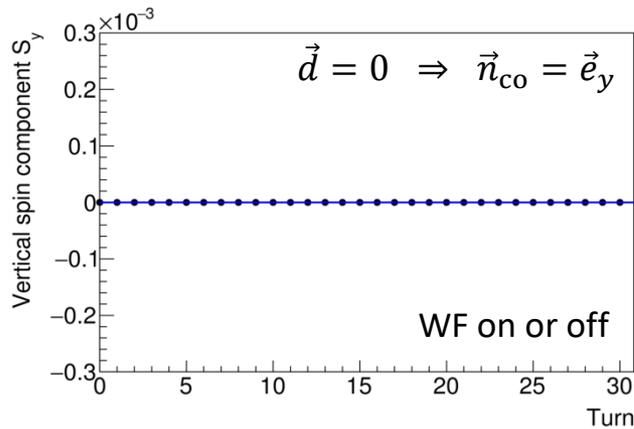


Extend turn scale

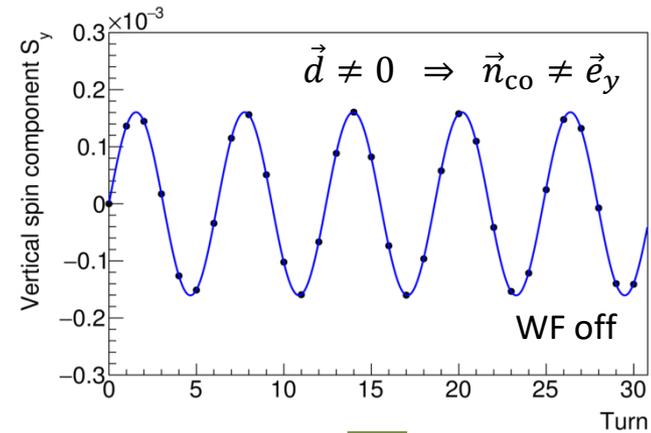


Polarization buildup induced by EDM

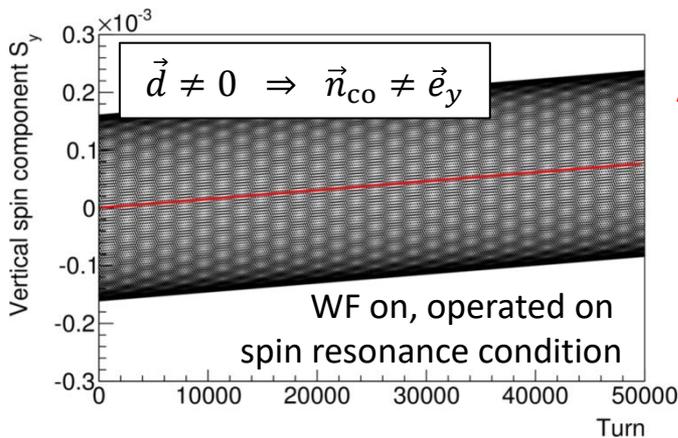
- Spin precessing perpendicular to spin closed orbit \vec{n}_{co}



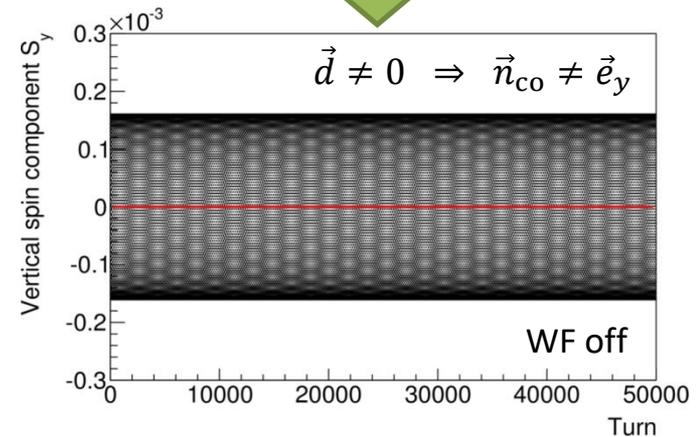
EDM $\neq 0$
WF off



Extend turn scale

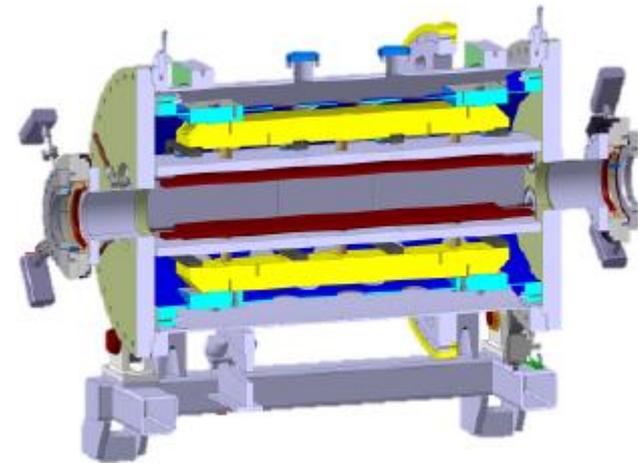


Activate WF



The Radiofrequency Wien filter (recap)

- Superposition of
 - Radial electric field $E_x \sim \cos(\omega t + \phi)$
 - Vertical magnetic field $B_y \sim \cos(\omega t + \phi)$
- Ratio adjusted to minimize Lorentz force contribution



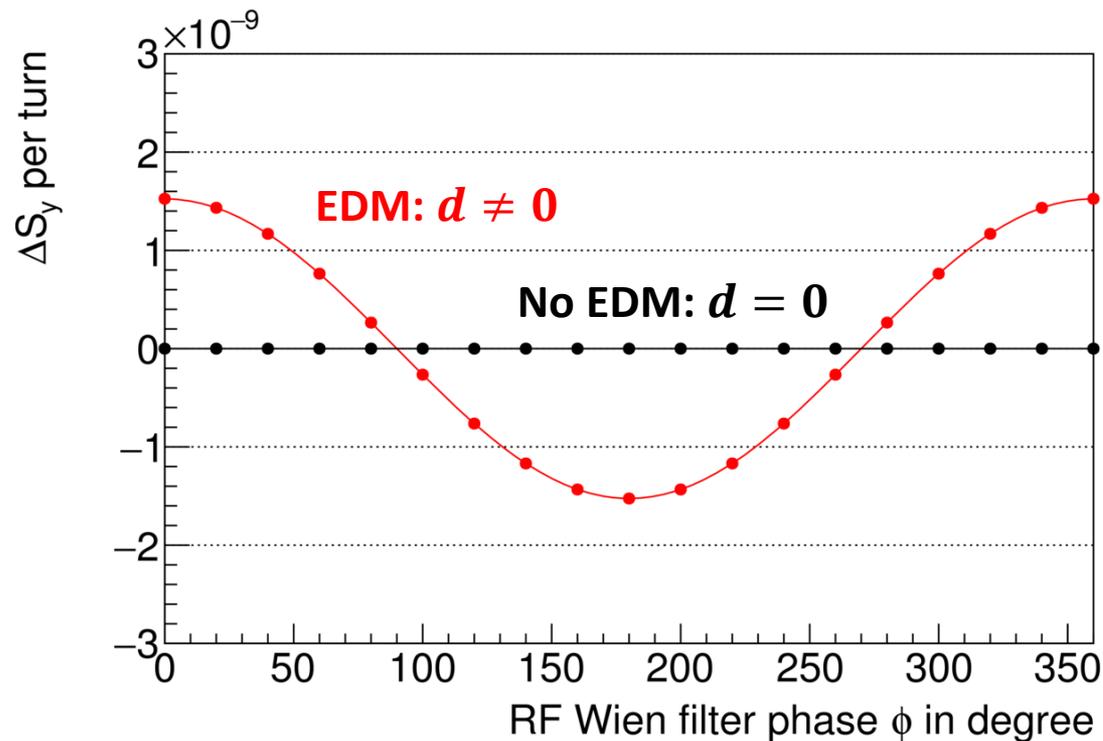
Source: Nucl. Instrum. Methods Phys. Res. A 828, 116 (2016)

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Wien filter rotates spin about vertical axis

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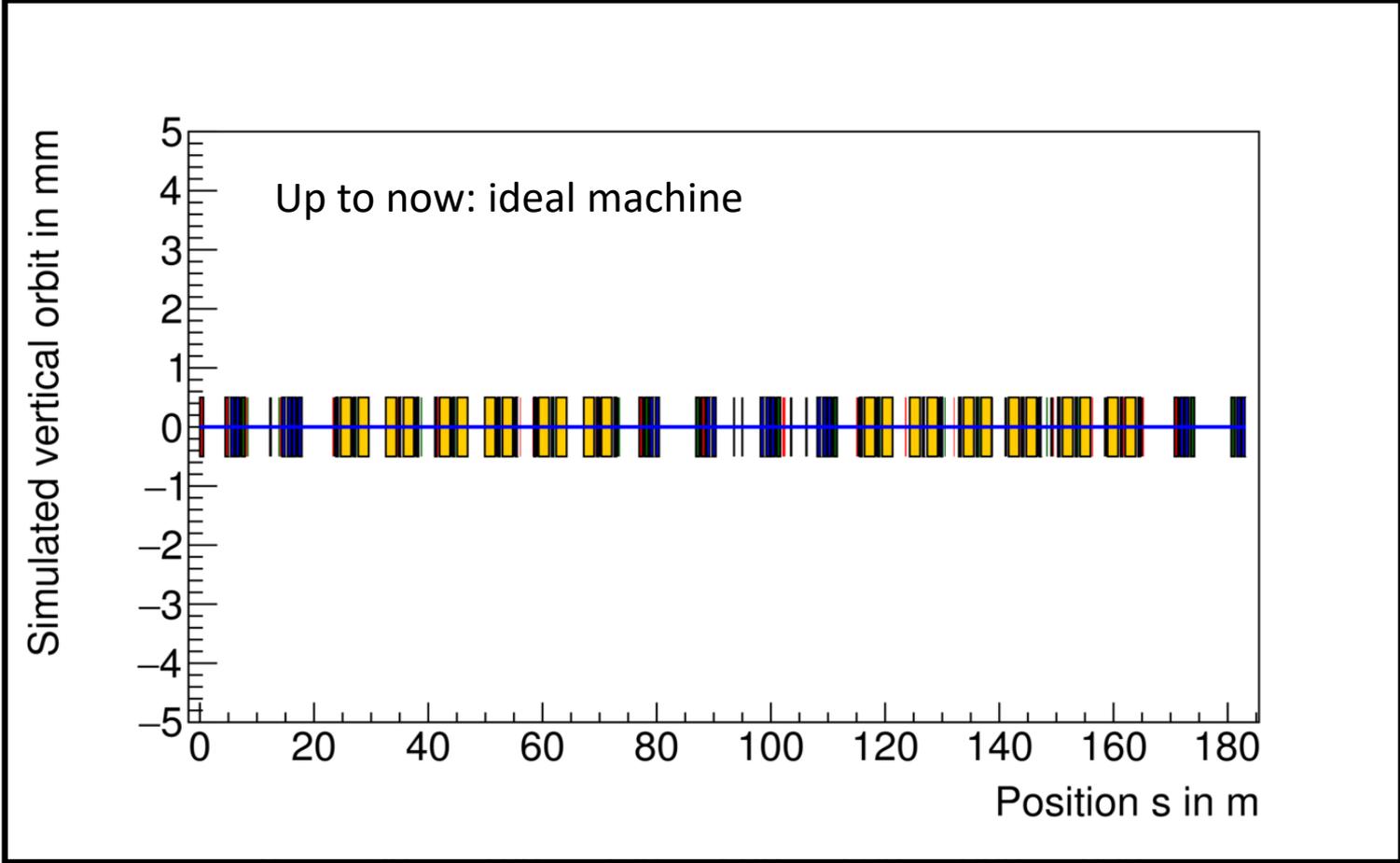
- Phase relation between initial spin orientation and RF Wien filter field affects slope of vertical polarization accumulation
- EDM magnitude determines amplitude



Phase dependence of signal

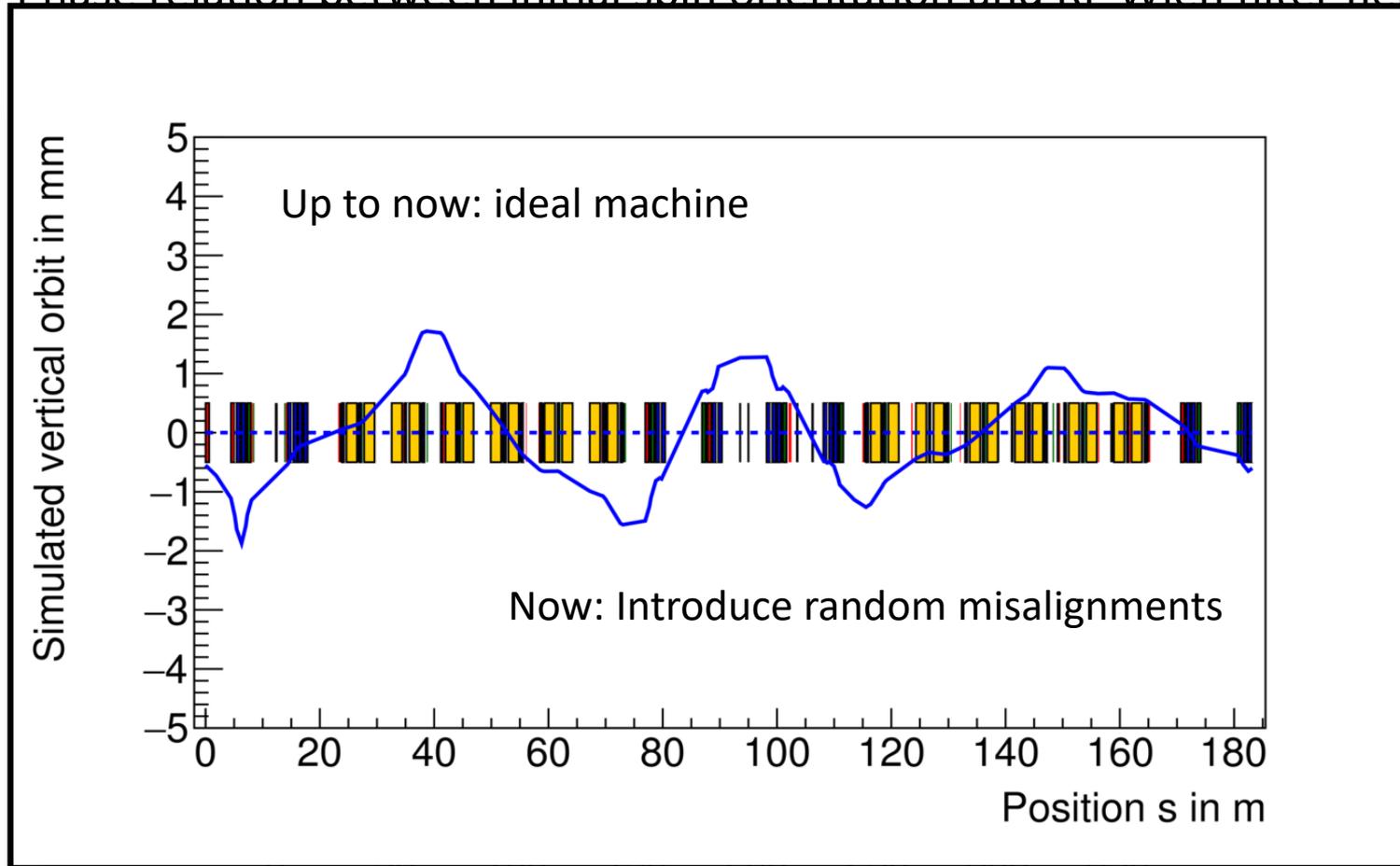
➤ Phase relation between initial spin orientation and RF Wien filter field

➤



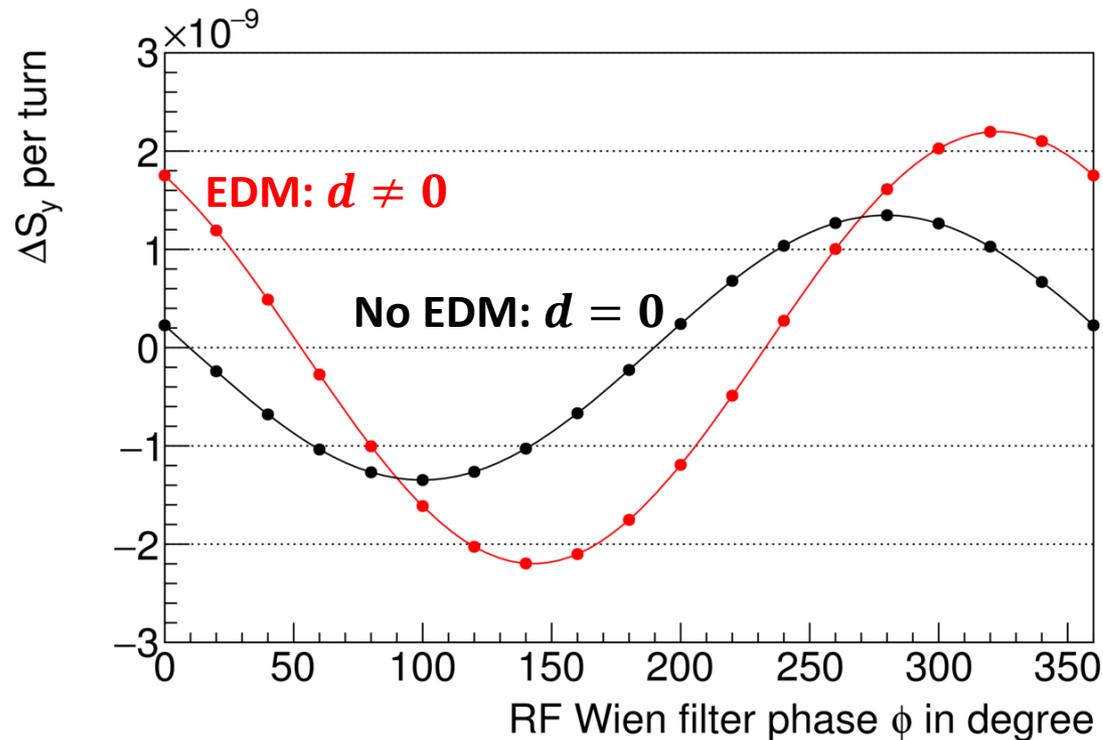
RF Wien filter phase ϕ in degree

- Phase relation between initial spin orientation and RF Wien filter field

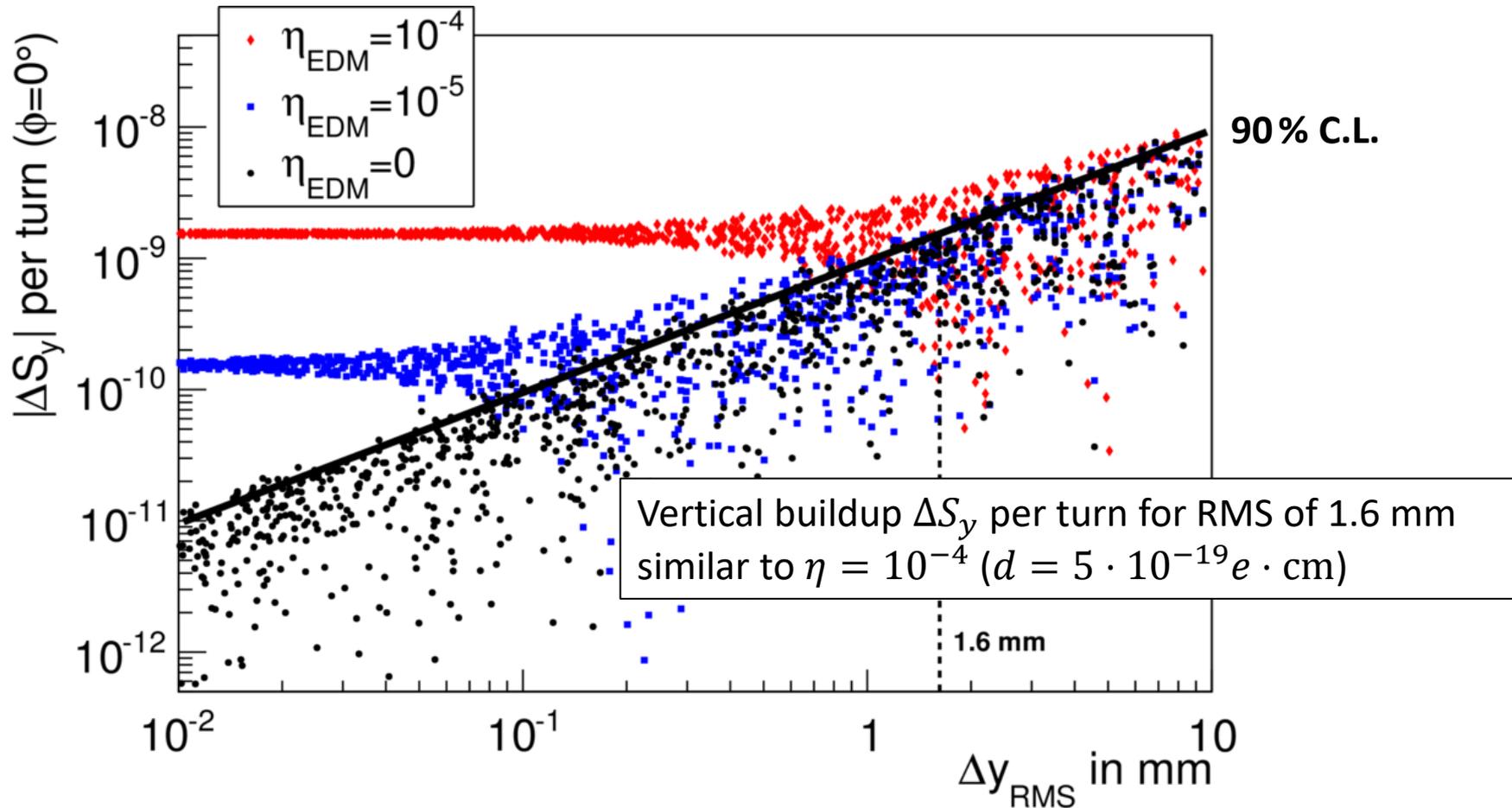


RF Wien filter phase ϕ in degree

- Randomly misaligned magnets introduce radial fields
 - Possible source of fake signal
 - Phase dependence of signal is changed
- Example:



Comparison to EDM signal



- Orbit: $\sigma_{d,\text{sys,orbit}} = 10^{-21} e \cdot \text{cm}$ requires RMS of $\sim 4 \mu\text{m}$

- Perform experiment with CW and CCW beam (consecutive cycles)
 - Flip sign of magnetic fields
 - Inject beam in opposite direction
 - Misalignments „preserved“

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

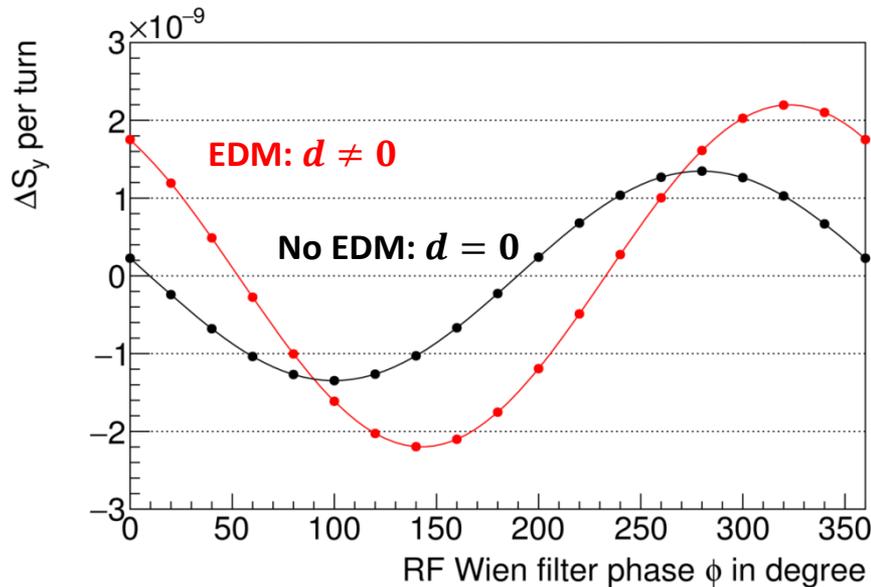
$$\vec{\Omega}_{\text{MDM}} = -\frac{q}{\gamma m} \left[(1 + G\gamma)\vec{B} + \left(G\gamma + \frac{\gamma}{1 + \gamma} \right) \frac{\vec{E} \times \vec{\beta}}{c} \right] \xrightarrow{\vec{\beta} \rightarrow -\vec{\beta}, \vec{B} \rightarrow -\vec{B}} -\vec{\Omega}_{\text{MDM}}$$

$$\vec{\Omega}_{\text{EDM}} = -\frac{q}{m} \frac{\eta}{2} \left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right] \xrightarrow{\vec{\beta} \rightarrow -\vec{\beta}, \vec{B} \rightarrow -\vec{B}} \vec{\Omega}_{\text{EDM}}$$

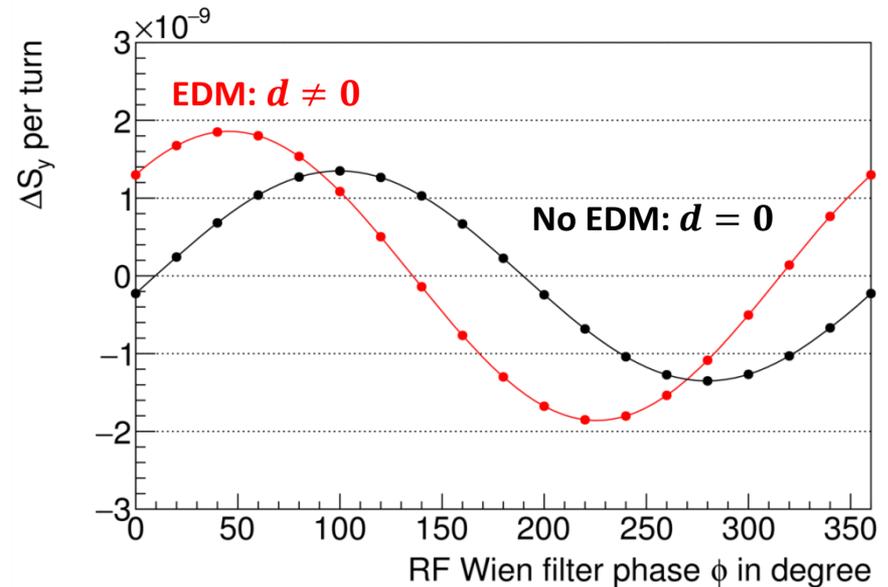
Idea of using CCW beam

- Perform experiment with CW and CCW beam (consecutive cycles)
 - Flip sign of magnetic fields
 - Inject beam in opposite direction
 - Misalignments „preserved“

Clockwise

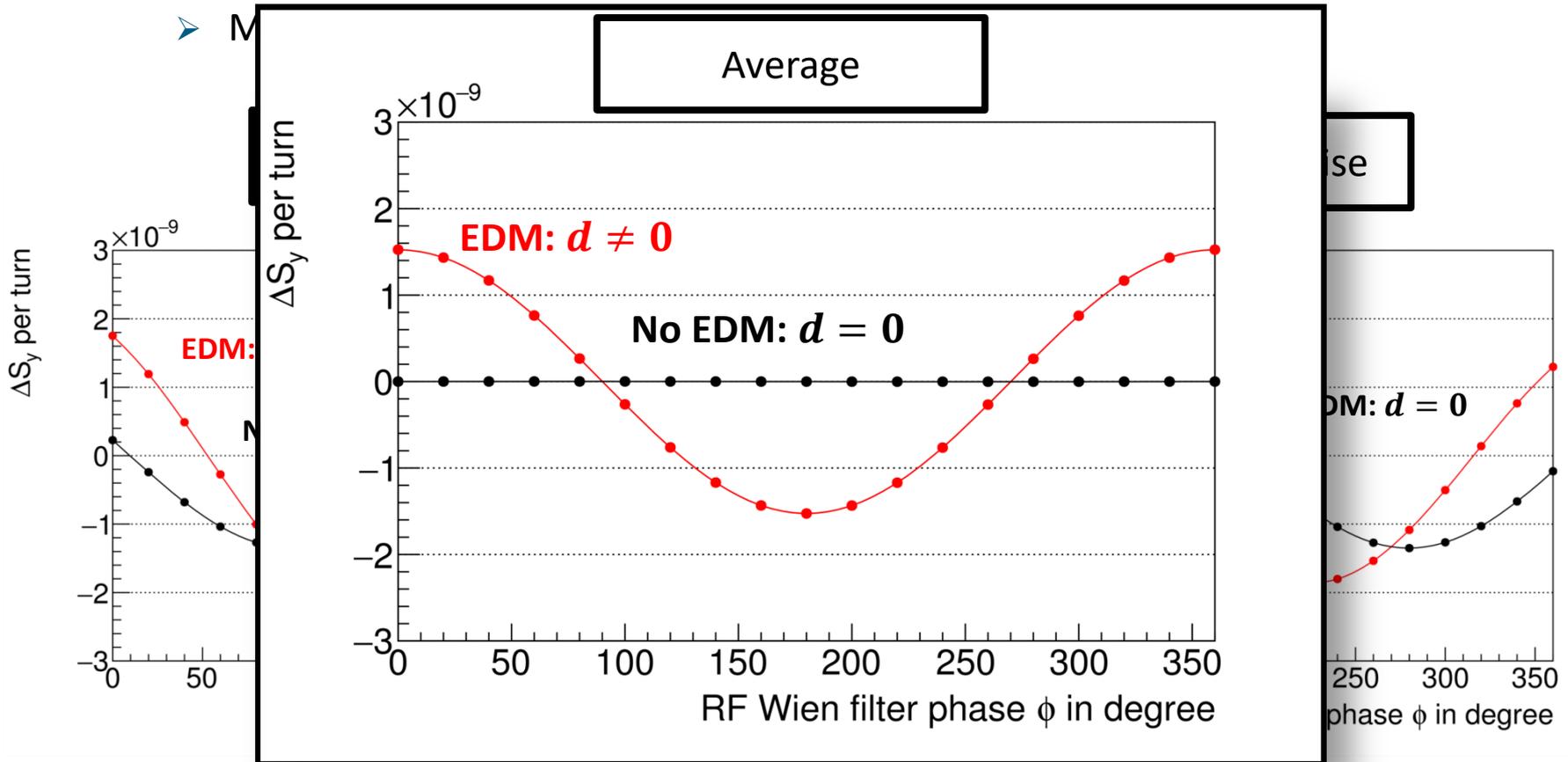


Counterclockwise

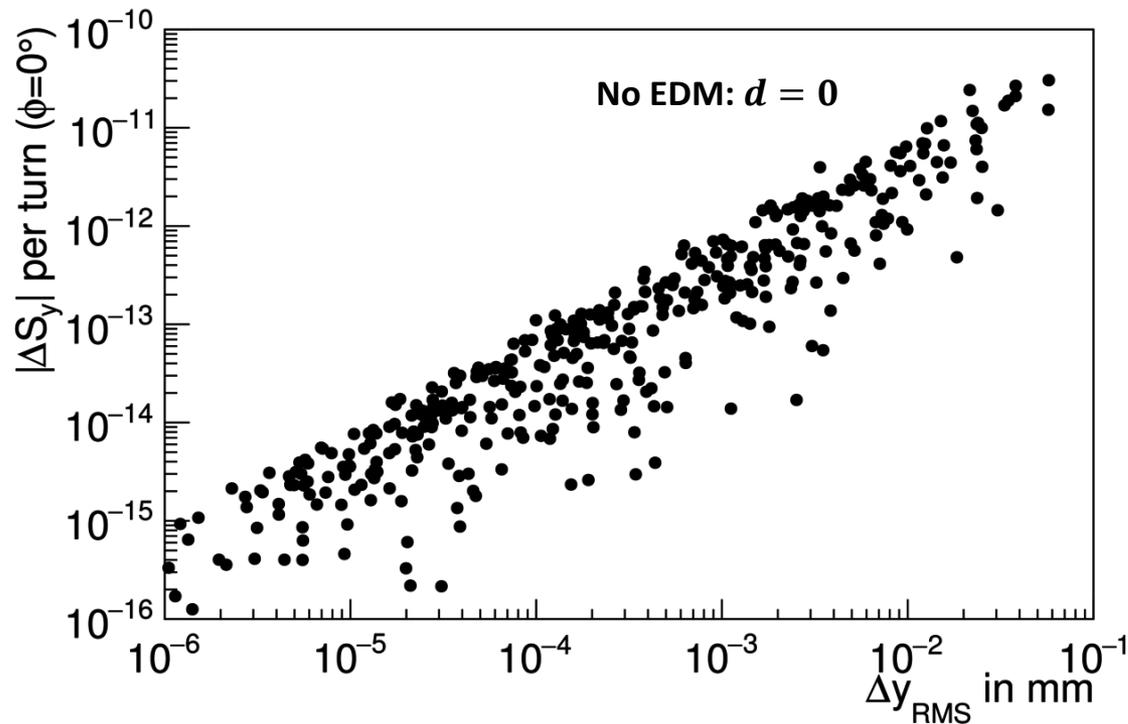


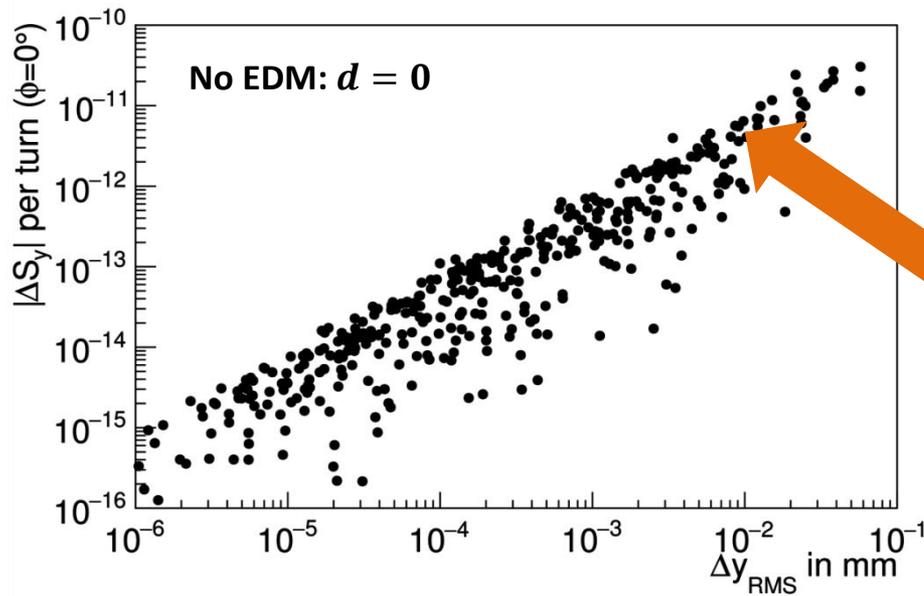
Idea of using CCW beam

- Perform experiment with CW and CCW beam (consecutive cycles)
 - Flip sign of magnetic fields
 - Inject beam in opposite direction
 - Measure

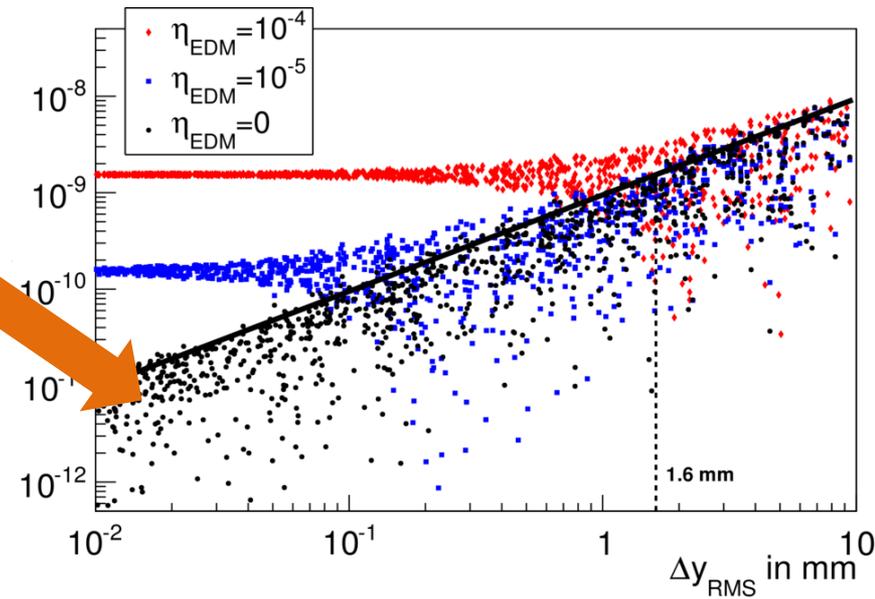


- Flip of magnetic fields might be incomplete
 - Orbits in CW and CCW scenario might be different
 - Different systematic contributions
 - Big advantage: now relative orbit measurements: $\Delta y_{\text{RMS}}(y_{\text{CW}} - y_{\text{CCW}})$
- Simulation:





based on deviations between CW and CCW orbits



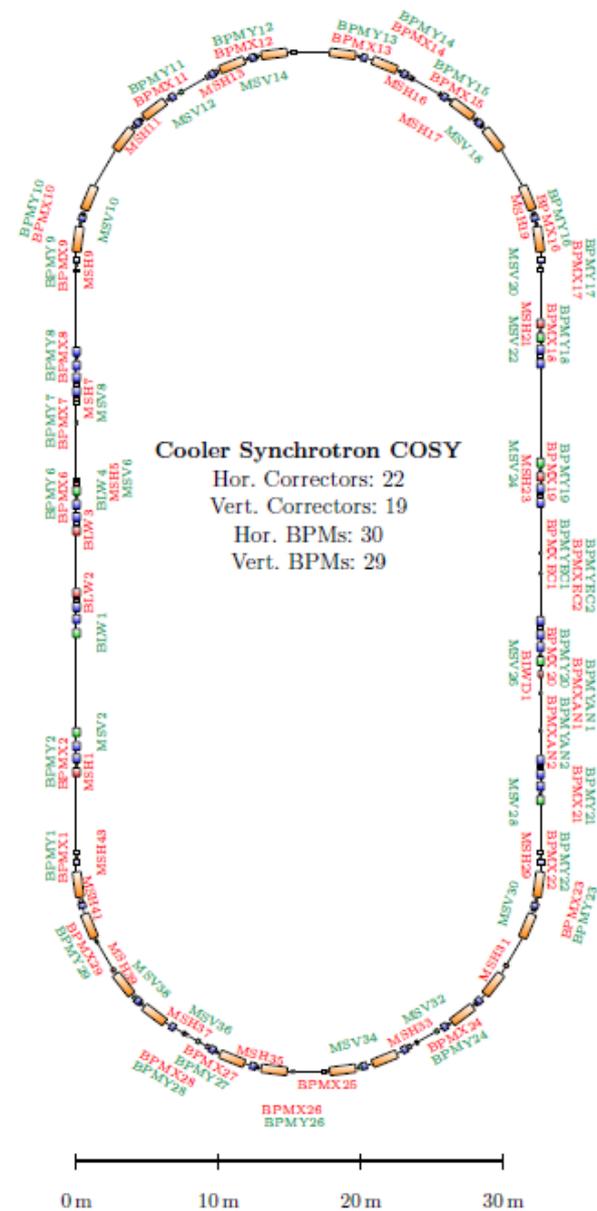
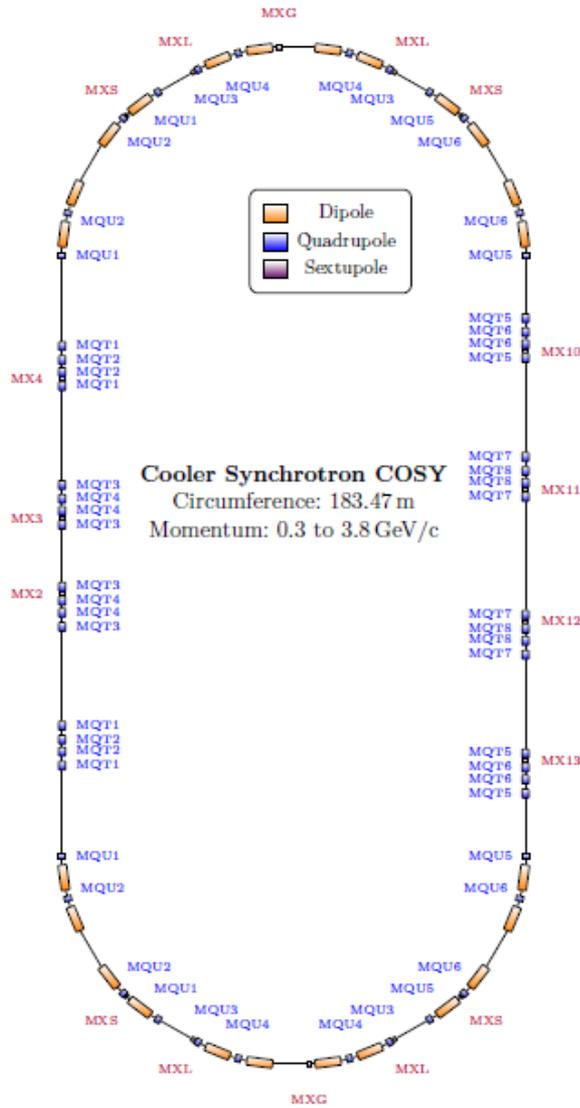
based on deviations of CW beam to reference axis

- Same proportionality between fake signal and orbit RMS

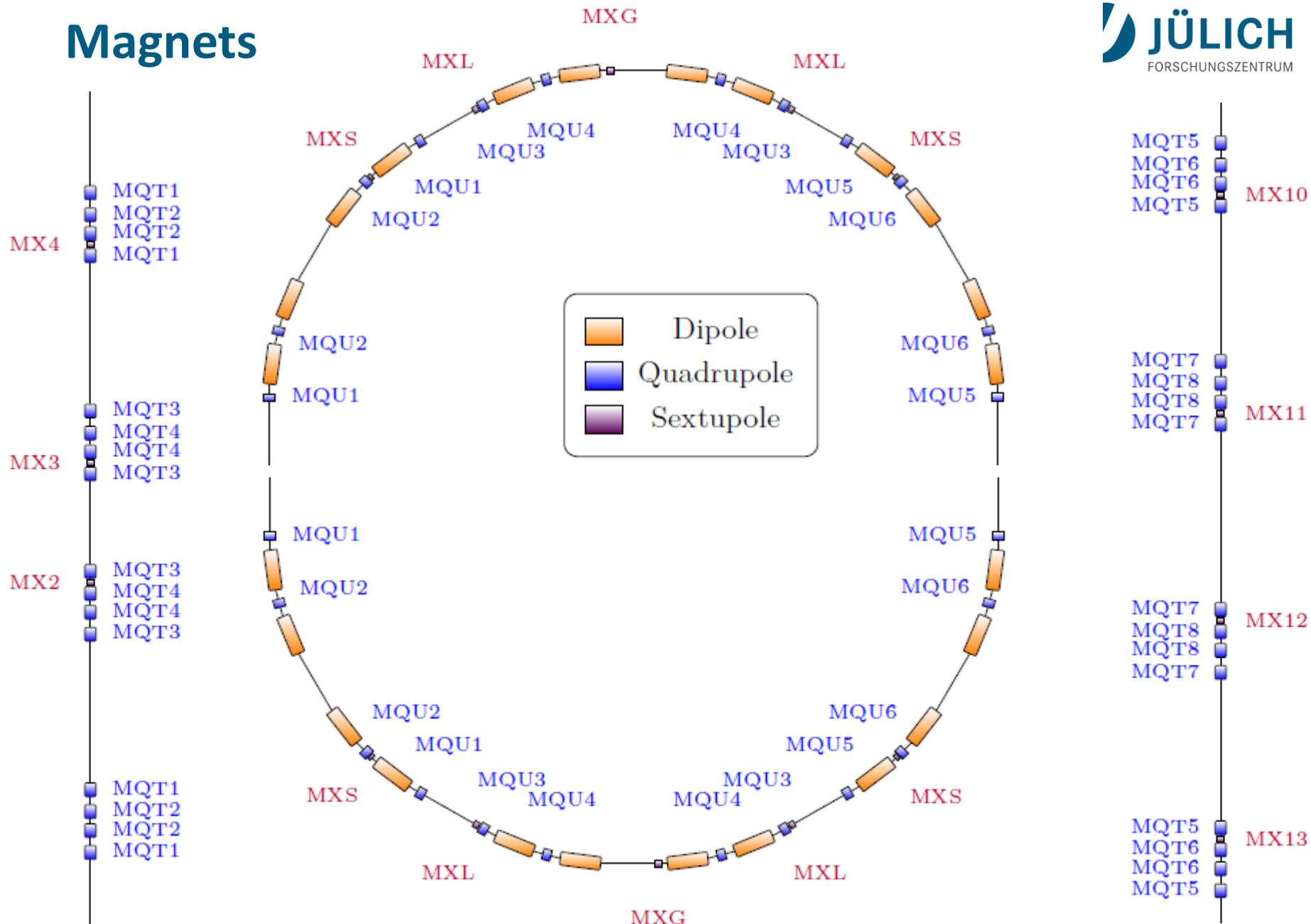
- **Search for CP violating sources to explain matter-antimatter-asymmetry**
 - Extend the scope of EDM measurements to charged hadrons
 - COSY, Jülich as test facility

- **First calculation of orbit related systematics**
 - $\Delta y_{RMS} \approx 1.6$ mm mimics EDM signal up to $d \approx 5 \cdot 10^{-19} e \cdot \text{cm}$
 - Very challenging experiment

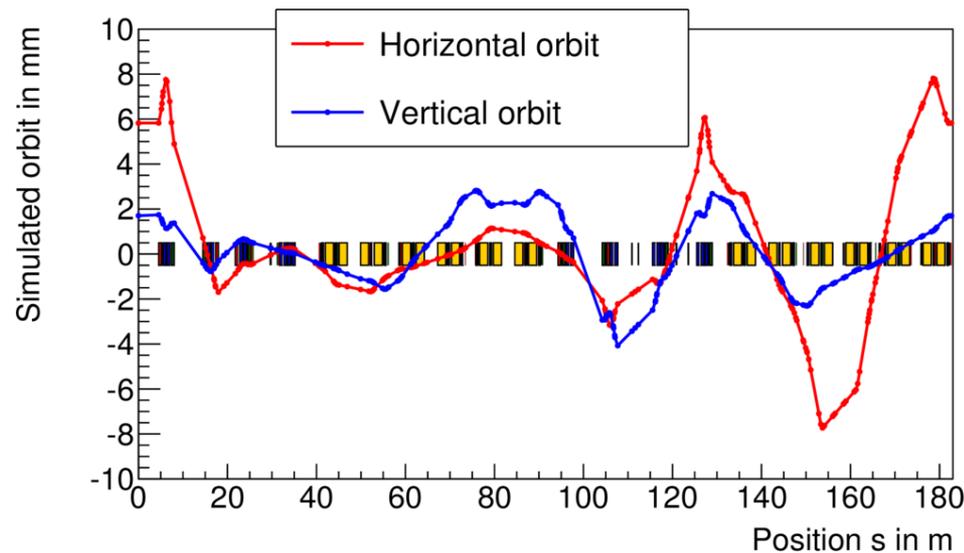
- **Study of CW/CCW beams**
 - Suppresses fake signals from misalignments
 - Non-perfect suppression in case of incomplete flip of magnetic fields
 - Vertical orbit measurements to estimate systematic effects are independent of BPM alignment



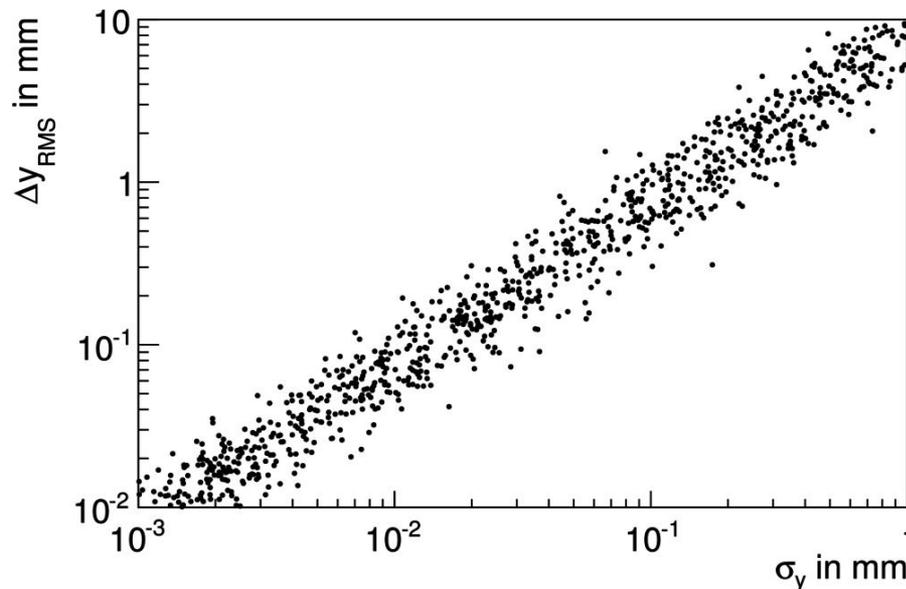
Magnets



- Magnet misalignments introduce additional fields
 - Can mimic EDM signal
- Also orbit is distorted:
 - Idea: investigate connection between orbit distortions and polarization
 - Consider i.e. quadrupole displacements



- Magnet misalignments introduce additional fields
 - Can mimic EDM signal
- Also orbit is distorted:
 - Idea: investigate connection between orbit distortions and polarization
 - Consider i.e. quadrupole displacements



- Radial fields B_x are used for beam focusing
 - Simulate vertically shifted quadrupoles
 - Gaussian distributed: $(\mu, \sigma) = (0, \sigma_y)$
- Vertical orbit RMS related to σ_y

- Equation of spin motion for relativistic particles in electromagnetic fields (Thomas-BMT equation) ($\vec{\beta}\vec{B} = \vec{\beta}\vec{E} = 0$):

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

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

$$\vec{\Omega}_{\text{EDM}} = -\frac{q\eta}{m2} \left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right]$$

$$\vec{\mu} = 2(G + 1) \cdot \frac{e}{2m} \vec{S}$$

$$\vec{d} = \eta \cdot \frac{e}{2mc} \vec{S}$$

	G
Proton	1.793
Deuteron	-0.143

$$|G| \gg |\eta|$$

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$$\vec{\Omega}_{\text{EDM}} = -\frac{q\eta}{m2} \left[\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right]$$

Simplifies for $\vec{d} = 0$ and $\vec{E} = 0$

$$\vec{\mu} = 2(G + 1) \cdot \frac{e}{2m} \vec{S}$$

$$\vec{d} = \eta \cdot \frac{e}{2mc} \vec{S}$$

	G
Proton	1.793
Deuteron	-0.143

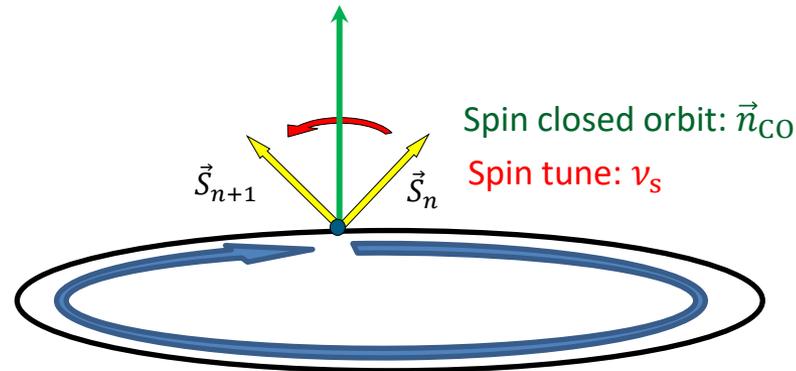
$$|G| \gg |\eta|$$

- Spin precession at COSY ($\vec{d} = 0$):

$$\frac{d\vec{S}}{dt} = \vec{\Omega}_{\text{MDM}} \times \vec{S} \quad \vec{\Omega}_{\text{MDM}} = -\frac{q}{\gamma m} [(1 + G\gamma)\vec{B}_y]$$

$$\frac{d\vec{p}}{dt} = \vec{\Omega}_{\text{cyc}} \times \vec{p} \quad \vec{\Omega}_{\text{cyc}} = -\frac{q}{\gamma m} \vec{B}_y$$

p_d	970 MeV/c
f_{rev}	750.6 kHz
ν_s	-0.16
$f_s - f_{\text{rev}}$	120 kHz



$\vec{S} \parallel \vec{n}_{\text{CO}}$ is preserved

$\vec{S} \perp \vec{n}_{\text{CO}}$ precesses

- Parametrization by axis and angle:

- Spin precession axis (stable spin axis): $\vec{n}_{\text{CO}} = \vec{e}_y$

- Spin precession angle per turn: spin tune: $\nu_s = \frac{\Omega_{\text{MDM}} - \Omega_{\text{cyc}}}{\Omega_{\text{cyc}}} = G\gamma$