

# Electric Dipole Moment Measurements at Storage Rings

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for the JEDI collaboration



Spin 2016, Urbana Champaign 2016

# Outline

- **Introduction & Motivation**

What are EDMs?, What do we know about EDMs?

Why are EDMs interesting?

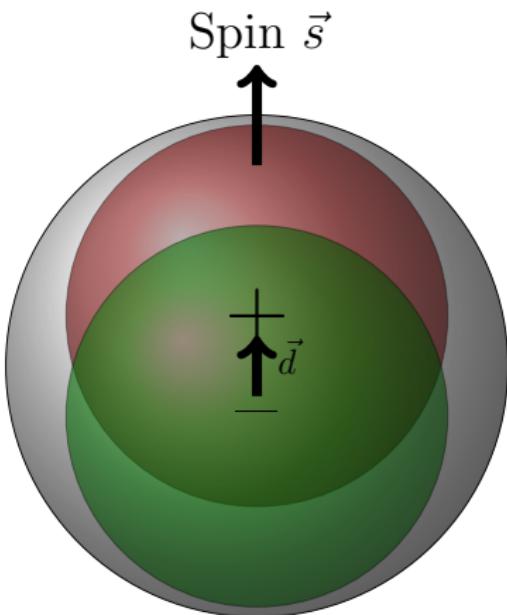
- **Experimental Methods**

How to measure charged particle EDMs?

- **Recent Achievements**

How do manipulate and measure a polarization with high precision!

# Electric Dipole Moments (EDM)



- separation of positive and negative charge
- fundamental property of particles  
(like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal  $\mathcal{T}$  and parity  $\mathcal{P}$  symmetry



July 2014

# PARTICLE PHYSICS BOOKLET

Extracted from the Review of Particle Physics  
K.A. Olive et al. (Particle Data Group),  
Chin. Phys. C, 38, 090001 (2014)

See <http://pdg.lbl.gov> for Particle Listings, complete reviews, and pdglive (our interactive database)

Chinese Physics C

Available from PDG of LBNL and CERN

**p**

$$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$$

Mass  $m = 1.00727646681 \pm 0.00000000009$  u

Mass  $m = 938.272046 \pm 0.000021$  MeV [a]

$|m_p - m_{\bar{p}}|/m_p < 7 \times 10^{-10}$ , CL = 90% [b]

$|\frac{q_p}{m_p}| / (\frac{q_p}{m_p}) = 0.99999999991 \pm 0.00000000009$

$|q_p + q_{\bar{p}}|/e < 7 \times 10^{-10}$ , CL = 90% [b]

$|q_p + q_e|/e < 1 \times 10^{-21}$  [c]

Magnetic moment  $\mu = 2.792847356 \pm 0.000000023$   $\mu_N$

$(\mu_p + \mu_{\bar{p}}) / \mu_p = (0 \pm 5) \times 10^{-6}$

Electric dipole moment  $d < 0.54 \times 10^{-23}$  e cm

Electric polarizability  $\alpha = (11.2 \pm 0.4) \times 10^{-4}$  fm<sup>3</sup>

Magnetic polarizability  $\beta = (2.5 \pm 0.4) \times 10^{-4}$  fm<sup>3</sup> (S = 1.2)

Charge radius,  $\mu p$  Lamb shift =  $0.84087 \pm 0.00039$  fm [d]

Charge radius,  $e p$  CODATA value =  $0.8775 \pm 0.0051$  fm [d]

Magnetic radius =  $0.777 \pm 0.016$  fm

Mean life  $\tau > 2.1 \times 10^{29}$  years, CL = 90% [e] ( $p \rightarrow$  invisible mode)

Mean life  $\tau > 10^{31}$  to  $10^{33}$  years [e] (mode dependent)

# $\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$ : EDM

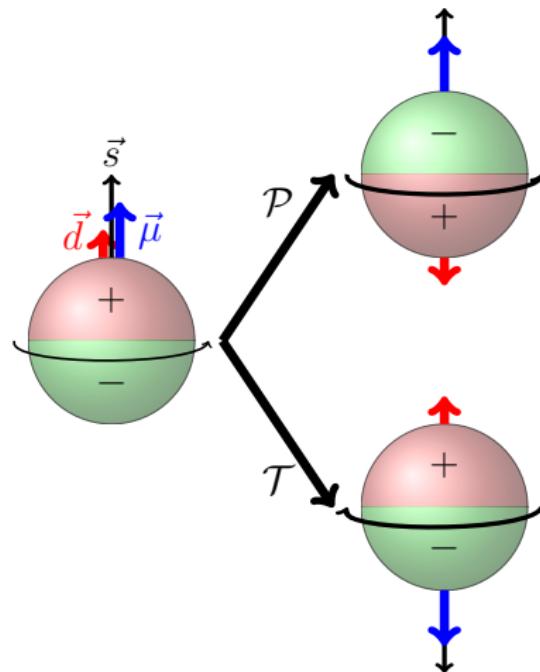
$\vec{\mu}$ : magnetic moment

both  $\parallel$  to spin

$$H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} - d \frac{\vec{s}}{s} \cdot \vec{E}$$

$$\mathcal{T}: H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{E}$$

$$\mathcal{P}: H = -\mu \frac{\vec{s}}{s} \cdot \vec{B} + d \frac{\vec{s}}{s} \cdot \vec{E}$$



⇒ EDM measurement tests violation of fundamental symmetries  $\mathcal{P}$  and  $\mathcal{T}$  ( $\stackrel{\text{CPT}}{=} \mathcal{CP}$ )

# $\mathcal{CP}$ -Violation and connection to EDMs

Standard Model	
<b>Weak interaction</b>	
CKM matrix	→ unobservably small EDMs
<b>Strong interaction</b>	
$\theta_{QCD}$	→ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	→ accessible by EDM measurements

# Matter-Antimatter Asymmetry

Excess of matter in the universe:

	observed	SCM* prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	$6 \times 10^{-10}$	$10^{-18}$

Sakharov (1967):  $\mathcal{CP}$  violation needed for baryogenesis

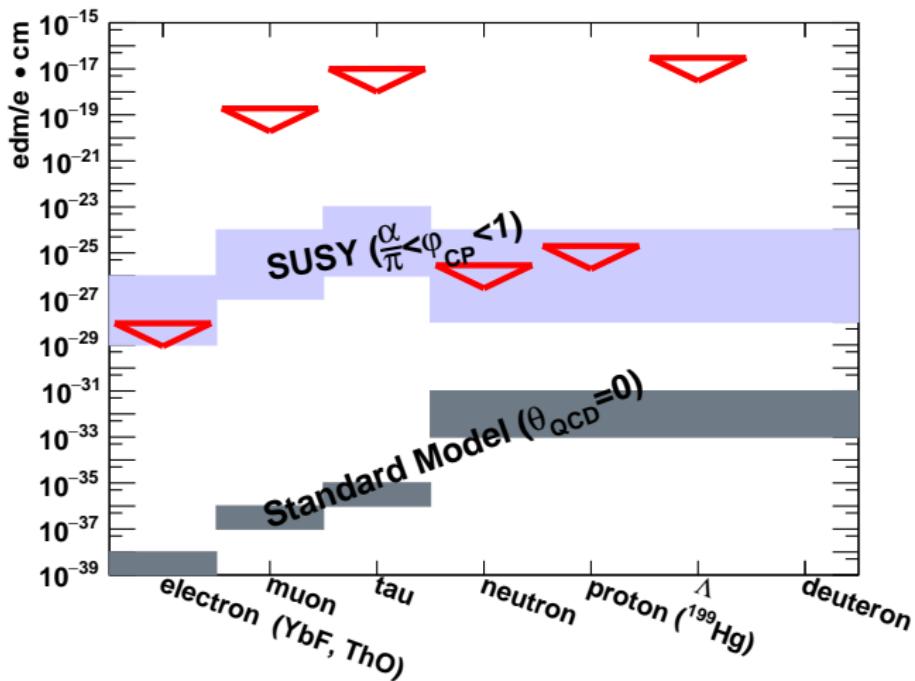
⇒ New  $\mathcal{CP}$  violating sources beyond SM needed to explain this discrepancy

They could show up in EDMs of elementary particles

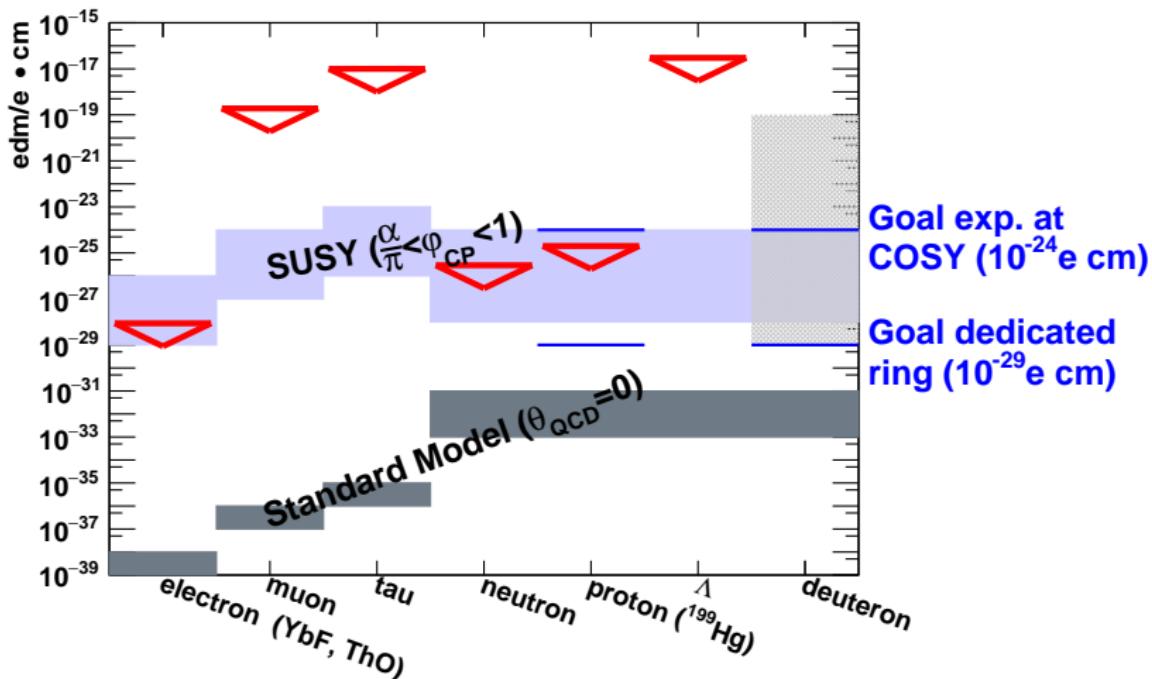
\* SCM: Standard Cosmological Model

What do we know about  
EDMs?

# EDM: Current Upper Limits



# EDM: Current Upper Limits



FZ Jülich: EDMs of **charged** hadrons:  $p, d, {}^3\text{He}$

## Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:  
 $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$  access to  $\theta_{QCD}$

EDM of one particle alone not sufficient to identify  $\mathcal{CP}$ -violating source

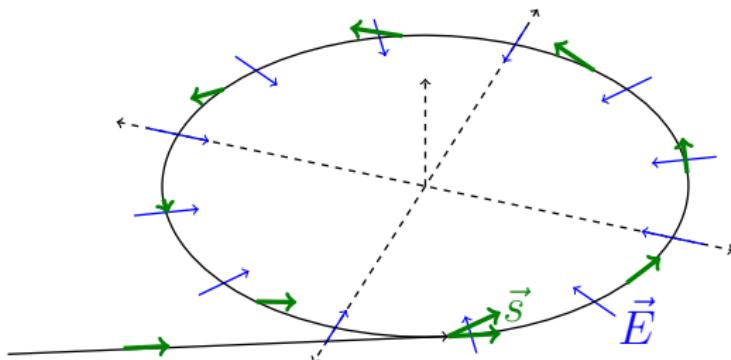
How to measure charged  
particle EDMs?

# Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, ...):

Interaction of  $\vec{d}$  with electric field  $\vec{E}$

For charged particles: apply electric field in a storage ring:



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

In general:

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

build-up of vertical polarization  $s_{\perp} \propto |\vec{d}|$

# Experimental Requirements

- high precision storage ring → **systematics**  
(alignment, stability, field homogeneity)
- high intensity beams ( $N = 4 \cdot 10^{10}$  per fill)
- polarized hadron beams ( $P = 0.8$ )
- long spin coherence time ( $\tau = 1000$  s),
- large electric fields ( $E = 10$  MV/m)
- polarimetry (analyzing power  $A = 0.6$ , acc.  $f = 0.005$ )

$$\sigma_{\text{stat}} \approx \frac{\hbar}{\sqrt{Nf\tau PAE}} \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29} \text{ e}\cdot\text{cm}$$

**challenge:** get  $\sigma_{\text{sys}}$  to the same level

# Spin Precession: Thomas-BMT Equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m} [\textcolor{red}{G}\vec{B} + \left( \textcolor{red}{G} - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{m}{es} \textcolor{blue}{d}(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}$$

BMT: Bargmann, Michel, Telegdi

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1.) pure electric ring

no  $\vec{B}$  field needed,  
CW/CCW beams simultaneously



works only for particles  
with  $G > 0$  (e.g.  $p$ )

BMT: Bargmann, Michel, Telegdi

# Spin Precession: Thomas-BMT Equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m} [G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{m}{es} \mathbf{d}(\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}$$



2.) combined ring

works for  $p, d, {}^3\text{He}, \dots$

both  $\vec{E}$  and  $\vec{B}$   
required

BMT: Bargmann, Michel, Telegdi

# Spin Precession: Thomas-BMT Equation

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s} = \frac{e}{m} [\textcolor{red}{G}\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{m}{es} \textcolor{red}{d} (\vec{E} + \vec{v} \times \vec{B})] \times \vec{s}$$



3.) pure magnetic ring	existing (upgraded) COSY ring can be used, shorter time scale	lower sensitivity, precession due to $\textcolor{red}{G}$ , i.e. no <b>frozen spin</b>
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BMT: Bargmann, Michel, Telegdi

## Recent Achievements:

How do manipulate and measure a polarization  
with high precision!

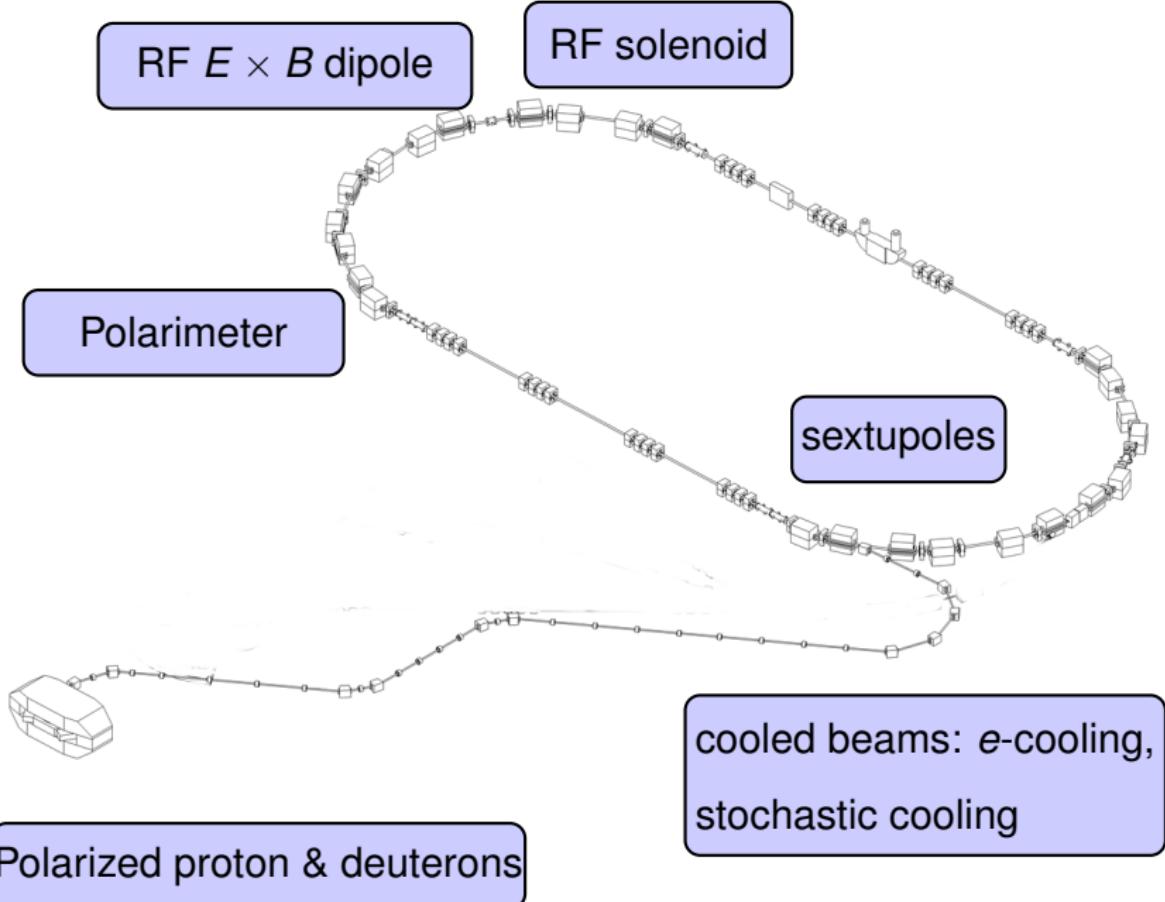
# Cooler Synchrotron COSY



COSY provides (polarized ) protons and deuterons with  
 $p = 0.3 - 3.7 \text{ GeV}/c$

⇒ **Ideal starting point for charged particle EDM searches**

# COSY



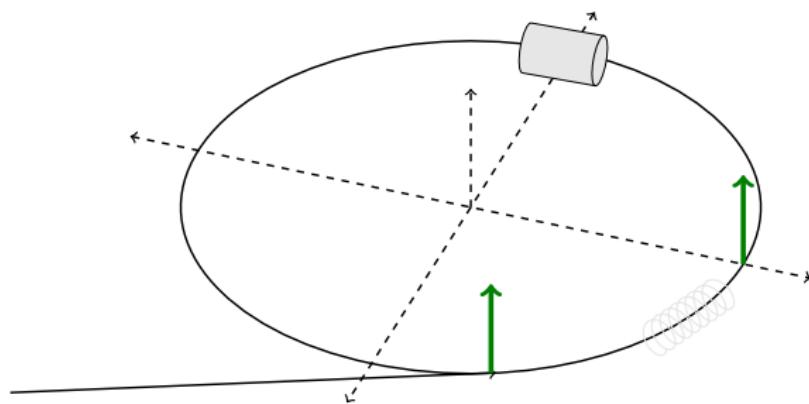
# R & D at COSY

- maximize spin coherence time (SCT) (→ E. Stephenson, Tue. 15.20)
- precise measurement of spin precession (spin tune)
- polarization feed back (→ N. Hempelmann, Tue. 14.45)
- spin tracking simulation tools, design of dedicated storage ring (→ M. Rosenthal, Tue. 14.30, E. Valetov, Tue. 11.30)
- RF- Wien filter design and construction (→ J. Slim, Tue. 14.55)
- tests of electro static deflectors (goal: field strength > 10 MV/m)
- development of high precision beam position monitors
- polarimeter development

More related talks on this conference: R. Talman (Tue. 11.55), B. Lorentz (Mon. 14.55), Y. Duteil (Mon. 14.30), W. Hillert (Tue. 12.20)

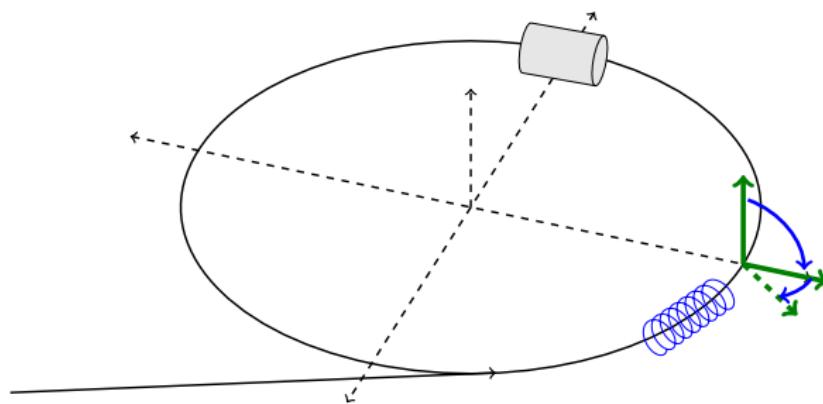
## Experimental Setup

- Inject and accelerate vertically polarized deuterons to  $p \approx 1 \text{ GeV}/c$



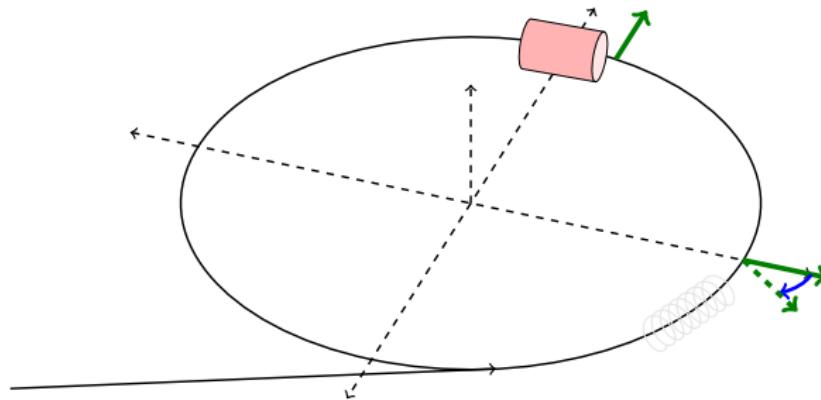
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- flip polarization with help of solenoid into horizontal plane, precession starts



# Experimental Setup

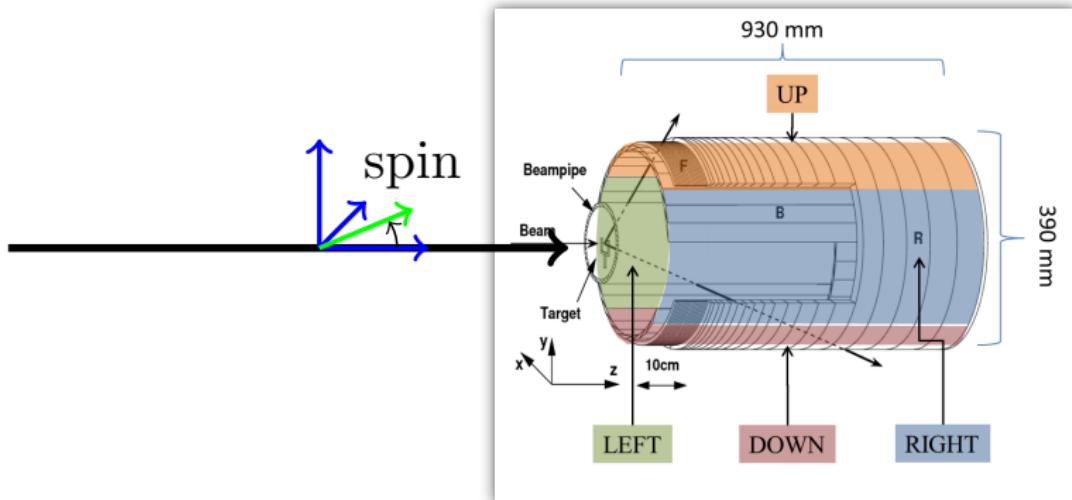
- Inject and accelerate vertically polarized deuterons to  $p \approx 1 \text{ GeV}/c$
- flip polarization with help of solenoid into horizontal plane, precession starts
- Extract beam slowly (in  $\approx 100 \text{ s}$ ) on target
- Measure asymmetry and determine spin precession



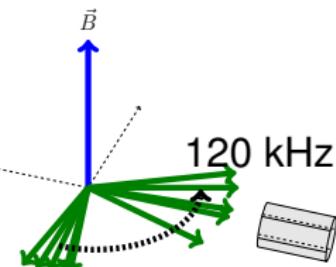
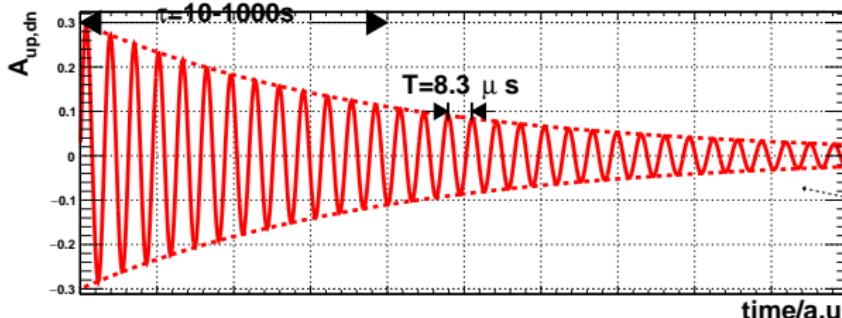
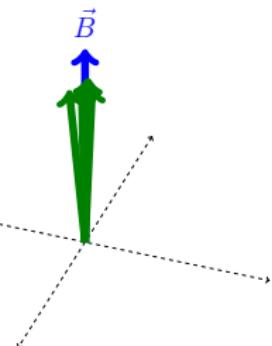
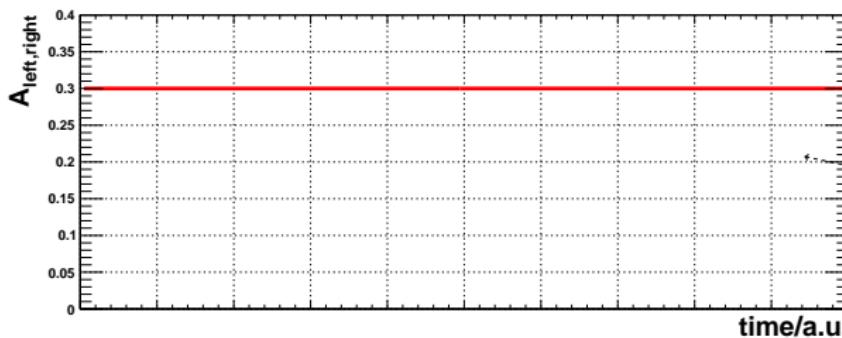
# Polarimeter

elastic deuteron-carbon scattering,  
consists of four scintillator segments: left, right, up, down

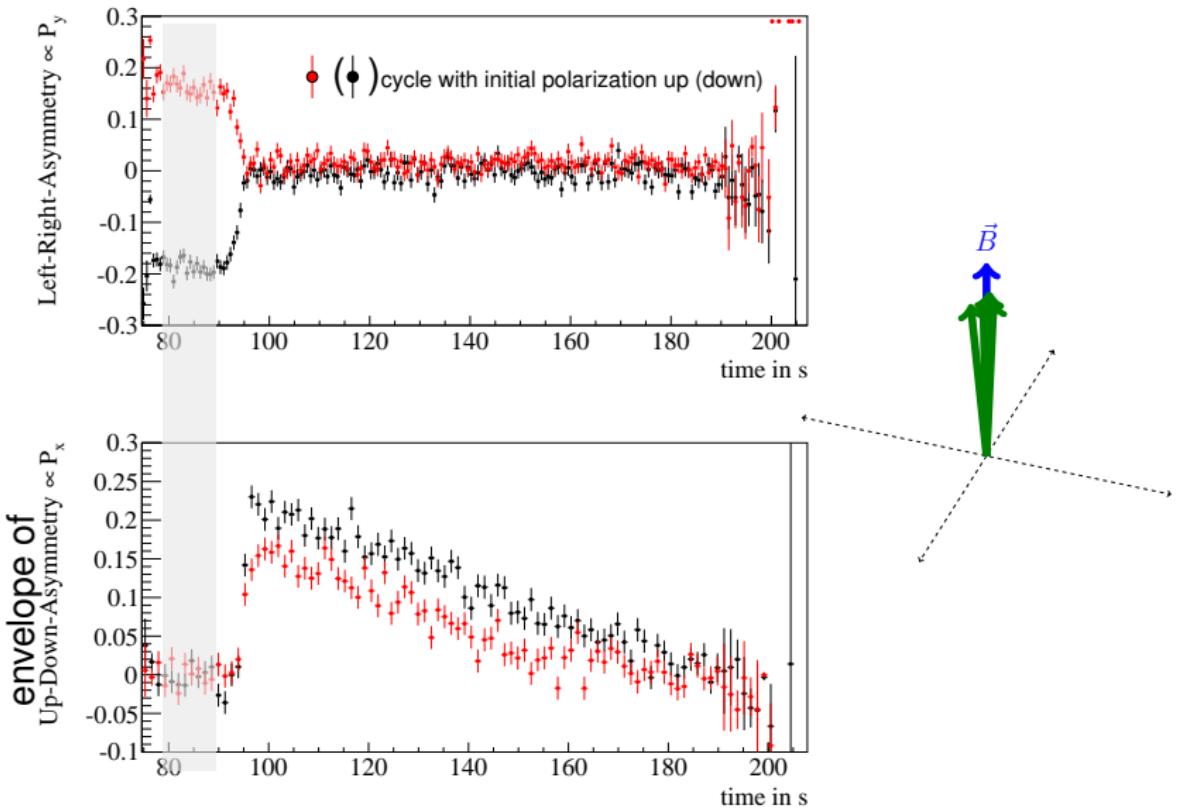
asymmetry  $A_{up,down} \propto$  horizontal polarization  $\rightarrow \nu_s = \gamma G$   
asymmetry  $A_{left,right} \propto$  vertical polarization  $\rightarrow d$



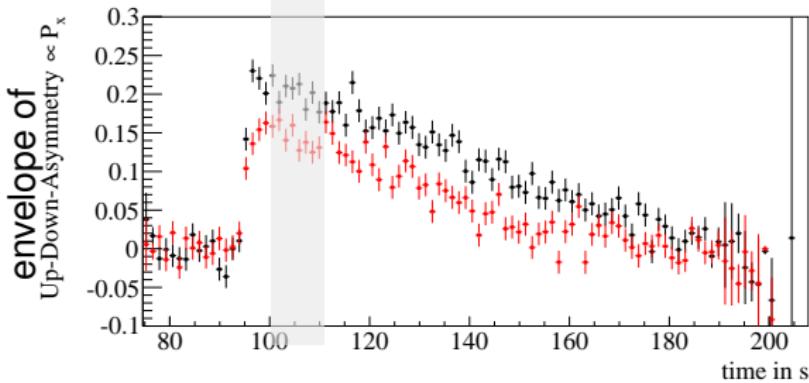
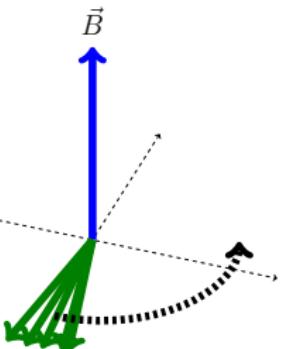
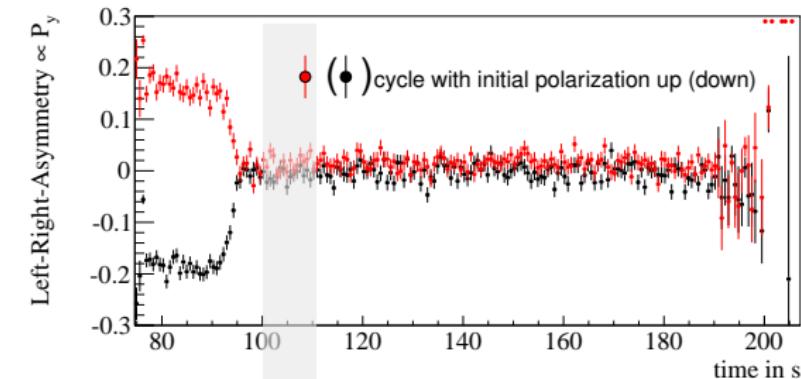
# Asymmetries



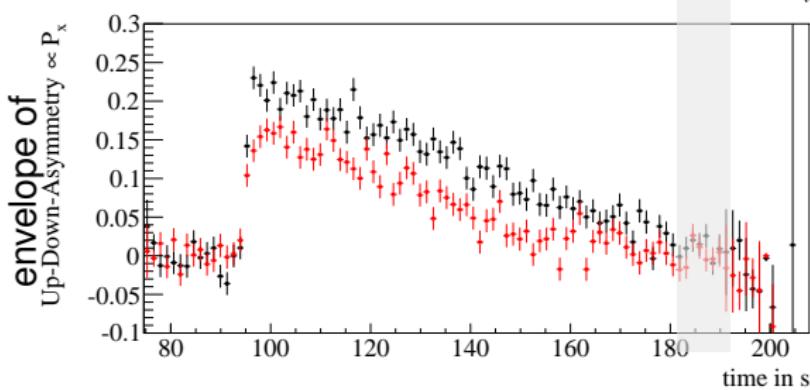
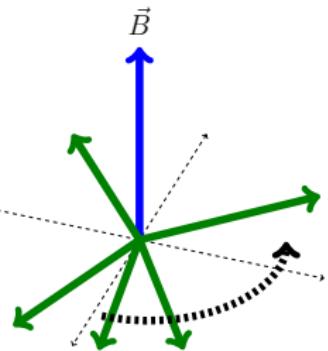
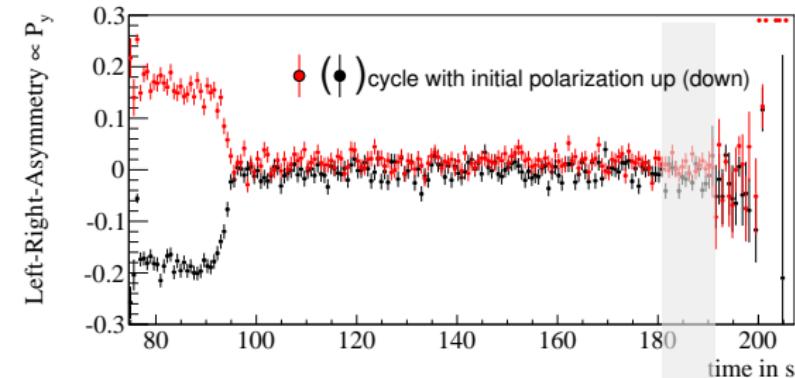
# Polarization Flip



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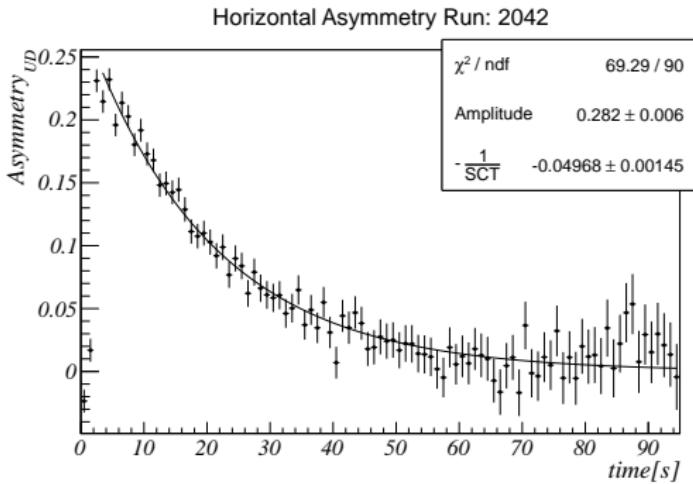
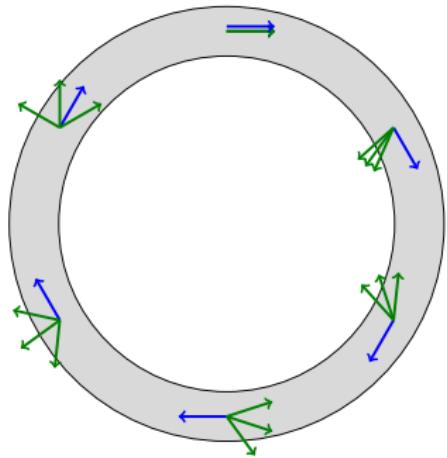


# Polarization Flip



# Results: Spin Coherence Time (SCT)

## Short Spin Coherence Time



unbunched beam

$$\Delta p/p = 10^{-5} \Rightarrow \Delta \gamma/\gamma = 2 \cdot 10^{-6}, T_{rev} \approx 10^{-6} \text{ s}$$

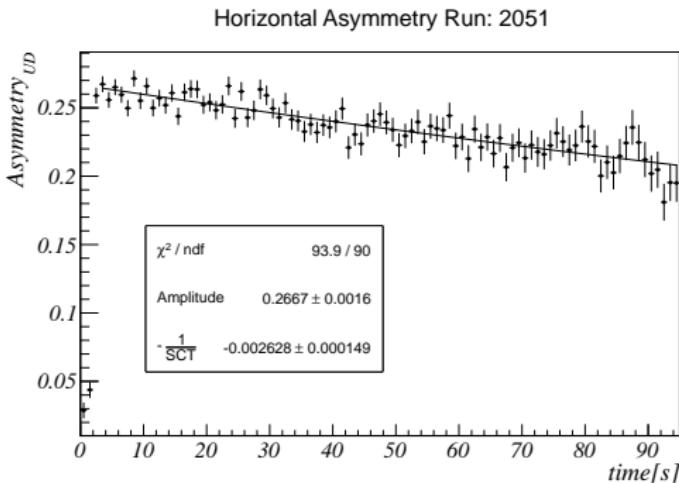
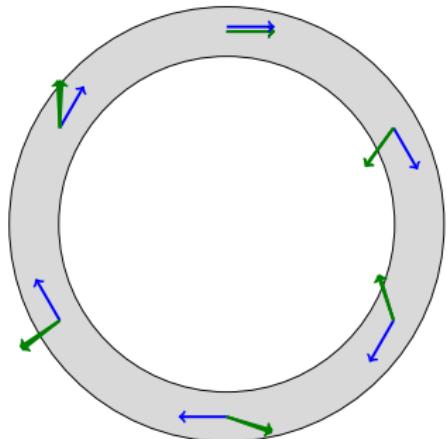
$\Rightarrow$  decoherence after  $< 1 \text{ s}$

bunched beam eliminates 1st order effects in  $\Delta p/p$

$\Rightarrow$  SCT  $\tau = 20 \text{ s}$

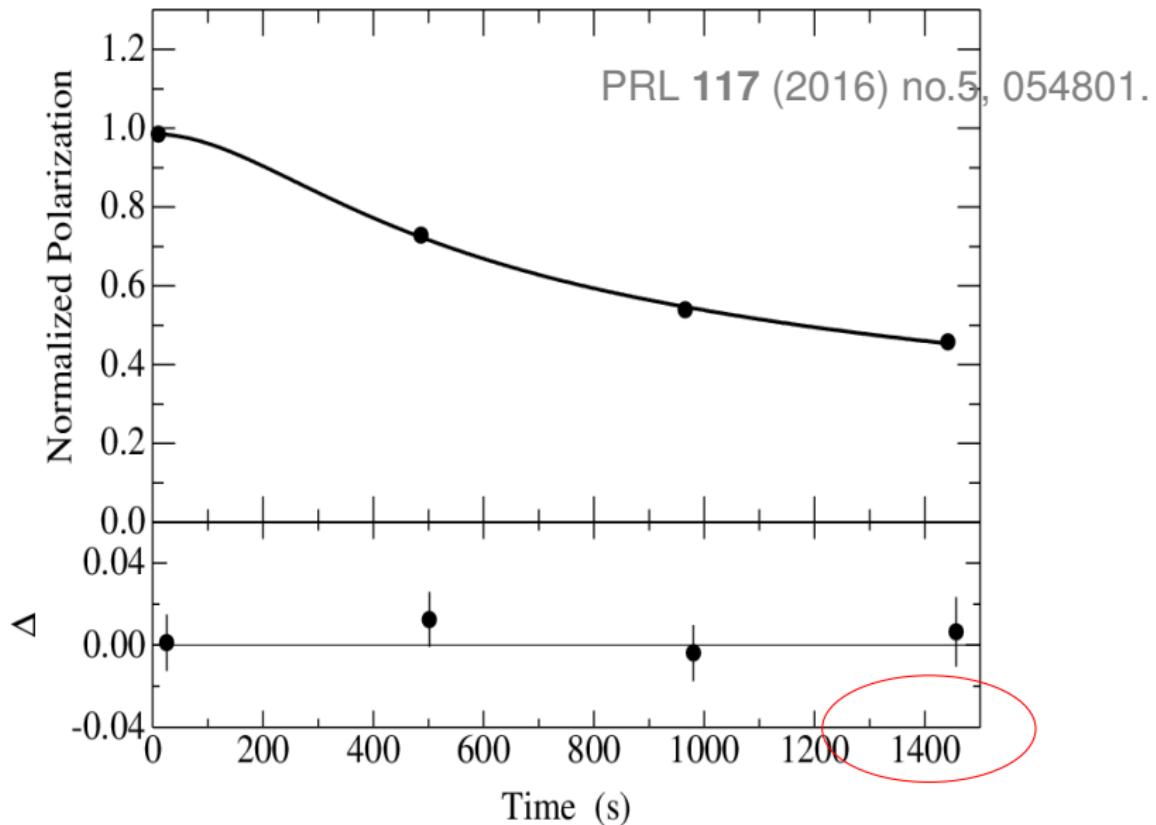
# Results: Spin Coherence Time (SCT)

## Long Spin Coherence Time

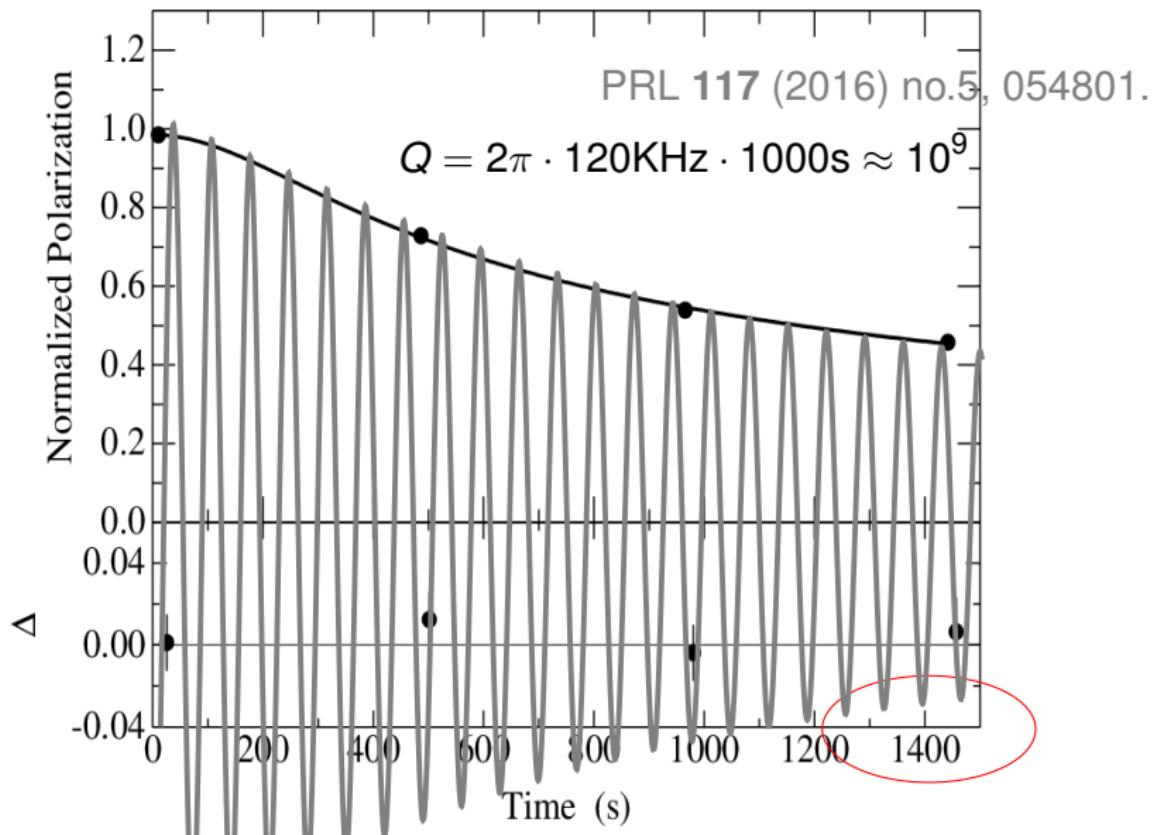


SCT of  $\tau = 400$  s, after correction with sextupoles  
(chromaticities  $\xi \approx 0$ )

# SCT: Longer Cycles

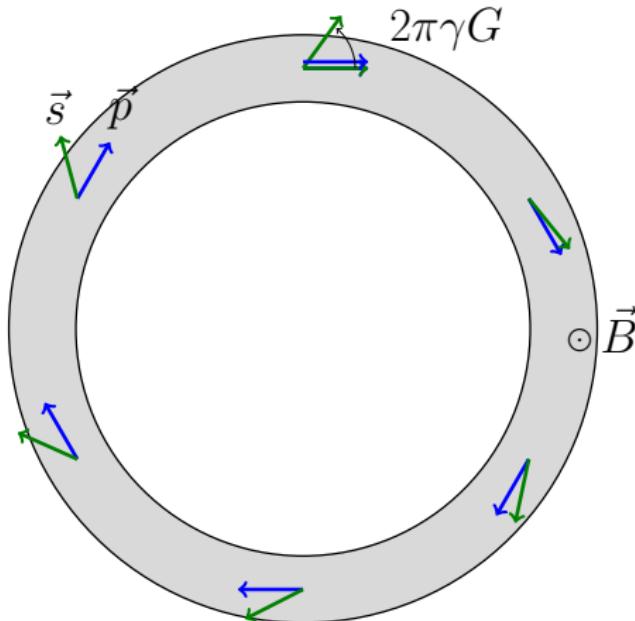


# SCT: Longer Cycles



## Spin Tune $\nu_s$

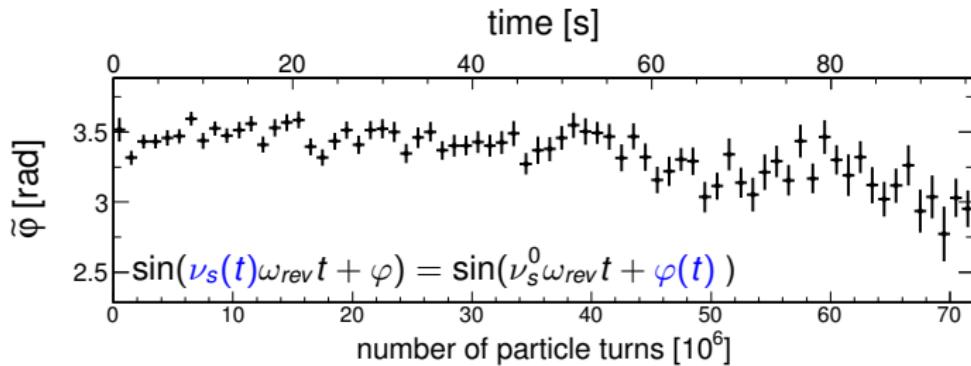
Spin tune:  $\nu_s = \gamma G = \frac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



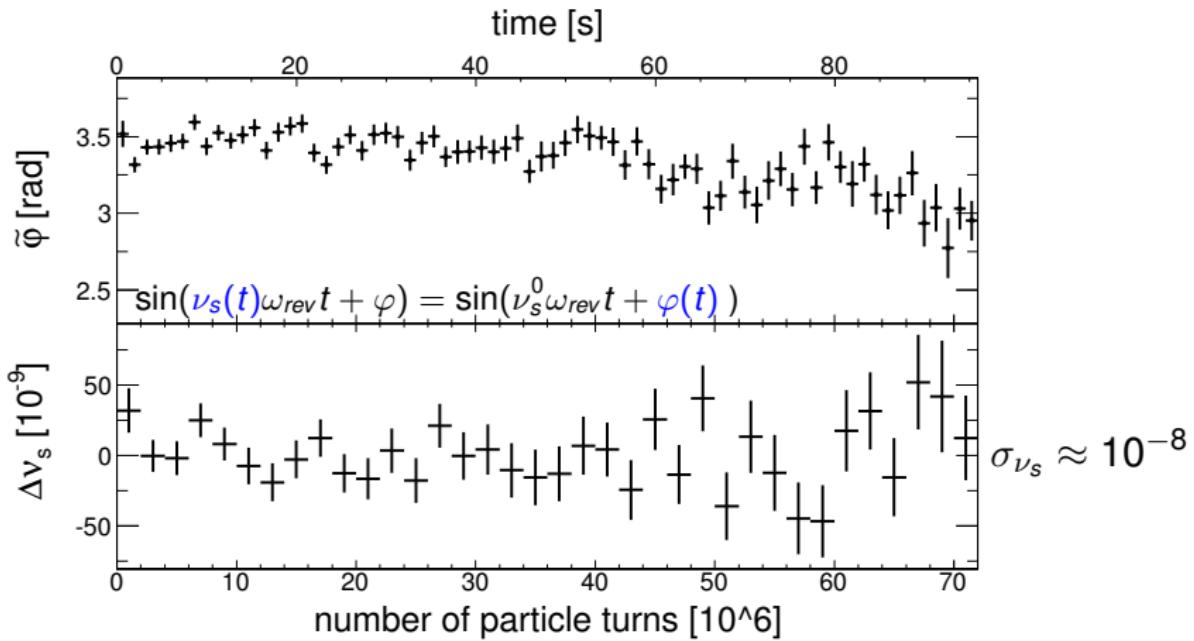
deuterons:  $p_d = 1 \text{ GeV}/c$  ( $\gamma = 1.13$ ),  $G = -0.14256177(72)$

$$\Rightarrow \nu_s = \gamma G \approx -0.161$$

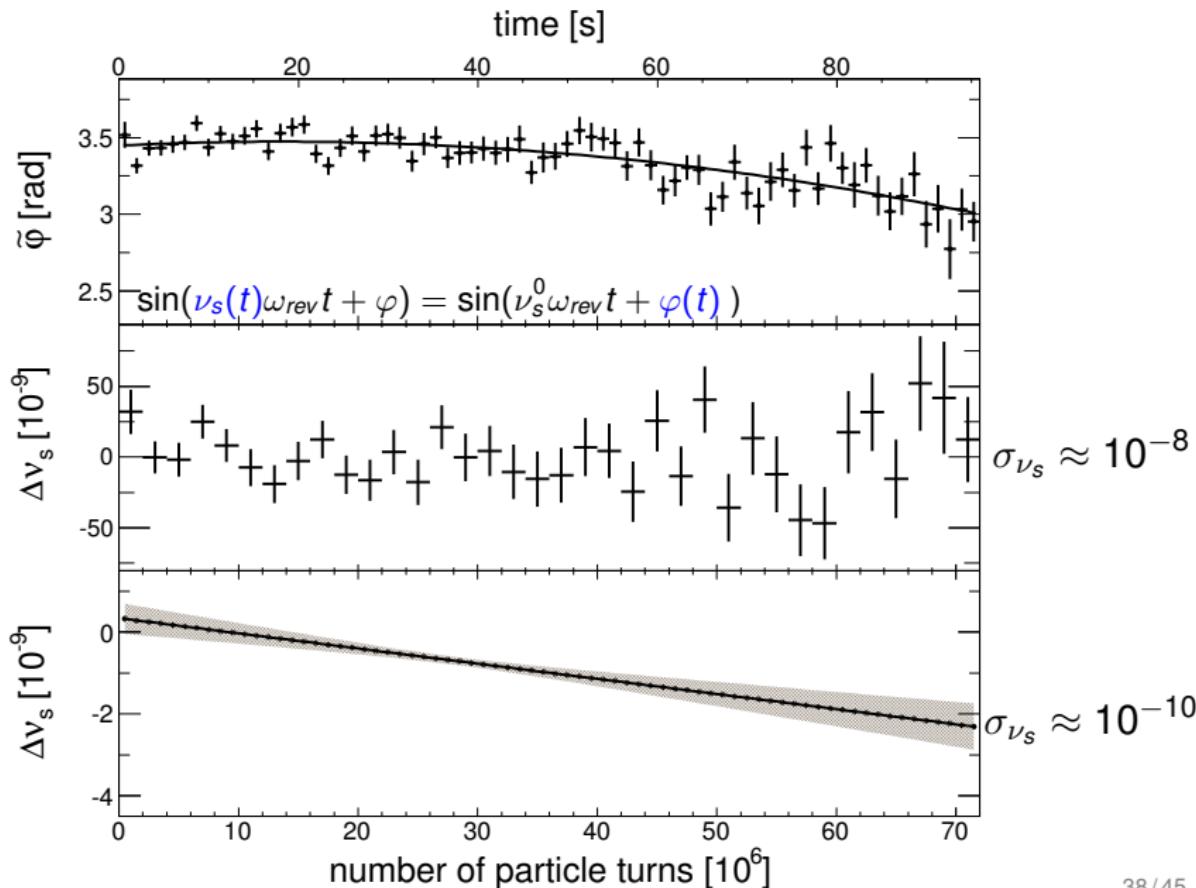
# Results spin tune



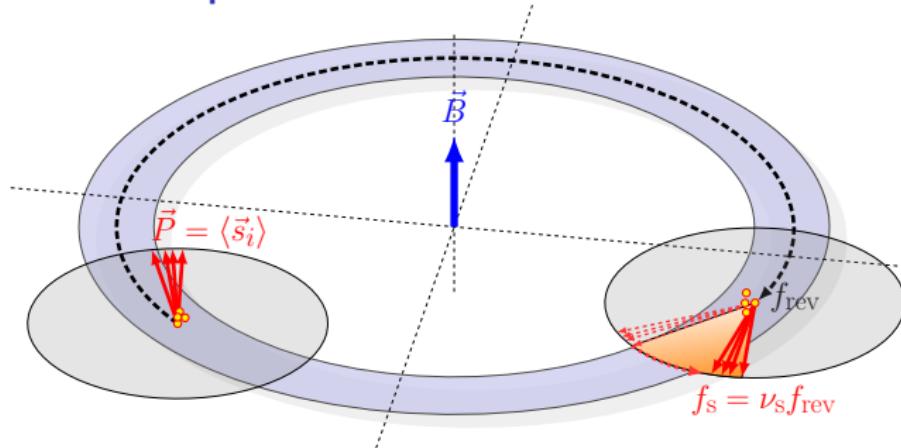
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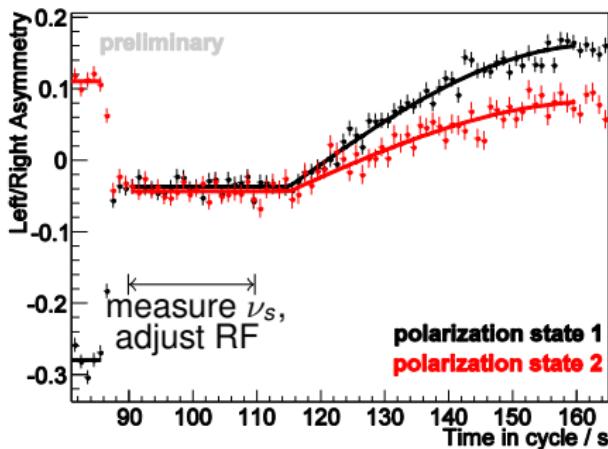


# Spin Tune Measurement



- precision  $10^{-10}$  in one cycle of  $\approx 100$  s  
(translated to angle, precision is  $2 \cdot \pi \cdot 10^{-10} = 0.6$  nrad)
- spin tune measurement can now be used as tool to investigate systematic errors
- spin tune measurement allows for feedback system to keep polarization aligned with momentum vector for dedicated ring or at a given phase with respect to radio-frequency Wien filter

# Spin Feed back system



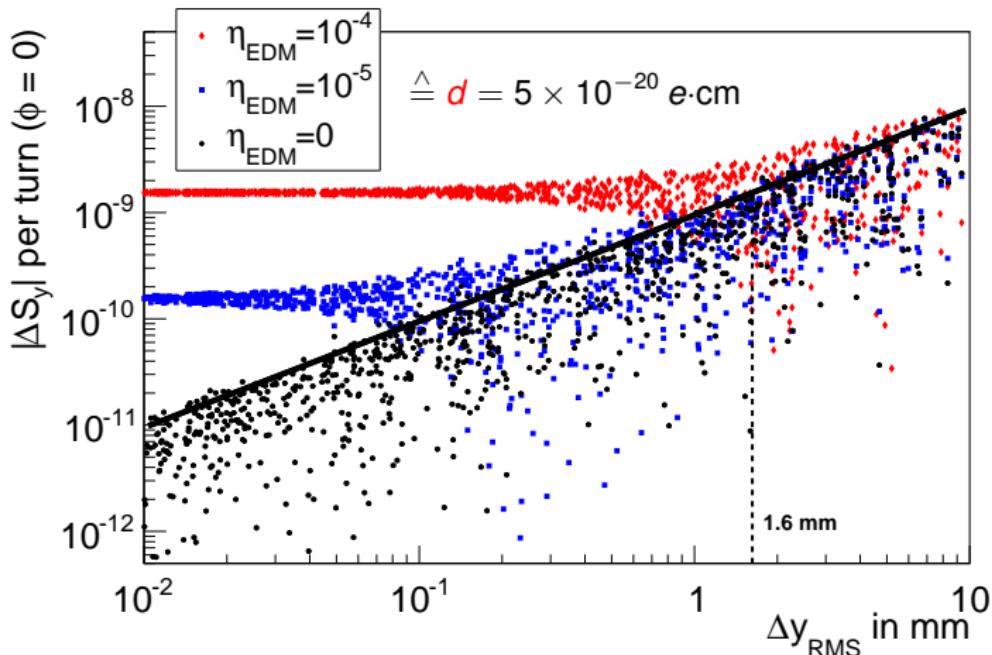
- polarization rotation in horizontal plane at  $t = 85$  s
- COSY rf changed during cycle in steps of 3.7 mHz ( $f_{\text{rev}} = 750603$  Hz) according to online  $\nu_s$  measurement,

- keeps phase between spin and RF solenoid constant
- solenoid (low amplitude) switched on at  $t = 115$  s
- polarization goes back to vertical direction
- mandatory for **frozen spin** in dedicated ring

# Simulations

- EDM signal is build-up of vertical polarization
- radial magnetic fields ( $B_r$ ) cause the same build-up
- misalignments of quadrupoles create for example unwanted  $B_r$
- $\Rightarrow$  Run simulations to understand systematic effects
- General problem: Track  $10^9$  particles for  $10^9$  turns!  
( $\rightarrow$  use transfer maps of magnet elements (code: COSY Infinity))
- orbit RMS  $\Delta y_{RMS}$  is measure of misalignments

## Spin Tracking



Random Misalignments from  $1\mu\text{m}$  to 1 mm,  
Use of CW/CCW beams requires only relative measurement of  
two beams

# JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 100 members  
(Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...)
- ≈ 10 PhD students
- close collaboration with srEDM collaboration in US/Korea



<http://collaborations.fz-juelich.de/ikp/jedi/index.shtml>

## Electric dipole moment

# Storage ring steps up search for electric dipole moments

The JEDI collaboration aims to use a storage ring to set the most stringent limits to date on the electric dipole moments of hadrons, describe **Paolo Lenisa, Jörg Pretz and Hans Ströher**.

The fact that we and the world around us are made of matter and only

Forschungszentrum Jülich



European  
Research  
Council

### Search for electric dipole moments using storage rings

PI: H. Ströher, (FZ Jülich),  
RWTH Aachen University,  
University of Ferrara  
Start: Oct, 1st, 2016

## Summary & Outlook

- **EDMs** of elementary particles are of high interest to disentangle various sources of  $\mathcal{CP}$  **violation** searched for to explain **matter - antimatter asymmetry** in the Universe
- EDM of **charged** particles can be measured in **storage rings**
- Experimentally very challenging because effect is tiny
- First promising results:

**spin coherence time:**  $\approx 1000$  s

**spin tune:**  $10^{-10}$  in 100 s

**feed back system** allows to control spin

**simulations** to understand systematics