Kent State University
5 December 2008

# Deuteron & proton EDM Experiment:

## Storage ring EDM experiment with $10^{-29}$ e·cm sensitivity using the "Frozen Spin Method"

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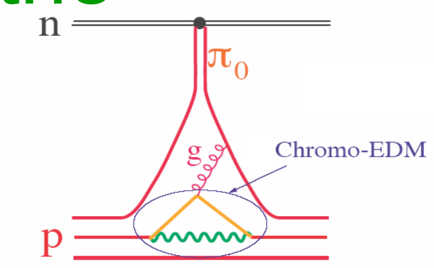
Brookhaven National Lab

- Utilizing the strong E-field present in the rest frame of a relativistic particle in a storage ring.
- Its physics reach is beyond the LHC scale and complementary to it.



# Physics at the Frontier, pursuing two approaches:

- Energy Frontier
- Precision Frontier

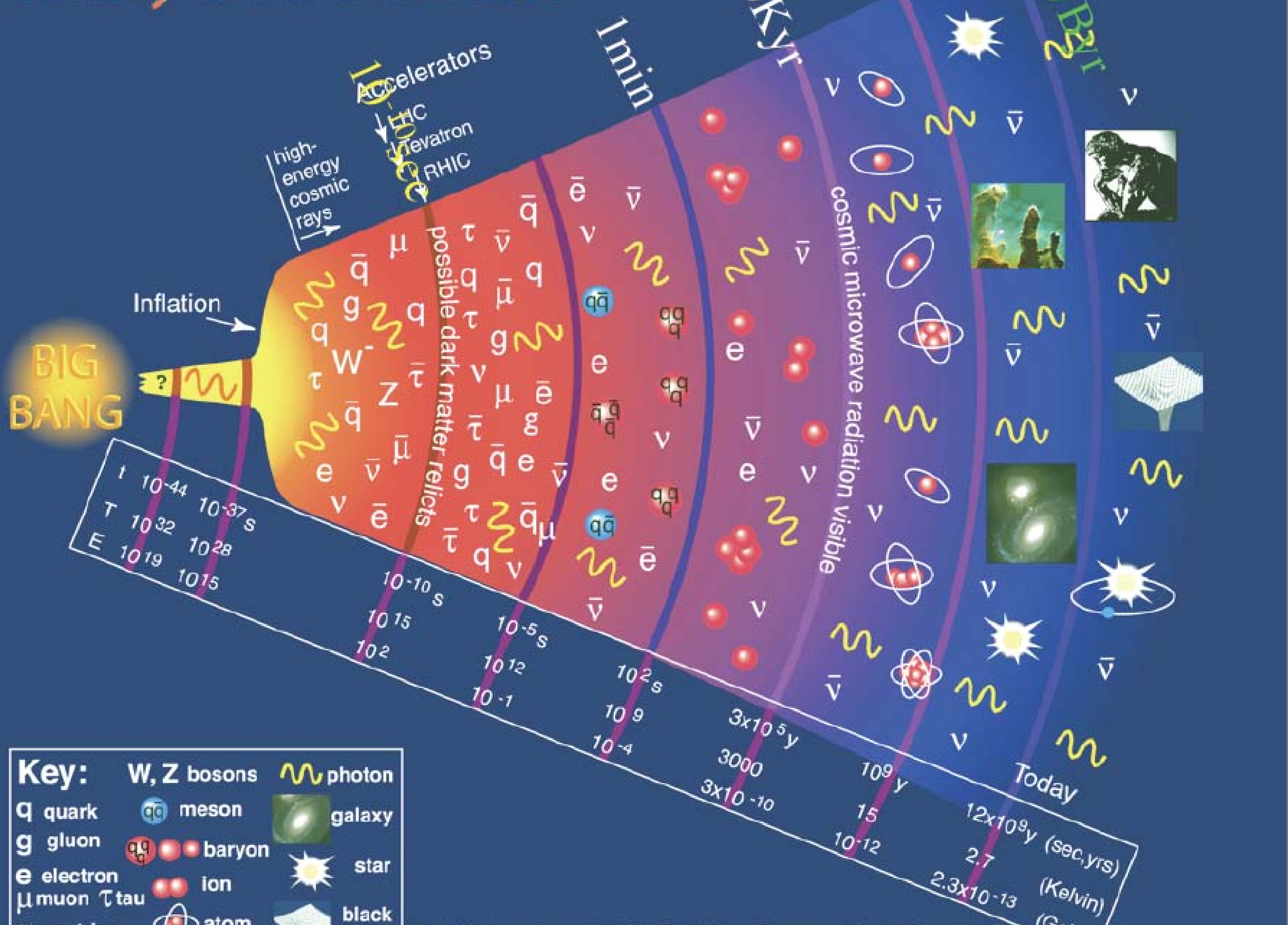
which are complementary and inter-connected. The next SM will emerge with input from both approaches.

# Physics of EDM

The Deuteron EDM at $10^{-29}$e·cm has a reach of ~300TeV or, if new physics exists at the LHC scale, $10^{-5}$ rad CP-violating phase.

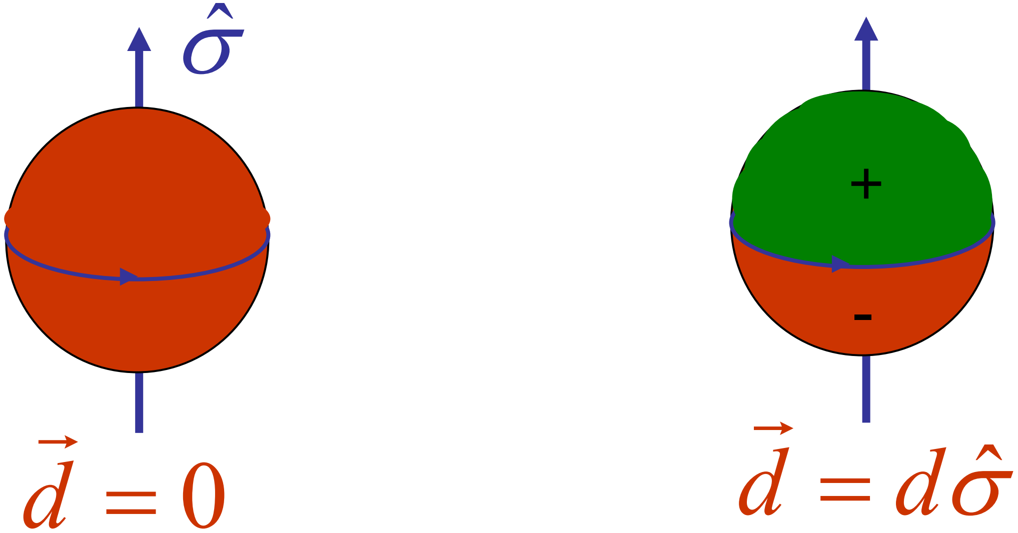
- **It can help resolve the missing mass (anti-matter) mystery of our universe.**

# History of the Universe

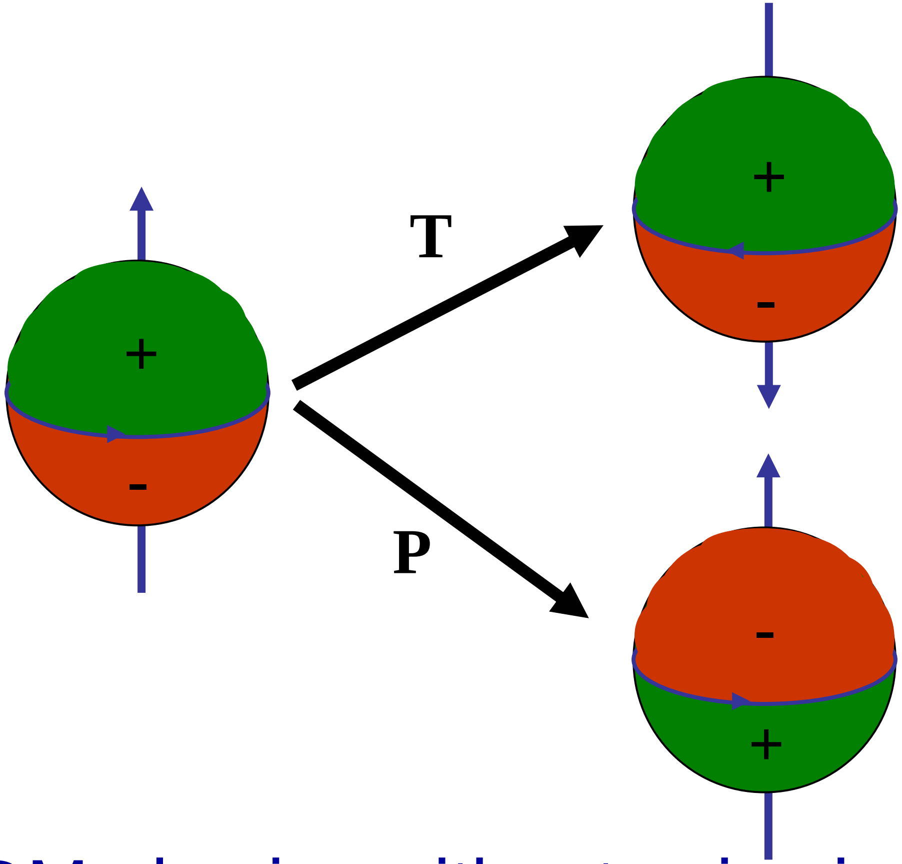


Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

# Spin is the only vector defining a direction of a “fundamental” particle with spin



# A Permanent EDM Violates both T & P Symmetries:



EDM physics without spins is not important
(batteries are allowed!)

# A Permanent EDM Violates both T & P Symmetries:

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\text{T}} H = -d\left(-\vec{\sigma}\right)\cdot\vec{E} = d\vec{\sigma}\cdot\vec{E}$$

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\text{P}} H = -d\vec{\sigma}\cdot\left(-\vec{E}\right) = d\vec{\sigma}\cdot\vec{E}$$

# How about Induced EDMs?

$$\vec{d} \propto d\vec{E}$$

$$H = -d\vec{E}\cdot\vec{E} \xrightarrow{\mathrm{T}} \text{OK}$$

$$H = -d\vec{E}\cdot\vec{E} \xrightarrow{\mathrm{P}} \text{OK}$$

$$H = -d\vec{\sigma}\cdot\vec{E}$$

1st order Stark effect. T, P Violation!

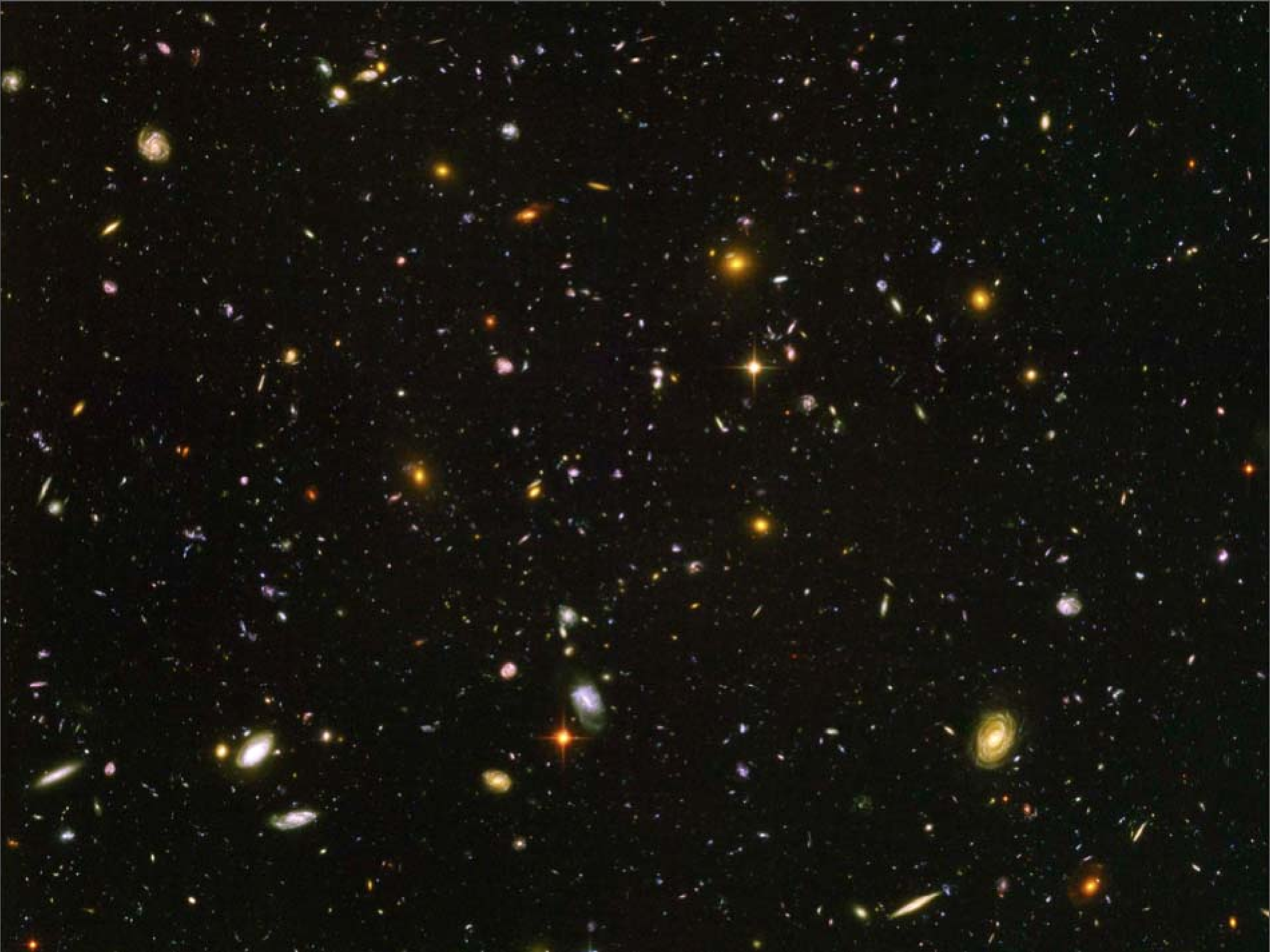
$$H = -d\vec{E}\cdot\vec{E}$$

2nd order Stark effect. Allowed!

T-Violation $\xrightarrow{\text{CPT}}$ CP-Violation

## Andrei Sakharov 1967:

*CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today....*

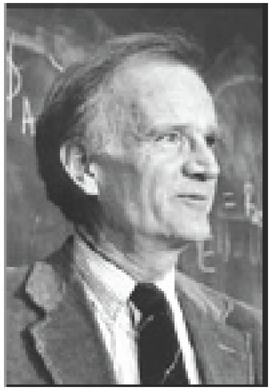


# CP-violation was discovered at BNL in 1964

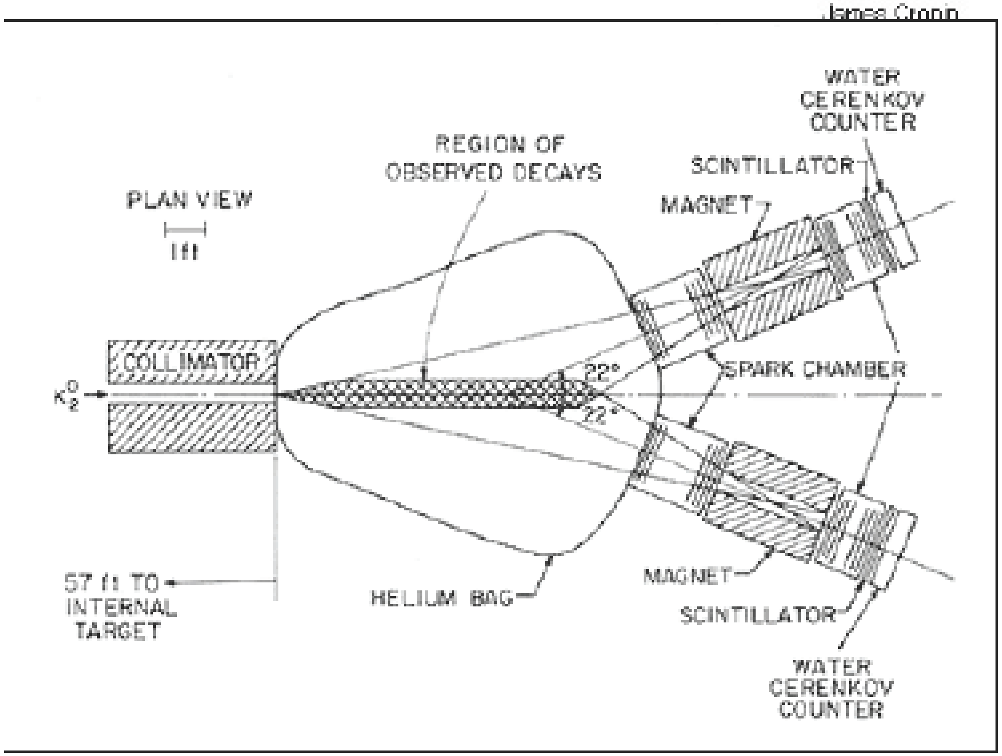
James W. Cronin and Val L. Fitch, both then of Princeton University, proposed using Brookhaven's AGS to verify a fundamental tenet of physics, known as CP symmetry, by showing that two different particles did not decay into the same products. They picked as their example neutral K mesons, which are routinely produced in collisions between a proton beam and a stationary metal target.

The experiment set out to show that in millions of collisions, the short-lived variety of K meson always decayed into two pi mesons, while the long-lived variety never did. But to their surprise, a "suspicious-looking hump" in the data showed an unexpected result that years of subsequent experimentation and theory have been unable to explain: occasionally, the long-lived neutral K meson does decay into two pi mesons. Cronin and Fitch had found an example of CP violation.

James Cronin



Val Fitch



Schematic of the experimental apparatus used by Cronin and Fitch.

# CP-violation is established

- The SM CP-violation is not enough to explain the apparent Baryon Asymmetry of our Universe by ~10 orders of magnitude.

- A new, much stronger CP-violation source is needed to explain the observed BAU.

# EDM Searches are Excellent Probes of Physics Beyond the SM:

Most models beyond the SM predict values within the sensitivity of current or planned experiments:

- SUSY
- Multi-Higgs
- Left-Right Symmetric …

The SM contribution is negligible…

# Short History of EDM

- 1950's neutron EDM experiment started to search for parity violation (before the discovery of P-violation)
- After P-violation was discovered it was realized EDMs require both P,T-violation
- 1960's EDM searches in atomic systems
- 1970's Indirect Storage Ring EDM method from the CERN muon g-2 exp.
- 1980's Theory studies on systems (molecules) w/ large enhancement factors
- 1990's First exp. attempts w/ molecules. Dedicated Storage Ring EDM method developed
- 2000's Proposal for sensitive dEDM exp. developed.

# Important Stages in an EDM Experiment

1. Polarize:state preparation, intensity of beams

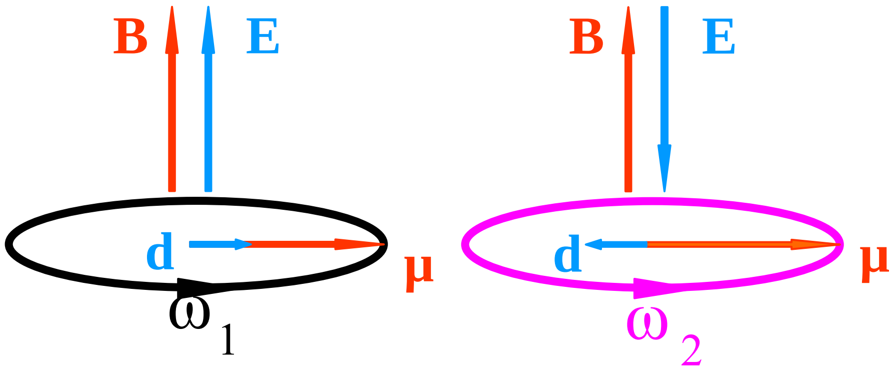
2. Interact with an E-field:the higher the better

3. Analyze:high efficiency analyzer

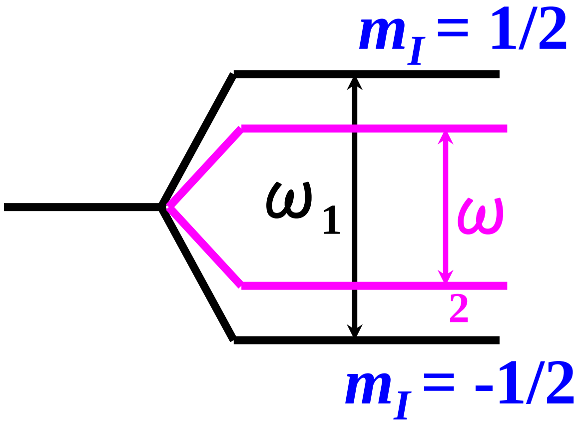
4. Scientific Interpretation of Result!  Easier for the simpler systems

# Measuring an EDM of Neutral Particles

$$H = -(d\,\mathbf{E} + \mu\,\mathbf{B}) \bullet \mathbf{I}/I$$



$$\omega_1 = \frac{2\mu B + 2dE}{\hbar} \qquad \omega_2 = \frac{2\mu B - 2dE}{\hbar}$$



$$d = \frac{\hbar(\omega_1 - \omega_2)}{4E}$$

**d = $10^{-25}$ e cm**

**E = 100 kV/cm**

⇒ **ω = $10^{-4}$ rad/s**

# EDM methods

- Neutrons: Ultra Cold Neutrons, apply large E-field and a small B-field. Probe frequency shift with E-field flip

- Atomic & Molecular Systems: Probe 1st order Stark effect

- Storage Ring EDM for charged particles: Utilize large E-field in rest frame-Spin precesses out of plane (Probe angular distribution changes)

# EDM method Advances

- Neutrons: advances in stray B-field effect reduction; higher UCN intensities

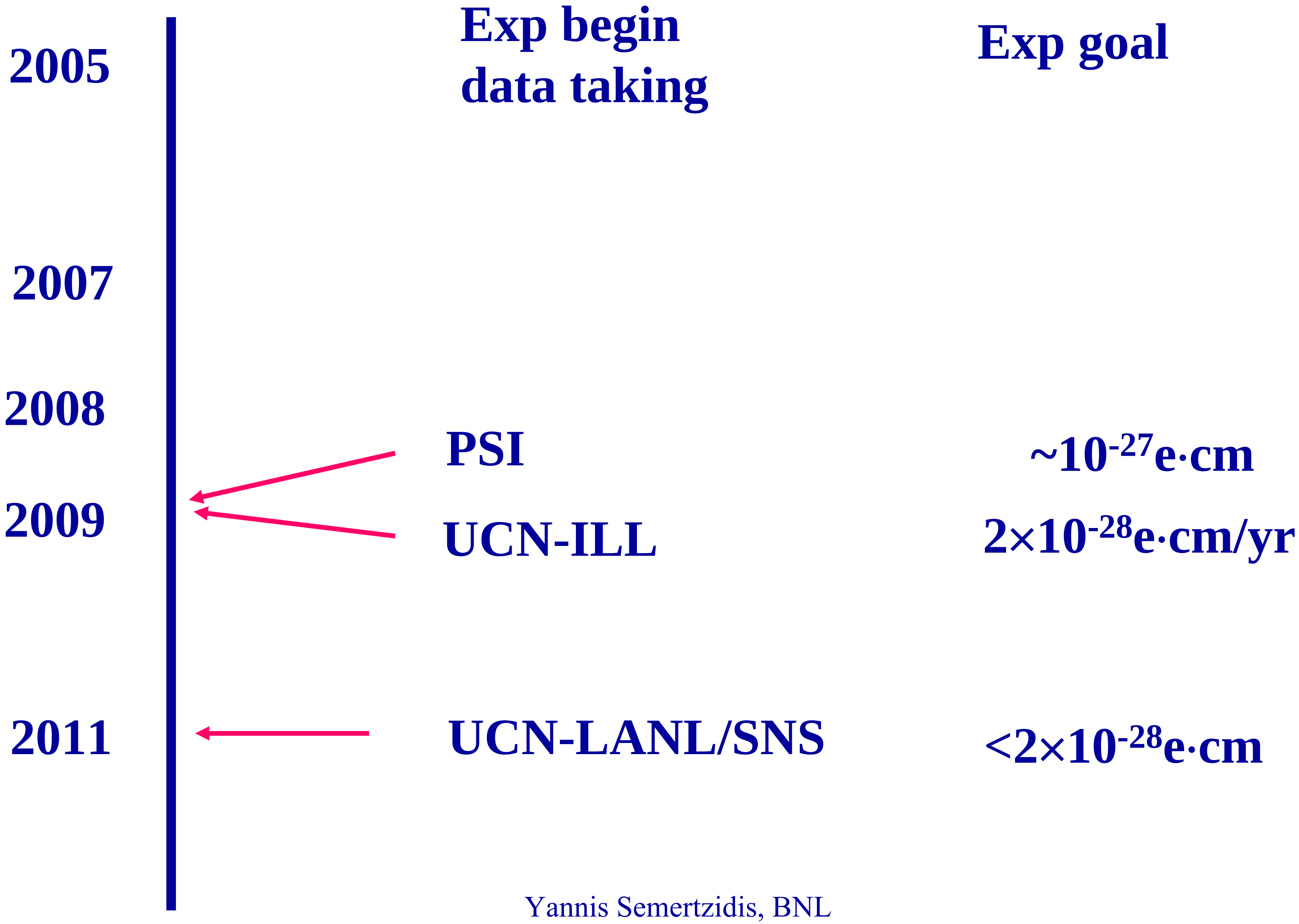
- Atomic & Molecular Systems: high effective E-field

- Storage Ring EDM for D, P: High intensity polarized sources well developed; High electric fields made available; spin precession techniques in SR well understood

# EDM method Weaknesses

- Neutrons: Intensity; High sensitivity to stray B-fields; Motional B-fields and geometrical phases
- Atomic & Molecular Systems: Low intensity of desired states; in some systems: physics interpretation
- Storage Ring EDM: some systematic errors different from g-2 experiment, geometrical phases…

# Neutron EDM Timeline



**Exp begin data taking**

**Exp goal**

**2005**

**2007**

**2008**

**2009**

**2011**

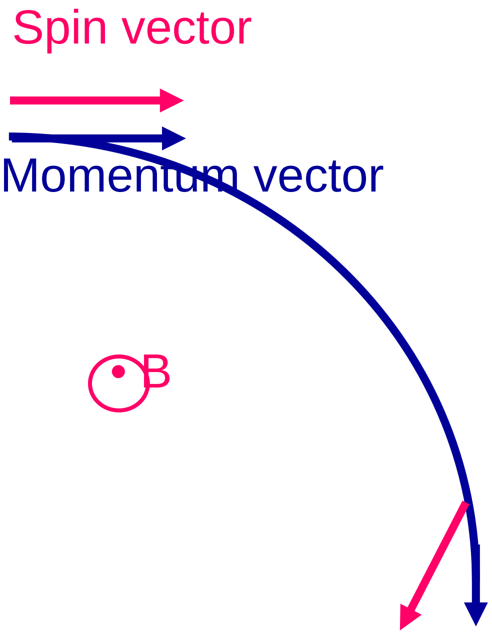
**PSI** $\sim 10^{-27}$ e·cm

**UCN-ILL** $2\times10^{-28}$ e·cm/yr

**UCN-LANL/SNS** $<2\times10^{-28}$ e·cm

# The Storage Ring EDM experiment

# The Principle of g-2



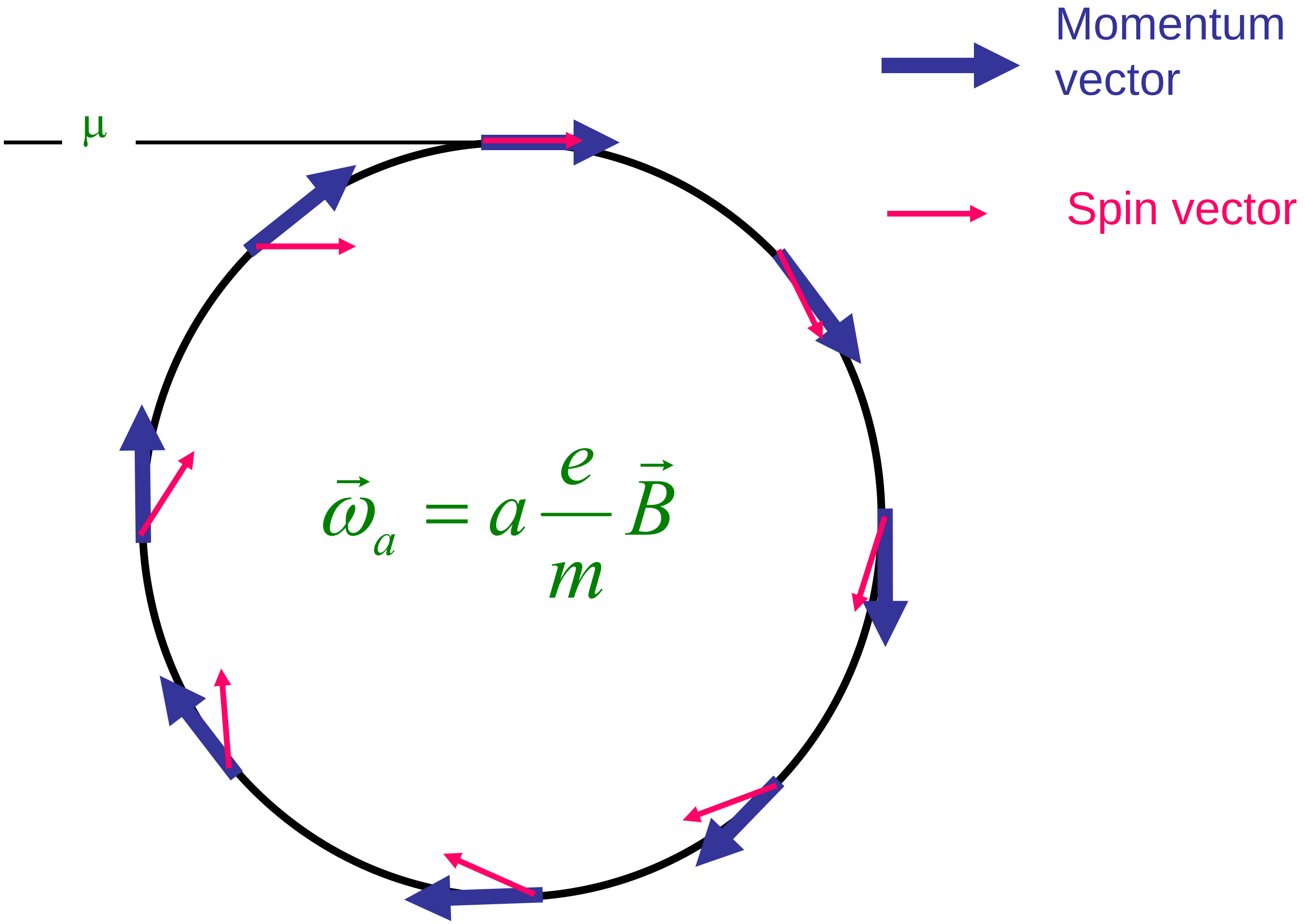
Non-relativistic case

$$\omega_c = \frac{eB}{m}$$

$$\omega_s = \frac{g}{2}\frac{eB}{m}$$

$$\omega_a = \omega_s - \omega_c = \frac{g}{2}\frac{eB}{m} - \frac{eB}{m} = \left(\frac{g-2}{2}\right)\frac{eB}{m} \Rightarrow \boxed{\omega_a = a\frac{eB}{m}}$$

# Spin Precession in g-2 Ring (Top View)

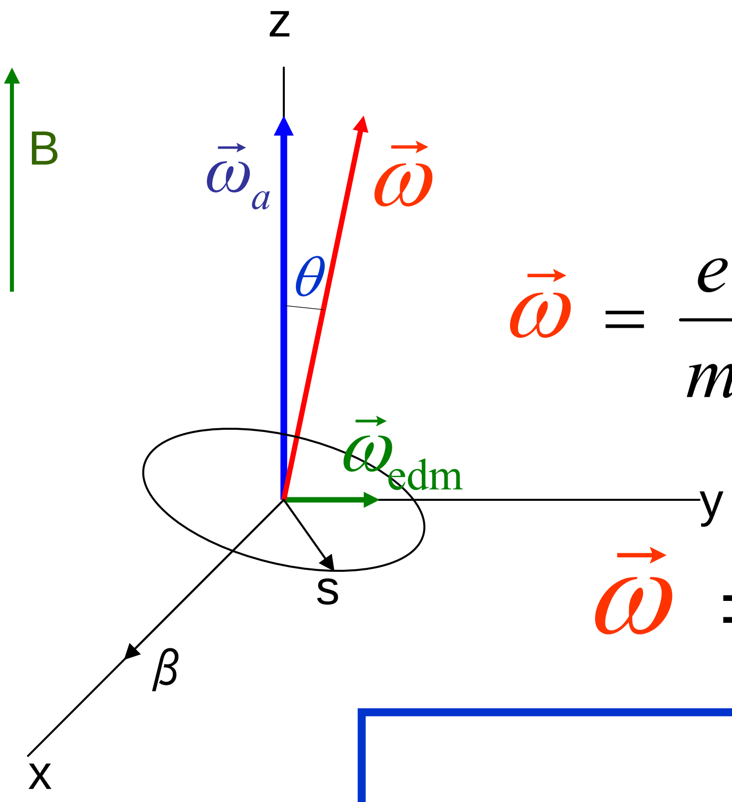


$$\vec{\omega}_a = a \frac{e}{m} \vec{B}$$

Yannis Semertzidis, BNL

- **The Muon Storage Ring: $B \approx 1.45T$, $P_\mu \approx 3$ GeV/c**

# Indirect Muon EDM limit from the g-2 Experiment



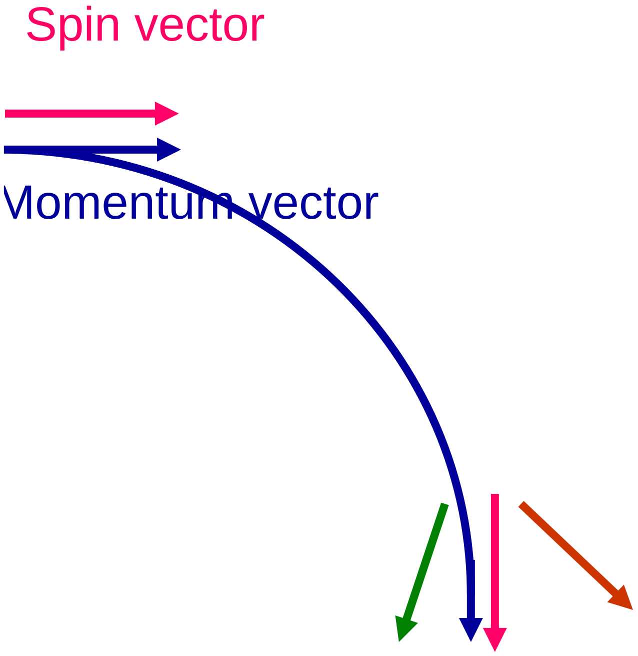
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\text{edm}}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

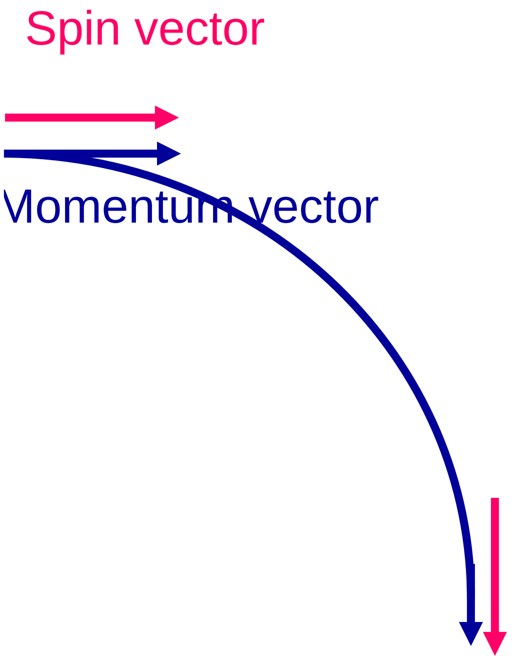
Ron McNabb's Thesis 2003: $< 2.7\times 10^{-19}\,\mathrm{e}\cdot\mathrm{cm}$ 95% C.L.

# Effect of Radial Electric Field



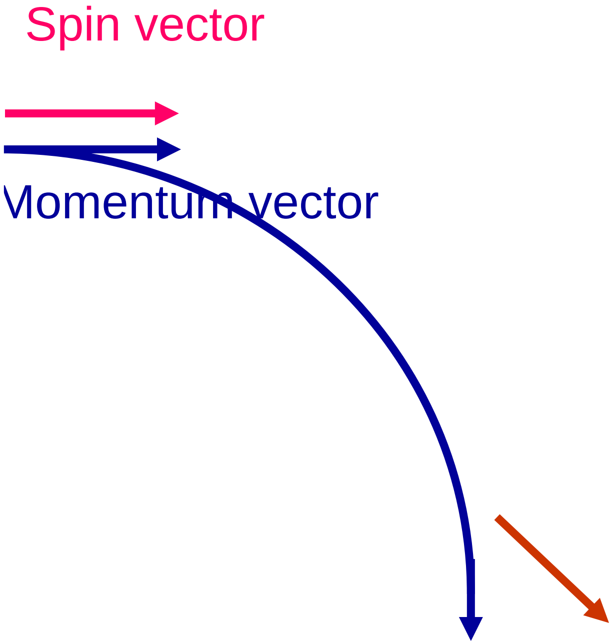
- Low energy particle
- …just right
- High energy particle

# Effect of Radial Electric Field



- …just right (magic P)

# Use of Radial Electric Field

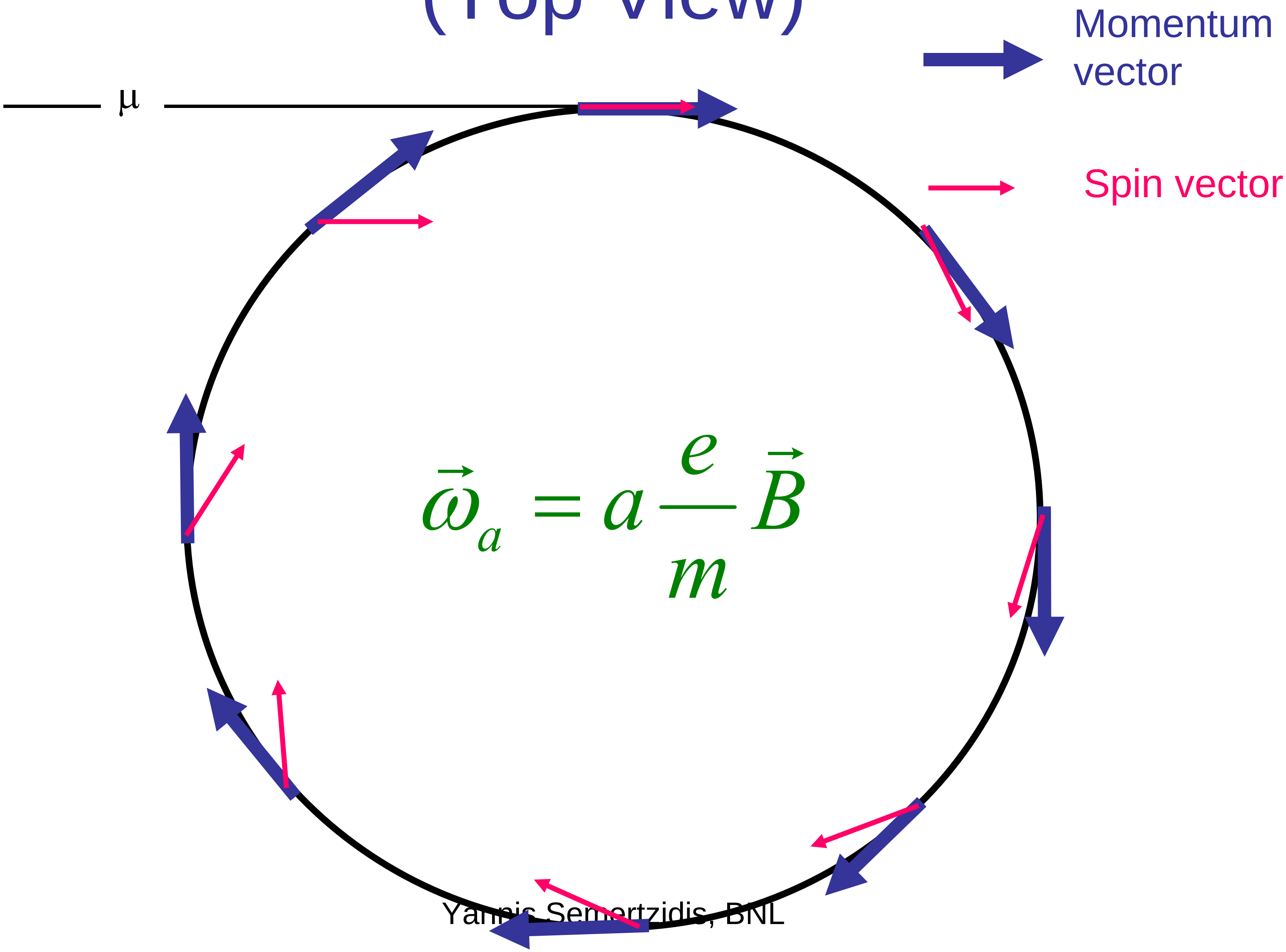


Spin vector

Momentum vector

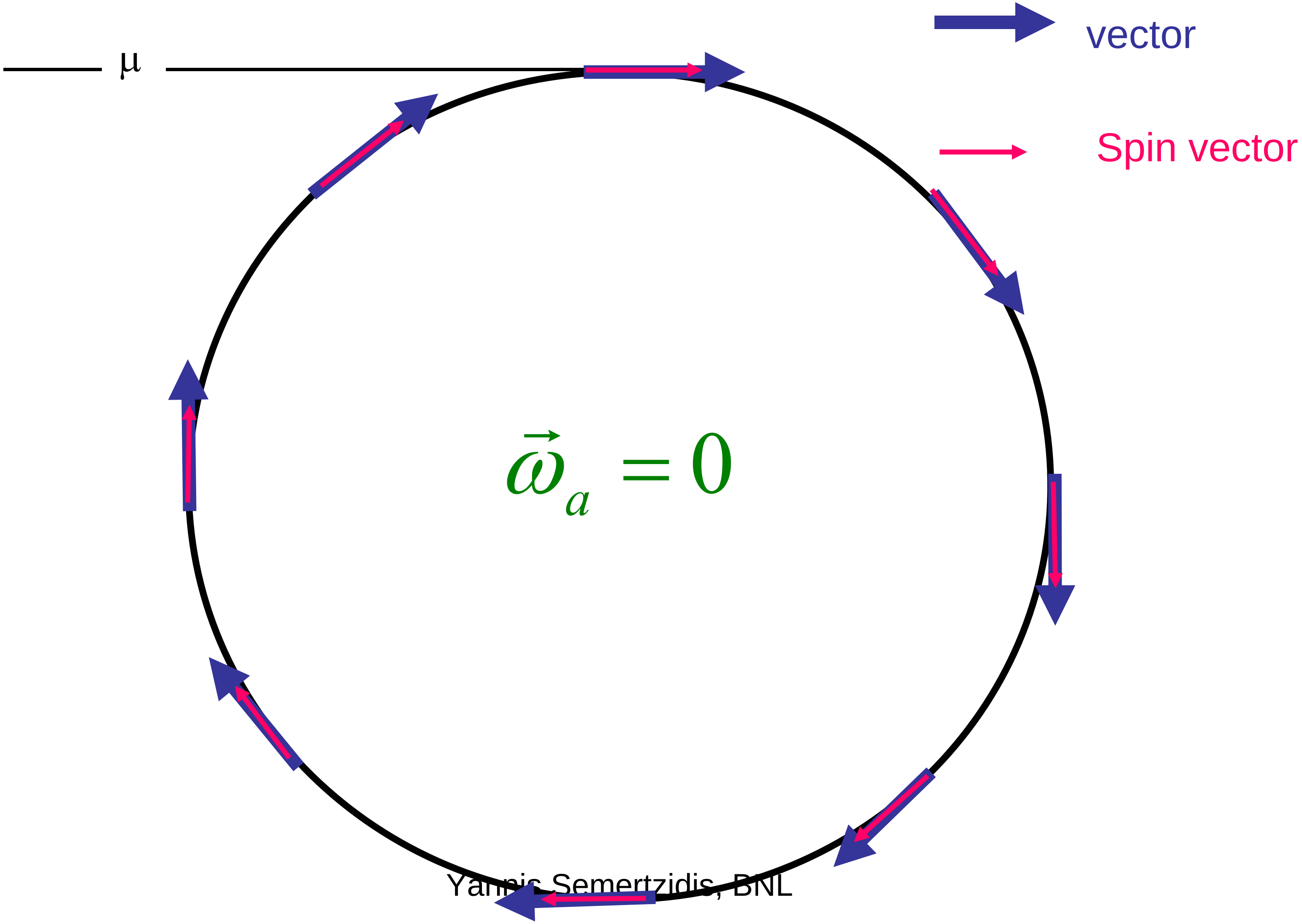
- Low energy particle

# Spin Precession in g-2 Ring (Top View)



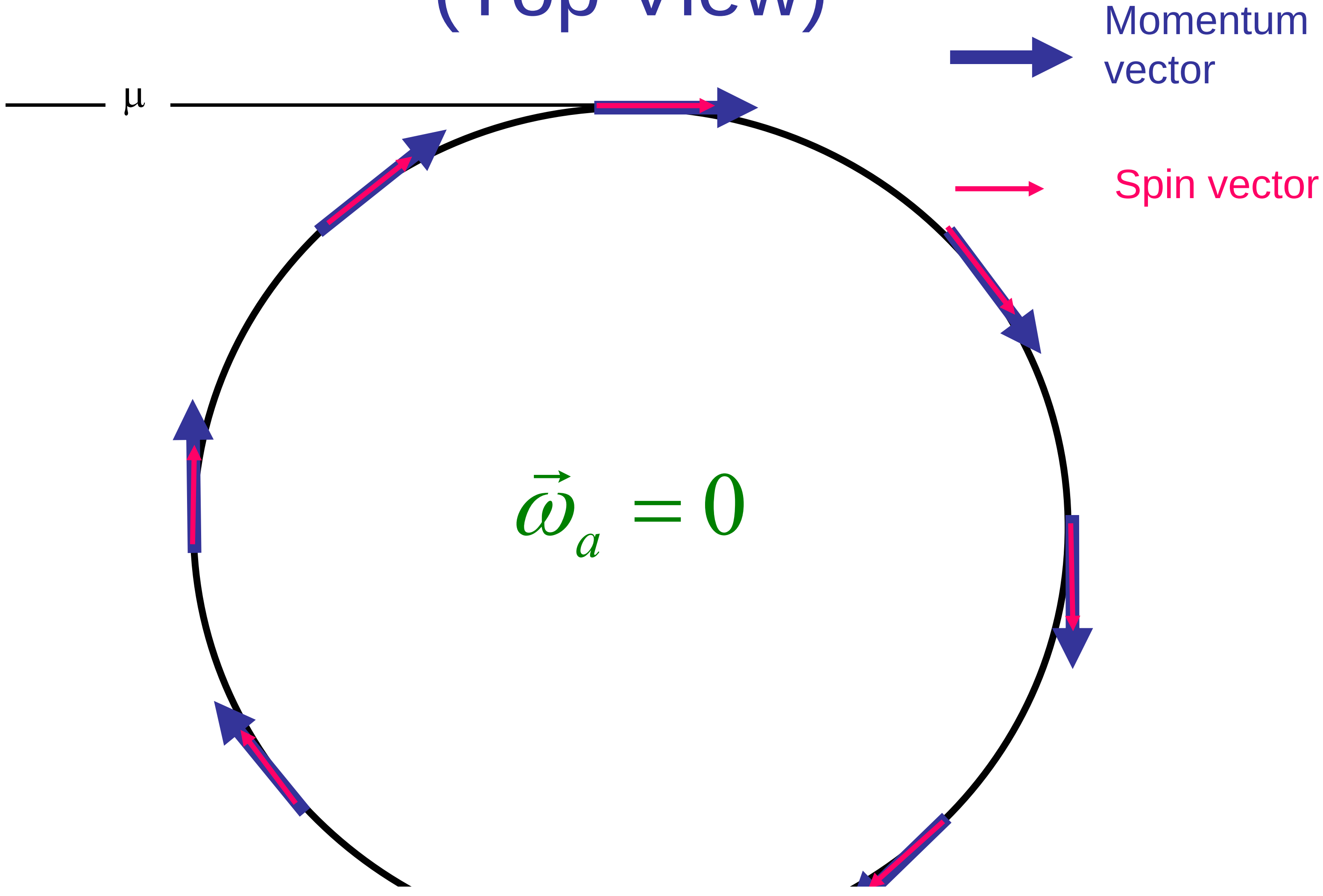
$$\vec{\omega}_a = a \frac{e}{m} \vec{B}$$

# Spin Precession in EDM Ring (Top View)



$$\vec{\omega}_a = 0$$

# Spin Precession in EDM Ring (Top View)



$$\vec{\omega}_a = 0$$

$$\Delta P_V = P\,\frac{\omega_{edm}}{\Omega}\,\sin(\Omega t + \theta_0), \qquad \Omega = \sqrt{\omega_{edm}^2 + \omega_a^2},$$

# (U-D)/(U+D) vs. Time, muon case

(U-D)/(U+D)

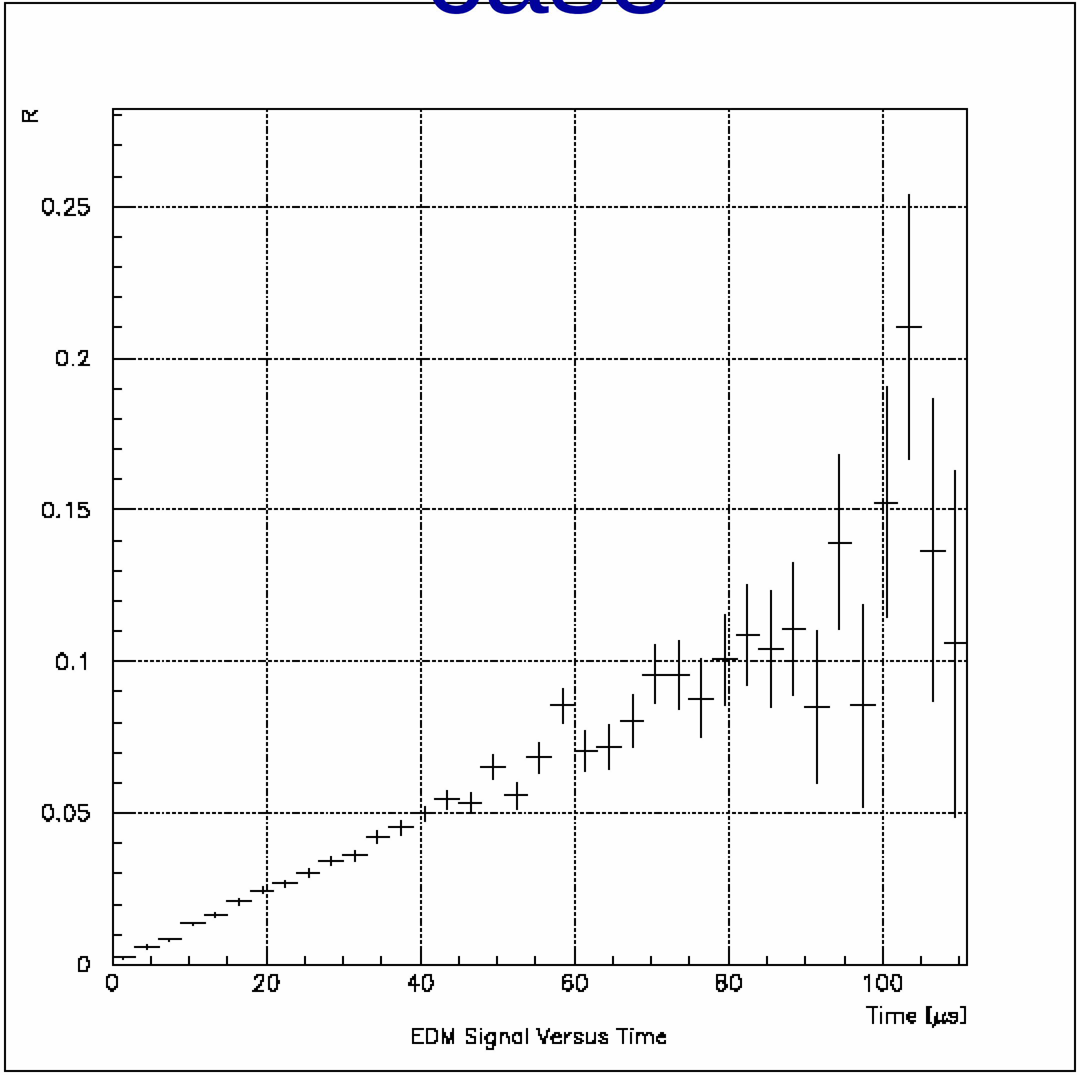


Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, versus time.

# The Electric Dipole Moment precesses in an Electric field

$$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$$

# Electric Dipole Moments in Magnetic Storage Rings

$$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$$

e.g. 1 T corresponds to 300 MV/m for relativistic particles

# Storage ring EDM: The deuteron case (proton is similar)

- High intensity sources (~$10^{11}$/fill)
- High vector polarization (~80%)
- High analyzing power for ~1 GeV/c (250MeV)
- Long spin coherence time possible (>$10^3$s)
- Large effective $E^*$-field

# Freezing Spin Precession: it depends on the $a$=(g-2)/2 value

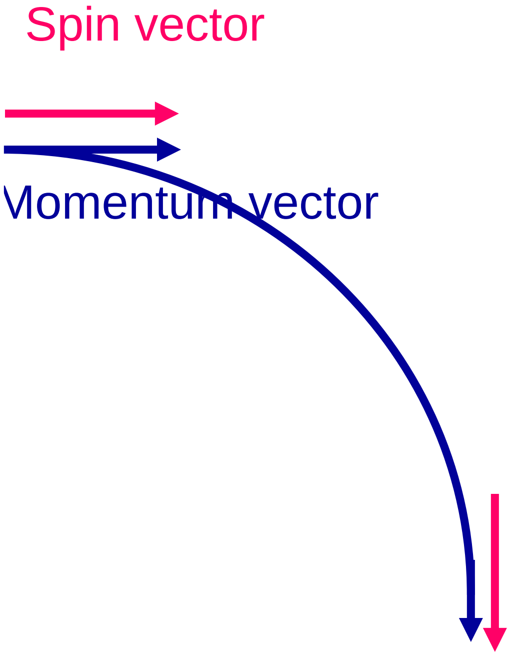
$$\vec{\omega}_a = \frac{e}{m}\left[a\vec{B} + \left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta}\times\vec{E}\right]$$

1. Magic momentum: Proton, sens.: 3x10$^{-29}$ ecm

- Making the dipole B-field = 0, the spin precession is zero at (magic) momentum (0.7 GeV/c for protons)

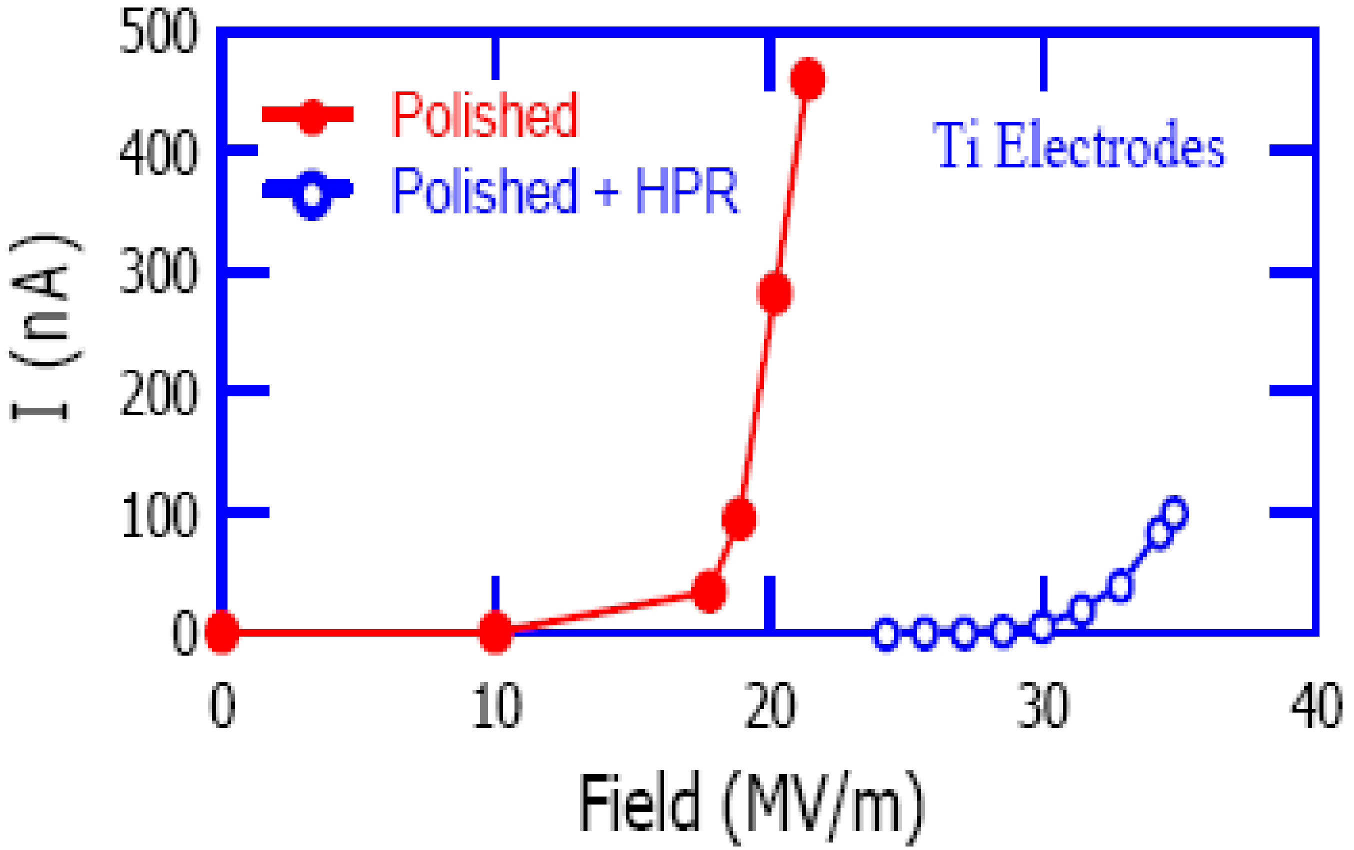
$$p = \frac{m}{\sqrt{a}}, \text{ i.e. the larger the } a \text{ the better!}$$

# Effect of Radial Electric Field



- …just right (magic P)

# E-field strength



The field emission with and without high pressure water rinsing (HPR).

Recent developments in achieving high E-field strengths makes this option appealing

# E-field strength

INITIATION OF ELECTRICAL BREAKDOWN IN VACUUM

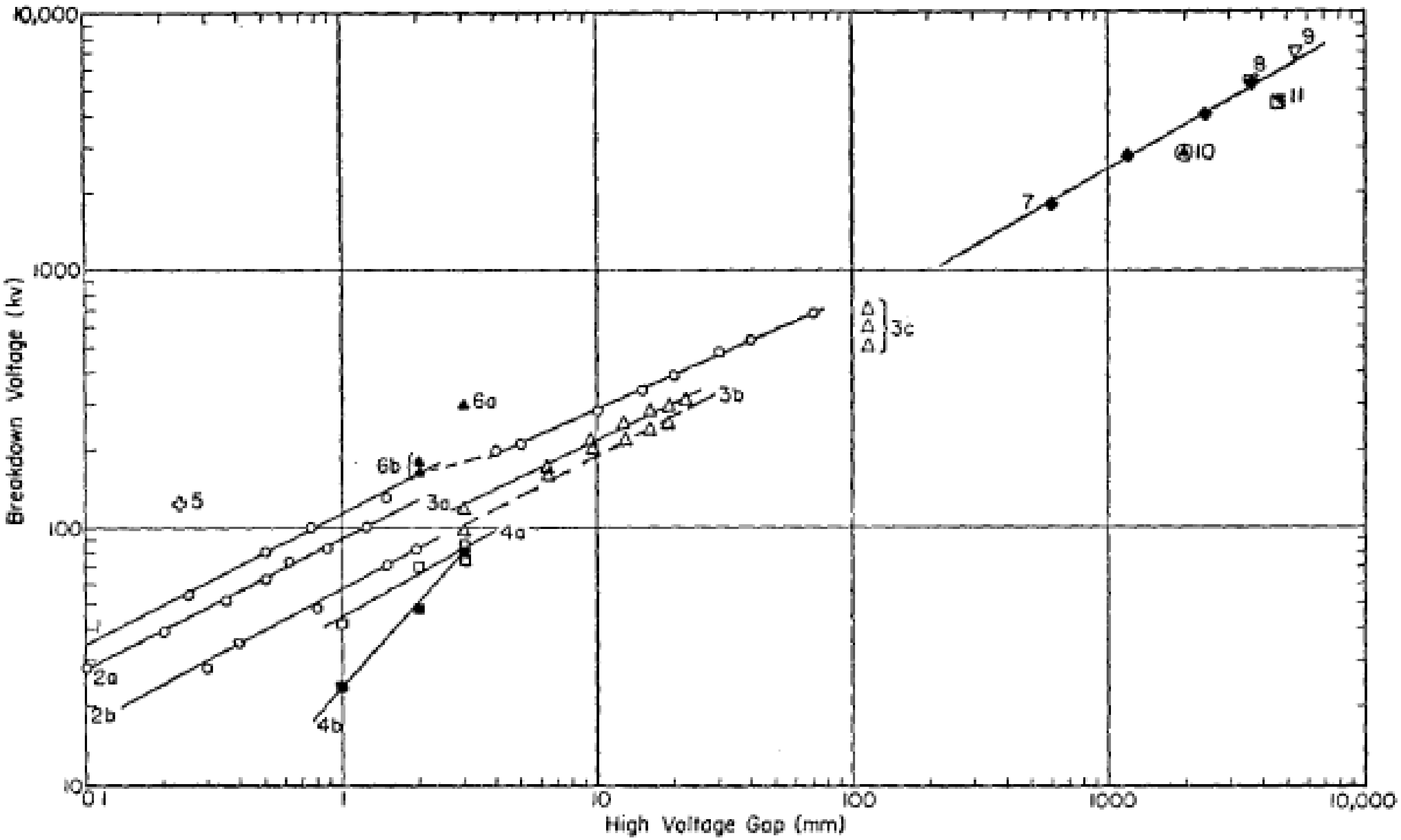


FIG. 1. Plot of data from the literature of breakdown voltage *vs* distance from highest to lowest potential electrode, for uniform-field and near-uniform-field geometry. Numbers on curves indicate sources as listed below.

2. Combined E&B-fields:

$$\vec{\omega}_a = \frac{e}{m}\left[a\vec{B} + \left(a - \left(\frac{m}{p}\right)^2\right)\vec{\beta}\times\vec{E}\right]$$

- Using a combination of dipole B-fields and radial E-fields to freeze the spin. The required E-field is

$\mathrm{E} \approx a\mathrm{Bc}\beta\gamma^2$, i.e. the smaller the $a$ the better!

Deuteron: Momentum 1 GeV/c, B=0.5 T, E=120KV/cm

Deuteron, sensitivity: $10^{-29}$ ecm

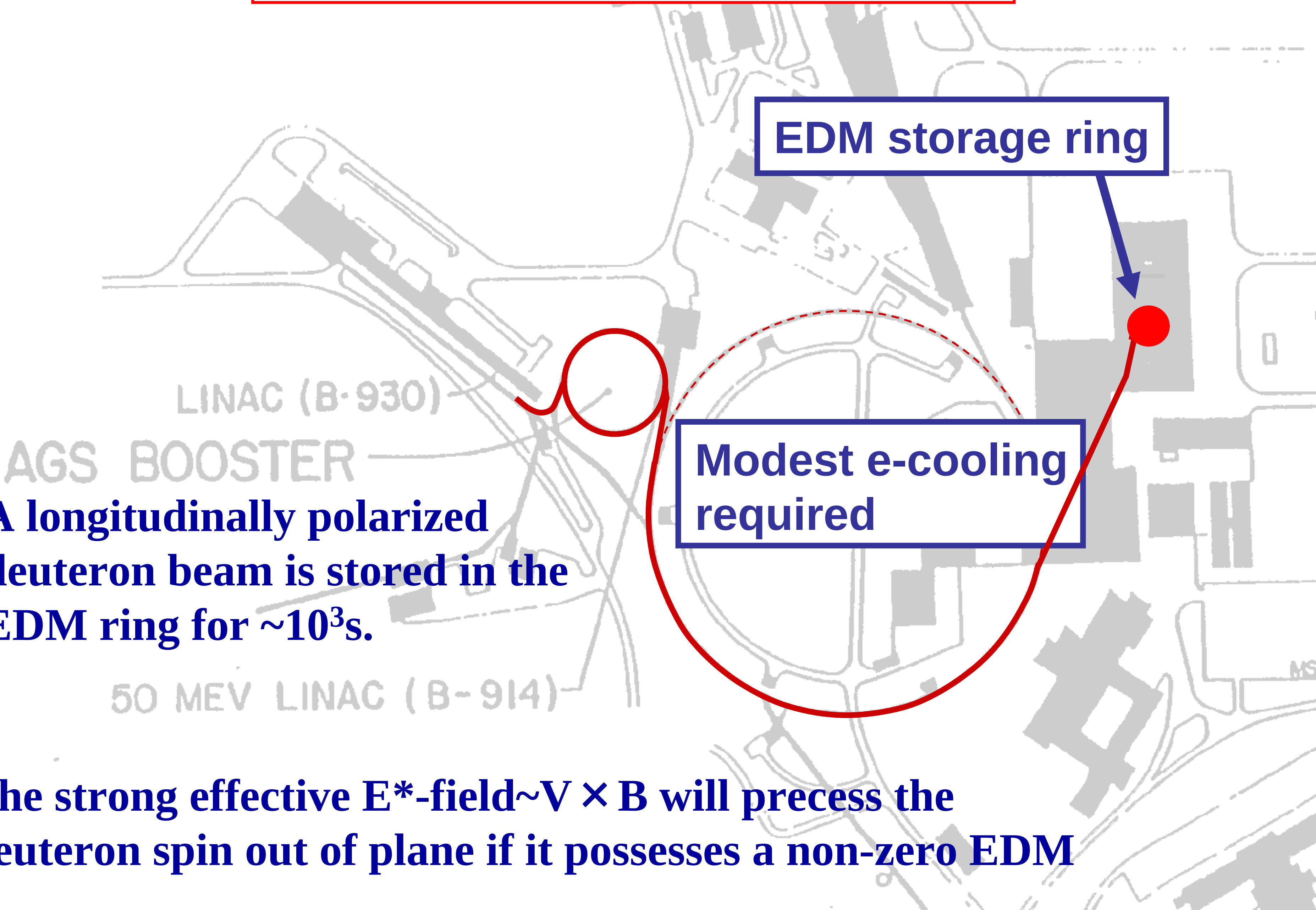
# Large $a$=(g-2)/2 vs. small $a$ value

$$\vec{\omega}_a = \frac{e}{m}\left[ a\vec{B} + \left( a - \left(\frac{m}{p}\right)^2 \right) \vec{\beta} \times \vec{E} \right]$$

Use a radial $E_r$-field to cancel the g-2 precession but use the VxB internal $E^*$-field to precess spin.

For 1 GeV/c deuteron momentum, V/c=0.5, B=0.5T and $E^*$ = 75MV/m; the effect is enhanced by $\sim E_r/(a\gamma^2)$

# deuteron EDM search at BNL

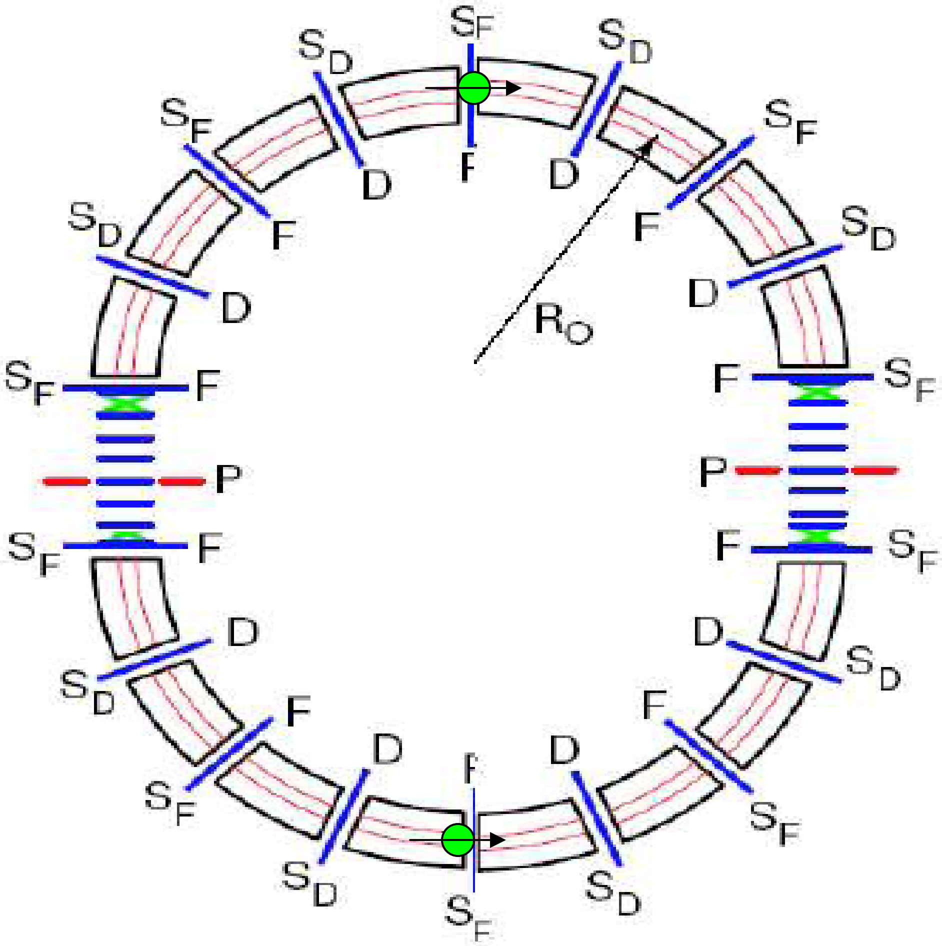


EDM storage ring

Modest e-cooling required

**A longitudinally polarized deuteron beam is stored in the EDM ring for ~$10^3$s.**

**The strong effective E*-field~V × B will precess the deuteron spin out of plane if it possesses a non-zero EDM**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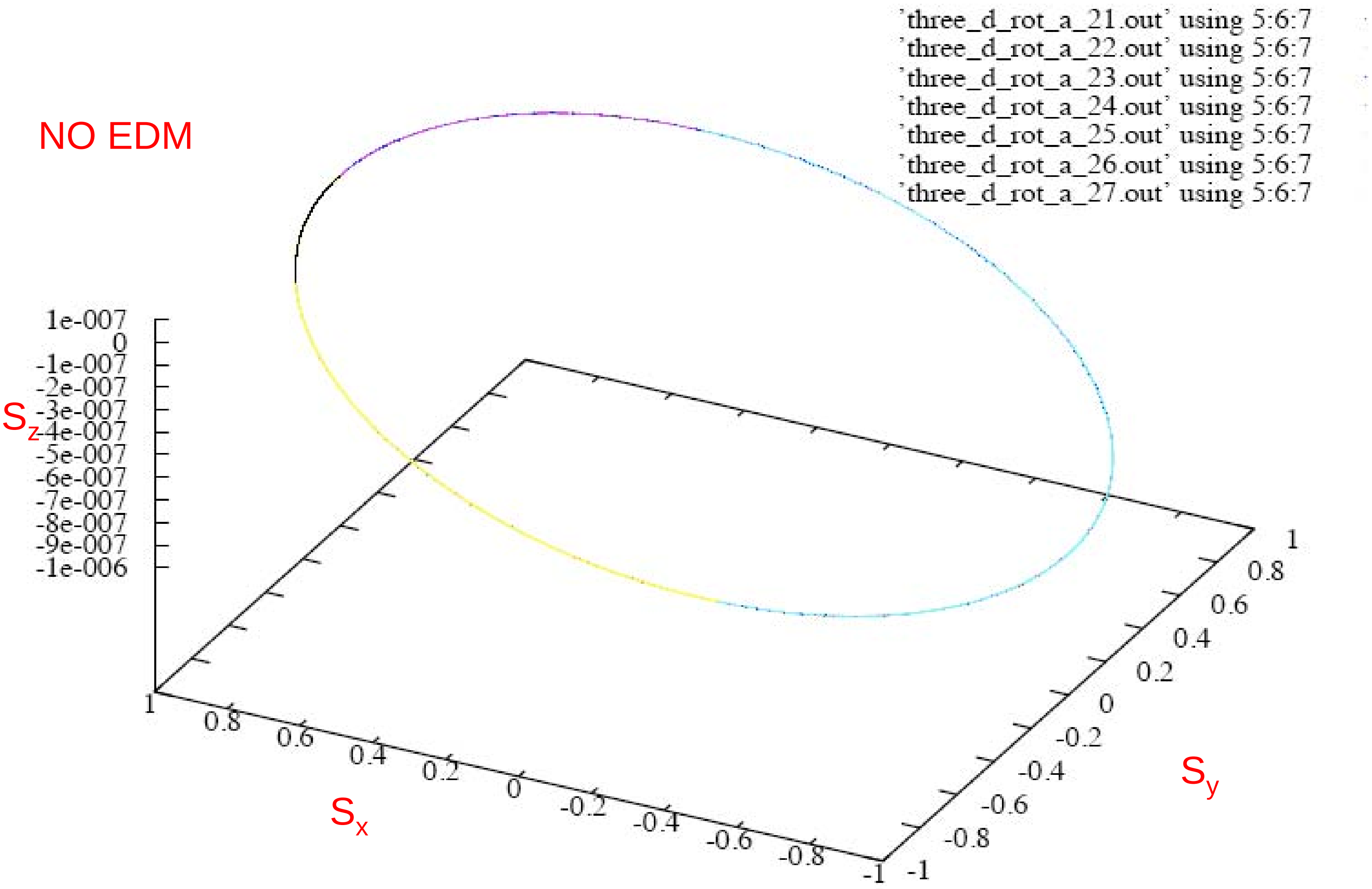
# The three spin components at the polarimeter location for different g-2 cancelation factors:

NO EDM



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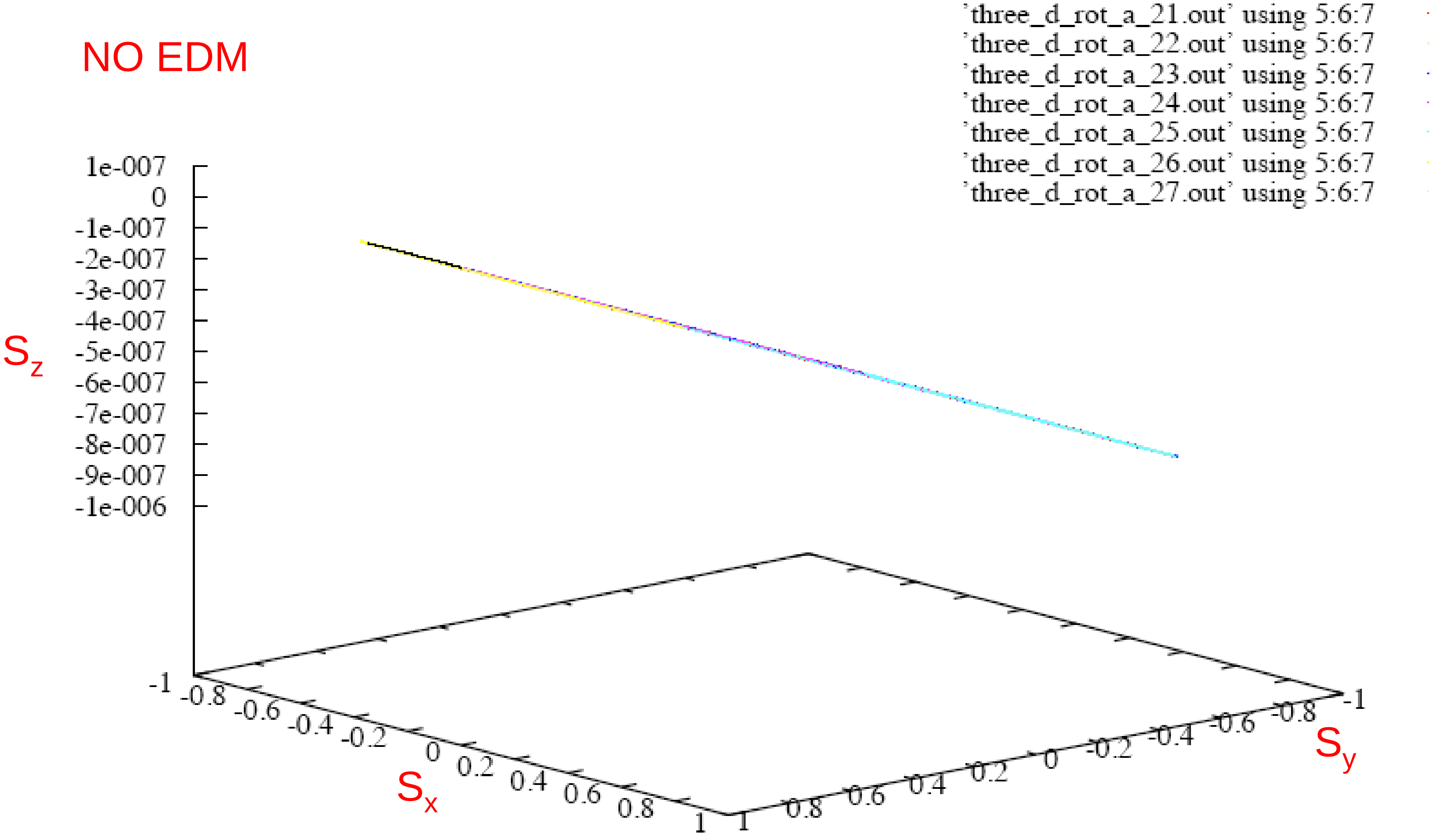

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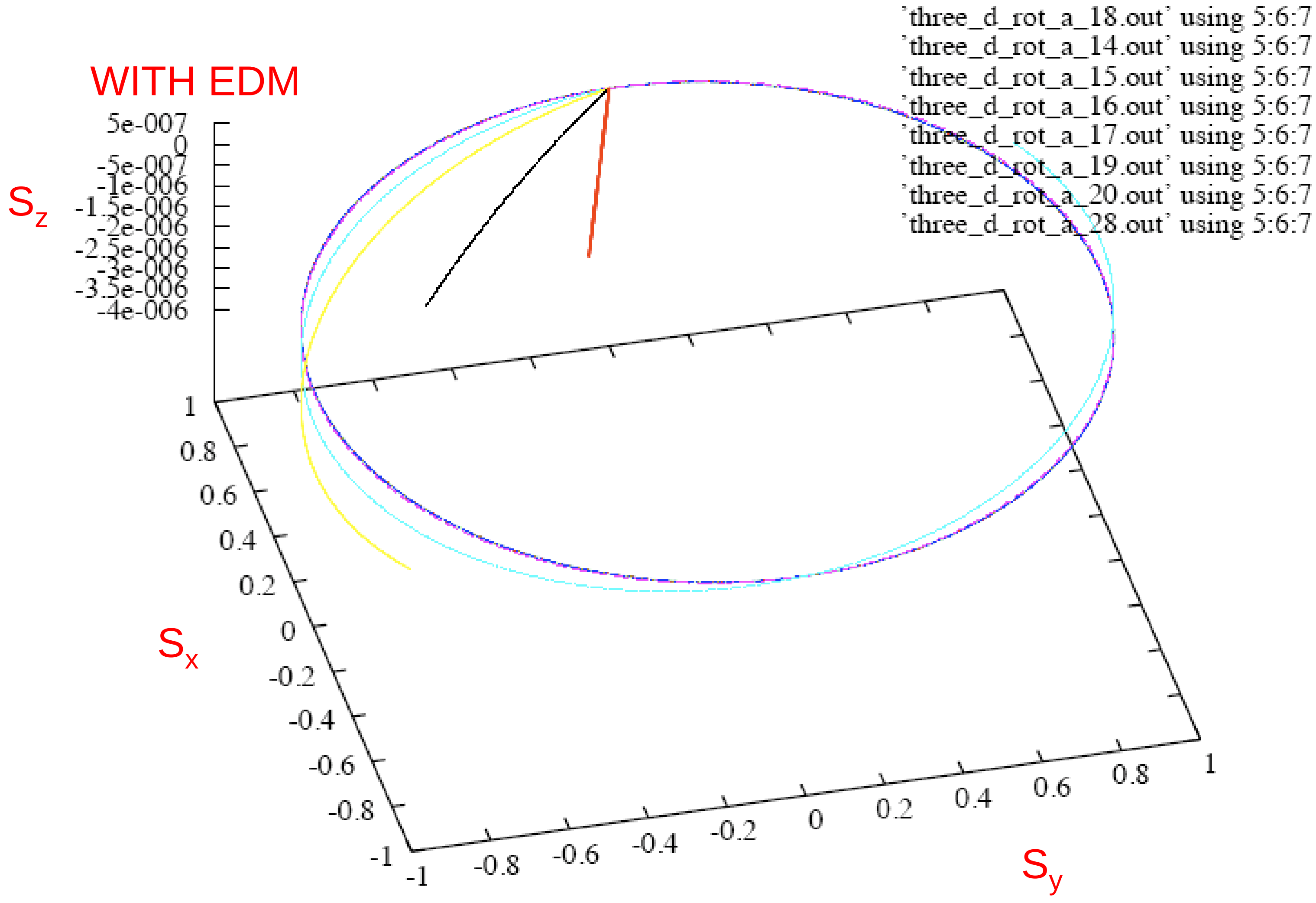
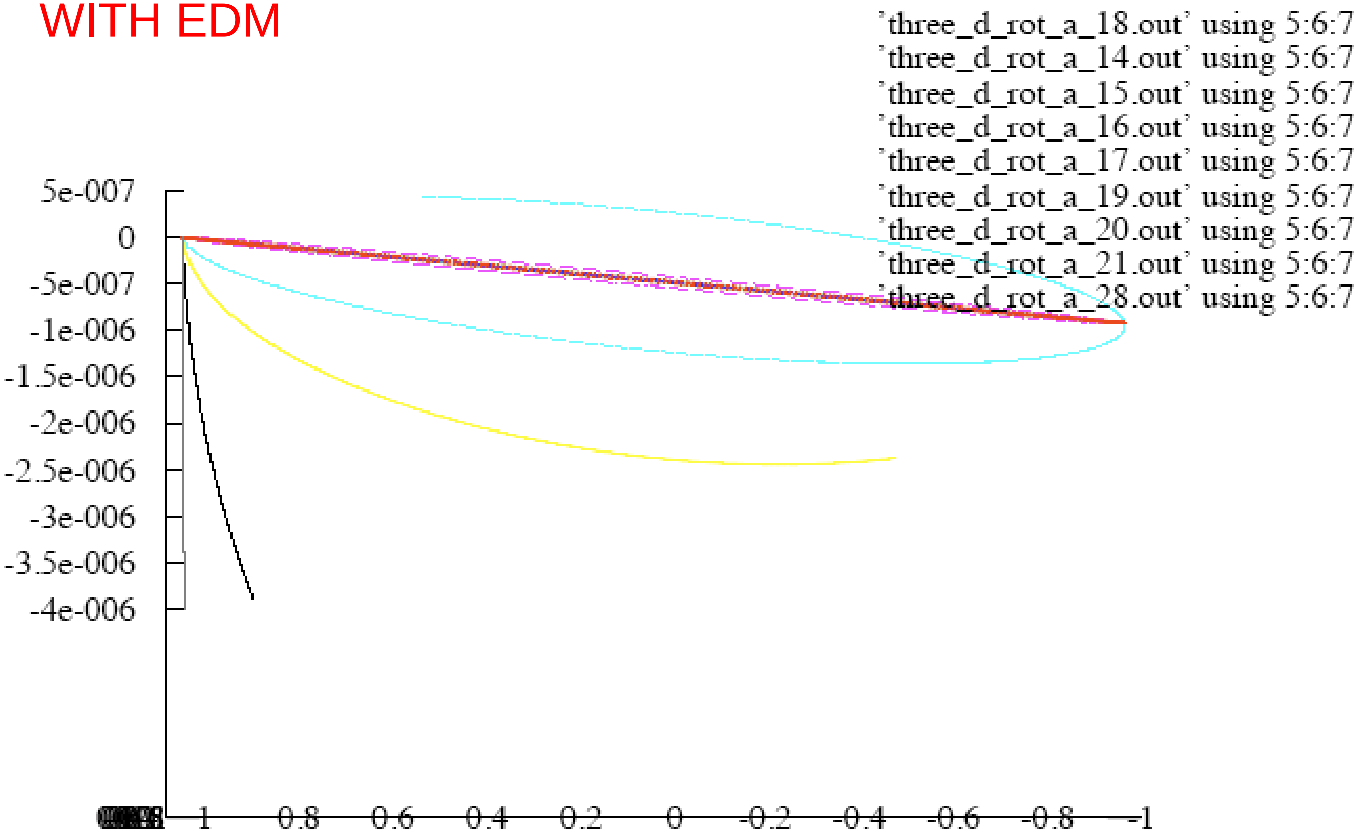


WITH EDM

# The three spin components at the polarimeter location for different g-2 cancelation factors:

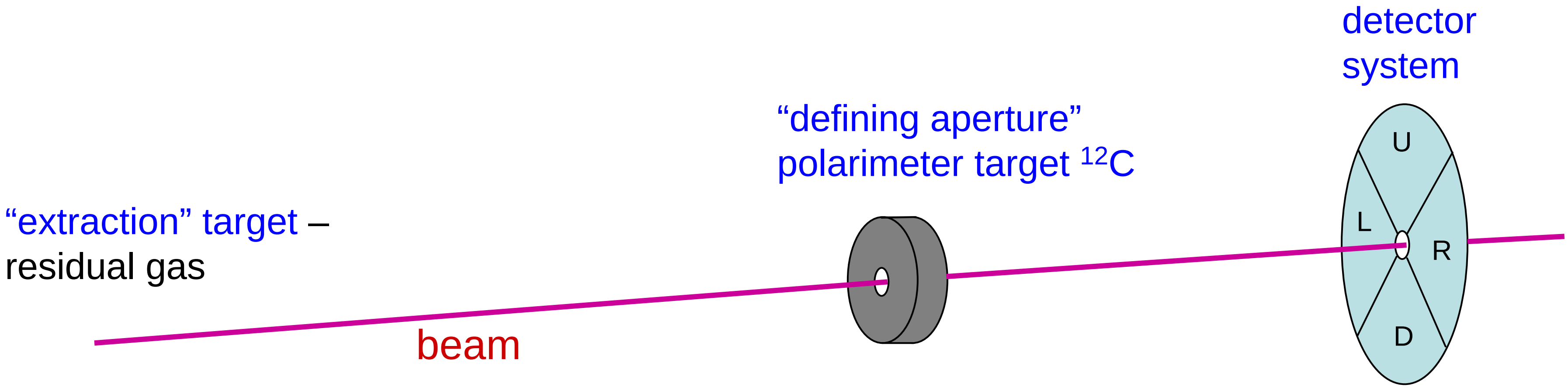
WITH EDM



$S_z$

$S_x$

# dEDM polarimeter principle: probing the deuteron spin components as a function of storage time



“extraction” target –
residual gas

beam

“defining aperture”
polarimeter target $^{12}$C

detector
system

$$\varepsilon_H = \frac{L-R}{L+R}$$

carries EDM signal
small
increases slowly with time

$$\varepsilon_V = \frac{D-U}{D+U}$$

carries in-plane precession signal

# Cross section and analyzing power

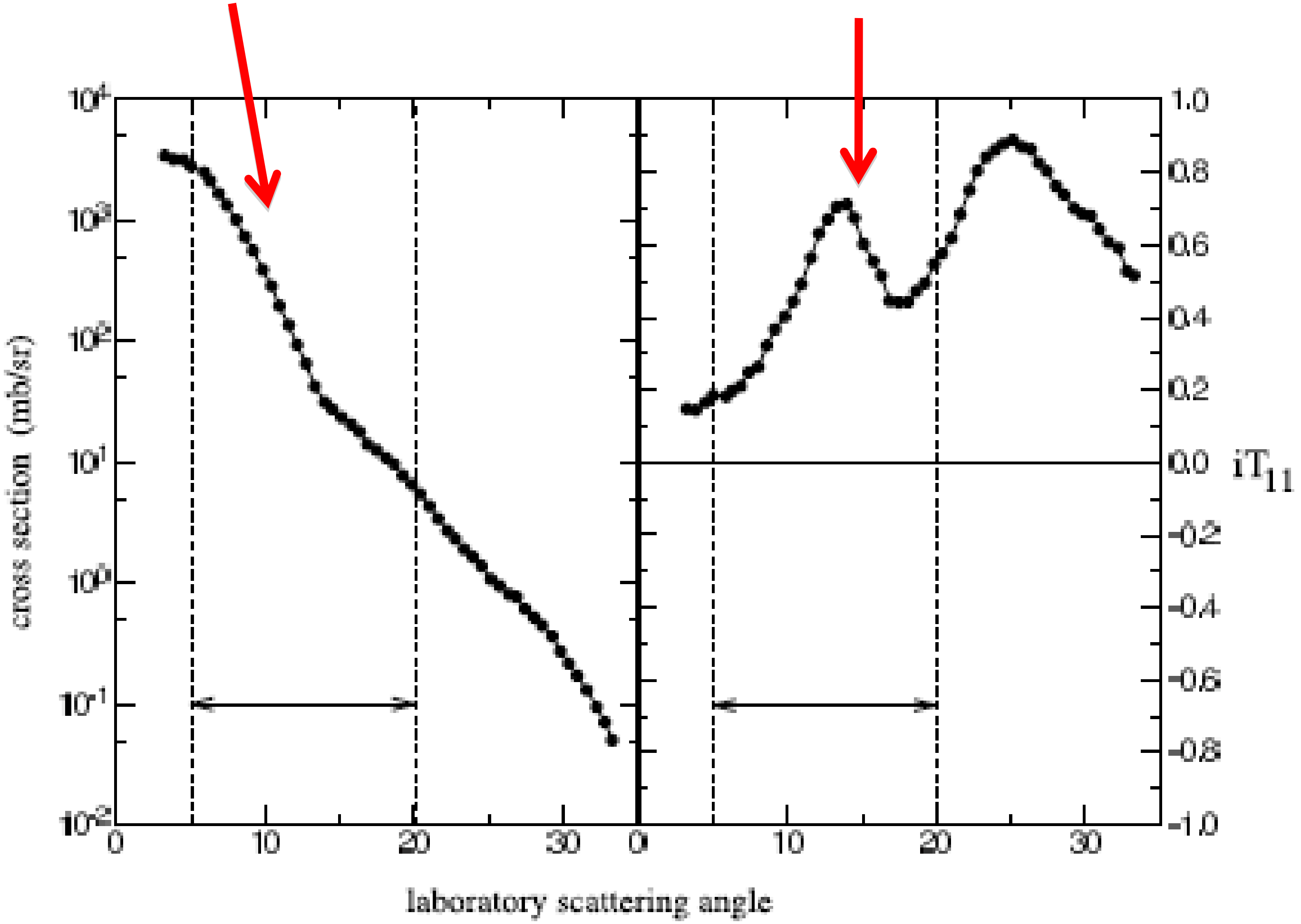


Figure 2: Deuteron elastic cross section and analyzing power at 270 MeV from carbon [29]. The dashed lines indicate the preferred acceptance limits for an EDM polarimeter.

$$\sigma_{pol} = \sigma_{unpol}\ \left(1 + 2\ it_{11}\ iT_{11} + t_{20}\ T_{20} + 2\ t_{21}\ T_{21} + 2\ t_{22}\ T_{22}\right),$$

# Deuteron Statistical Error (250MeV):

$$\boxed{\sigma_d \approx 8 \frac{\hbar a \gamma^2}{\sqrt{\tau_p} E_R (1+a) A P \sqrt{N_c f T_{Tot}}}}$$

$\tau_p$ : $10^3$s Polarization Lifetime (Coherence Time)

$A$ : 0.3 The left/right asymmetry observed by the polarimeter

$P$ : 0.8 The beam polarization

$N_c$: $4\times10^{11}$d/cycle The total number of stored particles per cycle

$T_{Tot}$: $10^7$s Total running time per year

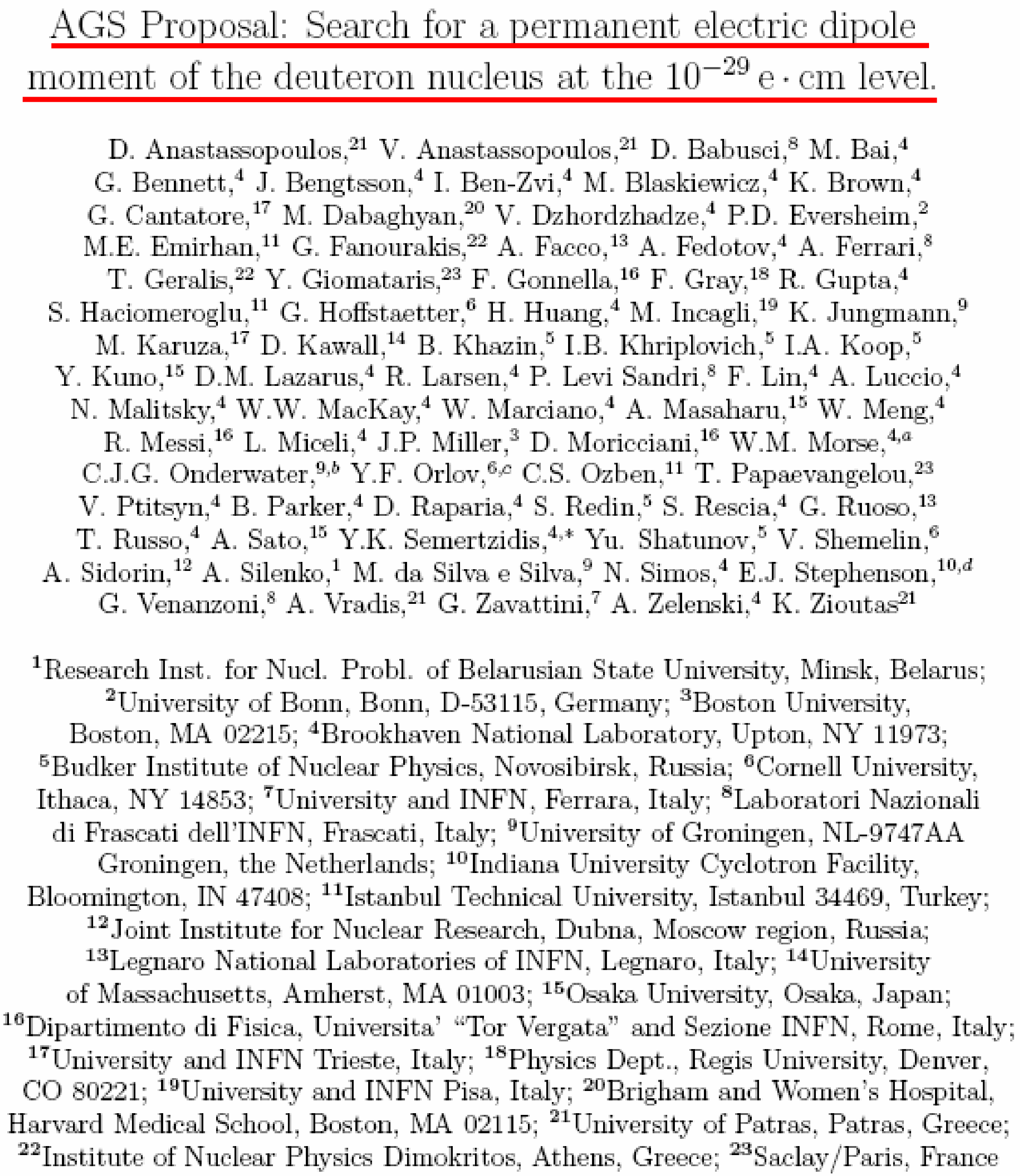
$f$ : 0.01 Useful event rate fraction

$E_R$ : 12 MV/m Radial electric field

$$\sigma_d \approx 10^{-29} \mathrm{e \cdot cm/year}$$

# **Storage Ring EDM Collaboration**

**www.bnl.gov/edm**



## AGS Proposal: Search for a permanent electric dipole moment of the deuteron nucleus at the $10^{-29}$ e · cm level.

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# Possible dEDM Timeline

**07 08 09 10 11 12 13 14 15 16 17**

- ✓ Spring 2008, Proposal to the BNL PAC
- 2008-2012 R&D phase; ring design
- Fall 2011, Finish systematic error studies:
  - a) spin/beam dynamics related systematic errors.
  - b) Polarimeter systematic errors studies with polarized deuteron beams
  - c) Finalize E-field strength to use
  - d) Establish Spin Coherence Time

- Start of 2012, finish dEDM detailed ring design

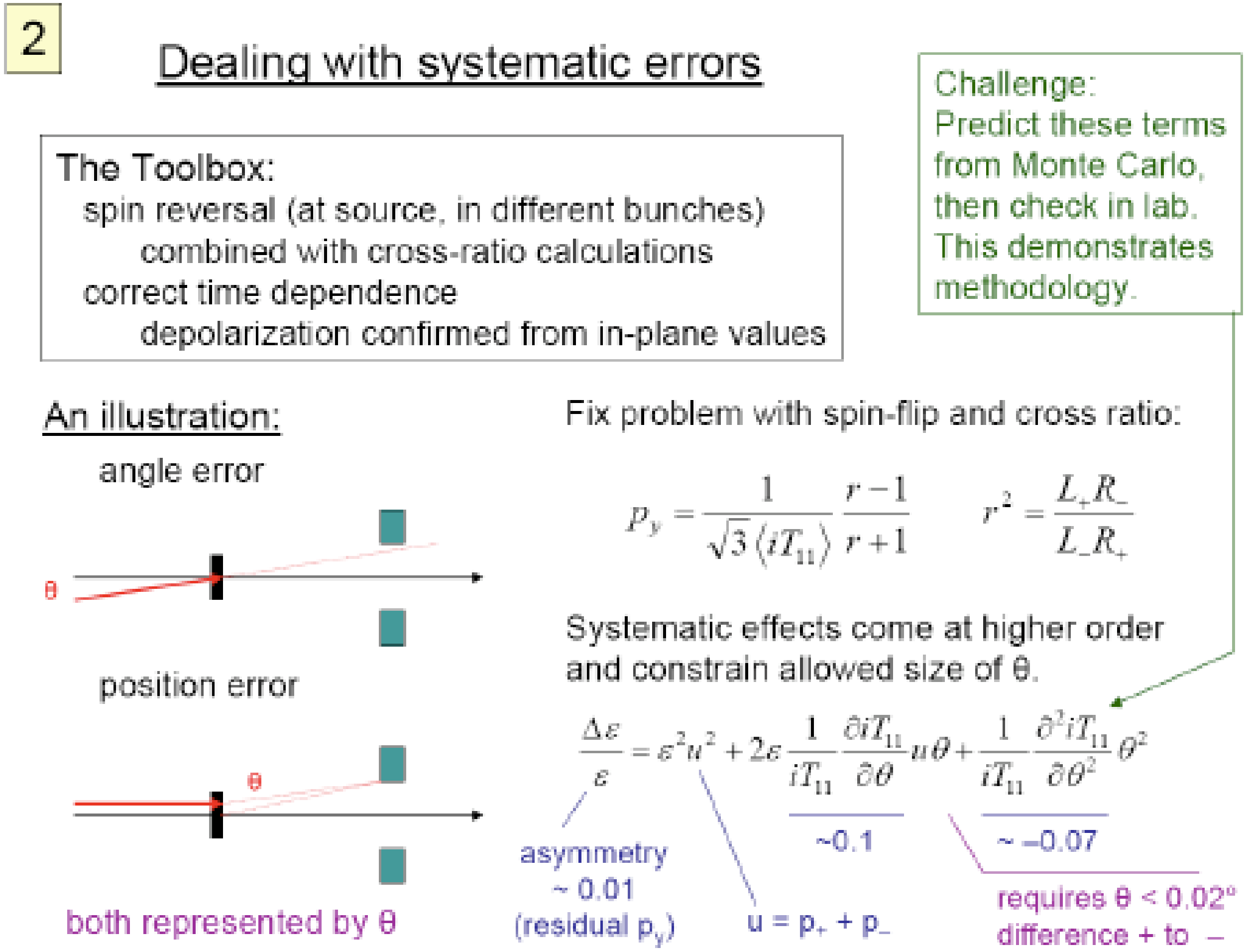
- Fall 2012, start ring construction
- Fall 2014, dEDM engineering run starts
- Fall 2015, dEDM physics run starts

# Main issues

- Polarimeter systematic errors to 1ppm (early to late times-not absolute!)
- Average vertical electric field very strict (CW and CCW injections need to repeat to ~$10^{-6}$m)
- E-field strength: 120kV/cm
- Average E-field alignment: $10^{-7}$ rad; stability.
- B-field and E-field combined. Geometrical phases: local spin cancellation ~$10^{-4}$. Stability?; Sensitive Fabry-Perot resonator to be developed
- Spin Coherence Time: ~$10^{3}$s

Polarimeter team

# Main polarimeter systematic errors



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## Dealing with systematic errors

The Toolbox:
  spin reversal (at source, in different bunches)
    combined with cross-ratio calculations
  correct time dependence
    depolarization confirmed from in-plane values

Challenge:
Predict these terms from Monte Carlo, then check in lab.
This demonstrates methodology.

An illustration:

angle error

position error

both represented by θ

Fix problem with spin-flip and cross ratio:

$$p_y = \frac{1}{\sqrt{3}\langle iT_{11}\rangle}\frac{r-1}{r+1} \qquad r^2 = \frac{L_+R_-}{L_-R_+}$$

Systematic effects come at higher order and constrain allowed size of θ.

$$\frac{\Delta\varepsilon}{\varepsilon} = \varepsilon^2 u^2 + 2\varepsilon \underbrace{\frac{1}{iT_{11}}\frac{\partial iT_{11}}{\partial\theta}}_{\sim 0.1} u\theta + \underbrace{\frac{1}{iT_{11}}\frac{\partial^2 iT_{11}}{\partial\theta^2}}_{\sim -0.07}\theta^2$$

asymmetry
~ 0.01
(residual $p_y$)

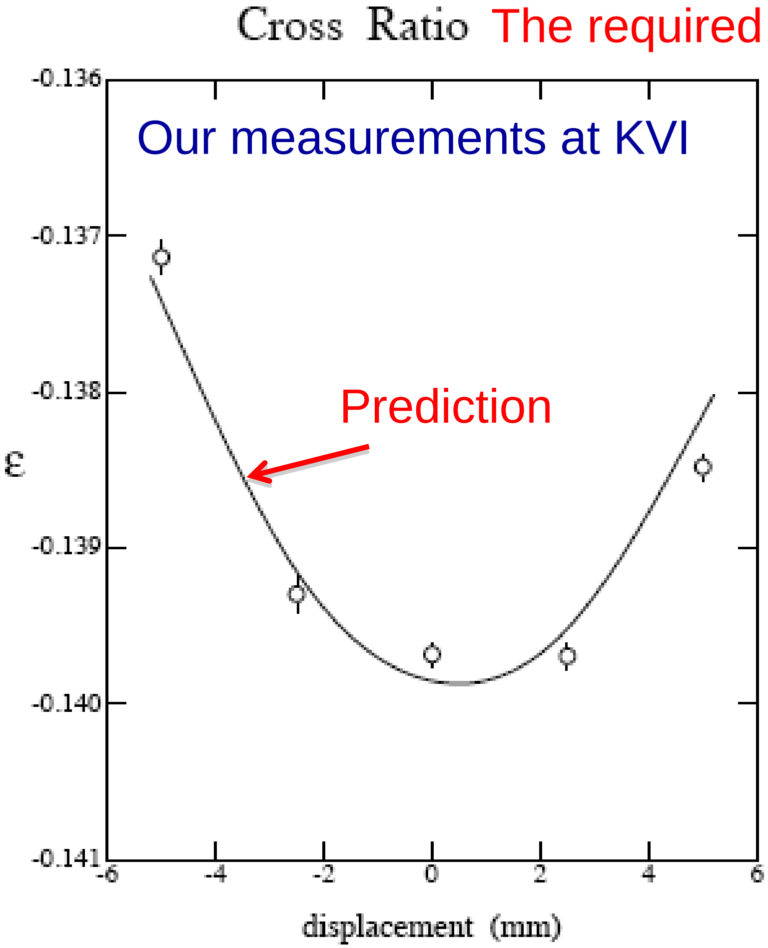
$u = p_+ + p_-$

requires θ < 0.02°
difference + to –

Figure 9, from reference [8]. The systematic errors in both beam direction angle and position change can be both represented by a requirement on the angle stability. 0.02° corresponding to 0.35 mrad is the required limit on the corresponding position stability.

# Off axis/angle systematic error

The required position stability: ~100 $\mu$m
The required beam axis stability: ~100 $\mu$rad



Our measurements at KVI

Prediction

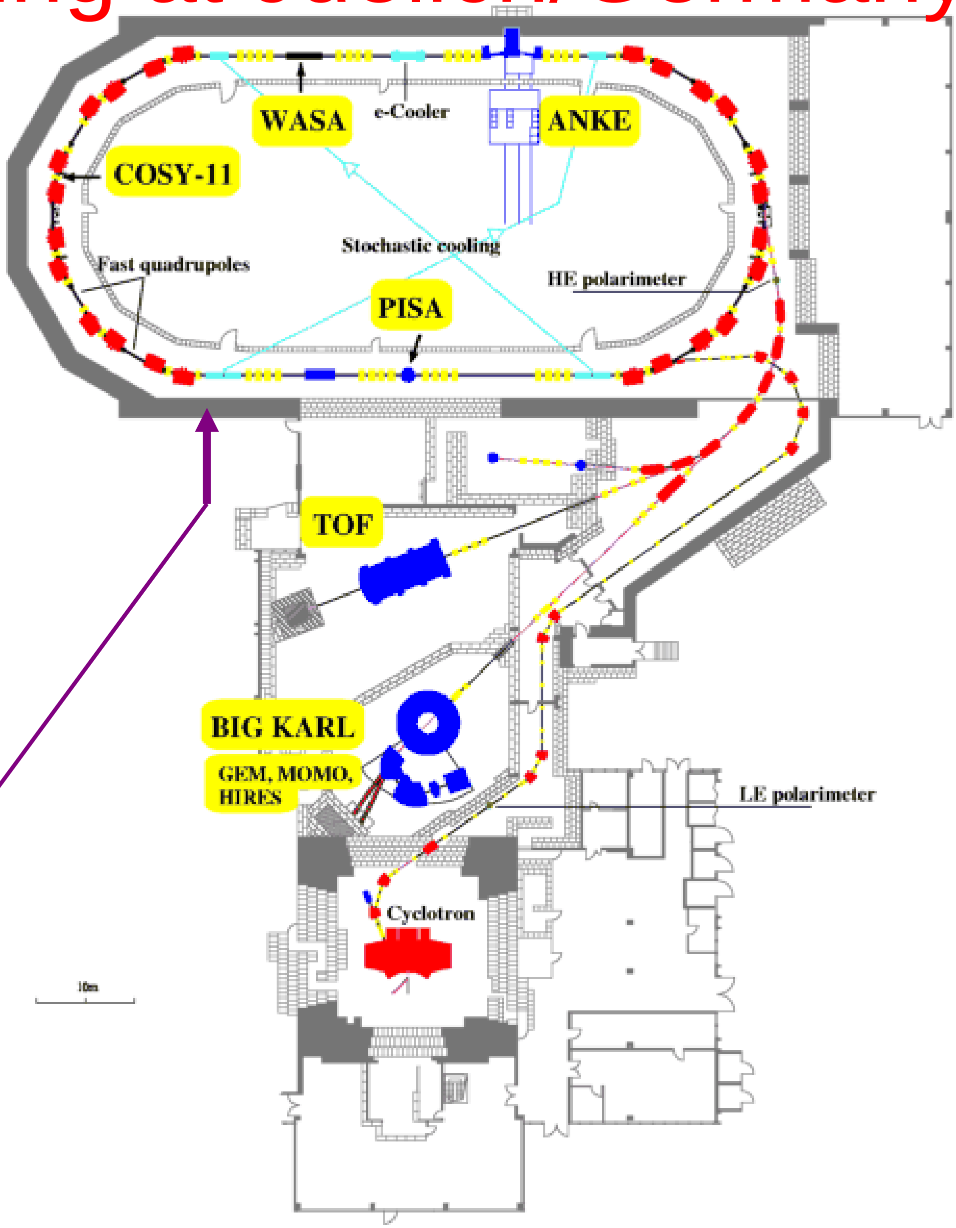
Figure 3: Measurements of the change in left-right asymmetry as the target position is moved horizontally. The solid line is an *a priori* prediction based on the older scattering measurements at 113 MeV. The curve has been offset vertically to match the average asymmetry. The errors shown are statistical only and do not include effects due to the setup of the beam position shifts and other systematic considerations.

Pickup electrodes monitor the beam axis direction to better than 10 $\mu$rad.
The polarimeter detector will be designed to have ~500 $\mu$m/event pointing accuracy, or better than 10 $\mu$m on the average position early to late.

Polarimeter team

# Tests at COSY ring at Juelich/Germany

Goals: Construct prototype dEDM polarimeter. Install in COSY ring for commissioning, calibration, and testing for sensitivity to EDM polarization signal and systematic errors.



Current location behind present EDDA detector.

Polarimeter team

# From the June 2008 run at COSY

Polarimeter team

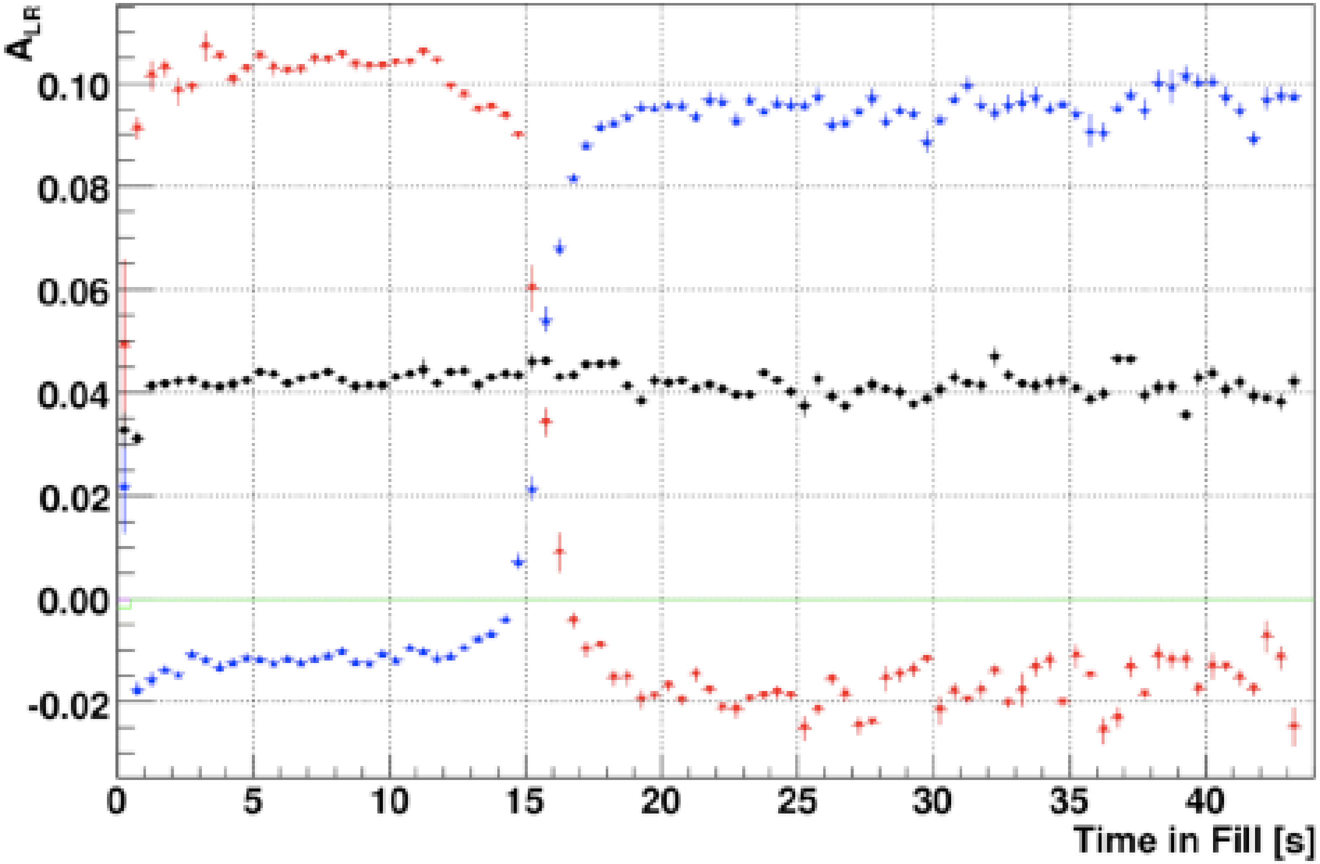
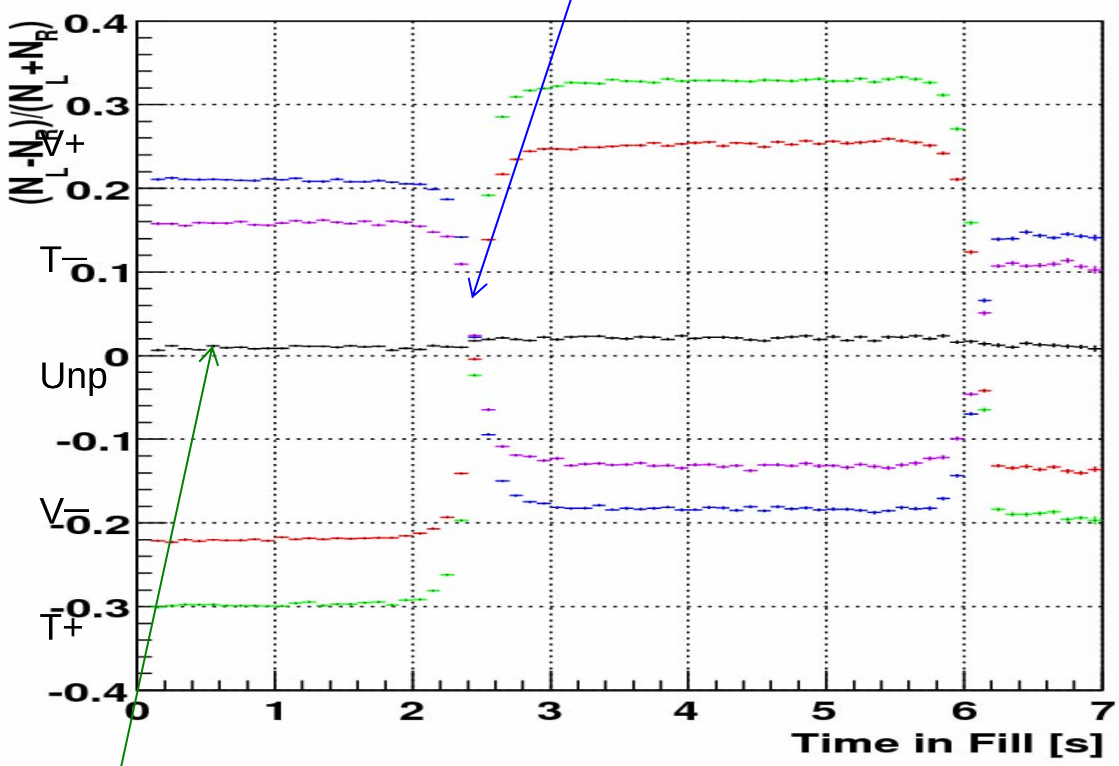


*Figure 3. Asymmetry measurements made continuously during a beam store for spin up (red), spin down (blue), and unpolarized states. At the same time the frequency of the RF solenoid is ramping through the 1 – Gγ resonance at 1030.048 kHz.*

# From the September 2008 run at COSY

Polarimeter team

Vector asymmetry



Resonance crossing
(full spin flip)

Unpolarized state has
some vector polarization
(note flip).

## General Plan

The usual asymmertry $\varepsilon = \frac{L-R}{L+R}$ changes in first order due to errors.

The cross ratio $\varepsilon_{CR} = \frac{r-1}{r+1} \quad r^2 = \frac{L_+ R_-}{L_- R_+}$ cancels first-order errors.

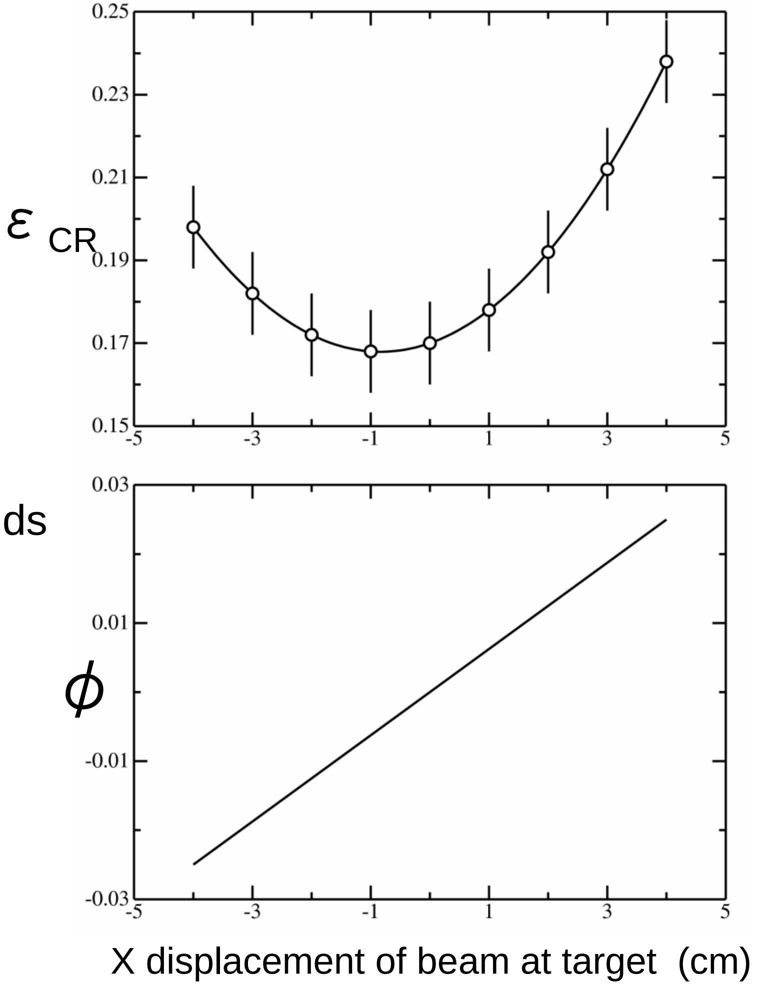
But this will have second-order errors. To cancel these, we need to know how they depend on the error, which is measured using something with a first-order dependence. Using the same quantities in an independent way:

$\varphi = \frac{s-1}{s+1} \quad s^2 = \frac{L_+ L_-}{R_+ R_-}$ can be such a parameter.

Polarimeter team

# Polarimeter team

Ideally,



Then, the cross-ratio deviations from flat are parametrized as a function of $\phi$.

The $\phi$ term depends simply on the error at the target (polarization tends to drop out).

Polarimeter team

# Polarimeter work by fall 2009

- We expect to get enough data at COSY for an early to late stability in asymmetry of ~50ppm (statistics limited).

E&B-fields team

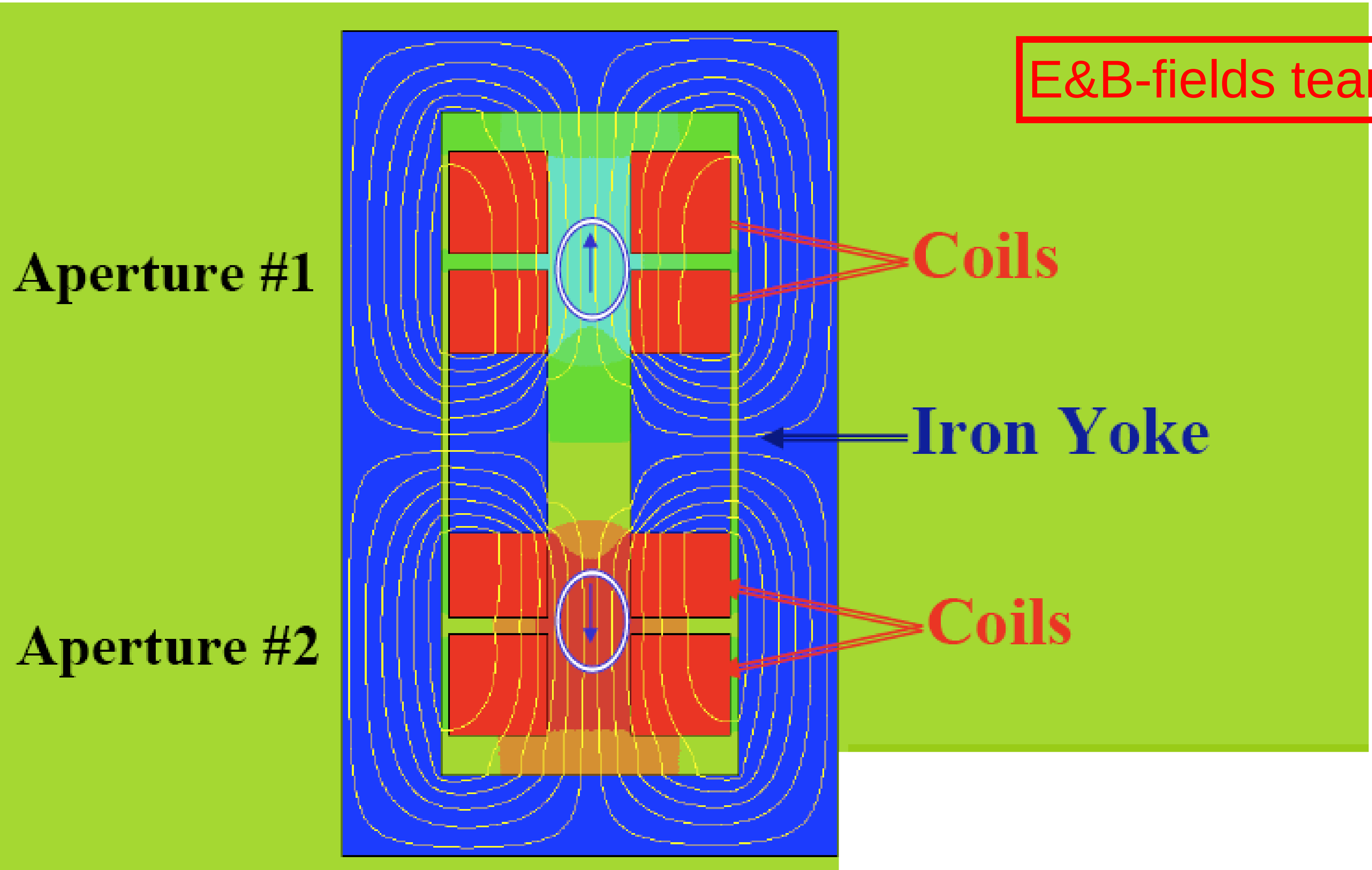
# Clock Wise (CW) and Counter Clock Wise (CCW) injections

- CW and CCW injections to cancel all T-reversal preserving effects.  EDM is T-violating and behaves differently.

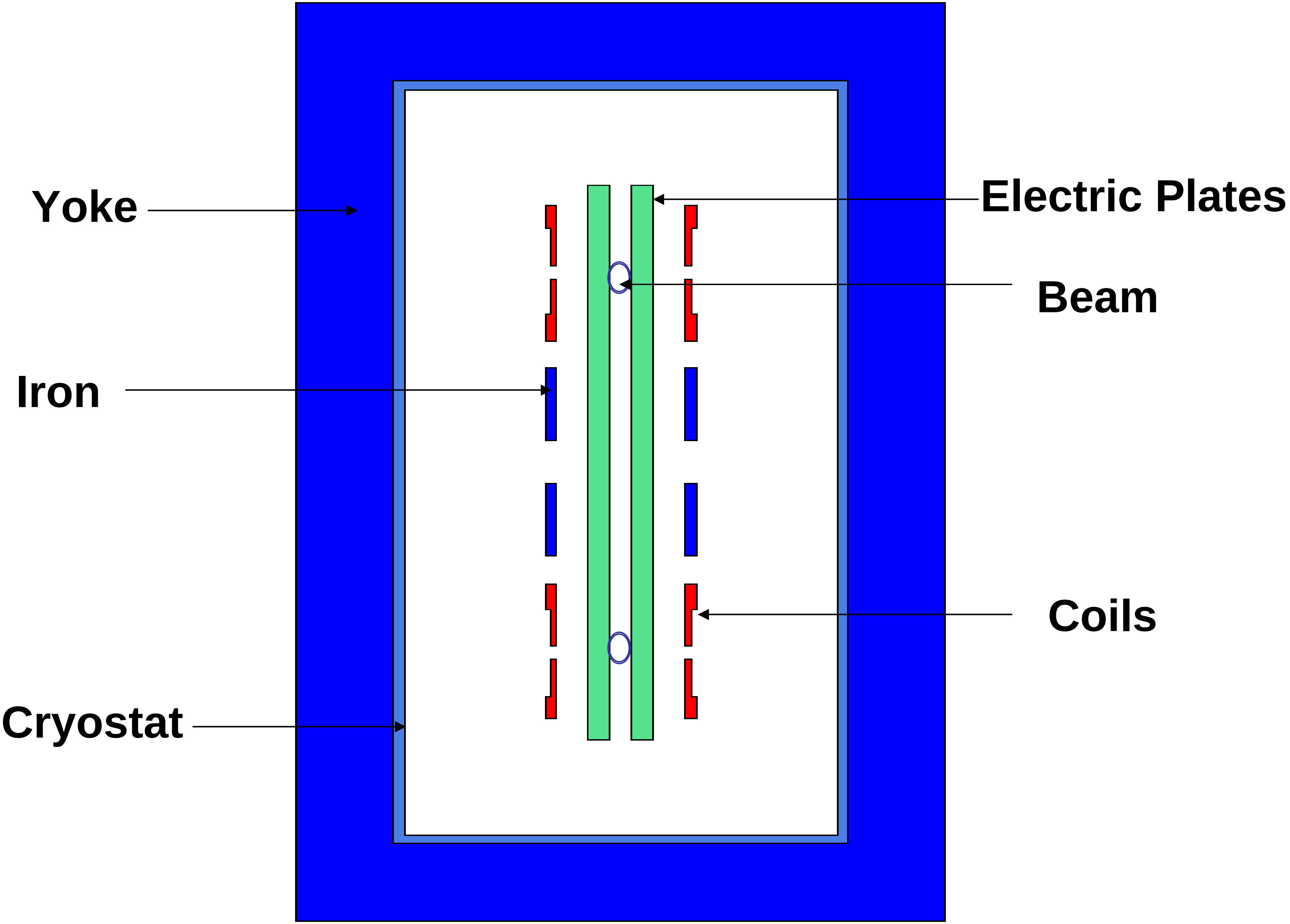
- Issue:  Stability of E-fields as a function of time

# Clock Wise (CW) and Counter Clock Wise (CCW) injections

Solution: Use the 2-in-1 magnet design for simultaneous CW and CCW storage.



# Schematic of dEDM Dipole (without support structure)



E&B-fields team

# Electric field work by fall 2009

- We expect to show 15MV/m (150kV/cm) for 2cm plate separation on prototypes (no B-field present).
- By spring 2010 we expect to show average plate alignment to $10^{-7}$ rad.

E&B-fields team

# Correction of Spin Frequency Perturbation

**Spin frequency perturbation comes from the second order effects of betatron and synchrotron violation:**

$$\frac{\Delta p}{p} = \left\langle \frac{\Delta p}{p} \right\rangle + \left( \frac{\Delta p}{p} \right)_0 \cos(\omega_s t + \phi_s)$$

$$\frac{\Delta\omega_a}{\omega_a} = a_p \left(\frac{\Delta p}{p}\right)^2 + a_x x^2 + a_y y^2$$

$$x(s) = \sqrt{\beta_x \varepsilon_x} \cos(\omega_y t + \phi_x) + D(s)\frac{\Delta p}{p}$$

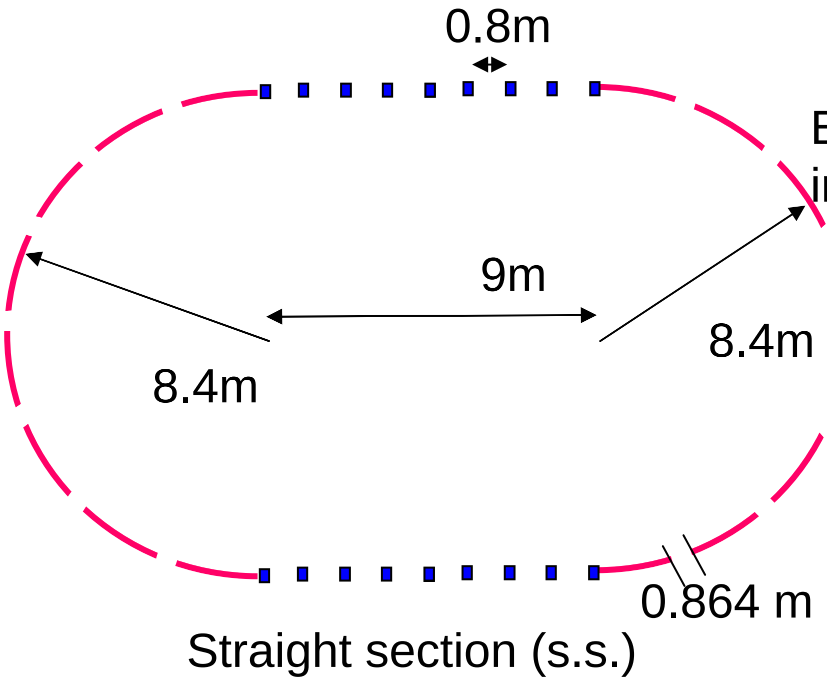
$$y(s) = \sqrt{\beta_y \varepsilon_y} \cos(\omega_y t + \phi_y)$$

**Sextupole produces a quadratic field as** $B_y^{sext} = B''(x^2 - y^2)$

**Conclusion:**

- **The proposed spin coherence time (SCT) is possible, in principle, with the help of sextupoles**
- **Three sets of sextupoles, locating at large dispersion** $D_x$ **, large horizontal beta function** $\beta_x$ **and large vertical beta function** $\beta_y$ **, and are needed for the correction of spin frequency perturbation respectively**

# The dEDM ring lattice



Bend section (BE), Quadrupoles and sextupoles in between BE sections

Ring circumference: 85m

Horizontal beam radius (95%): 6mm

16 free spaces (80cm) in the s.s. per ring
4 places in s.s. reserved for the kicker
1 free space for the RF cavity (normal)
1 free space for the AC-solenoid
2 polarimeters

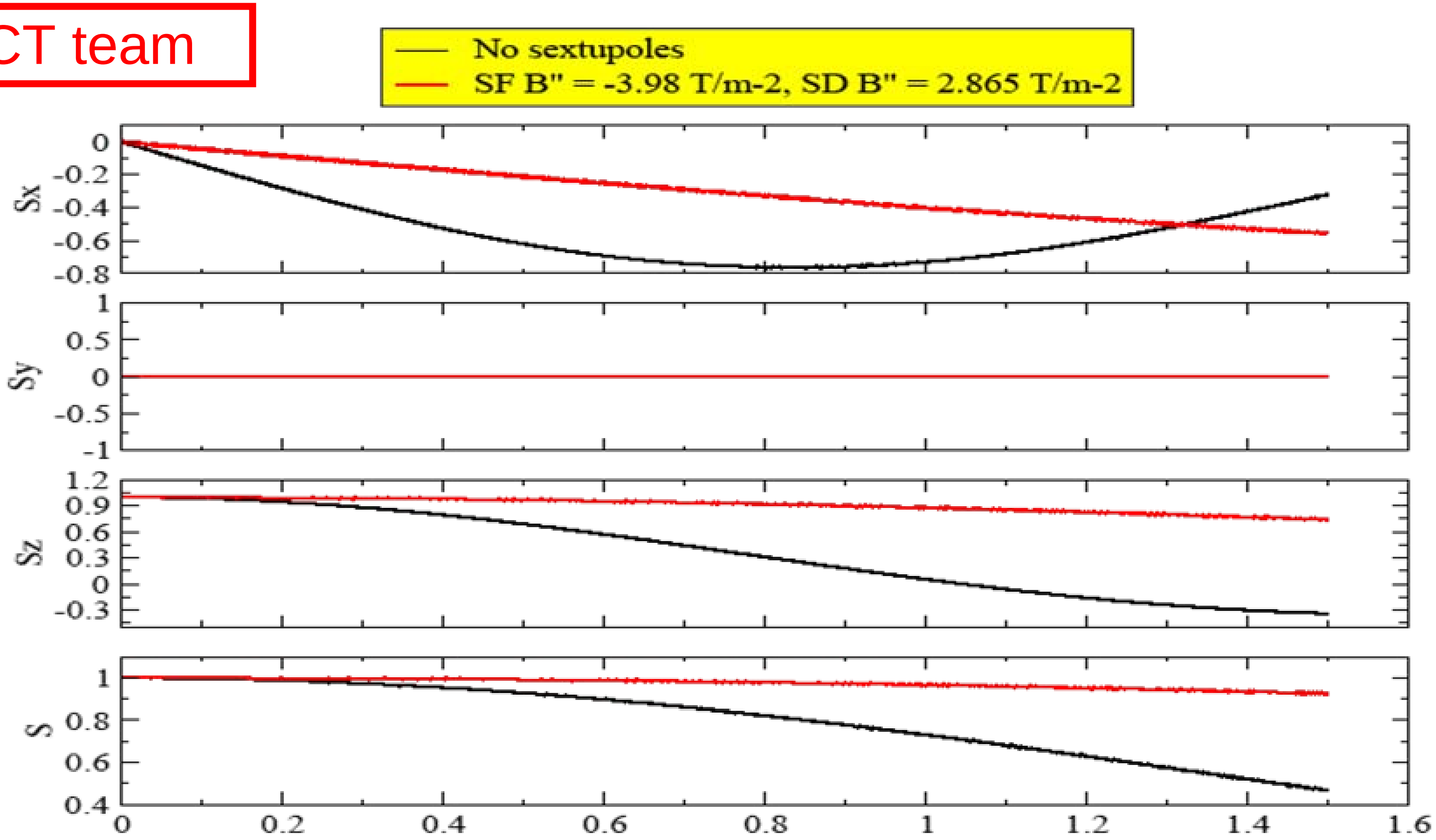
SCT team

# Simulation Conditions

- **Simulation tools : UAL (courtesy of N. Malitsky ) + SPINK (courtesy of A.U. Luccio )**
- **Multiparticles with Gaussian distribution**
- **All Initial spin vectors points to the longitudinal direction**
- **Distribution categories:**
  - **Horizontal distribution with** $\varepsilon_x = 3.0\pi mm - mrad$
  - **Vertical distribution with** $\varepsilon_y = 5.0\pi mm - mrad$
  - **Momentum spread** $\frac{\Delta p}{p} = 10^{-3}$
- **Definition of Sx, Sy, Sz, S**
  - **<Sx> : radial component of polarization**
  - **<Sy> : vertical component of polarization**
  - **<Sz> : longitudinal component of polarization**
  - **S :** $S = \sqrt{<S_x>^2 + <S_y>^2 + <S_z>^2}$
- **1 million turns ~ 1.5 second**

# Searching for optimum sextupoles (III)

SCT team



**Two sets of sextupoles are next to focusing and defocusing quads. Both horizontal and vertical motion are included.**

SCT team

# SCT work by fall 2009

- We expect to have (with simulation) ~50s of SCT.

# Proton vs. deuteron comparison

| **Particle** | **E-field needed** | **Dipole B-field needed (combined E&B fields)** | **Flipping field for CW, CCW injections** | **Sensitive Fabry-Perot resonator needed** |
|---|---|---|---|---|
| Proton | Yes | NO | NO | NO |
| Deuteron | YES | YES<br>(Space restrictions; $e^-$ trapping) | B: YES<br>E: No | YES |

# Proton vs. deuteron comparison

| **Particle** | **Local g-2 phase cancellation** | **SCT** | **Polarimeter** |
|---|---|---|---|
| Proton | It will be better than $10^{-7}$ by E-field design | No horizontal pitch effect | Simpler; A sweet spot at 0.7GeV/c |
| Deuteron | $10^{-4}$; requires high stability | Vertical & horizontal pitch effects | Tensor polarization; break-up protons |

# Proton vs. deuteron comparison

| **Particle** | **Ring circumference** | **Sensitivity** | **Running** |
|---|---|---|---|
| Proton | ~200m | $3\times10^{-29}$ e-cm /year | Simpler (no dipole B-field associated costs) |
| Deuteron | ~85m | $10^{-29}$ e-cm /year | B-field stability after flip; B-field running cost |

# Proton EDM on our way to deuteron?

1. Preparation for proton EDM could be ready in two years and ~$2M for R&D

2. Preparation for deuteron EDM could be ready in four years and ~$4-5M for R&D

# Physics strength comparison

| System | Current limit [e·cm] | Future goal | Neutron equivalent |
|---|---|---|---|
| Neutron | $<1.6\times10^{-26}$ | $\sim10^{-28}$ | $10^{-28}$ |
| $^{199}$Hg atom | $<2\times10^{-28}$ | $\sim2\times10^{-29}$ | $10^{-25}$-$10^{-26}$ |
| $^{129}$Xe atom | $<6\times10^{-27}$ | $\sim10^{-30}$-$10^{-33}$ | $10^{-26}$-$10^{-29}$ |
| Deuteron nucleus |  | $\sim10^{-29}$ | $3\times10^{-29}$-<br>$5\times10^{-31}$ |

# Hadronic EDMs

$$L_{\cancel{CP}} = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$

Order of magnitude estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

$$d_n\left(\bar{\theta}\right) \approx -d_p\left(\bar{\theta}\right) \approx 3.6\times10^{-16}\,\bar{\theta}\ \mathrm{e}\cdot\mathrm{cm} \rightarrow \bar{\theta} \leq 2\times10^{-10}$$

# Deuteron EDM

$$d_D = (d_n + d_p) + d_D^{\pi NN}$$

$$d_D(\bar{\theta}) \approx -10^{-16}\,\bar{\theta}\ \mathrm{e\cdot cm}$$

i.e. @ $10^{-29}$e·cm:

$$\bar{\theta} \leq 10^{-13}$$

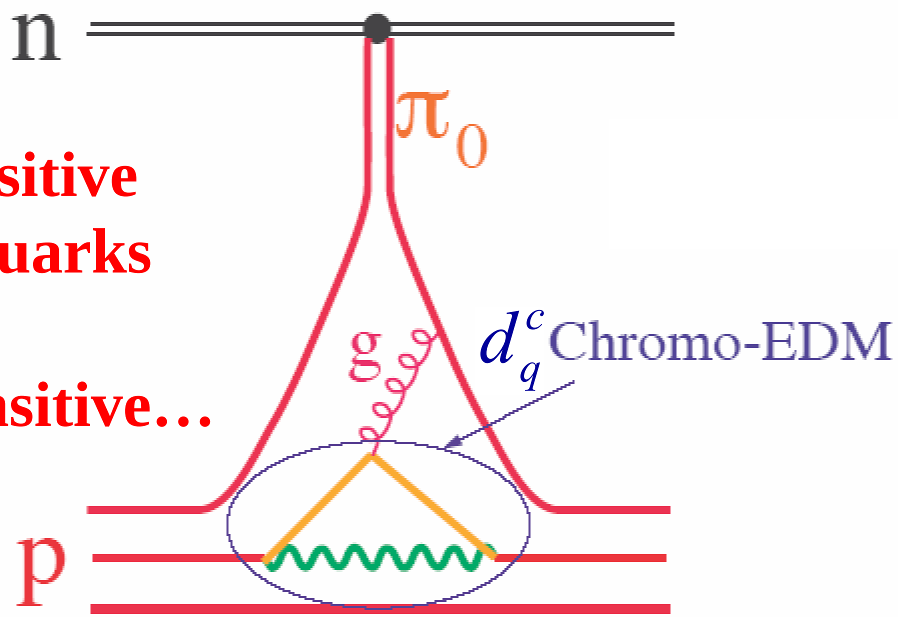
# Quark EM and Color EDMs

$$L_{\not{C}\not{P}} = -\frac{i}{2}\sum_q \bar{q}\left(d_q \sigma_{\mu\nu} F^{\mu\nu} + d_q^c \sigma_{\mu\nu} G^{\mu\nu}\right)\gamma_5 q$$

$$d_n \approx 1.4(d_d - 0.25 d_u) + 0.83e(d_d^c + d_u^c) + \underline{0.27e(d_d^c - d_u^c)},$$

$$d_D \approx (d_d + d_u) + \underline{6e(d_d^c - d_u^c)} - 0.2e(d_d^c + d_u^c).$$

**i.e. Deuterons and neutrons are sensitive to different linear combination of quarks and chromo-EDMs…**
**The Deuteron is ~20 times more sensitive…**



# If nEDM is discovered at $10^{-28}$ e•cm level?

- If $\bar{\theta}$ is the source of the EDM, then

$$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 1/3 \Rightarrow d_D \approx 3\times 10^{-29}\,\mathrm{e\cdot cm}$$

- If SUSY is the source of the EDM (isovector part of T - odd N - forces), then

$$d_D(\bar{\theta})/d_n(\bar{\theta}) \approx 20 \Rightarrow d_D \approx 2\times 10^{-27}\,\mathrm{e\cdot cm}$$

**The deuteron EDM is complementary to neutron and in fact has better sensitivity.**

# Physics Motivation of dEDM

- Currently: $\bar{\theta} \leq 10^{-10}$, Sensitivity with dEDM: $\bar{\theta} \leq 10^{-13}$

- **Sensitivity to new contact interaction: 3000 TeV**

- **Sensitivity to SUSY-type new Physics:**

$$dEDM \approx 10^{-24}\,\mathrm{e}\cdot\mathrm{cm} \times \sin\delta \times \left(\frac{1\,\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^2$$

The Deuteron EDM at $10^{-29}$e·cm has a reach of ~300TeV or, if new physics exists at the LHC scale, $10^{-5}$ rad CP-violating phase. Both are much beyond the design sensitivity of LHC.

# Deuteron, Proton EDM

- High sensitivity to non-SM CP-violation
- Negligible SM background
- Physics beyond the SM (e.g. SUSY) expect CP-violation within reach
- Complementary and better than nEDM
- Proton and deuteron EDM a good goal
- If observed it will provide a new, large source of CP-violation that could explain the Baryon Asymmetry of our Universe (BAU)