

Deuteron & proton EDM

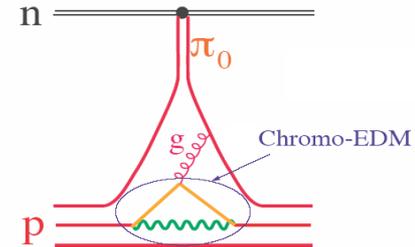
Experiment:

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

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- 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

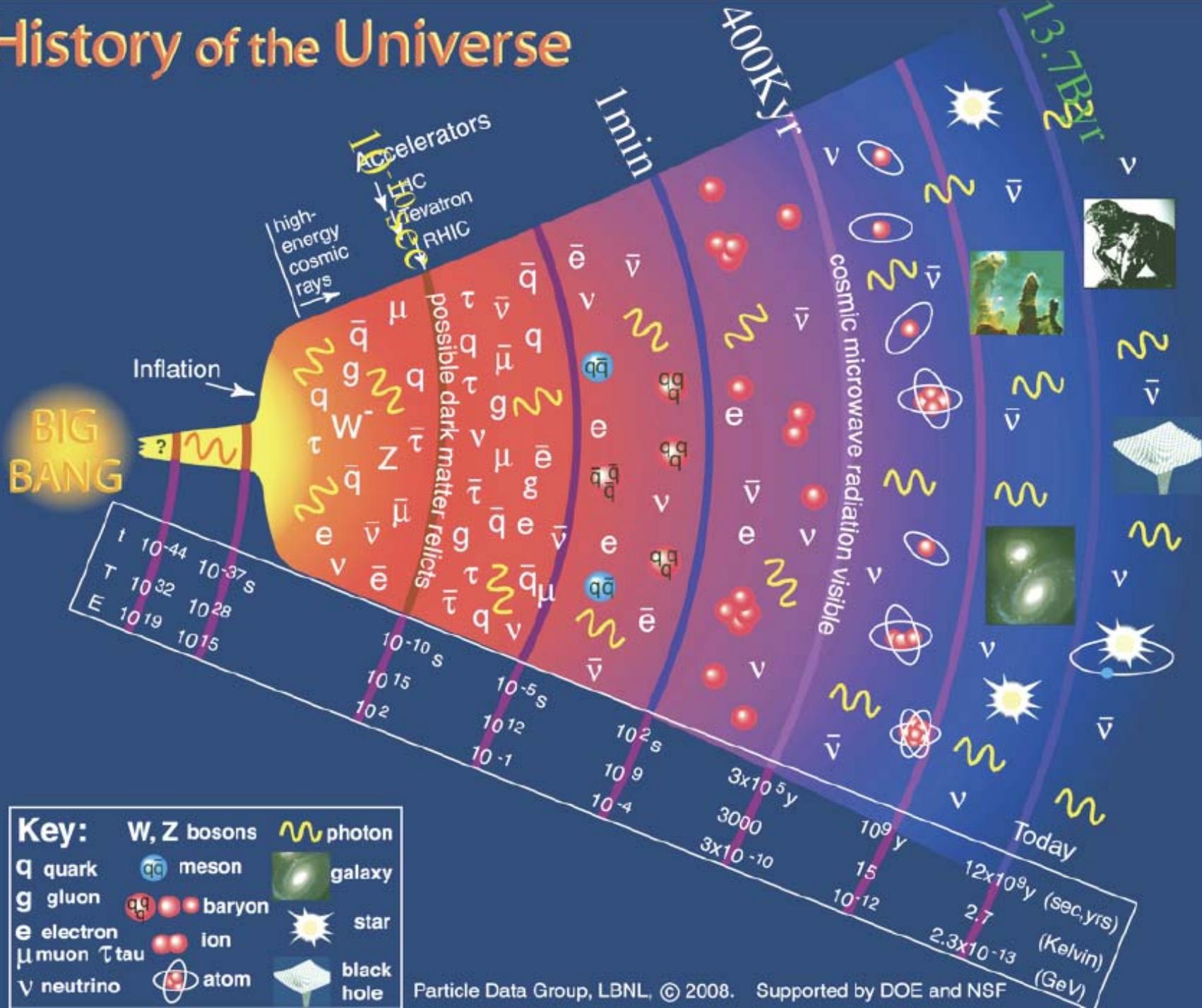
which are complementary and inter-connected. The next SM will emerge with input from both approaches.

Physics of EDM

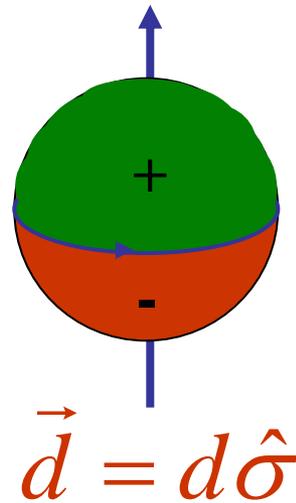
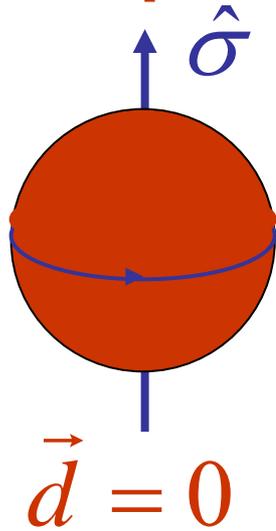
The Deuteron EDM at 10^{-29} e·cm has a reach of ~ 300 TeV or, if new physics exists at the LHC scale, 10^{-5} rad CP-violating phase.

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

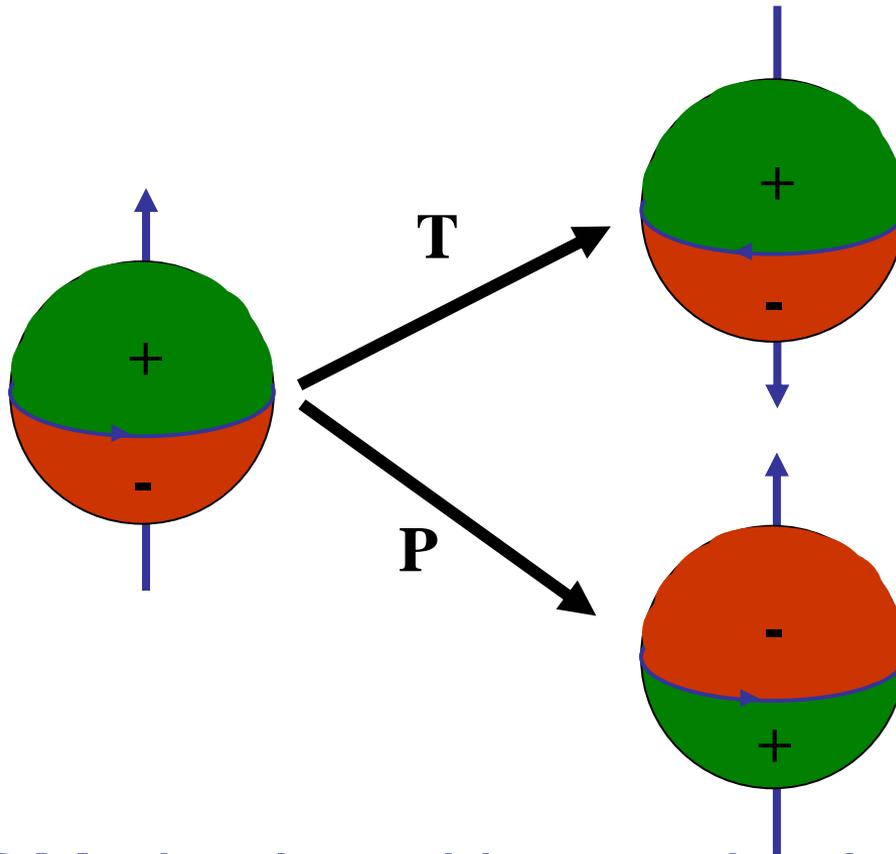
History of the Universe



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



A Permanent EDM Violates both T & P Symmetries:

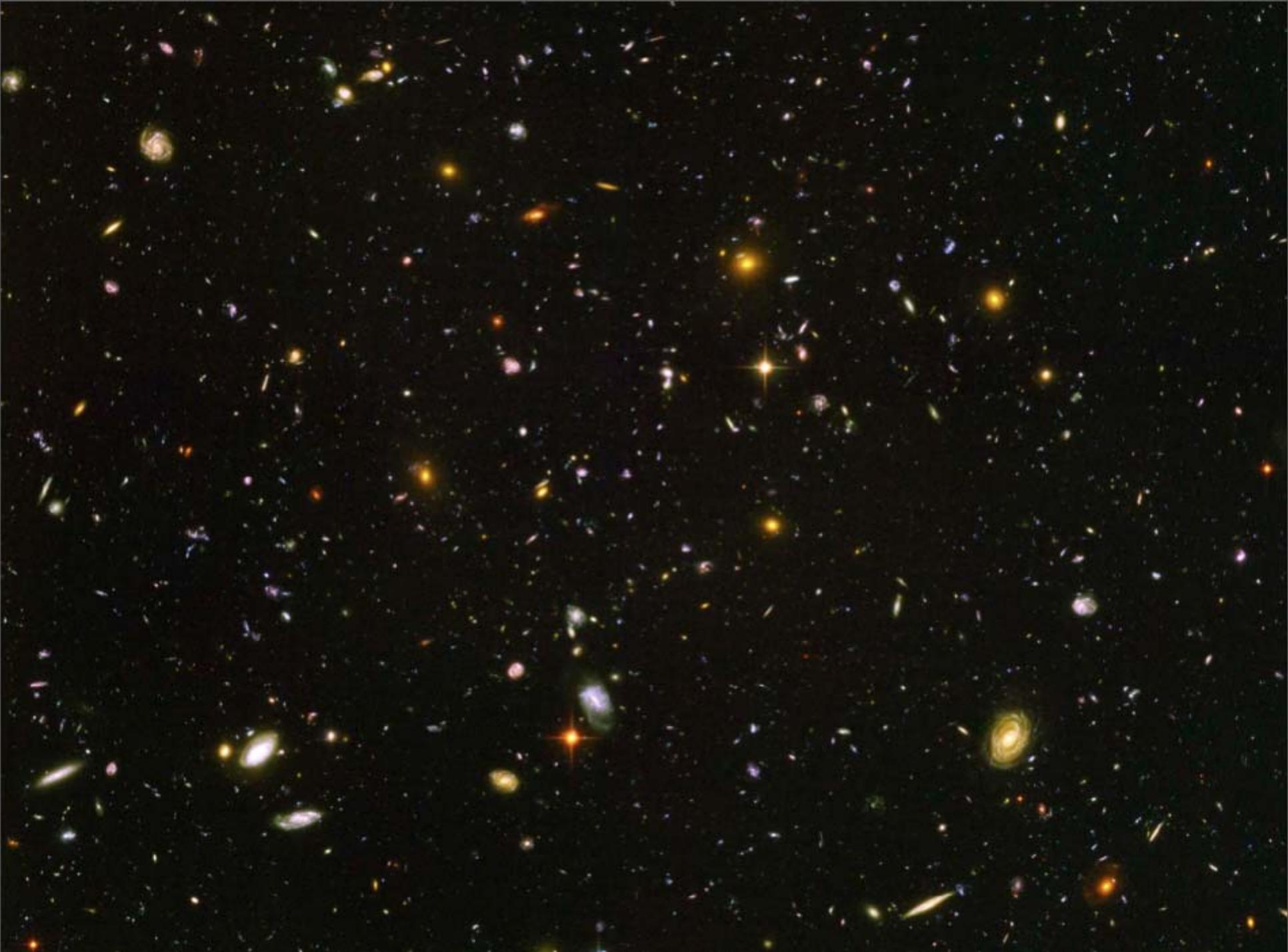


EDM physics without spins is not important
(batteries are allowed!)

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....



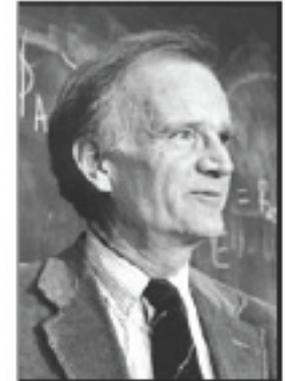
CP-violation was discovered at BNL in 1964

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.

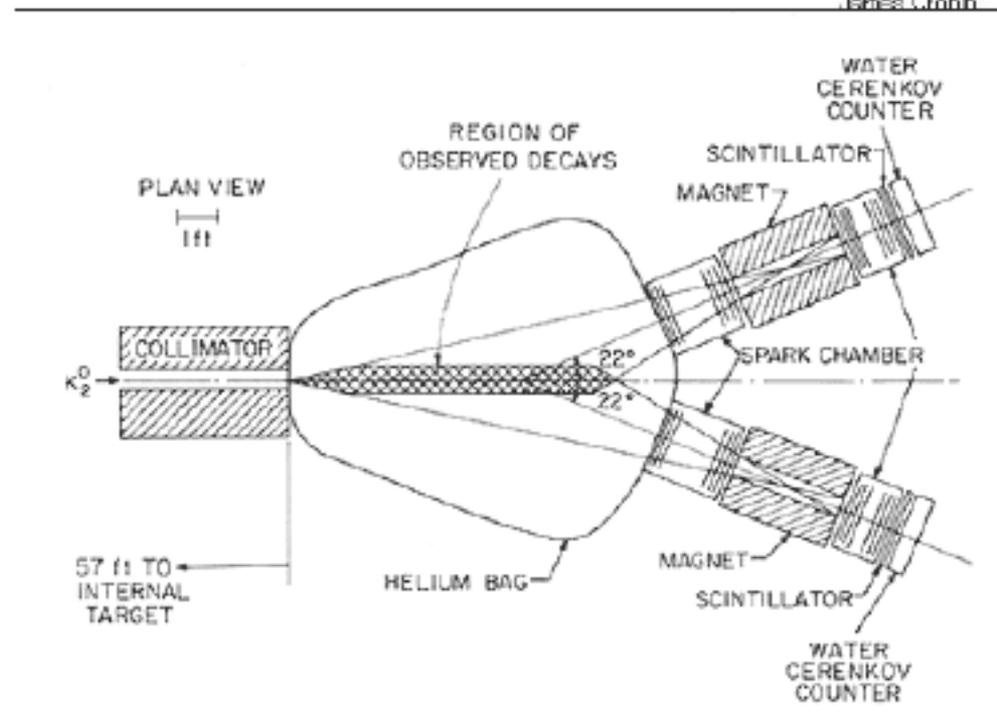
The experiment set out to show that in millions of collisions, the short-lived variety of K meson always decayed into two pi mesons, while the long-lived variety never did. But to their surprise, a "suspicious-looking hump" in the data showed an unexpected result that years of subsequent experimentation 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 **B**aryon **A**symmetry of our **U**niverse 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

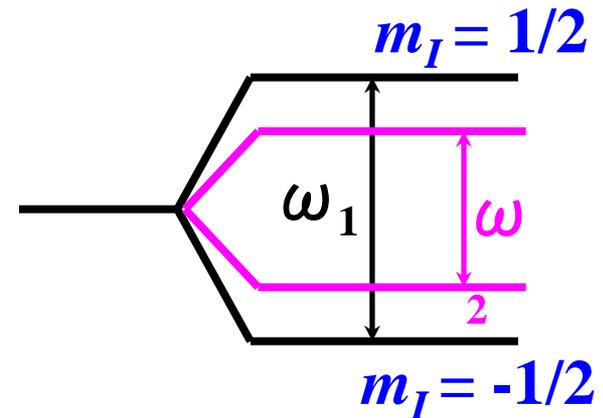
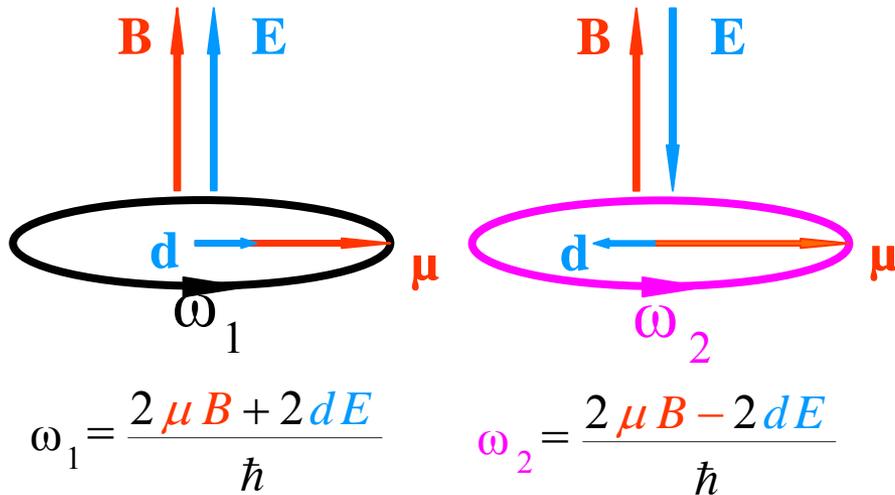
- **1950's** neutron EDM experiment started to search for parity violation (before the discovery of P-violation)
- After P-violation was discovered it was realized EDMs require both P,T-violation
- **1960's** EDM searches in atomic systems
- **1970's** Indirect Storage Ring EDM method from the CERN muon 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

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



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

$$d = 10^{-25} \text{ e cm}$$

$$E = 100 \text{ kV/cm}$$

$$\Rightarrow \omega = 10^{-4} \text{ rad/s}$$

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)

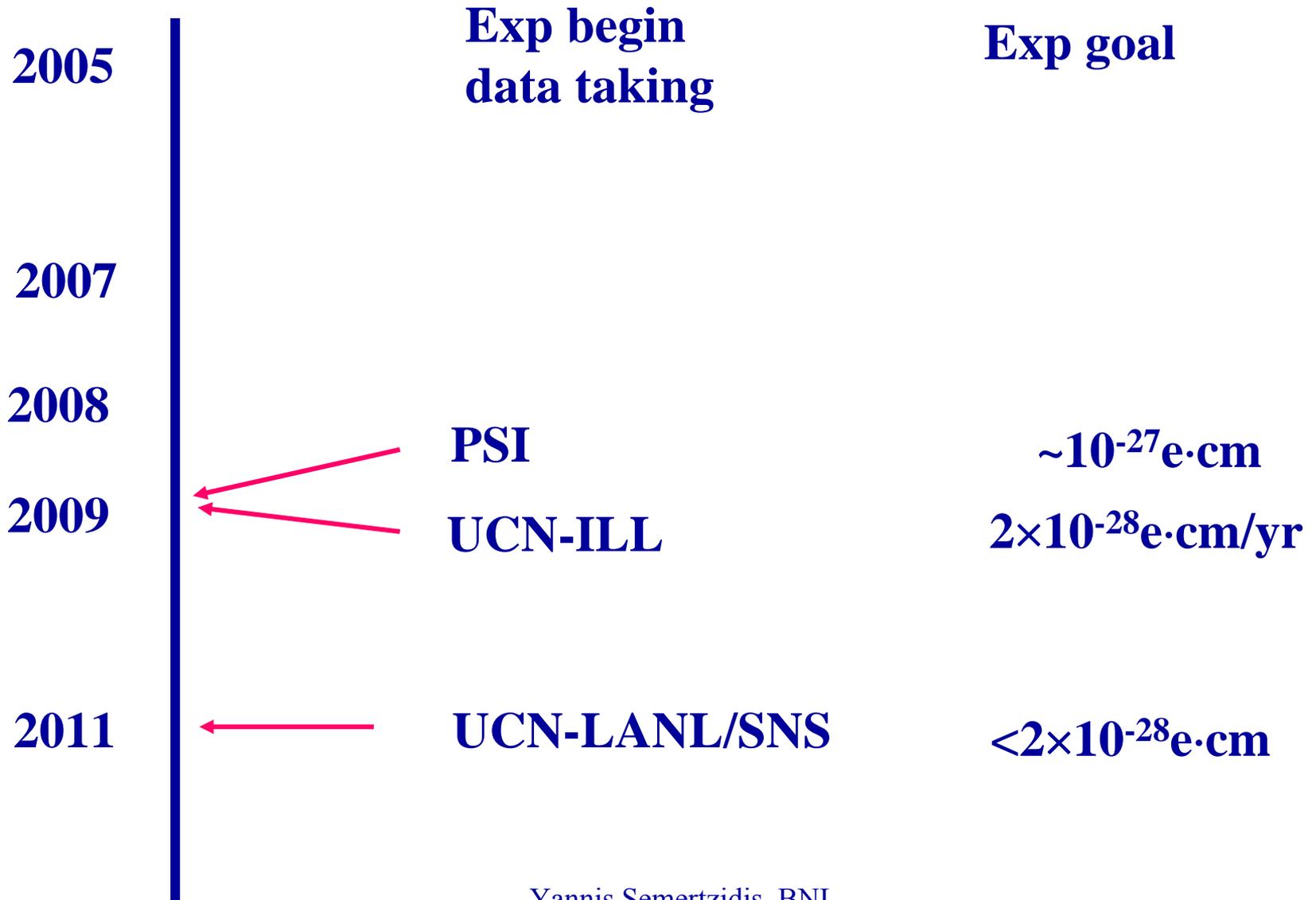
EDM method Advances

- 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



The Storage Ring EDM experiment

The Electric Dipole Moment precesses in an Electric field

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

Electric Dipole Moments in Magnetic Storage Rings

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

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

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

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

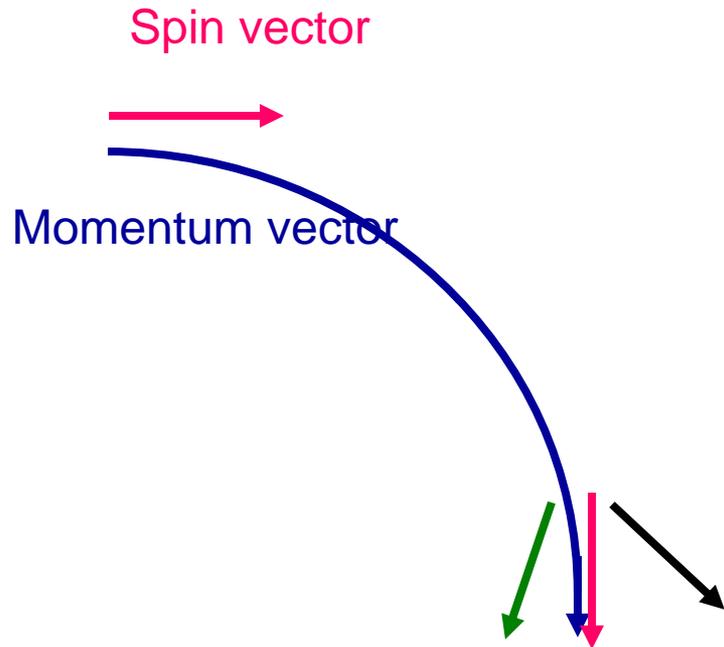
Freezing Spin Precession: it depends on the $a=(g-2)/2$ value

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

1. Magic momentum: Proton, sens.: 3×10^{-29} ecm
- Making the dipole B-field = 0, the spin precession is zero at (magic) momentum (0.7 GeV/c for protons)

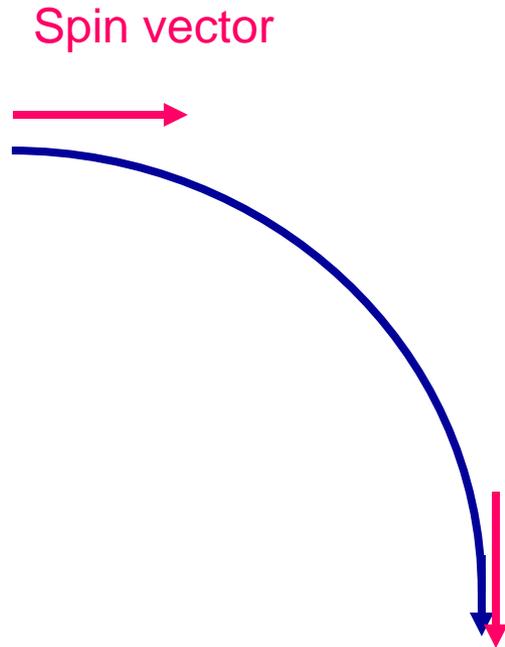
$$p = \frac{m}{\sqrt{a}}, \text{ i.e. the larger the } a \text{ the better!}$$

Effect of Radial Electric Field



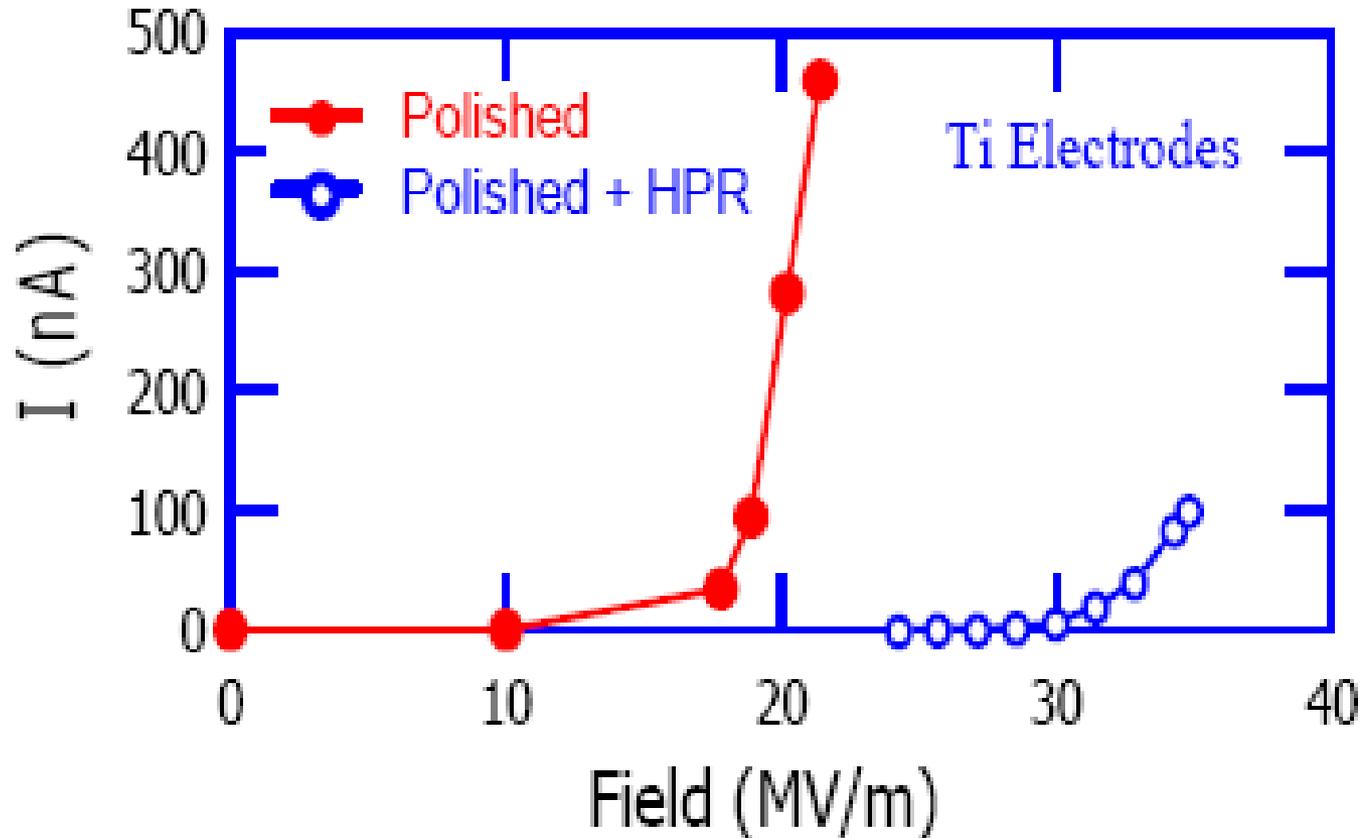
- Low energy particle
- ...just right
- High energy particle

Effect of Radial Electric Field



- ...just right, $P=0.7\text{GeV}/c$
for protons

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

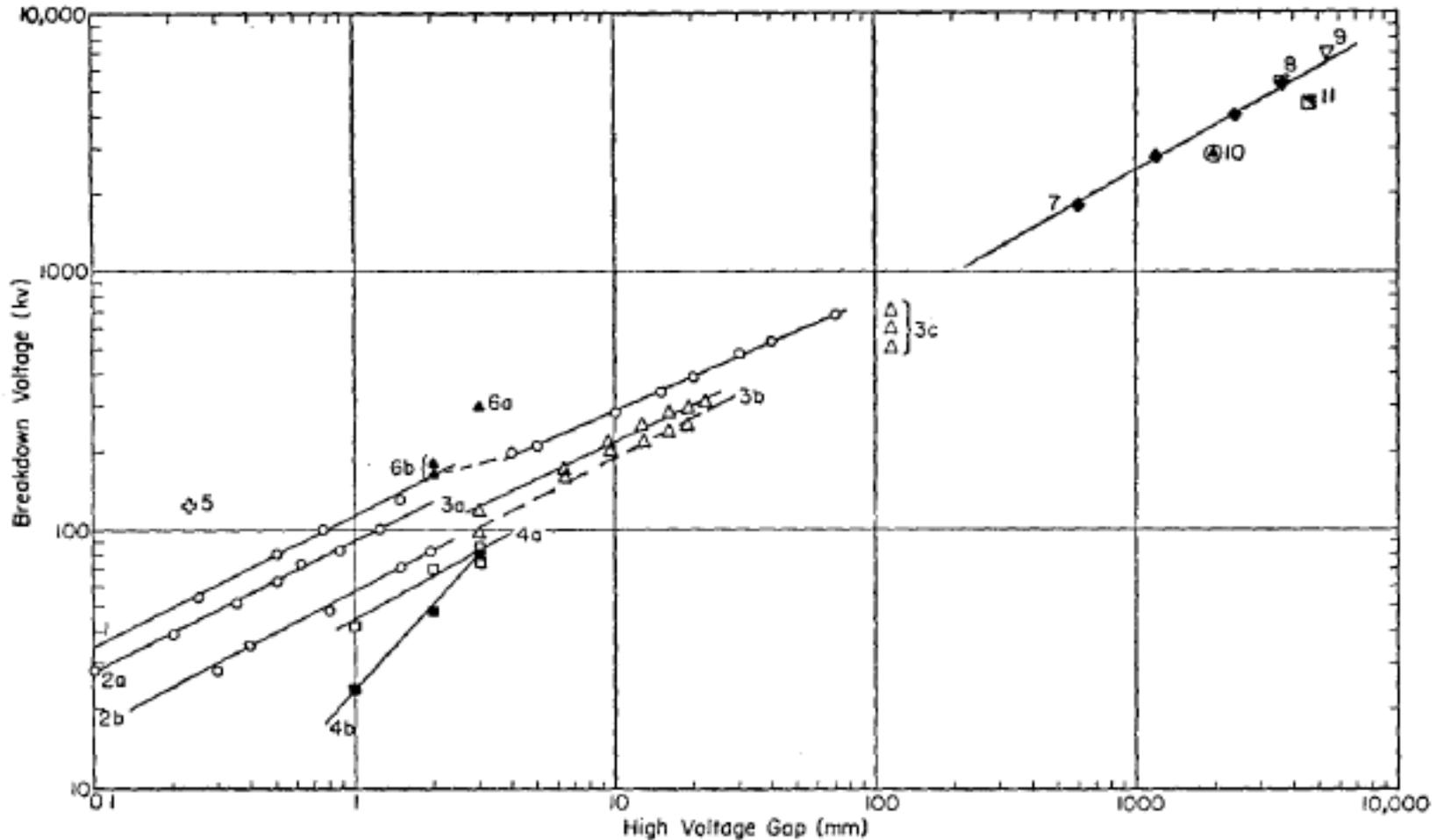


FIG. 1. Plot of data from the literature of breakdown voltage vs distance from highest to lowest potential electrode, for uniform-field and near-uniform-field geometry. Numbers on curves indicate sources as listed below.

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

$E \approx aBc\beta\gamma^2$, 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 $V \times B$ 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

LINAC (B-930)

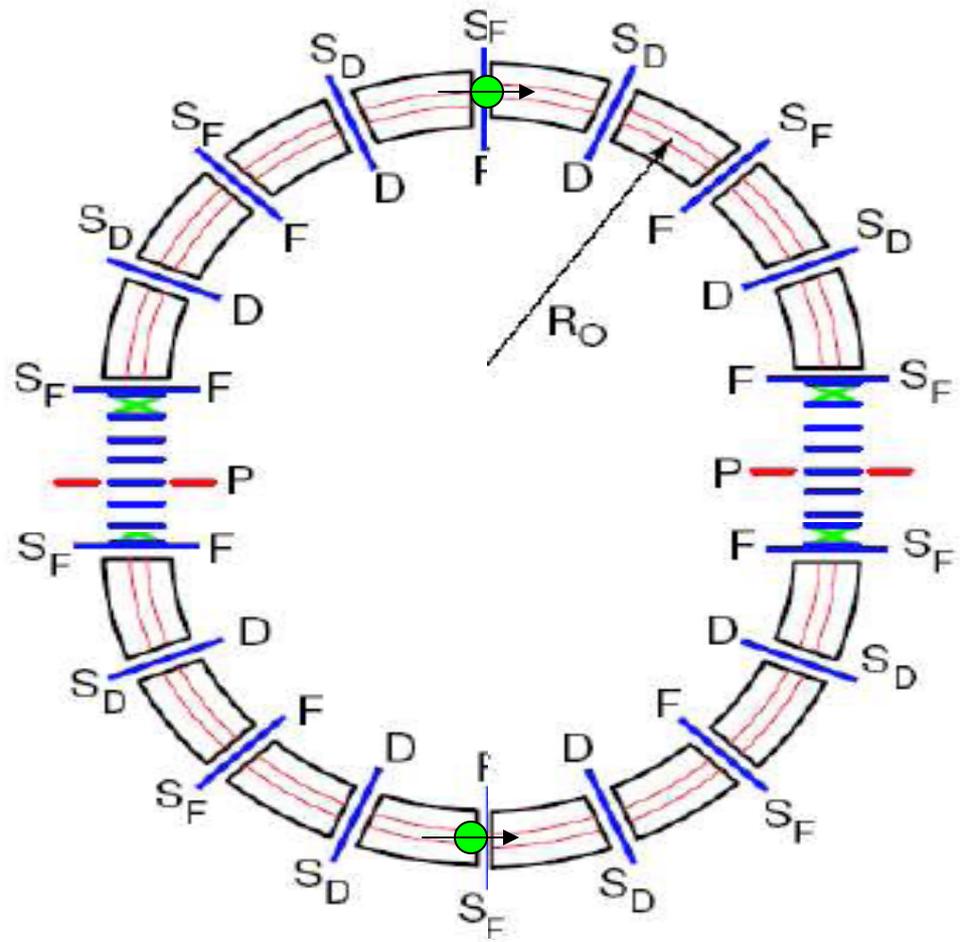
AGS BOOSTER

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

Modest e-cooling
required

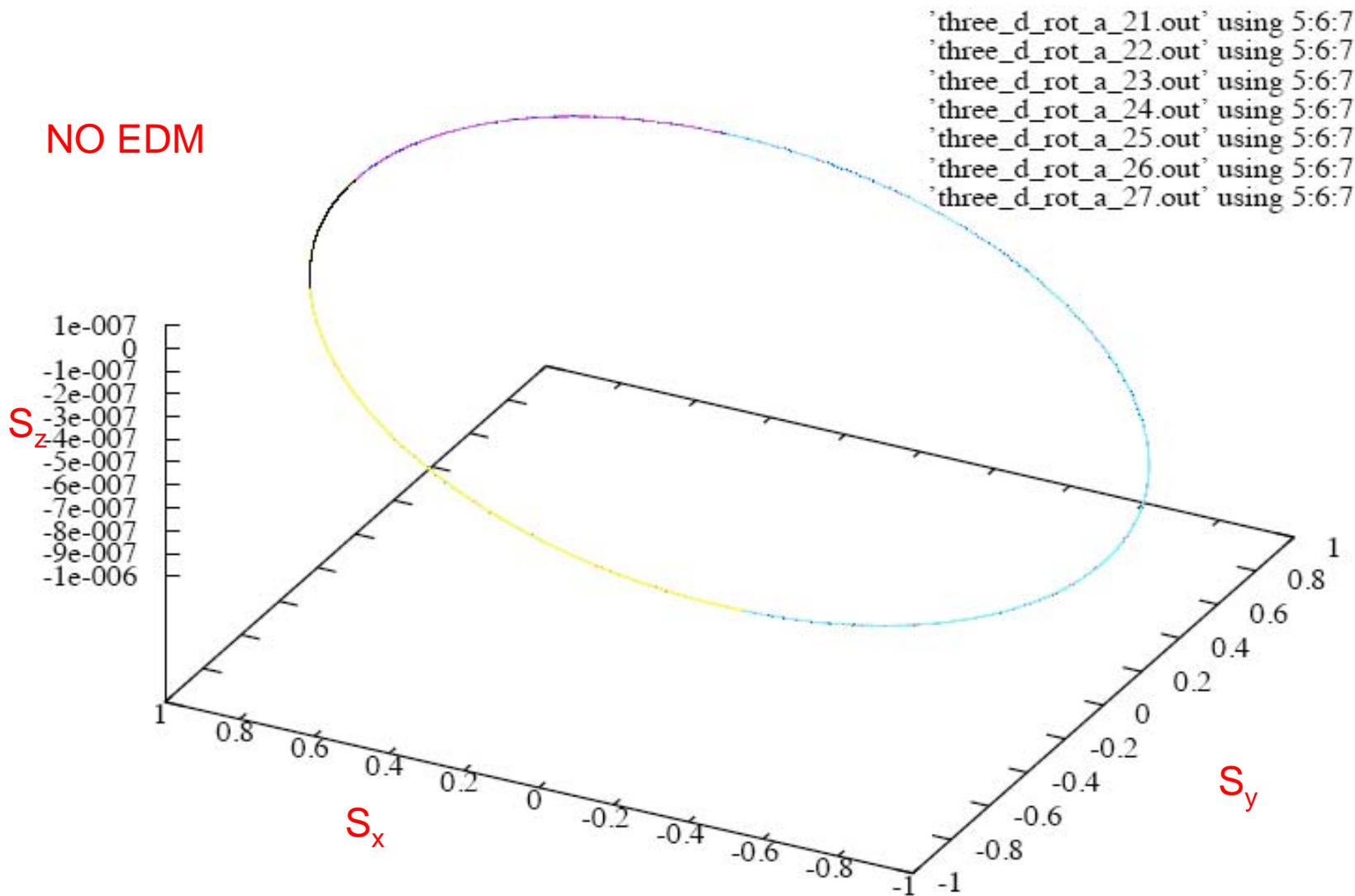
50 MEV LINAC (B-914)

The strong effective \mathbf{E}^* -field $\sim \mathbf{V} \times \mathbf{B}$ will precess the
deuteron spin out of plane if it possesses a non-zero EDM



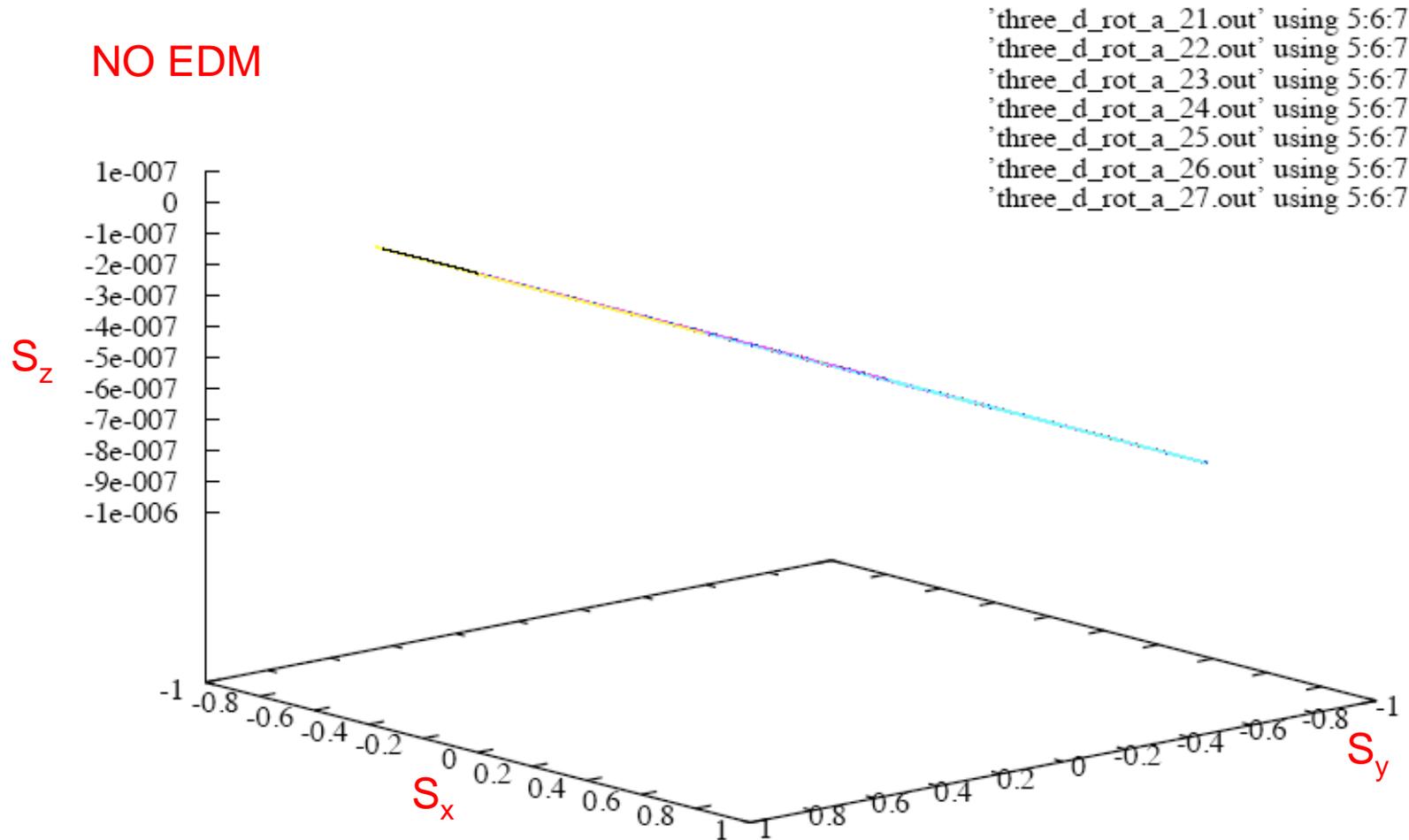
The three spin components at the polarimeter location for different g-2 cancelation factors:

NO EDM

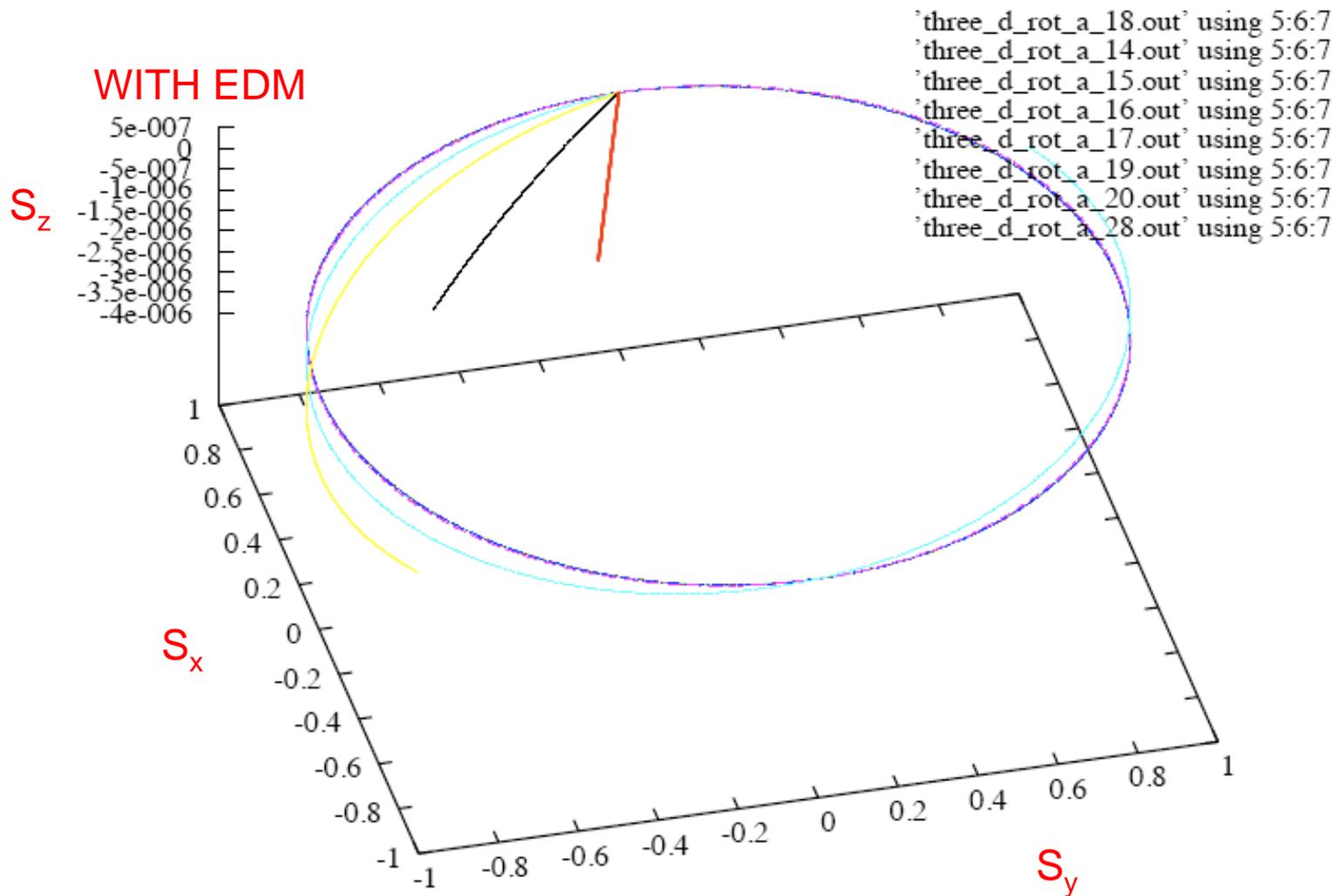


The three spin components at the polarimeter location for different g-2 cancelation factors:

NO EDM

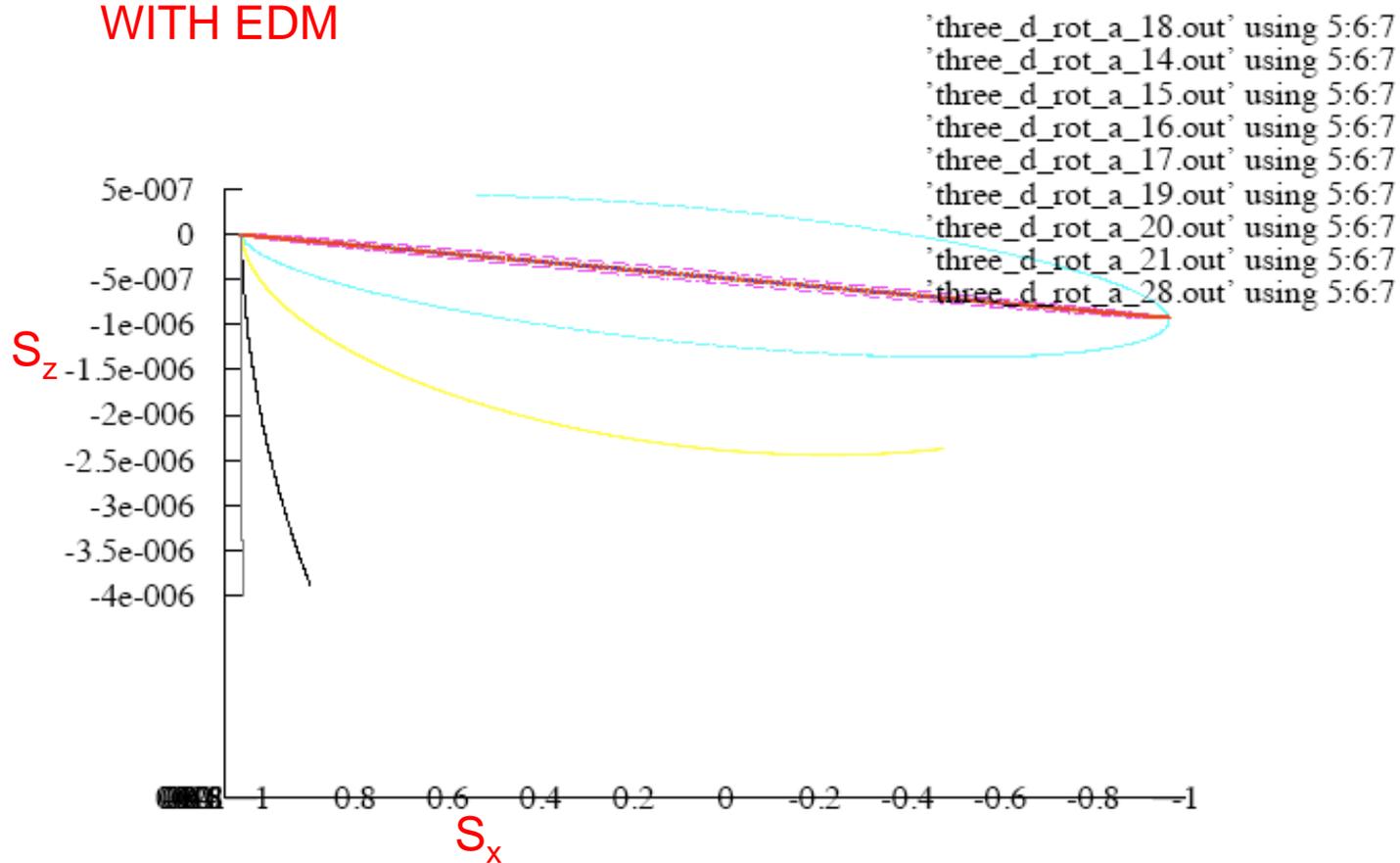


The three spin components at the polarimeter location for different g-2 cancelation factors:

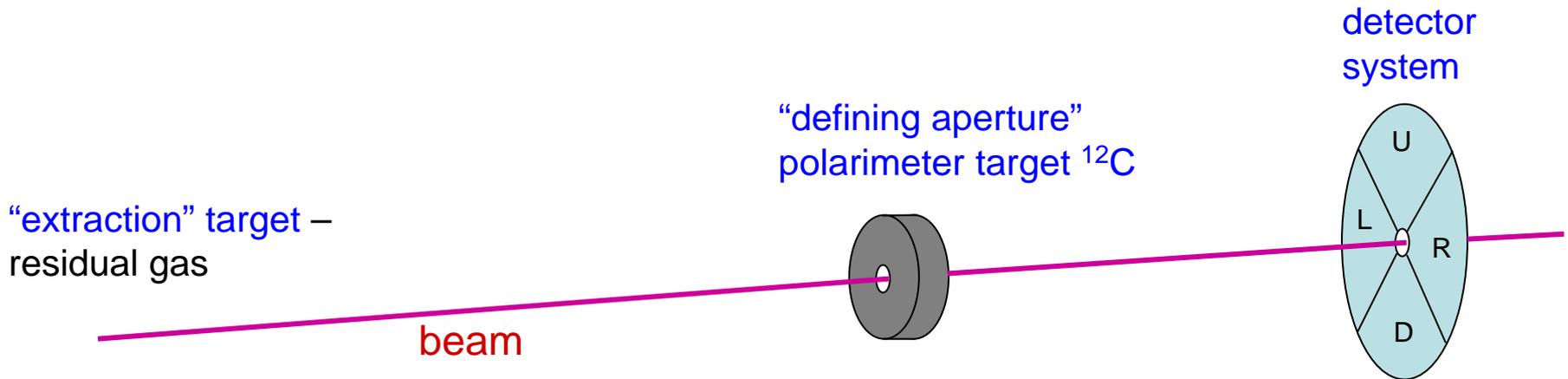


The three spin components at the polarimeter location for different g-2 cancelation factors:

WITH EDM



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



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

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

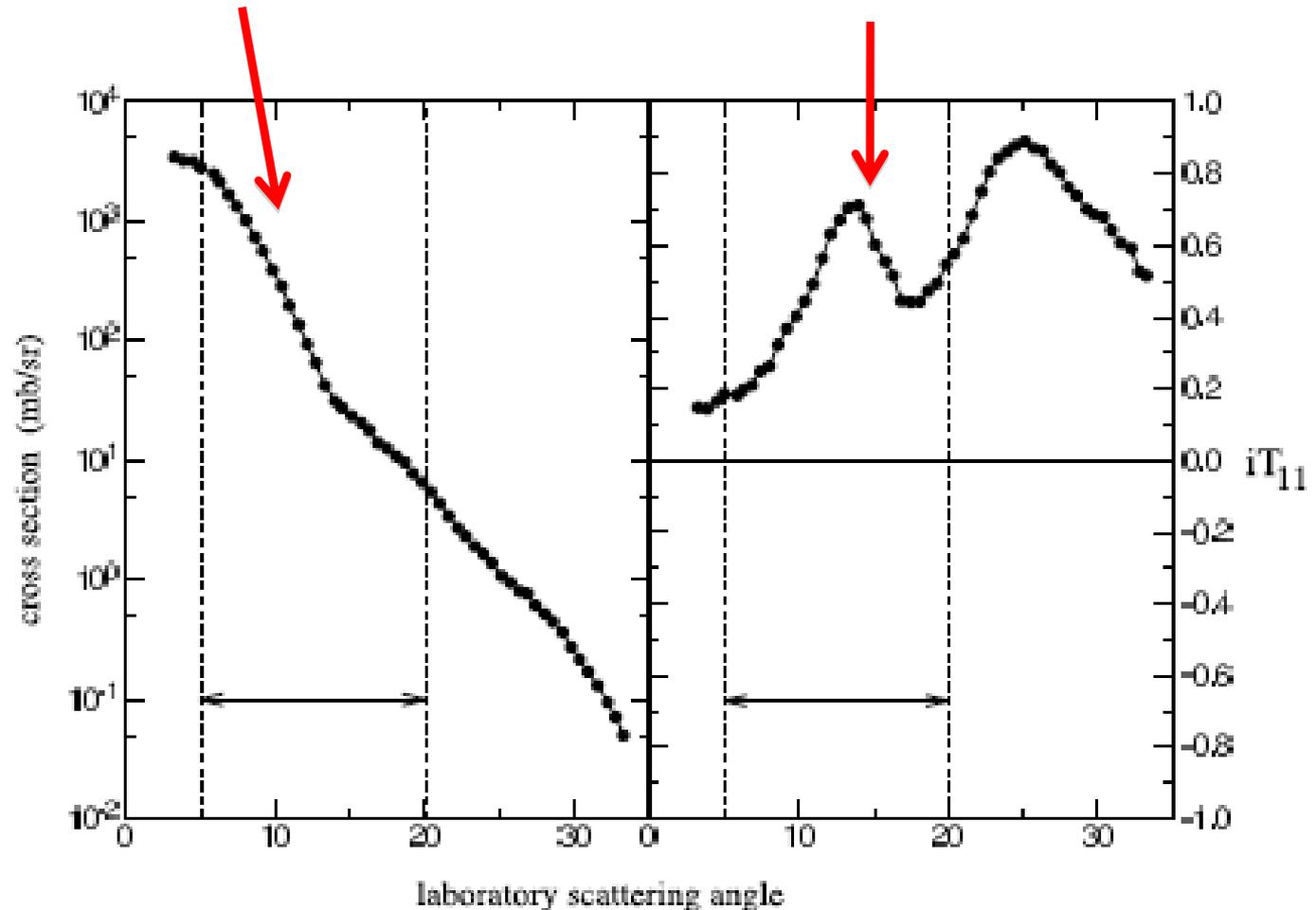


Figure 2: Deuteron elastic cross section and analyzing power at 270 MeV from carbon [29]. The dashed lines indicate the preferred acceptance limits for an EDM polarimeter.

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

Deuteron Statistical Error (250MeV):

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

- τ_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 : 4×10^{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

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

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 $\sim 10^{-6}$ 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 $\sim 10^{-4}$. Stability?; Sensitive Fabry-Perot resonator to be developed
- Spin Coherence Time: $\sim 10^3$ s

Main polarimeter systematic errors

2

Dealing with systematic errors

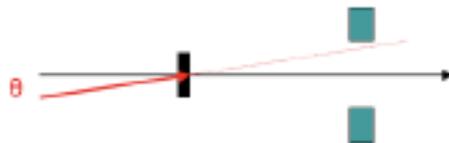
The Toolbox:

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

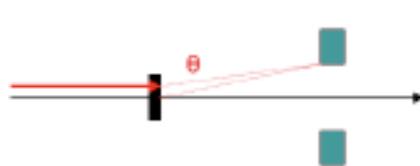
Challenge:
Predict these terms
from Monte Carlo,
then check in lab.
This demonstrates
methodology.

An illustration:

angle error



position error



both represented by θ

Fix problem with spin-flip and cross ratio:

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

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

$$\frac{\Delta \varepsilon}{\varepsilon} = \varepsilon^2 u^2 + 2\varepsilon \frac{1}{iT_{11}} \frac{\partial iT_{11}}{\partial \theta} u \theta + \frac{1}{iT_{11}} \frac{\partial^2 iT_{11}}{\partial \theta^2} \theta^2$$

~ -0.1
 ~ -0.07
 requires $\theta < 0.02^\circ$
 difference + to -

asymmetry
 ~ 0.01
 (residual p_y)

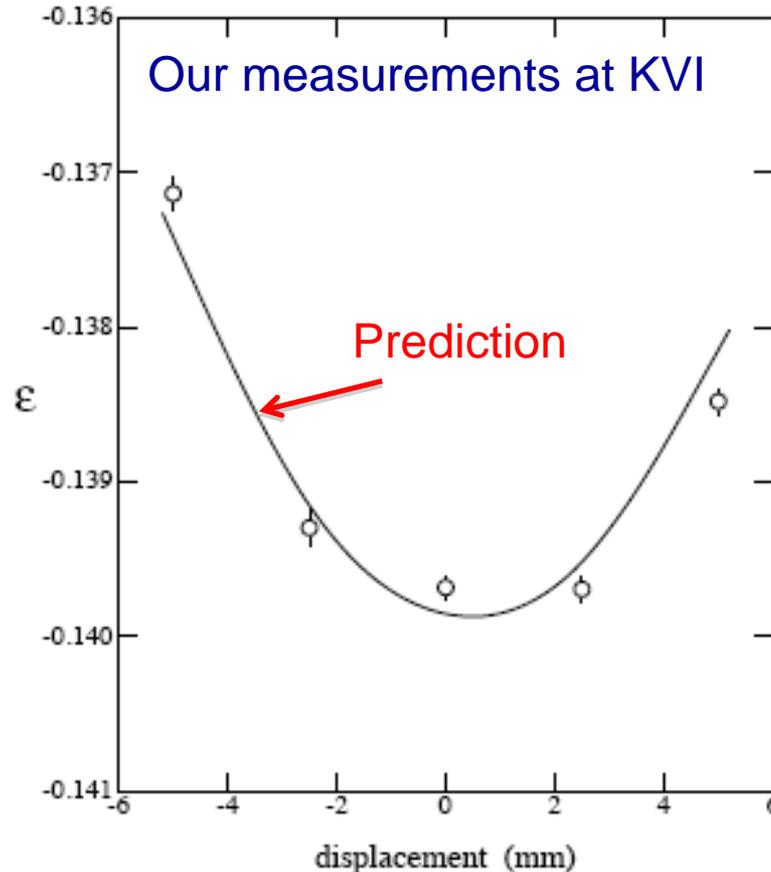
$u = p_+ + p_-$

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: $\sim 100 \mu\text{m}$

Cross Ratio The required beam axis stability: $\sim 100 \mu\text{rad}$



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

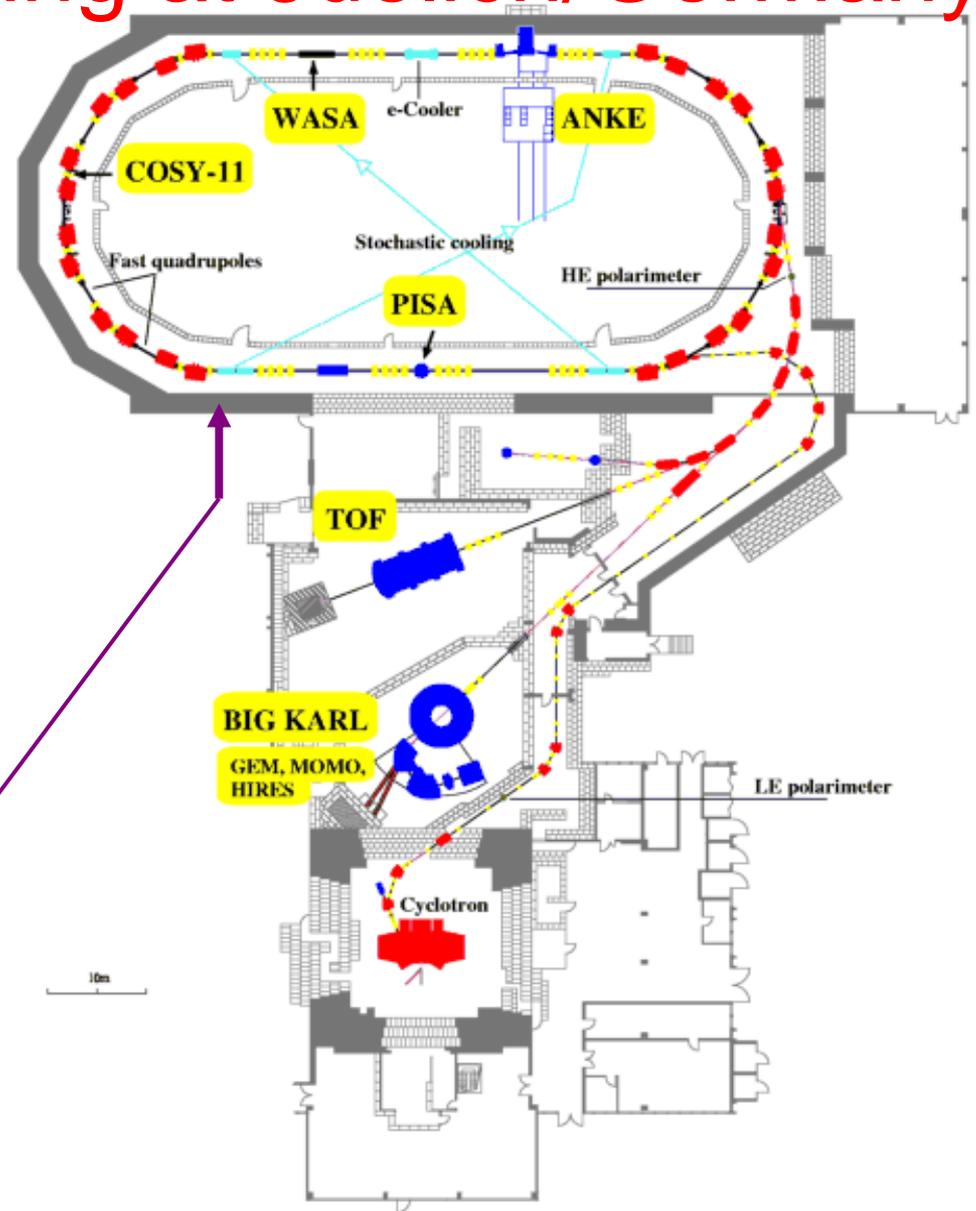
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Figure 3: Measurements of the change in left-right asymmetry as the target position is moved horizontally. The solid line is an *a priori* prediction based on the older scattering measurements at 113 MeV. The curve has been offset vertically to match 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.

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.



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From the June 2008 run at

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COSY

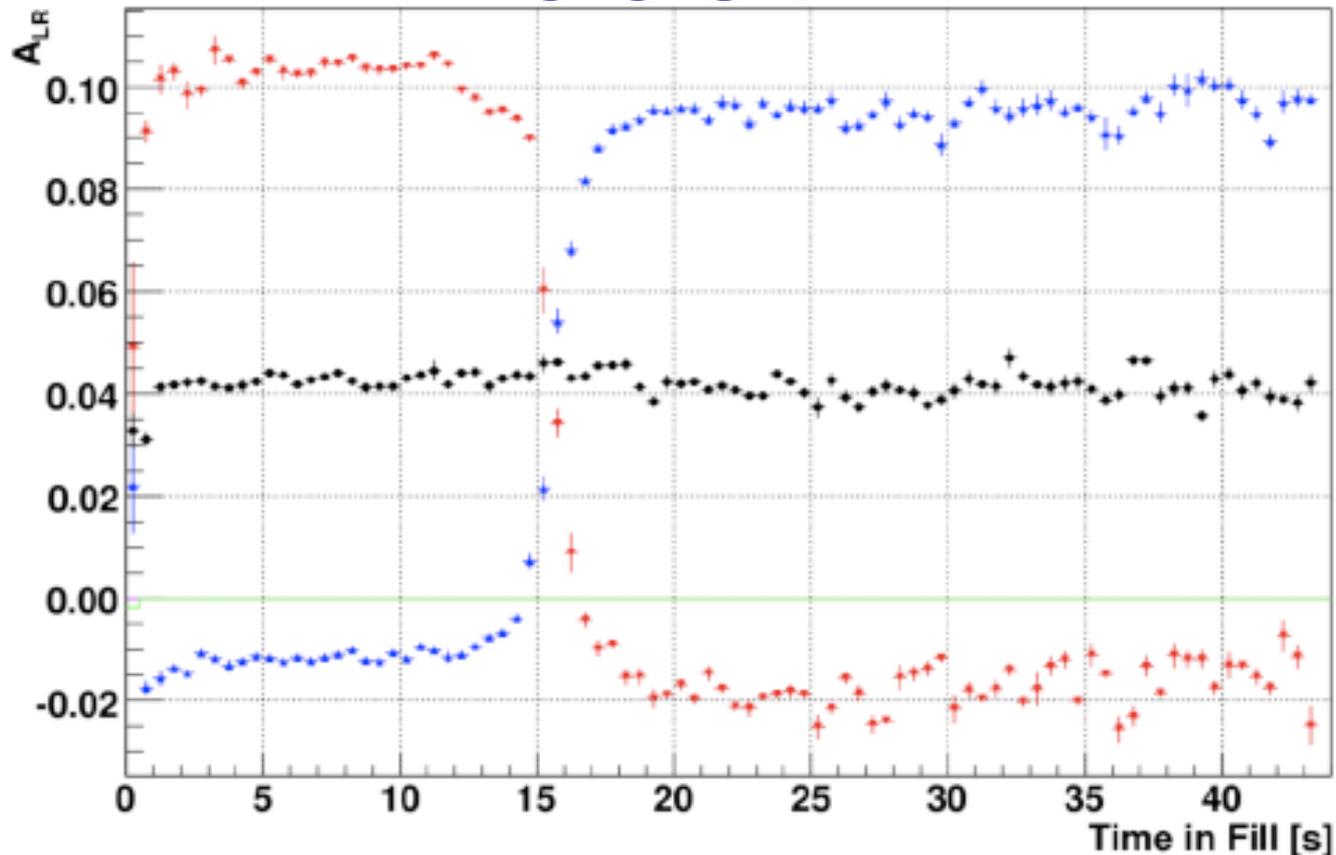
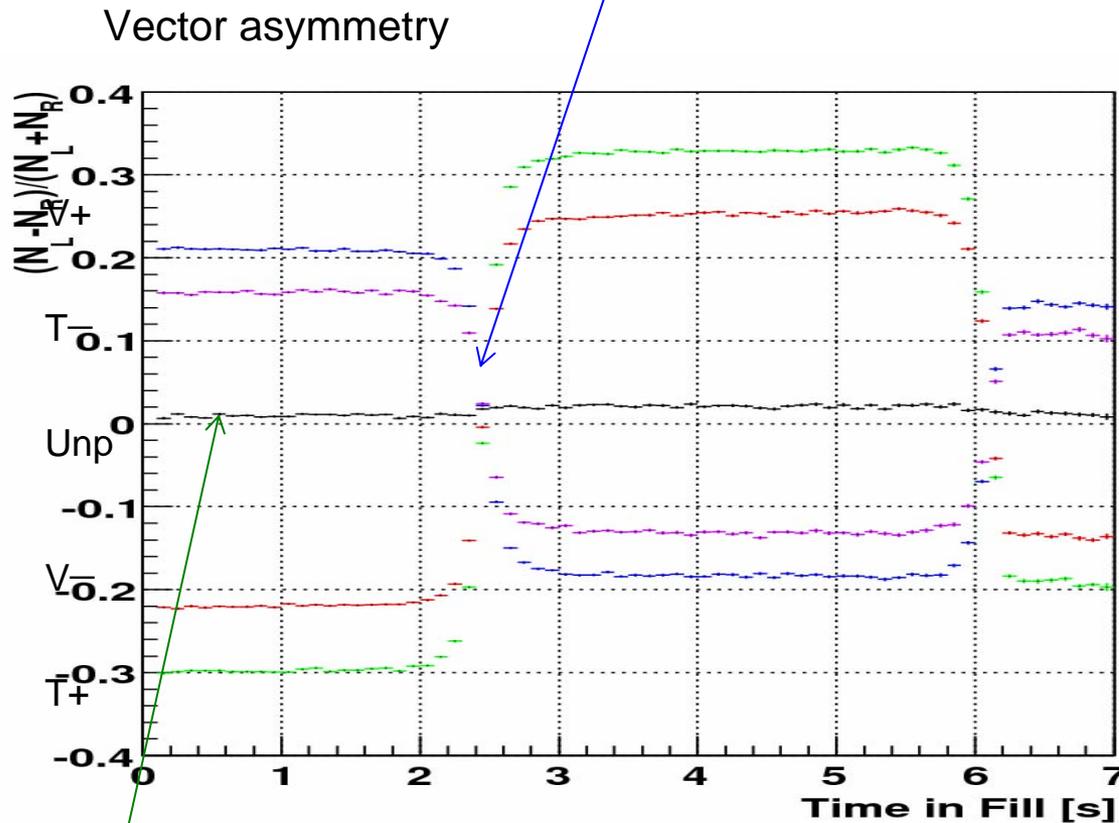


Figure 3. Asymmetry measurements made continuously during a beam store for spin up (red), spin down (blue), and unpolarized states. At the same time the frequency of the RF solenoid is ramping through the 1 – Gy resonance at 1030.048 kHz.

From the September 2008 run at COSY

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Resonance crossing
(full spin flip)



Unpolarized state has
some vector polarization
(note flip).

General Plan

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

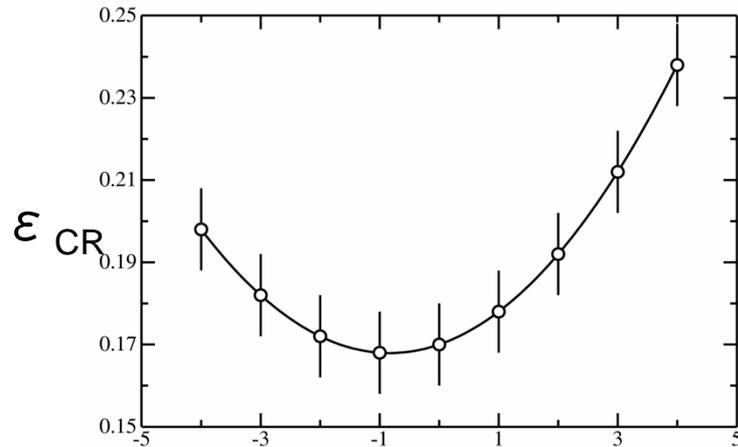
The cross ratio $\varepsilon_{CR} = \frac{r-1}{r+1}$ $r^2 = \frac{L_+R_-}{L_-R_+}$ cancels first-order errors.

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:

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

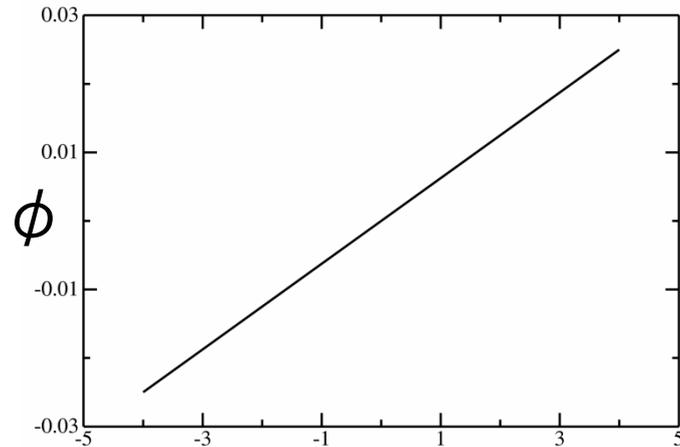
Ideally,

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

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



X displacement of beam at target (cm)

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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).

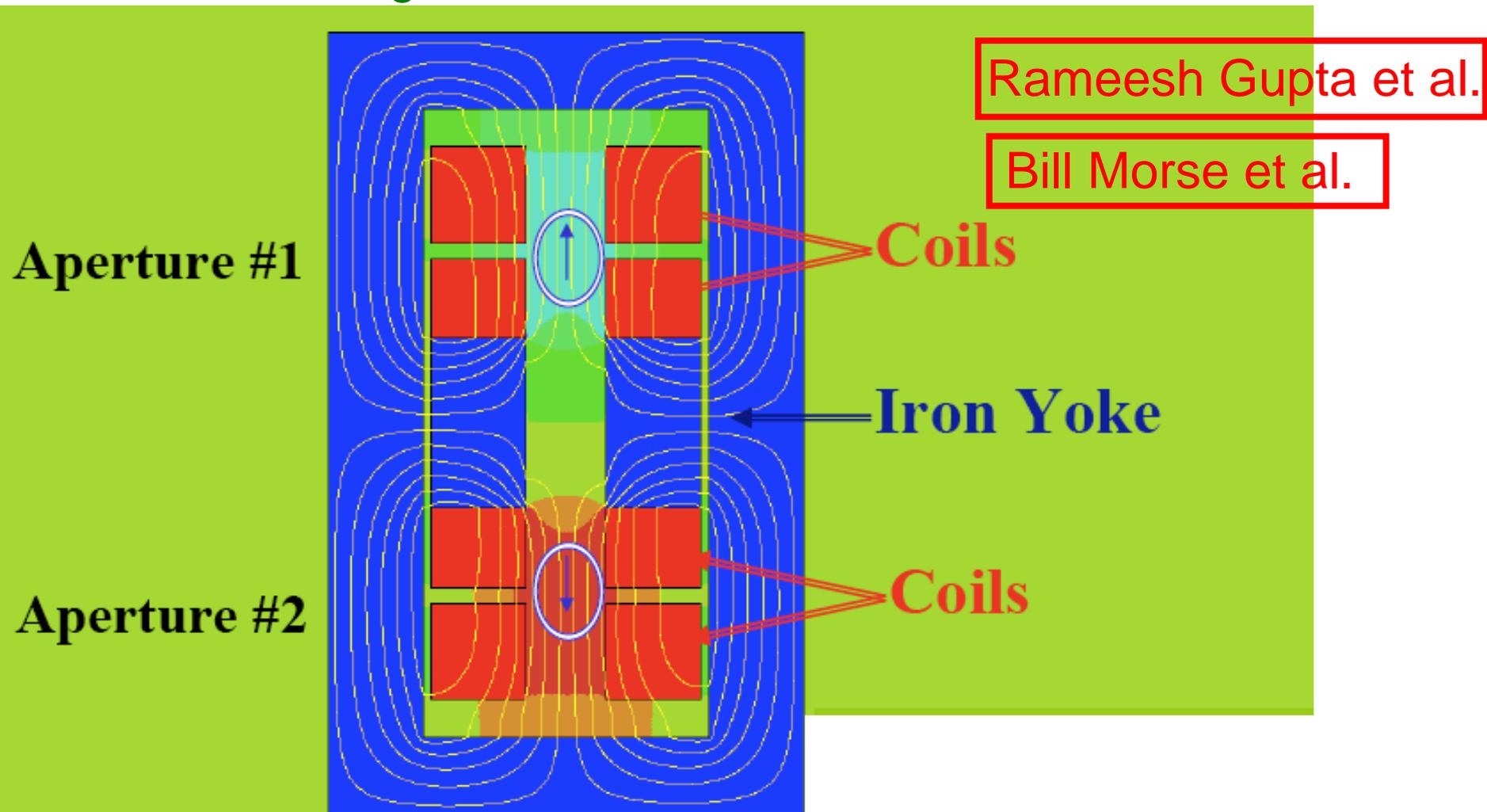
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Clock Wise (CW) and Counter Clock Wise (CCW) injections

- 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.



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.

Correction of Spin Frequency Perturbation

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

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

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

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

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

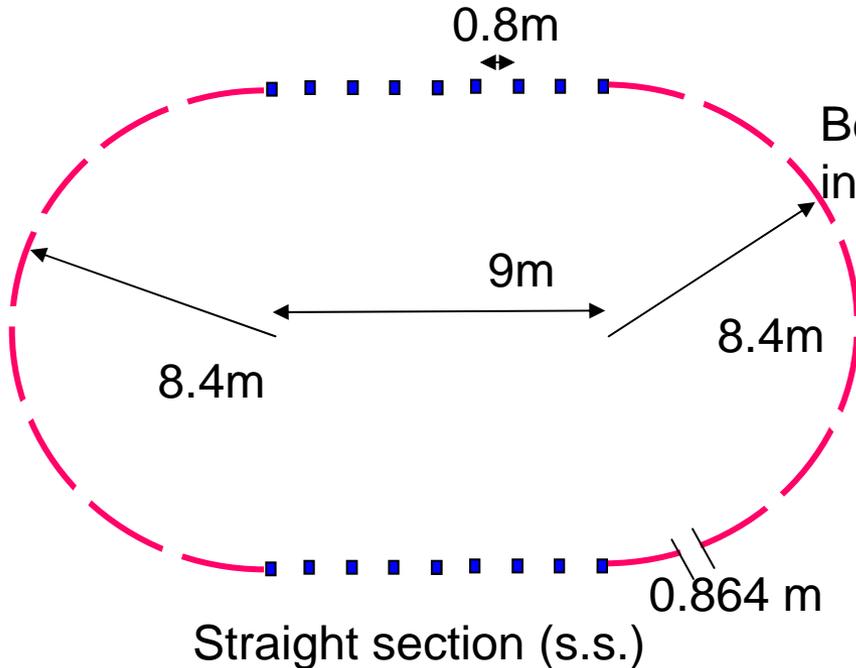
Sextupole produces a quadratic field as

$$B_y^{sext} = B'' (x^2 - y^2)$$

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 β_x and large vertical beta function β_y , and are needed for the correction of spin frequency perturbation respectively

The dEDM ring lattice



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

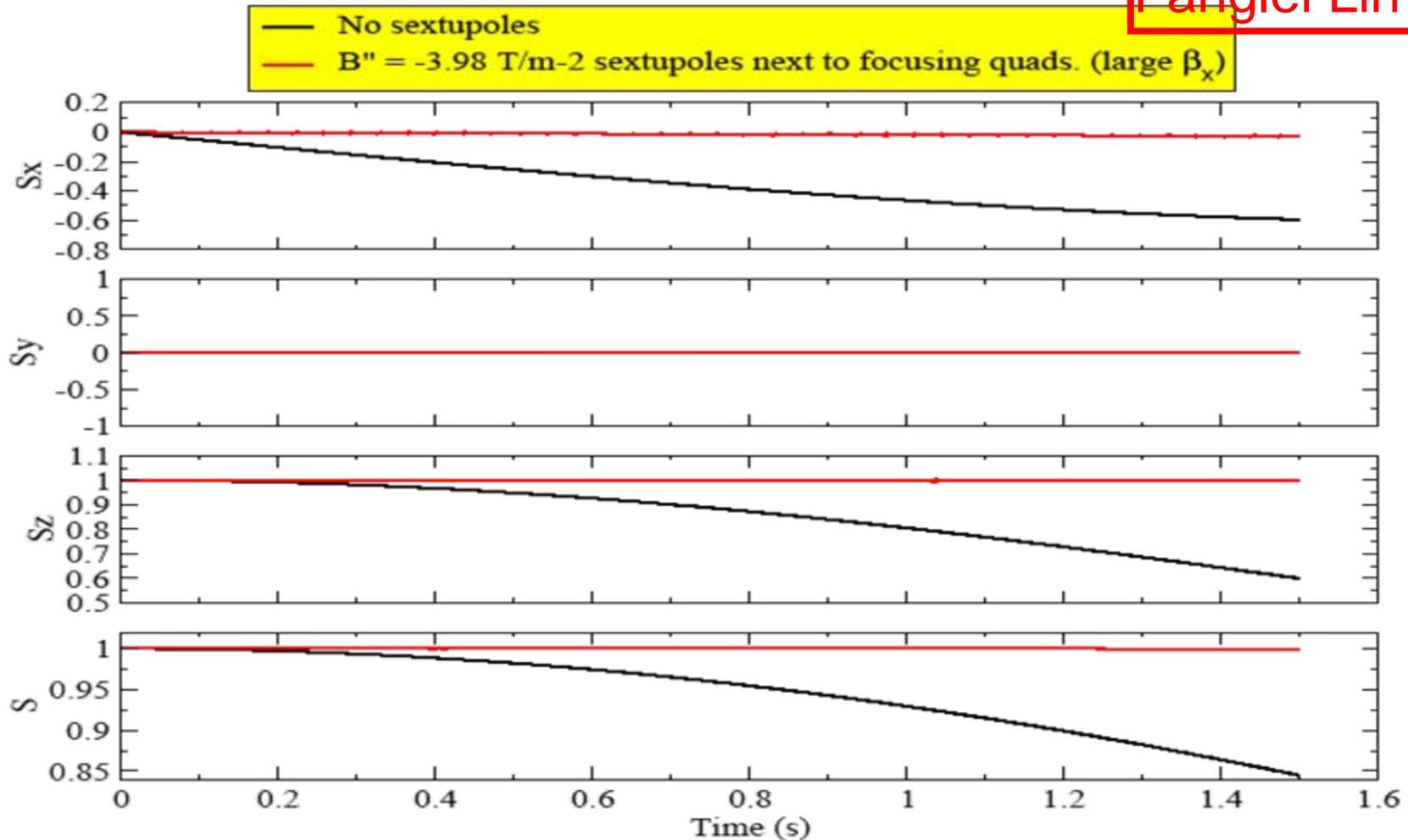
Simulation Conditions

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- **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 S_x, S_y, S_z, S**
 - ❖ **$\langle S_x \rangle$: radial component of polarization**
 - ❖ **$\langle S_y \rangle$: vertical component of polarization**
 - ❖ **$\langle S_z \rangle$: longitudinal component of polarization**
 - ❖ **S : $S = \sqrt{\langle S_x \rangle^2 + \langle S_y \rangle^2 + \langle S_z \rangle^2}$**
- **1 million turns ~ 1.5 second**

Searching for optimum sextupoles (I)

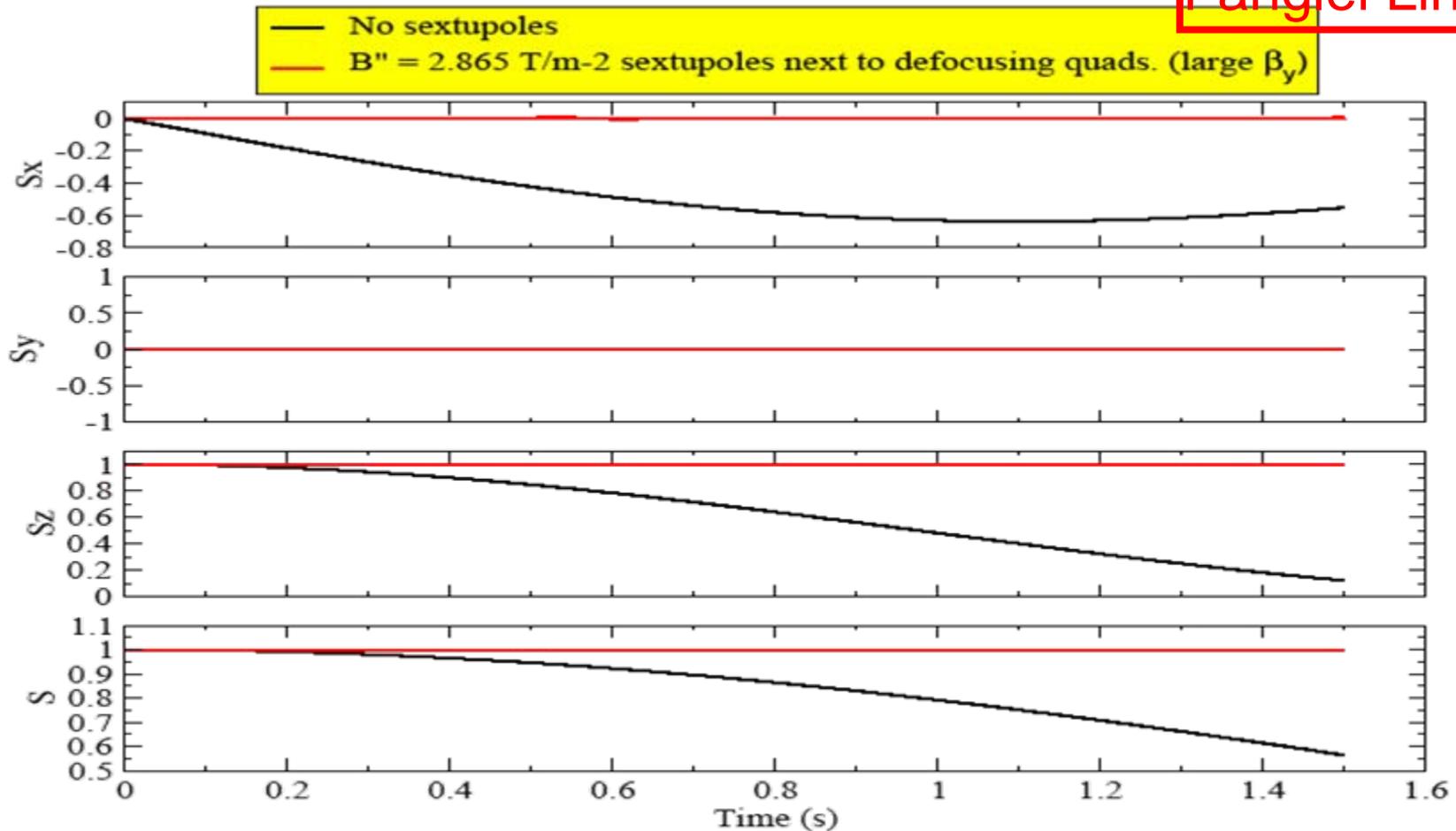
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The horizontal beta function is maximum at focusing quads. Those sextupoles next to focusing quads. are mainly used to correct the spin frequency perturbation due to the horizontal betatron motion.

Searching for optimum sextupoles (II)

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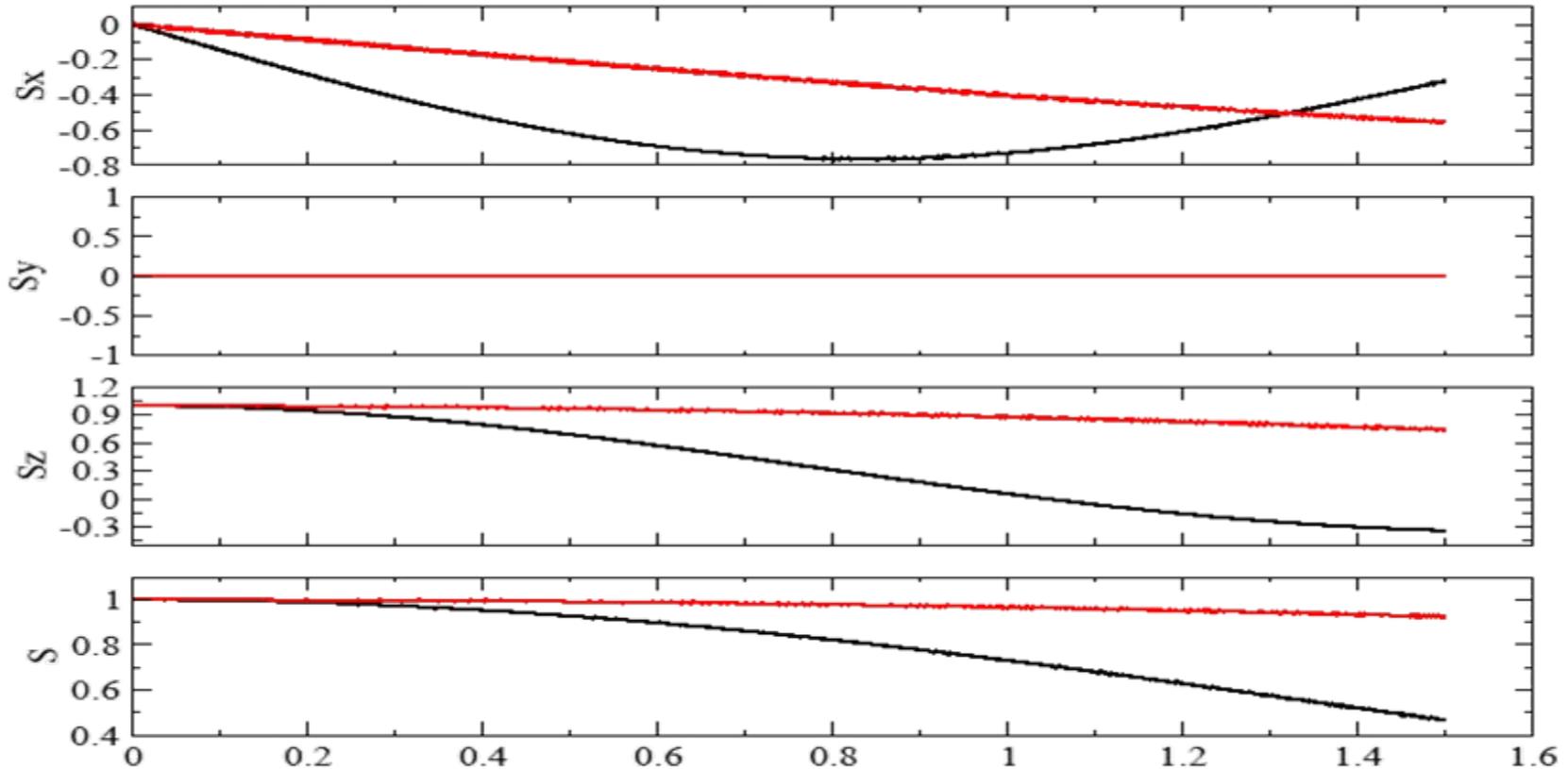


The vertical beta function is maximum at defocusing quads. Those sextupoles next to defocusing quads. are mainly used to correct the spin frequency perturbation due to the vertical betatron motion.

Searching for optimum sextupoles (III)

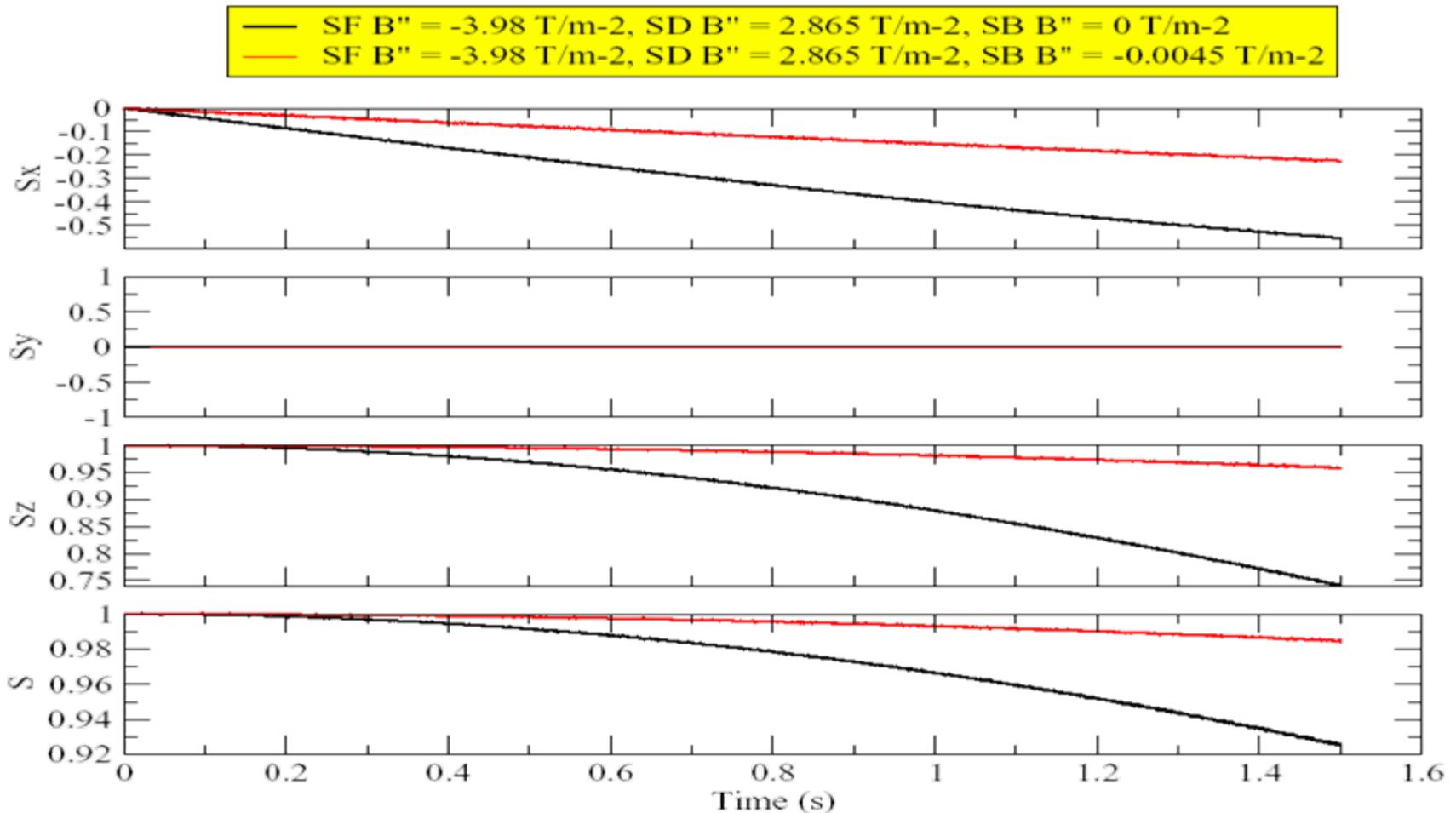
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— No sextupoles
— SF $B'' = -3.98 \text{ T/m}^2$, SD $B'' = 2.865 \text{ T/m}^2$



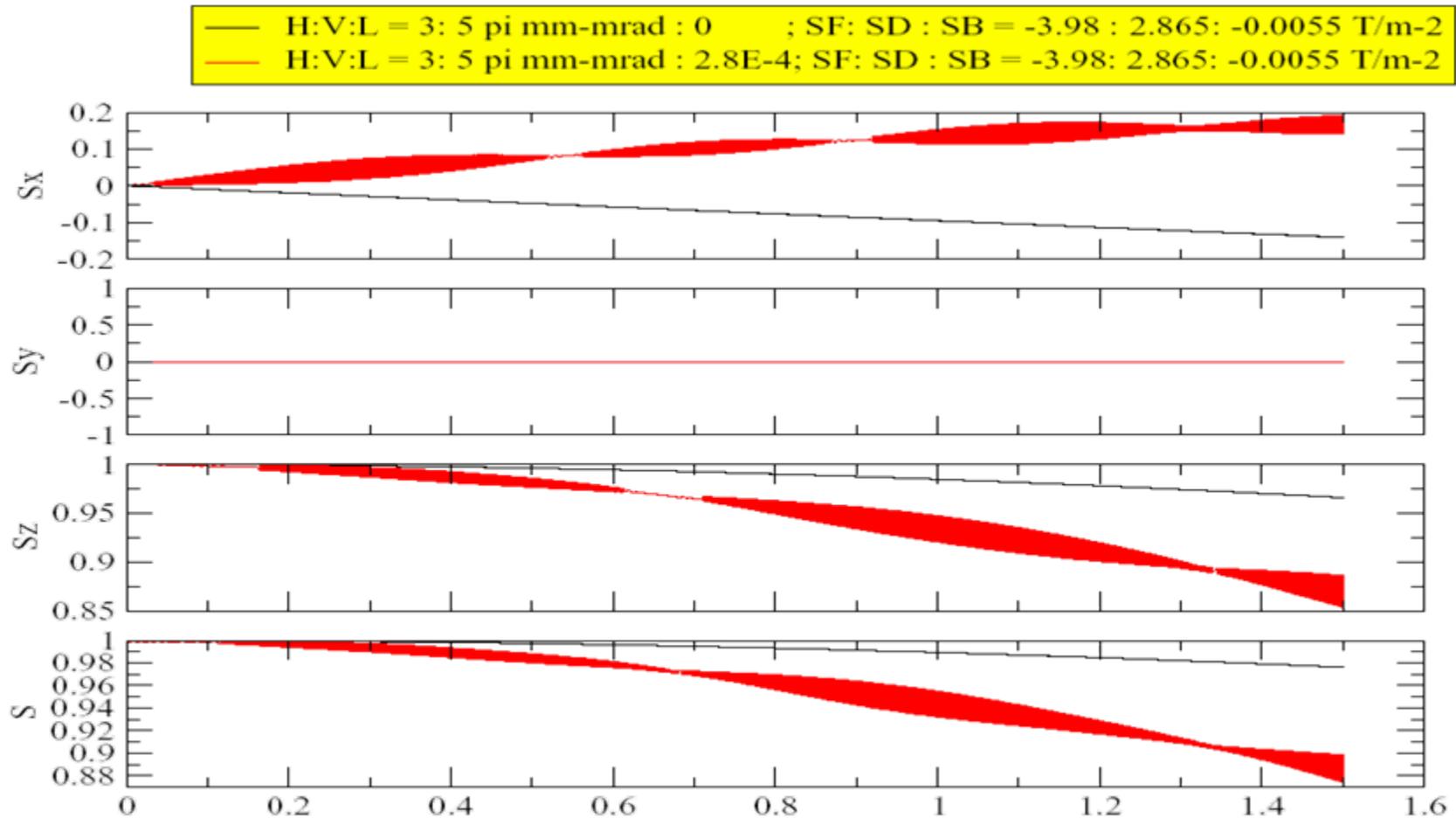
Two sets of sextupoles are next to focusing and defocusing quads.
Both horizontal and vertical motion are included.

Searching for optimum sextupoles (IV)



Besides two sets of sextupoles next to focusing and defocusing quads, a third set of sextupole component is introduced in the BE section . Both horizontal and vertical motion are included.

Searching for optimum sextupoles (V)



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Three sets of sextupoles are located next to focusing, defocusing quads and in the BE section . Particles with horizontal, vertical motion and momentum spread are included.

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 (Space restrictions; e ⁻ trapping)	B: YES 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 0.7 GeV/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	3×10^{-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 three years and ~\$2M for R&D
2. Preparation for deuteron EDM could be ready in four to five years and ~\$4-5M for R&D

Physics strength comparison

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

If nEDM is discovered at 10^{-28} e·cm level?

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

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

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

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

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:**

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

The Deuteron EDM at $10^{-29} \text{ e} \cdot \text{cm}$ has a reach of **$\sim 300 \text{ TeV}$** 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)