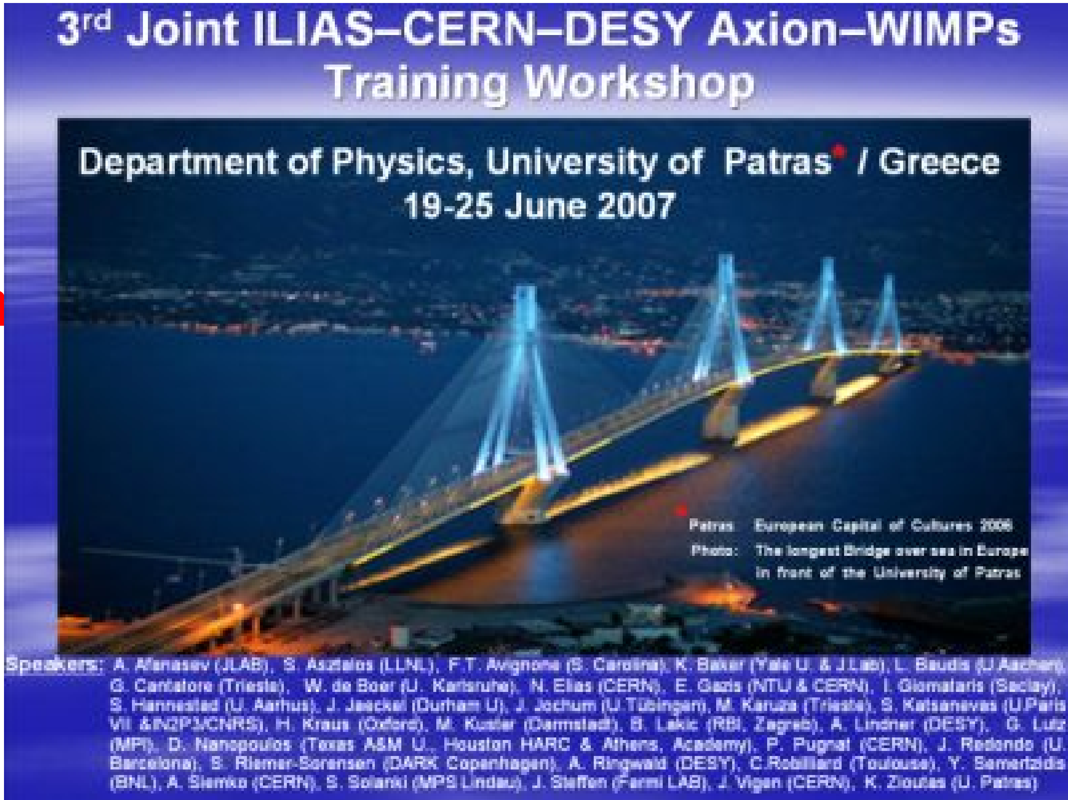
CP-Violation in hadronic systems

Yannis K. Semertzidis
Brookhaven National Lab

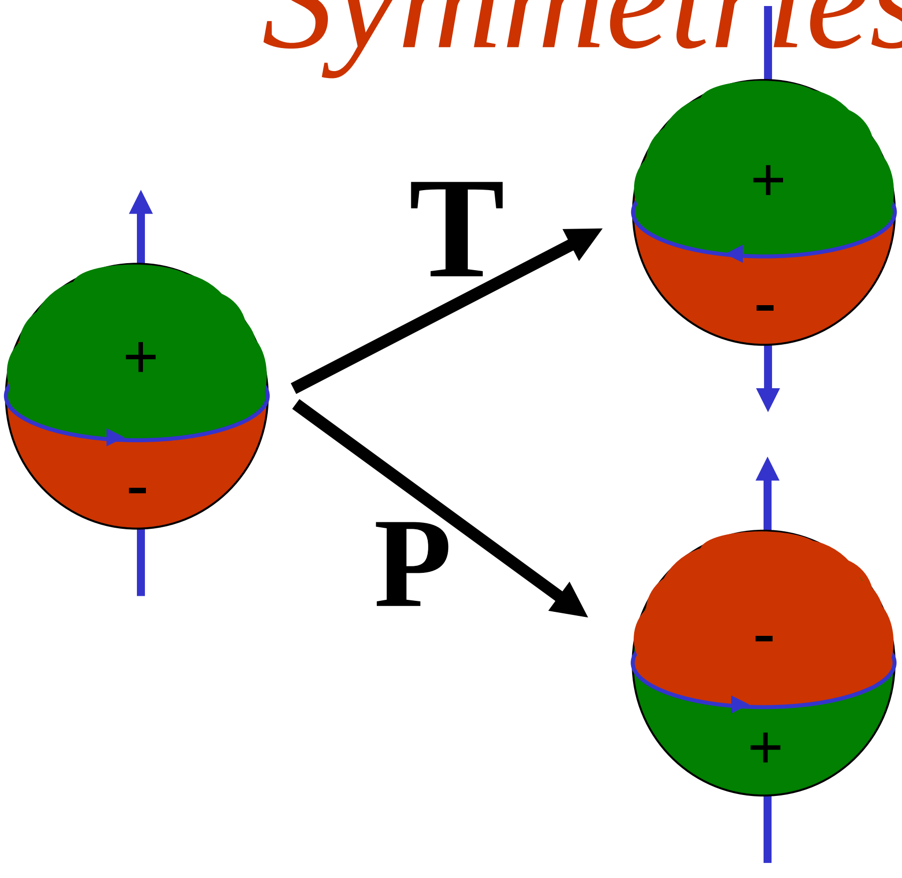
- Update on the deuteron EDM project (10^3 TeV, 10^{-5} rad CP-violating phase: beyond the design sensitivity of LHC)

- CP-violation in heavy ion collisions?



Study of hadronic CP-violation at BNL

A Permanent EDM Violates both T & P Symmetries:



A Permanent EDM Violates both T & P Symmetries:

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

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

CPT

T-Violation → 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….

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 …

SM background negligible…

Hadronic EDMs

$$L_{\not{CP}} = \bar{\theta}\,\frac{\alpha_s}{8\pi} G\tilde{G}$$

Order of magnitude estimation of the neutron EDM:

$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta}\cdot\left(6\times 10^{-17}\right)\mathrm{e\cdot cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

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

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

Why so small? Axions? CAST, ADMX,…

Deuteron (bare) nucleus 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

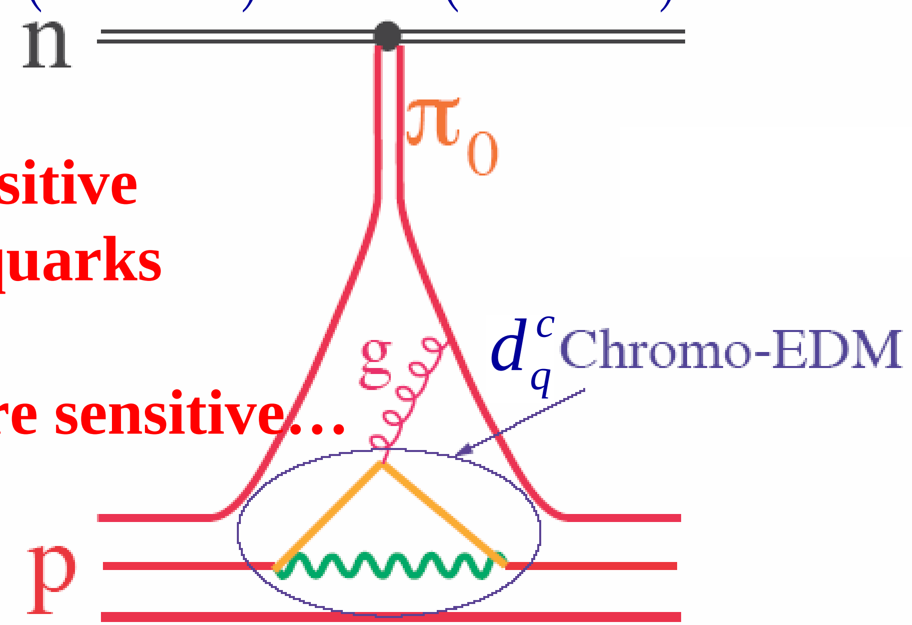
$$L_{\not{CP}} = -\frac{i}{2}\sum_q \bar{q}\left(d_q \sigma_{\mu\nu} F^{\mu\nu} + d_q^c \sigma_{\mu\nu} G^{\mu\nu}\right)\gamma_5 q$$

$$d_D\left(d_q, d_q^c\right) \approx 0.5\left(d_u + d_d\right) - 6e\left(d_u^c - d_d^c\right) - 0.2e\left(d_u^c + d_d^c\right)$$

$$d_n\left(d_q, d_q^c\right) \approx 0.7\left(d_d - 0.25 d_u\right) - 0.3e\left(d_u^c - d_d^c\right) + 0.8e\left(d_u^c + d_d^c\right)$$

i.e. deuterons and neutrons are sensitive to different linear combination of quarks and chromo-EDMs…

The Deuteron is up to 20 times more sensitive…



Deuteron vs. neutron sensitivity
…it depends on the source

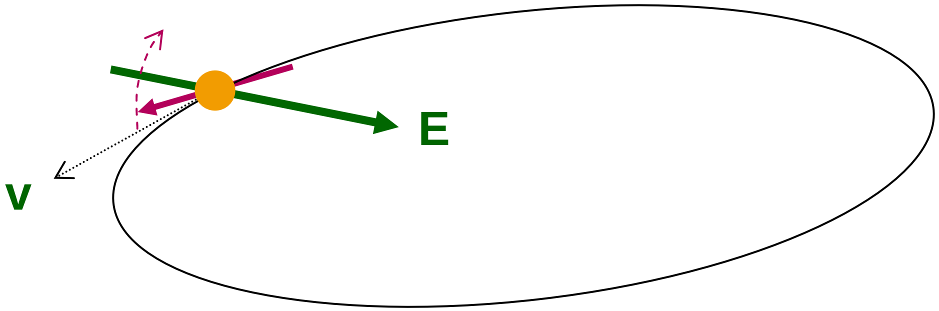
Color EDM: $$d_D\left(d_q^c\right) \approx 20 \times d_n\left(d_q^c\right)$$

$\bar{\theta}_{QCD}$: $$d_D\left(\bar{\theta}\right) \approx \frac{1}{3} \times d_n\left(\bar{\theta}\right)$$

What is the method?

EDM Signal: observe precession of spin in large electric field.

Technique: create large E field from $\gamma \mathbf{v} \times \mathbf{B}$ on polarized beam circulating in a ring.



Experiment: watch for spin that starts out along **v** to acquire a vertical component.

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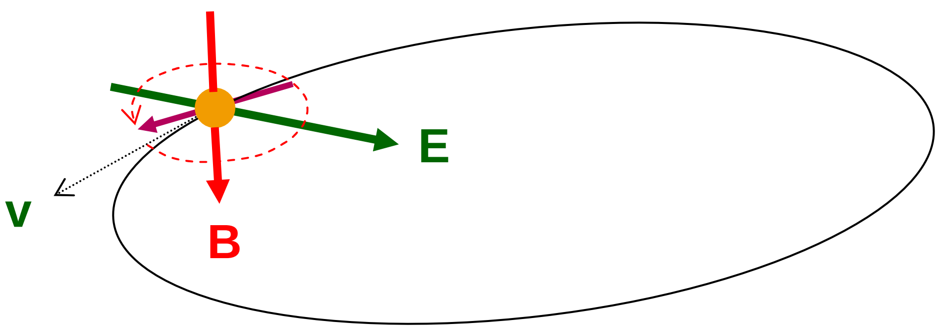


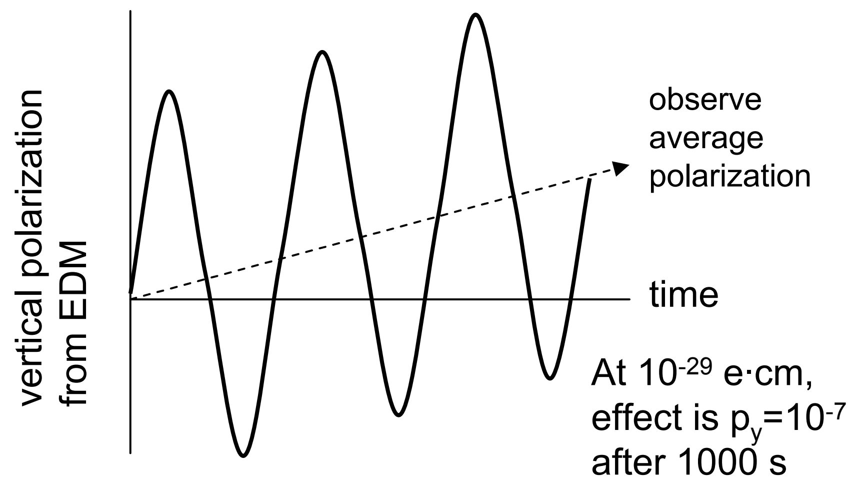
Experiment: watch for spin that starts out along **v** to acquire a vertical component.

But precession in magnetic field is much faster!

Main technical challenge: rapid spin precession due to magnetic moment cancels EDM every rotation.

Solution: create synchrotron-spin resonance to accumulate EDM signal.

with velocity oscillation synchronized to polarization:



Comparison With Other EDM Efforts

	Current Bound	Future Goal	$\sim d_n$ Equivalent
Neutron	$d_n < 3\times10^{-26}$ e-cm	$\sim 10^{-28}$ e-cm	10^{-28} e-cm
^{199}Hg atom	$d_{Hg} < 2\times10^{-28}$ e-cm	$\sim 2\times10^{-29}$ e-cm	$10^{-25}-10^{-26}$ e-cm
^{129}Xe atom	$d_{Xe} < 6\times10^{-27}$ e-cm	$\sim 10^{-30}-10^{-33}$ e-cm	$10^{-26}\sim10^{-29}$ e-cm
Deuteron	–	10^{-29} e-cm	$3\times10^{-29}-5\times10^{-31}$ e-cm

Deuteron Competitive - Better!

Marciano
9/2006

PAC recommendations, Sept. 2006

This letter proposes a search for a deuteron electric dipole moment using a stored beam. The goal is a statistical precision of about 10^{-29} e·cm; an appropriate level for an experiment we expect would take a number of years to develop. In this experiment, a longitudinally polarized beam develops a vertical spin component due to the torque of the motional electric field in the ring bending magnets acting on the electric dipole moment. The PAC is enthusiastic about this ingenious new approach to electric dipole moment searches. Because it is a new technique, however, there will be a daunting new set of false edm effects and associated systematic errors to consider. We believe it is very important to identify the most important of these difficulties and address them with a combination of simulation and measurement. We strongly encourage the collaboration to investigate the options for measurements in existing rings with polarized deuteron beams. Development of a program of simulations and tests should include, but not be limited to, complete characterization (intensity, size, energy, polarization) of the tails of the beam and their effects on the measurement, investigations of resonant extraction, considerations of correlations between energy and position in the 'extraction' region, and characterization of the effects of common lattice imperfections. Indeed, short of implementing the resonant enhancement of vertical polarization described in the proposal, measurements of zero left-right asymmetries at the requisite level must be demonstrated. A clear plan for near-term milestones including consideration of these issues (over perhaps a two-year period) should accompany any request to the laboratory for continued support.

Clearly there is enthusiasm for your continuing development of this experiment and I look forward to a plan as suggested in the last sentence of the recommendation.

PAC recommendations, March 2007

1.2 LoI: Search for a Deuteron Electric Dipole Moment Using a Charged Particle Storage Ring

The PAC remains enthusiastic about the novel storage ring approach to measuring the deuteron electric dipole moment (EDM), in which the velocity is modulated at the in-plane g-2 precession frequency to permit buildup of vertical polarization proportional to the EDM. The sensitivity goal of 10^{-29} e-cm is superior to that of all other hadronic EDM techniques currently under discussion, giving it the greatest potential reach for non-standard-model physics. Brookhaven is a natural host for such an experiment, given its expertise in polarized storage rings.

We are favorably impressed by the aggressive approach the collaboration has taken since Sept. 2006, planning polarimetry tests for KVI and COSY, and beginning investigation of spin dynamics systematic errors using analytic calculations and simulations. It is important that the run at COSY also provide calibration for the spin tracking simulations. New ideas are under discussion for correcting parasitic spin resonances which mimic the EDM signal.

This is a very challenging experiment. It will require a staged approach to reducing the systematic errors, as false EDM sources are identified and overcome. We realize that some basic concepts of the design are still being worked out, but it is essential that the collaboration now take a more structured approach to the project so BNL management can evaluate it in a timely fashion. The collaboration should immediately define the essential quantitative milestones that need to be met in order to prove the principle of the technique at a modest sensitivity, say 10^{-26} e-cm, and establish a work plan to accomplish this and future goals. This will require sustained, dedicated effort by several people. BNL support for the project should be tied to this work plan.

A Technical Review should take place in about a year to assess progress. The collaboration should aim within two years from now to establish whether the technique is viable and what the approximate cost of the experiment is, at a level that could pass a

Support for the Storage ring EDM

- Initial BNL support:

1. $$ for 1 post doc starting March, 2007 (goal to have the post doc by end of summer)
2. Limited $$ for travel

- Another request to BNL has been submitted for ~$700K (including 1 more post doc, support from CAD experts and visitors). Start date January, 2008.

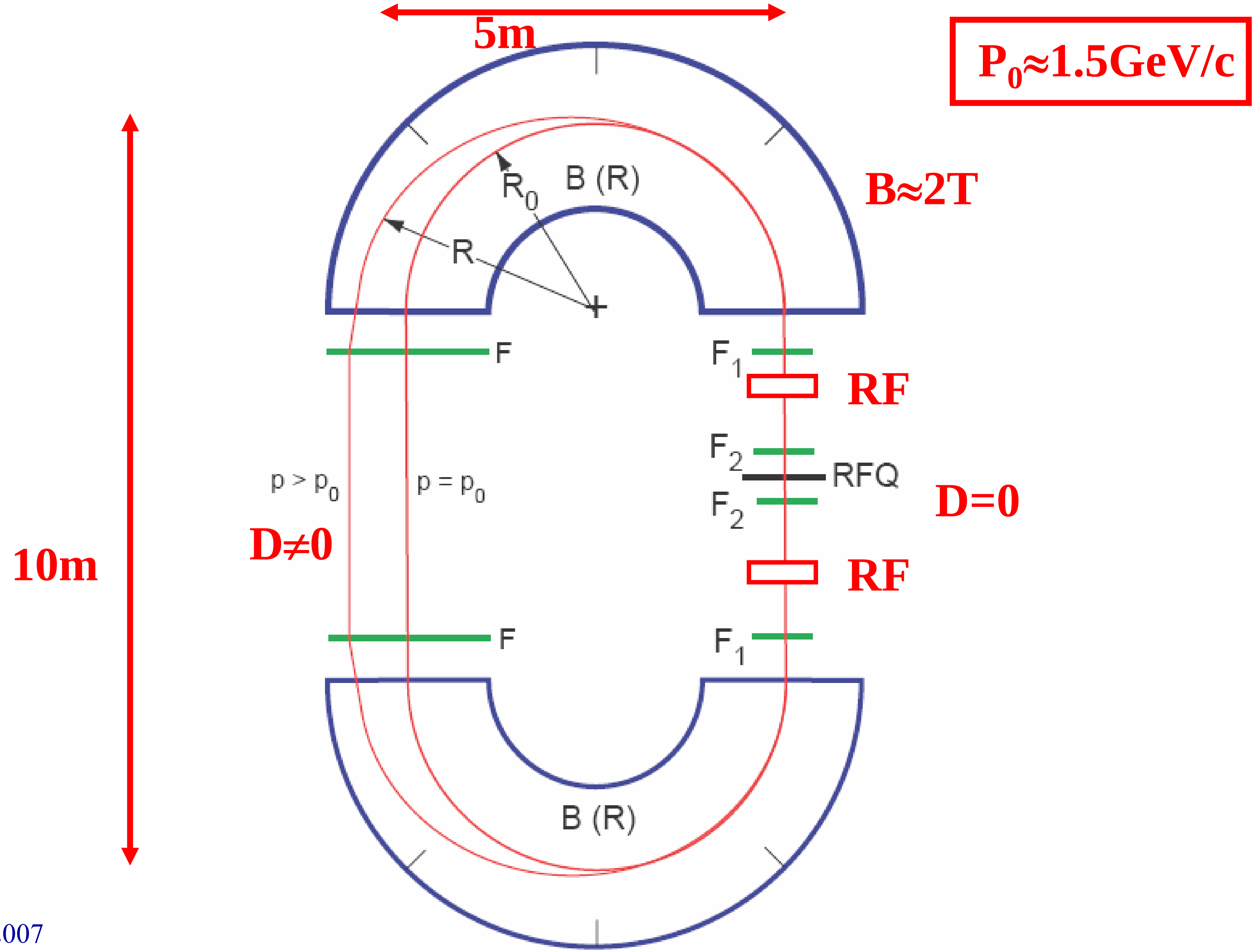
- 600 K€ already available from The Netherlands

At this point the dEDM in storage rings is recognized as an important method

Its high sensitivity goal and complementarity to nEDM make it a very strong case.

Systematic errors

Current lattice



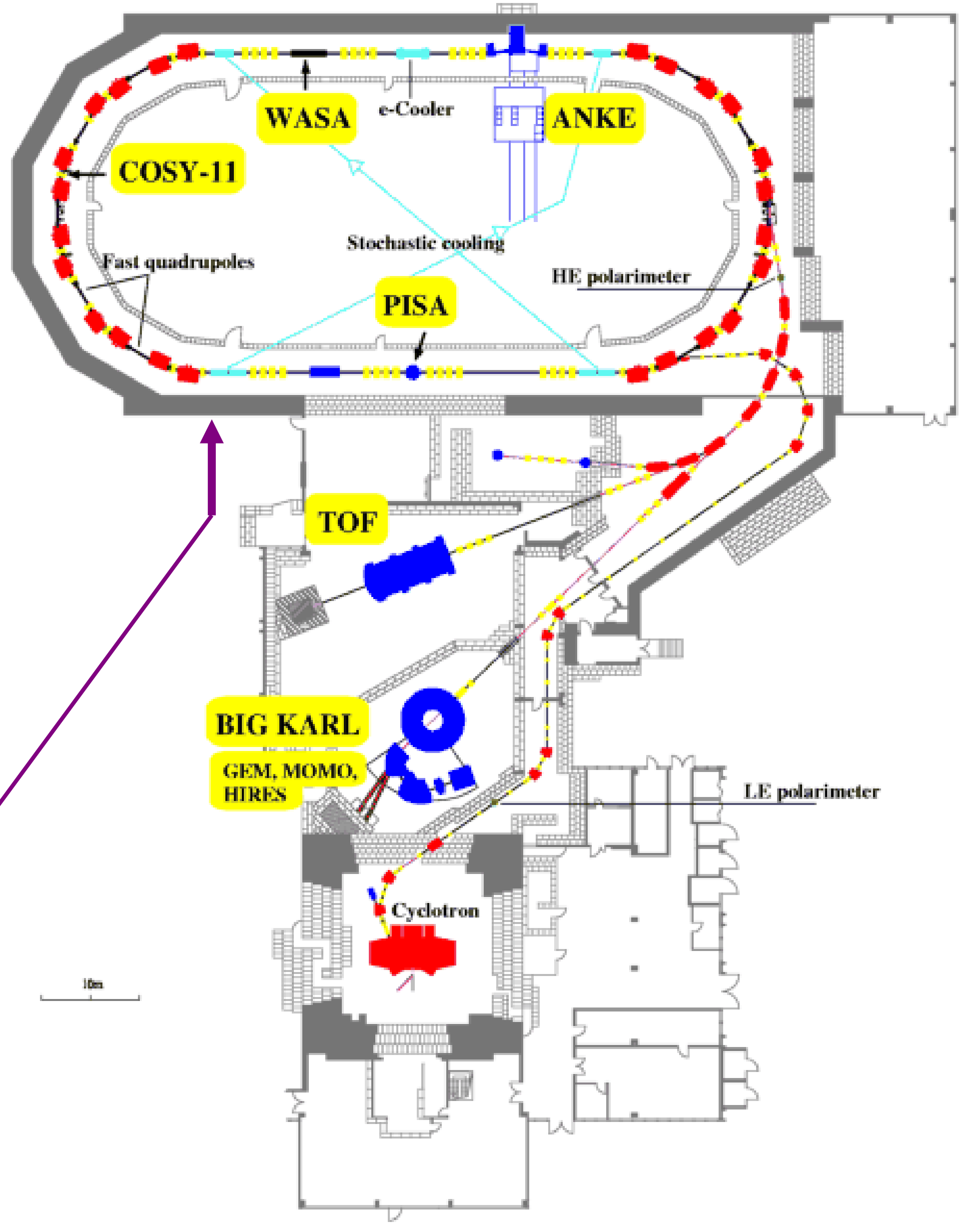
The potential errors

- Radial-vertical coupled oscillations
- Horizontal B-fields
- Electric fields
- Collective effects
- Instrumental alignment tolerances
- Polarimeter systematic errors

Polarimeter work at KVI (The Netherlands) and COSY (Germany)

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

Most likely location behind present EDDA detector.



Targeted work for Europe

- Polarimeter work
- Super stability monitoring
- DAQ for polarimeter (immediate) and experiment (longer term)

Where to build the dEDM experiment

BNL parameters/conditions

$\sim 5 \times 10^{10}$ deuterons / pulse with electron cooling.

Support from the accelerator physicists to study the spin related systematic errors (analytically and with spin tracking)

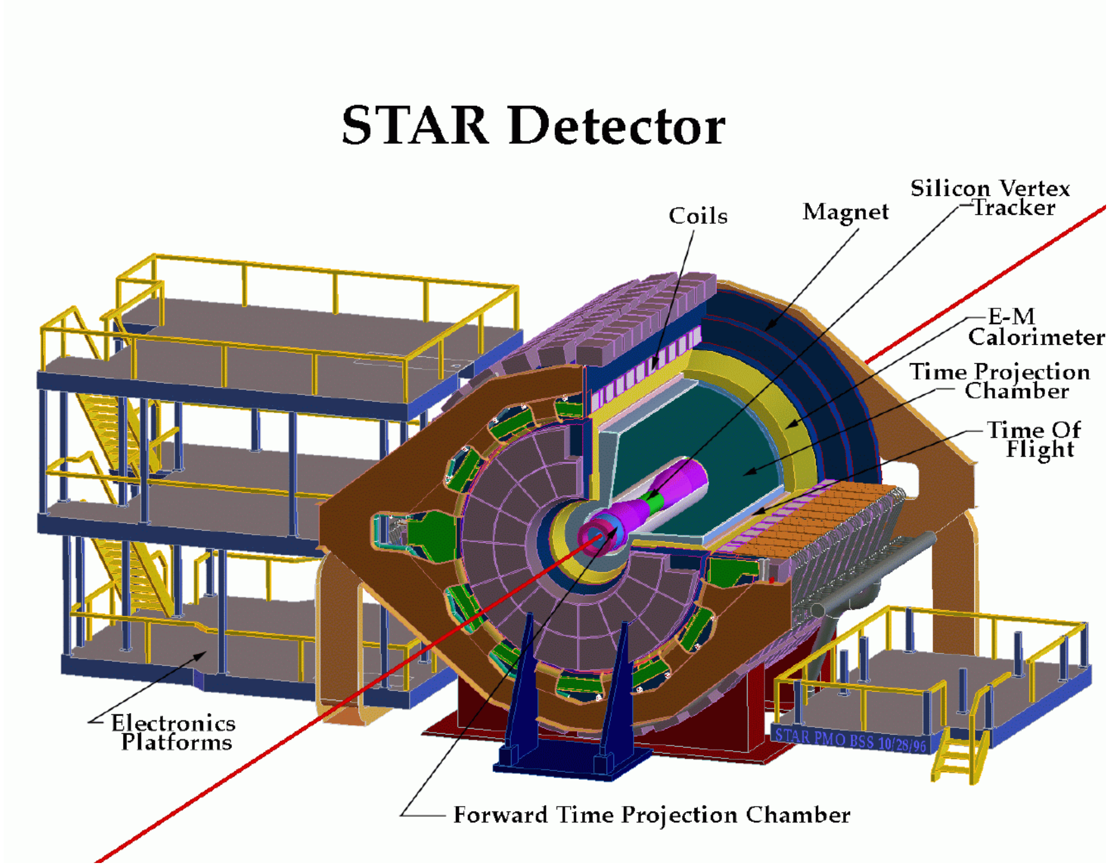
Part of the Nuclear Physics Long Range Plan

CERN parameters/conditions

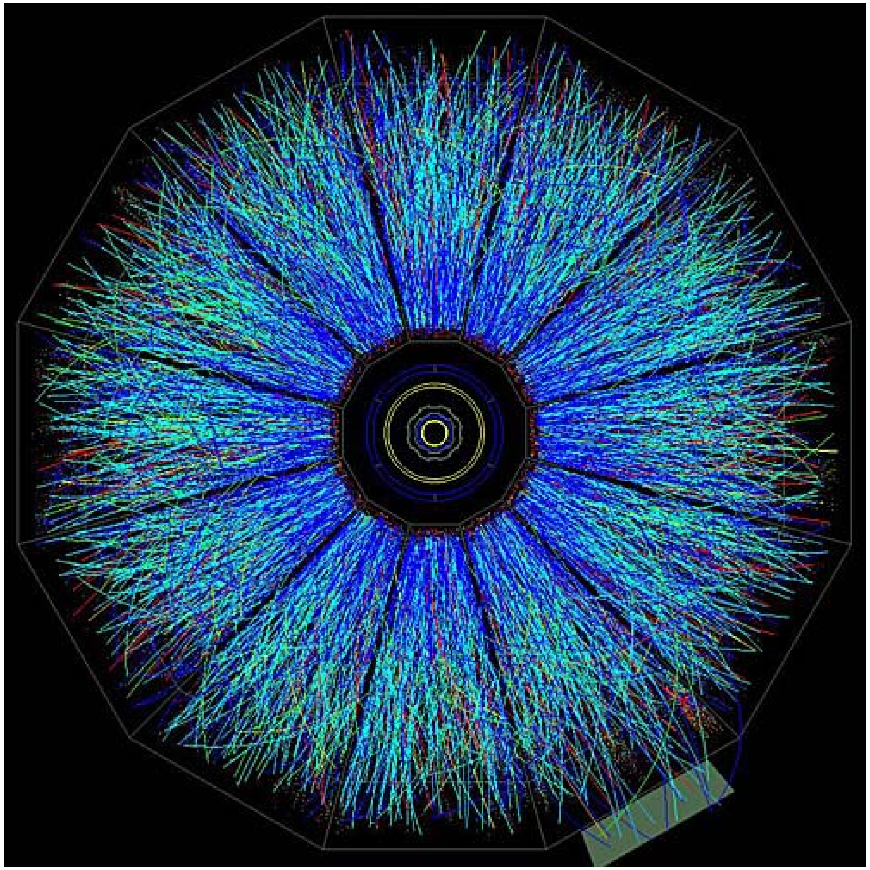
The beam would be less in numbers ($5x10^{10}$ deuterons / pulse) with electron cooling. The emittances would be 0.7 pi mm mrad, and dp/p ~ 5×10^{-6} (0.1 eV·s/nucl) (Michel Chanel of LEIR).

CERN would provide the deuterons, building, and power. Need to raise the capital funds for building the ring. (DOE/NSF involvement is still necessary)

Studying CP-violation at high temperatures using Heavy Ion Collisions

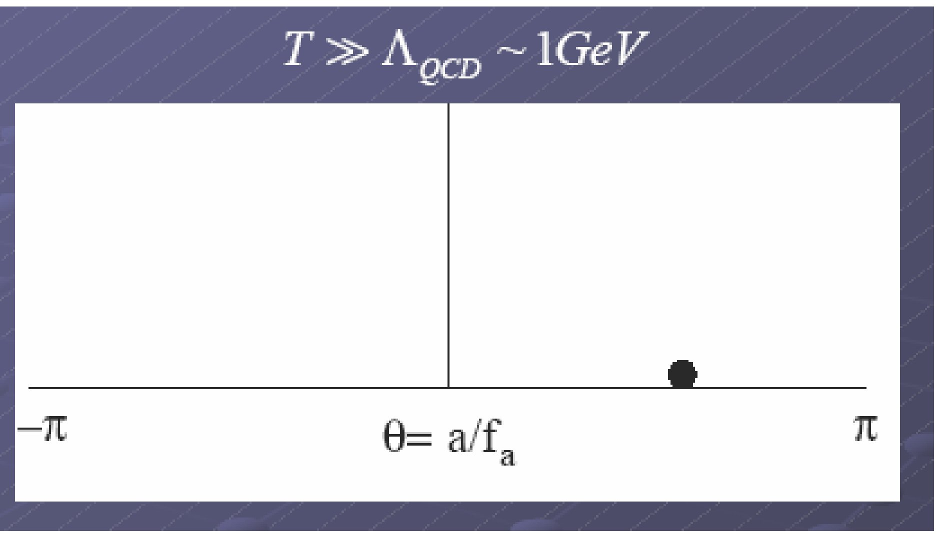


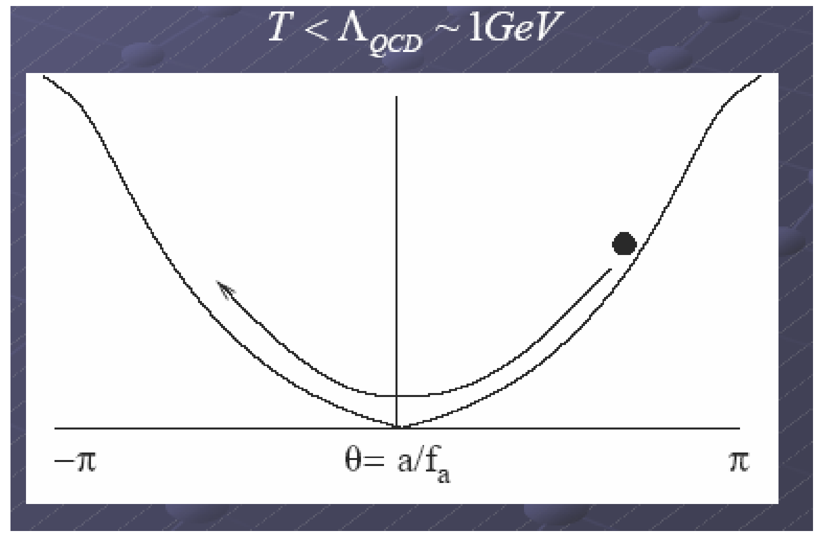
Heavy ion collisions produce many particles



- **Provide statistics**
- **Study matter in “hot” conditions**

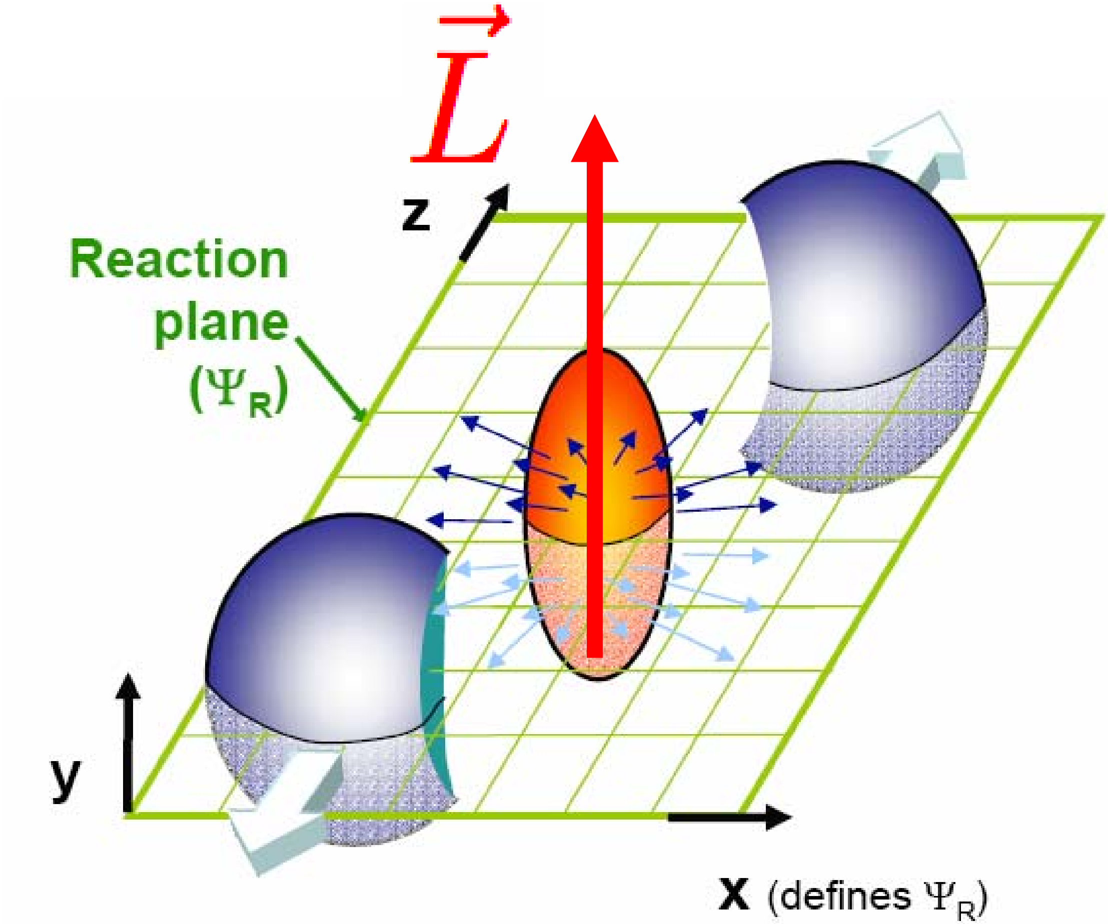
Theta values at high and low temperatures





K. Zurek

Azimuthal anisotropy = angular momentum



hep-ph:0706.1026v1

BNL-NT-07/24

Charge separation induced by $\mathcal{P}$–odd bubbles in QCD matter

Dmitri Kharzeev[1,*] and Ariel Zhitnitsky[2,†] **of DFSZ axions**

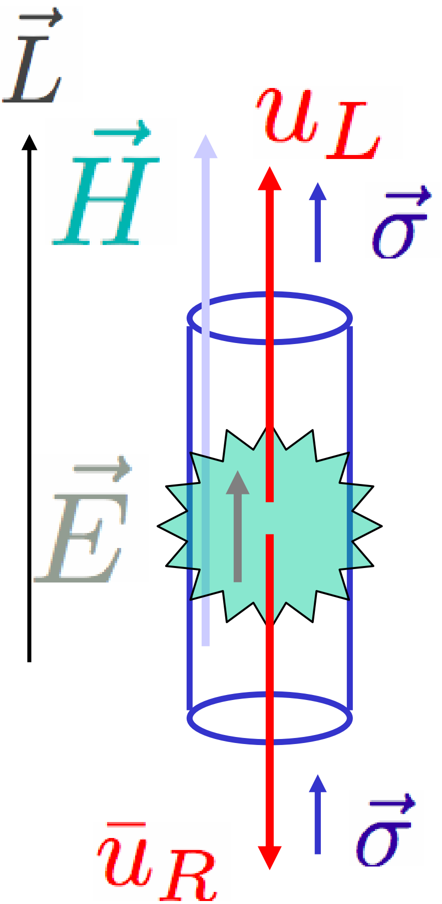
[1] *Physics Department, Brookhaven National Laboratory, Upton, NY 11973-5000, USA*
[2] *Department of Physics and Astronomy, University of British Columbia, Vancouver, BC, Canada, V6T 1Z1*

(Dated: June 7, 2007)

We examine the recent suggestion that $\mathcal{P}-$ and $C\mathcal{P}-$odd effects in QCD matter can induce electric charge asymmetry with respect to reaction plane in relativistic heavy ion collisions. General arguments are given which confirm that the angular momentum of QCD matter in the presence of non–zero topological charge should induce an electric field aligned along the axis of the angular momentum. A simple formula relating the magnitude of charge asymmetry to the angular momentum and topological charge is derived. The expected asymmetry is amenable to experimental observation at RHIC and LHC; we discuss the recent preliminary STAR result in light of our findings.

PACS numbers:

Magnetic vortices and CP violation



Analogs:

Dyons

Magnetic monopole - induced baryon decay

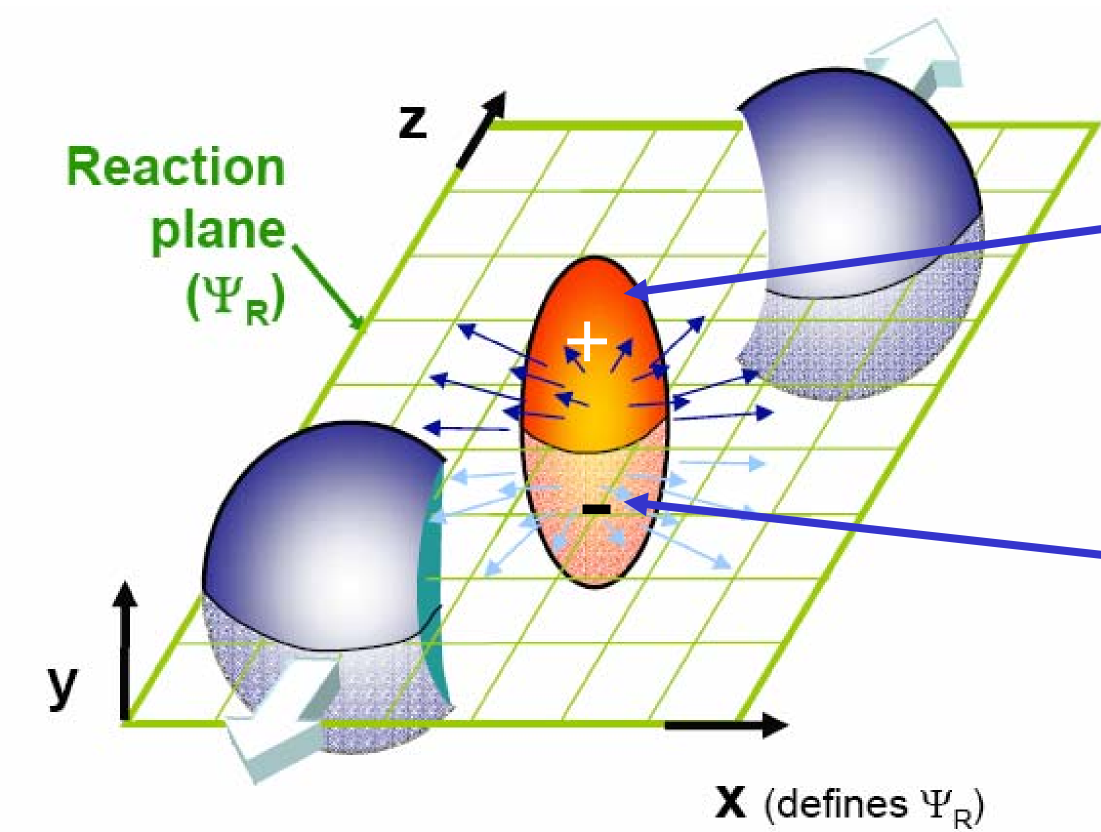
Cosmic strings

Chirality generation in superfluid ^{3}He

D. Kharzeev

....

Charge asymmetry w.r.t. reaction plane as a signature of strong CP violation



excess of positive charge

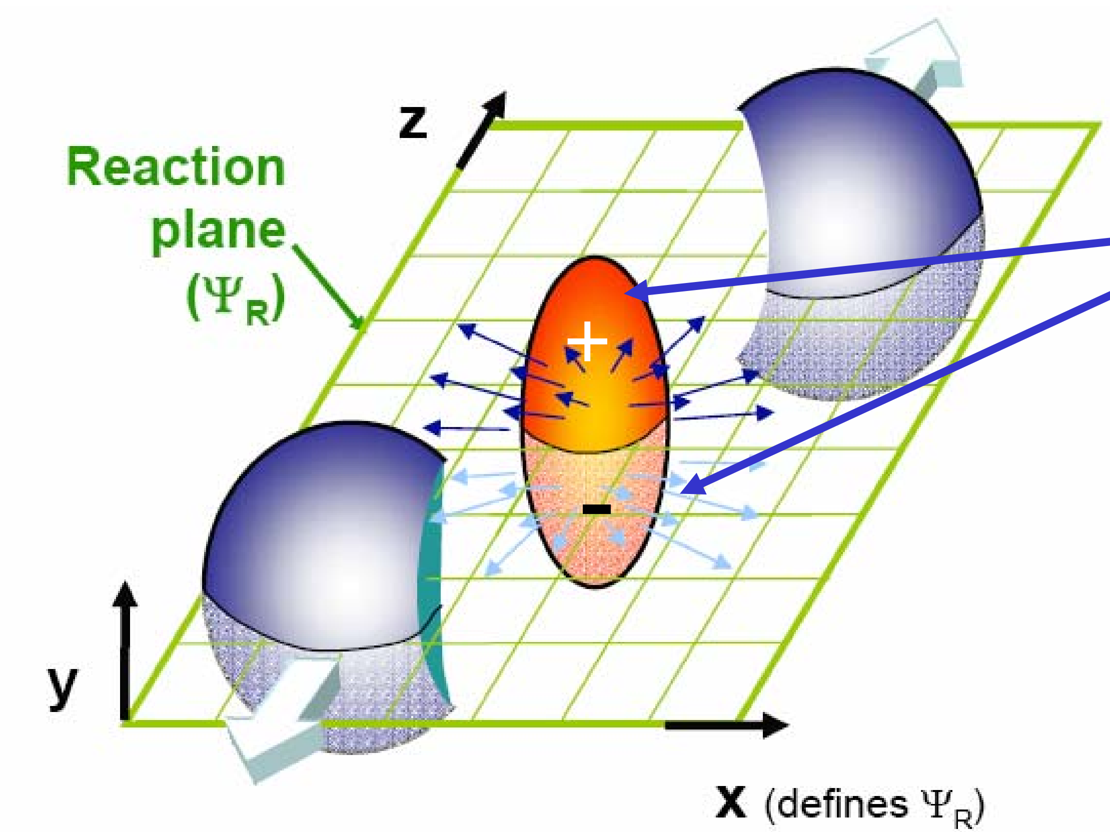
excess of negative charge

D. Kharzeev

Electric dipole moment of QCD matter!

DK, hep-ph/0406125

Charge asymmetry w.r.t. reaction plane as a signature of strong CP violation

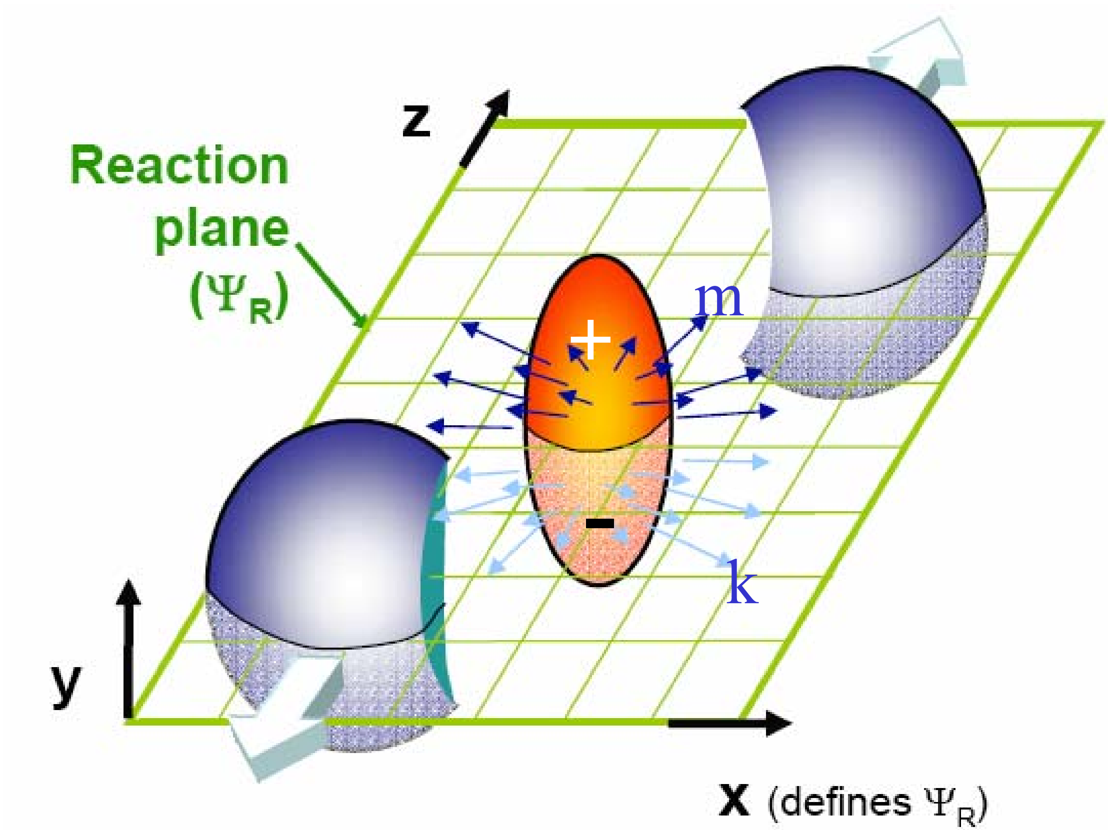


The charge asymmetry is proportional to the angular momentum of the system

Electric dipole moment of QCD matter!

DK, hep-ph/0406125

Charge asymmetry w.r.t. reaction plane: how to detect it?



We need
a sensitive measure
of the asymmetry

Improved method:
"mixed harmonics"
S.Voloshin, hep-ph/0406311

$$a^k a^m = \langle \sum_{ij} \sin(\varphi_i^k - \Psi_R) \ \sin(\varphi_j^m - \Psi_R) \rangle$$

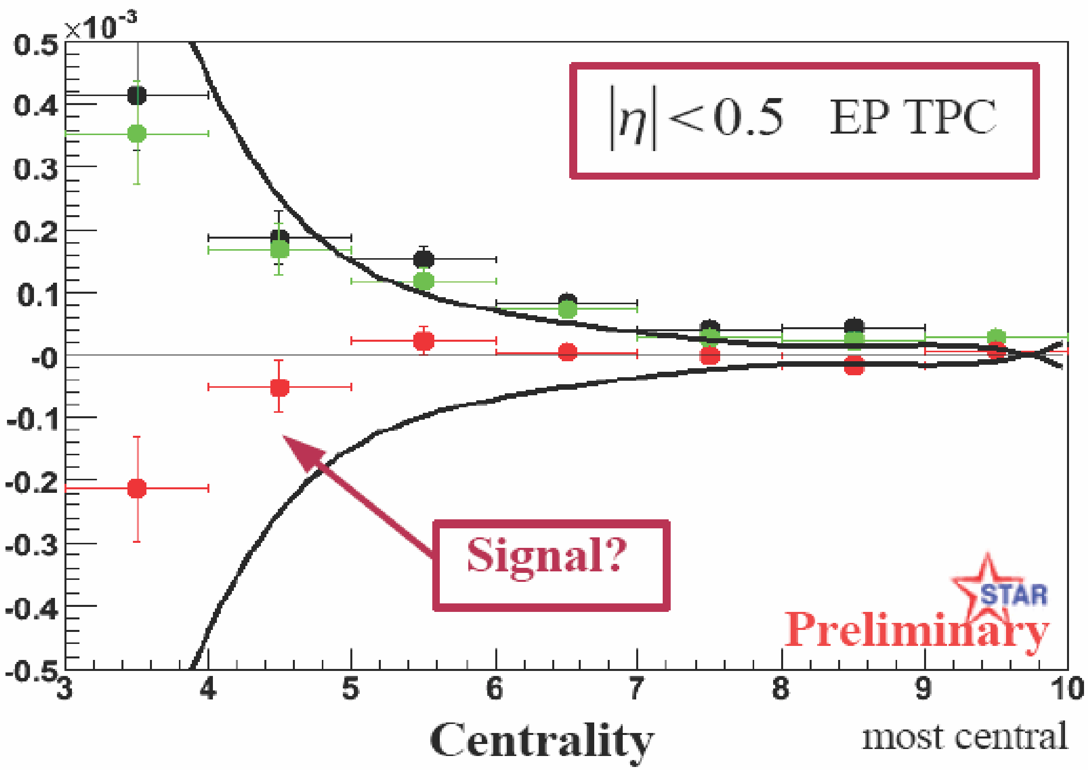
D. Kharzeev

Expect $a^+ a^+ = a^- a^- > 0; \quad a^+ a^- < 0$

Strong CP-Violation at High T?

AuAu@62GeV: TPC event plane $|\eta| < 0.5$

Lines are theory predictions
with topological charge Q=1



TPC event plane all charges

$[a_- a_-]_{[ch]}$	**black**
$[a_+ a_+]_{[ch]}$	**green**
$[a_+ a_-]_{[ch]}$	**red**

Very promising result

Main question

Do we see signal?
Is it robust with respect to different systematic checks?

I. Selyuzhenkov QM2005 (nucl-ex/0510069)

Systematic error studies

- Dependence of the plane and asymmetries on the charge of the particles?
- Dependence of the plane and asymmetries on the detectors used?

- Systematic error studies are not finished yet…

Conclusions

- EDM searches are sensitive methods for NEW, much stronger CP-violating sources
- Support from BNL started materializing

- <u>We are making progress in the studies of the EDM issues:</u>

1. <u>Spin related systematic errors</u>
2. <u>Polarimeter related issues</u>

- HI EDM effect under intense systematic error studies

Extra Slides

How about Induced EDMs?

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

$$H = -d\vec{E} \cdot \vec{E}$$ **T** → **OK**

$$H = -d\vec{E} \cdot \vec{E}$$ **P** → **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!

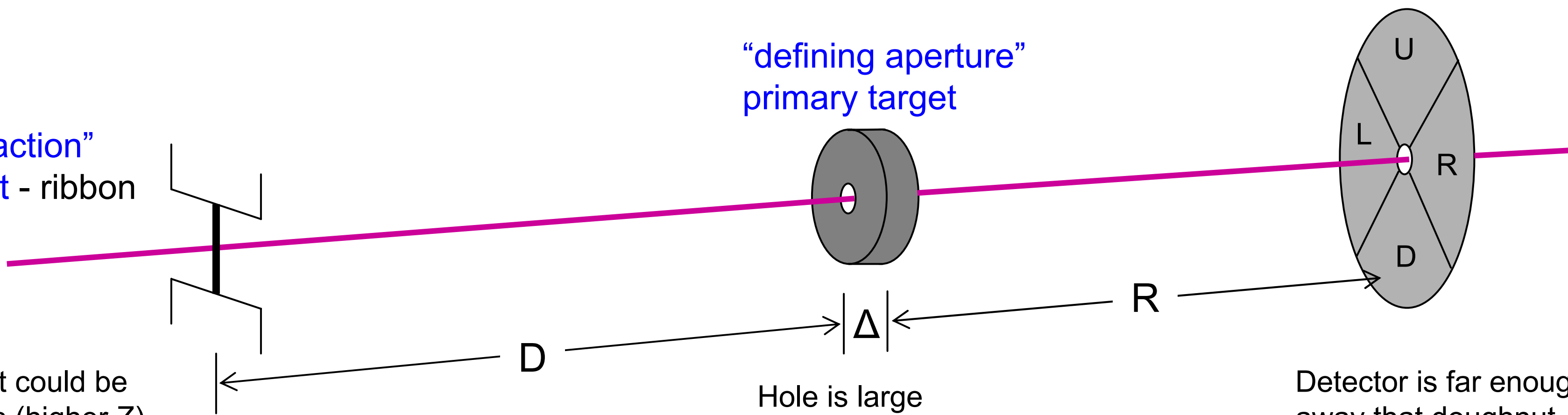
MDMs are Allowed…

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\mathbf{T}} H = -\mu\left(-\vec{\sigma}\right)\cdot\left(-\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\mathbf{P}} H = -\mu\left(\vec{\sigma}\right)\cdot\left(\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

Nuclear Scattering as Deuteron EDM polarimeter
“Dual target” technique

- make thick target defining aperture
- scatter into it with thin target



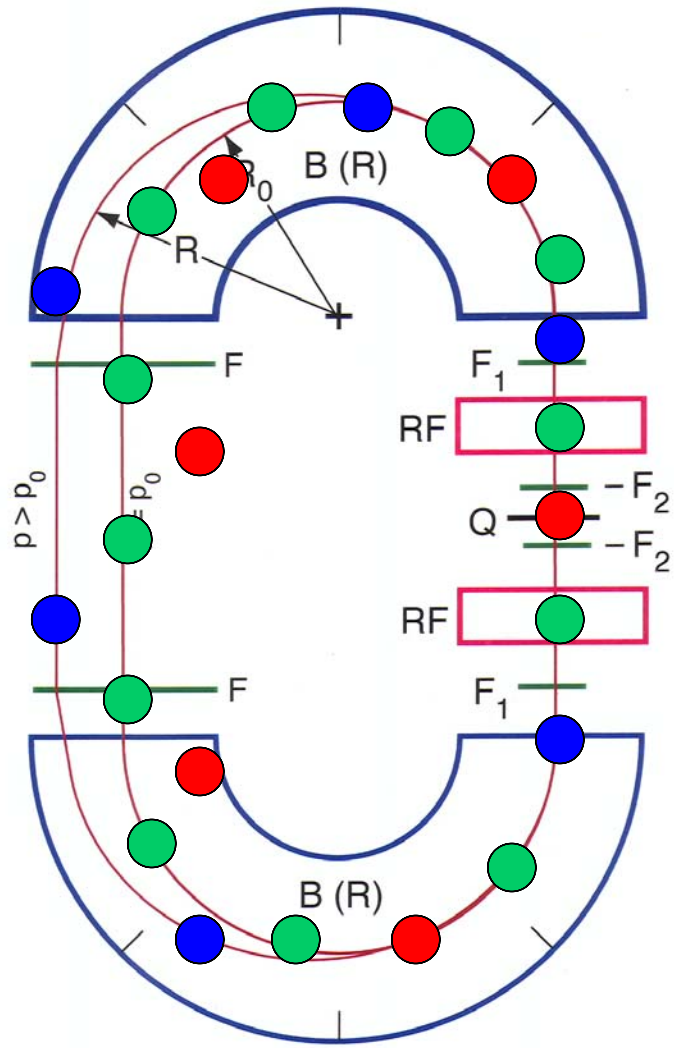
Target could be Ar gas (higher Z).

Target “extracts” by Coulomb scattering deuterons onto thick main target.

Hole is large compared to beam. Every-thing that goes through hole stays in the ring.

Detector is far enough away that doughnut illumination is not an acceptance issue: Δ < R.

Simultaneously Controlled Experiments



- **EDM: Spin Up**
- **EDM: Spin Down**
- **No EDM effect**

Why start with the deuteron?

Technically:

Polarized ion sources make intense beams, polarization >90%.
Forward angle deuteron scattering very sensitive to polarization.

Storage Ring EDM Collaboration

Presented to the BNL PAC, September 2006.

Additional for COSY:

- NFM Brantjes, KVI
- R Gebel, COSY
- K Jungman, KVI
- A Lehrach, COSY
- B Lorentz, COSY
- R Messi, U. Rome
- D Prasuhn, COSY
- M da Silva, KVI
- L Willmann, KVI
- HW Wilshut, KVI

Letter of Intent:
Development of a Resonance Method to Search for a Deuteron Electric Dipole Moment using a Charged Particle Storage Ring

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WHY do the storage ring EDM at BNL?

- Great physics opportunity; it will not be done at LHC
- The Infrastructure is here (polarized source, spin manipulating devices, …).
- Home of the successful (and sophisticated) muon g-2 experiment.
- The human factor: Hadron and spin expertise, the best in the world.
- Compatible with the lab mission: The nuclear physics lab of US, QCD Lab