Physics Symposium
BNL, 2 October 2007

Deuteron EDM and Muon g-2 (Dipole Moments in Storage Rings)

Yannis K. Semertzidis, BNL

- Muon g-2:
  - Strict test of SM
  - High Sensitivity to physics beyond the SM

- Deuteron EDM
  - High sensitivity to CP-violating physics beyond the SM

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

Muon g-2

- Inclusive test; integrate all known physics: QED, Weak, Strong plus New Physics, e.g. SUSY

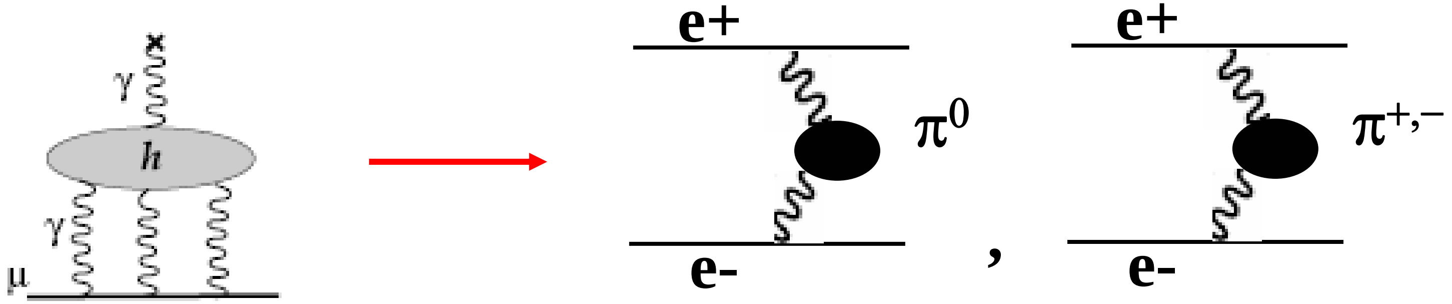
$$\Delta a_\mu^{\text{MSSM}} \simeq sign(\mu) 130\times 10^{-11} \tan\beta \left(\frac{100 \text{ GeV}}{M_{SUSY}}\right)^2$$

$$\Delta a_\mu^{\text{exp-th}} = a_\mu^{\text{exp}} - a_\mu^{\text{th}} = (295 \pm 88)\times 10^{-11}$$

- Current difference 3.4 σ; exp. error 0.5ppm, theory similar
- New g-2 effort improvement in error by a factor > 2
- Improvement in muon collection, beamline acceptance, open inflector, improved kicker, segmented detector
- Before LHC: Strongest exp. indication of SUSY to date
- After LHC: Best determination of tanβ, …
- May 07: **Nuclear Long Range Plan process**
  - **Aim at "Legacy" experiment Goal: 0.14 ppm overall error**
  - **Project is part of New Standard Model Initiative**
  - **Shift in planning concerning …**
    - **Running costs**
    - **DOE NP support**
    - **Joint funding by NP and HEP agencies**

Next development on Hadronic light by light

- Stan Brodsky: The theory treating the light by light contribution should also predict the cross section of the gamma-star production:



Effect	*Contribution* $\times 10^{11}$
QED	$(116\,584\,718.09 \pm 0.14_{5\text{loops}} \pm 0.08_{\alpha} \pm 0.04_{\text{masses}}) \times 10^{-11}$
Hadronic (lowest order)	$a_\mu^{(\text{HVP};1)} = (6901 \pm 42_{\text{exp}} \pm 19_{\text{rad}} \pm 7_{\text{QCD}})$
Hadronic (higher order)	$a_\mu^{(\text{HVP};\text{h.o.})} = (-97.9 \pm 0.9_{\text{exp}} \pm 0.3_{\text{rad}})$
Hadronic (light-by-light)	$a_\mu^{(\text{HLLS})} = (110 \pm 40)$
Electroweak	$a_\mu^{(\text{EW})} = (154 \pm 2_{\text{M}_\text{H}} \pm 1_{\text{had}})$

Deuteron EDM (violates both P and T Symmetries)

- High sensitivity to non-SM CP-violation
- Great sensitivity to SUSY, etc… T-odd Nuclear Forces
- Complementary and better than nEDM
- If observed it will provide a new, large source of CP-violation that could explain the Baryon/Anti-baryon asymmetry of our universe (BAU)

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

Physics Motivation

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

- Deuteron EDM at 10^{-29}e·cm has a reach of $>10^2$ TeV or, if new physics exist at the LHC scale, 10^{-5} rad CP-violating phase. Both are much beyond the design sensitivity of LHC.
- NP Long Range Plan includes strong support of dEDM development recognizing its physics potential.

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	$10^{-26} \sim 10^{-29}$ e-cm
Deuteron	–	10^{-29} e-cm	$3\times10^{-29} - 5\times10^{-31}$ e-cm

Deuteron Competitive – Better!

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9/2006

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

Storage ring EDM: The deuteron case

- High intensity sources (~10^{12}/fill)
- High vector polarization (>90%)
- High analyzing power (30-50% for P=0.8-1.5 GeV/c)
- Long spin coherence time possible (>100s)
- Large effective E^*-field=V×B, 1T→300MV/m

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

Storage Ring EDM Collaboration

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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Presented to the BNL PAC, September 2006.

PAC recommendation

Collaboration response

Please find below the recommendation of the NPP PAC from September.

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

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.

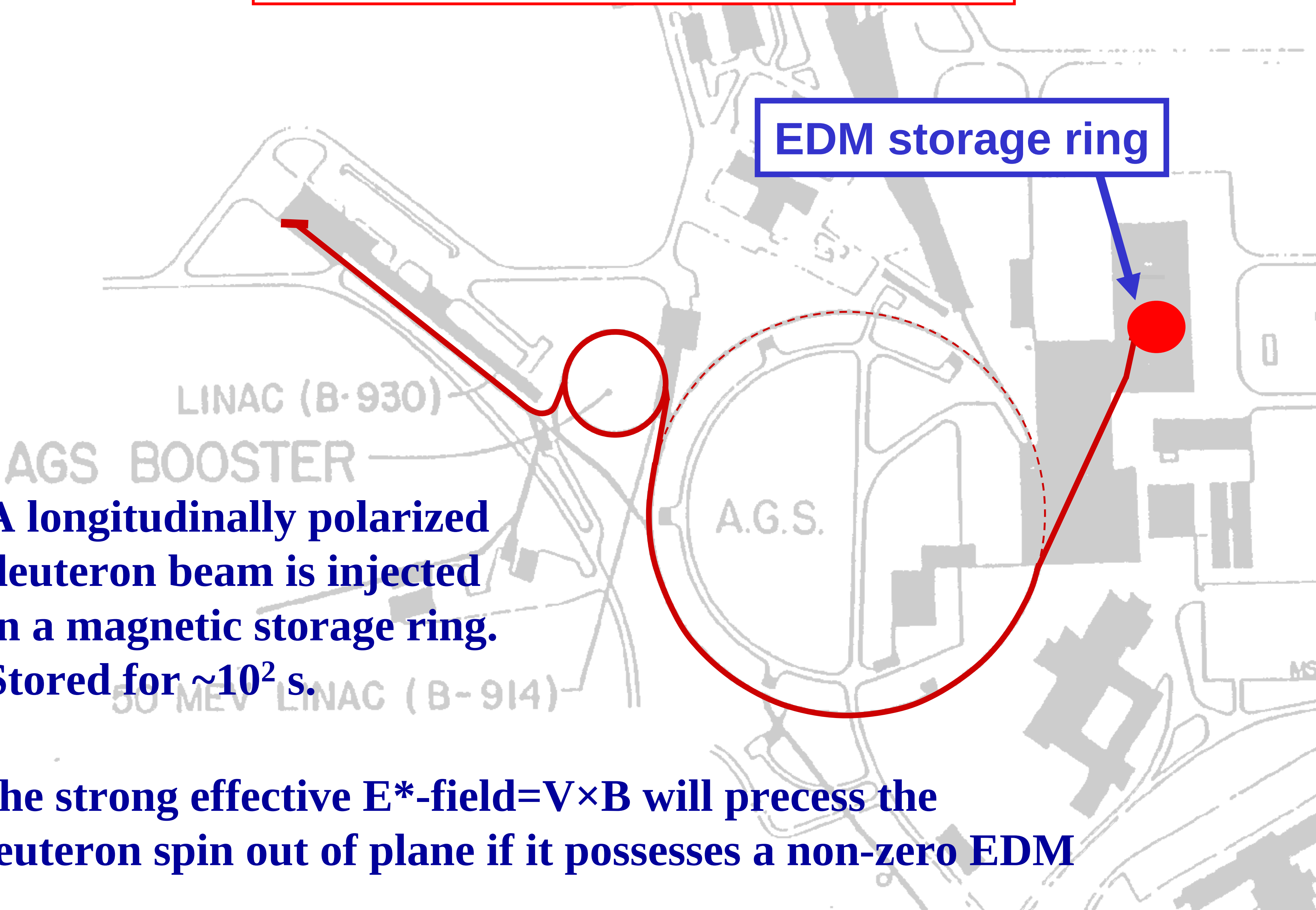
Clearly there is enthusiasm for your continuing development of this experiment and I look forward to a plan as suggested in the last sentence of the recommendation.

Study potential errors: Demonstrate that we can identify and quantify them. Find those that impose significant constraints on EDM ring design.

Make tests in a storage ring (KVI/COSY) with setup as close as possible to dEDM conditions.

Support for a significant LDRD…

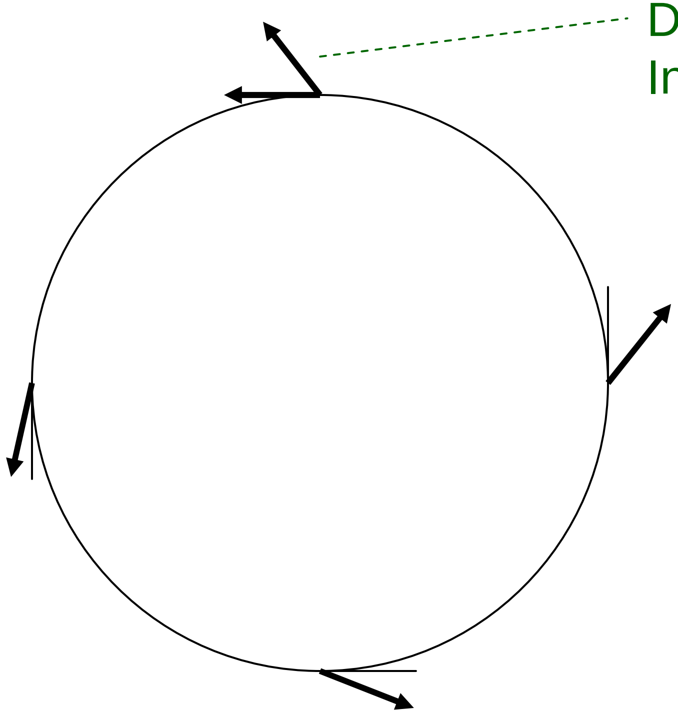
deuteron EDM search at BNL



A longitudinally polarized deuteron beam is injected in a magnetic storage ring. Stored for ~10^2 s.

The strong effective E*-field=V×B will precess the deuteron spin out of plane if it possesses a non-zero EDM

Top view of deuteron spin precession in ring. Optimizing the dEDM search…

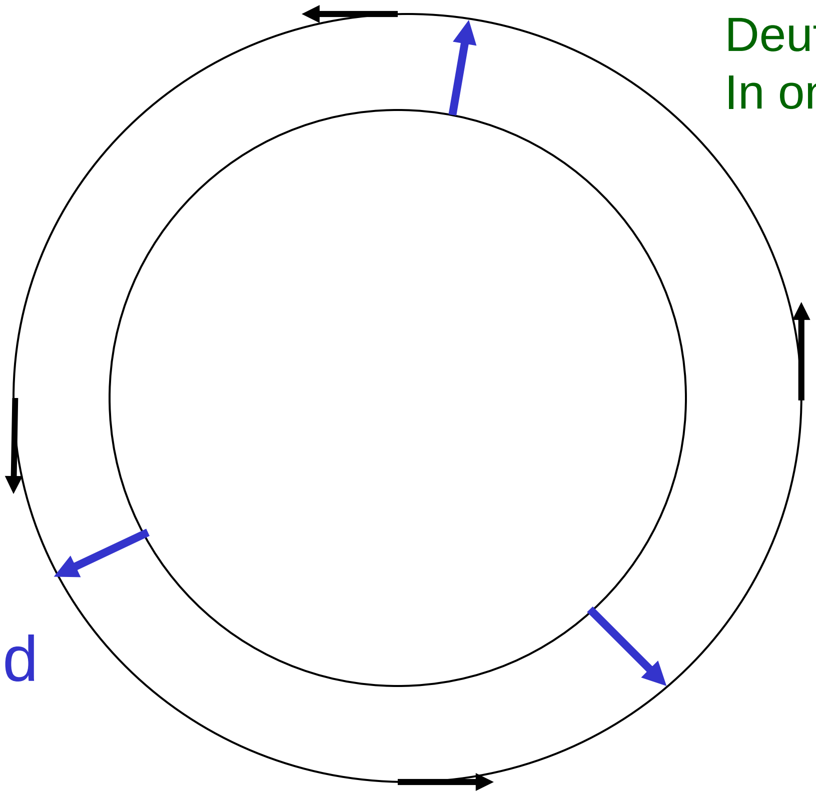


Deuteron anomalous moment = – 0.14.
In one revolution, spin lags momentum.

Idea: Use electric field to enlarge orbit and revolution time while keeping B constant.

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

Top view of deuteron spin precession in ring. Optimizing the dEDM search…



E field

Deuteron anomalous moment = – 0.14.
In one revolution, spin lags momentum.

Idea: Use electric field to enlarge orbit and revolution time while keeping B constant.

For some ratio of **E** and **B**, the lengthened path will be just right for the spin to track the velocity.

(Small precessions will be used for systematic checks.)

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

Cancel background with Symmetries

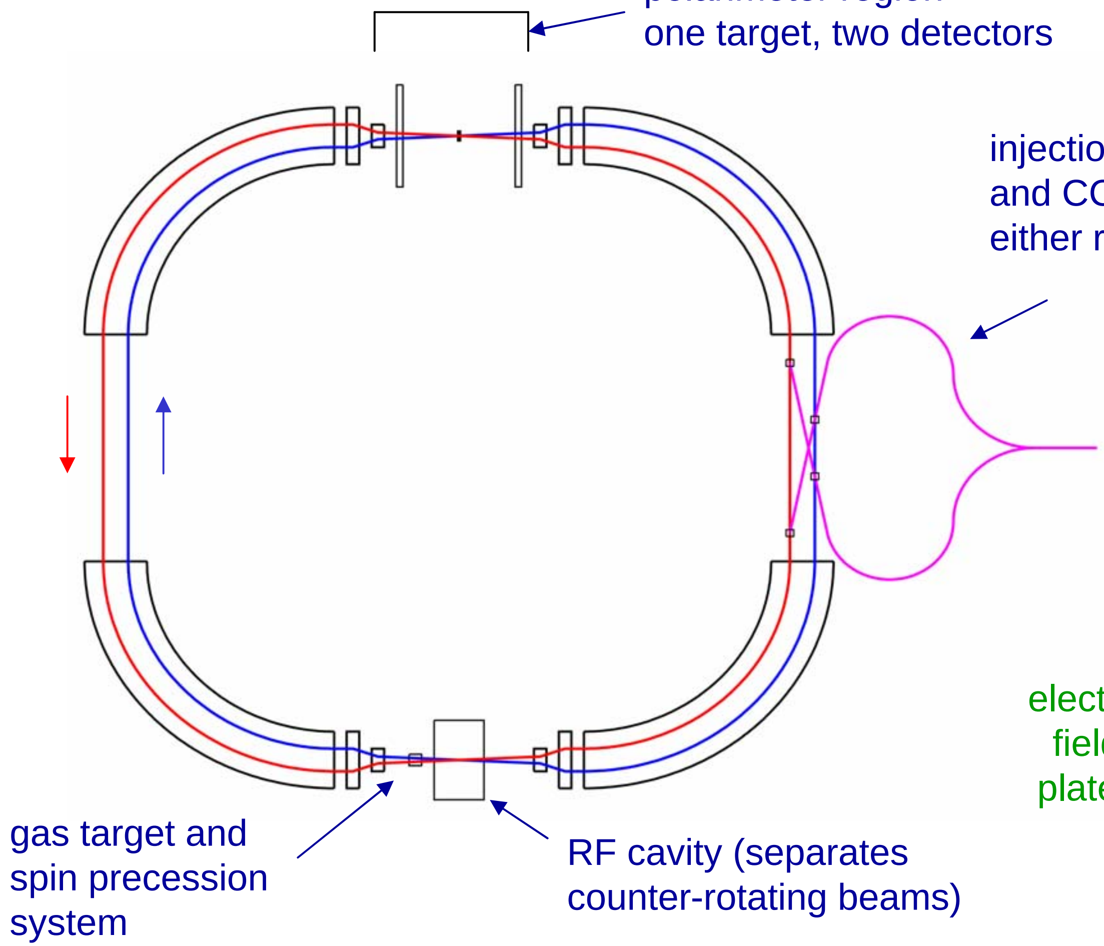
- CW and CCW injections cancel all T-reversal preserving effects. EDM is T-violating and behaves differently.

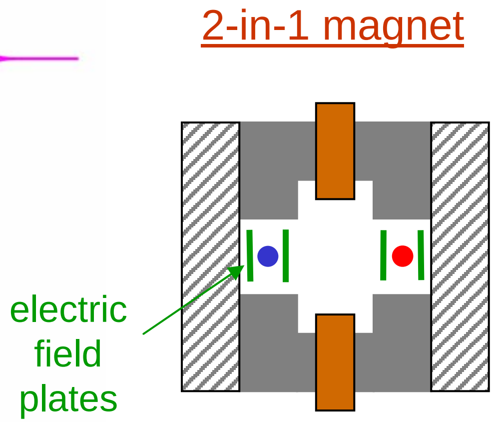
- Use Palmer's 2-in-1 magnet design for simultaneous CW and CCW storage
- Expected systematic error <10^{-29}e·cm
- Statistical error ~ 10^{-29}e·cm (statistics limited)

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

A high sensitivity dEDM ring geometry

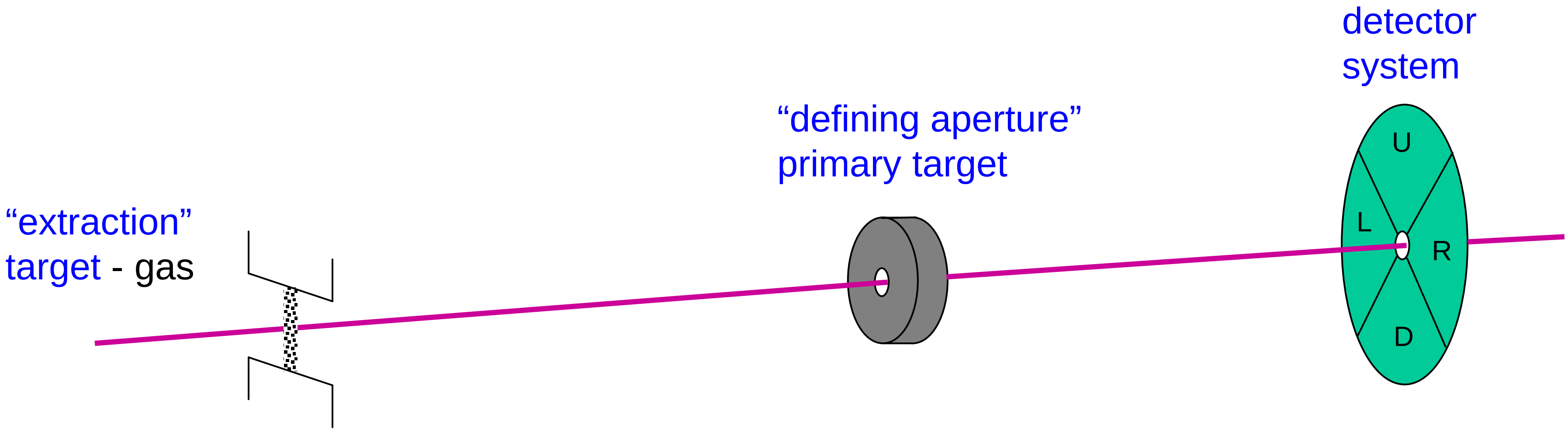
2-in-1 magnets in two intersecting storage rings geometry:





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

dEDM polarimeter principle



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

carries EDM signal
small
increases slowly with time

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

carries in-plane precession signal

Polarimeter requirements

High efficiency

need to measure time dependence of EDM signal
need to monitor in-plane precession (magnitude + phase)
sensitivity down to 10^{-7}

High analyzing power

choose carbon target: include elastic and
inelastic/transfer channels with low excitation energy
avoid breakup protons

Small and understood response to systematic errors

Use Symmetries

Running time approved at KVI-The Netherlands and COSY-Bonn/Germany for tests and development.

What's next

- Systematic error studies: study fully (analytically and tracking) spin/beam dynamics related systematic errors. CAD support. New addition to the group: Fanglei Lin started as of 1 October 2007 (Ph.D. thesis with S.Y. Lee and M. Bai)
- Polarimeter systematic errors studies with beams
- dEDM proposal in 2008
- The expertise and infra-structure is at BNL and the physics is very exciting. BNL is a natural place for the dEDM.

Extra Slides

$$d_n \simeq 3\times 10^{-16}\bar{\theta}\ e\text{-cm} + 1.4(d_d - 0.25 d_u) + 0.83(d_d^c + d_u^c) + 0.27(d_d^c - d_u^c)e$$

$$d_D \simeq -1\times 10^{-16}\bar{\theta}\ e\text{-cm} + (d_d + d_u) - 0.20(d_d^c + d_u^c) + \underline{6\ (d_d^c - d_u^c)e}$$

Complementary

$d_D / d_n \simeq -\frac{1}{3} \rightarrow \bar{\theta}$ source $\sim 10^{-13}$ Sensitivity!

$d_D / d_n \simeq 22 \rightarrow d_d^c - d_u^c$ dominates (eg SUSY)

If $d_D \neq 0$, Storage Ring $\rightarrow d_p + d_{He}$ ...

Compelling Probe of SUSY, LR, Multi-Higgs ...

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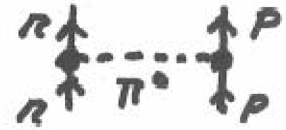
9/2006

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

Nuclear Theory Clean

$d_D = d_n + d_p + d_D^{\text{Nuclear}}$



$I = 1$

Pion P+S interaction

Violates P+T, Large!

S–P States Mix → d_D

No Electron (Schiff) Shielding (in Atoms)

$d_{\text{Deuterium}} \sim 10^{-7}\, d_{\text{Deuteron}}$

d_D^{Nuclear} Generally Dominates

Eg. $\bar{\theta}$ of QCD (Currently $\bar{\theta} < 10^{-10}$)

$d_u + d_d$ of quarks

$d_u^c + d_d^c$ color (gluon) edms

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

Generic Loop Prediction: $d \sim \frac{e g^2}{16\pi^2} \frac{m_q}{M^2} \sin\delta$

$d \sim 10^{-24}\, e\text{-cm} \times \sin\delta \times \left(\frac{1\,\text{TeV}}{M}\right)^2$

SUSY → $d_n \sim 10^{-25} - 10^{-28}\, e\text{-cm} \sim d_D$ (Observable)

δ very small or $M > 1\,\text{TeV}$ (SUSY CP Crisis)?

If LHC discovers SUSY < 1 TeV

$d_n, d_D \ldots d_p, d_{He^3}$ Sort Phase Structure.. (Complementary)

If LHC Fails To Find SUSY

d_D probes up to $M \sim 1000\,\text{TeV}$! (Spectacular!)

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

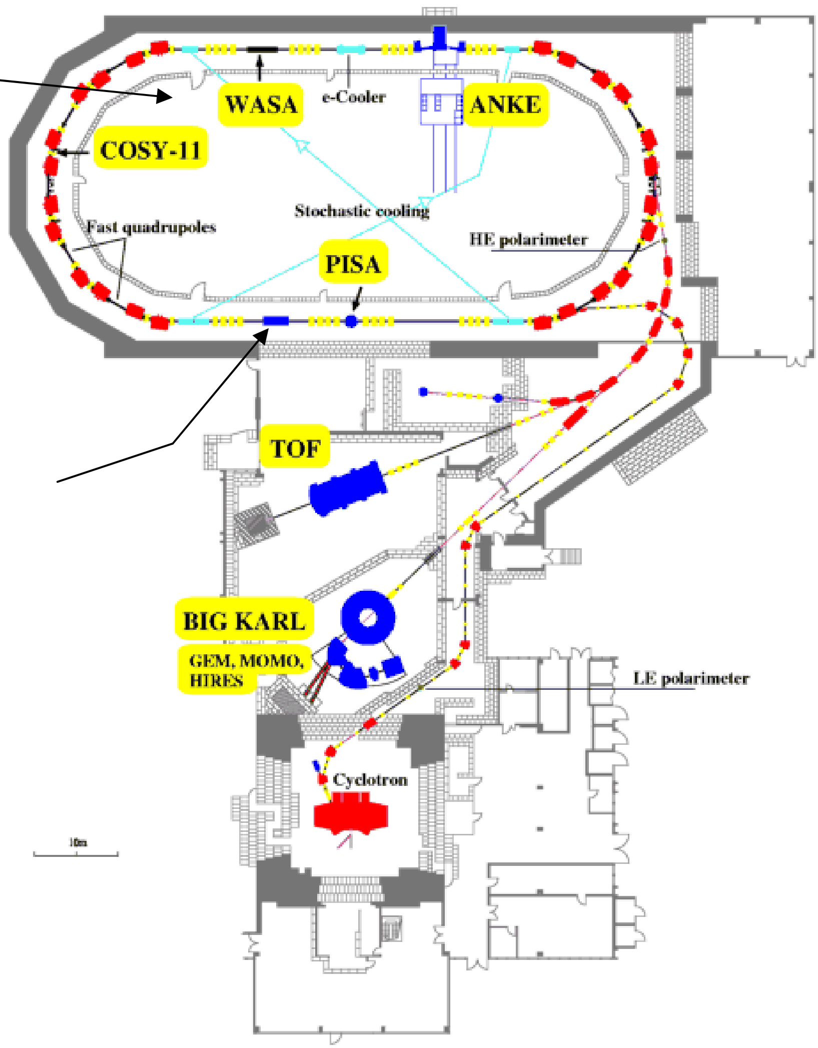
Polarimeter studies at KVI/The Netherlands

Study of systematics:
- analyze all effects in terms of
  - drivers (errors in position, angle, energy, etc.)
  - sensitivities (expanded in derivatives)
  - analysis method

Run is scheduled for 6-9 Nov., 2007
Support by dEDM LDRD

Run plan at COSY/Jölich-Germany

broad range
data from
WASA



polarimeter
test data
from EDDA

Developments needed

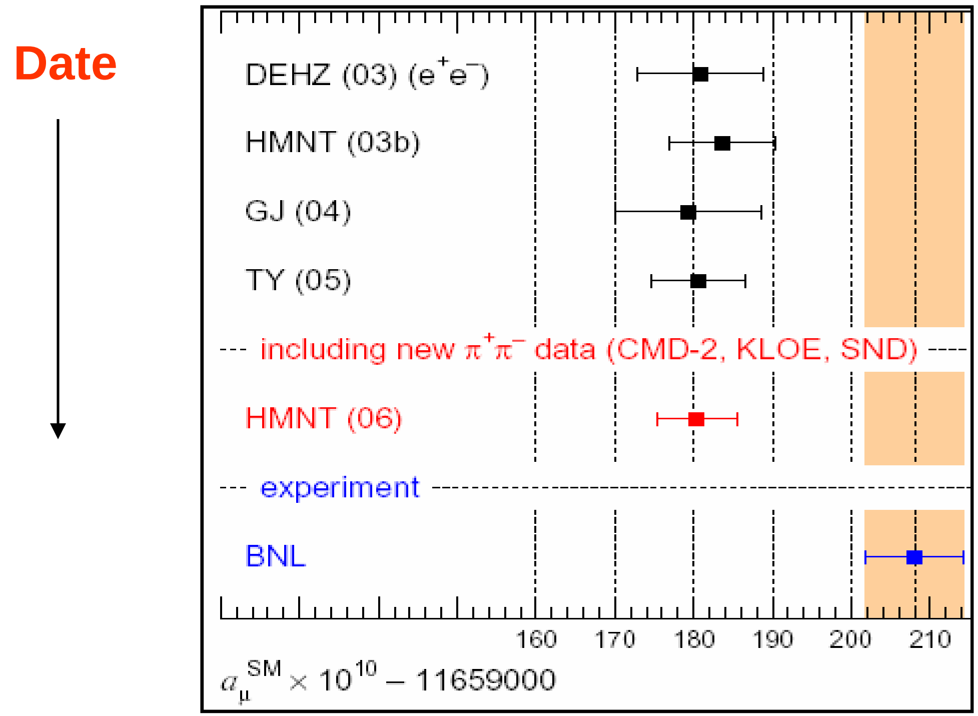
- annular carbon targets (EDDA)
- needle carbon (CH_2) (WASA)

Running time goals:

Demonstrate high efficiency (~ 4 %)
Precess polarization into horizontal plane and track it with time
Measure data on carbon using WASA

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

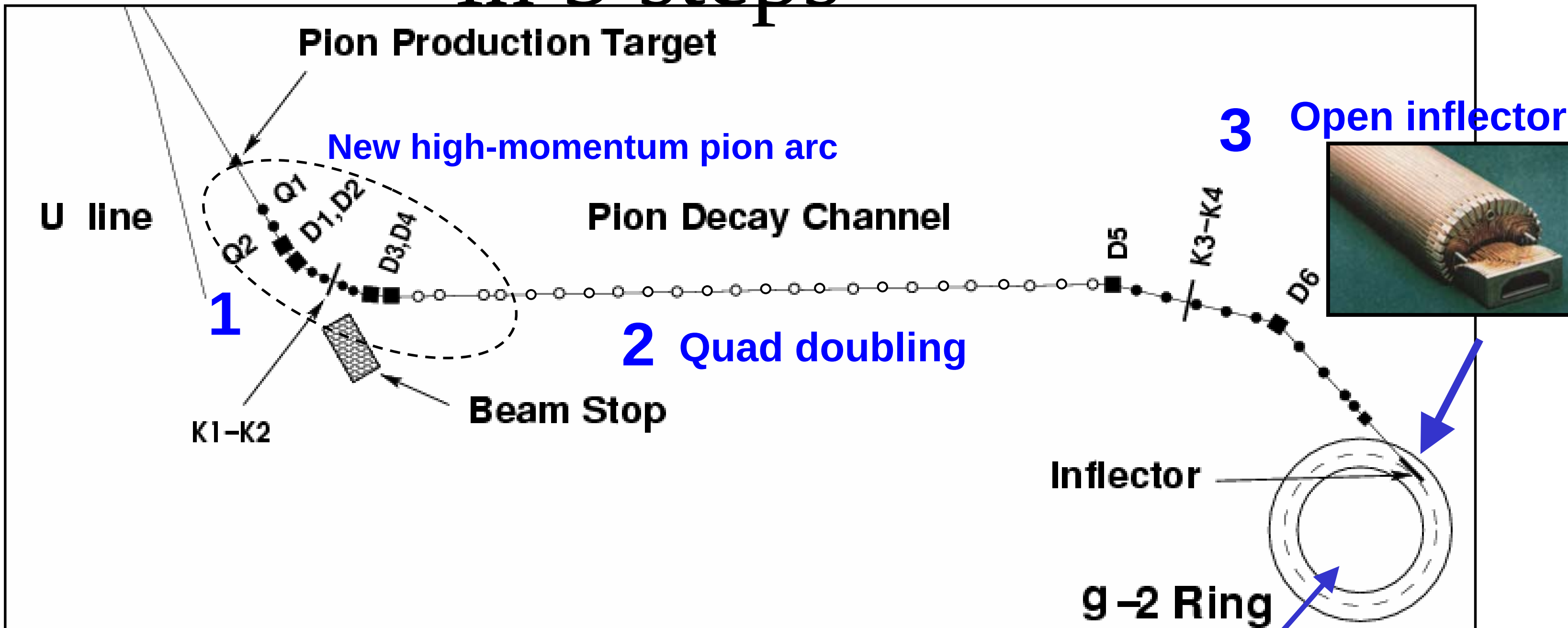
The science is now more compelling than ever



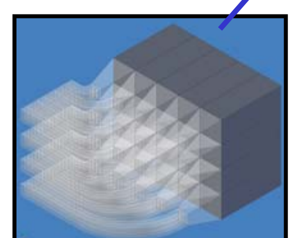
$$\Delta a_\mu(\text{expt-thy}) = (29.5 \pm 8.8) \times 10^{-10}\ (3.4\ \sigma)$$

Based on de Rafael's theory summary (2007), using inputs from Davier (2006) and HMNT (2006). Rep.Prog.Phys. **70**, 795 (2007).

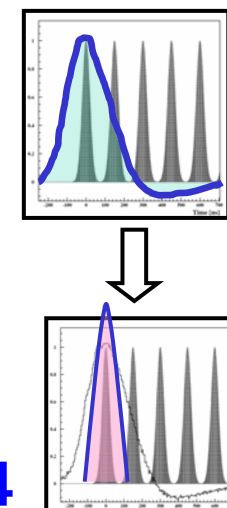
Original proposal: More Muons: Our plan in 5 steps



- x 5 more muons
- Pion flash reduced (eliminated)
- Segmented detectors
- Systematics reduced



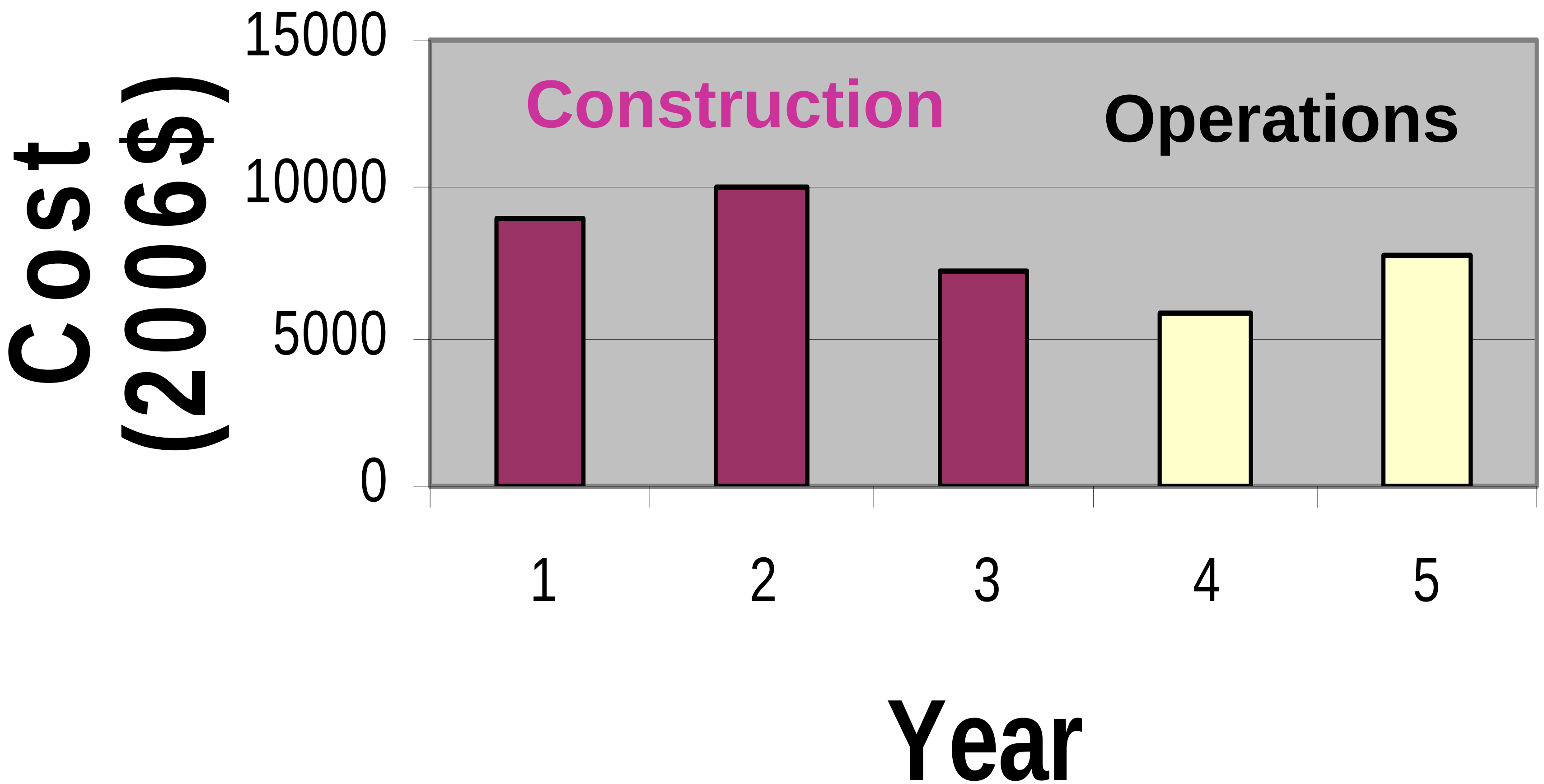
5 **Segmented detectors**



4 **Improved kicker**

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

Funding Profile by Year



Milestones/Timeline (by FY)

-1 **Beamline design – backward/forward decision; detector prototype; simulations of injection, scraping, CBO damping; decide on scope of cryo work; begin tube/base development**

0

- **+9 Months ; Begin electronics engineering**

  - Engineering on beamline, Cryo

+1 **- Start to order long leadtime items e.g. Inflector, rad-hard front-end magnets, etc.; Refurbish storage ring; develop on-line; develop NMR tools for 0.1 ppm.**

+2

+3

- **Shim magnet, improve on absolute calibration**

  - Finish construction, few weeks of low intensity beam

+4

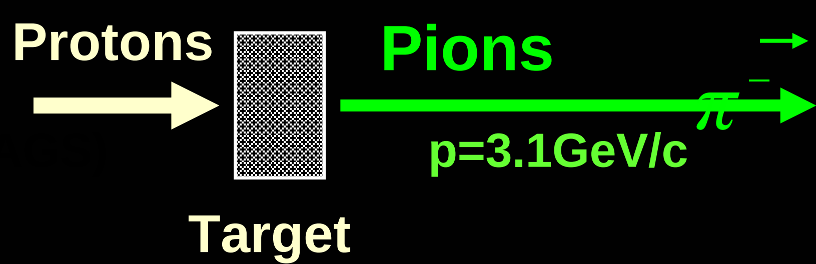
- **Commission experiment, engineering and short physics run**

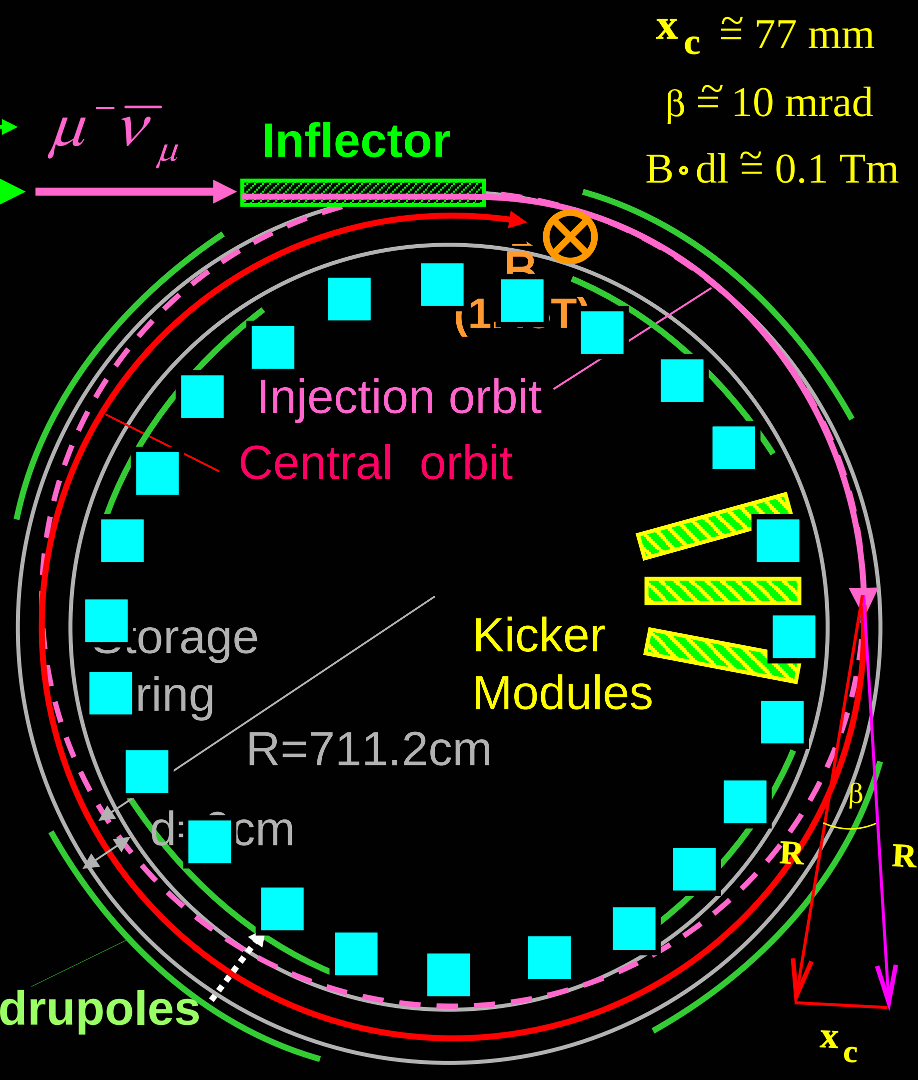
+5

- **Major data collection run**

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

Experimental Technique





- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

E969 needs 5 times the muon flux that E821 stored.

- **Open inflector** **x 2**
- **Quadruple the quadrupoles** **x 2 – 3**

Beam increase design factor **x 4 – 6**

E969 New Baseline – 0.25 ppm total error

- **Systematic error goals remain:**
  - for ω_a: **0.1 ppm**
  - for ω_p: **0.1 ppm**
- **Statistical error goal relaxed:**
  - **for ω_a: 0.2 ppm**
- **Total Error Goal:**
  - **a_μ: 0.25 ppm**
- **Forward beam with 4x quadrupoles**
- **New detectors / electronics**
- **Upgraded NMR system**

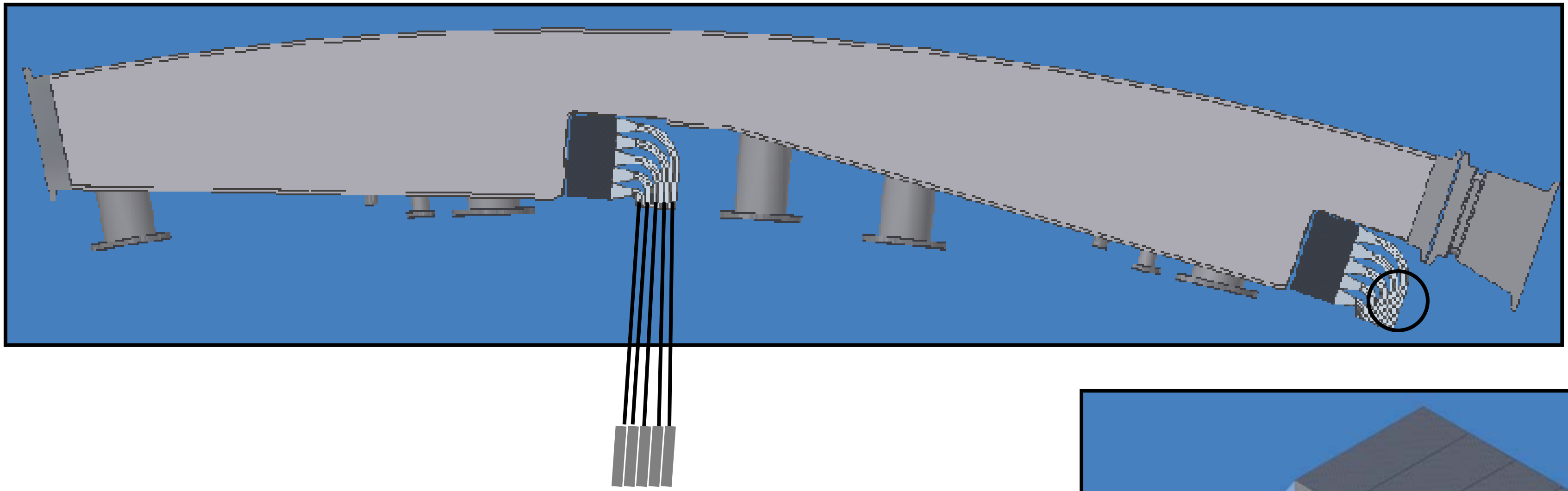
The error budget for E969 represents a continuation of improvements already made during E821

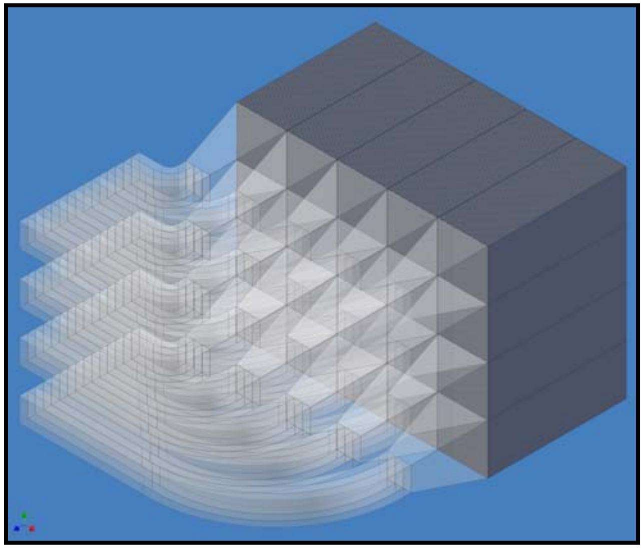
Systematic uncertainty (ppm)	1998	1999	2000	2001	E969 Goal
Magnetic field – ω_p	0.5	0.4	0.24	0.17	0.1
Statistical uncertainty (ppm)	4.9	1.3	0.62	0.66	0.2
Total Uncertainty (ppm)	5.0	1.3	0.73	0.72	0.25

- **Field improvements:** **better trolley calibrations, better tracking of the field with time, temperature stability of room, improvements in the hardware**
- **Precession improvements** **will involve new scraping scheme, lower thresholds, more complete digitization periods, better energy calibration**

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

New segmented detectors of tungsten / scintillating- fiber ribbons to deal with pile-up





- **System fits in available space**
- **We know how to cost and build it. (prototype under construction)**
- **Calibration method reasonable**
- **Bases will be gated.**
- **New custom electronics and DAQ**

E969 Costs (2006 M$)

Baselining costs	0.4
AGS/Booster Rehab including ES&H	11.7
Construction (44% contingency)	12.2
Universities (27% contingency)	2.4
Operations (includes FTEs to support cryo and external beam operations)	13.6
Total Costs	40.2

Cost Summary: E969 Construction

	M$	Contingency
• **Experiment Construction, Direct Costs**		
– G-2 Ring and building	$ 0.56	21%
– V/V1 Beam Line modifications	$ 2.59	18%
– Inflector (open ends)	$ 0.64	19%
– E-Quad rebuild	$ 0.13	15%
– Additional muon Kicker	$ 0.41	15%
– Cryogenic plant rehab	$ 0.74	233%
– Ring Vacuum System	$ 0.16	29%
– Equipment Testing	$ 0.69	20%
– Project Office	$ 0.37	20%
• **Sub-Total, direct costs**	$ 6.3	
• **Indirects (reduced)**	$ 2.2	
• **Contingency (44%)**	$ 3.7	
• **Sub-Total, with indirects**	$ 12.2	
• **University (Detectors/DAQ)**	$ 2.4	
• **Total**	**$ 14.6**	

FY 2006 $'s

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

Cost Summary: AGS/Booster Restoration to High Intensity

AGS/Booster, Direct Costs	M$	Contingency
– Electrical Modifications	$ 2.11	22%
– Mechanical Modifications	$ 1.25	20%
– RF System Modifications	$ 0.67	22%
– Instrumentation	$ 0.34	20%
– Project Support	$ 0.33	34%
– Controls	$ 0.16	24%
– ES&H (CAPS)	$ 2.63	28%
Sub-Total, direct costs	$ 7.5	
Indirects (reduced)	$ 1.9	
Contingency (24%)	$ 2.3	
Total	**$ 11.7**	

FY 2006 $'s

E969 Operations Cost Summary

FY 2006 $'s

1st	12	0	3	$ 5.8
2nd	20	0	15	$ 7.8
Total	34	0	18	$ 13.6

If warranted to push beyond 0.25 ppm, an additional 10-15 week run with RHIC adds ~$6-7M

Field systematic uncertainties, ordered by importance

Source	E821 (ppm)	E969 (ppm)	Comment
Calibration of trolley probe	**0.09**	**0.06**	Improved shimming in the calibration region; improved registration of trolley location in ring
Interpolation with fixed probes	**0.07**	**0.06**	Repairs and retuning of a number of probes to improve the sampling of the ring field
Absolute calibration	**0.05**	**0.05**	Could improve using a ^{3}He based probe
Trolley measurements of B0	**0.05**	**0.02**	More frequent trolley runs; mechanical maintenance of trolley drive and garage; Extensive measurements of trolley NMR probe active volumes
Muon distribution	**0.03**	**0.02**	Simulations of storage ring; improved shimming
"Other"	**0.10**	**0.05**	
eddy currents			*in situ* measurement of eddy currents
higher multipoles			Improved shimming
trolley temp and PS response			Modifications to trolley and PS
Total	**0.17**	**0.11**	

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

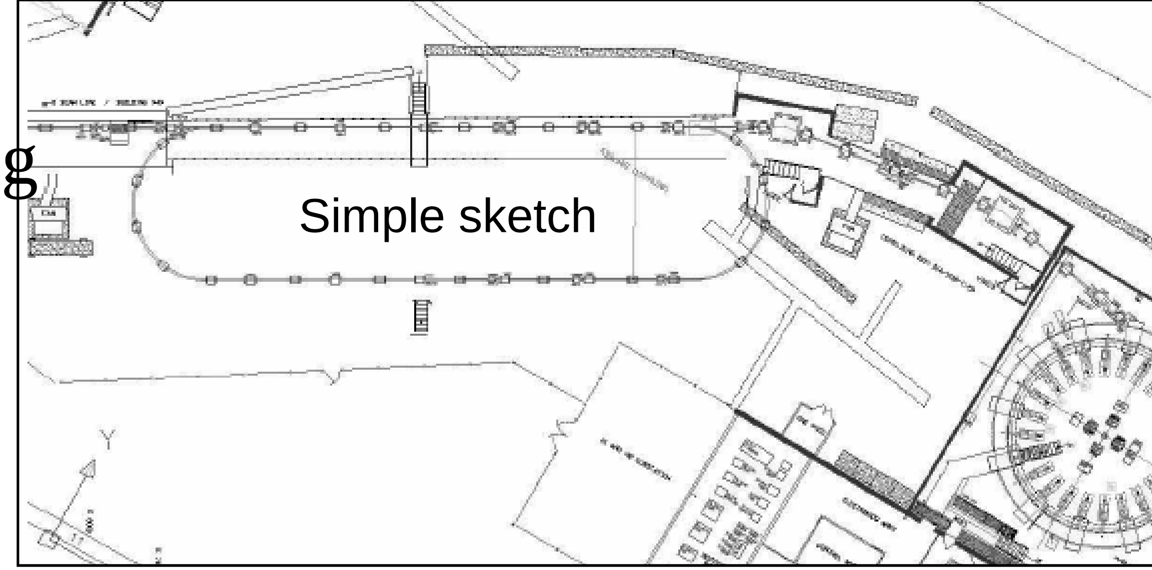
Precession frequency systematic uncertainties, ordered by importance

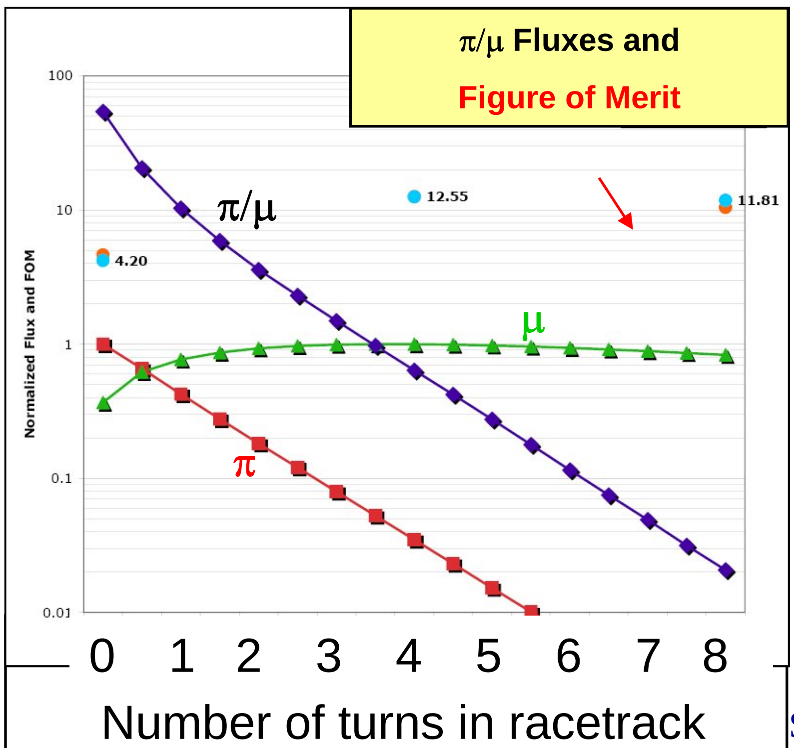
Source	**E821 (ppm)**	**E969 (ppm)**	**Comments**
Gain stability	**0.12**	**0.03**	Full WFD samples recorded; stability of laser calibration with local reference detectors; single-phase WFDs
Lost muons	**0.09**	**0.04**	New scraping scheme; improved kick
Pileup: T method Q method (not applicable)	**0.08**	**0.07**	Recording all samples, no threshold, will eliminate ambiguity from low-energy pulses
CBO: coherent betatron oscillations	**0.07**	**0.04**	Improved kick; new scraping; taller calorimeters
E and pitch correction	**0.05**	**0.05**	Should be improved with better storage ring simulation, but we keep it as is for now
Timing shifts	**0.02**	**0.01**	Laser calibration; precision determined by amount of data collected
AGS background	**0.01**	**0.01**	Sweeper magnet maintained
Fit procedure and bin width	**0.06**	**0.01**	Limited by number of simulated trials performed
Vertical waist	**0.03**	**0.01**	CBO related; see above
Other small effects	**< 0.03**	**< 0.02**	These either scale with the data set size or from the simulations demonstrating "no effect"
Total	**0.21**	**0.11**	

MAR:
Muon Accumulator Ring

Studies to do:

- **Practical lattice layout**
- **Fast kicker**
- **Selection of real elements**
- **Practical floorplan**
- **Shielding**





Strawman design

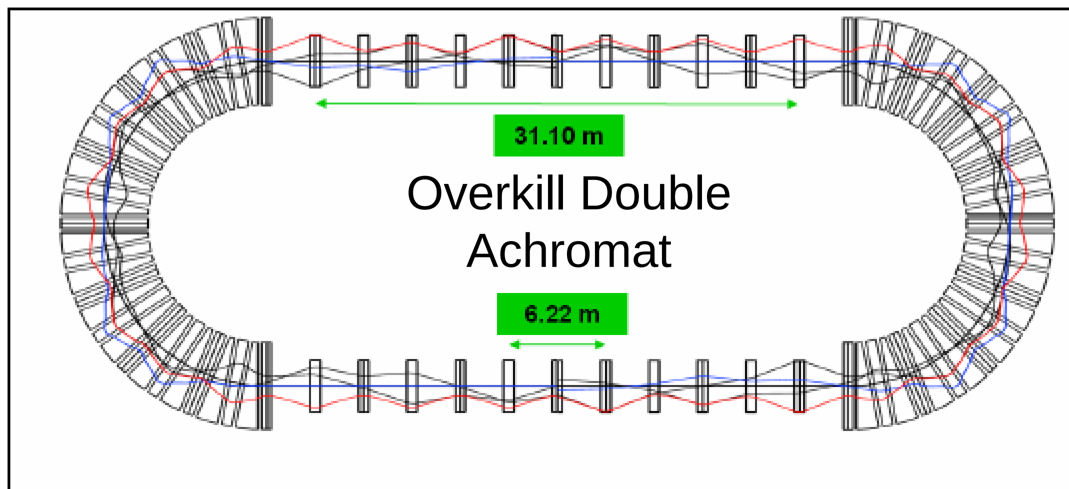


Figure 11: Sketch of MAR from Cosy-Infinity

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

SM contributions and uncertainties

Table 1: Standard-model contributions to the muon anomalous magnetic dipole moment, a_μ. All values are taken from Ref. [10].Possible improvements in errors on the hadronic corrections are also listed. As additional e^+e^- data become available, the error listed for radiative corrections will decrease.

Effect	*Contribution* $\times 10^{11}$	*Future* σ
QED	$(116\,584\,718.09 \pm 0.14_{5\text{loops}} \pm 0.08_{\alpha} \pm 0.04_{\text{masses}}) \times 10^{-11}$	
Hadronic (lowest order)	$a_\mu^{(\text{HVP};1)} = (6901 \pm 42_{\text{exp}} \pm 19_{\text{rad}} \pm 7_{\text{QCD}})$	$\pm 30_{\text{exp}} \pm 8_{\text{rad}} \pm 7_{\text{QCD}}$
Hadronic (higher order)	$a_\mu^{(\text{HVP};\text{h.o.})} = (-97.9 \pm 0.9_{\text{exp}} \pm 0.3_{\text{rad}})$	
Hadronic (light-by-light)	$a_\mu^{(\text{HLLS})} = (110 \pm 40)$	16.5
Electroweak	$a_\mu^{(\text{EW})} = (154 \pm 2_{M_H} \pm 1_{\text{had}})$	