Feebly coupled particles, ALPs etc. at Future Accelerators (storage ring proton EDM)

Yannis K. Semertzidis, KAIST and IBS-CAPP

On behalf of the storage ring EDM Collaboration:

Future accelerators 2023
Corfu, Greece 4/28/2023

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis *[6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

[1] *Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2] *Argonne National Laboratory, Lemont, Illinois, USA*
[3] *Boston University, Boston, Massachusetts, USA*
[4] *Brookhaven National Laboratory, Upton, New York, USA*
[5] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[6] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon, Korea*
[7] *Cornell University, Ithaca, New York, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[9] *Helmholtz-Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[10] *Indiana University, Bloomington, Indiana, USA*
[11] *Istanbul Technical University, Istanbul, Turkey*
[12] *JLAB, Newport News, Virginia, USA*
[13] *Johns Hopkins University, Baltimore, Maryland, USA*
[14] *Joint Institute for Nuclear Research, Dubna, Russia*
[15] *Physics Dept., KAIST, Daejeon, Korea*
[16] *Physics Dept., Korea University, Seoul, Korea*
[17] *Michigan State University, East Lansing, Michigan, USA*
[18] *National Institute for Nuclear Physics (INFN-Frascati), Rome, Italy*
[19] *National Institute for Nuclear Physics (INFN-Pisa), Pisa, Italy*
[20] *NCSR Demokritos Institute of Nuclear and Particle Physics, Athens, Greece*
[21] *Northern Illinois University, DeKalb, Illinois, USA*
[22] *Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[23] *Regis University, Denver, Colorado, USA*
[24] *Royal Institute of Technology, Division of Nuclear Physics, Stockholm, Sweden*
[25] *Scuola Normale Superiore di Pisa, Pisa, Italy*
[26] *Stanford University, Stanford, California, USA*
[27] *Stony Brook University, Stony Brook, New York, USA*
[28] *TRIUMF, Vancouver, British Columbia, Canada*
[29] *UMass Amherst, Amherst, Massachusetts, USA*
[30] *Universität Hamburg, Hamburg, Germany*
[31] *University of California at Berkeley, Berkeley, California, USA*
[32] *University of Kentucky, Lexington, Kentucky, USA*
[33] *University of Liverpool, Liverpool, UK*
[34] *University of Michigan, Ann Arbor, Michigan, USA*
[35] *University of Molise, Campobasso, Italy*
[36] *University of Patras, Dept. of Physics, Patras-Rio, Greece*
[37] *University of Rijeka, Rijeka, Croatia*
[38] *University of Trieste and National Institute for Nuclear Physics (INFN-Trieste), Trieste, Italy*
[39] *University of Virginia, Charlottesville, Virginia, USA*

The Collaboration members:

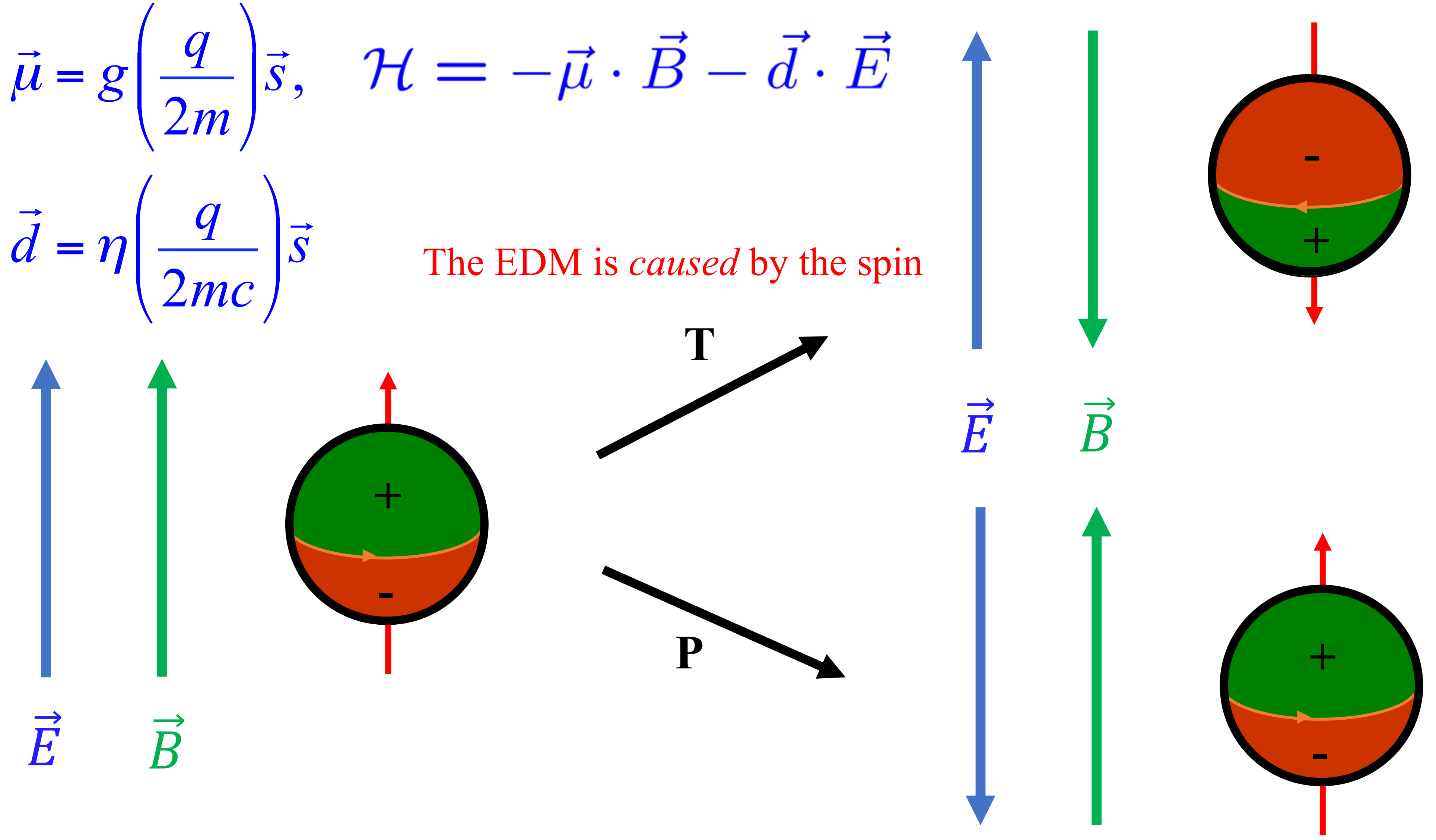
- Muon g-2; Hadronic storage rings; hadronic polarimeters; High precision beam and spin dynamics simulations; High voltage experts; Magnetic field experts in measurements, shielding/shimming;…

Electric Dipole Moments

A Permanent EDM Violates both T & P Symmetries:

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}, \quad \mathcal{H} = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

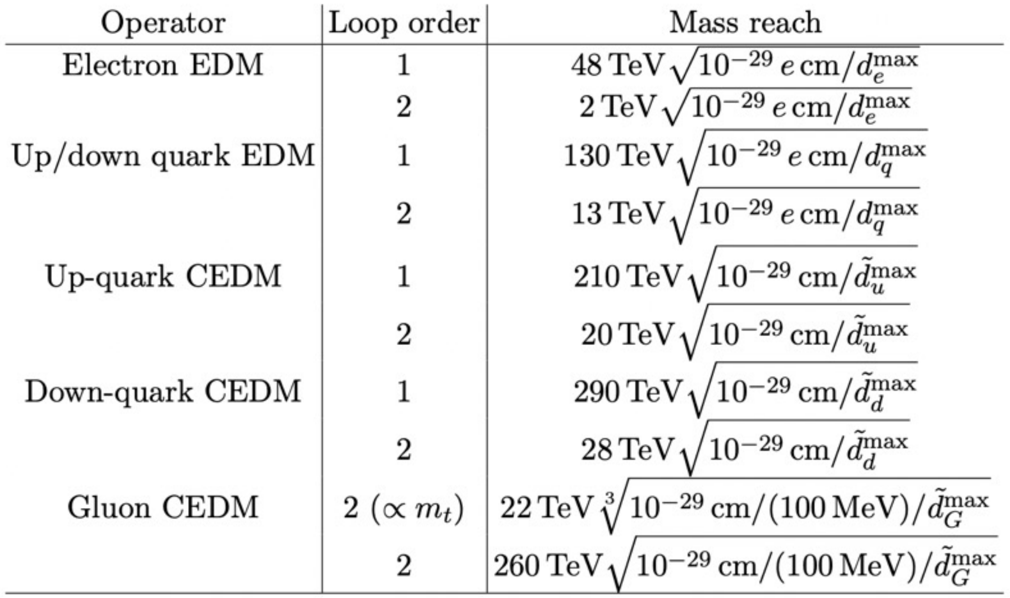
$$\vec{d} = \eta\left(\frac{q}{2mc}\right)\vec{s}$$



The EDM is *caused* by the spin

Reminder: batteries are allowed in the SM!

Snowmass paper on EDMs, why many EDMs:



Operator	Loop order	Mass reach
Electron EDM	1	$48\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_e^{\max}}$
	2	$2\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_e^{\max}}$
Up/down quark EDM	1	$130\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_q^{\max}}$
	2	$13\,\text{TeV}\sqrt{10^{-29}\,e\,\text{cm}/d_q^{\max}}$
Up-quark CEDM	1	$210\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_u^{\max}}$
	2	$20\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_u^{\max}}$
Down-quark CEDM	1	$290\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_d^{\max}}$
	2	$28\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/\tilde{d}_d^{\max}}$
Gluon CEDM	2 ($\propto m_t$)	$22\,\text{TeV}\sqrt[3]{10^{-29}\,\text{cm}/(100\,\text{MeV})/\tilde{d}_G^{\max}}$
	2	$260\,\text{TeV}\sqrt{10^{-29}\,\text{cm}/(100\,\text{MeV})/\tilde{d}_G^{\max}}$

TABLE I. Crude estimate of the mass reach of different operators. See text for explanation of the notation and assumptions used in deriving the estimates.

$$
\begin{aligned}
d_n = &-(1.5 \pm 0.7) \cdot 10^{-3}\ \bar{\theta}\, e\,\text{fm} \\
&-(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (0.0027 \pm 0.016) d_s \\
&-(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d + (50 \pm 40)\,\text{MeV}\,e\,\tilde{d}_G\,.
\end{aligned}
$$

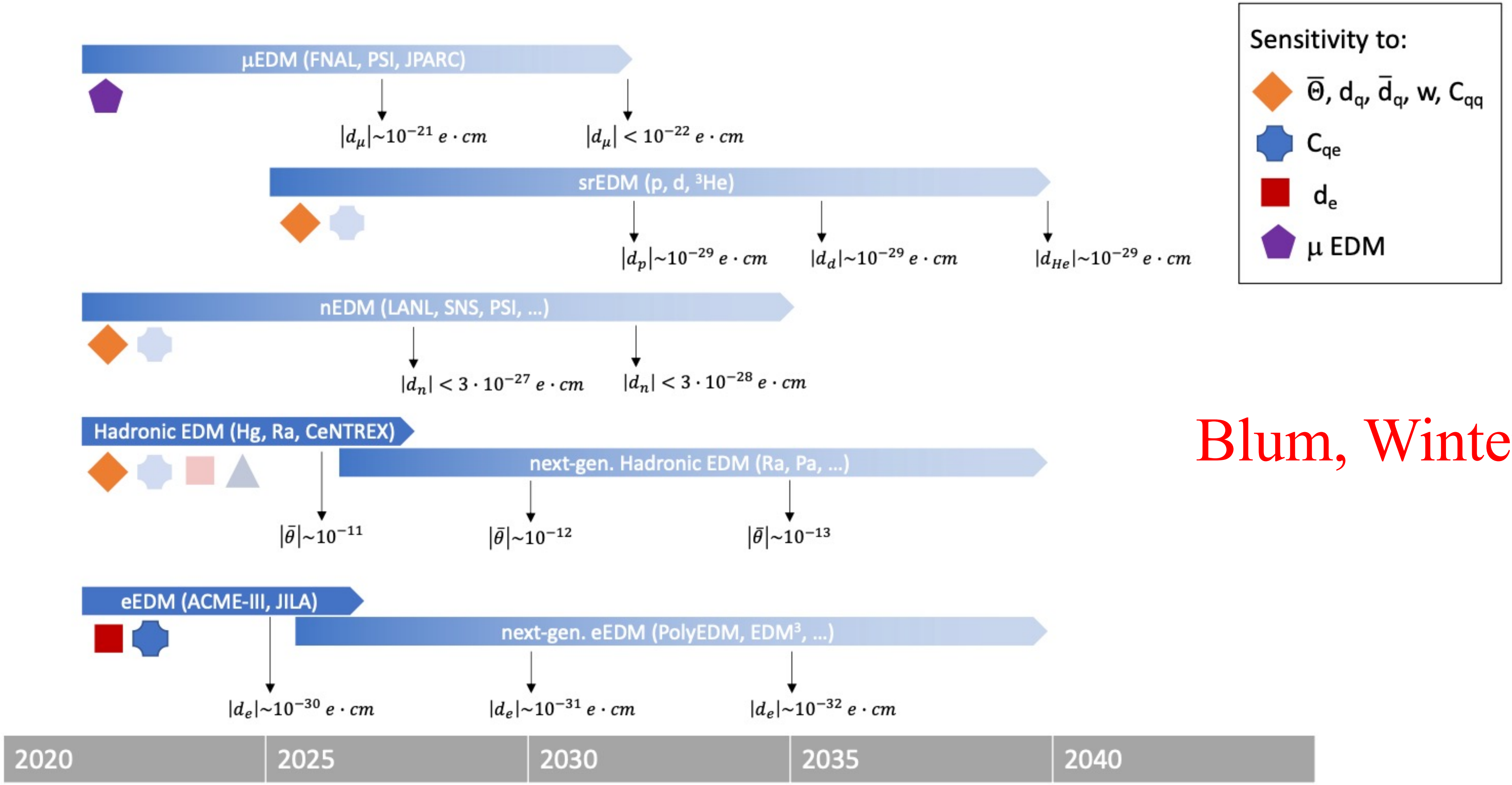
arXiv:2203.08103v1 [hep-ph] 15 Mar 2022

Electric dipole moments and the search for new physics

Ricardo Alarcon,[1] Jim Alexander,[2] Vassilis Anastassopoulos,[3] Takatoshi Aoki,[4] Rick Baartman,[5] Stefan Baeßler,[6,7] Larry Bartoszek,[8] Douglas H. Beck,[9] Franco Bedeschi,[10] Robert Berger,[11] Martin Berz,[12] Tanmoy Bhattacharya,[13,a] Michael Blaskiewicz,[14] Thomas Blum,[15,b] Themis Bowcock,[16] Kevin Brown,[14] Dmitry Budker,[17,18] Sergey Burdin,[16] Brendan C. Casey,[19] Gianluigi Casse,[20] Giovanni Cantatore,[21] Lan Cheng,[22] Timothy Chupp,[20] Vince Cianciolo,[23] Vincenzo Cirigliano,[13,24,c] Steven M. Clayton,[25] Chris Crawford,[26] B. P. Das,[27] Hooman Davoudiasl,[14] Jordy de Vries,[28,29,d] David DeMille,[30,31,e] Dmitri Denisov,[14] Milind V. Diwan,[14] John M. Doyle,[32] Jonathan Engel,[33] George Fanourakis,[34] Renee Fatemi,[35] Bradley W. Filippone,[36] Nadia Fomin,[37] Wolfram Fischer,[14] Antonios Gardikiotis,[38,3] R. F. Garcia Ruiz,[39] Claudio Gatti,[40] James Gooding,[16] Peter Graham,[41] Frederick Gray,[42] W. Clark Griffith,[43] Selcuk Haciomeroglu,[44] Gerald Gwinner,[45] Steven Hoekstra,[46,47] Georg H. Hoffstaetter,[2] Haixin Huang,[14] Nicholas R. Hutzler,[48,f] Marco Incagli,[10] Takeyasu M. Ito,[25,g] Taku Izubuchi,[49] Andrew M. Jayich,[50] Hoyong Jeong,[51] David Kaplan,[52] Marin Karuza,[53] David Kawall,[54] On Kim,[44] Ivan Koop,[55] Valeri Lebedev,[19] Jonathan Lee,[56] Soohyung Lee,[44] Kent K. H. Leung,[57] Chen-Yu Liu,[58,9,h] Joshua Long,[58,9] Alberto Lusiani,[59,10] William J. Marciano,[14] Marios Maroudas,[3] Andrei Matlashov,[44] Nobuyuki Matsumoto,[60] Richard Mawhorter,[61] Francois Meot,[14] Emanuele Mereghetti,[13] James P. Miller,[62] William M. Morse,[63,i] James Mott,[62,19] Zhanibek Omarov,[44,64] Chris O'Shaughnessy,[25] Cenap Ozben,[65] SeongTae Park,[44] Robert W. Pattie Jr.,[66] Alexander N. Petrov,[67,68] Giovanni Maria Piacentino,[69] Bradley R. Plaster,[26] Boris Podobedov,[14] Matthew Poelker,[70] Dinko Pocanic,[71] V. S. Prasannaa,[27] Joe Price,[16] Michael J. Ramsey-Musolf,[72,73] Deepak Raparia,[14] Surjeet Rajendran,[52] Matthew Reece,[74,j] Austin Reid,[58] Sergio Rescia,[14] Adam Ritz,[75] B. Lee Roberts,[62] Marianna S. Safronova,[76] Yasuhiro Sakemi,[77] Andrea Shindler,[78] Yannis K. Semertzidis,[44,64,k] Alexander Silenko,[79] Jaideep T. Singh,[80] Leonid V. Skripnikov,[67,68] Amarjit Soni,[14] Edward Stephenson,[58] Riad Suleiman,[81] Ayaki Sunaga,[82] Michael Syphers,[83] Sergey Syritsyn,[84] M. R. Tarbutt,[85] Pia Thoerngren,[86] Rob G. E. Timmermans,[87] Volodya Tishchenko,[14] Anatoly V. Titov,[67,68] Nikolaos Tsoupas,[14] Spyros Tzamarias,[88] Alessandro Variola,[40] Graziano Venanzoni,[10] Eva Vilella,[16] Joost Vossebeld,[16] Peter Winter,[89,l] Eunil Won,[51] Anatoli Zelenski,[14] Yan Zhou,[90] and Konstantin Zioutas[3]

[1] *Arizona State University, Tempe, AZ 85287, USA*
[2] *Cornell University, Ithaca, New York, USA*
[3] *University of Patras, Dept. of Physics, Patras-Rio, Greece*
[4] *The University of Tokyo, Meguro-ku, Tokyo, Japan*
[5] *TRIUMF, Vancouver, British Columbia, Canada*
[6] *University of Virginia, 382 McCormick Road, Charlottesville, VA 22903, USA*
[7] *Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN 37830, USA*
[8] *Bartoszek Engineering, Aurora, IL 60506, USA.*
[9] *University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA*
[10] *National Institute for Nuclear Physics (INFN-Pisa), Pisa, Italy*
[11] *Philipps-Universitaet Marburg, Fachbereich Chemie,*
Hans-Meerwein-Str. 4, 35032 Marburg, Germany
[12] *Michigan State University, East Lansing, Michigan, USA*
[13] *T-2, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[14] *Brookhaven National Laboratory, Upton, New York, USA*
[15] *Department of Physics, University of Connecticut, USA*
[16] *University of Liverpool, Liverpool, UK*
[17] *Helmholtz-Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[18] *University of California at Berkeley, Berkeley, California, USA*

EDM timelines, from Snowmass 2021 (2022).



Blum, Winter *et al.*

Figure 3-1. *Timelines for the major current and planned EDM searches with their sensitivity to the important parameters of the effective field theory (see Fig. 3-2 for details). Solid (shaded) symbols indicate each experiment's primary (secondary) sensitivities. Measurement goals indicated by the black arrows are based on current plans of the various groups.*

Snowmass paper on EDMs

Neutron EDM

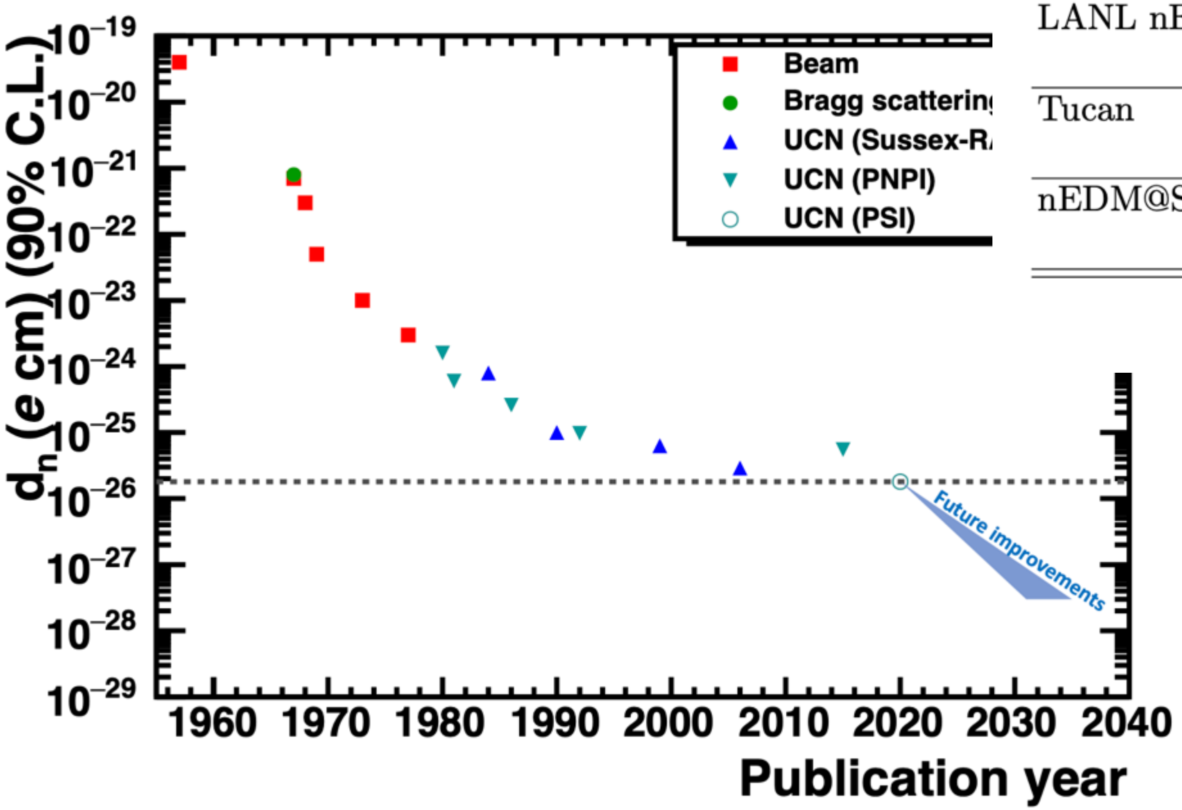
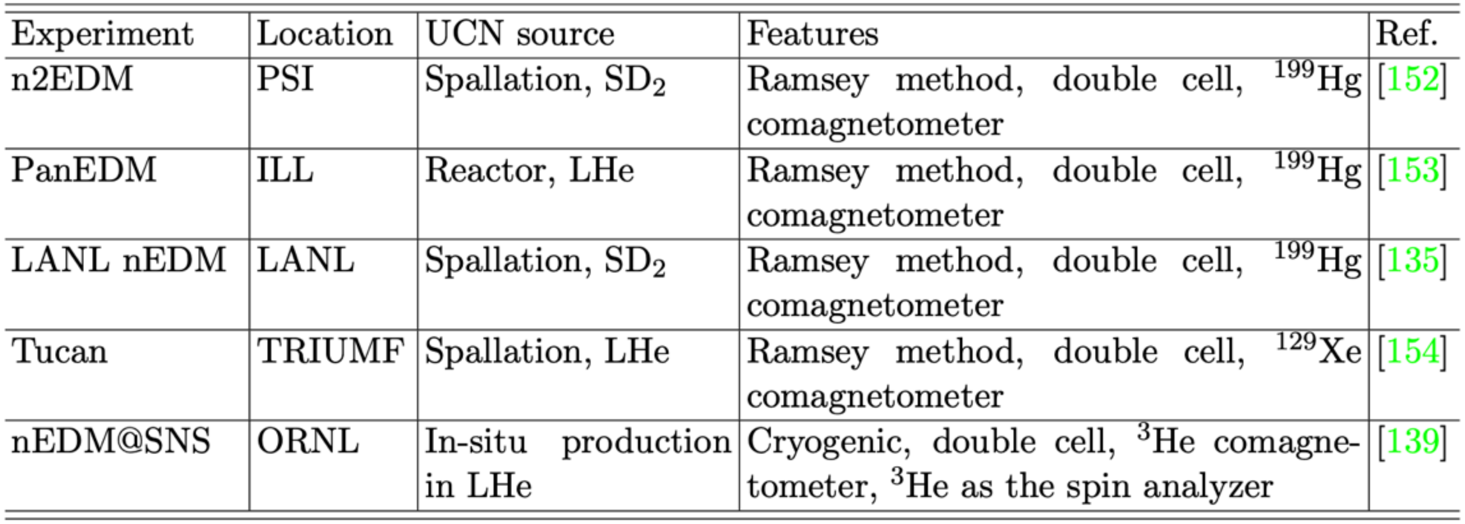


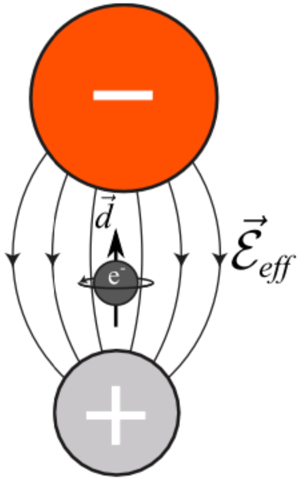
FIG. 3. Evolution of the nEDM results along with projected future results



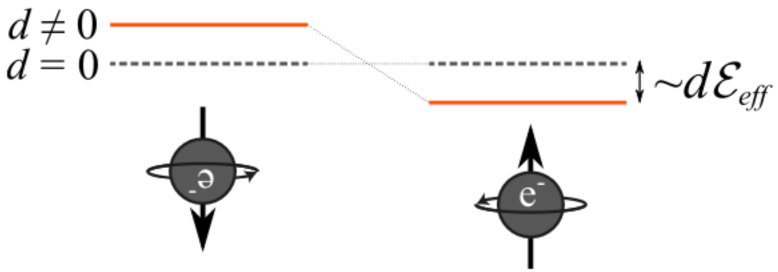
Experiment	Location	UCN source	Features	Ref.
n2EDM	PSI	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer	[152]
PanEDM	ILL	Reactor, LHe	Ramsey method, double cell, ^{199}Hg comagnetometer	[153]
LANL nEDM	LANL	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer	[135]
Tucan	TRIUMF	Spallation, LHe	Ramsey method, double cell, ^{129}Xe comagnetometer	[154]
nEDM@SNS	ORNL	In-situ production in LHe	Cryogenic, double cell, ^{3}He comagnetometer, ^{3}He as the spin analyzer	[139]

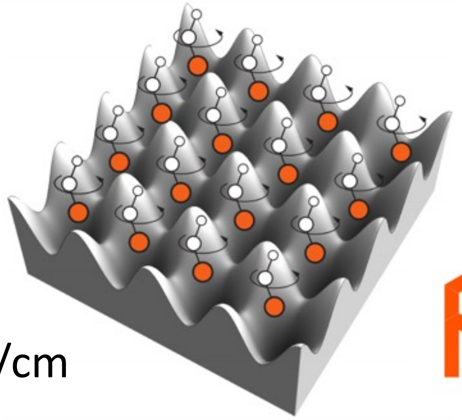
TABLE III. A list of the nEDM experiments that are being developed

Snowmass paper on EDMs



Effective E-field with polar molecules: order GV/cm





PolyEDM

Figure: Laser-cooled polyatomic molecules, optically trapped, with full quantum control. Such a platform can be used to access new physics at the PeV scale.

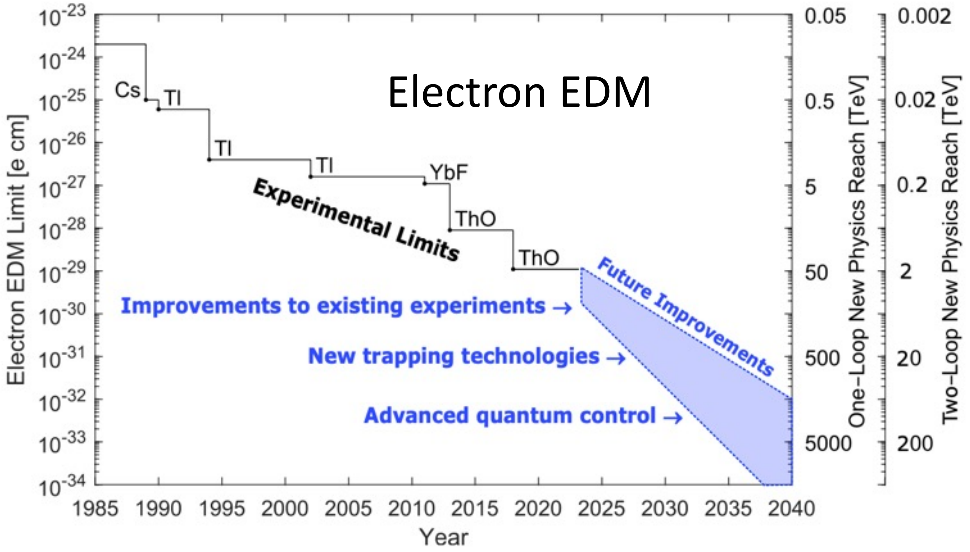
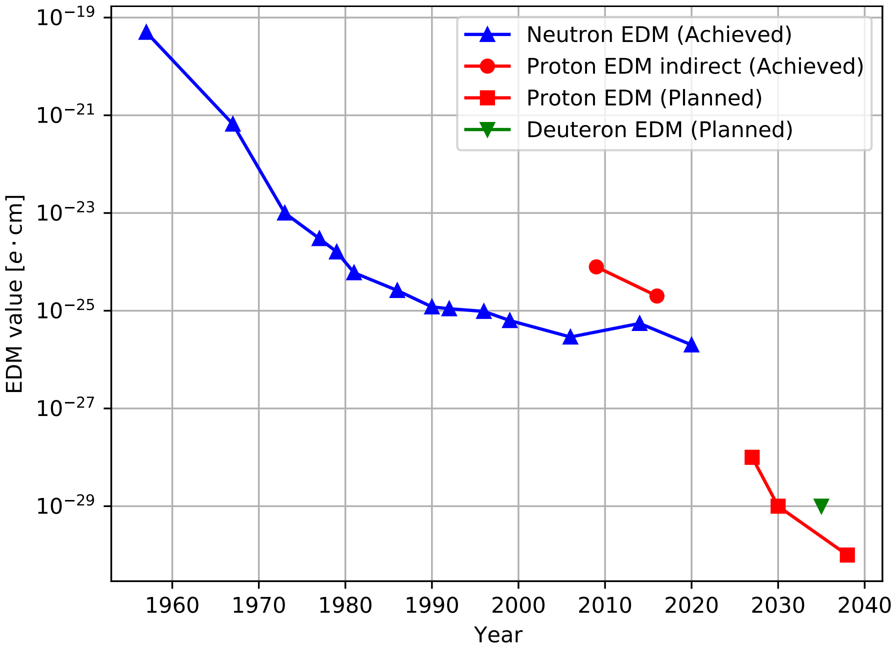


FIG. 5. Electron EDM limits versus time, along with new physics reach for one-loop and two-loop effects (see Eq. 2). All electron EDM experiments to date use AMO techniques. The solid line indicates the most sensitive experimental limit, including the species used. The shaded area indicates potential future improvements discussed in the text. Improvements in the next few years are driven largely by improvements to existing experiments and are quite likely, though as we go more into the future the projection becomes increasingly speculative and uncertain.

Storage ring EDM experiment

- Snowmass white paper: next steps - CDR, proposal, TDR
- 10^{-29} *e*-cm; fits in BNL AGS tunnel
    - World-class, high intensity polarized sources for protons, deuterons, ^{3}He, other nuclei
    - ring design PRD105:032001 (2022), storage ring experiment Rev.Sci.Instrum.87:115116 (2016)
- Possible interesting results within a decade (compatible with EIC schedule)
- Competitive EDM sensitivity:
    - New-Physics reach ~10^3 TeV.
    - Best probe on Higgs CPV, Marciano
        - proton is better than H→ $\gamma\gamma$
        - 30x better than electron with same EDM.
    - Three orders of magnitude improvement in θ_{QCD} sensitivity.
    - Direct axion dark matter reach (best exp. sensitivity at very low frequencies).

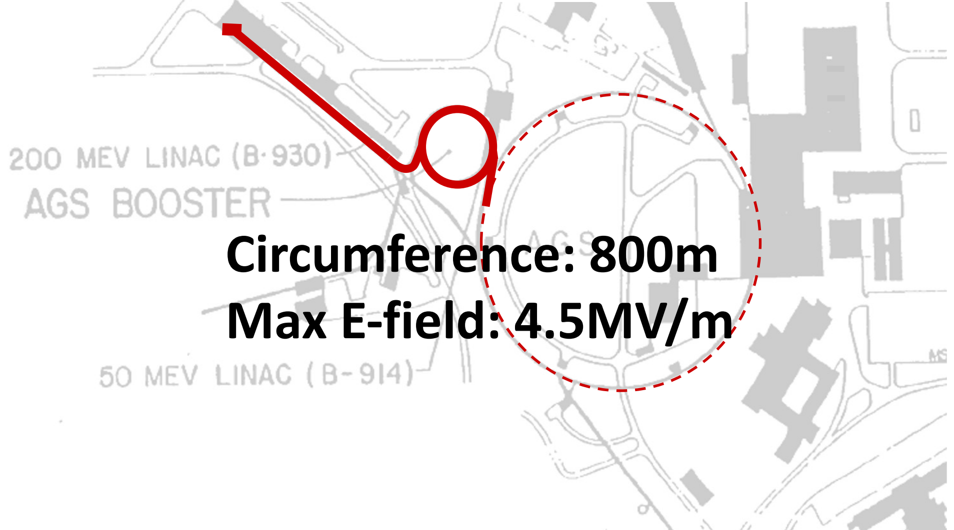


The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

[1] *Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2] *Argonne National Laboratory, Lemont, Illinois, USA*
[3] *Boston University, Boston, Massachusetts, USA*
[4] *Brookhaven National Laboratory, Upton, New York, USA*
[5] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[6] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon, Korea*
[7] *Cornell University, Ithaca, New York, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[9] *Helmholtz-Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[10] *Indiana University, Bloomington, Indiana, USA*
[11] *Istanbul Technical University, Istanbul, Turkey*

arXiv:2205.00830v1 [hep-ph] 25 Apr 2022



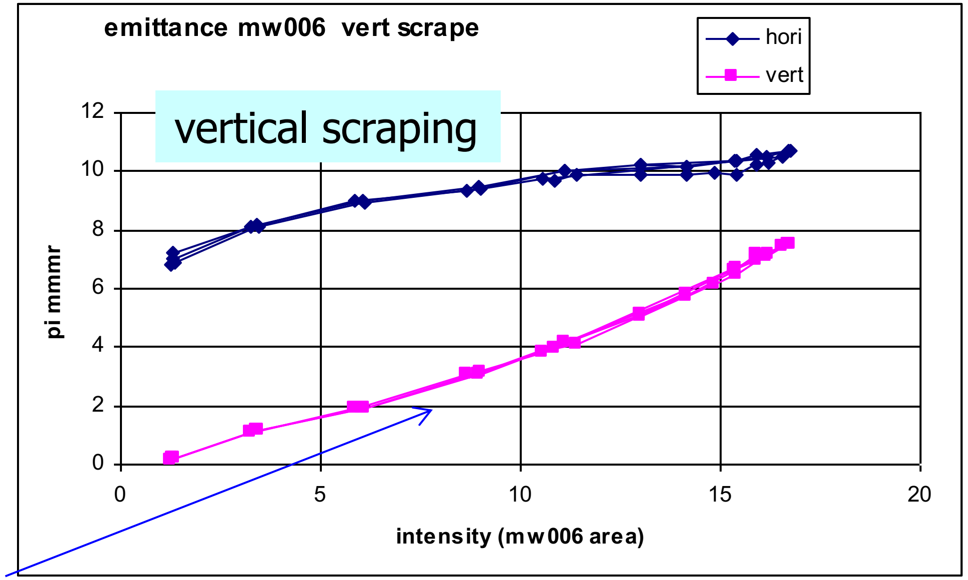
Circumference: 800m

Max E-field: 4.5MV/m

High intensity polarized proton Beam at BNL

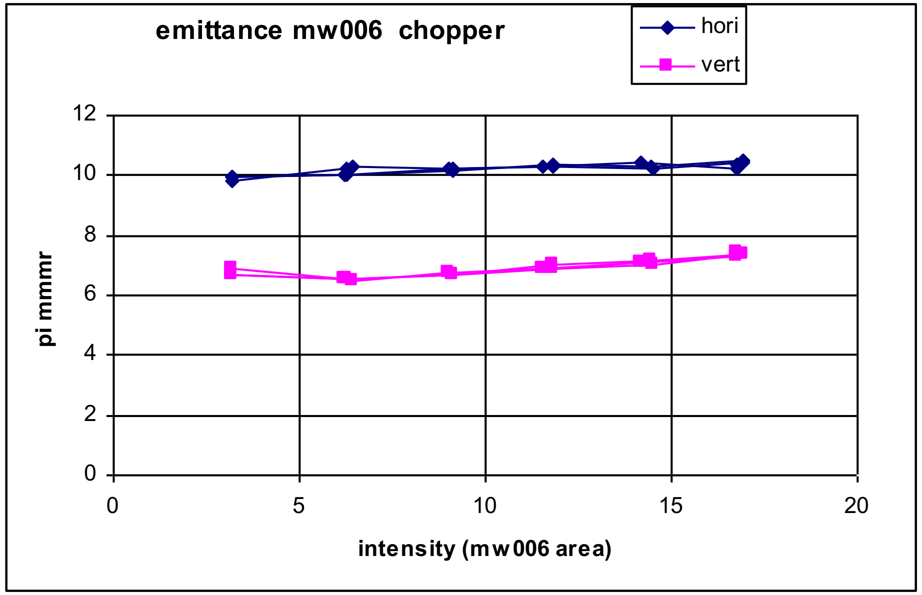
Proton intensity at Booster input $3*10^{11}$. The vertical scale is normalized 95% emittance.

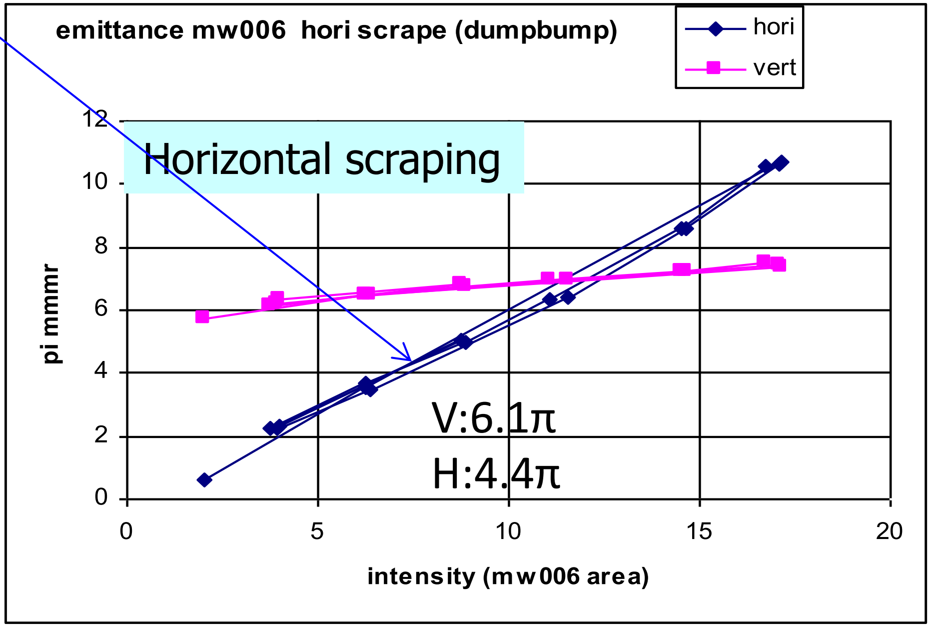
The corresponding normalized rms emittance at 10^{11} is 0.7π horizontal, 1.0π vertical for horizontal scraping.



@10^{11}

Intensity: 15~2e11 protons





Large statistics available, opportunity for great sensitivity improvement in EDMs

CAPP-Physics: strong CP-problem and axion dark matter

- Dark Matter and CP-violation are both on the top ten most important Particle Physics questions

- The axion coupling is feeble, it requires the effective application of latest state of the art technology and lots of ingenuity (high-risk, high-physics-potential)

- CAPP (est. October 16, 2013) has acquired the equipment and has developed the technology, know-how, and infra-structure to effectively probe the 1-8 GHz in the next five years at DFSZ sensitivity. CAPP reached top of its field in less than ten years.

- Projection: All the interesting axion frequencies will be probed globally in the next 10-20 years

Institute for Basic Science
ibs
기초과학연구원
CAPP
Center for
Axion and Precision
Physics Research

Dark Matter and Isaac Newton (1642-1726)

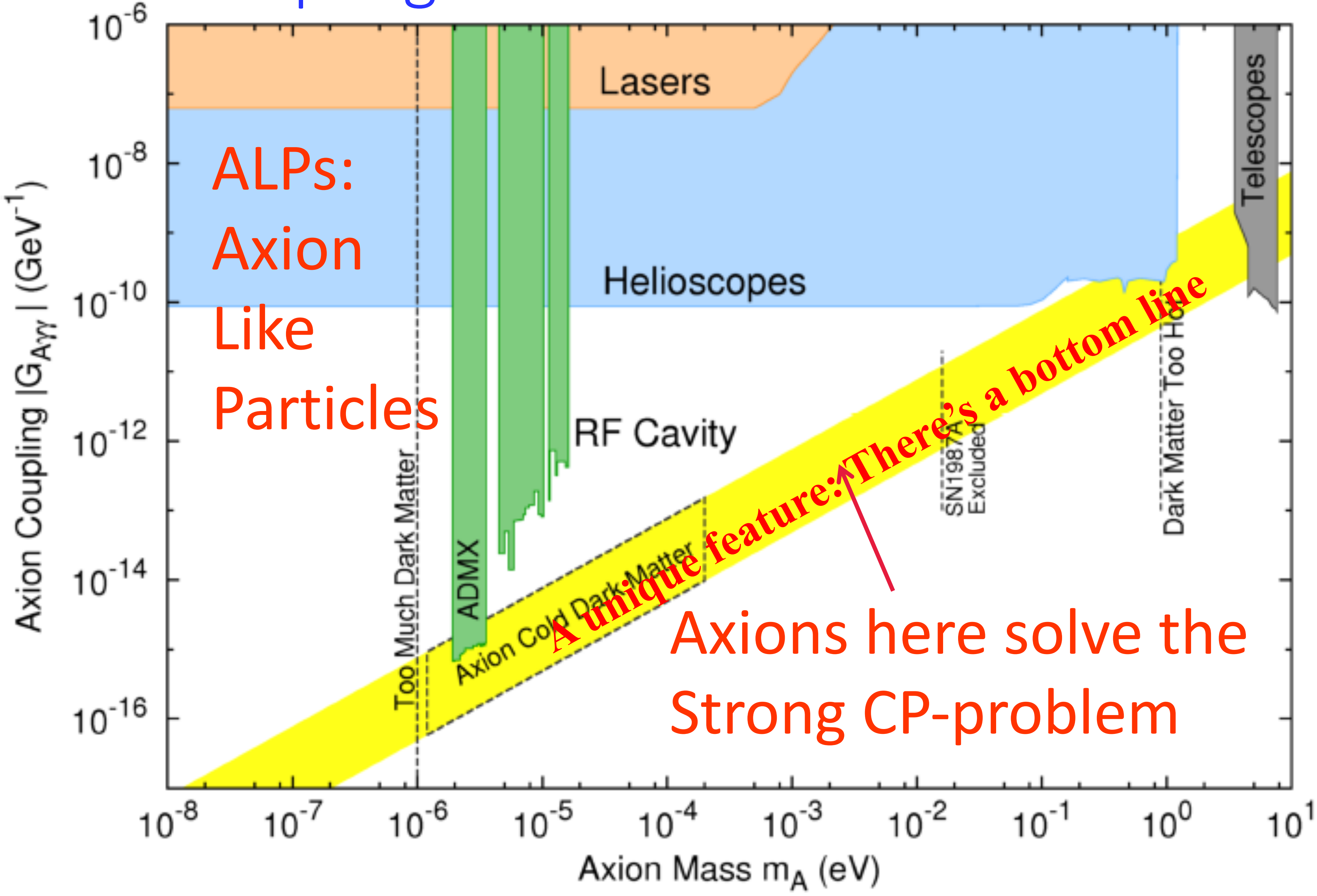
Isaac Newton unified the Physics phenomena: falling of an apple with the planet, moon, star, sattelite, comet motions, under Gravity!

He clarified the view of Heavens for Humanity!

He also gave us the ability to see what cannot be seen with ordinary methods. Looking from deviations from his rules we are able to sense the presence of Dark Matter.

A dark matter discovery is of High Order!

Axion coupling vs. axion mass

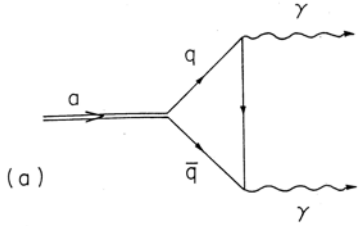


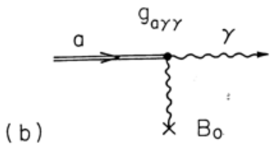
ALPs:
Axion
Like
Particles

A unique feature: There's a bottom line

Axions here solve the Strong CP-problem

Axion Couplings





- Gauge fields:
  - Electromagnetic fields (microwave cavities)
  - $$L_{\text{int}} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$
  - Gluon Fields (Oscillating EDM: CASPEr, storage ring EDM)

$$L_{\text{int}} = \frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

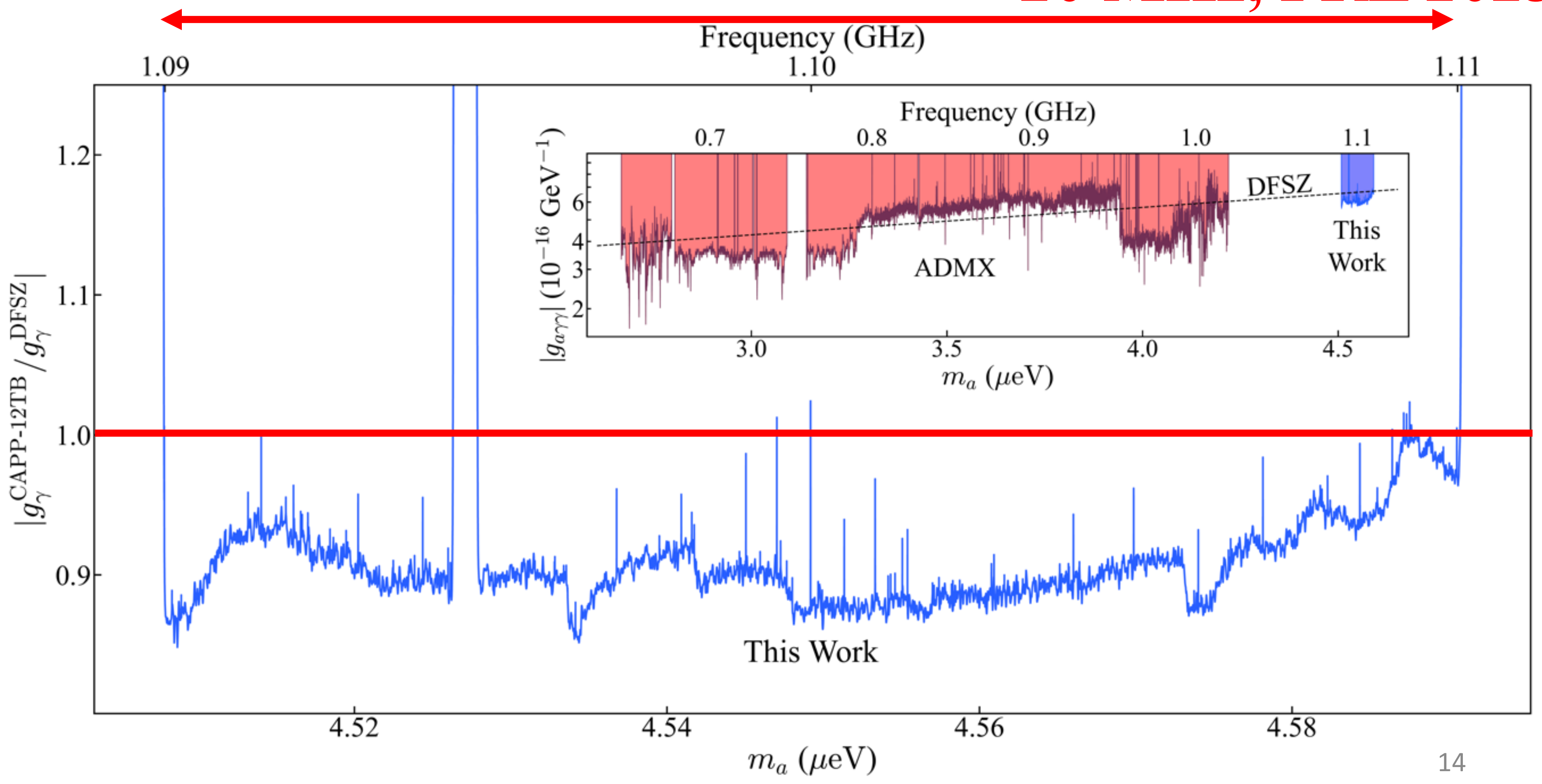
- Fermions (coupling with axion field gradient, pseudomagnetic field, CASPEr-Electric, ARIADNE; GNOME)

$$L_{\text{int}} = \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

CAPP-12TB RUN4, engineering run, spring 2022

CAPP in the DFSZ club. **Axion search around 4.55 μeV (1.09 – 1.11 GHz) with DFSZ sensitivity, scanning at 1.4MHz/day**

20 MHz, PRL 2023



DFSZ

CAPP-12TB RUN4, engineering run, spring 2022

PHYSICAL REVIEW LETTERS **130,** 071002 (2023)

Axion Dark Matter Search around 4.55 μeV with Dine-Fischler-Srednicki-Zhitnitskii Sensitivity

Andrew K. Yi,[1,2] Saebyeok Ahn,[1,2] Çağlar Kutlu,[1,2] JinMyeong Kim,[1,2] Byeong Rok Ko,[2,*] Boris I. Ivanov,[2] HeeSu Byun,[2] Arjan F. van Loo,[3,4] SeongTae Park,[2] Junu Jeong,[2] Ohjoon Kwon,[2] Yasunobu Nakamura,[3,4] Sergey V. Uchaikin,[2] Jihoon Choi,[2,†] Soohyung Lee,[2] MyeongJae Lee,[2,‡] Yun Chang Shin,[2] Jinsu Kim,[1,2] Doyu Lee,[2,§] Danho Ahn,[1,2] SungJae Bae,[1,2] Jiwon Lee,[1,2] Younggeun Kim,[2] Violeta Gkika,[2] Ki Woong Lee,[2] Seonjeong Oh,[2] Taehyeon Seong,[2] DongMin Kim,[2] Woohyun Chung,[2] Andrei Matlashov,[2] SungWoo Youn,[2] and Yannis K. Semertzidis[2,1]

[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea*
[2]*Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon 34051, Republic of Korea*
[3]*RIKEN Center for Quantum Computing (RQC), Wako, Saitama 351-0198, Japan*
[4]*Department of Applied Physics, Graduate School of Engineering, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan*

(Received 19 October 2022; revised 9 December 2022; accepted 12 January 2023; published 16 February 2023)

We report an axion dark matter search at Dine-Fischler-Srednicki-Zhitnitskii sensitivity with the CAPP-12TB haloscope, assuming axions contribute 100% of the local dark matter density. The search excluded the axion-photon coupling $g_{a\gamma\gamma}$ down to about 6.2×10^{-16} GeV^{-1} over the axion mass range between 4.51 and 4.59 μeV at a 90% confidence level. The achieved experimental sensitivity can also exclude Kim-Shifman-Vainshtein-Zakharov axion dark matter that makes up just 13% of the local dark matter density. The CAPP-12TB haloscope will continue the search over a wide range of axion masses.

DOI: 10.1103/PhysRevLett.130.071002

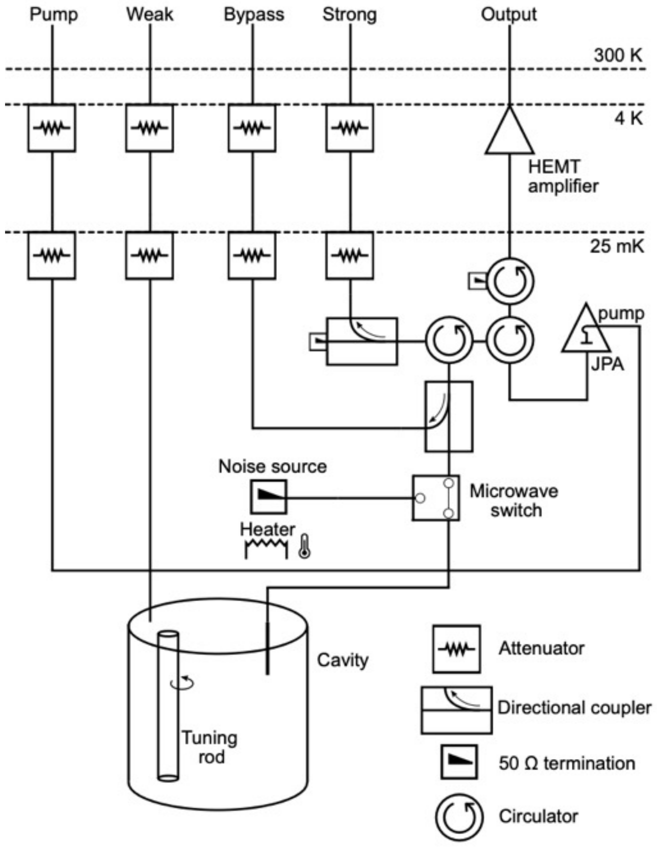


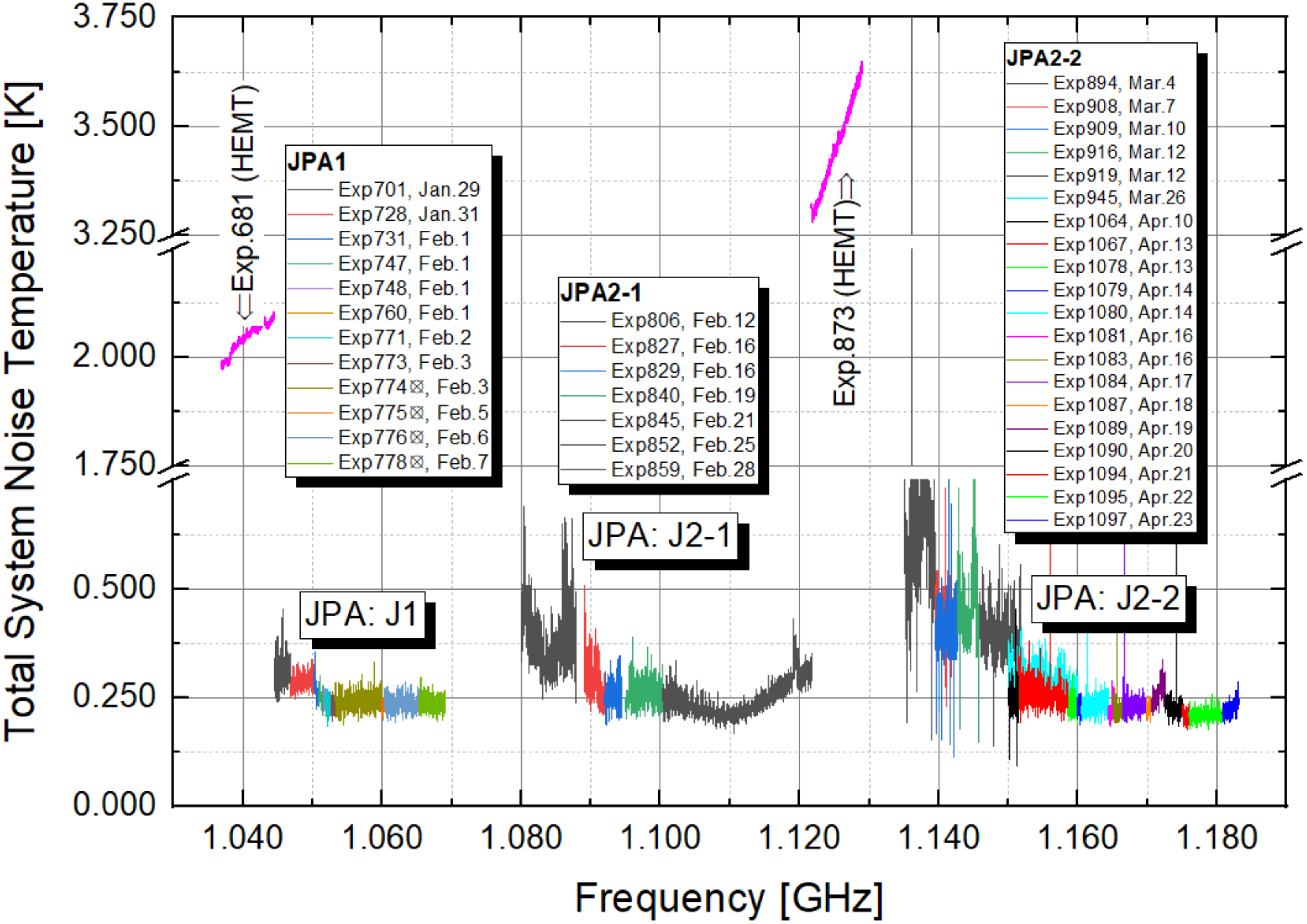
FIG. 2: CAPP-12TB receiver diagram.

A 37 liter cavity at below than 30mK, low noise readout system

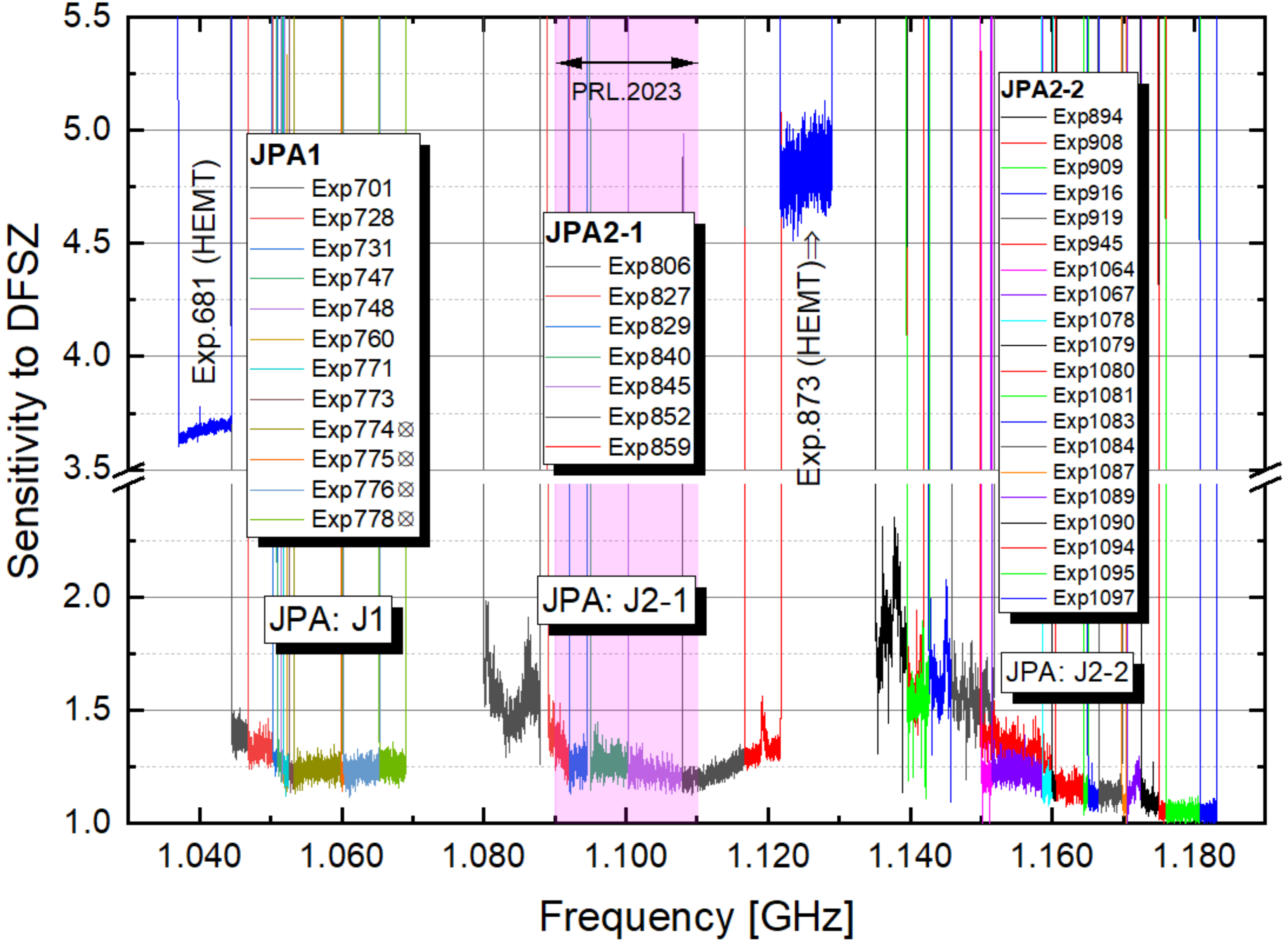
12T, 320mm aperture Nb_3Sn magnet, Oxford Instr.

New data: CAPP-MAX, as of April 2023

Achieved already sensitivity (preliminary), scanning at 3MHz/day



New data: CAPP-MAX, as of April 2023



PRELIMINARY

Reaching ~120 MHz at DFSZ sensitivity by end of April 2023

Institute for Basic Science, South Korea
2011: Major Investment in Basic Sciences

- IBS-CAPP is scanning at DFSZ sensitivity for axions over 1 GHz.

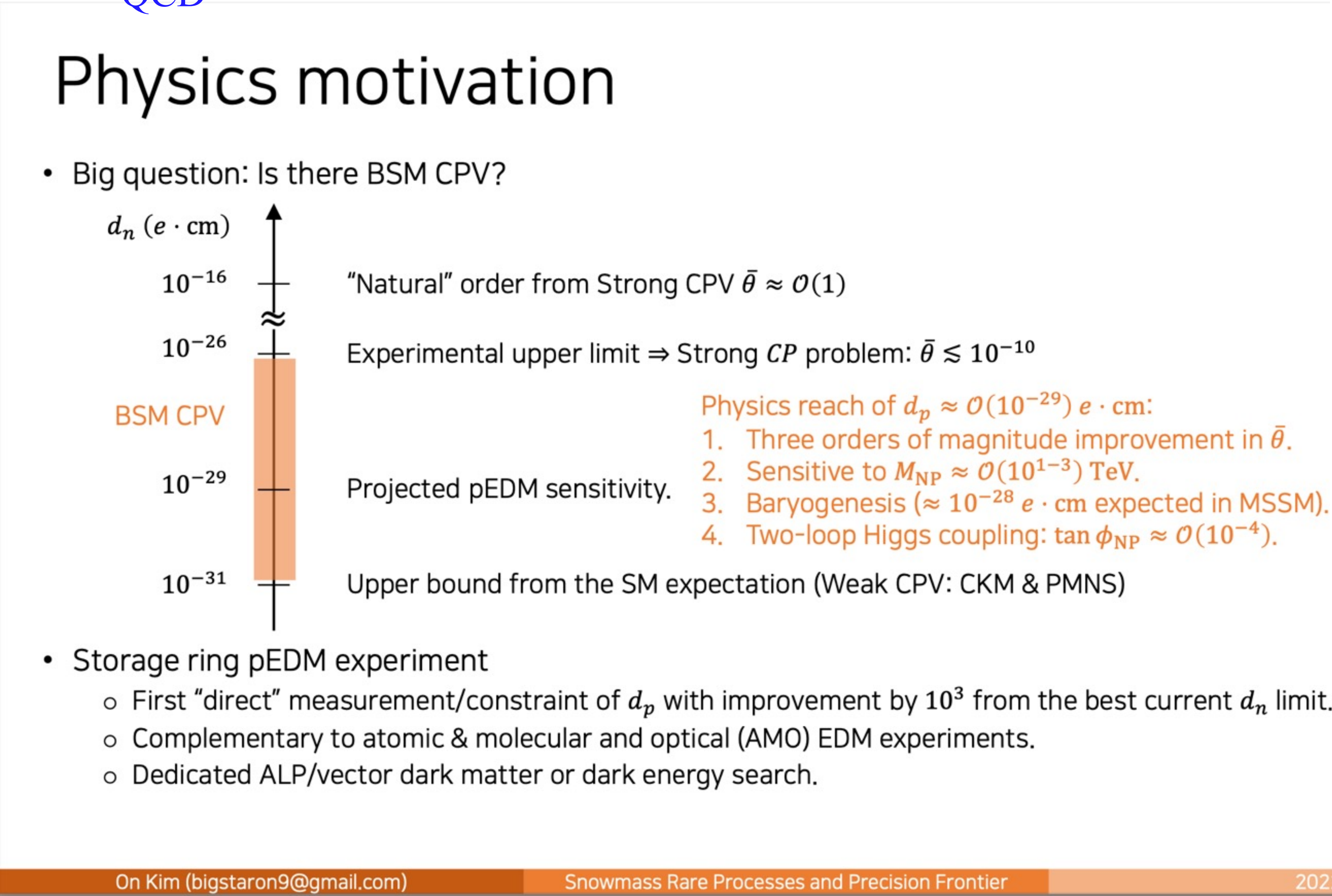
- IBS-CAPP with its many innovations including its HTS-cavities ($Q>10^7$ at 8T) is currently on top of its field internationally in less than ten years since its establishment!

- IBS-CAPP has demonstrated that the original IBS idea was correct: have a great idea and if selected, IBS will fund it for ten years to materialize it.

The storage ring EDM Physics

Two main physics goals of pEDM

- CP-violation probing New Physics up to 10^3 TeV
- θ_{QCD} and axion dark matter



Physics motivation

- Big question: Is there BSM CPV?

$d_n\ (e \cdot \mathrm{cm})$

10^{-16} "Natural" order from Strong CPV $\bar{\theta} \approx \mathcal{O}(1)$

10^{-26} Experimental upper limit ⇒ Strong CP problem: $\bar{\theta} \lesssim 10^{-10}$

BSM CPV

Physics reach of $d_p \approx \mathcal{O}(10^{-29})\ e \cdot \mathrm{cm}$:

1. Three orders of magnitude improvement in $\bar{\theta}$.
2. Sensitive to $M_{\mathrm{NP}} \approx \mathcal{O}(10^{1-3})$ TeV.
3. Baryogenesis ($\approx 10^{-28}\ e \cdot \mathrm{cm}$ expected in MSSM).
4. Two-loop Higgs coupling: $\tan \phi_{\mathrm{NP}} \approx \mathcal{O}(10^{-4})$.

10^{-29} Projected pEDM sensitivity.

10^{-31} Upper bound from the SM expectation (Weak CPV: CKM & PMNS)

- Storage ring pEDM experiment
  - First "direct" measurement/constraint of d_p with improvement by 10^3 from the best current d_n limit.
  - Complementary to atomic & molecular and optical (AMO) EDM experiments.
  - Dedicated ALP/vector dark matter or dark energy search.

On Kim (bigstaron9@gmail.com) Snowmass Rare Processes and Precision Frontier 2022 July 20th 9

The storage ring proton EDM experiment

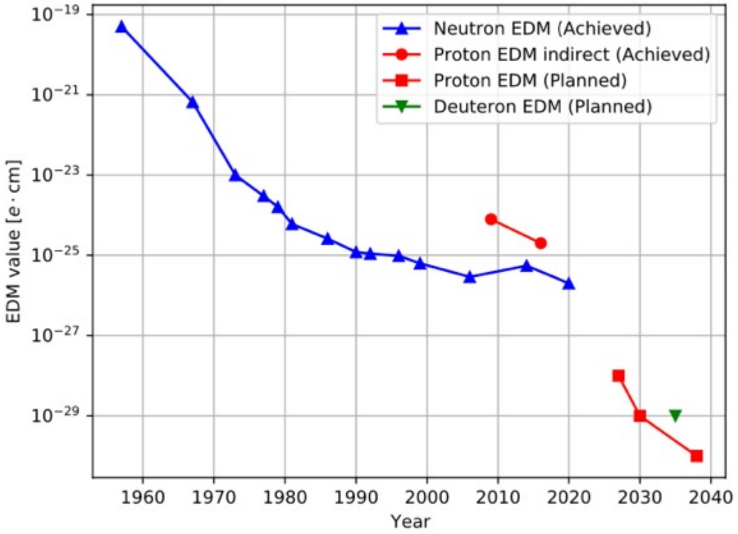
arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

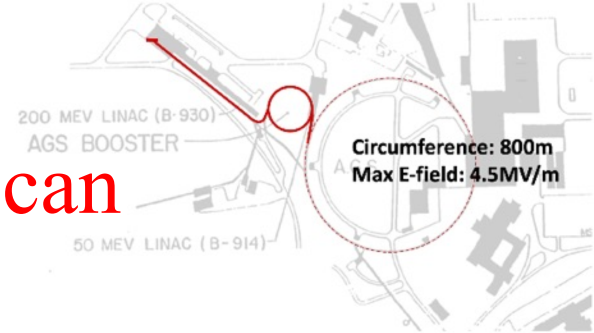
Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

[1] *Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2] *Argonne National Laboratory, Lemont, Illinois, USA*
[3] *Boston University, Boston, Massachusetts, USA*
[4] *Brookhaven National Laboratory, Upton, New York, USA*
[5] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[6] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon, Korea*
[7] *Cornell University, Ithaca, New York, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[9] *Helmholtz-Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[10] *Indiana University, Bloomington, Indiana, USA*
[11] *Istanbul Technical University, Istanbul, Turkey*

Timeline

- Snowmass/white paper, CDR, proposal/TDR, prototype/string-test, ring construction (3-5 years), storage (2-3 years) to first publication
- Cost estimation currently at BNL
- Possible interesting results within a decade.



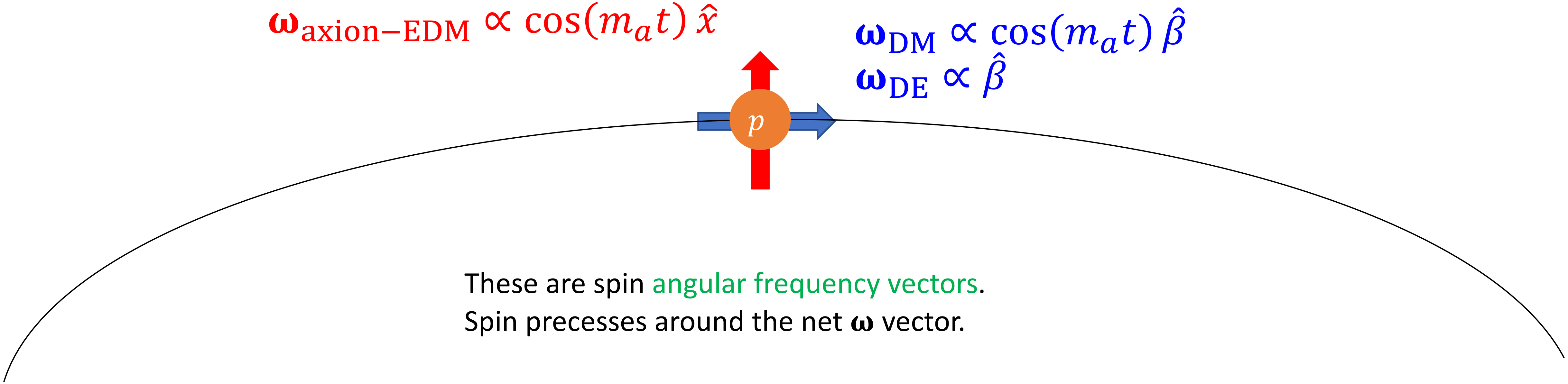


A long road to final sensitivity, but confident we can reach the goals, based on muon g-2 experience

Storage ring probes of DM/DE

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

- Couplings with dark matter (DM) and dark energy (DE)
  - ALP DM-EDM ($g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}$) ⇒ oscillating EDM at m_a. For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.
  - ALP or vector DM wind ($g_{aNN} \nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE wind ⇒ anomalous longitudinal B field.



These are spin angular frequency vectors.
Spin precesses around the net $\boldsymbol{\omega}$ vector.

Storage ring probes of DM/DE

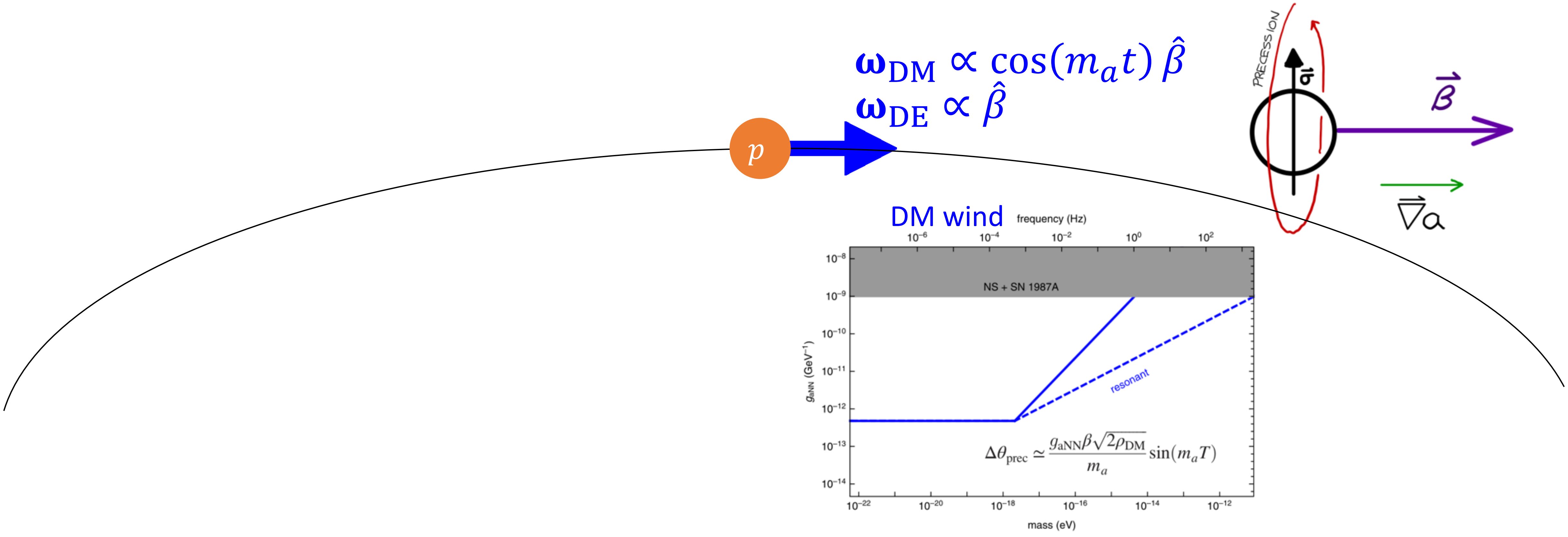
- Couplings with dark matter (DM) and dark energy (DE)

P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

  - ALP or vector DM wind ($g_{aNN}\nabla a \cdot \hat{\sigma}_N$) ⇒ anomalous longitudinal oscillating B field.
  - DE wind ⇒ anomalous longitudinal B field.

Storage ring is an optimal probe for wind coupling since β is large!

$$\boldsymbol{\omega}_{\mathrm{DM}} \propto \cos(m_a t)\,\hat{\beta}$$
$$\boldsymbol{\omega}_{\mathrm{DE}} \propto \hat{\beta}$$

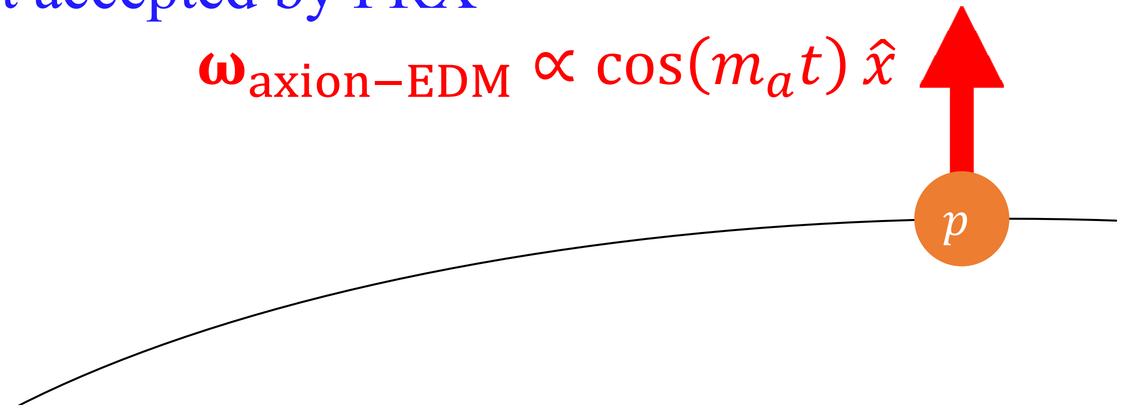


Storage ring probes of DM/DE

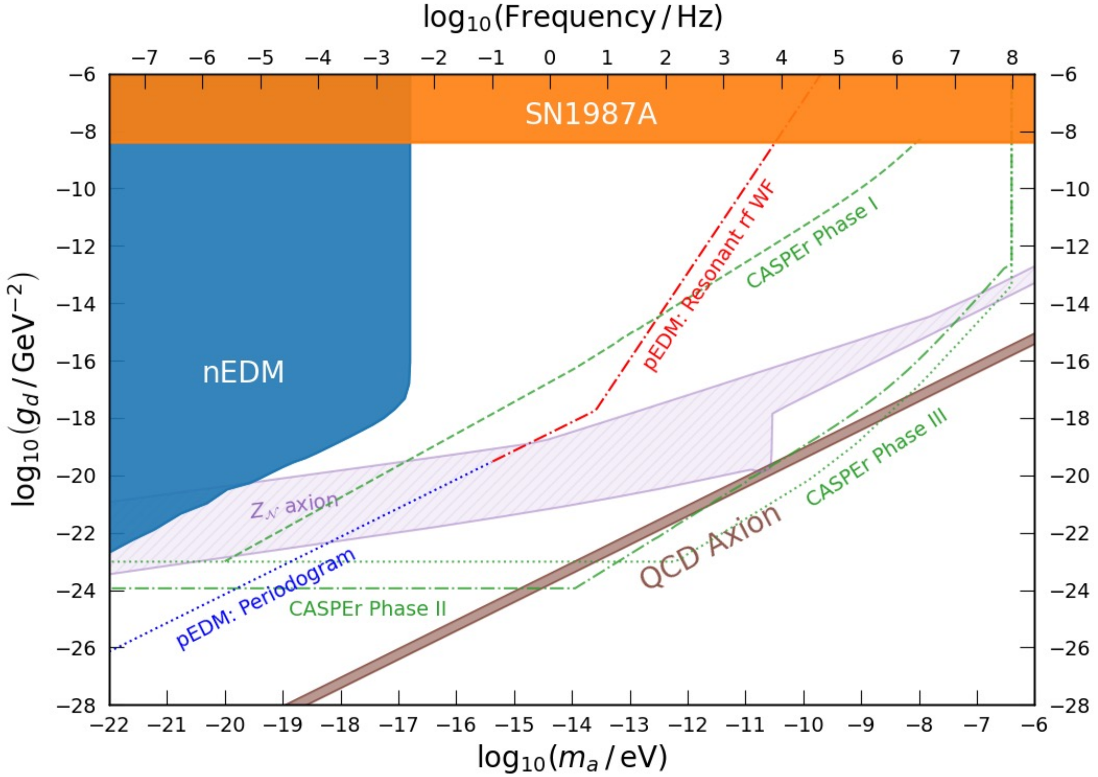
P. Graham and S. Rajendran, PRD **88**, 035023 (2013)
P. Graham et al., PRD **103**, 055010 (2021)

- Couplings with dark matter (DM) and dark energy (DE)
  - ALP DM-EDM $(g_{aN\gamma} a \hat{\sigma}_N \cdot \mathbf{E}) \Rightarrow$ oscillating EDM at m_a. For the QCD axion: $d_N^{\mathrm{QCD}} \approx 10^{-34} \cos(m_a t)\ e \cdot \mathrm{cm}$.

First experimental application at COSY 2019-2022
Paper just accepted by PRX


$\boldsymbol{\omega}_{\mathrm{axion-EDM}} \propto \cos(m_a t)\ \hat{x}$

ALP-EDM coupling



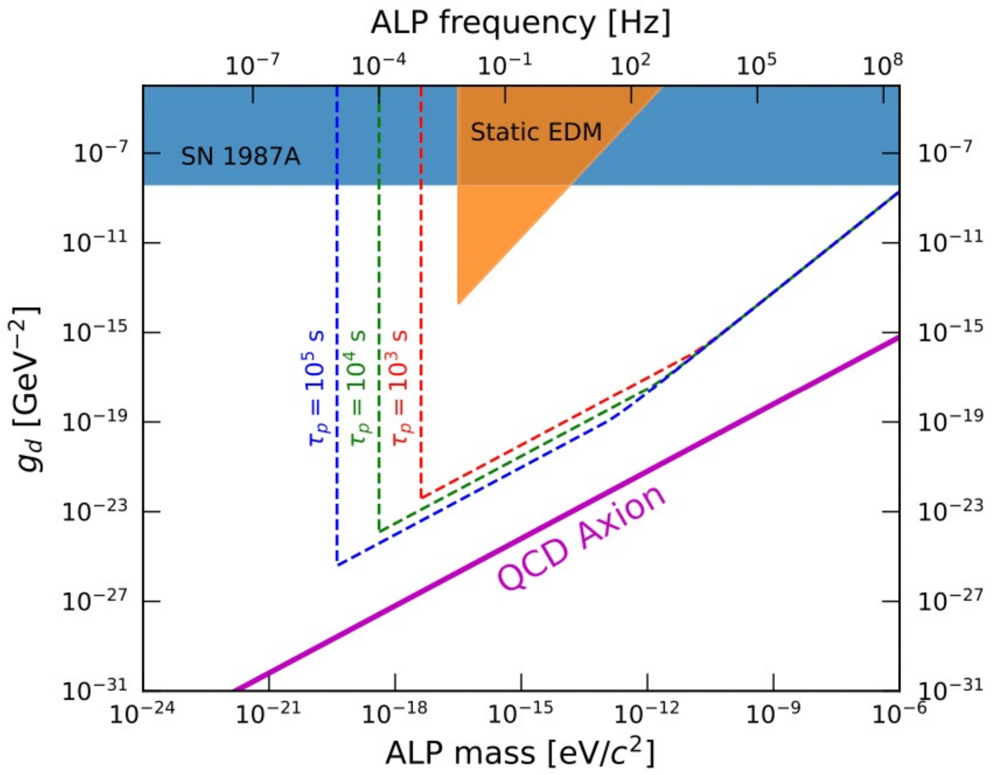
- Storage ring probes of axion-induced oscillating EDM
  S. Chang *et al.*, PRD **99**, 083002 (2019).
- Complementary method using an rf Wien filter
  On Kim and Y. Semertzidis, PRD **104**, 096006 (2021)
- Parasitic measurement with pEDM experiment
  - Low frequency: Periodogram analysis.
  - High frequency: Resonant rf Wien filter.

Storage ring proton/deuteron EDM

- Oscillating EDMs, Graham & Rajendran, PRD88, 035023, 2013
- Resonance: axion dark matter and g-2 frequencies (PRD99, 083002, 2019 and EPJ C80, 107, 2020). First run spring 2019 at COSY/Juelich/Germany.
- Storage ring probe of DM and DE (PRD103, 055010, 2021)
- New method with RF-Wien…, On Kim (PRD104, 096006, 2021), great advantage on systematic errors

The RF-Wien filter is NOT operating at the g-2 frequency, avoiding spin dynamics systematic error!

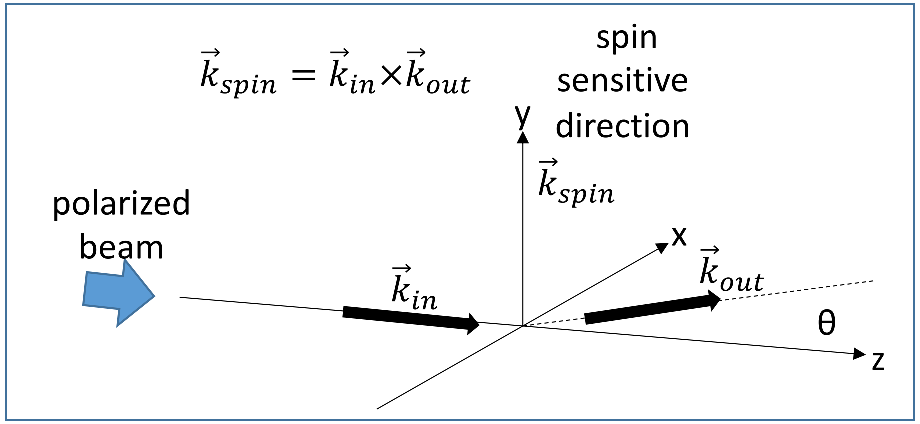
It can be fully implemented in the present muon g-2 ring by injecting polarized protons and/or deuterons

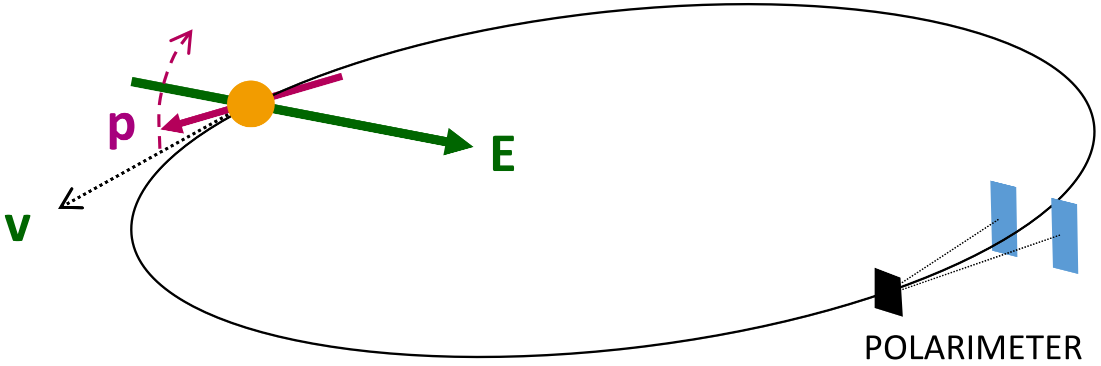


Storage ring pEDM at $10^{-29}e$-cm, best hadronic EDM exp.

- High physics reach at hundreds of TeV New-Physics mass scale, improve sensitivity to θ_{QCD} by three orders of magnitude. Best sensitivity to Higgs CPV
- If found, it can help explain the matter-antimatter asymmetry of the universe
- Direct search for low/very low frequency axion dark matter
- The opportunity: High intensity polarized proton and deuteron beams available. The natural beam lifetime is also long, potential for very high statistical accuracy
- The challenge: Systematics, mostly related to ring alignment, high statistical accuracy helps...

Storage ring Electric Dipole Moments





Phys. Rev. Lett. 93, 052001 (2004)

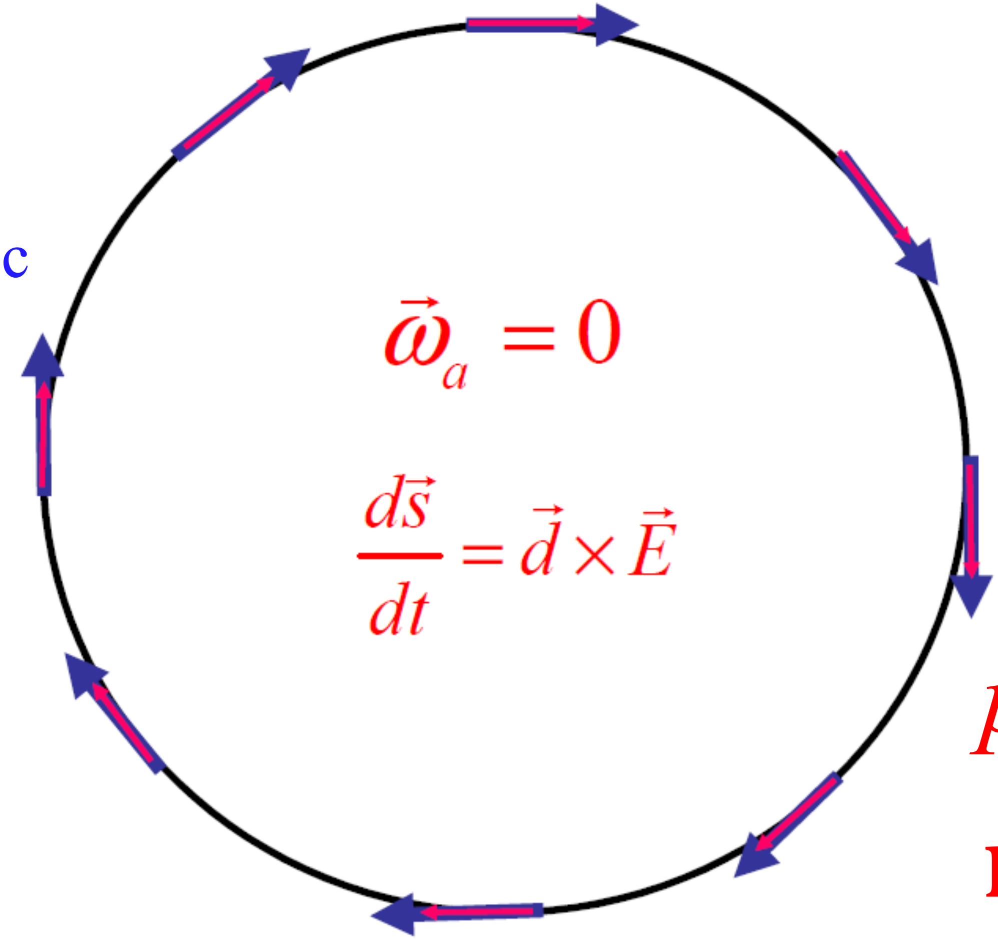
Frozen spin method:

- Spin aligned with the momentum vector
- Radial E-field precesses EDM/spin vertically
- Monitoring the spin using a polarimeter

Storage Ring EDM experiments, frozen spin method

Pure electric bending, w/ “magic” momentum

F.J.M. Farley *et al.*, “A new method of measuring electric dipole moments in storage rings,” Phys. Rev. Lett. 93, 052001 (2004).



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

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

The origins of the method trace right back to the muon g-2 experiment.

$p = \frac{mc}{\sqrt{a}}$, a: magnetic moment anomaly

Electric fields: Freezing the g-2 spin precession

$$\vec{\omega}_a = -\frac{q}{m}\left[a - \left(\frac{mc}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c} = 0$$

- The g-2 spin precession is zero at “magic” momentum (3.1GeV/c for muons,…), so the focusing system can be electric

$$p = \frac{mc}{\sqrt{a}}, with\ a = G = \frac{g-2}{2}, \gamma_m = \sqrt{1 + 1/a}$$

- The “magic” momentum concept with electric focusing was first used in the last muon g-2 experiment at CERN, at BNL & FNAL.

Proton Statistical Error (233MeV): 10^{-29} *e*-cm

Phys. Rev. D **104**, 096006 (2021)

$$\boxed{\sigma_d = \frac{2.33\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}}$$

τ_p : 2×10^3s Polarization Lifetime (Spin Coherence Time)
A : 0.6 Left/right asymmetry observed by the polarimeter
P : 0.8 Beam polarization
N_c : 4×10^{10}p/cycle Total number of stored particles per cycle (10^3s)
T_{Tot}: 2×10^7s Total running time per year
f : 1% Useful event rate fraction (efficiency for EDM)
E_R : 4.5 MV/m Radial electric field strength

Systematic errors

^{3}He Co-magnetometer in nEDM experiment

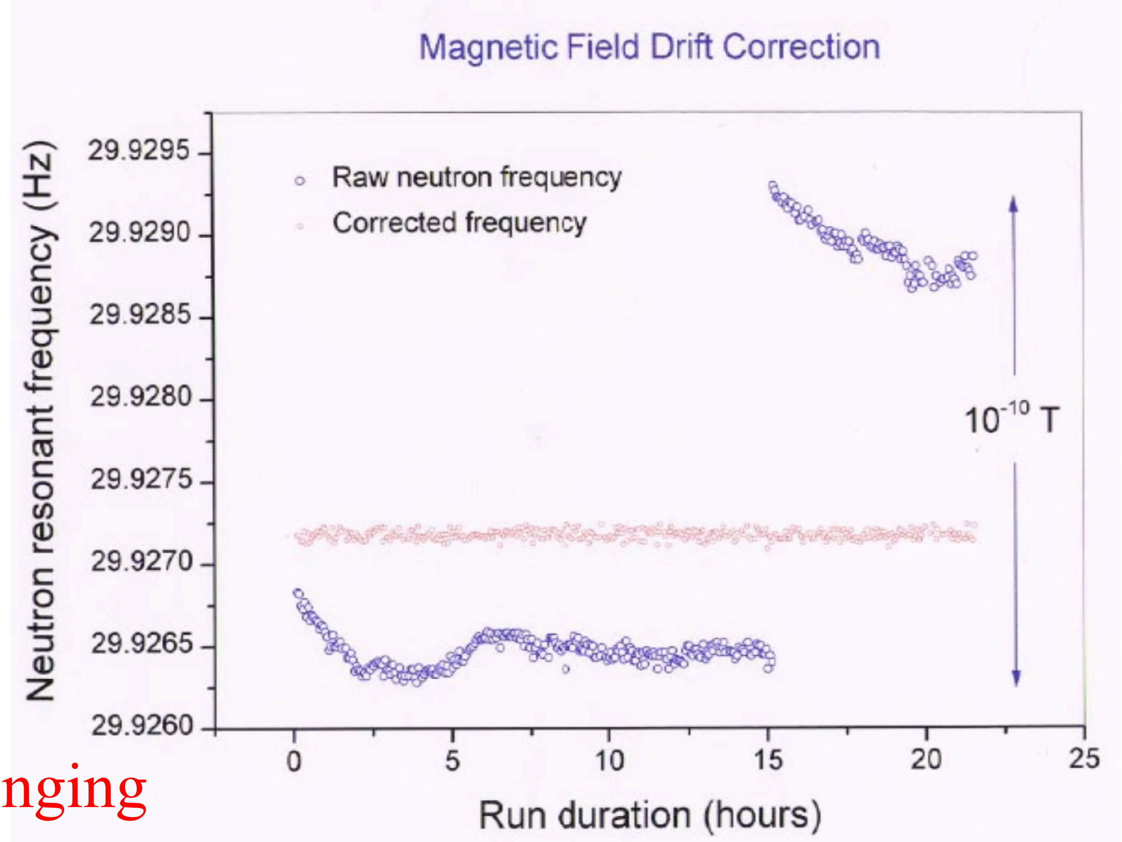
If nEDM = 10^{-26} e·cm,

10 kV/cm → 0.1 μHz shift

≅ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.



All EDM experiments are extremely challenging
Same with storage rings, muon g-2/EDM, proton EDM,…

Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ Z^2 → ^{3}He EDM << 10^{-30} e-cm

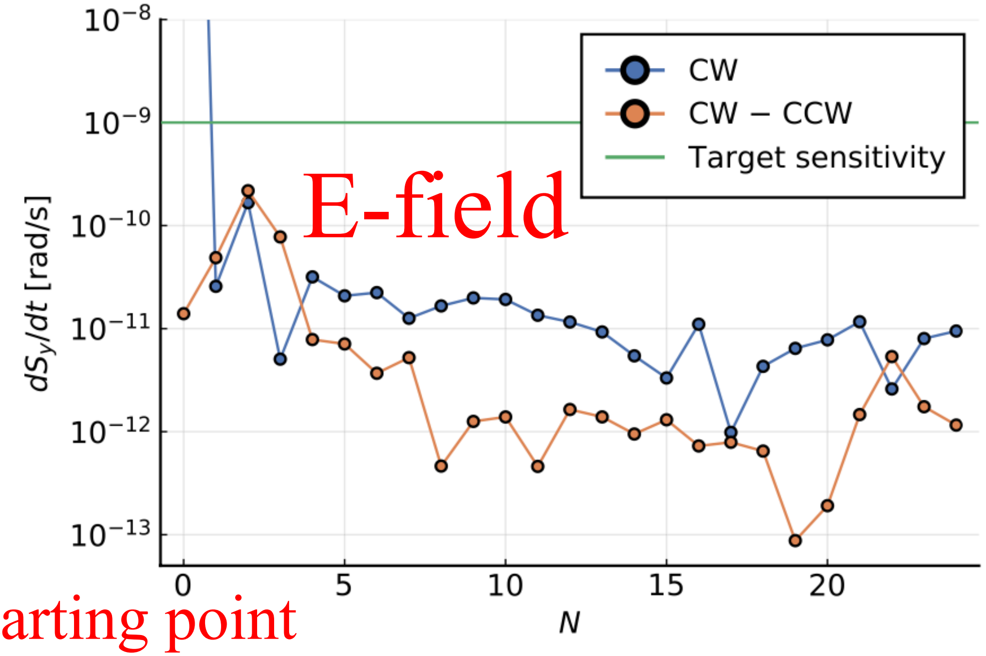
Under gravity, the center of mass of He-3 is higher than UCN by Δh ≈ 0.13 cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B=10^{-3}$.

Storage Ring Electric Dipole Moments exp. options

Fields	**Example**	**EDM signal term**	**Comments**
Dipole magnetic field **(B)** **(Parasitic)**	Muon g-2	Tilt of the spin precession plane. **(Limited statistical sensitivity due to spin precession)**	Eventually limited by geometrical alignment. **Requires consecutive CW and CCW injection to eliminate systematic errors**
Combination of electric & and magnetic fields **(E, B)** **(Combined lattice)**	Deuteron, ^{3}He, proton, muon, etc.	Mainly: $\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B}\right)}$	High statistical sensitivity. **Requires consecutive CW and CCW injection with main fields flipping sign to eliminate systematic errors**
Radial Electric field **(E)** & Electric focusing **(E)** **(All electric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Requires demonstration of adequate sensitivity to radial B-field syst. error**
Radial Electric field **(E)** & Magnetic focusing **(B)** **(Hybrid, symmetric lattice)**	Proton, etc.	$\boxed{\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}}$	Large ring, CW & CCW storage. **Only lattice to achieve direct cancellation of main systematic error sources (its own "co-magnetometer").** GOLD STANDARD!

Effect as a function of azimuthal harmonic *N*

COMPREHENSIVE SYMMETRIC-HYBRID RING DESIGN FOR A … PHYS. REV. D **105,** 032001 (2022)



A solid starting point

FIG. 7. *Longitudinal polarization case* $S_s = 1$, sensitive to EDM. Vertical spin precession rate vs $E_y = 10$ V/m field N harmonic around the ring azimuth. For $N = 0$, the precession rate for the CW (or CCW) beam is around 5 rad/s. The difference of the precession rates for CR beams (orange) is below the target sensitivity for all N. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

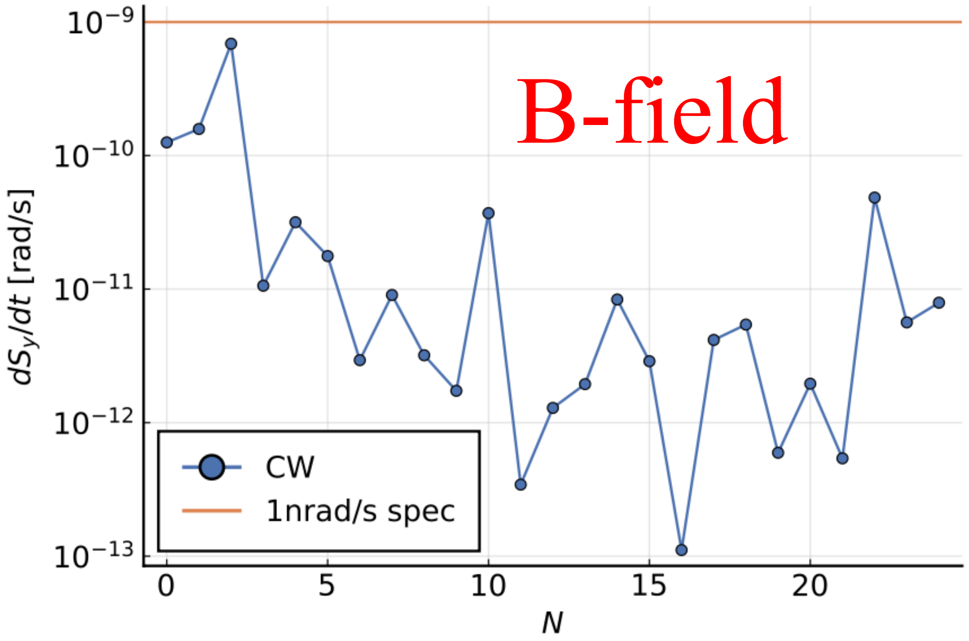
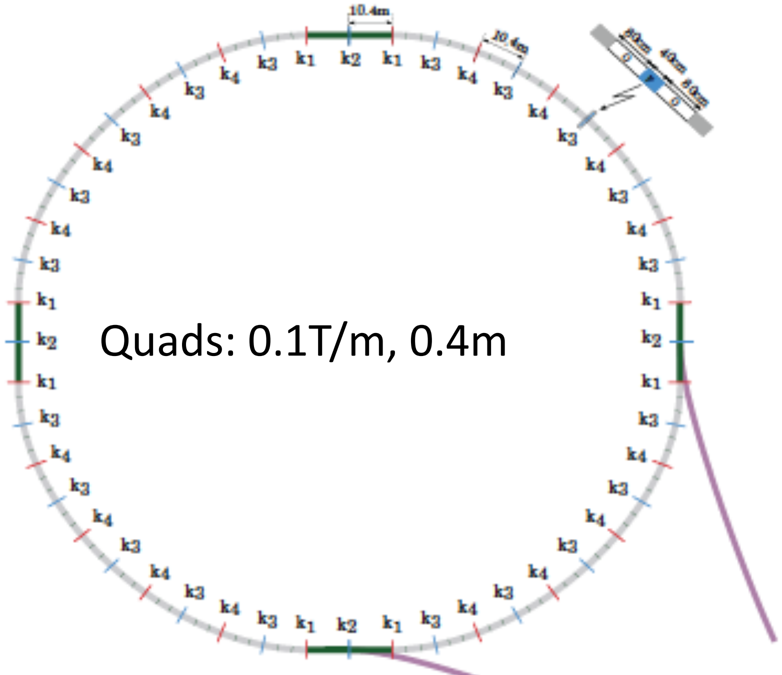
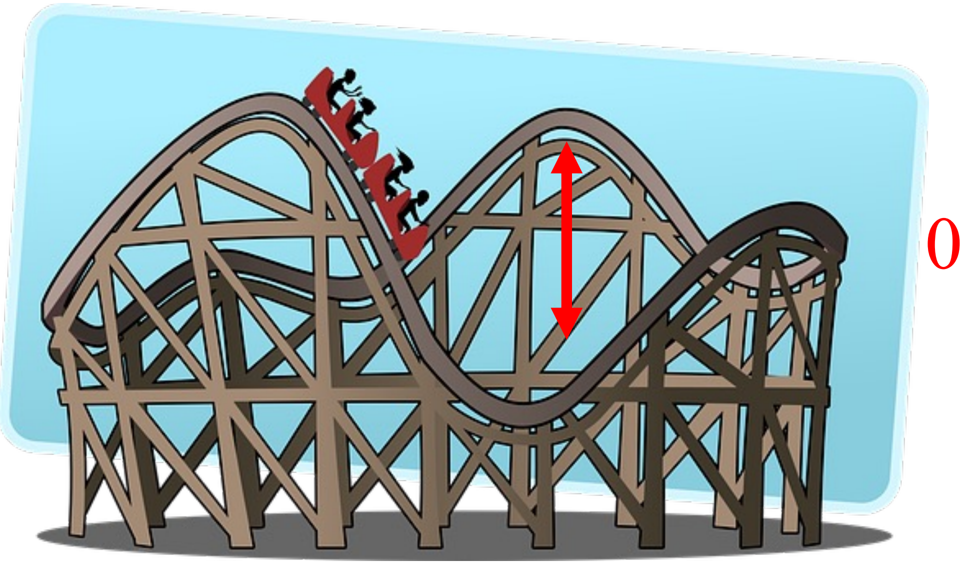


FIG. 8. *Longitudinal polarization case* $S_s = 1$, *CW beam only.* Vertical spin precession rate vs $B_x = 1$ nT field N harmonic around the ring azimuth. The magnetic field amplitude is chosen to be similar to beam separation requirements in Sec. IV A, and more than $B_x = 1$ nT splits the CR beams too much. Irregularities of the low values are due to the inability to determine the exact precession rate from the simulation results. Hence, the points only show a statistical upper limit of the possible vertical precession rate; actual rates could be lower. More about this is in Appendix B.

Ring planarity:
The average vertical speed in deflectors needs to be zero!

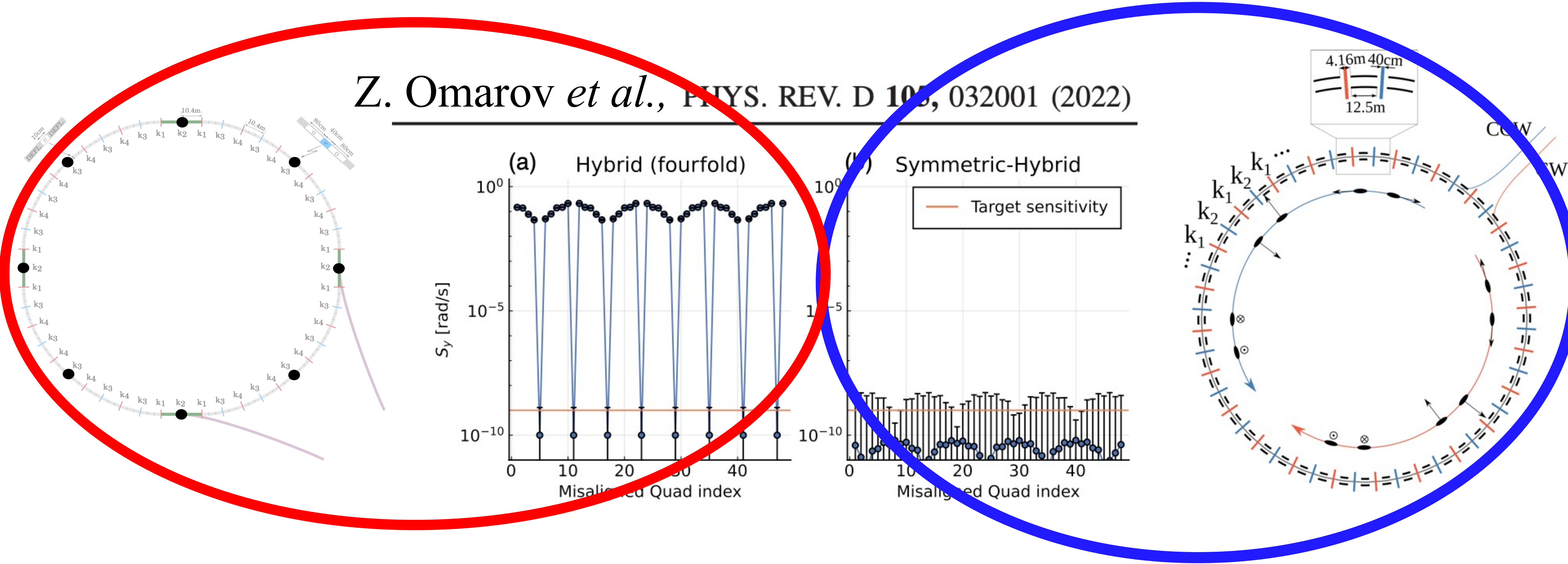


Quads: 0.1T/m, 0.4m



0.1 mm

Hybrid, symmetric lattice storage ring. Great for systematic error reduction.



Z. Omarov *et al.*, PHYS. REV. D 105, 032001 (2022)

Sensitivity of radially polarized beams (sensitive to V. Dark Matter/Dark Energy, P. Graham *et al.*, PRD, 055 010, 2021), most sensitive to vertical velocity problem

EDM is probed with longitudinally polarized beams, less sensitive to this effect by $>10^3$

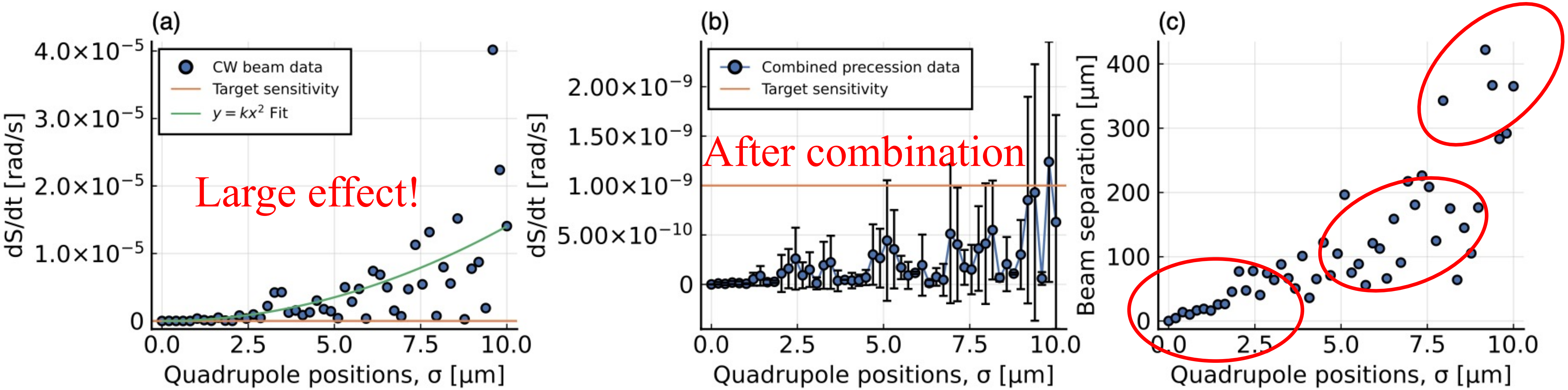
Use radially polarized beams to align the ring (spin based alignment) and monitor background

Vertical velocity and geometrical phase effects:

Magnetic quadrupoles 0.2T/m, positioning accuracy dominates background B-fields

Mitigation by flipping quad polarity in ~10^5 separate beam injections

ZHANIBEK OMAROV *et al.* PHYS. REV. D **105,** 032001 (2022)



Large effect!

After combination

FIG. 9. (a) *Longitudinal polarization case, CW beam only*. Vertical spin precession rate (absolute) vs random misalignments of quadrupoles in both x, y directions by rms σ with different seeds per each point (when the same seeds are used everywhere, the $y = kx^2$ fit is perfect, meaning that every point can be extrapolated to any rms σ value using this functional form). Combination with CCW and quadrupole polarity switching achieves large cancellation—see part (b). (b) *CW and CCW beam and with quadrupole polarity switching*. Total combination as presented in Appendix C. Notably, the background vertical spin precession rate (absolute) stays below the target sensitivity. Irregularity of the points is discussed in Appendix B. (c) Correspondence between CR beam separation and rms σ quadrupole misalignments.

Classification of systematic errors at 10^{-29} *e*-cm for hybrid-symmetric lattice

- ✓Alternate magnetic focusing allows simultaneous CW & CCW storage and
  - Shields against external B-fields.
  - Vertical dipole E-fields eliminated (its own "co-magnetometer"), unique feature of this lattice.

- ✓Symmetric lattice significantly reduces systematic errors associated with vertical velocity (major source). Using
  - Radial polarization direction for first ring lattice alignment.
  - Longitudinal, radial and vertical polarization directions, sensitive to EDM and/or systematic errors.

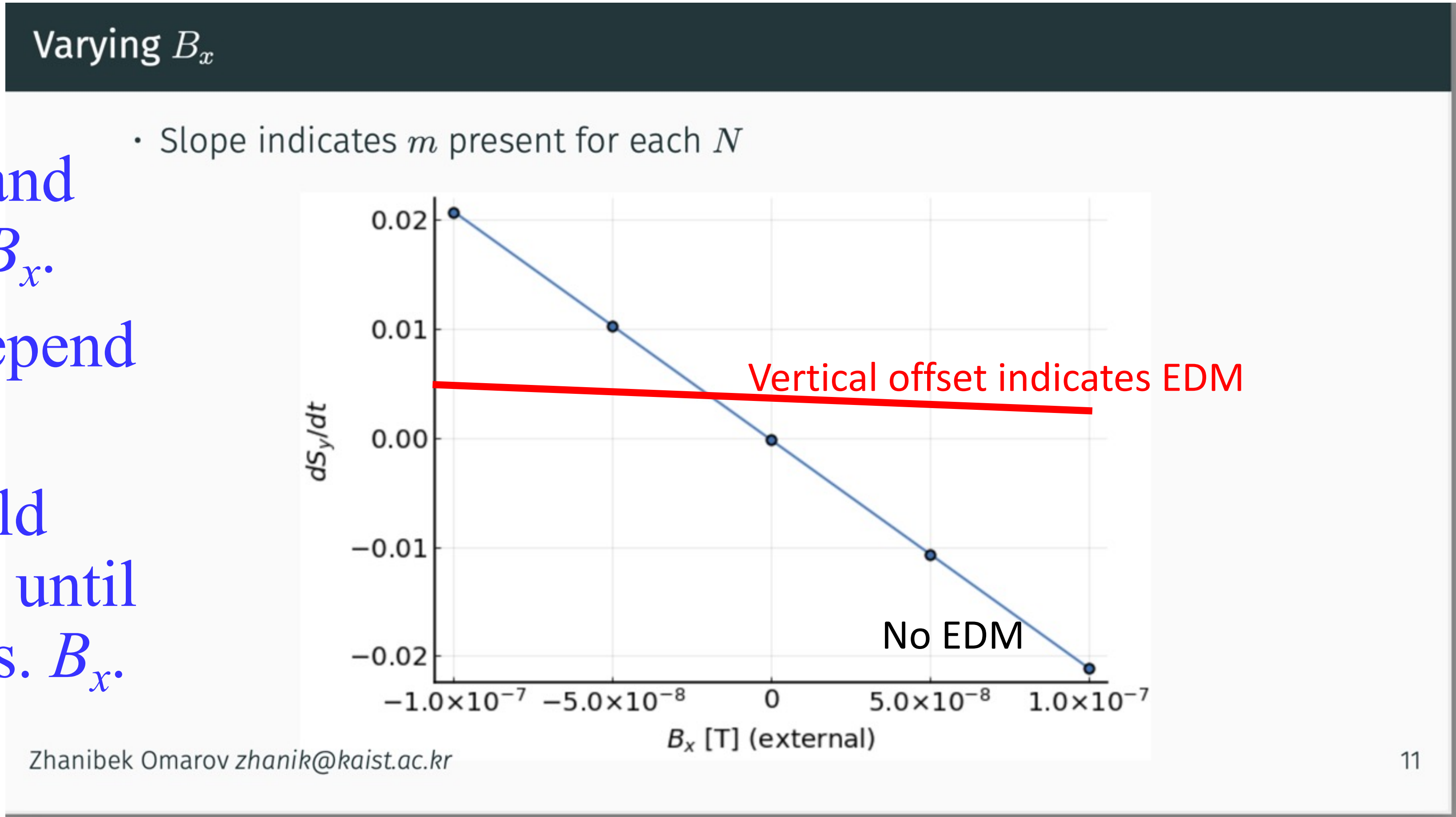
- ✓Set strict ring planarity requirements <0.1mm; CW & CCW beam separation <0.01mm, and quad current flipping resolve issues with geometrical phases. Key issue: stability. Design the ring with stability in mind.

Spin-based alignment/background reduction for greater order than dipole E-fields

- Omarov's method: a combination of background fields can create false EDM signals. Artificially inflate one component to reduce the other.

From Zhanibek Omarov's presentation

- Vary the radial B-field (B_x) and observe the ds_y/dt slope vs. B_x.
- The EDM signal does not depend on the value of B_x.
- Tune out the background field (here electric field focusing) until we get zero slope in ds_y/dt vs. B_x.



Varying B_x

- Slope indicates m present for each N

Vertical offset indicates EDM

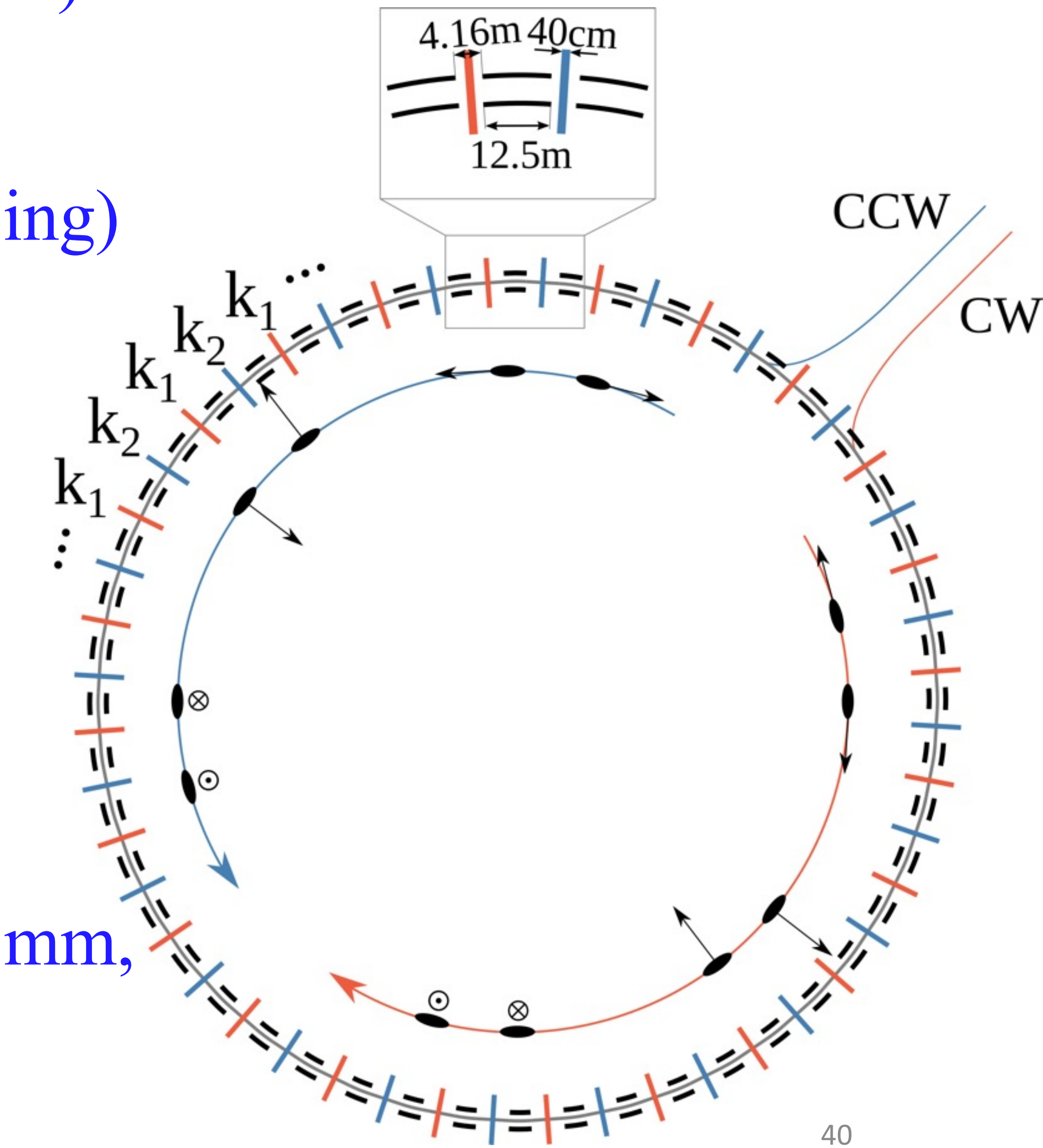
No EDM

Zhanibek Omarov *zhanik@kaist.ac.kr*

11

Symmetries against systematic errors

- Clock-wise (CW) vs. Counter-Clock-Wise (CCW)
  - Eliminates vertical Electric field background
- Hybrid lattice (electric bending, magnetic focusing)
  - Shields against background magnetic fields
- Highly symmetric lattice (24 FODO systems)
  - Eliminates vertical velocity background
- Positive and negative helicity
  - Reduce polarimeter systematic errors
- Flat ring to 0.1 mm, beams overlap within 0.01 mm, spin-based alignment, quad current flipping
  - Geometrical phases; High-order vertical E-fields



Protons in a hybrid-symmetric ring: no new technology required

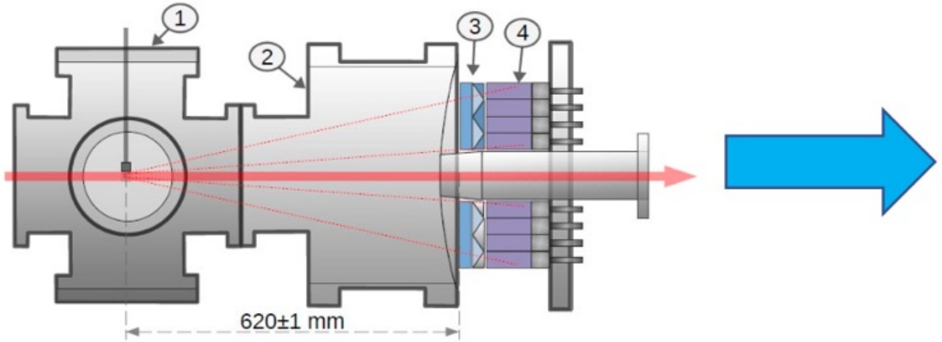
- No need to develop/test new technology
  - Simultaneous CW/CCW beam storage is possible
  - Electric field ~4.5 MV/m with present technology
  - Hybrid/symmetric ring options are simple. Large tune in both planes, beam position monitor (BPM) tasks are achievable with present technology.
  - Estimated SCT are large, injection into ring works, while all primary systematic error sources are kept small.

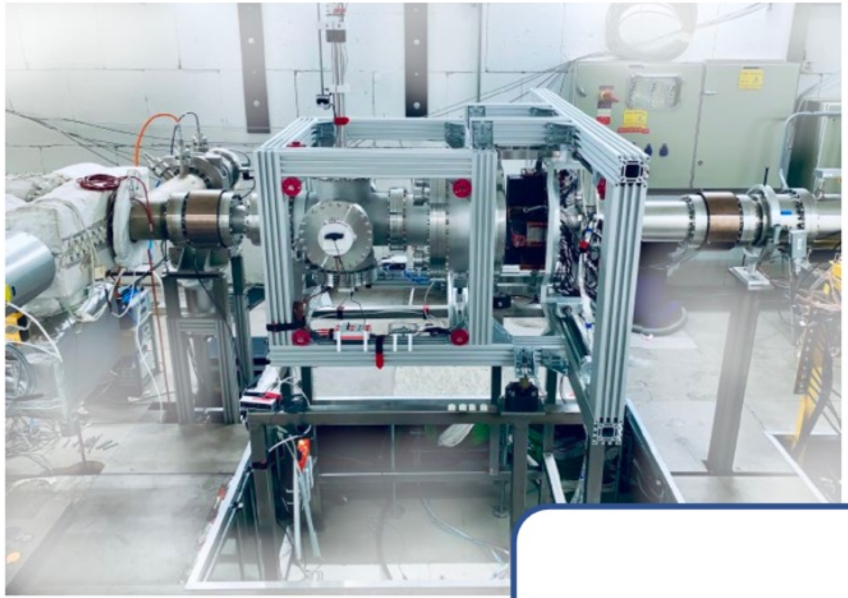
- Do a "lattice string test", assemble 1/48th of the ring and test for
  - Cross talk between systems (E-field bending plates, magnetic quads, BPMs,…)
  - Time stability of voltage, position and direction of fields
  - Check/monitor ground stability alignment due to tides, vehicle motion, magnet powering,…

- After protons, add dipole magnetic field in bending sections:
  - Can do proton, deuteron, ^{3}He, muons,…

COSY results

1. With left-right detectors, forward-reverse polarization, there is enough redundancy to correct polarimeter systematic errors below 10 μrad (achieved, 4-day run). No obstacles see to further reductions to 1 μrad.[1]
2. Although unstable against depolarization, field corrections extend polarization lifetime past 1000 s.[2]
3. Feedback tied to polarization phase in plane can hold spin direction constant to within 0.1 rad.[3]
4. A polarimeter prototype works.[4]





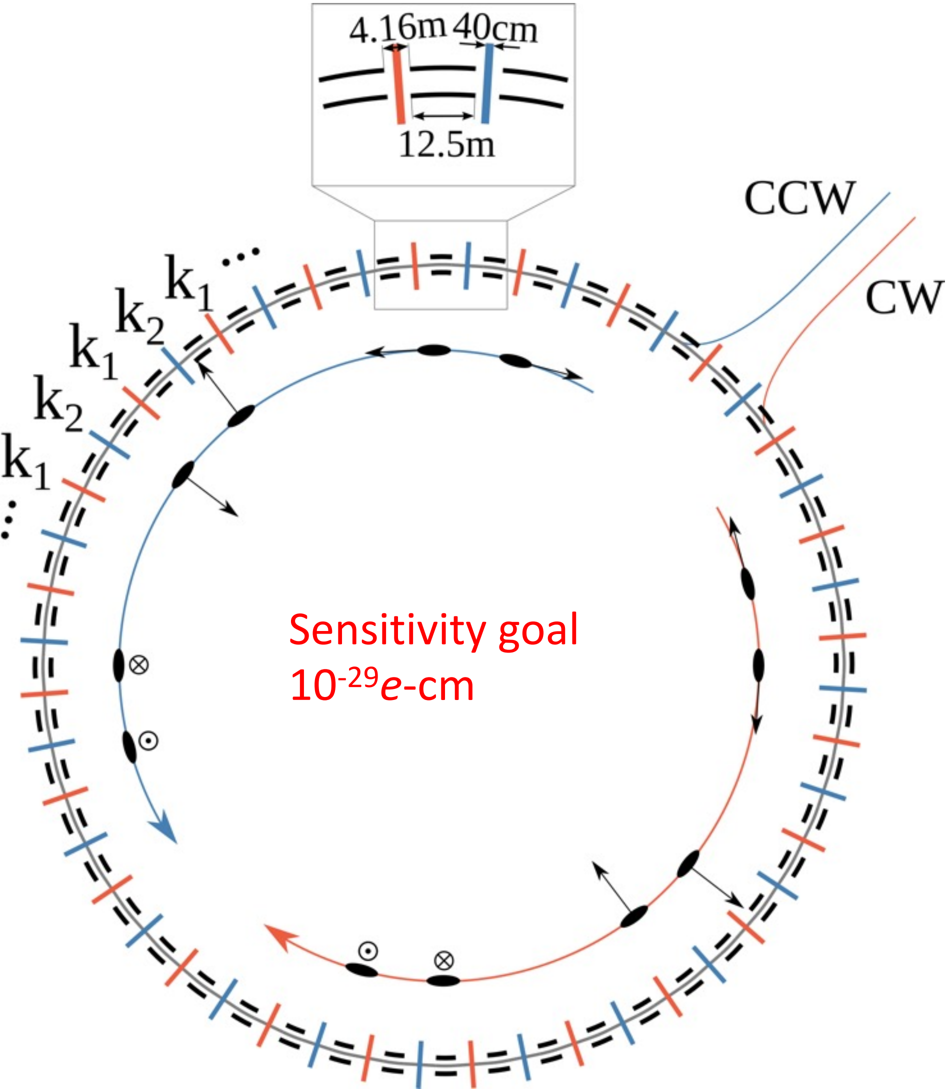
All tests were made with 0.97 GeV/c deuteron beam.

[1] NIM A 664, 49 (2012)
[2] PRL 117, 054801 (2016)
[3] PRL 119, 014801 (2017)
[4] JINST 15, P12005 (2020)

Slide by Ed Stephenson

Hybrid, symmetric lattice storage ring, designed by Val. Lebedev (FNAL)

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)



Sensitivity goal 10^{-29}*e*-cm

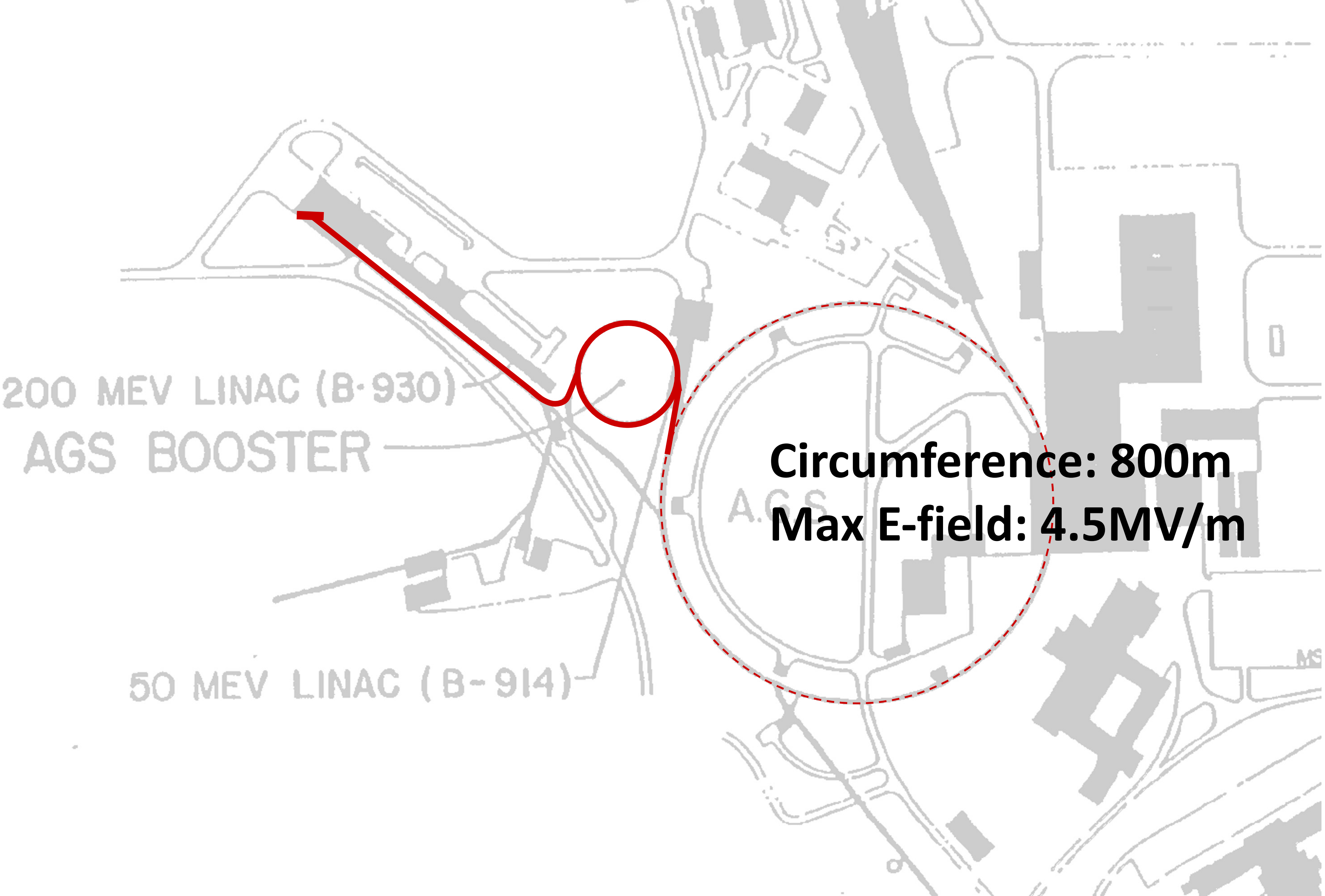
TABLE I. Ring and beam parameters for Symmetric Hybrid ring design

Quantity	Value
Bending Radius R_0	95.49 m
Number of periods	24
Electrode spacing	4 cm
Electrode height	20 cm
Deflector shape	cylindrical
Radial bending E-field	4.4 MV/m
Straight section length	4.16 m
Quadrupole length	0.4 m
Quadrupole strength	±0.21 T/m
Bending section length	12.5 m
Bending section circumference	600 m
Total circumference	799.68 m
Cyclotron frequency	224 kHz
Revolution time	4.46 μs
$\beta_x^{\max}$, $\beta_y^{\max}$	64.54 m, 77.39 m
Dispersion, $D_x^{\max}$	33.81 m
Tunes, Q_x, Q_y	2.699, 2.245
Slip factor, $\eta = \frac{dt}{t} / \frac{dp}{p}$	-0.253
Momentum acceptance, (dp/p)	5.2×10^{-4}
Horizontal acceptance [mm mrad]	4.8
RMS emittance [mm mrad], ϵ_x, ϵ_y	0.214, 0.250
RMS momentum spread	1.177×10^{-4}
Particles per bunch	1.17×10^{8}
RF voltage	1.89 kV
Harmonic number, h	80
Synchrotron tune, Q_s	3.81×10^{-3}
Bucket height, $\Delta p/p_{\text{bucket}}$	3.77×10^{-4}
Bucket length	10 m
RMS bunch length, σ_s	0.994 m

Low risk

Strong focusing

The proton EDM in the AGS tunnel at BNL

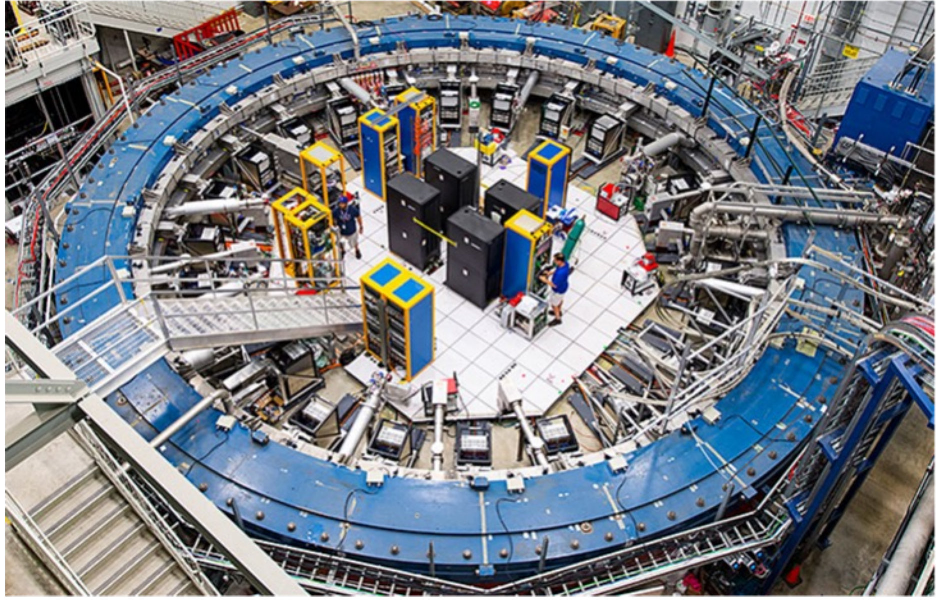


Circumference: 800m
Max E-field: 4.5MV/m

John Benante, Bill Morse in AGS tunnel, plenty of room for the EDM ring.

Muon g-2 experiment

- Muon g-2 results announcement at Fermilab, April 2021 reached >3B people.
- The collaboration developed several new tools for systematic error probing.
- High-precision numerical integrators for beam/spin dynamics simulations,…
- Bill Morse and Lee Roberts are the recipients of the APS 2023 Panofsky Prize.



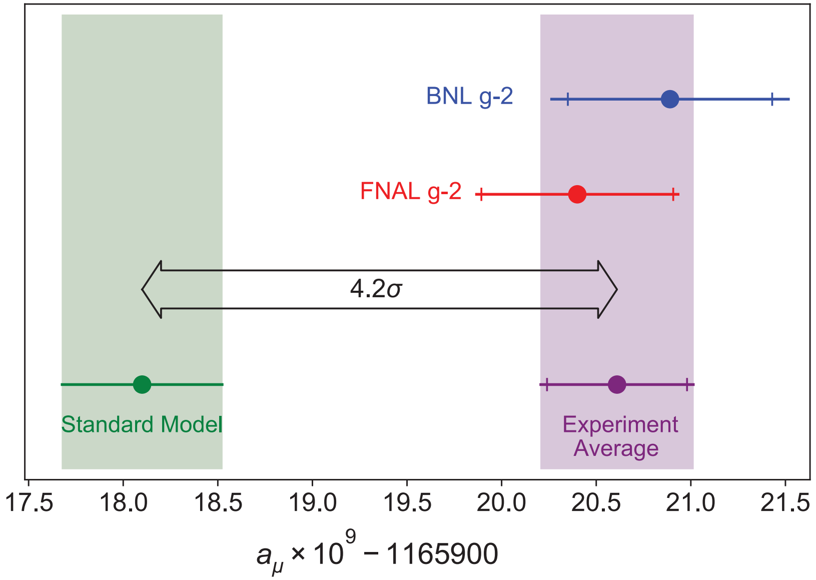
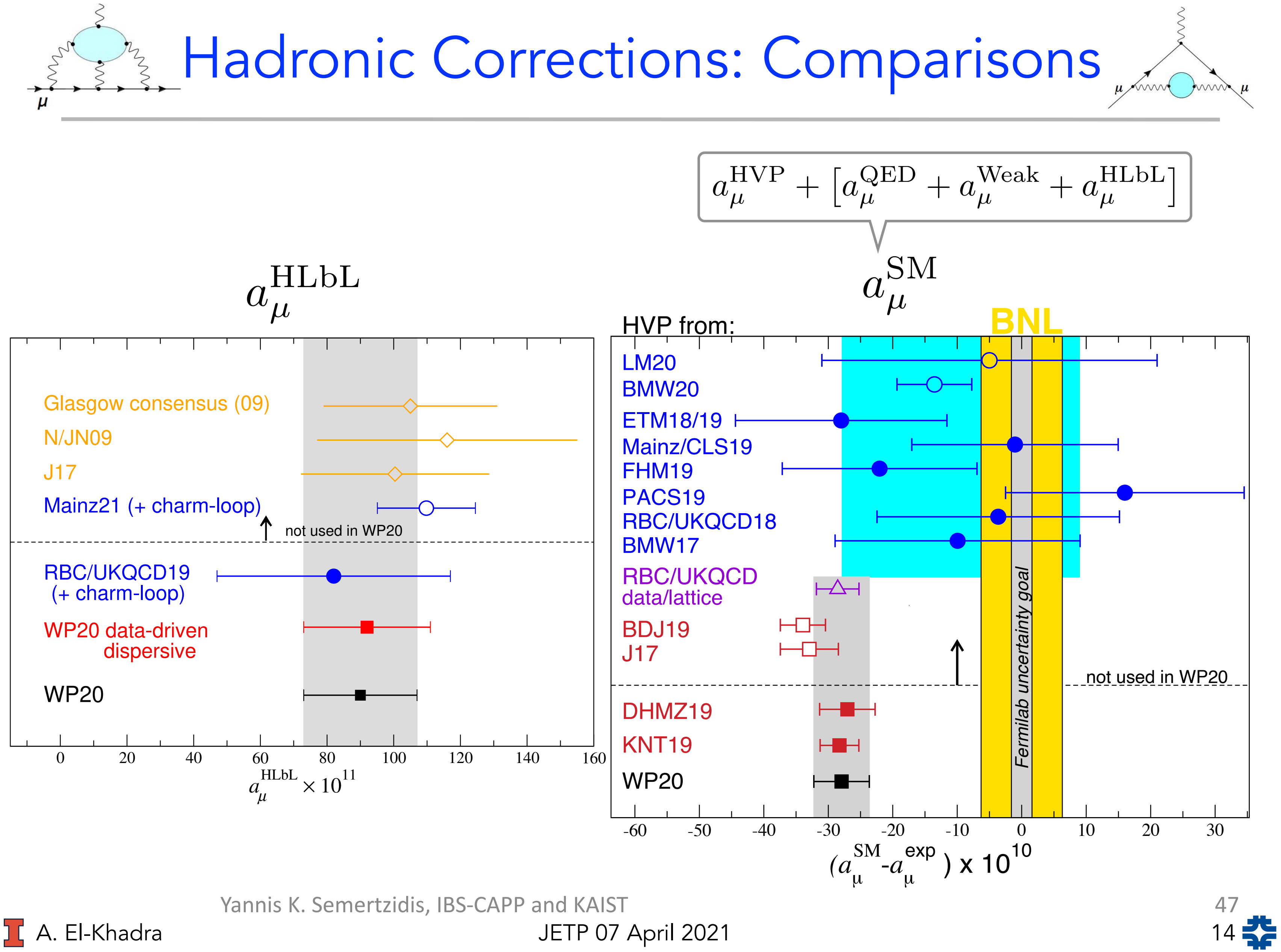


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

Muon g-2 announcement, theory vs. theory

- Theory :



Hadronic Corrections: Comparisons

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{HVP}} + [a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{Weak}} + a_\mu^{\mathrm{HLbL}}]$$

A. El-Khadra JETP 07 April 2021 14

Bill Morse, Lee Roberts 2023 Panofsky Prize

- We built the largest single diameter (15m) superconducting magnet coil at the time. Moved it across the country to repeat the experiment.
- Uniformity of B-field (1.5T) in cross-section to better than 10^{-6} measured it (absolute) to better than 10^{-7} calibrated with two independent methods
- Developed a trolley system measuring the B-field in situ (>5000 points)
- Introduced a new DC inflector with innovative B-field shield at 3T without being detectable at storage region <10 cm away
- Built a fast (200ns, 300G) magnet (kicker) without ferrite, measured the pulsed B-field eddy currents to 10^{-8} requiring enormous dynamic range
- Developed electrostatic quads with twice the CERN gradient; measured the Electric field gradient.
- Our calorimeter detectors had to have time stability, early to late in storage, of <20ps, measured it <2ps; gain stability to 10^{-4}
- Used combinatorics to remove pileup pulses; segmented calo detectors
- Traceback system monitoring motion in real time, without affecting muons
- Used RF, riding on the quads, for 30 us to adjust coherent beam motion and reduce muon losses, both by an order of magnitude
- …
- Project manager (Chris Polly, Fermilab) received DOE management Prize

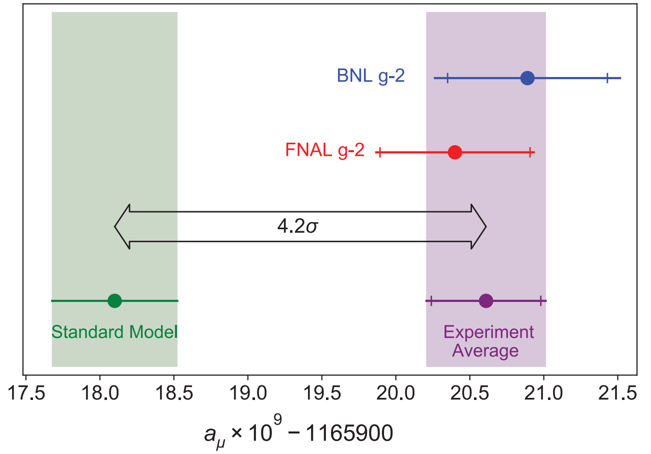
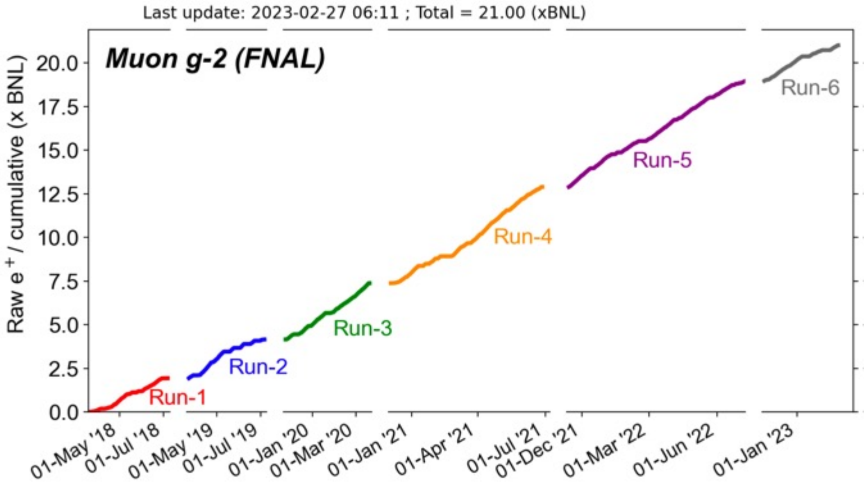


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

On time, on budget

Bill Morse, Lee Roberts 2023 Panofsky Prize



- We built the largest single diameter (15m) superconducting magnet coil at the time. Moved it across the country to repeat the experiment.
- Uniformity of B-field (1.5T) in cross-section to better than 10^{-6} measured it (absolute) to better than 10^{-7} calibrated with two independent methods
- Developed a trolley system measuring the B-field in situ (>5000 points)
- Introduced a new DC inflector with innovative B-field shield at 3T without being detectable at storage region <10 cm away
- Built a fast (200ns, 300G) magnet (kicker) without ferrite, measured the pulsed B-field eddy currents to 10^{-8} requiring enormous dynamic range
- Developed electrostatic quads with twice the CERN gradient; measured the Electric field gradient.
- Our calorimeter detectors had to have time stability, early to late in storage, of <20ps, measured it <2ps; gain stability to 10^{-4}
- Used combinatorics to remove pileup pulses; segmented calo detectors
- Traceback system monitoring motion in real time, without affecting muons
- Used RF, riding on the quads, for 30 us to adjust coherent beam motion and reduce muon losses, both by an order of magnitude
- …
- Project manager (Chris Polly, Fermilab) received DOE management Prize

On time, on budget, delivered!

Summary

- ✓EDM physics is must do, exciting and timely, CP-violation, ~10^3 TeV New-Physics reach, Unique axion physics, DM/DE. Effort similar to muon g-2.

- ✓Hybrid, symmetric ring lattice and spin-based alignment. Minimized systematic error sources. Statistics and systematics of pEDM to better than $10^{-29}e$-cm.

- ✓Snowmass encouraged BNL to come up with a technically strong proposal for a storage ring proton EDM. BNL is currently funding the cost estimate of the experiment. Next, critical, do well in P5 process. Need strong support to finish all studies, TDR → proposal → construction.

- ✓Great progress in statistics and systematics promises two to three orders improvement in sensitivity of eEDM, nEDM, μEDM, and pEDM within the current and next decade.

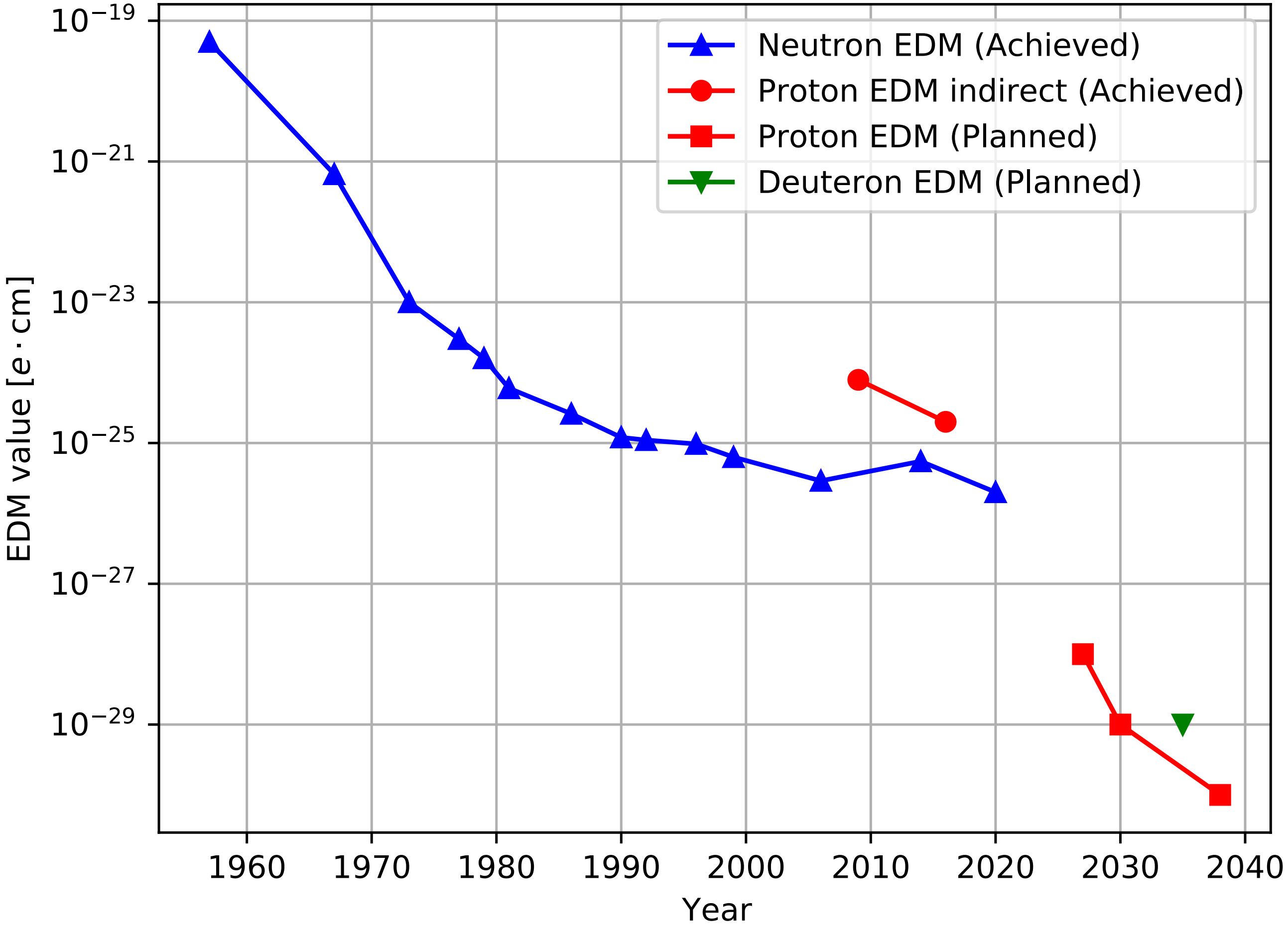
References

1. Z. Omarov *et al.,* Comprehensive Symmetric-Hybrid ring design for pEDM experiment at below 10^{-29}*e*-cm, Phys. Rev. D 105, 032001 (2022)
2. On Kim *et al.,* New method of probing an oscillating EDM induced by axionlike dark matter…, Phys. Rev. D 104 (9), 096006 (2021)
3. P.W. Graham *et al.,* Storage ring Probes for Dark Matter and Dark Energy, Phys. Rev. D 103 (5), 055010 (2021)
4. S. Haciomeroglu and Y.K. Semertzidis, Hybrid ring design in the storage-ring proton EDM experiment, Phys. Rev. Accel. Beams 22 (3), 034001 (2019)
5. S.P. Chang *et al.,* Axionlike dark matter search using the storage ring EDM method, Phys. Rev. D 99 (8), 083002 (2019)
6. S. Haciomeroglu *et al.,* SQUID-based Beam Position Monitor, *PoS* ICHEP2018 (2019) 279
7. N. Hempelmann *et al.,* Phase locking the spin precession in a storage ring, Phys. Rev. Lett. 119 (1), 014801 (2017)
8. G. Guidoboni *et al.,* How to reach a Thousand-second in-plane Polarization Lifetime with 0.97 GeV/c Deuterons in a storage ring, Phys. Rev. Lett. 117 (5), 054801 (2016)
9. V. Anastassopoulos *et al.,* A storage ring experiment to detect a proton electric dipole moment, Rev. Sci. Instrum. 87 (11), 115116 (2016)
10. E.M. Metodiev *et al.,* Analytical benchmarks for precision particle tracking in electric and magnetic rings, NIM A797, 311 (2015)
11. E.M. Metodiev *et al.,* Fringe electric fields of flat and cylindrical deflectors in electrostatic charged particle storage rings, Phys. Rev. Accel. Beams 17 (7), 074002 (2014)
12. W.M. Morse *et al.,* rf Wien filter in an electric dipole moment storage ring: The “partially frozen spin” effect, Phys. Rev. Accel. Beams 16 (11), 114001 (2013)
13. N.P.M. Brantjes *et al.,* Correction systematic errors in high-sensitivity deuteron polarization measurements, Nucl. Instrum. Meth. A664, 49 (2012)
14. G.W. Bennett *et al.,* An improved limit on the muon electric dipole moment, Phys. Rev. D 80, 052008 (2009)
15. F.J.M. Farley *et al.,* A new method of measuring electric dipole moments in storage rings, Phys. Rev. Lett. 93, 052001 (2004)
16. …

Extra slides

Timeline

- Snowmass/white paper, CDR, proposal/TDR, prototype/string-test, ring construction (3-5 years), storage (2-3 years) to first publication
- Effort similar to muon g-2 experiments (under evaluation at BNL)
- Possible interesting results within a decade.

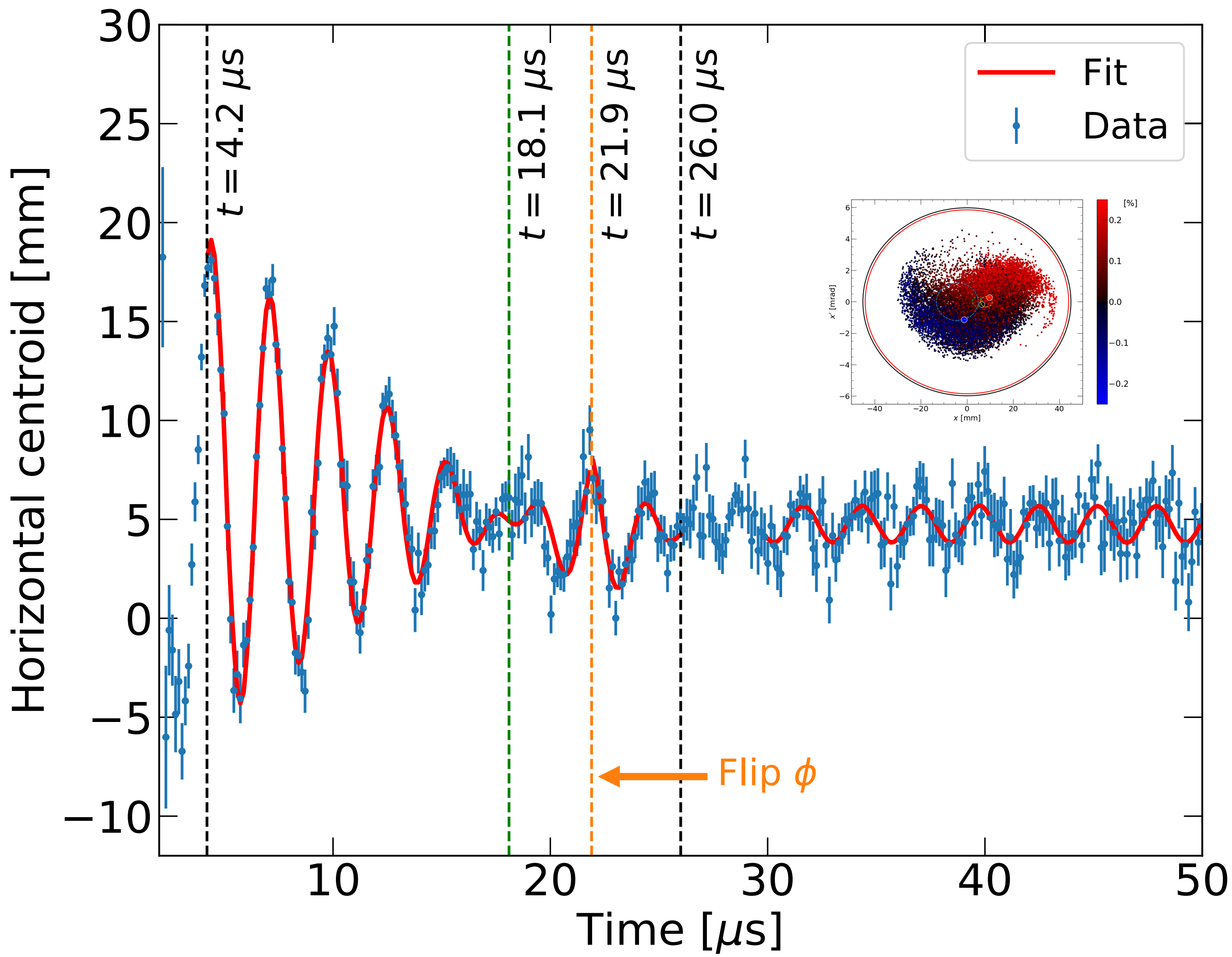


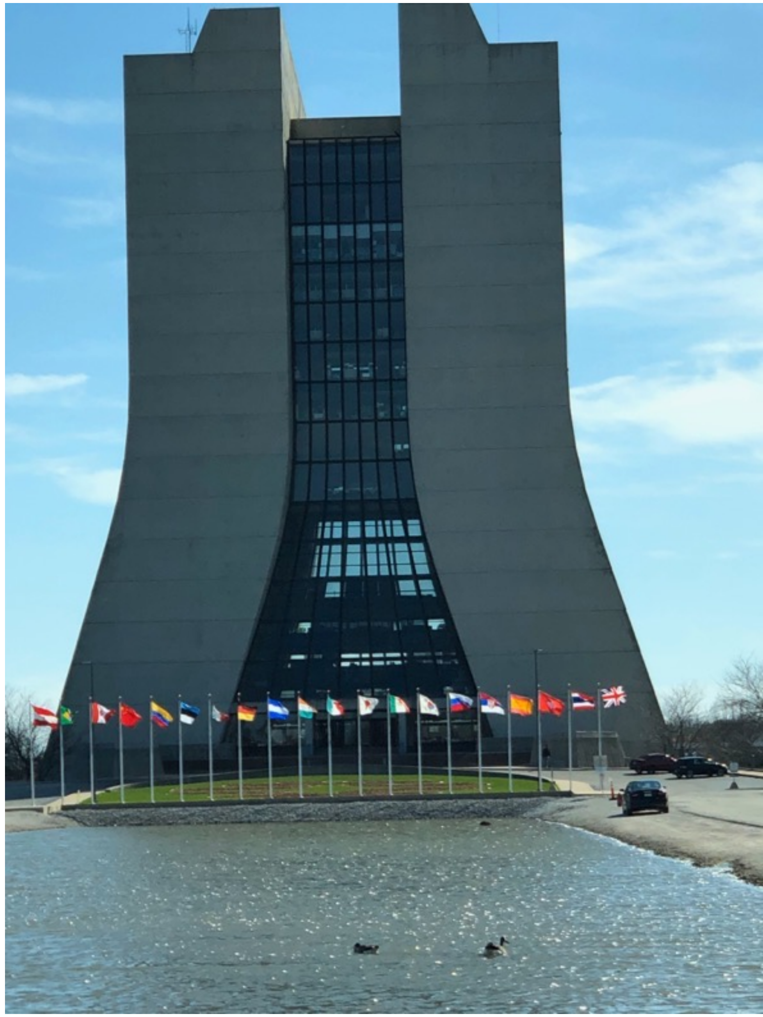
System	Risk factor, comments
Ring construction, beam storage, stability, IBS	Low. Strong (alternate) focusing, a ring prototype has been built (AGS analog at BNL) in 60's. Lattice elements placement specs are ordinary. Intra-beam-scattering (IBS) OK below transition.
E-field strength	Low. Plate-units are similar to those ran at Tevatron with higher specs.
E-field plates shape	Medium. Make as flat as conveniently possible. Probe and shim out high order fields by intentionally splitting the CR-beams (using B_r)
Spin coherence time	Low. Ordinary sextupoles will provide $>10^3$s.
Beam position monitors (BPM), SQUID-based BPMs.	Medium. Ordinary BPMs and hydrostatic level system (HLS) to level the ring to better than 0.1mm; SQUID-based or more conventional BPMs to check CR-beams split to 0.01mm.
High-precision beam/spin simulations, efficient software	Low. Cross-checking our results routinely with independent programs and by several teams
Polarimeter	Low. Mature technology available

Large Surface Area Electrodes

Parameter	Tevatron pbar-p Separators	BNL K-pi Separators	pEDM (low risk)
Length/unit	2.6m	4.5m	5 × 2.5m
Gap, E-field	5cm, 7.2 MV/m	10cm, 4 MV/m	4cm, 4.5 MV/m
Height	0.2m	0.4m	0.2m
Number	24	2	48
Max. HV	±(150-180)KV	±200KV	±90KV

RF CBO amplitude reduction (data from muon g-2 experiment)





On Kim *et al,* New J. Phys. **22** (2020) 063002

Hadronic Electric Dipole Moments

Input to hadronic EDM

- Theta-QCD (part of the SM)

- CP-violation sources beyond the SM

  Several alternative simple systems could provide invaluable complementary information (e.g. proton, neutron and ^{3}He, deuteron,…).

EDMs of different systems (Marciano)

θ_{QCD}:

$$d_n \simeq -d_p \simeq 3\times 10^{-16}\,\overline{\theta}\ \text{e}\cdot\text{cm}$$

$$d_D\left(\overline{\theta}\right)/d_N\left(\overline{\theta}\right)\approx 1/3$$

Super-Symmetry (SUSY) model predictions:

$$d_n \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) - 0.27e\left(d_u^c - d_d^c\right)$$

$$d_p \simeq 1.4\left(d_d - 0.25 d_u\right) + 0.83e\left(d_u^c + d_d^c\right) + 0.27e\left(d_u^c - d_d^c\right)$$

$$d_D \simeq \left(d_u + d_d\right) - 0.2e\left(d_u^c + d_d^c\right) - 6e\left(d_u^c - d_d^c\right)$$

$$d_N^{I=1} \simeq 0.87\left(d_u - d_d\right) + 0.27e\left(d_u^c - d_d^c\right) \qquad d_N^{I=1} = \left(d_p - d_n\right)/2$$

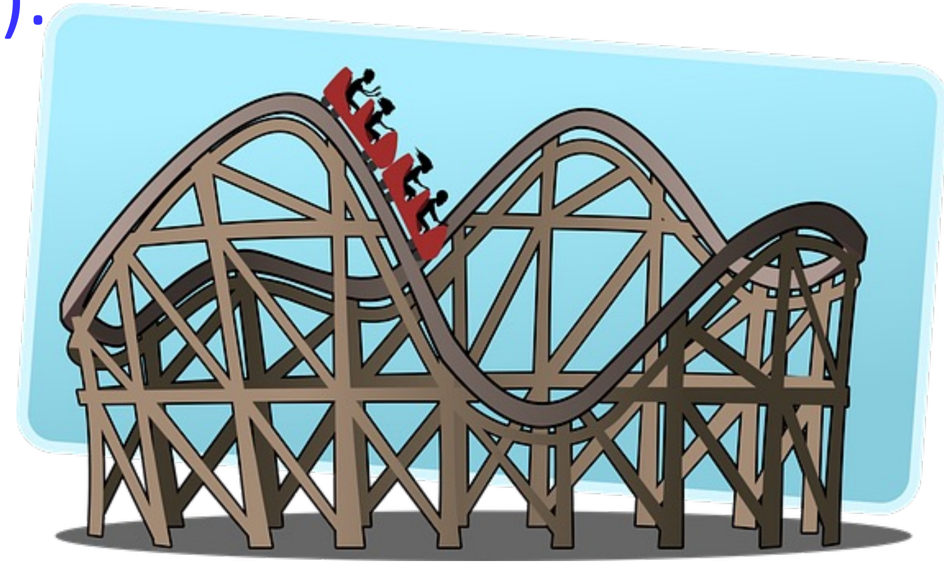
$$d_N^{I=0} \simeq 0.5\left(d_u + d_d\right) + 0.83e\left(d_u^c + d_d^c\right) \qquad d_N^{I=0} = \left(d_p + d_n\right)/2$$

Ring planarity critical to control geometrical phase errors

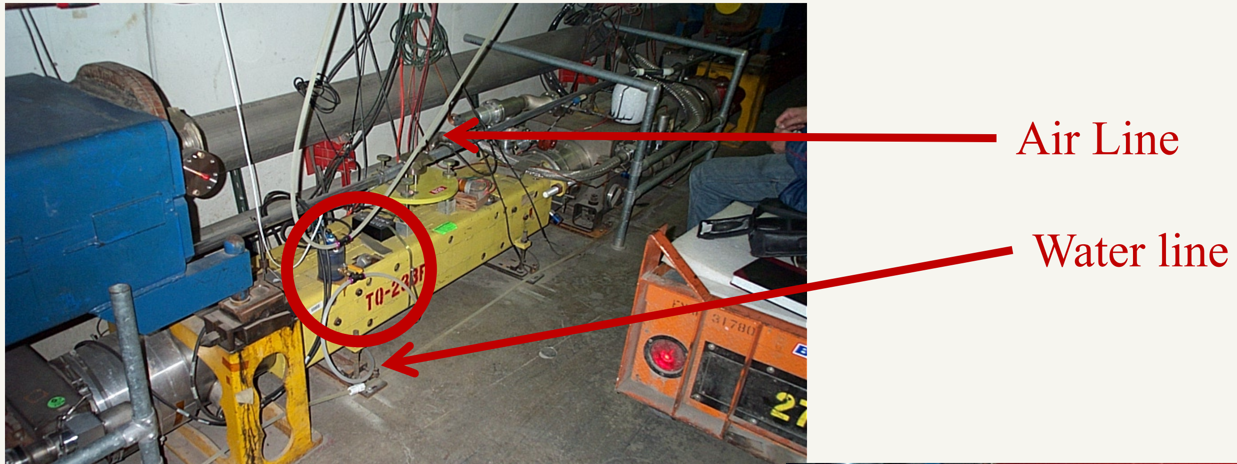
- Numerous studies on slow ground motion in accelerators,
  Hydrostatic Level System for slow ground motion studies at Fermilab.
  (Part of the linear collider studies!)

- Thorough review by Vladimir Shiltsev (FNAL):

https://arxiv.org/pdf/0905.4194.pdf



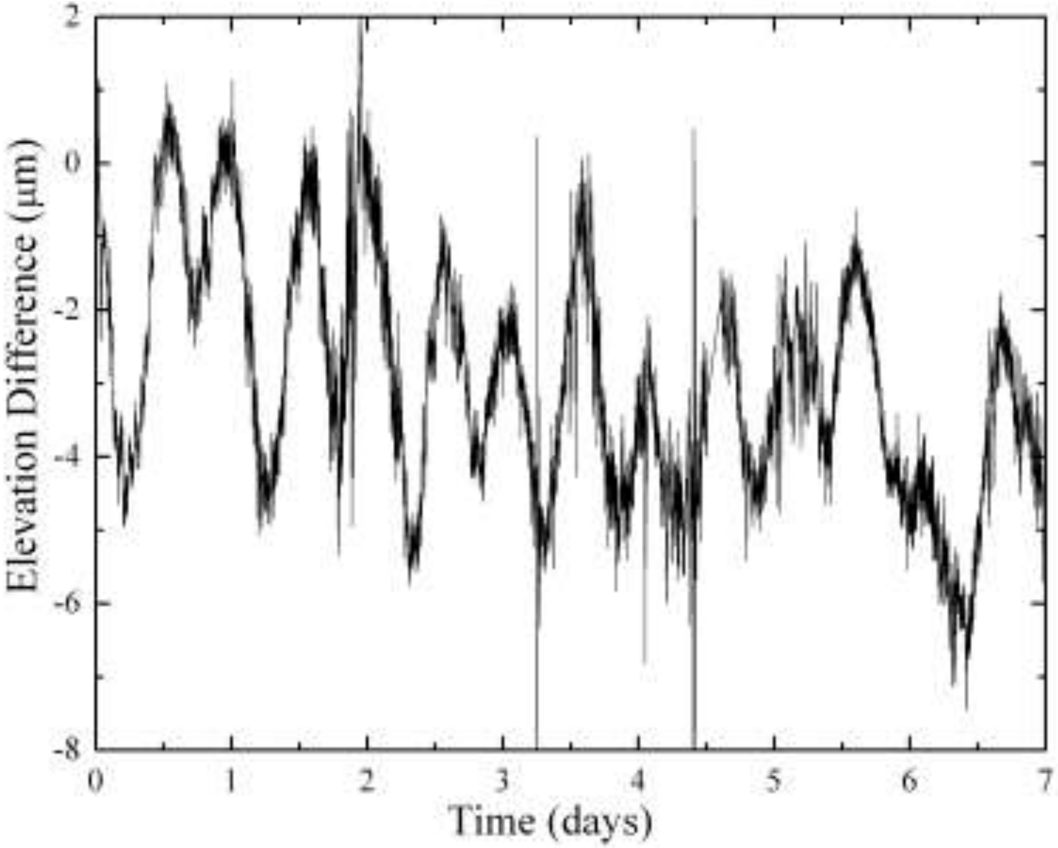
Tevatron Sensors on Quad



In the circle is a water level pot on a Tevatron quadrupole

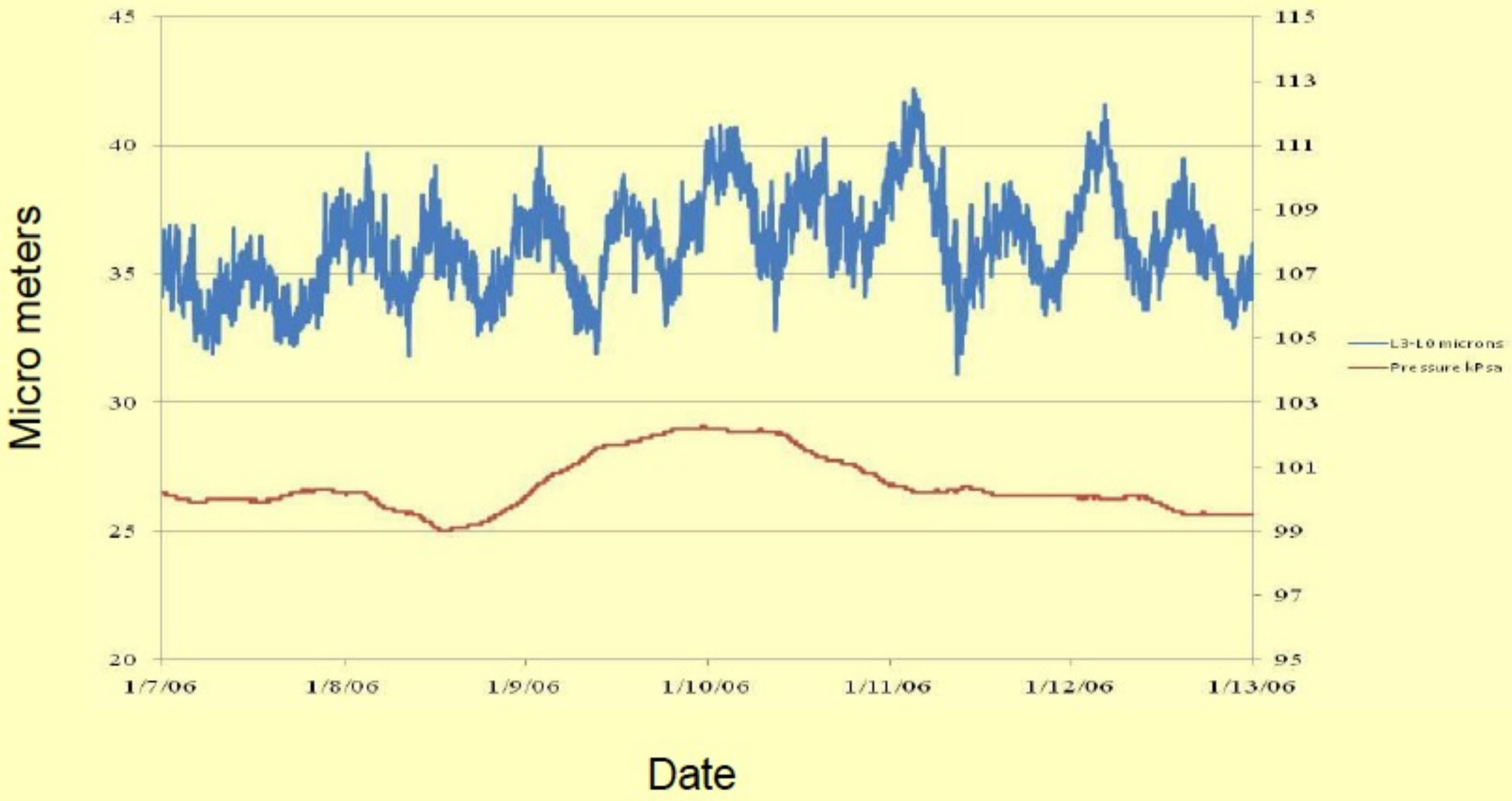
HLS measurements at Fermilab

Fig.35. HLS probe on Tevatron accelerator focusing magnet.



MINOS Tidal Data

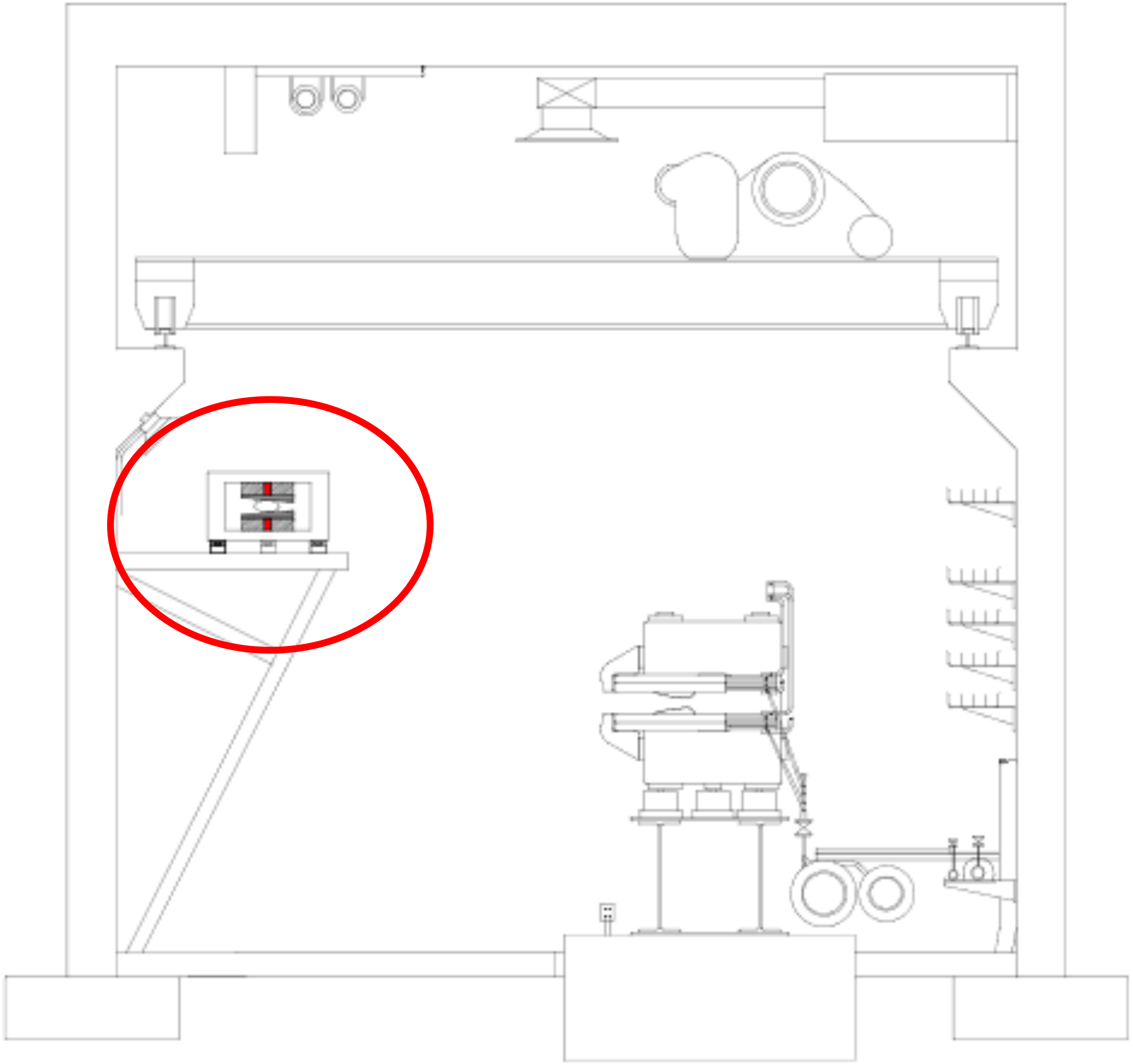
Difference in two sensors 90 meters apart

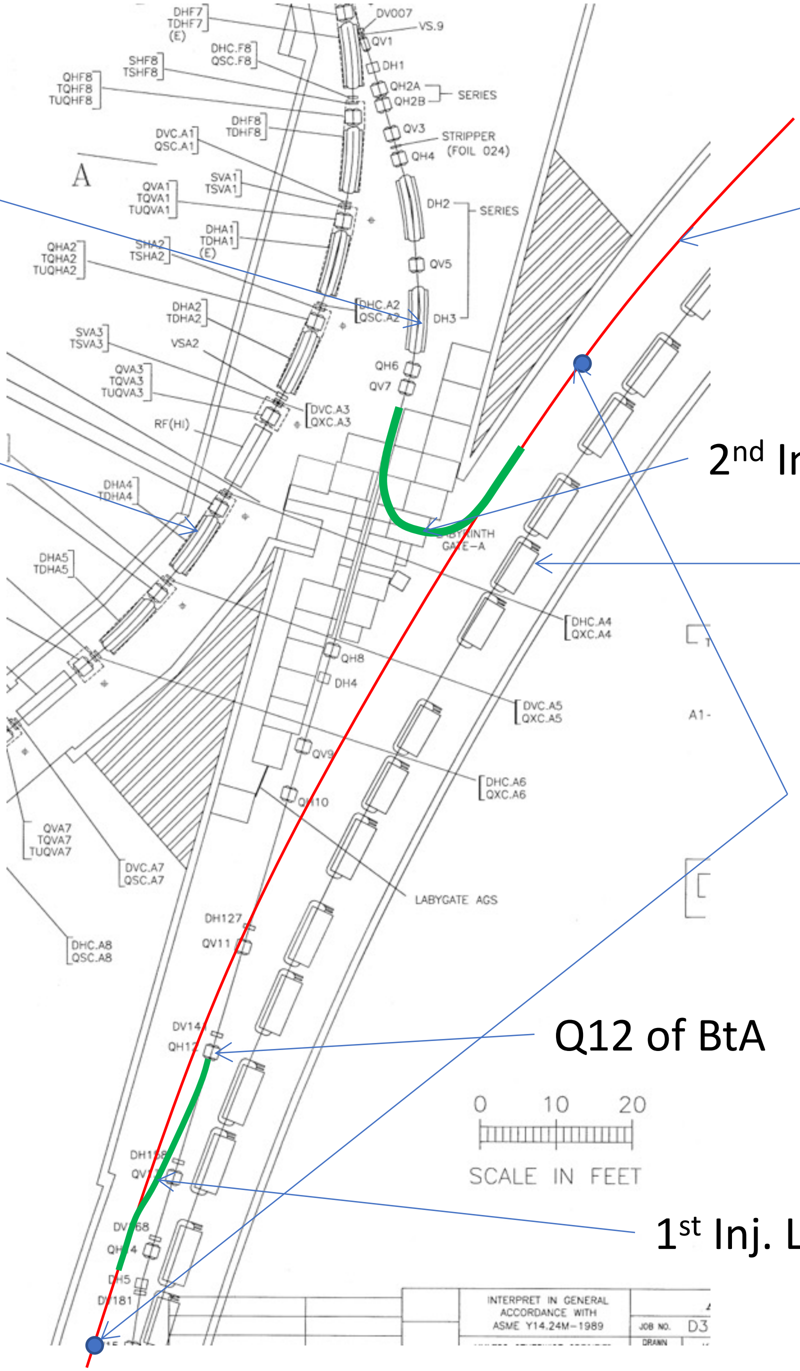


J T Volk Fermilab Dec 2008

Sketch of the AGS Accumulator Ring

- It was sketched for 1.5GeV ring. Space needed: 1mX1m.





Booster-to-AGS BtA

Booster

Proposed EDM Ring

2nd Inj. Line

AGS

Beam Injection points

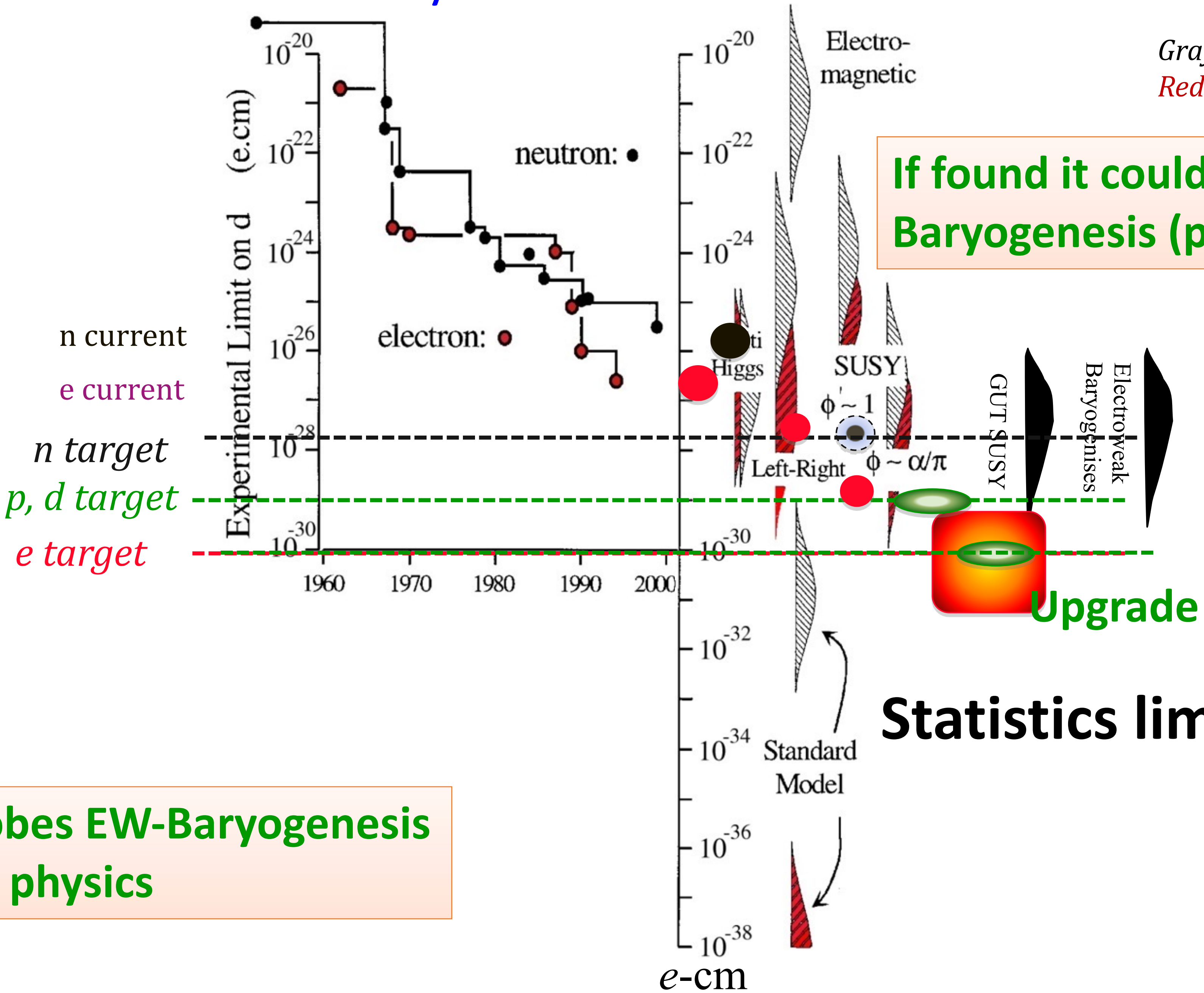
Q12 of BtA

1st Inj. Line

Sensitivity to Rule on Several New Models

Gray: Neutron
Red: Electron

If found it could explain Baryogenesis (p, d, n (or ^{3}He))

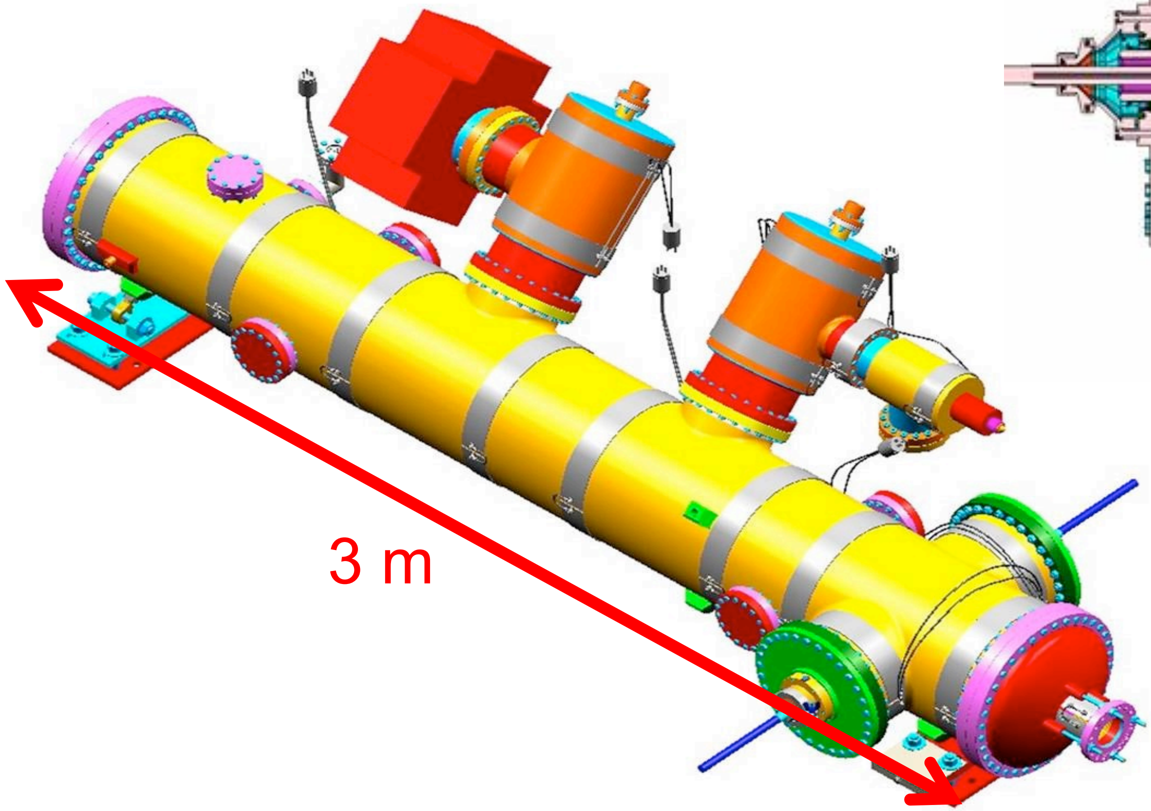


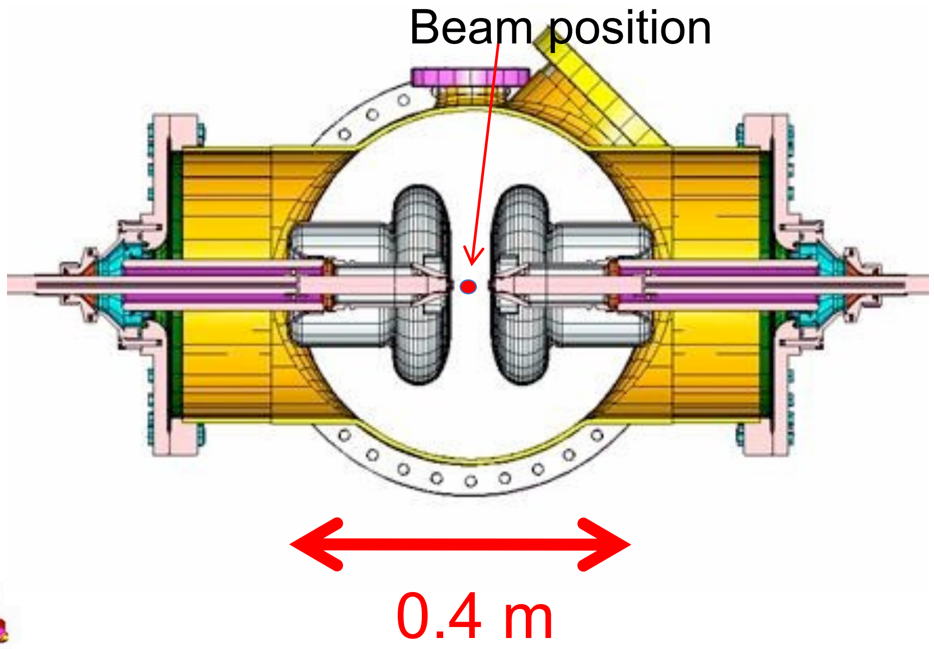
Statistics limited

pEDM probes EW-Baryogenesis and axion physics

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

E-field plate modules: The (24) FNAL Tevatron ES-separators ran for years with harder specs





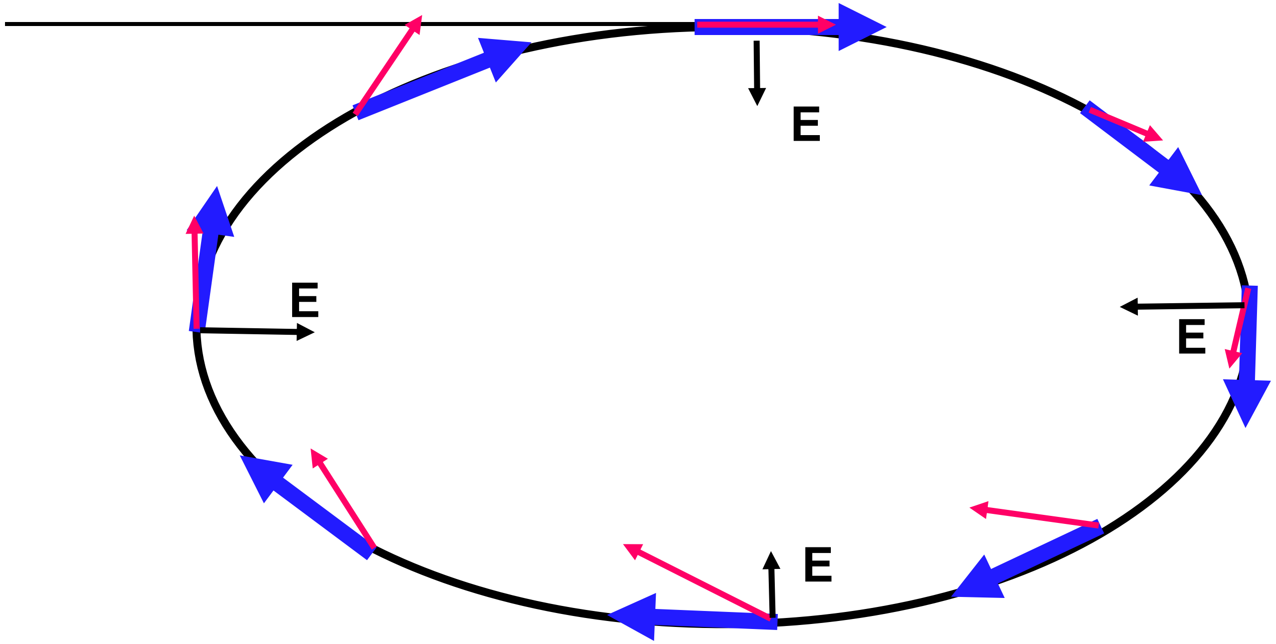
Physics strength comparison (Marciano)

System	Current limit [e·cm]	Future goal	Neutron equivalent
Neutron	$<1.6 \times 10^{-26}$	$\sim 10^{-28}$	10^{-28}
^{199}Hg atom	$<7 \times 10^{-30}$	$<10^{-30}$	10^{-26}
^{129}Xe atom	$<6 \times 10^{-27}$	$\sim 10^{-29}$-10^{-31}	10^{-25}-10^{-27}
Deuteron nucleus		$\sim 10^{-29}$	3×10^{-29}- 5×10^{-31}
Proton nucleus	$<2 \times 10^{-25}$	$\sim 10^{-29}$	10^{-29}

From theta-QCD

From SUSY-like CPV

The spin precession relative to momentum in the plane is kept near zero. A vert. spin precession vs. time is an indication of an EDM (*d*) signal.



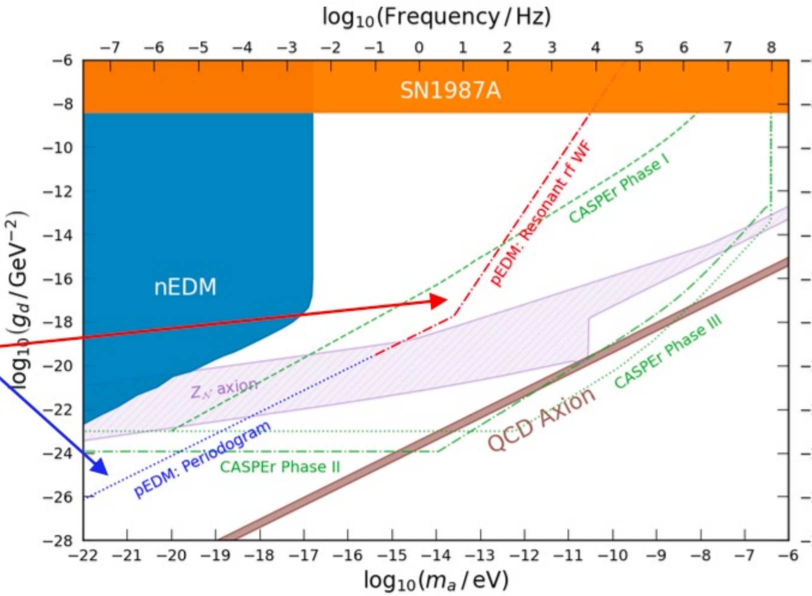
$$\vec{\omega}_a = 0 \qquad \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Snowmass paper on pEDM

ALP-EDM coupling

Signature Vertical rotation of polarization.
Setup Longitudinal initial polarization.
Sensitivity

Storage ring pEDM



P. Graham and S. Rajendran, PRD 88, 035023 (2013)
S. Chang *et al.*, PRD 99, 083002 (2019)
On Kim and Y. Semertzidis, PRD 104, 096006 (2021)

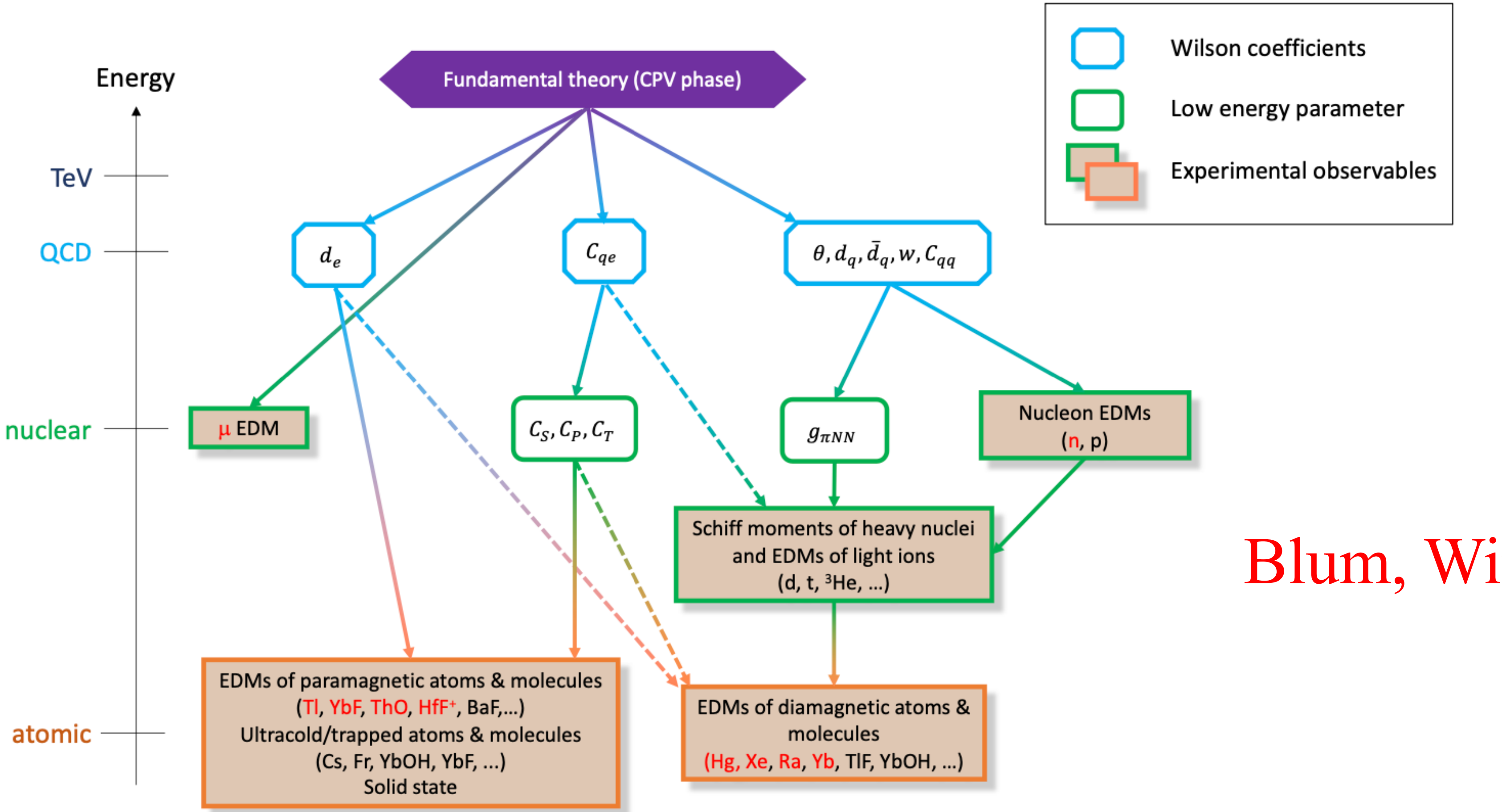
arXiv:2205.00830v1 [hep-ph] 25 Apr 2022

The storage ring proton EDM experiment

Jim Alexander[7], Vassilis Anastassopoulos[36], Rick Baartman[28], Stefan Baeßler[39,22], Franco Bedeschi[19], Martin Berz[17], Michael Blaskiewicz[4], Themis Bowcock[33], Kevin Brown[4], Dmitry Budker[9,31], Sergey Burdin[33], Brendan C. Casey[8], Gianluigi Casse[34], Giovanni Cantatore[38], Timothy Chupp[34], Hooman Davoudiasl[4], Dmitri Denisov[4], Milind V. Diwan[4], George Fanourakis[20], Antonios Gardikiotis[30,36], Claudio Gatti[18], James Gooding[33], Renee Fatemi[32], Wolfram Fischer[4], Peter Graham[26], Frederick Gray[23], Selcuk Haciomeroglu[6], Georg H. Hoffstaetter[7], Haixin Huang[4], Marco Incagli[19], Hoyong Jeong[16], David Kaplan[13], Marin Karuza[37], David Kawall[29], On Kim[6], Ivan Koop[5], Valeri Lebedev[14,8], Jonathan Lee[27], Soohyung Lee[6], Alberto Lusiani[25,19], William J. Marciano[4], Marios Maroudas[36], Andrei Matlashov[6], Francois Meot[4], James P. Miller[3], William M. Morse[4], James Mott[3,8], Zhanibek Omarov[15,6], Cenap Ozben[11], SeongTae Park[6], Giovanni Maria Piacentino[35], Boris Podobedov[4], Matthew Poelker[12], Dinko Pocanic[39], Joe Price[33], Deepak Raparia[4], Surjeet Rajendran[13], Sergio Rescia[4], B. Lee Roberts[3], Yannis K. Semertzidis [*6,15], Alexander Silenko[14], Amarjit Soni[4], Edward Stephenson[10], Riad Suleiman[12], Michael Syphers[21], Pia Thoerngren[24], Volodya Tishchenko[4], Nicholaos Tsoupas[4], Spyros Tzamarias[1], Alessandro Variola[18], Graziano Venanzoni[19], Eva Vilella[33], Joost Vossebeld[33], Peter Winter[2], Eunil Won[16], Anatoli Zelenski[4], and Konstantin Zioutas[36]

[1] *Aristotle University of Thessaloniki, Thessaloniki, Greece*
[2] *Argonne National Laboratory, Lemont, Illinois, USA*
[3] *Boston University, Boston, Massachusetts, USA*
[4] *Brookhaven National Laboratory, Upton, New York, USA*
[5] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[6] *Center for Axion and Precision Physics Research, Institute for Basic Science, Daejeon, Korea*
[7] *Cornell University, Ithaca, New York, USA*
[8] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[9] *Helmholtz-Institute Mainz, Johannes Gutenberg University, Mainz, Germany*
[10] *Indiana University, Bloomington, Indiana, USA*
[11] *Istanbul Technical University, Istanbul, Turkey*

EDM theory, from Snowmass process.



Blum, Winter *et al.*

Figure 3-2. *Flowdown diagram from the fundamental physics at high energy scales, to the Wilson coefficients of the effective field theory, low energy parameters, and the experimental CPV observables. Color outlines of the various boxes inidcate the different energy scales. Solid arrows between the boxes indicate strong connection, whereas dashed arrows indicate weaker influence onto the lower lying parameter. Experimental systems shown in red have already been used in EDM searches; those shown in black (as well as many of those in red) are being developed for future searches. This figure was adapted from [12].*

Polarimeter analyzing power at P_{magic} is great

Analyzing power can be further optimized

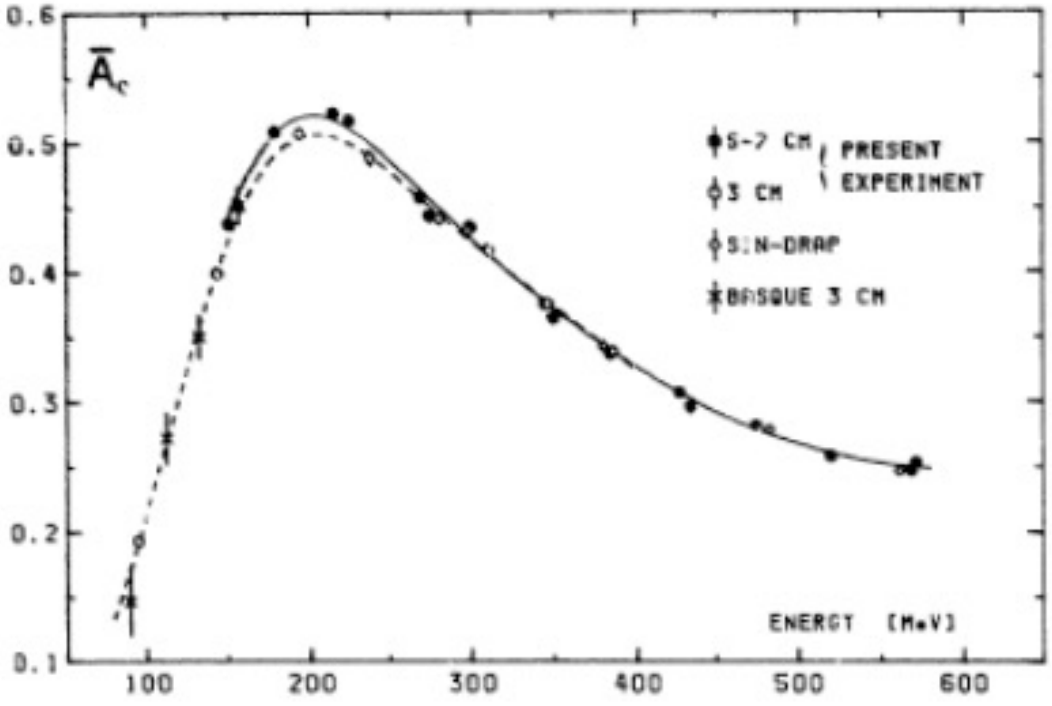
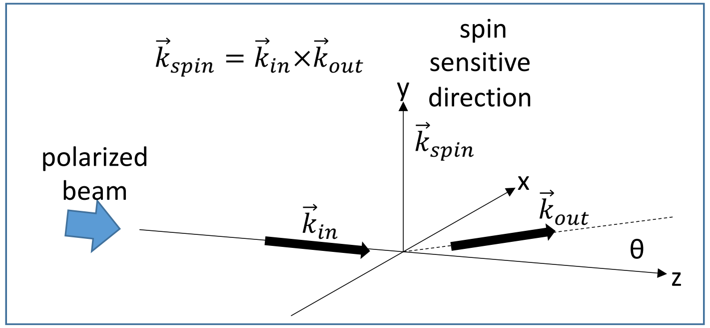
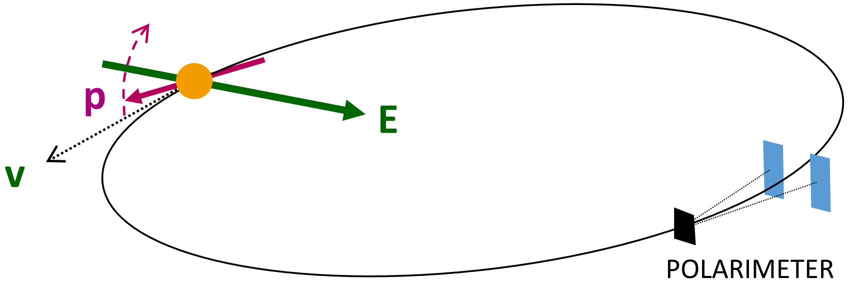


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. E
only

Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.



$\vec{k}_{spin} = \vec{k}_{in} \times \vec{k}_{out}$ spin sensitive direction



Concept and systematics tested with polarized beams at KVI/The Netherlands and COSY/Germany since late 2000’s

Spin Coherence Time

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (second order effects)

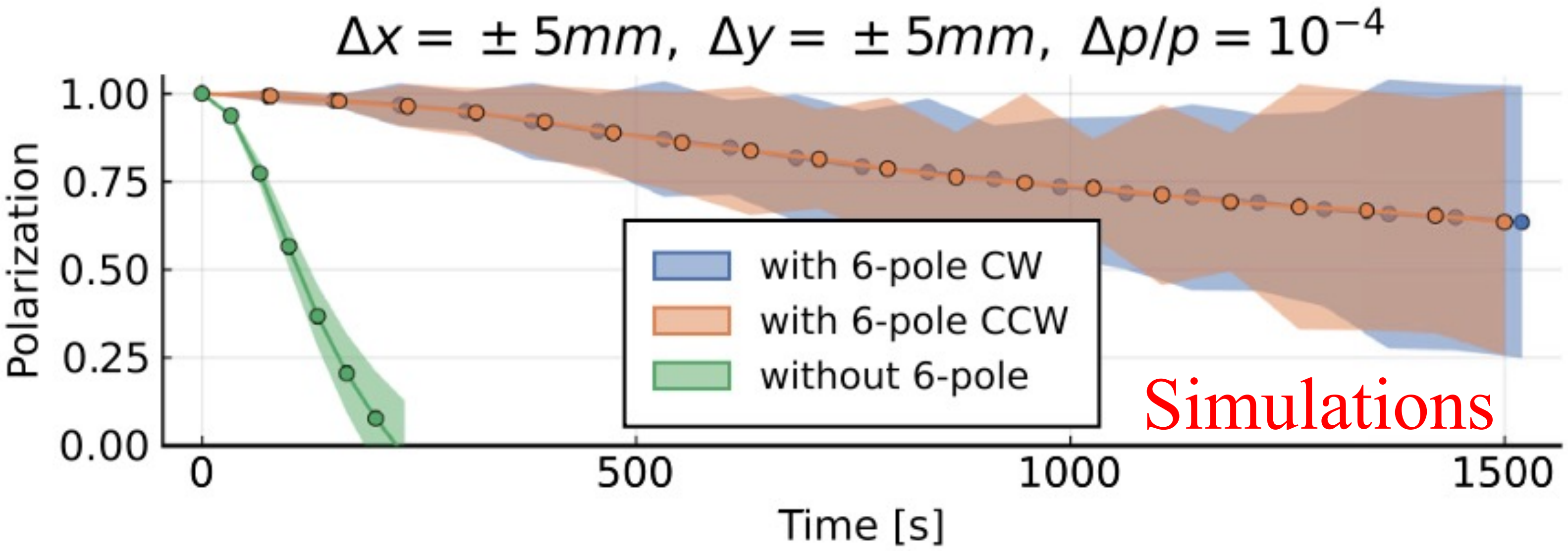
- They Cause a spread in the g-2 frequencies:

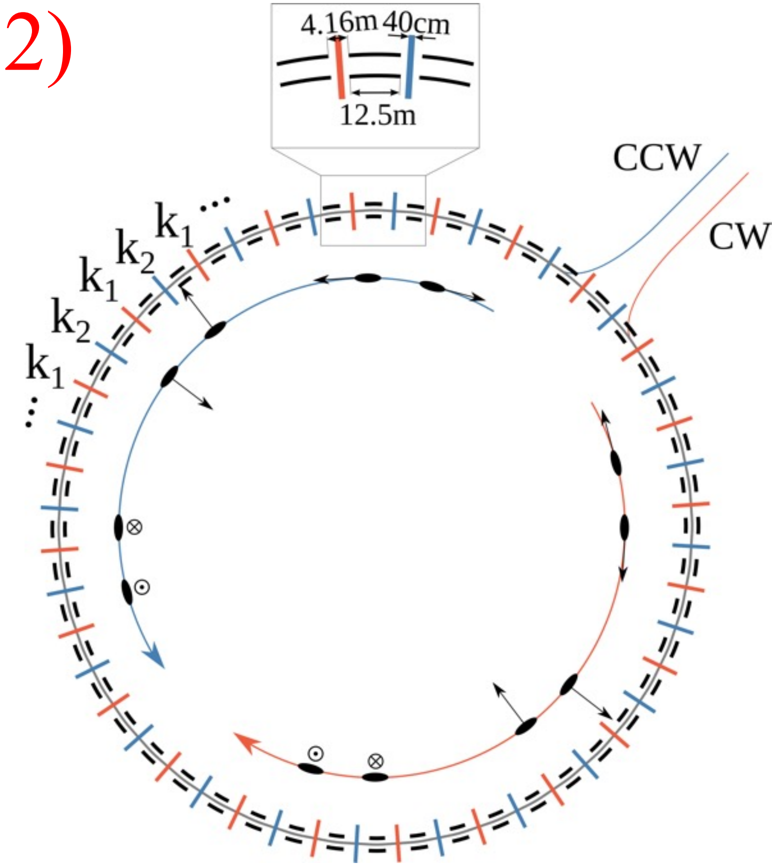
$$d\omega_a = a\vartheta_x^2 + b\vartheta_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Correct by tuning plate shape/straight section length plus fine tuning with sextupoles (current plan) or cooling (mixing) during storage (under evaluation).

Hybrid, symmetric lattice storage ring. Spin Coherence Time with sextupoles

Z. Omarov *et al.*, PHYS. REV. D **105**, 032001 (2022)





Hybrid (magnetic and elecric) sextupoles were used to achieve long SCT.

Concept using sextupoles developed by Yuri Orlov early in 2000’s (Deuterons),
Novosibirsk in the 1980’s (electrons/positrons)
Confirmed with polarized Deuteron beams at COSY in 2010’s