



CAPP

Center for
Axion and Precision
Physics Research



7 August 2016
IBS special session, ICHEP2016, Chicago

Axion dark matter search and the Storage ring proton EDM experiment

Yannis Semertzidis, CAPP/IBS and KAIST

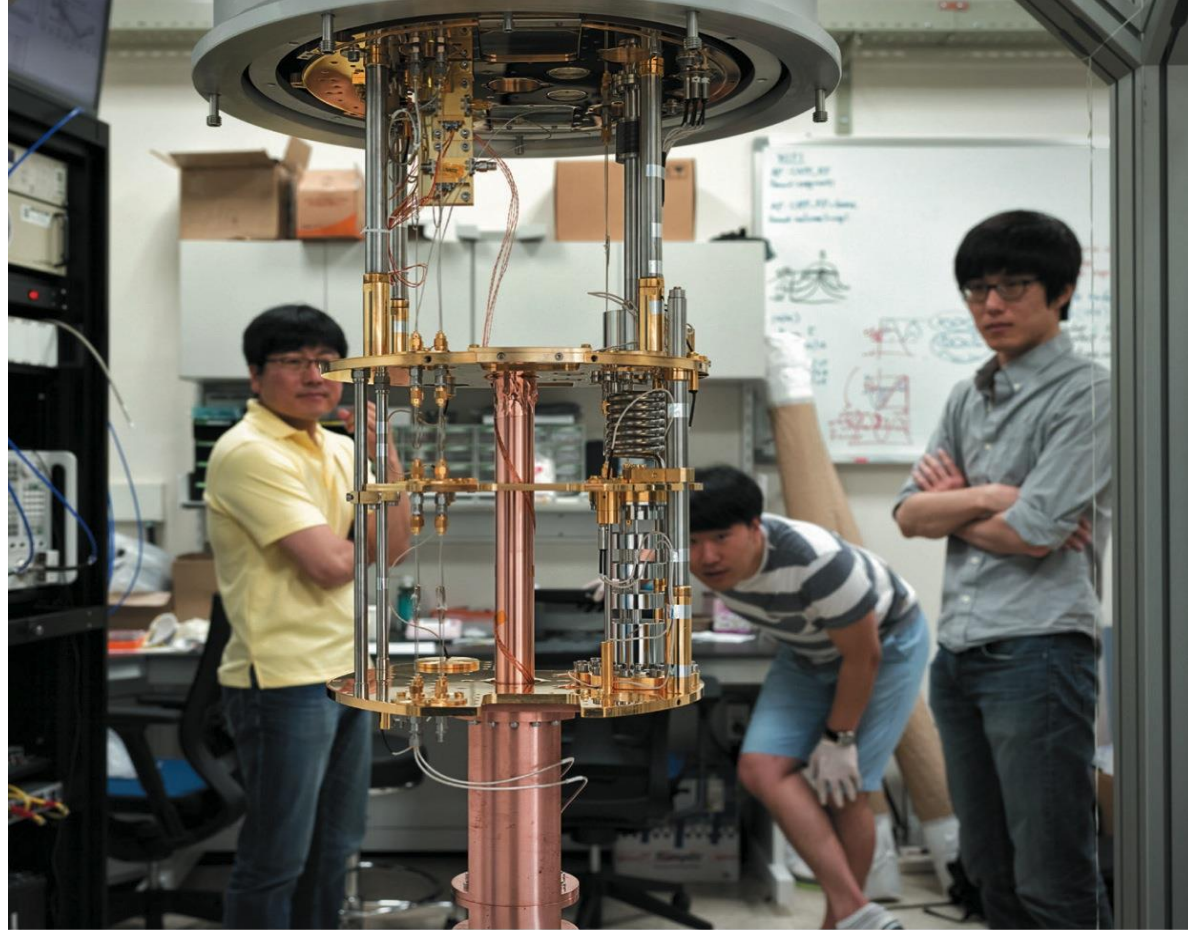
Axion dark matter search

- Infrastructure completion well underway.
- Plan to answer whether axions are the dark matter...

Proton, deuteron sensitive EDM

- Storage ring p,d EDMs @ $<10^{-29}$ e-cm level
- Probing NP $\sim 10^3$ - 10^4 TeV
- Storage ring EDMs: Great physics opportunity

Nature Article about our center in Korea: Nature V 534, 2 June 2016



South Korea's Nobel dream

The Asian nation spends more of its economic output on research than anywhere else in the world. But it will need more than cash to realize its ambitions.

BY MARK ZASTROW

Behind the doors of a drab brick building in Daejeon, South Korea, a major experiment is slowly taking shape. Much of the first-floor lab space is under construction, and one glass door, taped shut, leads directly to a pit in the ground. But at the end of the hall, in a pristine lab, sits a gleaming cylindrical apparatus of copper and gold. It's a prototype of a device that might one day answer a major mystery about the Universe by detecting a particle called the axion — a possible component of dark matter.

If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. "It will transform Korea, there's no question about it," says physicist Yannis Semertzidis, who leads the US\$7.6-million-per-year centre at South Korea's premier technical university, KAIST. But there's a catch: no one knows whether axions even exist. It's the kind of high-risk, high-reward project

SHIN WOOJUNG-JAE



 SHIN Hee-Sup Center for Cognition and Sociality	 KIM Eunjoon Center for Synaptic Brain Dysfunctions	 OH Young-Geun Center for Geometry and Physics	 RYOO Ryong Center for Nanomaterials and Chemical Reactions	 SURH Charles Academy of Immunology and Microbiology
 HYEON Taeghwan Center for Nanoparticle Research	 KIM Kimoon Center for Self-assembly and Complexity	 KIM V. Narry Center for RNA Research	 NOH Tae Won Center for Correlated Electron Systems	 CHANG Sukbok Center for Catalytic Hydrocarbon Functionalizations
 LEE Young Hee Center for Integrated Nanostructure Physics	 NAM Chang Hee Center for Relativistic Laser Science	 NAM Hong Gil Center for Plant Aging Research	 YEOM Han Woong Center for Artificial Low Dimensional Electronic Systems	 KIM Seong-Gi Center for Neuroscience Imaging Research
 KIM Yeongduk Center for Underground Physics	 SEMERTZIDIS Yannis Center for Axiom and Precision Physics Research	 CHOI Kiwoon Center for Theoretical Physics of the Universe	 RUOFF Rodney Center for Multidimensional Carbon Materials	 GRANICK Steve Center for Soft and Living Matter
 KIM Jin-Soo Center for Genome Engineering	 Flach Sergej Center for Theoretical Physics of Complex Systems	 MYUNG Kyungjae Center for Genome Integrity	 CHO Minhaeng Center for Molecular Spectroscopy and Dynamics	 KOH Gou Young Center for Vascular Research

Center for Axiom and Precision Physics research. Established 15 October, 2013 at KAIST.

Center for Axion and Precision Physics Research: CAPP/IBS at KAIST, Korea



- Four groups, goal: ~60 people within 3-5 years
- 15 research fellows, ~20 graduate students
- 10 junior/senior staff members
- Engineers, Technicians
- Future: Dedicated IBS building at KAIST

Summer 2015

KUSP

KOREA
UNDERGRADUATE/GRADUATE/H.S.
SCIENCE PROGRAM



KUSP

KOREA
UNDERGRADUATE/GRADUATE/H.S.
SCIENCE PROGRAM

Center for Axion
&
Precision Physics



Korea Undergraduate / Graduate / H.S. Science Program (KUSP) CAPP/IBS at KAIST, Summer 2016



We are happy to answer any of your questions about KUSP 2016. Please contact us!

KUSP team: +82-42-350-8168, +82 -42-350-8166 / kusp@ibs.re.kr

multicultural environment, which will extremely enrich personal experience.

Though it will be held in Korea, KUSP is an international program and thereby the official language will be English.

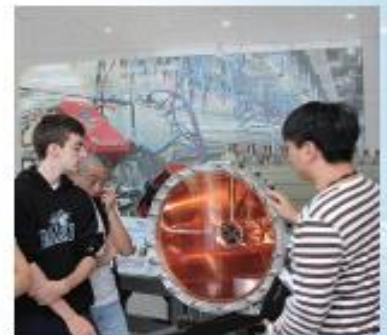
1. Date <http://kusp.ibs.re.kr/>

July 4 - August 5, 2016 (5 weeks)

2. Target students

- International and domestic undergraduate and graduate students in physics or related disciplines (e.g. electric engineering, computer science, mathematics, etc.)
- Highly motivated high school students

3. Eligibility



KUSP, July, 2016



CAPP, April, 2016



CAPP-Physics

- Establish Experimental Particle Physics group.

Involved in important physics questions:

- Strong CP problem
- Cosmic Frontier (**Dark Matter axions**)
- Storage ring proton EDM (most sensitive hadronic EDM experiment, flavor conserving CP-violation, **BAU**)
- Muon $g-2$; muon to electron conversion (flavor physics)

CAPP/IBS's Physics goals address some of the most important issues

<https://www.quantamagazine.org>



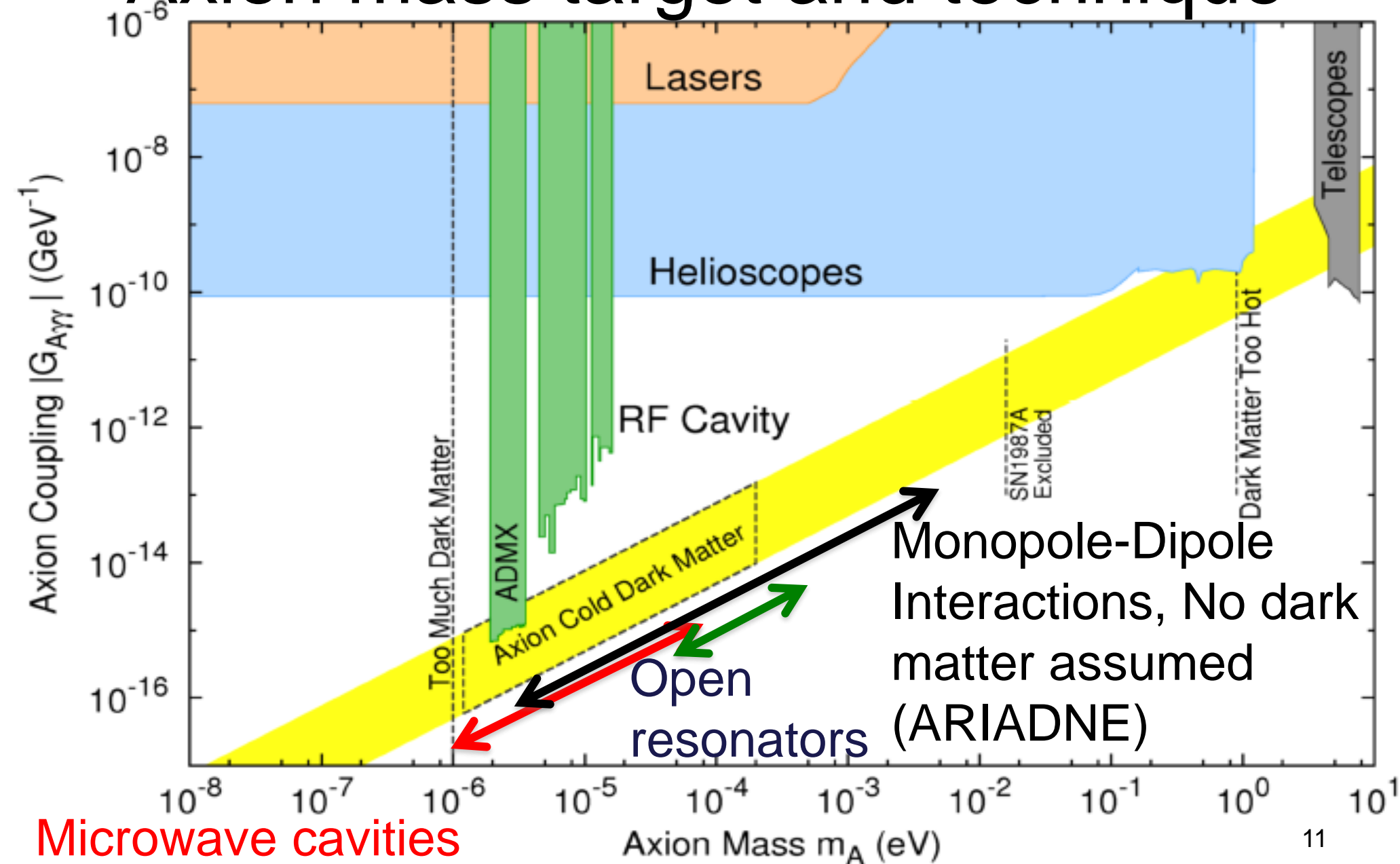
Theories of Everything, Mapped

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Axion mass target and technique

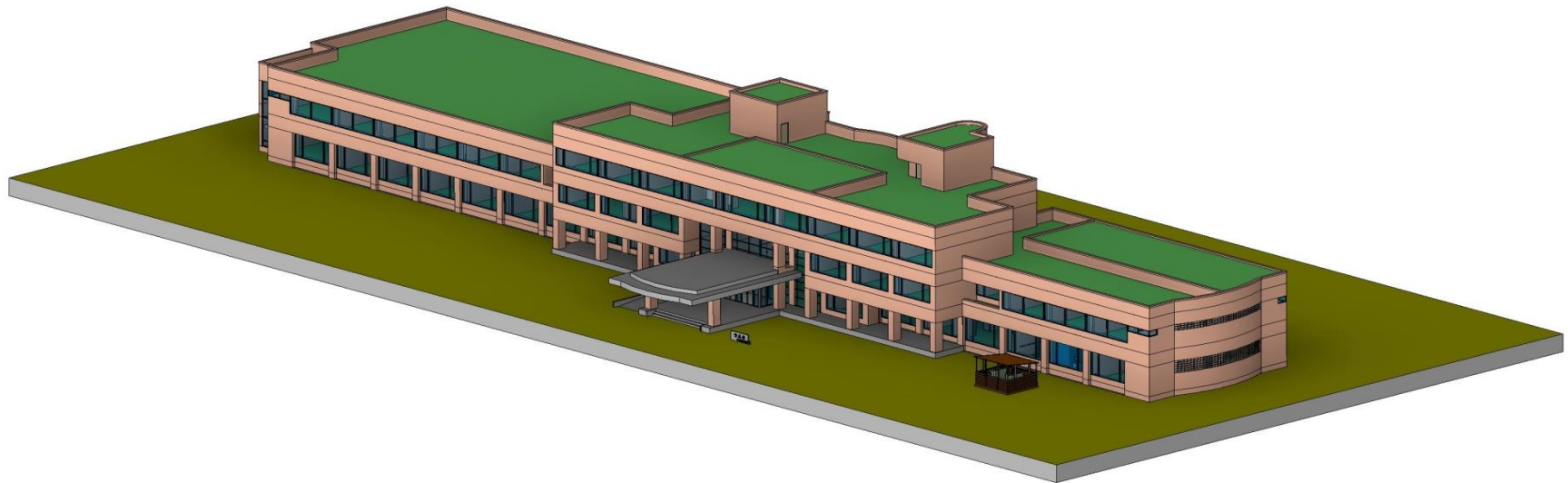


Axion exp. development plan

	2014	2015	2016	2017	2018
Magnet	Prototype, testing of cable characteristics.		25T, 10cm inner bore design	Work on 35T, 10cm inner bore construction	Magnet delivery of 35T, 10cm bore
Lab space	Temporary building: Lab design and preparation		Occupation		
Axion dark matter	Proc. Equipment Study res. geom.	Development of high Q resonators		Production of high-Q resonators	
Electronics, amplifiers	Establ. Collabor. w/ KRISS	Design for 1-10GHz Obtain JPAs, test. Develop higher freq. ampl.		Ampl. deliveries from KRISS	
Axion cavity Exp.	Design of exp., procure a low field magnet		Experimental setup. First test run.		Swap magnets

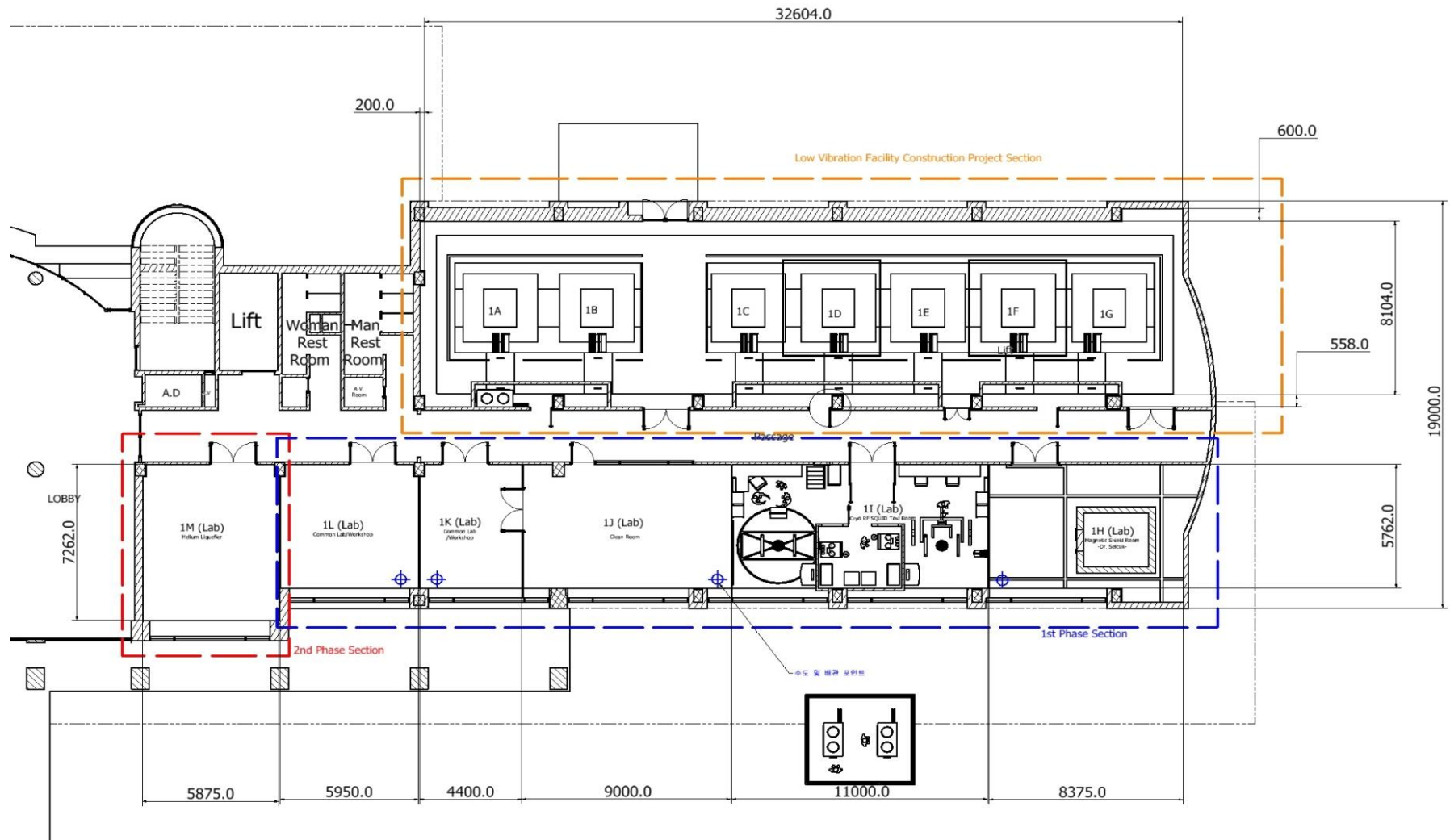
-Creation Hall-

CAPP Research Bldg. at KAIST Munji Campus

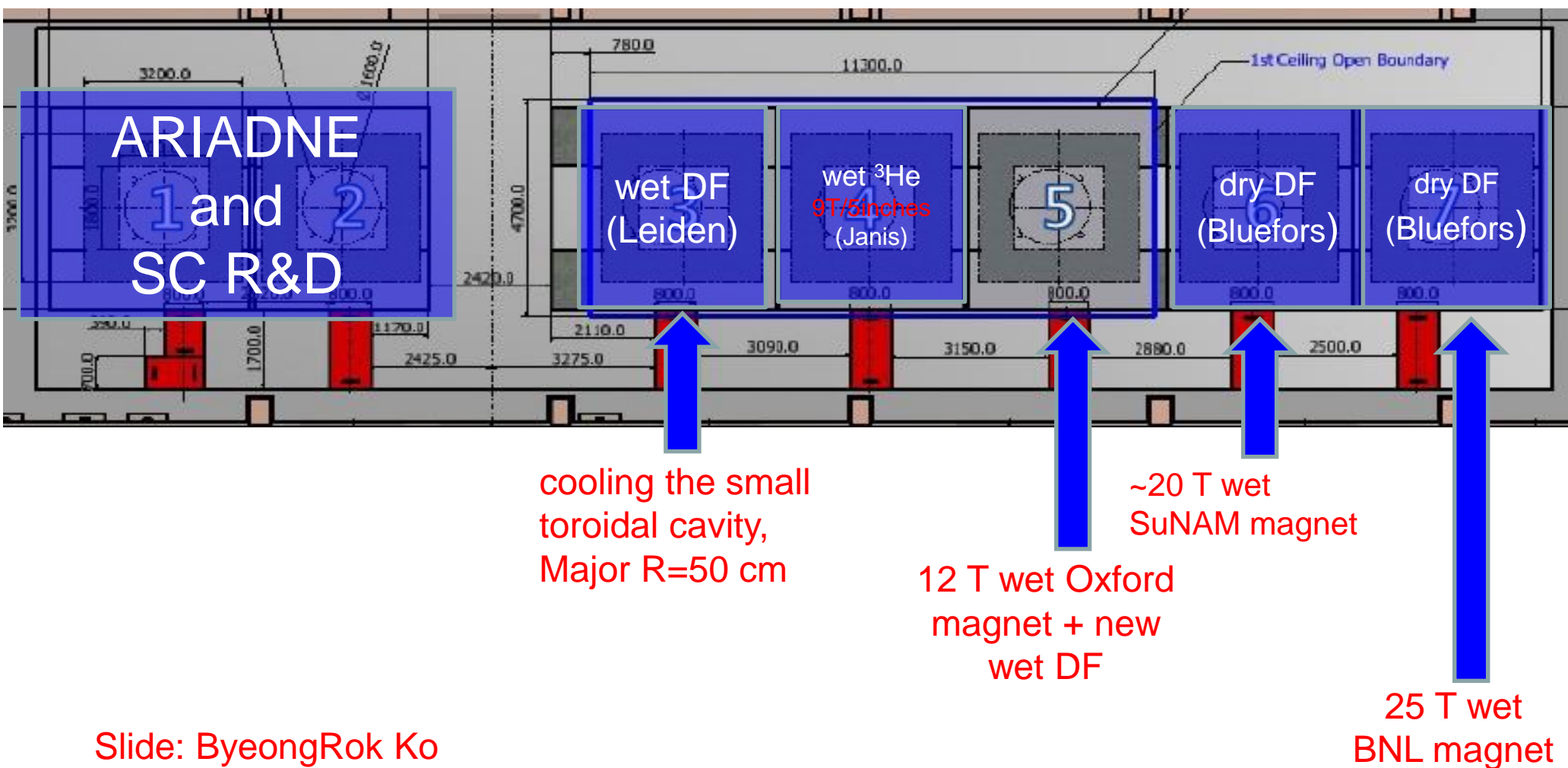


-1st Floor Drawing-

Seven, low vibration pits, two with magnetic shielding



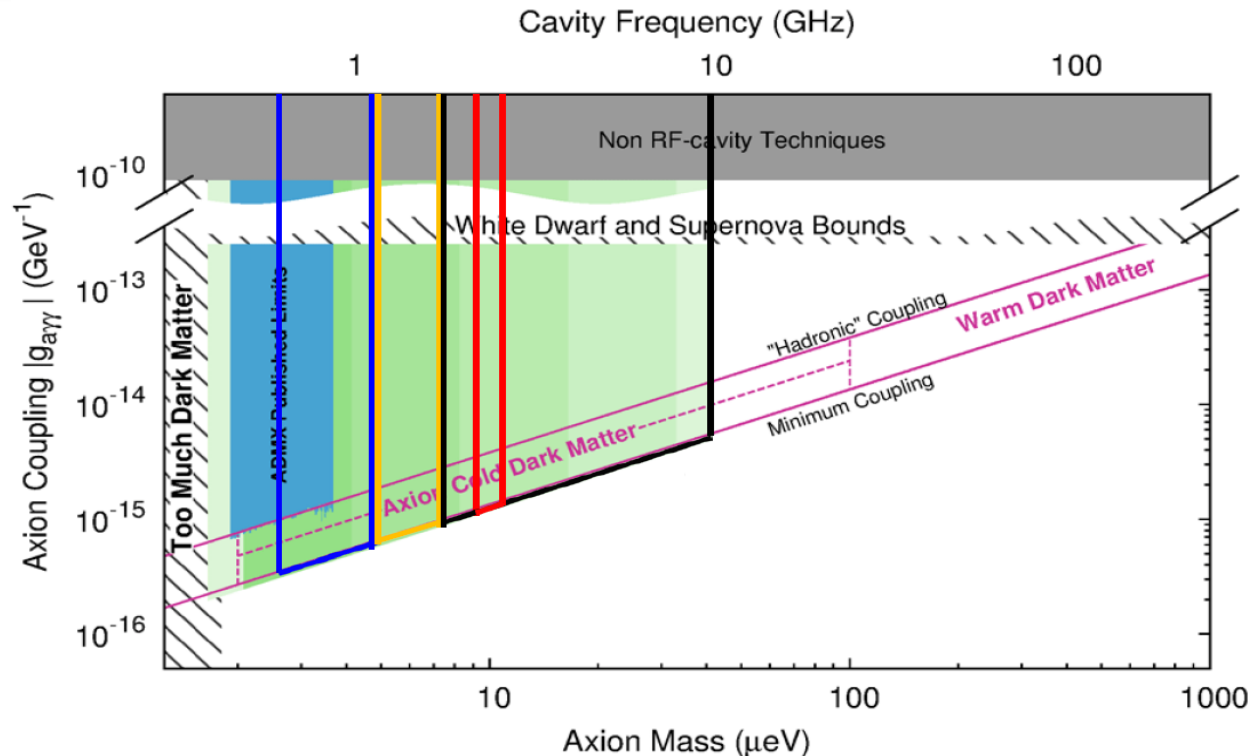
LVP assignment



Slide: ByeongRok Ko

Expected axion mass range per magnet

location	magnet	Fridge	Search range
C105	dry 8T/110mm	dry DF	
C105	dry 8T/155mm	dry DF	
Pit3	wet 12T/180mm toroid	wet DF (need ~50 liters ^3He)	1~2 GHz
Pit4	wet 9T/5inches	wet ^3He	
Pit5	wet 12T/320mm	wet DF (need ~50 liters ^3He)	0.5~1.3 GHz
Pit6	wet 20T/65mm	dry DF	3~4 GHz
Pit7	wet 25T/100mm	dry DF	2~10 GHz



Slide: ByeongRok Ko

Present magnet acquisition plan

Magnet source	Status	2016	2017	2018	2019	2020
BNL magnet	Outsourcing (to be approved)					
Oxford magnet	NFEC (approved)					
SuNAM magnet	NFEC (to be approved)					
Small toroidal magnet	Outsourcing (plan)					

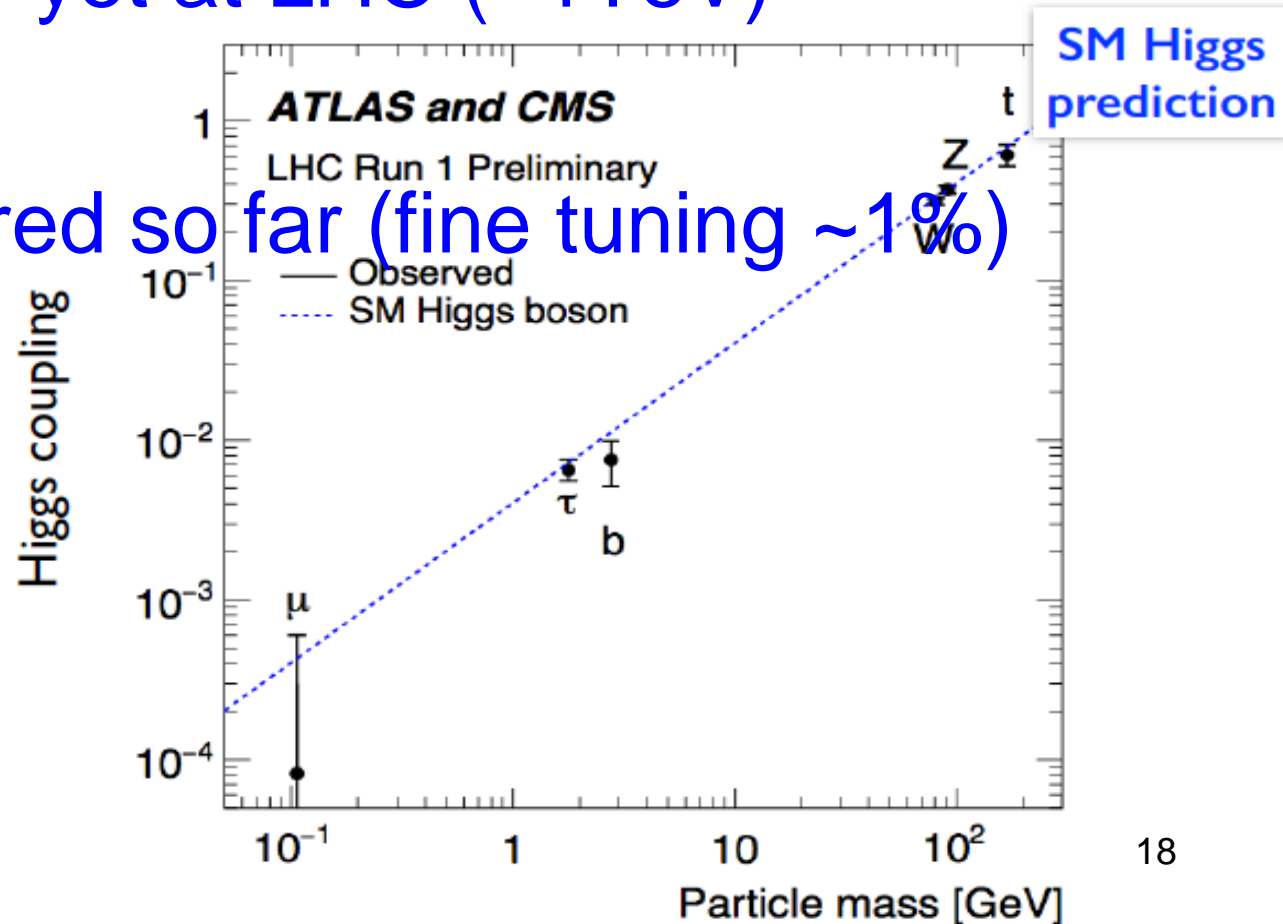
--two R&D magnets presently here:

- 1) wet magnet (9 T/5 inches) and ^3He system
- 2) dry magnet (8 T/155 mm) and DF system

--one wet DF (Leiden) and one dry DF (Bluefors)

Status in HEP-NP

1. LHC discovered the Higgs
2. No sight of SUSY yet at LHC ($\sim 1\text{TeV}$)
3. No EDM discovered so far (fine tuning $\sim 1\%$)
4. What's next?





another universes)

Alex Pomarol, CERN & UAB

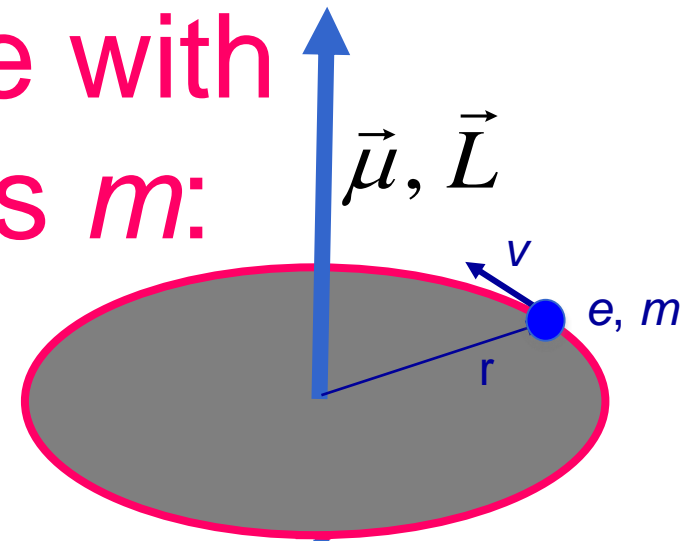
A balanced approach is best...!



Fig. 1: 95% of the universe are made of two mysterious substances, dark matter and dark energy that cannot be explained in the Standard Model. By their very names it is clear that these things are somehow hidden from our view. New particles could hide by being very massive or by having extremely feeble interactions. It is clear that we need to look in all possible directions. In our quest for new physics high energy and low energy/high precision experiments nicely complement each other and together hopefully answer our questions to Nature.

Storage Ring Muon g-2: Rigorous Test of the Standard Model

A circulating particle with charge e and mass m :



- Angular momentum

$$L = mvr$$

- Magnetic dipole moment $\vec{\mu} = g \frac{e\hbar}{2m} \frac{\vec{L}}{\hbar} = g\mu_B \frac{\vec{L}}{\hbar}, g = 1$

$$\mu = IA = \frac{e}{2\pi r / v} \pi r^2 = \frac{erv}{2} \frac{L}{mvr} = \frac{e\hbar}{2m} \frac{L}{\hbar} = \mu_B \frac{L}{\hbar}$$

(μ_B : Bohr magneton)

Dirac: For particles with intrinsic angular momentum (spin S)

$$\vec{\mu} = g \frac{e}{2m} \vec{S}, g = 2$$

In a magnetic field (B), there is a torque:

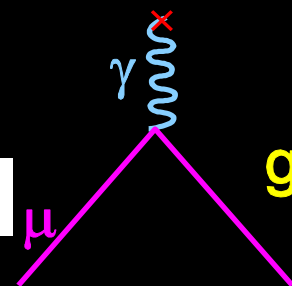
$$\vec{\tau} = \vec{\mu} \times \vec{B} \Rightarrow \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$$

g-factors:

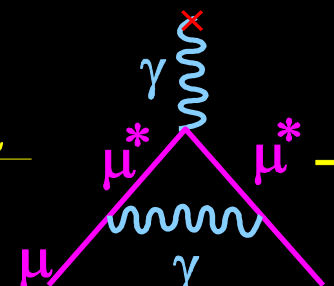
- Proton ($g_p=+5.586$) and the neutron ($g_n=-3.826$) are composite particles.
- The ratio $g_p/g_n=-1.46$ close to the predicted $-3/2$ was the first success of the constituent quark model.
- The g_e-2 (of the electron) is non-zero mainly due to quantum field fluctuations involving QED. A “soup” of virtual particles coming in and out of existence...
- The anomalous magnetic moment of leptons can be estimated with high accuracy

Today we can estimate and measure with high accuracy many possible states

$$g = 2 + \frac{\alpha}{\pi} + c_2 \left(\frac{\alpha}{\pi}\right)^2 + \dots$$



Dirac
Stern-Gerlach



Schwinger
Kusch-Foley



$$a(\text{QED}) = \frac{1}{2} \frac{\alpha}{\pi} + C_2 \left(\frac{\alpha}{\pi}\right)^2 + C_3 \left(\frac{\alpha}{\pi}\right)^3 + C_4 \left(\frac{\alpha}{\pi}\right)^4 + C_5 \left(\frac{\alpha}{\pi}\right)^5 + \dots$$

Electron Magnetic Dipole Moment

D. Hanneke, S. Fogwell, and G. Gabrielse, PRL **100**, 120801 (2008)

$$\vec{\mu} = -g \left(\frac{e}{2m} \right) \vec{s}$$

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

$$g / 2 = 1.001\,159\,652\,180\,73\,(28)\,[0.28\,\text{ppt}]$$

$$\begin{aligned} \frac{g}{2} = & 1 + C_2 \left(\frac{\alpha}{\pi} \right) + C_4 \left(\frac{\alpha}{\pi} \right)^2 + C_6 \left(\frac{\alpha}{\pi} \right)^3 + C_8 \left(\frac{\alpha}{\pi} \right)^4 \\ & + C_{10} \left(\frac{\alpha}{\pi} \right)^5 + \dots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}, \quad (4) \end{aligned}$$

It's a triumph of QED!

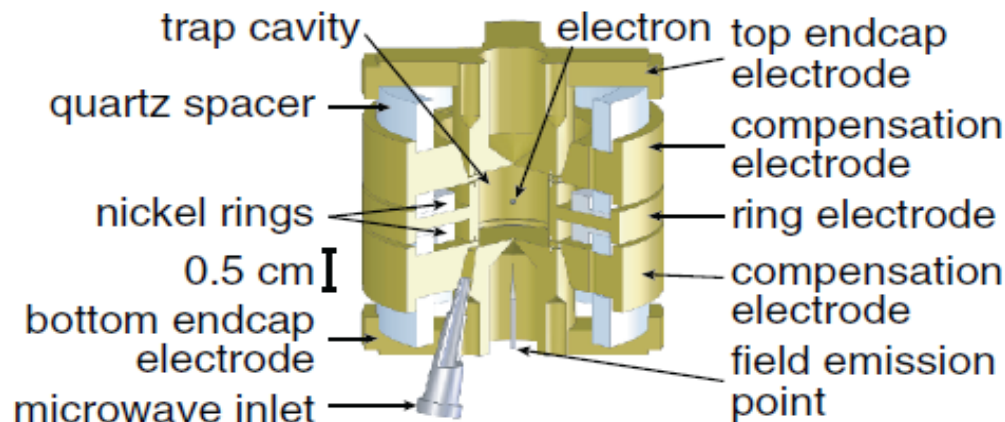


FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

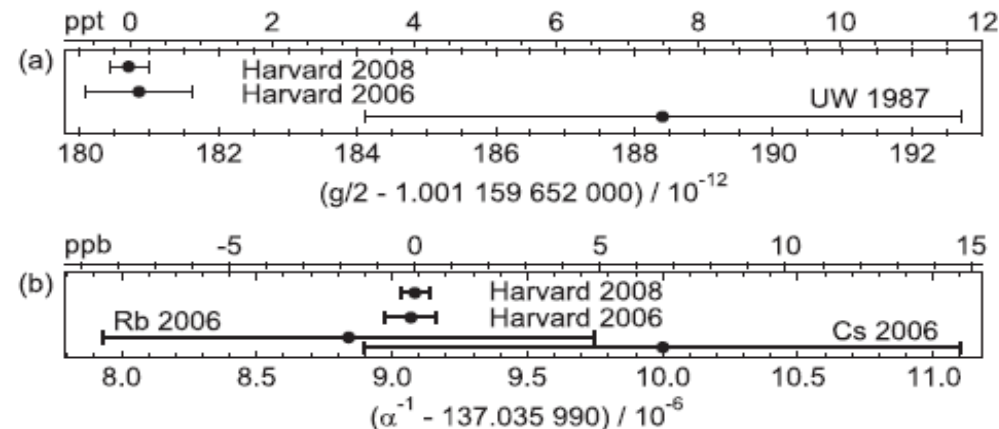


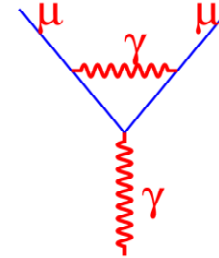
FIG. 1. Most accurate measurements of the electron $g/2$ (a), and most accurate determinations of α (b).

g-factors: Muon case

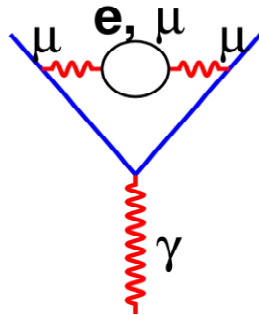
- The $g_\mu - 2$ is more sensitive to a class of particles than the $g_e - 2$ by $(m_\mu/m_e)^2 \sim 40,000$. Muon is sensitive to a ...thicker “soup” of virtual particles.
- Muons are sensitive to W, Z, and New Physics, e.g. SUSY: neutralino

$g - 2$ for the muon, SM contributions

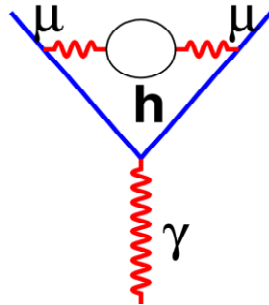
Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$



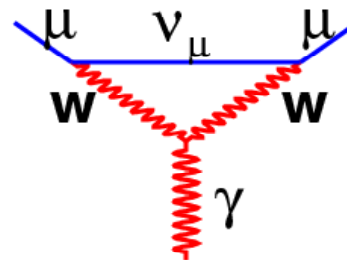
Other standard model contributions :



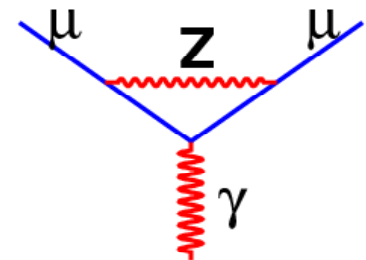
QED



hadronic



weak



Muons (heavier than electrons) are more sensitive to weak interaction forces (standard model (SM))

Muons become (sometimes) 10^3 times heavier!



Weak interactions

Spin Precession Rate at Rest

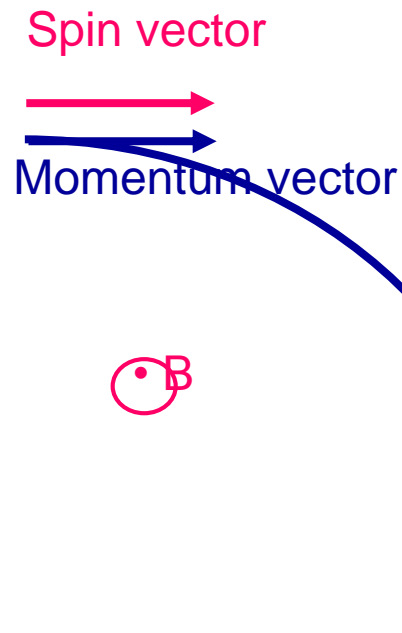
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

There is a large asymmetry in this equation: μ is relatively large, d is compatible with zero

The Principle of g-2

At rest : $\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$

Spin vector
Momentum vector



Moving: Thomas precession!

$$W_c = \frac{eB}{mg}$$

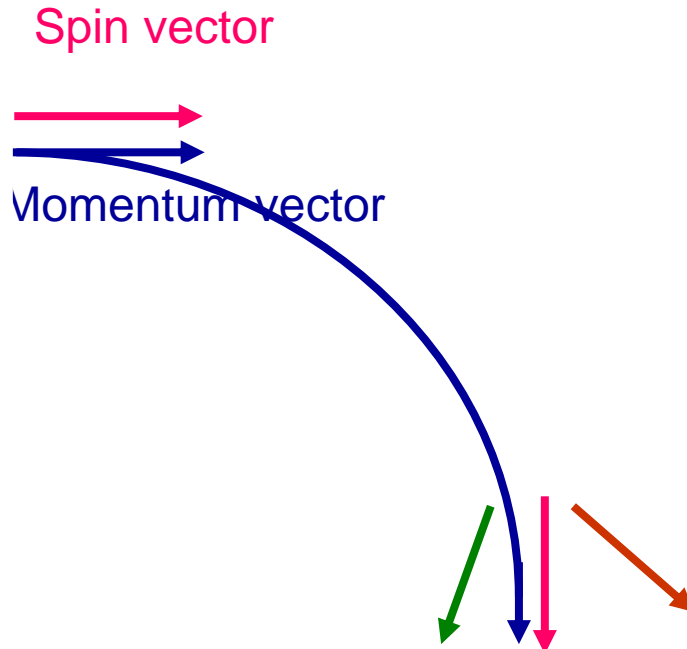
$$W_s = \frac{g}{2} \frac{eB}{m} + (1 - g) \frac{eB}{mg}$$

$$W_a = W_s - W_c = \left(\frac{g - 2}{2} \right) \frac{eB}{m} \Rightarrow W_a = a \frac{eB}{m}$$

Independent of velocity!

Effect of Radial Electric Field

Spin vector
Momentum vector



- Low energy particle

- ...just right

- High energy particle

Breakthrough concept: Freezing the horizontal spin precession due to E-field

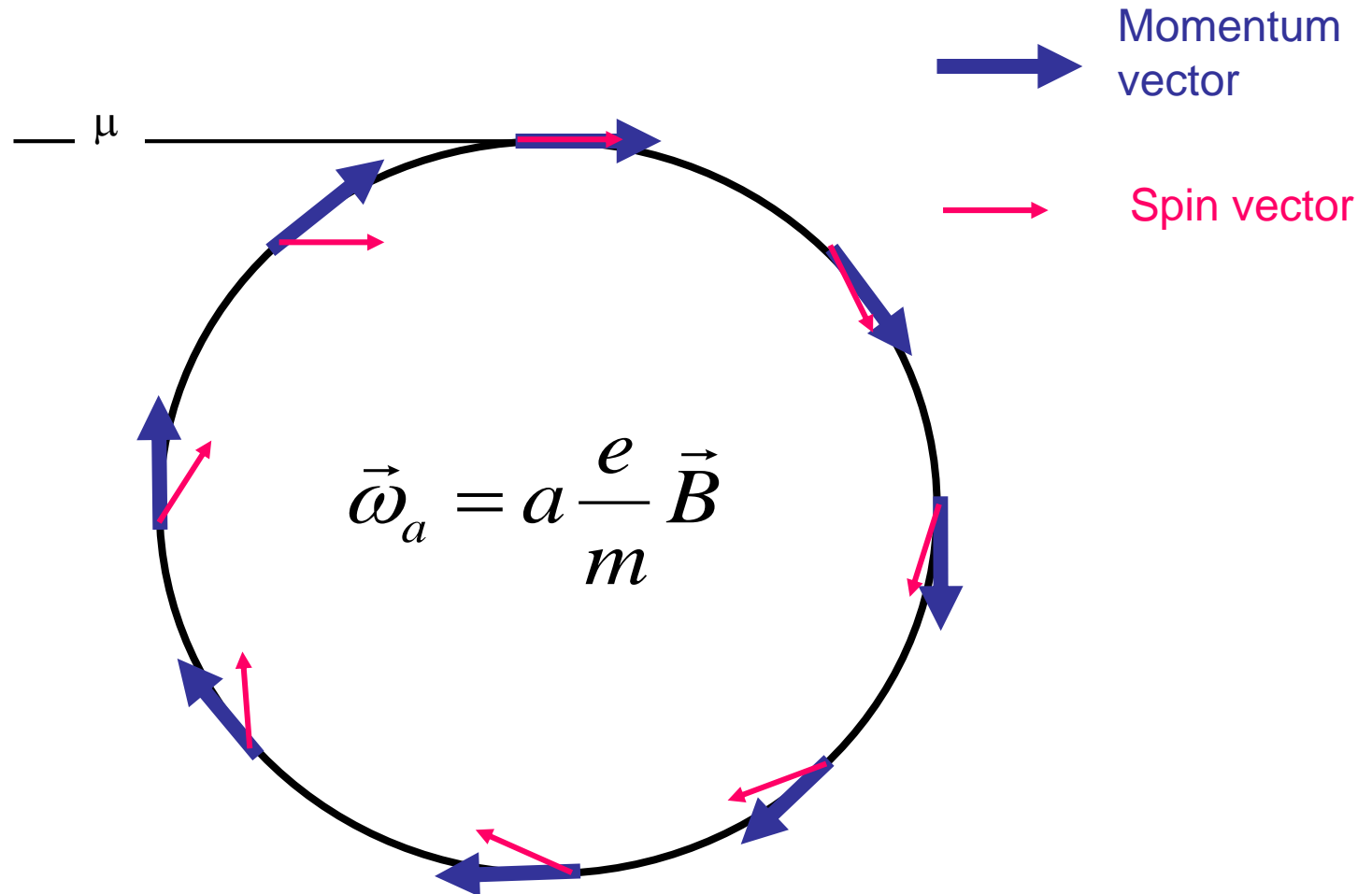
$$\vec{\omega}_a = -\frac{q}{m} \left\{ a\vec{B} - \left[a - \left(\frac{mc}{p} \right)^2 \right] \frac{\vec{\beta} \times \vec{E}}{c} \right\}$$

Muon g-2 focusing is electric: The spin precession due to E-field is zero at “magic” momentum (3.1 GeV/c for muons, 0.7 GeV/c for protons,...)

$$p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g-2}{2}$$

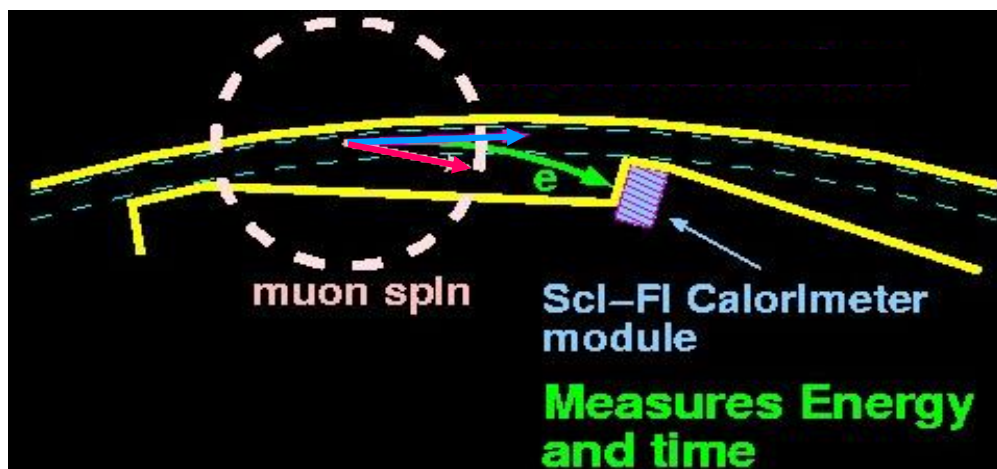
The “magic” momentum concept was used in the muon g-2 experiments at CERN, BNL, and ...now at FNAL.

Spin Precession in g-2 Ring (Top View)

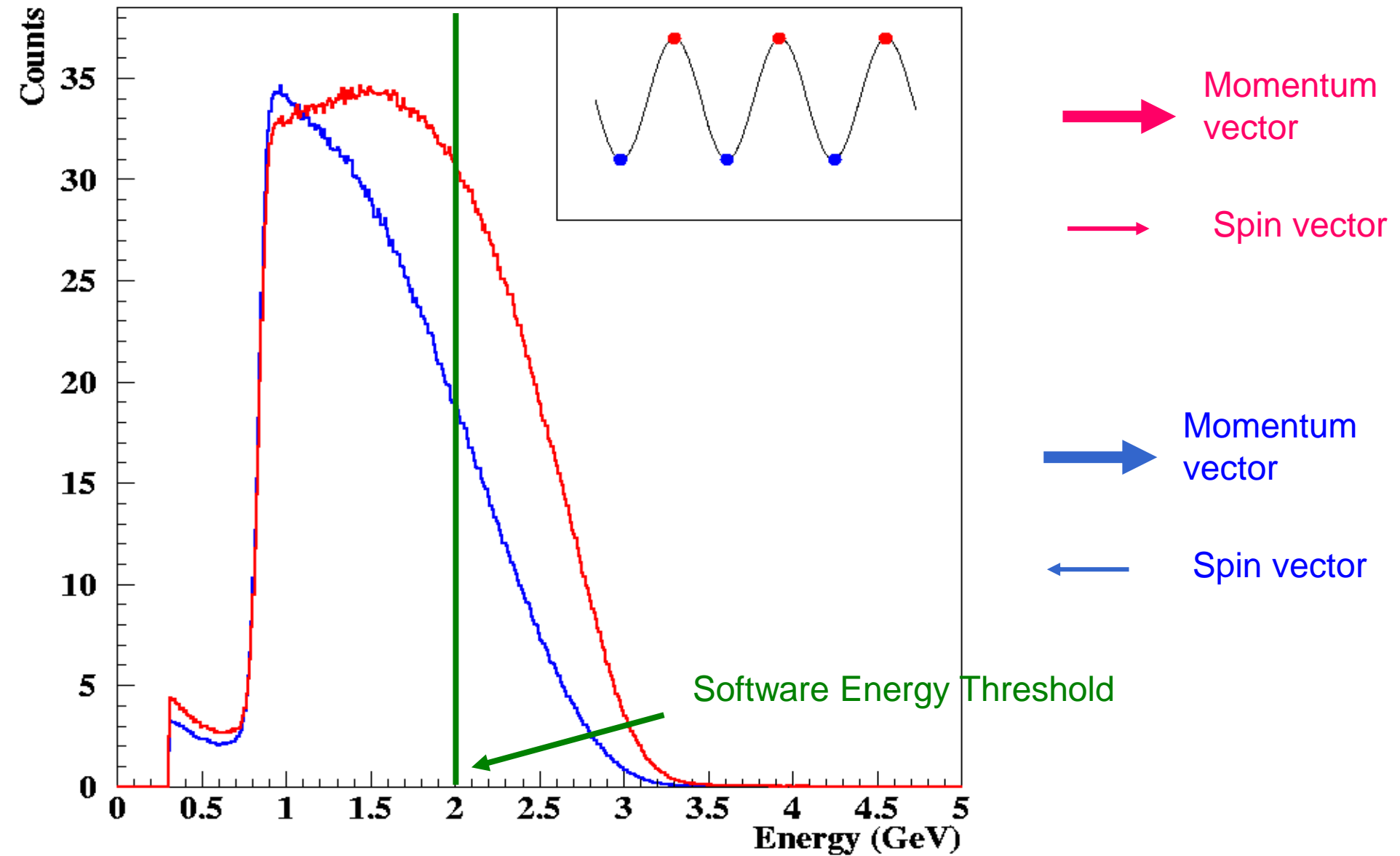


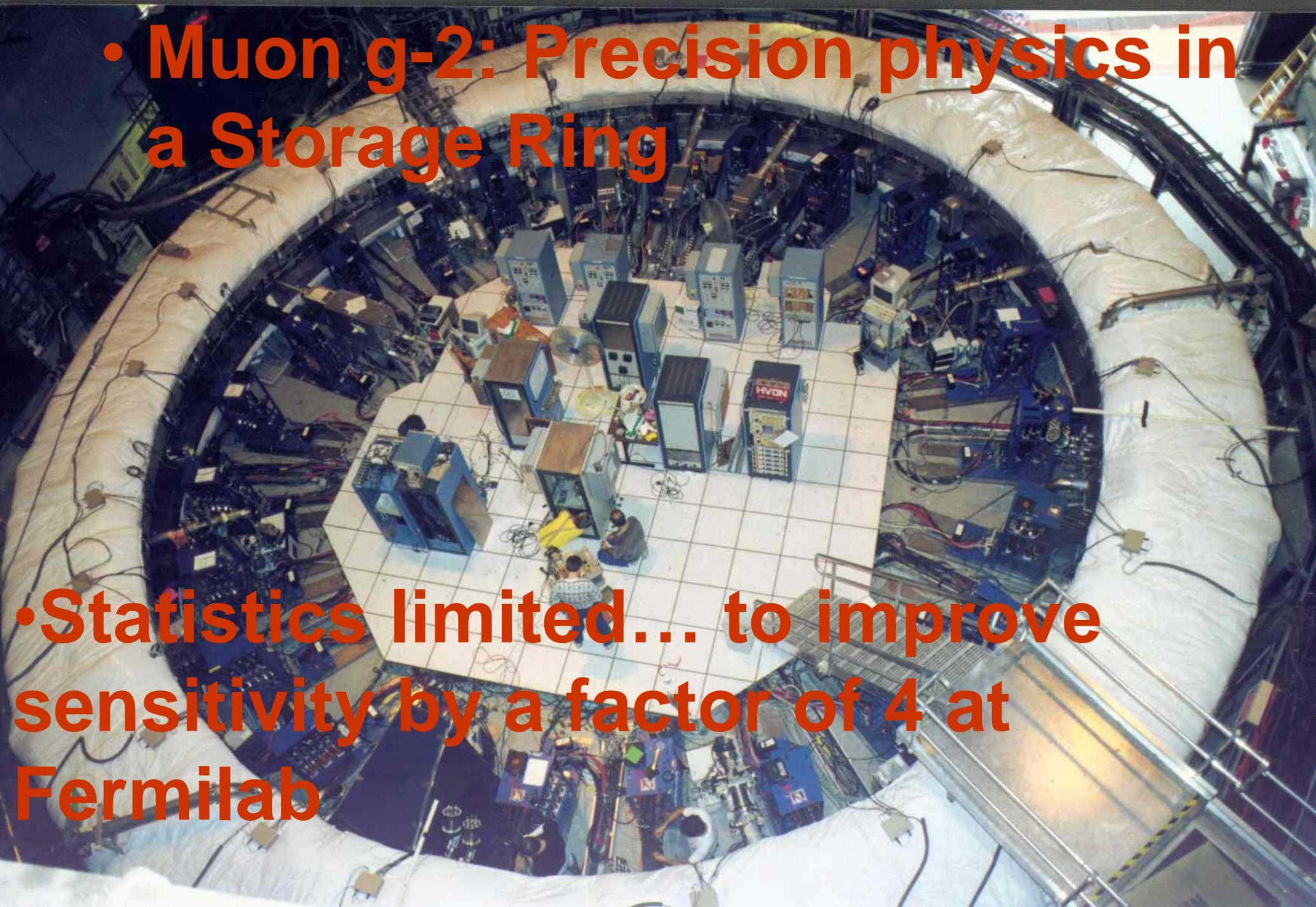
The electric focusing does not influence the g-2 precession rate

Detectors and vacuum chamber



Energy Spectrum of Detected Positrons depends on spin direction



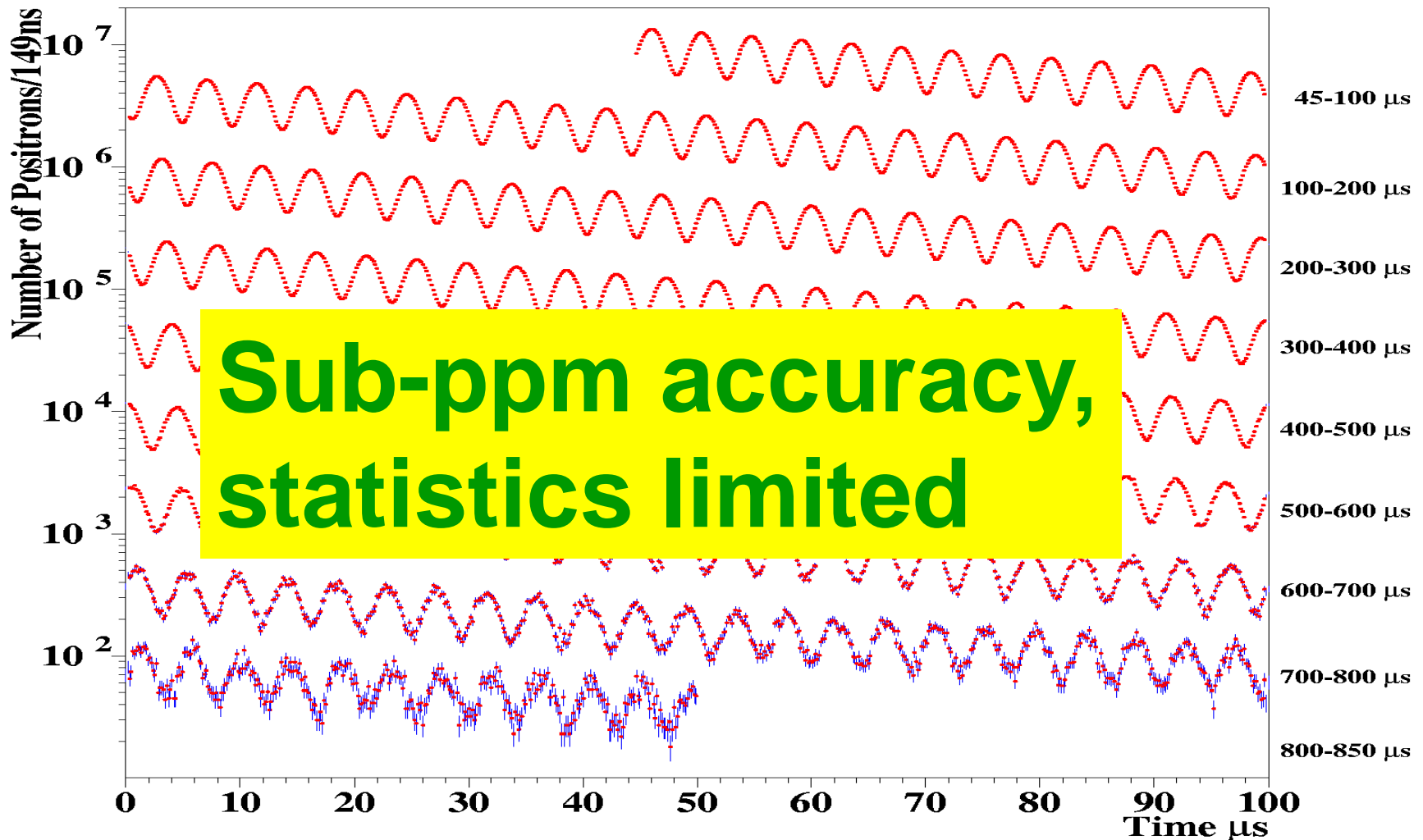
An aerial photograph of the Muon g-2 experiment's storage ring at Fermilab. The ring is a large, circular structure with a white, insulated outer wall. Inside the ring, a central platform is covered with a white tiled floor. On this platform, several large, blue, rectangular electronic modules are arranged in a circular pattern. A person in a white shirt is visible on the platform, working with the equipment. The surrounding area is filled with various cables, pipes, and structural elements of the facility.

- Muon g-2: Precision physics in a Storage Ring

- Statistics limited... to improve sensitivity by a factor of 4 at Fermilab

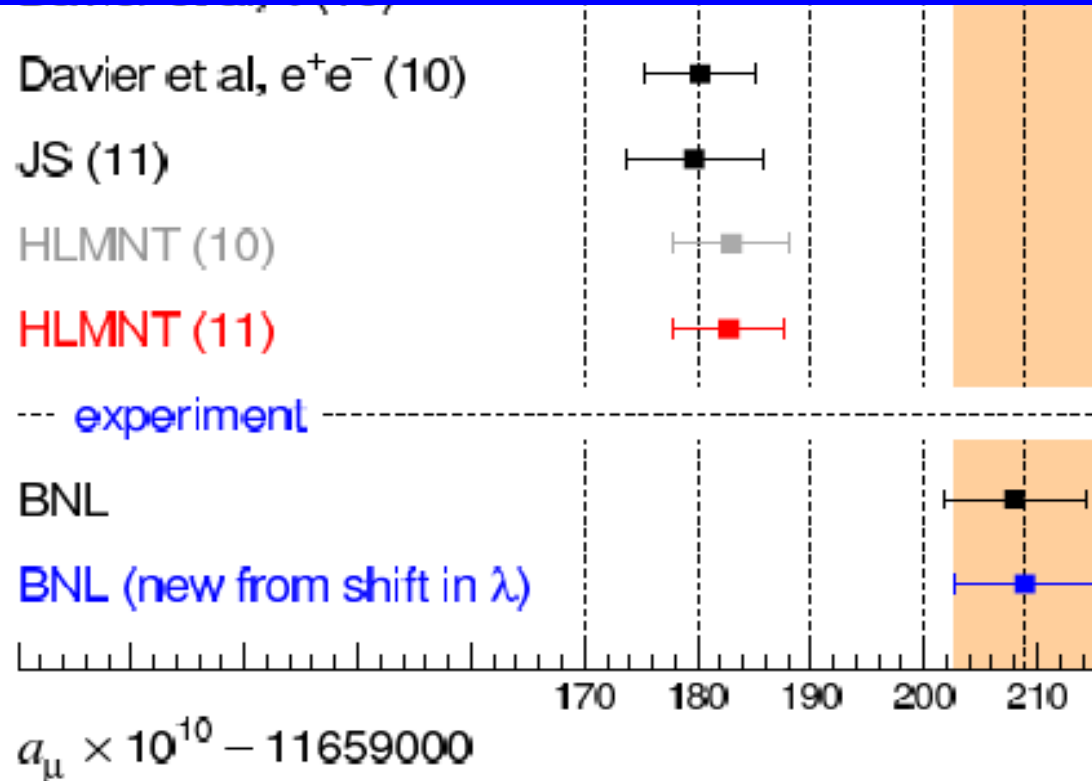
Muon g-2: 4 Billion e^+ with $E > 2\text{GeV}$

$$dN / dt = N_0 e^{-\frac{t}{\tau}} \left[1 + A \cos(\omega_a t + \phi_a) \right]$$



Comparison of Theory/Experiment

The result is 3.5 s.d. away from theory! What is it?



Yannis Semertzidis

Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL

The muon ring moved to Fermilab (22 June – 25 July 2013)



The muon ring arrived at Fermilab





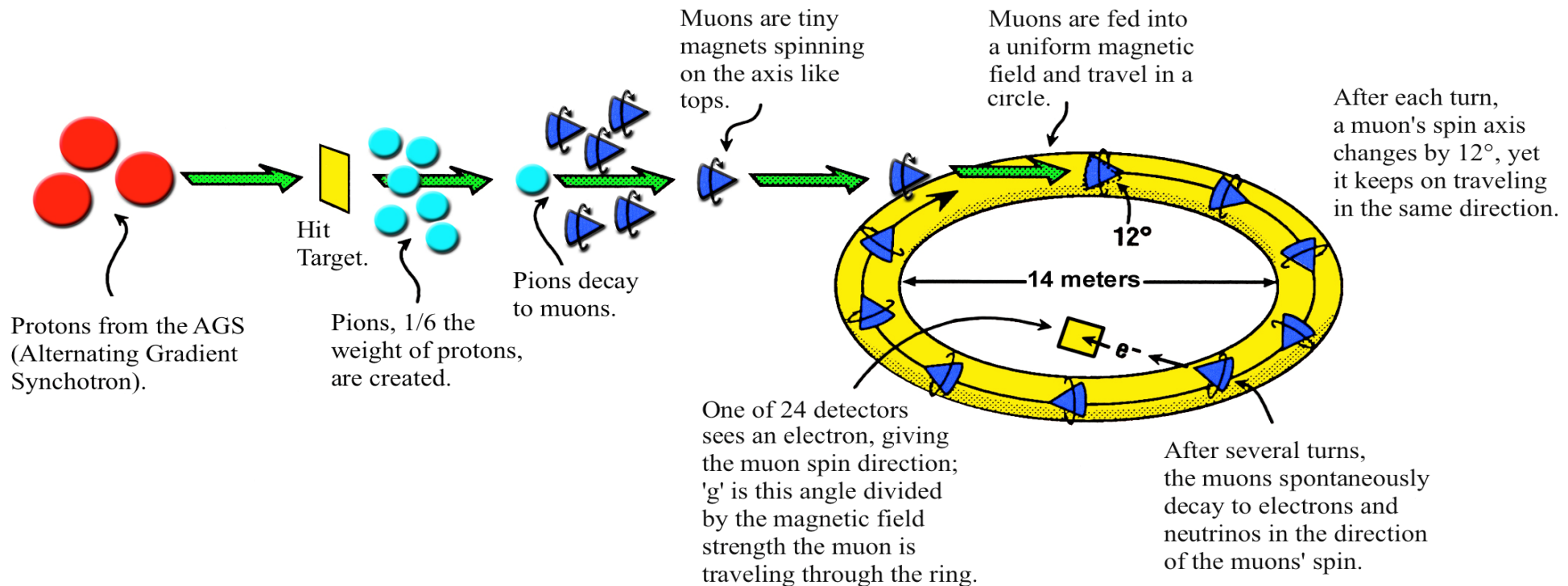


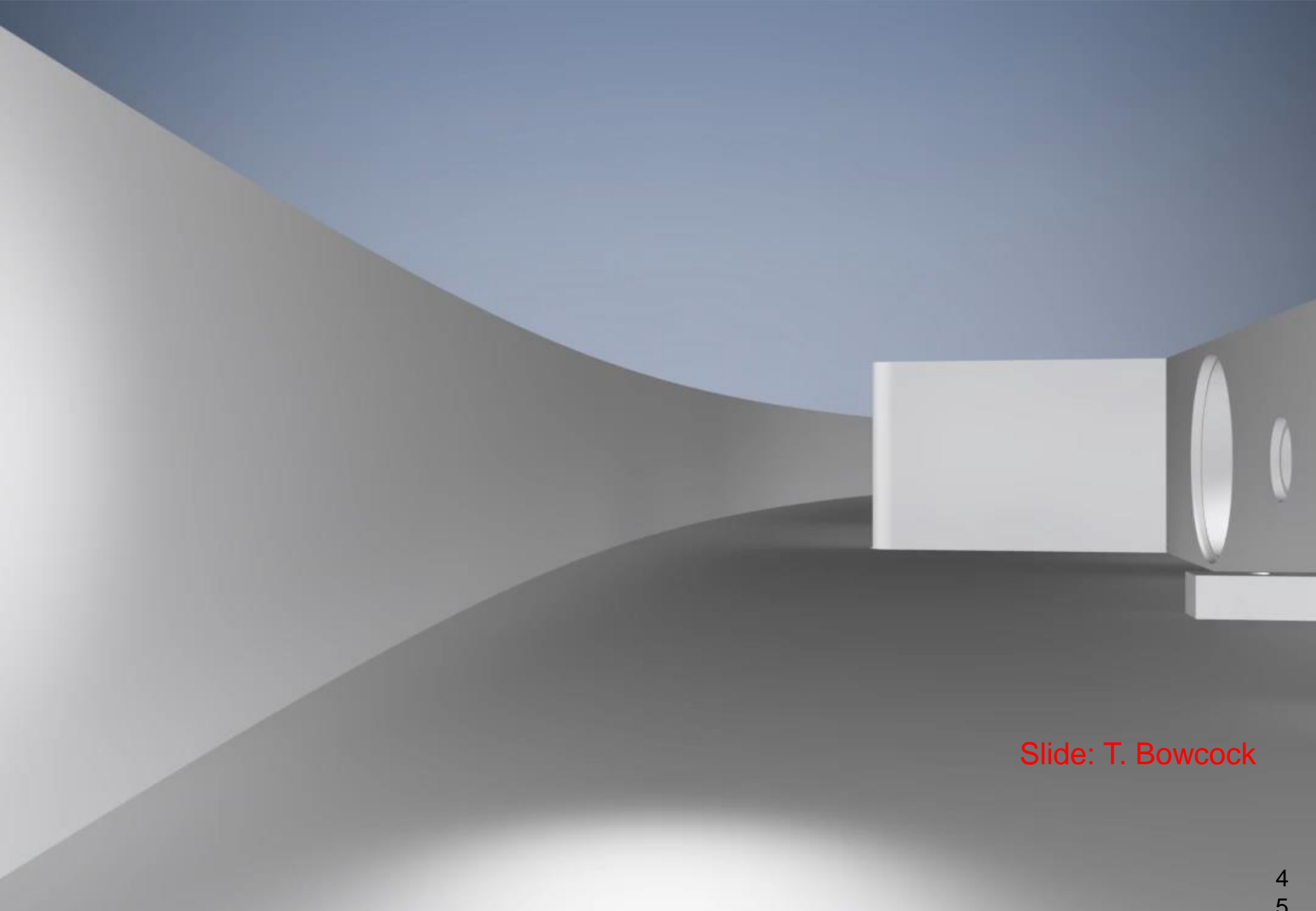
The ring has been reassembled and fully powered to 1.45T! First data: 2017

Muon g-2 experiment: Best challenge to the Standard Model

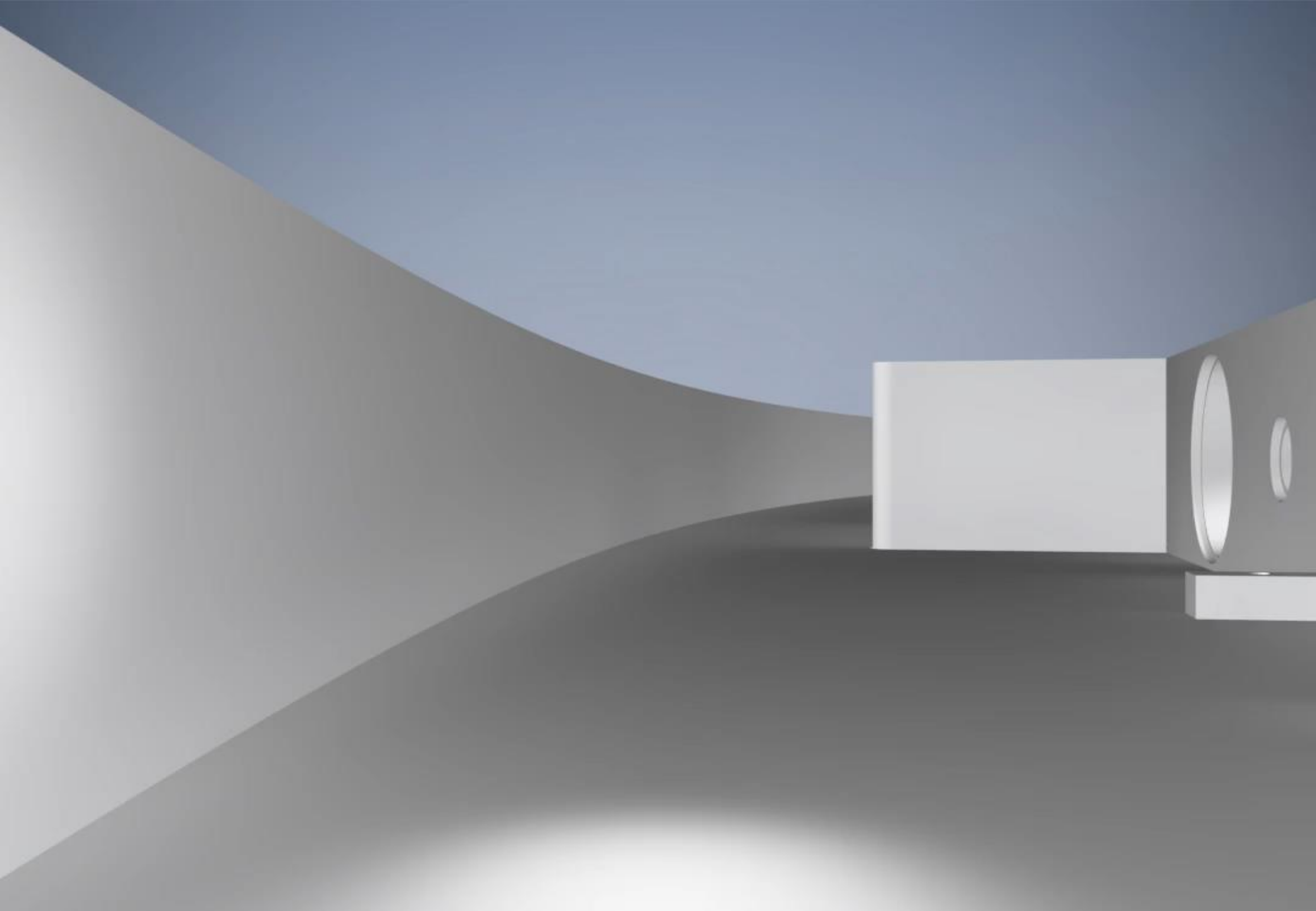
- E821 at BNL: 1997-2004
- E969 at FNAL: first data in 2017

LIFE OF A MUON: THE g-2 EXPERIMENT





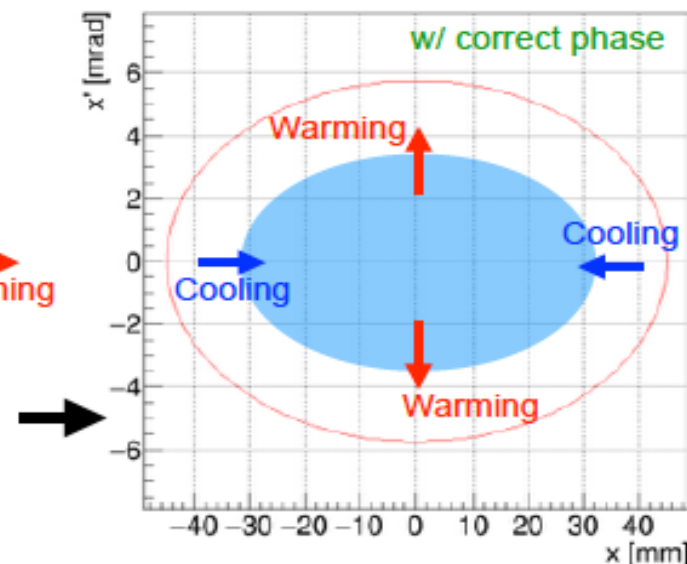
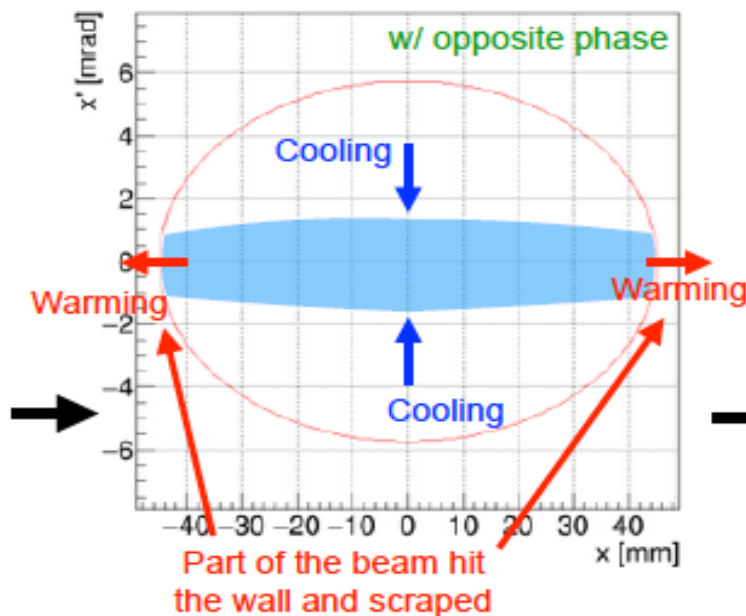
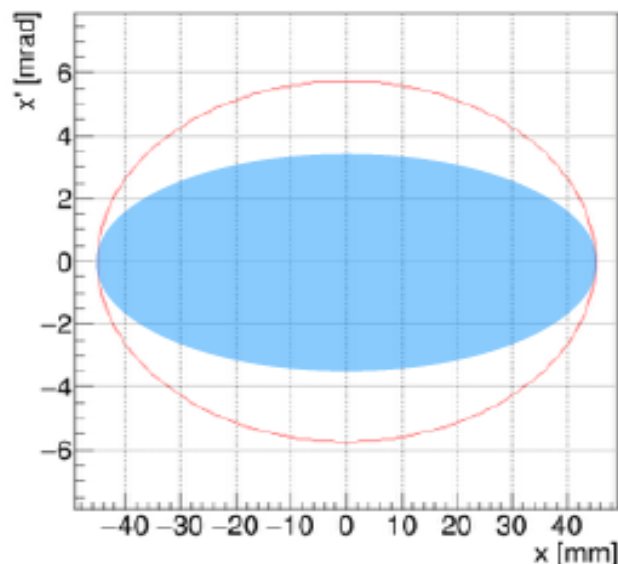
Slide: T. Bowcock



Systematic errors for the muon g-2 exp. at BNL and at FNAL (projections)

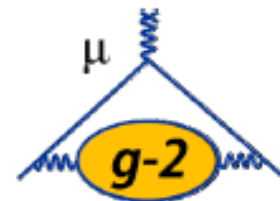
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	20
Pileup	80	low-energy threshold	
		Low-energy samples recorded	40
		calorimeter segmentation	
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

- RF matching can be another solution for the scraping
- Stretching the beam with opposite phase, and bring it back with correct phase



Simulation: Dr. Soohyung Lee

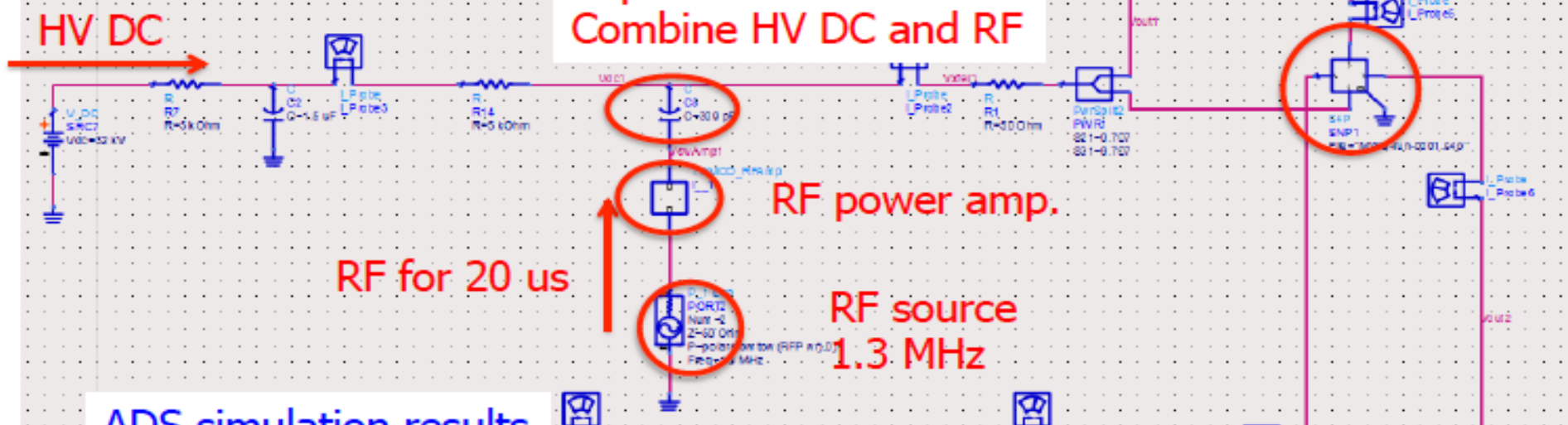
Circuit simulation



QUAD plates
~ 300 pF

ADS simulation

Capacitor
Combine HV DC and RF

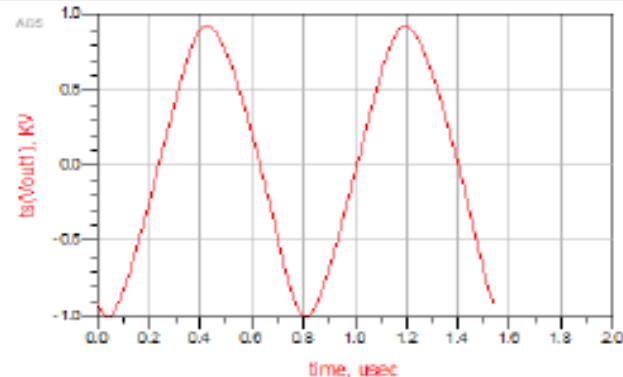
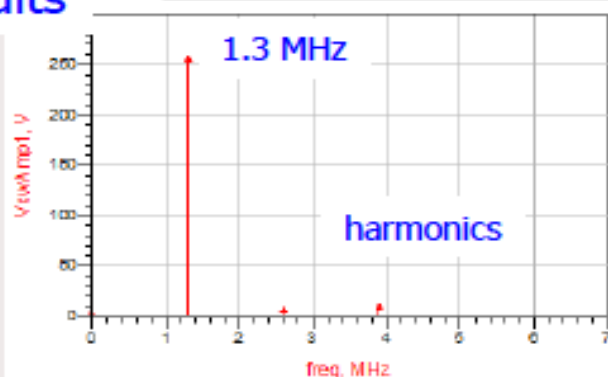


RF for 20 us

RF power amp.

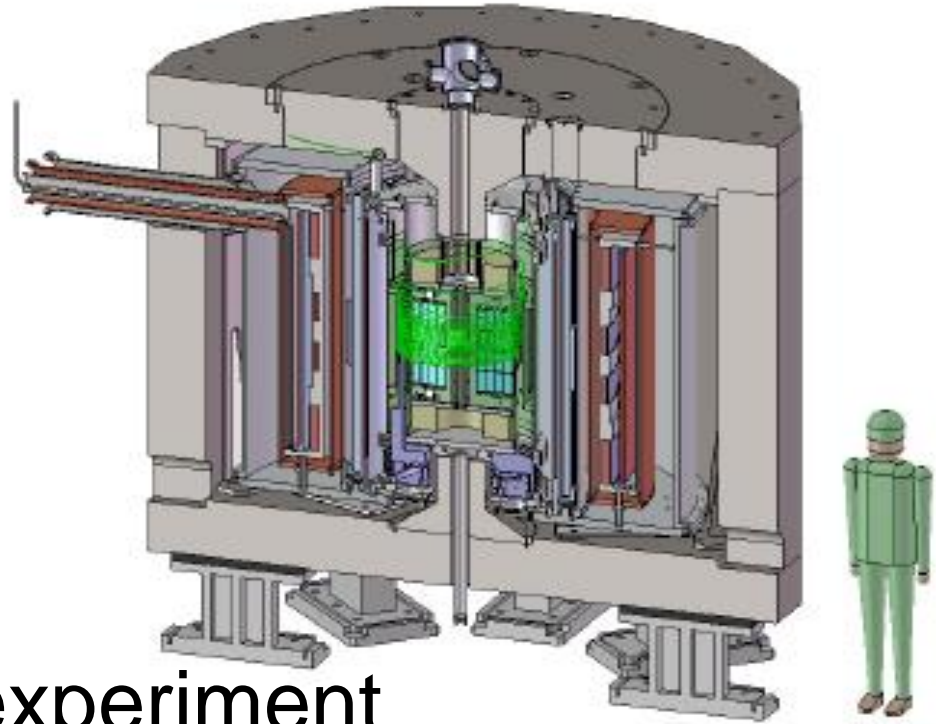
RF source
1.3 MHz

ADS simulation results



Slide: Dr. YoungIm Kim

J-PARC Muon g-2 experiment

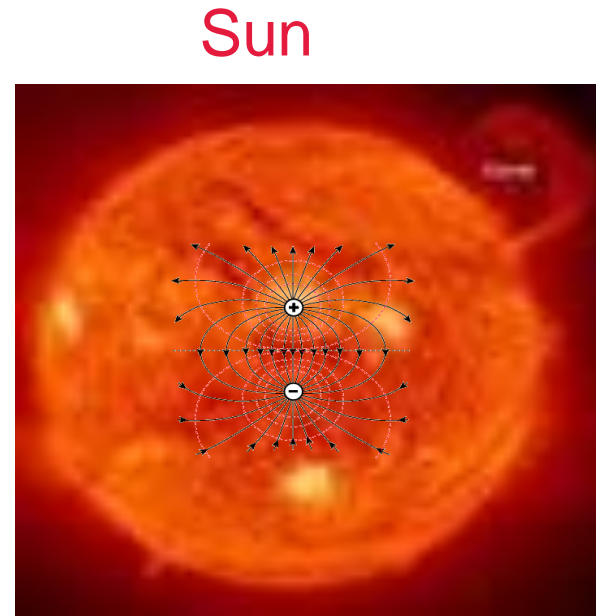
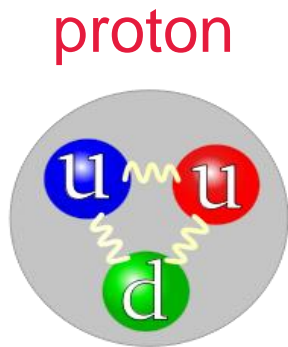


- Totally independent experiment
- Very different systematic errors
- Much more uniform B-field
- Accepting all muon decays

Fundamental particle EDM: study of CP-violation beyond the Standard Model

Proton EDM proposal: $d=10^{-29}\text{e}\cdot\text{cm}$

- High sensitivity experiment:
- Blowing up the proton to become as large as the sun, the sensitivity to charge separation along N-S would be $r < 0.1\text{ }\mu\text{m}$!



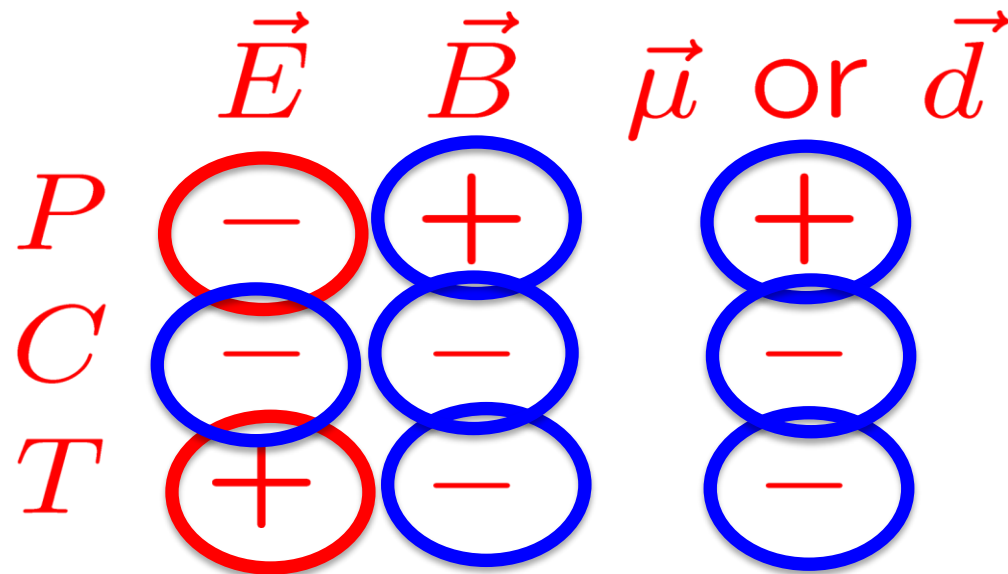
$$\vec{d} = q\vec{r}$$

Electric Dipole Moments: P and T-violating when $\vec{d} //$ to spin

$$\vec{\mu} = g \left(\frac{q}{2m} \right) \vec{s},$$

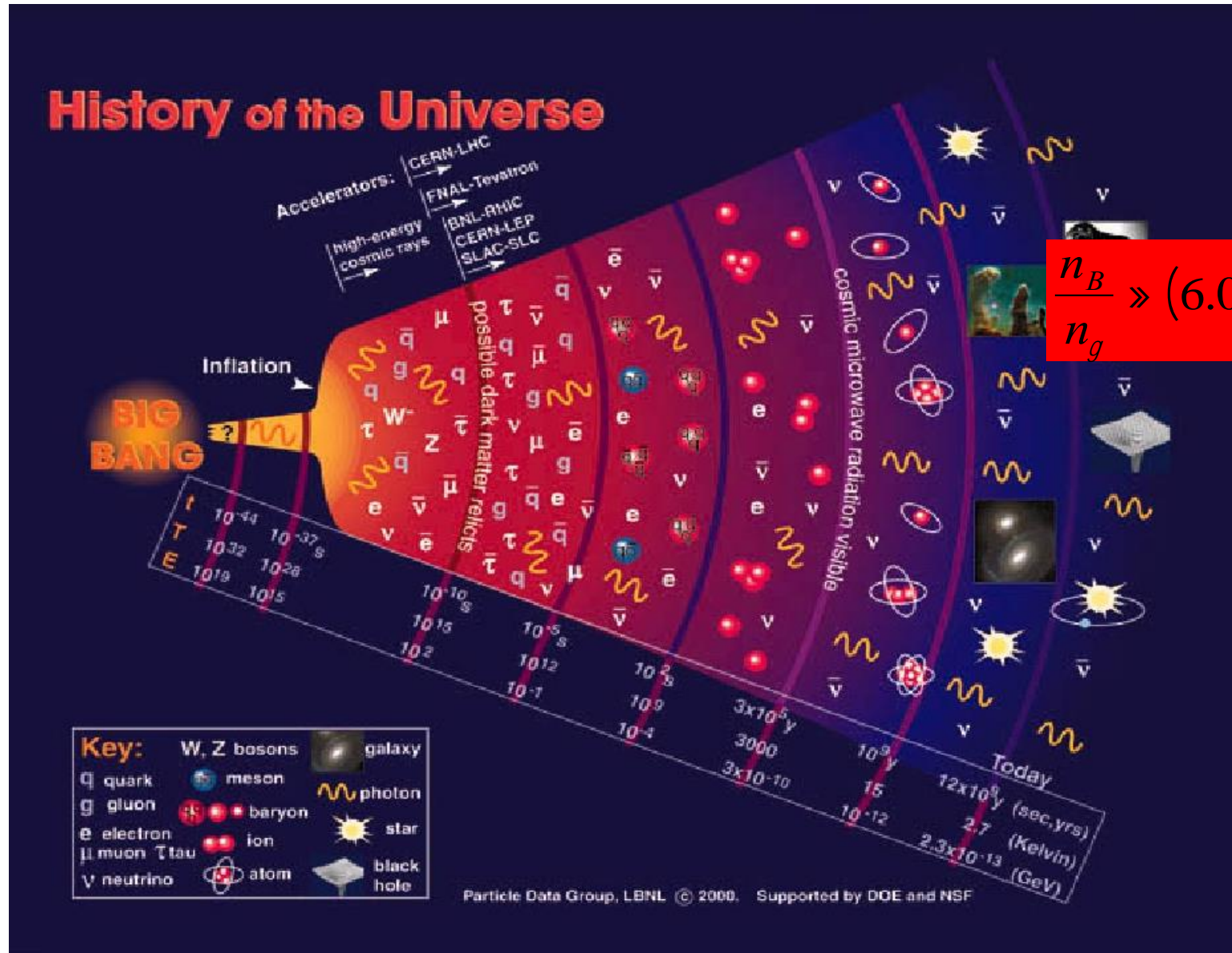
$$\vec{d} = \eta \left(\frac{q}{2mc} \right) \vec{s}$$

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$



T-violation: assuming CPT cons. \rightarrow CP-violation

Why is there so much matter after the Big Bang:



We see:

$$\frac{n_B}{n_g} \gg (6.08 \pm 0.14) \times 10^{-10}$$

From the SM:

$$\frac{n_B}{n_g} \gg 10^{-18}$$



Andrei Sakharov 1967:

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

CP-violation is established

- The observed SM CP-violation is not enough to explain the apparent **B**aryon **A**symmetry of our **U**niverse by ~ 10 orders of magnitude (only good for about ten to a hundred galaxies!).
- A new, much stronger CP-violation source is needed to explain the observed **BAU**.

Purcell and Ramsey:

“The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle...becomes a purely experimental matter”

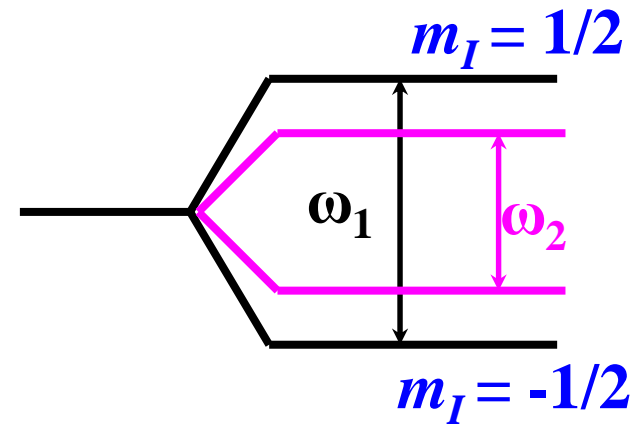
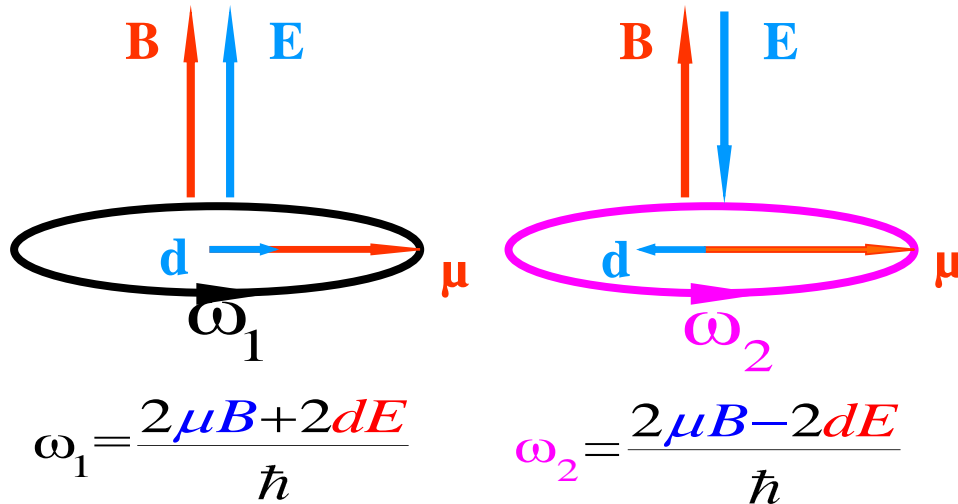


Phys. Rev. 78 (1950)



Measuring an EDM of Neutral Particles

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



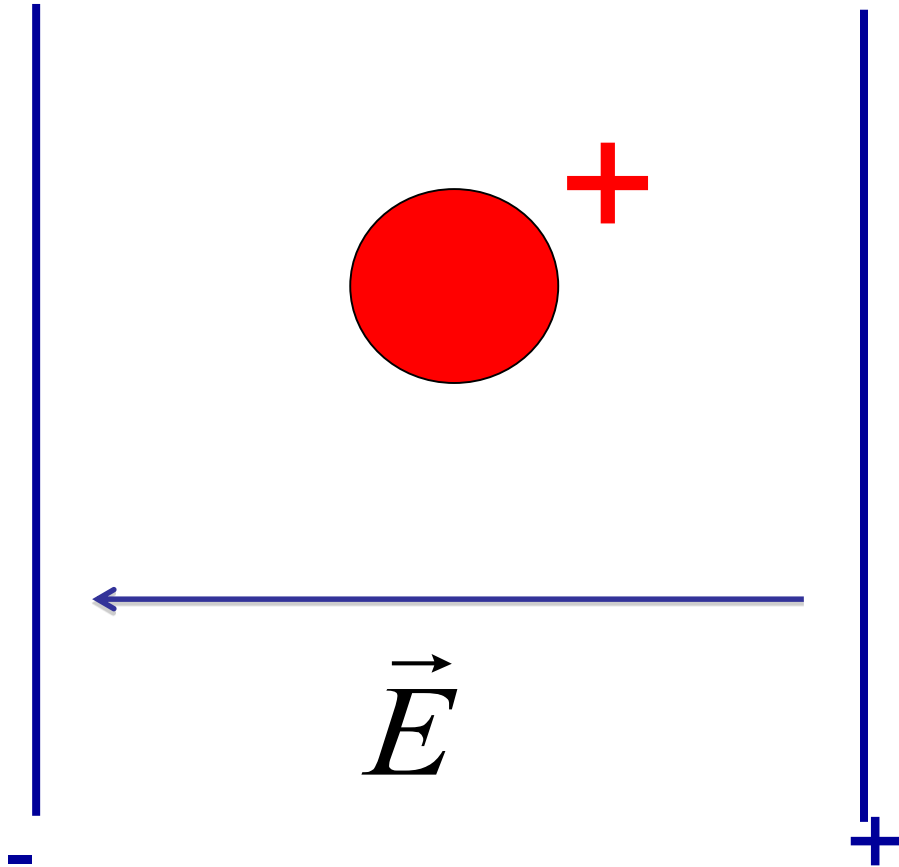
$$d = \frac{\hbar(\omega_1 - \omega_2)}{4E}$$

$$d = 10^{-29} \text{ e cm}$$

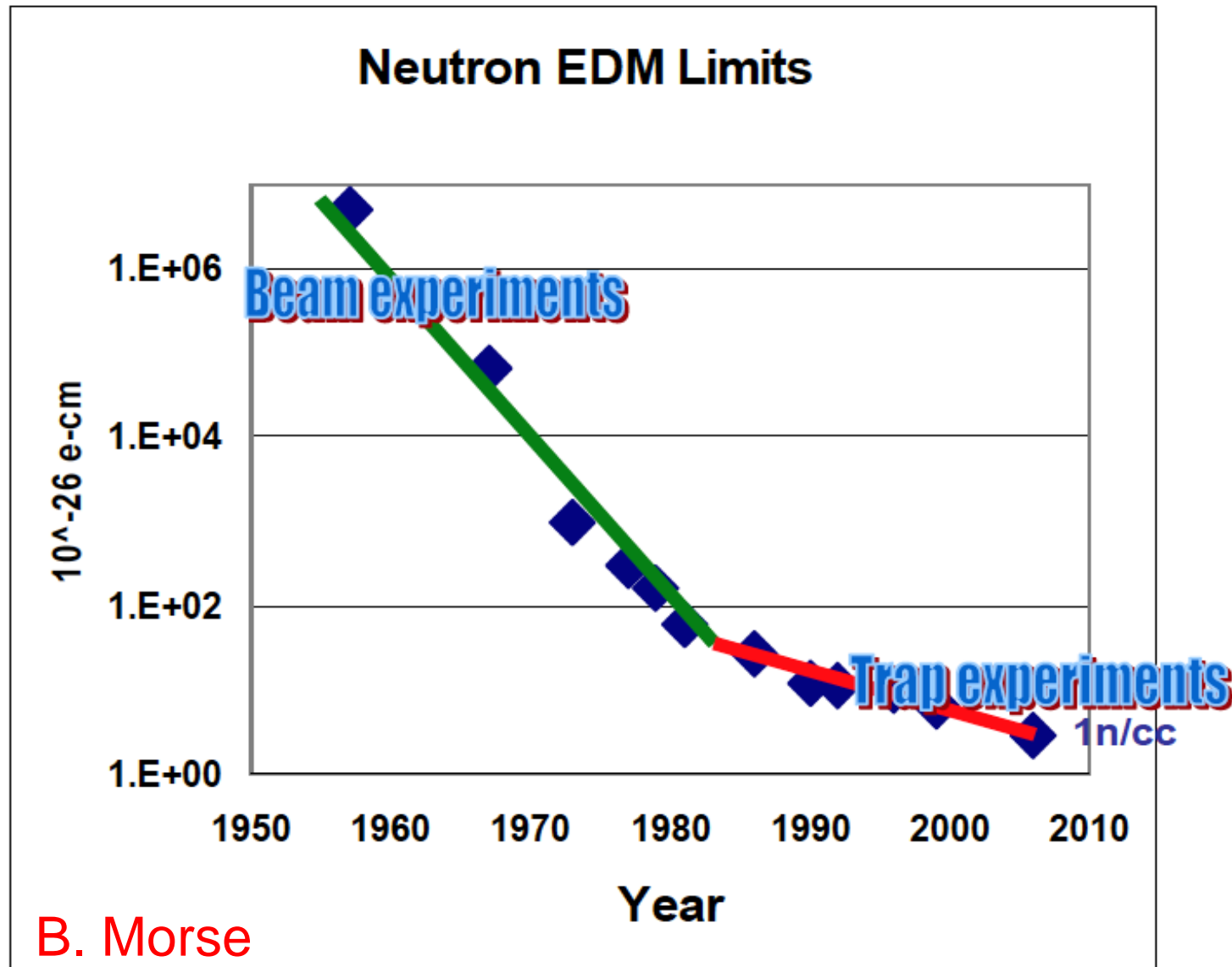
$$E = 100 \text{ kV/cm}$$

$$\omega_d = 5 \text{ nrad/s}$$

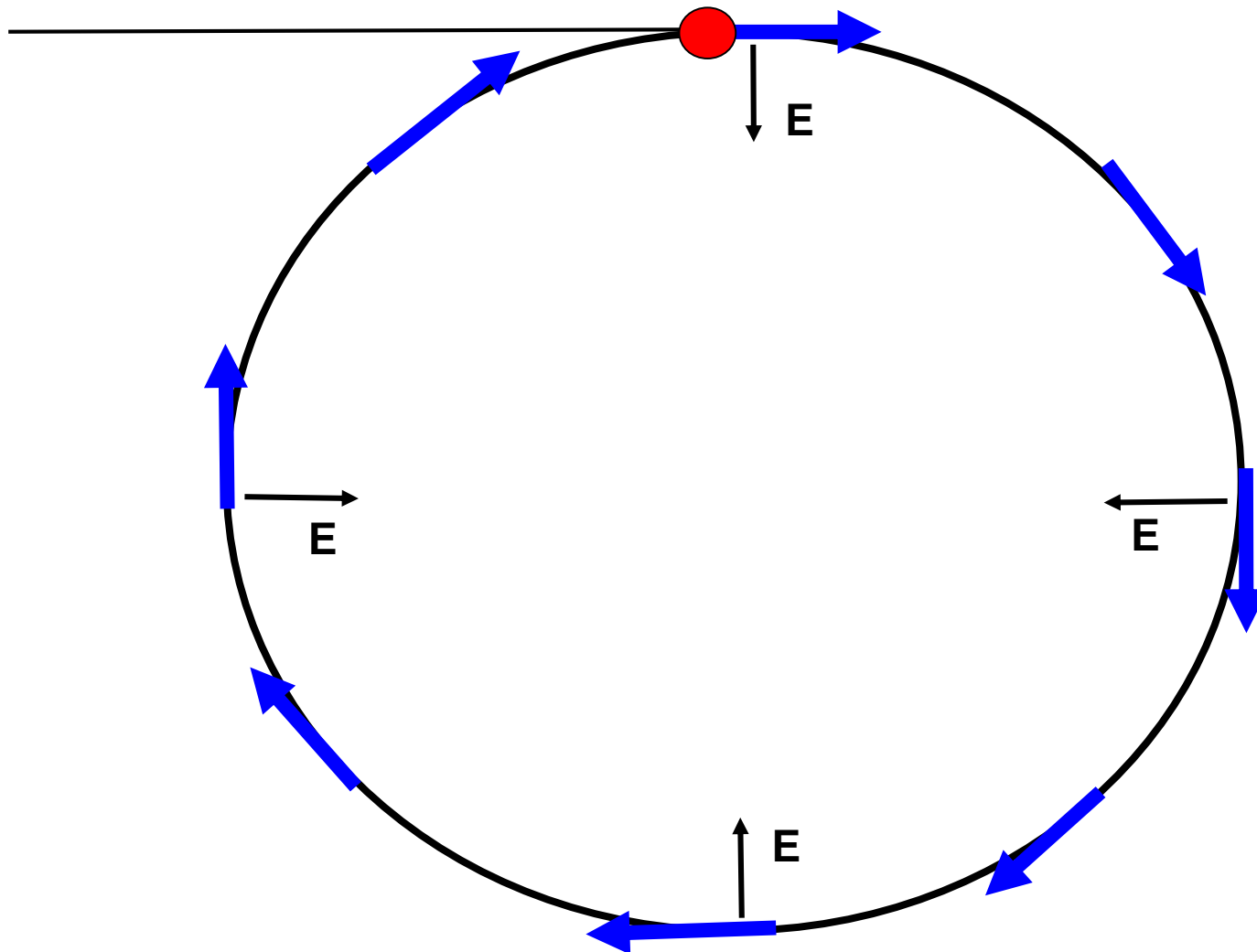
A charged particle between Electric Field plates would be lost right away...



Proton storage ring EDM experiment is combination of beam + a trap



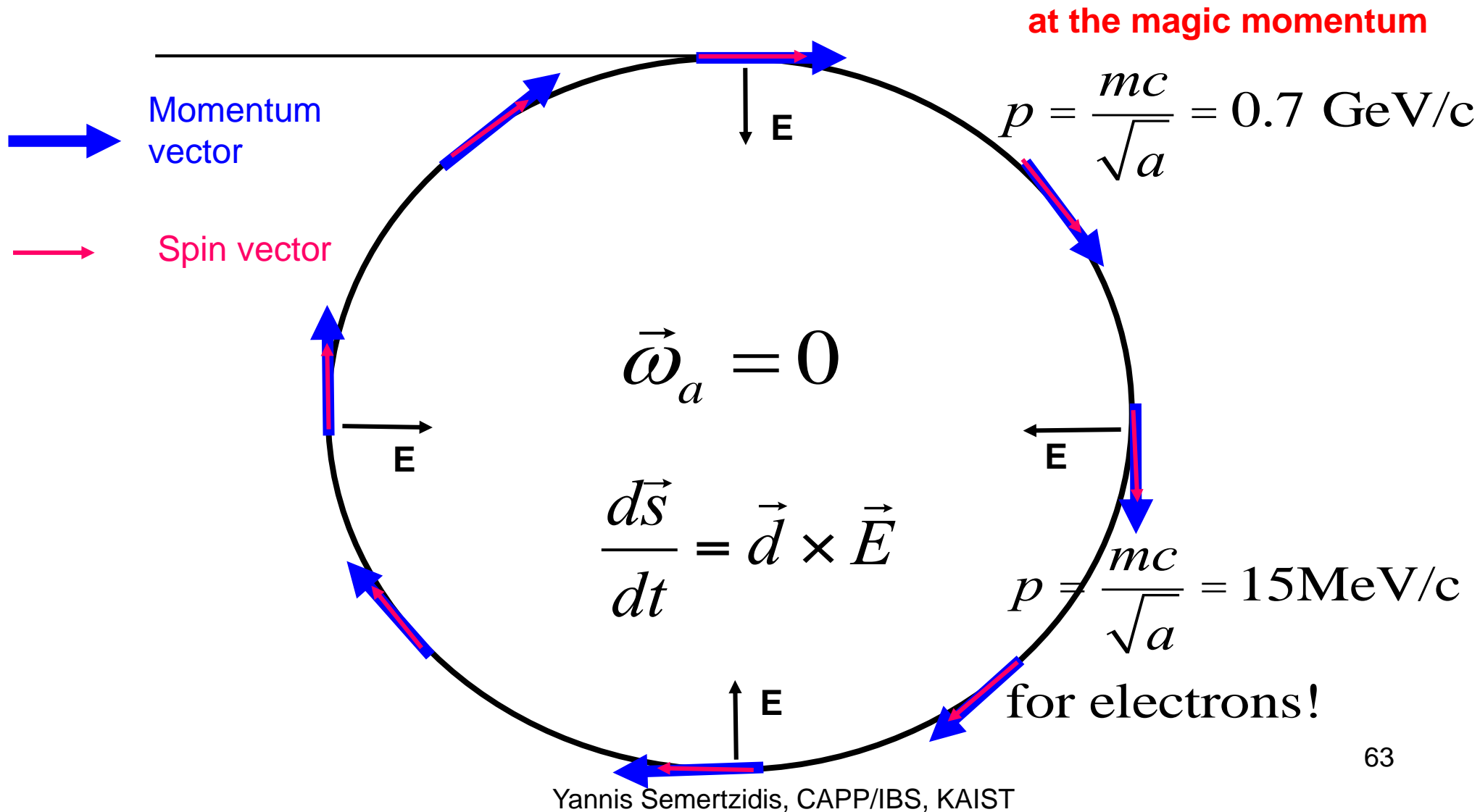
Stored beam: The radial E-field force is balanced by the centrifugal force.



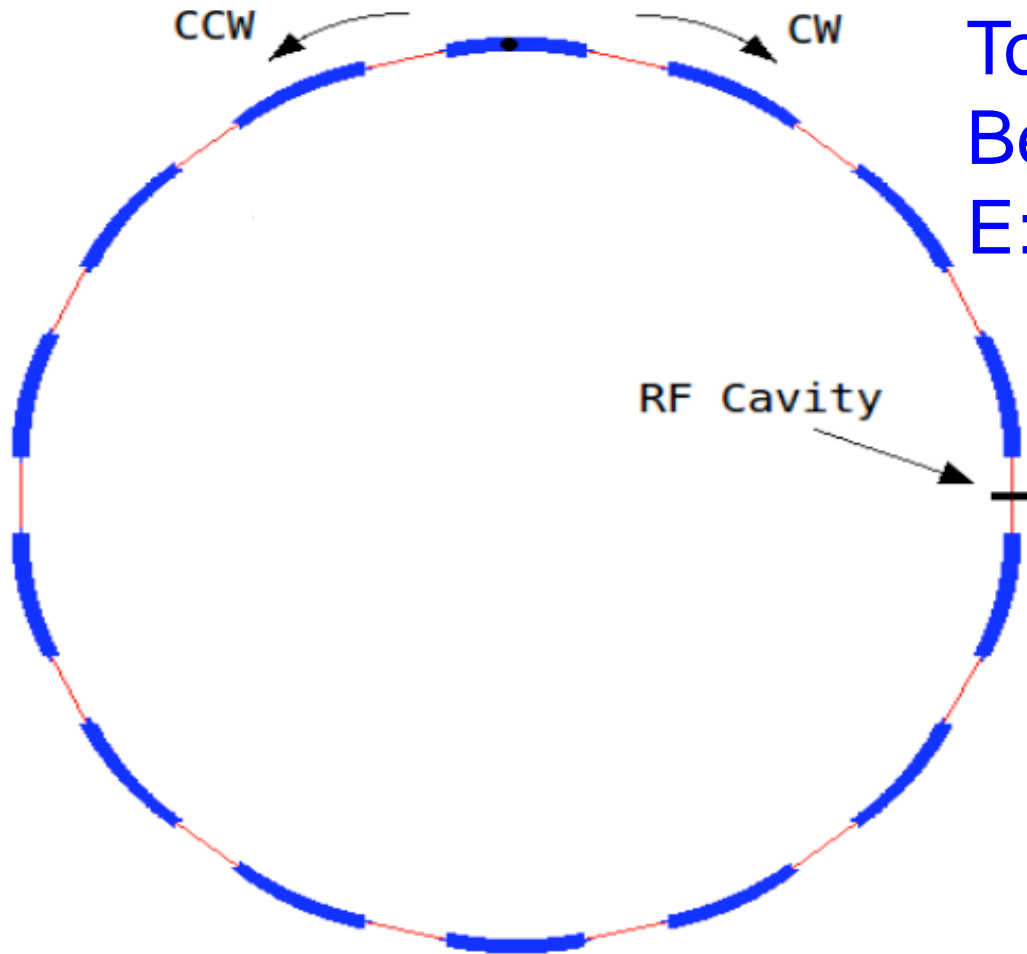
The Electric Dipole Moment precesses in an Electric field

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

The proton EDM uses an **ALL-ELECTRIC** ring: spin is aligned with the momentum vector



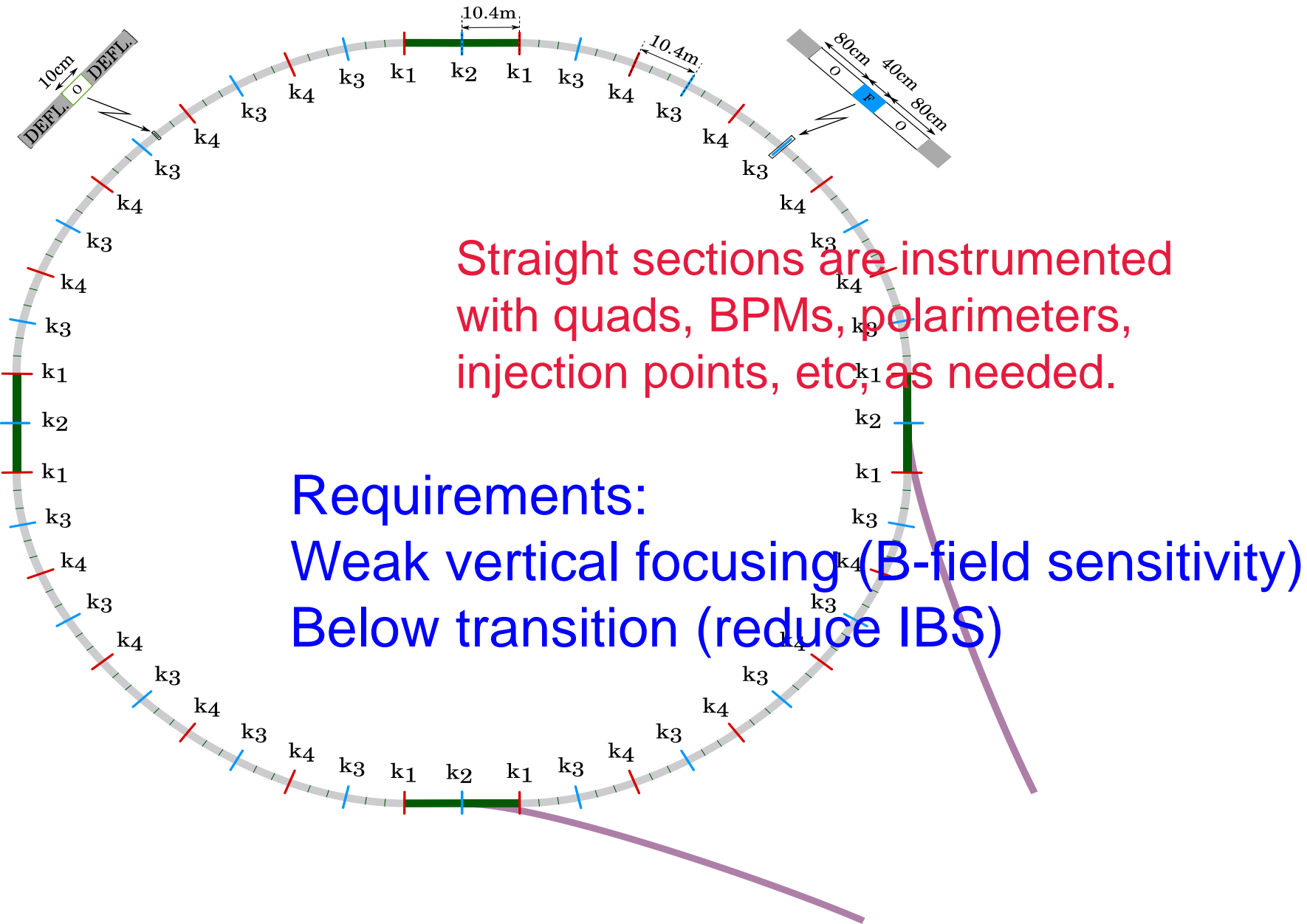
Example: The proton EDM ring



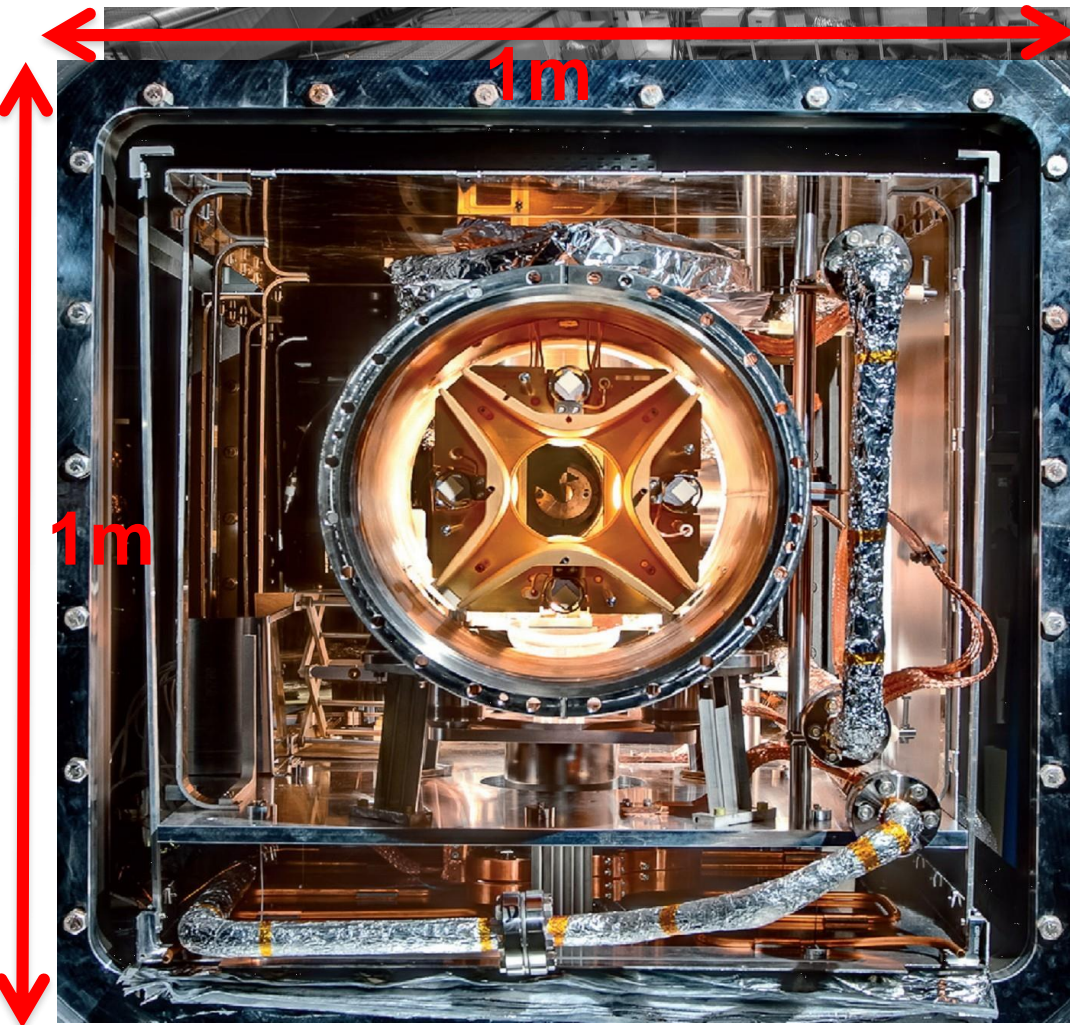
Total circumference: 300 m
Bending radius: 40 m
E: 10 MV/m

Weak vertical focusing
Stronger horizontal focusing

The proton EDM ring (alternate gradient)



Currently: CSR, Heidelberg,
35 m circ., 10^{-13} Torr



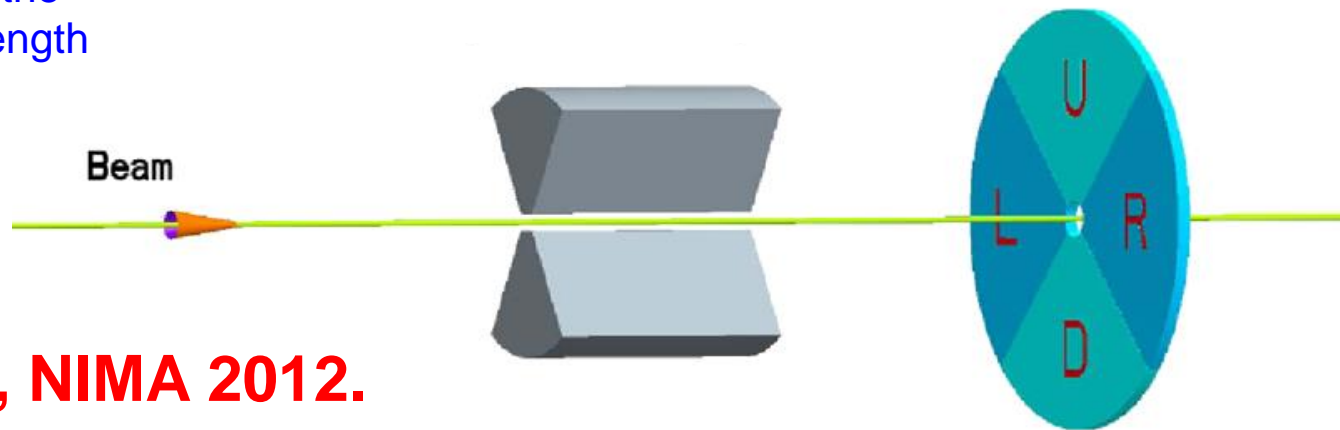
Monitoring the proton spin
direction as a function of time:
Proton Polarimeter

pEDM polarimeter principle (placed in a straight section in the ring): probing the proton spin components as a function of storage time

Extraction: lowering the vertical focusing strength

“defining aperture”
polarimeter target

Micro-Megas detector,
GEMs, MRPC or Si.



Brantjes et al., NIMA 2012.

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

carries EDM signal
increases slowly with time

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

carries in-plane (g-2)
precession signal

Large polarimeter analyzing power ($A > 50\%$) at $P_{\text{magic}} = 700 \text{ MeV}/c$.

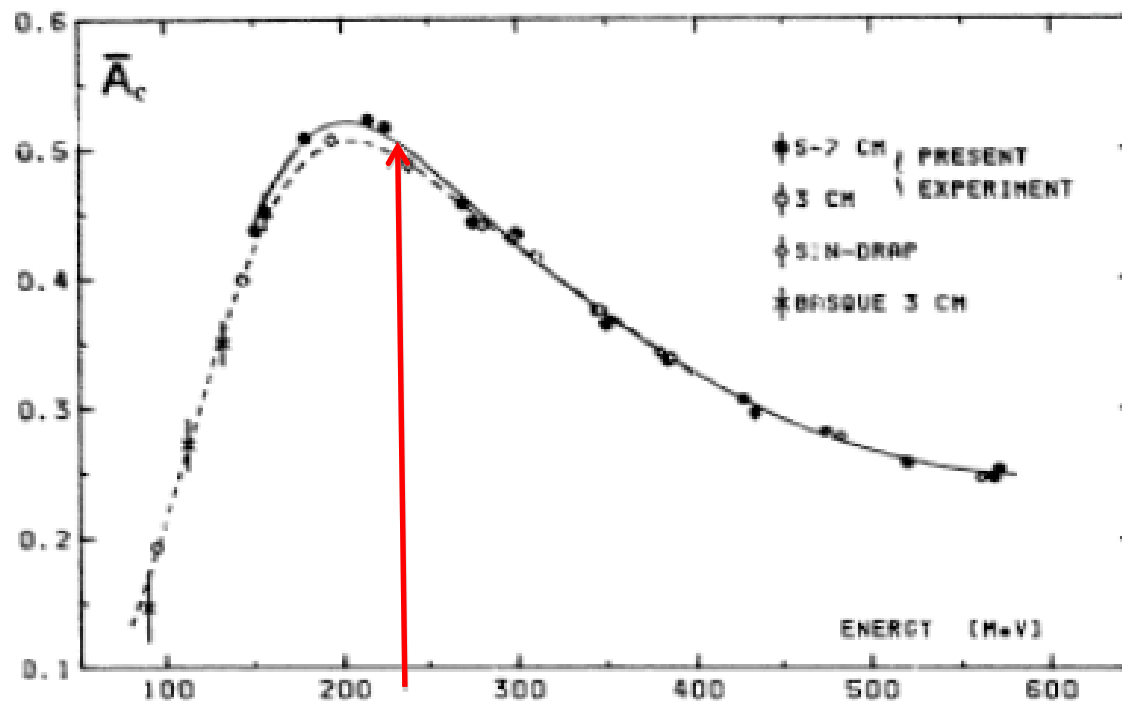
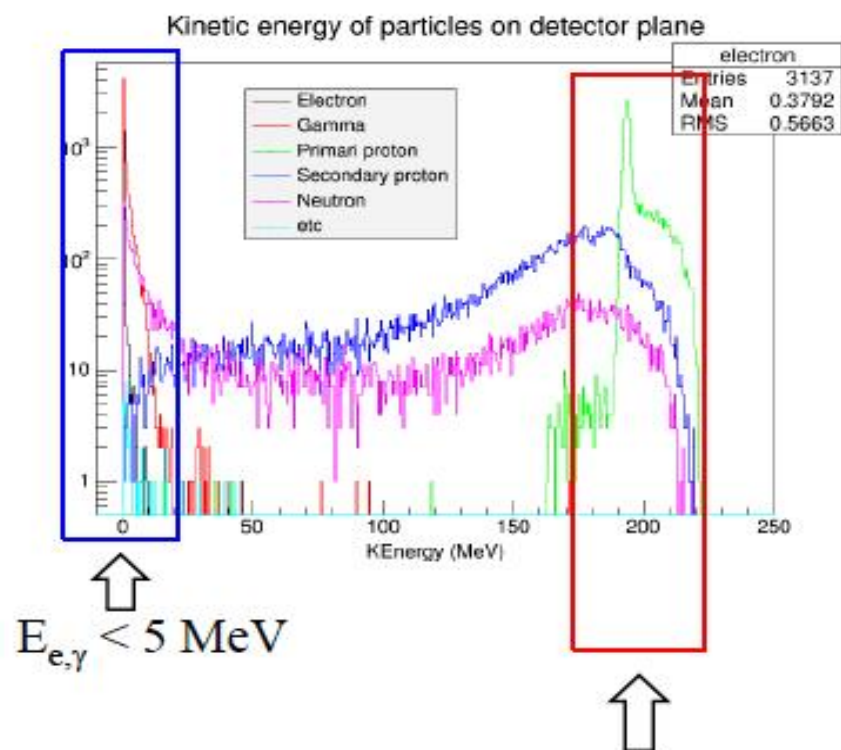


Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only

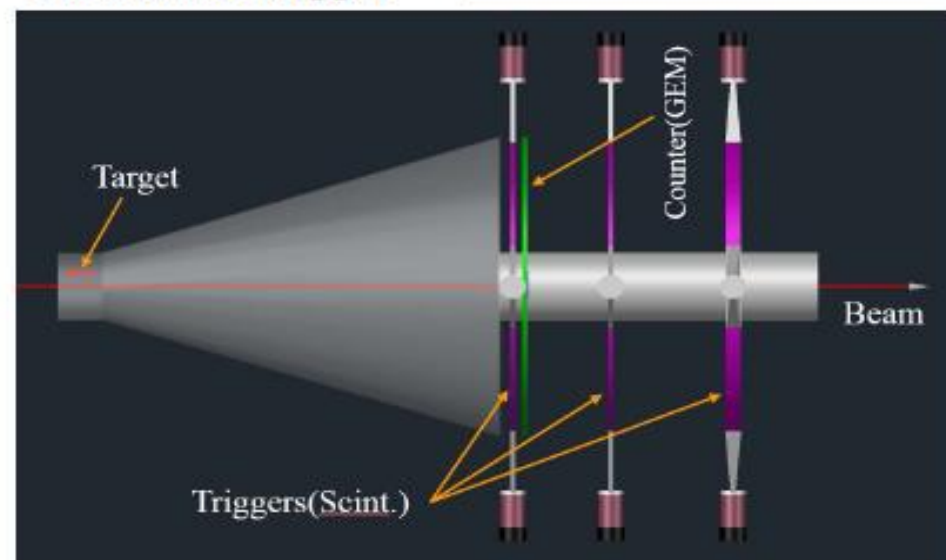
Fig.4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of $0.7 \text{ GeV}/c$ corresponds to 232 MeV .

Purifying signals and improving FOM

Slide: Dr. SeongTae Park



Coincidence trigger



Final triggers are formed from the coincidence of the three scintillation counters.

Storage Ring Proton EDM Breakthrough:

Statistics!

Instead of using the secondary, low intensity beams, use the original proton beam!

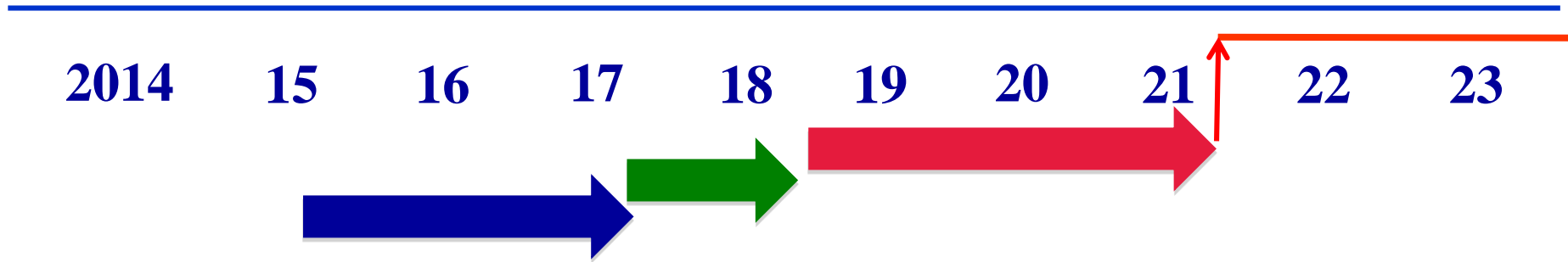
Proton Statistical Error (230MeV):

$$\sigma_d = \frac{2\hbar}{E_R P A \sqrt{N_c f \tau_p T_{tot}}}$$

- τ_p : 10^3 s Polarization Lifetime (Spin Coherence Time)
 A : 0.6 Left/right asymmetry observed by the polarimeter
 P : 0.8 Beam polarization
 N_c : 10^{11} p/cycle Total number of stored particles per cycle
 T_{Tot} : 10^7 s Total running time per year
 f : 1% Useful event rate fraction (efficiency for EDM)
 E_R : 7 MV/m Average radial electric field strength

$$\sigma_d = 1.0 \times 10^{-29} \text{ e-cm / year}$$

Technically driven pEDM timeline

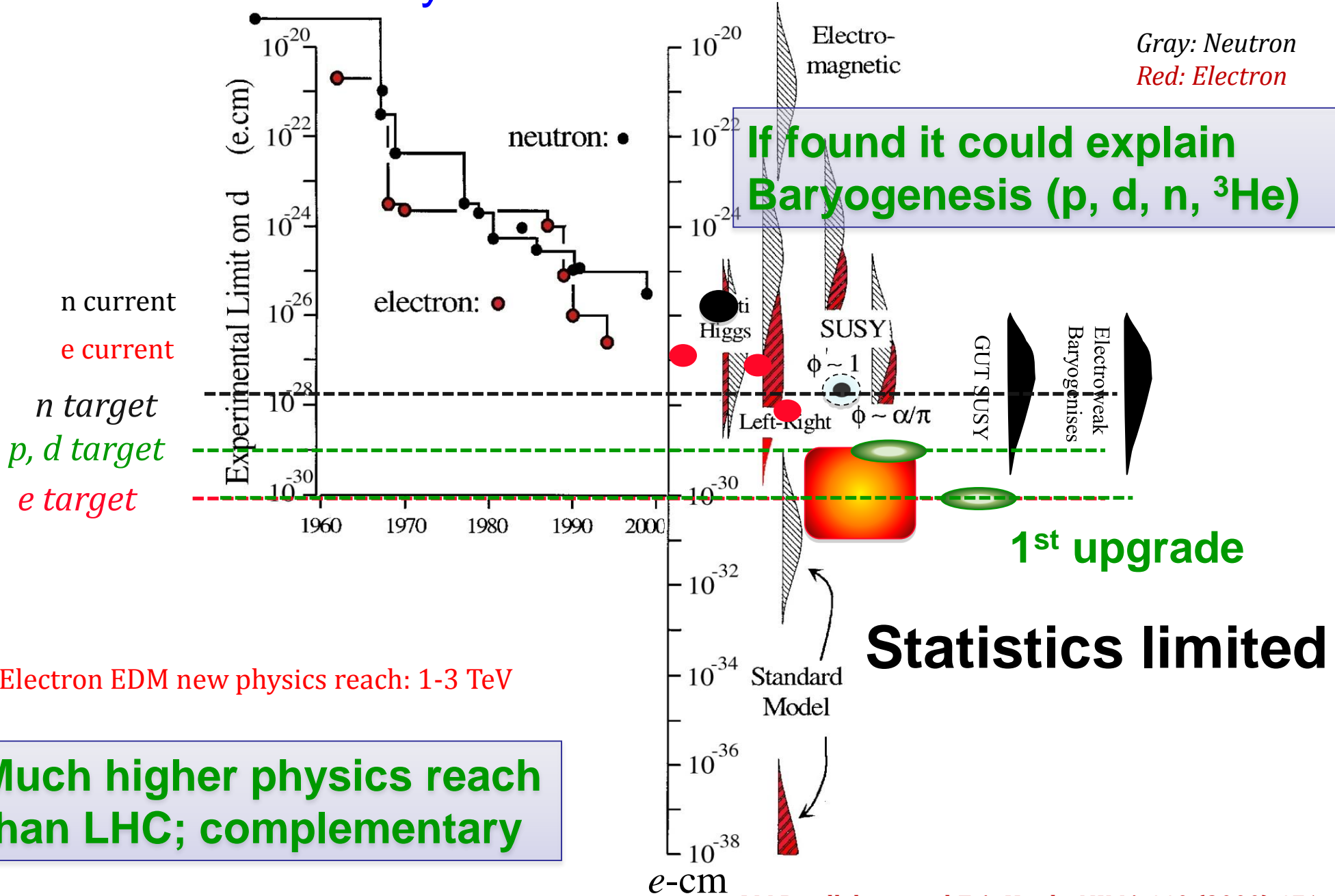


- Two years systems development (R&D); CDR; ring design, TDR, installation
- CDR by fall of 2017
- Proposal to a lab: fall 2017

Let's indulge on proton sensitivity

- Spin coherence time (10^4 seconds), stochastic cooling-thermal mixing, ...
- Higher beam intensity, smaller IBS
- Reliable E-field 15 MV/m with negligible dark current
- >5% efficient polarimeter, run longer
- Potential gain $>10^2$ in statistical sensitivity: $\sim 10^{-30}$ - 10^{-31} e-cm!

Sensitivity to Rule on Several New Models



Marciano, CM9/KAIST/Korea, Nov 2014

Generic Physics Reach of $d_p \sim 10^{-29} \text{e-cm}$

$$\begin{aligned} d_p &\sim 0.01 (m_p / \Lambda_{\text{NP}})^2 \tan \phi^{\text{NP}} e / 2m_p \\ &\sim \mathbf{10^{-22} (1 \text{TeV} / \Lambda_{\text{NP}})^2 \tan \phi^{\text{NP}} \text{e-cm}} \end{aligned}$$

If ϕ^{NP} is of $O(1)$, $\Lambda_{\text{NP}} \sim \underline{3000 \text{TeV}}$ Probed!

If $\Lambda_{\text{NP}} \sim O(1 \text{TeV})$, $\phi_{\text{NP}} \sim 10^{-7}$ Probed!

Unique Capabilities!

Importance and Promise of Electric Dipole Moments

Frank Wilczek

January 22, 2014

The additional symmetry has another remarkable consequence. It predicts the existence of a new very light, very weakly interacting spin 0 particle, the *axion*. The possible existence of axions raises the stakes around these ideas, because it entails major cosmological consequences. Indeed, if axions exist at all, they must provide much of the astronomical “dark matter”, and quite plausibly most of it.

Better bounds on θ , or especially an actual determination of its value, would allow us to sharpen these considerations considerably. Better measurements of fundamental electric dipole moments are the most promising path to such bounds, or measurement.

P5: Particle Physics Project Prioritization Panel setup by DOE and NSF. It took more than a year for the HEP community to come up with the report.

In 2014 we have received the P5 endorsement for the proton EDM experiment under all funding scenarios!

Storage ring EDM

- High precision experiments: Proton EDM experiment is a must do.
- Complementary approach to:
 - LHC in Europe
 - ILC in Japan
 - Very large hadron collider (SppC) in China
 - Neutrino Physics in the USA

Why should we be part of it

- High precision experiments can provide the next breakthrough in HEP/NP.
- Needed as input to indicate New-Physics level before next large accelerator project.
- Great for students, post docs, faculty. Well rounded physics education, opportunities for new ideas.

Recent important dates

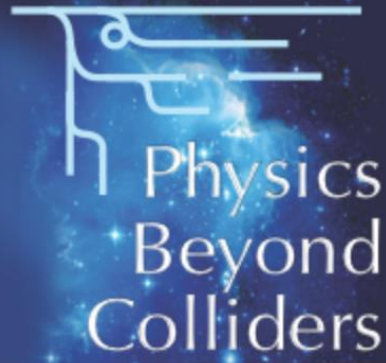
- April 21, Thursday, srEDM collaboration meeting, KAIST, South Korea
- April 22, Friday morning, Pioneering workshop on EDMs, Daejeon, South Korea
- May 11, Wednesday, 12:00 – 18:00 Precision tracking for spin/beam dynamics, part of IPAC2016, Busan, South Korea

srEDM Collaboration Meeting at KAIST, KAIST, 21 April, 2016.



Next important dates

- September 6 & 7, we are presenting the proton EDM method at CERN:



Physics Beyond Colliders Kickoff Workshop

6-7 September 2016
CERN
Europe/Zurich timezone

Summary

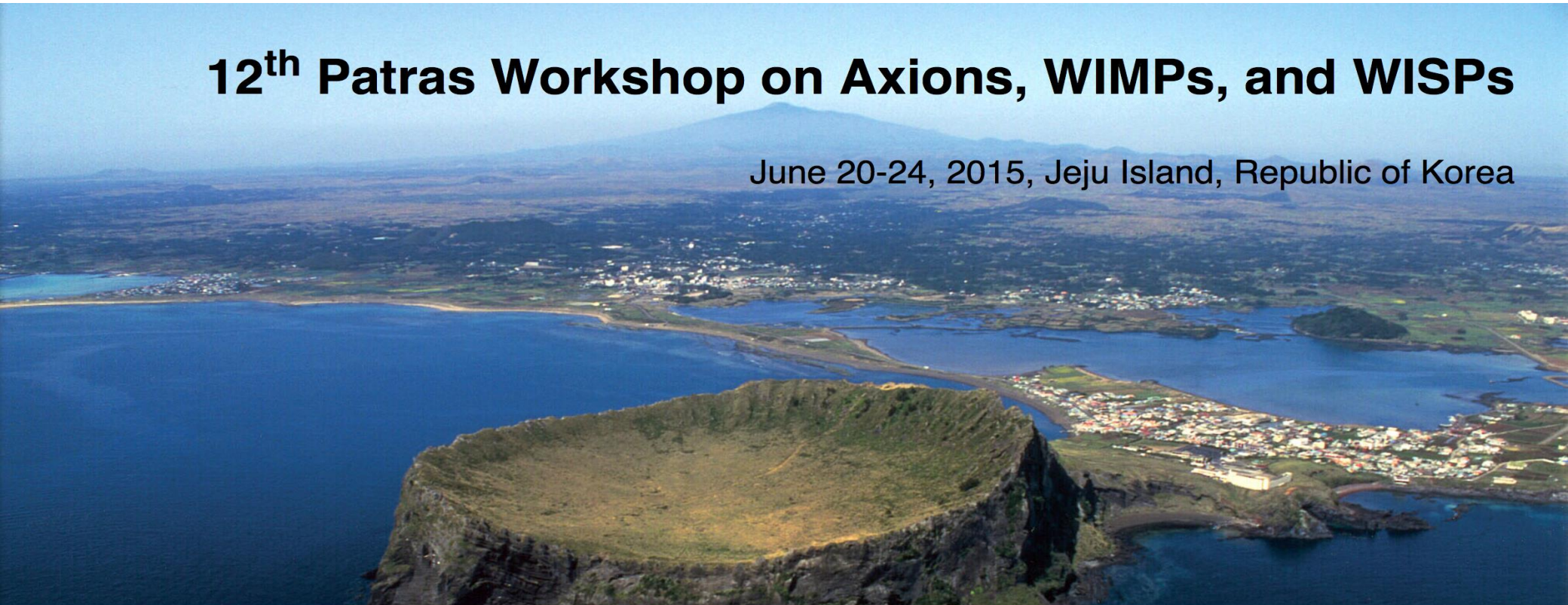
- The axion dark matter effort is going very well, according to schedule (next talk: Dr. Woohyung Chung)
- Storage ring EDM effort is timely
- Ultimate sensitivity for $p < 10^{-29}-10^{-30}$ e-cm
- SUSY-like physics reach: 10^3-10^4 TeV, it can show the way ahead.
- It's an immense Physics opportunity for Korea and the world.

Extra slides

<https://axion-wimp2016.desy.de>

12th Patras Workshop on Axions, WIMPs, and WISPs

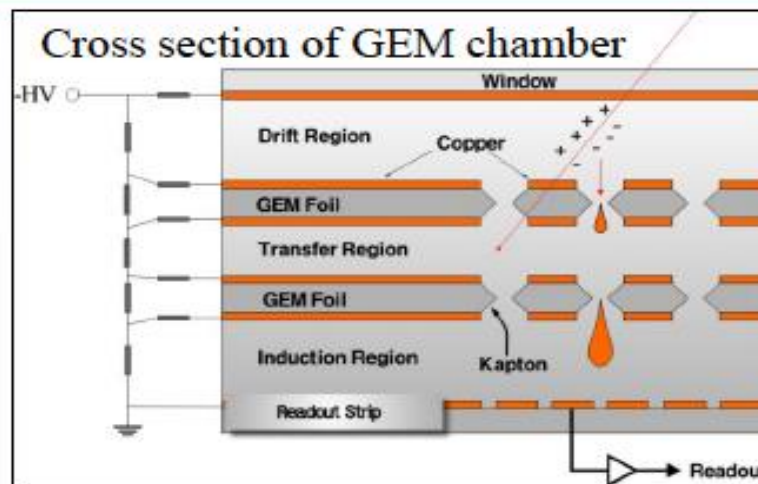
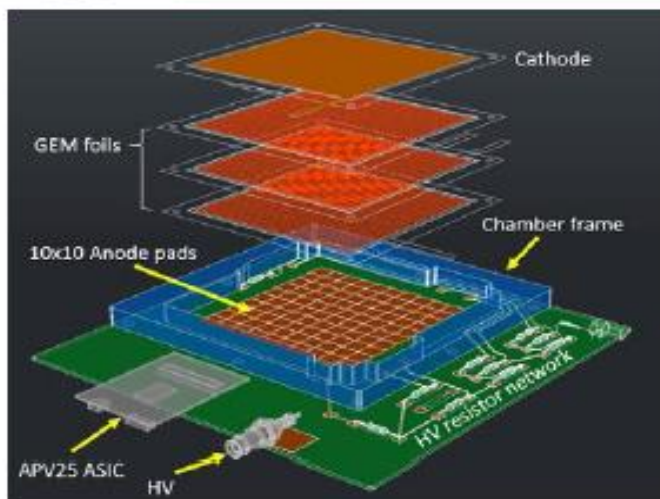
June 20-24, 2015, Jeju Island, Republic of Korea



June 20 - 24, 2016

Republic of Korea, Jeju Island

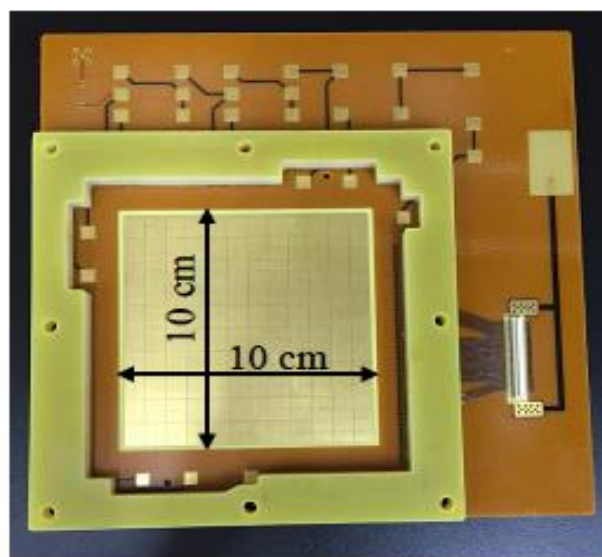
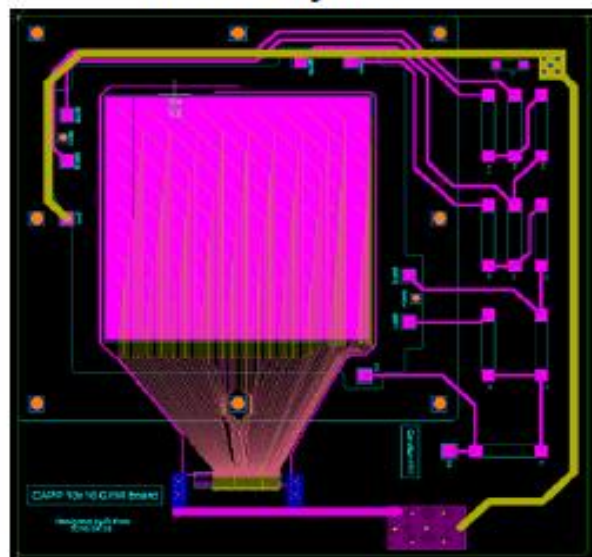
10x10 cm² test detector



10x10 GEM foil

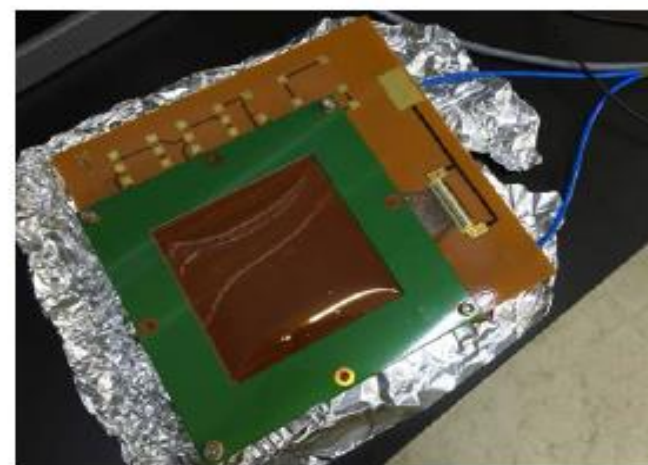
PCB layout

Slide: Dr. SeongTae Park

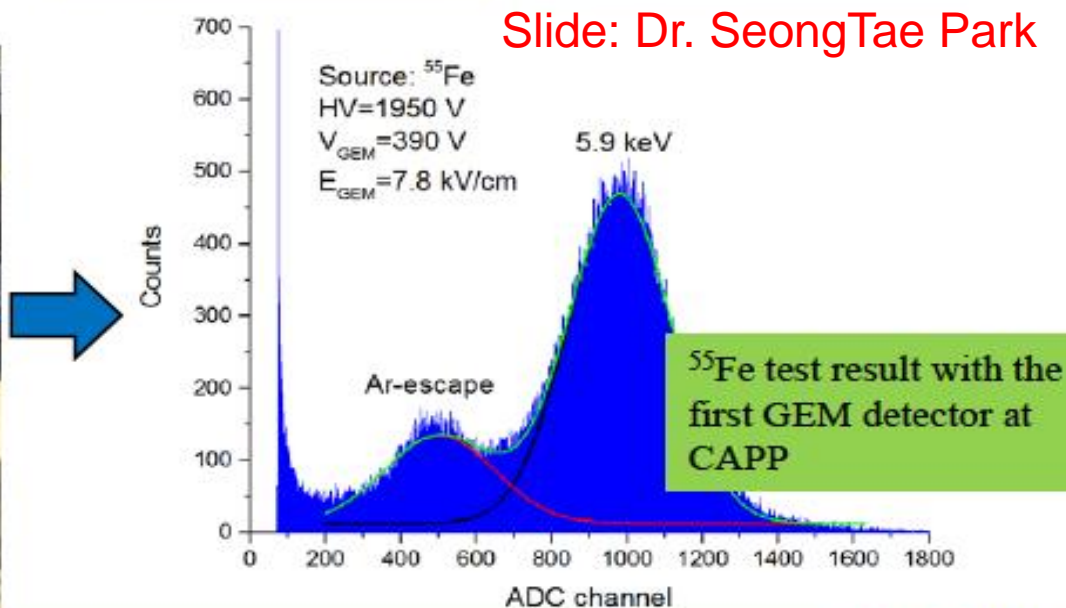
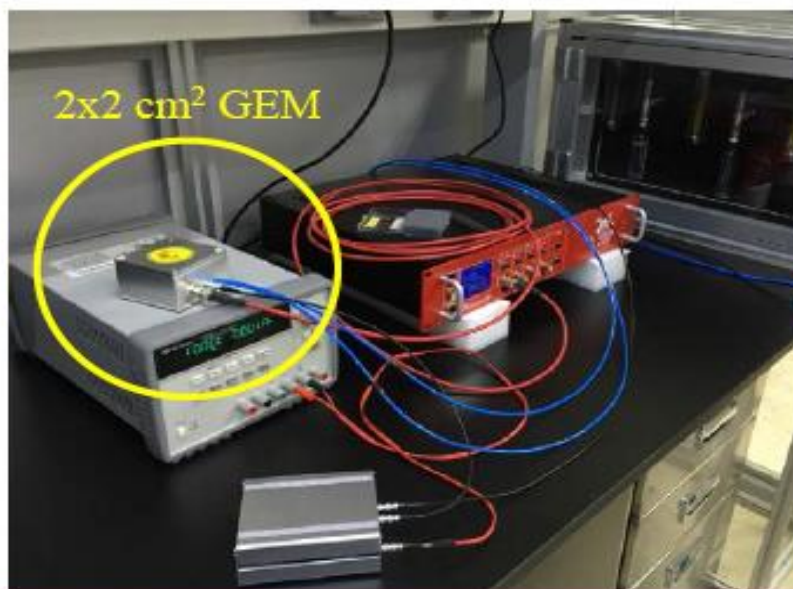


Under assembling.

Will be tested soon and go beam test with APV25.



New polarimeter lab is ready



Spin Coherence Time: need $\sim 10^3$ s

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

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

$$d\omega_a = a\mathcal{G}_x^2 + b\mathcal{G}_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Present design parameters allow for 10^3 s.
- Much longer SCT with thermal mixing (S.C.)?

Main Devices



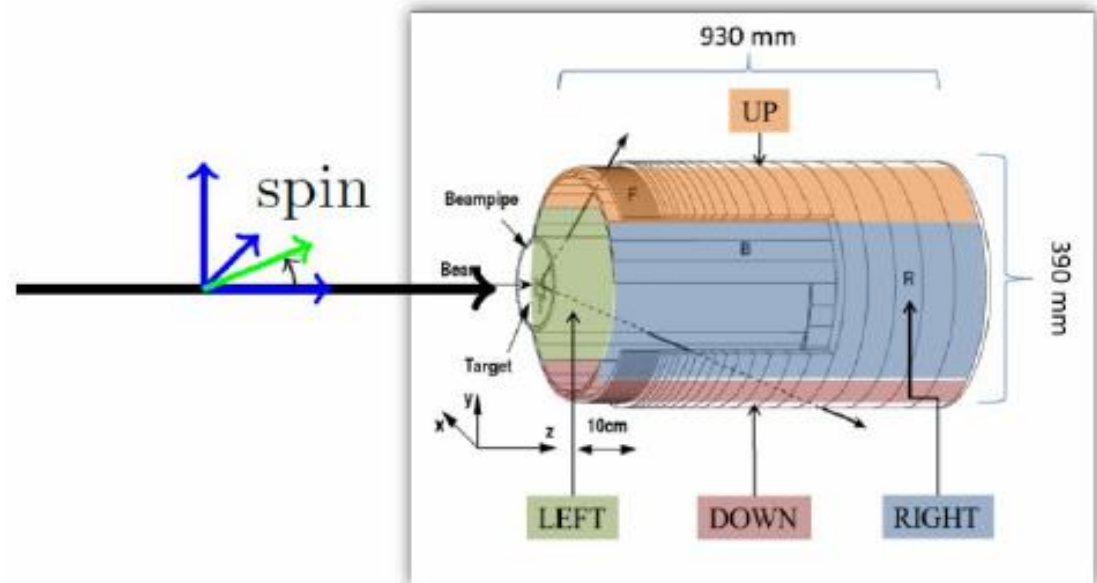
COSY:

- $\approx 184\text{m}$ circumference
- (Un)polarized proton/deuteron beams
- Momentum range: $0.3\text{-}3.7\text{GeV}/c$
- Electron/stochastic cooling

Martin Gaisser/CAPP

Edda Polarimeter:

- Scintillator rings and bars
- Carbon target
- Polarimeter not ideal but best we have!



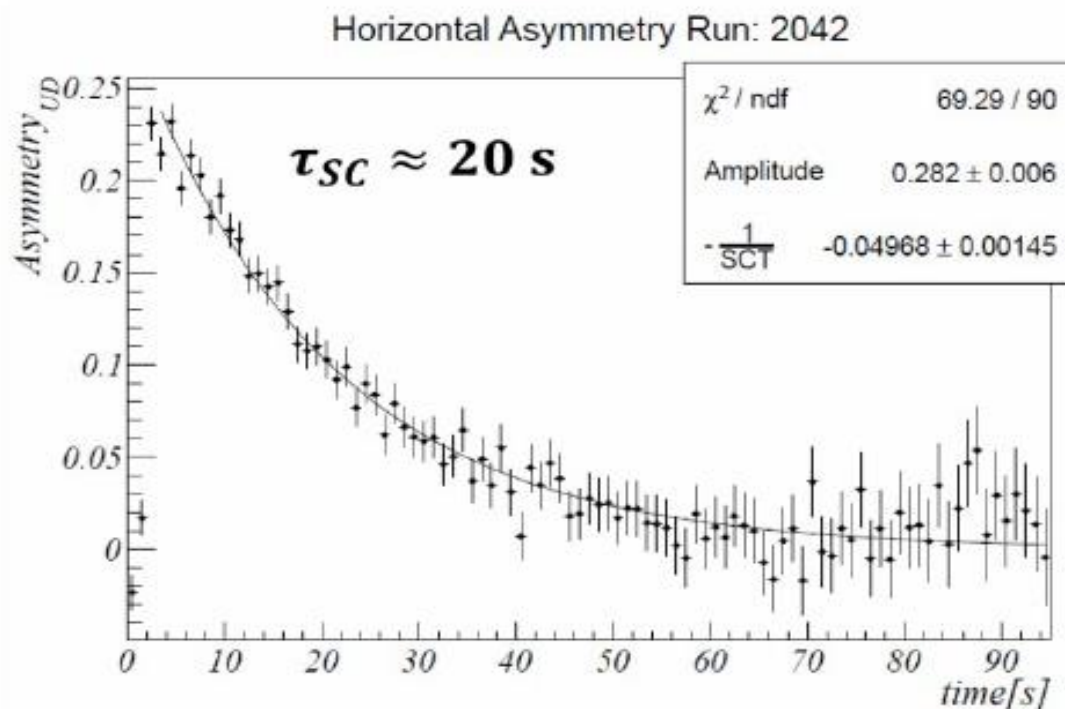
Measurement Principle

Beam Preparation:

- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Martin Gaisser/CAPP

Watch decay of up-down asymmetry (horizontal polarization)

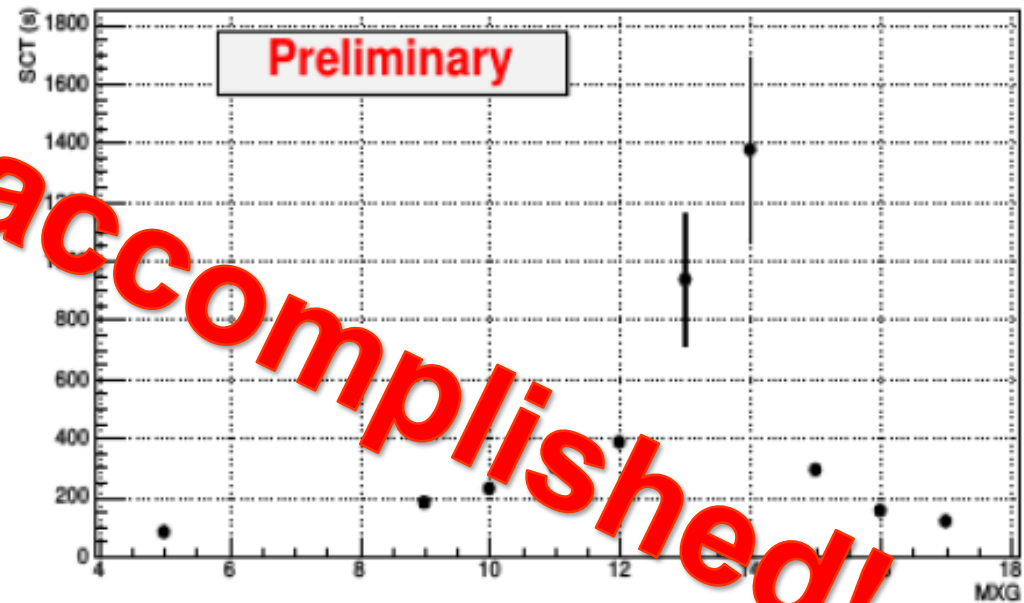


Sextupole Scans

Martin Gaisser/CAPP



← obtain this picture by rastering the MXS-MXG plane, maximum SCT lies on zero chromaticity lines



Sextupole strength

The proton EDM ring evaluation Val Lebedev (Fermilab)

Beam intensity 10^{11} protons limited by IBS

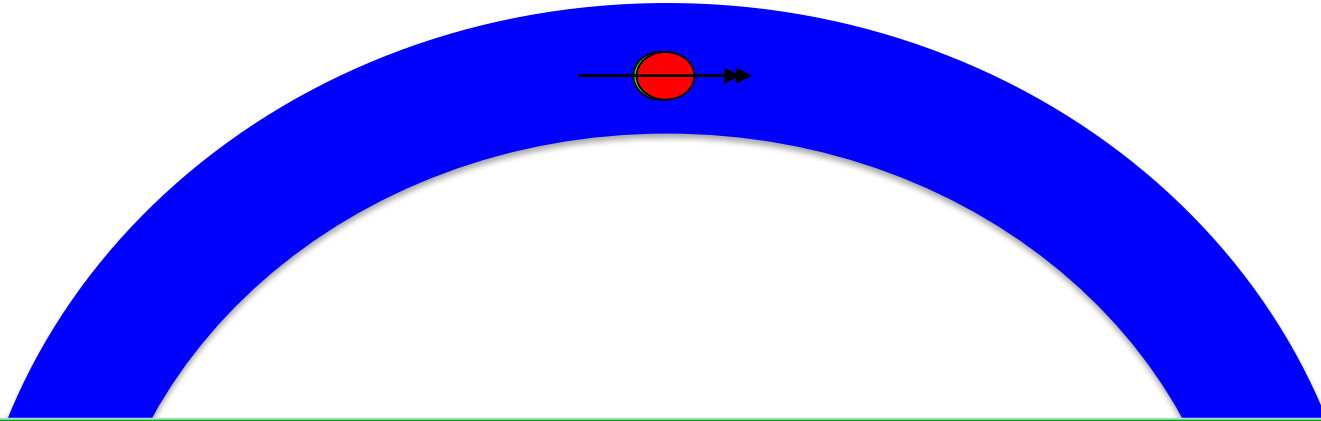
	Soft focusing	Strong focusing
Circumference, m	263	300
Q_x/Q_y	1.229/0.456	2.32/0.31
Particle per bunch	$1.5 \cdot 10^8$	$7 \cdot 10^8$
Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$	0.0046/0.0066	0.0146/0.0265
Rms emittances, x/y, norm, μm	0.56/1.52	0.31/2.16
Rms momentum spread	$1.1 \cdot 10^{-4}$	$2.9 \cdot 10^{-4}$
IBS growth times, x/y/s, s	300/(-1400)/250	7500
RF voltage, kV	13	10.3
Synchrotron tune	0.02	0.006

Systematic errors

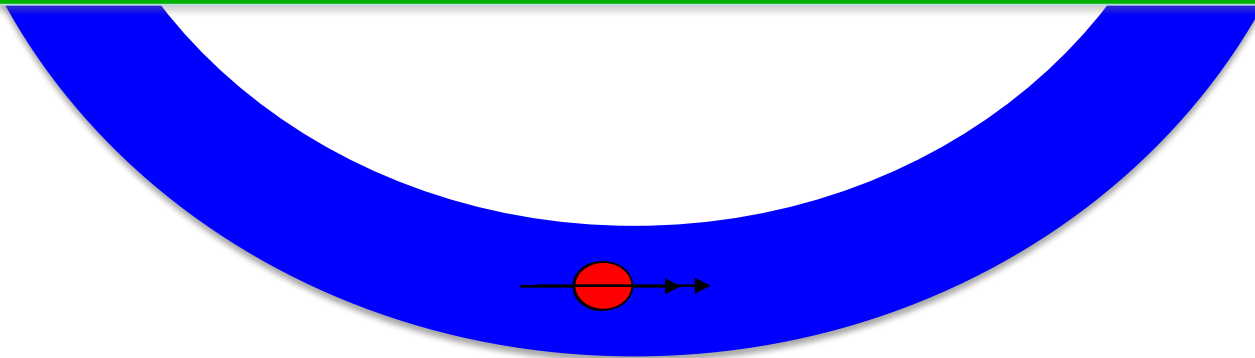
TABLE III. Main systematic errors of the experiment and their remediation.

Effect	Remediation
Radial B-field	SQUID BPMs with $1 \text{ fT}/\sqrt{\text{Hz}}$ sensitivity eliminate it.
Geometric phase	Plate alignment to better than $100 \mu\text{m}$, plus CW and CCW storage. Reducing B-field everywhere to below $10\text{-}100 \text{ nT}$. BPM to $100 \mu\text{m}$ to control the effect.
Non-Radial E-field	CW and CCW beams cancel the effect.
Vert. Quad misalignment	BPM measurement sensitive to vertical beam oscillation common to CW and CCW beams.
Polarimetry	Using positive and negative helicity protons in both the CW and CCW directions cancels the errors.
Image charges	Using vertical metallic plates except in the quad region. Quad plates' aspect ratio reduces the effect.
RF cavity misalignment	Limiting longitudinal impedance to $10\text{k}\Omega$ to control the effect of a vertical angular misalignment. CW and CCW beams cancel the effect of a vertically misplaced cavity.

Clock-wise (CW) & Counter-Clock-wise Storage

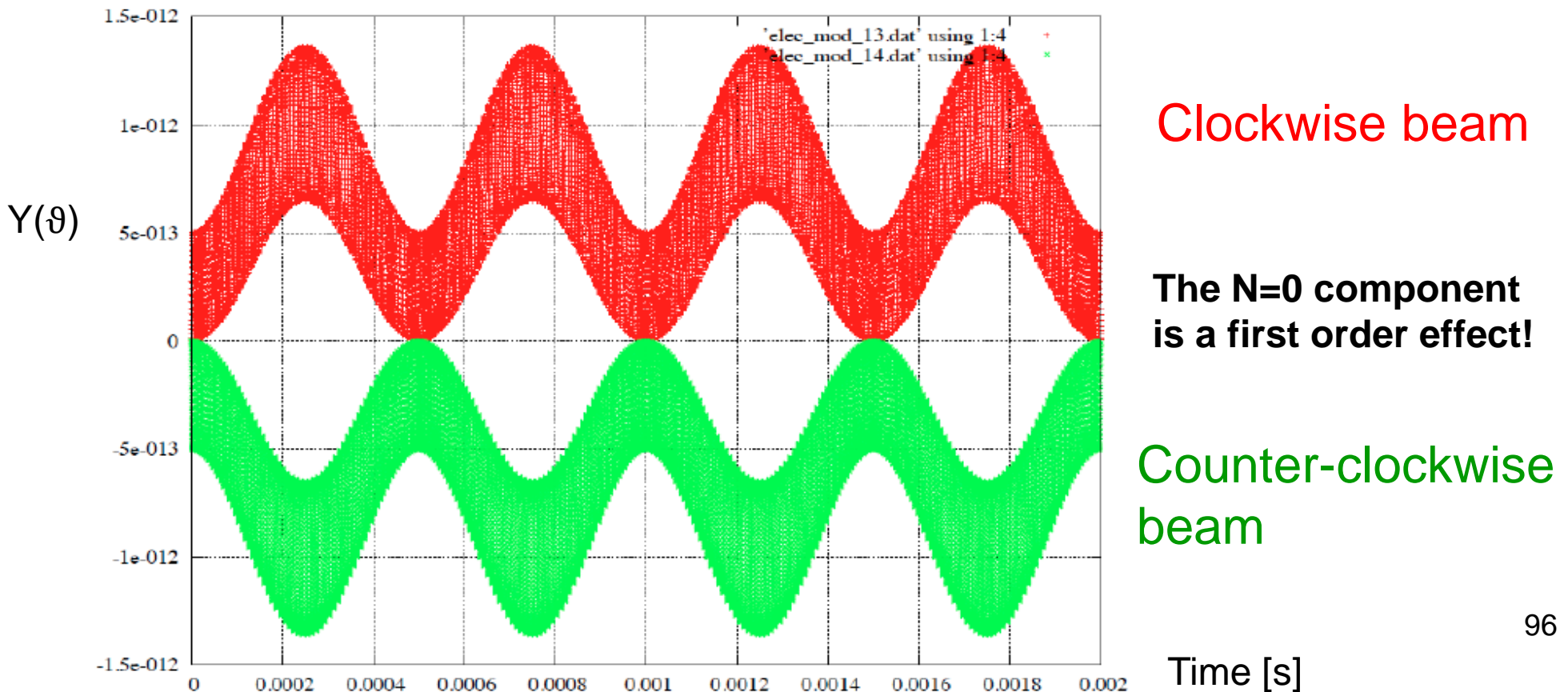


Total current: zero. Any radial magnetic field in the ring sensed by the stored particles will cause their vertical splitting.



Distortion of the closed orbit due to N^{th} -harmonic of radial B-field

$$y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0 (Q_y^2 - N^2)} \cos(N\vartheta + \varphi_N)$$



SQUID BPM to sense the vertical beam splitting at 1-10kHz

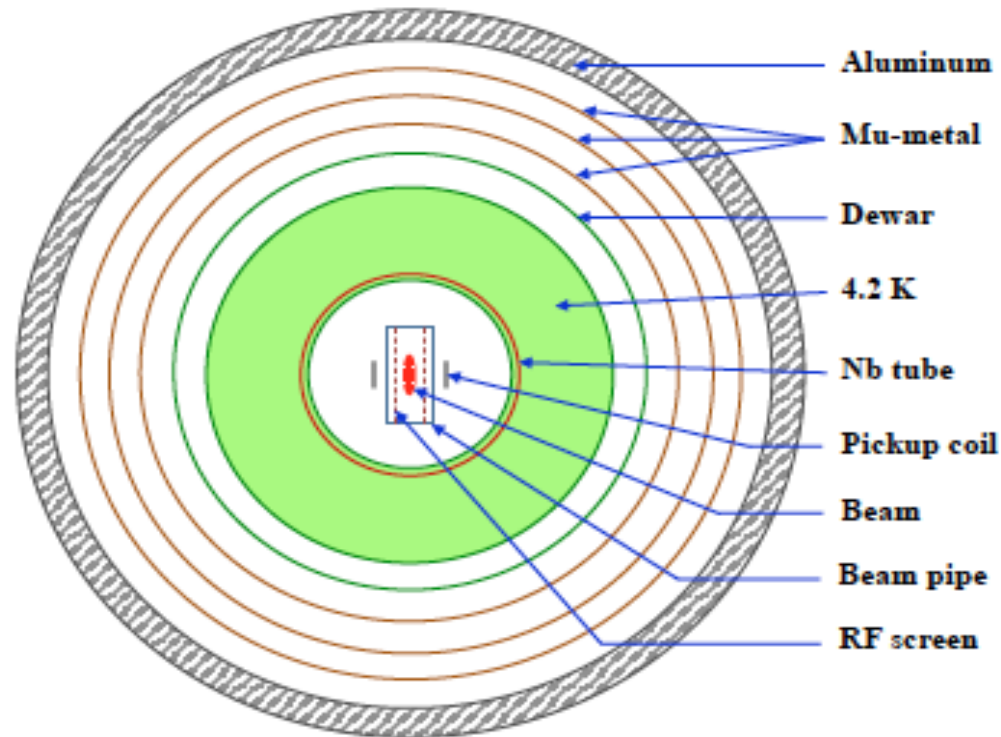
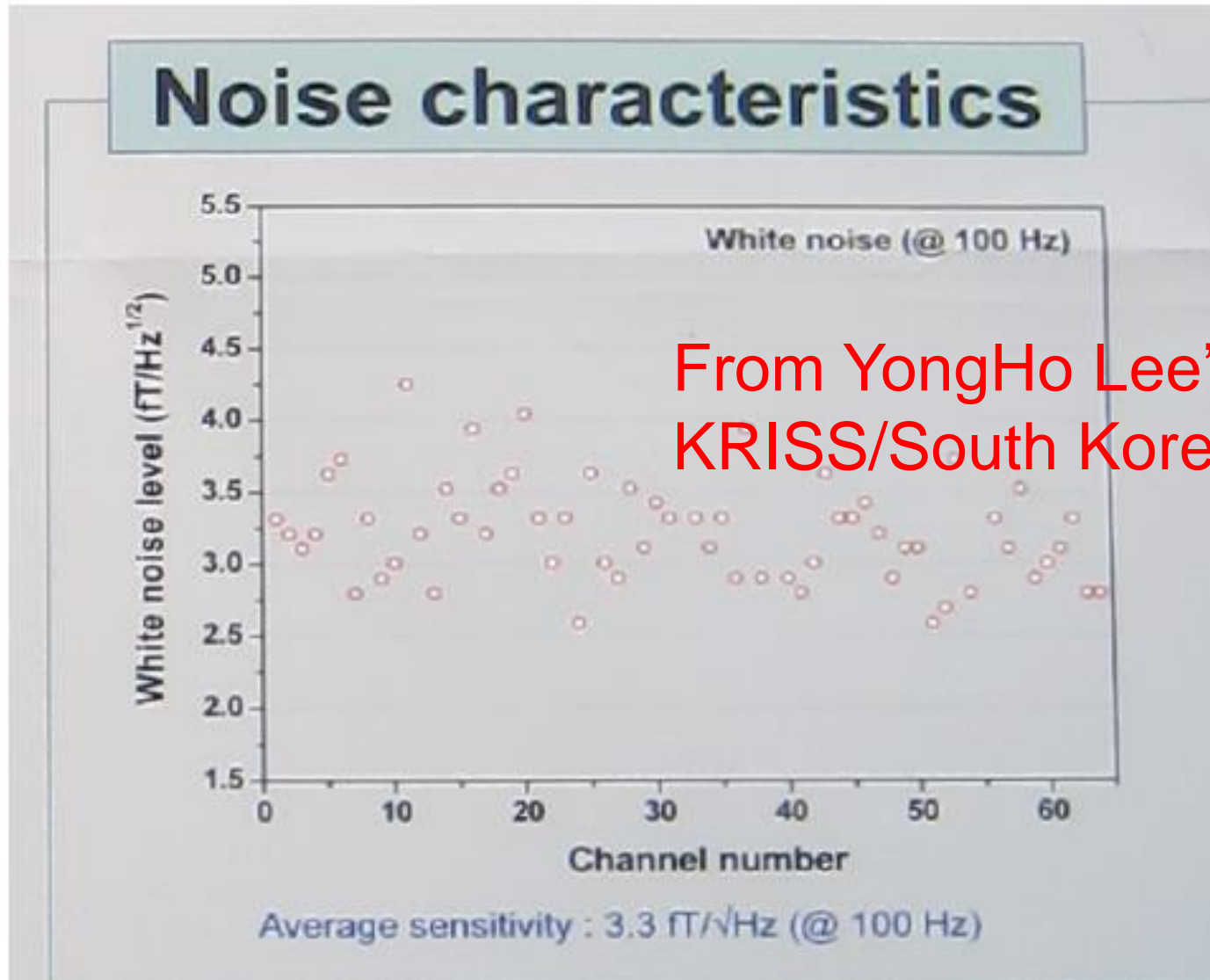


FIG. 3. A schematic of a possible SQUID BPM station. The system is shielded with a superconducting Nb tube, Al tube for RF-shield, and several mu-metal layers.

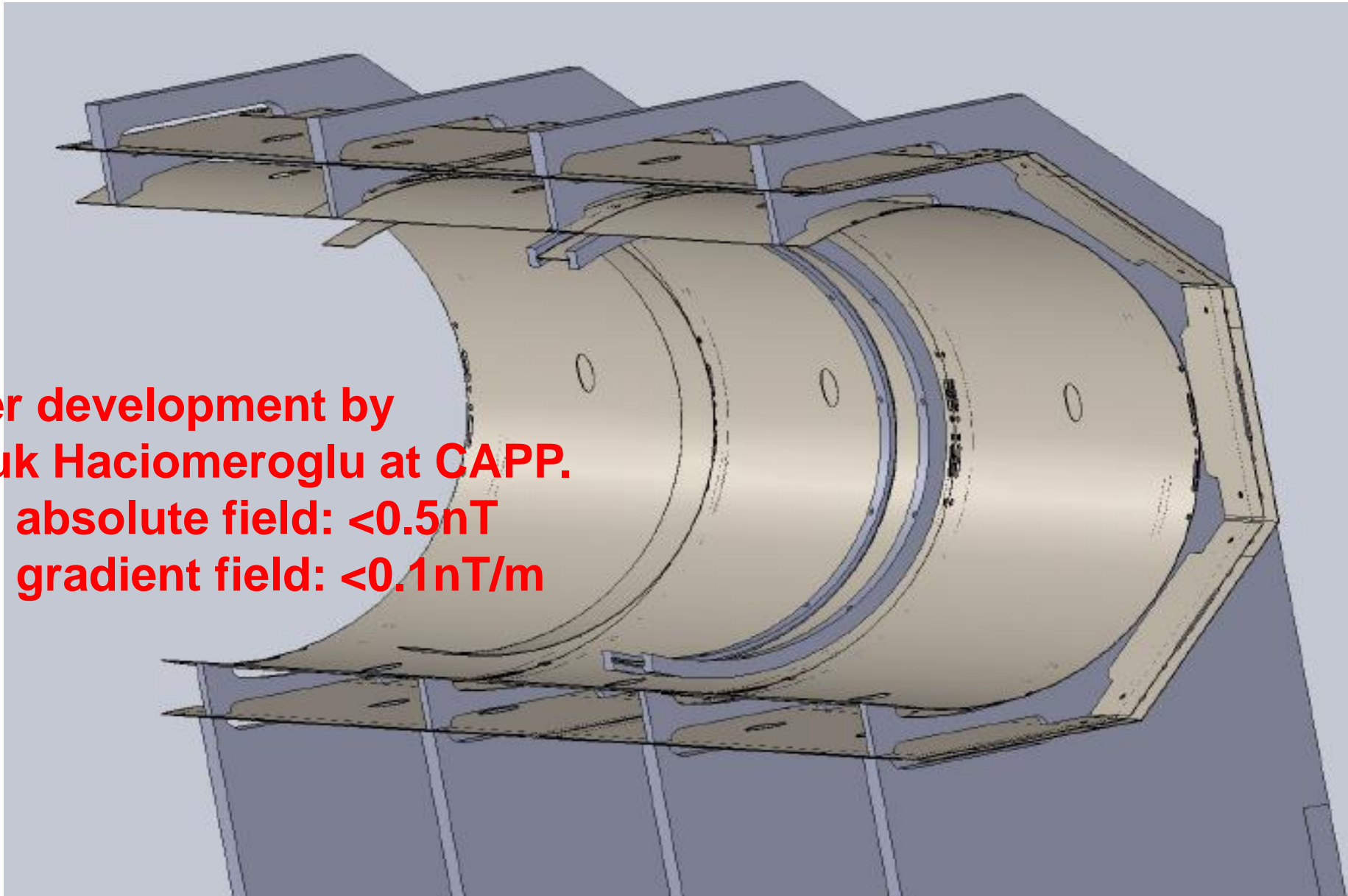
Total noise of (65) commercially available SQUID gradiometers at KRISS



From YongHo Lee's group
KRISS/South Korea

Peter Fierlinger, Garching/Munich

Under development by
Selcuk Haciomeroglu at CAPP.
Need absolute field: $<0.5\text{nT}$
Need gradient field: $<0.1\text{nT/m}$



Peter Fierlinger, Garching/Munich

Shipped to Korea for integration



Achieved so far:
Absolute field: $<0.5\text{nT}$
Gradient field: $<2.0\text{nT/m}$
Almost there!

Major characteristics of a successful **E**lectric **D**ipole **M**oment Experiment

- Statistical power:
 - High intensity beams
 - Long beam lifetime
 - Long Spin Coherence time
 - An indirect way to cancel B-field effect
 - A way to cancel geometric phase effects
 - Control detector systematic errors
 - Manageable E-field strength, negligible dark current
- The storage ring Proton EDM method has it all!**

Storage ring proton EDM method


- All-electric storage ring. Strong radial E-field to confine protons with “magic” momentum. The spin vector is aligned with momentum horizontally.
- High intensity, polarized proton beams are injected Clockwise and Counter-clockwise with positive and negative helicities. Great for systematics (e.g., geometrical phases).
- Great statistics: up to $\sim 10^{11}$ particles with primary proton beams and small phase-space parameters.

What has been accomplished?

- ✓ Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
- ✓ Precision beam/spin dynamics tracking.
- ✓ Stable lattice, IBS lifetime: $\sim 10^4$ s (Lebedev, FNAL)
- ✓ Spin coherence time 10^3 s; role of sextupoles understood (using stored beams at COSY).
- ✓ Feasibility of required electric field strength >10 MV/m, 3cm plate separation (JLab)
- ✓ Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!
- ✓ (Paper already published or in progress.)

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	$<10^{-29}$		$10^{-25}\text{-}10^{-26}$
^{129}Xe atom	$<6 \times 10^{-27}$	$\sim 10^{-30}\text{-}10^{-33}$	$10^{-26}\text{-}10^{-29}$
Deuteron nucleus		$\sim 10^{-29}$	$3 \times 10^{-29}\text{-}$ 5×10^{-31}
Proton nucleus	$<7 \times 10^{-25}$	$\sim 10^{-29}\text{-}10^{-30}$	$10^{-29}\text{-}10^{-30}$



PAC/Snowmass strong endorsement

- BNL PAC on EDM proposal (2008): “enthusiastic endorsement of the physics...need to demonstrate feasibility of systems”
- Snowmass writeup: “...Ultimately the interpretability of possible EDMs in terms of underlying sources of CP violation may prove sharpest in simple systems such as neutron and proton,...”
- FNAL PAC EDM EOI (2012): “The Physics case for such a measurement is compelling since models with new physics at the TeV scale (e.g., low energy SUSY) that have new sources of CP-violation can give contributions of this order.... The PAC recommends that Fermilab and Brookhaven management work together, and with potential international partners, to find a way for critical R&D for this promising experiment to proceed.”

The challenge

- The electron EDM experiment needs an efficient polarimeter at 15MeV/c. $FOM = \sqrt{f A^2} > 0.01$.
- Young scientist positions (YS) at IBS/Korea, Research Funds: 300M KRW/year for five years!
- Senior scientist positions (SS) at IBS/Korea, Research Funds: 500M KRW/year for three years!

http://www.ibs.re.kr/eng/sub04_04_01.do

Storage Ring EDM Collaboration

- Aristotle University of Thessaloniki, Thessaloniki/Greece
- Research Inst. for Nuclear Problems, Belarusian State University, Minsk/Belarus
- Brookhaven National Laboratory, Upton, NY/USA
- Budker Institute for Nuclear Physics, Novosibirsk/Russia
- Royal Holloway, University of London, Egham, Surrey, UK
- Cornell University, Ithaca, NY/USA
- Institut für Kernphysik and Jülich Centre for Hadron Physics Forschungszentrum Jülich, Jülich/Germany
- Institute of Nuclear Physics Demokritos, Athens/Greece
- University and INFN Ferrara, Ferrara/Italy
- Laboratori Nazionali di Frascati dell'INFN Frascati/Italy
- Joint Institute for Nuclear Research, Dubna/Russia
- Indiana University, Indiana/USA
- Istanbul Technical University, Istanbul/Turkey
- University of Massachusetts, Amherst, Massachusetts/USA
- Michigan State University, East Lansing, Minnesota/USA
- Dipartimento di Fisica, Università "Tor Vergata" and Sezione INFN, Rome/Italy
- University of Patras, Patras/Greece
- CEA, Saclay, Paris/France
- KEK, High Energy Accel. Res. Organization, Tsukuba, Ibaraki 305-0801, Japan
- University of Virginia, Virginia/USA

>20 Institutions

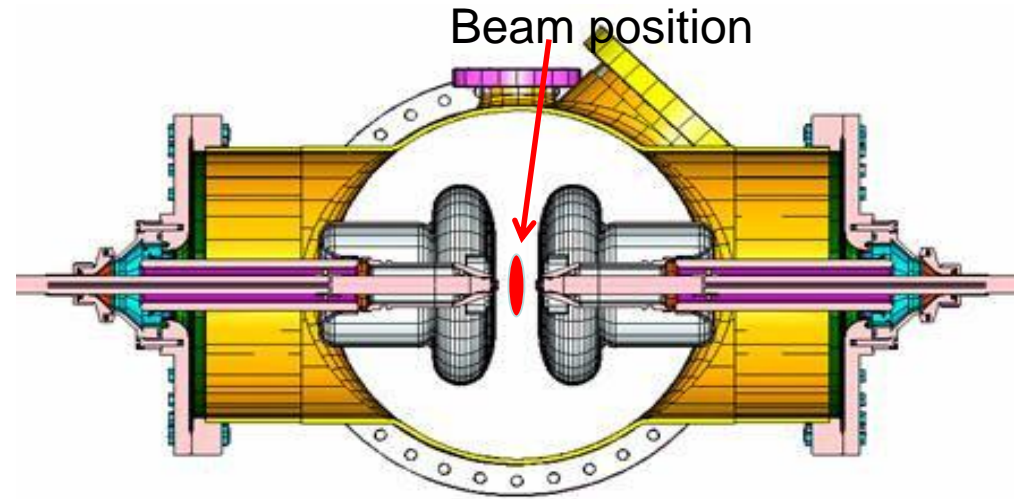
>80 Collaborators

<http://www.bnl.gov/edm>

Why now?

- Exciting progress in electron EDM using molecules.
- Several neutron EDM experiments under development to improve their sensitivity level.
- Proton EDM has large STATISTICAL sensitivity; great way to handle SYSTEMATICS.

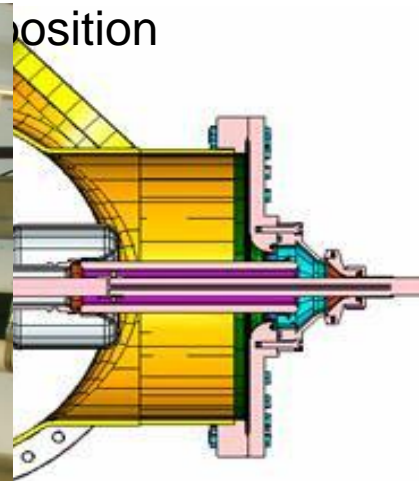
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators



0.4 m

3 m

E-field plate module: Similar to the (26) FNAL Tevatron ES-separators



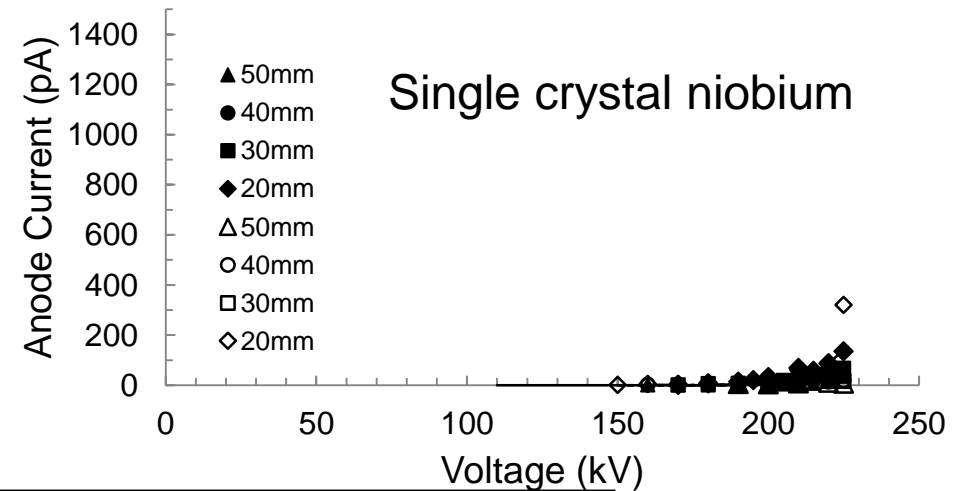
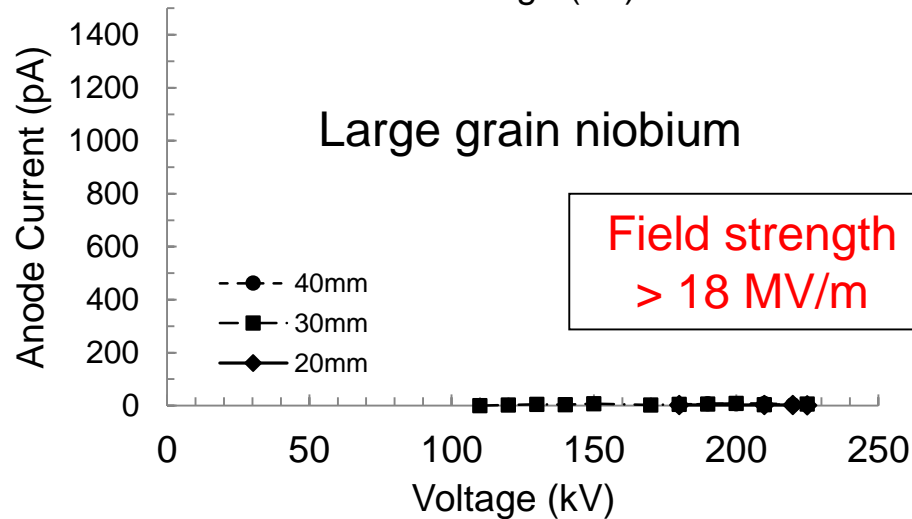
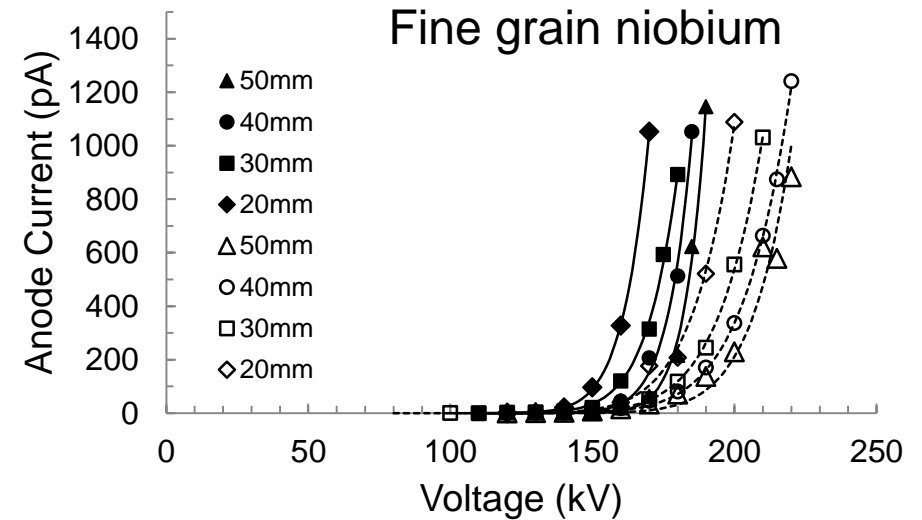
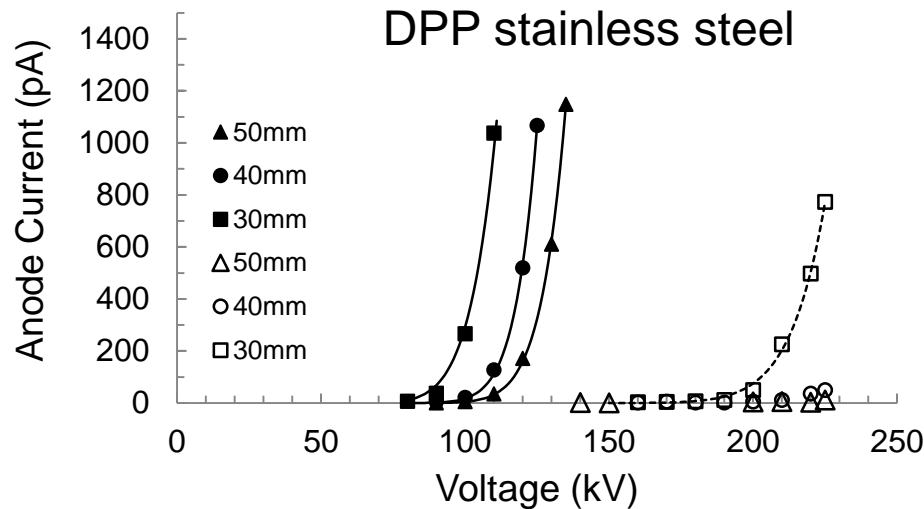
Why a large radius ring (sr pEDM)?

1. Electric field needed is moderate ($\leq 10\text{MV/m}$). New techniques with coated Aluminum is a cost savings opportunity.
2. Long horizontal Spin Coherence Time (SCT) w/out sextupoles. The EDM effect is acting for time $\sim \text{SCT}$.

Field Emission from Niobium

Work of M. BastaniNejad
Phys. Rev. ST Accel. Beams, 15,
083502 (2012)

Buffer chemical polish: less time consuming than diamond paste polishing



Conventional High Voltage processing: solid data points
After Krypton Processing: open data points

CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \dots d_D$

Magnitudes of $\approx 10^{-28}$ expected for Baryogenesis

Atomic, Molecular, Neutron, **Storage Ring** (All important)

Marciano

CP violation phase in: ***Hee, $H\gamma\gamma$, Htt, 2HD Model...***

Uniquely explored by 2 loop edms! Barr-Zee effect

May be our only window to Hee, Huu and Hdd couplings

Guided by experiment: $H \rightarrow \gamma\gamma$ ($H \rightarrow \tau^+\tau^-$, $\mu^+\mu^-$) etc.

Updates Anxiously Anticipated!

The Higgs may be central to our existence!

Electric Dipole Moments in Magnetic Storage Rings

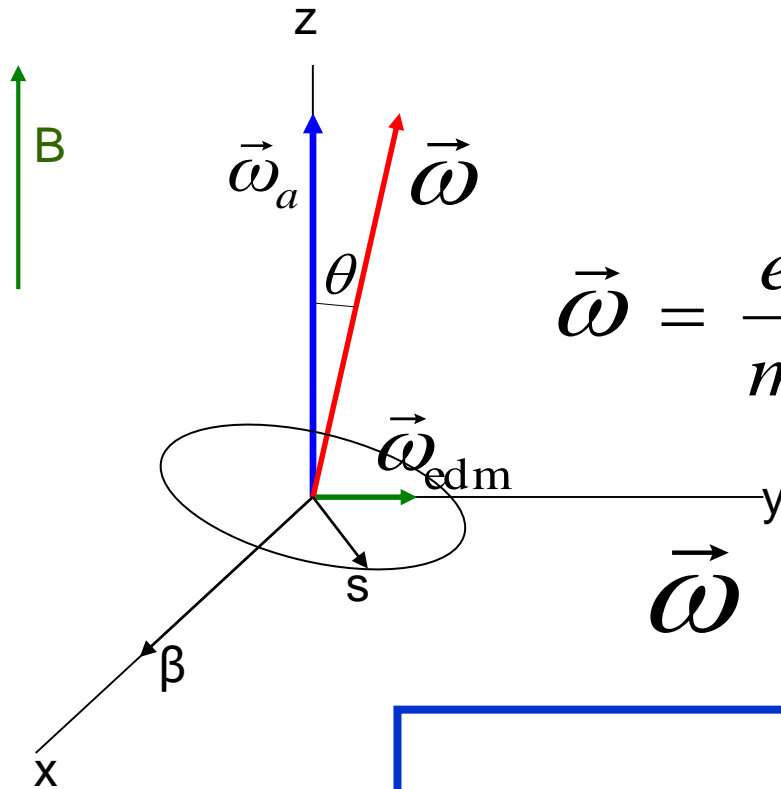
$$\frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B})$$

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

Storage Ring Electric Dipole Moments

Fields	Example	EDM term	Comments
Dipole magnetic field (B)	Muon g-2	Tilt of the spin precession plane. (Limited sensitivity due to spin precession)	Eventually limited by geometrical alignment. Requires CW and CCW injection to eliminate systematic errors
Combination of electric and magnetic fields (E, B)	Deuteron, ³ He, proton, etc.	Mainly: $\frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B})$	Most powerful. Small ring. Need to build combined B and E-field system. Reduce vertical E-field.
Radial Electric field (E)	Proton, etc.	$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$	Large ring, CW & CCW storage. Simplest to achieve. Reduce radial B-field.

Indirect Muon EDM limit from the g-2 Experiment



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

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

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

Ron McNabb's Thesis 2003:

$$< 2.7 \times 10^{-19} \text{ e} \cdot \text{cm} \text{ 95\% C.L.}$$

Yannis Semertzidis

Two different labs could host the storage ring EDM experiments

- AGS/BNL, USA: proton “magic” (simpler) ring
- COSY/IKP, Jülich/Germany: deuteron or a combination ring



Anomalous magnetic moment factors

$$\frac{1}{\gamma^2 - 1} - G = 0 \rightarrow \gamma = \sqrt{\frac{1}{G} + 1}$$

→ $G > 0$ for $\gamma > 1$, if only electric fields are applied

$$\gamma = \sqrt{\frac{1}{G} + 1} \Leftrightarrow p = \frac{m}{\sqrt{G}}$$

$$\begin{aligned} \mu_p / \mu_N &= \mathbf{2.792\,847\,356\,(23)} \rightarrow G_p = 1.7928473565 \\ \mu_d / \mu_N &= \mathbf{0.857\,438\,2308\,(72)} \rightarrow G_d = -0.14298727202 \\ \mu_{\text{He-3}} / \mu_N &= \mathbf{-2.127\,497\,718\,(25)} \rightarrow G_{3\text{He}} = -4.1839627399 \end{aligned}$$

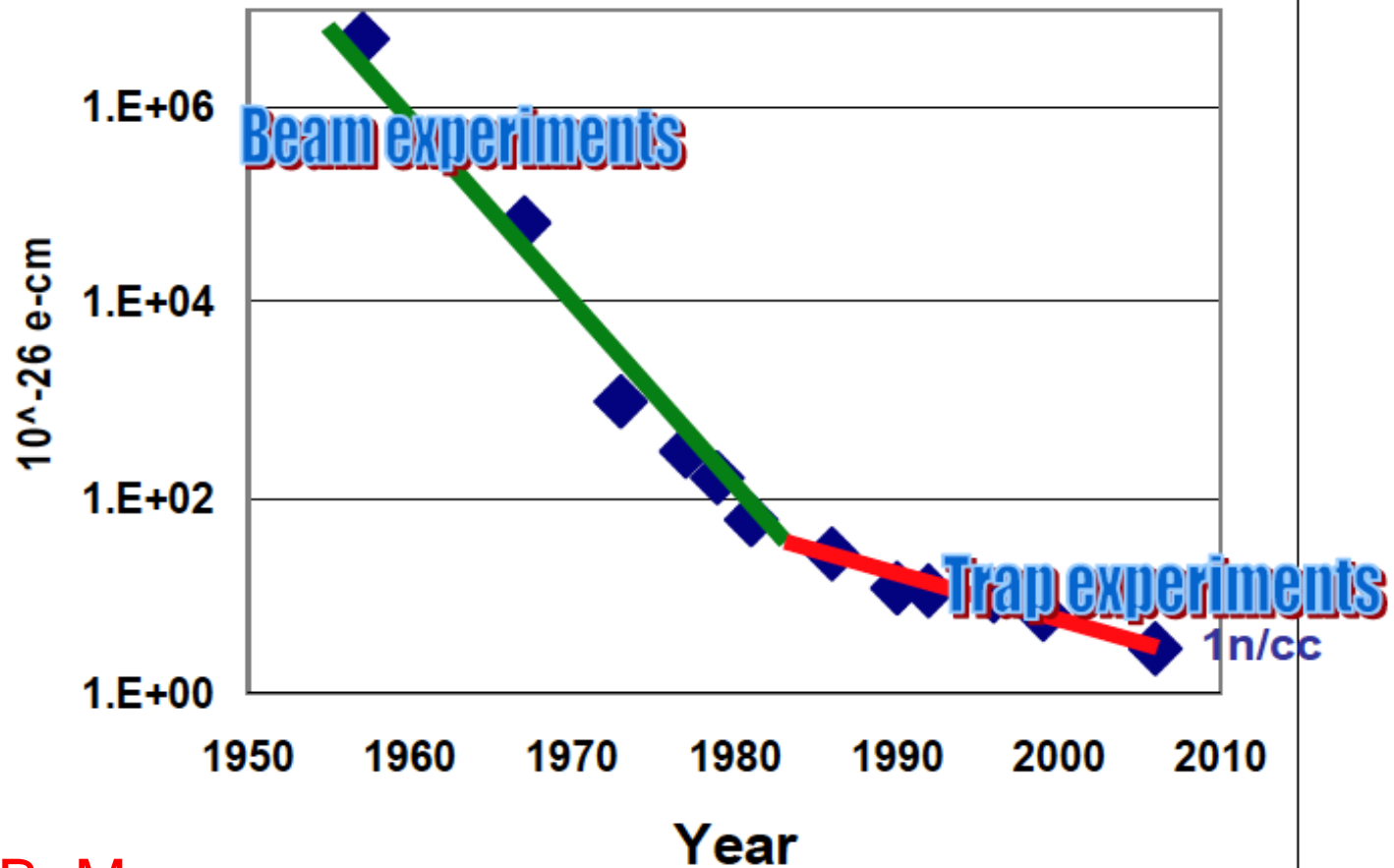
$$\text{Nuclear magneton: } \mu_N = e\hbar / (2m_p c) = 5.050\,783\,24\,(13) \cdot 10^{-27} \text{ J T}^{-1}$$

→ Magic momentum for protons: $p = 700.74 \text{ MeV}/c$

→ Deuterons, He-3:

$$E_r = \frac{GB\phi\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GB\phi\beta\gamma^2$$

Neutron EDM Limits





The nEDM@PSI collaboration

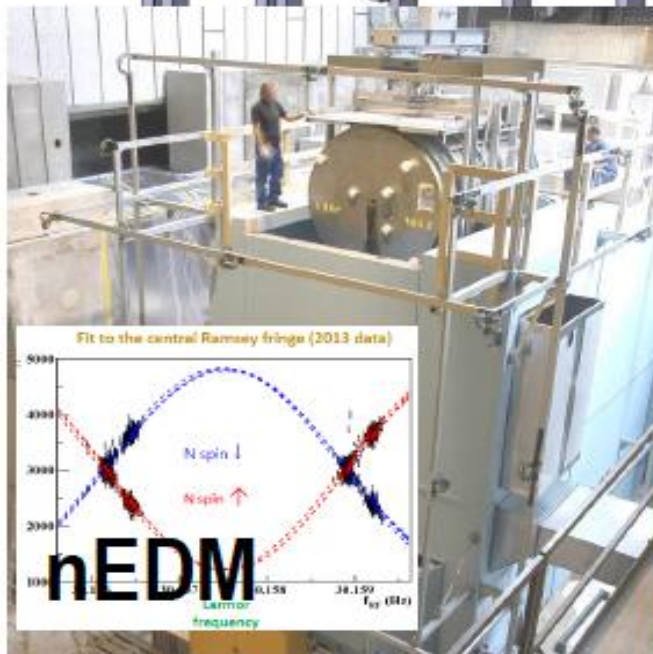
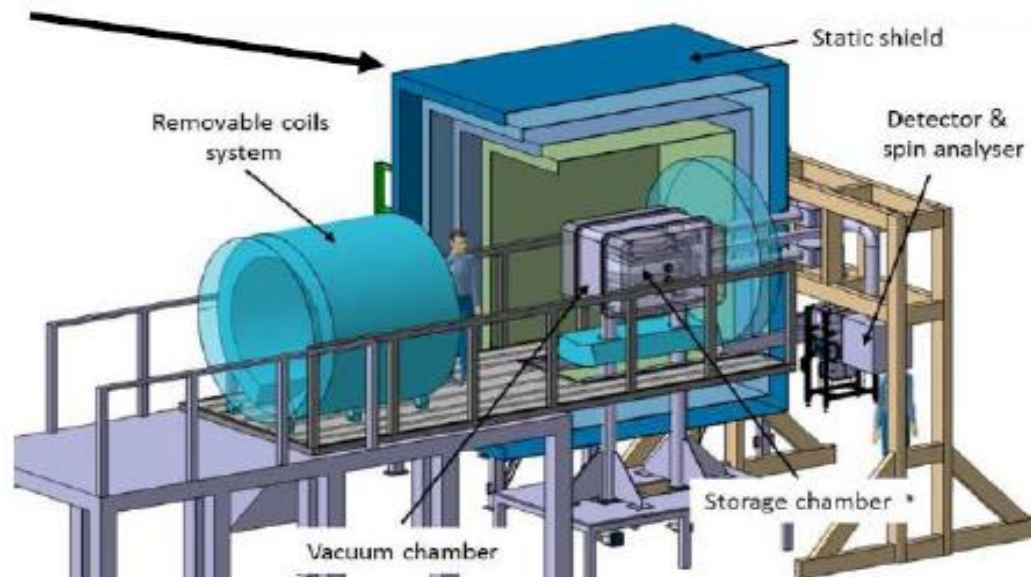
13 Institutions, 7 Countries, 50 individuals



PAUL SCHERRER INSTITUT



n2EDM



The target sensitivity
for nEDM is 10^{-26} ecm or better,
for n2EDM 10^{-27} ecm or better

Key Features of nEDM@SNS

Brad Filippone

- Sensitivity: $\sim 2 \times 10^{-28}$ e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- **Polarized ^3He co-magnetometer**
 - Also functions as neutron spin precession monitor via spin-dependent n- ^3He capture cross section using wavelength-shifted scintillation light in the LHe
 - Ability to vary influence of external B-fields via “dressed spins”
 - Extra RF field allows synching of n & ^3He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
 - Can vary ^3He diffusion (mfp)- big change in geometric phase effect on ^3He

Arguably the most ambitious of all neutron EDM experiments

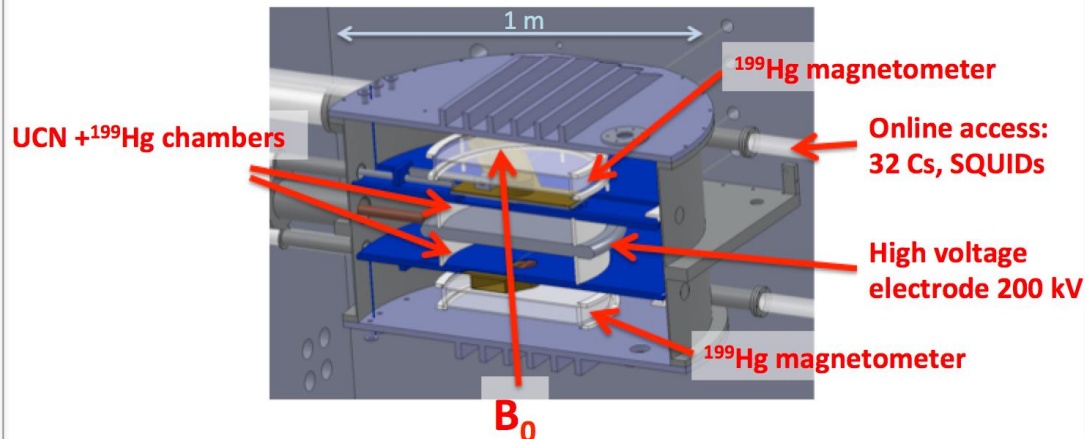
History/Status of nEDM@SNS

- **2011:** NSAC Neutron Subcommittee
- **2013:** Critical R&D successfully demonstrated
- **2014-2017:** Critical Component Demonstration (CCD) phase begun
 - Build working, full-scale, prototypes of technically-challenging subsystems (use these in the full experiment)
 - 4yr NSF proposal for 6.5M\$ CCD funded
 - DOE commitment of $\approx 1.8\text{M}\$/\text{yr}$ for CCD
- **2018-2020:** Large scale Integration and Conventional Component Procurement
- **2021:** Begin Commissioning and Data-taking

The TUM EDM experiment

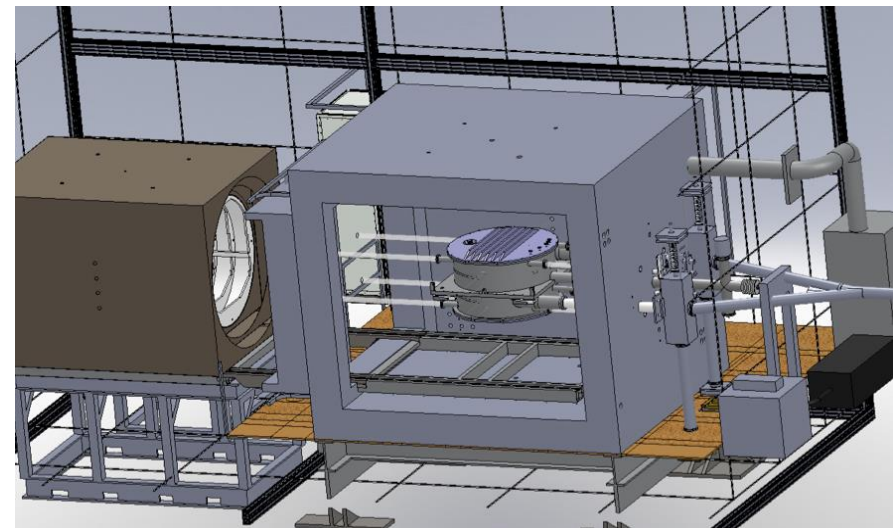
- Initially a 'conventional' Ramsey experiment
- UCN trapped at room temperature, ultimately cryogenic trap
- Double chamber with co-magnetometer option
- ^{199}Hg , Cs, ^{129}Xe , ^3He , SQUID magnetometers
- Portable and modular setup, including magnetically shielded room
- Ultimate goal: 10^{-28} ecm sensitivity, staged approach (syst. and stat.)

Double chamber in SF6 container



I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)

Modular shield setup

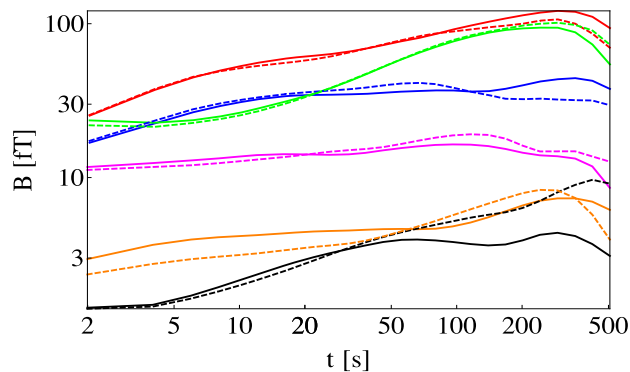


E.g.: passive magnetic shielding factor > 6 million @ 1 mHz
(without ext. compensation coils!)

I. Altarev et al., arXiv:1501.07408

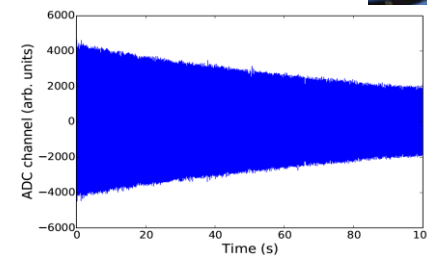
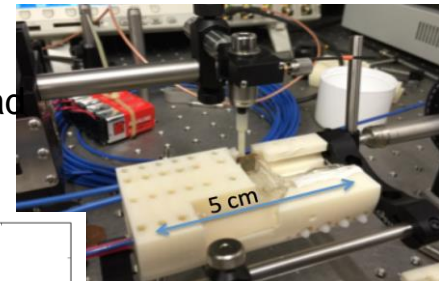
I. Altarev et al., , arXiv:1501.07861

- The smallest gradients over an extended volume ever realized: < 50 pT / m stable gradient over EDM cell volume
- Residual field drift < 5 fT in typical Ramsey cycle time
- Hg and Cs magnetometry on < 20 fT level:



1.5m

Cs sensor head assembly



Raw ^{199}Hg FPD signal

- Basically all magnetic field related systematics under control

Peter Fierlinger, TUM, magnetic shielding factor $> 6M$ at 1mHz!

I. Altarev et al., arXiv:1501.07408
I. Altarev et al., , arXiv:1501.07861



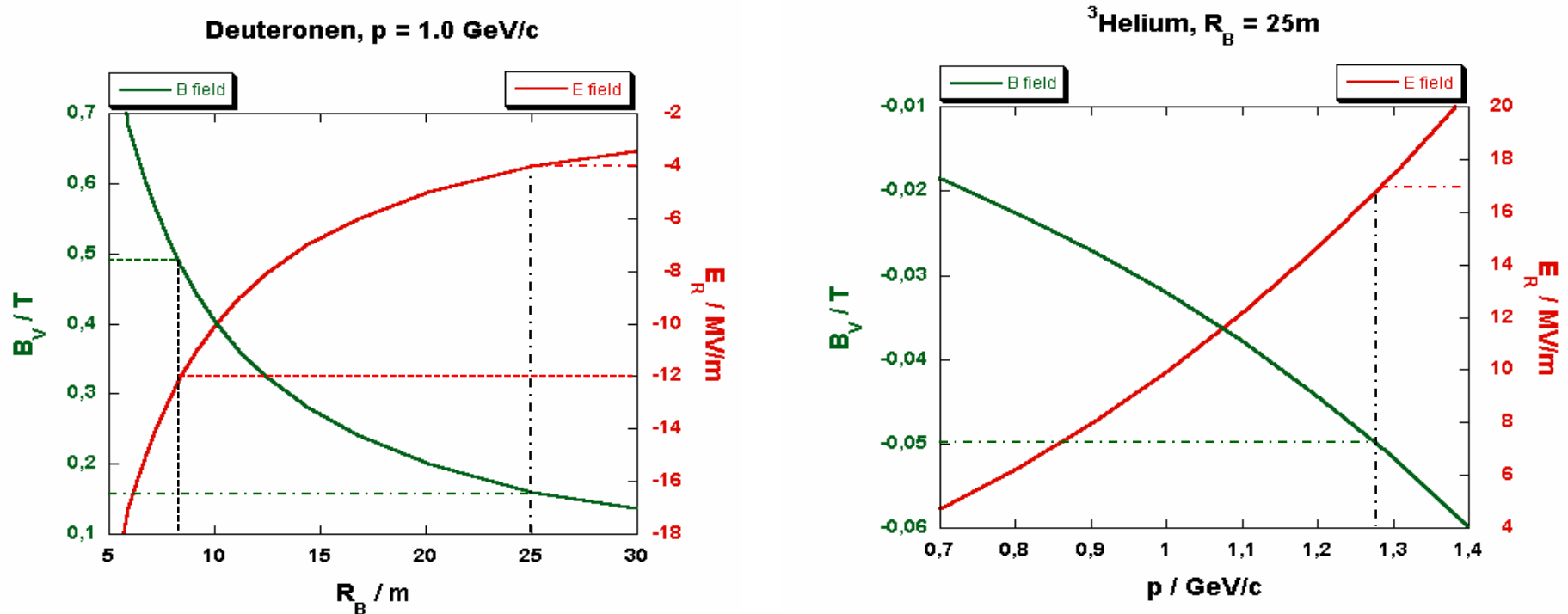
Physics Today, August 2015

No New-Physics breakthrough
from anywhere...

Freezing Spin Motion with E- and B-Fields

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

$$E_R = \frac{GB_V c \beta \gamma^2}{1 - G\beta^2 \gamma^2} \cong GB_V c \beta \gamma^2$$



Protons: $p_p = 0.701 \text{ GeV/c}$, $E_R = 16.8 \text{ MV/m}$, $B_V = 0 \text{ T} \rightarrow R_B = 25 \text{ m}$

Various options for EDM@COSY, Juelich

EDM with E- and B-Fields for different Particles

„all-in-one“ storage ring

Protons: $p_p = 0.701 \text{ GeV/c}$

$E_R = 16.8 \text{ MV/m}$, $B_V = 0 \text{ T}$

Deuterons: $p_d = 1.0 \text{ GeV/c}$

$E_R = -4.0 \text{ MV/m}$, $B_V = 0.16 \text{ T}$

Helium-3: $p_{3\text{He}} = 1.285 \text{ GeV/c}$

$E_R = 17.0 \text{ MV/m}$, $B_V = -0.05 \text{ T}$

„all-in-one“ storage ring

Protons: $p_p = 0.527 \text{ GeV/c}$

$E_R = 16.8 \text{ MV/m}$, $B_V = 0.02 \text{ T}$

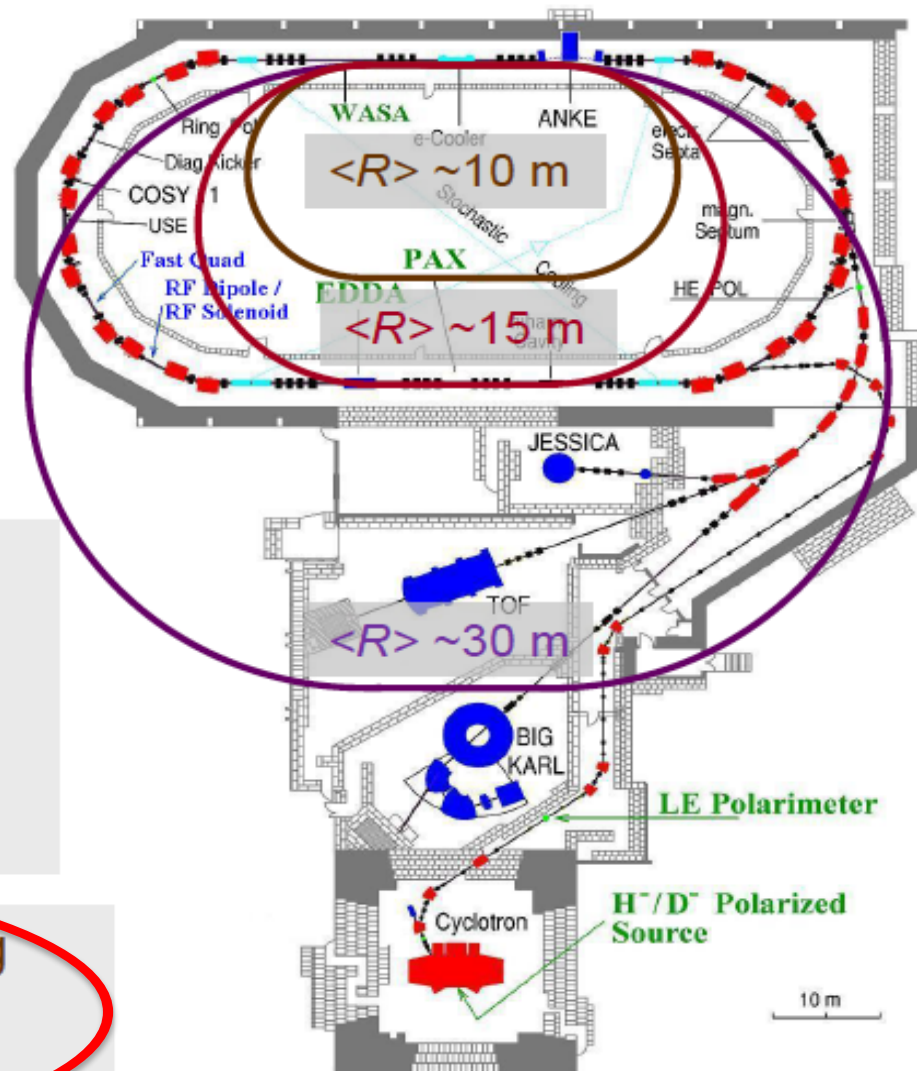
Deuterons: $p_d = 1.0 \text{ GeV/c}$

Helium-3: $p_{3\text{He}} = 0.946 \text{ GeV/c}$

Dedicated deuteron storage ring

Deuterons: $p_d = 1.0 \text{ GeV/c}$

$E_R = -12.0 \text{ MV/m}$, $B_V = 0.48 \text{ T}$



EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)
- CP-violating sources beyond the SM

Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron,...).

pEDM at $10^{-29} \text{e}\cdot\text{cm}$ is > an order of magnitude more sens. than the best current nEDM plans

Hadronic contribution (had1)

Cannot be calculated from pQCD alone because it involves low energy scales.

However, by dispersion theory, this $a_\mu(\text{had1})$ can be related to

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

measured in e^+e^- collisions.

$$a_\mu(\text{had}, 1) = \left(\frac{\alpha m_\mu}{3\pi} \right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

