http://web.tdli.sjtu.edu.cn/kimsiang84/

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Muon g-2/EDM experiments and their requirements to future muon sources

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2020 EMuS & MOMENT General Meeting

Dec 11-12, 2020

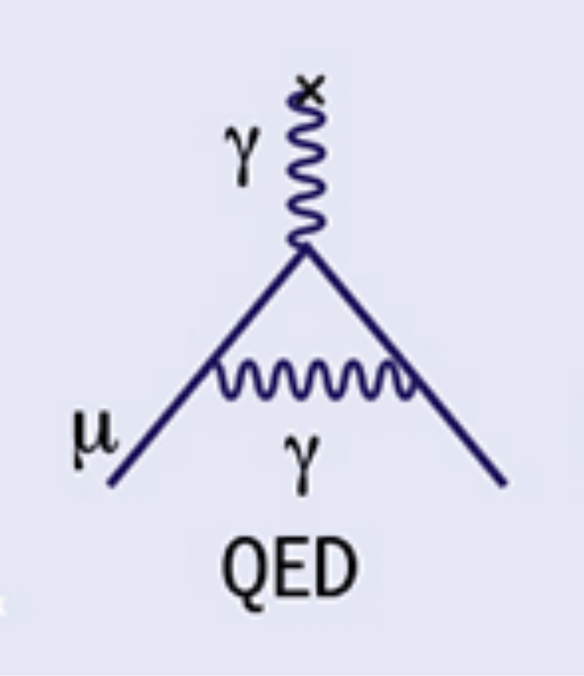
Outline

- Physics Motivation
  - Muon magnetic dipole moment and electric dipole moment
- Muon g-2/EDM
  - Fermilab, J-PARC, PSI
- Future g-2/EDM
  - Possibilities at CSNS - EMuS and HEMS
- Summary

About Magnetic Dipole Moment (MDM)

- For a charged, spin-1/2 particle, intrinsic angular momentum (spin) generates magnetic dipole moment

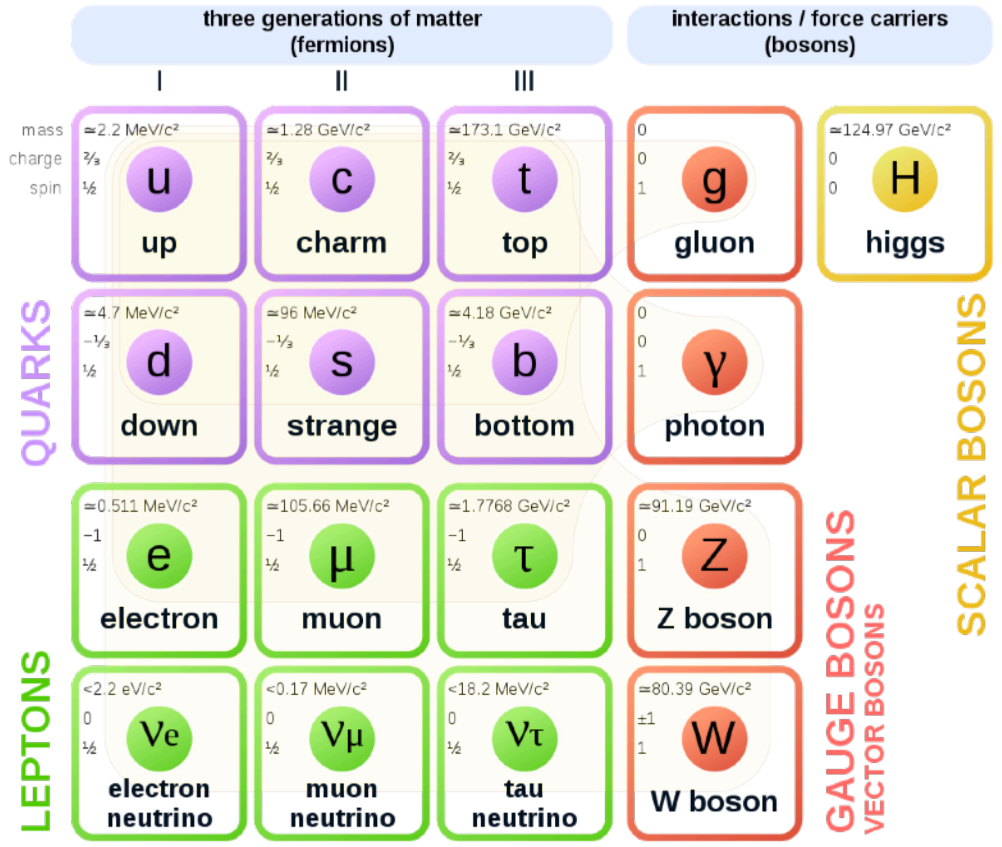
$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$



- g = 2 for a “free” Dirac particle, g > 2 due to quantum fluctuation
- Measurement of g-factor for proton (5.6) and neutron (-3.8) hinted at their internal structures

- Measuring the size of quantum corrections reveals particle and interaction content of the universe
- The “anomalous magnetic moment (AMM)”

$$a = \frac{g-2}{2}$$

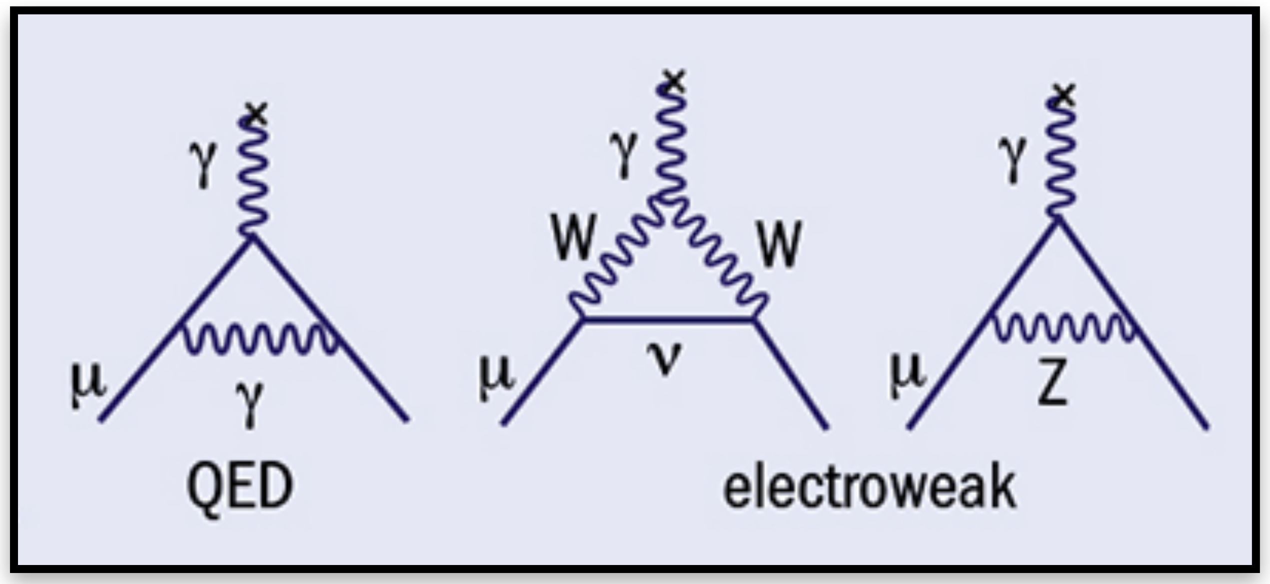


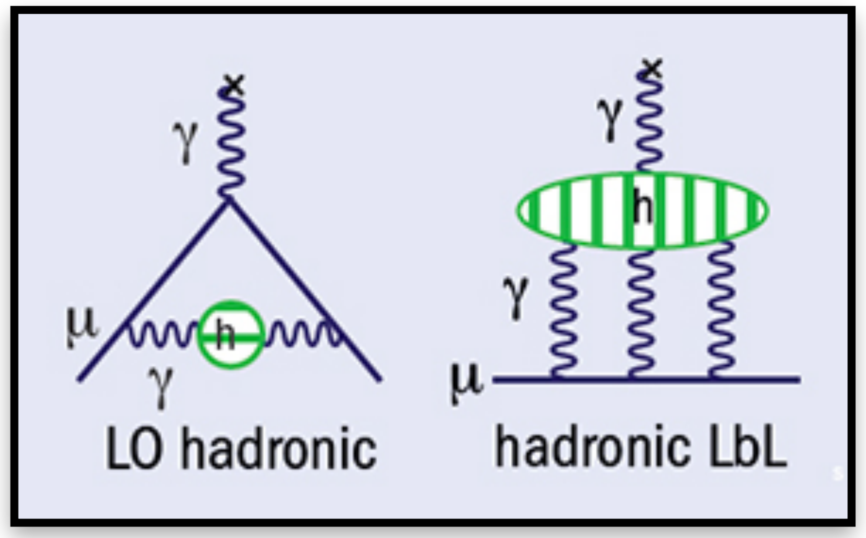
	three generations of matter (fermions) I	II	III	interactions / force carriers (bosons)	
mass charge spin	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	SCALAR BOSONS
	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<2.2 eV/c² 0 ½ νe electron neutrino	<0.17 MeV/c² 0 ½ νμ muon neutrino	<18.2 MeV/c² 0 ½ ντ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	GAUGE BOSONS VECTOR BOSONS

+ ???

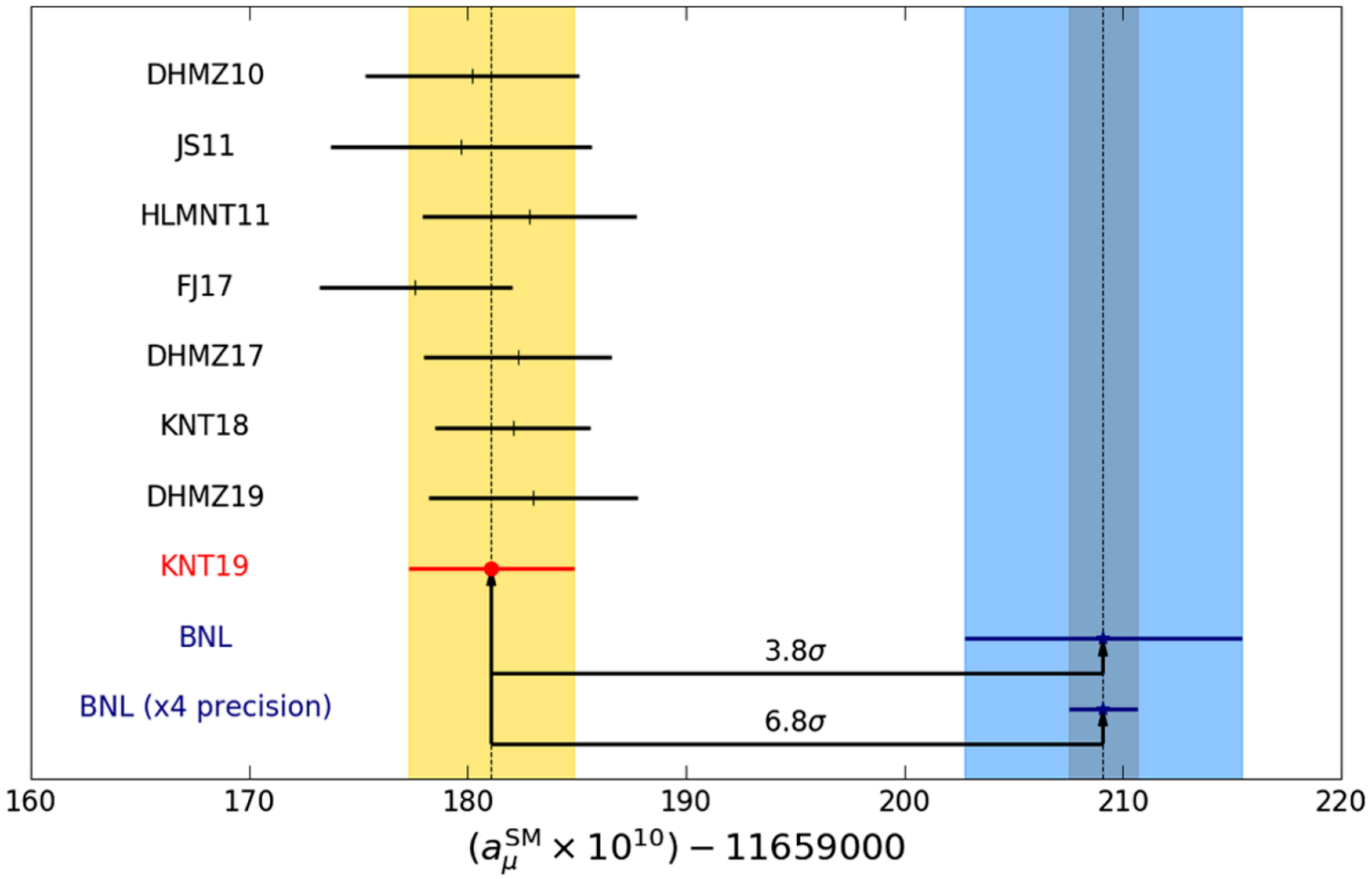
Muon g-2: A longstanding puzzle

SM Prediction

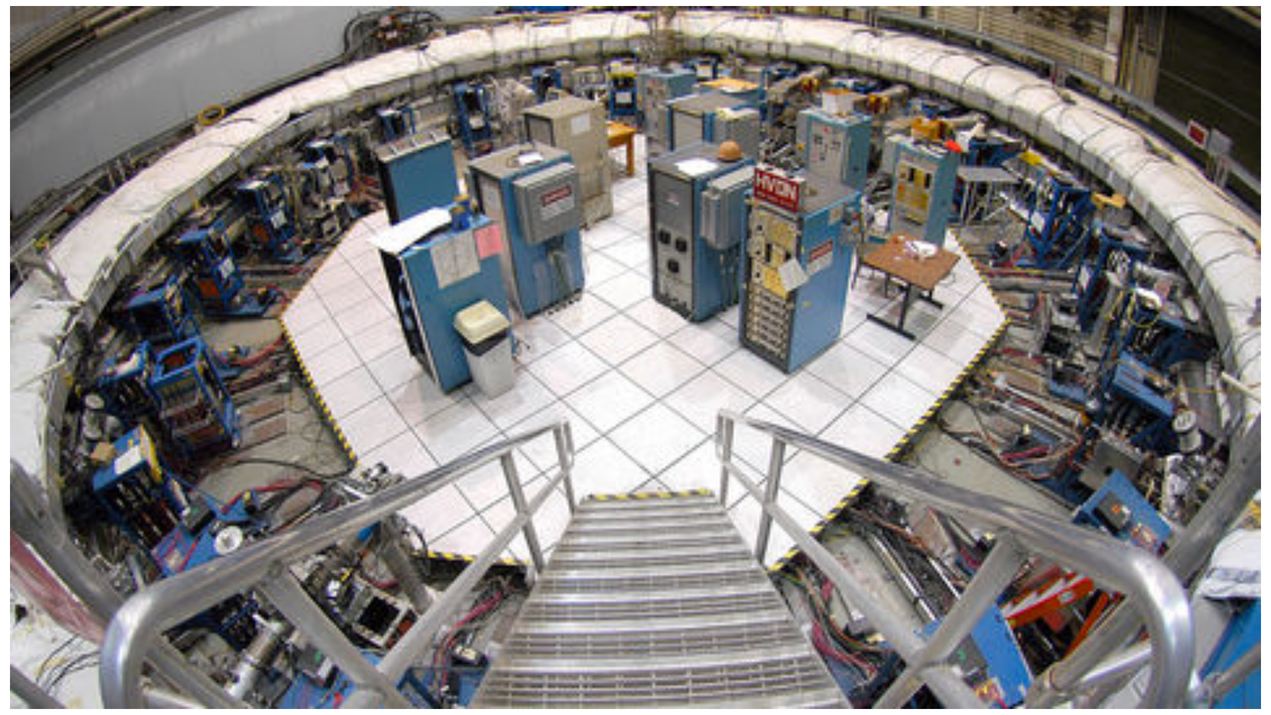




Phys Rev D101 014029



Measurement



G.W.Bennett et al., Phys. Rev. D 73, 072003

Picture credit: BNL

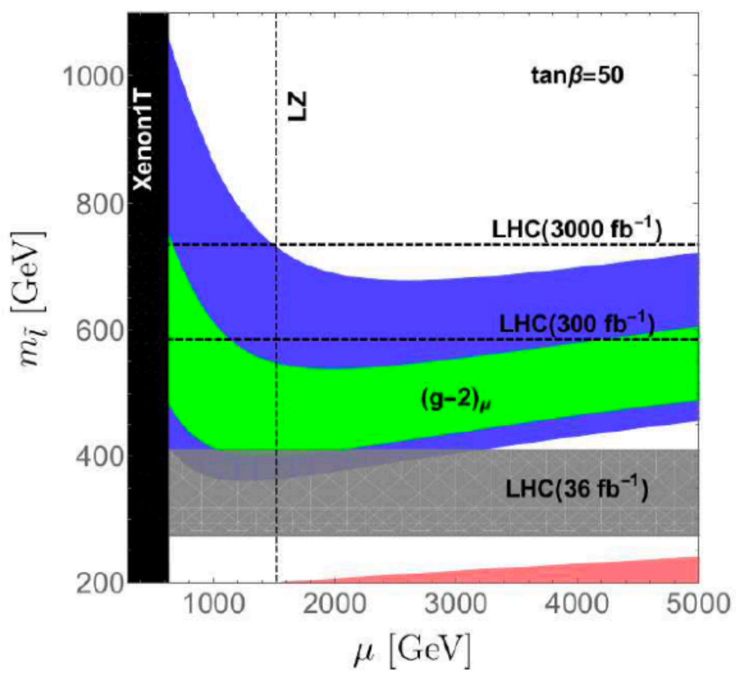
What is the Nature trying to tell us?

- Error in the theory?
- Error in the experiment?
- New Physics?

Which BSM models can accommodate this deviation?

Standard MSSM

[Cox, Han, Yanagida '18]. . .
[Endo, Hamaguchi, Iwamoto, Kitahara '20],[Chakraborti, Heinemeyer, Saha '20]
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]



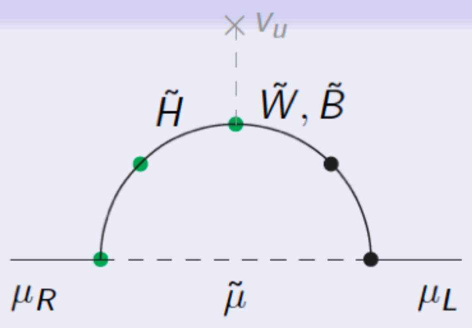
[e.g.: Cox, Han, Yanagida '18]:

$\tilde{B}\tilde{W}$ coannihilation, $\Delta m = 15$GeV

MSSM: Complicated situation!

Many constraints,
many relevant (non-traditional)
parameter regions

MSSM: well motivated, can explain large deviation (but. . .)

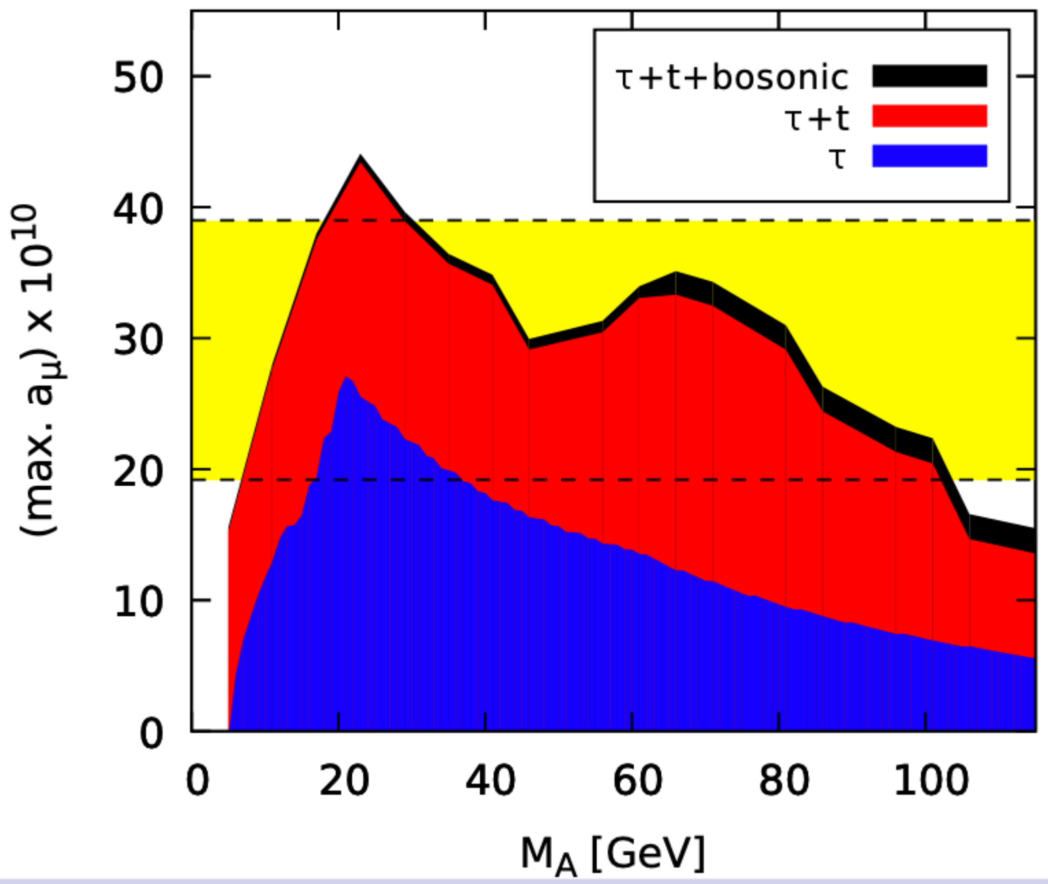


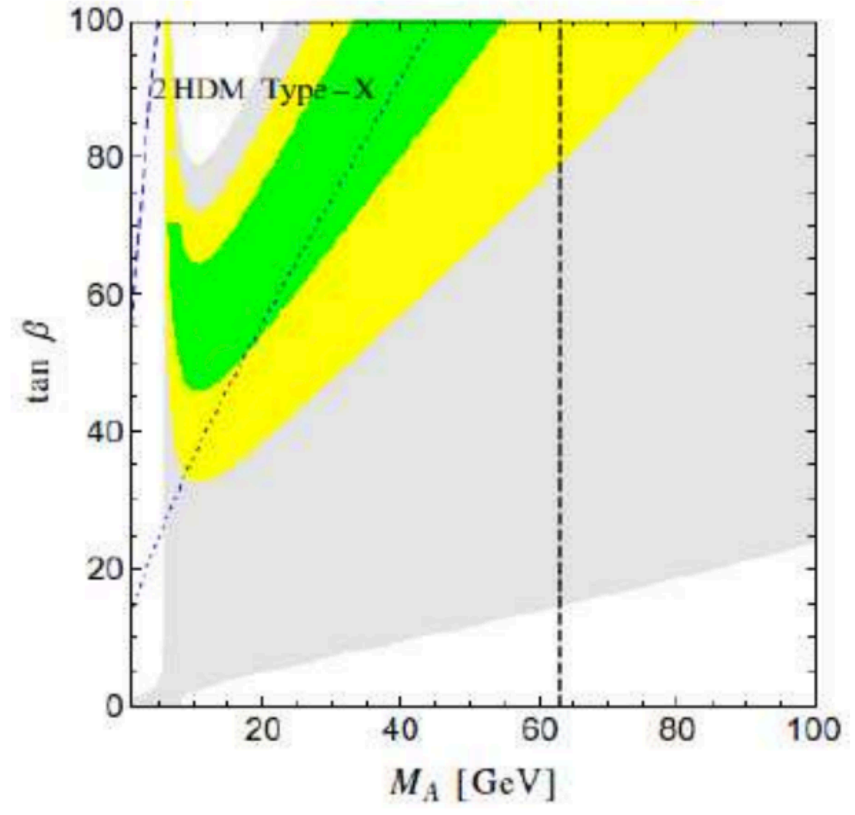
- LHC + Dark Matter ⇒ mass patterns!
- Co-annihil. regions; large $\mu \equiv m_{\tilde{H}}$; Wino-LSP; . . .
- Excludes many simple scenarios (MSugra, . . .)

Two-Higgs Doublet Model

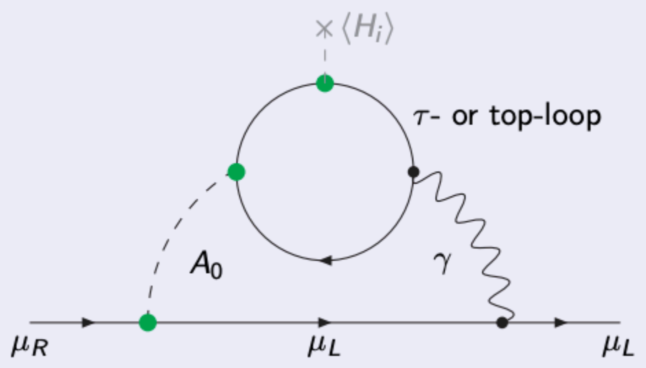
$M_H = M_{H^\pm} = 250$ GeV

[Broggio,Chun,Passera,Patel,Vempati '14]. . .
. . .[Cherchiglia,DS,Stöckinger-Kim '17]



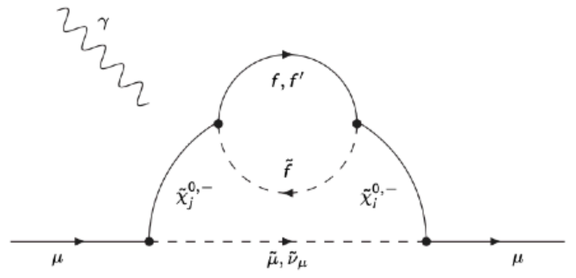


a_μ in the 2-Higgs doublet model?



Results: a_μ explained in tightly constrained parameter space;
testable by many observables: $Z \to \tau\tau$, τ- and b-decays, LHC $gg \to A, H \to \tau\tau$, future ILC?

Many models! General ideas still viable (SUSY, THDM, LQ, VLL, . . .)
But: restricted parameter space! Specific scenarios excluded!



Muon g-2: Very active community

Physics Reports 887 (2020) 1–166

Contents lists available at ScienceDirect

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The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C.M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[14,*], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[18,*], C.T.H. Davies[19], M. Della Morte[20], S.I. Eidelman[21,22,*], A.X. El-Khadra[23,24,*], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D.W. Hertzog[33], A. Hoecker[34], M. Hoferichter[14,35,*], B.-L. Hoid[36], R.J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[26,37,*], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M.K. Marinković[46,47], P. Masjuan[48,49], A.S. Meyer[37], H.B. Meyer[12,13], T. Mibe[1,*], K. Miura[12,13,3], S.E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[12,*], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C.F. Redmer[12], B.L. Roberts[57,*], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[60,*], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18], M.N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C.A. Dominguez[67], A.E. Dorokhov[68], V.P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C.S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J.R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A.S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P.B. Mackenzie[24], W.J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E.T. Neil[77], A.V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A.E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E.P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A.S. Zhevlakov[78]

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$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HVP,\,LO}} + a_\mu^{\mathrm{HVP,\,NLO}} + a_\mu^{\mathrm{HVP,\,NNLO}} + a_\mu^{\mathrm{HLbL}} + a_\mu^{\mathrm{HLbL,\,NLO}}$$
$$= 116\,591\,810(43) \times 10^{-11}\,.$$

$$a_\mu^{\mathrm{exp}} = 116\,592\,089(63) \times 10^{-11}$$

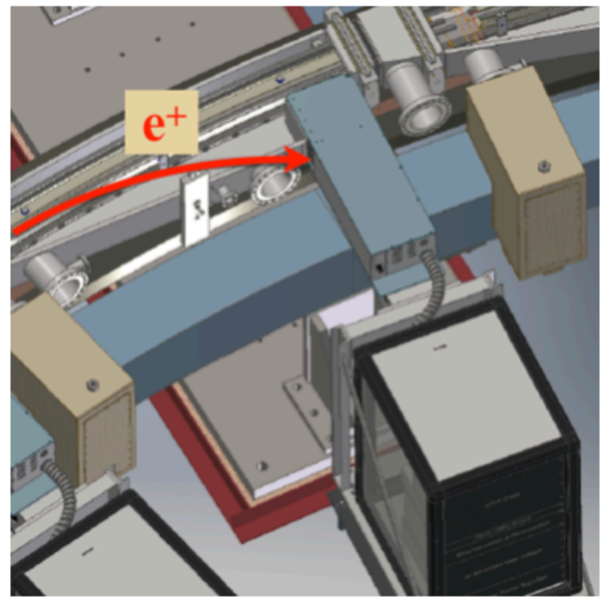
$$\Delta a_\mu := a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 279(76) \times 10^{-11}$$

T. Aoyama et al., Phys. Rept. 887 (2020) 1-166

Muon g-2: Fermilab vs J-PARC

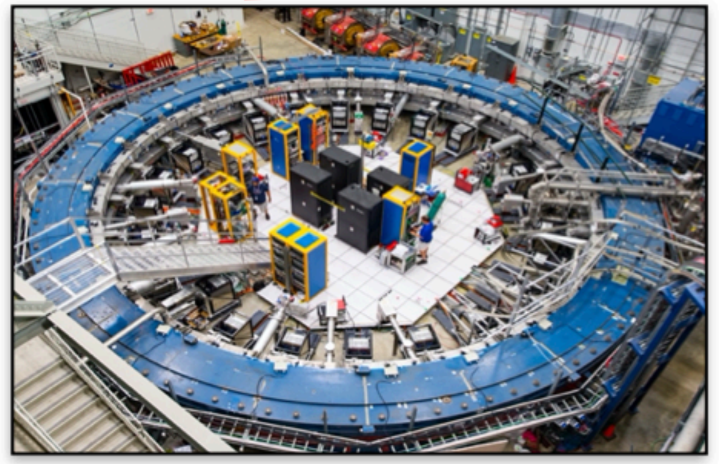
Very different systematics!
Important crosschecks!

2018-2022++

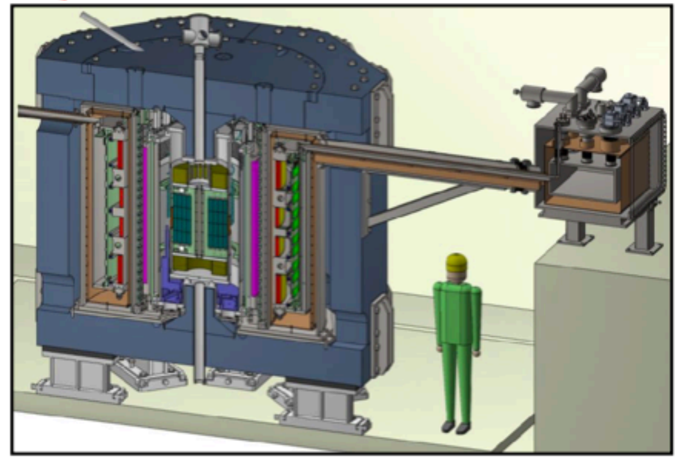


Calorimetry

3.1 GeV/c μ^+

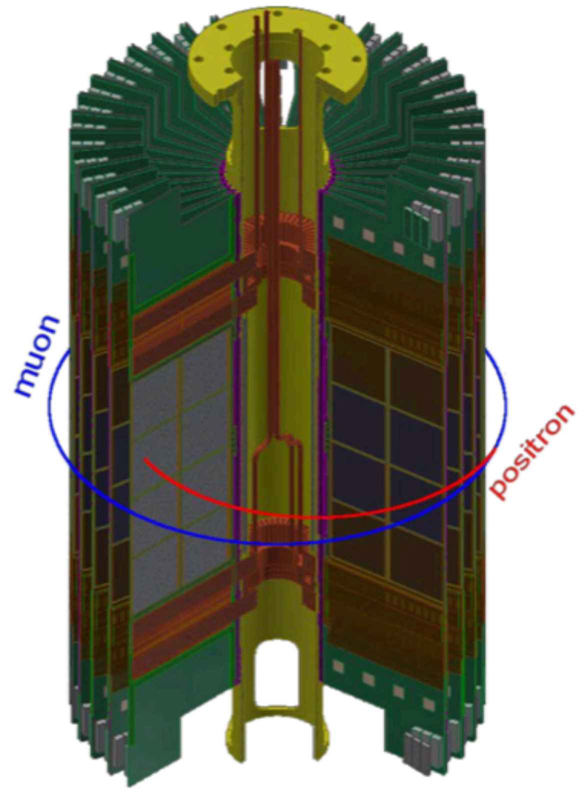


0.3 GeV/c μ^+



Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

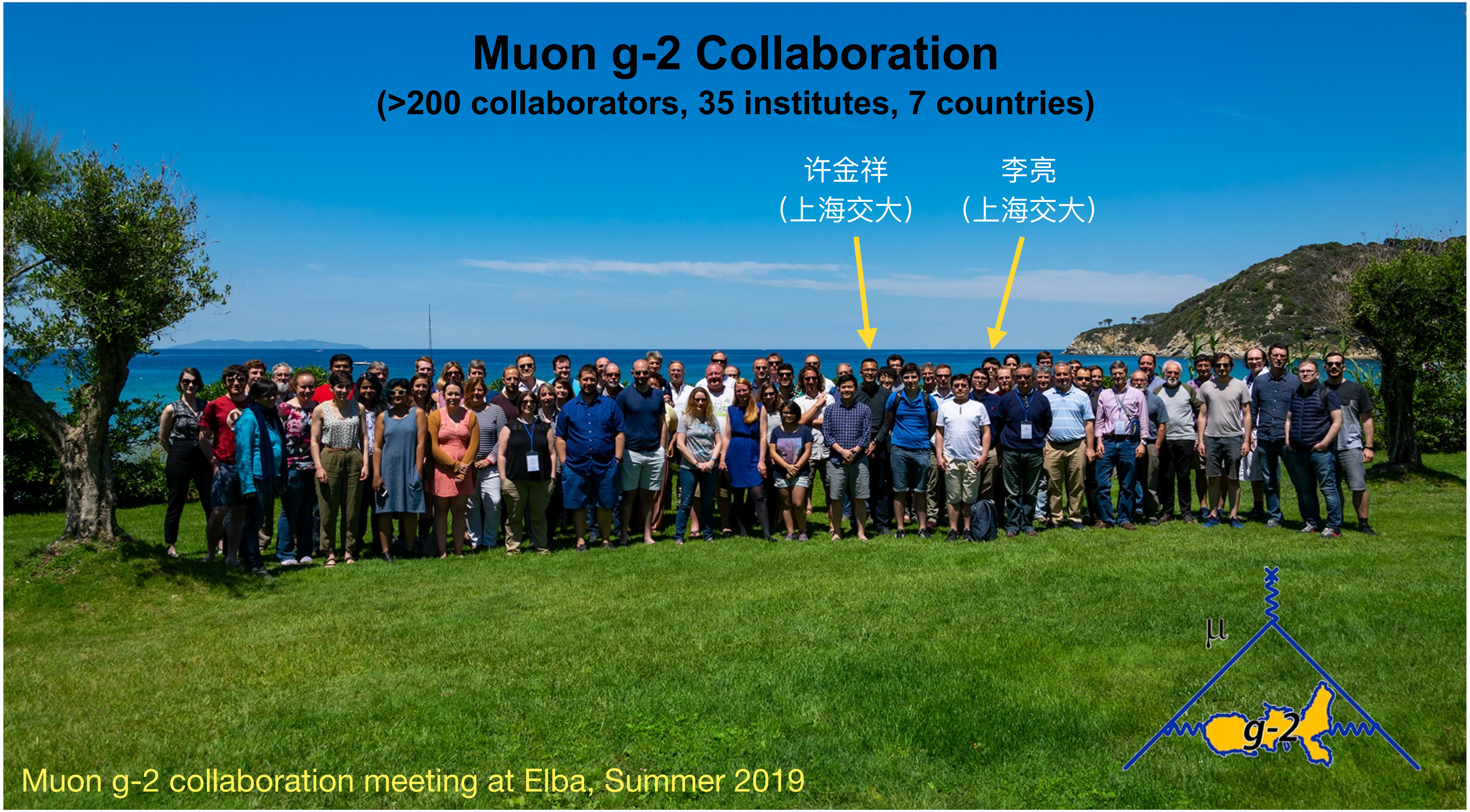
2025-



Tracking

Muon g-2 Collaboration

(>200 collaborators, 35 institutes, 7 countries)



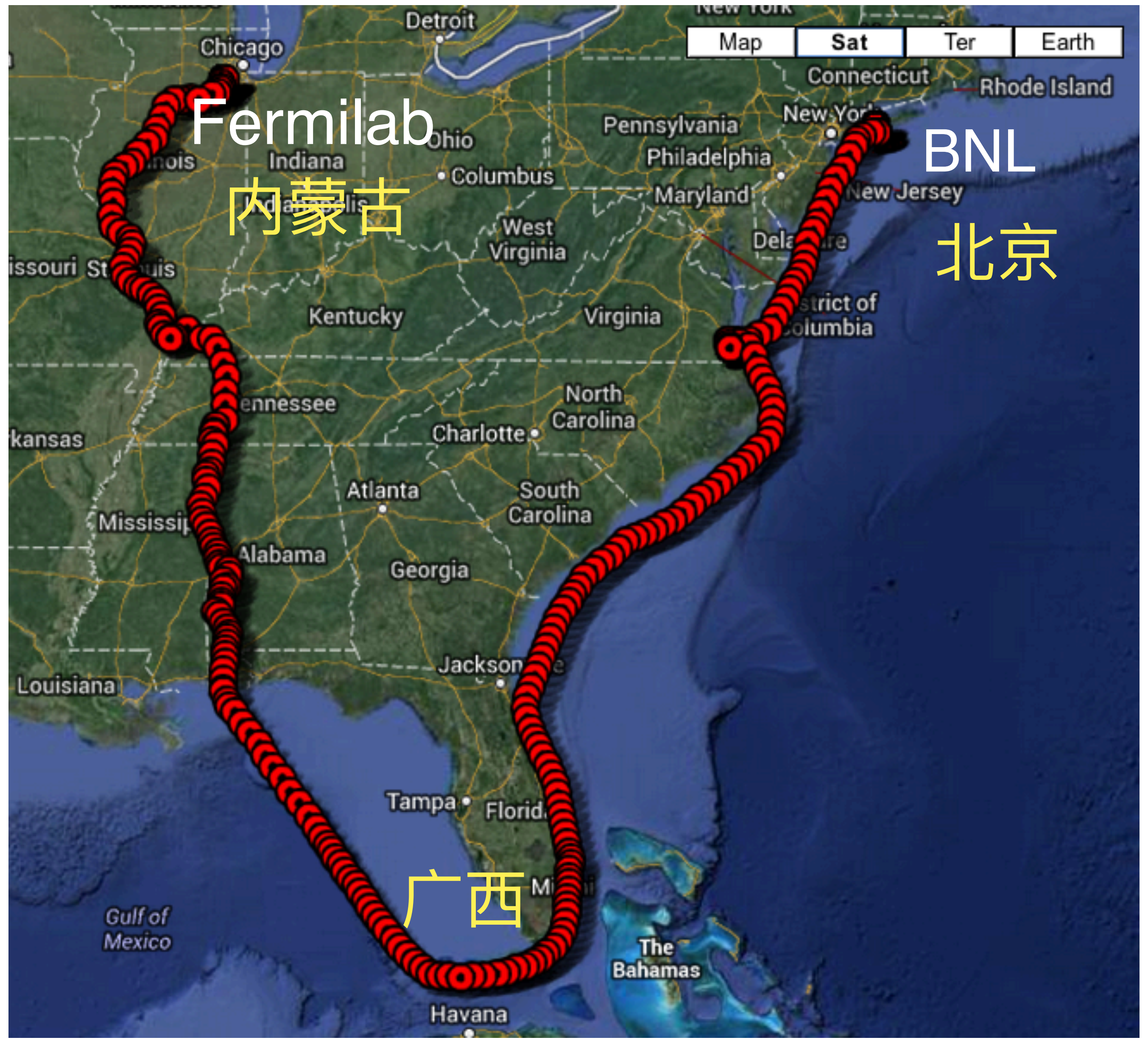
许金祥
（上海交大）

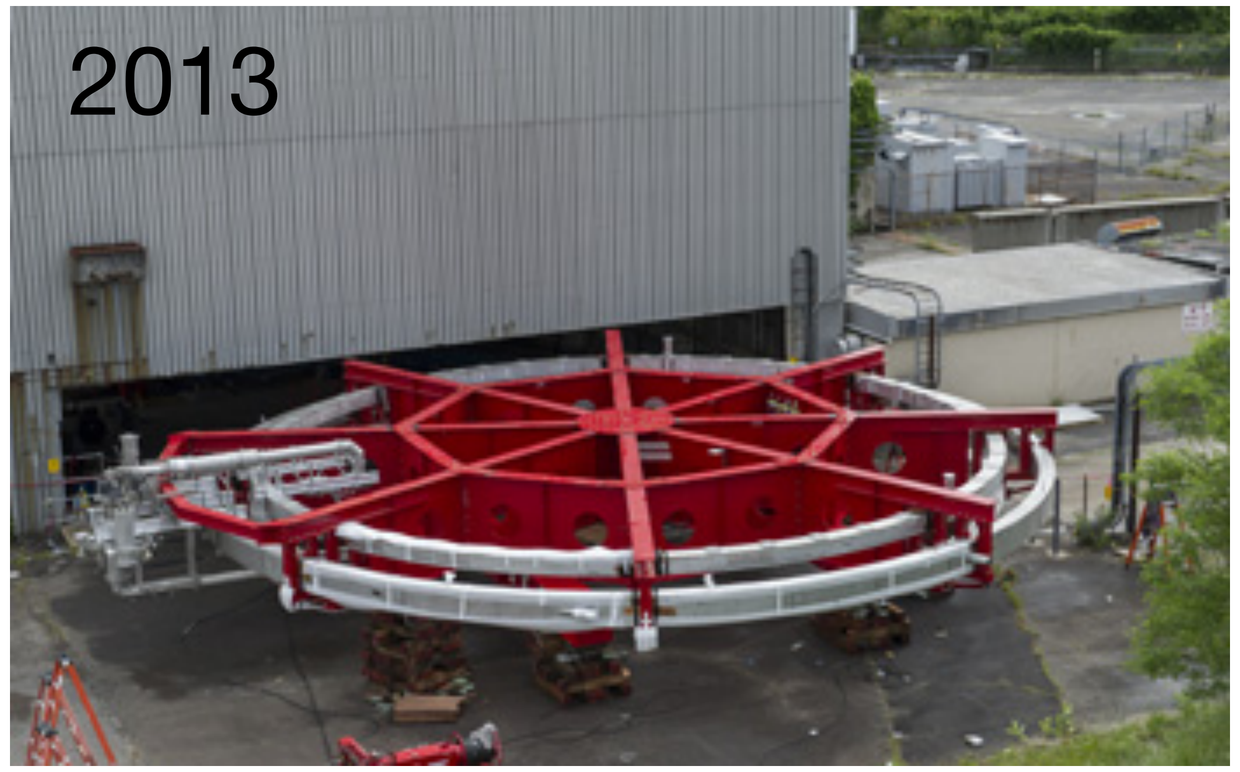
李亮
（上海交大）

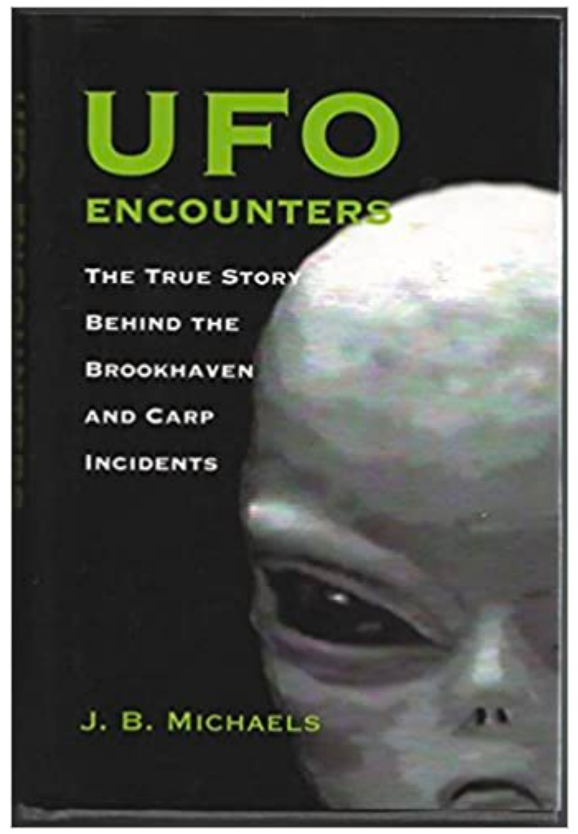
Muon g-2 collaboration meeting at Elba, Summer 2019

We include: Particle-, Nuclear-, Atomic-, Optical-, Accelerator-, and Theory Physicists
And we combine our effort to measure a single value, g-2, to 140 ppb (BNL - 540 ppb)!

The Big Move (2013)

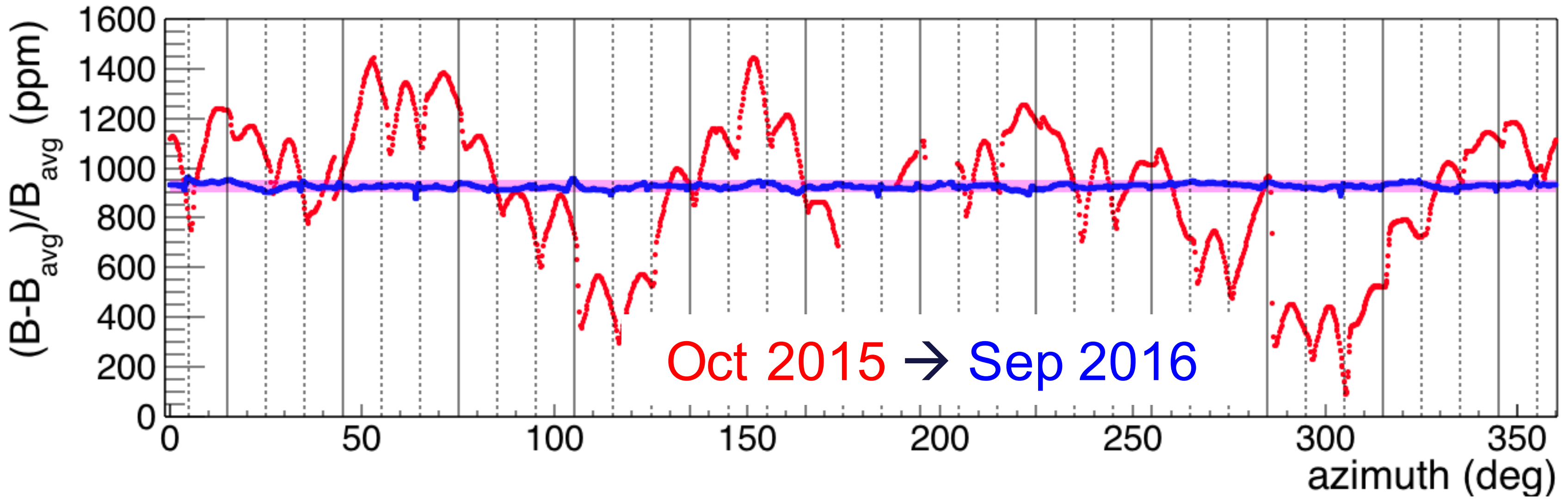


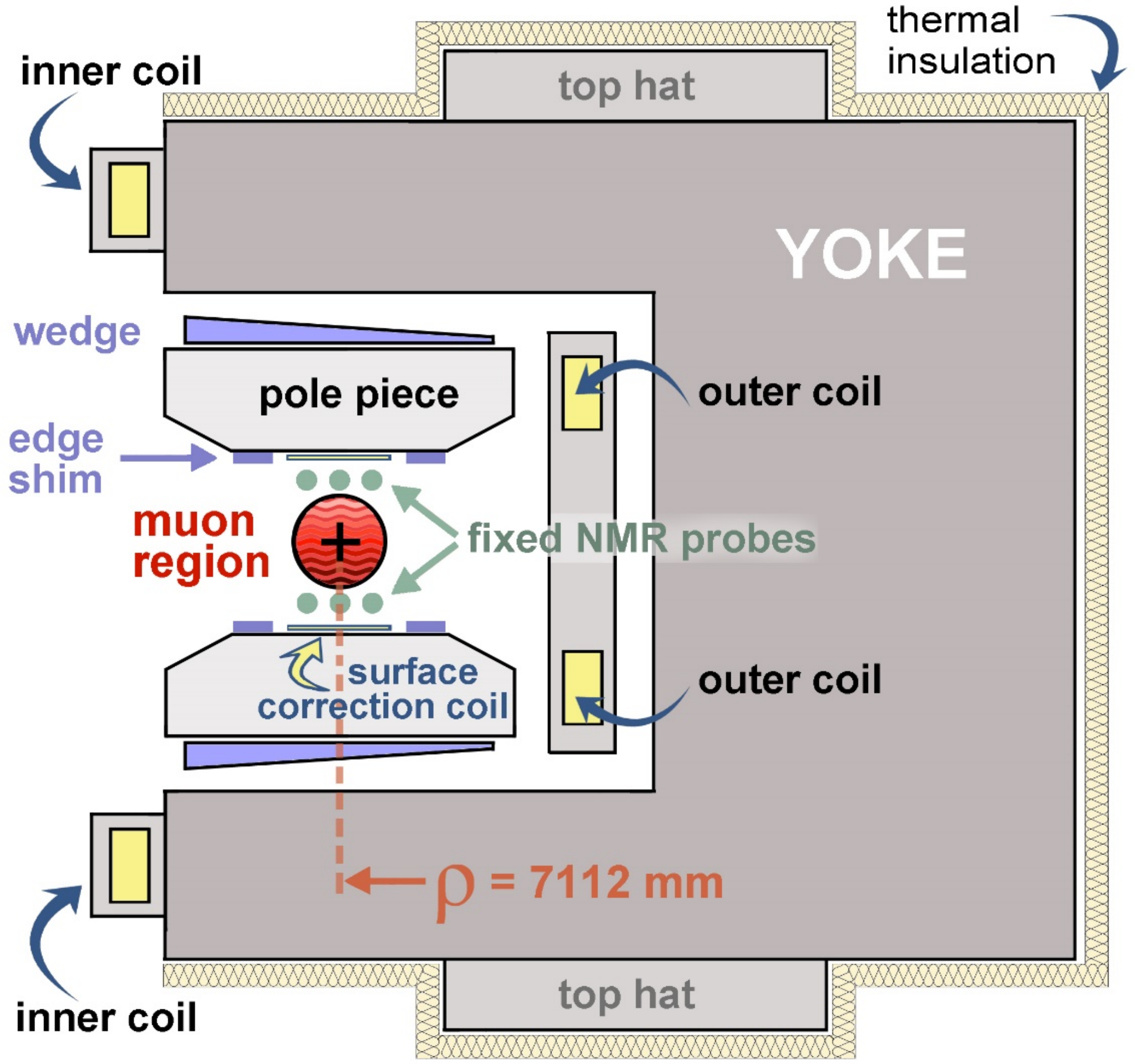




B=1.45 T

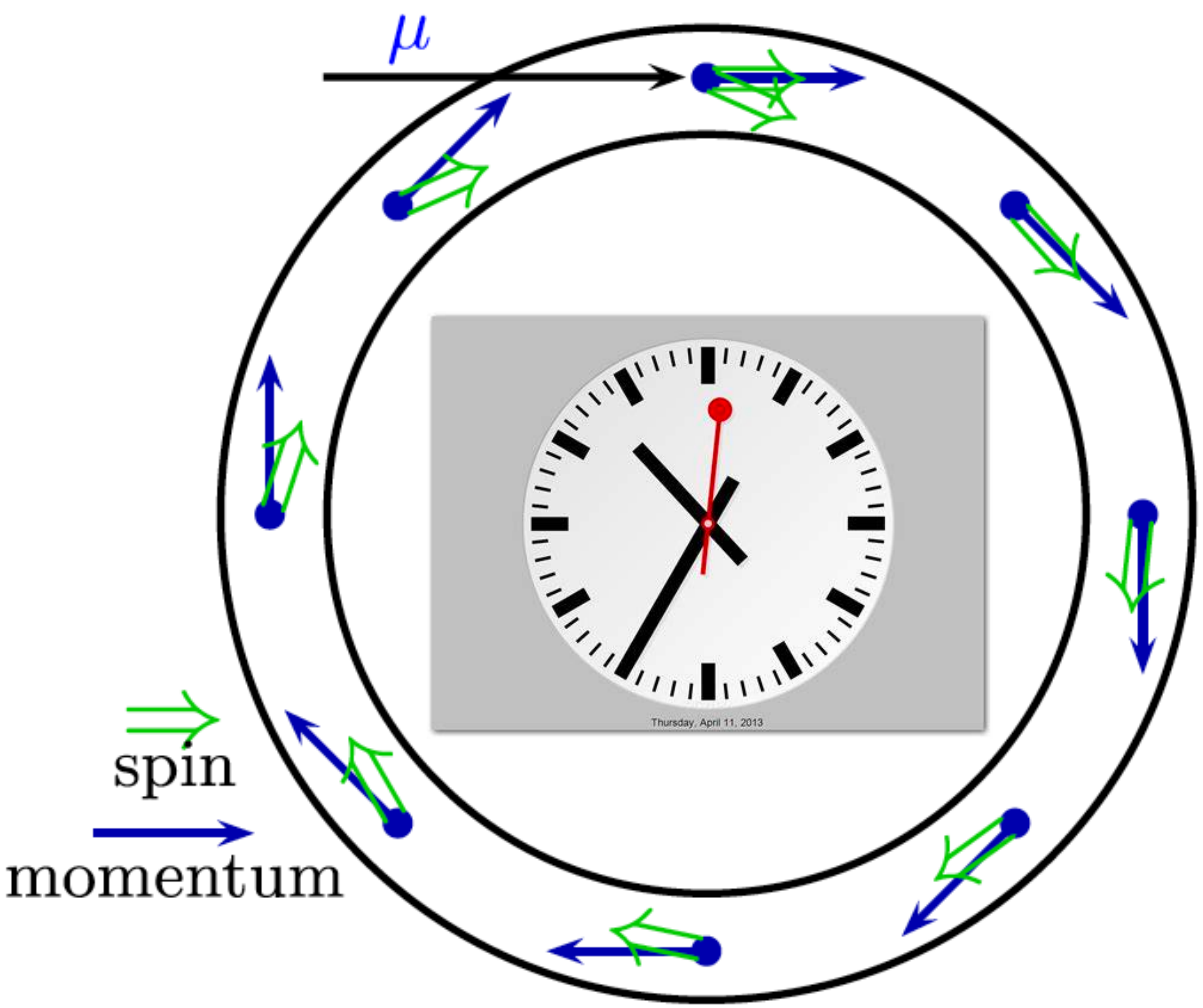
Rough Shimming	RMS [ppm]	p-p [ppm]
FNAL	10	75
BNL	30	230





g-2 Magnet in Cross Section

Principle of g-2 measurement



Larmor **Thomas**

$$\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

Cyclotron

$$\omega_c = \frac{eB}{\gamma m}$$

$$\omega_a = \omega_s - \omega_c = (\frac{g-2}{2})\frac{eB}{m}$$

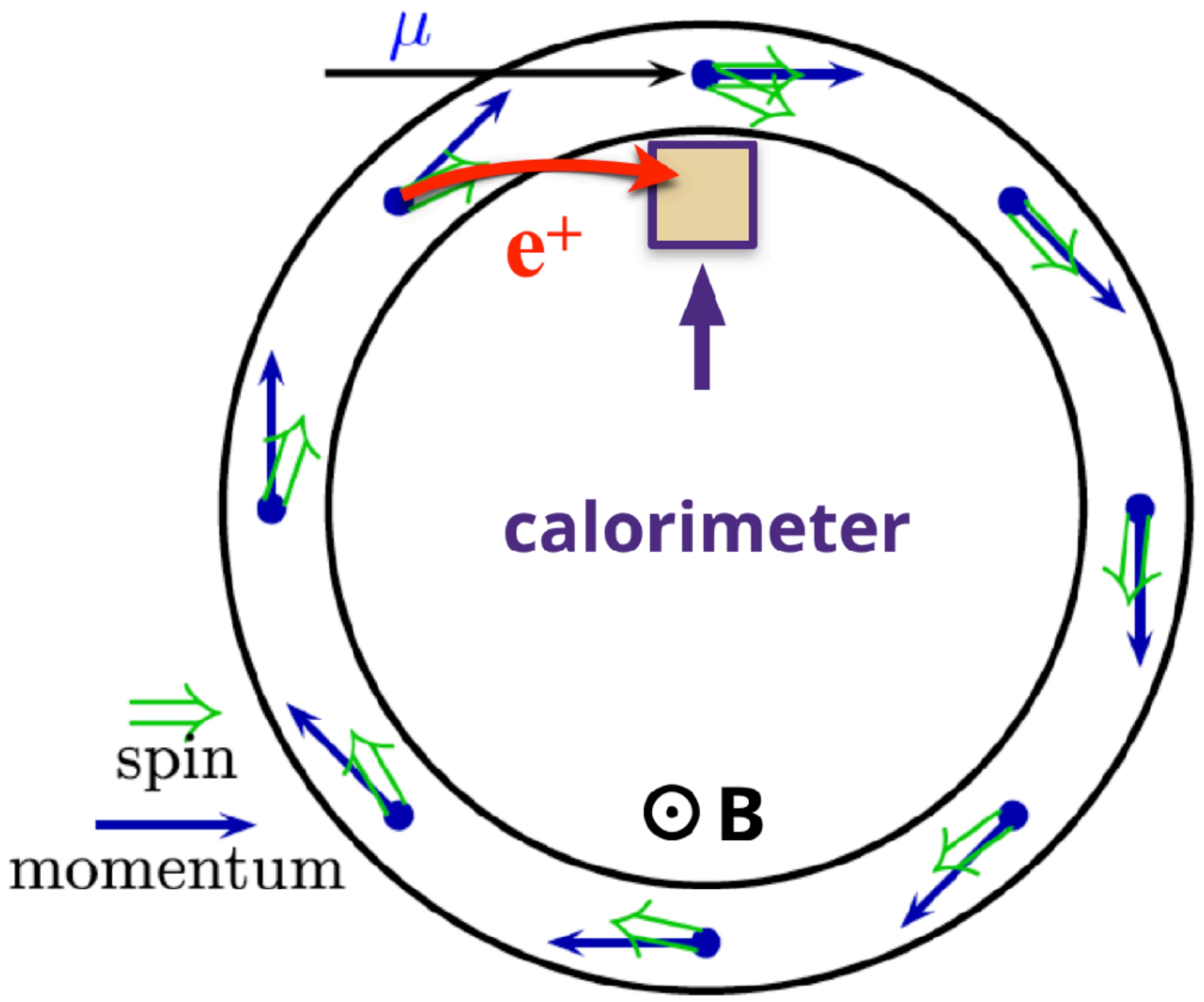
measure difference in frequency precisely

$$\omega_a = a_\mu \frac{eB}{m}$$

homogenous field and precise field measurement

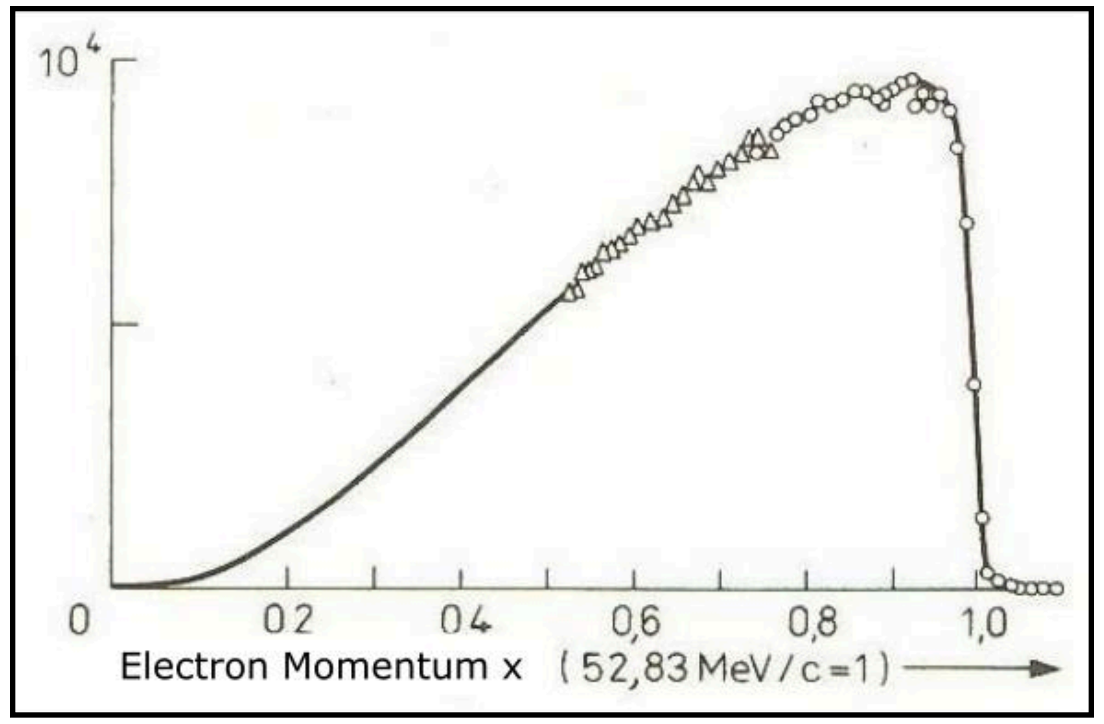
Modulation of energy spectrum vs g-2 phase

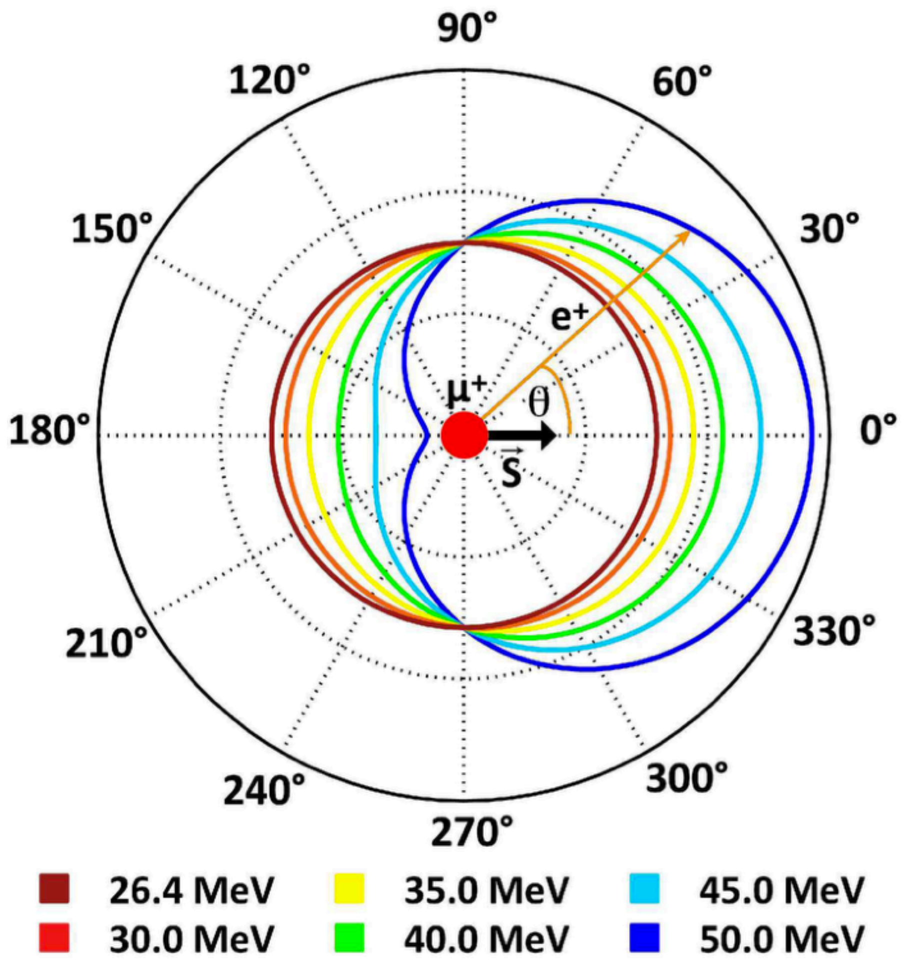
$$\omega_a = a_\mu \frac{eB}{m}$$



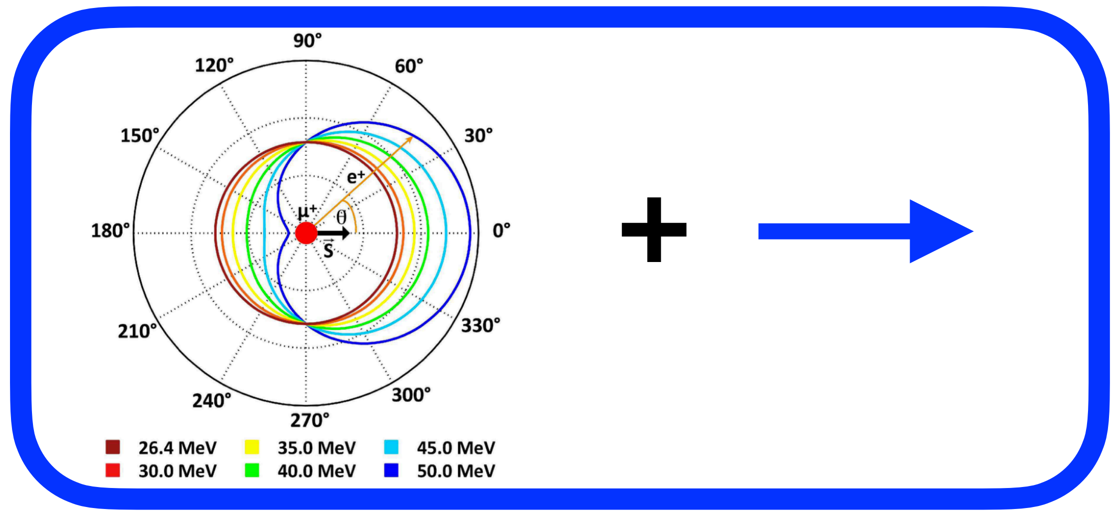
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

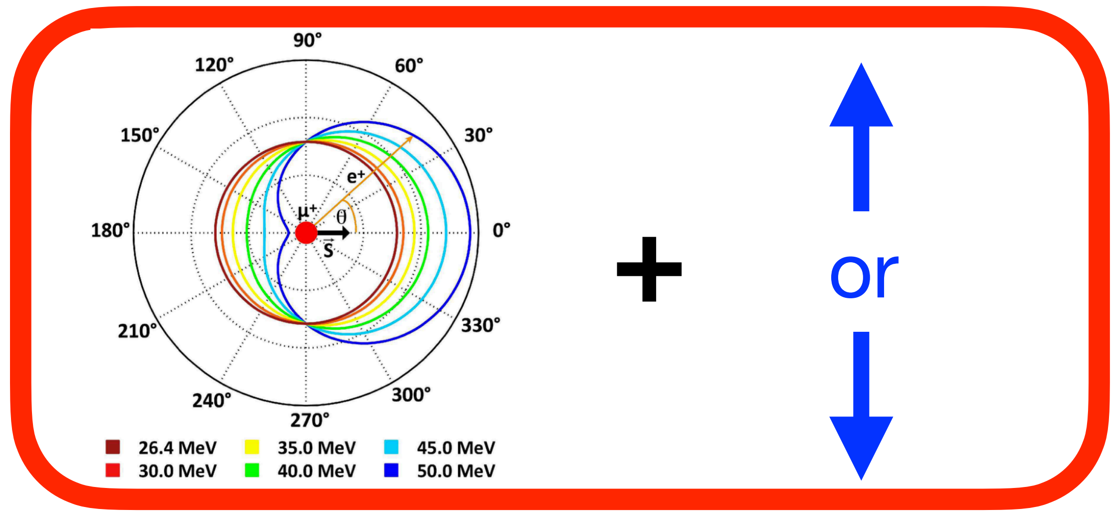
Parity violation in weak decay!

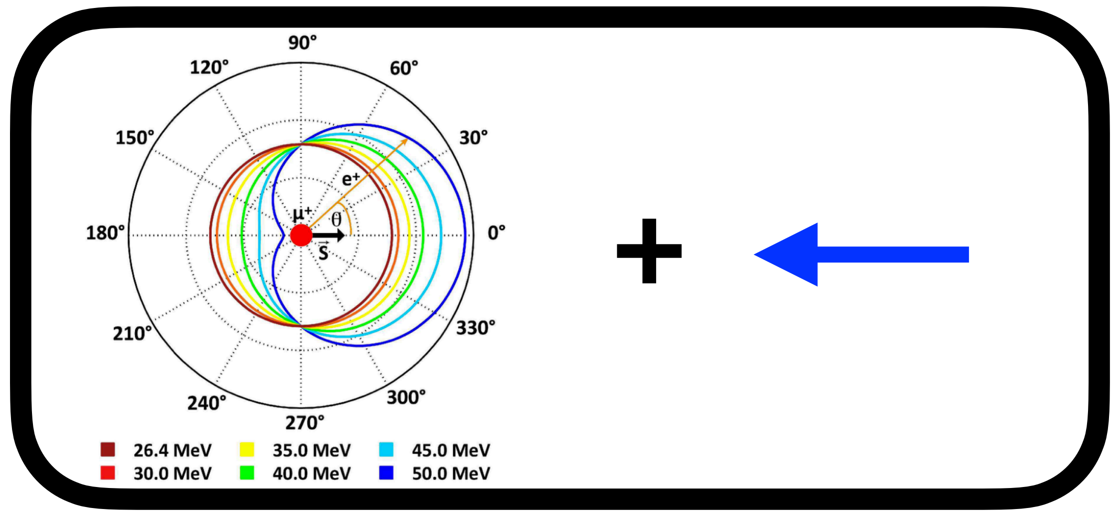


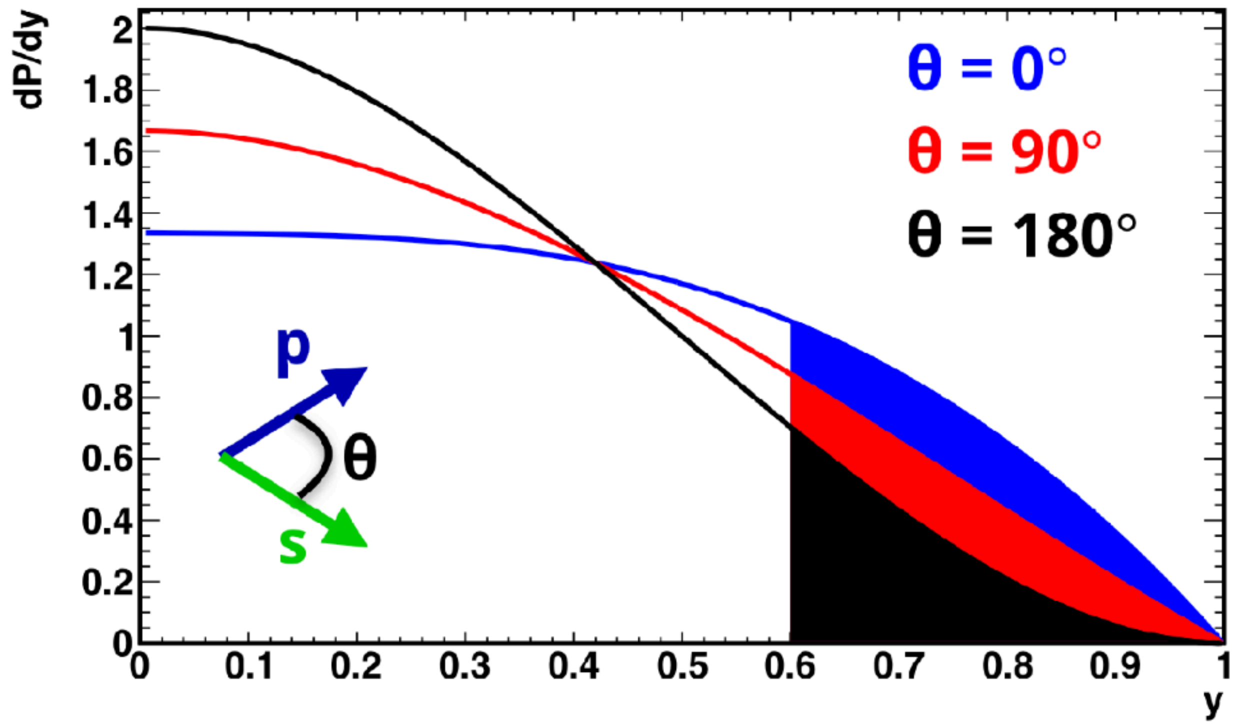


High energy positron follows muon spin! (rest frame)



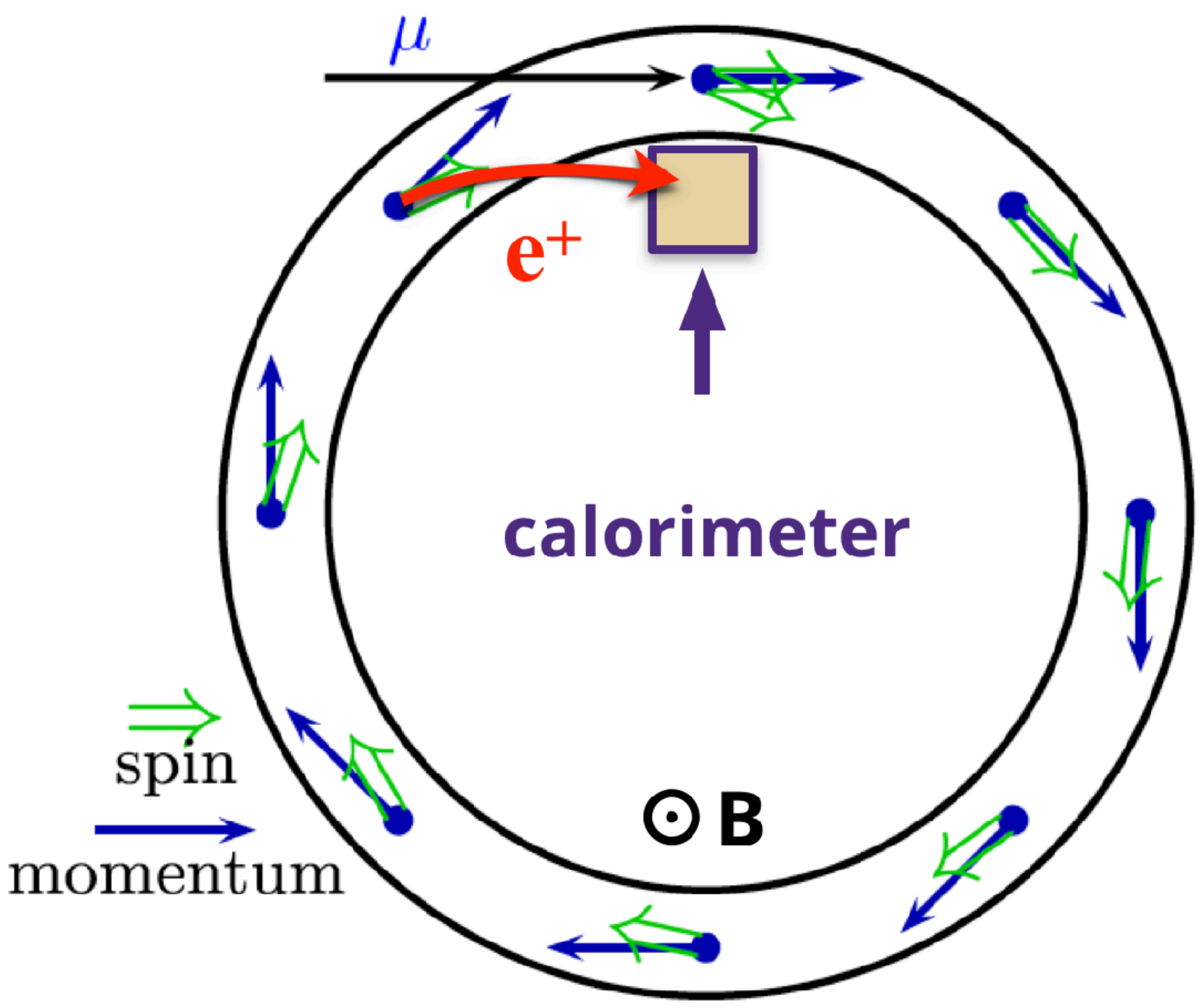


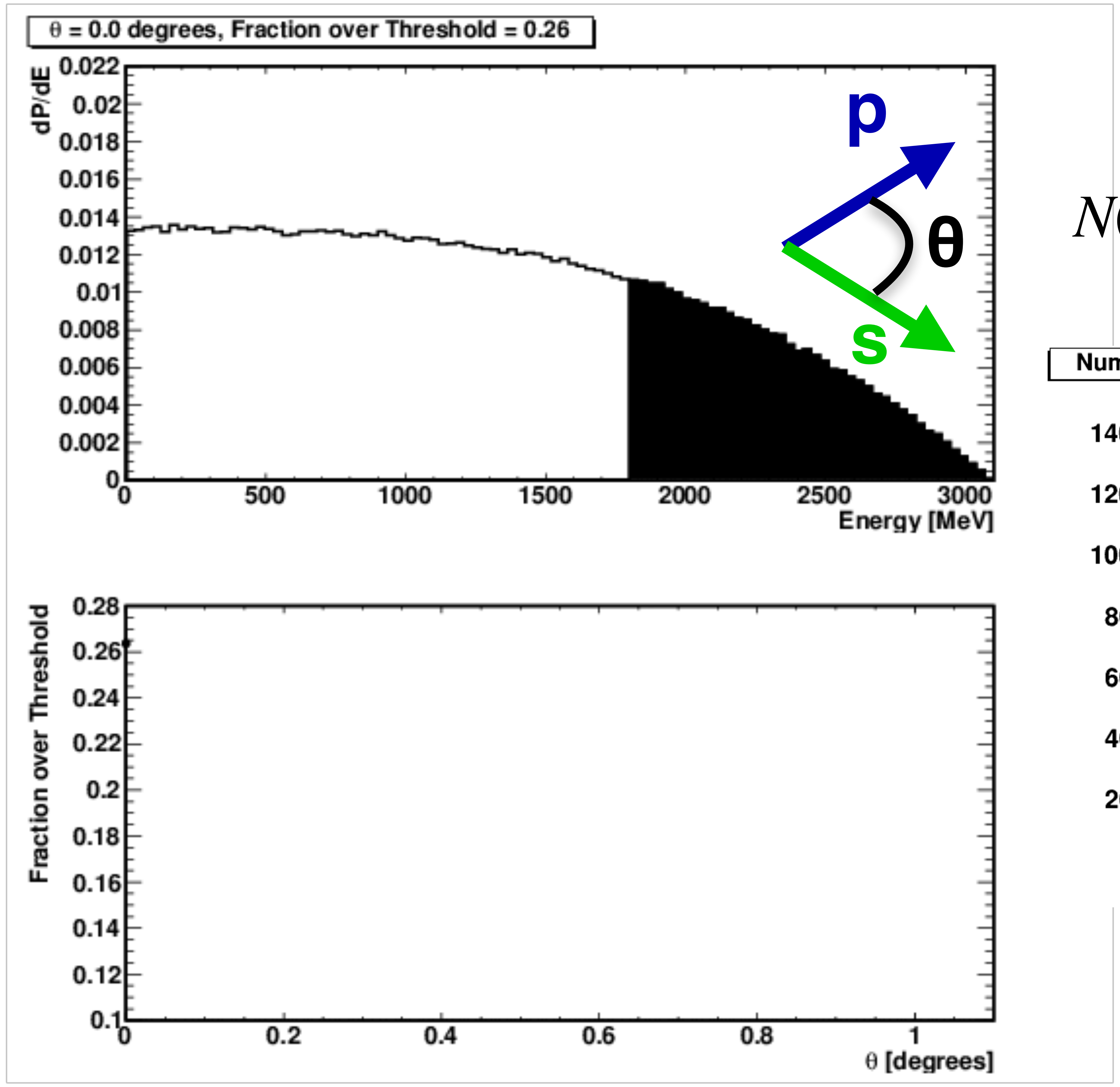




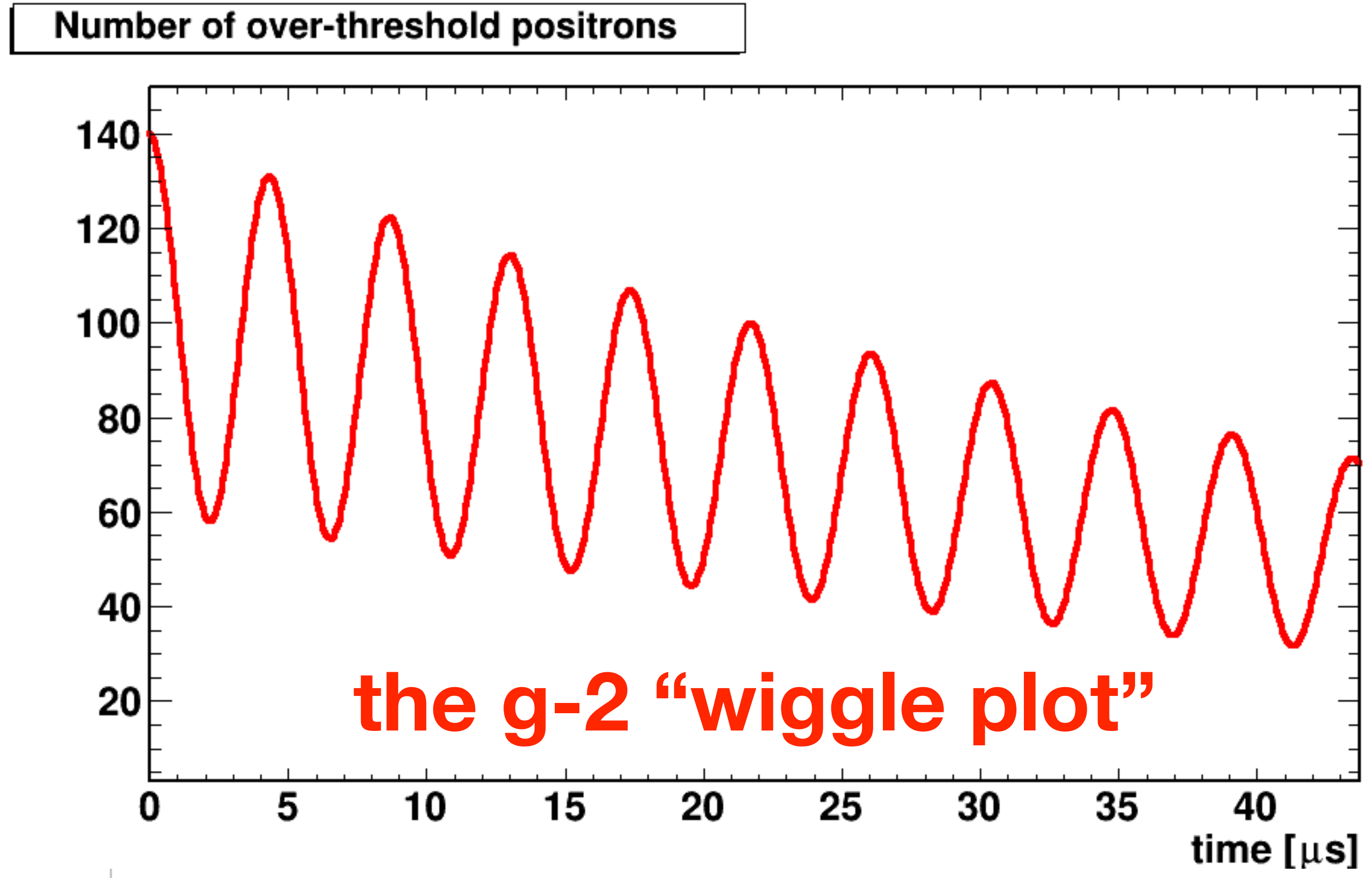
Frequency extraction: fitting the modulation

$$\boxed{\omega_a = a_\mu \frac{eB}{m}}$$





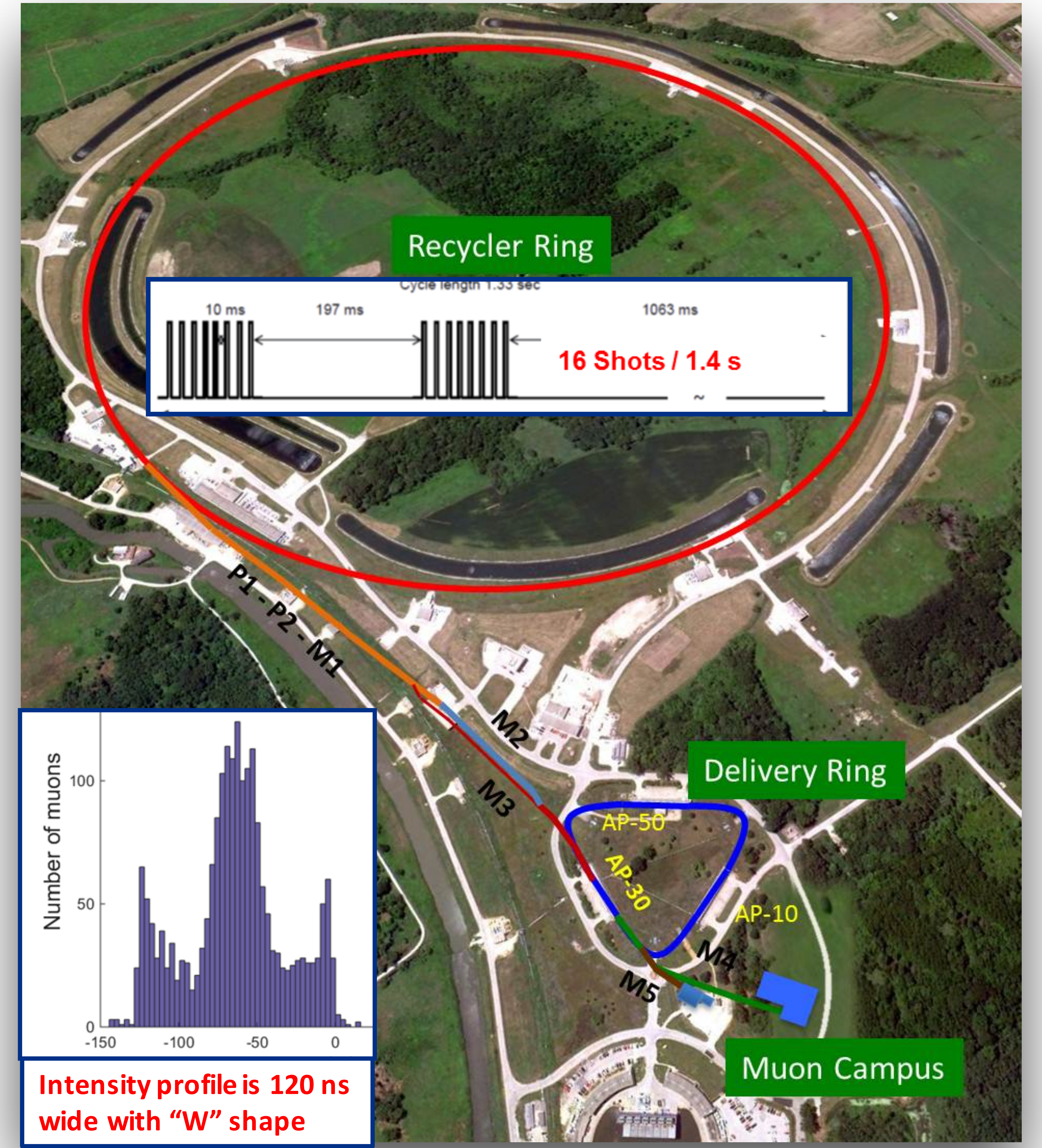
$$N(t) = N_0 e^{-t/\tau}\left[1 + A_\mu \cos(\omega_a t + \phi)\right]$$



the g-2 “wiggle plot”

Polarized muon beam from FNAL accelerator

- 8 GeV p batches into Recycler Ring
- Each batch split into 4 bunches of 10^{12} protons
- Extract 1 by 1 to hit target
- Long beam line to collect $\pi^+ \rightarrow \mu^+$
- p/π/μ enter Delivery Ring
  - π decay away, μ extracted, p aborted
- 3.1 GeV/c μ^+ enter storage ring (~10^6 μ^+/bunch, 1-2% stored)
- Goal to collect ~ 21x BNL (1.6×10^{11} detected positrons)

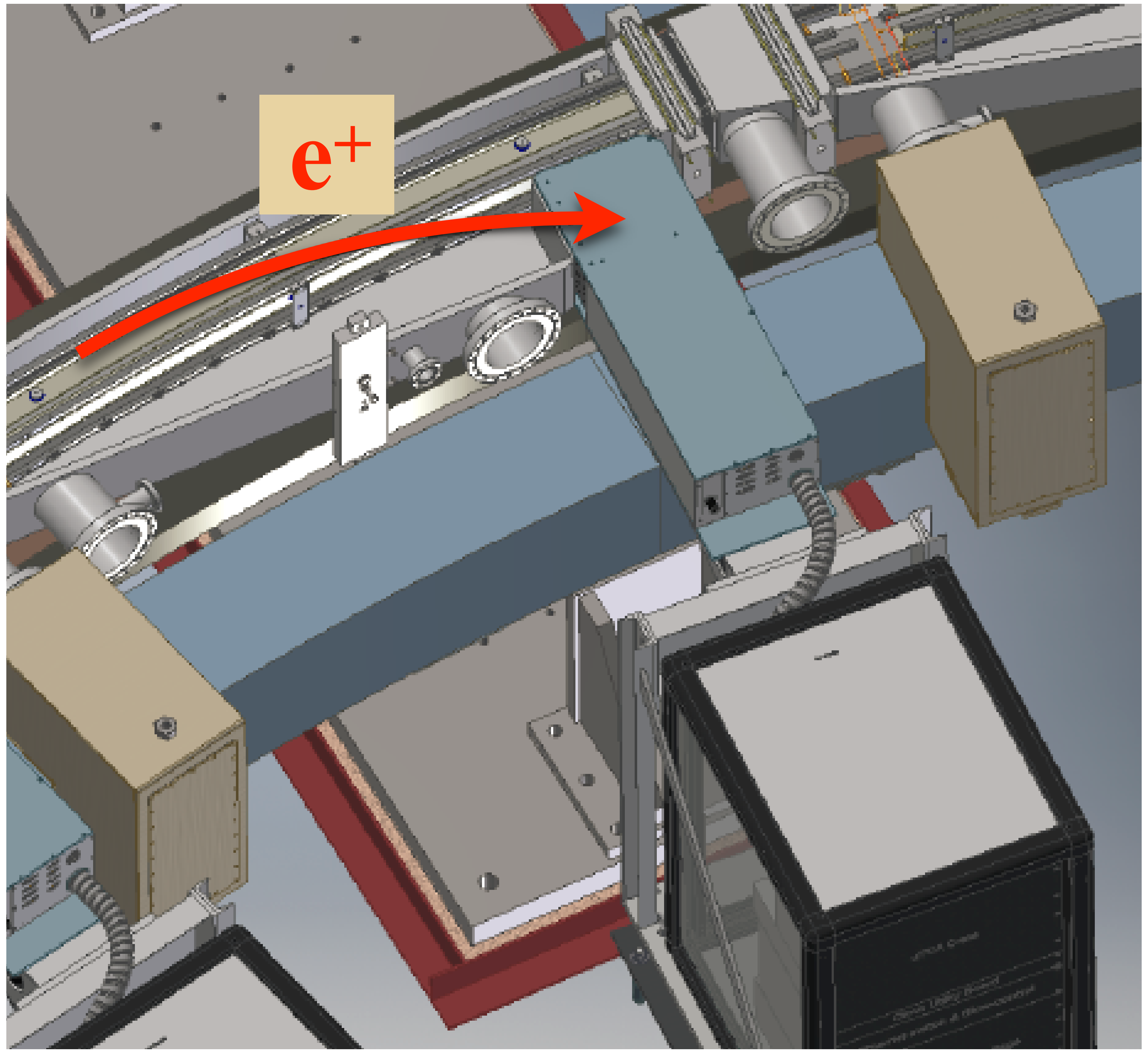


Intensity profile is 120 ns wide with "W" shape

The Muon Campus and MC1

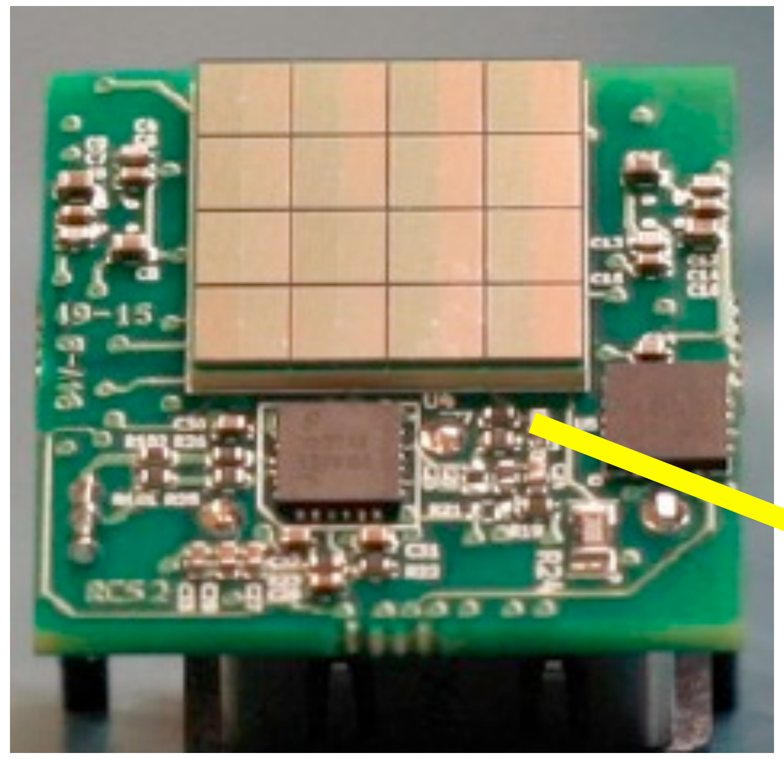
Muon beam

Calorimeters measure positron time and energy

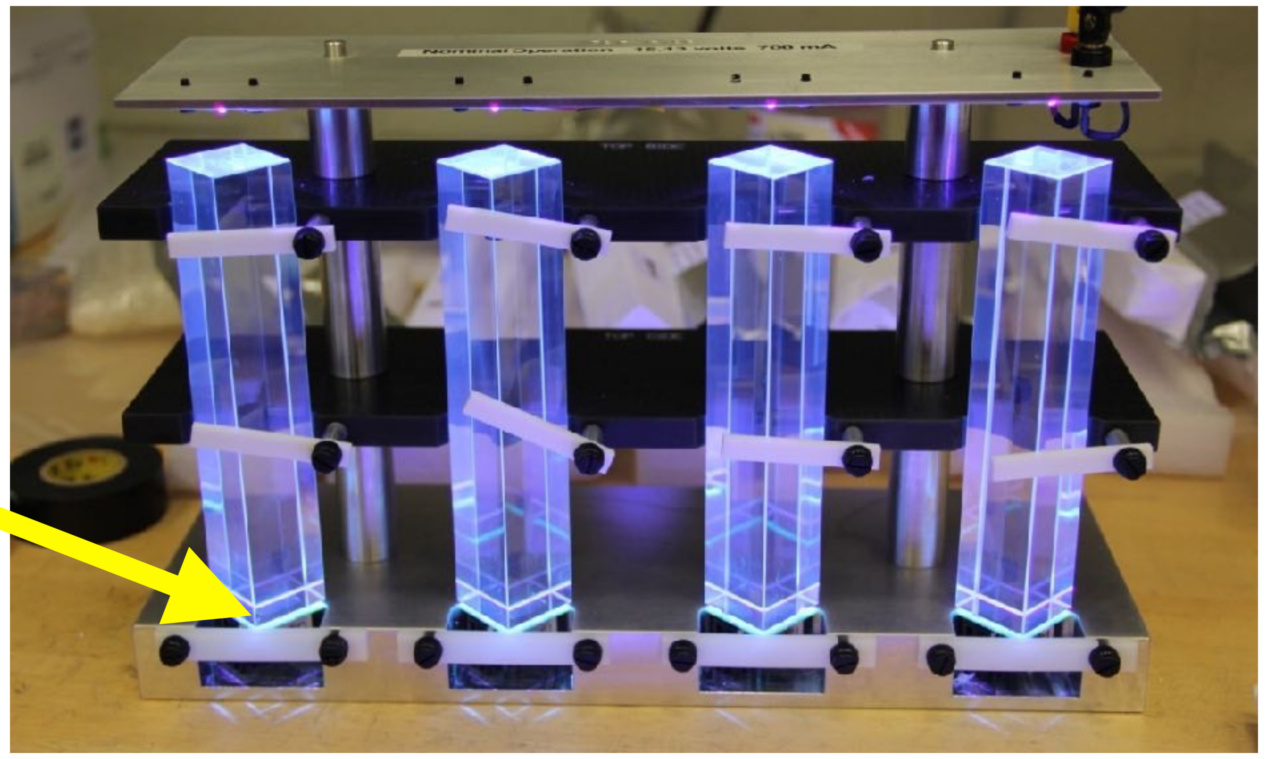


Decay positron curving in and striking a calorimeter

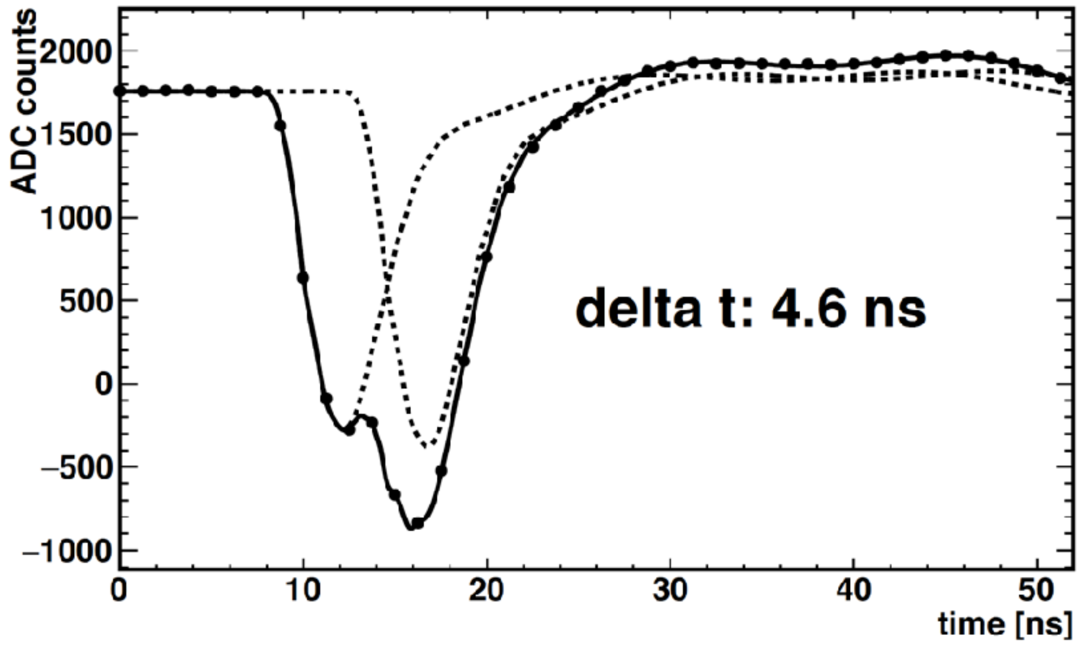
SiPM



PbF$_2$

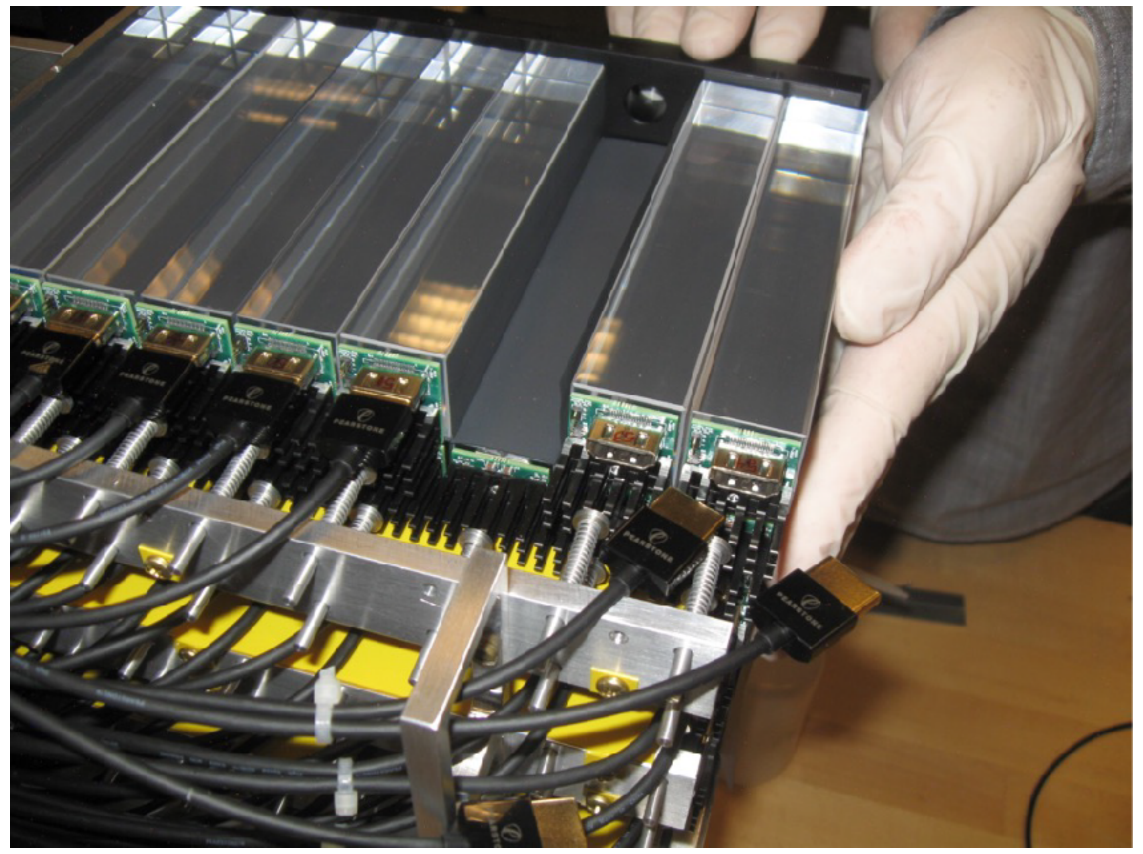


pileup separation



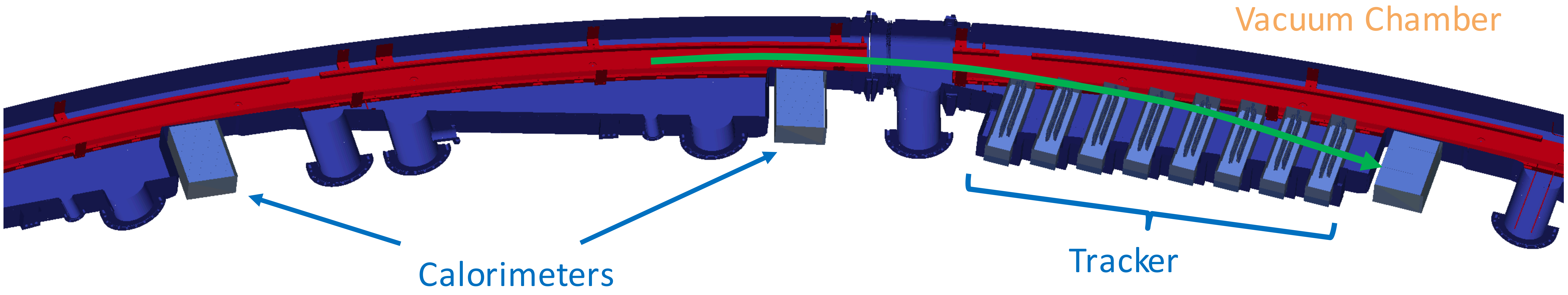
PMT-like signal, B-field operation, 100% separation > 2.5 ns

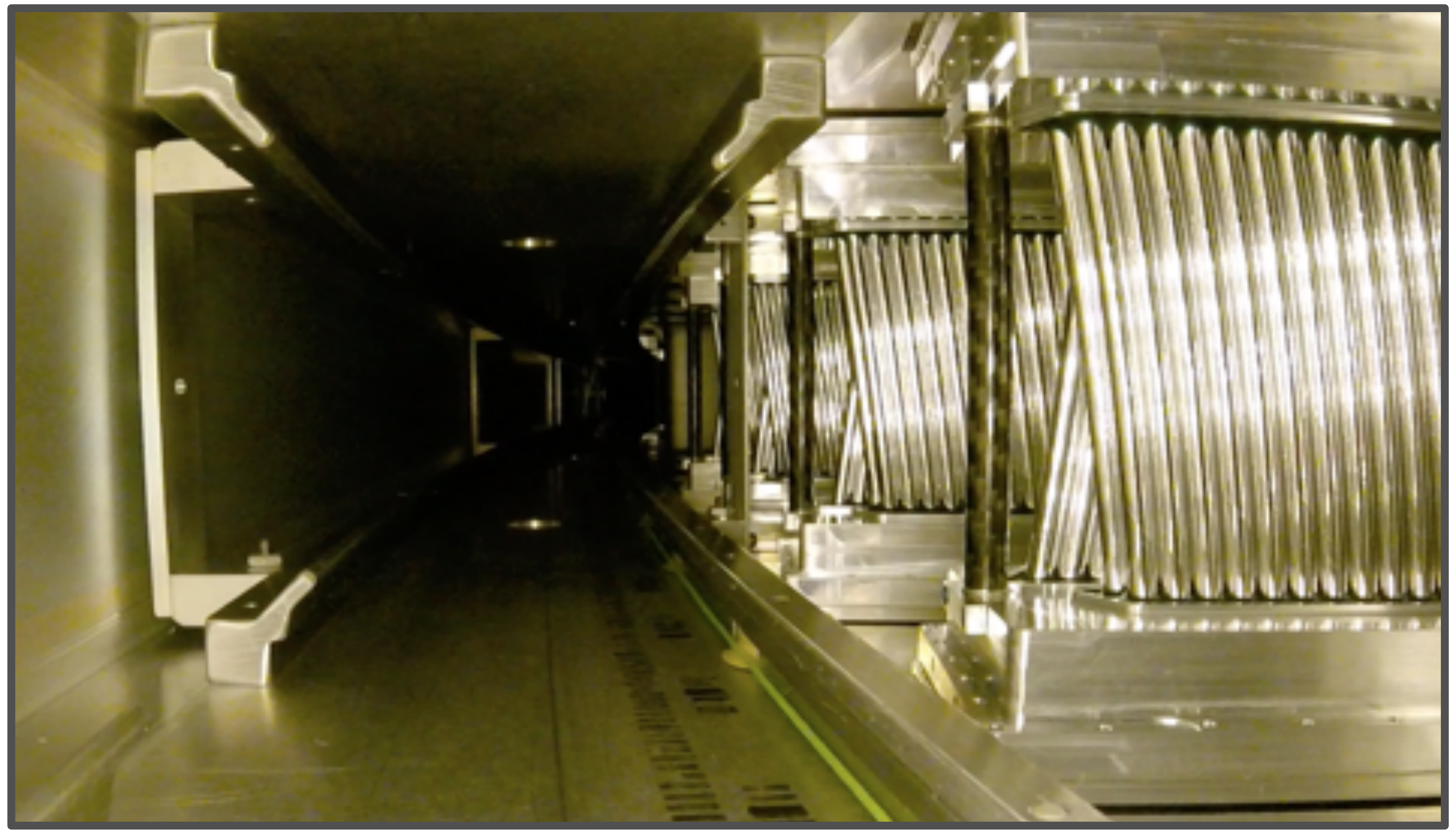
Opened up calorimeter

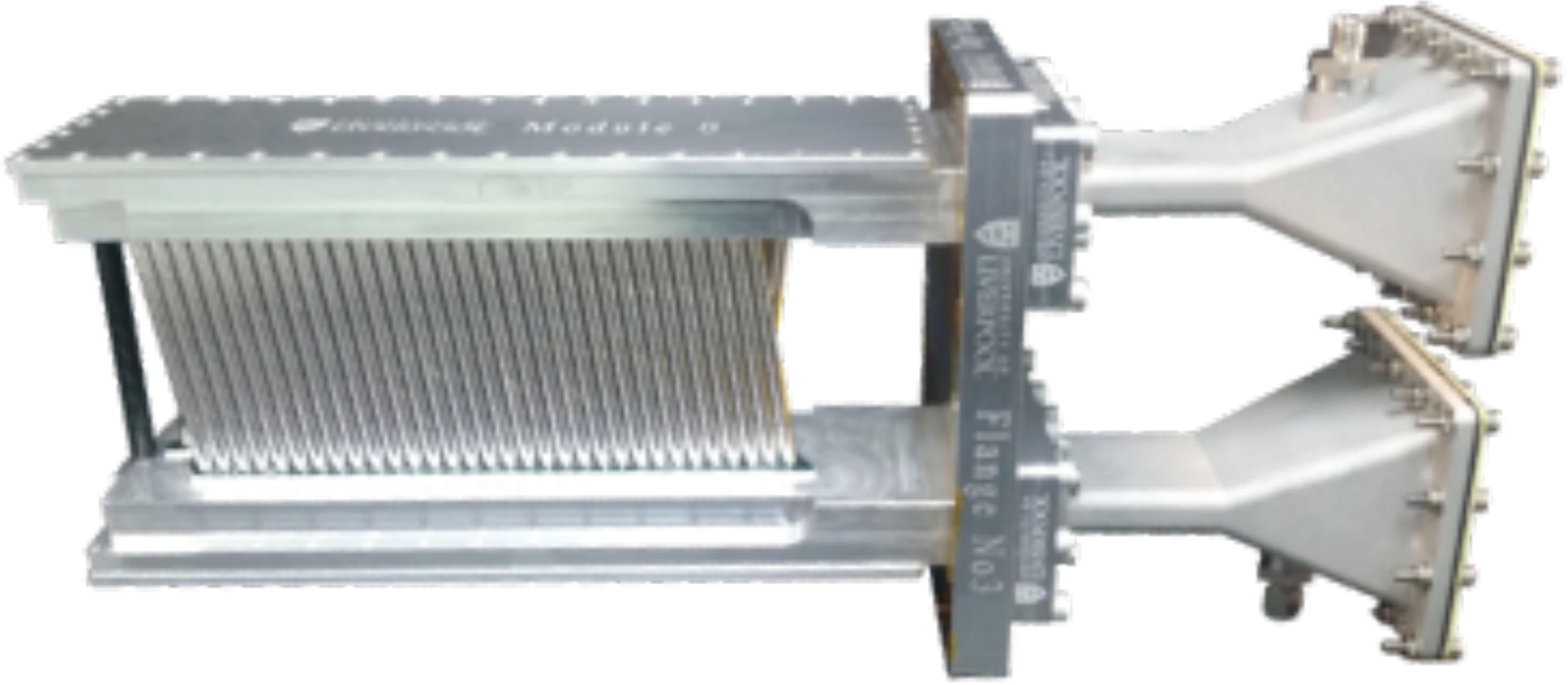


Stacking crystals

Trackers extrapolate e^+ to muon decay position

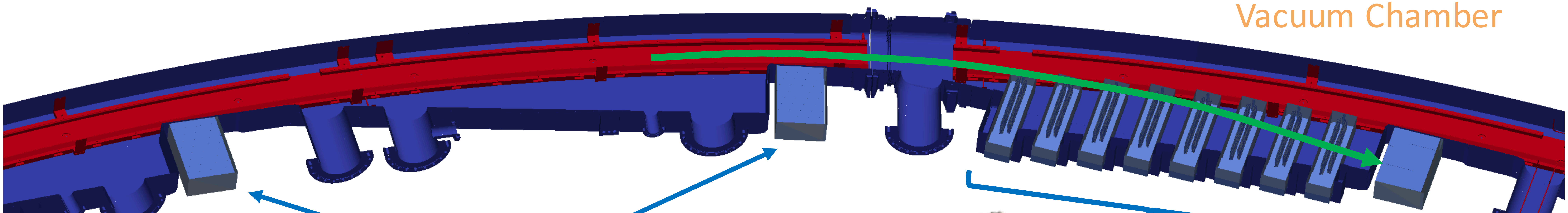


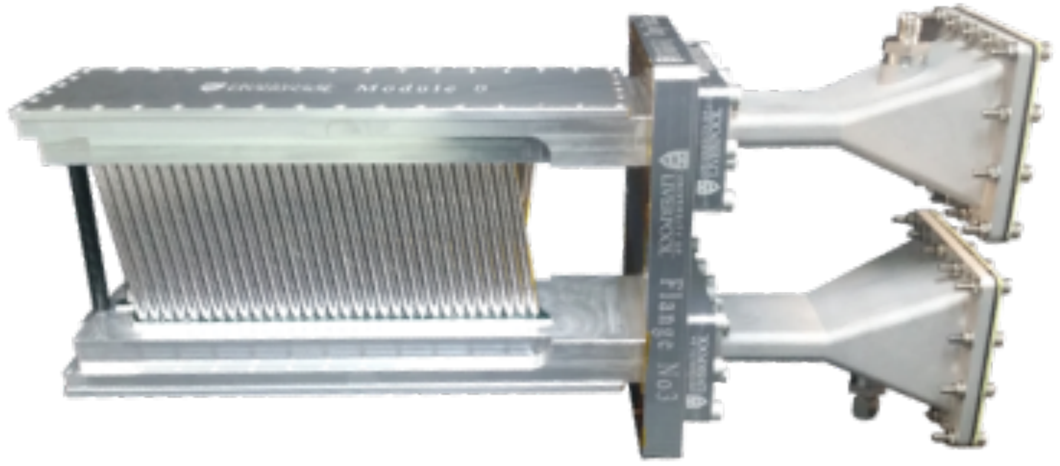


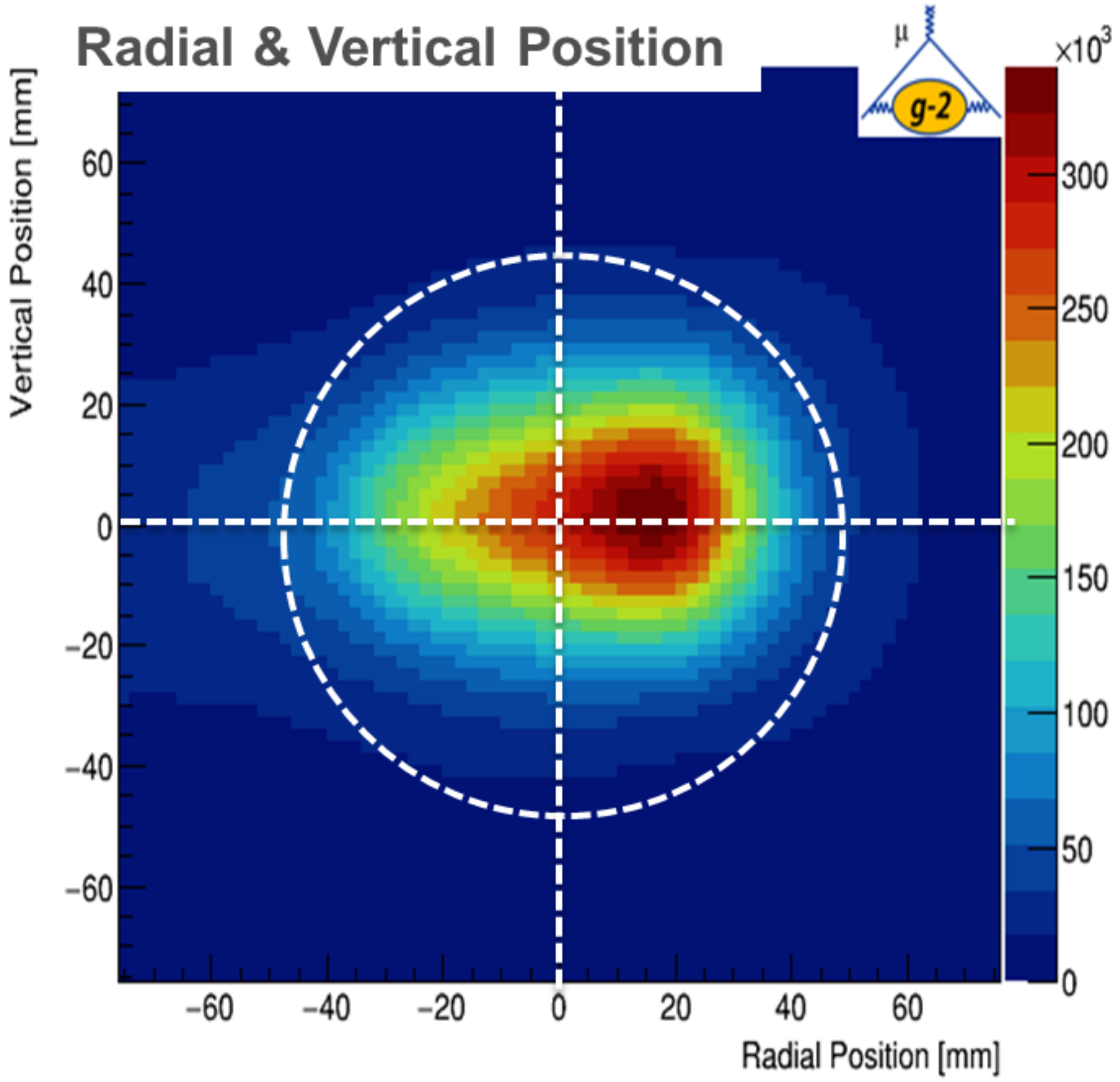


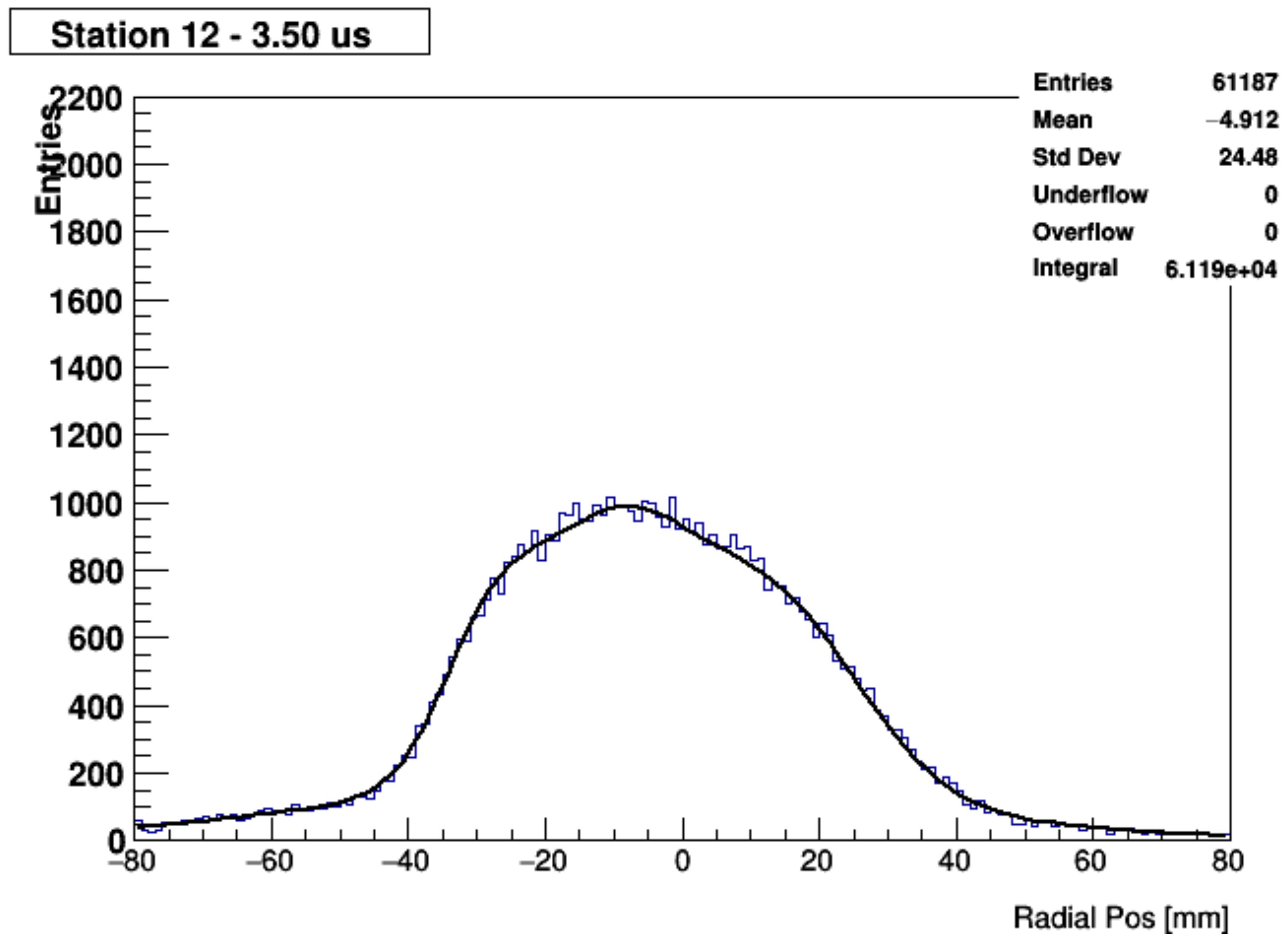
The SWISS KNIFE for g-2 experiment

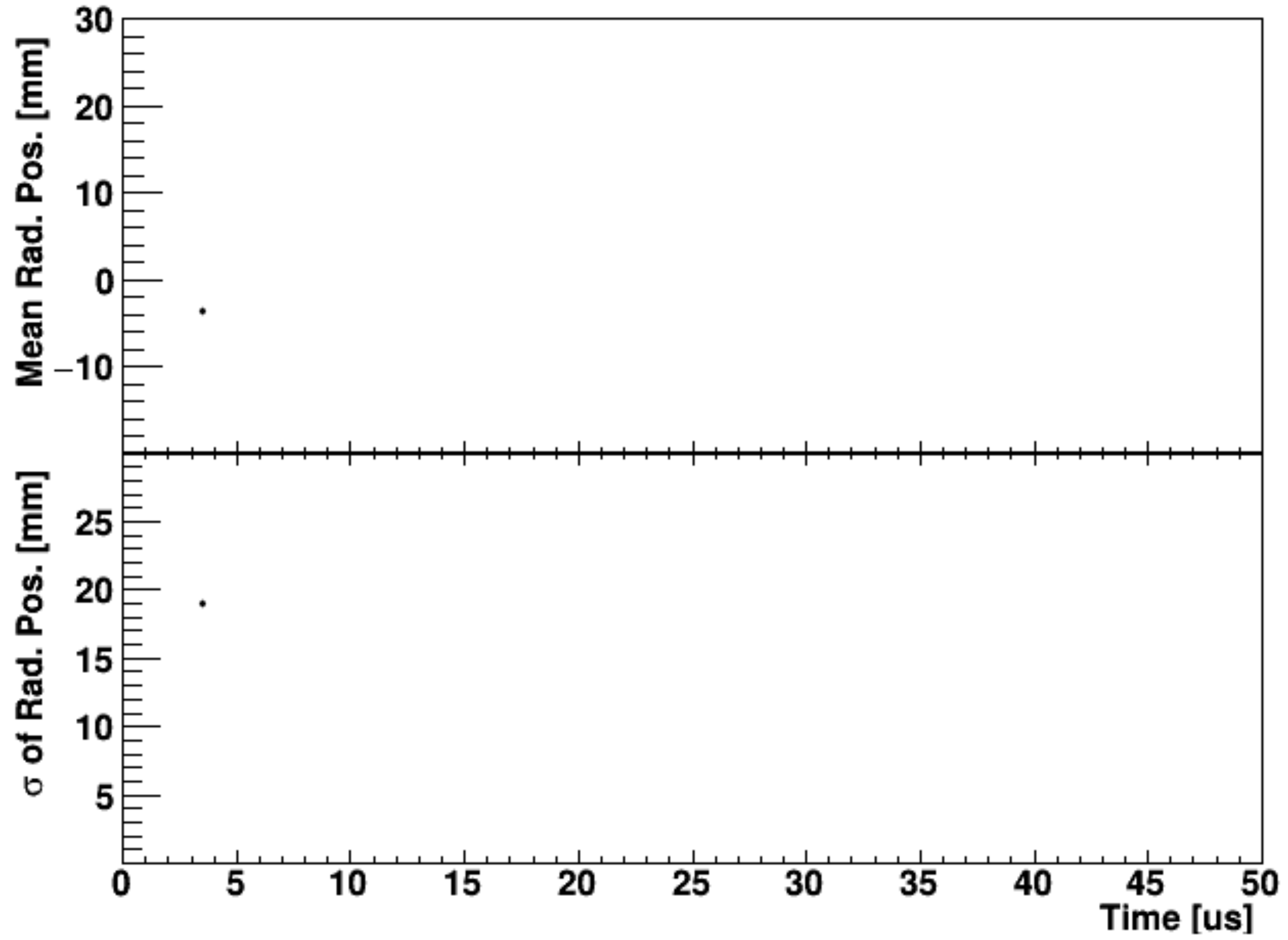
Trackers extrapolate e^+ to muon decay position





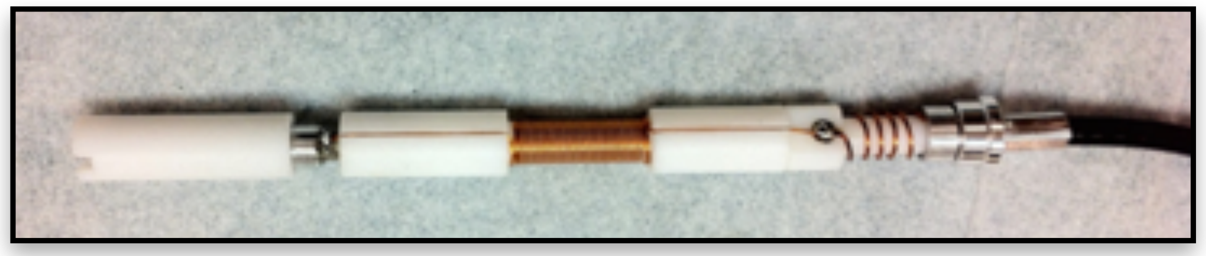






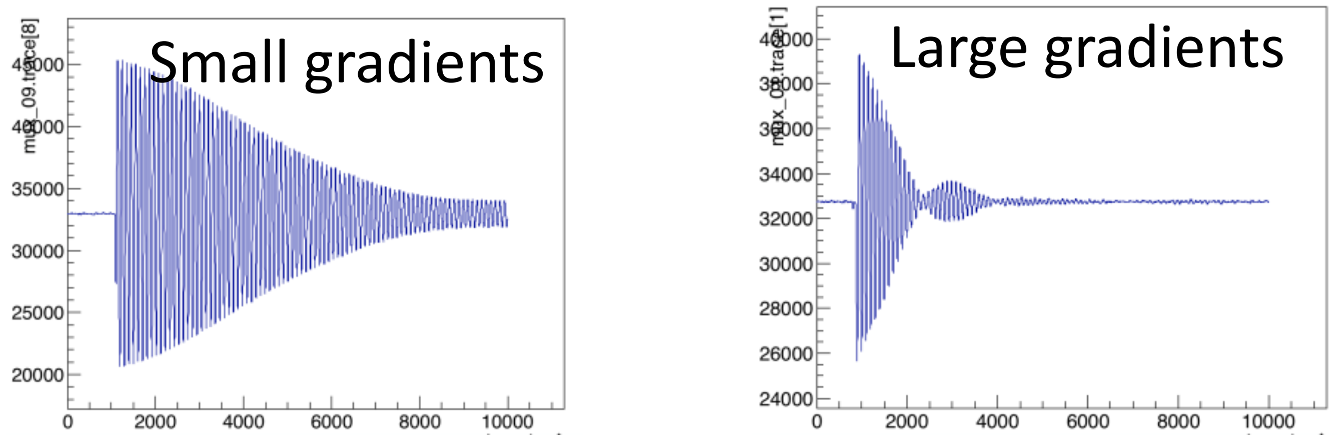
NMR probes measure magnetic fields

A 25-element **pNMR Trolley** was used to map the field during rough shimming adjustments (see video)

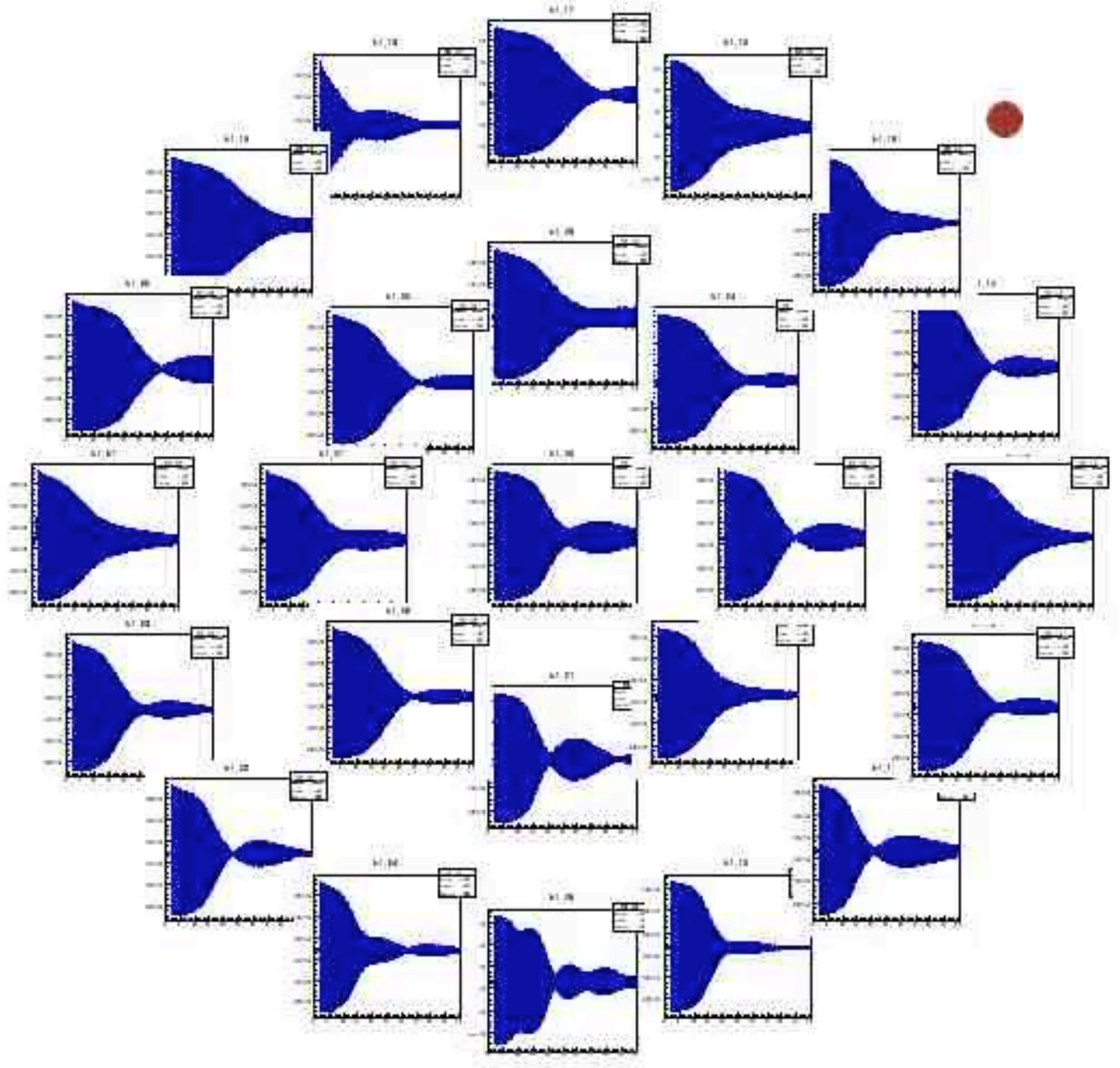


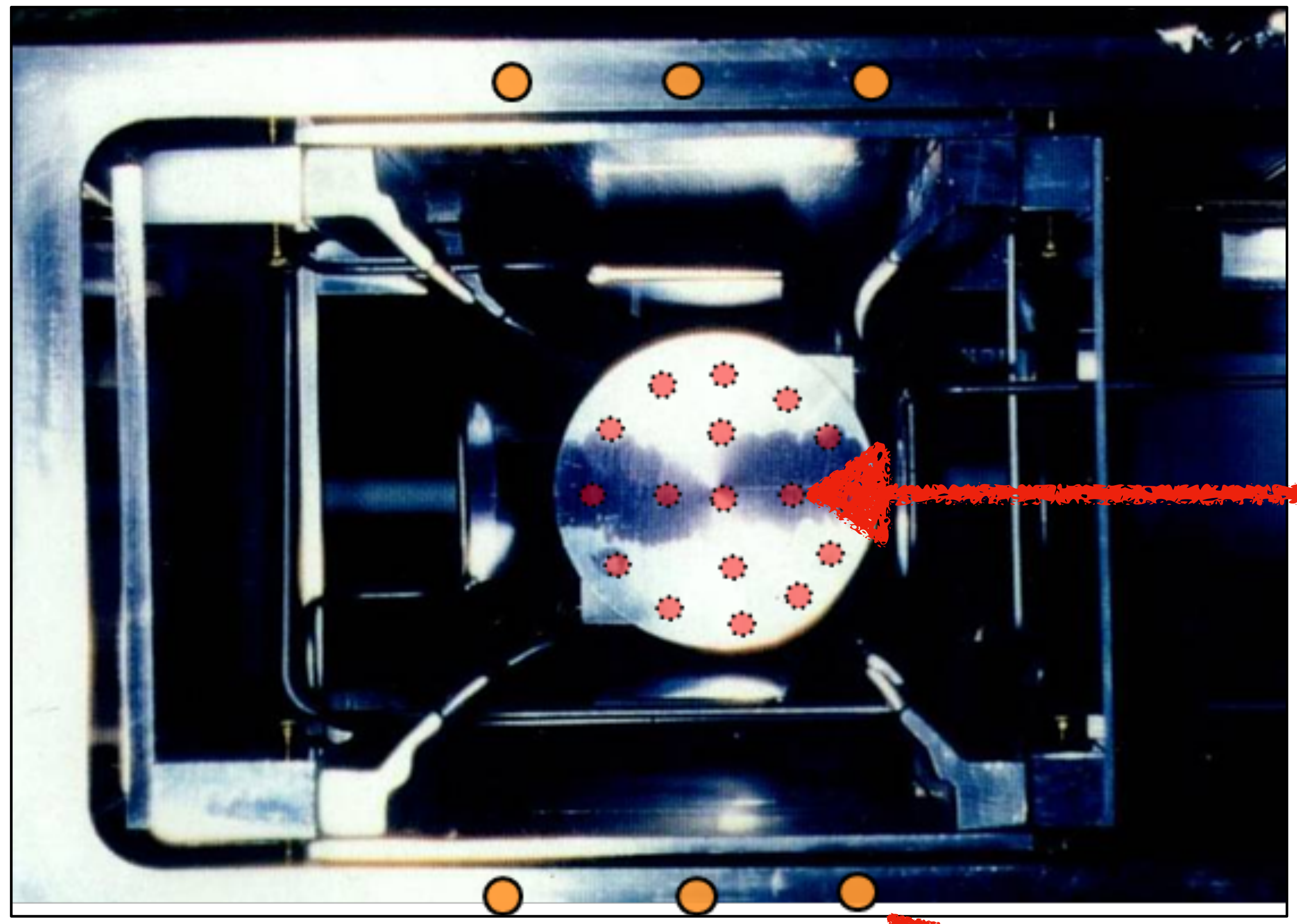
A 17-element **pNMR Trolley** maps the field IN VACUUM during running periods

(FID) Waveforms with ~10 ppb resolution

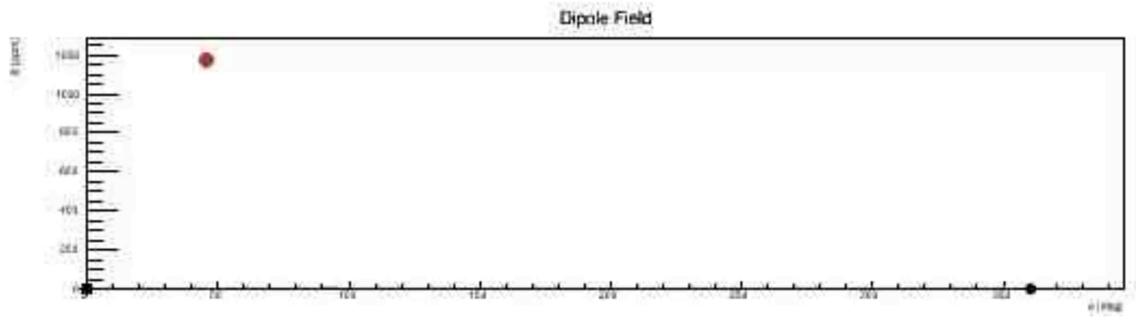


Shimming Trolley Probe Matrix

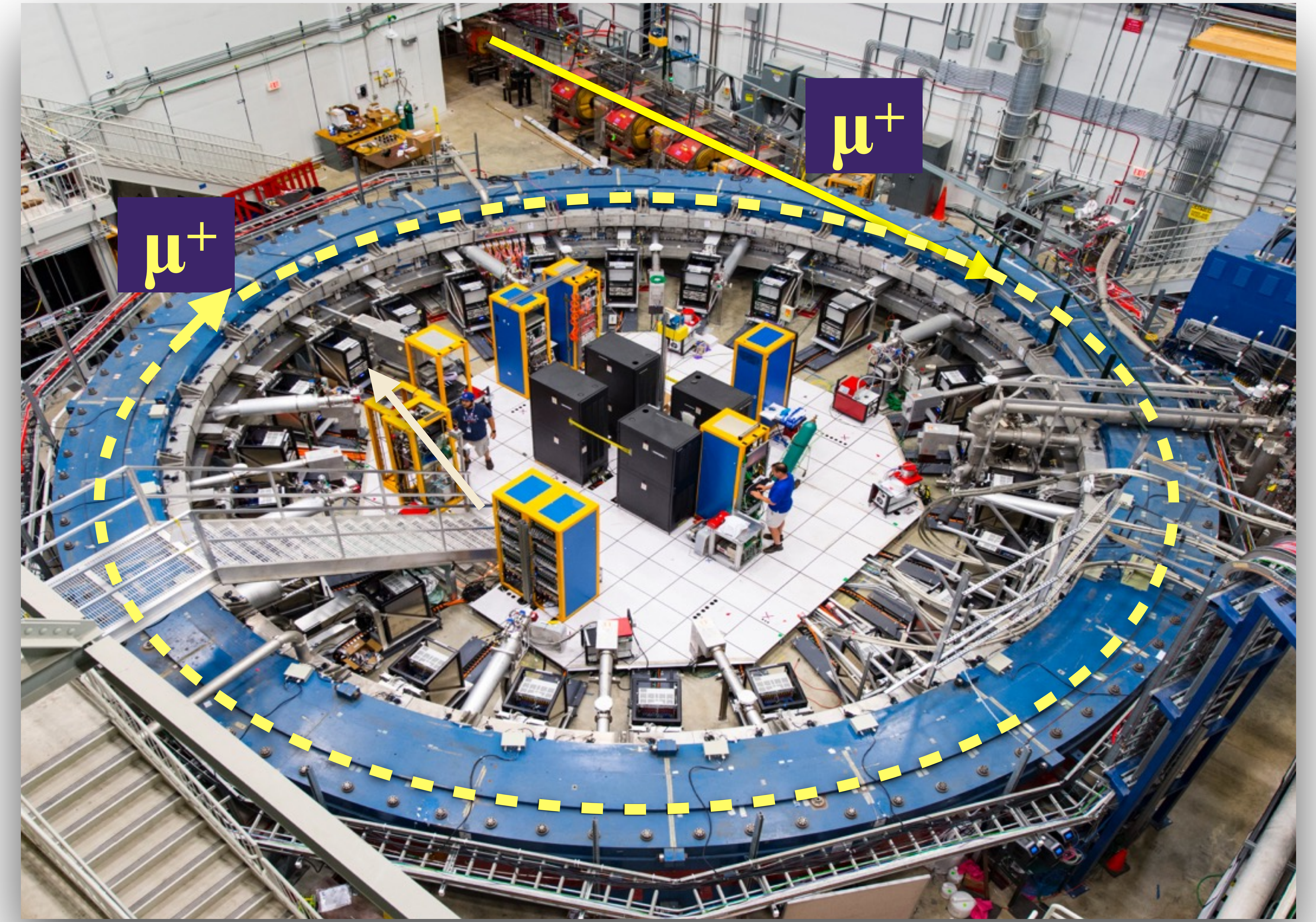




378 **Fixed Probes** above and below the vacuum chamber measure the field continuously throughout the experiment

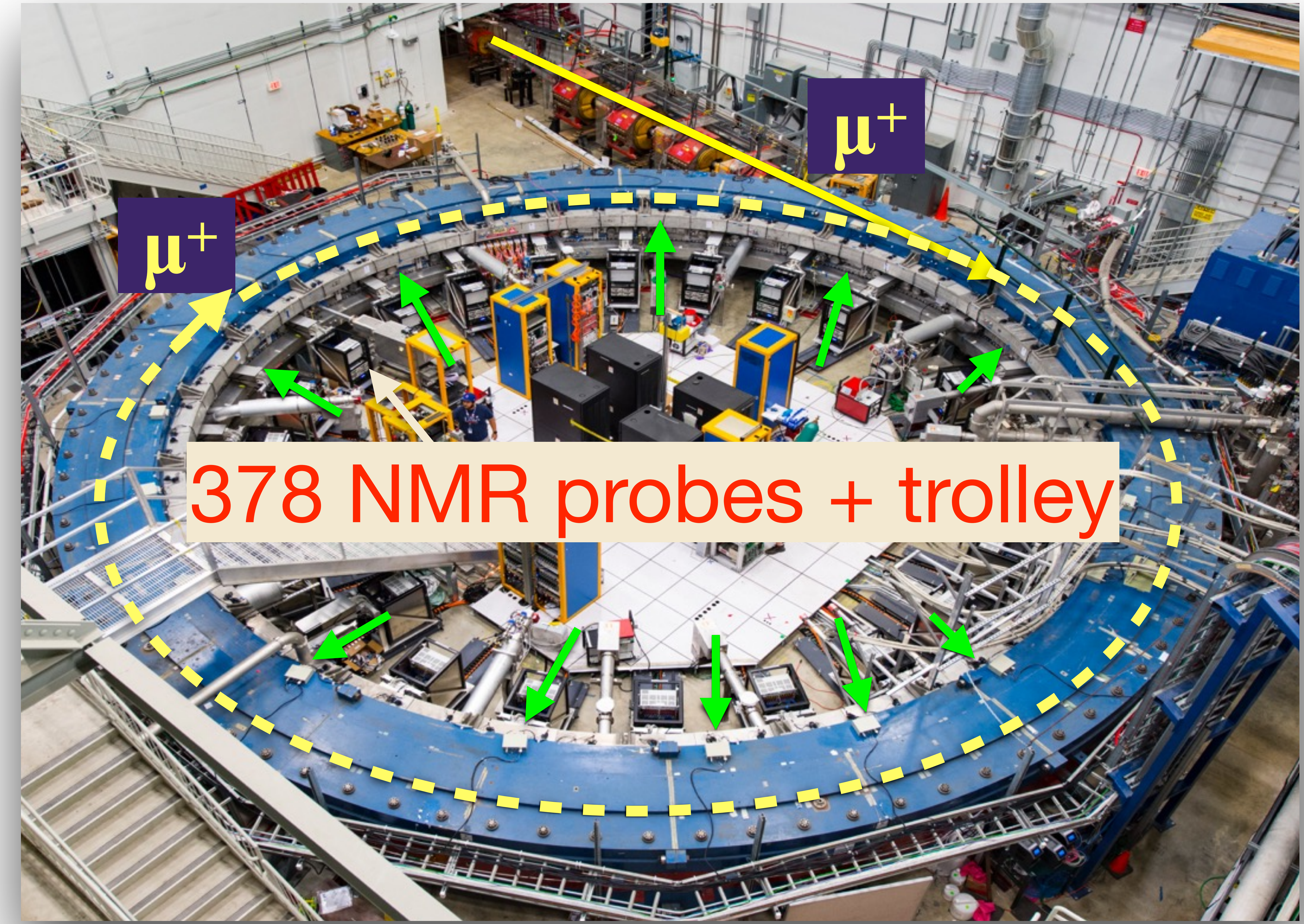


Combining 3 keys together

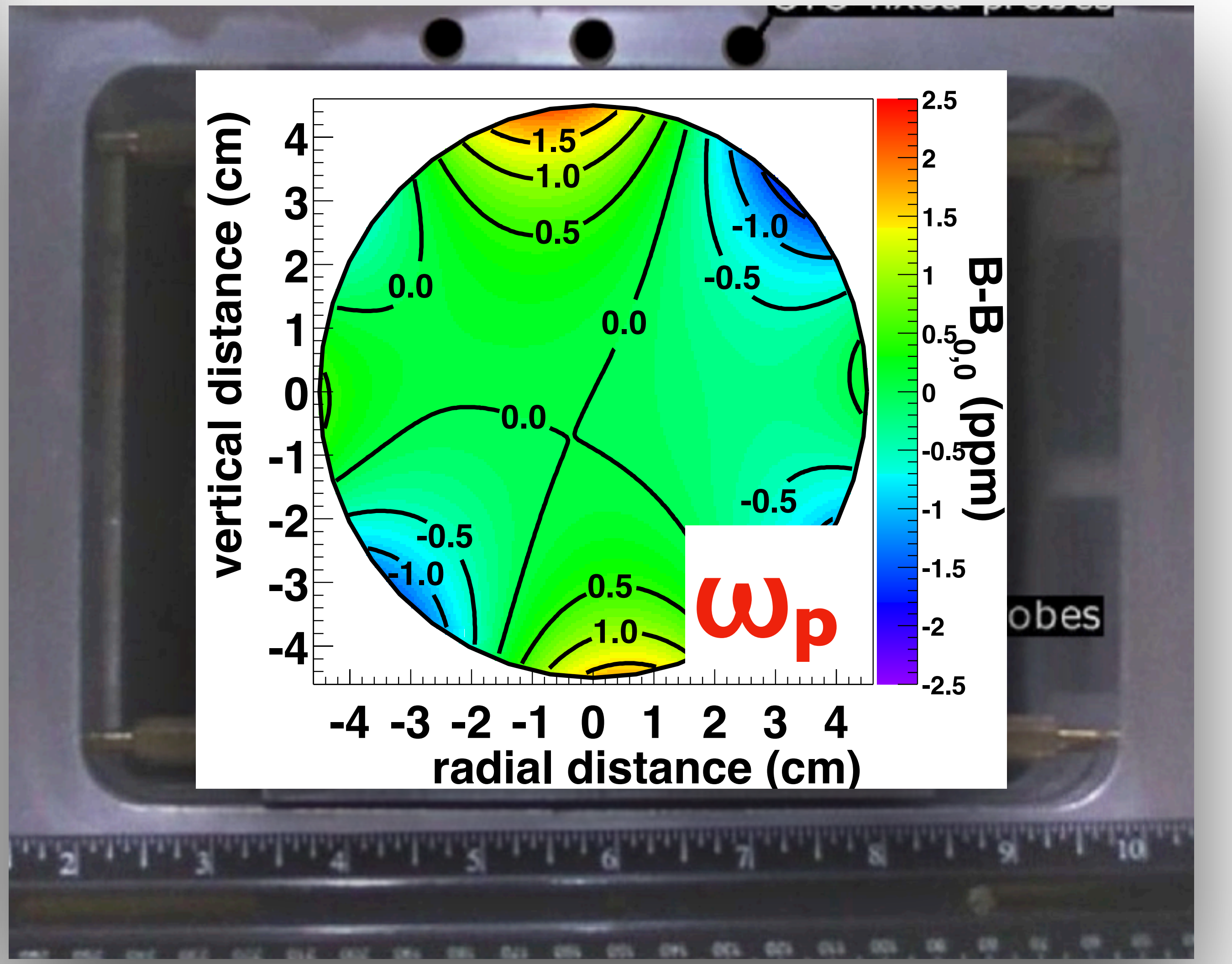


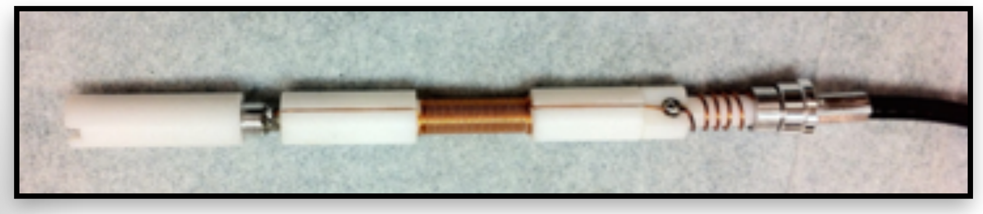
1. Spin polarized muons from Fermilab beamline

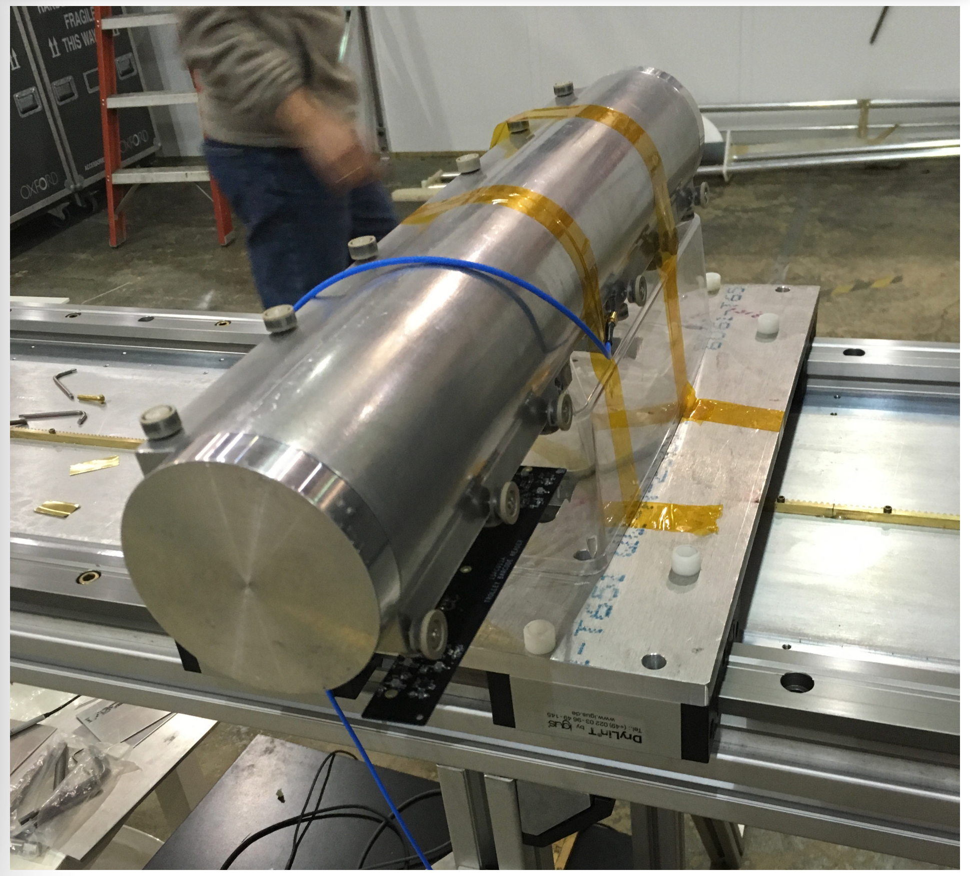
Combining 3 keys together



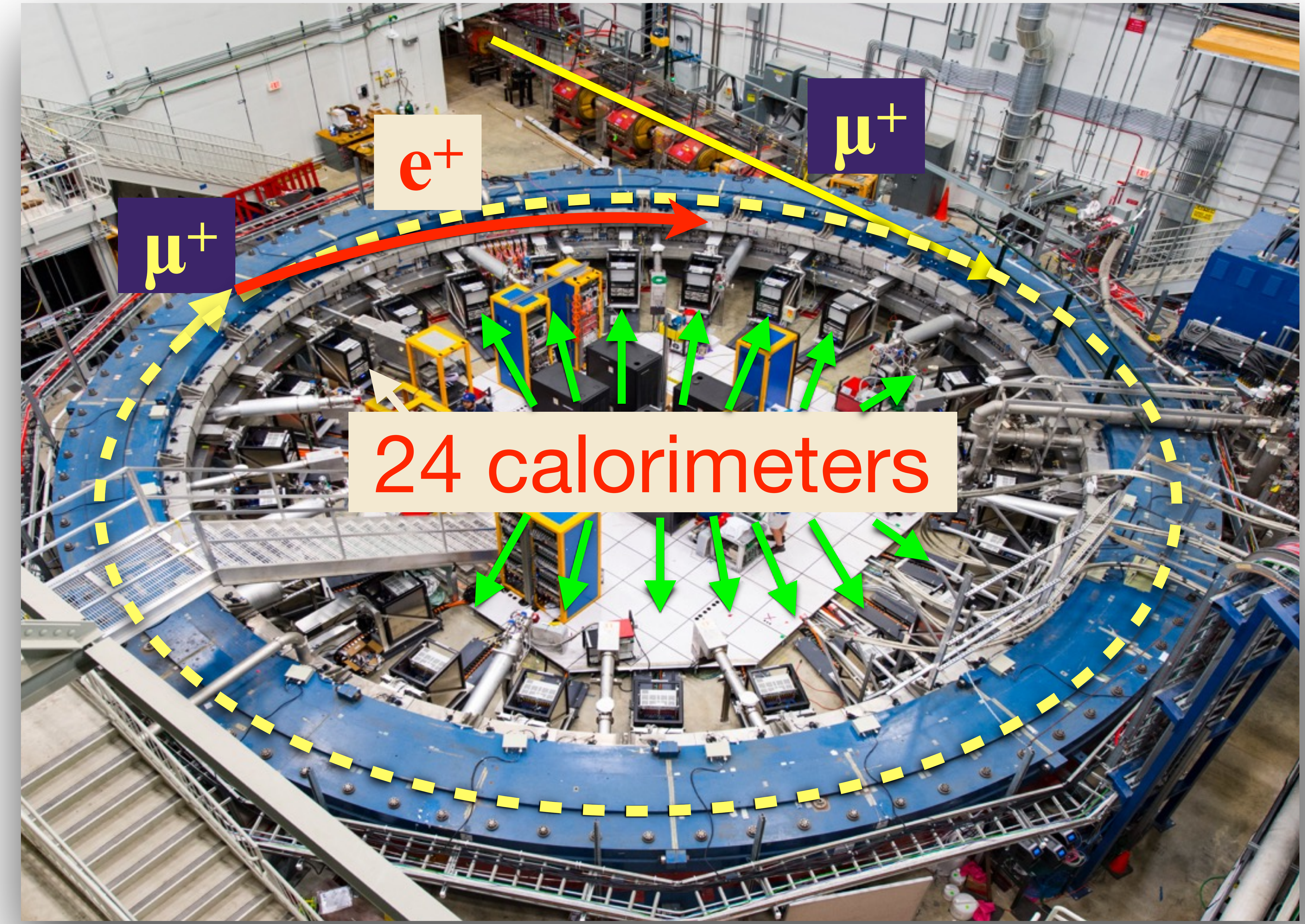
1. Spin polarized muons from Fermilab beamline
2. Magnetic storage ring & NMR probes measuring B-field



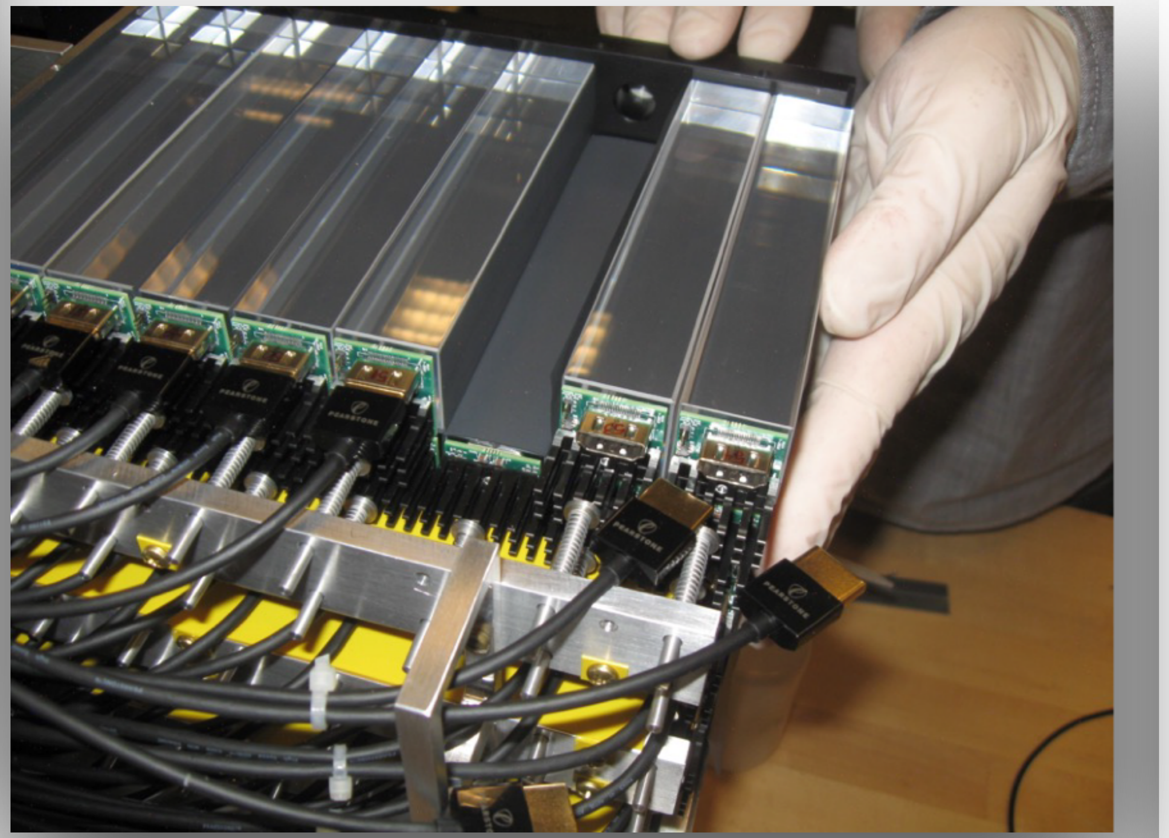


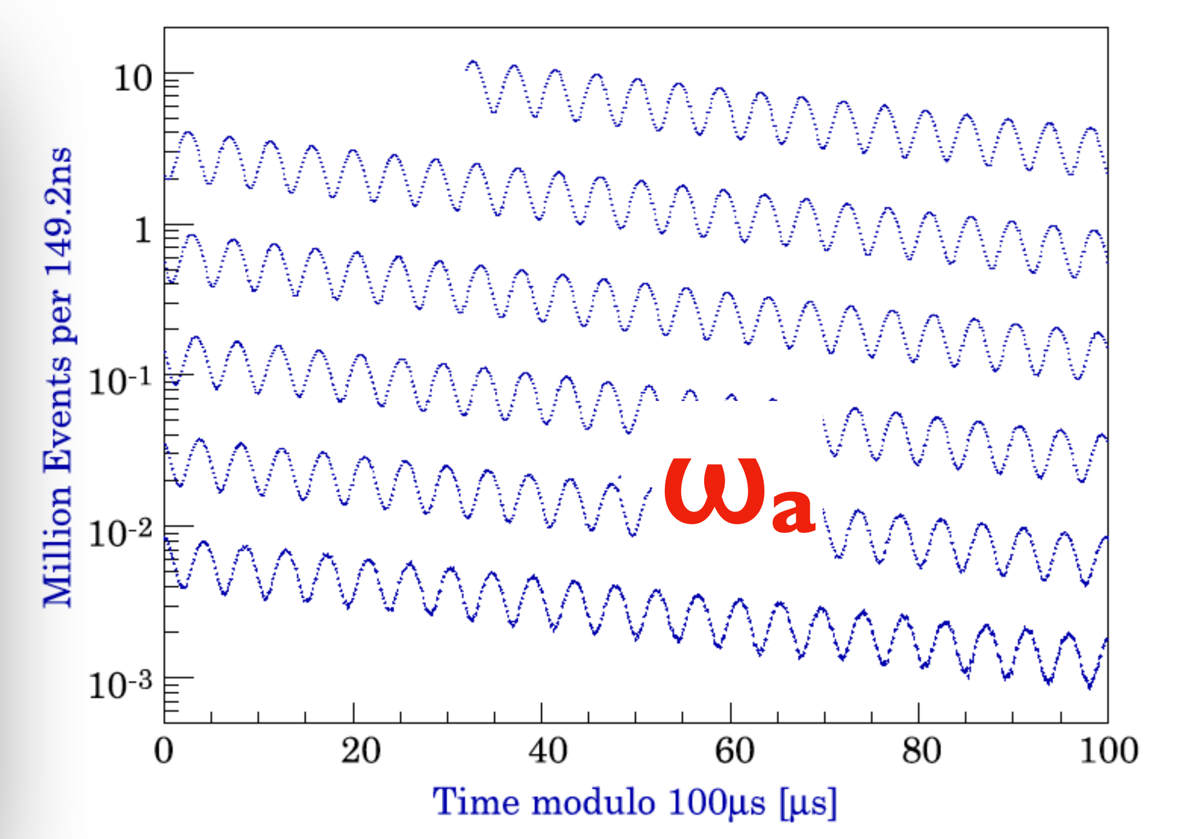


Combining 3 keys together



1. Spin polarized muons from Fermilab beamline
2. Magnetic storage ring & NMR probes measuring B-field
3. Calorimeters measuring positron energy and time





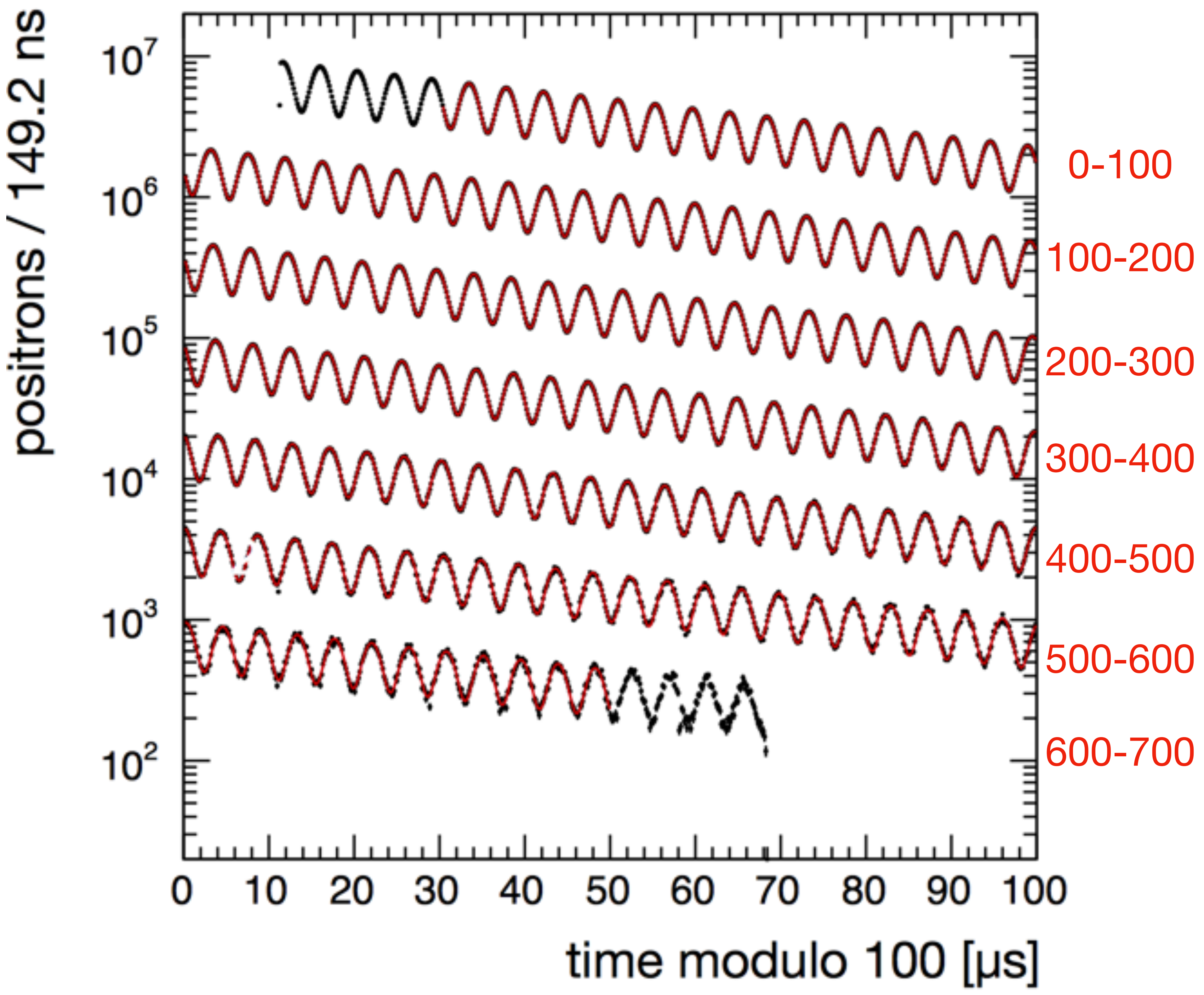
A typical muon precession measurement

$$N(t) = N_0 \cdot e^{-t/\tau}[1 + A_0 \cos(\omega_a(R) + \phi_0)]$$

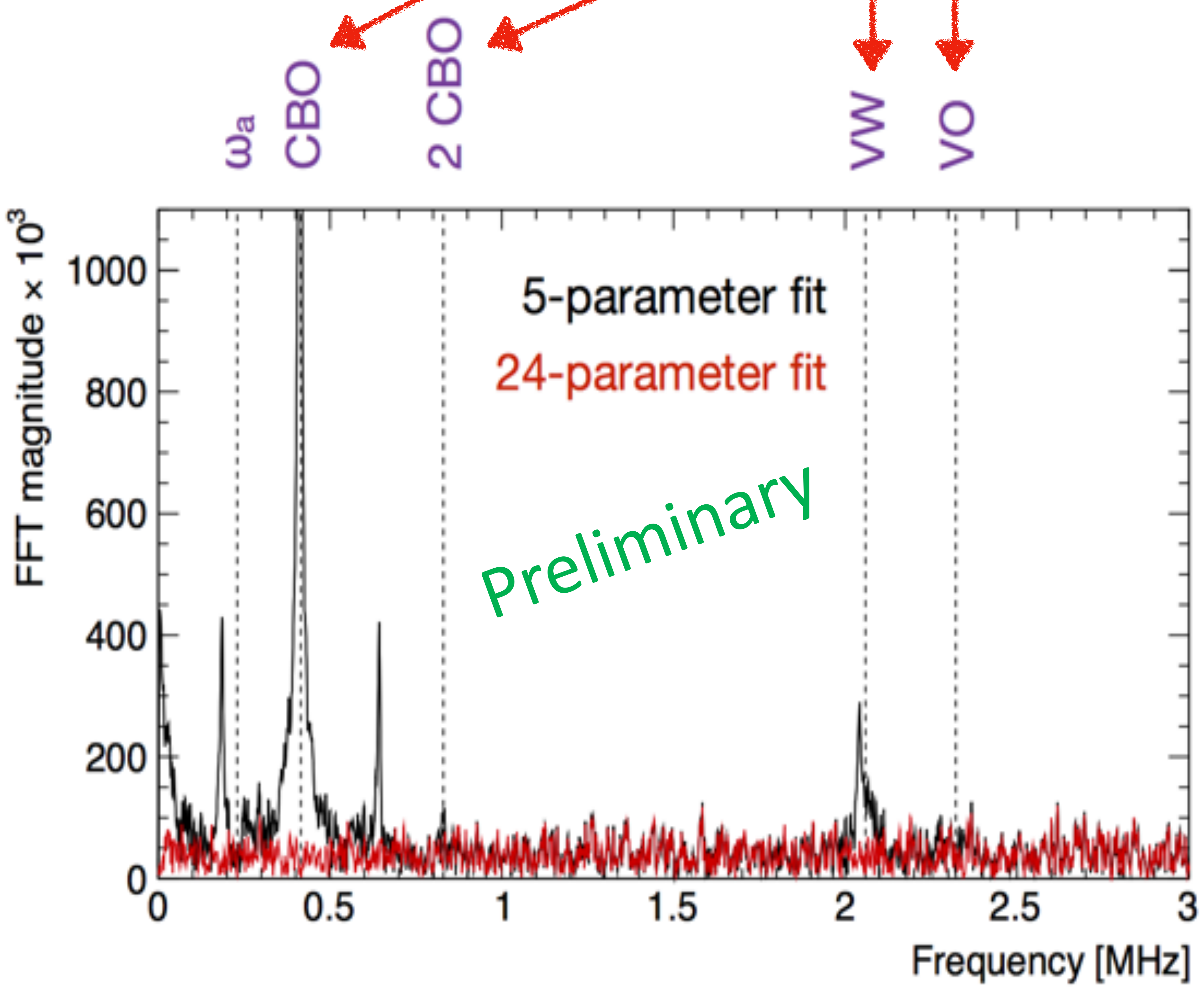
A “naïve” 5-parameter fit

$$N(t) = N_0 \cdot \Lambda(t) \cdot N_{1\mathrm{CBO}}(t) \cdot N_{2\mathrm{CBO}}(t) \cdot N_{VW}(t) \cdot N_{VO}(t) \cdot e^{-t/\tau}\left[1 + A_0 \cdot A_{1\mathrm{CBO}}(t) \cdot \cos(\omega_a(R) \cdot t + \phi_0 + \phi_{1\mathrm{CBO}}(t))\right]$$

Understanding beam dynamics essential in nailing down the frequency



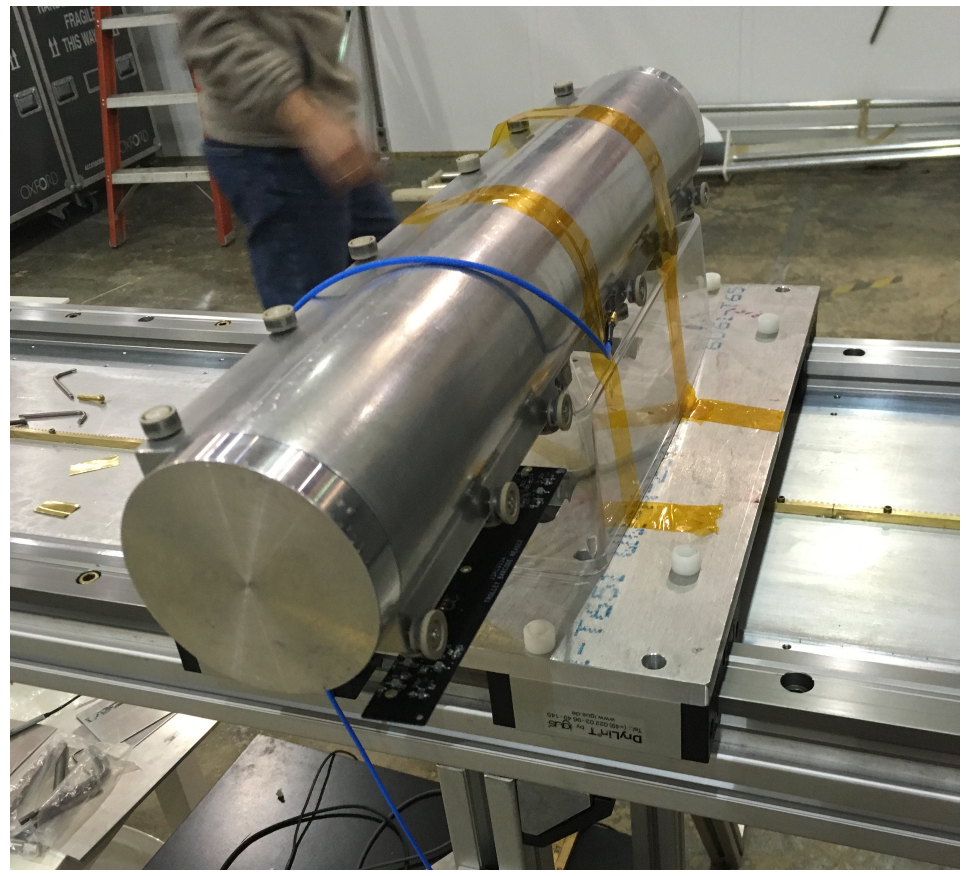
Muon precession data + Fit

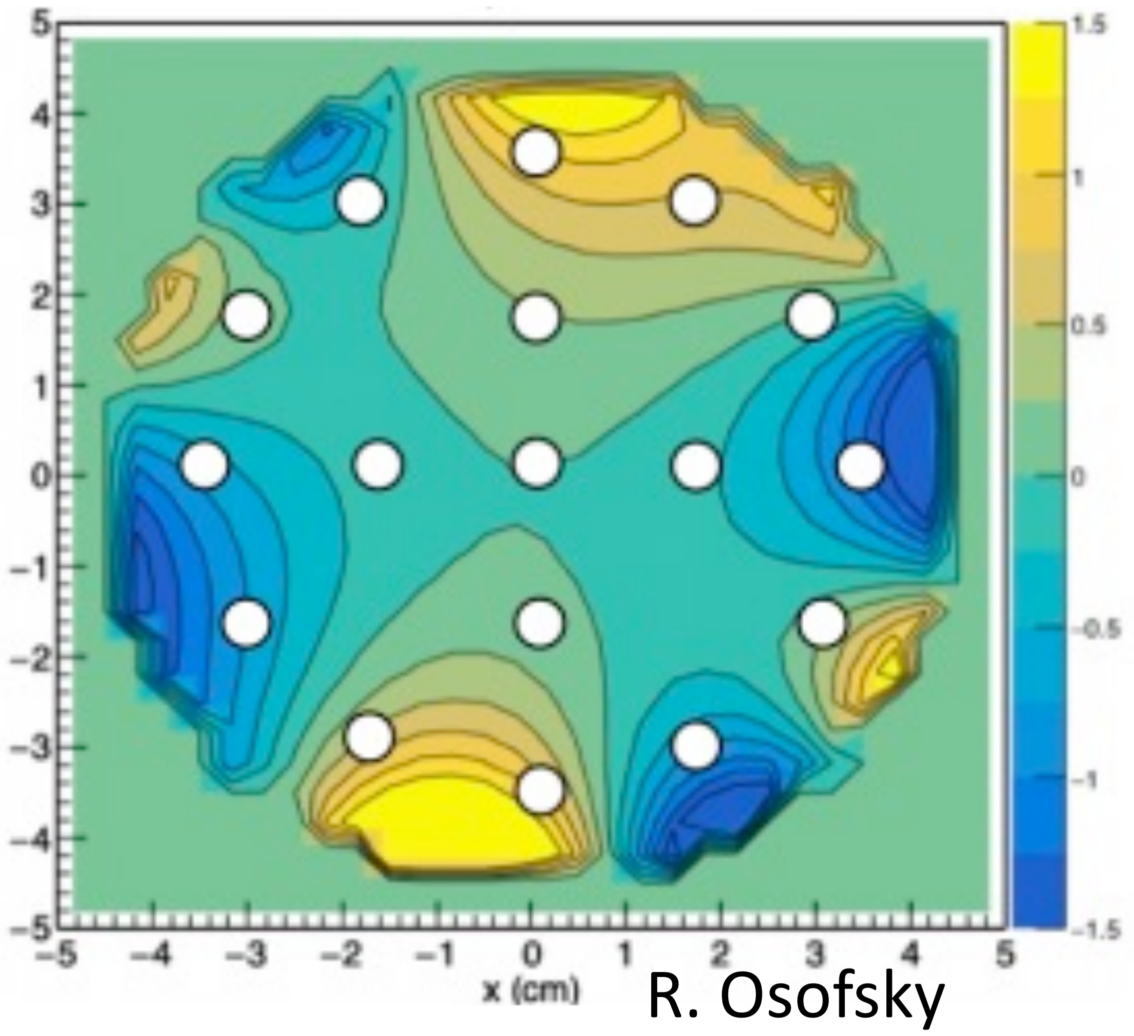


With correct function, the residuals are flat (as they must be) and the χ^2 is good and fit results are stable

A typical field measurement

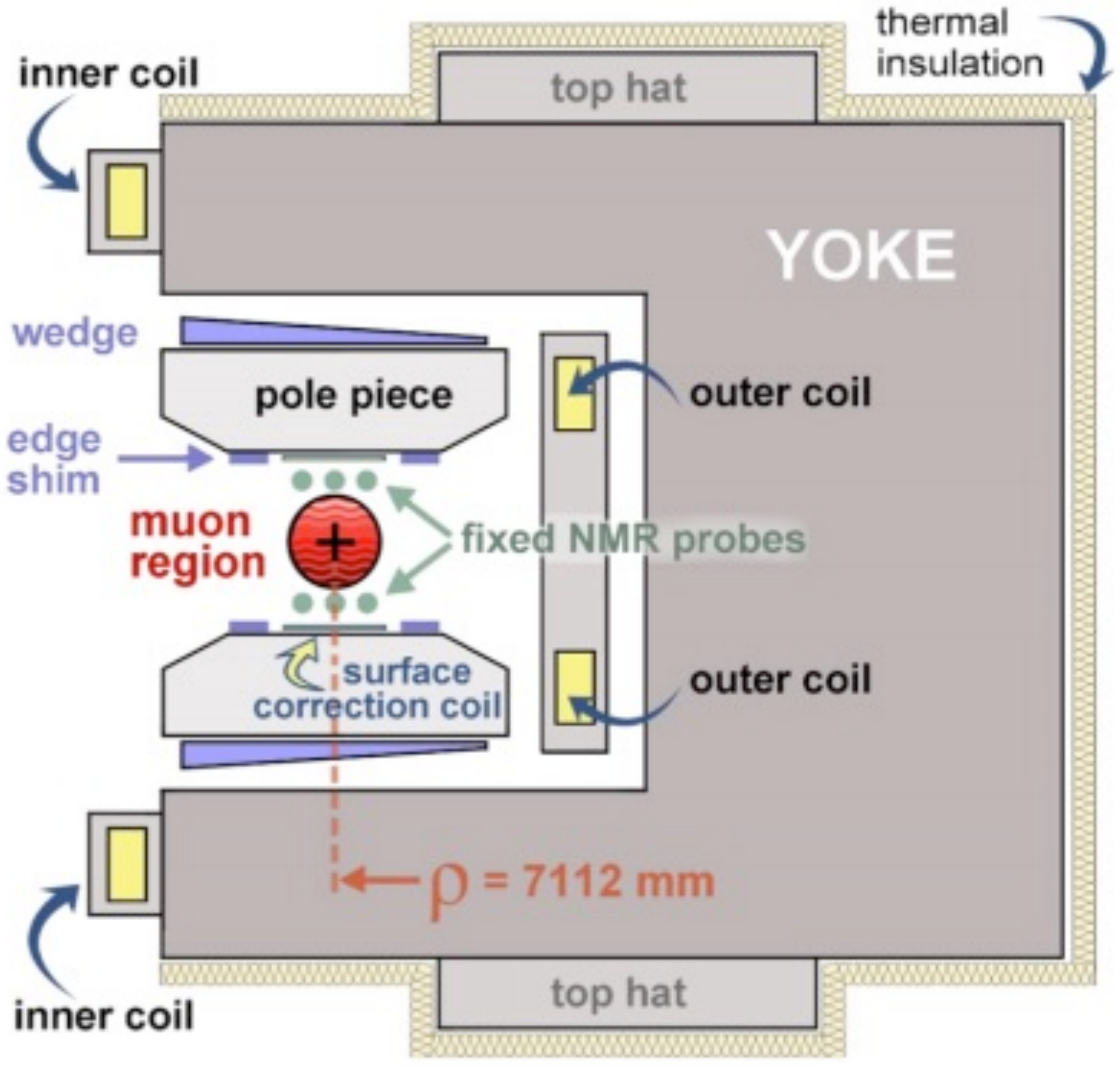
- Trolley maps full azimuth every few days
- Fixed probes monitor between trolley runs
- Field map is interpolated between trolley runs using fixed probe information



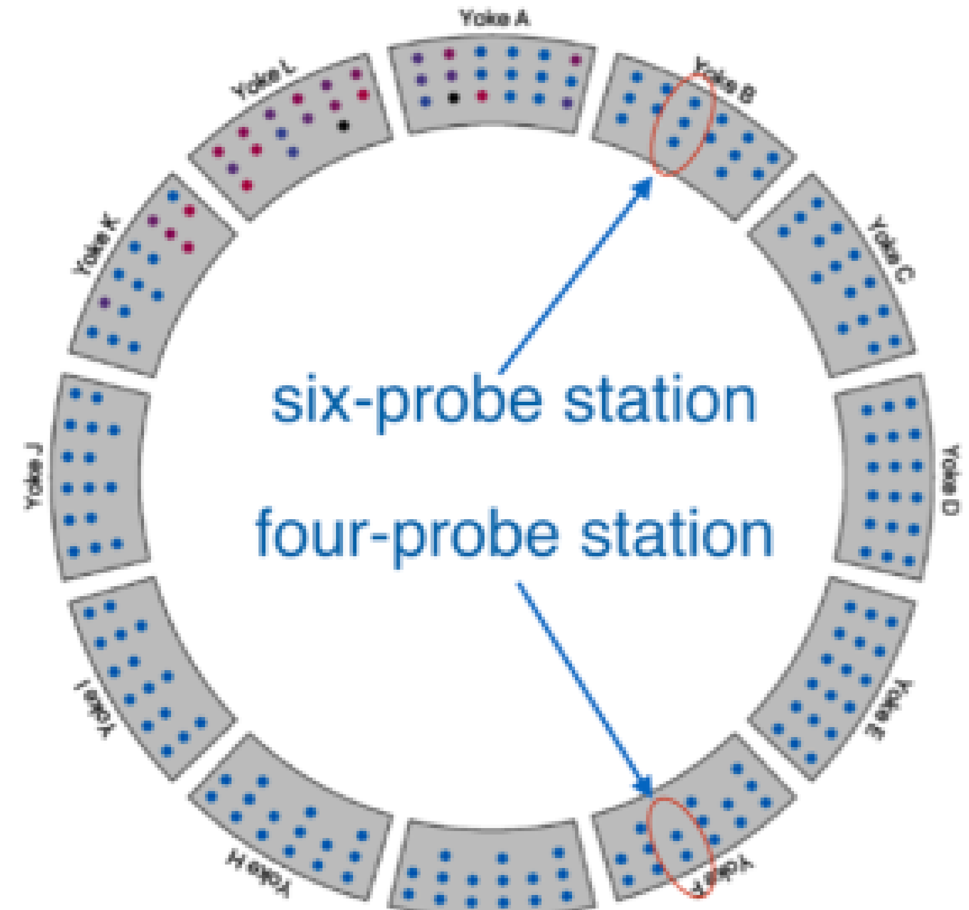


R. Osofsky

Field map in muon region

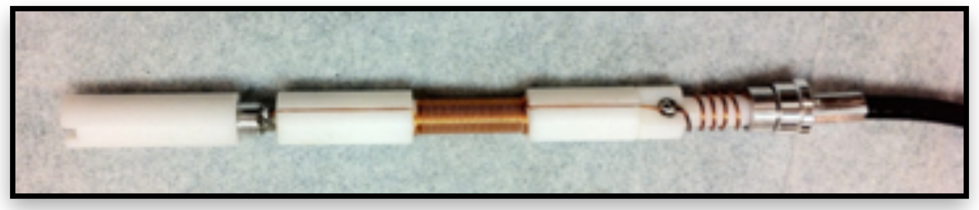


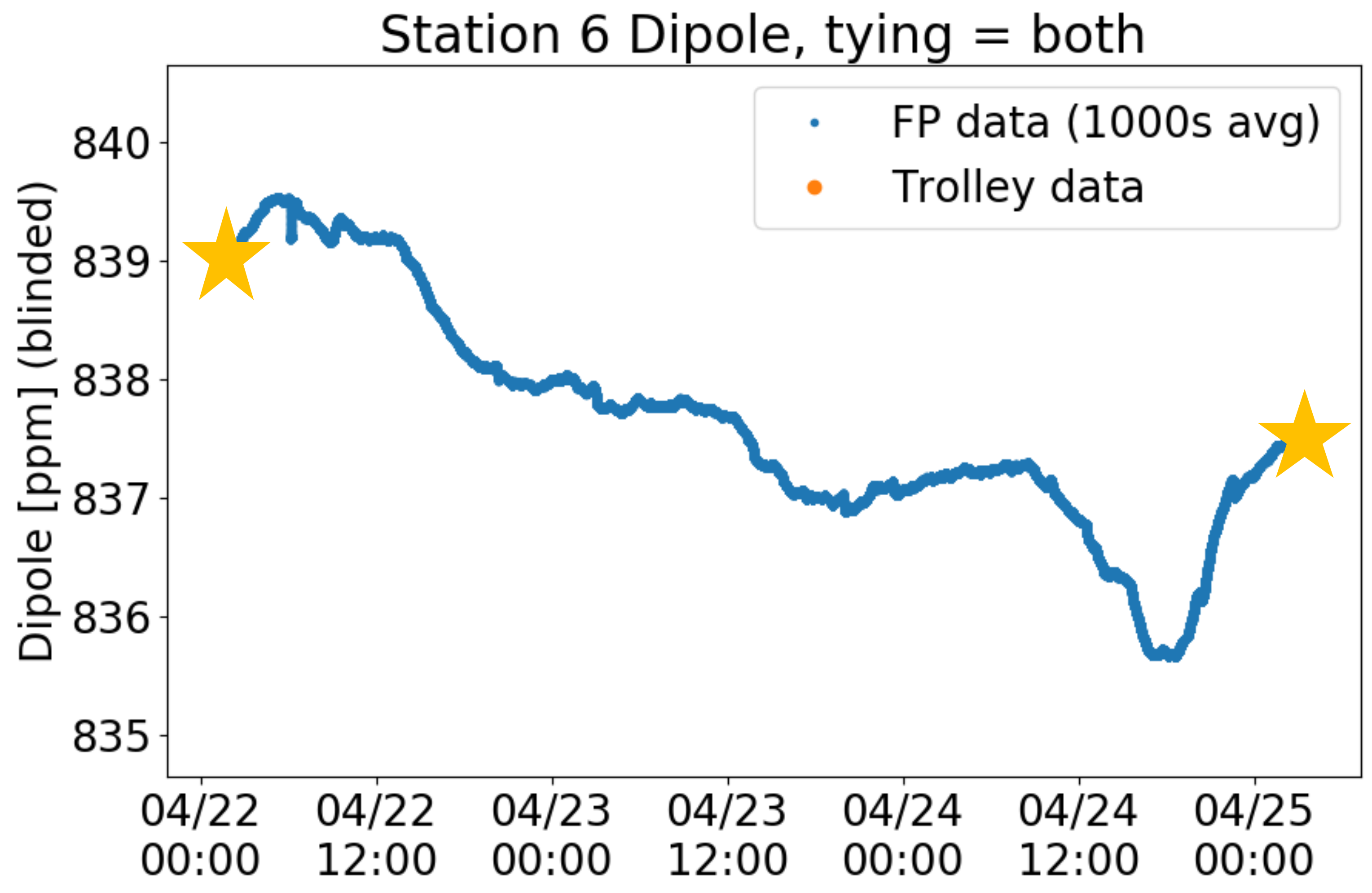
E. Swanson



M. Smith

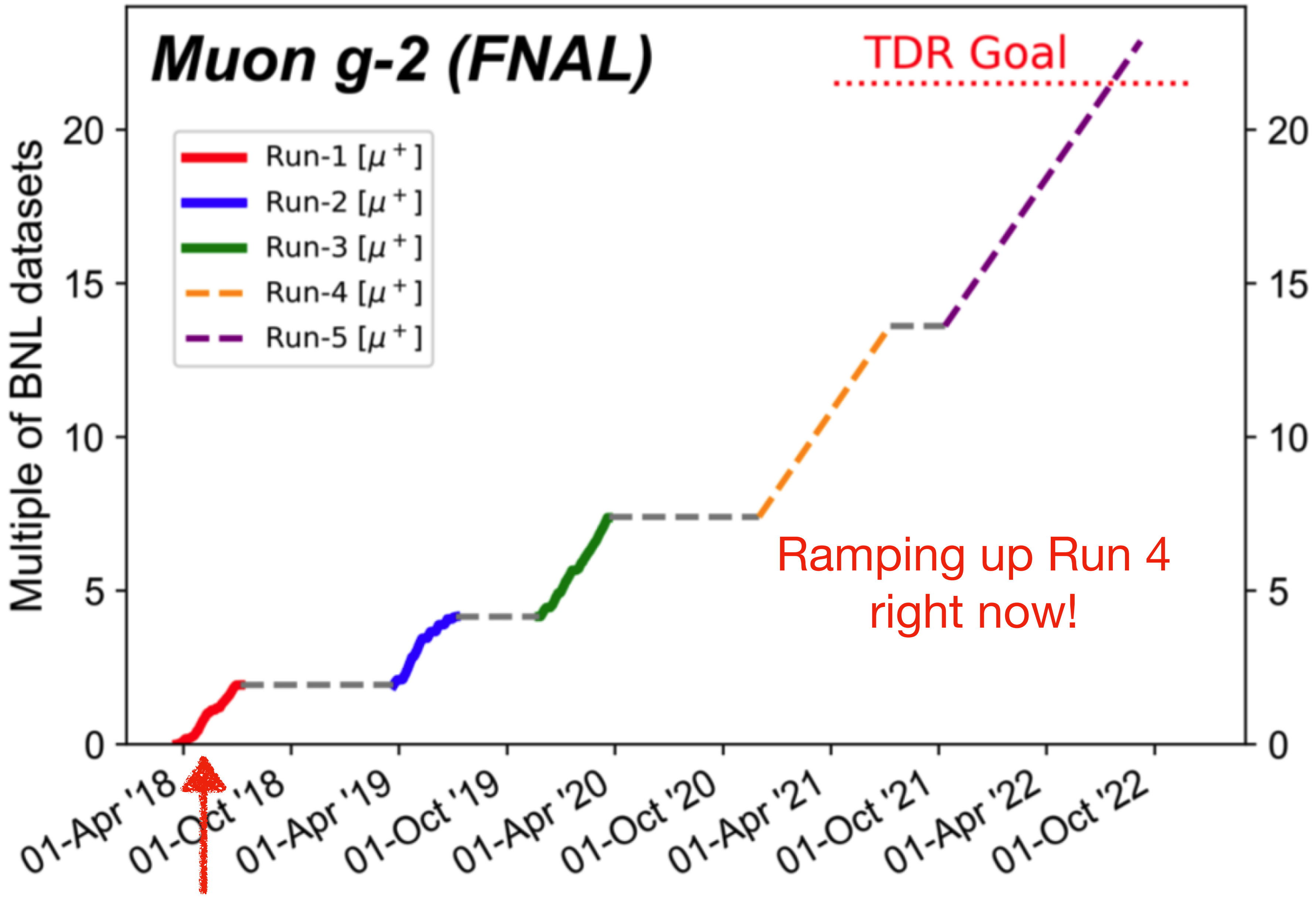
Fixed probes





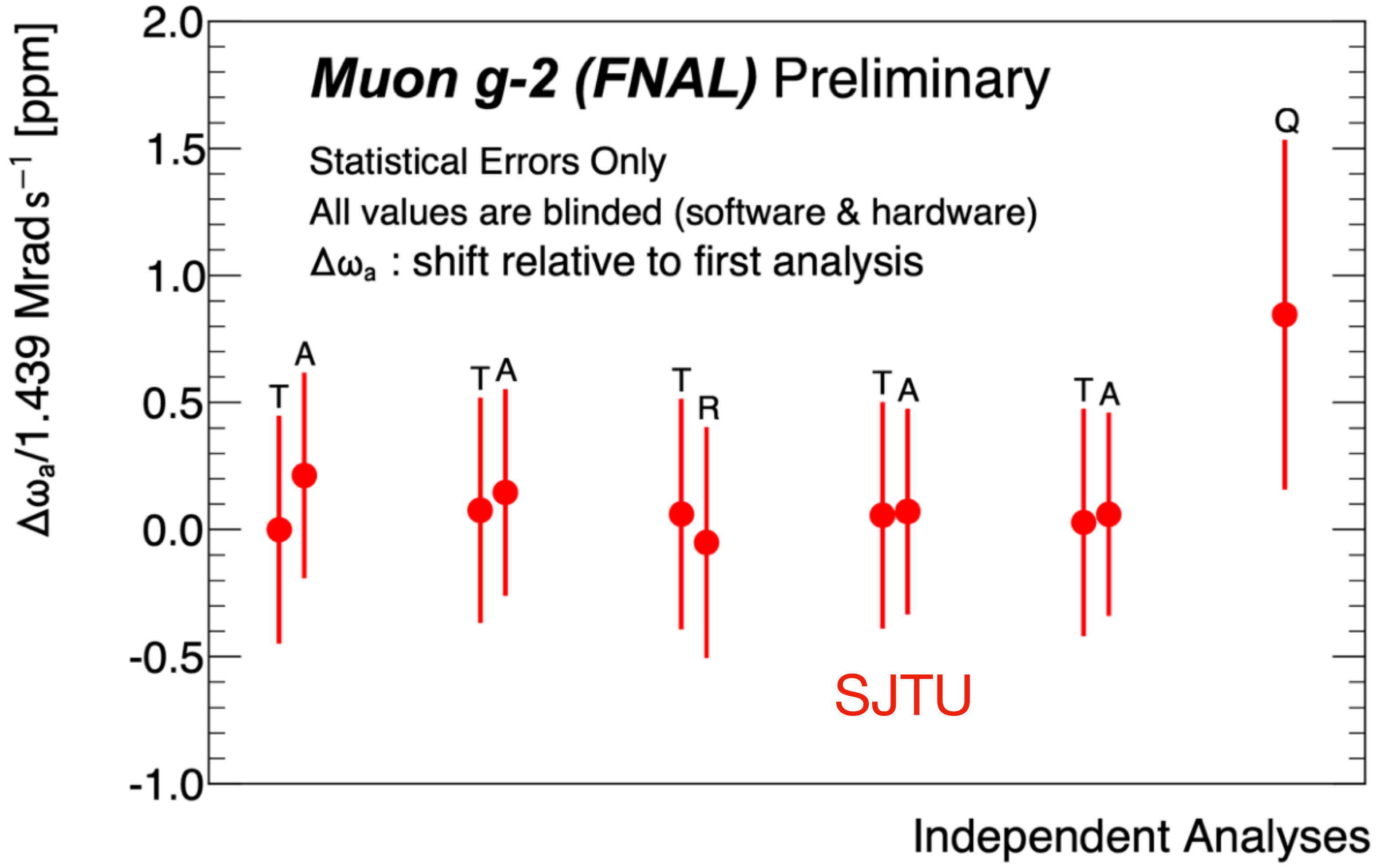
S. Charity

Current status



Ramping up Run 4 right now!

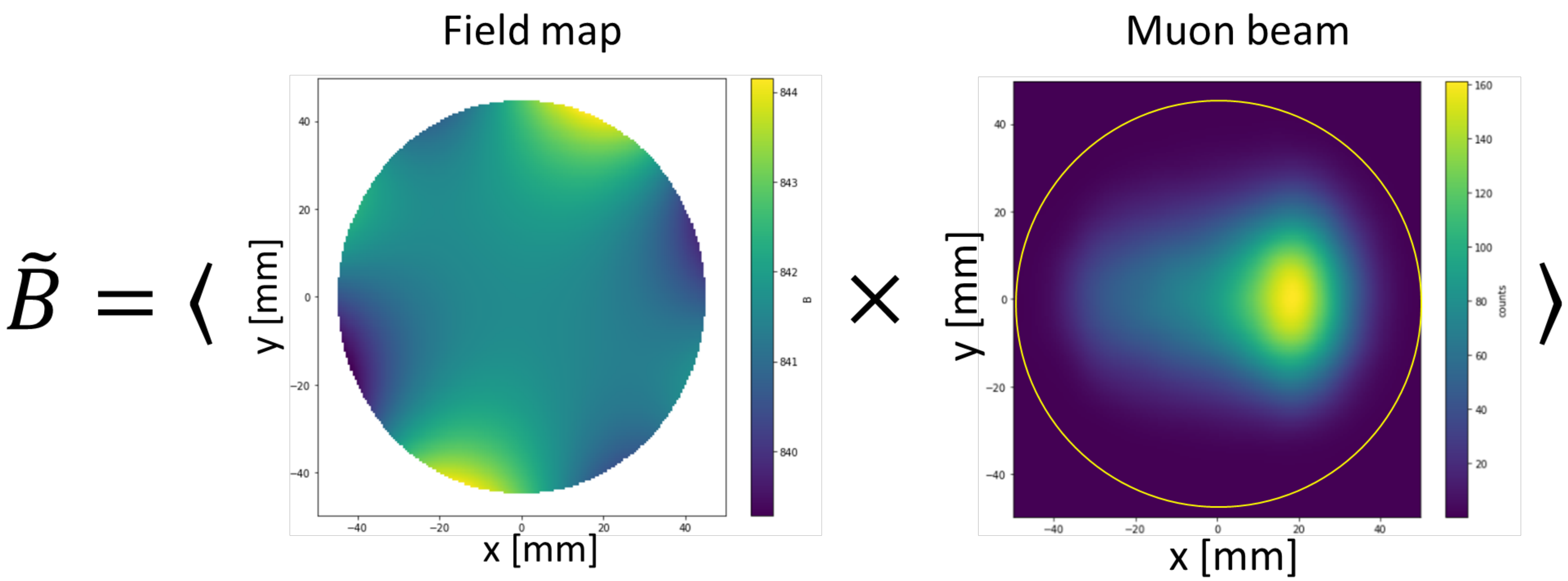
Relative unblinding completed for Run 1



SJTU

Take home messages:

- Collected > 7x BNL data over 3 years
- Systematics well below statistics (~450 ppb) for Run 1
- We are almost there (really)
  - We are leaving no stone uncovered in checking and double/triple/quadruple check blinded results
- As we go "beyond BNL", we are learning a lot with much better instruments and modeling
- Thank you for your patience and interest!



$$\tilde{B} = \langle \quad \times \quad \rangle$$

Field and beam maps, systematics finalizing.
Preliminary results showed small systematics < 100 ppb.

MDM vs Electric Dipole Moment (EDM)

- Elementary particles can have an EDM:

$$\boxed{\vec{d} = \eta \frac{q}{2mc} \vec{s}}$$

EDM

$$\boxed{\vec{\mu} = g \frac{q}{2m} \vec{s}}$$

MDM

- In electric and magnetic fields, the Hamiltonian is

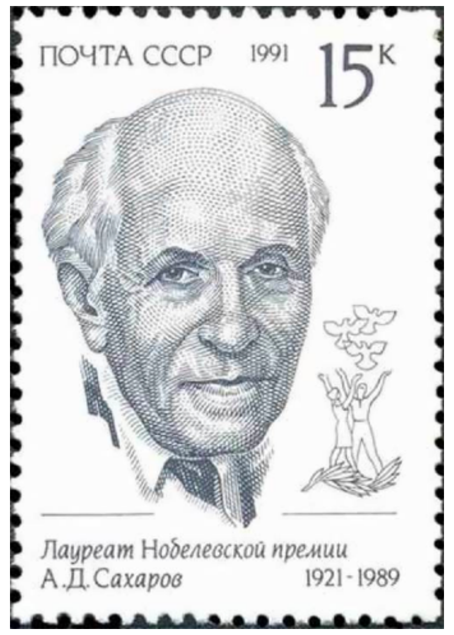
$$\boxed{H = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}}$$

- A permanent EDM violates both P and T invariance.
- If CPT is an unbroken symmetry → CP violation

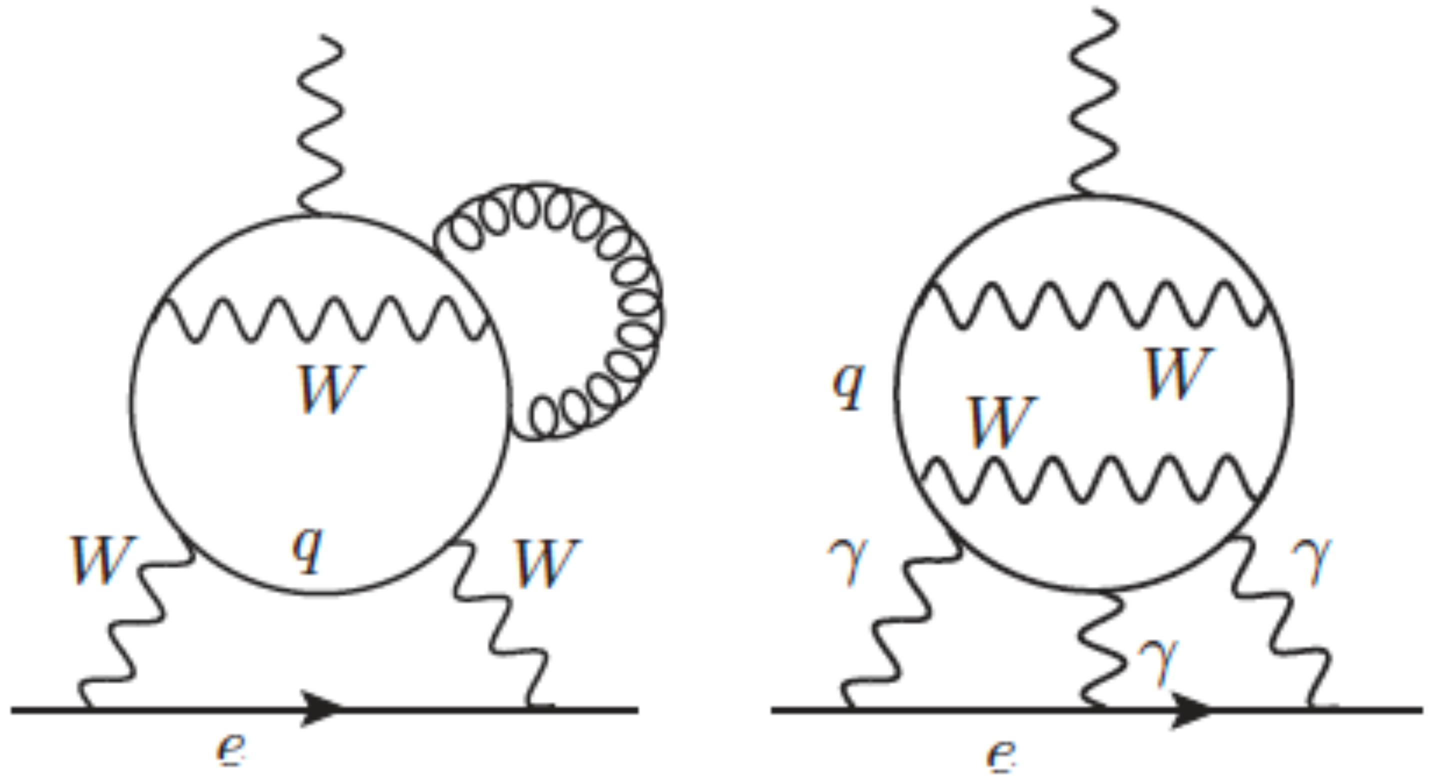
	E	B	μ or d
P	-	+	+
C	-	-	-
T	+	-	-

CP violation and Matter-antimatter asymmetry

A. D. Sakharov JETP Lett.-USSR 5,24 (1967)



- CP violation = One of the Sakharov conditions to create the Baryon Asymmetry in the Universe (BAU)
- Searching for non-zero EDM → probing matter-antimatter imbalance!
- In the Standard Model, tiny EDMs are generated by the CP violating phase in the CKM matrix (~10^{-40}-10^{-30} e cm)

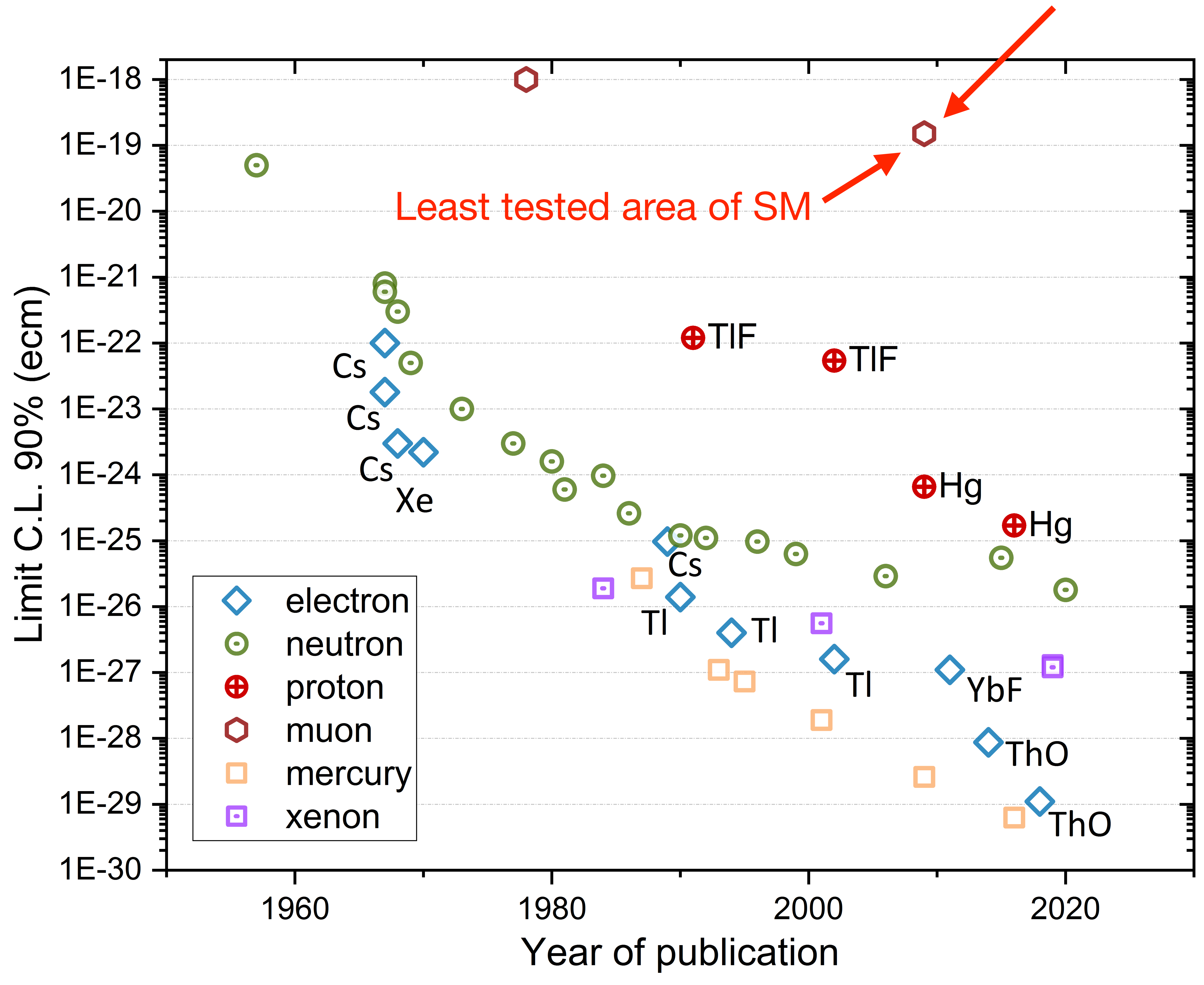


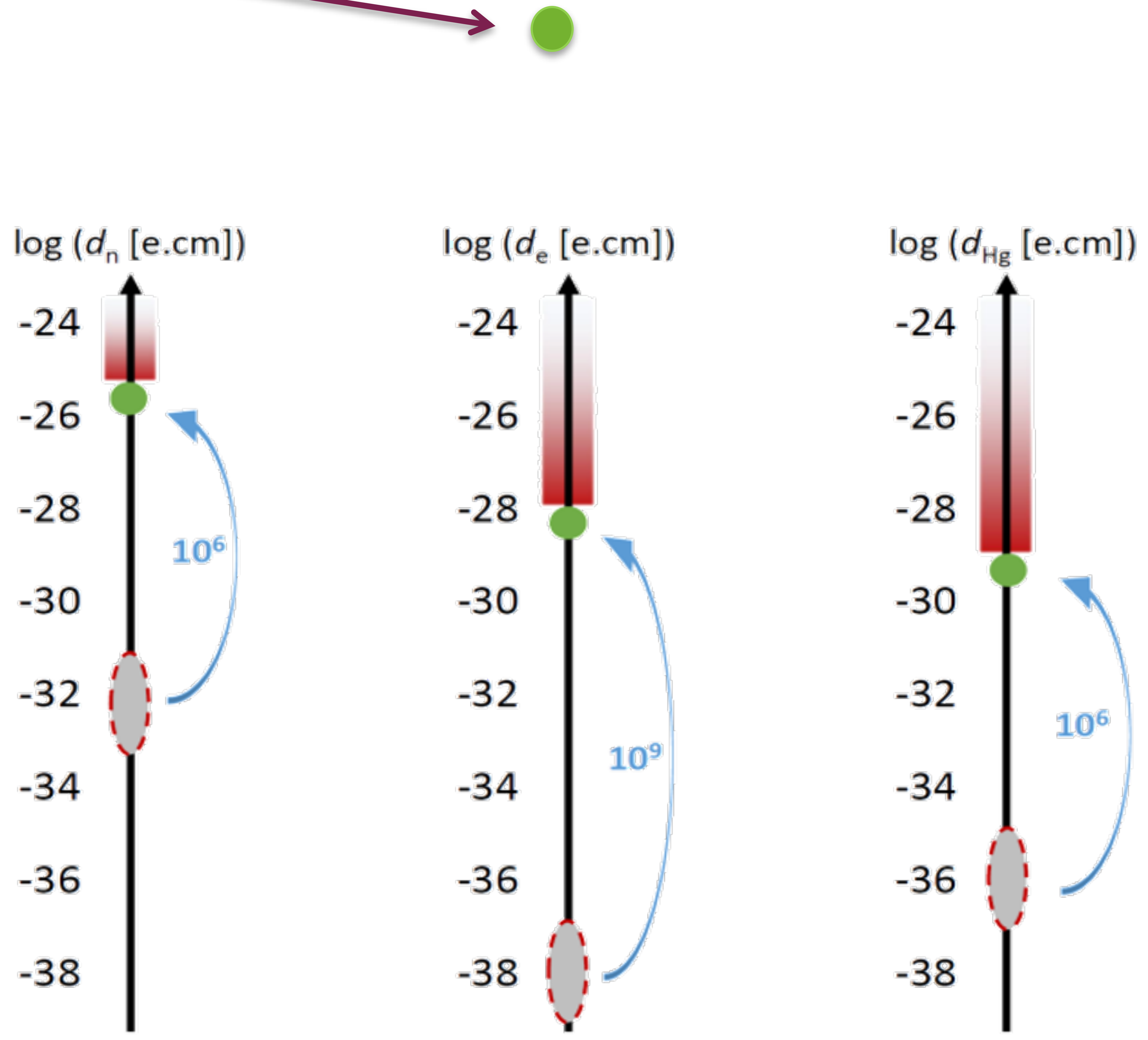
- An EDM signal > SM prediction → new source of CP violation → new Physics!

About SM's EDM Prediction: M. Pospelov and A. Ritz,, Phys. Rev. D89, 056006 (2014)

EDM Overview

Current muon limit



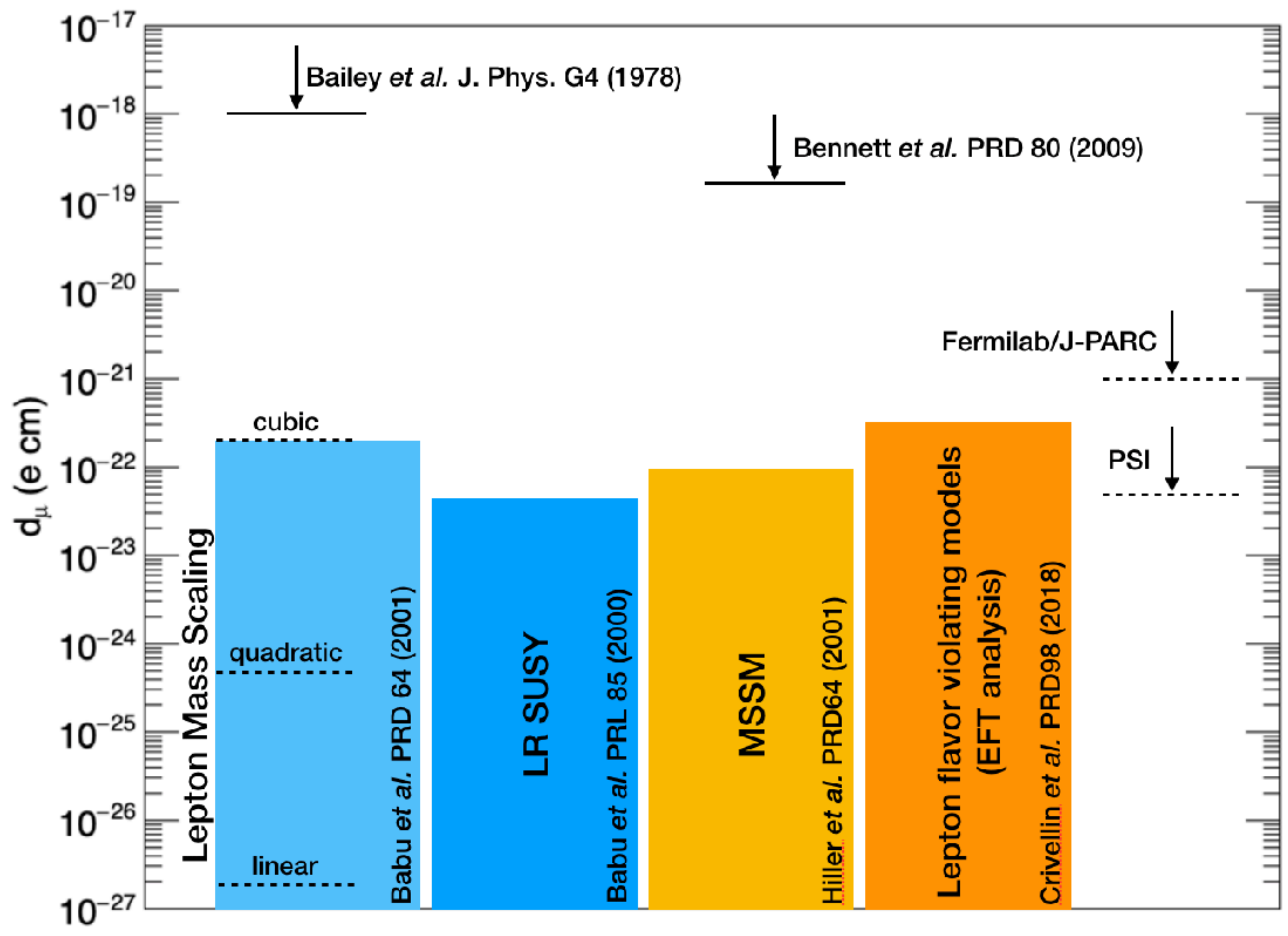


$O(10^{-42})$

What is so special about muon?

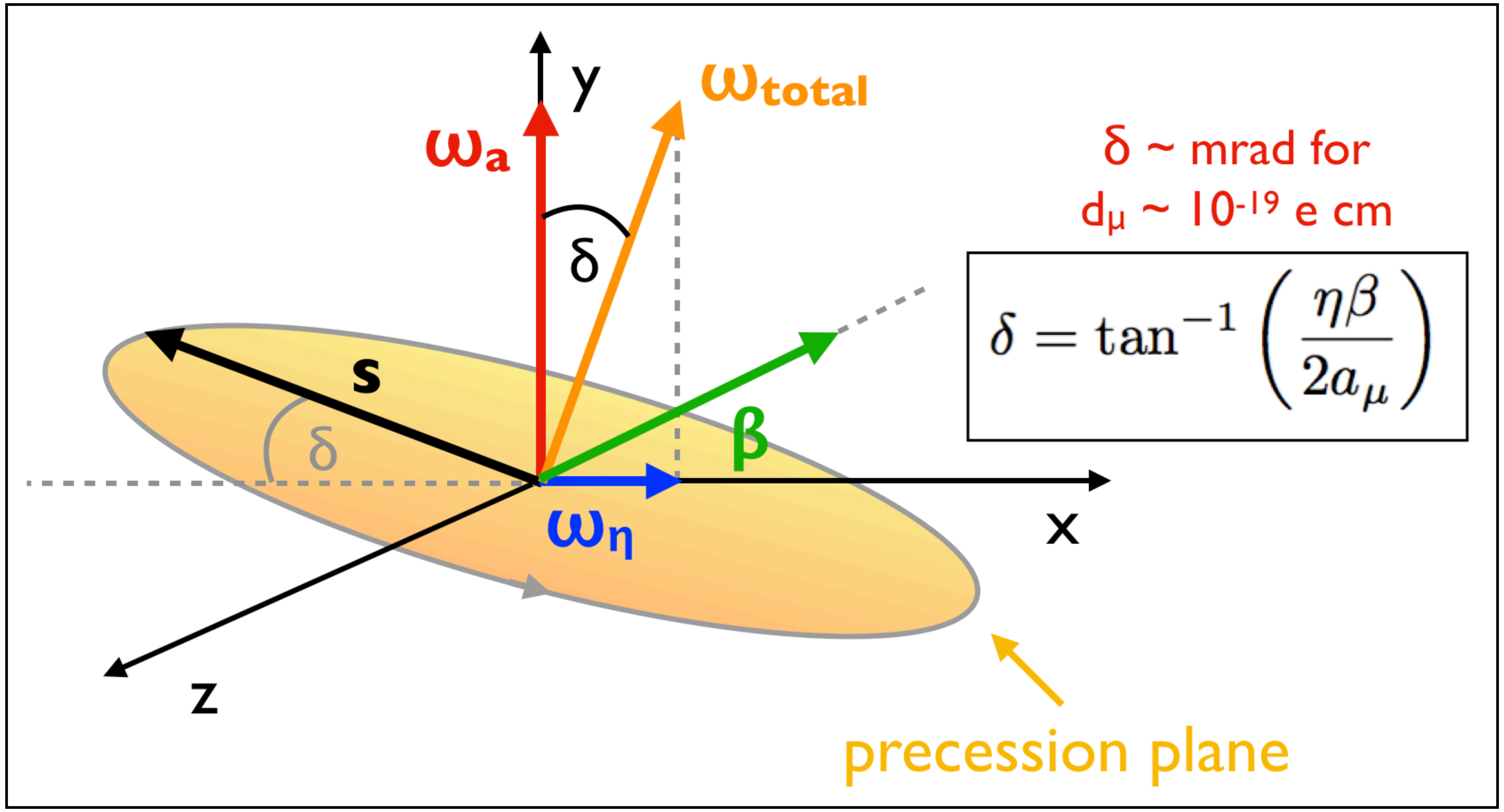
- All searches involve 1st generation particles (e, p, n, Hg, ..), except for the muon (2nd generation, the only direct measurement on a charged particle)
- Present limit from BNL, $d_\mu < 1.8 \times 10^{-19}$ e cm (95% C.L.)
- Linear mass scaling in the SM + d_e limits imply $d_\mu \sim 10^{-27}$ e cm
- However, BSM models predict quadratic or even cubic scaling!
  → d_μ could be as high as $\sim 10^{-22}$ e cm
- Moreover, Muon g-2 experiments measure contributions from both MDM and EDM!

$$\boxed{\omega_{tot} = \sqrt{{\omega_a}^2 + {\omega_\eta}^2}}$$



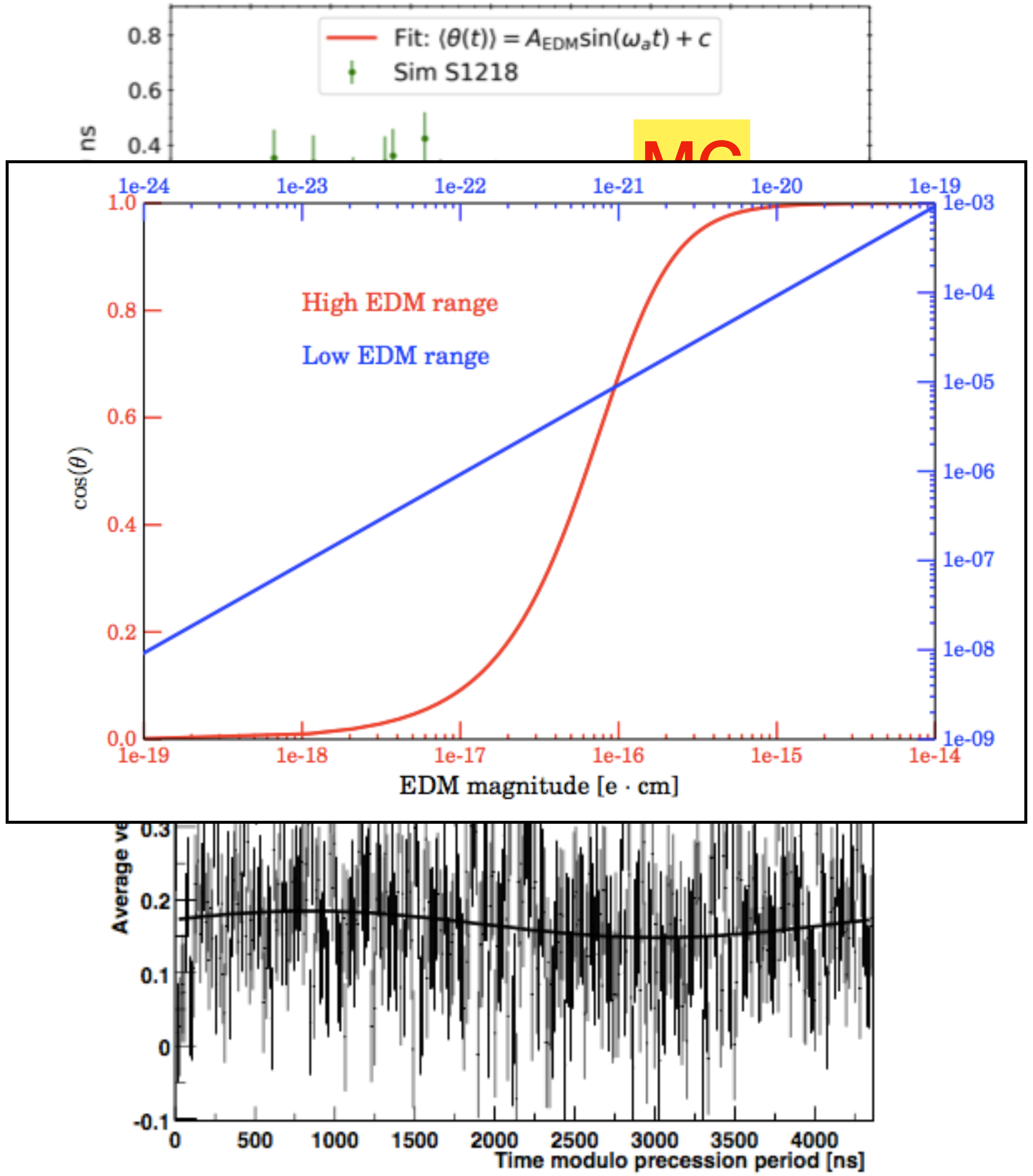
Electron EDM: V. Andreev et al. (ACME), Nature 562, 355 (2018)

Parasitic approach for muon EDM search



δ ~ mrad for $d_\mu \sim 10^{-19}$ e cm

$$\delta = \tan^{-1}\left(\frac{\eta\beta}{2a_\mu}\right)$$



Existence of an EDM causes the precession plane to tilt
→ vertical oscillating of the positron emission angle

Frozen-spin technique for EDM search

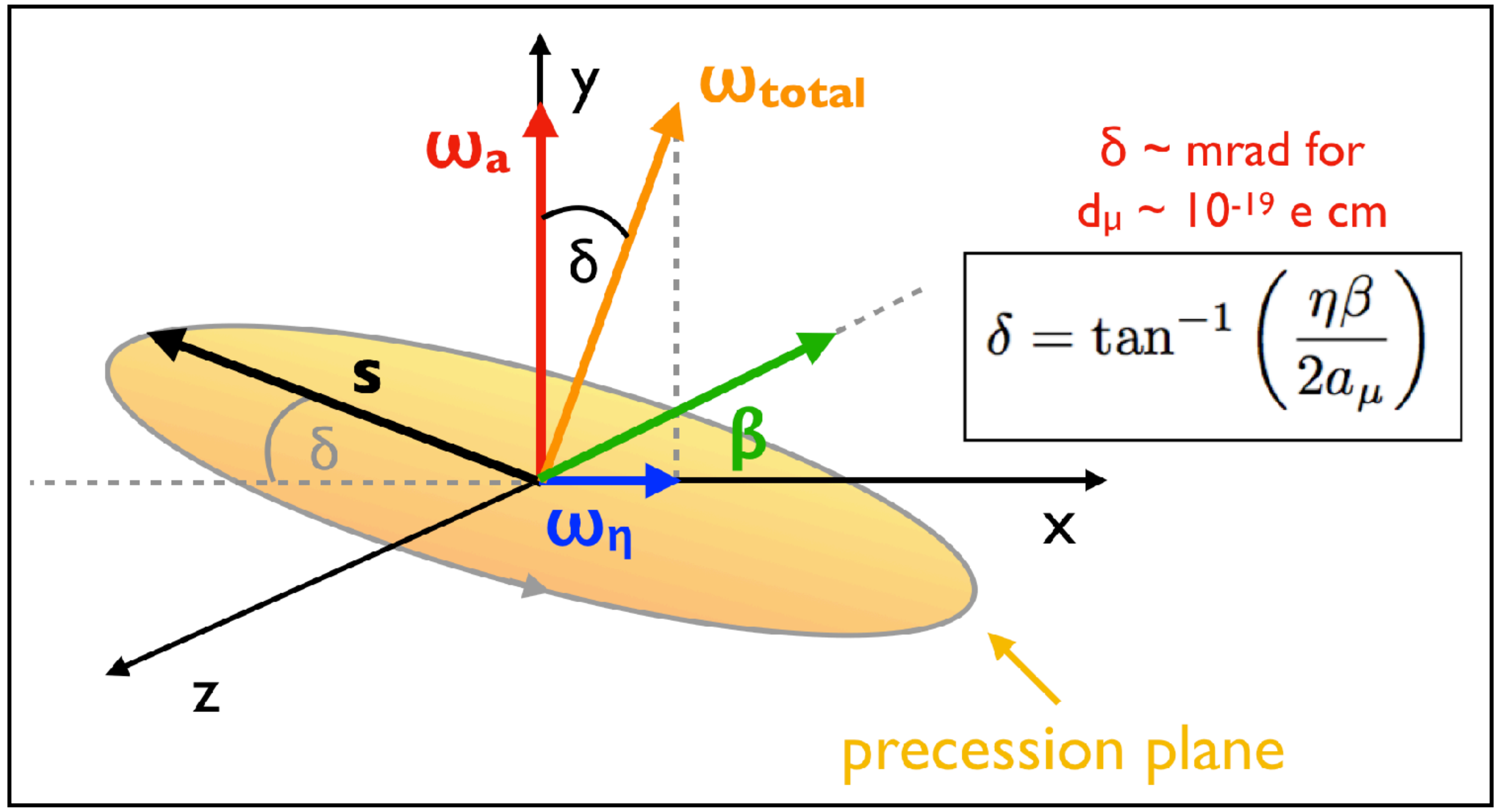
$$\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m}\left\{\xcancel{\boxed{a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}} + \boxed{\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)}\right\}$$

ω_a : AMM

ω_η: EDM

BNL, FNAL: use $\gamma = 29.3$
J-PARC: no E-field focusing

J-PARC, PSI: **$E \sim aBc\beta\gamma^2$**
J-PARC: storage ring lattice, <R> ~ 11 m
PSI: compact storage ring, <R> ~ 0.3 m

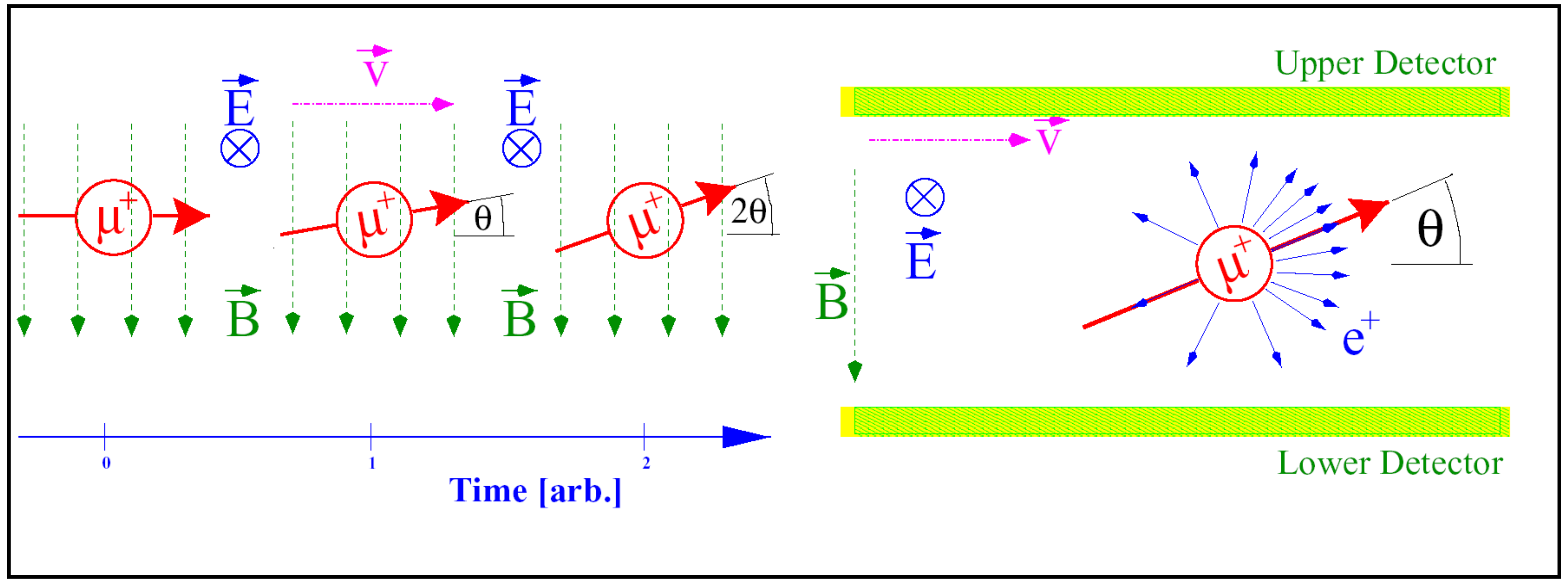


δ ~ mrad for $d_\mu \sim 10^{-19}$ e cm

$$\delta = \tan^{-1}\left(\frac{\eta\beta}{2a_\mu}\right)$$

The “parasitic” approach with g-2

(performed or proposed at BNL, FNAL and J-PARC)



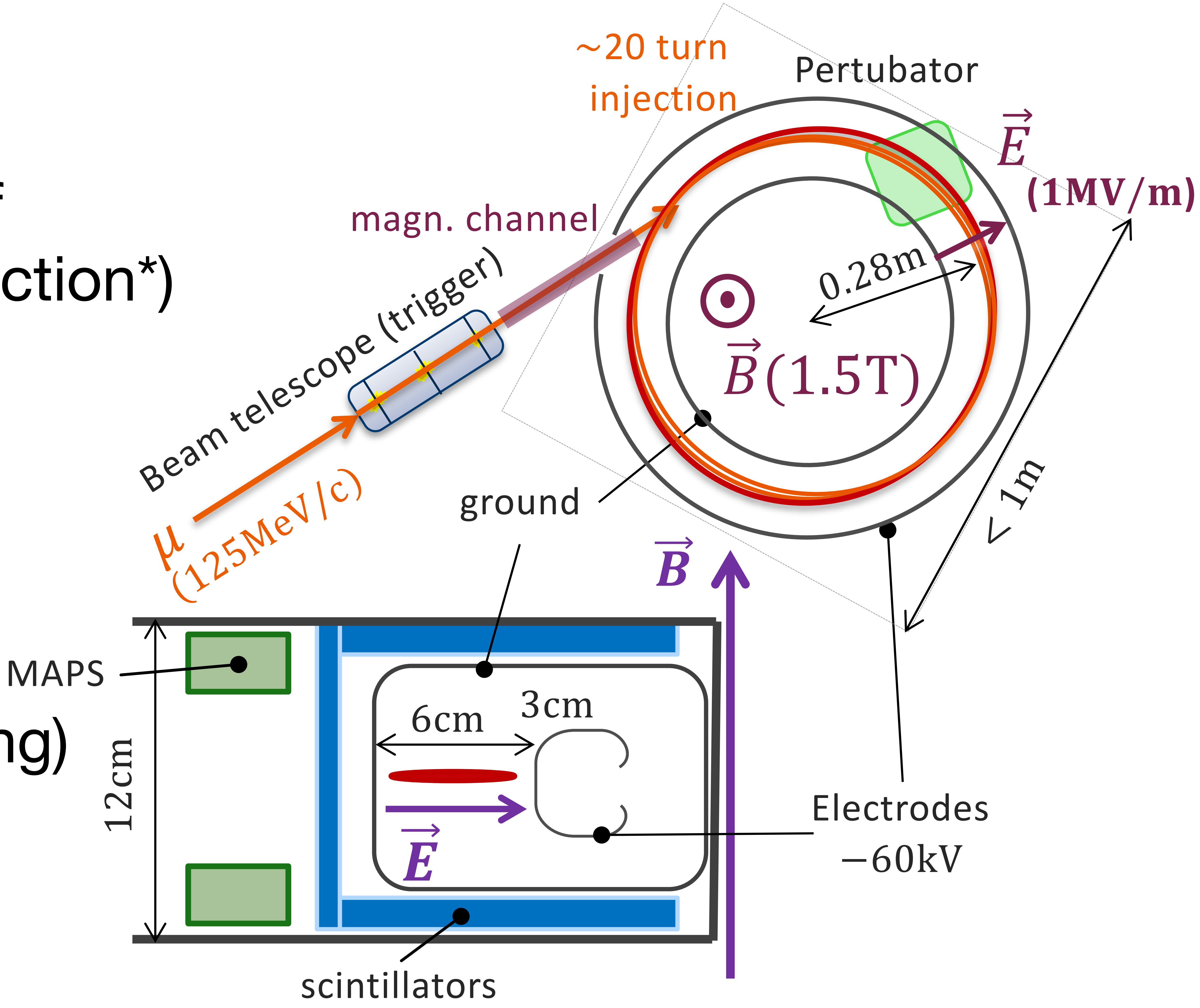
The “frozen-spin” approach

(proposed at J-PARC, PSI)

Compact storage ring at PSI

A. Crivellin, M. Hoferichter, and P. Schmidt-Wellenburg, Phys. Rev. D 98, 113002 (2018)

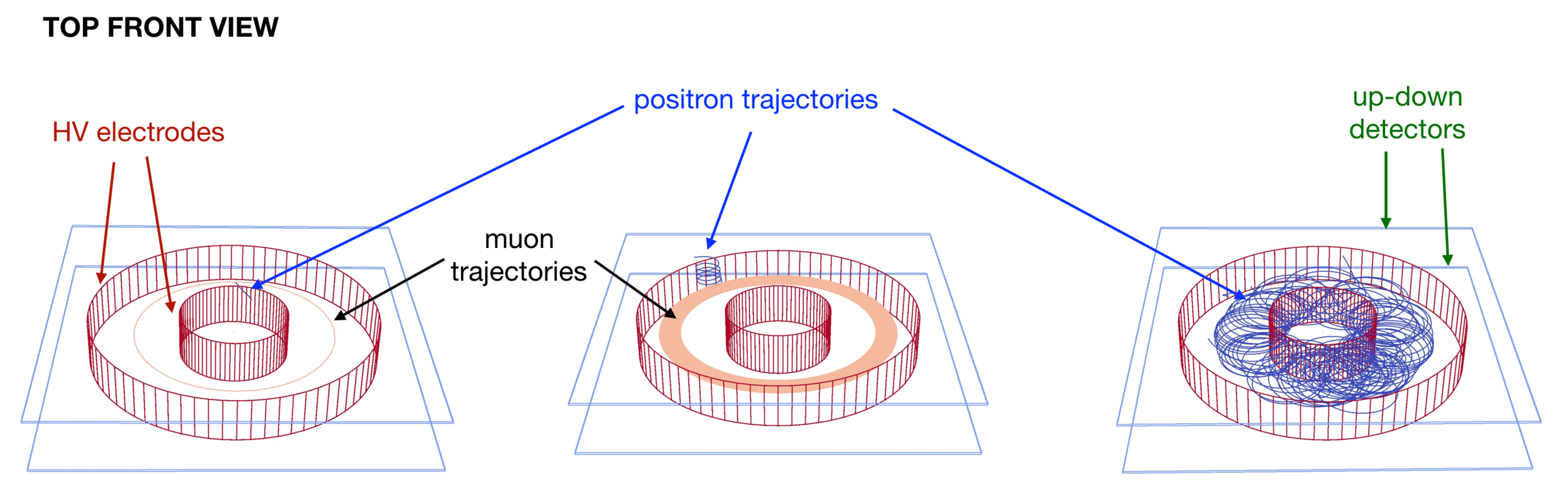
- Weak focusing magnet
- Polarized μ-beam
- Trigger from beam telescope for start of inflector ramp (resonance ½ integer injection*)
- One muon at a time ~200 kHz rate
- Tracking detector for positrons (resolution ~0.25×0.25 mm²)
- Detector prototype:
  - Combination of scintillating tiles (timing) and thin MAPS (track, momentum)
  - Optional calorimeter



A. Adelmann *et al.* JPG 37(2010)085001

* H. Yamada et al. NIMA467/368(2001)

Current status: beam injection & storage simulation

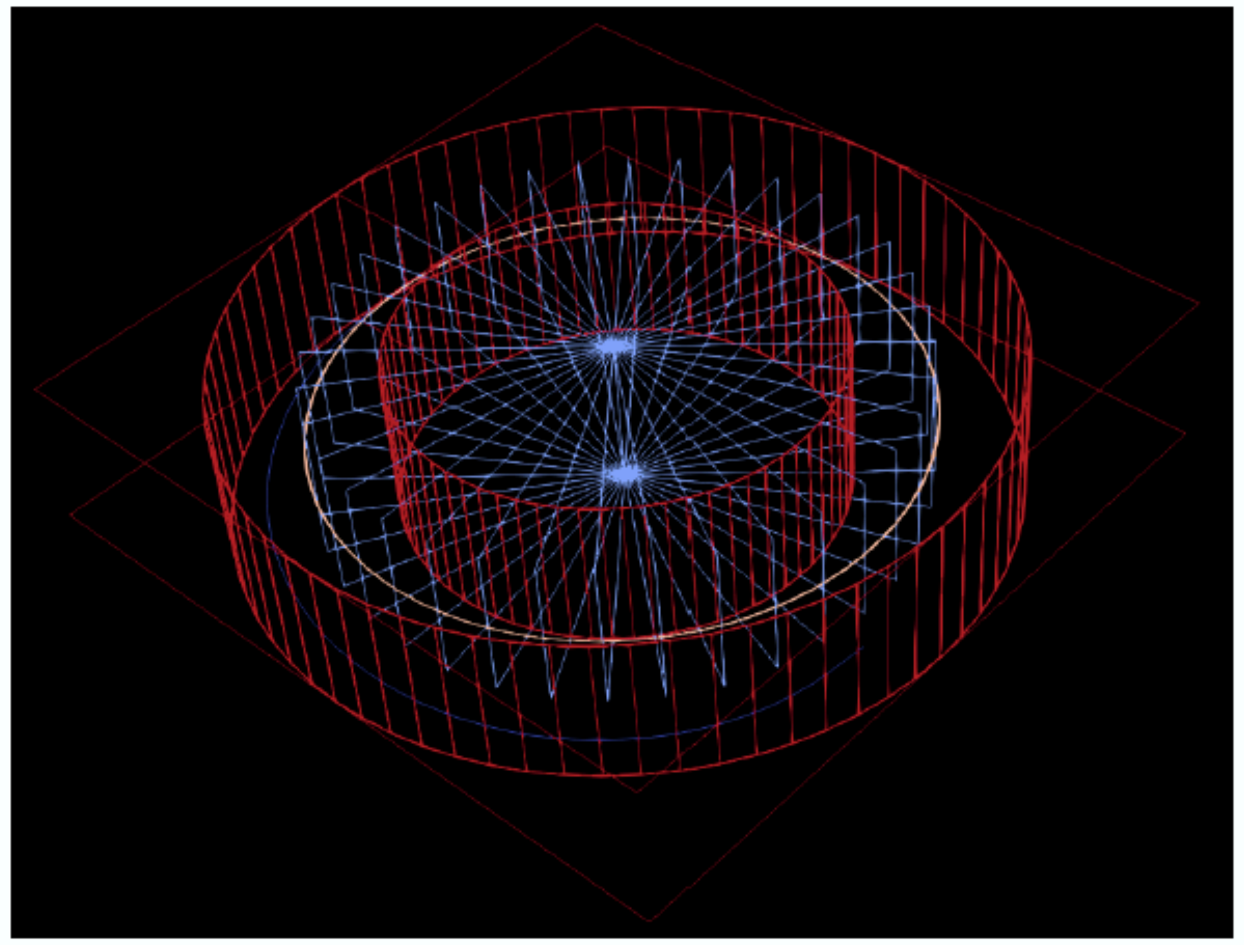


(a) 1.5 T dipole magnet [1 muon decay]

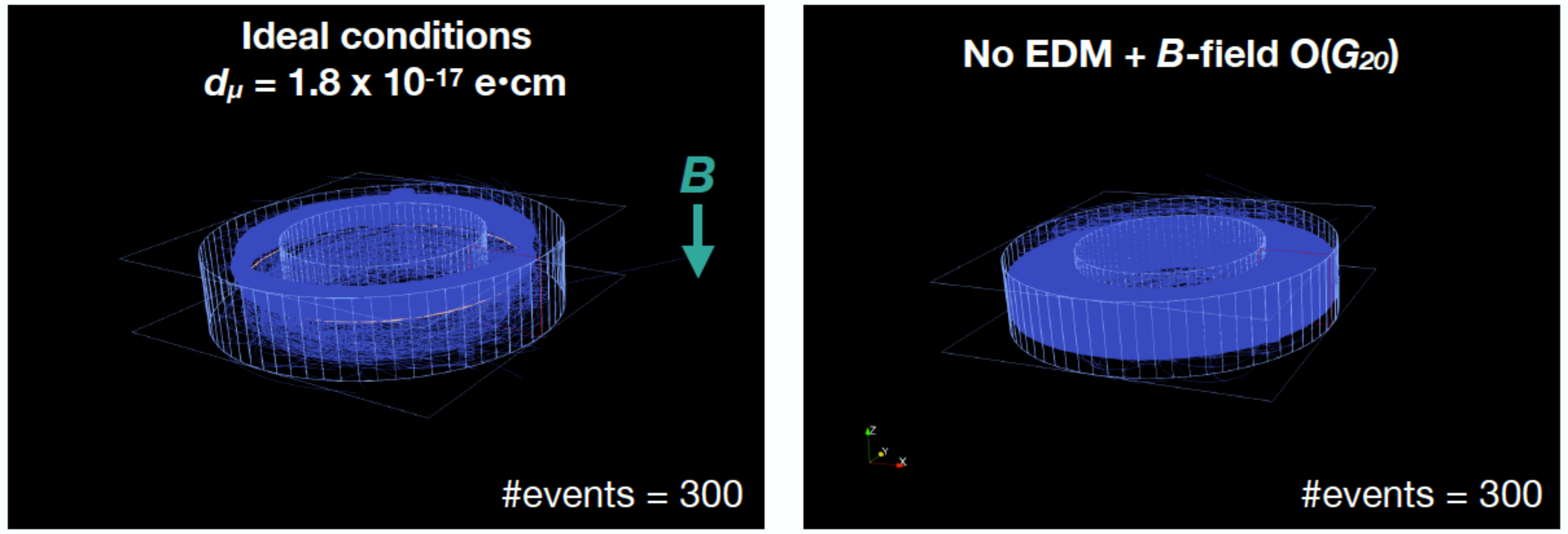
(b) weak-focusing magnet (n=0.2) [1 muon decay]

(c) weak-focusing magnet (n=0.2) [10 muon decays]

- 36 vanes
- Tracker outer edge
  → 4 mm away from the orbit
- Detector requirement study underway
  - detector geometry
  - #vanes
  - #hits required to precisely reconstruct the angle and momentum etc…



Systematics study on-going (gradient field)



- Similarly, general form of the B-field up to G_{20} is given by

$$\vec{B} = B_z' \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} + \partial_z B_z' \begin{pmatrix} -x/2 \\ -y/2 \\ z \end{pmatrix} + \partial_z^2 B_z' \begin{pmatrix} -xz \\ -yz \\ z^2 - (x^2+y^2)/2 \end{pmatrix},$$

$$\text{where } B_z' = \alpha z^2 + \beta z + \epsilon$$

- Let B_z be -1.5 T at the origin, then

$$\epsilon = -1.5 \text{ [T]}$$

- The radial B-field component causes false EDM signal and considering the orbital plane,

$$\omega_e(d_\mu = 1.8 \times 10^{-17} e \cdot \text{cm}) = \gamma_\mu < B_r(z=0) >$$

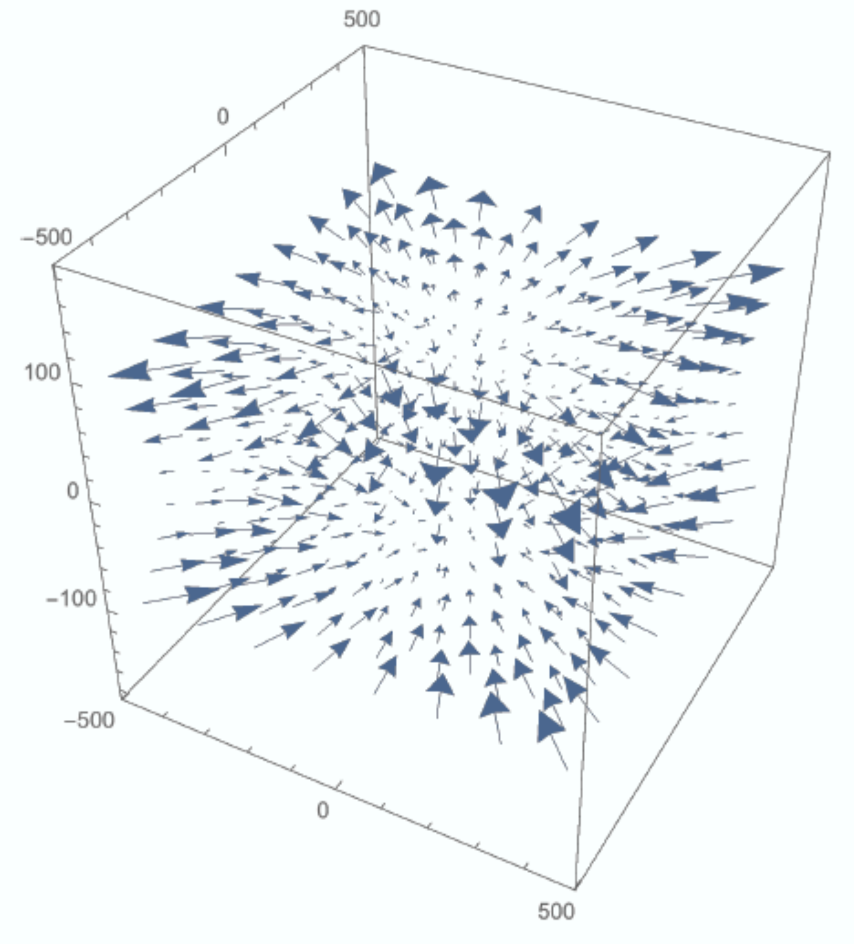
gives

$$\beta = (G_{10} =) - 2.213... \text{ [nT/mm]}$$

- Now α can be any arbitrary value and this time

$$\alpha = -0.1 \text{ [}\mu\text{T/mm}^2\text{]}$$

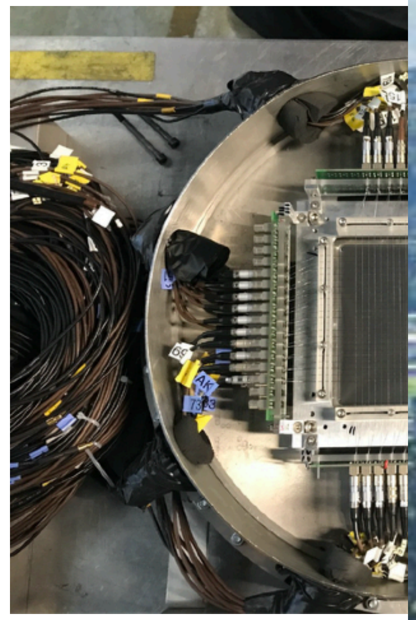
is used by checking the stability of μ orbits

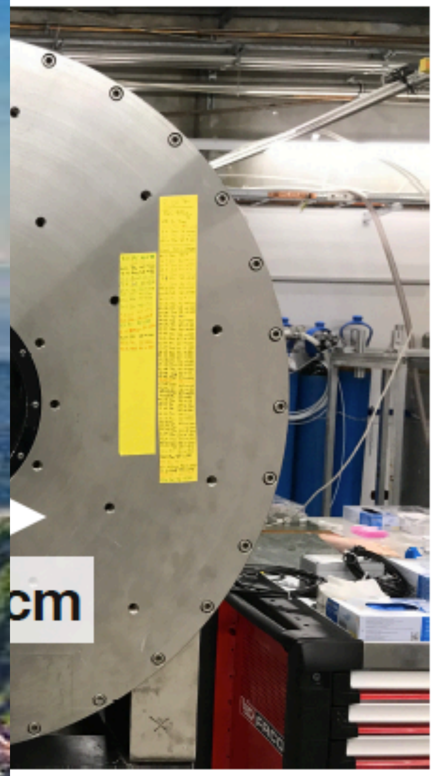


Only plot radial B-field

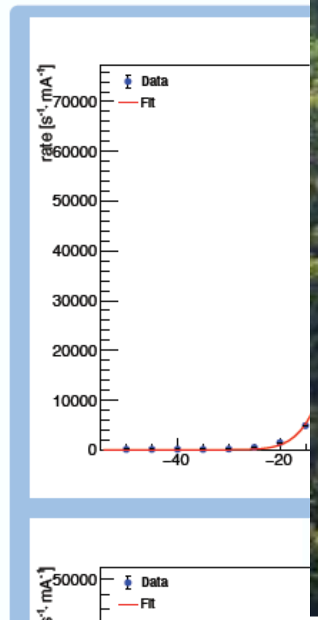
Current status: annual beam time at PSI

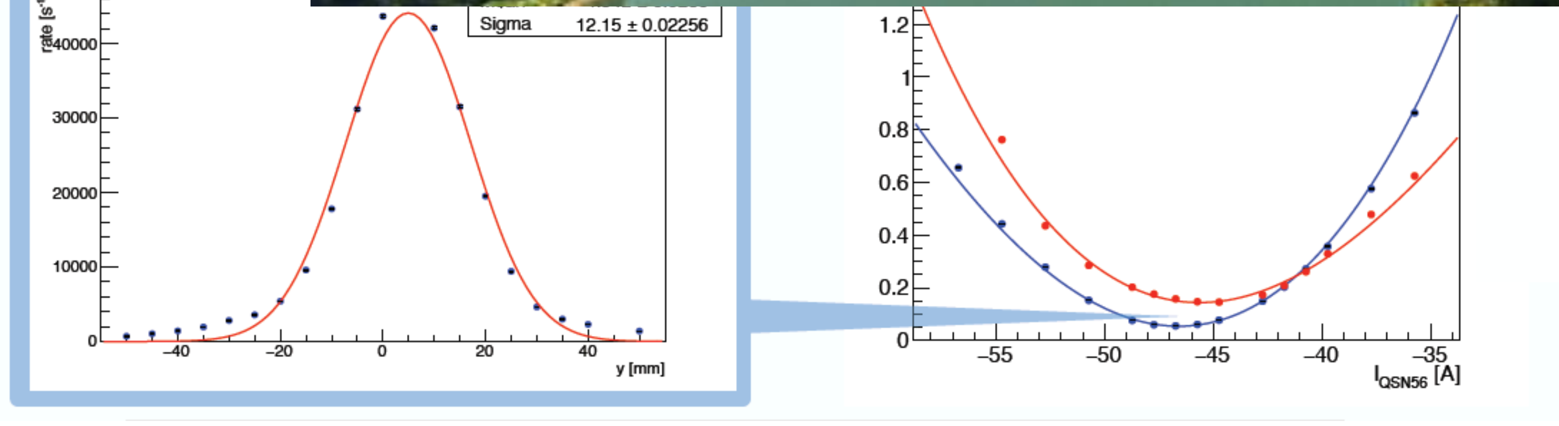
Test bea

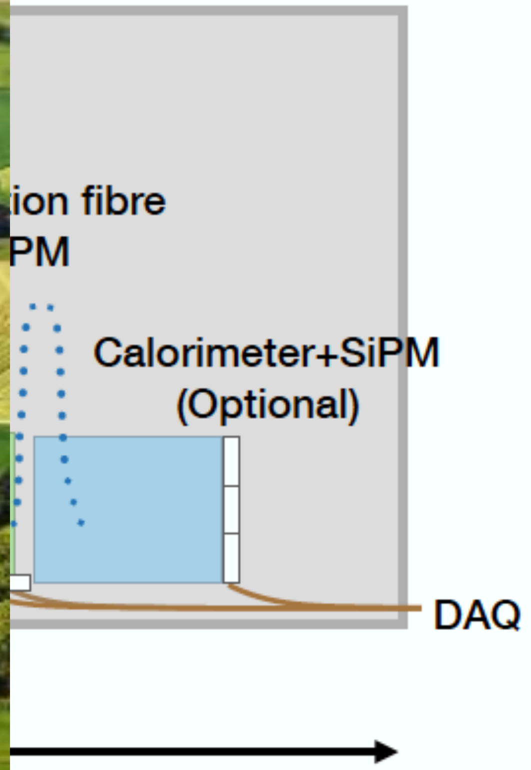




Beam siz







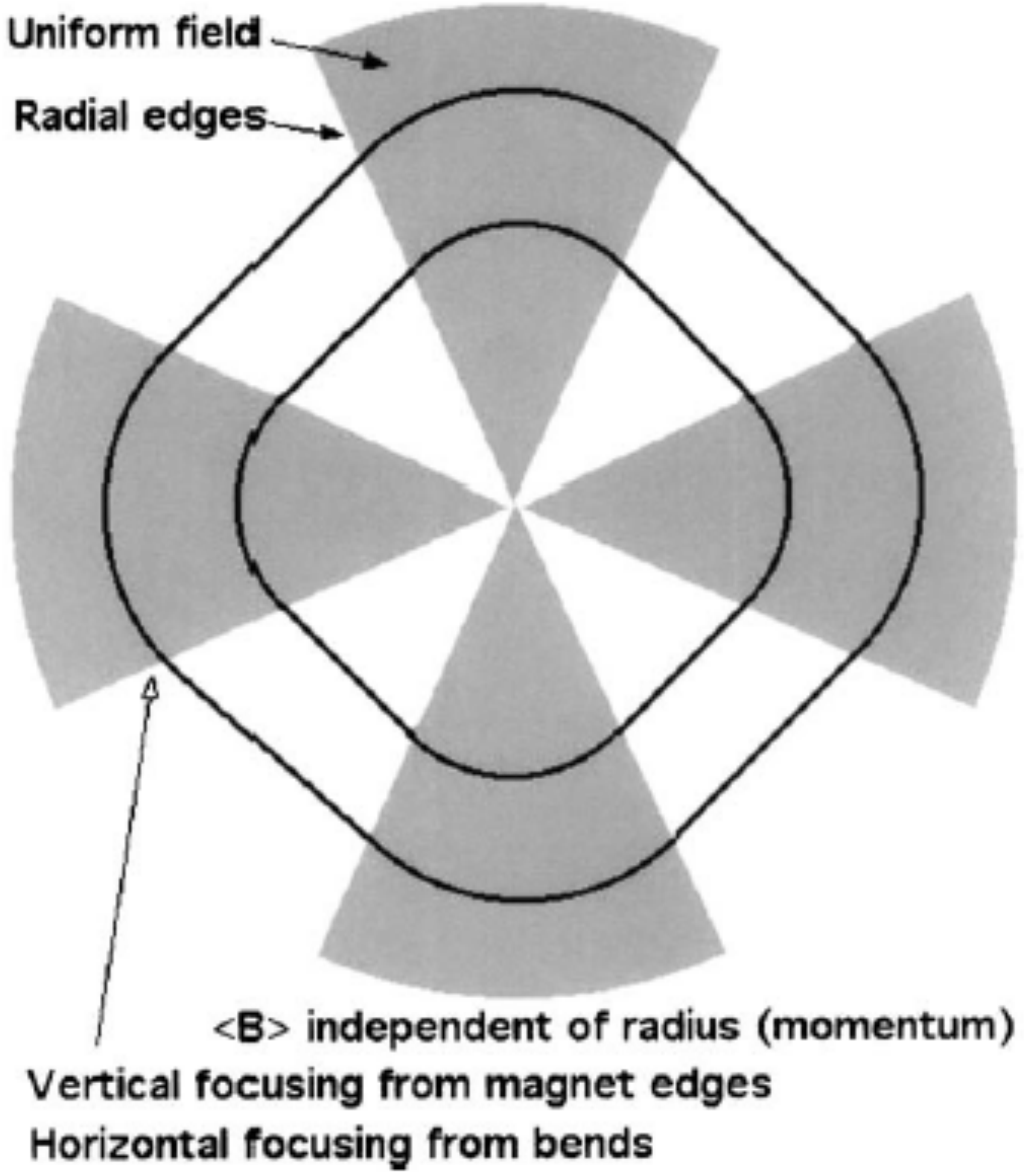
R_{μ}: 6.2 × 10^{6} μ^{+}/s @2.2 mA
Horizontal emittance: 105.24 mm•mrad
Vertical emittance: 33.28 mm•mrad

Test beam 2020
(I was supposed to be there,
oh well ……)

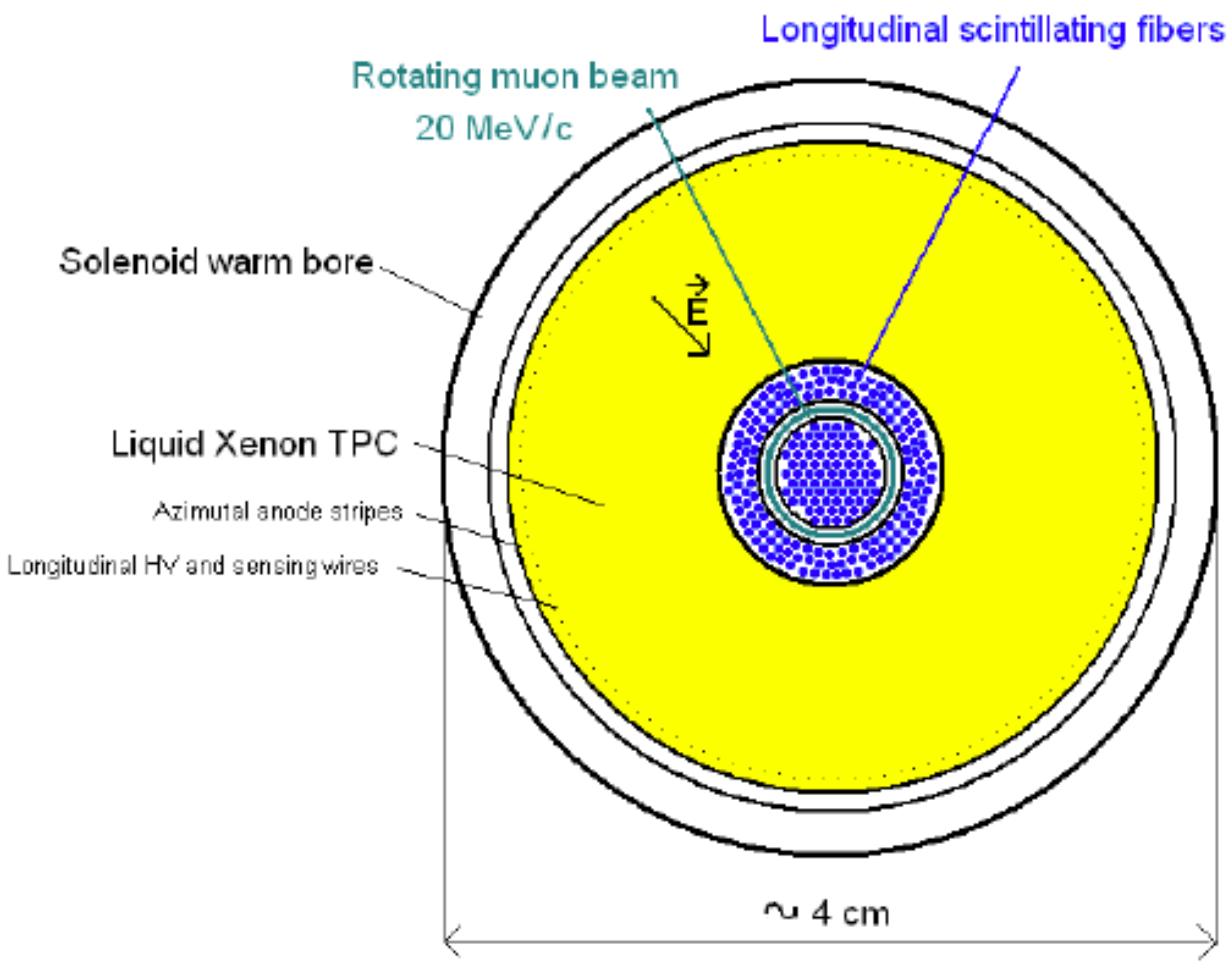
How to go beyond 100 ppb?

- High momentum and high B-field approaches are being proposed in the past
  - Farley 15 GeV
  - Taqqu 20-T field

$$\frac{\delta\omega_a}{\omega_a} = \frac{1}{\omega_a}\cdot\frac{\sqrt{2}}{\gamma\tau_\mu AP}\cdot\frac{1}{\sqrt{N}} \approx \frac{0.0398}{\sqrt{N}}.$$



F.J.M. Farley, 523 (2004) 251–255



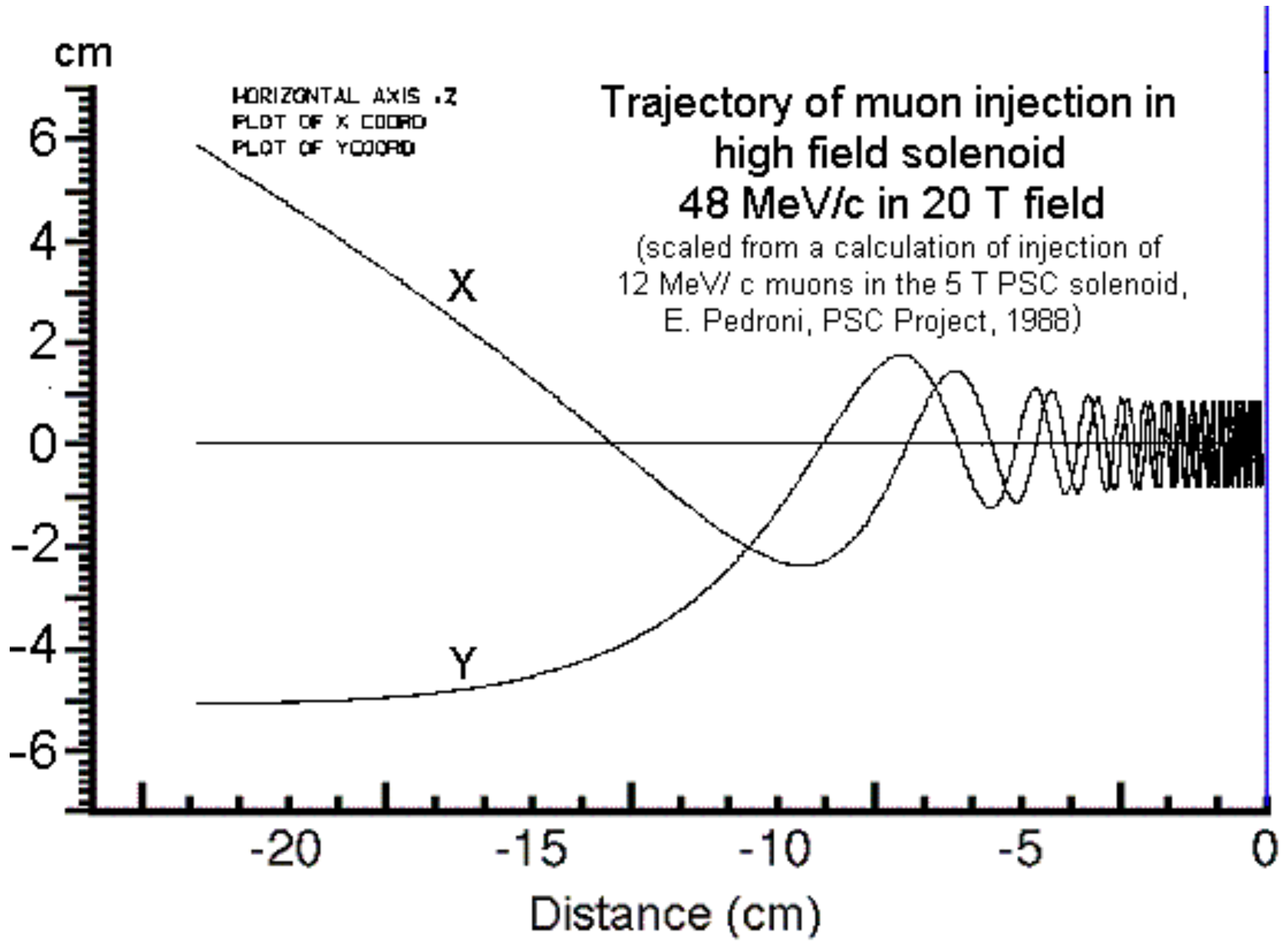

Trajectory of muon injection in high field solenoid
48 MeV/c in 20 T field
(scaled from a calculation of injection of 12 MeV/ c muons in the 5 T PSC solenoid, E. Pedroni, PSC Project, 1988)

			Figure of merit
Experiment	B-field	γ	B γ
Brookhaven	1.5 T	29.4	44
J-Park	3 T	3	9
PSI	20 T	1	20

D. Taqqu, Poster at PSI 2013, PSI

How to go beyond 10^{-23} ecm?

- Low momentum lattice and compact storage ring approaches are being proposed in the past
  - J-PARC PRISM 500 MeV/c - Lattice storage ring
  - PSI 200 MeV/c - Compact storage ring

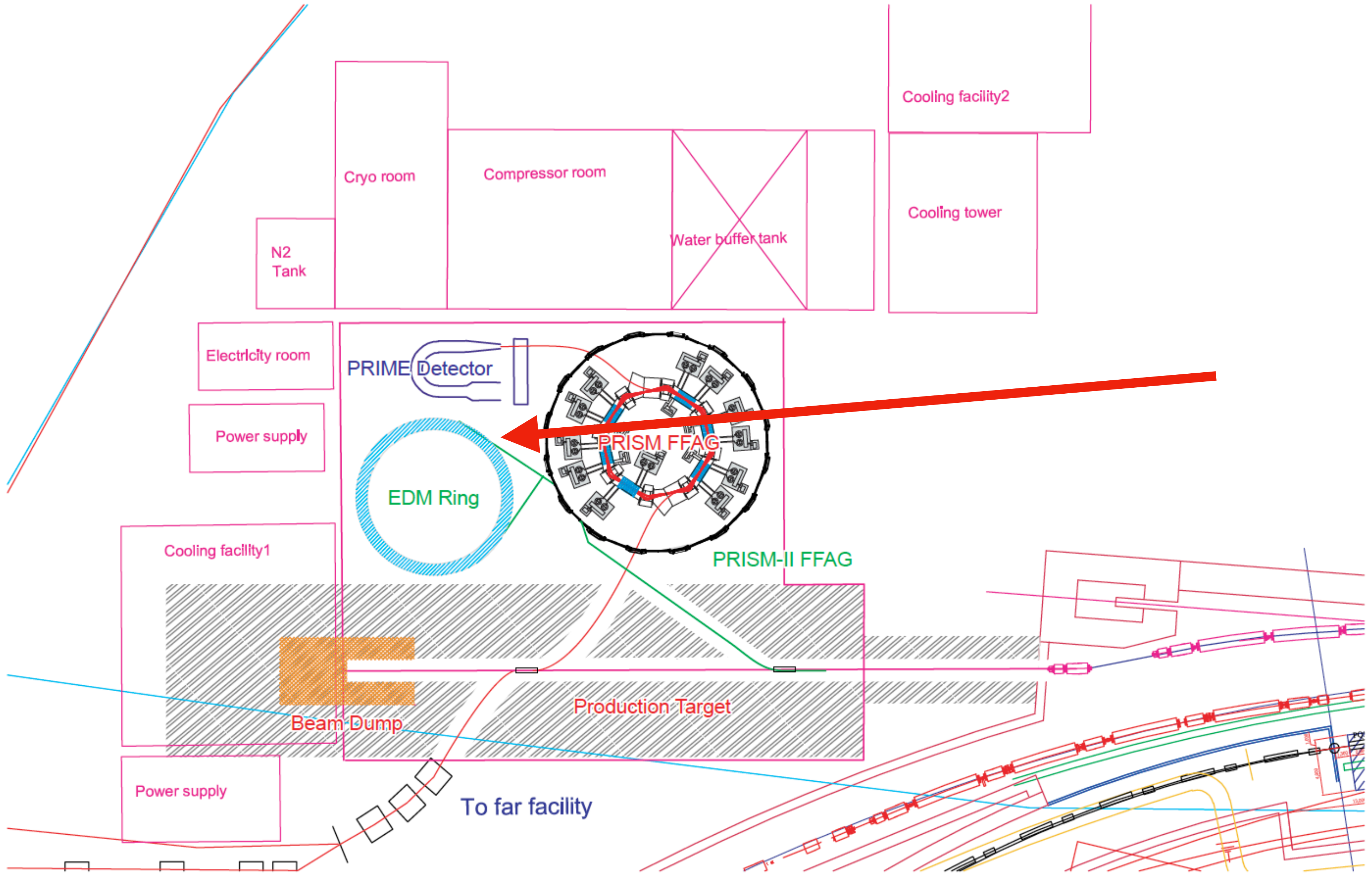
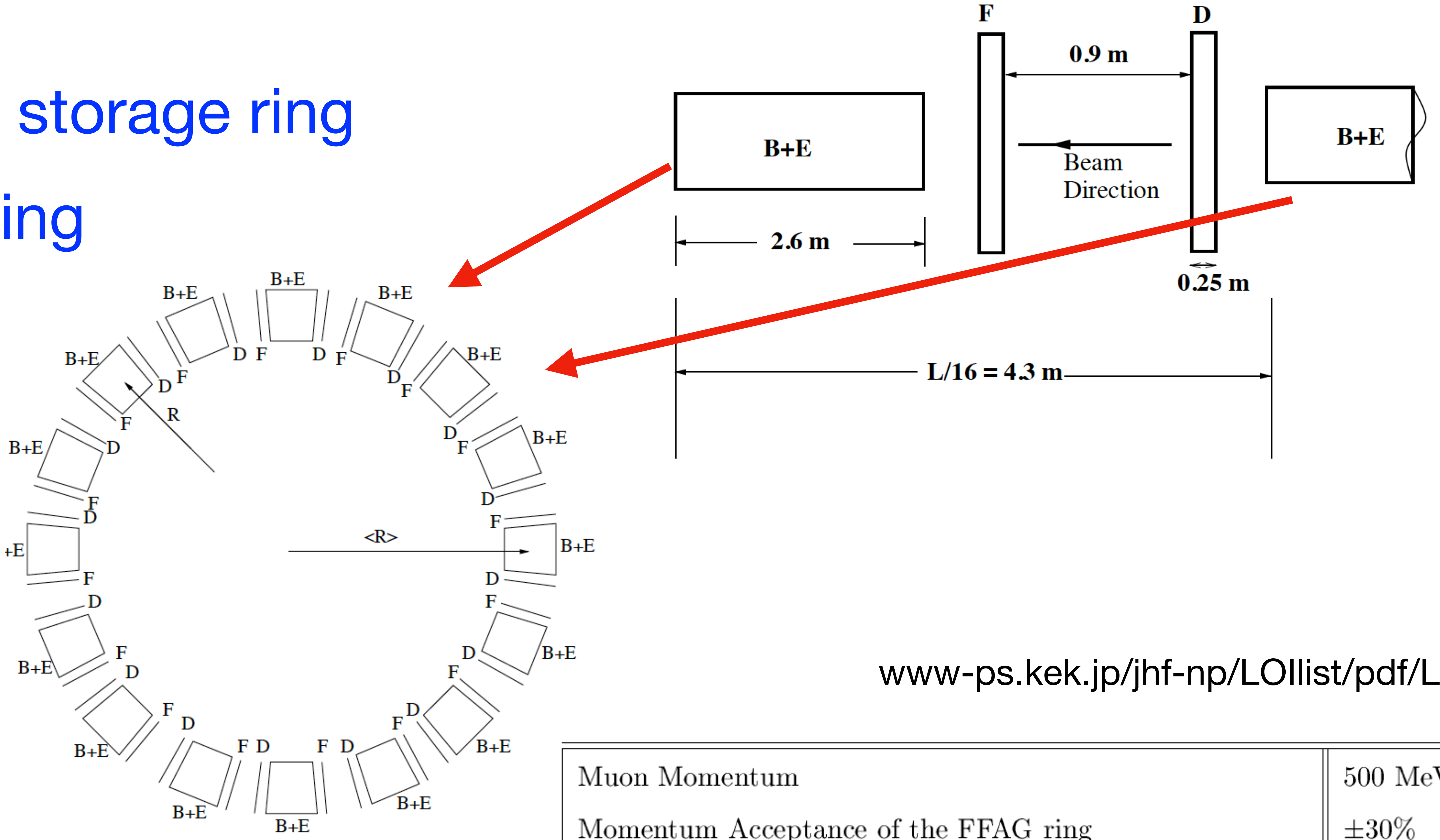
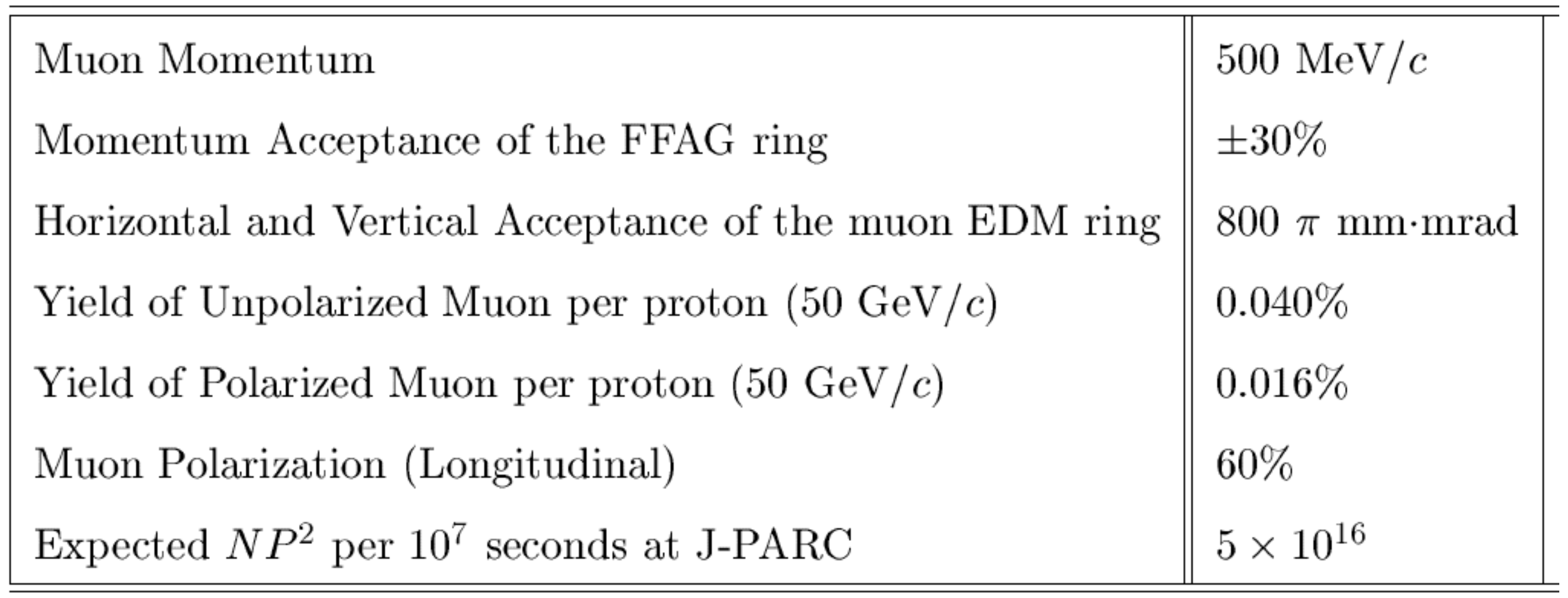


Figure 9.3: A possible layout of the near facility where PRISM and PRISM-II are installed.



www-ps.kek.jp/jhf-np/LOIlist/pdf/L22.pdf



Muon Momentum	500 MeV/c
Momentum Acceptance of the FFAG ring	±30%
Horizontal and Vertical Acceptance of the muon EDM ring	800 π mm·mrad
Yield of Unpolarized Muon per proton (50 GeV/c)	0.040%
Yield of Polarized Muon per proton (50 GeV/c)	0.016%
Muon Polarization (Longitudinal)	60%
Expected NP^2 per 10^7 seconds at J-PARC	5×10^{16}

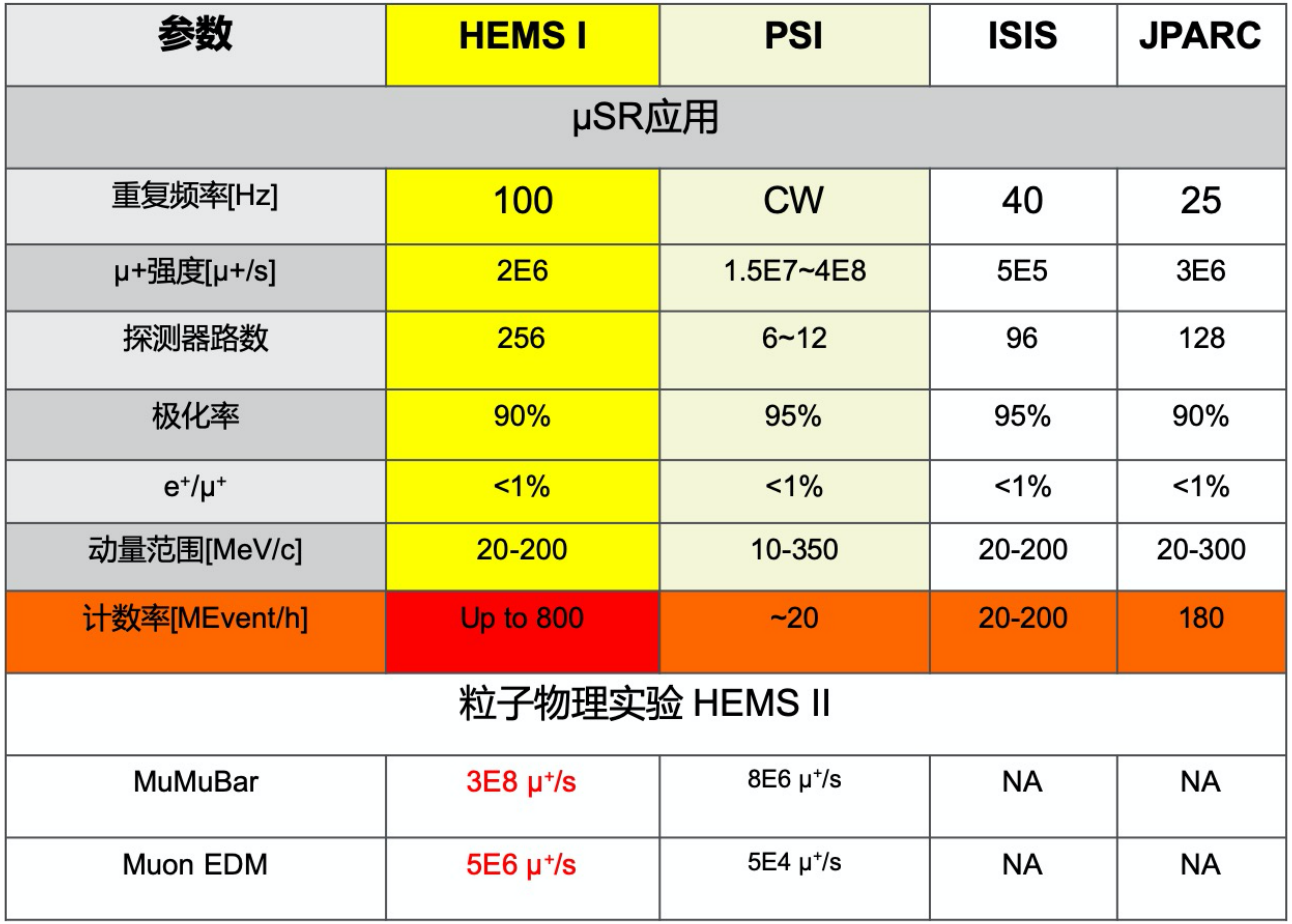
Beam quality for precision muon measurements

- A typical surface muon source has an emittance of $1000\pi\ \mathrm{mm} \cdot \mathrm{mrad}$
- Such a beam is not suitable for storage ring experiments (g-2/EDM)
  - Small acceptance for the storage ring (1-2% storage for FNAL Muon g-2)
  - Large systematic bias if there is a large momentum spread
  - Therefore cooling or phase-space compression is needed
- Available/proposed techniques (improvement in emittance/phase-space)
  - PSI muCool - Helium gas target + E/B field (10^{10} phase space, 1 eV - 1 mm)
  - PSI muE4 (muSR) - Solid rare gases + re-acceleration (15 eV→0-30 keV, 20 eV spread)
  - J-PARC muon g-2/edm - Mu production + ionization + re-acceleration (~ 1000)
  - US/UK/Japan MuCool - Ionization cooling (a few hundreds)

General requirements for future experiments

- Quantity
  - At least 10^{14} muons will be needed to improve the experiments by an order of magnitude (10s of ppb for g-2, 10^{-24} e·cm for EDM)
  - Assuming 3 years of data taking (50% duty cycle), a minimum of 2 x 10^{6}/s “good” muons will be needed
  - A typical acceptance of 1% or less implies at least 2 x 10^{8}/s of incoming muons (without cooling)
  - To reduce pileup rate, 100 bunch/s or more is desired
- Quality
  - Reducing beam emittance will be critical for compact storage ring experiments
  - Less important for lattice-type experiments but will help in reducing systematics

Possibilities at CSNS



参数	HEMS I	PSI	ISIS	JPARC
μSR应用				
重复频率[Hz]	100	CW	40	25
μ+强度[μ+/s]	2E6	1.5E7~4E8	5E5	3E6
探测器路数	256	6~12	96	128
极化率	90%	95%	95%	90%
e^+/μ^+	<1%	<1%	<1%	<1%
动量范围[MeV/c]	20-200	10-350	20-200	20-300
计数率[MEvent/h]	Up to 800	~20	20-200	180
粒子物理实验 HEMS II				
MuMuBar	3E8 μ^+/s	8E6 μ^+/s	NA	NA
Muon EDM	5E6 μ^+/s	5E4 μ^+/s	NA	NA

Courtesy 鲍煜

- High rEpetition rate Muon Source (HEMS) at CSNS
  - Still under R&D (Yu Bao)
  - HEMS I - Could be used for the phase I of g-2/EDM experiments
  - HEMS II - Could reach precision comparable with current g-2/EDM experiments
  - Definitely worth exploring given that there are no dedicated muon source for muon physics experiments

Summary

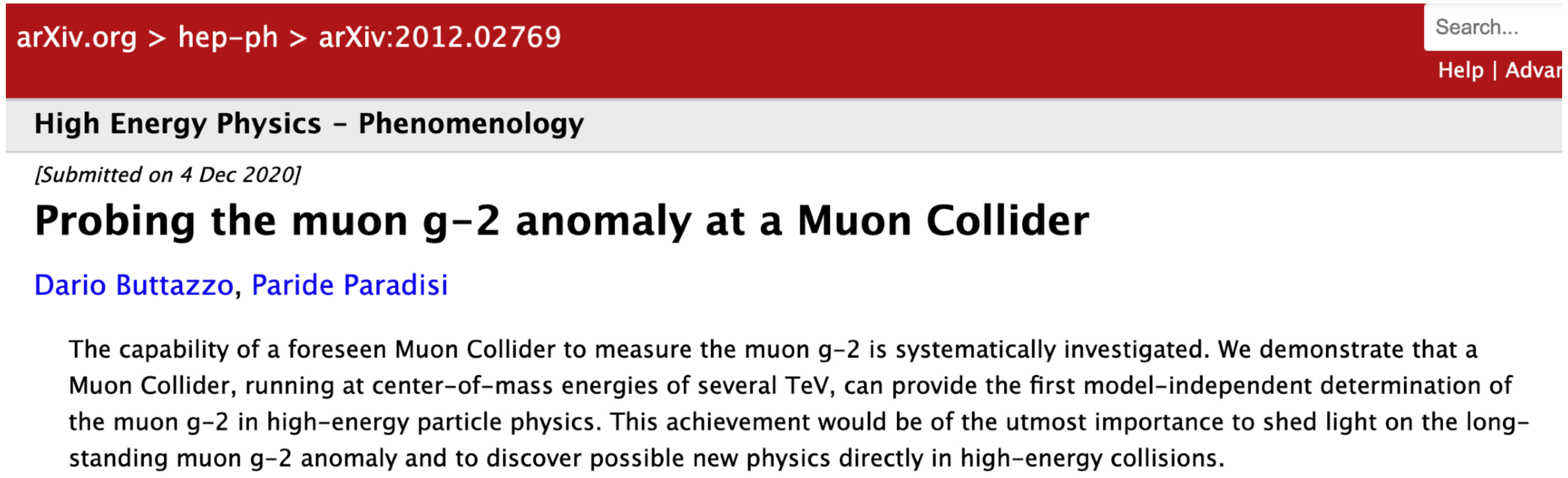
- Muon is a highly sensitive probe for BSM physics
- Muon g-2 experiment at Fermilab is close in releasing the first result
- Will provide a hint to the community where the New Physics might be
- Various muon programs at the Intensity Frontier will benefit from it
  - Muon EDM? Muon-specific force? Lepton universality violation? etc
- Encouraging development for muon physics community in China:
  - The first high-intensity muon source EMuS will soon be built at CSNS (~ 5 years)
  - Another high-momentum (~GeV/c) muon beam a possibility at HIAF (5-10 years)
  - The MACE experiment (Mu-Mubar conversion) could reach world-best limit in 10 years
  - Both projects (Muon g-2 and EDM are supported by NSFC, Thank you very much!!!)

Thanks !

李政道研究所
Tsung-Dao Lee Institute

上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

New Idea: Crazy idea?



High Energy Physics – Phenomenology

[Submitted on 4 Dec 2020]

Probing the muon g-2 anomaly at a Muon Collider

Dario Buttazzo, Paride Paradisi

The capability of a foreseen Muon Collider to measure the muon g-2 is systematically investigated. We demonstrate that a Muon Collider, running at center-of-mass energies of several TeV, can provide the first model-independent determination of the muon g-2 in high-energy particle physics. This achievement would be of the utmost importance to shed light on the long-standing muon g-2 anomaly and to discover possible new physics directly in high-energy collisions.

https://arxiv.org/abs/2012.02769

$$\sigma_{\mu\mu\to c\bar{c}} \approx 100\,\mathrm{fb}\left(\frac{\sqrt{s}}{3\,\mathrm{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2$$

$$\sigma^{\mathrm{SM}}_{\mu\mu\to Zh} \approx 122\,\mathrm{ab}\left(\frac{10\,\mathrm{TeV}}{\sqrt{s}}\right)^2 \qquad \sigma_{\mu\mu\to Zh} \approx 38\,\mathrm{ab}\left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2 .$$

$$\sigma^{\mathrm{SM}}_{\mu\mu\to t\bar{t}} \approx 1.7\,\mathrm{fb}\left(\frac{10\,\mathrm{TeV}}{\sqrt{s}}\right)^2 \qquad \sigma_{\mu\mu\to t\bar{t}} = \frac{s}{6\pi}\frac{|C_T^{\mu t}(\Lambda)|^2}{\Lambda^4}N_c \approx 58\,\mathrm{ab}\left(\frac{\sqrt{s}}{10\,\mathrm{TeV}}\right)^2\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2 .$$

$$\sigma^{\mathrm{SM}}_{\mu\mu\to h\gamma} \approx 3.7\times10^{-3}\,\mathrm{ab}\left(\frac{30\,\mathrm{TeV}}{\sqrt{s}}\right)^2 \qquad \sigma^{\mathrm{cut}}_{\mu\mu\to h\gamma} \approx 0.53\,\mathrm{ab}\left(\frac{\Delta a_\mu}{3\times10^{-9}}\right)^2 .$$

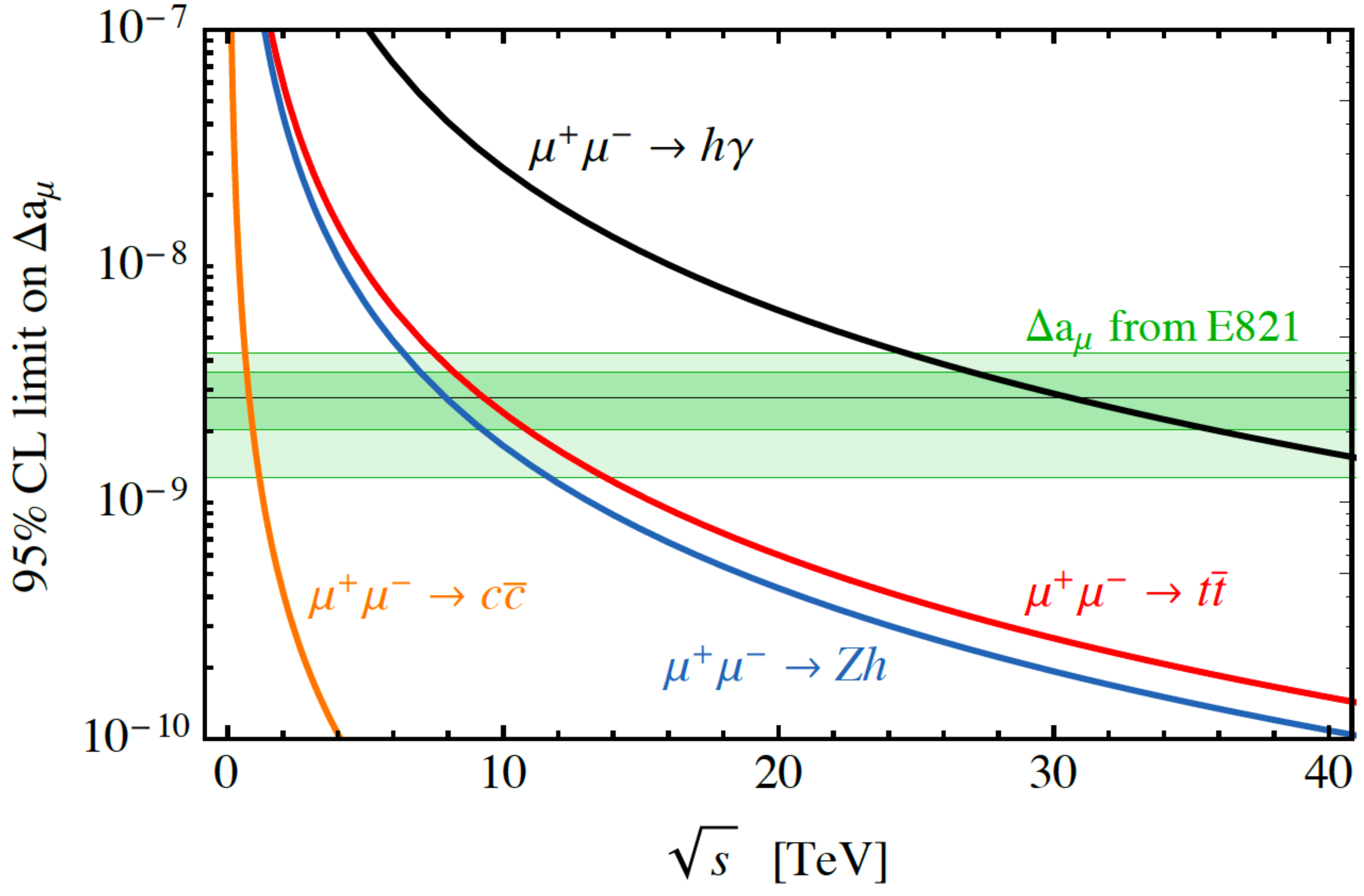


FIG. 2. 95% C.L. reach on the muon anomalous magnetic moment Δa_μ as a function of the collider center-of-mass energy $\sqrt{s}$ from the processes $\mu^+\mu^- \to h\gamma$ (black), $\mu^+\mu^- \to hZ$ (blue), $\mu^+\mu^- \to t\bar{t}$ (red), and $\mu^+\mu^- \to c\bar{c}$ (orange).

The HL-LHC will take over in 2026, with the goal of reaching **3000 fb^{-1} by 2037.**

References for Muon EDM

Year	Location	Publication	Limit [e cm] (95% C.L.)
1958	Columbia University	PRL 1, 144 (1958)	2.9 x 10^{-15}
1960	Columbia University	PR 118, 1086 (1960)	3.3 x 10^{-16}
1960	CERN	Il Nuovo Cimento XVII 3 (1960)	1.5 x 10^{-16}
1961	CERN	Il Nuovo Cimento XXII 5 (1961)	2.8 x 10^{-17}
1978	CERN	J. Phys. G 4, 345 (1978)	1.05 x 10^{-18}
2003	J-PARC	2003 (LOI) [J-PARC L22]	O(10^{-24})
2006	PSI	J. Phys. G 37, 085001 (2010)	7 x 10^{-23}
2009	BNL	PRD 80, 052008 (2009)	1.8 x 10^{-19}
2022?	FNAL	[FERMILAB-PROPOSAL-0989] (2009)	O(10^{-21})
2026?	J-PARC	[KEK_J-PARC-PAC2009-06] (2009)	O(10^{-21})
2027?	PSI	PRD 98, 113002 (2018)	5 x 10^{-23}

4 orders of magnitude in 50 years