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

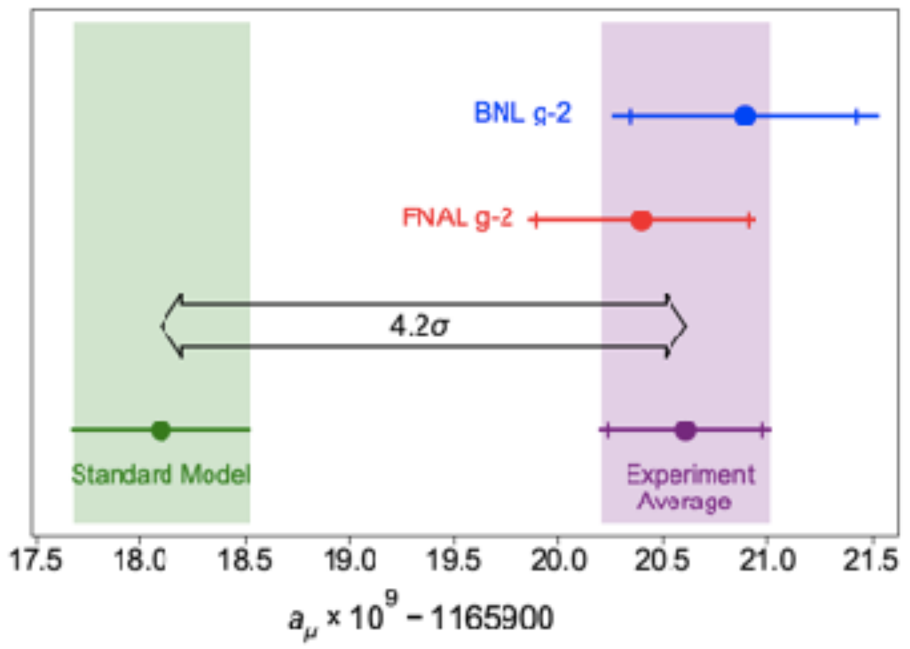
李政道研究所
Tsung-Dao Lee Institute
上海交通大学
SHANGHAI JIAO TONG UNIVERSITY

费米实验室缪子g-2实验:首批物理结果

许金祥 (Kim-Siang Khaw)

江苏省青年物理学家论坛
2021年5月11日@南京大学

μ
g-2



美国 (2015-2019)
华盛顿大学-博士后

瑞士 (2011-2015)
苏黎世联邦理工学院-博士

日本 (2005-2011)
京都大学-学士
东京大学-硕士

中国 (2019-)
交大-李政道学者，副教授

马来西亚
高中毕业

京都大学校友专访@费米实验室

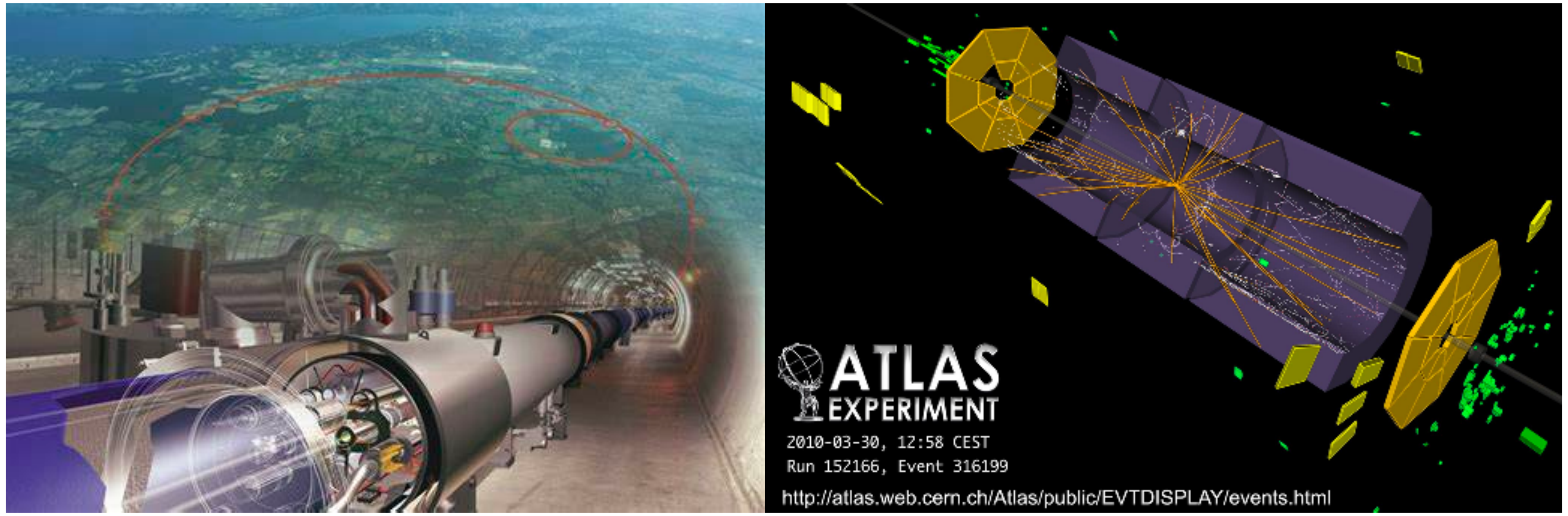
and then due to the interaction between the spin and the magnetic field,

Alumni profiles: "Free Thinkers"-Kim Siang Khaw-

448 views

高精度前沿（High-precision frontier）

- 通过精确计算和精确测量验证
  - 理论计算和框架
  - 实验方法
- 从偏差中找出
  - 未知的物理或粒子
- 不仅限于粒子物理
  - 天文学等领域也有非常多的例子（海王星的发现）



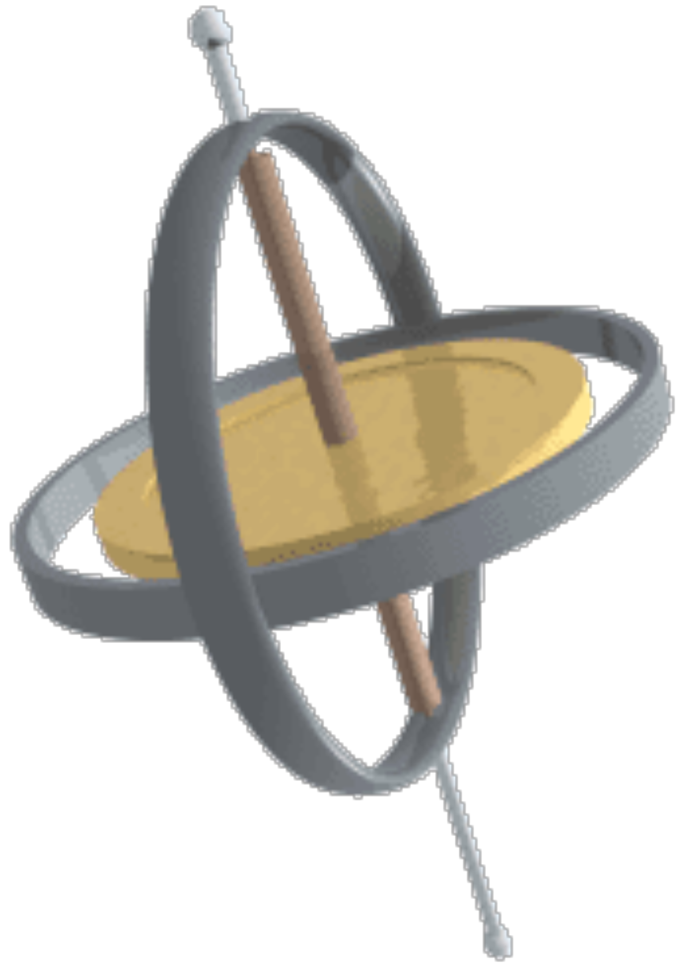
与大家更为熟悉的“高能量前沿”互补！

基本粒子的磁矩

基本粒子的磁矩

- 质量 m，电荷 e，内禀角动量（自旋）$\vec{S}$ 的基本粒子的磁矩
- g-因子是比例系数，代表着磁矩的强度
  - 粒子的自旋在磁场中会进行进动运动（陀螺）
  - 可以通过测量进动频率获得g-因子

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



$$\omega_s = g\frac{eB}{2m}$$

电子的磁矩：狄拉克理论预言

- 1928年狄拉克（Dirac）结合狭义相对论和量子力学
  - 自旋为1/2的带电基本粒子g=2

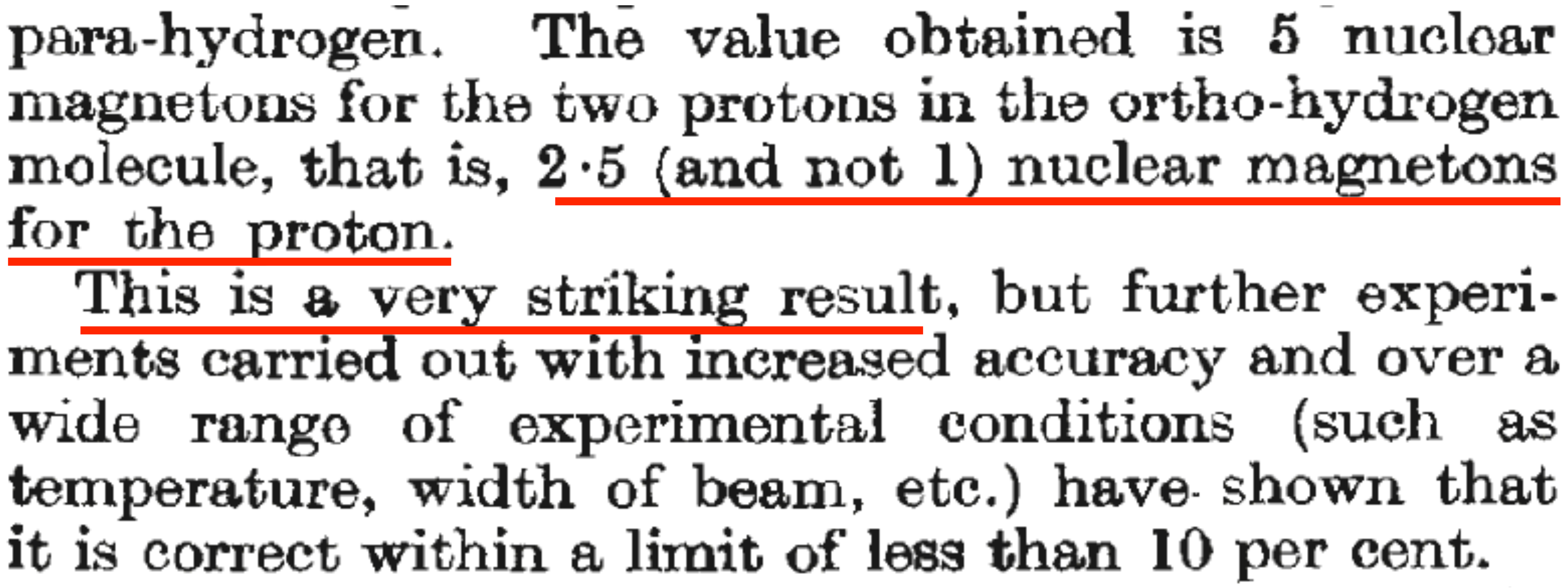
$$\left(\frac{1}{2m}(\vec{P}+e\vec{A})^2+\frac{e}{2m}\vec{\sigma}\cdot\vec{B}-eA^0\right)\psi_A=(E-m)\psi_A$$

- 与当时的斯特恩-盖拉赫(Stern-Gerlach)实验吻合！
- 之后20年的实验结果也符合g=2的狄拉克预言！

P. A. M. Dirac, Proc. R. Soc. A 118, 351 (1928)

质子的磁矩

- 在狄拉克的理论取得重大成果之后，大家纷纷转向其它粒子
- 1933年，斯特恩和埃斯特曼测量了质子的g-因子
  - 结果：$g_p \sim 5!$（首个“反常”磁矩）



para-hydrogen. The value obtained is 5 nuclear magnetons for the two protons in the ortho-hydrogen molecule, that is, 2·5 (and not 1) nuclear magnetons for the proton.

This is a very striking result, but further experiments carried out with increased accuracy and over a wide range of experimental conditions (such as temperature, width of beam, etc.) have shown that it is correct within a limit of less than 10 per cent.

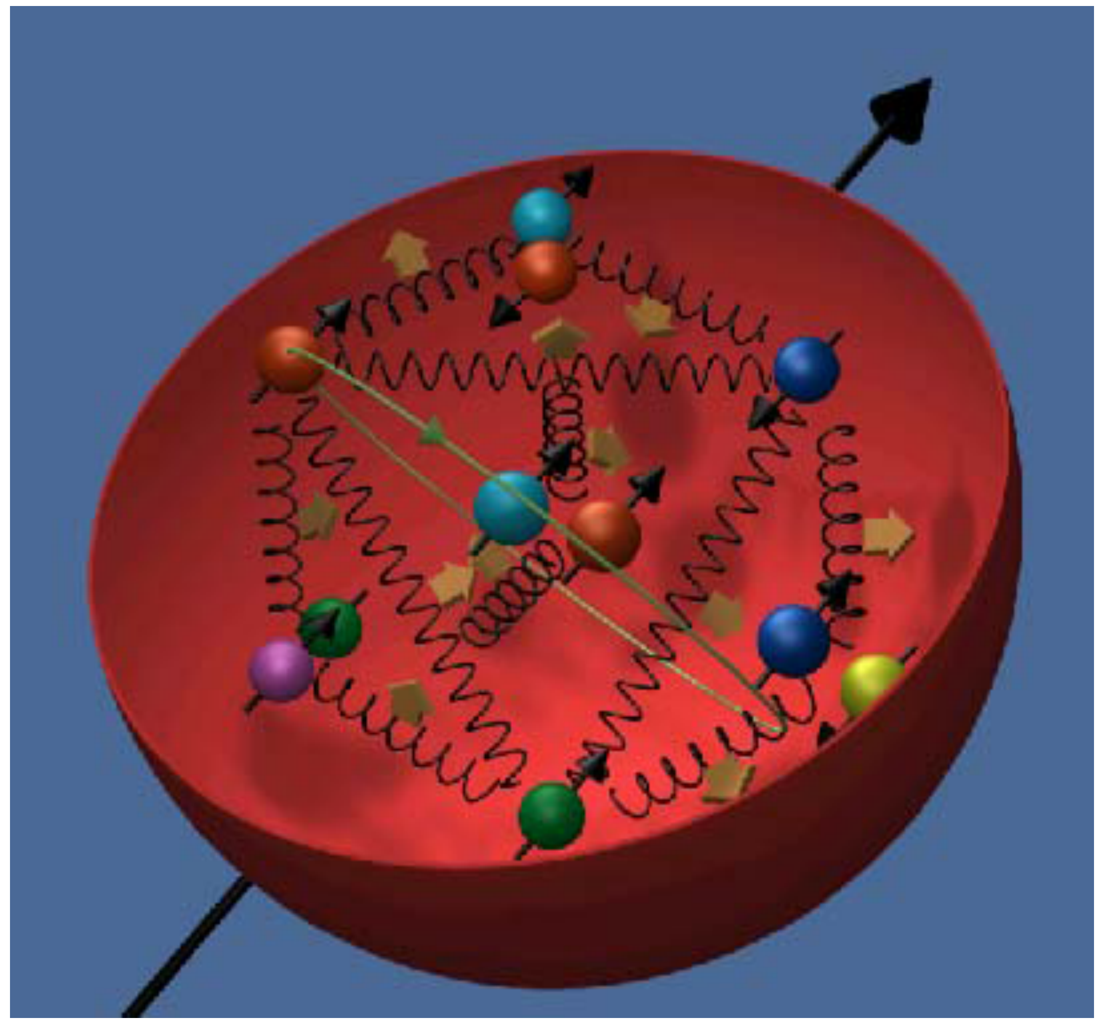
“Don't you know the Dirac theory?
It is obvious that g_p=2!”
泡利（Pauli）

Nature 132, 169–170 (1933)
Z. Phys. 85 4 (1933)
Z. Phys. 85 17 (1933)

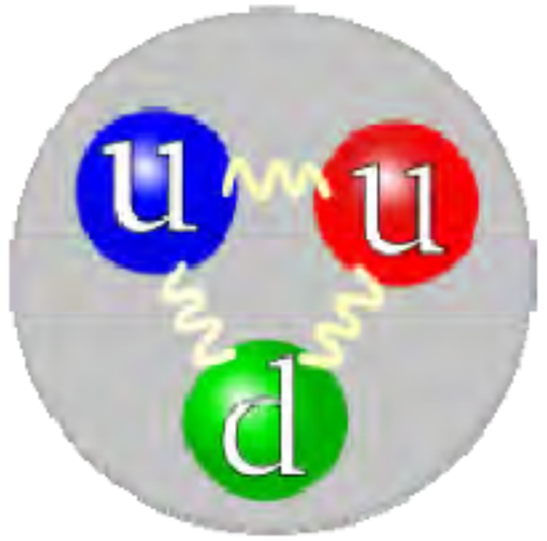
中子的磁矩

- 同年，拉比（Isidor Rabi）通过重氢核间接测量中子的g-因子
  - 结果：g_n ~ 3.8! (不带电粒子竟然有磁矩？)

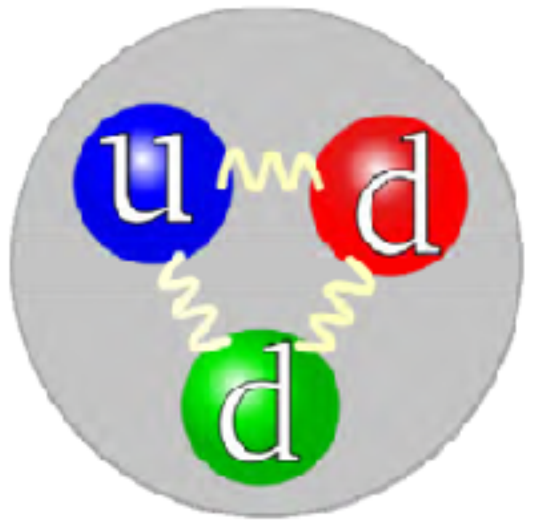
$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$



30多年之后出现夸克模型



质子

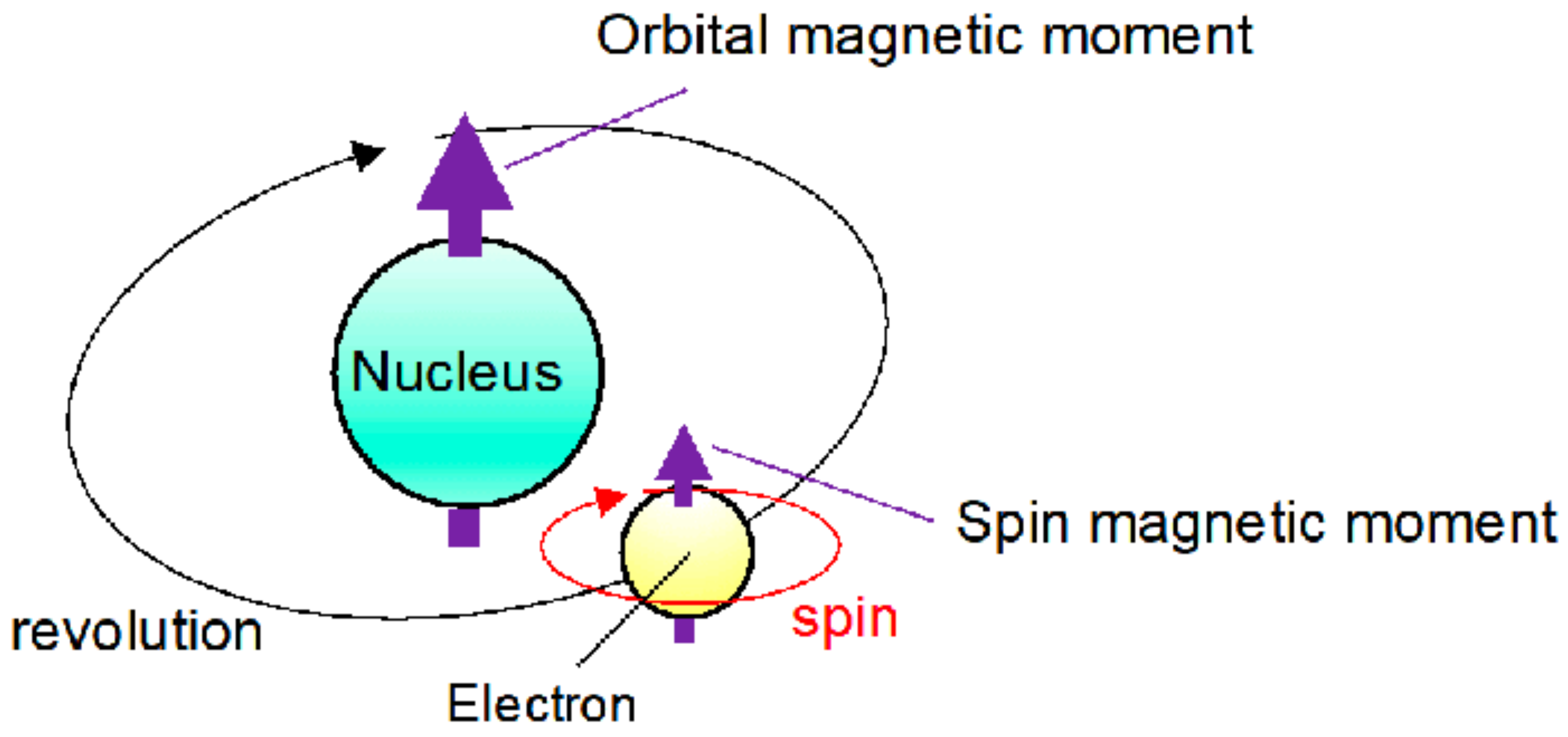


中子

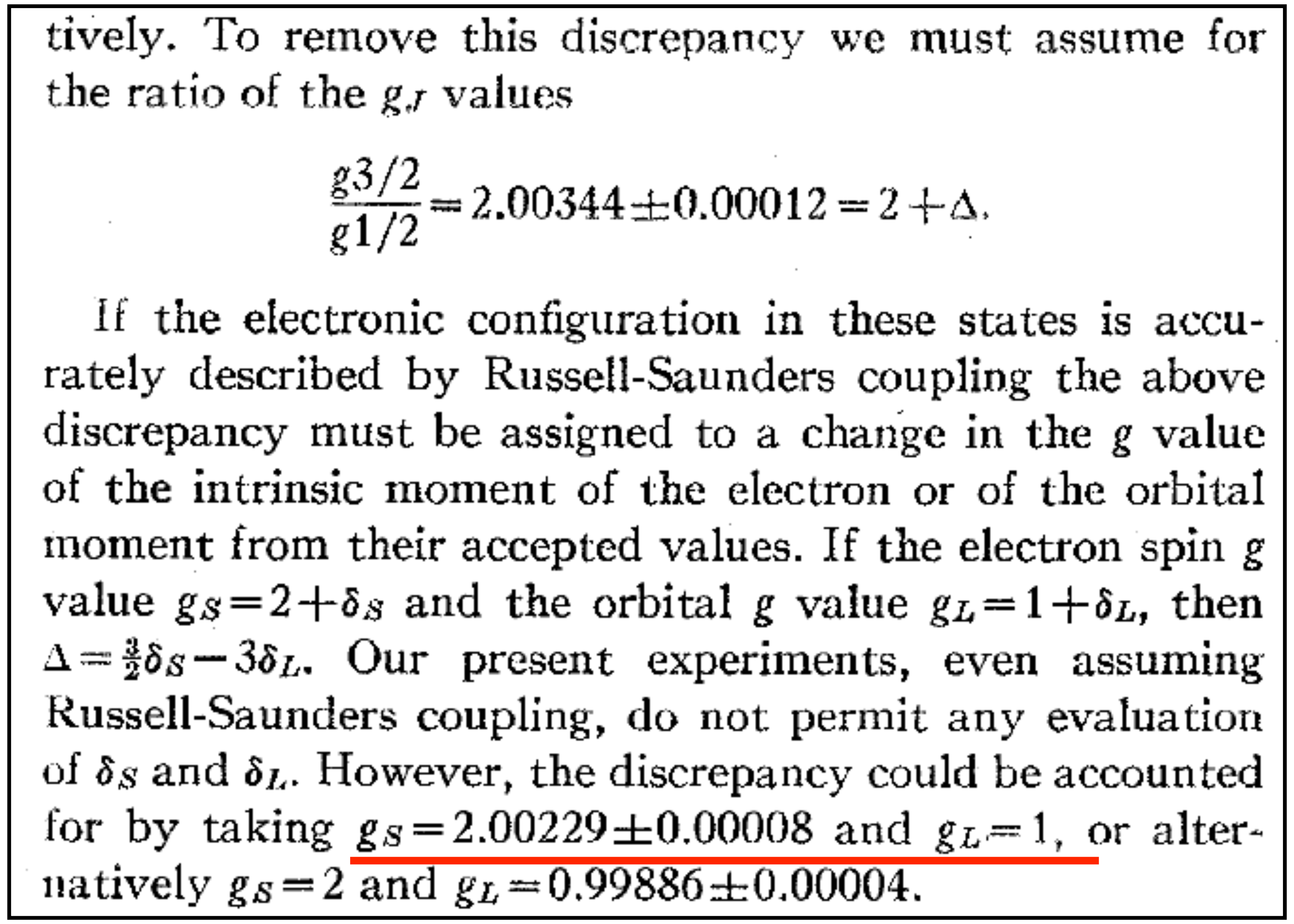
Phys. Rev. 46, 163 (1934)

类氢原子的超精细结构

- 超精细能级差（hyperfine structure）的理论计算和测量值有偏差
  - 三个原子系统（氢原子，重氢原子，镓原子）
- 自旋磁矩或者轨道磁矩的g-因子需要修正！



库什（Kusch）和弗利（Foley）


tively. To remove this discrepancy we must assume for the ratio of the g_J values

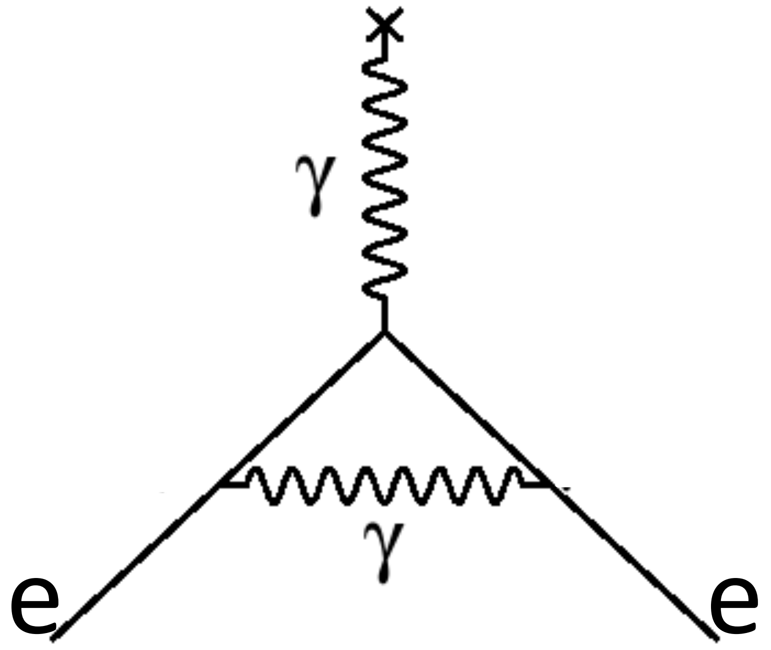
$$\frac{g3/2}{g1/2}=2.00344\pm0.00012=2+\Delta.$$

If the electronic configuration in these states is accurately described by Russell-Saunders coupling the above discrepancy must be assigned to a change in the g value of the intrinsic moment of the electron or of the orbital moment from their accepted values. If the electron spin g value $g_S=2+\delta_S$ and the orbital g value $g_L=1+\delta_L$, then $\Delta=\frac{2}{3}\delta_S-3\delta_L$. Our present experiments, even assuming Russell-Saunders coupling, do not permit any evaluation of δ_S and δ_L. However, the discrepancy could be accounted for by taking $\underline{g_S=2.00229\pm0.00008 \text{ and } g_L=1}$, or alternatively $g_S=2$ and $g_L=0.99886\pm0.00004$.

J.E. Nafe, E.B. Nelson and I.I. Rabi, Phys. Rev. 71 (1947), 914-915
D.E. Nagle, R.S. Julian and J.R. Zacharias, Phys. Rev. 72 (1947), 971-971
P. Kusch and H.M. Foley, Phys. Rev. 72 (1947), 1256-1257

量子电动力学（QED）

- 朱利安·施温格（Julian Schwinger）知道了实验结果之后立即展开“量子辐射修正”的理论计算
  - 库什和弗里的推算：$g_e = 2.00229(8)$
  - 施温格的计算值：$g_e \approx 2(1 + \frac{\alpha}{2\pi}) \approx 2.00232$
- 理论计算值和实验值一致！

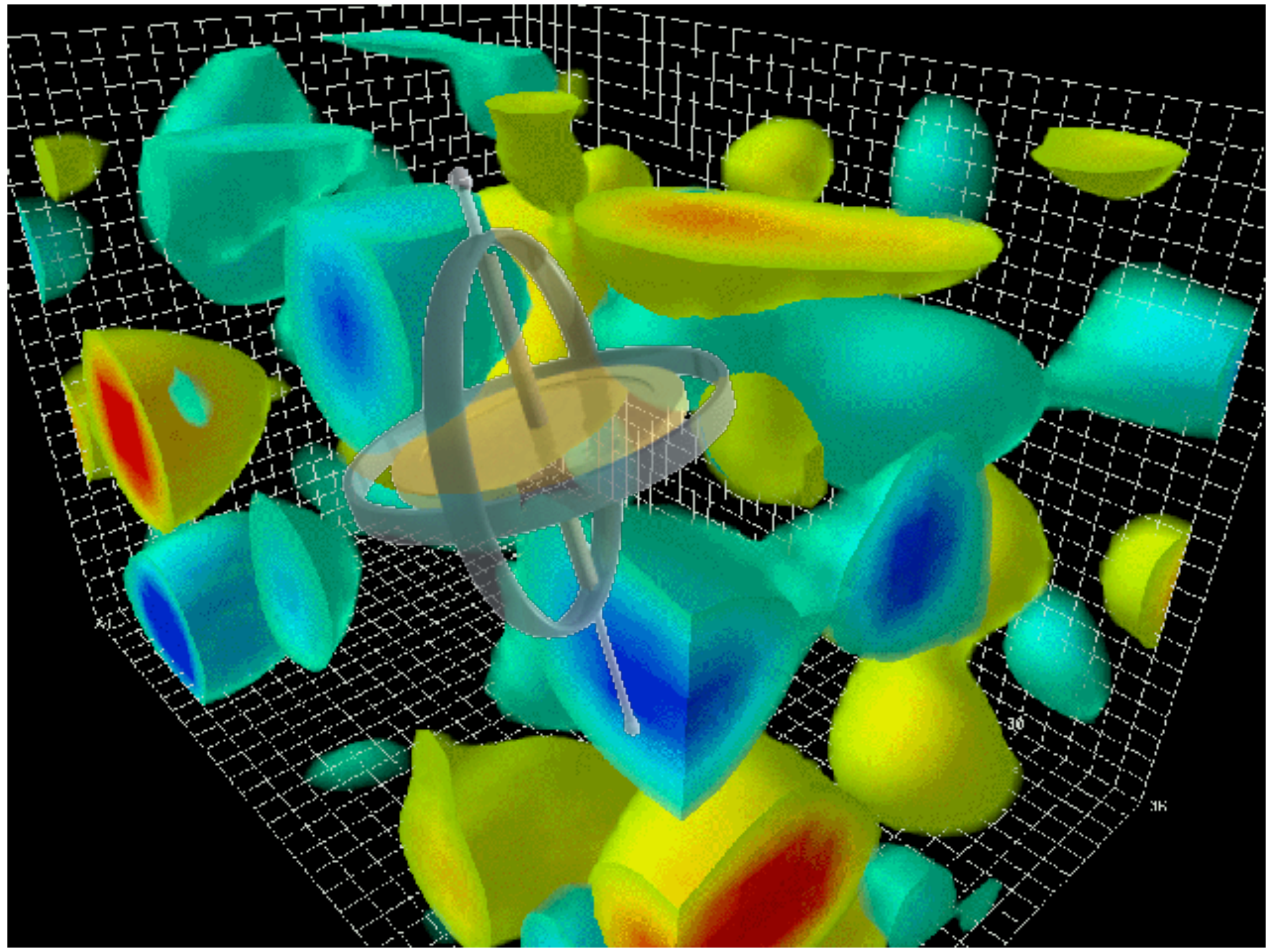


Phys. Rev. 73 (1948) 416-417

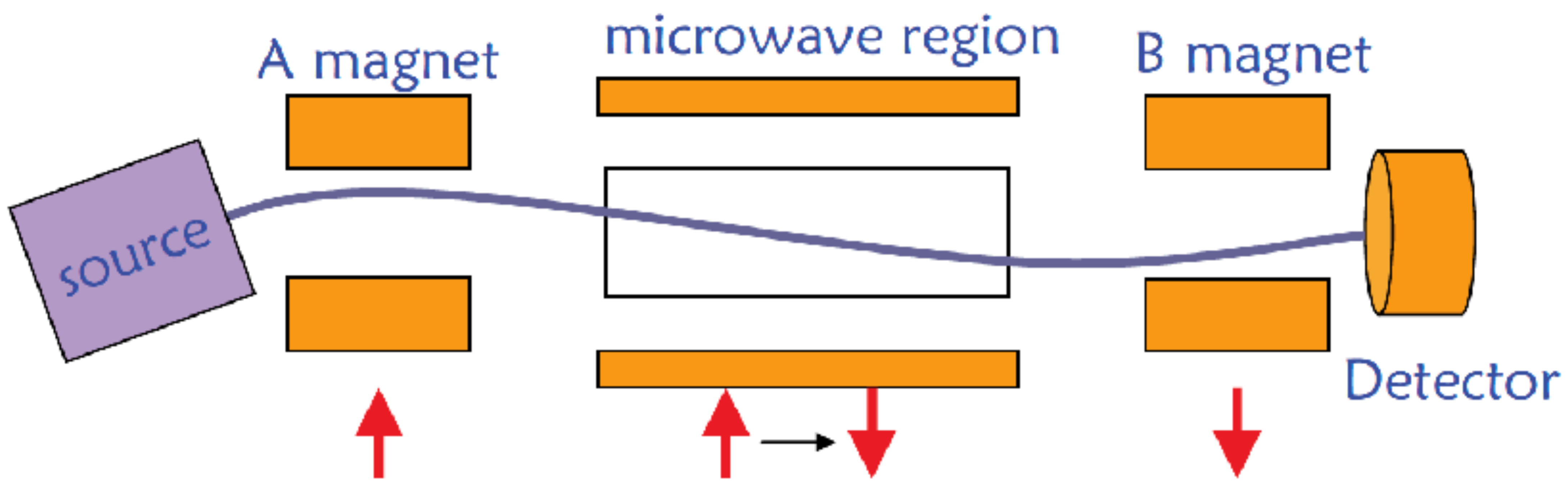
真空中的虚粒子

- 由于量子涨落，真空中频繁出现又迅速消失的虚粒子
- 这些虚粒子影响了粒子和磁场的相互作用
  - 需要对g-因子进行修正！
- 反常磁矩的定义 a = (g-2)/2 (与预言值g=2的百分比差异)

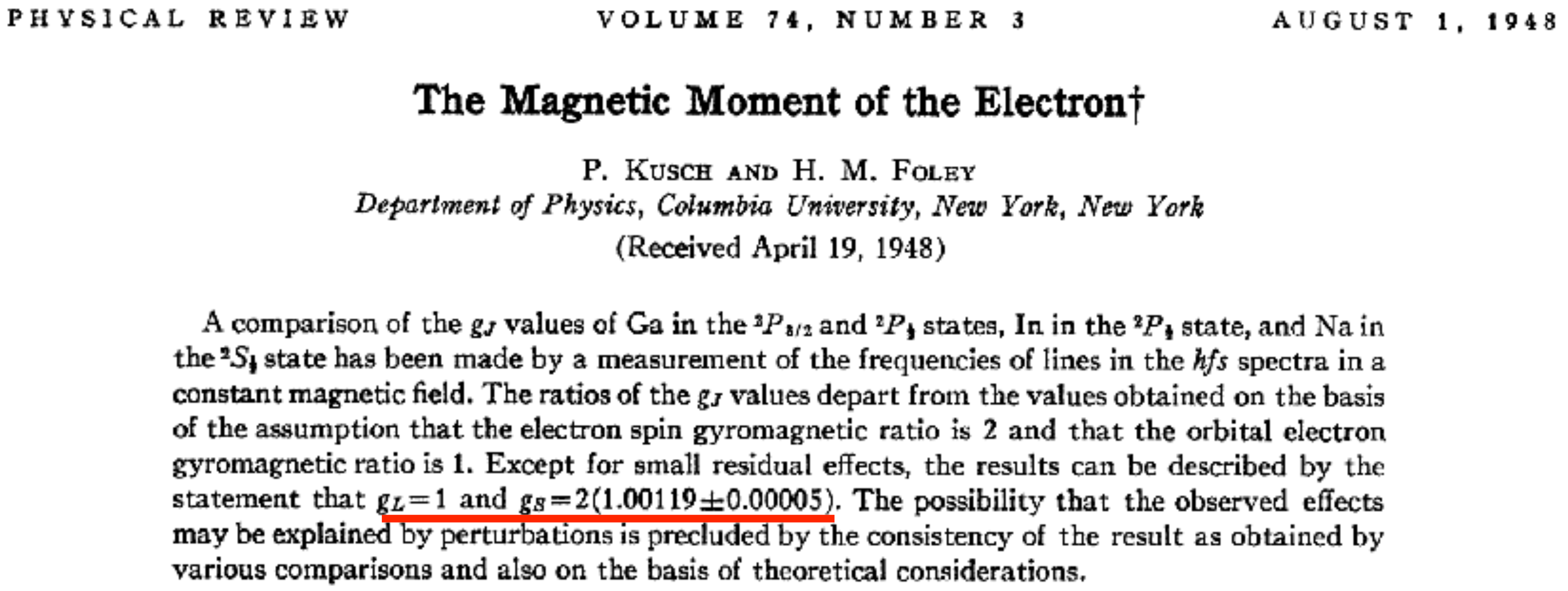
$$\Delta E \Delta t \geq \frac{h}{2\pi}$$



电子反常磁矩的发现



- 在1948年，库什（Kusch）和弗利（Foley）利用原子束磁共振实验技术进一步提高精度
- 通过对镓和钠的超精细能级差的测量获得结论
  - $g_e = 2.00238(10)$!
- 电子的反常磁矩 $a=(g-2)/2=0.1\%$



PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. Kusch and H. M. Foley
Department of Physics, Columbia University, New York, New York
(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{1/2}$ states, In in the $^2P_{1/2}$ state, and Na in the $^2S_{1/2}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L=1$ and $g_S=2(1.00119\pm0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

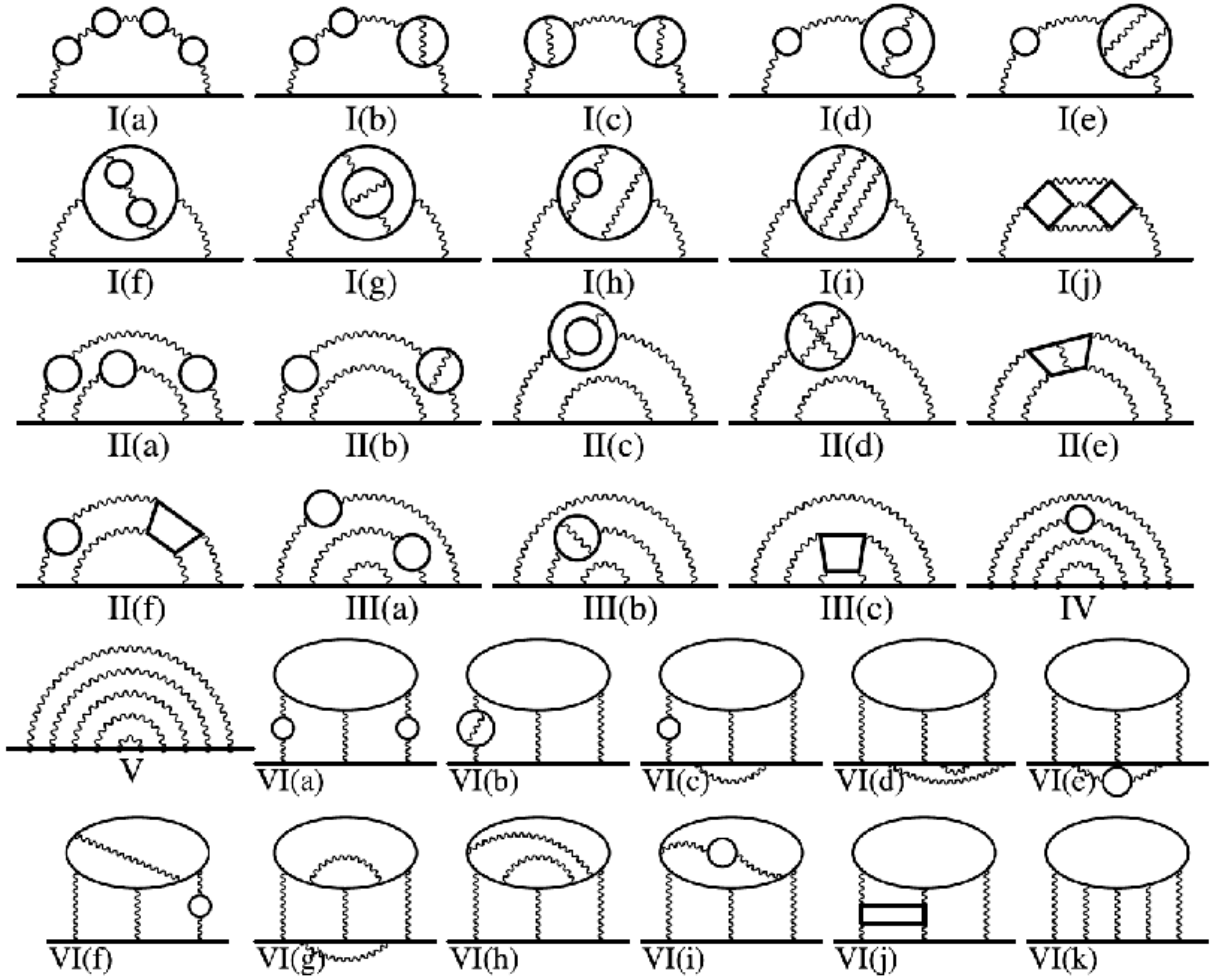
P. Kusch and H. M. Foley, Phys. Rev. 74, 250–263 (1948)

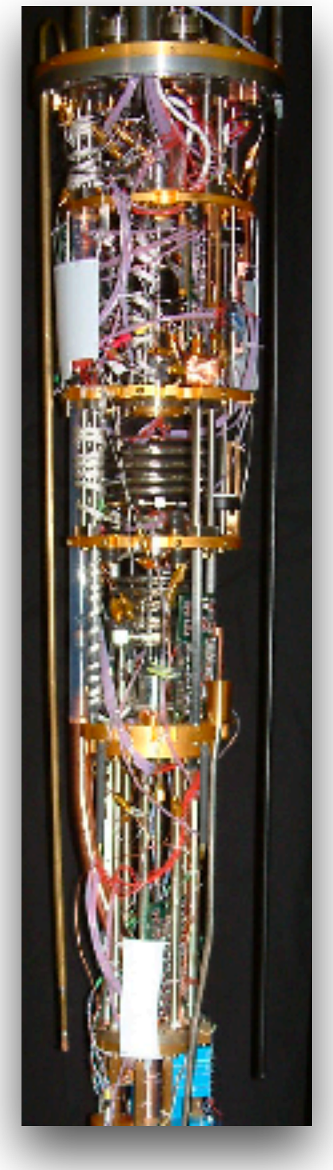
电子反常磁矩的最新结果

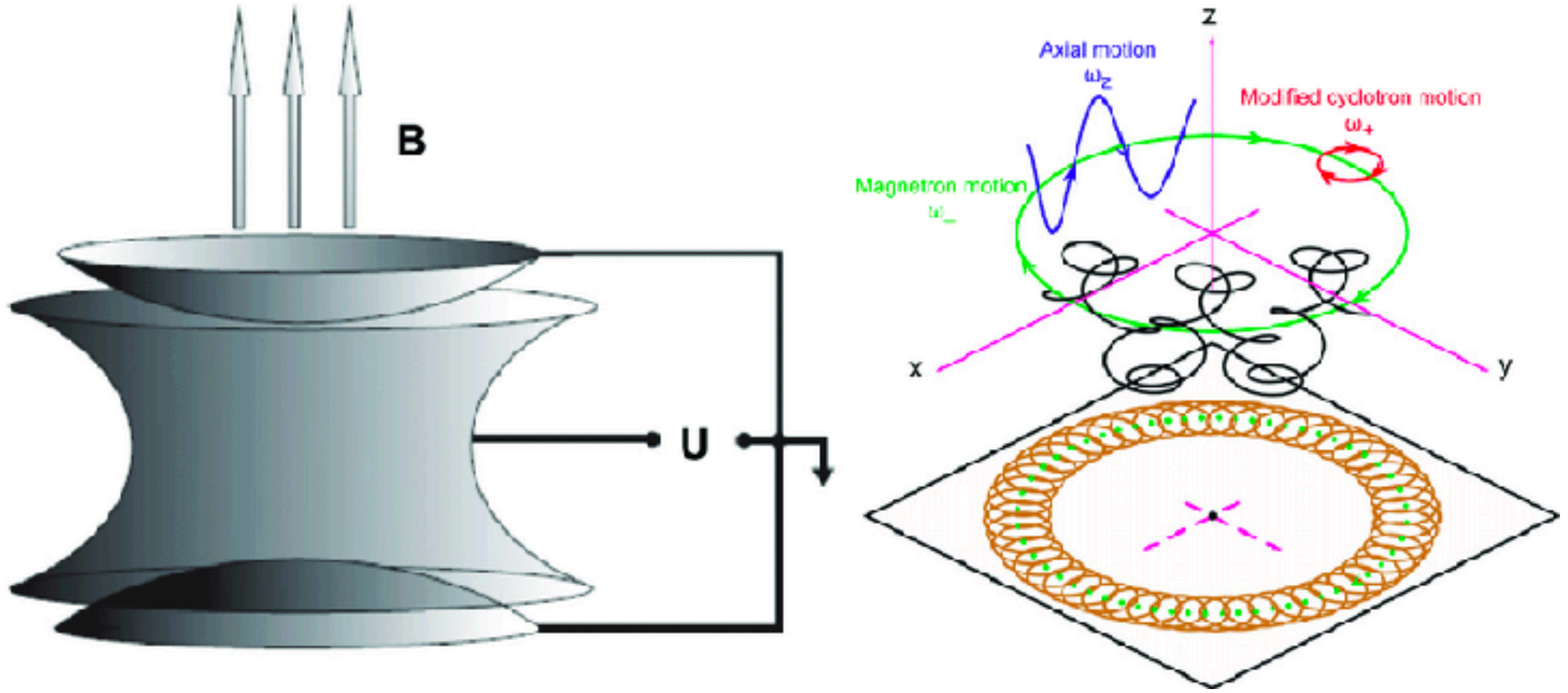
QED共12672张费曼图

- 目前已经计算到5圈图，共12672个费曼图
- 最新的理论值：2.002 319 304 360 50(19)
- 最新的实验值：2.002 319 304 361 46(56)

惊人的一致性！





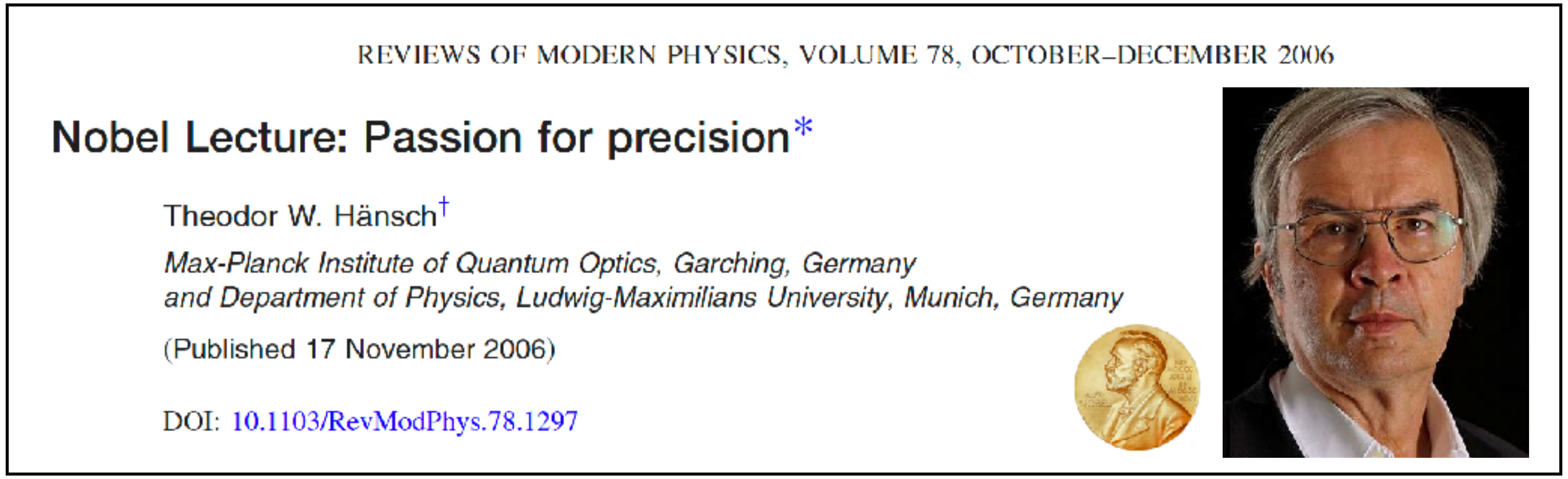


D. Hanneke et al., Phys. Rev. A 83, 052122

T. Aoyama et al., Phys. Rev. Lett. 109 (2012) 111807

高精度的来源：测频率！

特奥多尔·亨施，2005年诺奖



REVIEWS OF MODERN PHYSICS, VOLUME 78, OCTOBER–DECEMBER 2006

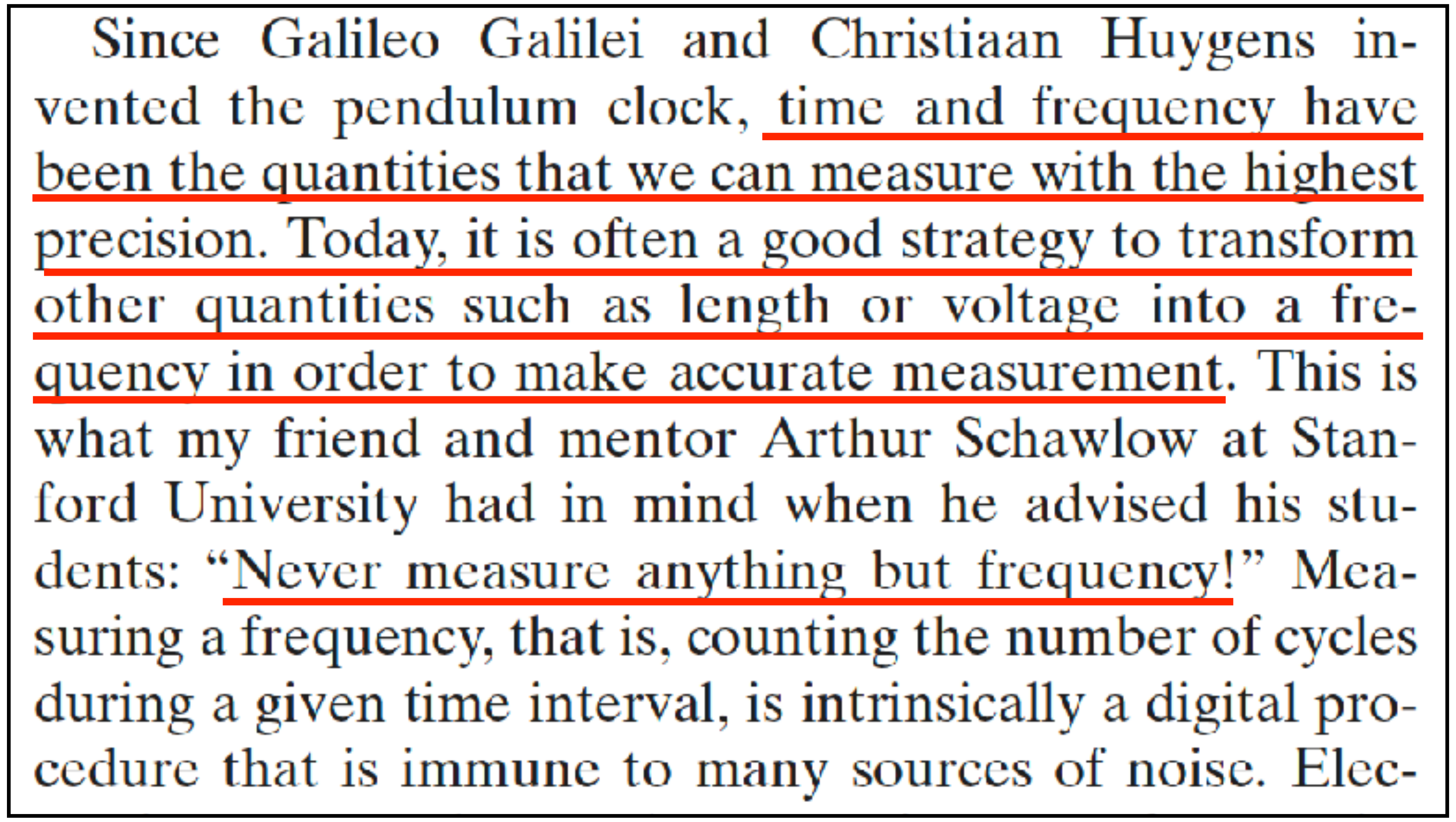
Nobel Lecture: Passion for precision[*]

Theodor W. Hänsch[†]

Max-Planck Institute of Quantum Optics, Garching, Germany
and Department of Physics, Ludwig-Maximilians University, Munich, Germany

(Published 17 November 2006)

DOI: 10.1103/RevModPhys.78.1297



Since Galileo Galilei and Christiaan Huygens invented the pendulum clock, time and frequency have been the quantities that we can measure with the highest precision. Today, it is often a good strategy to transform other quantities such as length or voltage into a frequency in order to make accurate measurement. This is what my friend and mentor Arthur Schawlow at Stanford University had in mind when he advised his students: "Never measure anything but frequency!" Measuring a frequency, that is, counting the number of cycles during a given time interval, is intrinsically a digital procedure that is immune to many sources of noise. Elec-

阿瑟·肖洛 Arthur Schawlow
激光之父1981年诺奖

Never measure anything
but frequency!

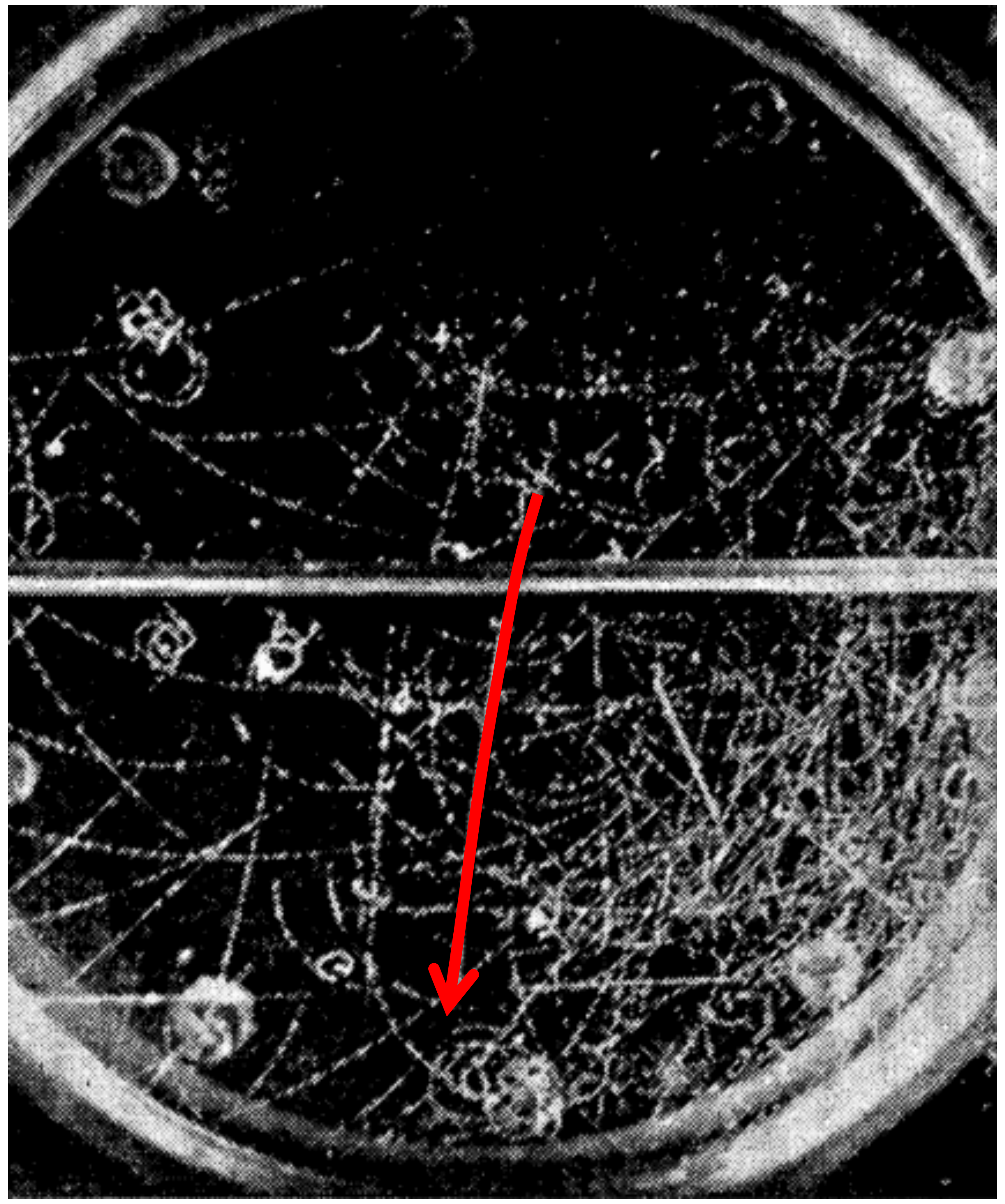
小总结

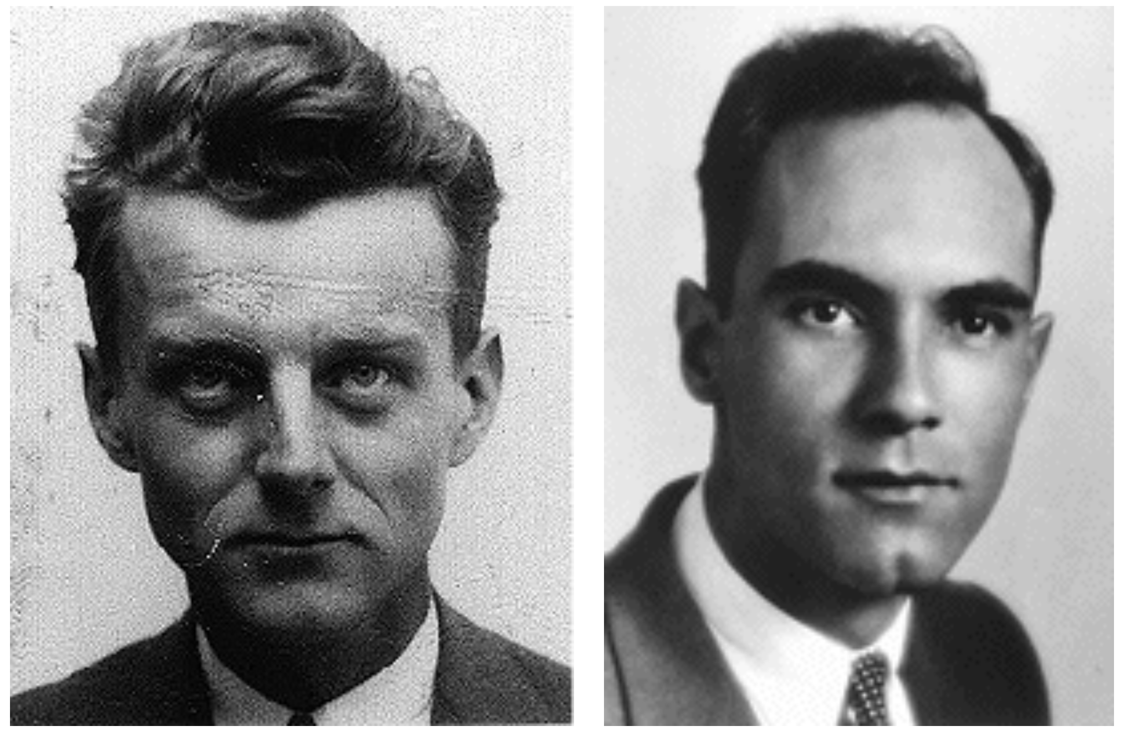
- 研究的对象和物理量：基本粒子的磁矩
- 通过精确计算和测量
    - 推动相对论量子力学的发展
    - 电子为基本粒子，质子和中子为复合粒子
    - 推动量子电动力学的发展

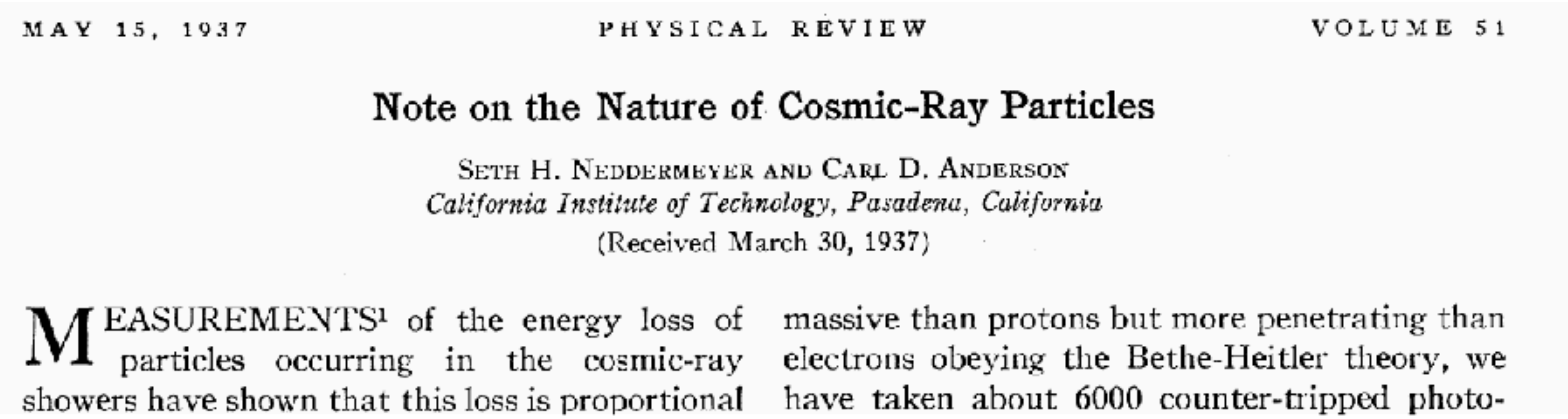
缪子反常磁矩

缪子的发现

Pike’s Peak, CO







MAY 15, 1937 PHYSICAL REVIEW VOLUME 51

Note on the Nature of Cosmic-Ray Particles

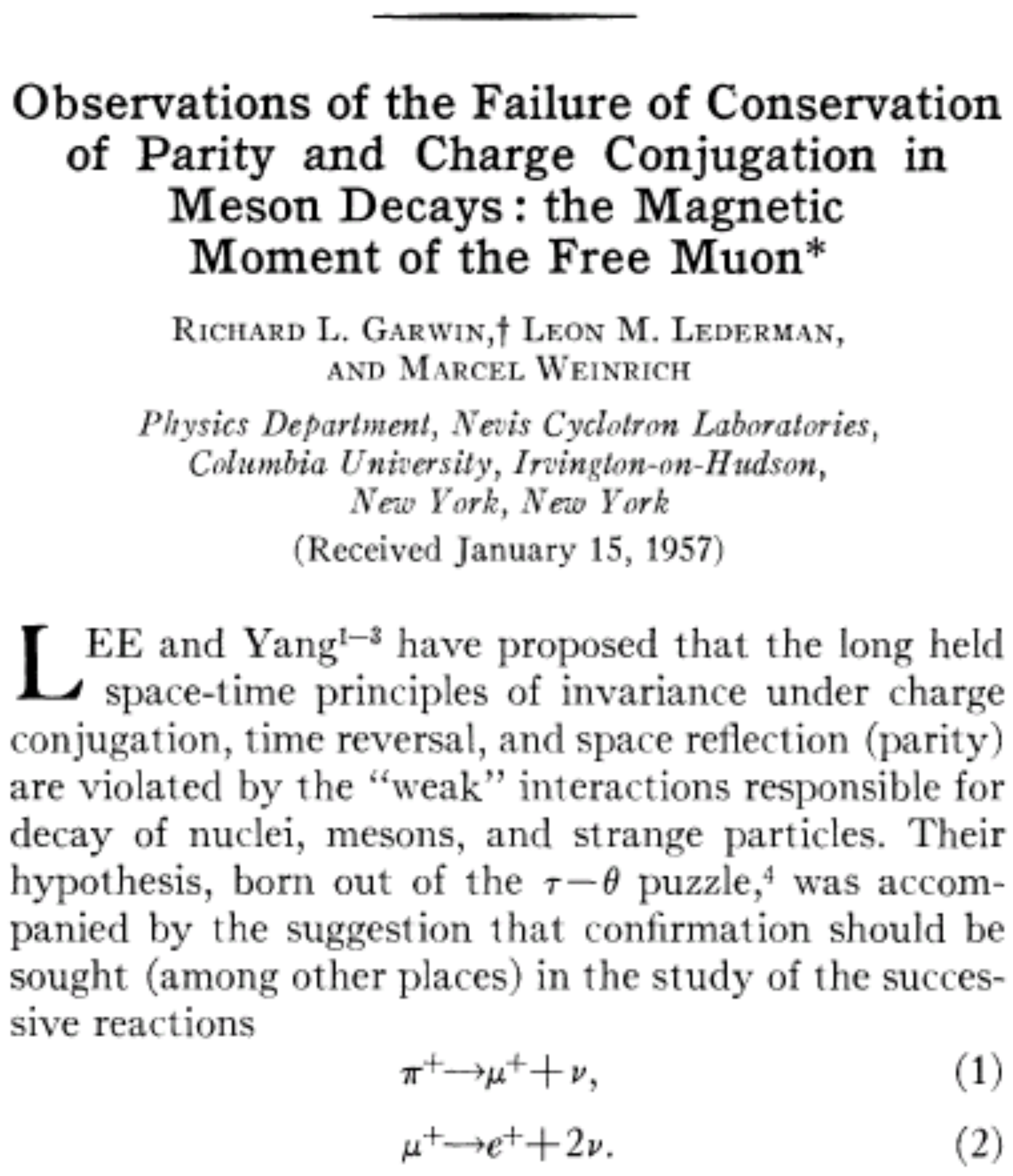
Seth H. Neddermeyer and Carl D. Anderson
California Institute of Technology, Pasadena, California
(Received March 30, 1937)

Measurements[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photo-

Who ordered that?

I. Rabi

缪子磁矩的首次测量



Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

Richard L. Garwin,† Leon M. Lederman,
and Marcel Weinrich

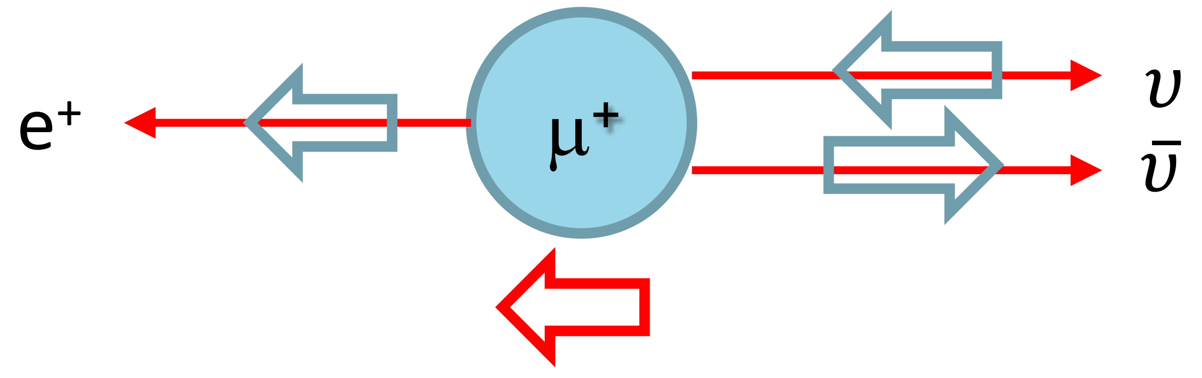
Physics Department, Nevis Cyclotron Laboratories,
Columbia University, Irvington-on-Hudson,
New York, New York

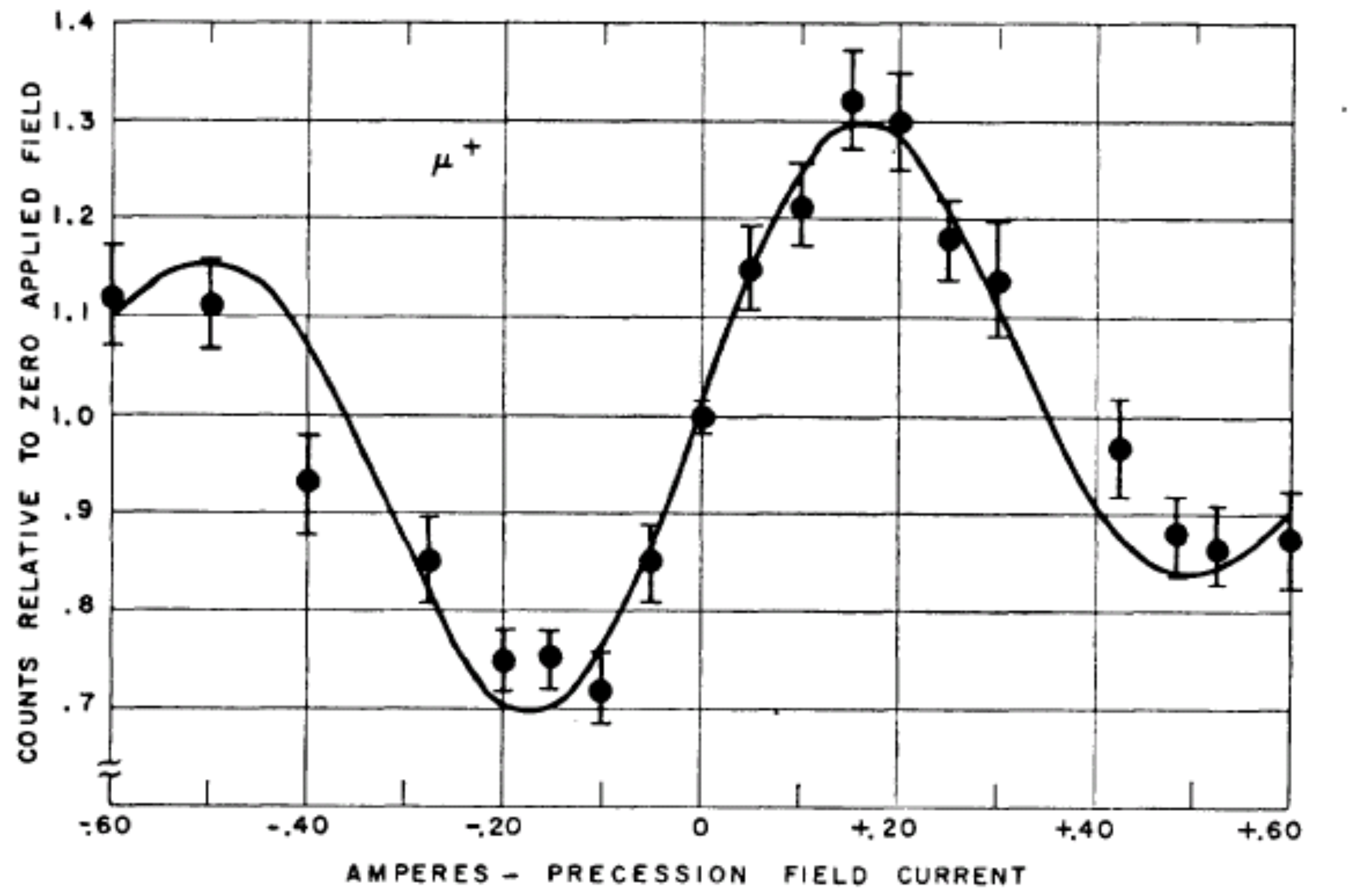
(Received January 15, 1957)

Lee and Yang[1–3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \quad (1)$$

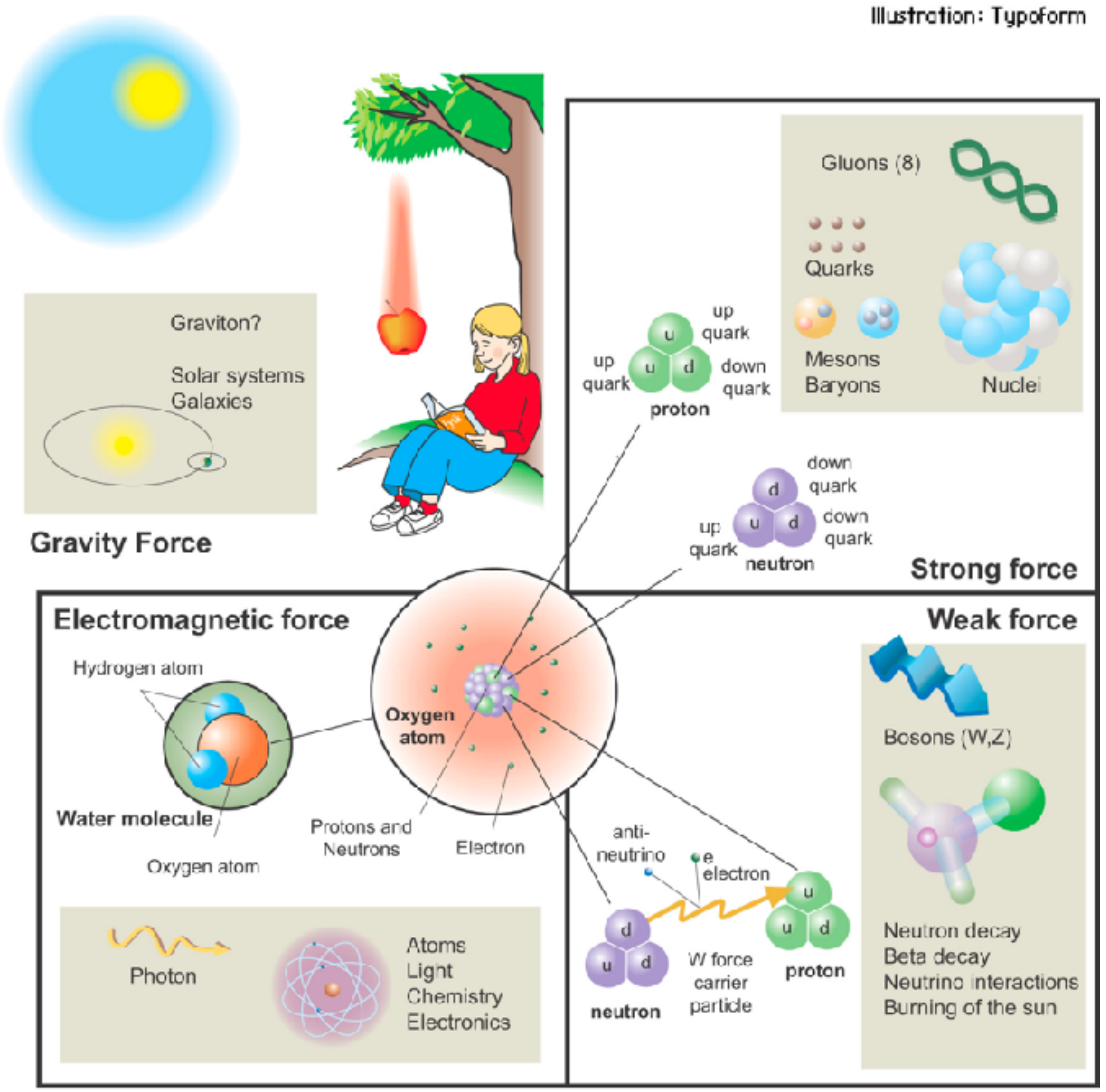
$$\mu^+ \rightarrow e^+ + 2\nu. \quad (2)$$

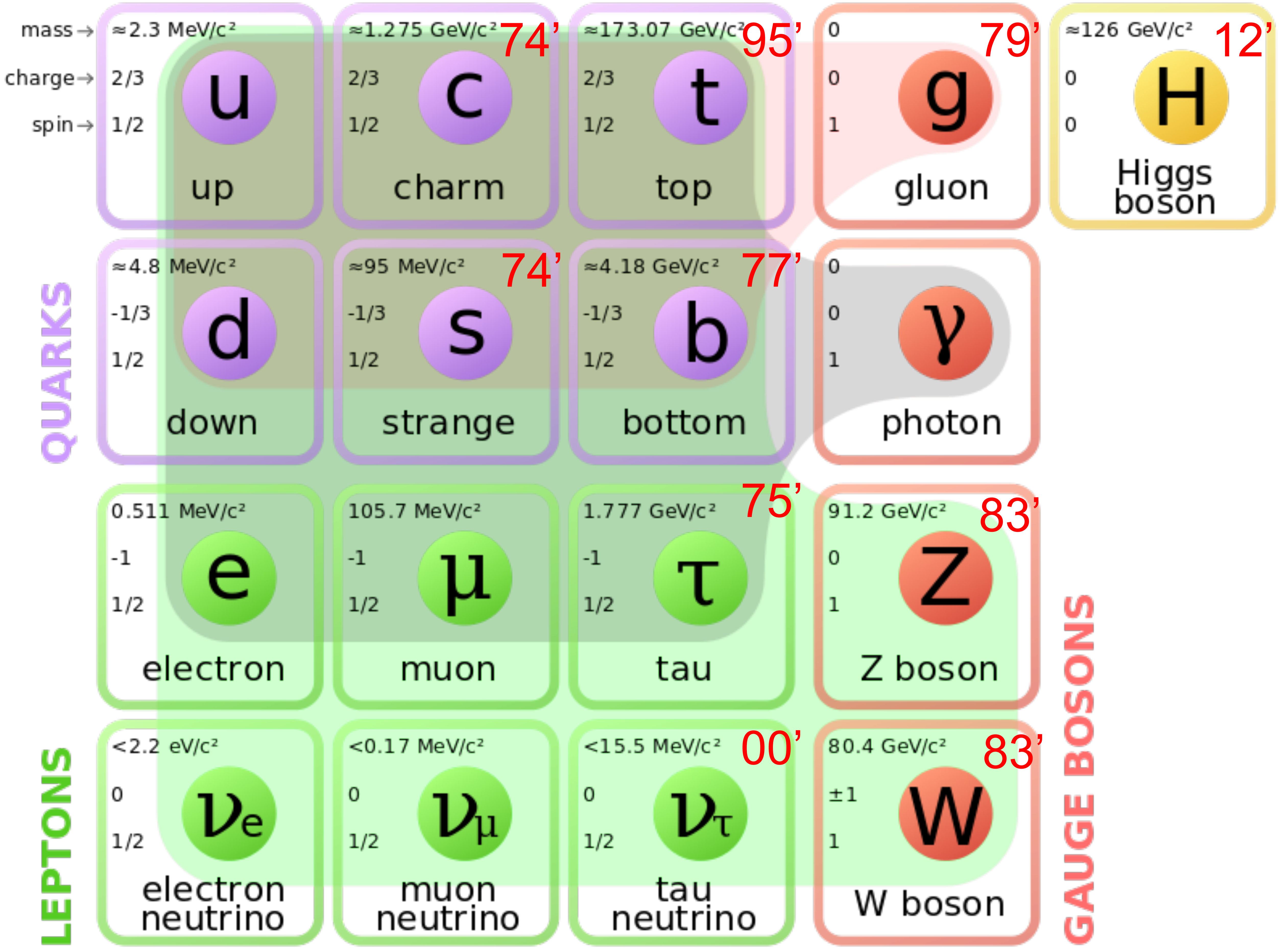




- 通过研究极化缪子在磁场中的衰变得到
  - 缪子的衰变过程对宇称不守恒
  - 缪子的g-因子=2.00 ± 0.10（自旋1/2）
- 之后的精确测量显示缪子是电子的“亲兄弟”（而不是电子的激发态）

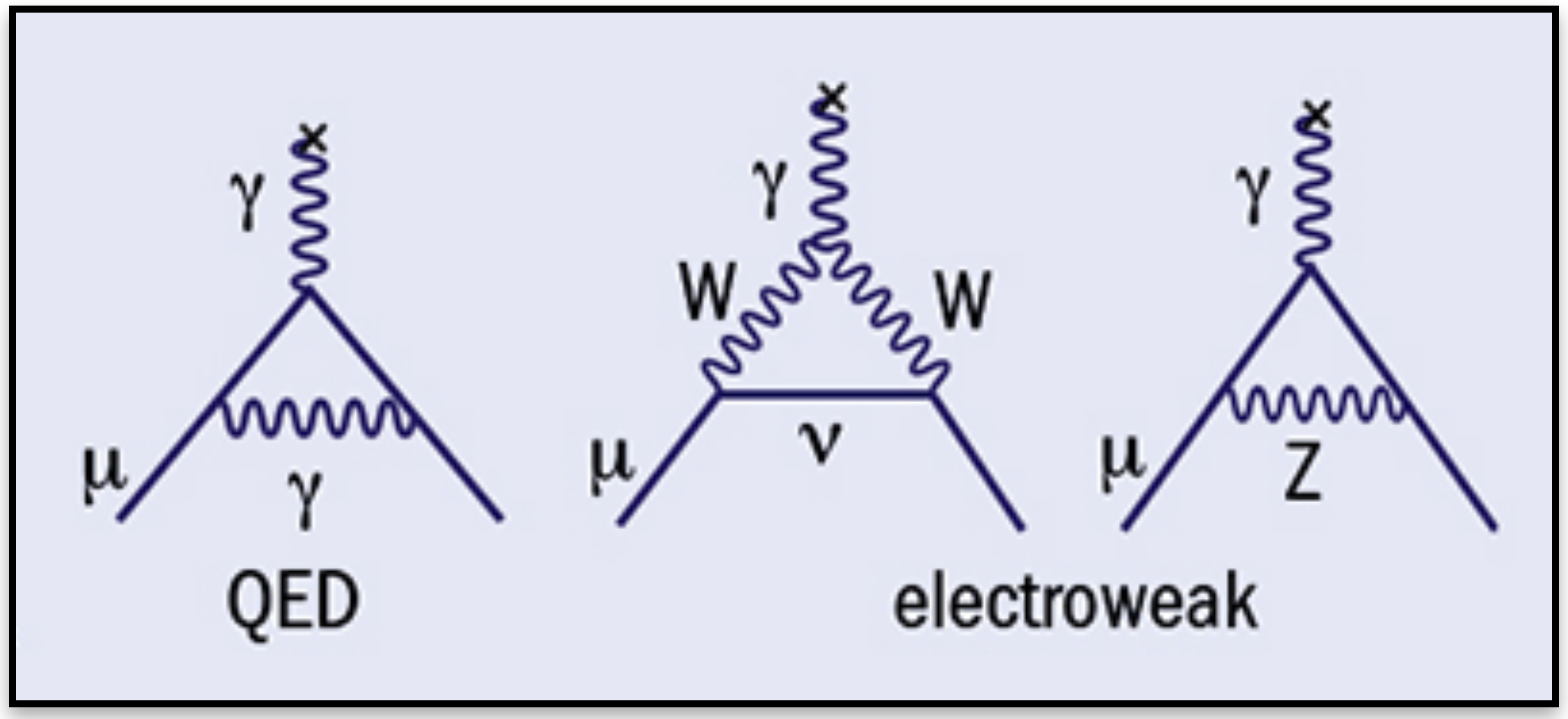
粒子物理目前最好的理论：标准模型



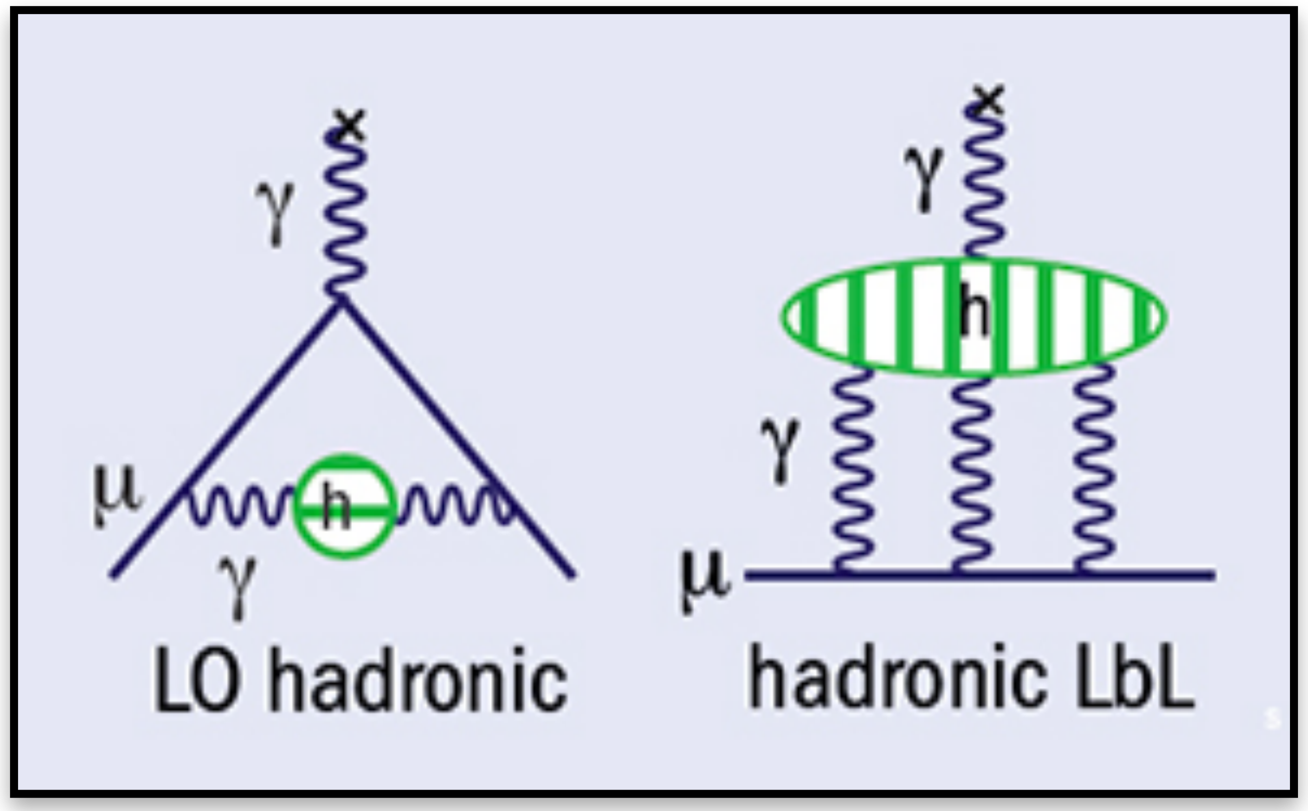


缪子为自旋1/2的第二代轻子

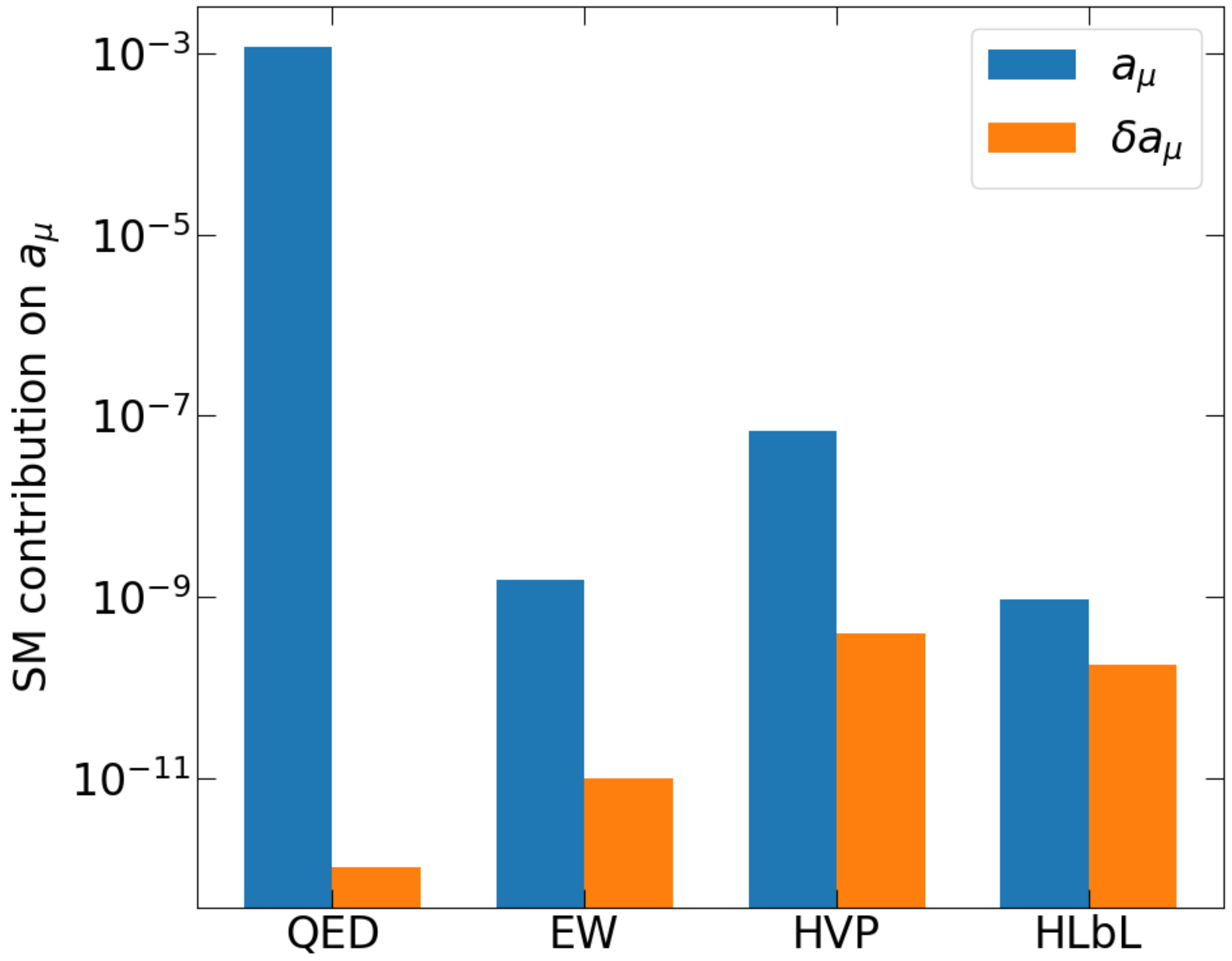
缪子反常磁矩的理论计算值



电动力学　　电弱相互作用



强相互作用



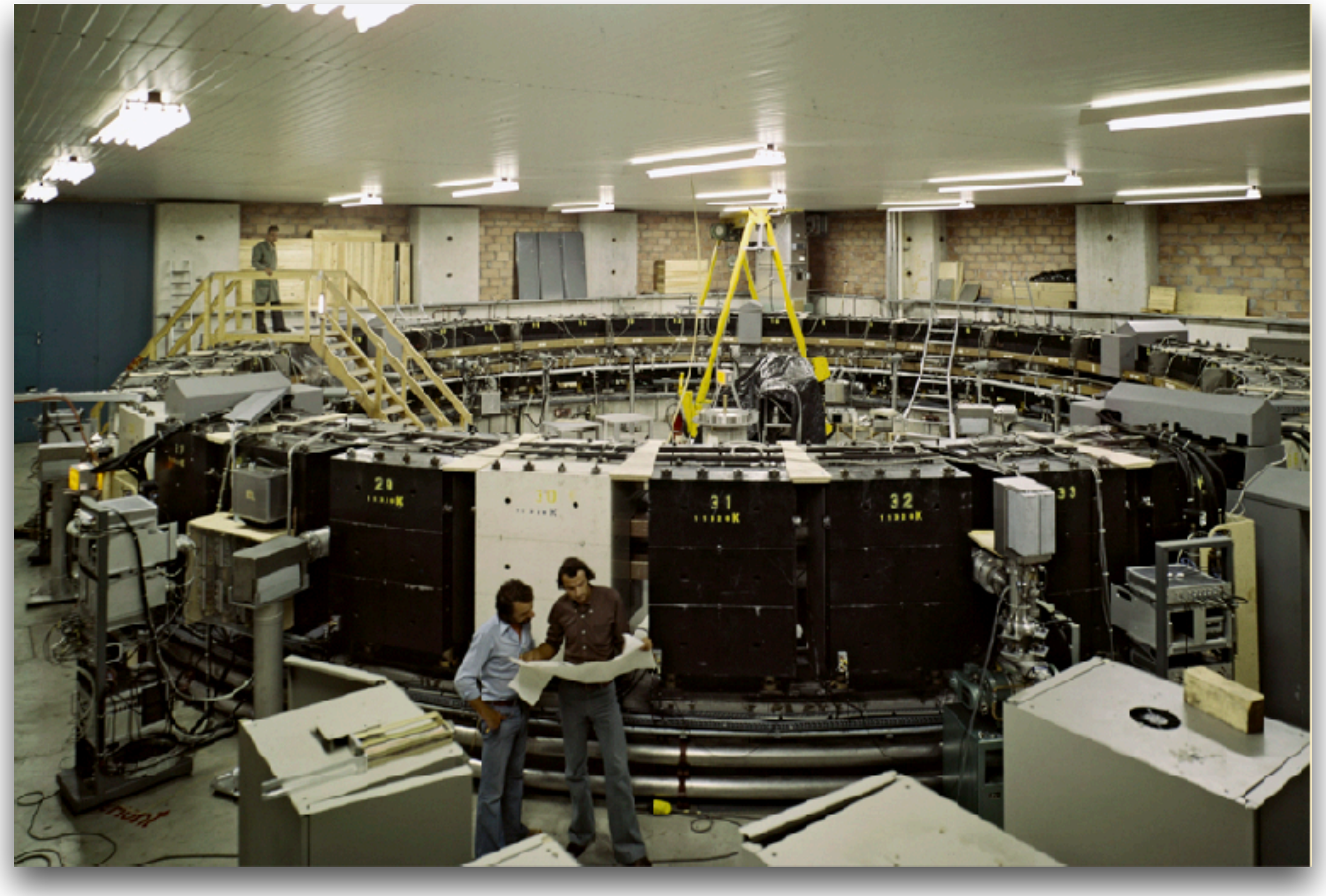
$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HVP} + a_\mu^{\rm HLbL}$$
$$= 116\,591\,810\,(43)\times 10^{-11}$$

0.37 ppm!

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

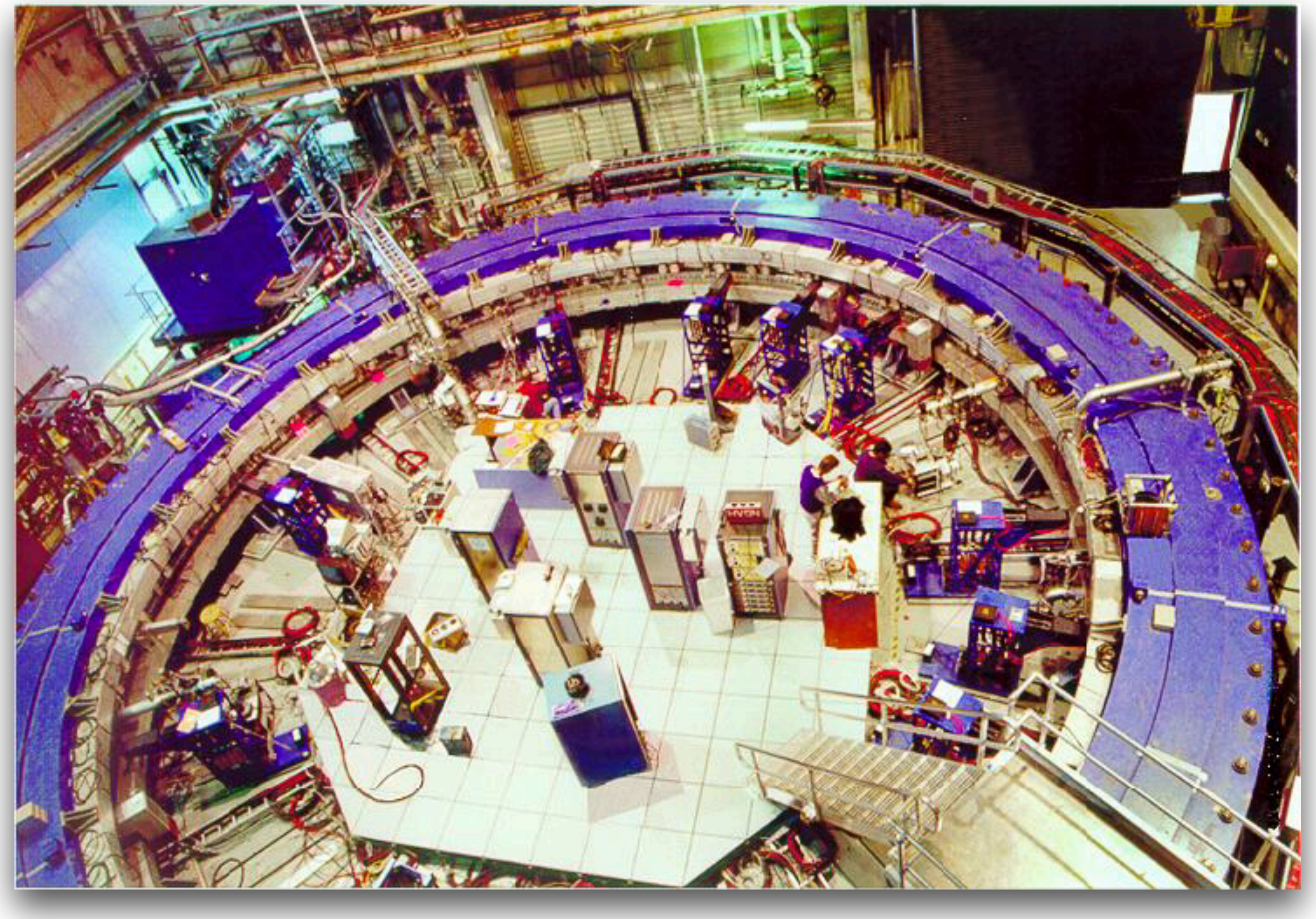
J. Bailey et al., Nucl. Phys. B 150 (1979) 1-75
G. Bennett et al., Phys. Rev. D73, (2006) 072003

缪子反常磁矩的实验测量值



欧洲核子研究中心（CERN）
1960-1970年代
7.3 ppm

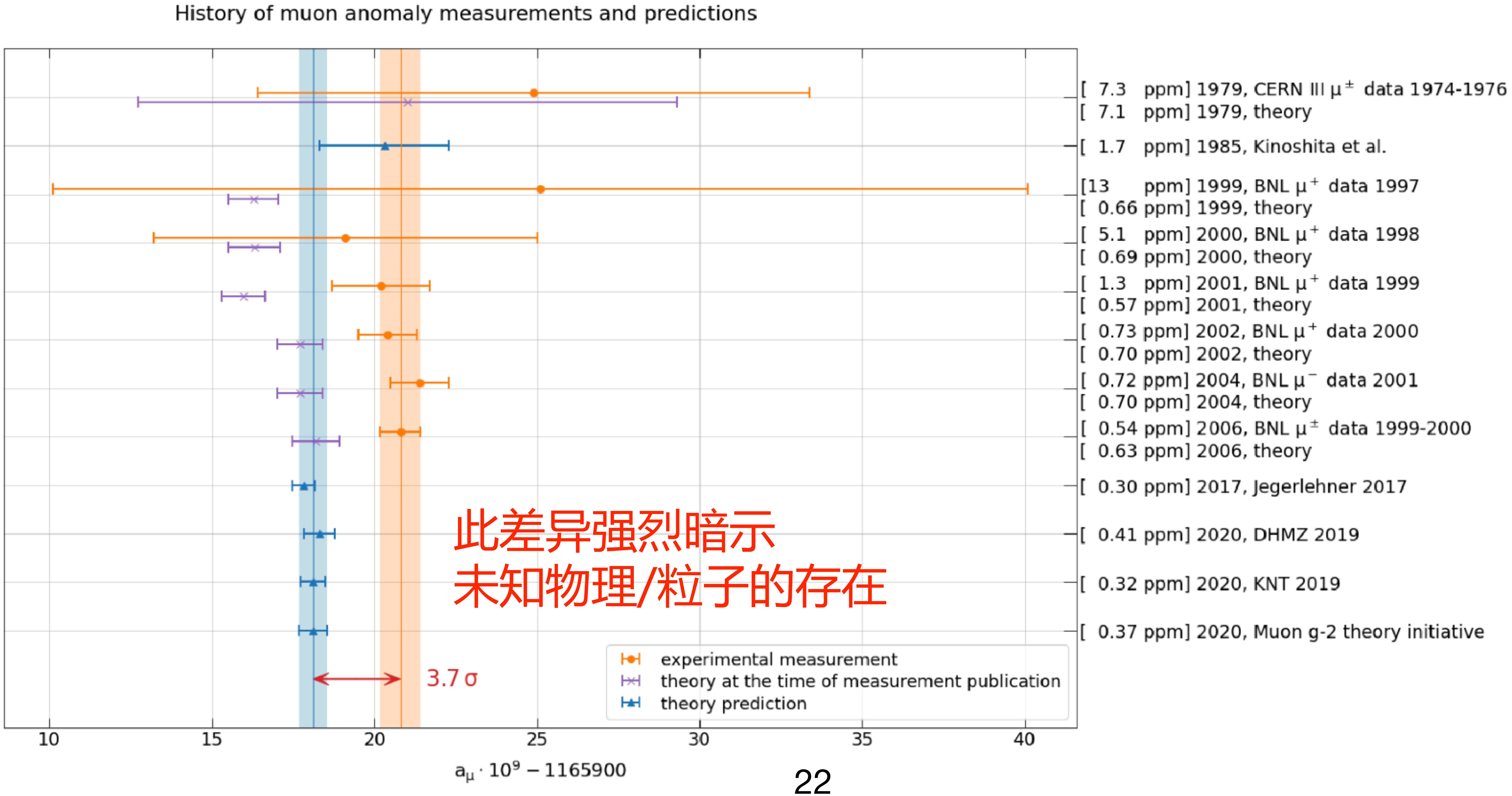
超导磁铁缪子储存环



布鲁克海文国家实验室（BNL）
1980-2000年代
0.54 ppm

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

缪子反常磁矩：理论和实验50年的耕耘



此差异强烈暗示
未知物理/粒子的存在

磁铁大搬迁（2013年）


Fermilab
Brookhaven
Jul 2013
Jun 2013
EMMERT
OVERSIZE LOAD
Big Move
UFO
ENCOUNTERS
The True Story
Behind the
Brookhaven
and Carp
Incidents
J. B. Michaels

重新组装超导磁铁储存环

费米实验室缪子g-2实验（2011年成立）

2017年试运行前集合影

缪子储存环

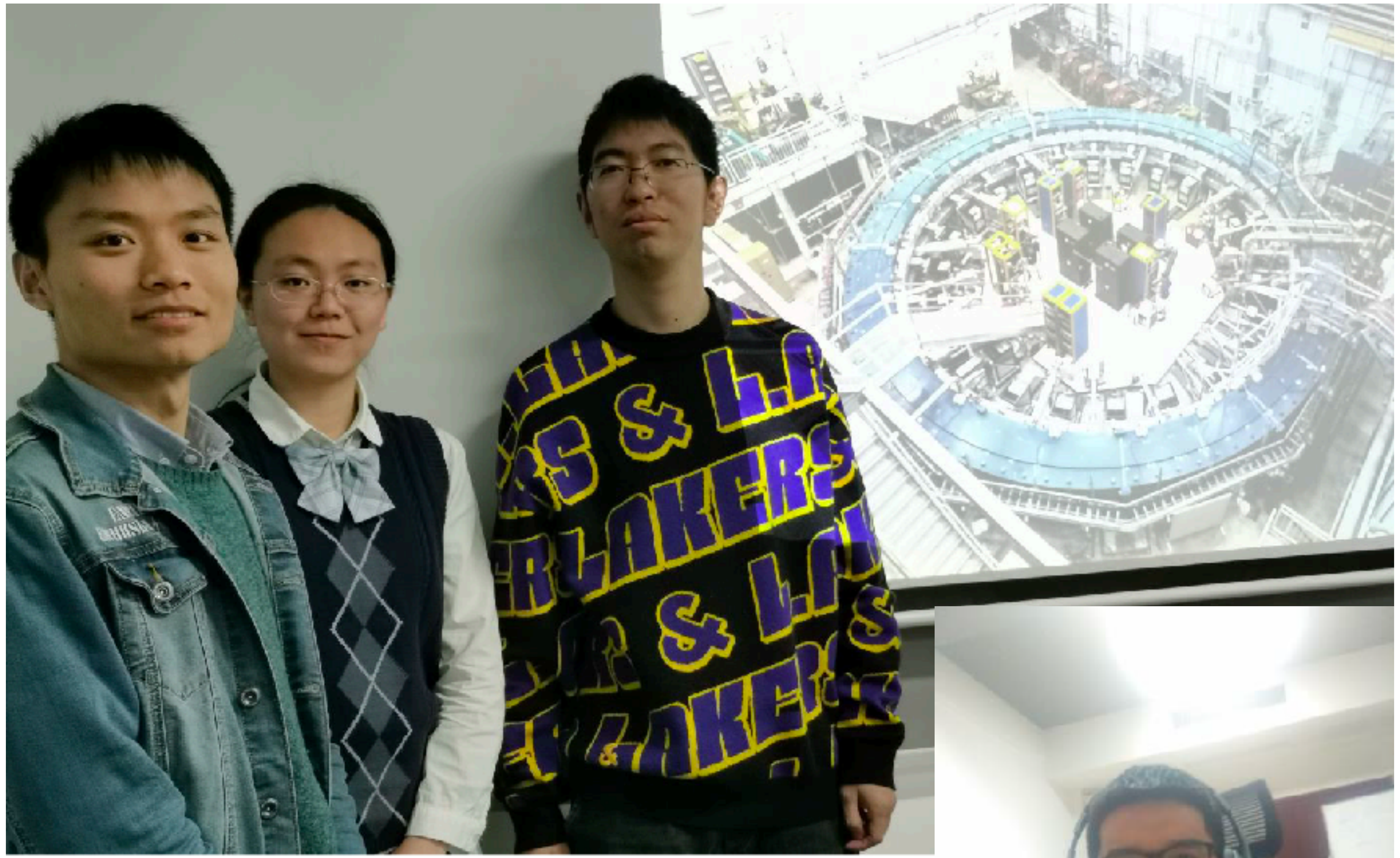
Muon g-2 Collaboration

(>200 collaborators, 35 institutes, 7 countries)

- USA
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Kentucky
  - Massachusetts
  - Michigan
  - Michigan State
  - Mississippi
  - North Central
  - Northern Illinois
  - Regis
  - Virginia
  - Washington
- USA National Labs
  - Argonne
  - Brookhaven
  - Fermilab
- China
  - Shanghai Jiao Tong
- Germany
  - Dresden
  - Mainz
- Italy
  - Frascati
  - Molise
  - Naples
  - Pisa
  - Roma Tor Vergata
  - Trieste
  - Udine
- Korea
  - CAPP/IBS
  - KAIST
- Russia
  - Budker/Novosibirsk
  - JINR Dubna
- United Kingdom
  - Lancaster/Cockcroft
  - Liverpool
  - Manchester
  - University College London

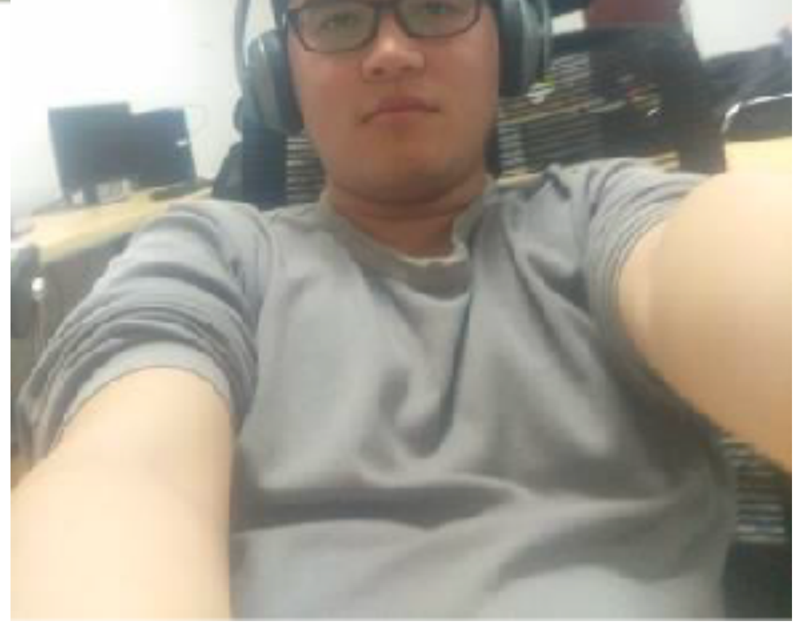
合作组会议@意大利厄尔巴岛，2019年夏天

上海交大缪子g-2团队（2名博士后，4名研究生）



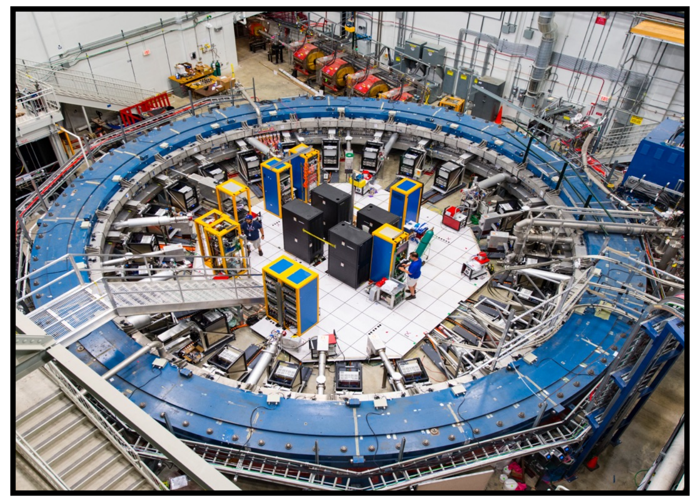
上海交通大学
物理与天文学院
School Of Physics And Astronomy, SJTU

李政道研究所
Tsung-Dao Lee Institute



非一般粒子物理实验：学科交叉实验

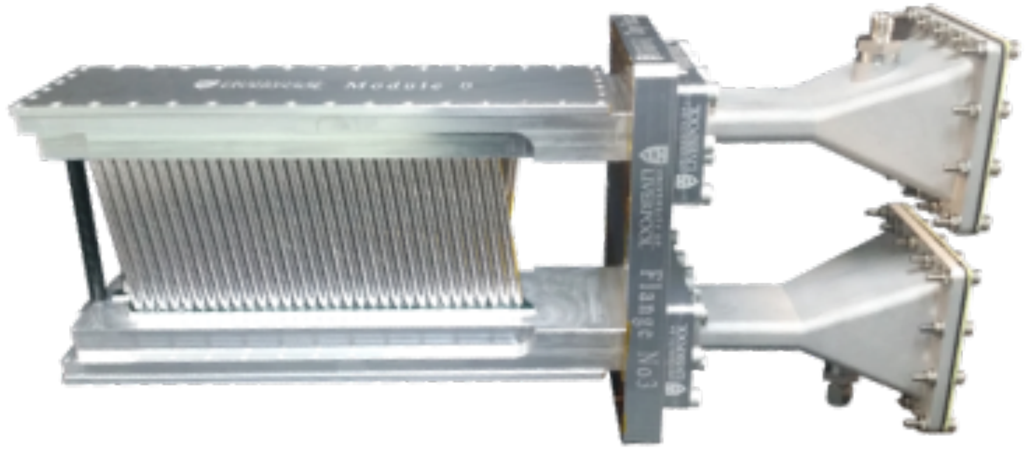
加速器物理



束流动力学

超导储存环

纯缪子束流

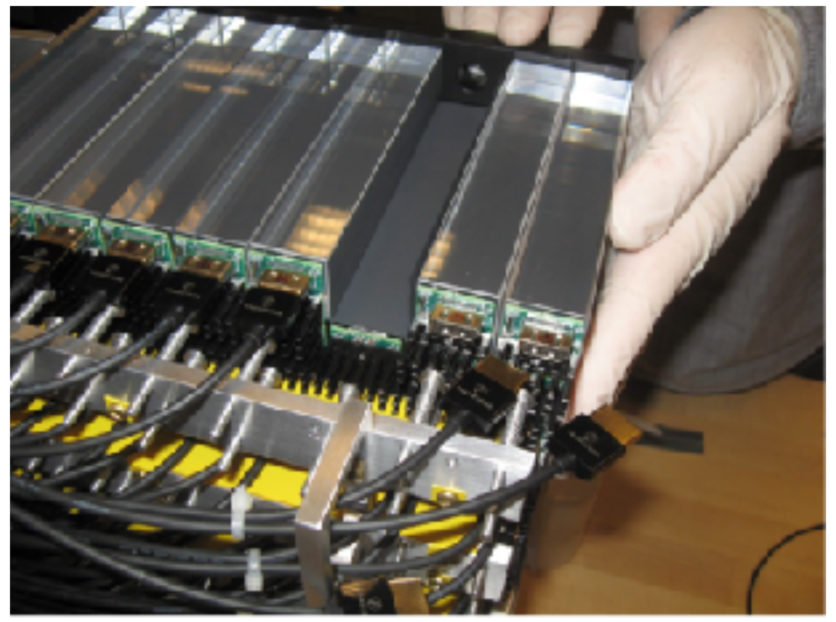


高频数据采集

径迹探测器

量能器

高能物理



缪子

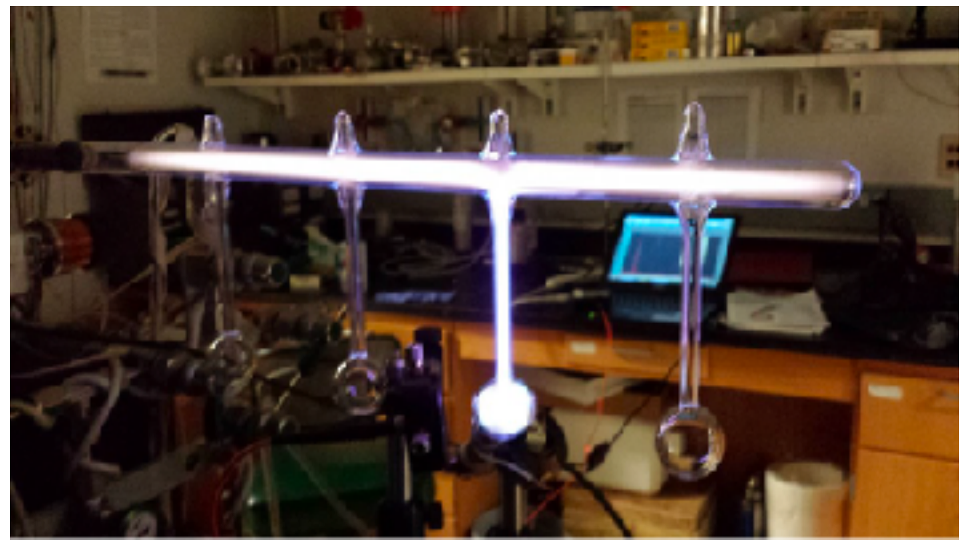
反常磁矩

原子分子与光学

光抽运

磁力计

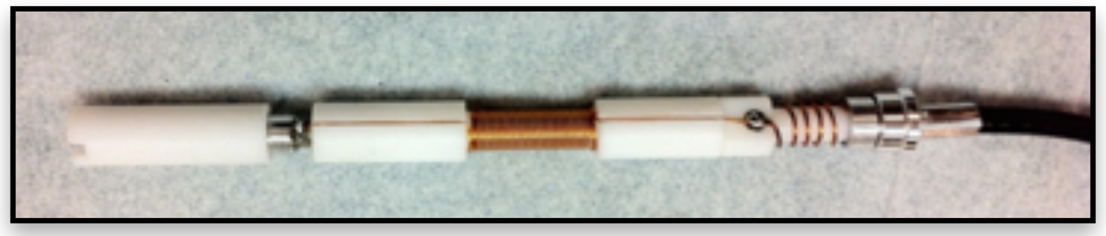
激光系统



核磁共振

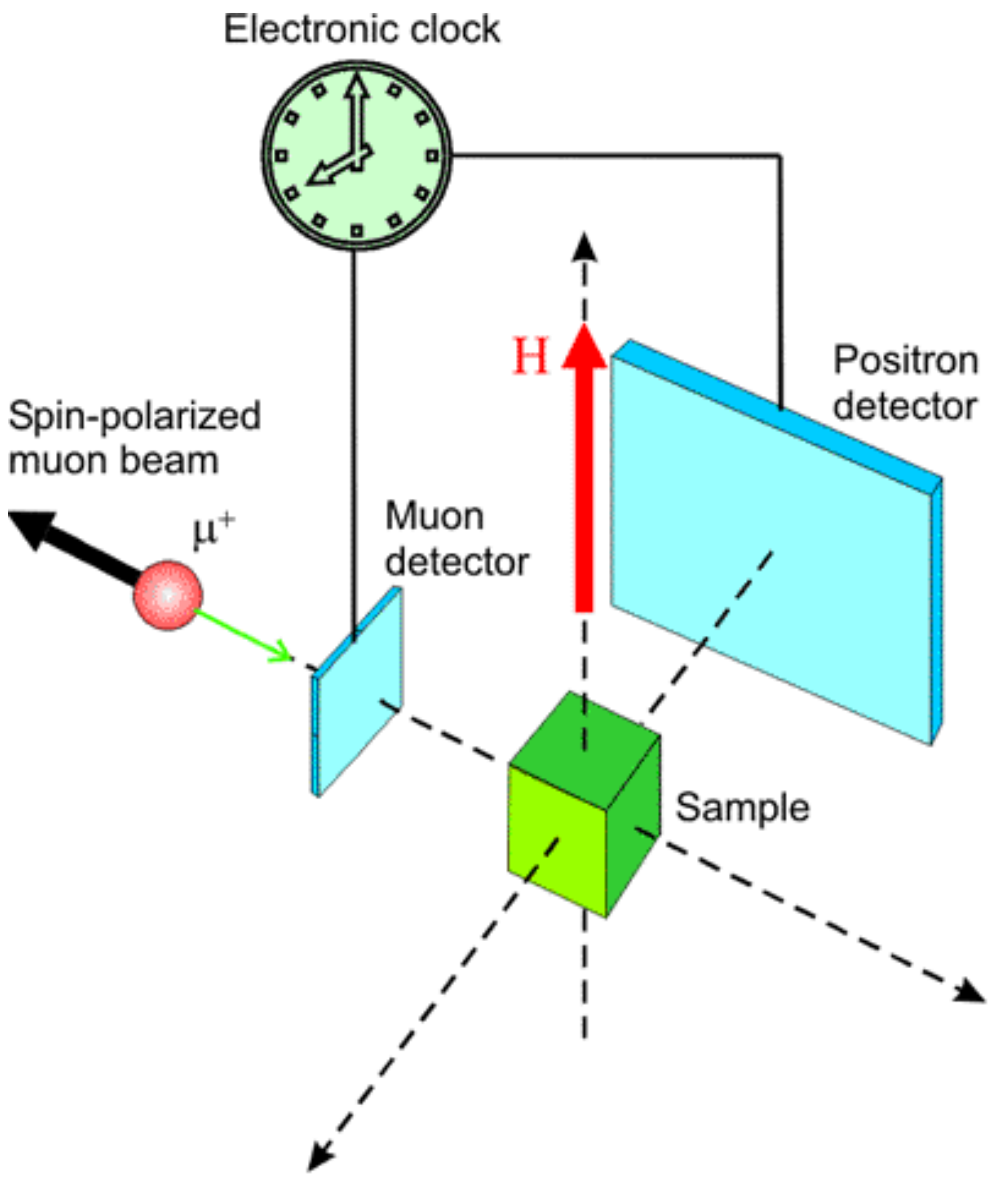
磁场精确测量

核物理



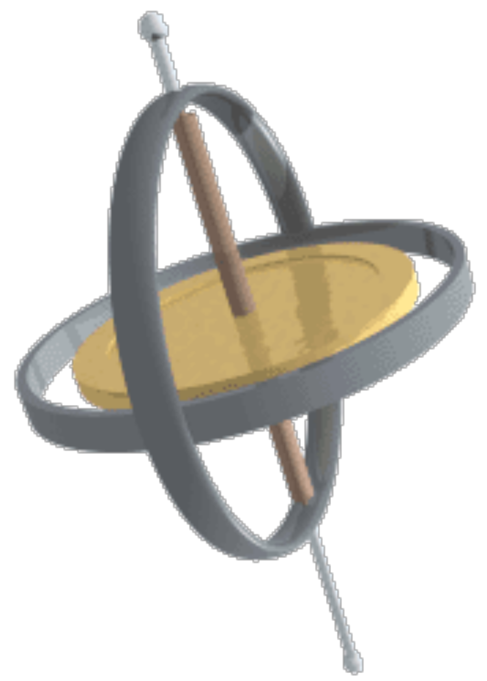
缪子磁矩（g-因子）的测量原理

静止的缪子

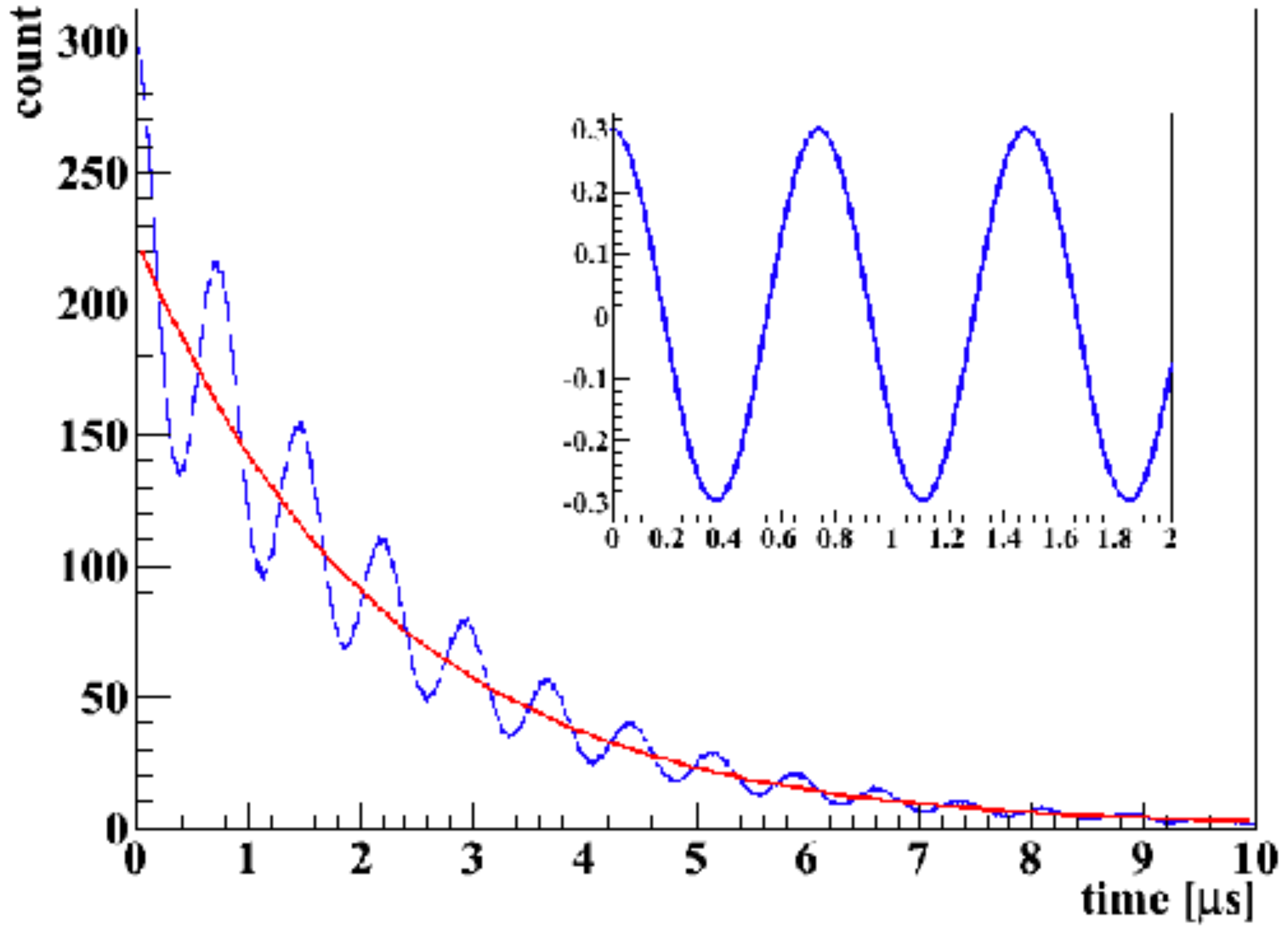


- 缪子的平均寿命2.2微妙
  - 衰变成电子和两个中微子 $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
- 由于宇称不守恒，电子的平均方向=缪子的自旋方向
- 所探测到的电子数以进动频率震荡
  - 从拟合可得到频率

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

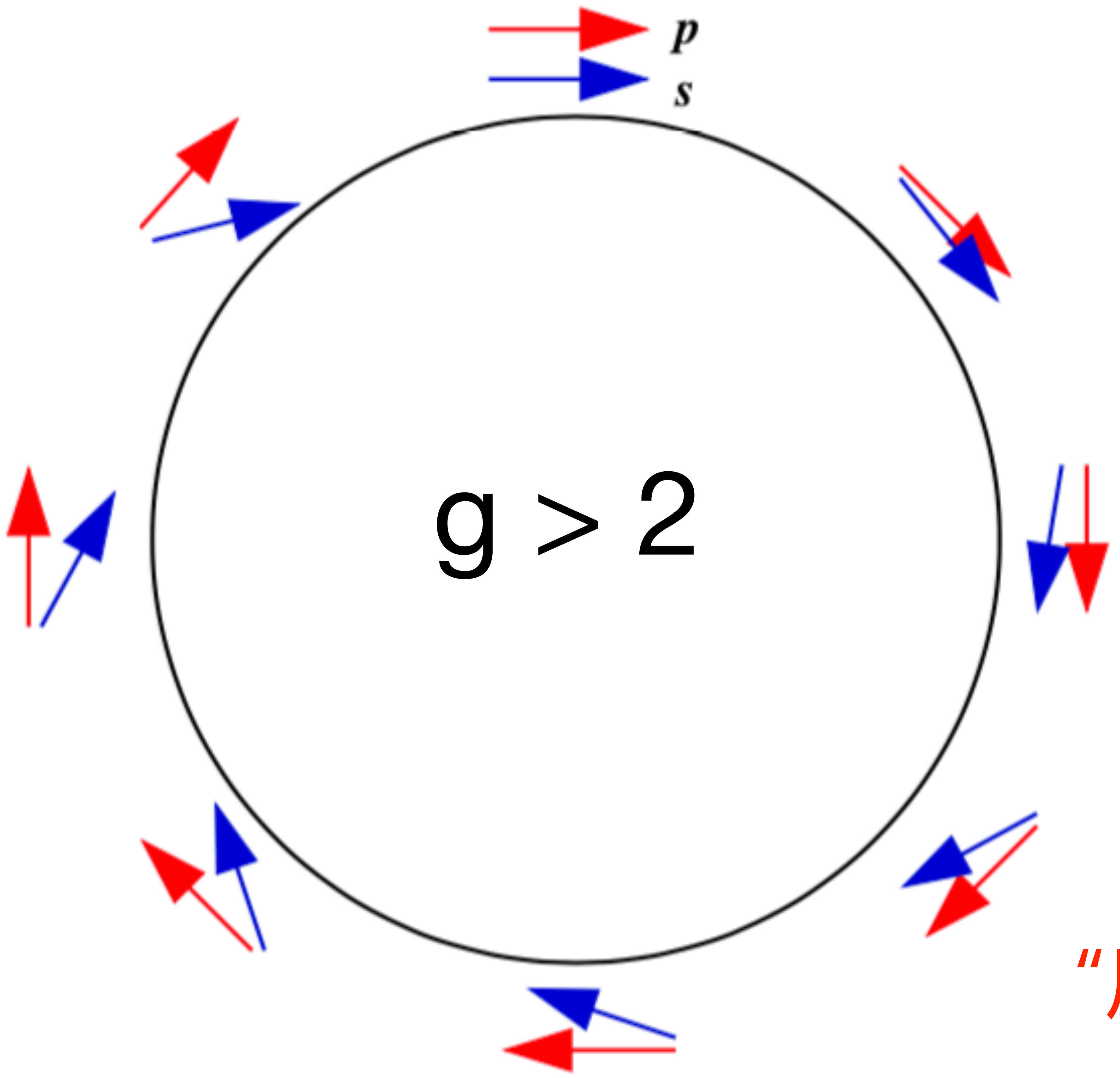


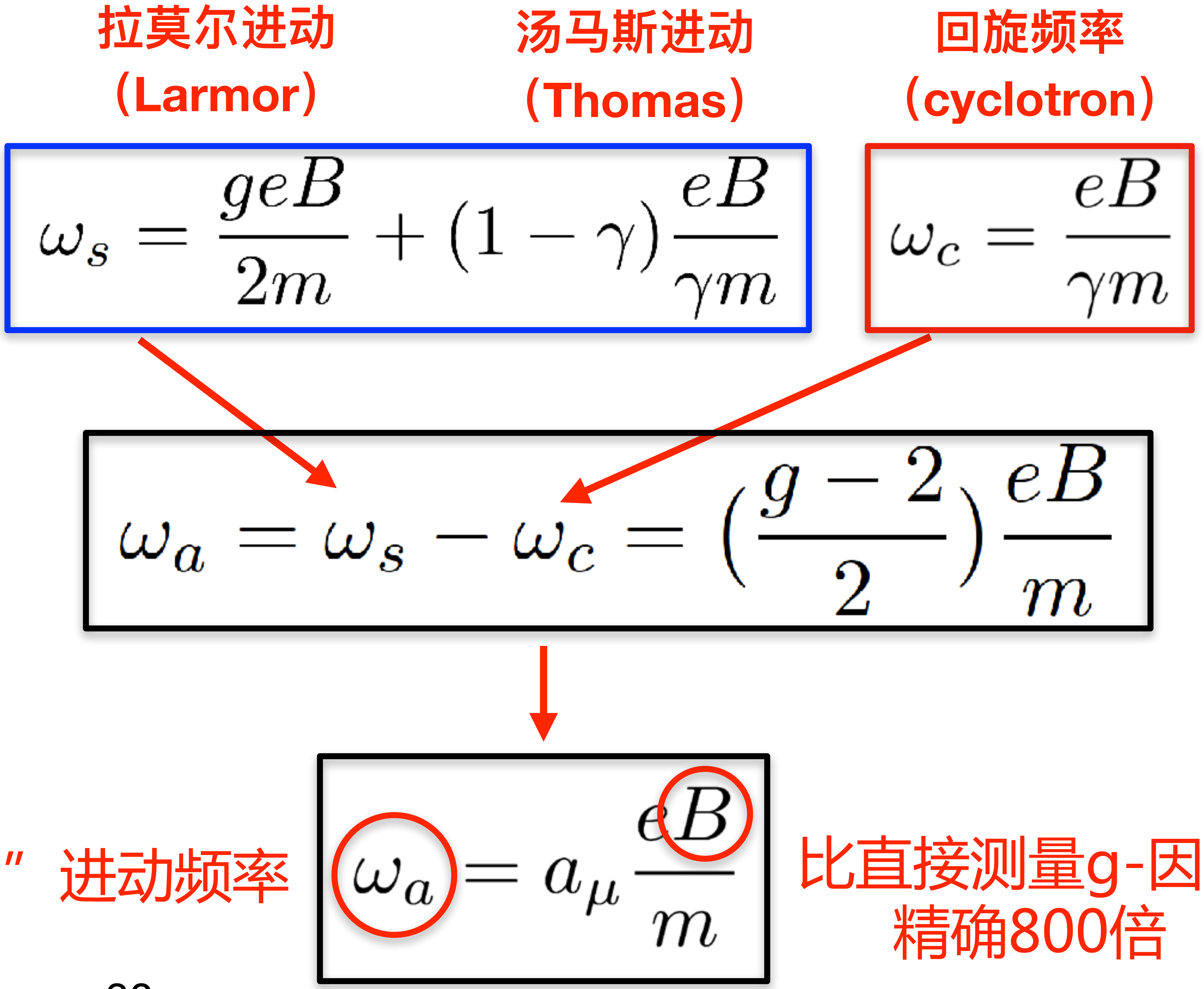
$$\omega_s = g\frac{eB}{2mc}$$



缪子反常磁矩（g-2）的测量原理

接近光速飞行的缪子





拉莫尔进动（Larmor）

汤马斯进动（Thomas）

回旋频率（cyclotron）

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

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

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

“反常”进动频率

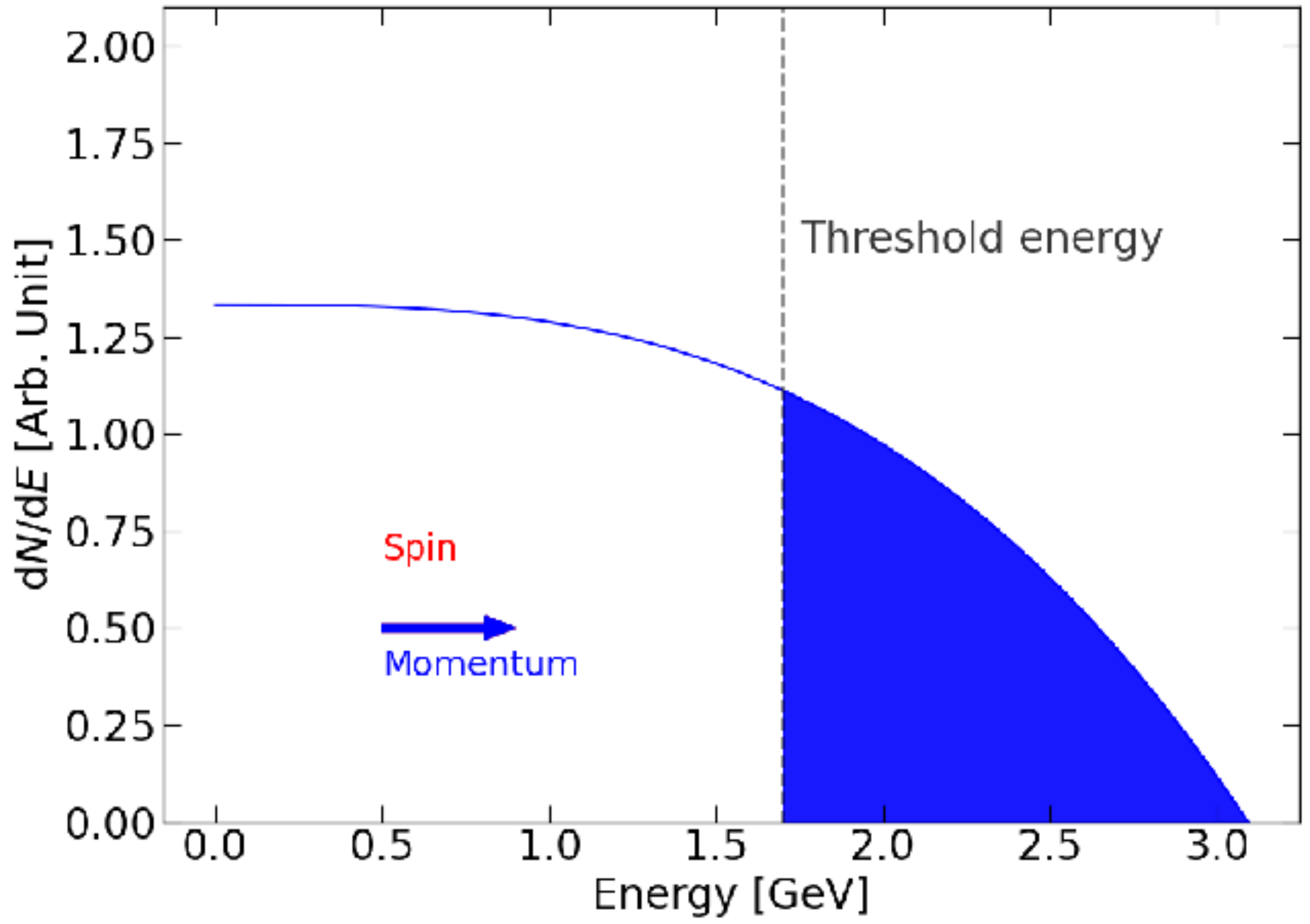
$$\boxed{\omega_a = a_\mu \frac{eB}{m}}$$

比直接测量g-因子精确800倍

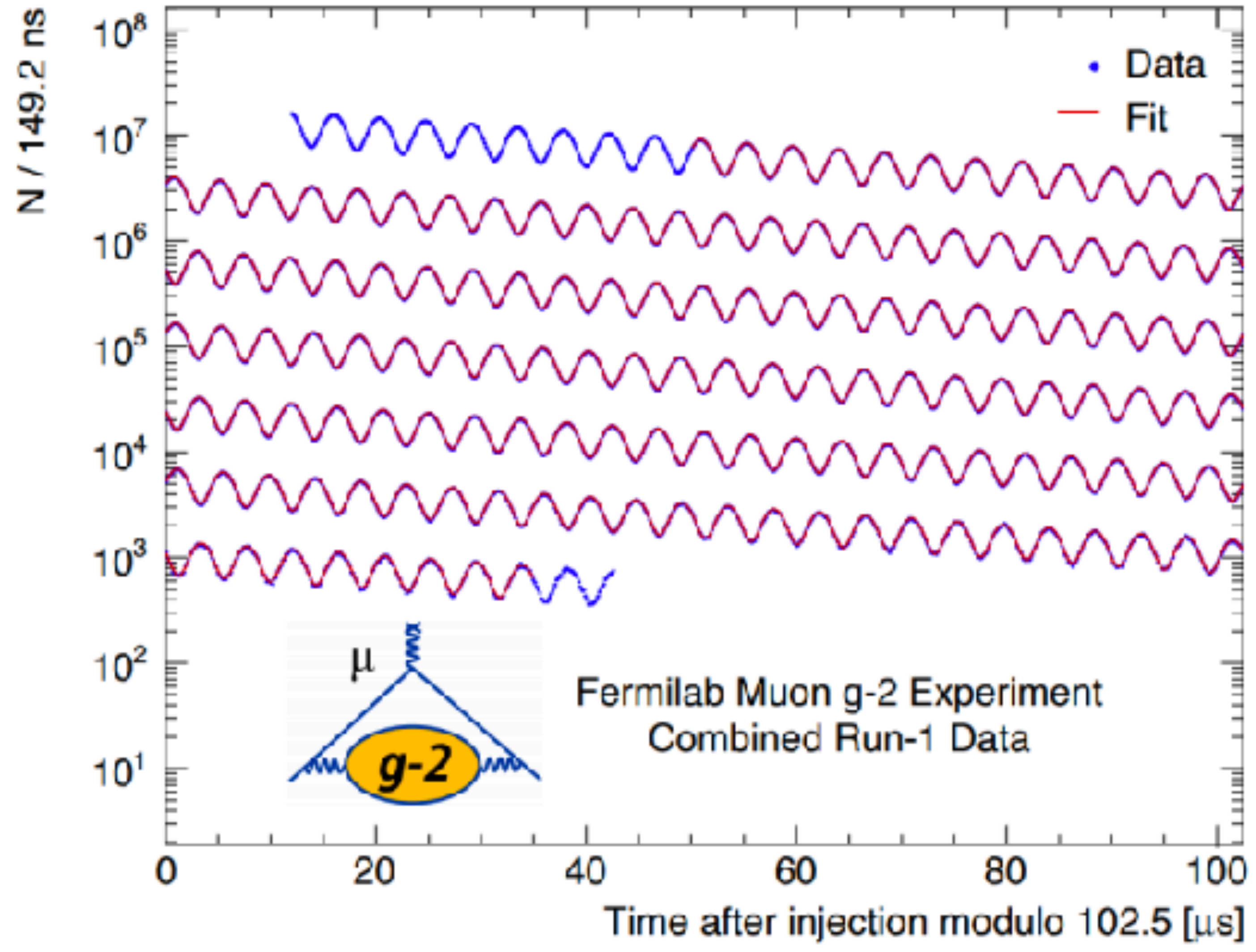
反常进动频率的测量手法

- 缪子以接近光速的速度飞行
  - 当自旋和动量往同方向：最多高能电子
  - 当自旋和动量往反方向：最少高能电子
- 和静止缪子同样拟合方法获得频率
  - 不同的是这个是反常进动频率

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



通过高能电子数量的震荡
获得反常进动频率！



磁场的测量手法

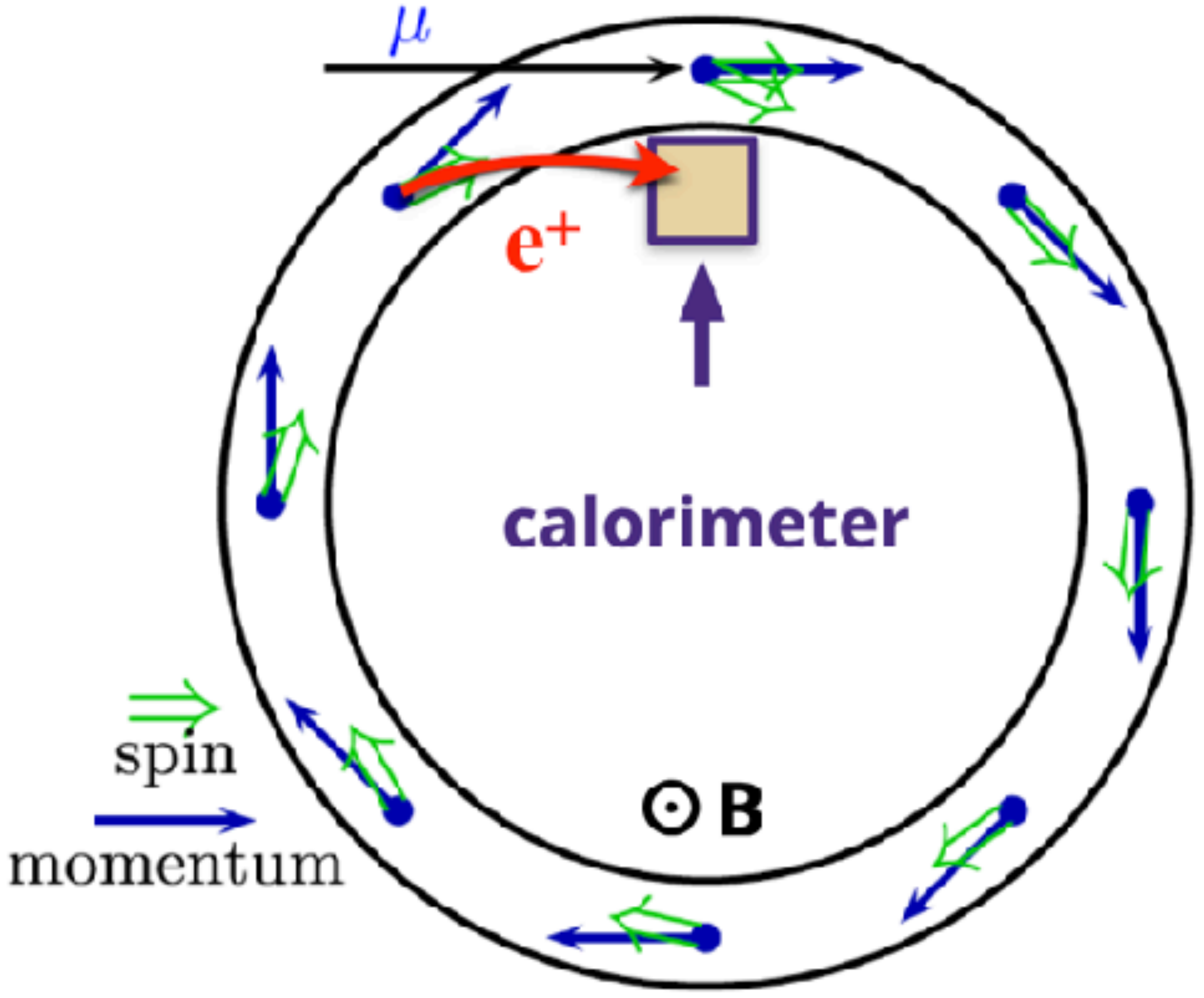
$$\boxed{\omega_a = a_\mu \frac{e B}{m}}$$

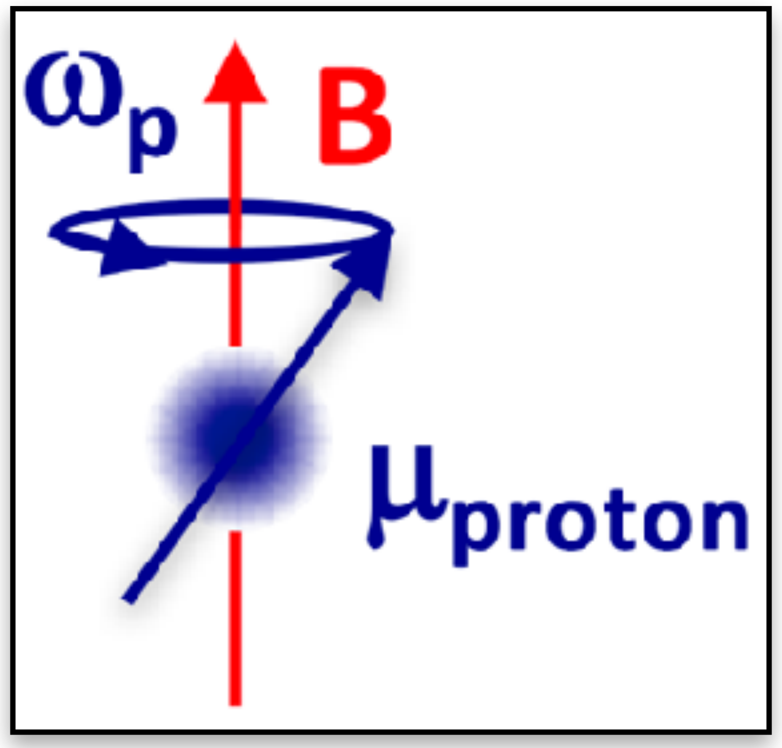
质子的进动频率和磁场

$$\boxed{B = \frac{\hbar \omega_p}{2\mu_p}}$$

电子磁矩的定义

$$\boxed{\mu_e = g_e \frac{e\hbar}{4m_e}}$$





核磁共振探针

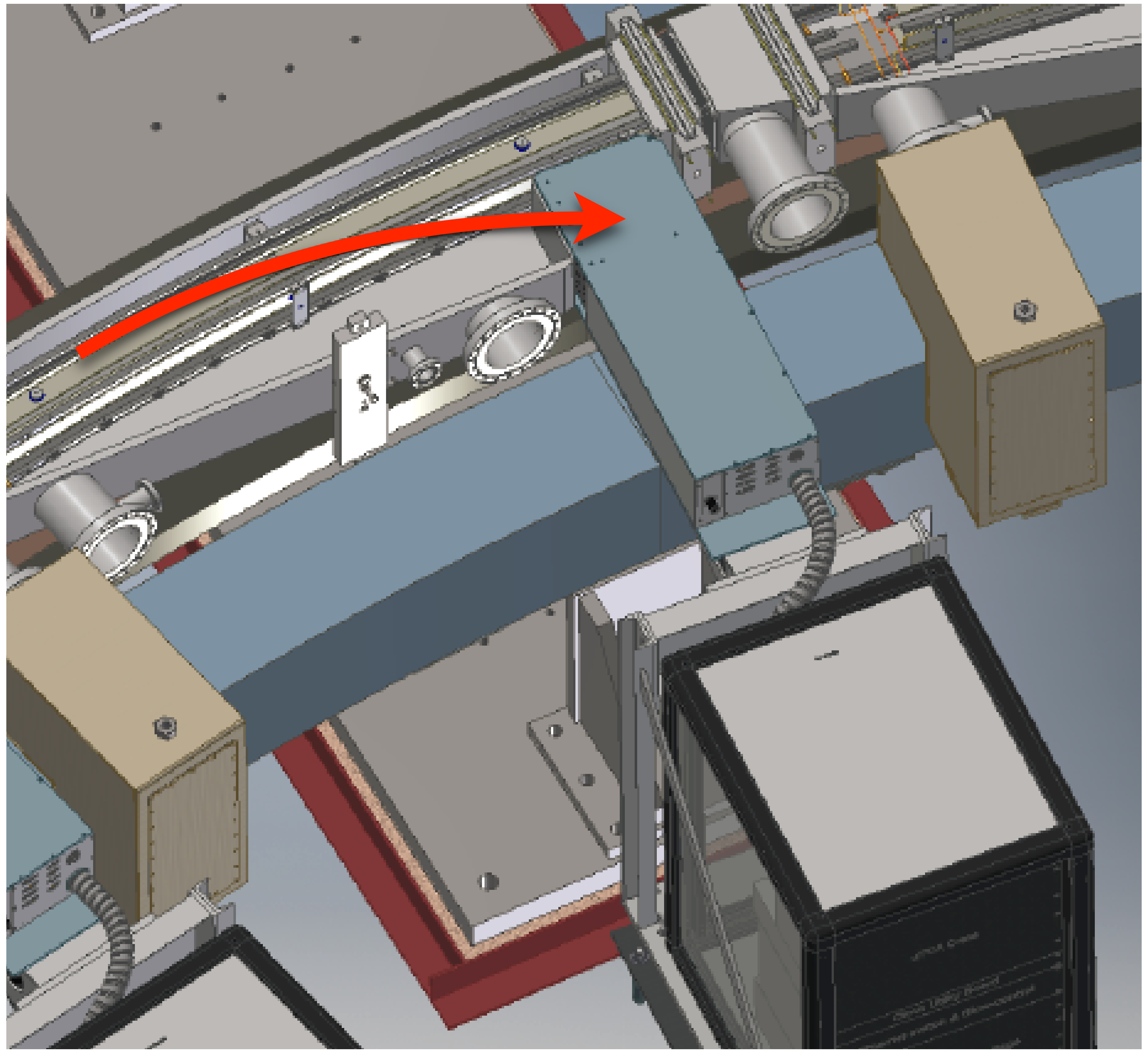
g-2实验测量的两个频率

$$a_\mu^{\text{Exp}} = \underbrace{\frac{g_e}{2}}_{0.3\text{ ppt}} \boxed{\frac{\omega_a}{\tilde{\omega}_p}} \underbrace{\frac{m_\mu}{m_e}}_{22\text{ ppb}} \underbrace{\frac{\mu_p}{\mu_e}}_{3\text{ ppb}}$$

缪子的第一视角视频

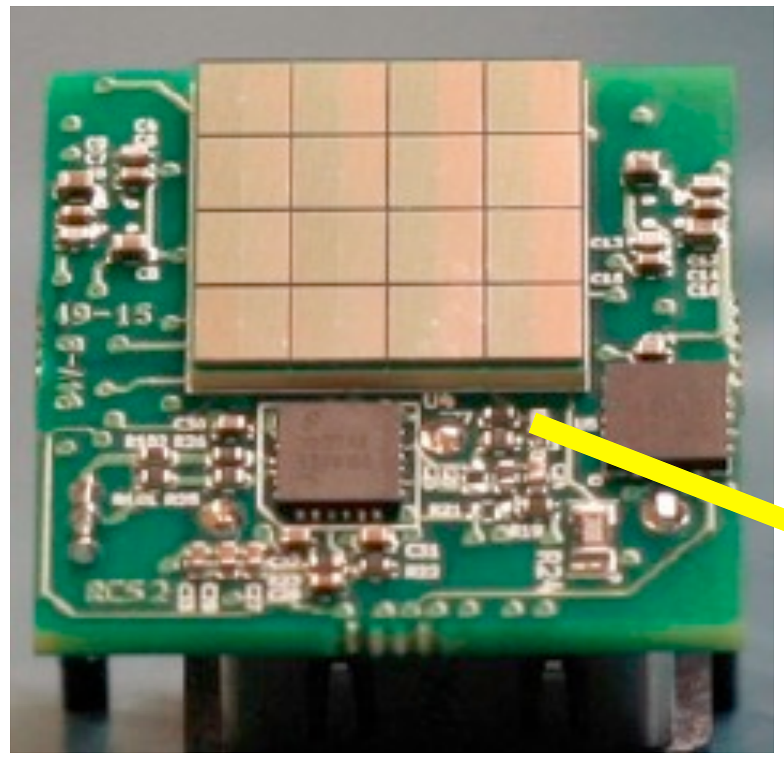
模拟和实际

电磁量能器捕捉衰变电子

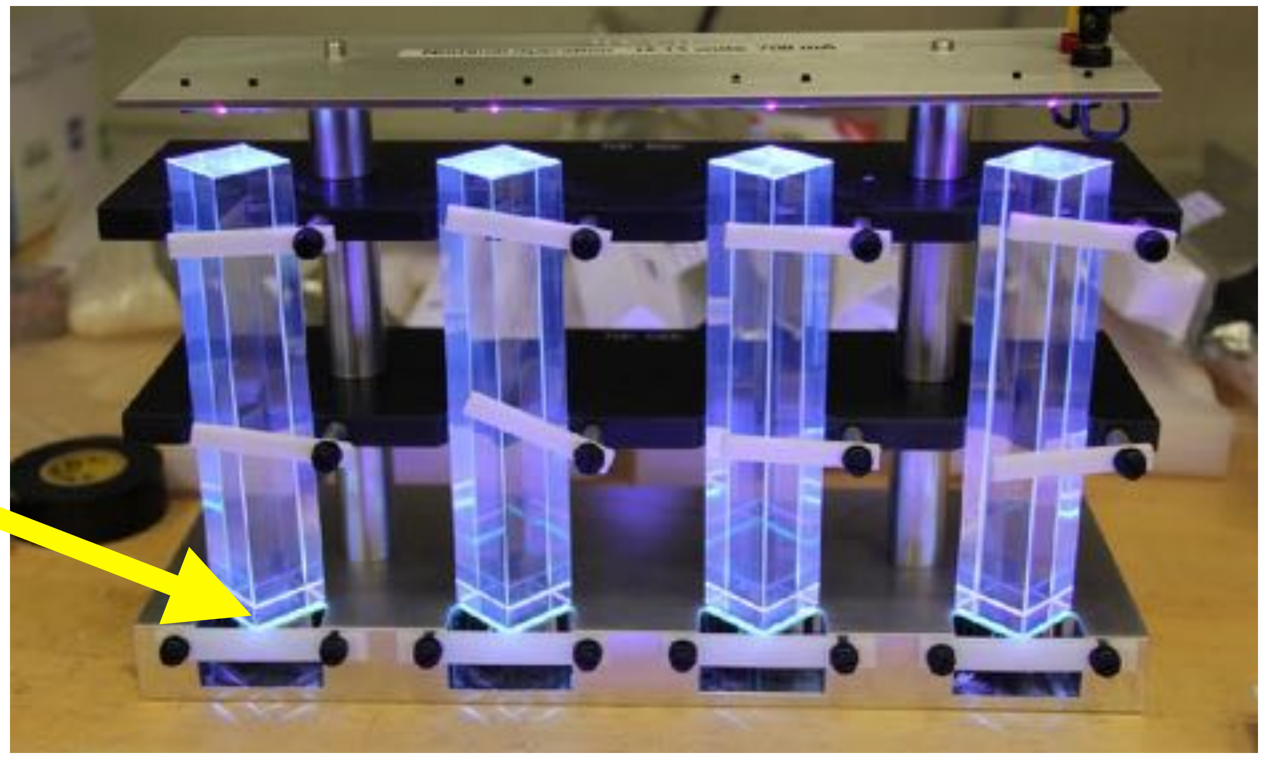


电子轨道向储存环内部弯曲

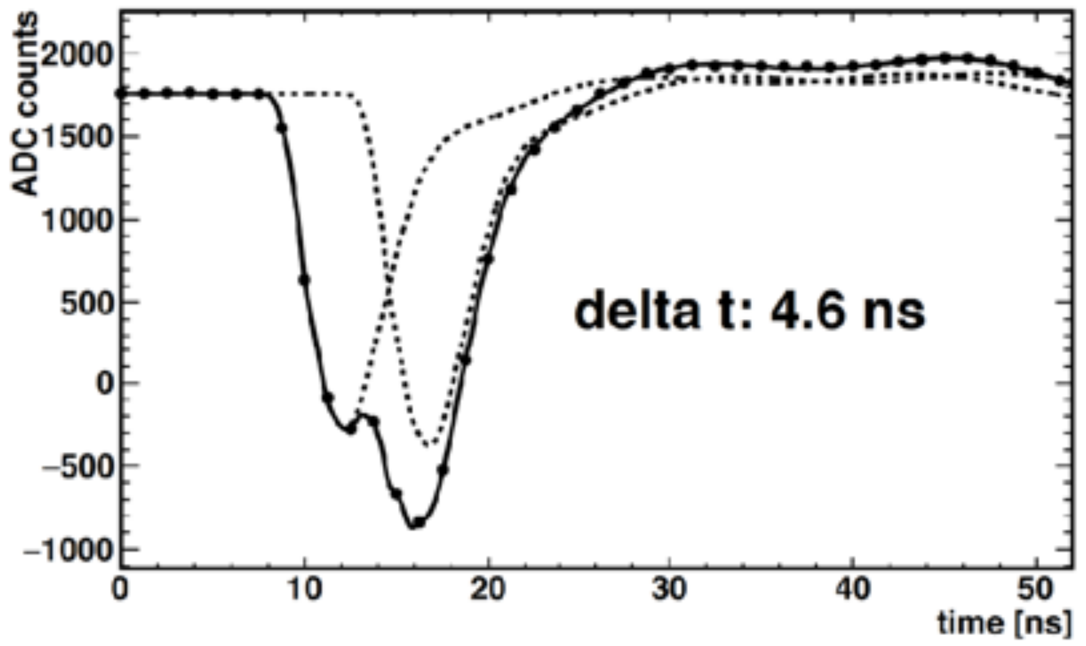
硅光电倍增管



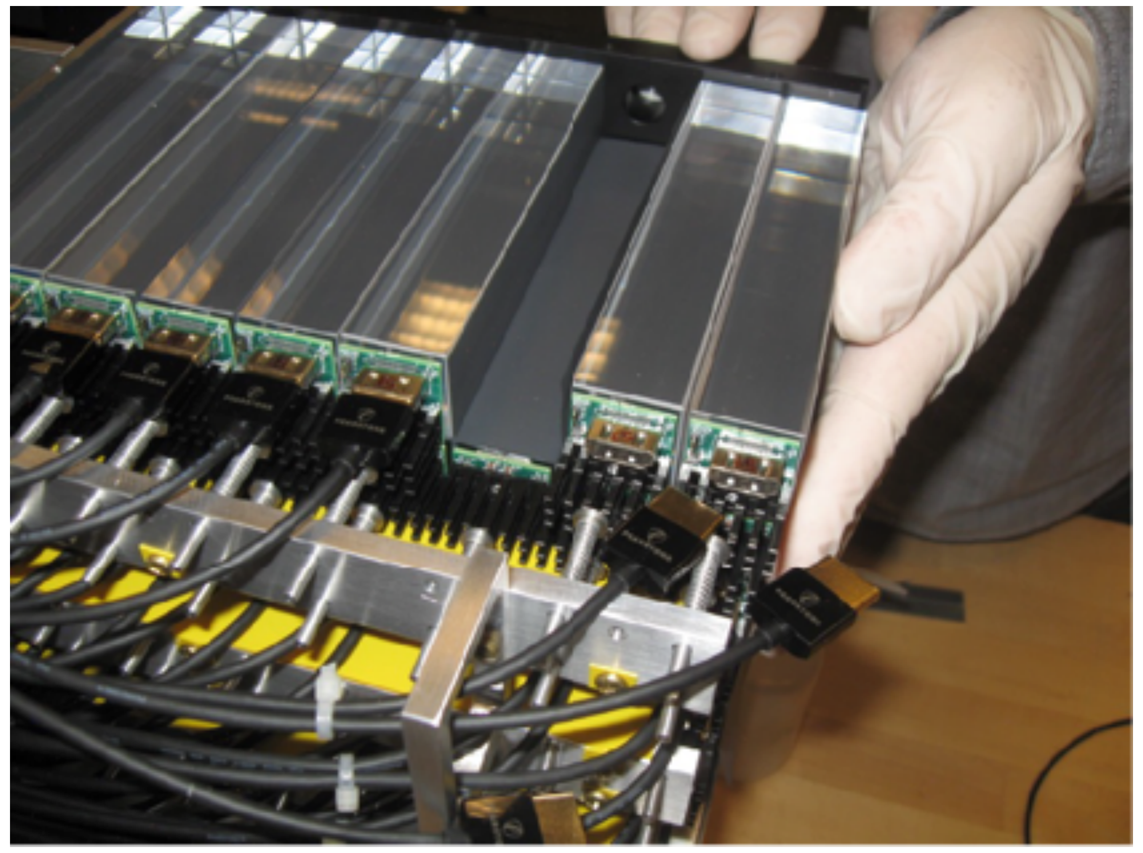
氟化铅



高时间分辨率

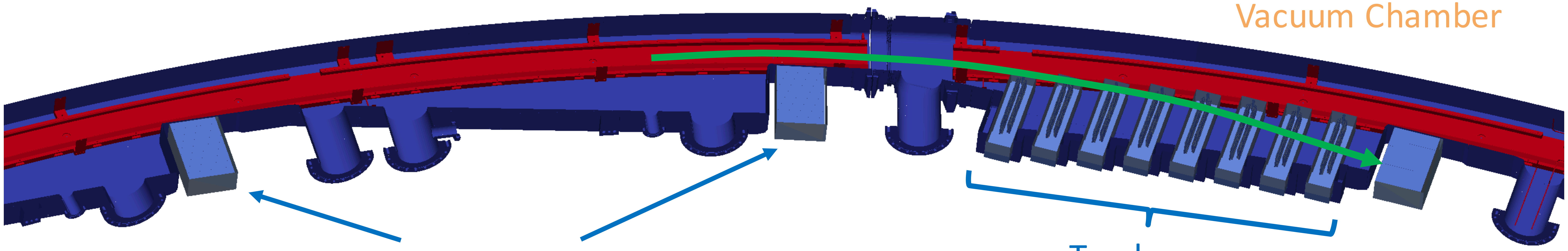


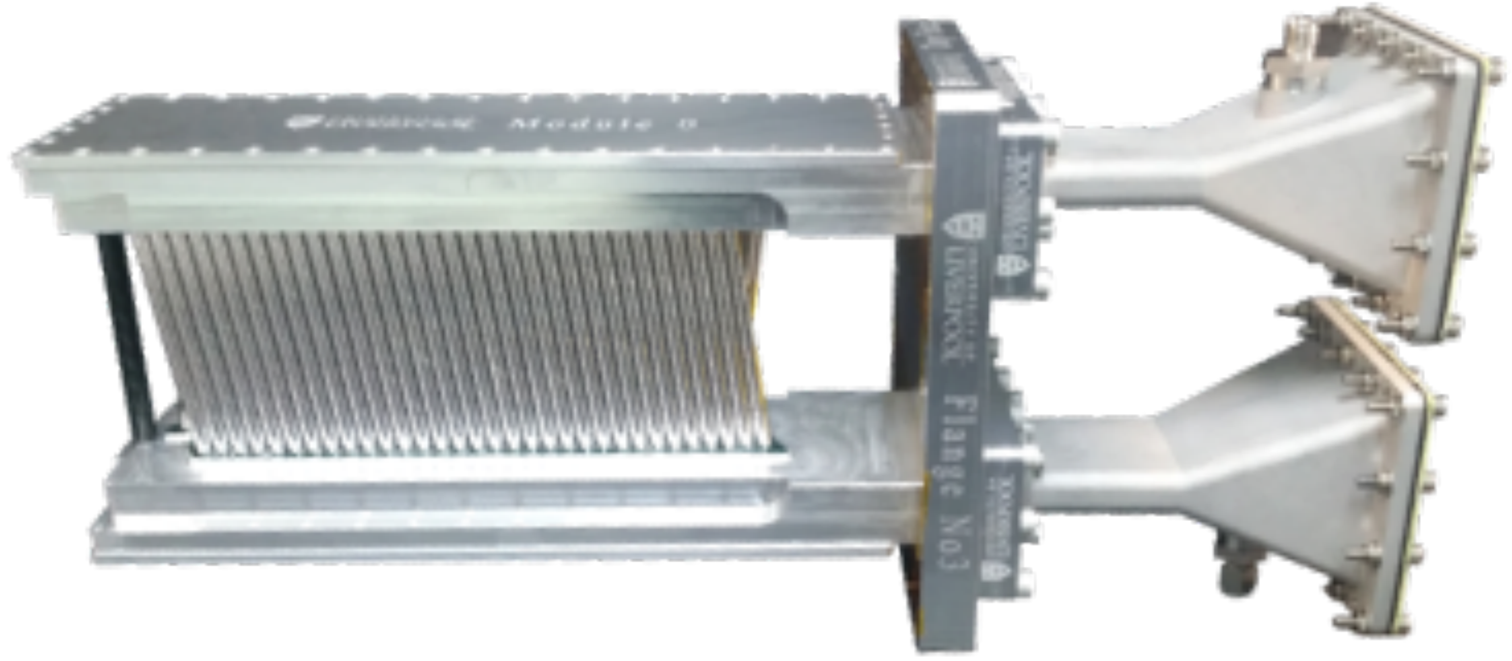
量能器前端电子学



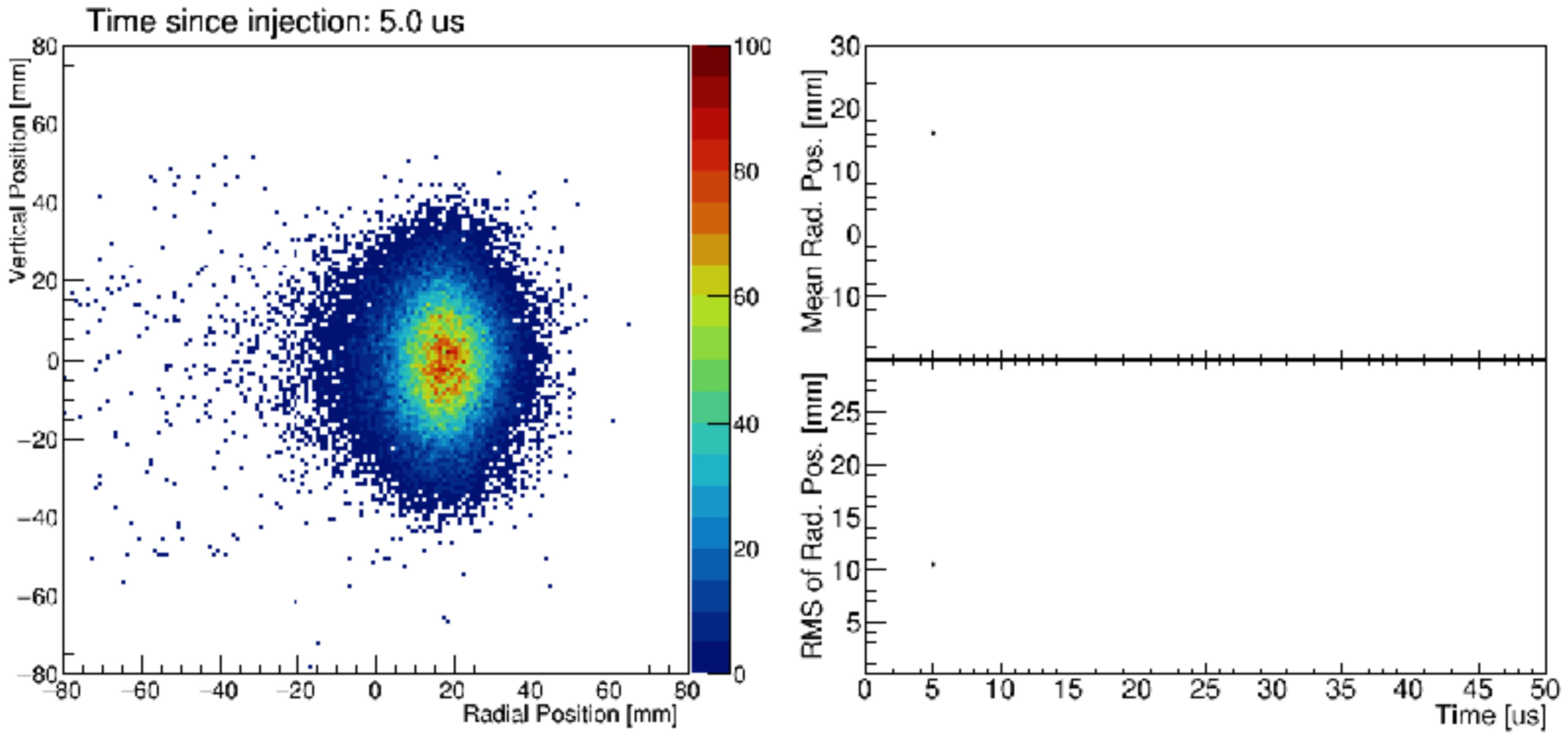
堆积晶体

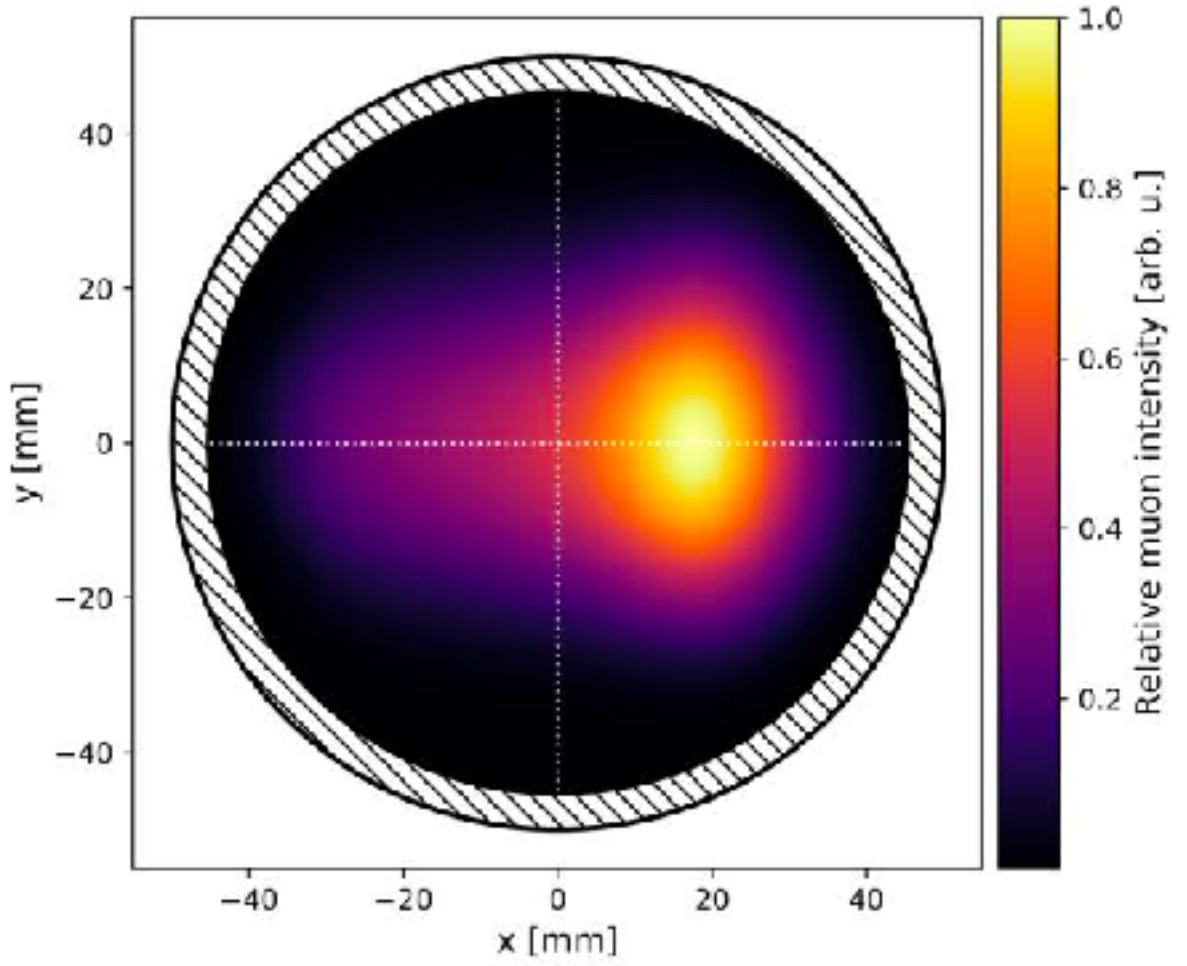
径迹探测器重建缪子衰变位置





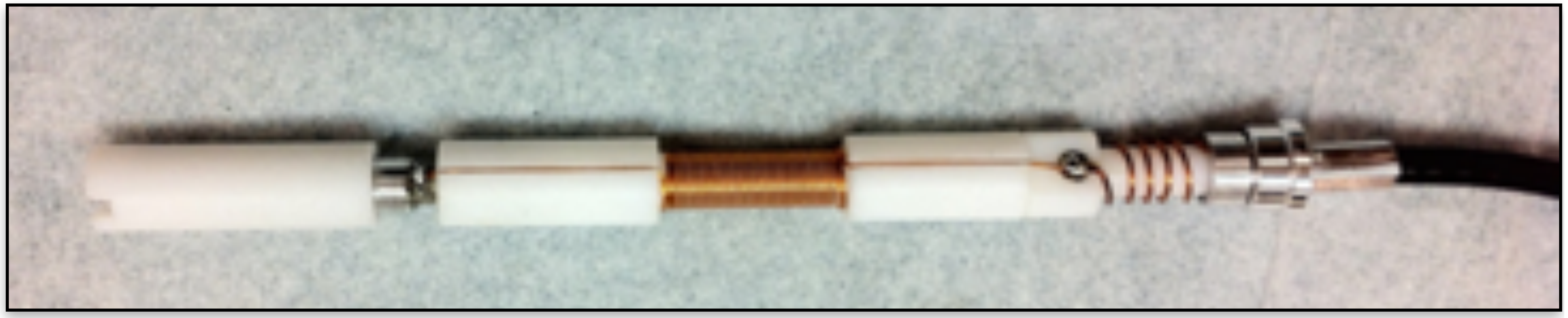
麦拉麦管探测器
(Straw tube trackers)

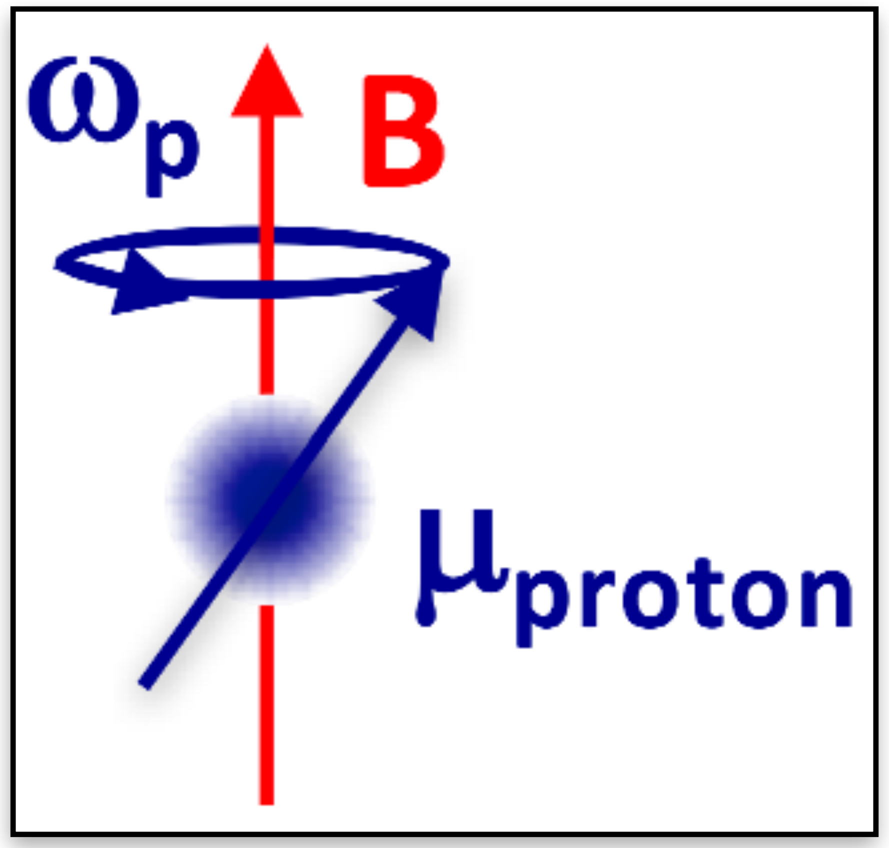




缪子的空间分布

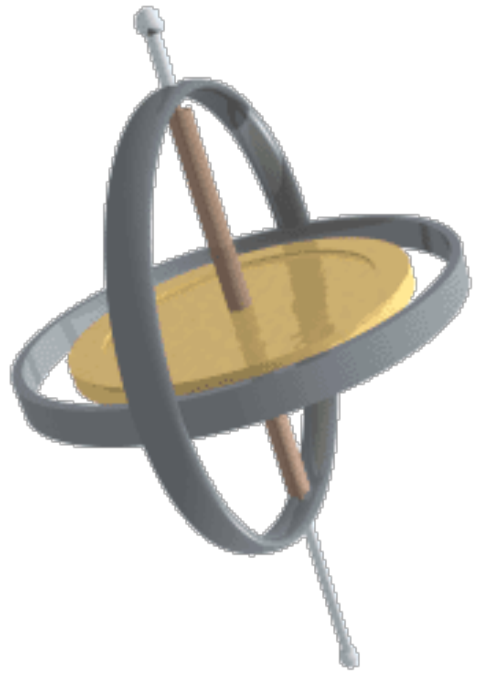
利用核磁共振技术（NMR）精确测量磁场

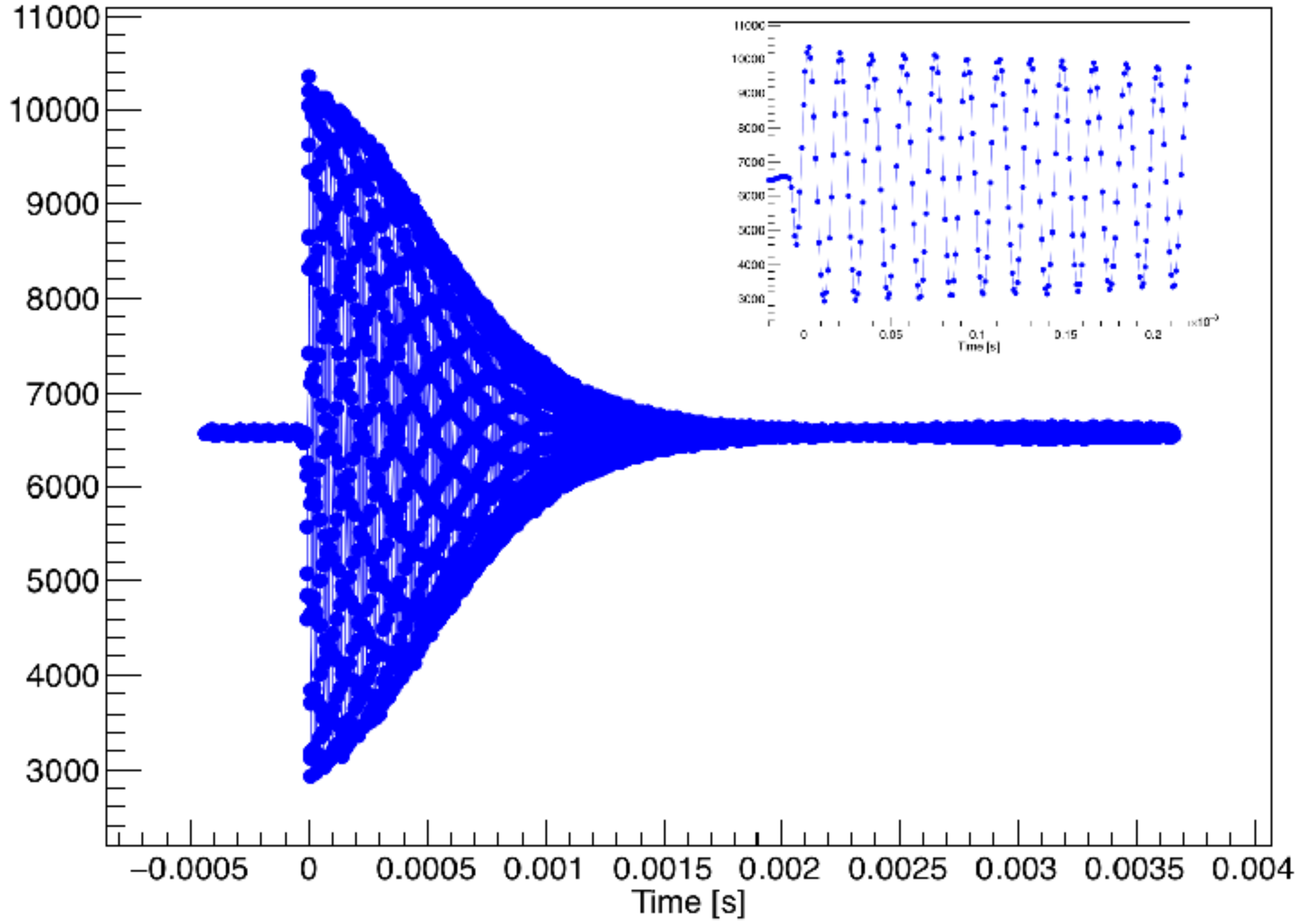




质子自旋的进动频率

$$\omega_p = g\frac{eB}{2mc}$$

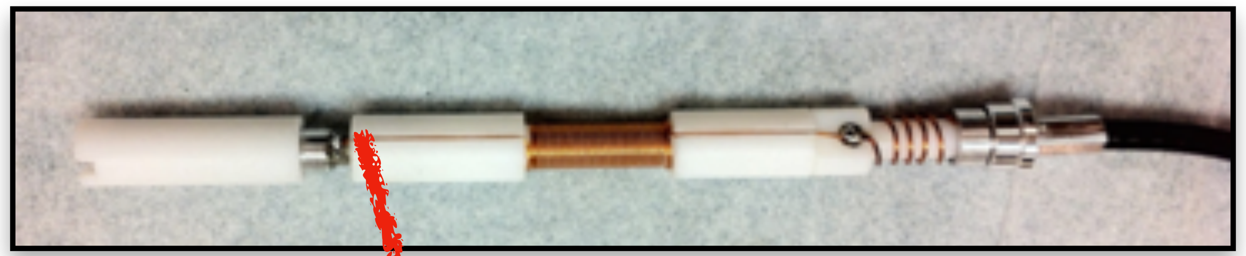


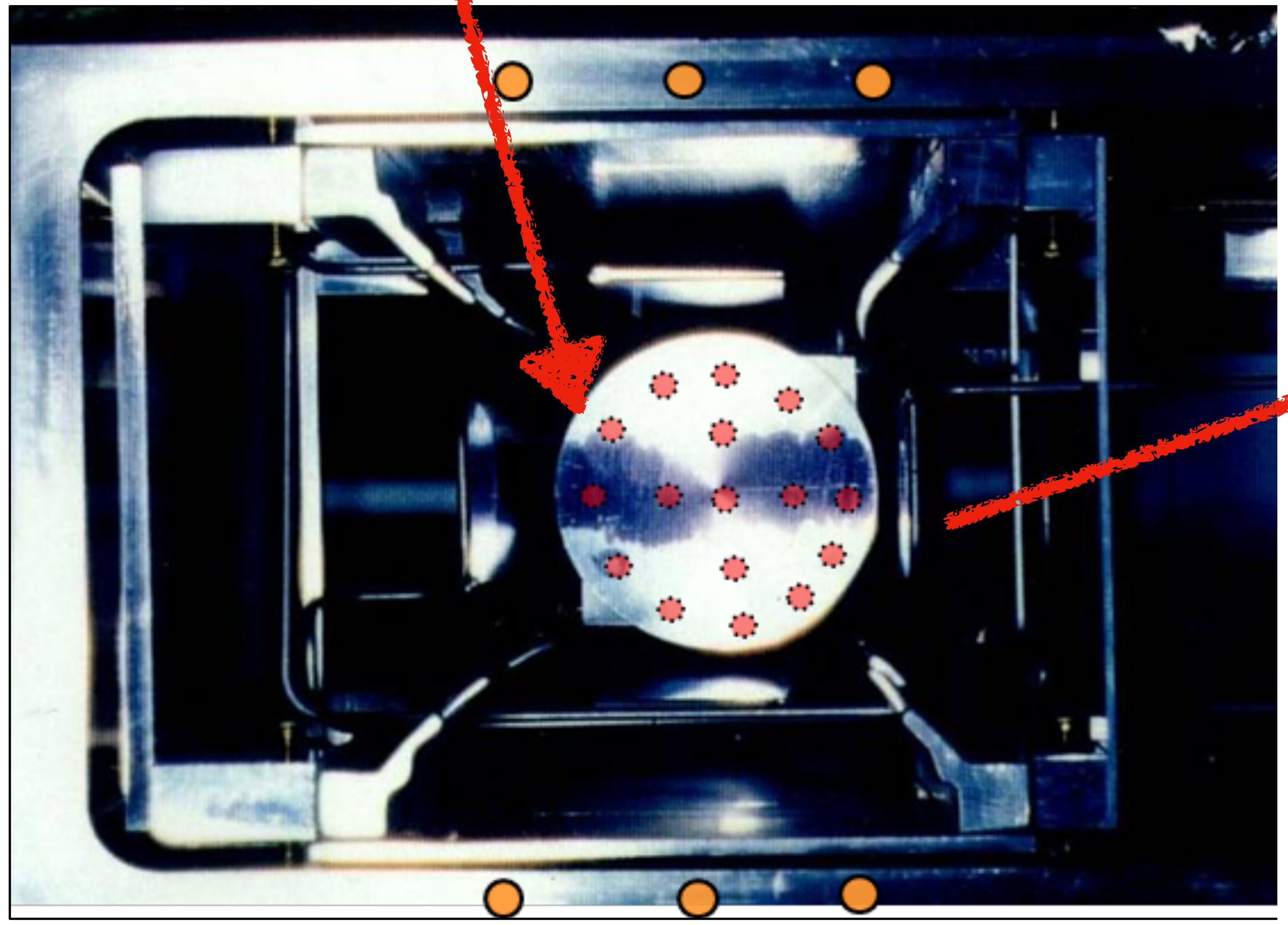


核磁共振的自由感应衰减
(Free Induction Decay)

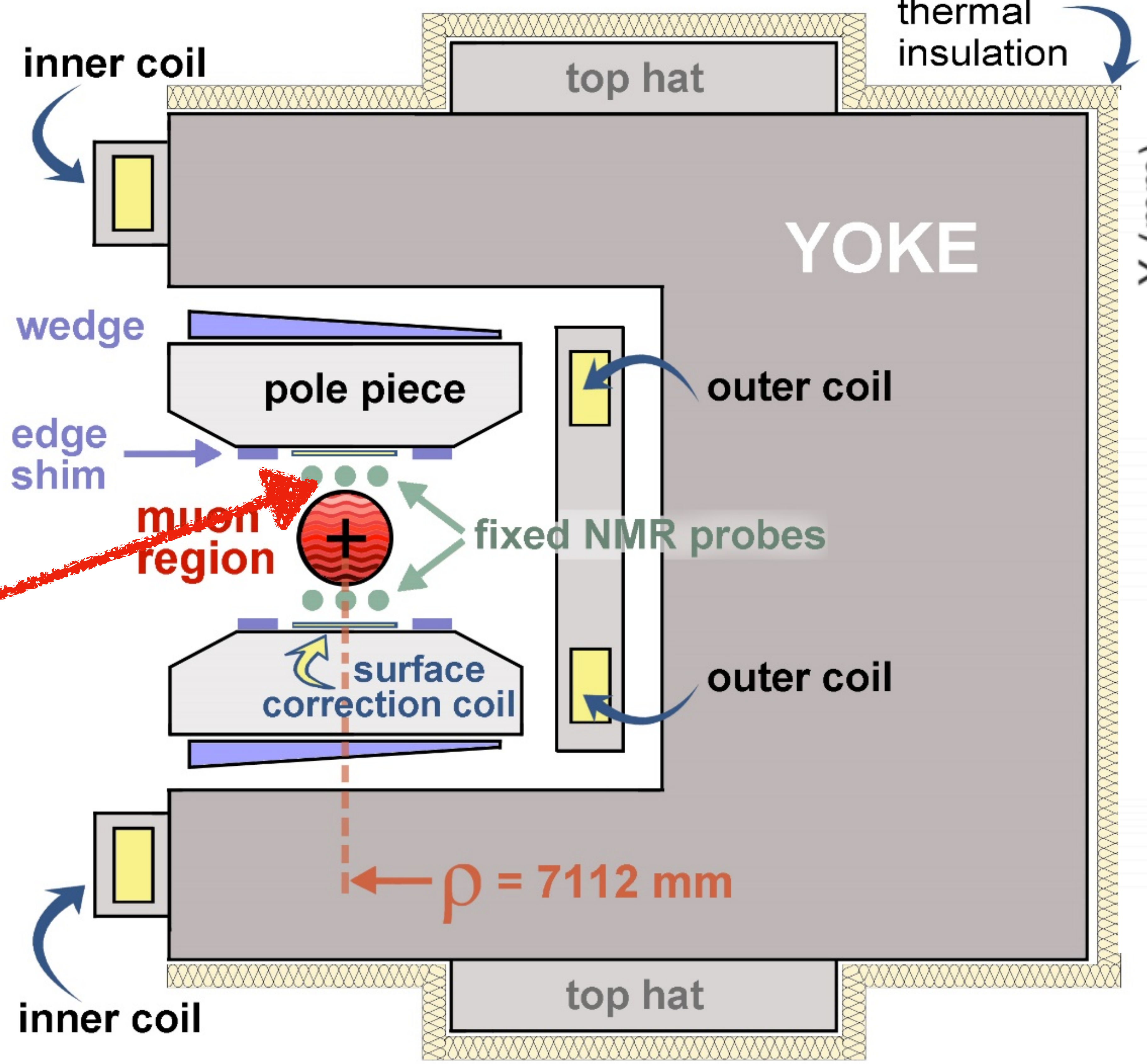
利用核磁共振技术精确测量磁场

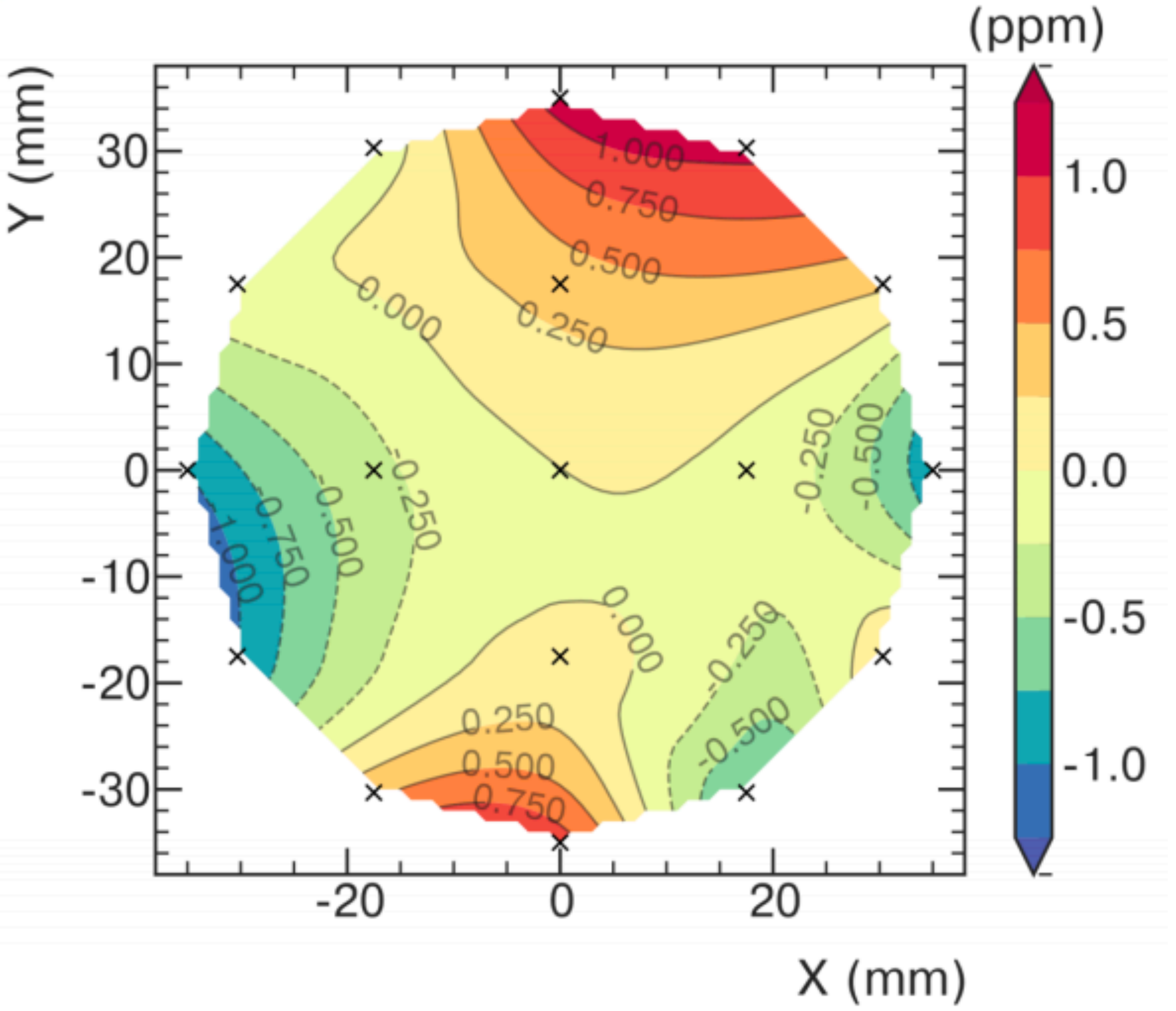
核磁共振探针
(NMR probe)





储存环的横截面



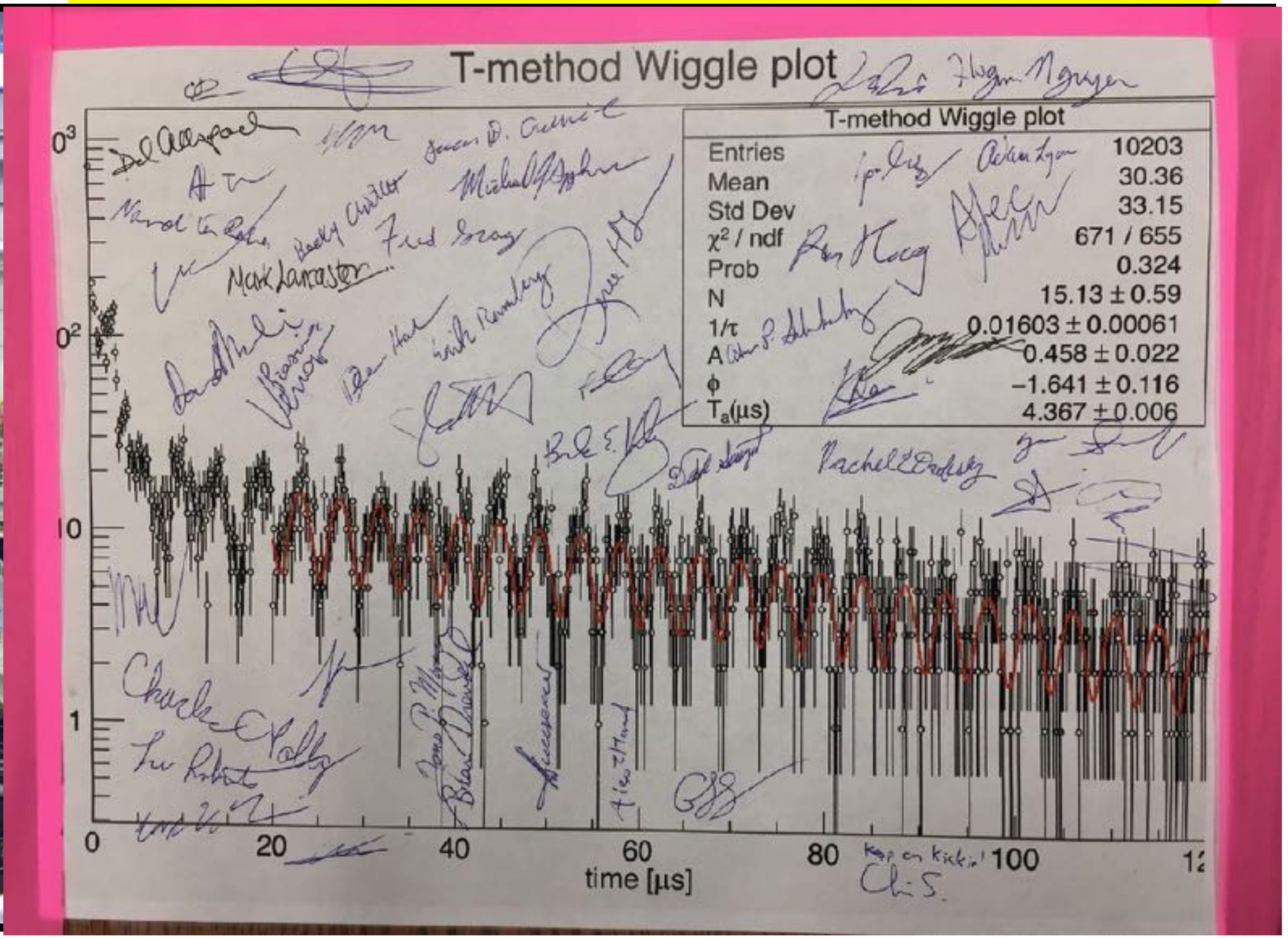


所测得磁场
（百万分之一的均匀度）

NMR台车 ＋~400个固定NMR探针

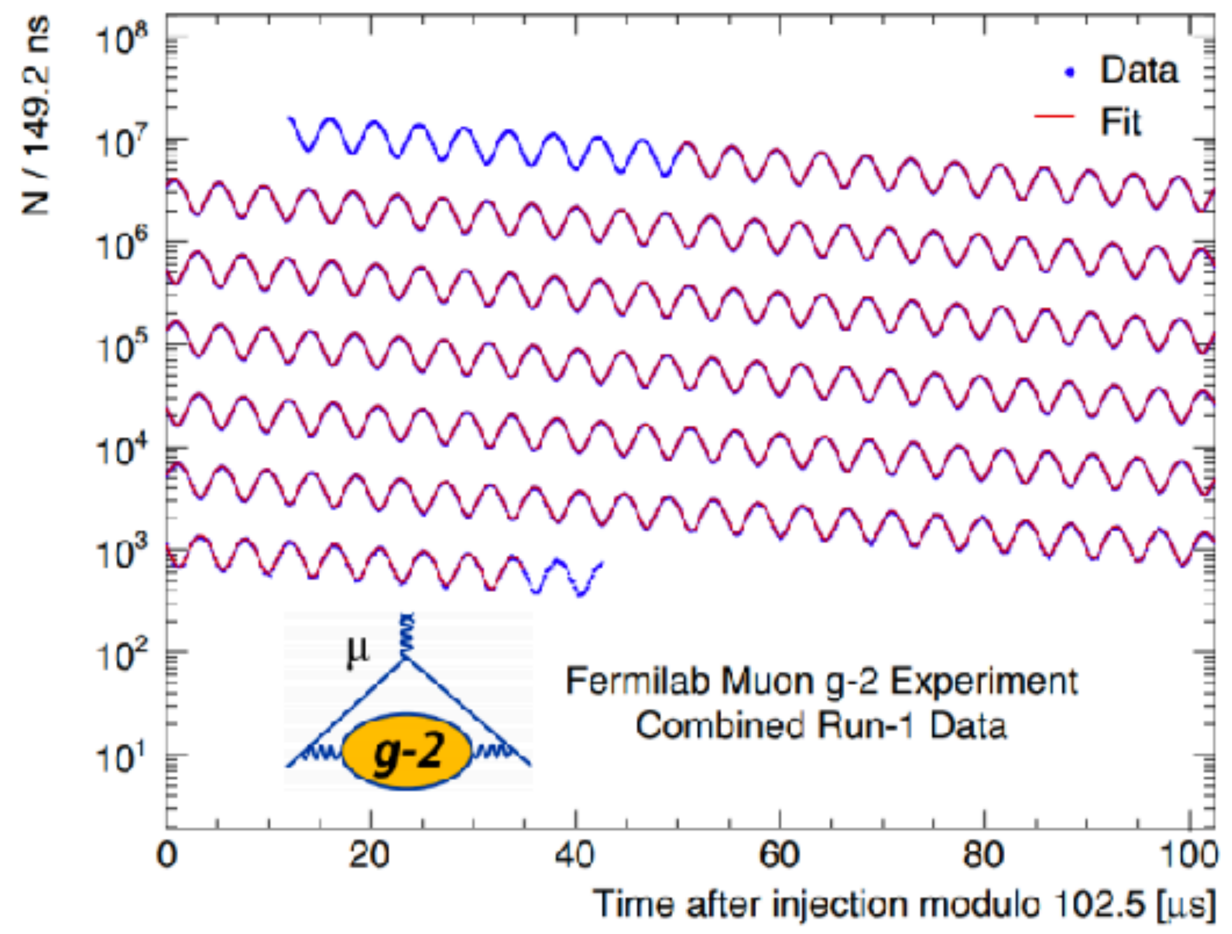
试运行(2017年夏天)+第一批数据（2018年春天）

The first wiggle plot in ~16 years!
(plot by K.S. Khaw)

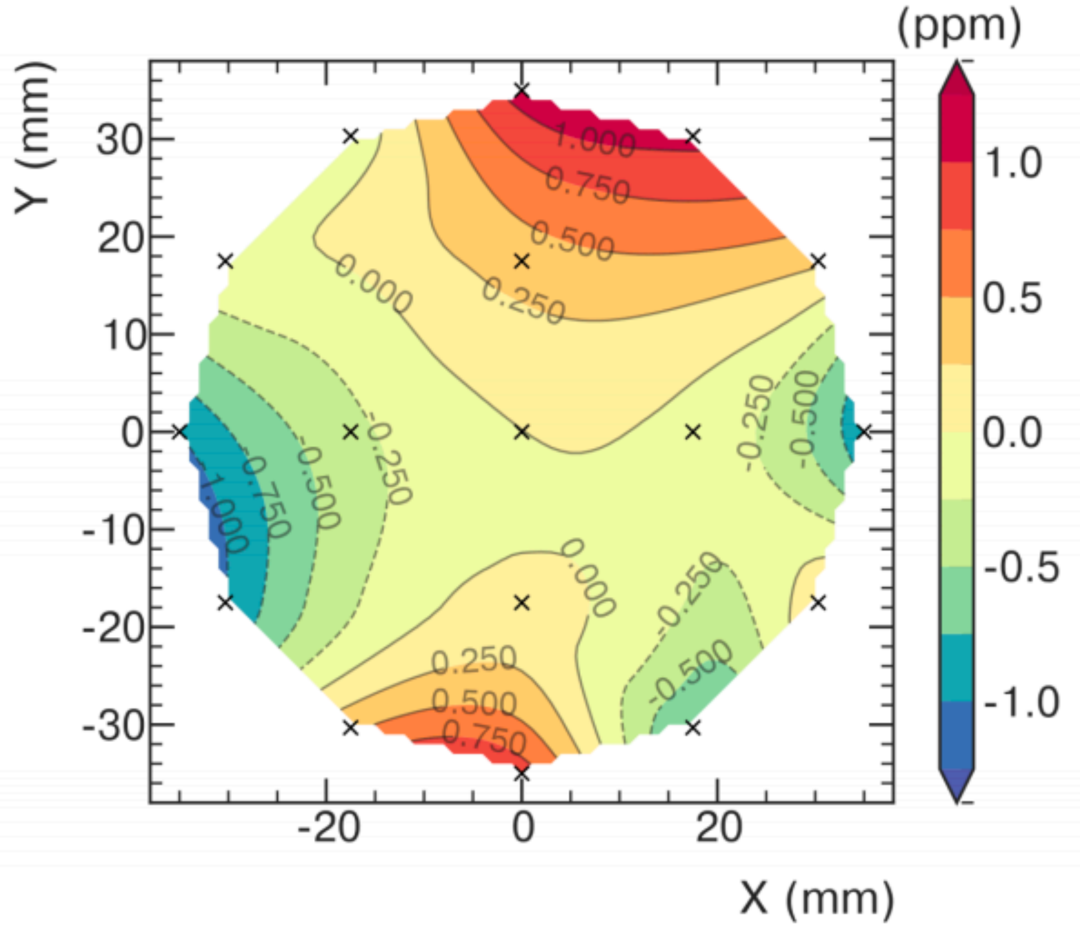


缪子反常磁矩测量的三大主要部分

反常进动频率

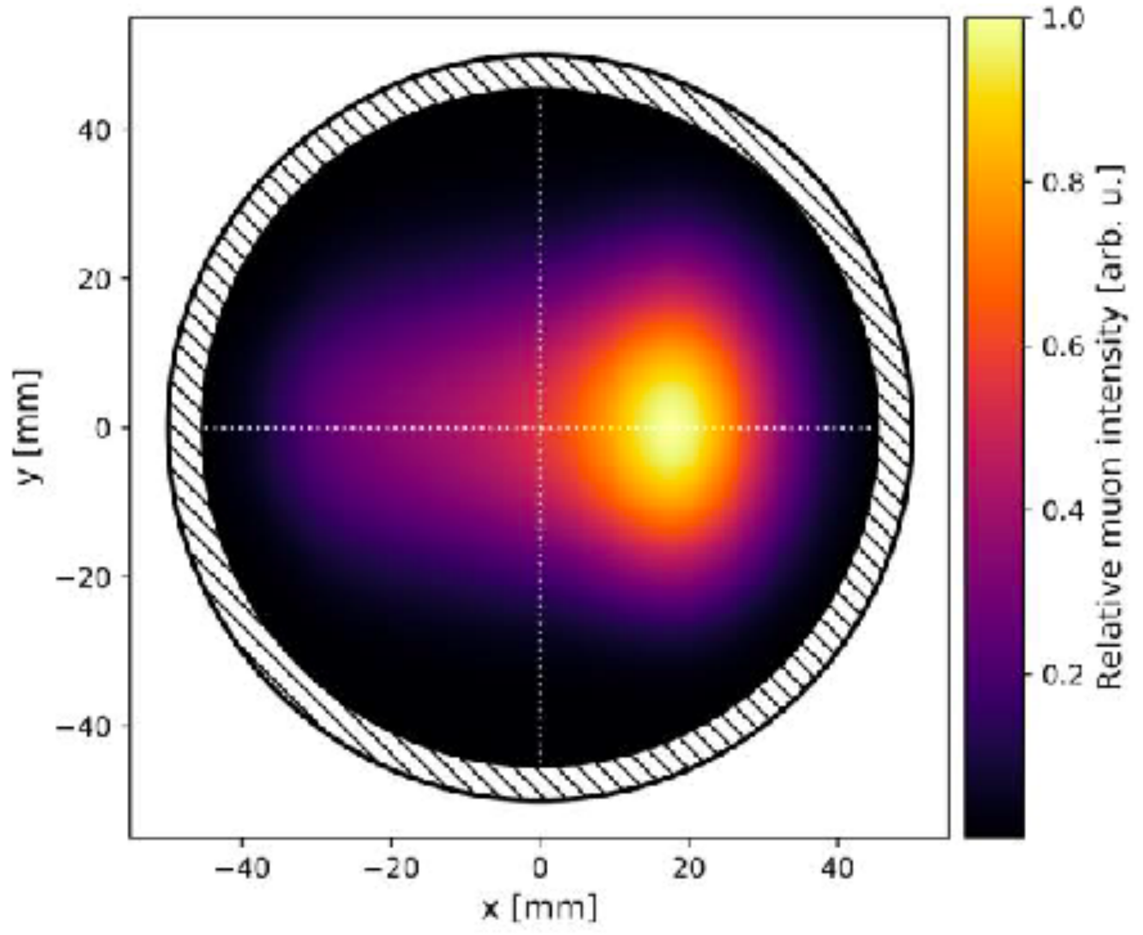


$$\text{反常磁矩} = \frac{\omega_a}{\omega_p \otimes \rho(r)} =$$



磁场分布

$\otimes$



缪子的空间分布

实际上的计算公式

其它更精确的基本常数

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$\tilde{\omega}'_p(T)$	Proton Larmor precession frequency in a spherical water sample. Temperature dependence known to < 1ppb/°C. Metrologia **13**, 179 (1977), Metrologia **51**, 54 (2014), Metrologia **20**, 81 (1984)
$\frac{\mu_e(H)}{\mu'_p(T)}$	Measured to 10.5 ppb accuracy at T = 34.7°C Metrologia **13**, 179 (1977)
$\frac{\mu_e}{\mu_e(H)}$	Bound-state QED (exact) Rev. Mod. Phys. **88** 035009 (2016)
$\frac{m_\mu}{m_e}$	Known to 22 ppb from muonium hyperfine splitting Phys. Rev. Lett. **82**, 711 (1999)
$\frac{g_e}{2}$	Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)

束流动力学修正

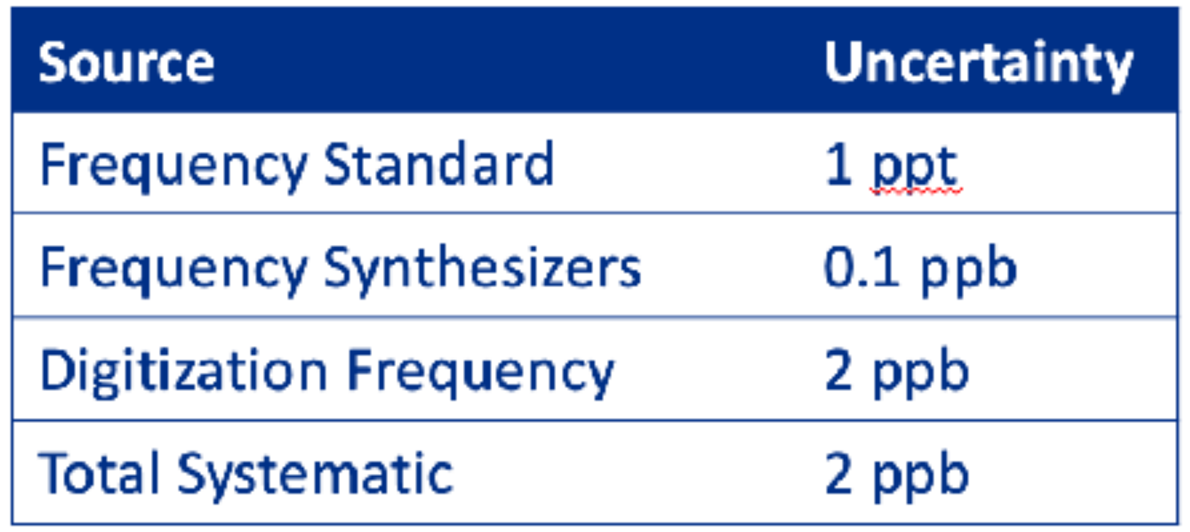
瞬态场修正

$$R'_\mu = \left(\frac{f_{clock}\cdot\omega_a^{meas}\cdot(1+\overbrace{C_e+C_p+C_{ml}+C_{pa}}^{\text{Corrections due to beam dynamics}})}{f_{calib}\cdot\omega'_p(x,y,\phi)\otimes M(x,y,\phi)\cdot(1+\underbrace{B_k+B_q}_{\text{Corrections due to transient magnetic fields}})} \right)$$

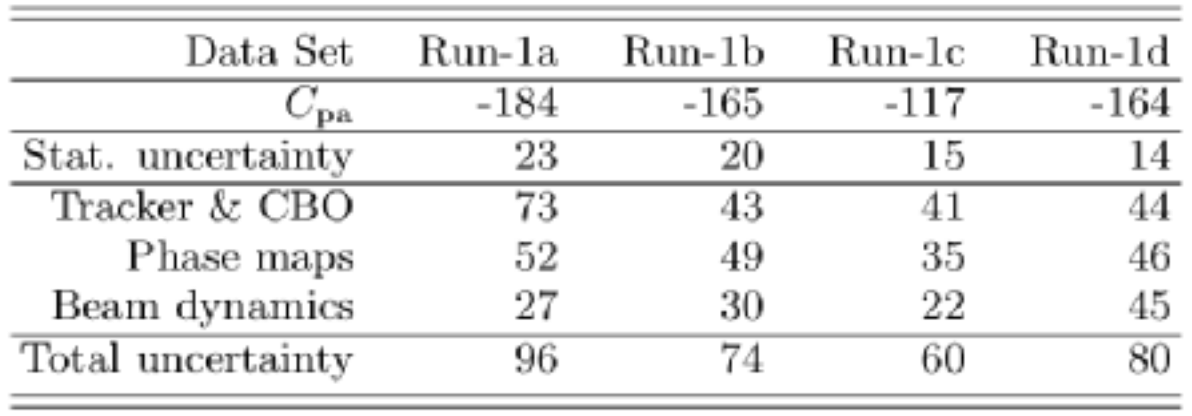
$\tilde{\omega}'_p(T)$ = Proton Larmor precession frequency in a spherical water sample weighted for muon distribution

系统误差表

考虑每一个可能的系统误差

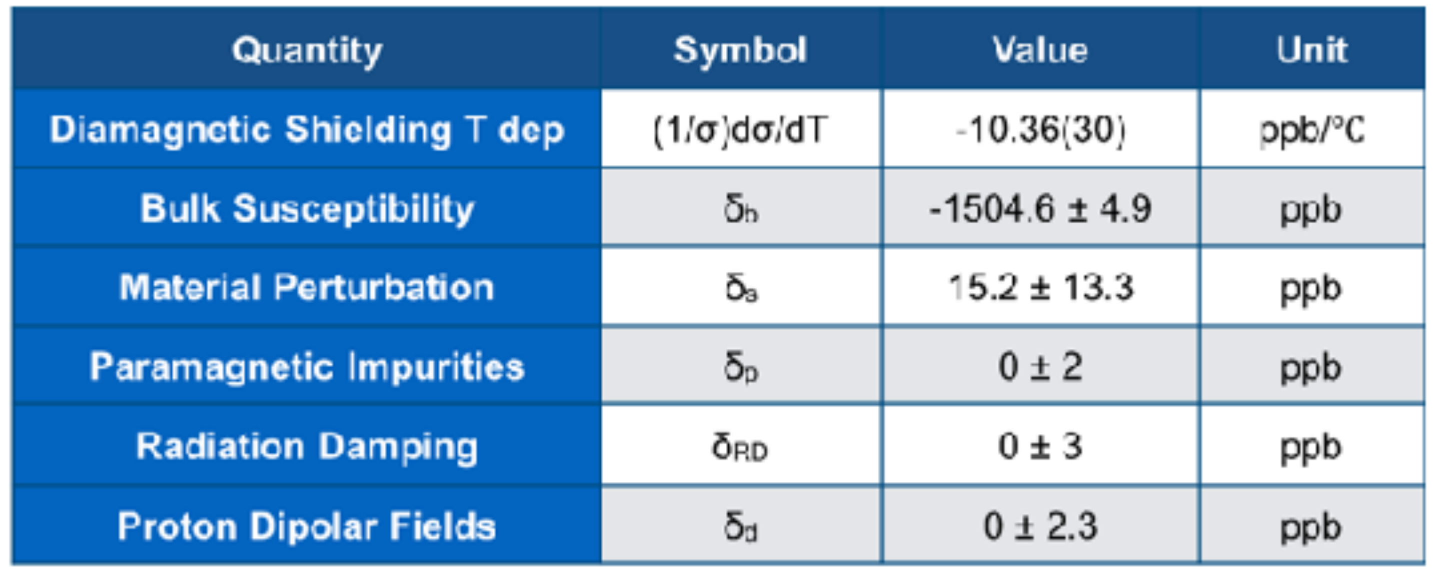


Source	Uncertainty
Frequency Standard	1 ppt
Frequency Synthesizers	0.1 ppb
Digitization Frequency	2 ppb
Total Systematic	2 ppb

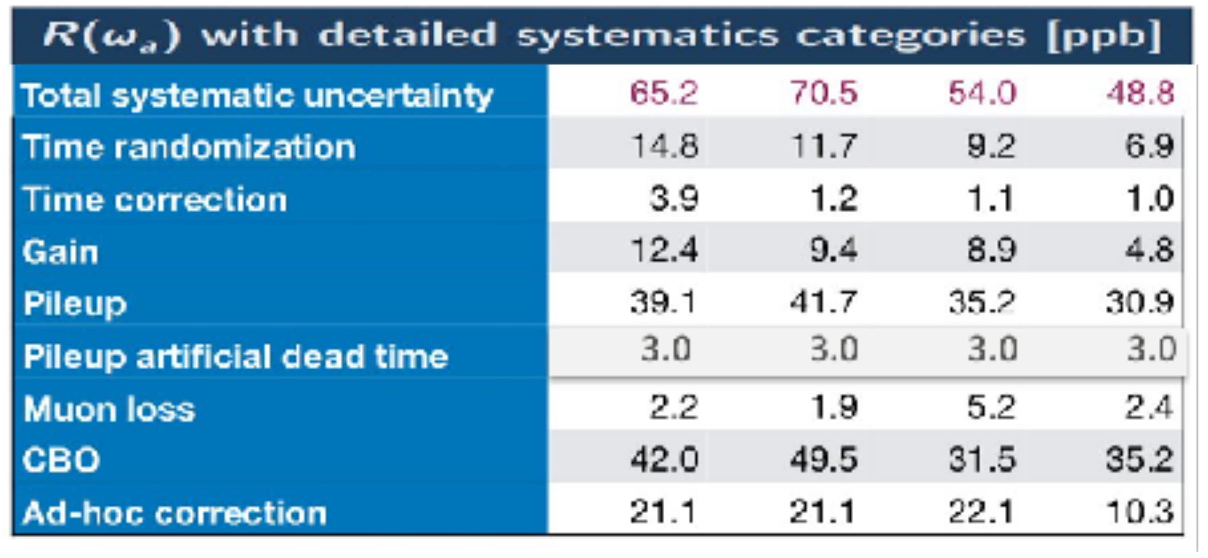


Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

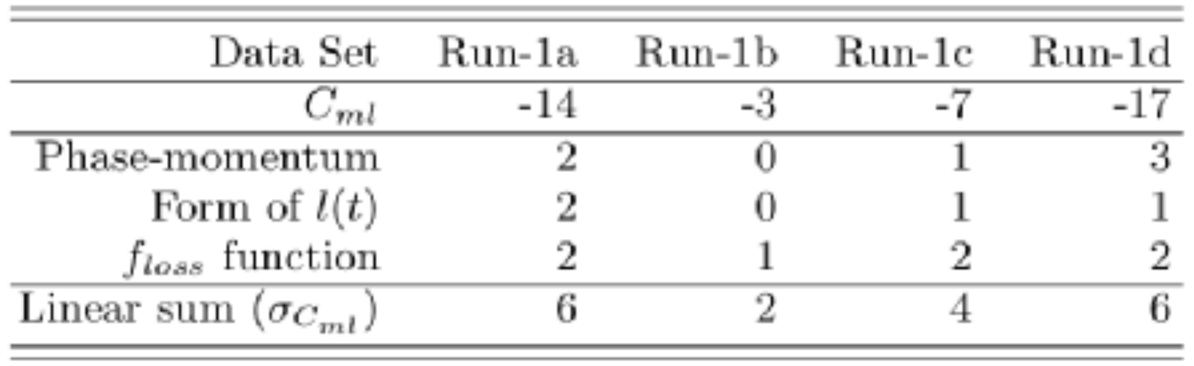
	correction [ppb]				uncertainty [ppb]			
Dataset	1a	1b	1c	1d	1a	1b	1c	1d
1. Tracker and calo effects	-	-	-	-	9.2	13.3	15.6	19.7
2. COD effects	1.6	1.5	1.7	1.4	5.2	4.7	5.2	4.9
3. In-fill time effects	-1.9	-2.3	-1.2	-4.1	-	-	-	-
Total	**-0.3**	**-0.8**	**0.5**	**-2.7**	**10.6**	**14.1**	**16.5**	**20.3**



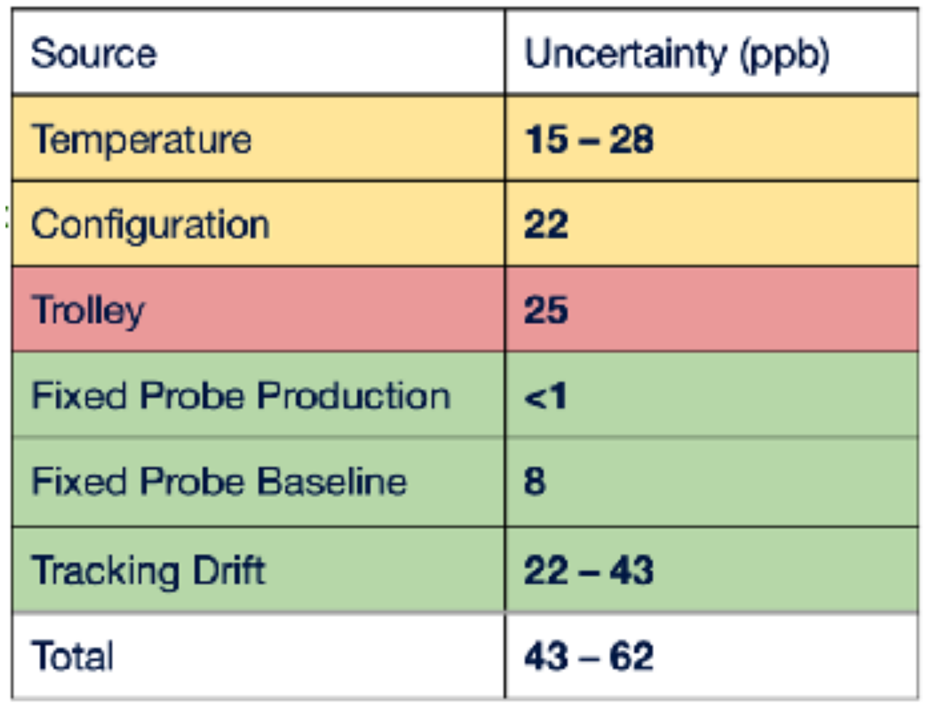
Quantity	Symbol	Value	Unit
Diamagnetic Shielding T dep	$(1/\sigma)d\sigma/dT$	-10.36(30)	ppb/°C
Bulk Susceptibility	δ_b	-1504.6 ± 4.9	ppb
Material Perturbation	δ_s	15.2 ± 13.3	ppb
Paramagnetic Impurities	δ_p	0 ± 2	ppb
Radiation Damping	δ_{RD}	0 ± 3	ppb
Proton Dipolar Fields	δ_d	0 ± 2.3	ppb



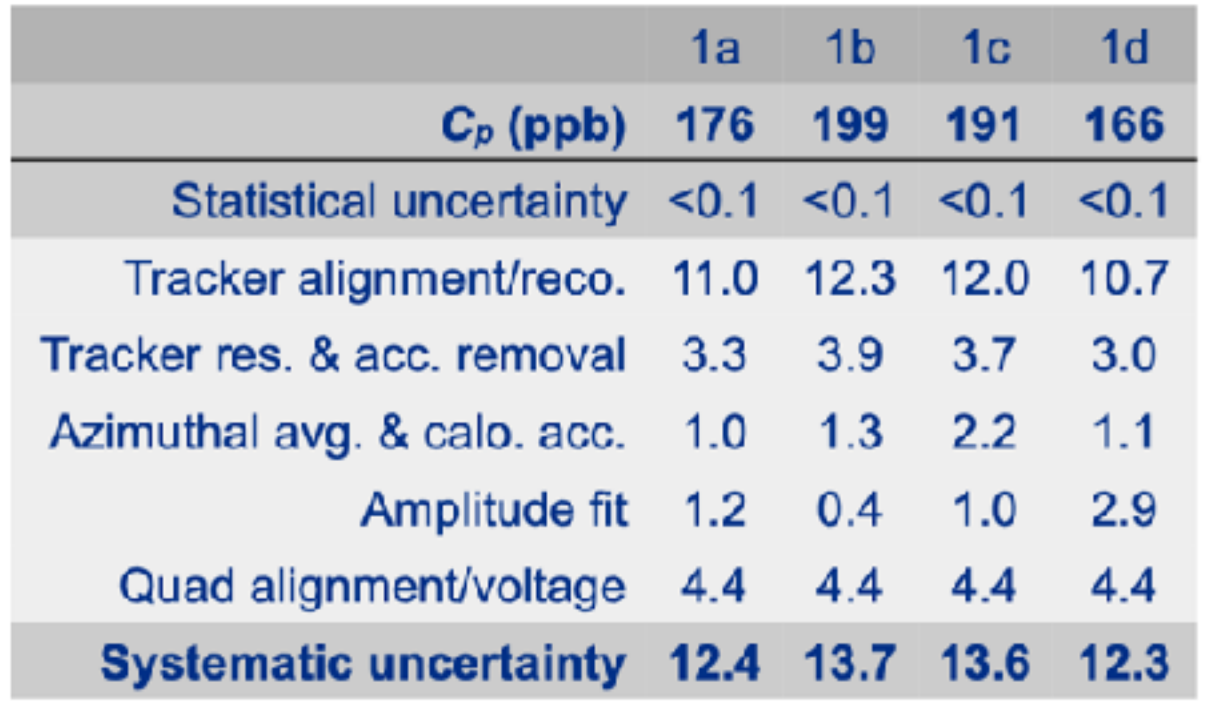
$R(\omega_a)$ with detailed systematics categories [ppb]				
Total systematic uncertainty	65.2	70.5	54.0	48.8
Time randomization	14.8	11.7	9.2	6.9
Time correction	3.9	1.2	1.1	1.0
Gain	12.4	9.4	8.9	4.8
Pileup	39.1	41.7	35.2	30.9
Pileup artificial dead time	3.0	3.0	3.0	3.0
Muon loss	2.2	1.9	5.2	2.4
CBO	42.0	49.5	31.5	35.2
Ad-hoc correction	21.1	21.1	22.1	10.3



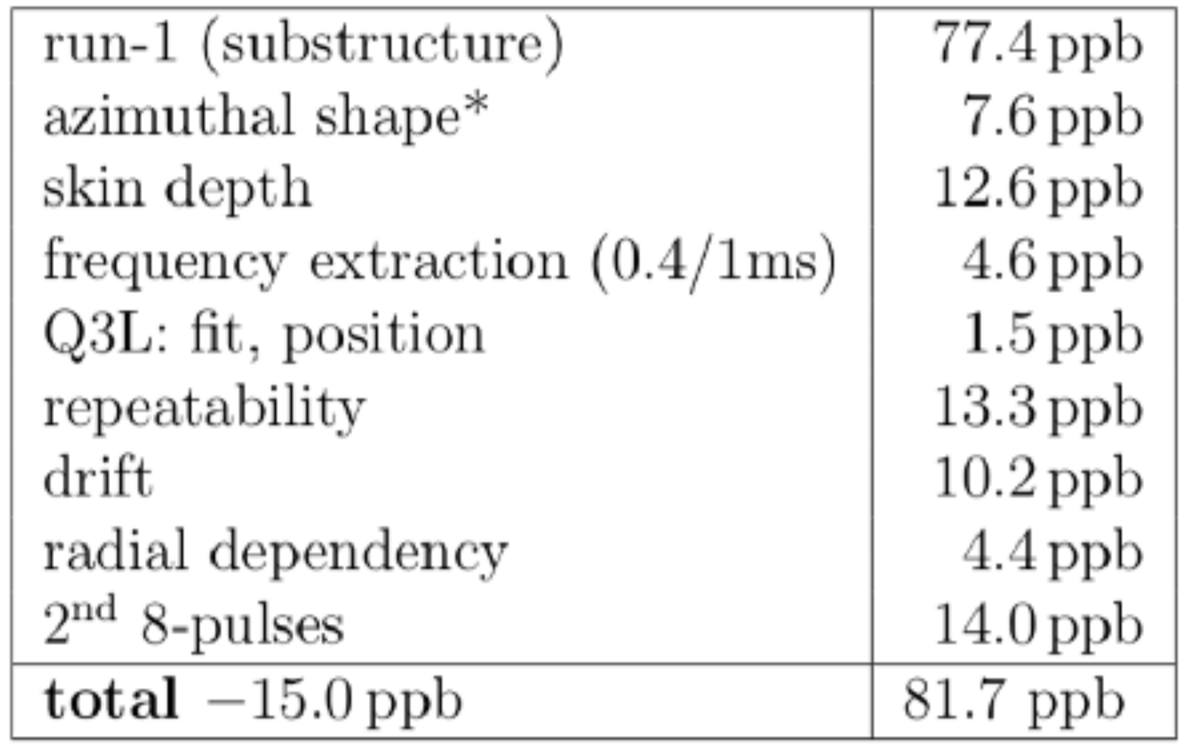
Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6



Source	Uncertainty (ppb)
Temperature	**15 – 28**
Configuration	**22**
Trolley	**25**
Fixed Probe Production	**<1**
Fixed Probe Baseline	**8**
Tracking Drift	**22 – 43**
Total	**43 – 62**

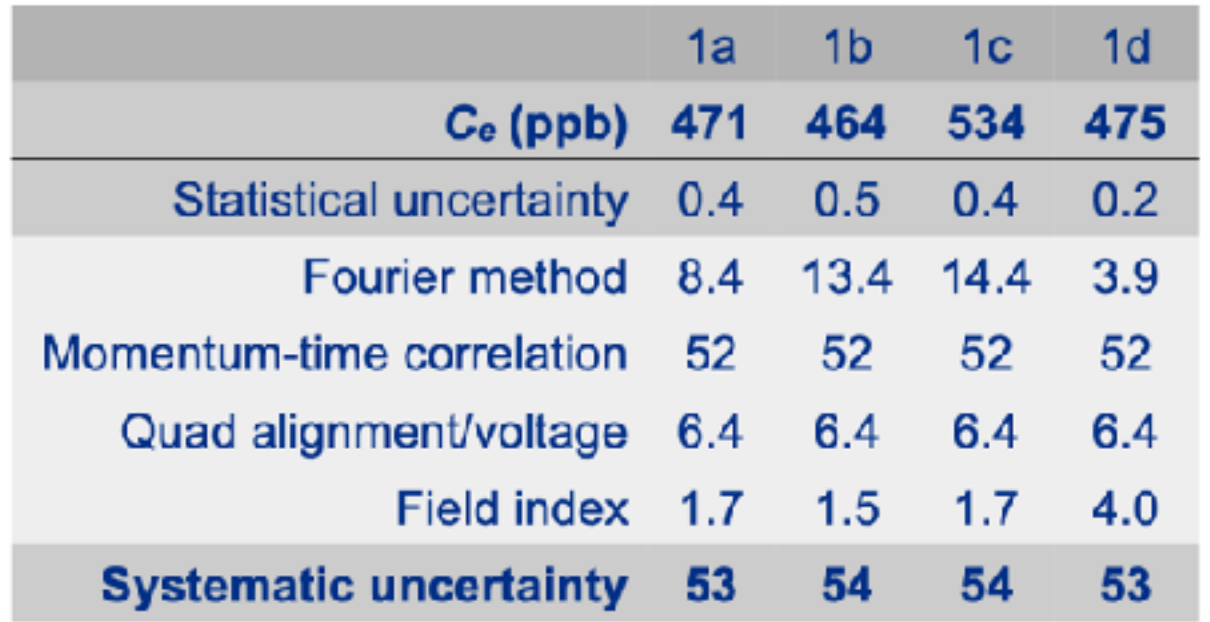


	1a	1b	1c	1d
C_p (ppb)	**176**	**199**	**191**	**166**
Statistical uncertainty	<0.1	<0.1	<0.1	<0.1
Tracker alignment/reco.	11.0	12.3	12.0	10.7
Tracker res. & acc. removal	3.3	3.9	3.7	3.0
Azimuthal avg. & calo. acc.	1.0	1.3	2.2	1.1
Amplitude fit	1.2	0.4	1.0	2.9
Quad alignment/voltage	4.4	4.4	4.4	4.4
Systematic uncertainty	**12.4**	**13.7**	**13.6**	**12.3**

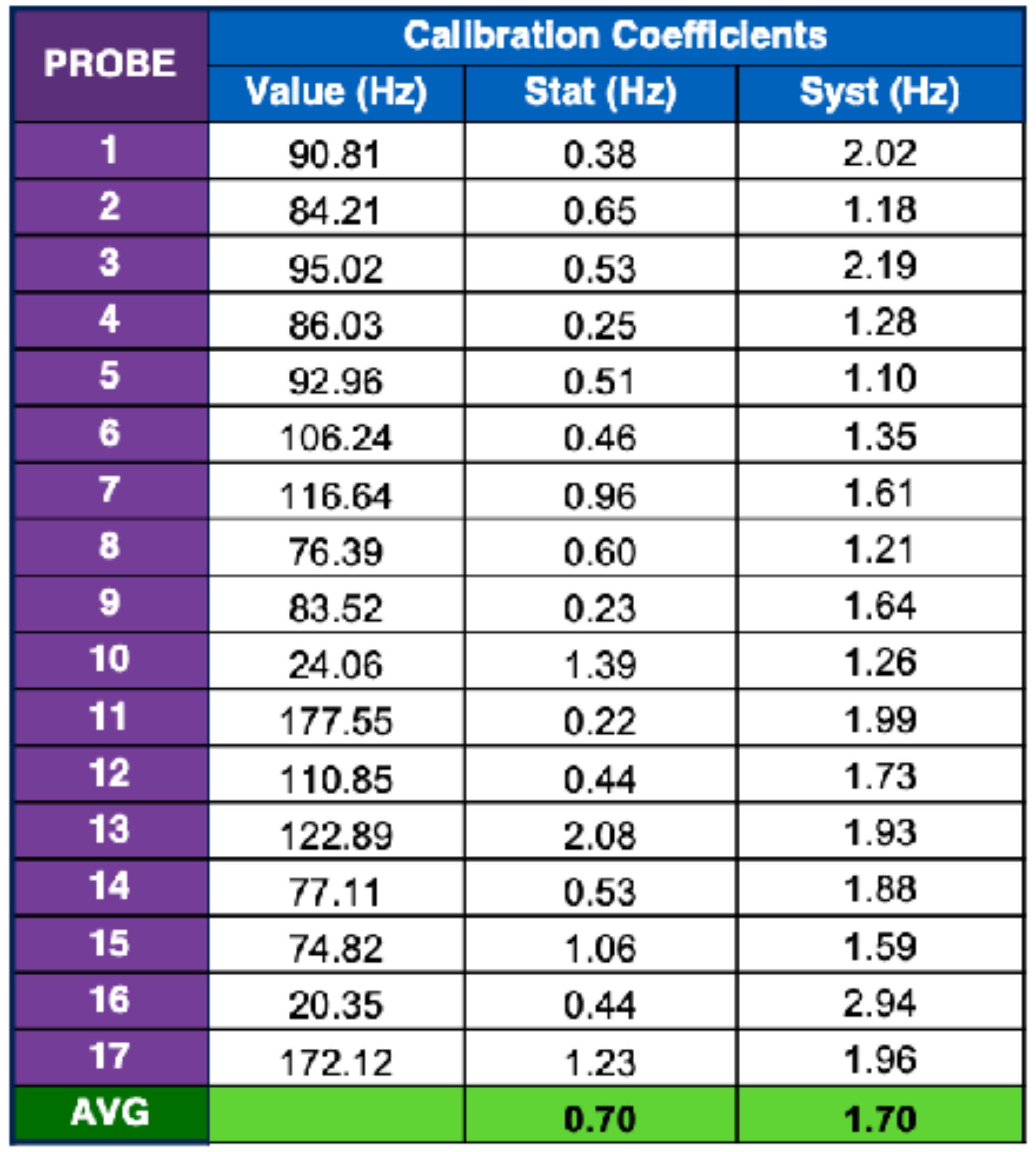


run-1 (substructure)	77.4 ppb
azimuthal shape*	7.6 ppb
skin depth	12.6 ppb
frequency extraction (0.4/1ms)	4.6 ppb
Q3L: fit, position	1.5 ppb
repeatability	13.3 ppb
drift	10.2 ppb
radial dependency	4.4 ppb
2nd 8-pulses	14.0 ppb
total −15.0 ppb	81.7 ppb

Run-1 Estimate:
B_k = -27.4 ± 37 ppb



	1a	1b	1c	1d
C_e (ppb)	**471**	**464**	**534**	**475**
Statistical uncertainty	0.4	0.5	0.4	0.2
Fourier method	8.4	13.4	14.4	3.9
Momentum-time correlation	52	52	52	52
Quad alignment/voltage	6.4	6.4	6.4	6.4
Field index	1.7	1.5	1.7	4.0
Systematic uncertainty	**53**	**54**	**54**	**53**

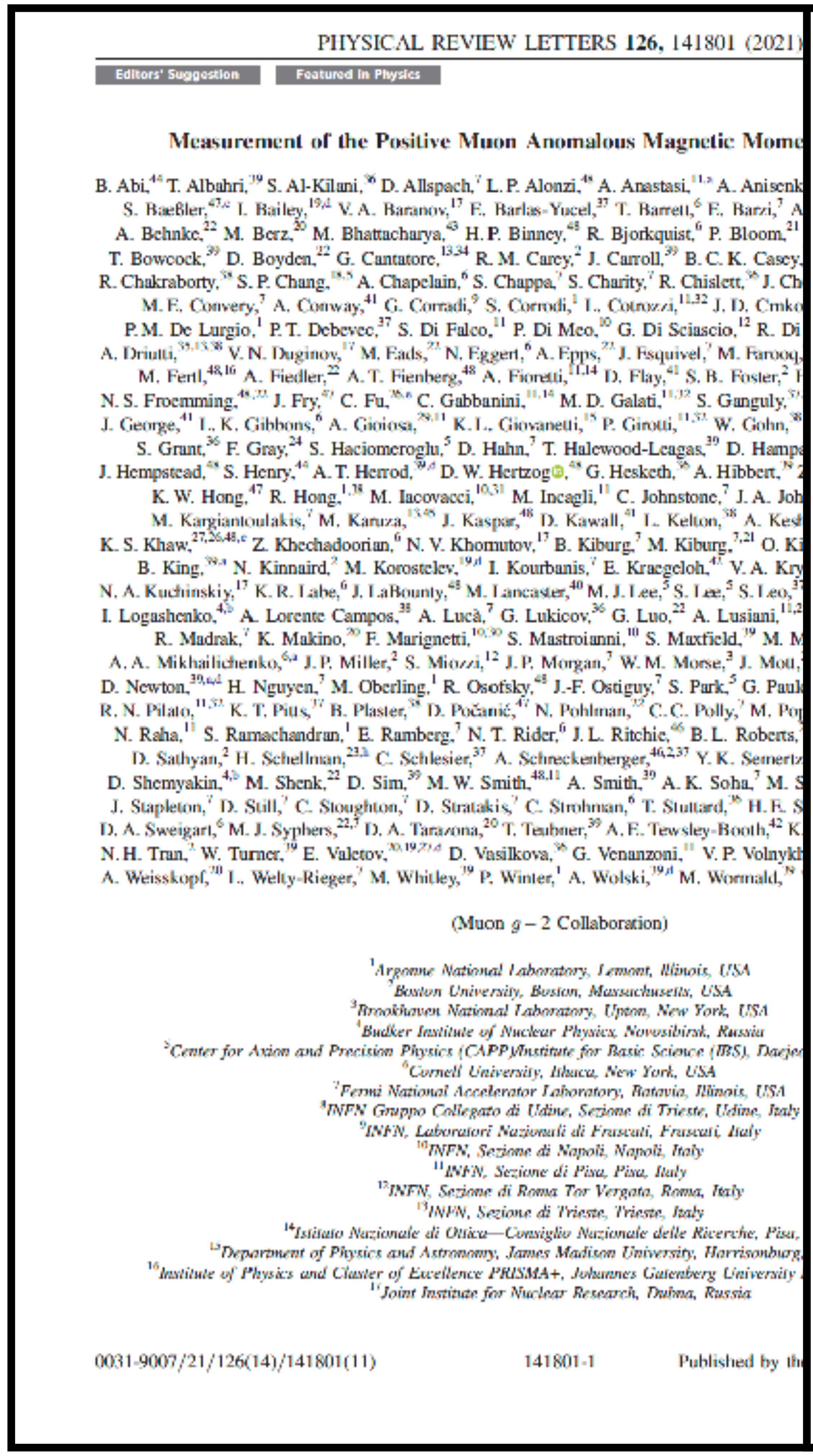


PROBE	Calibration Coefficients		
	Value (Hz)	Stat (Hz)	Syst (Hz)
1	90.81	0.38	2.02
2	84.21	0.65	1.18
3	95.02	0.53	2.19
4	86.03	0.25	1.28
5	92.96	0.51	1.10
6	106.24	0.46	1.35
7	116.64	0.96	1.61
8	76.39	0.60	1.21
9	83.52	0.23	1.64
10	24.06	1.39	1.26
11	177.55	0.22	1.99
12	110.85	0.44	1.73
13	122.89	2.08	1.93
14	77.11	0.53	1.88
15	74.82	1.06	1.59
16	20.35	0.44	2.94
17	172.12	1.23	1.96
AVG		**0.70**	**1.70**

测量结果的论文

11+35+29+34～110页

《物理评论系列》首次为某个实验同时发布4篇文章（PRL, PRA, PRD, PRAB）



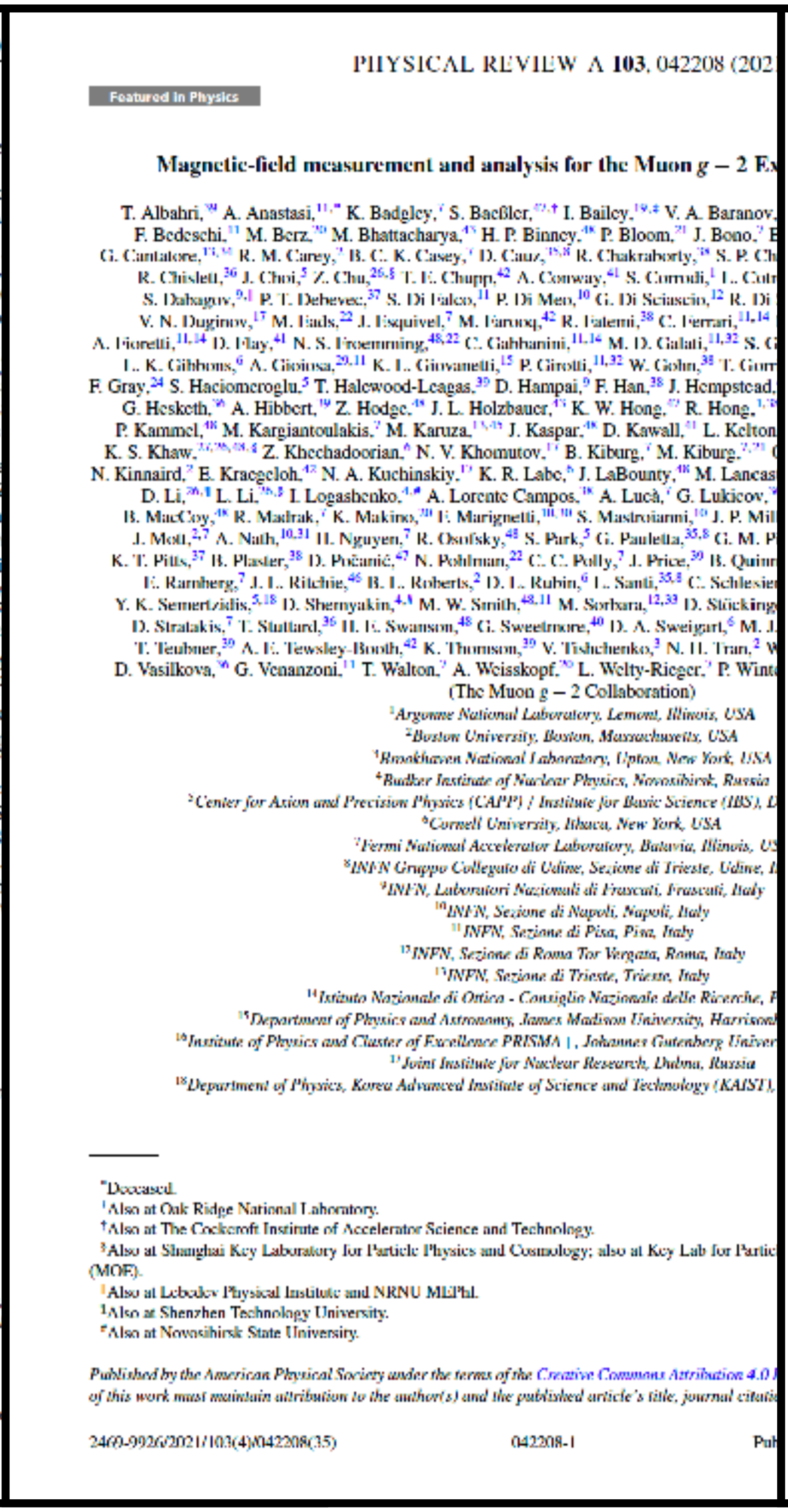
PHYSICAL REVIEW LETTERS 126, 141801 (2021)

Editors' Suggestion Featured in Physics

Measurement of the Positive Muon Anomalous Magnetic Mome

(Muon $g-2$ Collaboration)

0031-9007/21/126(14)/141801(11) 141801-1 Published by th



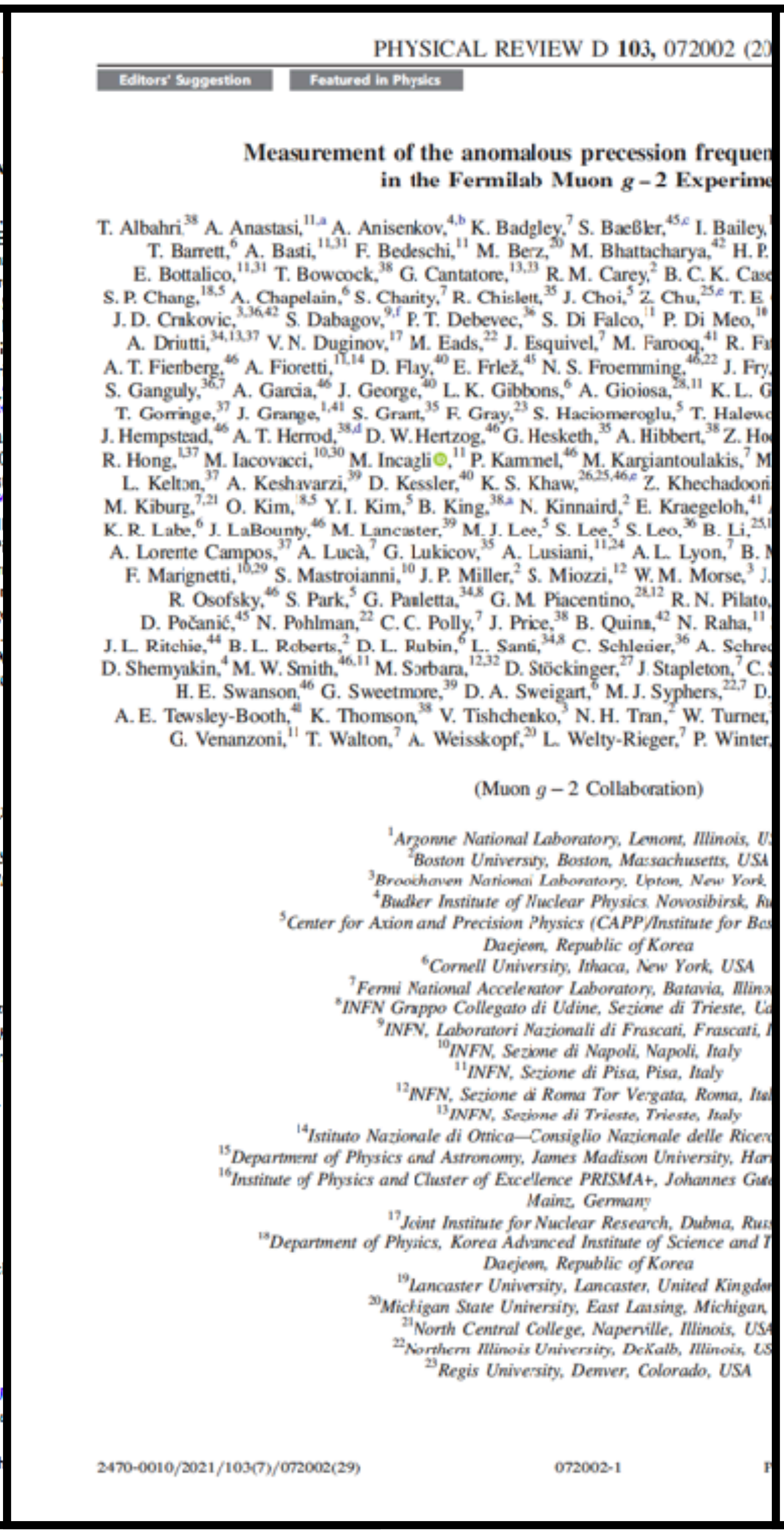
PHYSICAL REVIEW A 103, 042208 (202

Featured in Physics

Magnetic-field measurement and analysis for the Muon $g-2$ Ex

(The Muon $g-2$ Collaboration)

2469-9926/2021/103(4)/042208(35) 042208-1



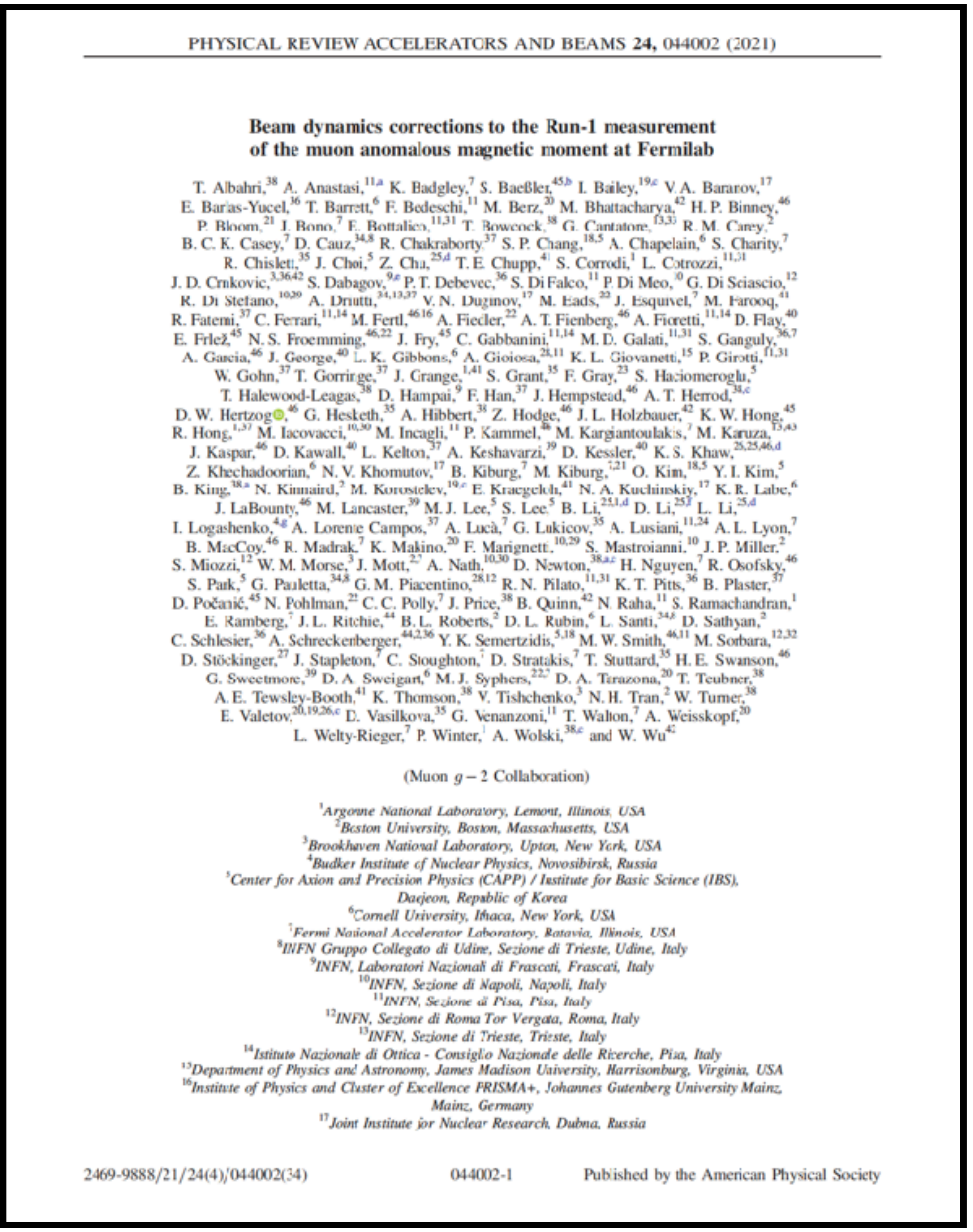
PHYSICAL REVIEW D 103, 072002 (20

Editors' Suggestion Featured in Physics

Measurement of the anomalous precession frequen
in the Fermilab Muon $g-2$ Experim

(Muon $g-2$ Collaboration)

2470-0010/2021/103(7)/072002(29) 072002-1



PHYSICAL REVIEW ACCELERATORS AND BEAMS 24, 044002 (2021)

Beam dynamics corrections to the Run-1 measurement
of the muon anomalous magnetic moment at Fermilab

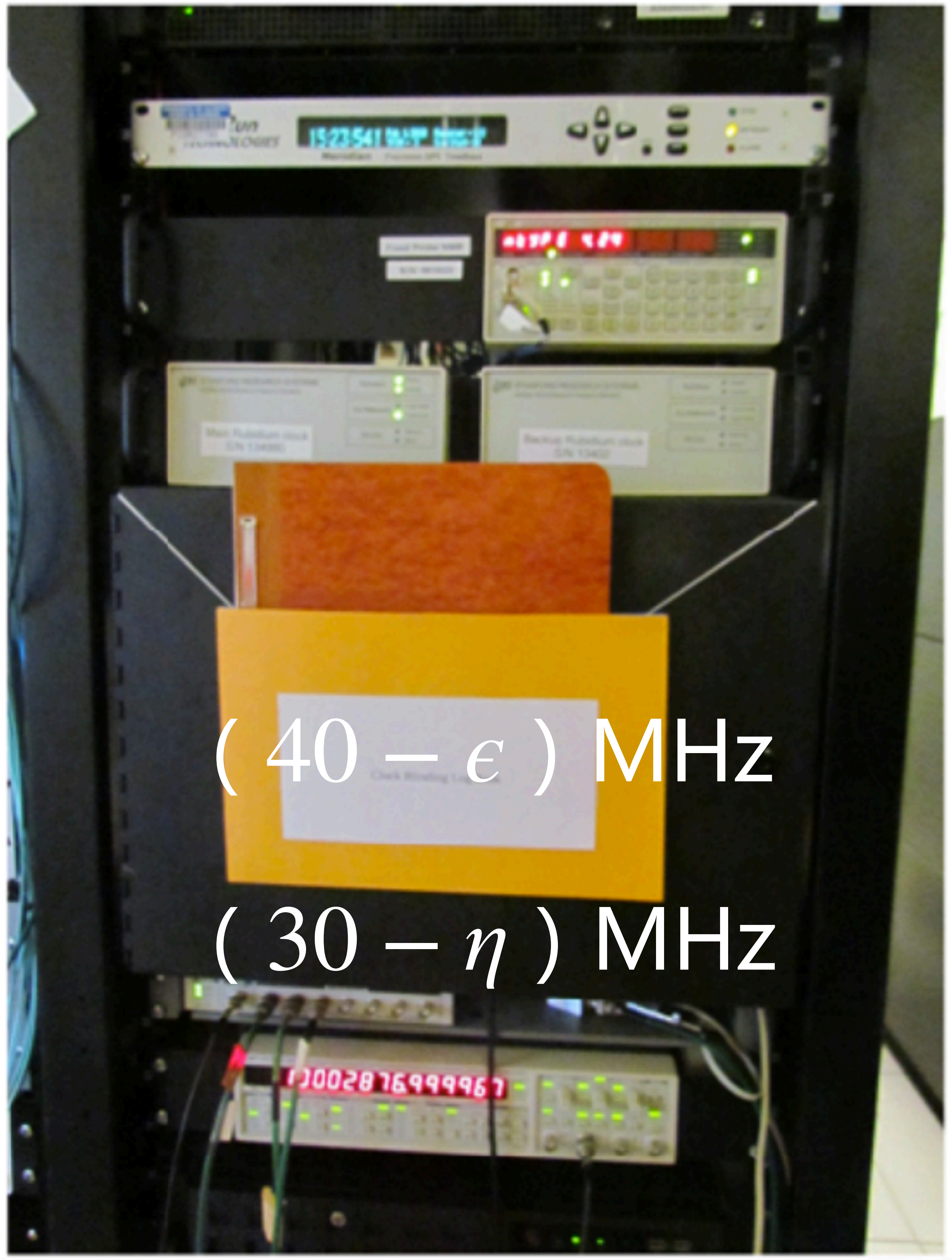
(Muon $g-2$ Collaboration)

2469-9888/21/24(4)/044002(34) 044002-1 Published by the American Physical Society

双盲分析法-硬件和软件

Locked Clock Panel

合作组以外的费米实验室两名成员把精确时钟的频率调成我们不知道的值（$40-\epsilon$）MHz
把数值藏在两个信封（费米实验室，华盛顿大学）



每周过来检查监控时钟的稳定度

揭盲当晚

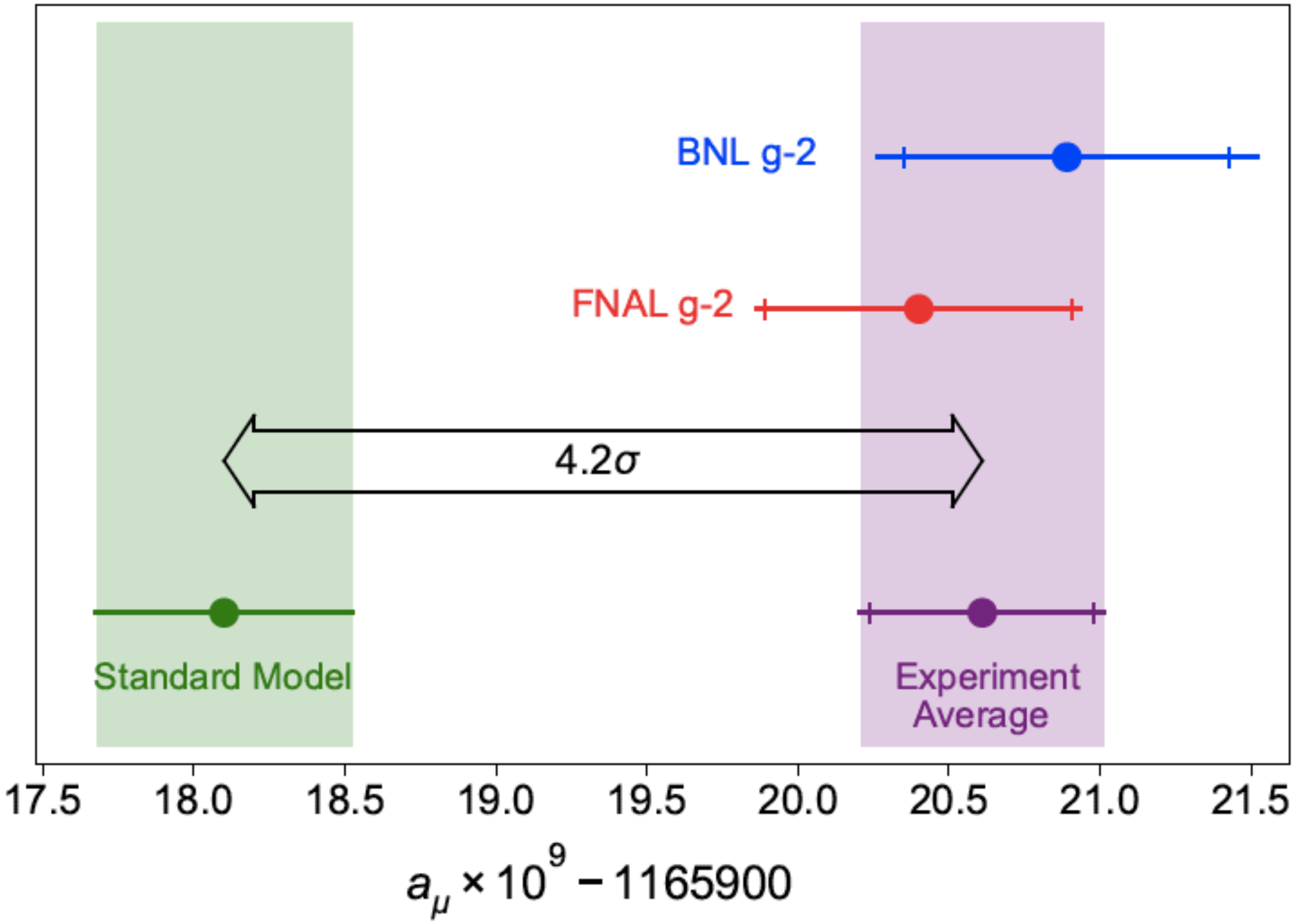
2021年2月25日晚上11点58分

- 合作组共170人左右参与，通过全体表决一致决定揭开谜底

$$g_\mu(\text{Theory Initiative}) = 2.00233183620(86)$$

$$g_\mu(\text{BNL + Fermilab}) = 2.00233184122(82)$$

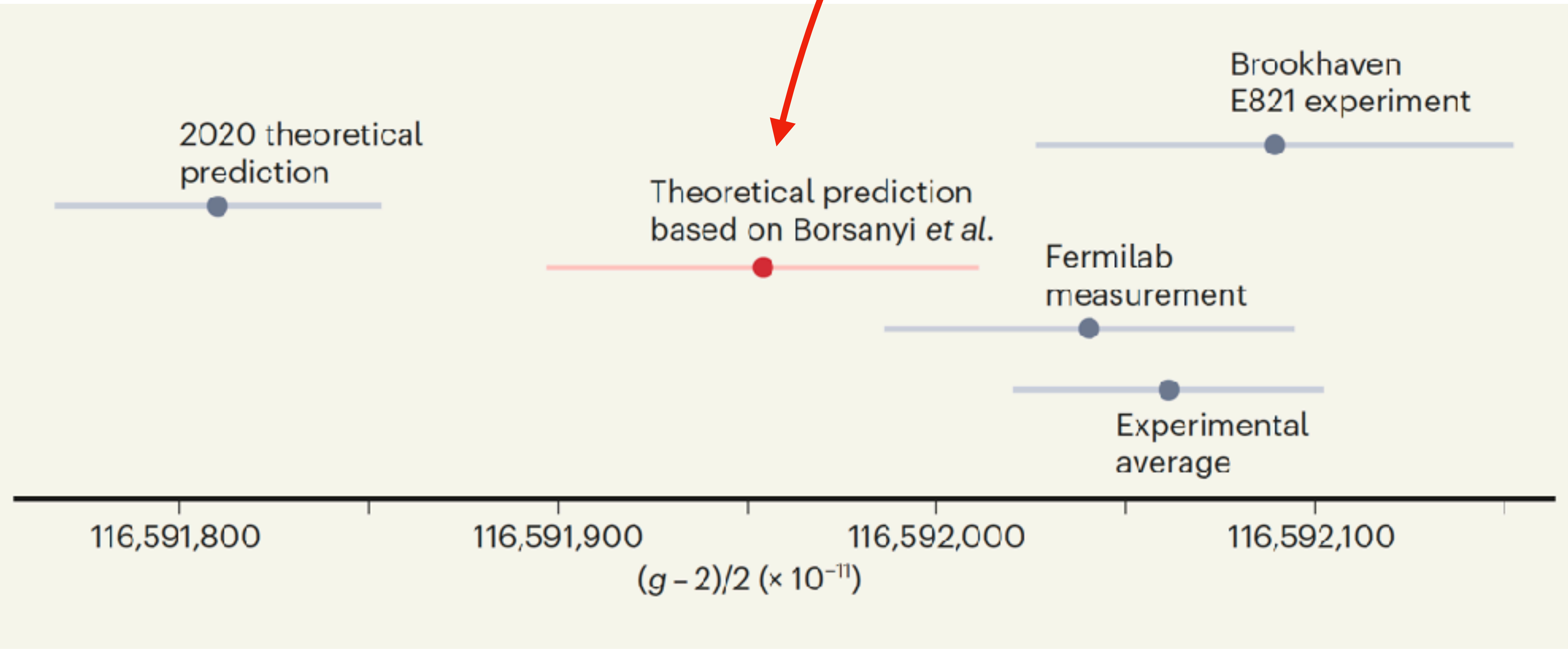
缪子反常磁矩实验结果

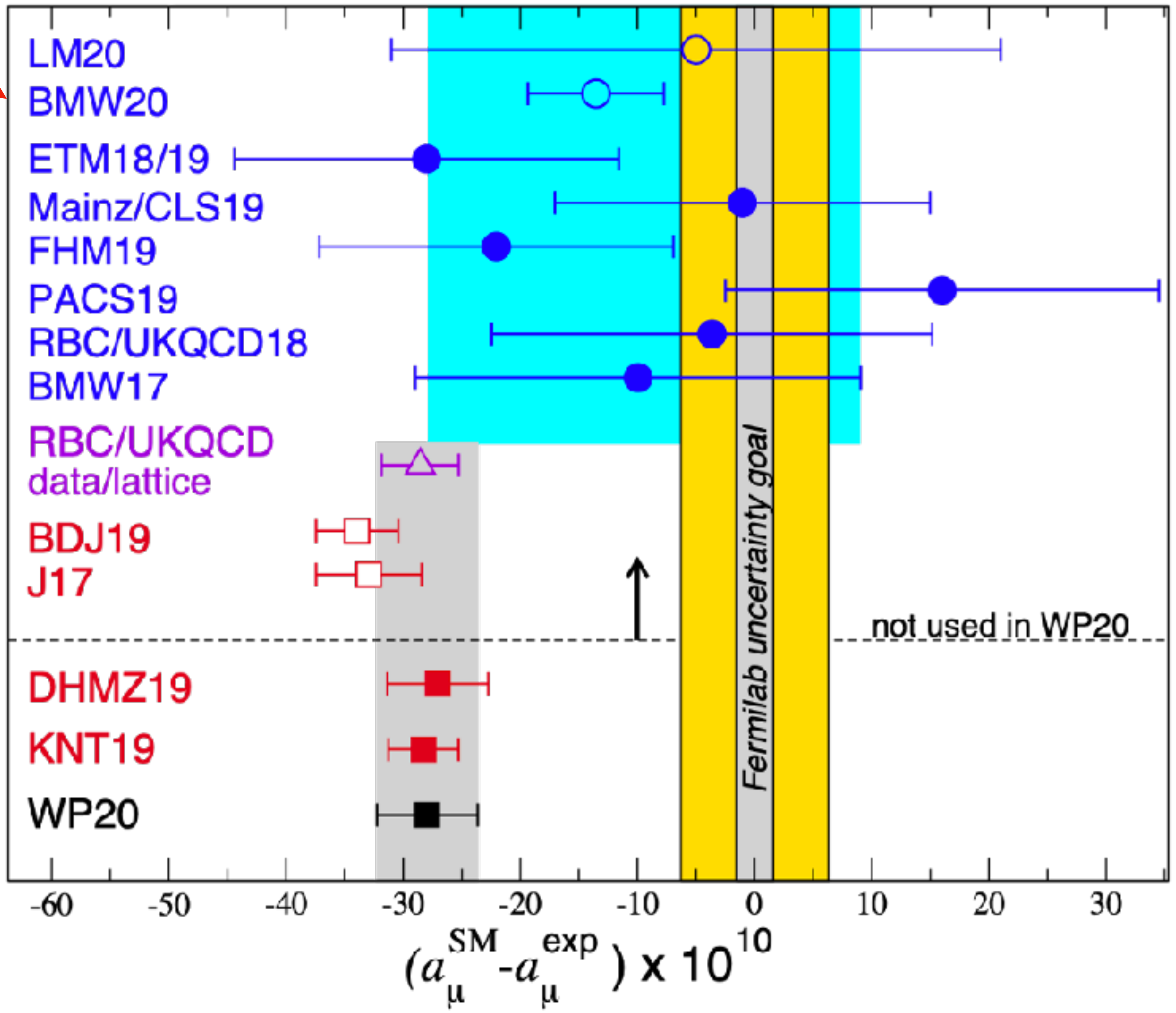


g_μ(Theory Initiative) = 2.00233183620(86)

g_μ(BNL + Fermilab) = 2.00233184122(82)

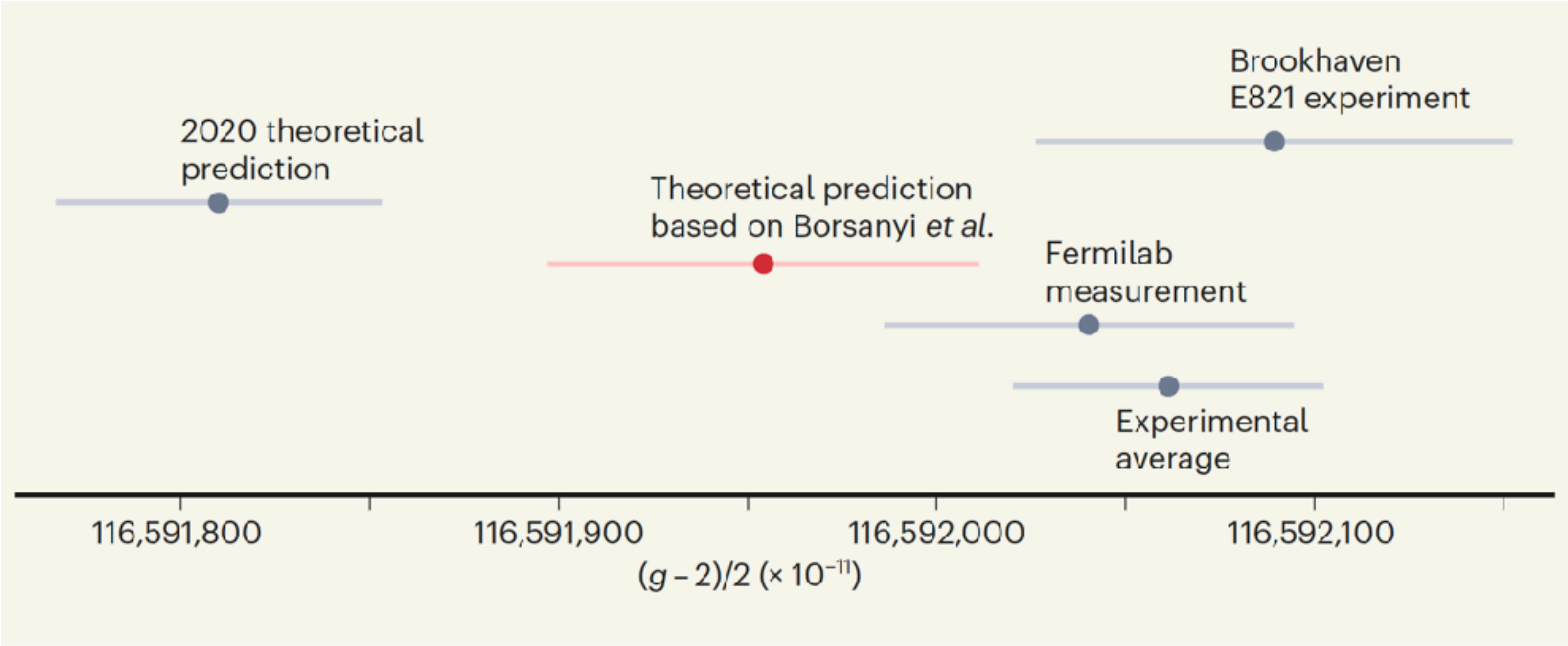
格点QCD最新结果

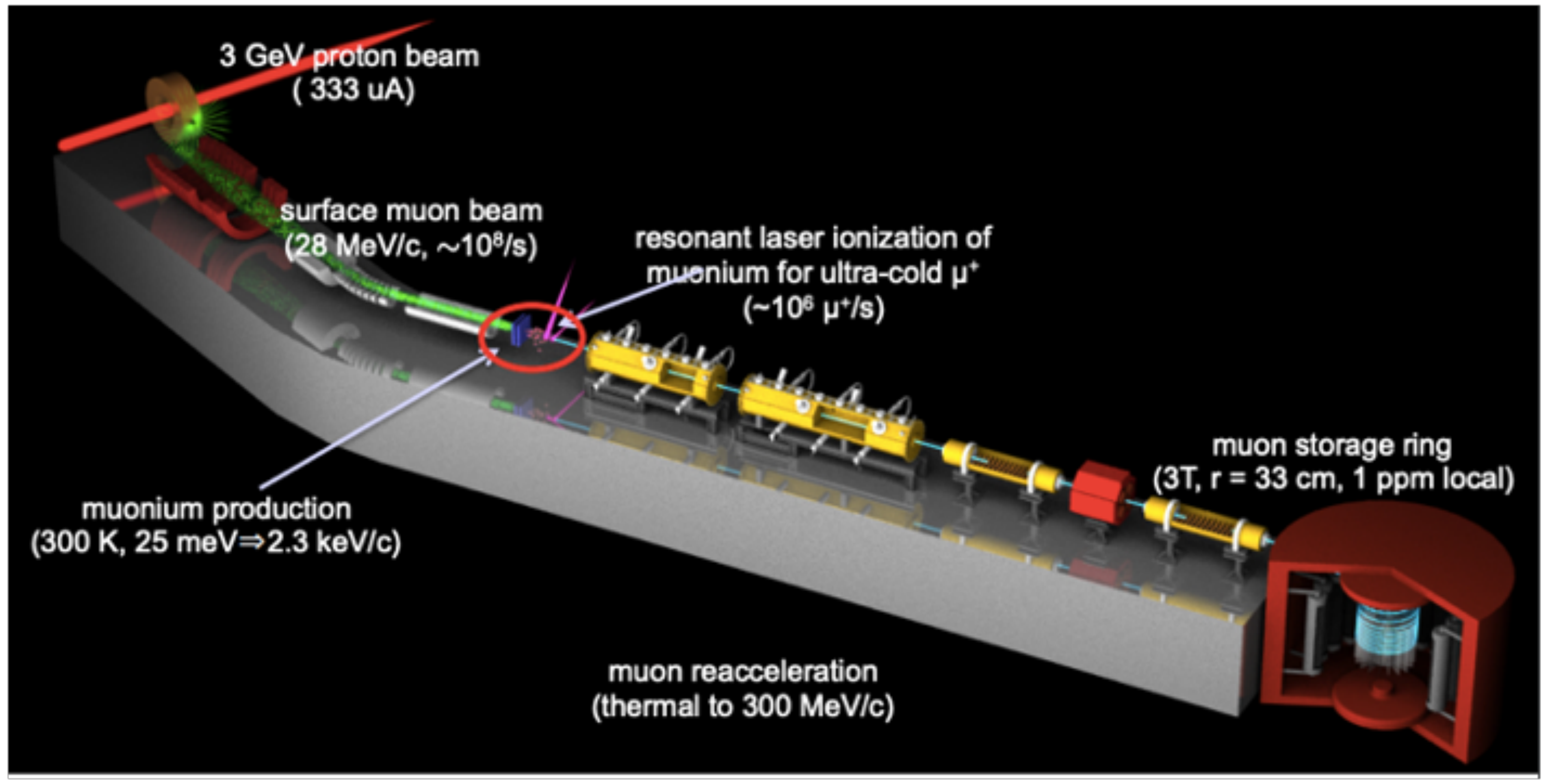

2020 theoretical prediction
Theoretical prediction based on Borsanyi *et al.*
Brookhaven E821 experiment
Fermilab measurement
Experimental average
116,591,800
116,591,900
116,592,000
116,592,100
$(g-2)/2$ ($\times 10^{-11}$)


LM20
BMW20
ETM18/19
Mainz/CLS19
FHM19
PACS19
RBC/UKQCD18
BMW17
RBC/UKQCD data/lattice
BDJ19
J17
not used in WP20
DHMZ19
KNT19
WP20
Fermilab uncertainty goal
-60
-50
-40
-30
-20
-10
0
10
20
30
$(a_\mu^{SM} - a_\mu^{exp}) \times 10^{10}$

未来展望

- 新物理还是QCD计算有未被发现系统偏差？
  - 实验会提供更精确的测量（4倍左右）
  - 日本J-PARC也将提供独立的测量结果
  - Theory Initiative也将展开严格的验证
- 未来10年将会有新发现
- 敬请期待！





总结

- 精确测量是实验之母、科学之母
  - 不断更新对宇宙的认知，推动建立更基础的理论框架
  - 理论和实验互相验证，带动了粒子物理和相关领域的发展
- “十年磨一剑”的科研精神
  - 锲而不舍，精益求精
  - 细节之处见英雄！

交大李所和粒子所联办2021年粒子物理暑期学校

Joint TDLI & INPAC Summer School in Particle Physics 2021

July 5-9, 2021

Location: TDLI, SJTU and online

Organizing Committee: Kim-Siang Khaw, Shu Li, Kun Liu, Yue Meng, Wei-Hao Wu, Dong-Lian Xu

Students with 2-3 years of university physics education are invited to apply at:
https://indico-tdli.sjtu.edu.cn/event/412/

Description:

This summer school aims to provide a pedagogical introduction and overview of our profound understanding of the microscopic world and its connection to the entire Universe. The school will also cover recent experimental developments in dark matter, neutrino, collider and muon physics where significant progress have been achieved.

Scientific Program:

- Standard Model
- Beyond the Standard Model
- Precision Muon Physics
- Dark Matter
- Neutrino
- Collider Physics
- Electronics in Particle Physics Experiments
- Quantum Field Theory
- Lattice Quantum Chromodynamics
- Nuclear Physics
- Nuclear Astrophysics

Application deadline: May 31, 2021
Contact: ziyang@sjtu.edu.cn

Onsite participation will be limited to 50 students.
Selected candidates will be contacted via email.

提供奖学金（住宿，伙食，车费等等）
热烈欢迎大二~大三本科生报名参加（名额有限）
请通过以下网址报名：
https://indico-tdli.sjtu.edu.cn/event/412/