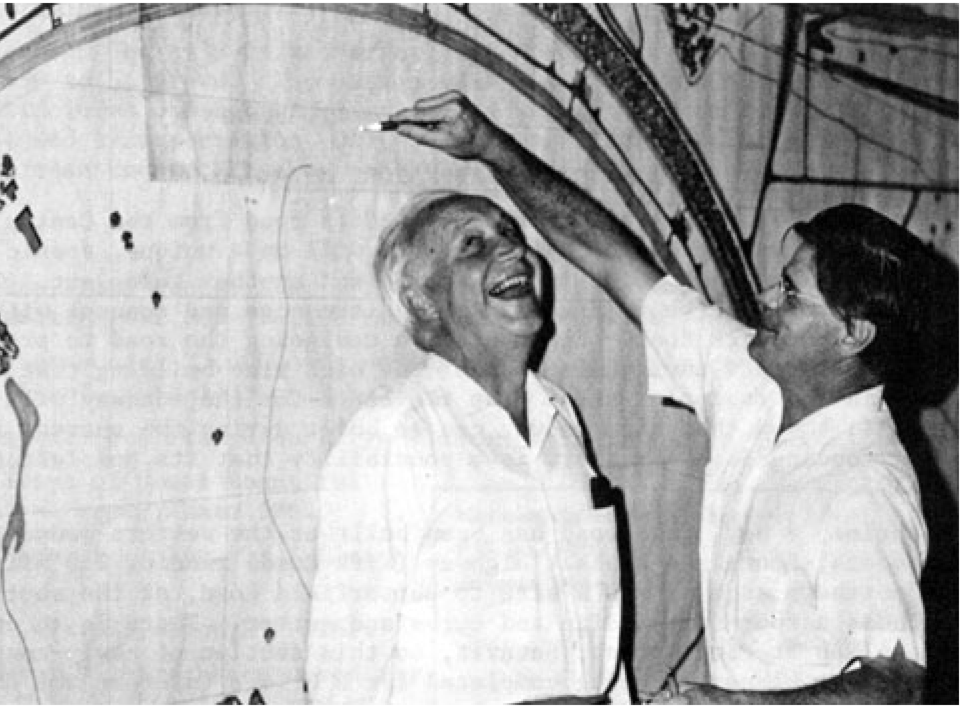
News from Fermilab: 50+ years; g-2; Planck scale

Chris Stoughton

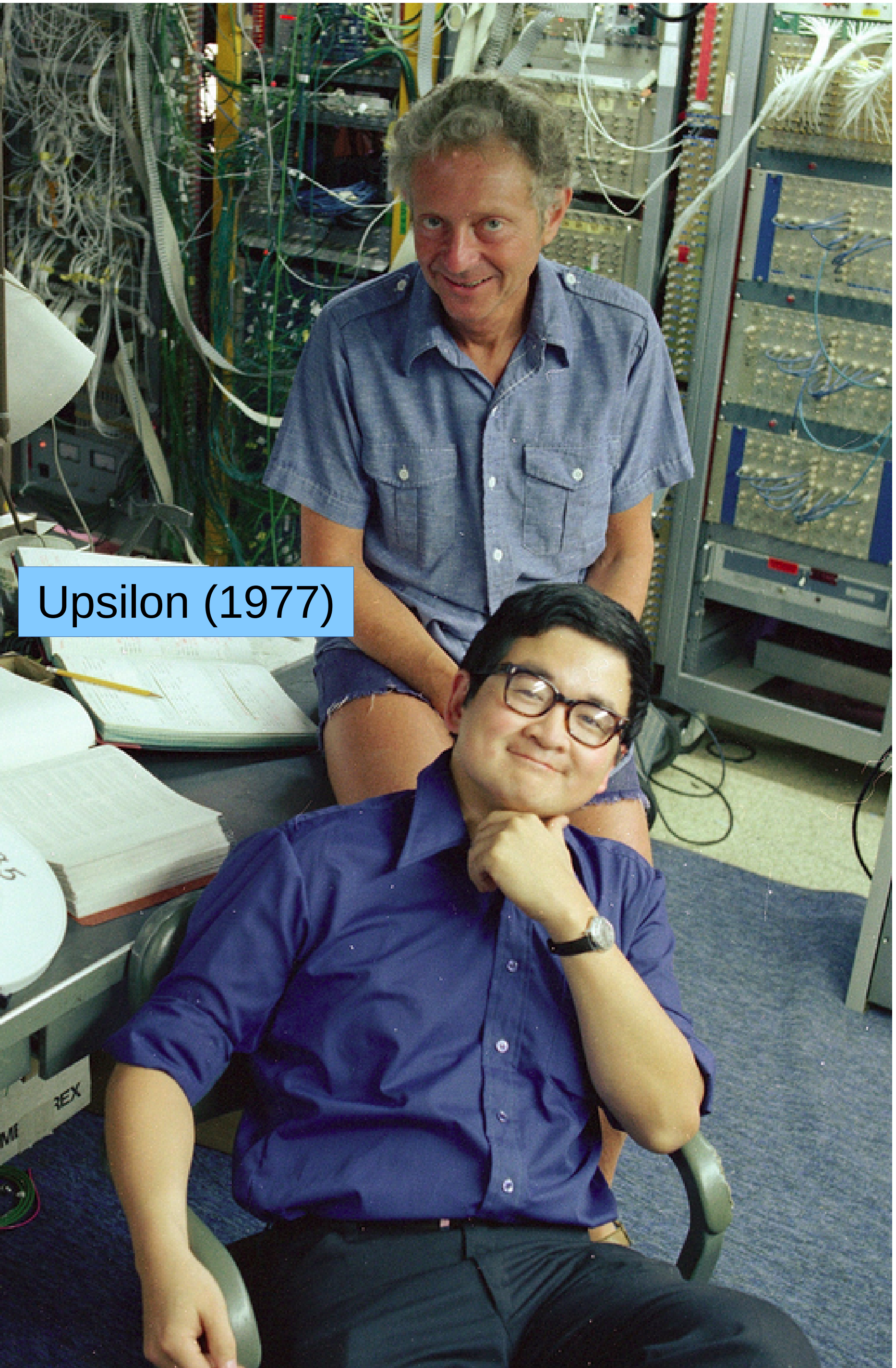
Fermilab: 50+ years



Robert R. Wilson, NAL Director, and
Willibald Jentschke, CERN DG,
Sept. 1, 1971

"It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with those things. It has to do with, are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. It has nothing to do directly with defending our country except to help make it worth defending." — Robert R. Wilson, answering Congress' question on how the new accelerator will affect the nation's security.

A brief history of Fermilab: b, t, ν_τ, Higgs

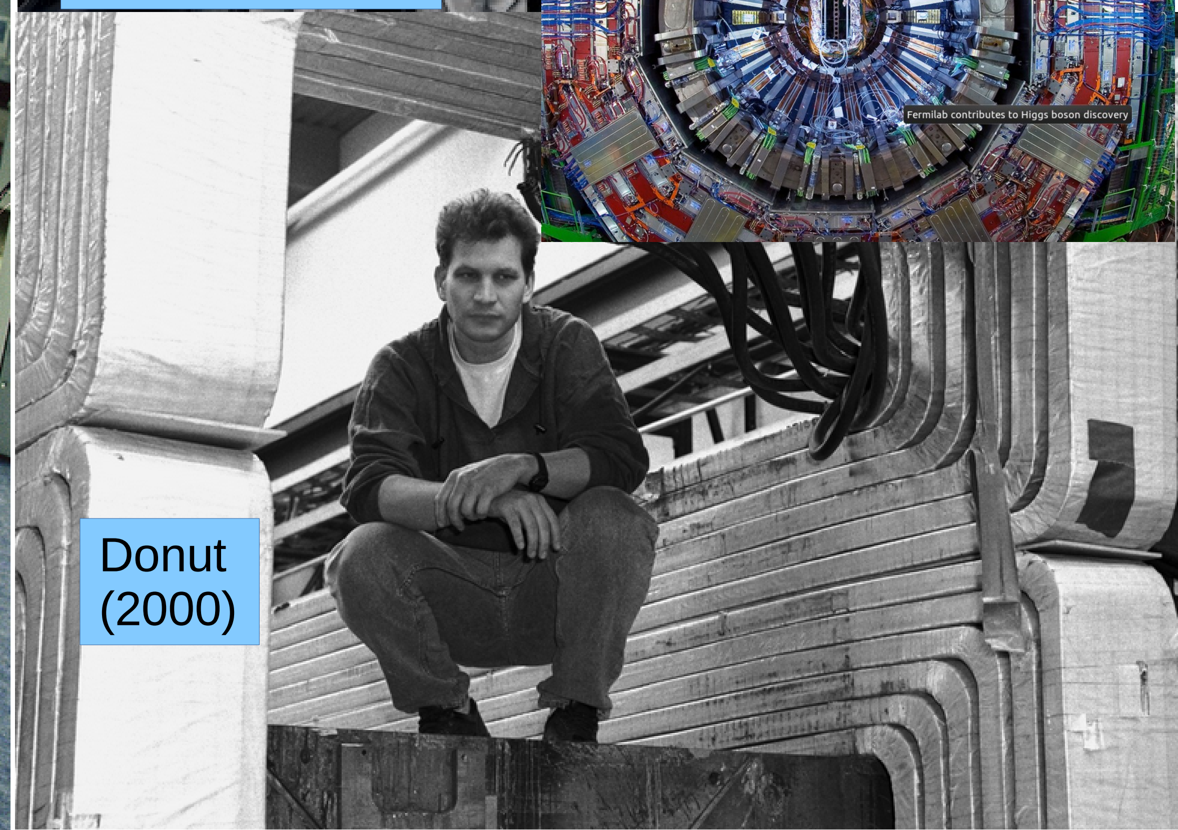


Upsilon (1977)

CDF/D0 (1995)

The comprehensive version:

http://50.fnal.gov/

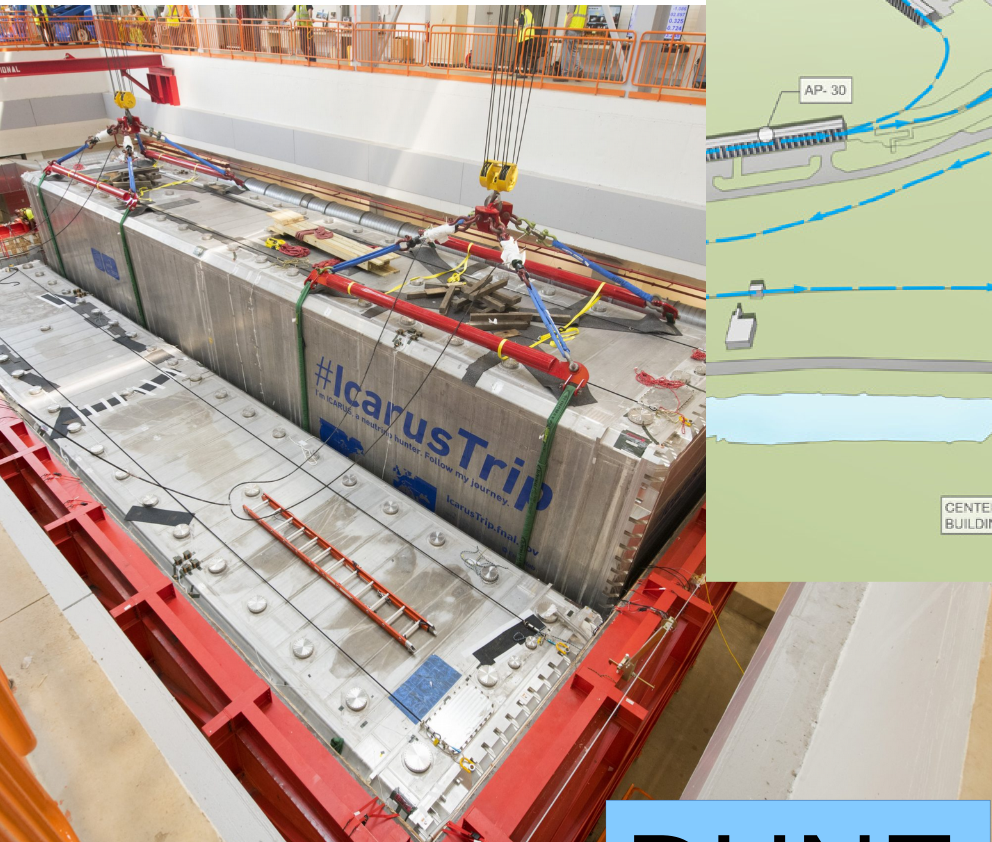


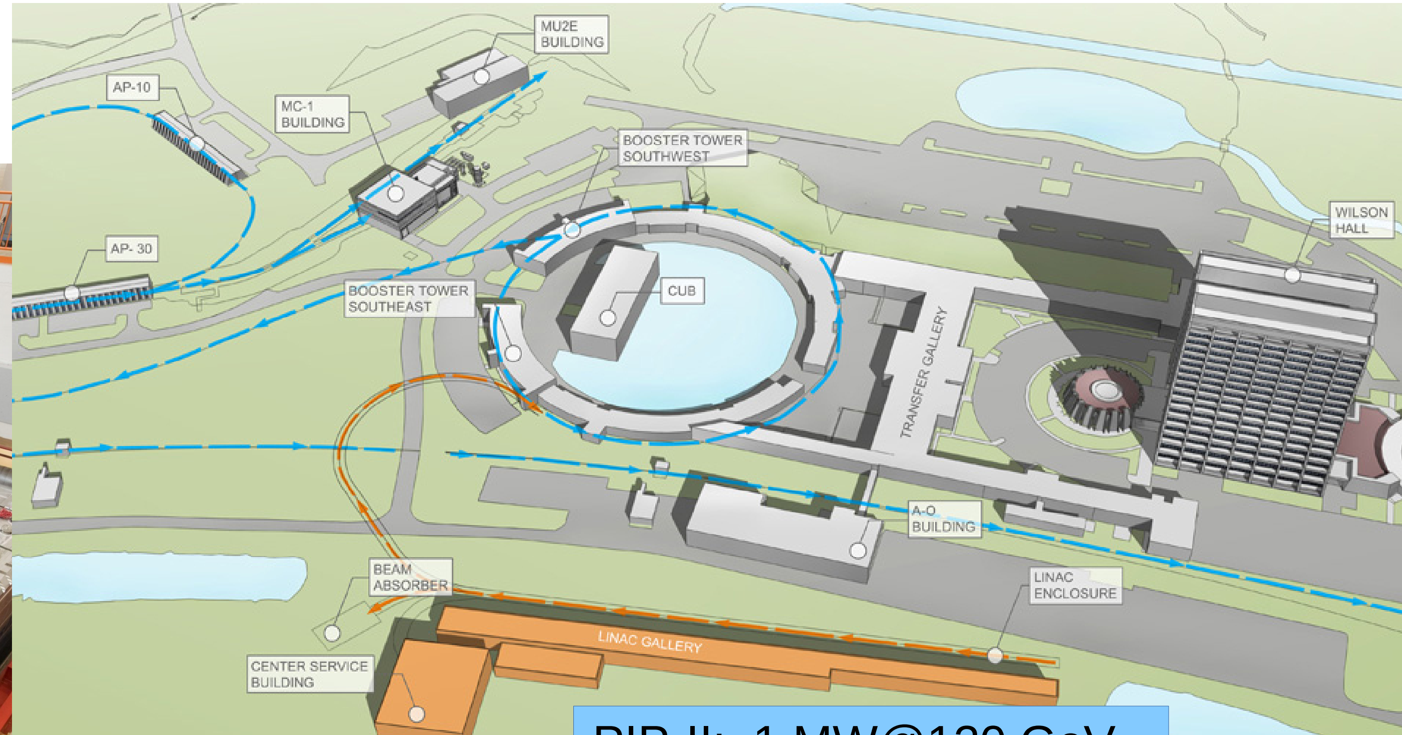
Donut (2000)

Astrophysics

Theoretical Astrophysics Group (Schramm, Turner, Kolb)
Sloan Digital Sky Survey
Dark Energy Camera
South Pole Telescope 3G
Future: DESI, LSST, CMB-S4

The next 50+

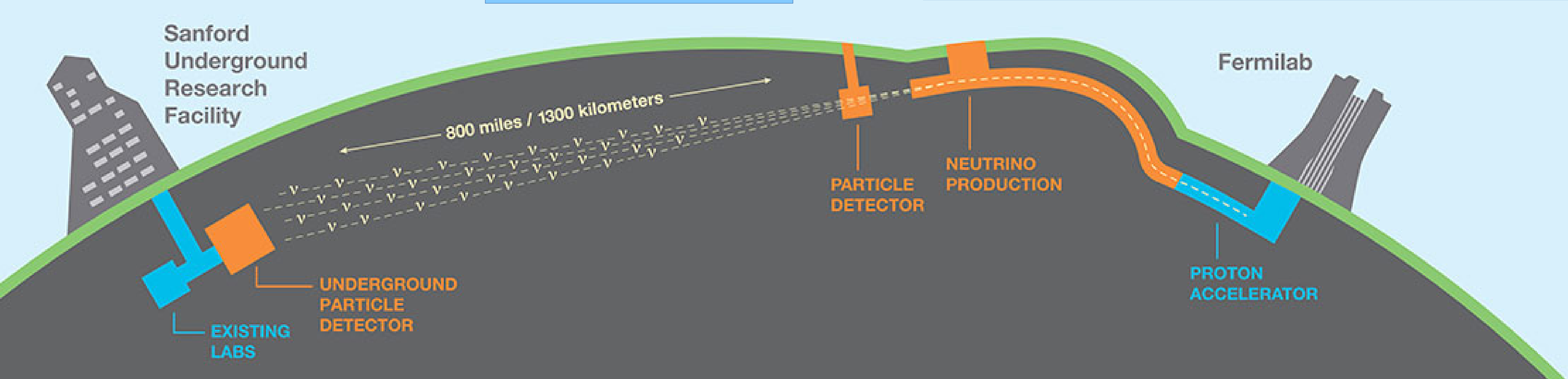




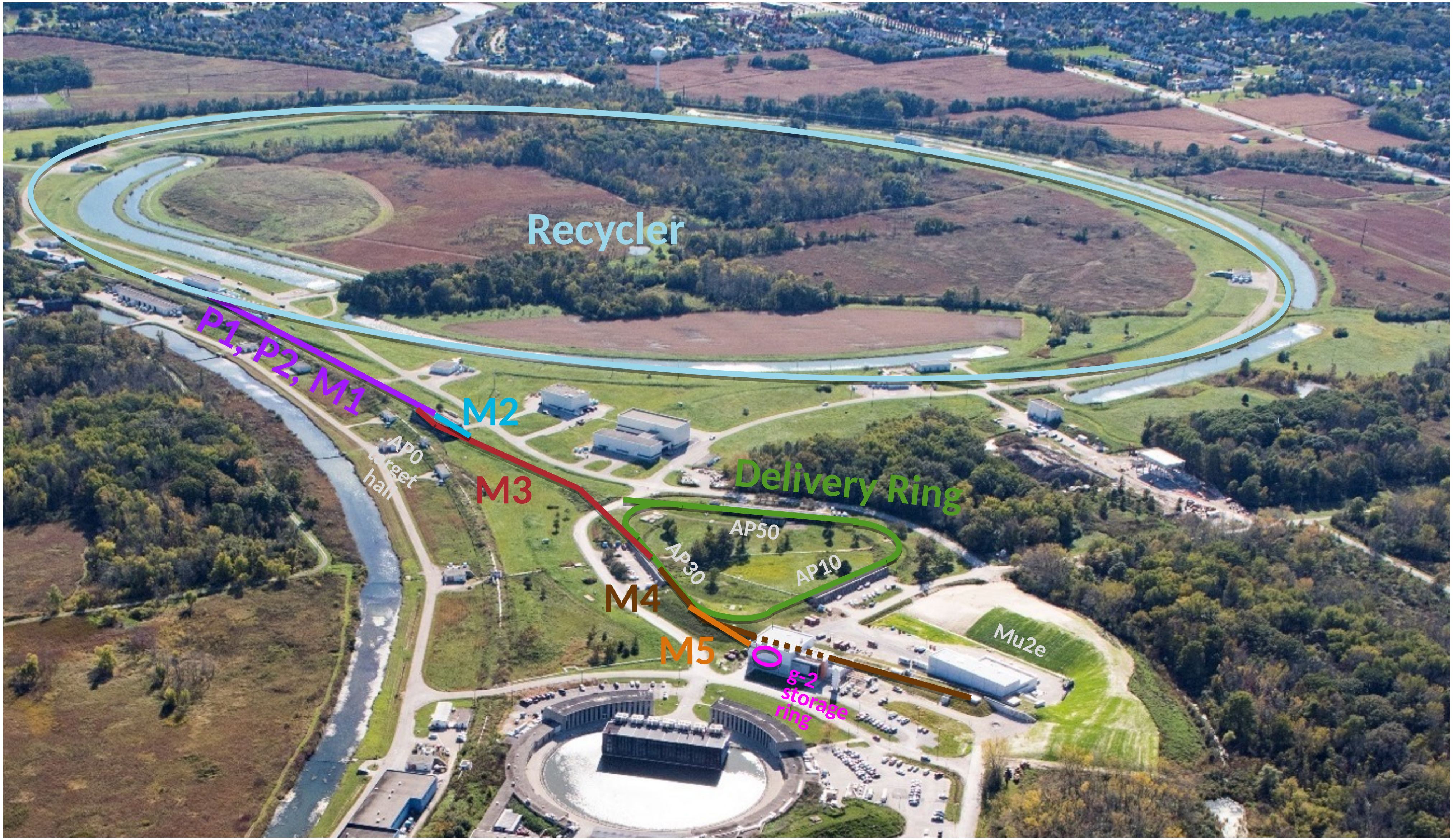
PIP-II: 1 MW@120 GeV

Direct Detection of Dark Matter:
- ADMX
- SuperCDMS
- LUX-ZEPLIN
- SENSEI

DUNE

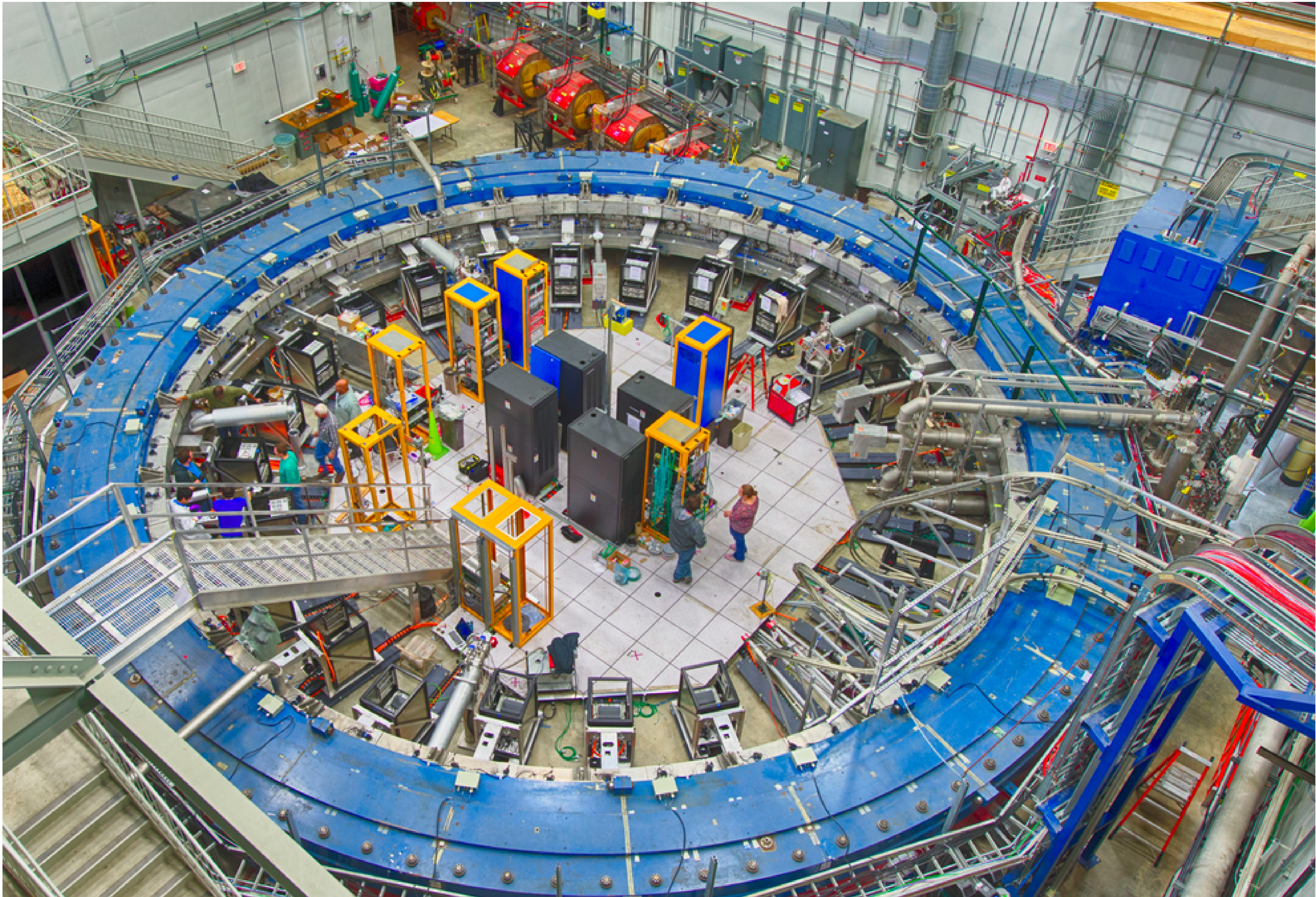


Muon Campus – Fermilab's Back yard

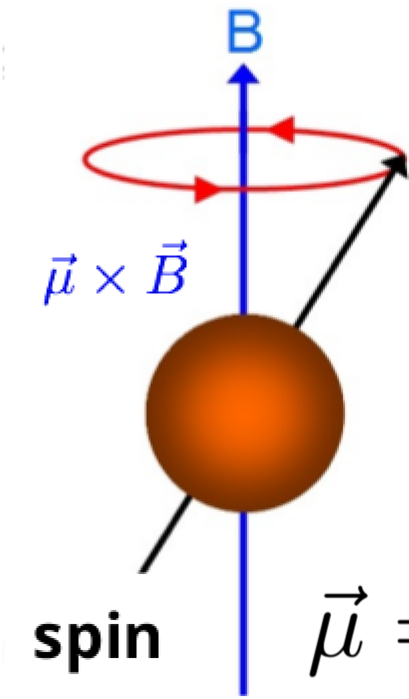


Fermilab

Fermilab Muon g-2



Spin and Magnetic Moment



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

Larmor precession

$$\omega_s = \frac{geB}{2m}$$

"g" is the Gyromagnetic Ratio:

Classical: g=1
[Stern-Gerlach (1922)]
Pauli: g=2 for (isolated) point particle (1928)
Otto Stern: g=5.6 for proton (1933)
Rabi, and Stern g=-3.8 for neutron (1934+)
Kusch&Foley e=2.00238 for electron(1948)
Schwinger 2(1+α/π) (1948)

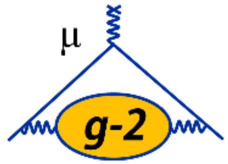
Garwing, Lederman, Weinrich 2.01 ± 0.4% (1957)

Cern I 4300 ppm (1965)
Cern II 270 ppm (1968)
Cern III 7 ppm (1979)

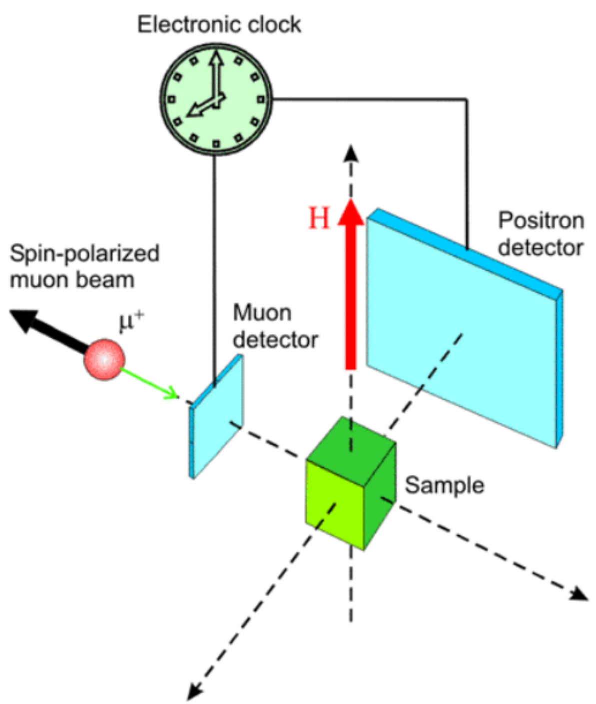
BNL 0.54 ppm (1999)

FNAL Goal: 0.140 ppm

Measure g directly



Muon spin rotation (μSR)



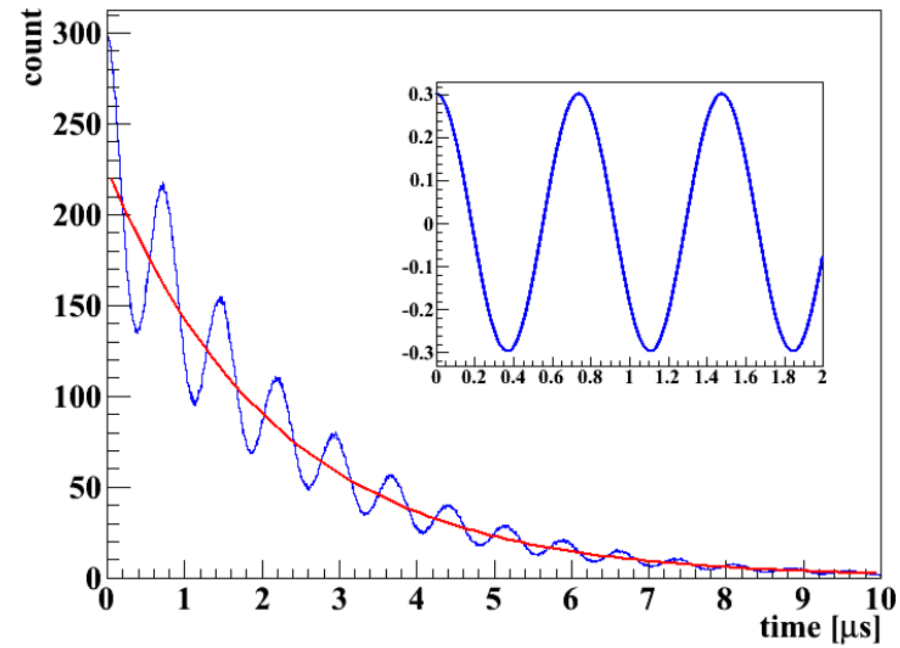
(Rest frame) Parity violation prefers positron emitted in the muon spin direction

lifetime

decay asymmetry

spin precession frequency

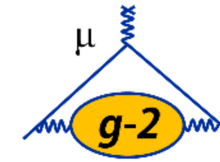
$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$



g = 2mω/eB

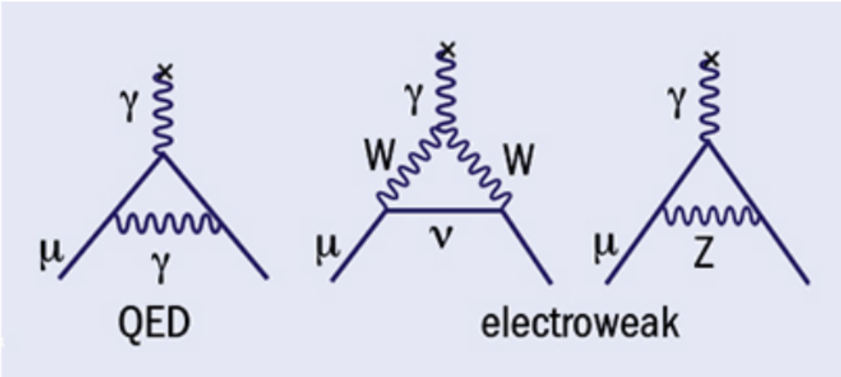
So, why bother?

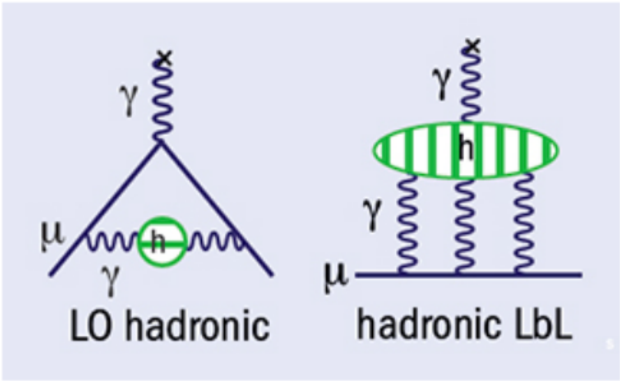
Convenient to deal with the “anomalous magnetic moment” $a = \frac{g-2}{2}$



Muon g-2: Theory (2018)

Contribution	a_μ Value (x 10^{-11})
QED[1] (Tenth-order)	116 584 718.95 ± 0.08
Hadronic VP (lo) [DHMZ-17][2]	6 931 ± 34
Hadronic VP (lo) [KNT-18][3]	6 933 ± 25
Hadronic VP (nlo) [DHMZ-17][2]	-98.7 ± 0.7
Hadronic VP (nlo) [KNT-18][3]	-98.2 ± 0.4
Hadronic VP (nnlo)[4]	12.4 ± 0.1
Hadronic LbL (lo + nlo) [5,6]	101 ± 26
Electroweak[7]	153.6 ± 1.0
Total SM [DHMZ-17]	116 591 818 ± 43
Total SM [KNT-18][3]	116 591 821 ± 36

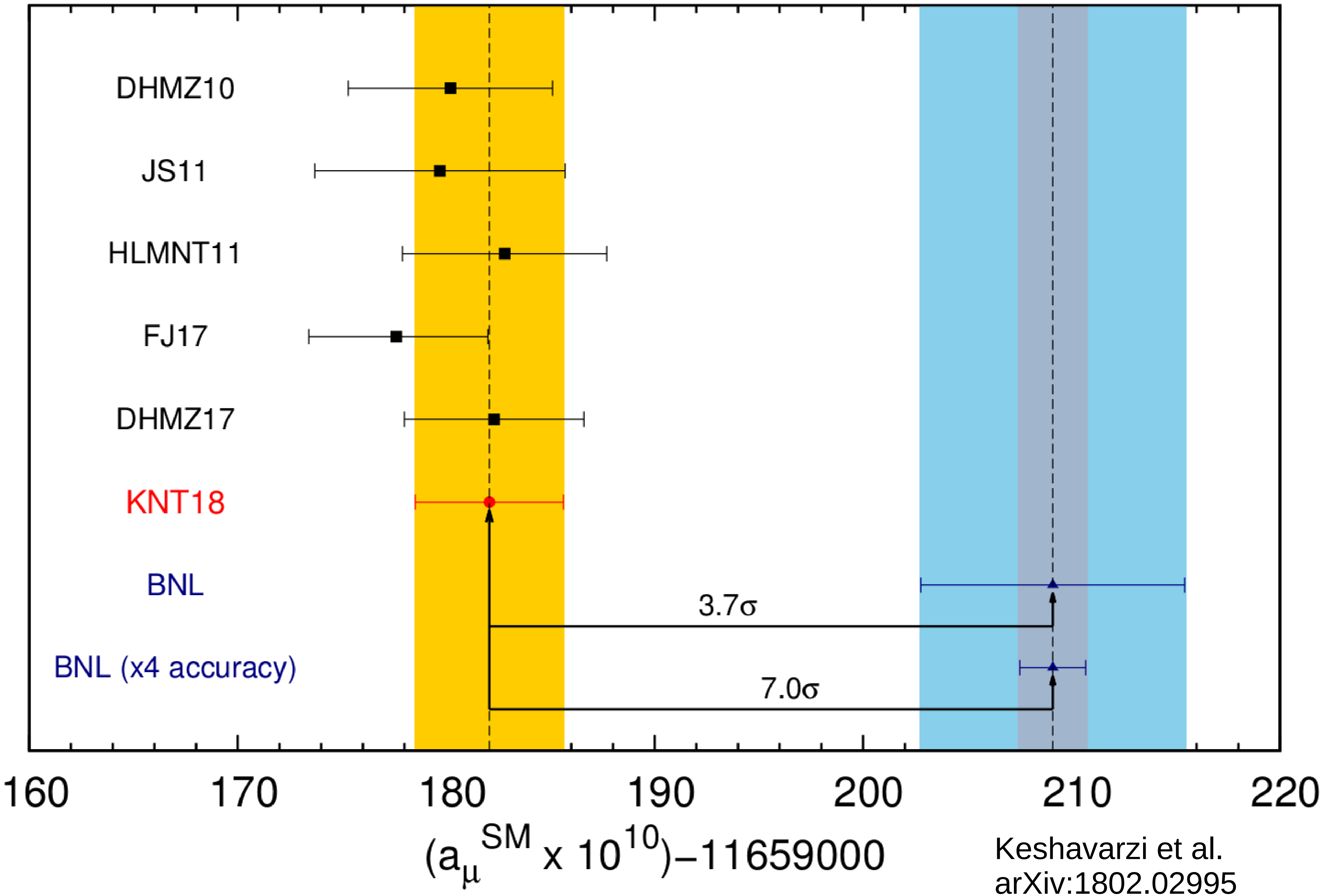




[1]Phys. Rev. Lett. 109 (2012) 111808; [2]arXiv:1706.09436; [3]Keshavarzi et al., arXiv:1802.02995; [4]Phys. Lett. B 734 (2014) 144; [5]Phys. Lett. B 735 (2014) 90; [6]EPJ Web Conf. 118 (2016) 01016; [7]Phys. Rev. D 88 (2013) 053005

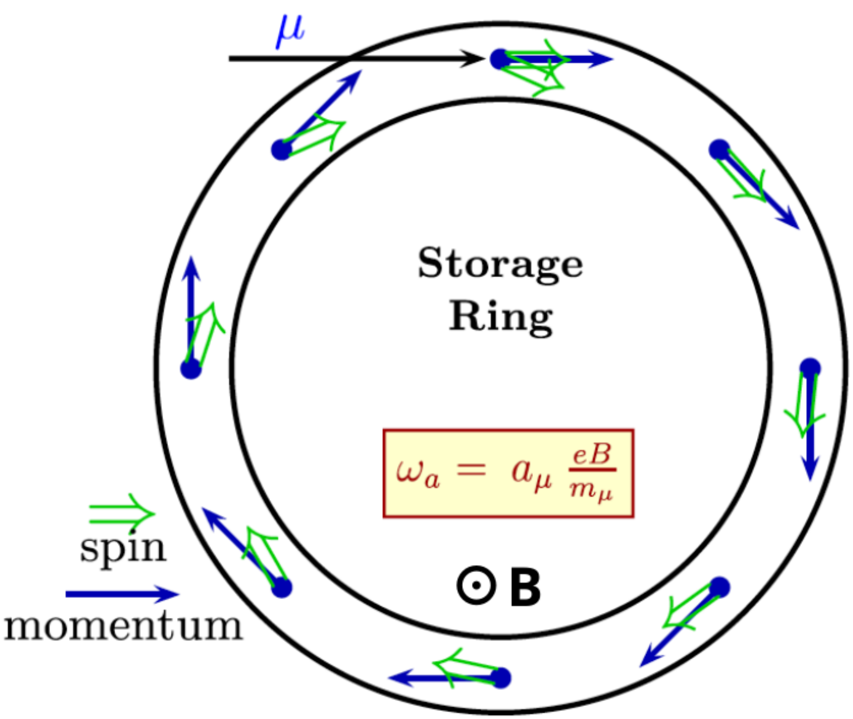
Courtesy of Kim Siang Khaw

Standard Model ← → Measurement



Use a muon storage ring

Principle of Muon g-2 experiment



Larmor Thomas

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

Cyclotron

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

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

measure difference in frequency precisely

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

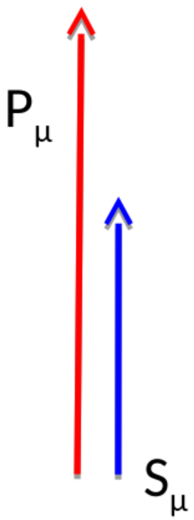
homogenous field and precise field measurement

In π center of mass reference frame, the ν and μ spins are aligned with their momentum vectors

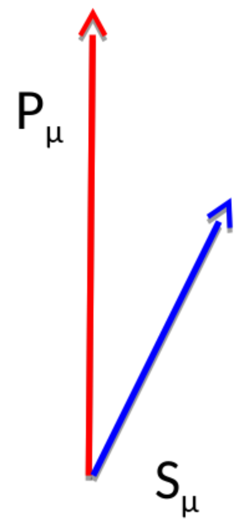
In lab frame, select high momentum μ for 90% polarization.

Positron from muon decay aligned with spin

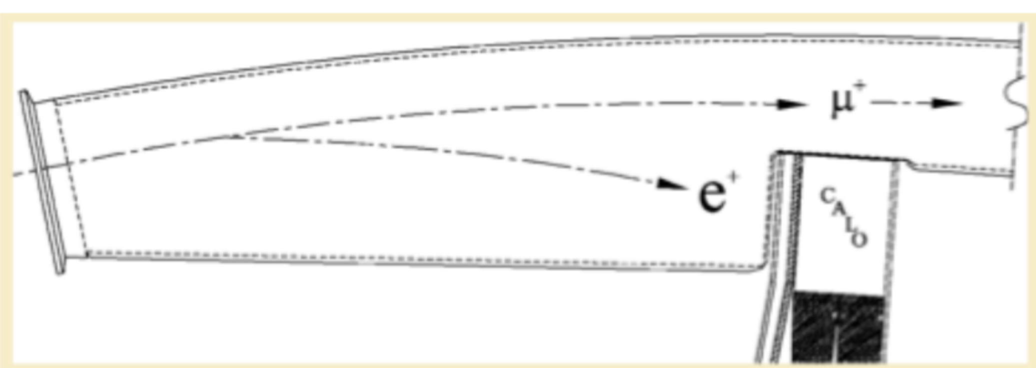
In muon CM, positron direction tends to align with muon spin: $1 + A_\mu (\cos\theta) / 3$



Positrons gets additional boost
if P_μ and S_μ are aligned



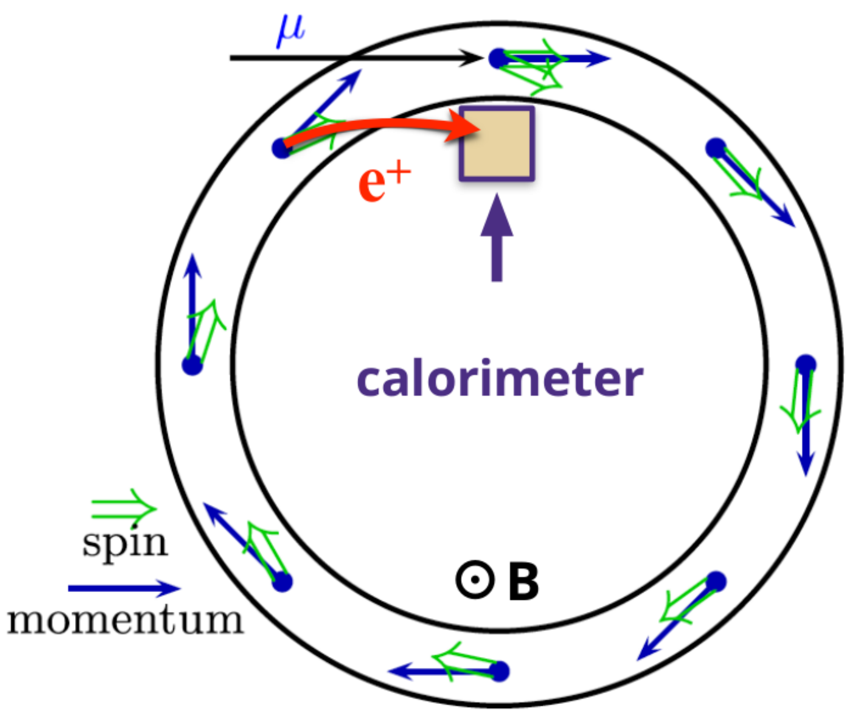
Positrons get less boost
if P_μ and S_μ are not aligned



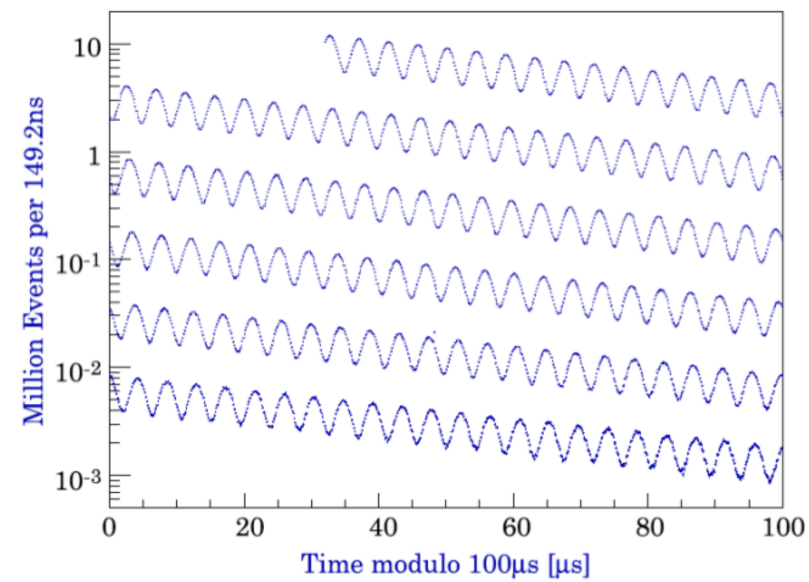
Calorimeter would see a Time-varying Positron Energy Distribution with frequency $\omega_a = \omega_S - \omega_C$.

Detect positron from muon decay

Principle of Muon g-2 experiment



The "wiggle" plot



measure difference in frequency precisely

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

~ 0.23 MHz
~ 4.37 μs

Extracting a_μ

CODATA 2017

-0.001 519 270 380(5) [3 ppb]
Hydrogen Maser

0.0037072064(20) [540 ppb]
E821

$$a_\mu^{\mathrm{Exp}} = \frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

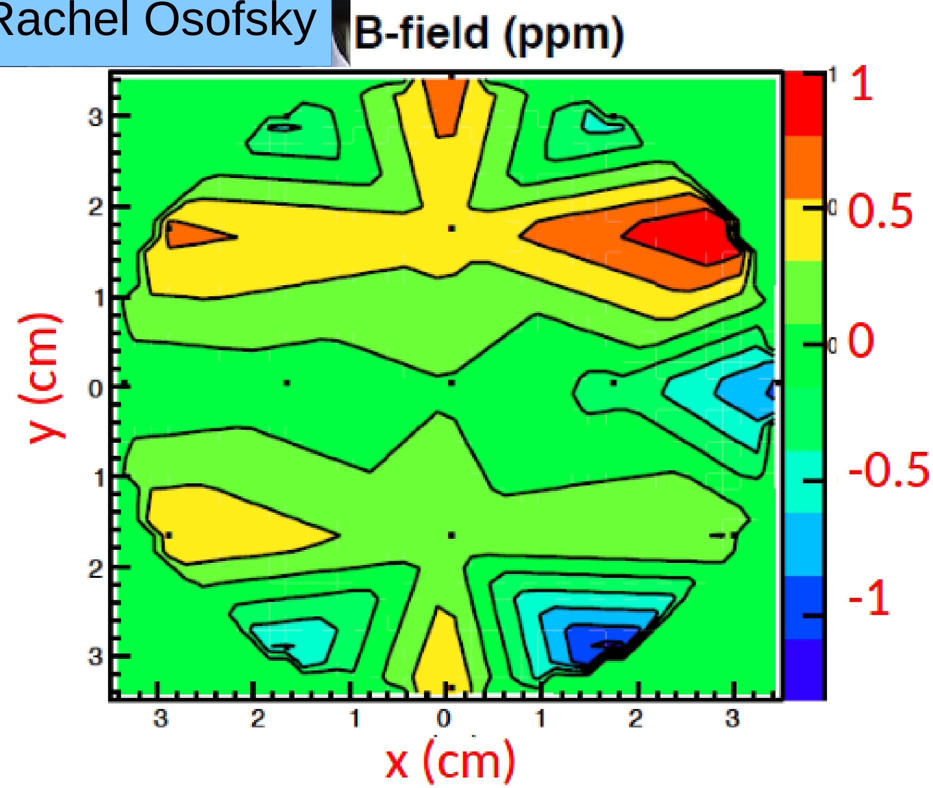
-2.002 319 304 361 82(52) [0.26 ppt]
Electron g-2 + QED

206.768 2826(46) [22 ppb]
Muonium Hyperfine Structure

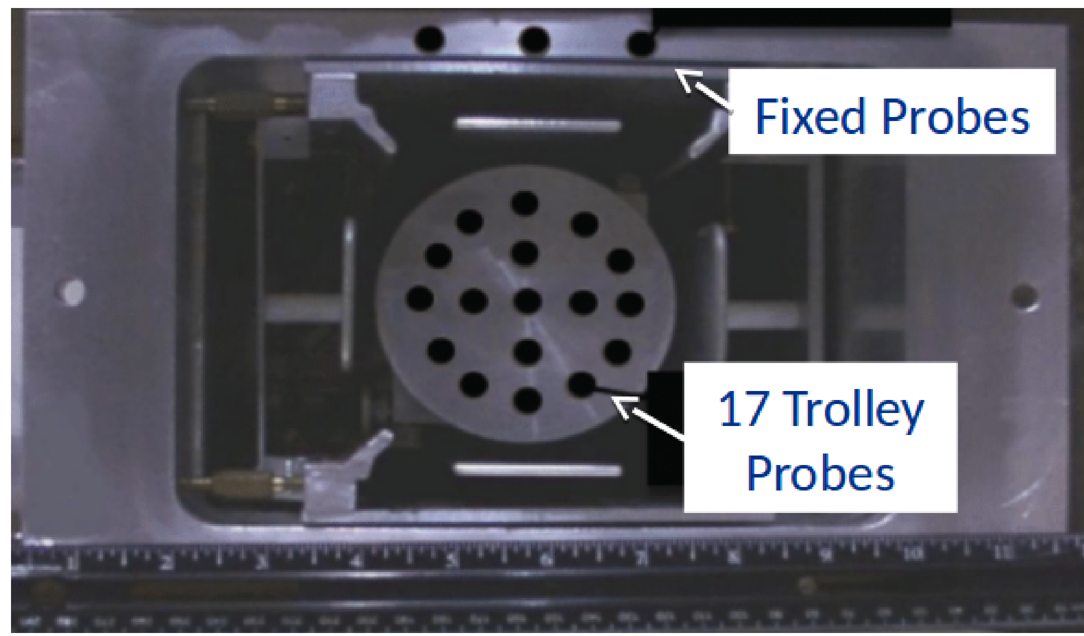
Note: the B field is not here directly.
We sample the B field with protons in NMR probes to calibrate.

pNMR probes: trolly, fixed, plunging

$$\widetilde{\omega}_p$$

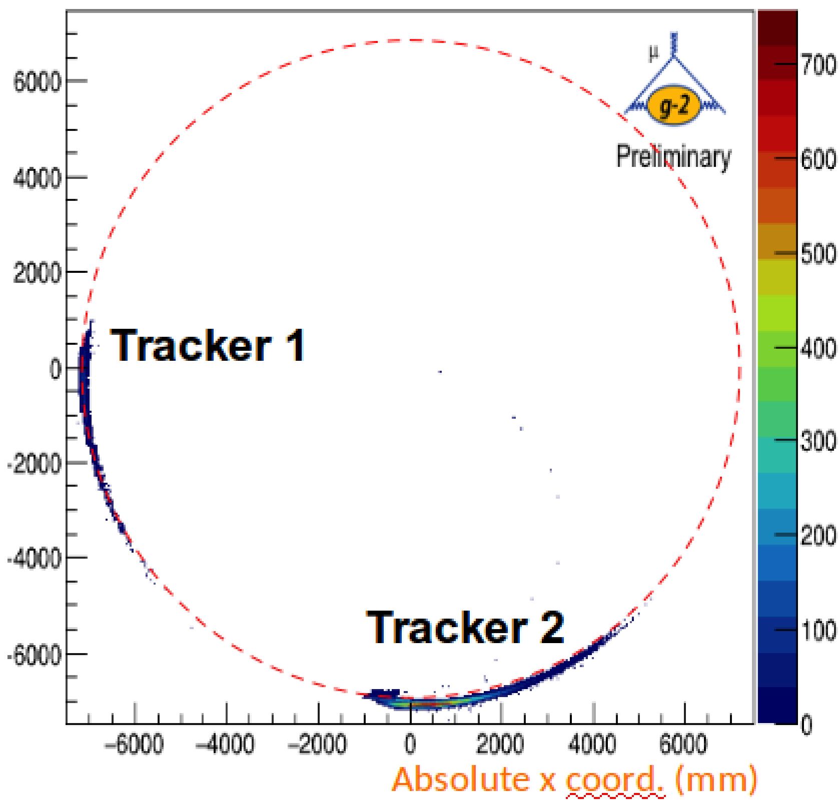


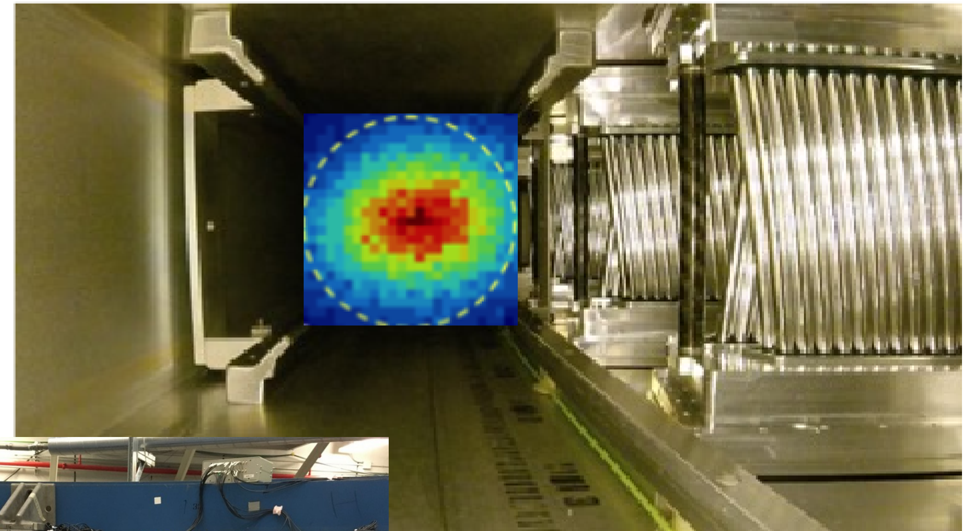
The "trolley" inside the beam "pipe"

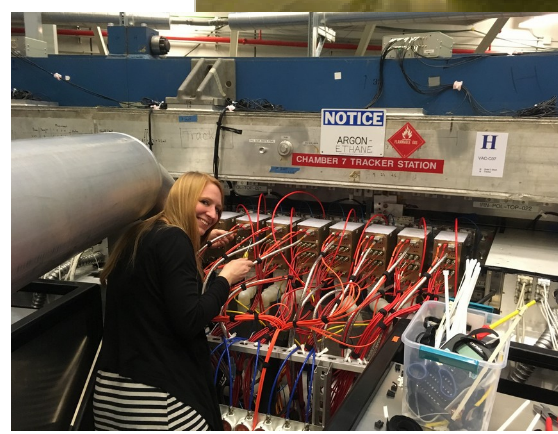


- A ***Trolley*** runs inside the beam pipe to map periodically the field by a set of pNMR probes : 1 run of ~3h is performed every 3d
- A set of 378 fixed probes are located in 72 locations in azimuth

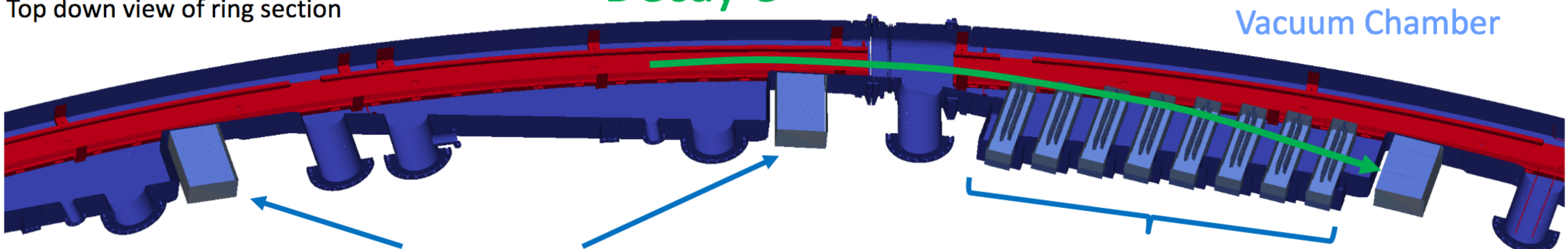
Track muon locations in storage ring







$$\tilde{\omega}_p$$



Convolve B with muon distribution

$$\widetilde{\omega}_p$$

Measure B using pNMR probes

Mechanically adjust steel

Coils adjust dipole

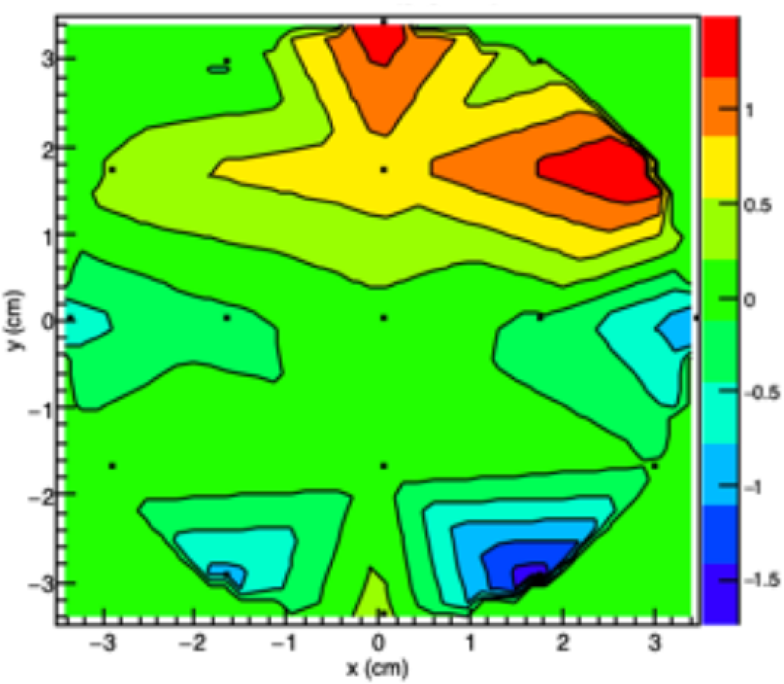
Thermally control steel

Instrument 2 stations with straw tubes

“u”,”v” planes

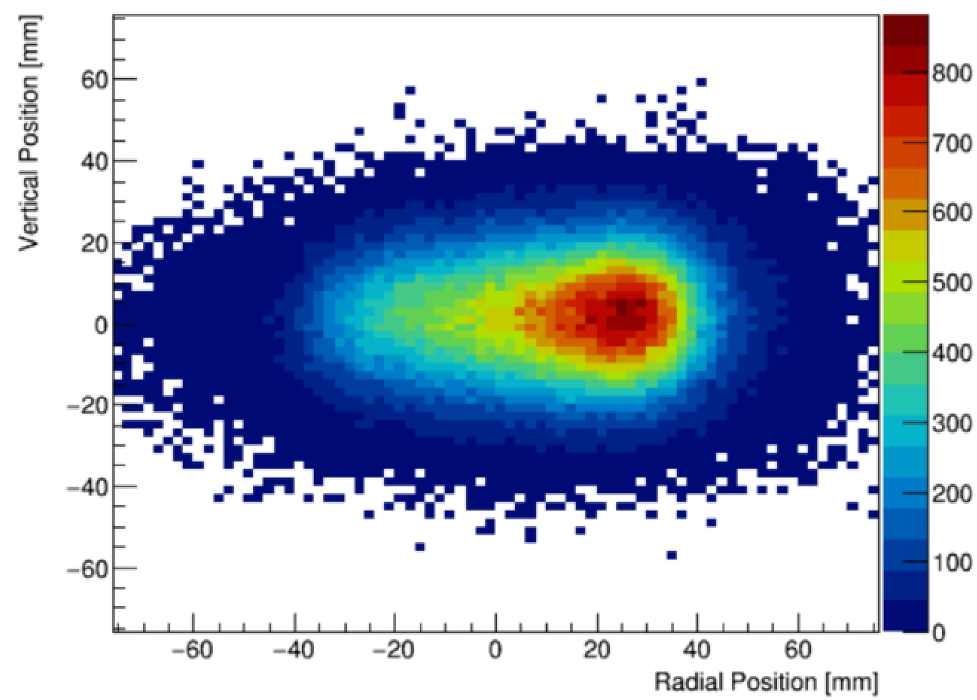
Trace back to tangent

NMR map of field

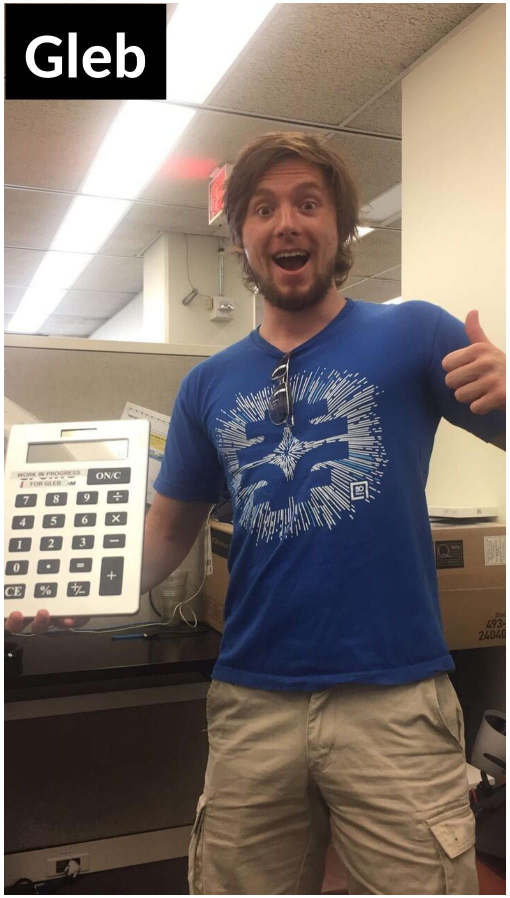


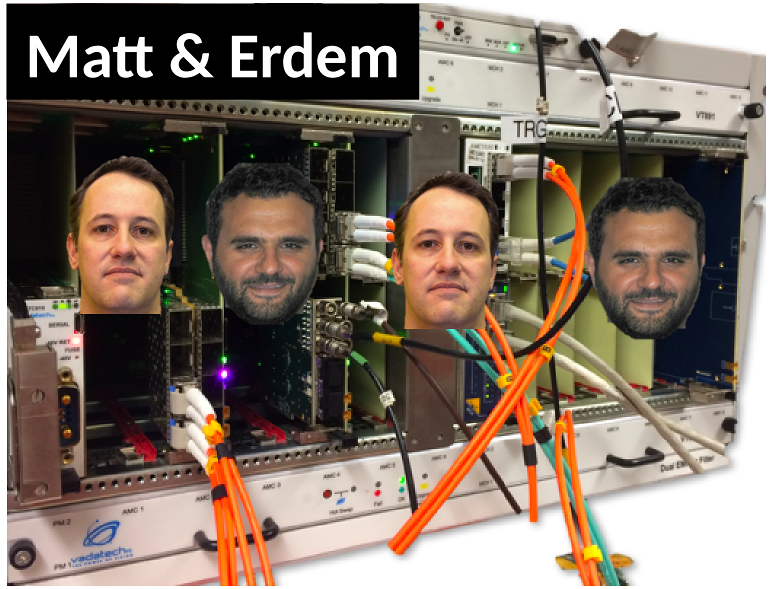
x

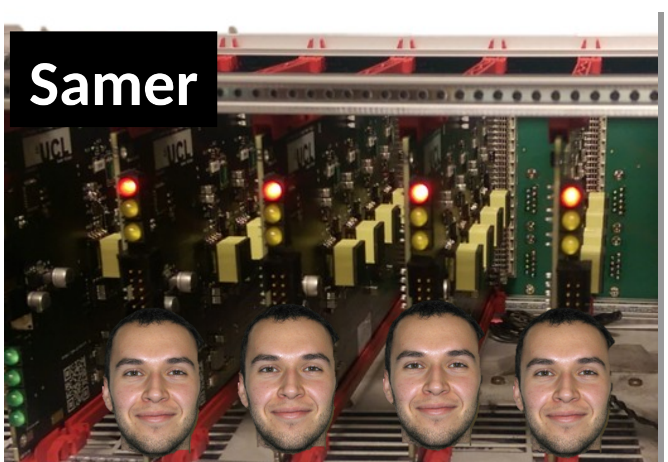
Muon distribution

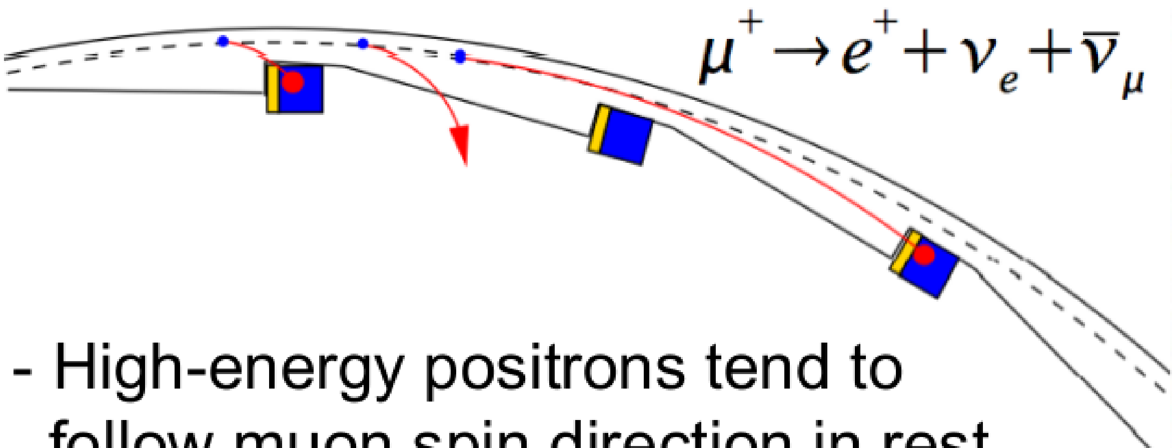


UCL Team



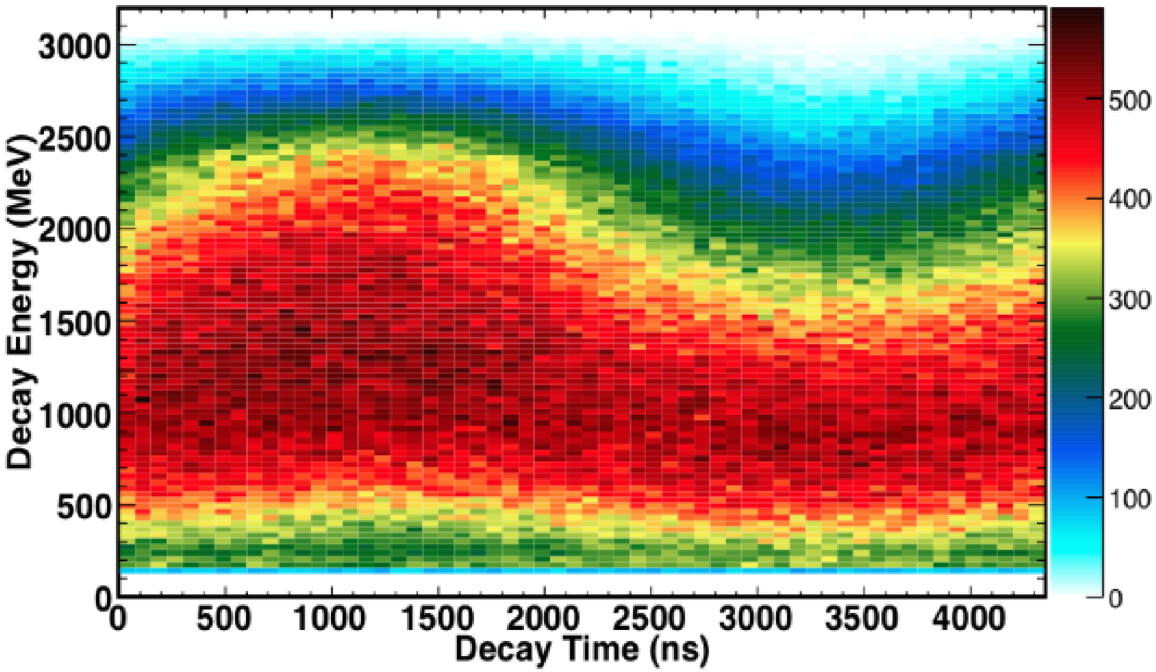


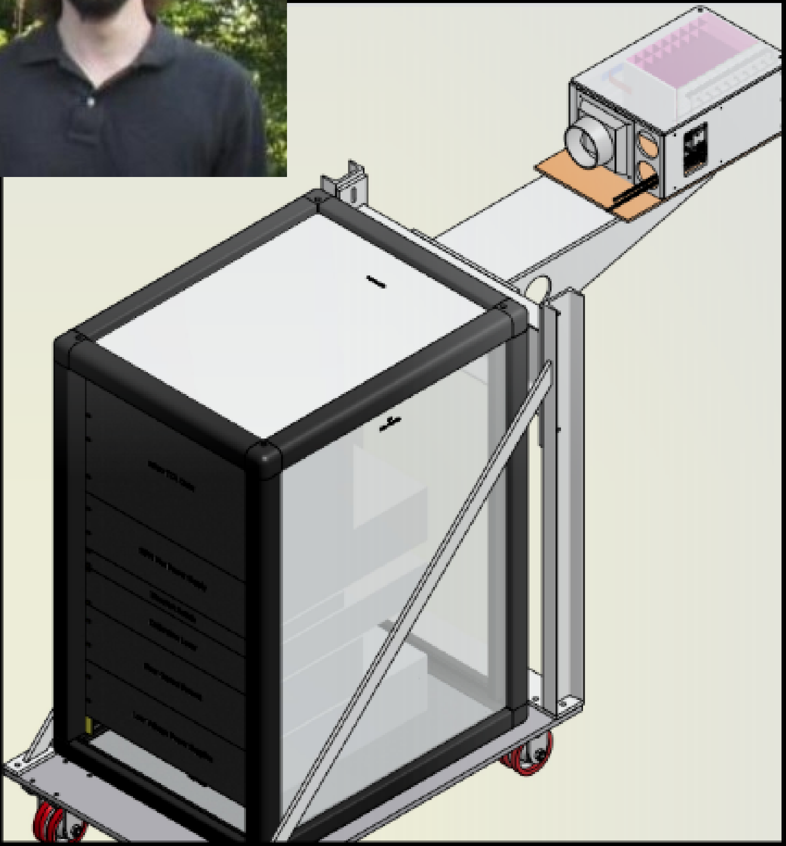




Jarek Kaspar et al.

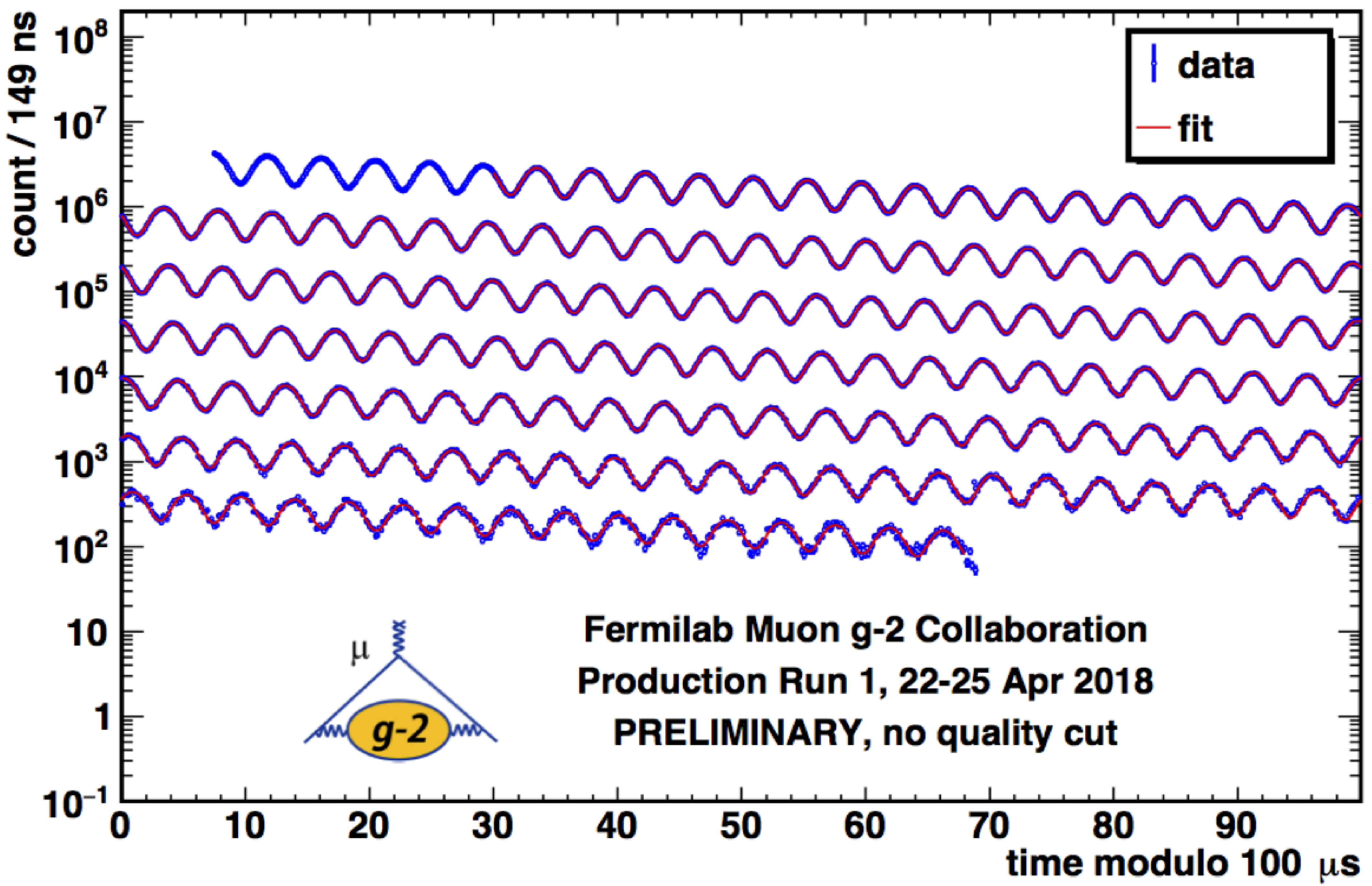
- High-energy positrons tend to follow muon spin direction in rest frame; consider boost to lab frame:





Positrons detected in 24 calorimeters around inner circumference of ring.

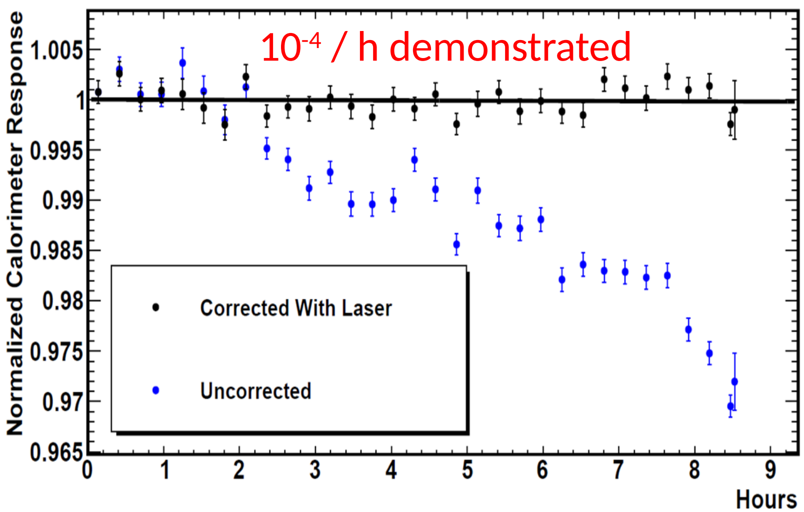
- T method: accept pulses > 1.86 GeV threshold that maximizes $\sqrt{N}A$
- Q method: total energy vs. time

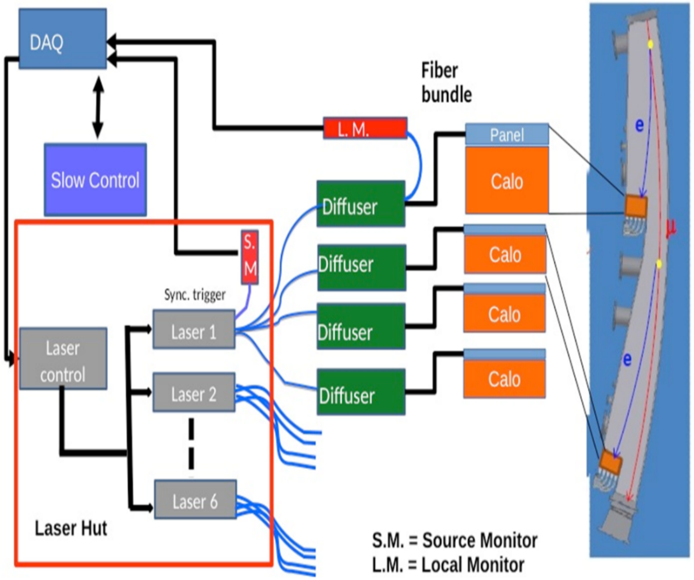


Spectrum from ~60 hours of stable running over 4 days

Calorimeter gain stability established to ~few x 10^{-4}

Test Beam Data

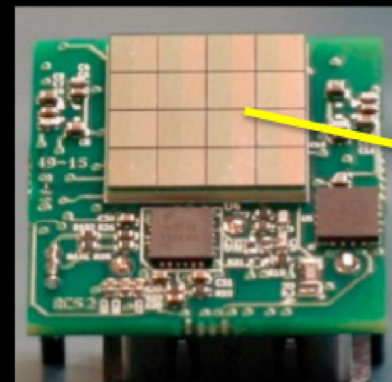


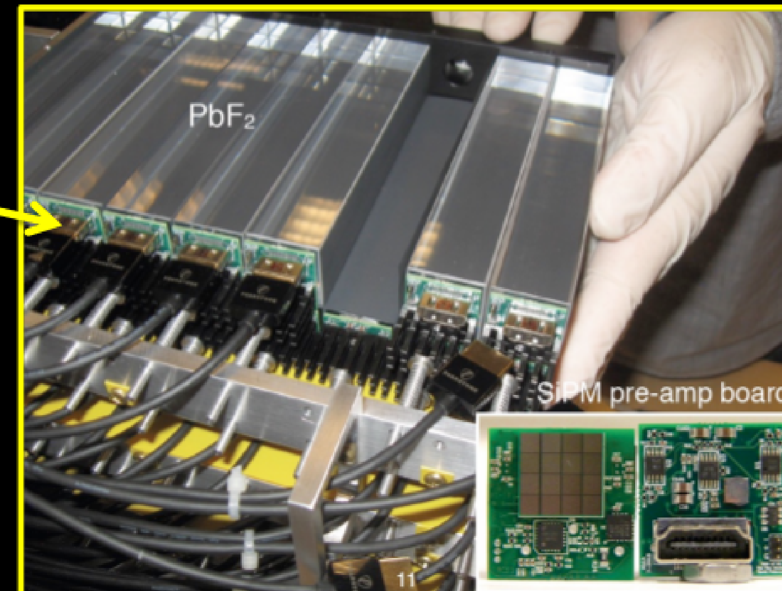


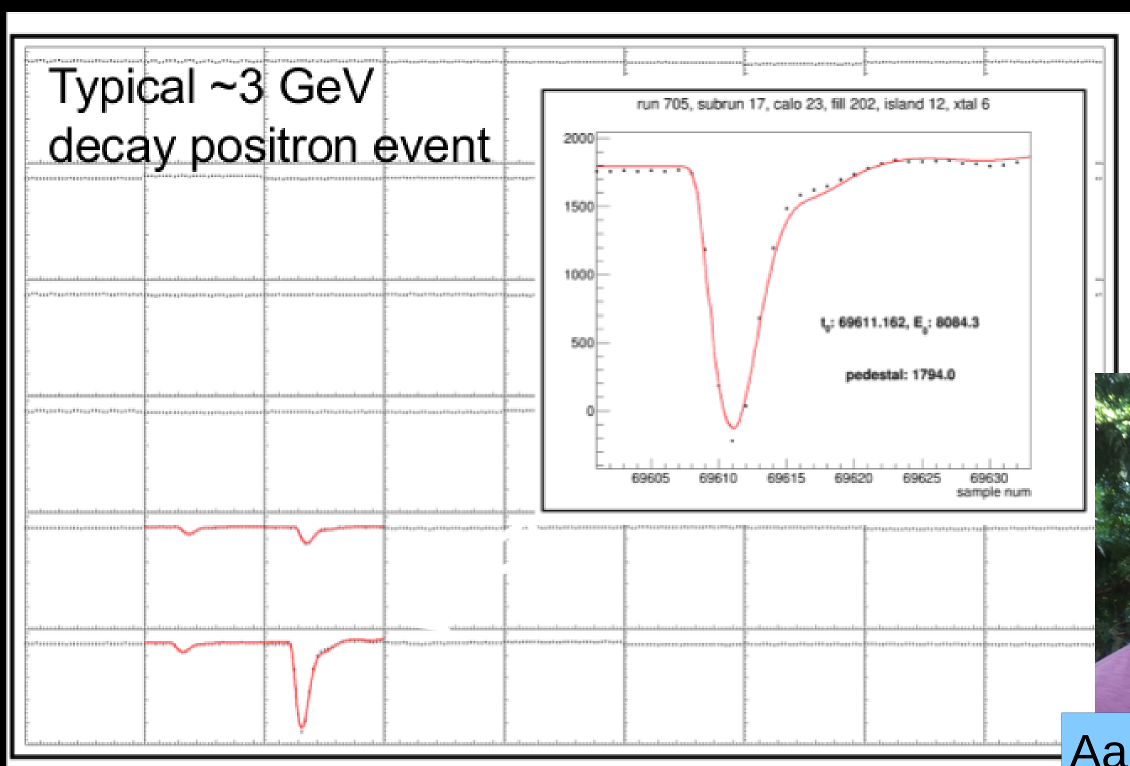
State-of-the-art Laser-based calibration system also allows for pseudo data runs for DAQ

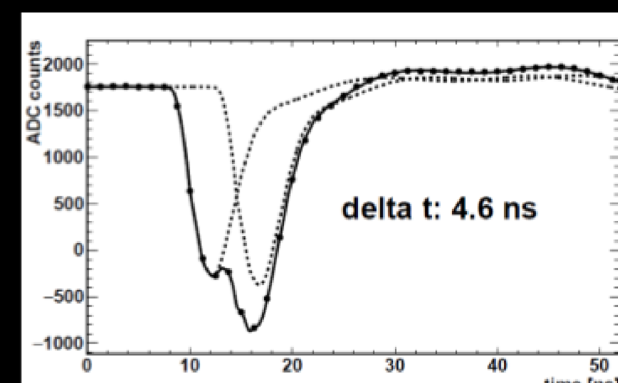
Calorimeters: pulse separation in space and time

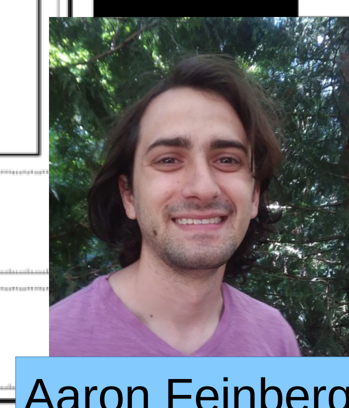
- 24 calorimeters
- Each segmented into 9x6 array of PbF_2 Cerenkov crystals.
- Instrumented with silicon photomultiplier (MPPC) arrays.
- Continuously digitized with 800 MSPS sampling.
- Pulses selected and recorded by algorithms in online GPU (graphics processing unit) cluster.

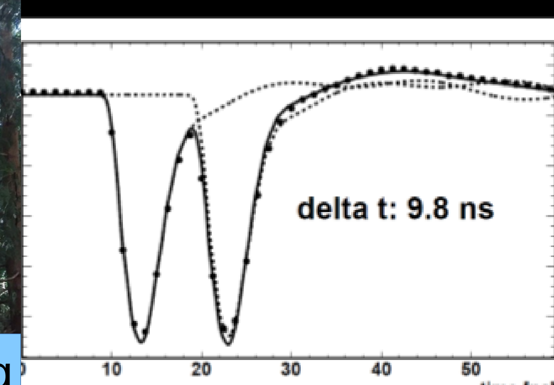




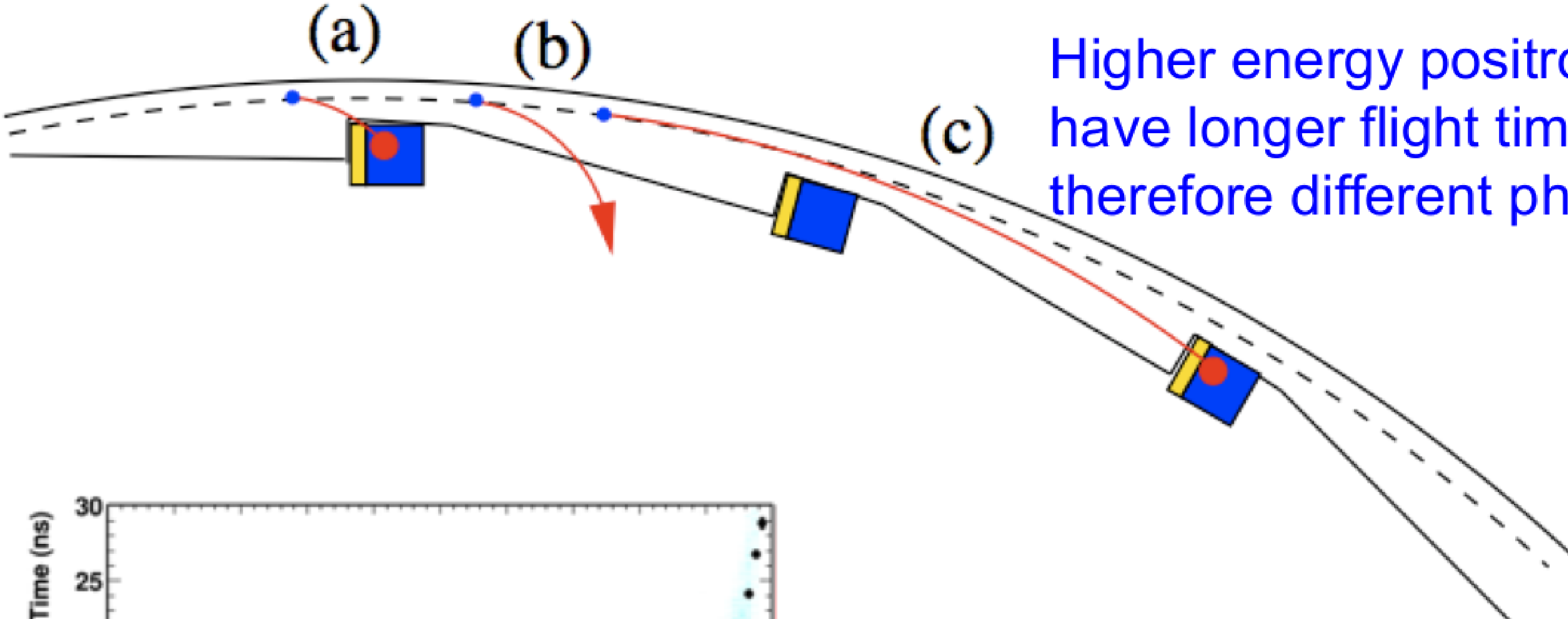




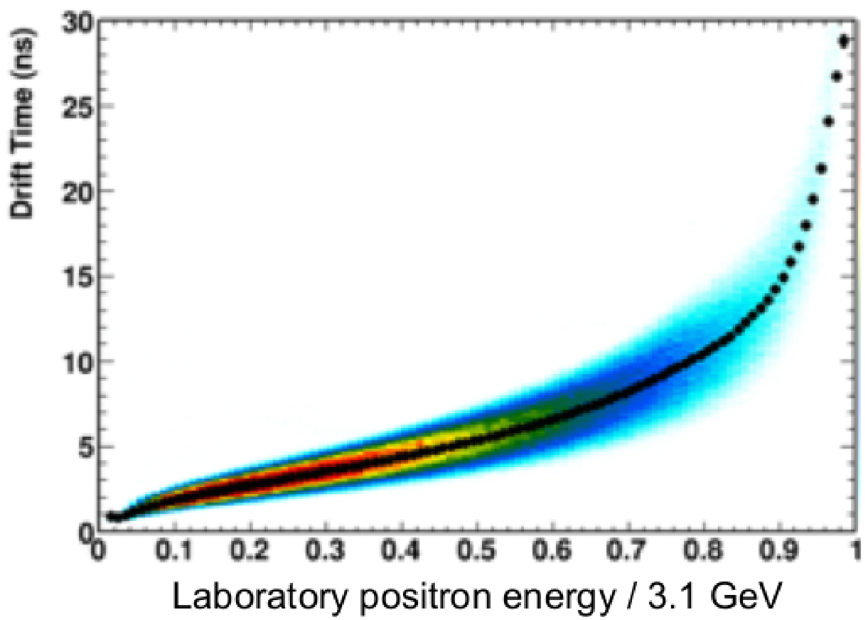




Overlapping pulses ("pileup")



Higher energy positrons have longer flight time and therefore different phase.



If two 1.4 GeV positrons add up to one 2.8 GeV count, they have the wrong phase by ~15 ns = ~20 mrad. The proportion of these events decreases over the fill.

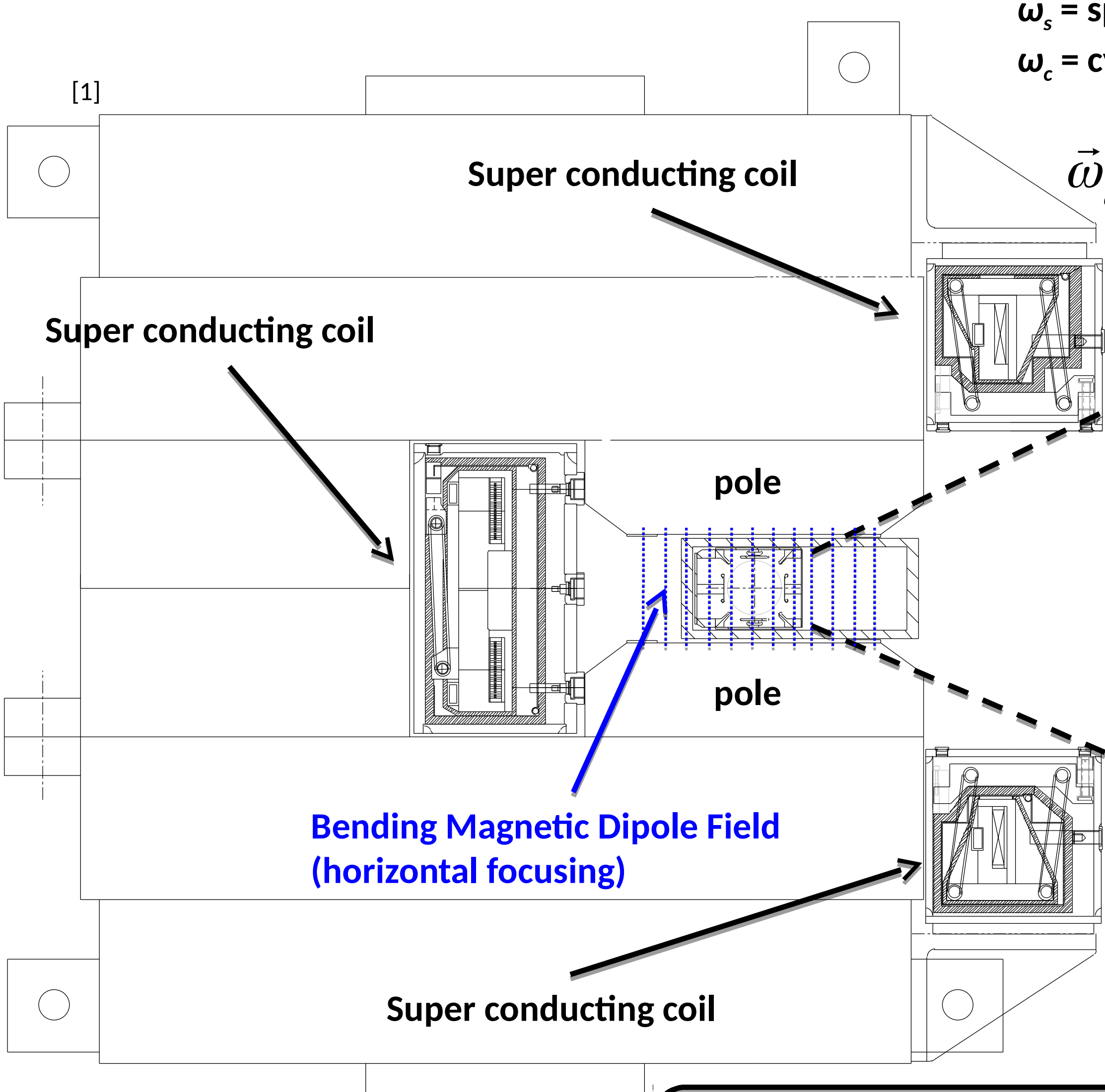
Early-to-late phase shift alters the fitted frequency.

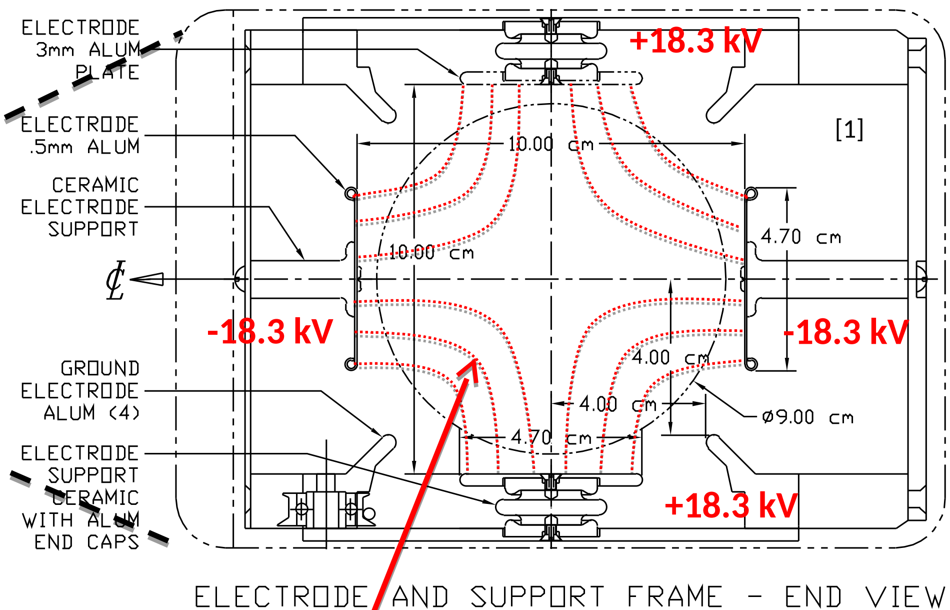
Experiment uses a weak focusing muon storage ring.

ω_a = anomalous precession frequency
ω_s = spin precession frequency
ω_c = cyclotron frequency

0 when γ = 29.3 => p_μ = 3.094 GeV/c

$$\vec{\omega}_a \approx \vec{\omega}_s - \vec{\omega}_c \approx -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$





Scraping sets bottom, Q2 inner, and Q4 outer plates to ±13.1 kV.

Horizontal And Vertical Tunes:

$$\nu_x \approx \sqrt{1-n}$$

$$\nu_y \approx \sqrt{n}$$

Vertical Focusing Electric Quadrupole Field

[1] Y. K. Semertzidis *et al.*, Nucl. Instrum. Meth. A **503**, 458 (2003). doi:10.1016/S0168-9002(03)00999-9

Two corrections to "Wiggle Plot"

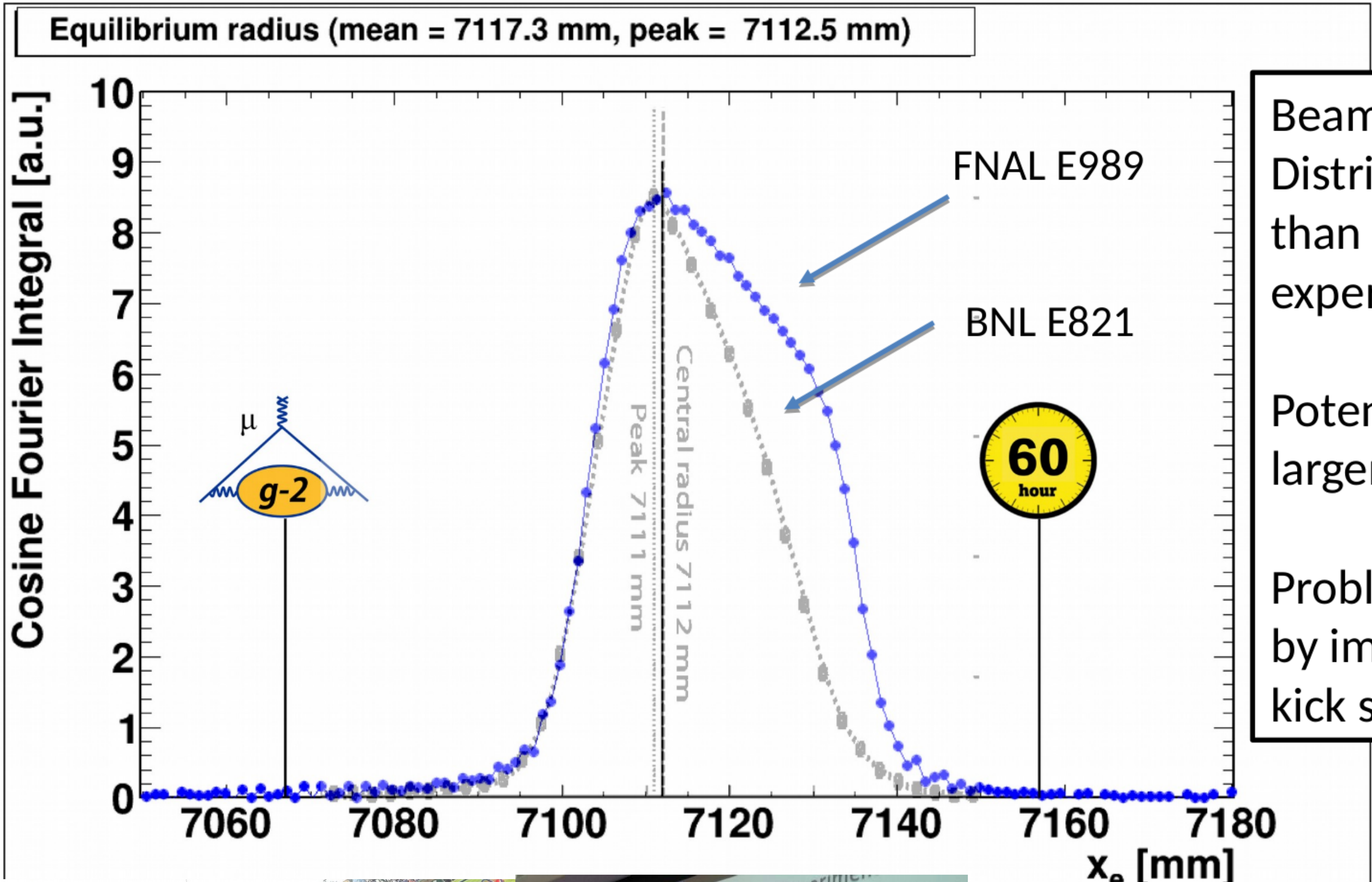
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}}_{\text{Quad E-fields}} - \underbrace{a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}.\vec{B}\right)\vec{\beta}}_{\text{Vertical Motion}}\right]$$

1. E-field Correction : 0.25-0.5 ppm (depending on kicker voltage)
- position uncertainty / misalignment of quad plates
- deviation of beam from equilibrium radius / magic momentum

2. Pitch Correction : 0.25 ppm
- due to (small) vertical betatron oscillation

BNL had O(10%) uncertainties on these corrections

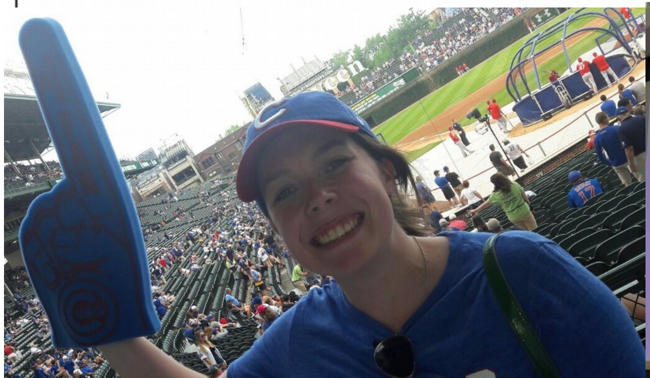
Momentum Distribution

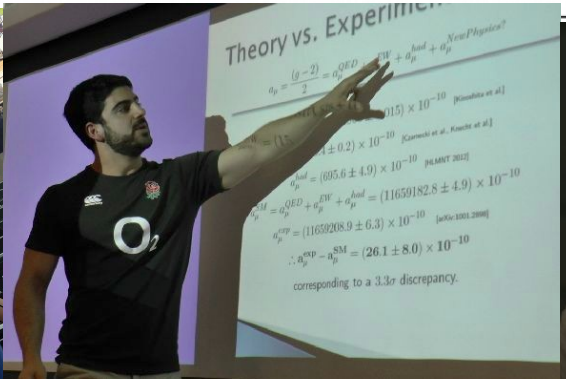


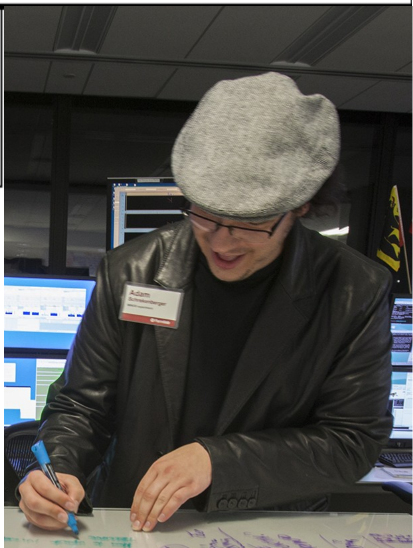
Beam Momentum Distribution is wider than previous experiment.

Potentially requires larger corrections.

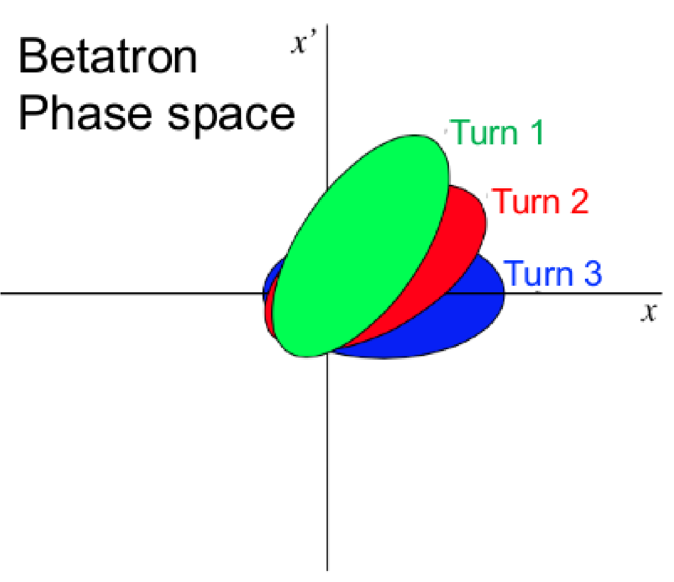
Problem will be fixed by improving the kick strength

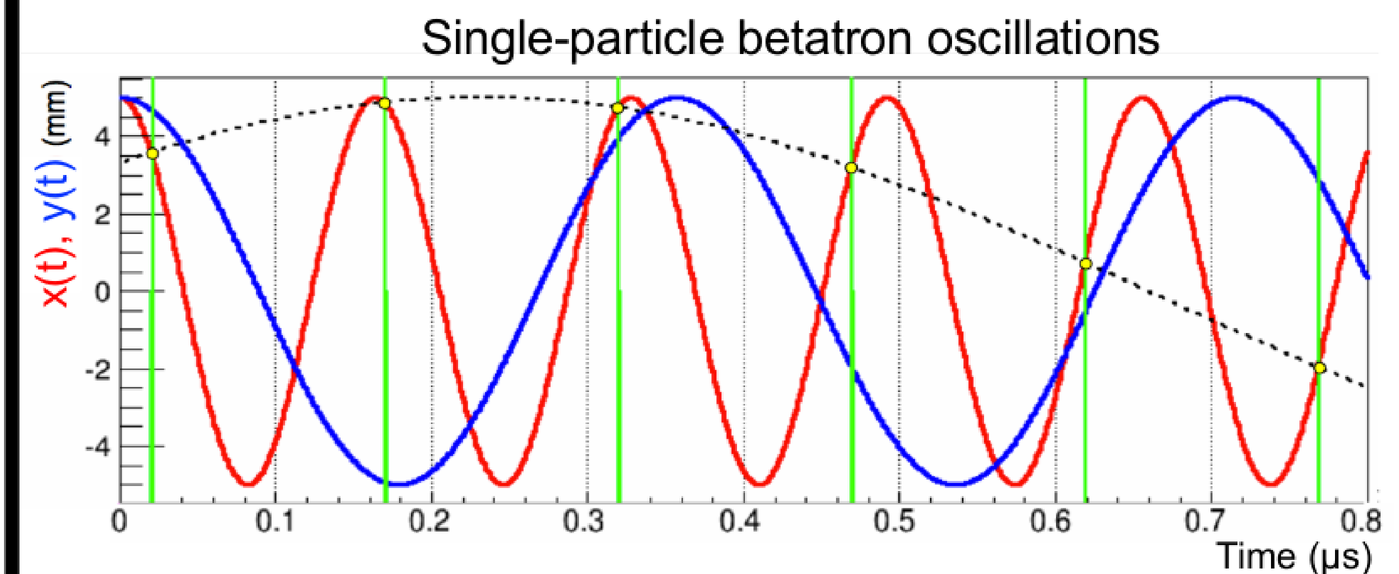




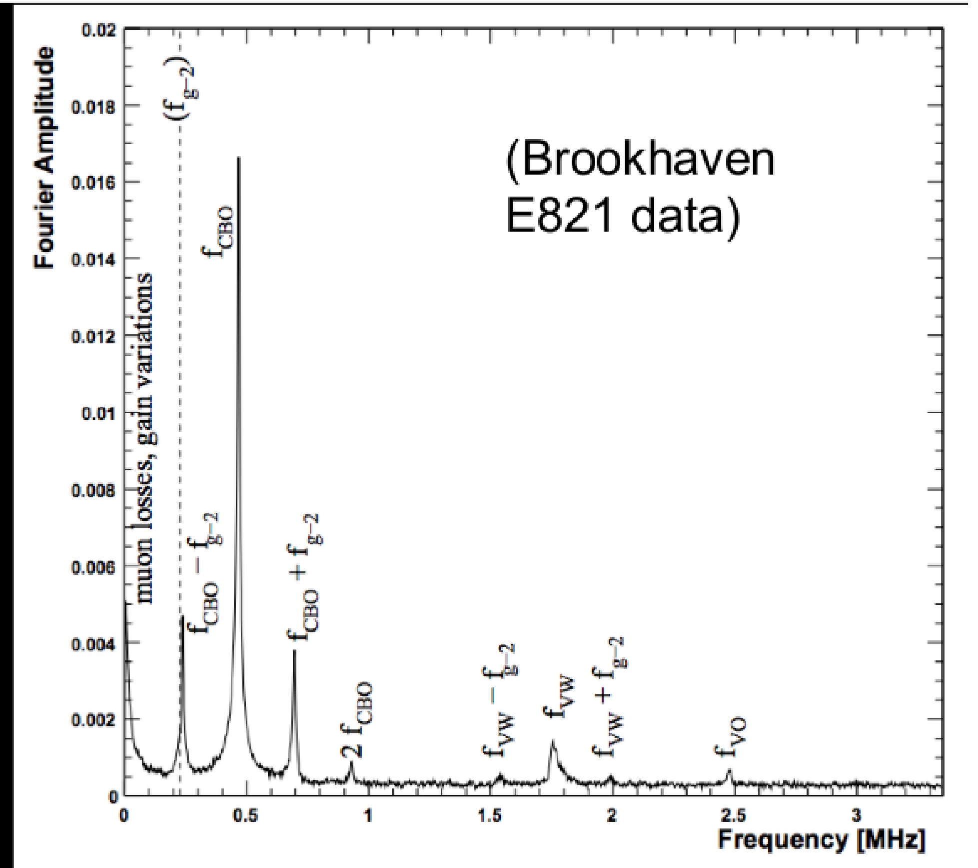


Coherent Betatron Oscillations



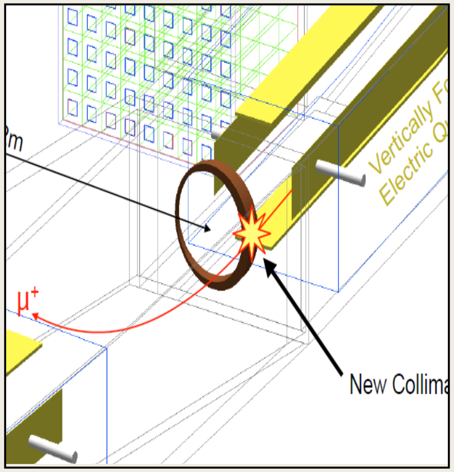


- "Swimming" and "breathing" motions caused by focusing a beam that only fills part of the phase space
- Stroboscopic observation at $\omega_{CBO} = \omega_x - \omega_c$
- Possible interference between ω_{CBO} and $2\omega_a$
- Quadrupole voltage now limited (18.3 kV) by vacuum: running at "low-n" solution with $\omega_{CBO} < 2\omega_a$. (Intend to raise to 32 kV for "high-n" with $\omega_{CBO} > 2\omega_a$.)



One of the Systematic Errors: Muons Lost from Storage Ring

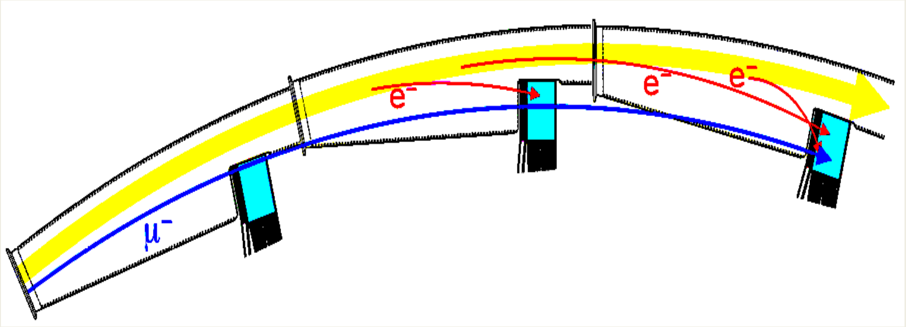
- Muons that get kicked out by the collimators and punch through calorimeters (MIPs) during measurement
- Need to determine: how many muons are lost, and where they originated
- The loss rate is time dependent and needs to be incorporated in the muon precession frequency fit

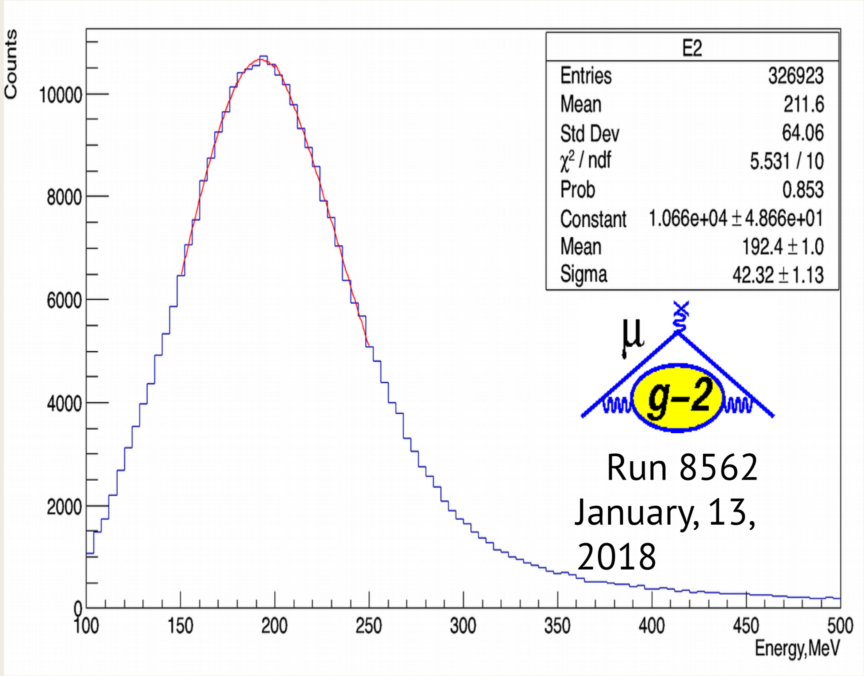


Collimators to remove muons outside the 9-cm-diameter storage region

How do we detect them?

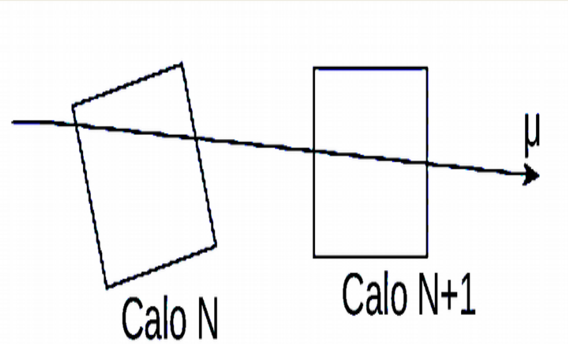
- Muons can pass through many calorimeters without stopping





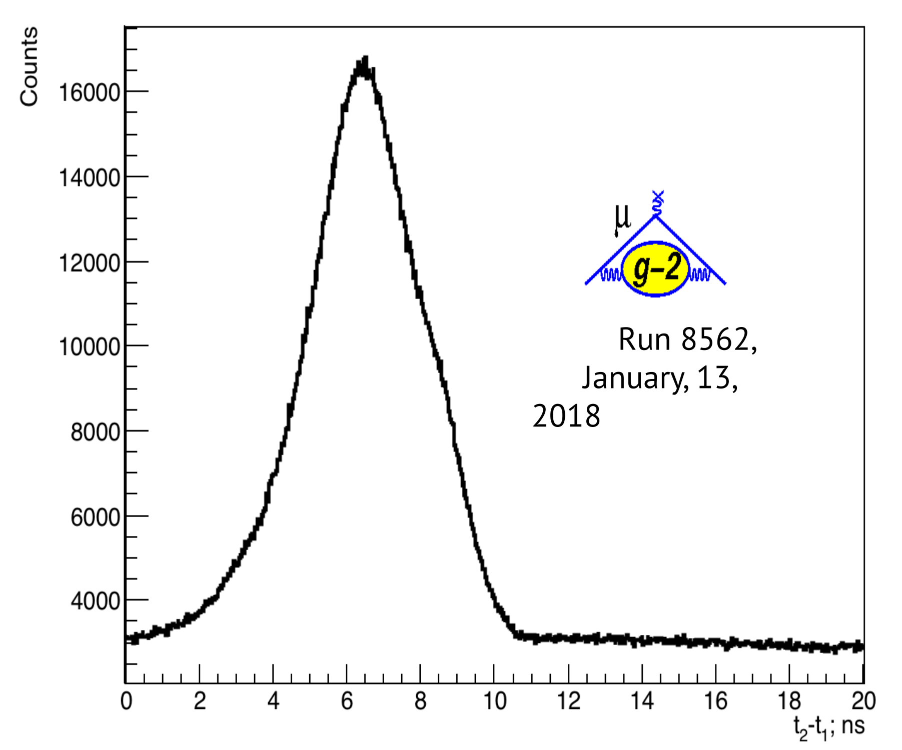
3 GeV muons (MIPs) deposit of order 200 MeV as they pass through a calorimeter

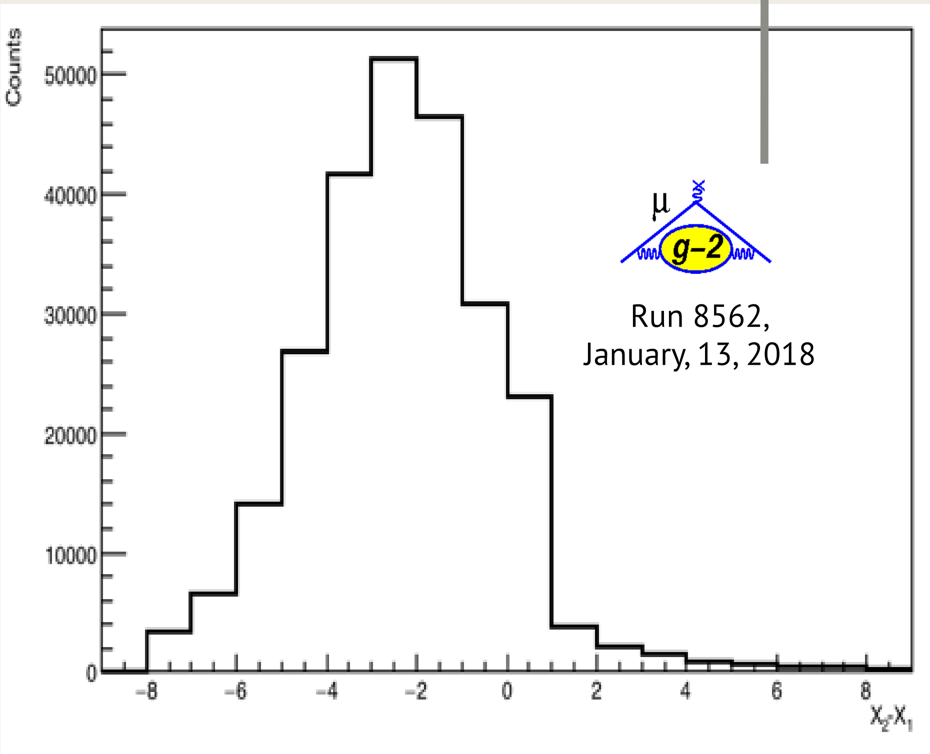
One of the Systematic Errors: Muons Lost from Storage Ring



Towards Ring

Use energy, position, and time to identify "lost muon" events





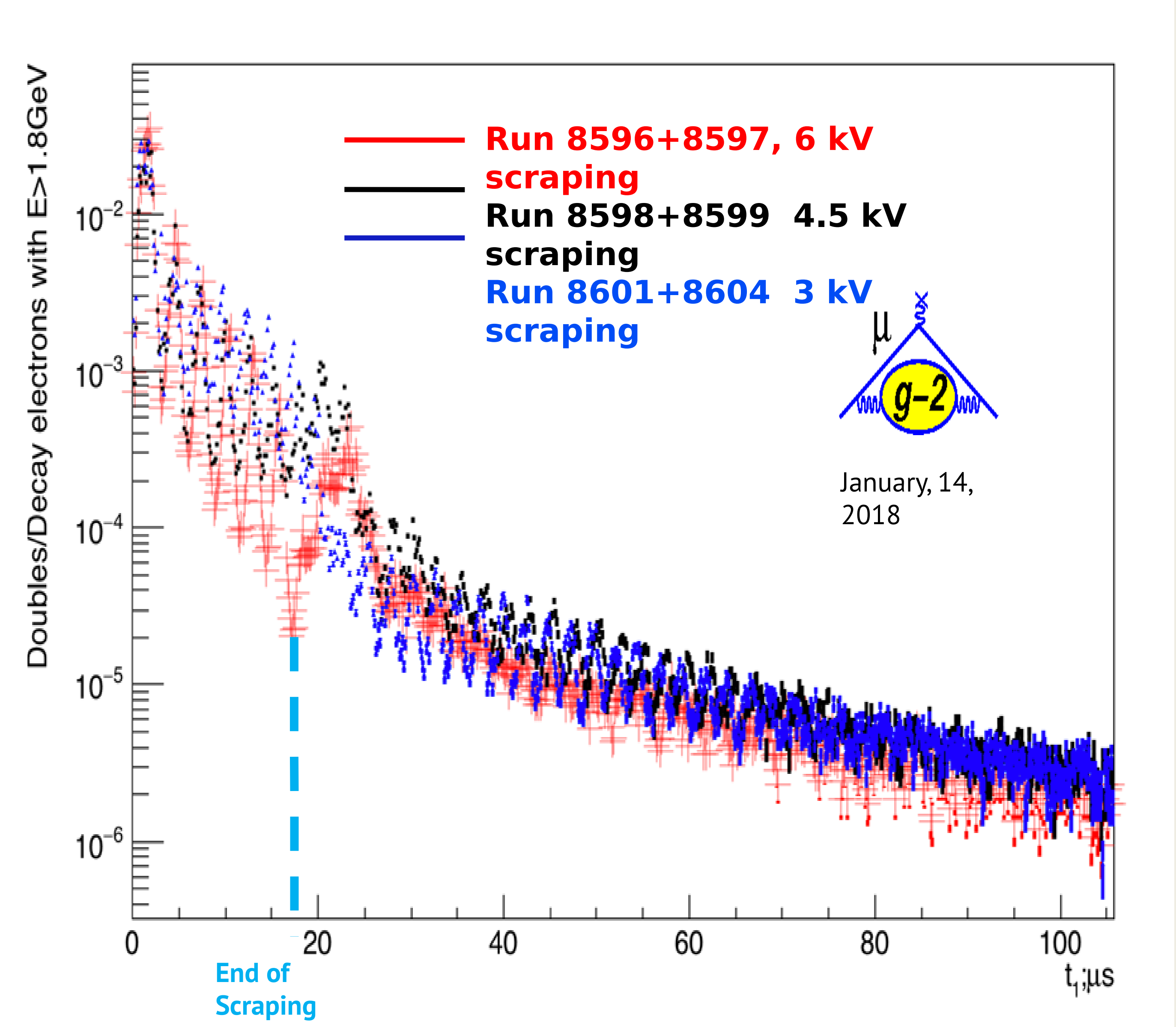
Coincidence time window between two consecutive calorimeters

MIPs move radially inward when going from 1st Calorimeter to 2nd Calorimeter

Lost muon signal useful for tuning injection parameters, e.g. inflector, quad scraping, kicker settings and radial field

Fractional Muon Losses as a function of time under different scraping voltages

Sudeshna Ganguly



ω_a Systematics

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
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

Scientific collaboration

US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- North Central
- Regis
- UT Austin
- Virginia
- Washington

Italy

- Frascati
- Molise
- Naples
- Pisa
- Roma 2
- Trieste
- Udine

China

- Shanghai

Germany

- Dresden

Russia

- JINR/Dubna
- Novosibirsk

England

- Lancaster
- Liverpool
- University College London

Korea

- CAPP/IBS
- KAIST

7 countries

34 institutions

~185 authors

National Labs

- Argonne
- Brookhaven
- Fermilab

Financial support

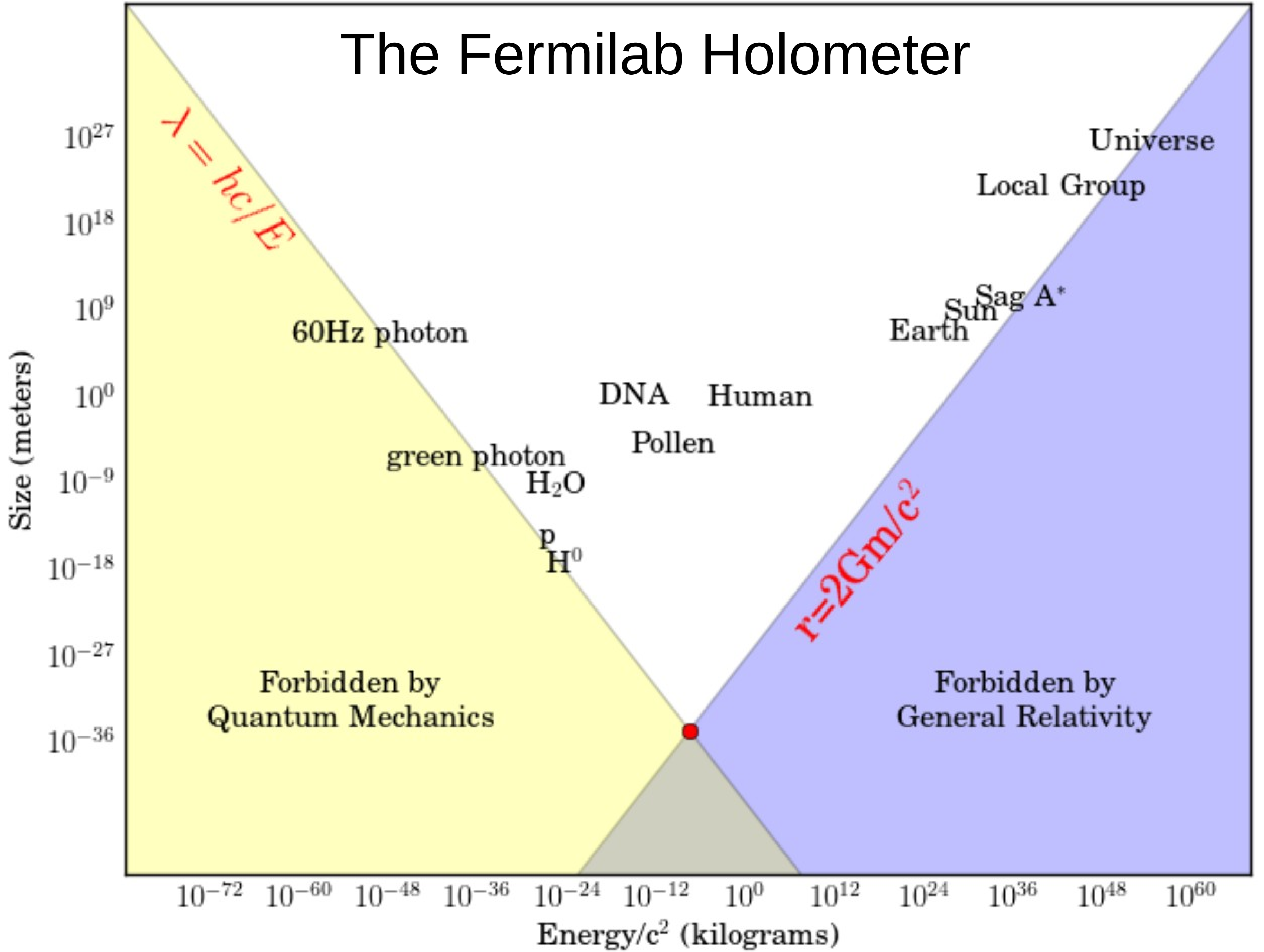
U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

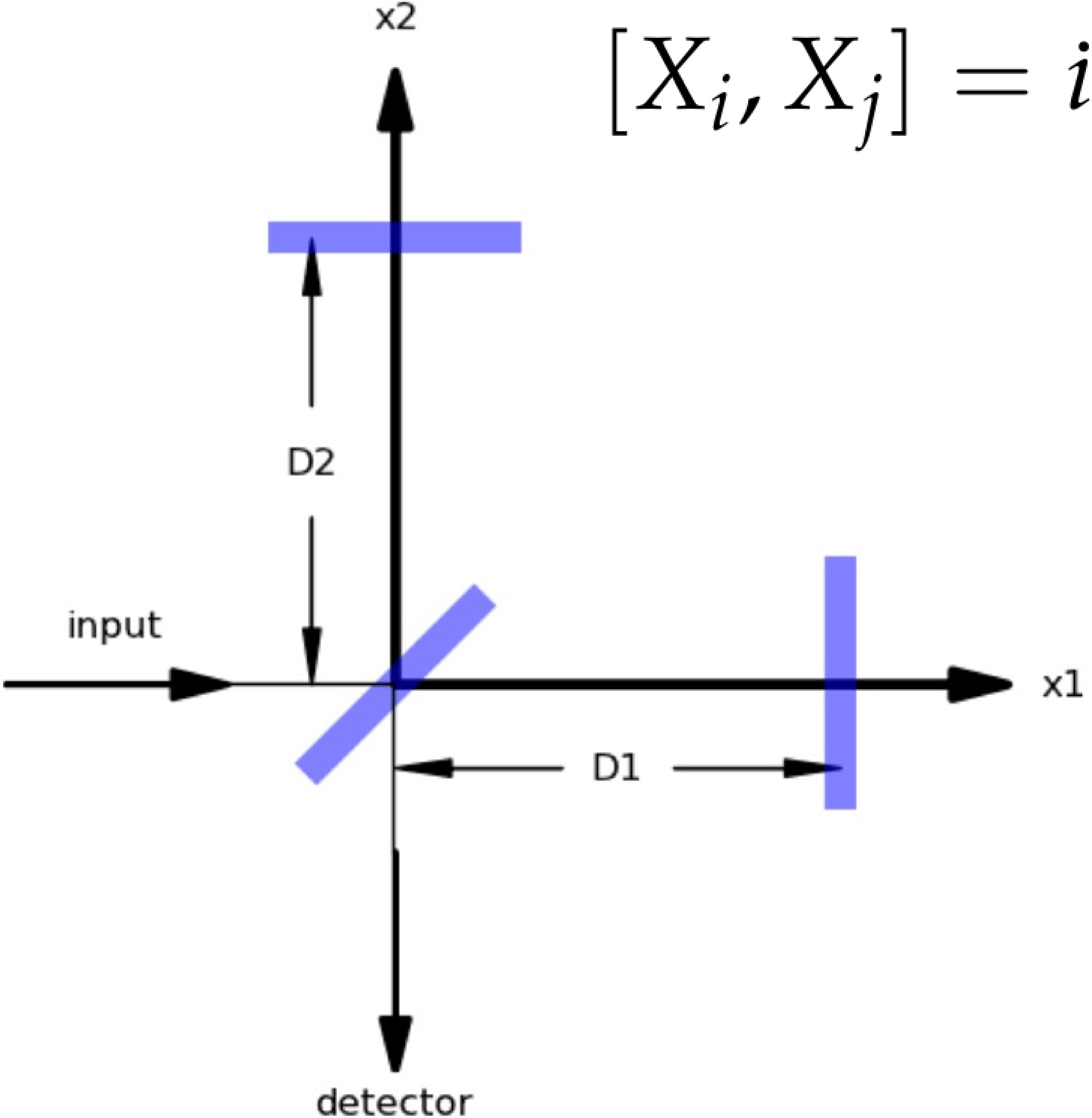
...with substantial contributions from funding agencies in China, Germany, Italy, Russia, South Korea, and the United Kingdom.

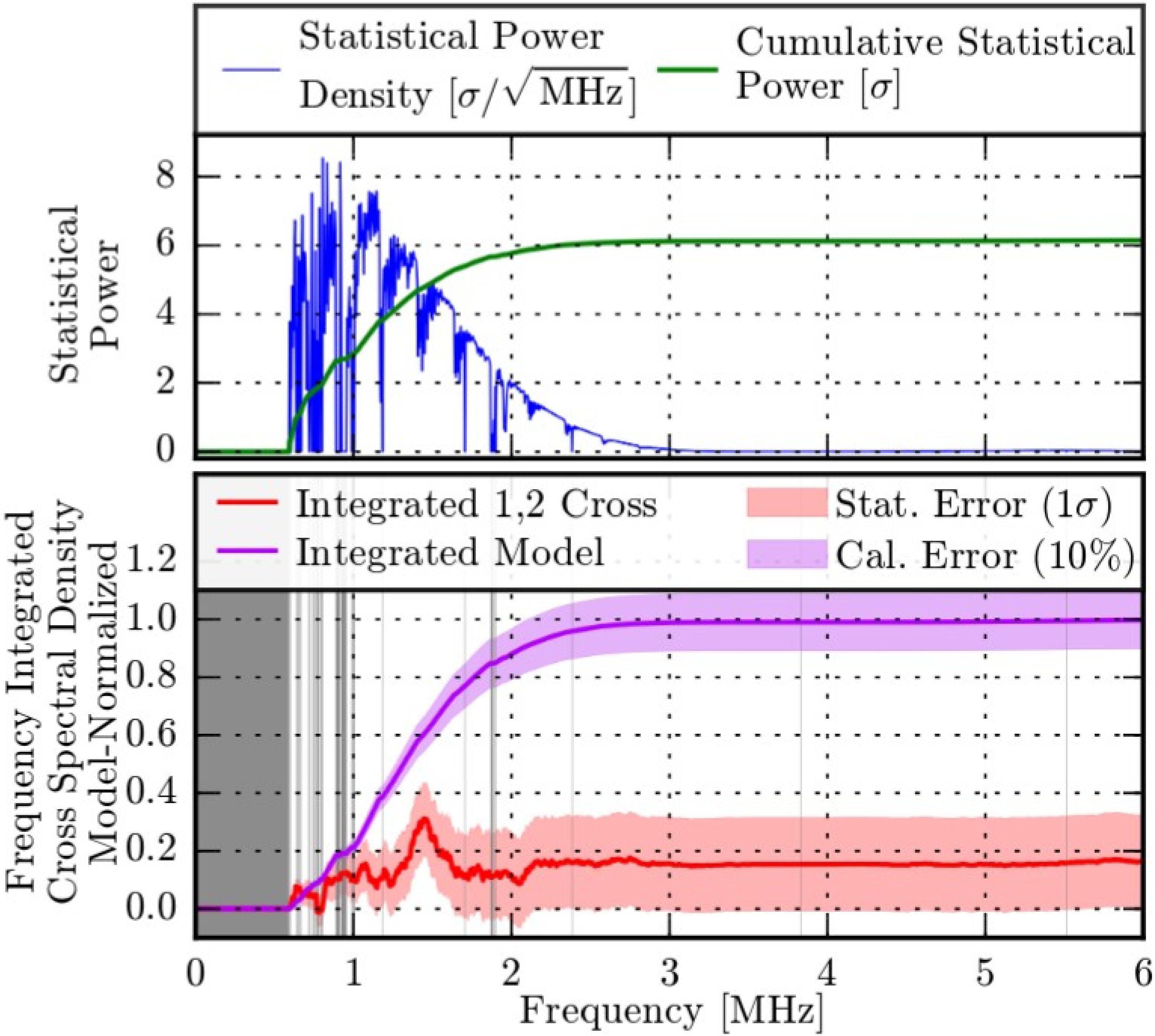
8 Countries, 35 Institutions, 190 Collaborators

The Fermilab Holometer



$$[X_i, X_j] = iX_k \epsilon_{ijk} \ell'_P$$





Statistical Power Density $[\sigma/\sqrt{\mathrm{MHz}}]$
Cumulative Statistical Power $[\sigma]$
Statistical Power
8
6
4
2
0
Integrated 1,2 Cross
Integrated Model
Stat. Error (1σ)
Cal. Error (10%)
Frequency Integrated Cross Spectral Density Model-Normalized
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
Frequency [MHz]

See also:

Statistical Model of Exotic Rotational Correlations in Emergent Space-Time arXiv:1607.03048
Inflation with Spooky Correlations arXiv:1811.03283
Quantum-enhanced correlated interferometry for fundamental physics tests arXiv:1810.13386