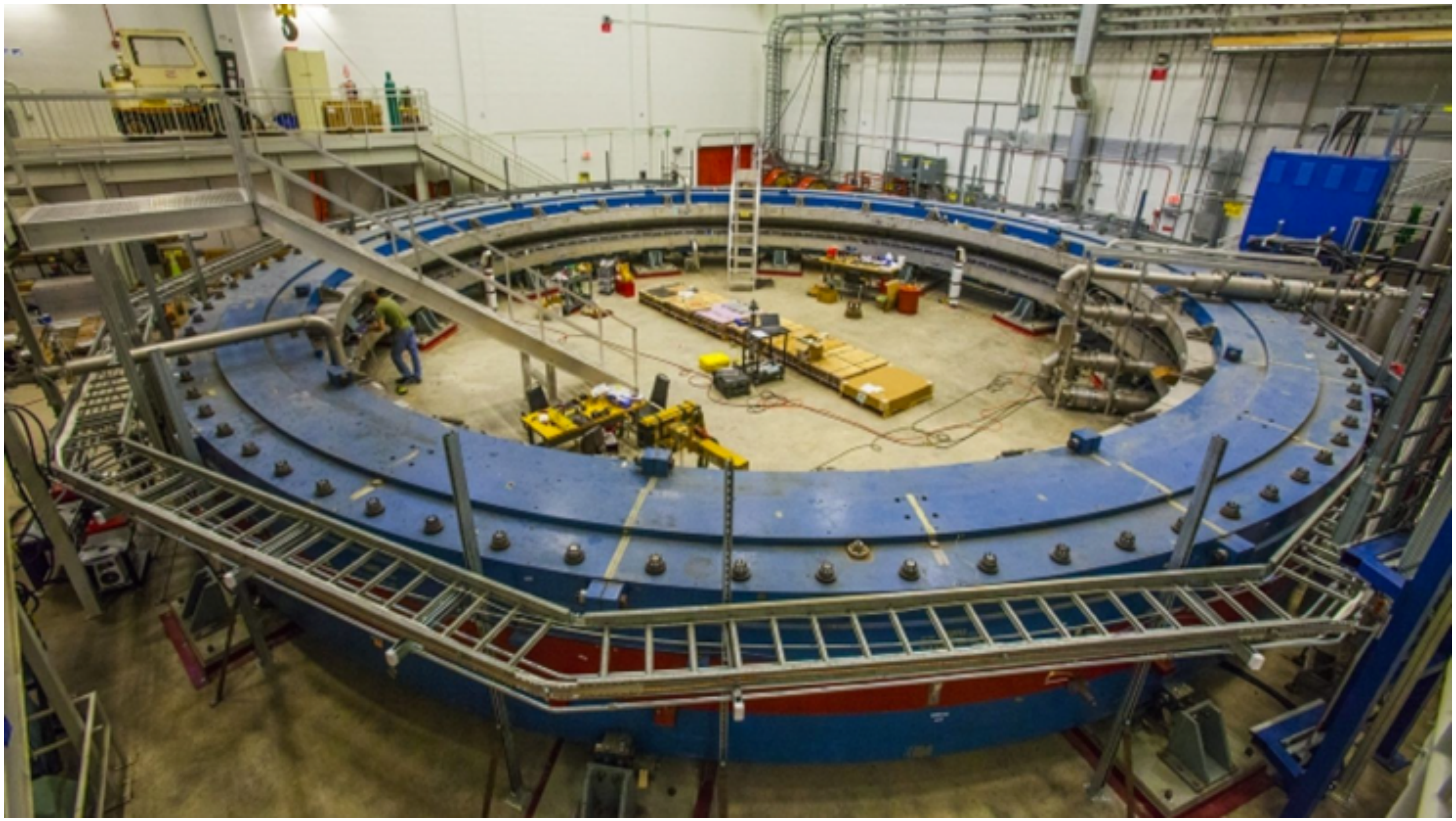
The Muon g-2 experiment at FNAL

Kim Siang Khaw
University of Washington

for the Muon g-2 collaboration (E989)

HISEBSM 2016
2016-08-04

Just in case you forget everything in the next 45 minutes ……



Remember this:
We will be measuring how fast a muon spin rotates, relative to its momentum, in a magnetic storage ring and compare it to the SM prediction (at ~ 140 ppb level)

What is g-2?

- For a point-like particle, g is a factor that relates its spin to its magnetic moment

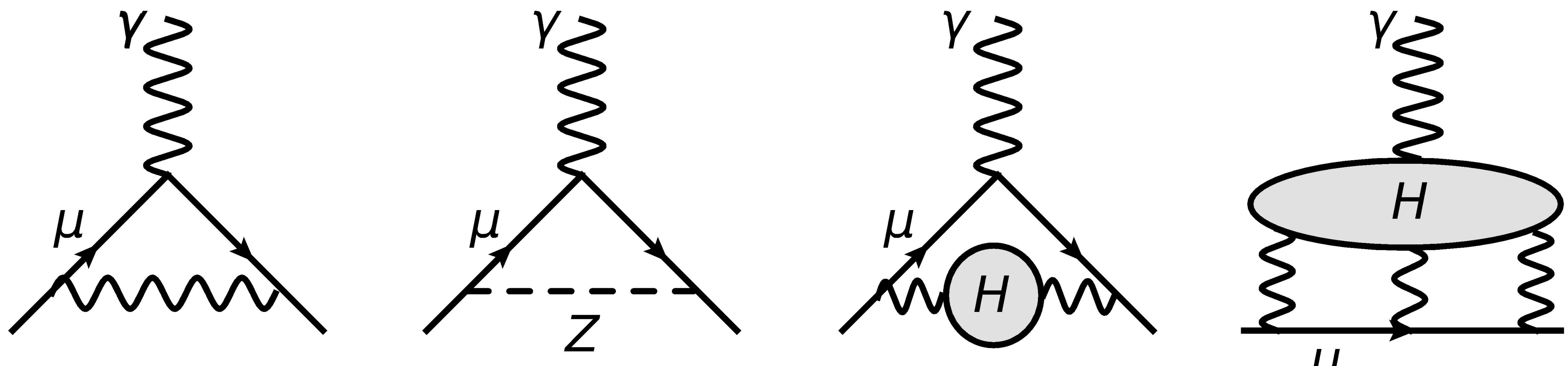
$$\vec{\mu} = g \left(\frac{e}{2m}\right) \vec{S}$$

- For a spin-1/2 particle, g = 2 from free Dirac equation
- g > 2 in interacting QFT (radiative corrections)

$$\frac{g-2}{2} \equiv a_\mu$$

"anomalous" magnetic moment

a_μ in the Standard Model

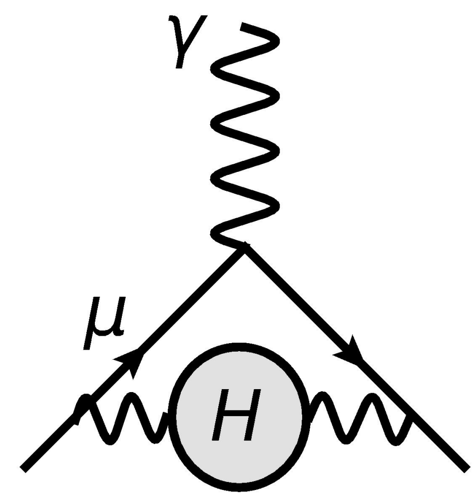


a_μ (SM) = a_μ(QED) + a_μ(Electroweak) + a_μ(HVP) + a_μ(HLbL)

SM Contribution	Value ± Error ($\times 10^{11}$)	Ref
QED (5 loops)	116584718.951 ± 0.080	[Aoyama et al., 2012]
HVP LO	6923 ± 42	[Davier et al., 2011]
	6949 ± 43	[Hagiwara et al., 2011]
HVP NLO	-98.4 ± 0.7	[Hagiwara et al., 2011]
		[Kurz et al., 2014]
HVP NNLO	12.4 ± 0.1	[Kurz et al., 2014]
HLbL	105 ± 26	[Prades et al., 2009]
Weak (2 loops)	153.6 ± 1.0	[Gnendiger et al., 2013]
SM Tot (0.42 ppm)	116591802 ± 49	[Davier et al., 2011]
(0.43 ppm)	116591828 ± 50	[Hagiwara et al., 2011]
(0.51 ppm)	116591840 ± 59	[Aoyama et al., 2012]

Courtesy
T. Blum

a_μ in the Standard Model



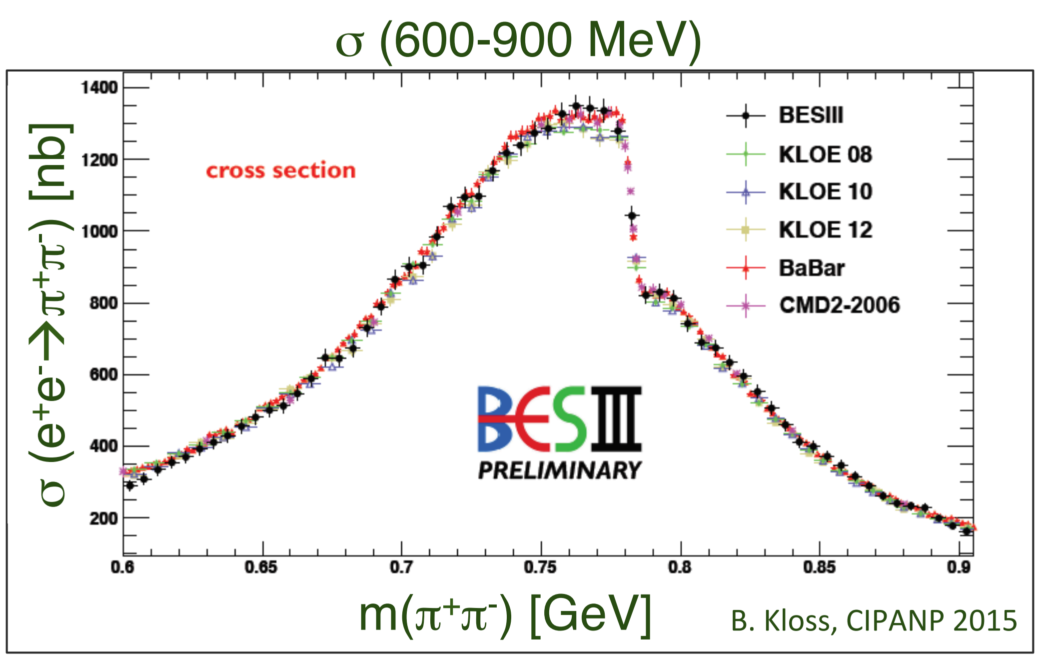
a_μ(HVP)

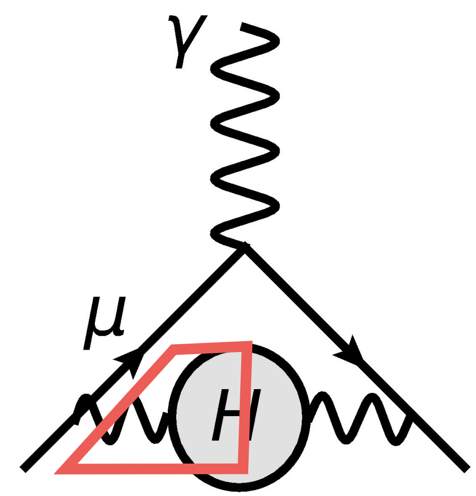
- pQCD difficult below 2 GeV
→ best prediction using e^+e^- to hadronic cross section data and a dispersion integral   arXiv:1507.02943

$$a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\text{th}}}^{\infty} ds\ \frac{1}{s}\hat{K}(s)\sigma_{\text{had}}(s)$$

- Improvements (50% reduction) expected in the next few years (VEPP-2000, BES-III, BaBar, KLOE-2, BELLE-II)
- Several efforts using lattice QCD

a_μ in the Standard Model





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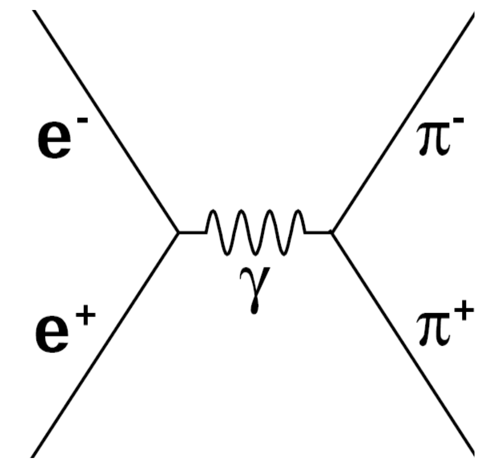

e^+e^- to hadrons

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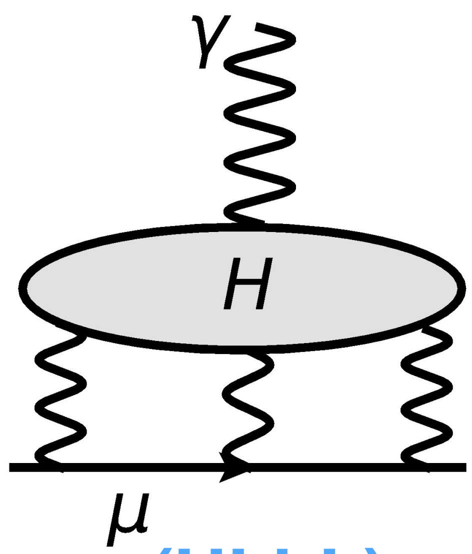
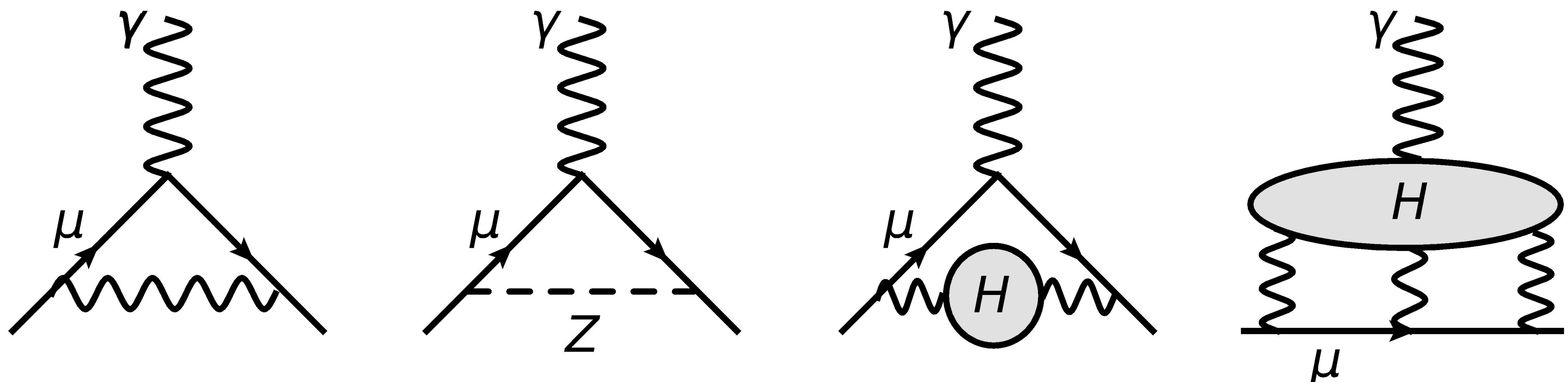


- non-perturbative, so far use of model calculations based on theorem and constraints from pQCD
- several independent evaluations, different in details but in good agreement in leading-order contribution
- recently lots of progress from the lattice QCD arXiv:1511.05198
- within 3-5 years, 10% estimate is possible

a_μ in the Standard Model



$$a_\mu\,(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Electroweak}) + a_\mu(\mathrm{HVP}) + a_\mu(\mathrm{HLbL})$$

Workshop on "Flavour changing and conserving processes" 2015 (FCCP2015)

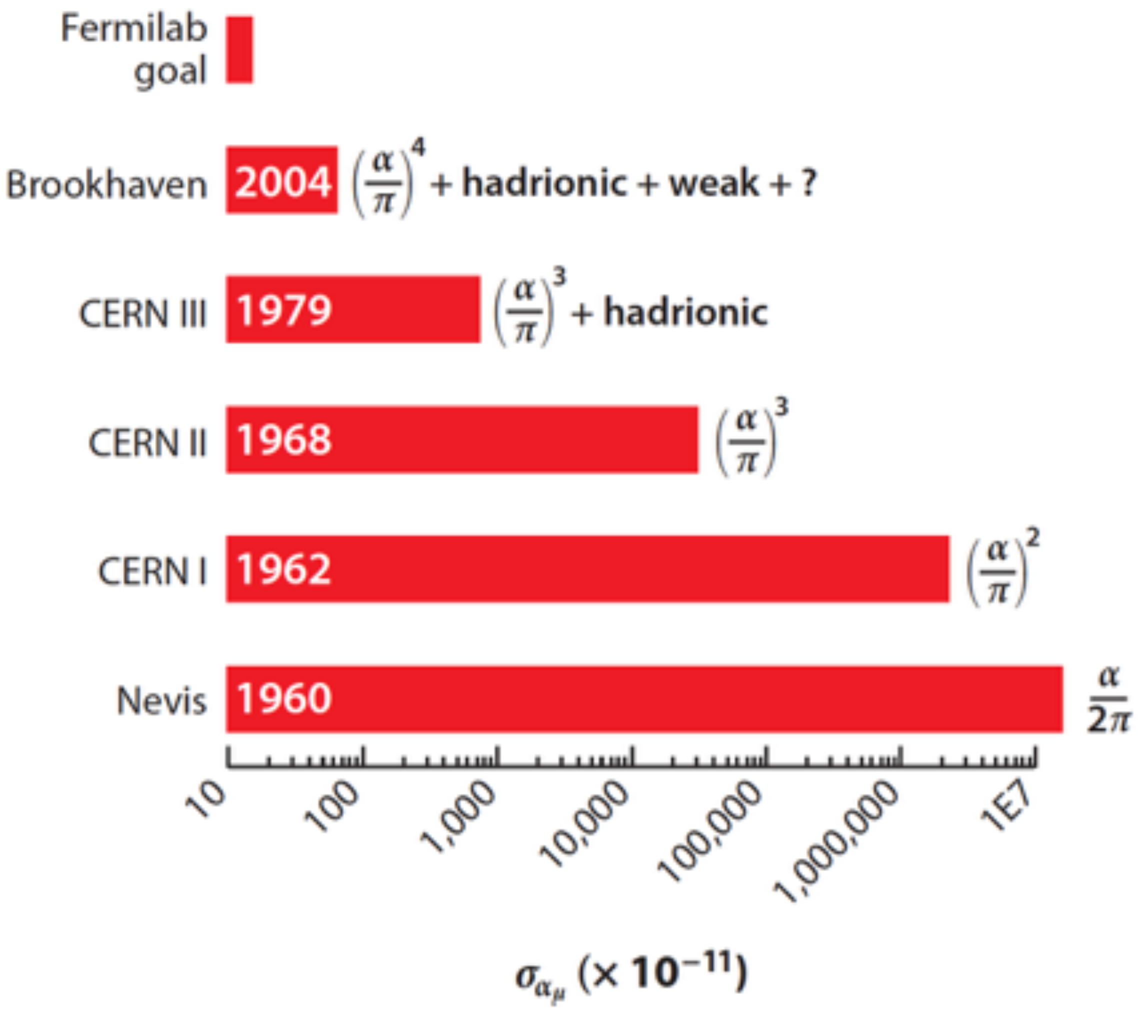
10-12 September 2015 *Villa Orlandi, Anacapri, Capri Island, Italy*

Europe/Rome timezone

~ 20 talks about Muon g-2

http://www.epj-conferences.org/articles/epjconf/abs/2016/13/contents/contents.html

a_μ extracted from experiments



Experiment	Beam	Measurement	$\delta a_\mu / a_\mu$
Columbia-Nevis(1957) [2]	μ^+	$g = 2.00 \pm 0.10$	
Columbia-Nevis(1959) [3]	μ^+	$0.001\,13^{+(16)}_{-(12)}$	12.4%
CERN 1(1961) [4]	μ^+	0.001 145(22)	1.9%
CERN 1(1962) [5]	μ^+	0.001 162(5)	0.43%
CERN 2(1968) [6]	$\mu^\pm$	0.001 166 16(31)	265 ppm
CERN 3(1975) [7]	$\mu^\pm$	0.001 165 895(27)	23 ppm
CERN 3(1979) [8]	$\mu^\pm$	0.001 165 911(11)	7.3 ppm
BNL E821(2000) [9]	μ^+	0.001 165 919 1(59)	5 ppm
BNL E821(2001) [10]	μ^+	0.001 165 920 2(16)	1.3 ppm
BNL E821(2002) [11]	μ^+	0.001 165 920 3(8)	0.7 ppm
BNL E821(2004) [12]	μ^-	0.001 165 921 4(8)(3)	0.7 ppm
World Average(2004) [12,13]	$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm

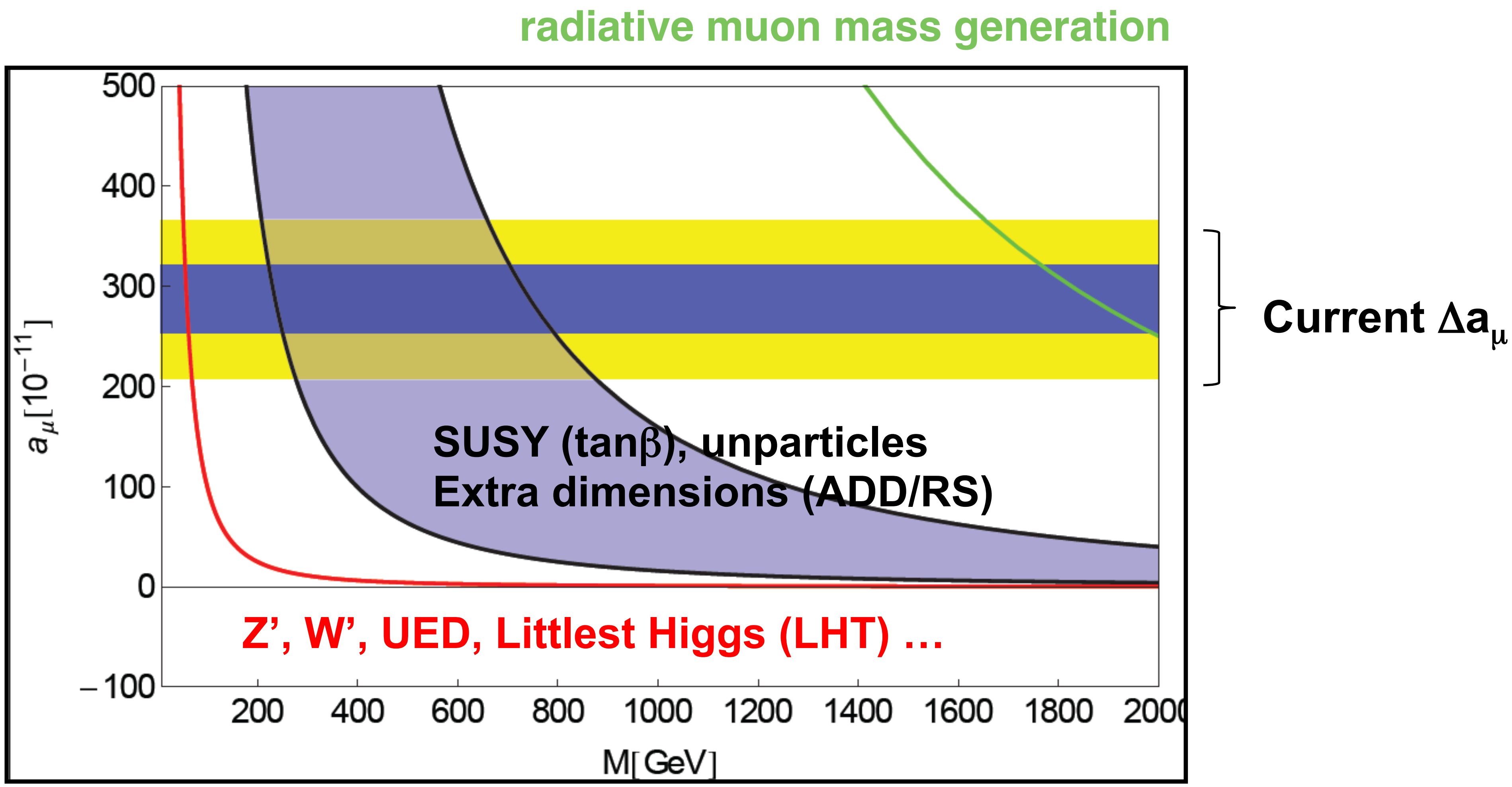
- Almost 60 years since the first measurement
- Very nice interplay between theory and experiment
- Provided very good tests for the SM(QED, EW and Had.)

Comparing these two ……

$$a_\mu\,(EXP) - a_\mu\,(SM) = (286 \pm 80) \times 10^{-11}$$

- 3.3 to 3.6 σ effect depending on the model
- Mistakes in the theoretical calculations?
- Systematics unaccounted for in the experiment?
- Or perhaps we are seeing new physics?

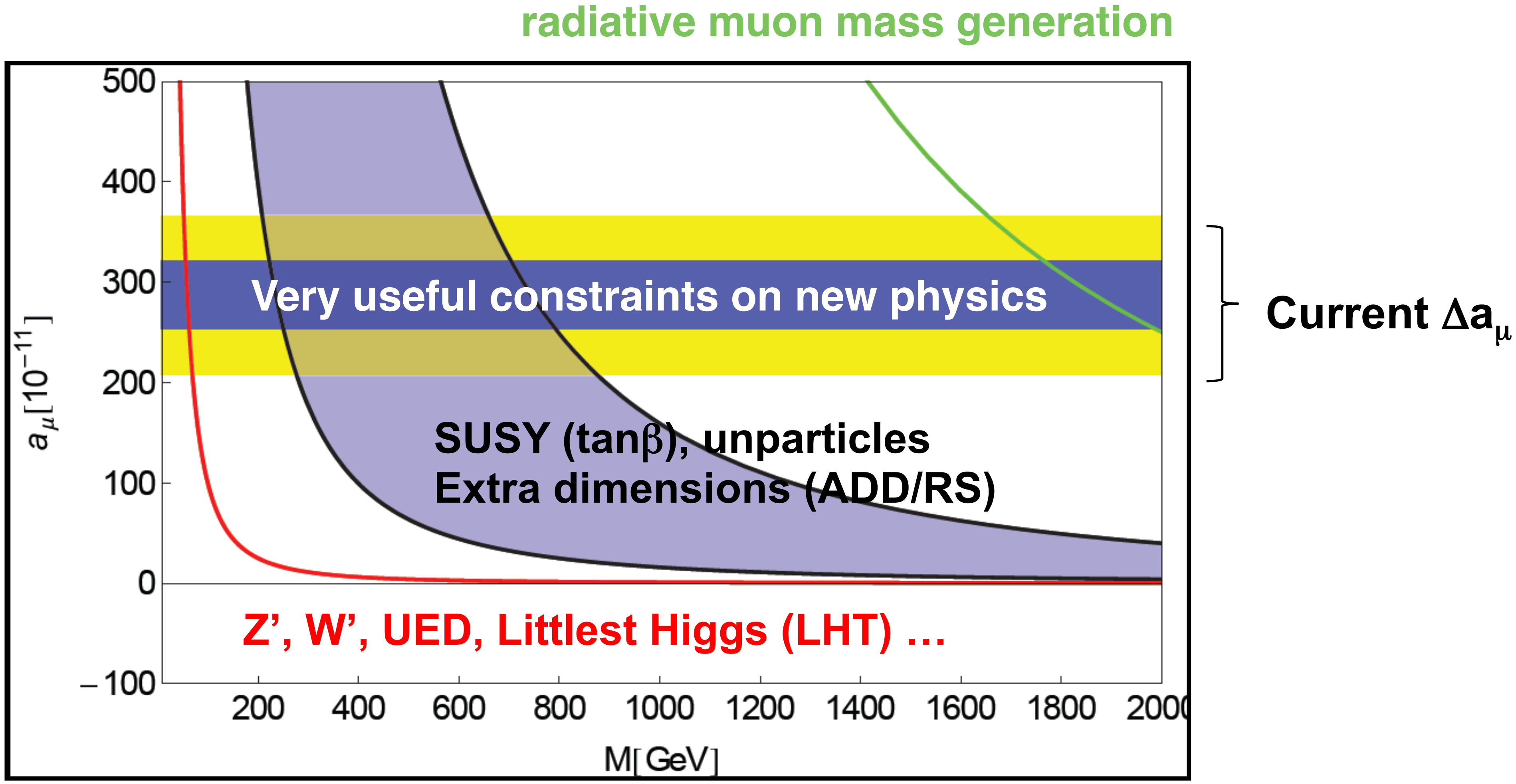
Possible New Physics



In any case, we need new experiments to improve the precision to shed light on the discrepancy

→ FNAL Muon g-2 experiment
(also, E34 at JPARC)

Possible New Physics



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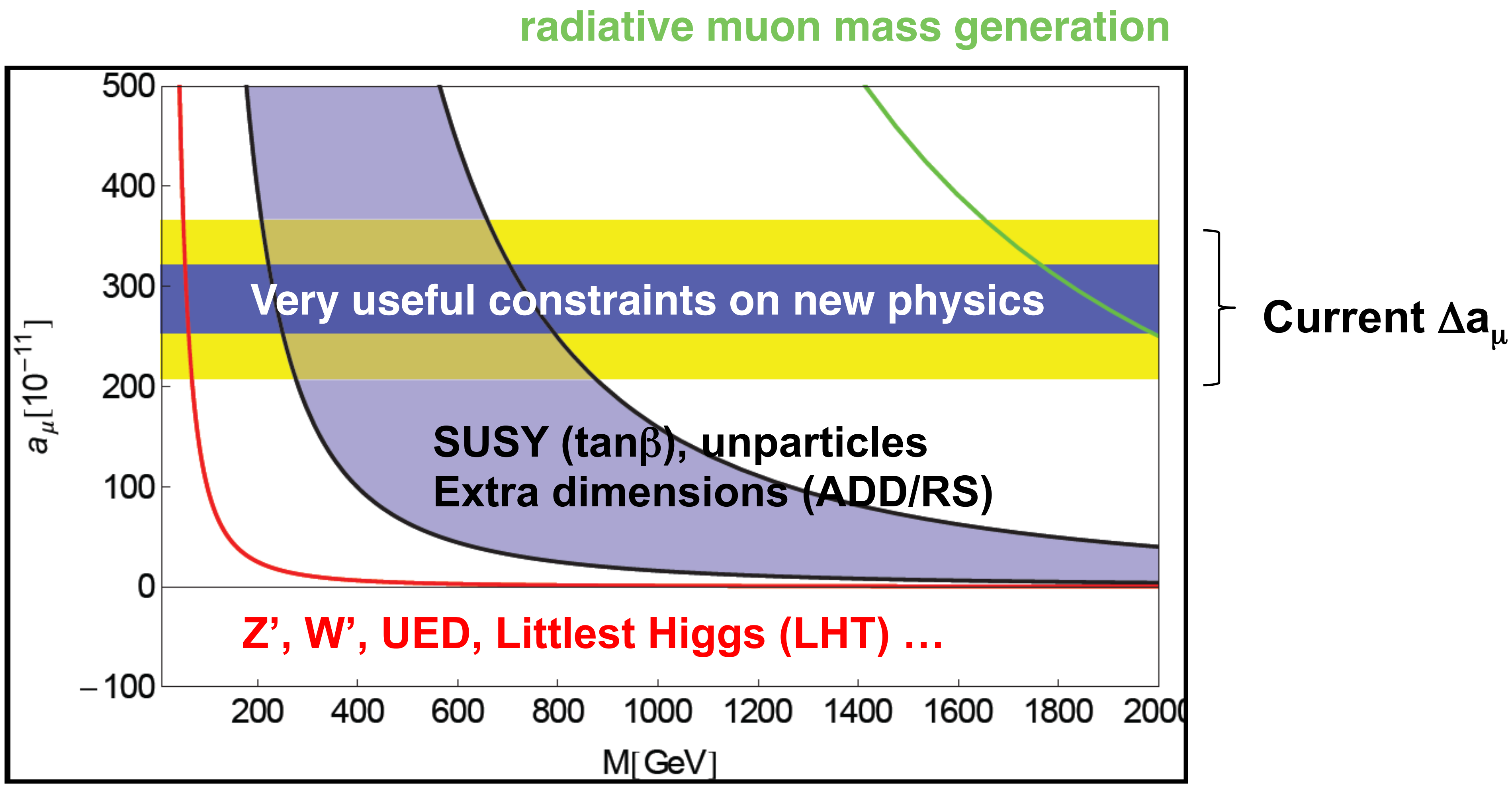


arXiv.org > hep-ph > arXiv:1512.06715

High Energy Physics – Phenomenology

750 GeV Diphoton Resonance, 125 GeV Higgs and Muon g−2 Anomaly in Deflected Anomaly Mediation SUSY Breaking Scenario

Fei Wang, Lei Wu, Jin Min Yang, Mengchao Zhang

(Submitted on 21 Dec 2015 (v1), last revised 2 Jun 2016 (this version, v3))

The Muon g-2 Collaboration at FNAL

34 Institutes
169 Members

US Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- Texas, Austin
- Virginia
- Washington
- York College

US National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati
- Roma 2
- Udine
- Pisa
- Naples
- Trieste
- UNIMOL

China
- Shanghai

Netherlands
- Groningen

Germany
- Dresden

England
- University College
- London
- Liverpool

Korea
- CAPP/IBS & KAIST

Russia:
- Dubna
- Novosibirsk

a_μ extraction from experiments

this is what we will measure

0.0037072064(20) [**540 ppb**]
E821

-0.001 519 270 384(12) [8 ppb]
Muonium HFS

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

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

206.768 2843(52) [25 ppb]
Muonium 1S-2S

***0.46 ppm statistical; 0.28 ppm systematics**

CODATA 2015

Systematic budget for ω_a

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

Systematic budget for ω_p

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
Total systematic error on ω_p	170		70

Goals: ω_a and ω_p (540→140 ppb)

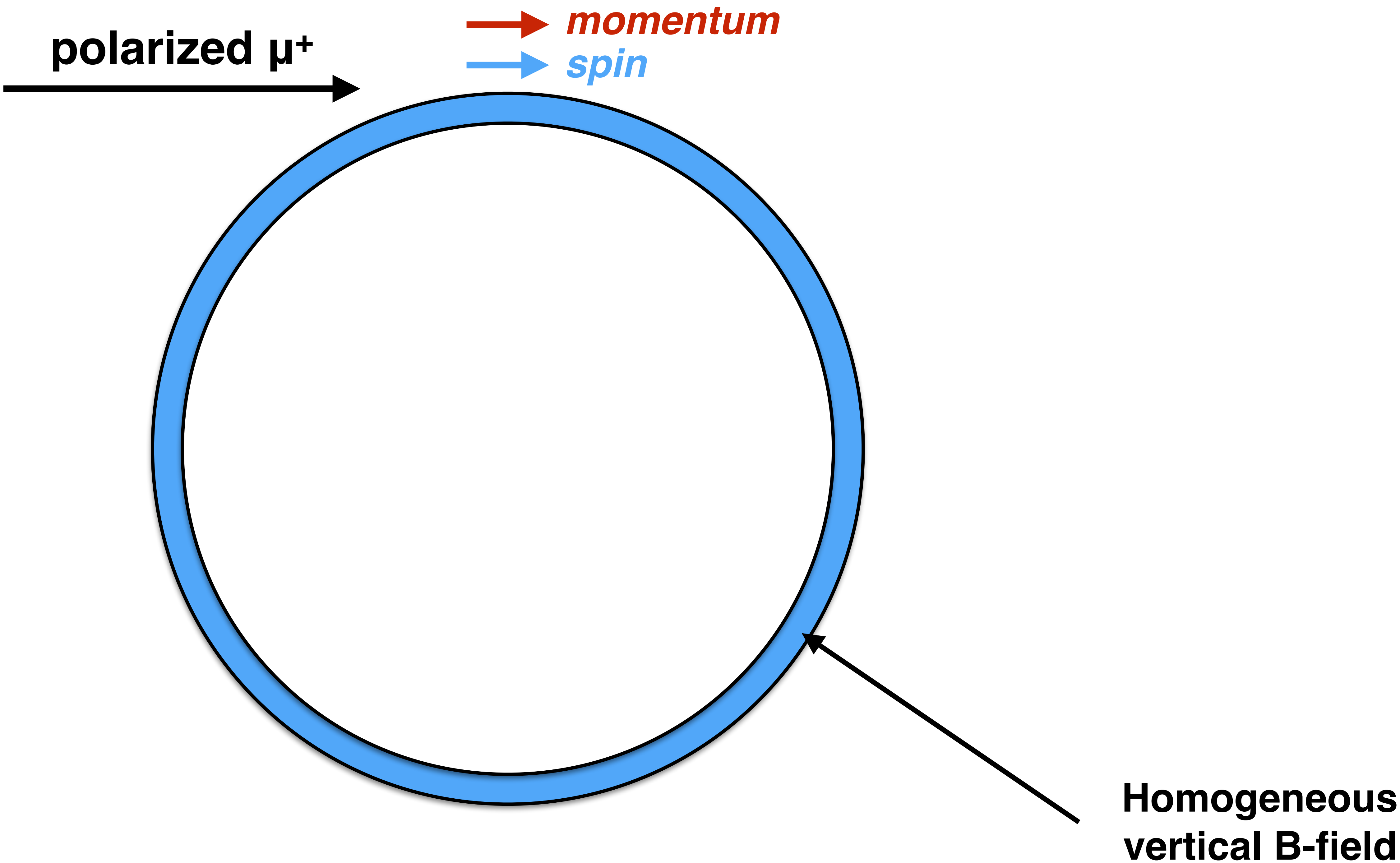
- **Statistics at 100 ppb**
  - 1.5 x 10^{11} events in the final fit (21x more muons)
  - multiple independent blind analyses and fitting methods
- **Systematics at 70 ppb (3x improvement)**
  - Better separation of pileup events
  - Gain stability of the calorimeter
  - etc

anomalous precession frequency: ω_a

- **Systematics at 70 ppb (2x improvement)**
  - Better NMR probes
  - Modern instrumentation for DAQ
  - etc

proton Larmor precession frequency: ω_p

Measurement principles



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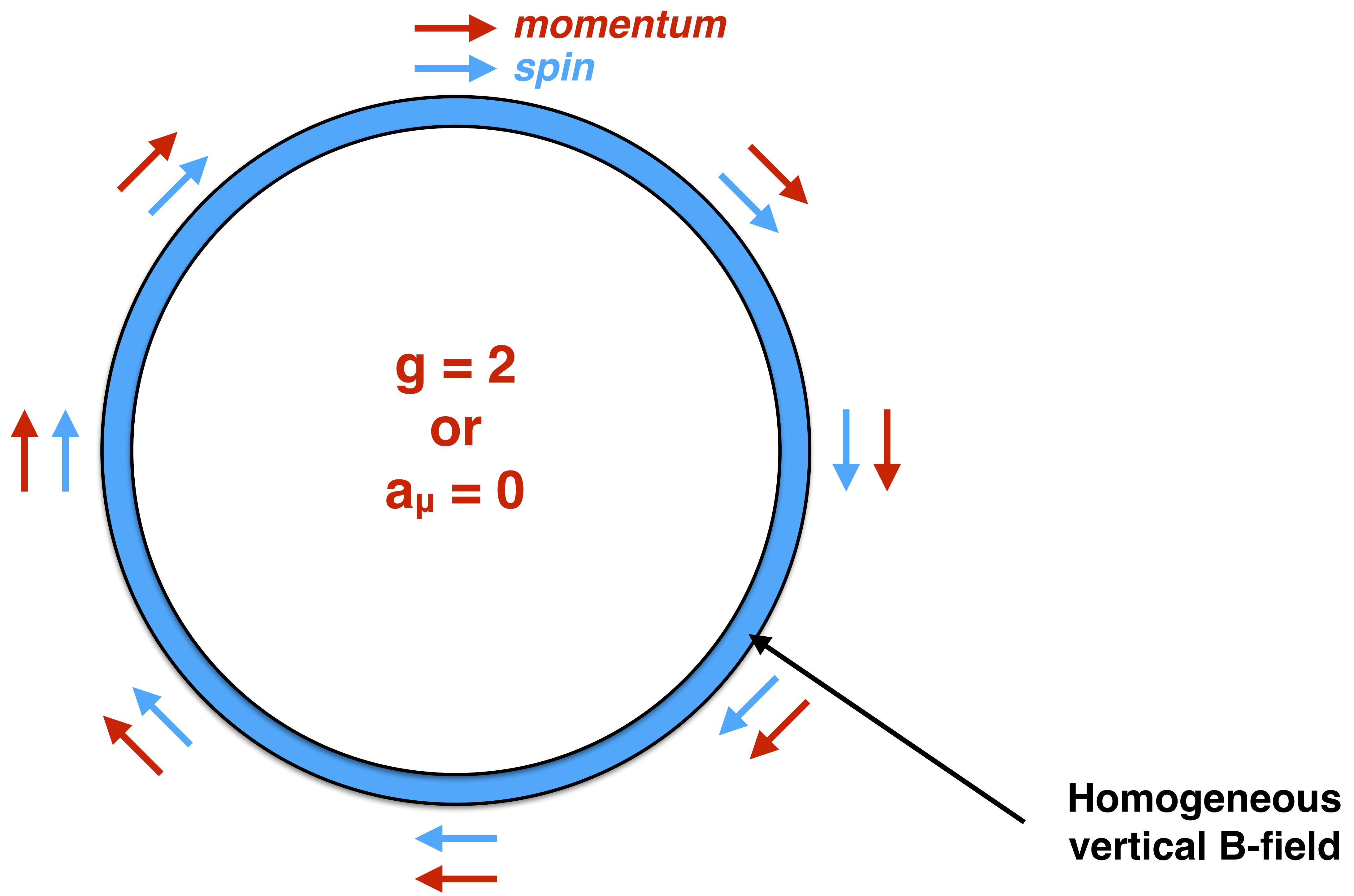

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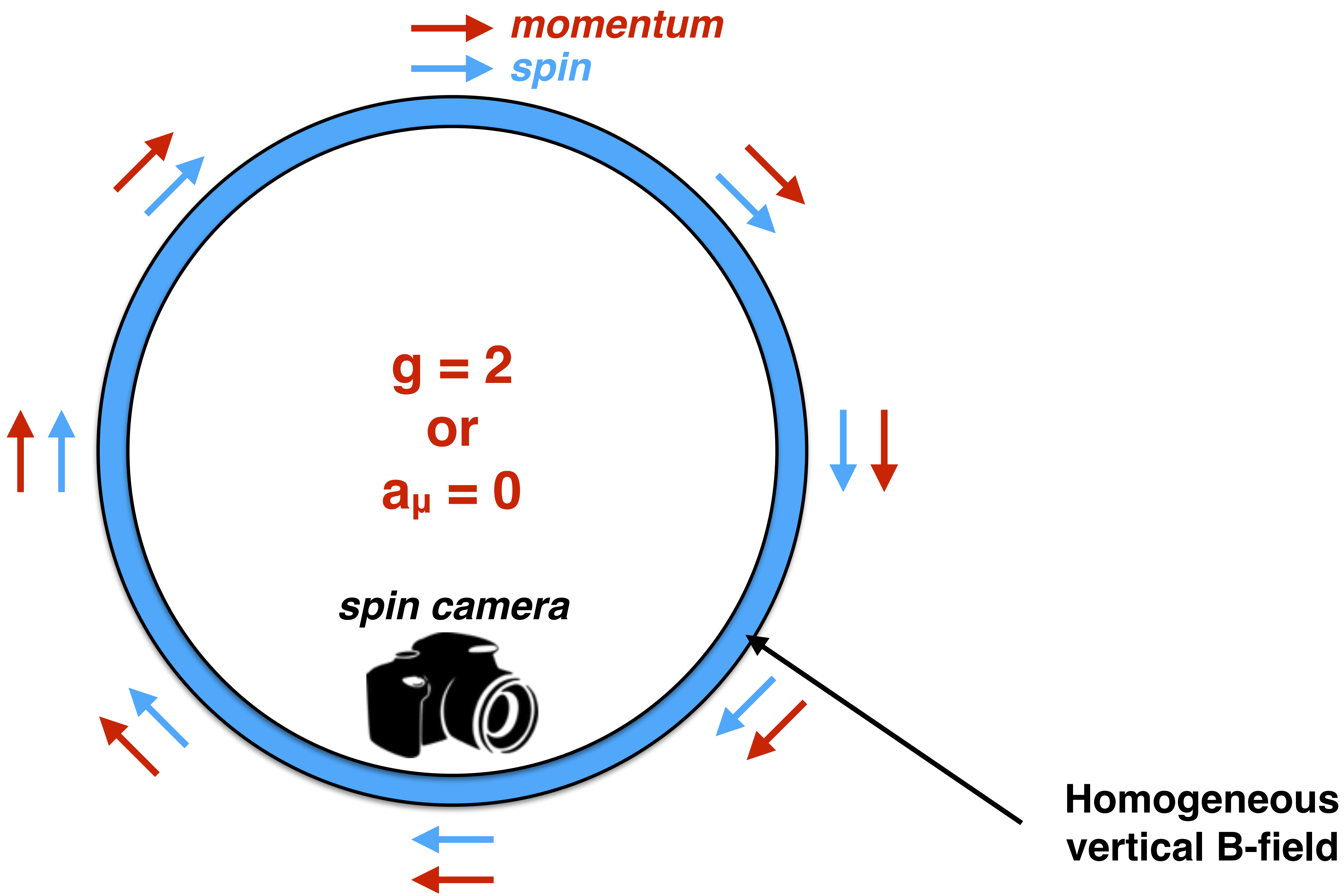

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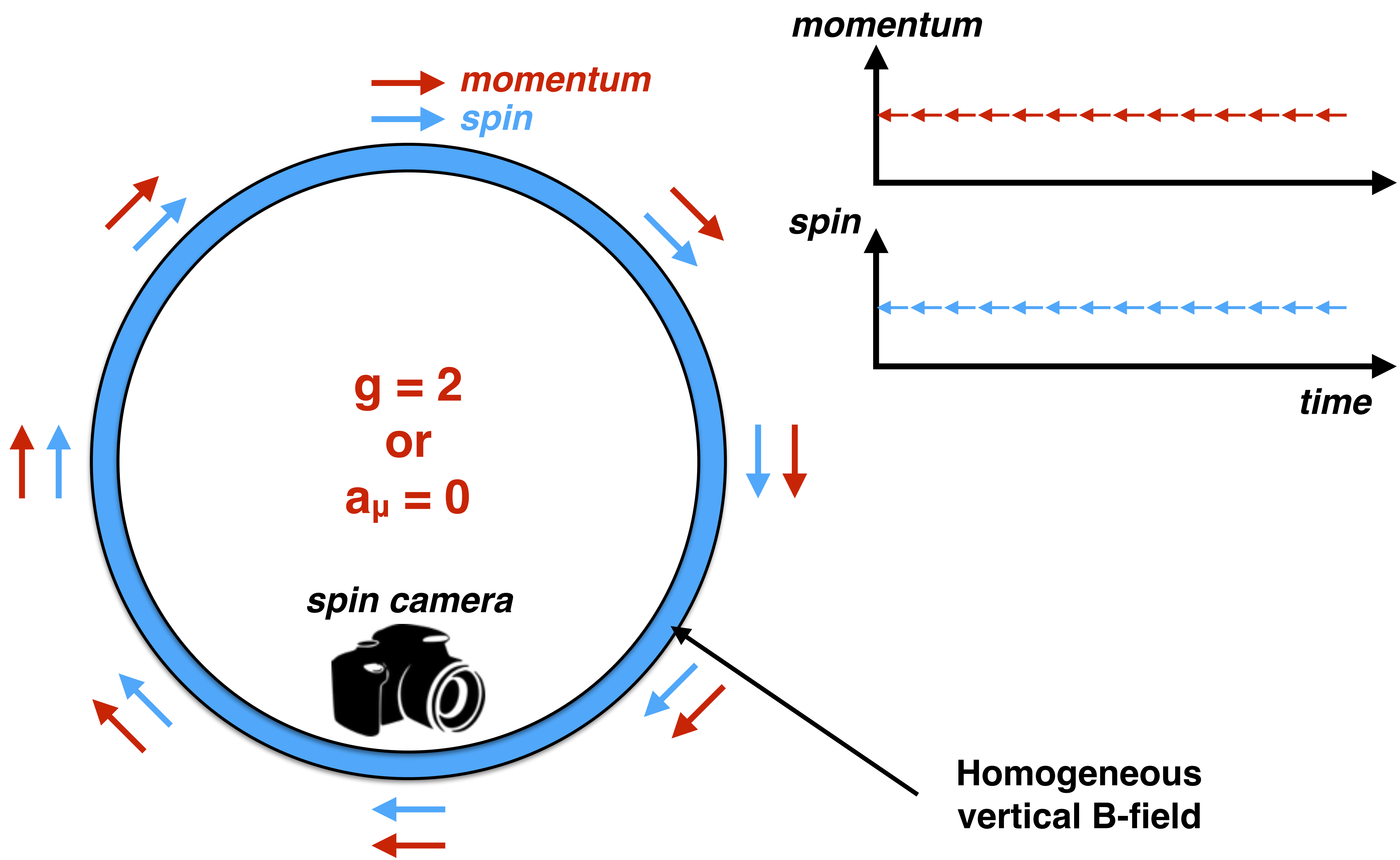

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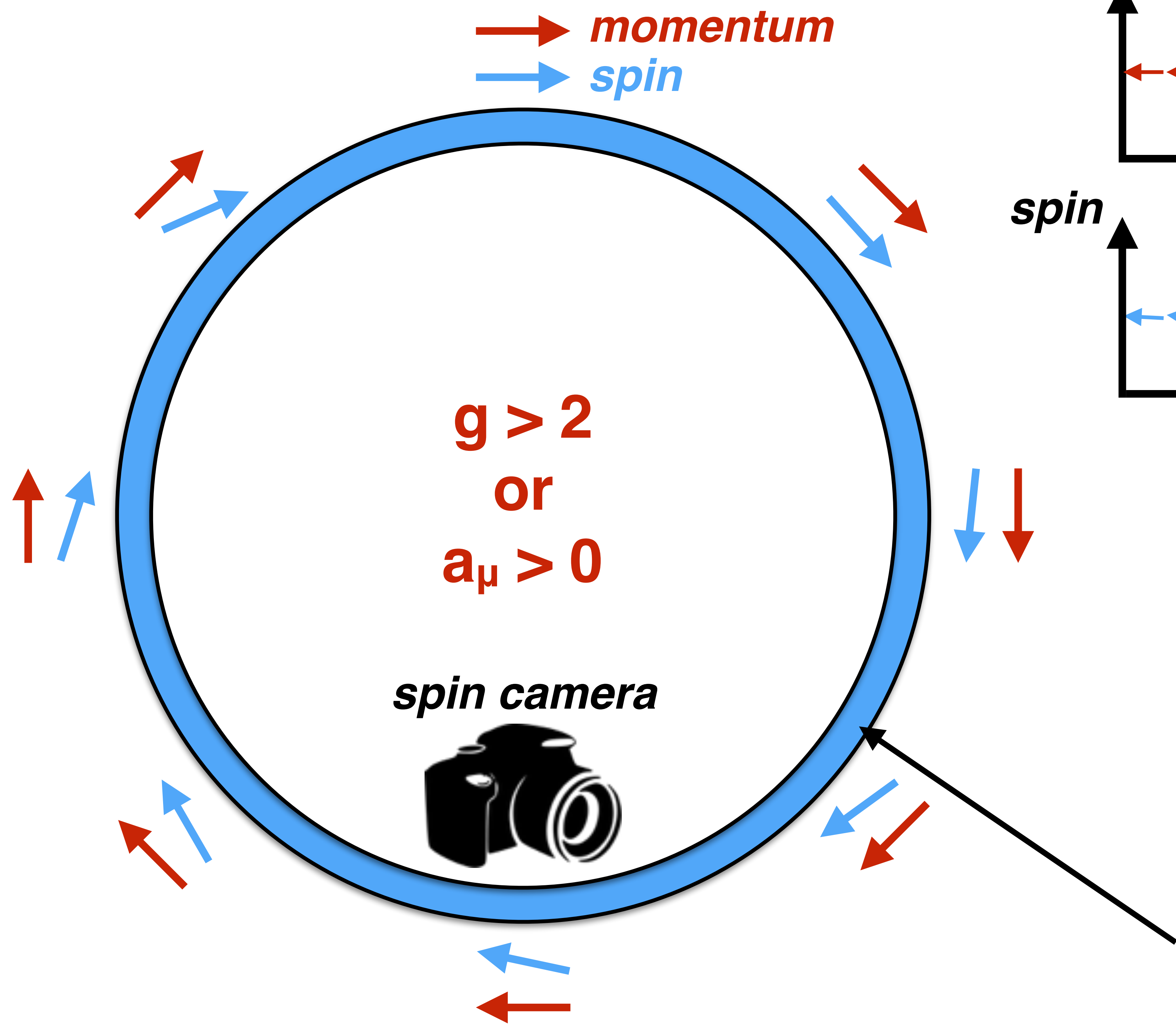

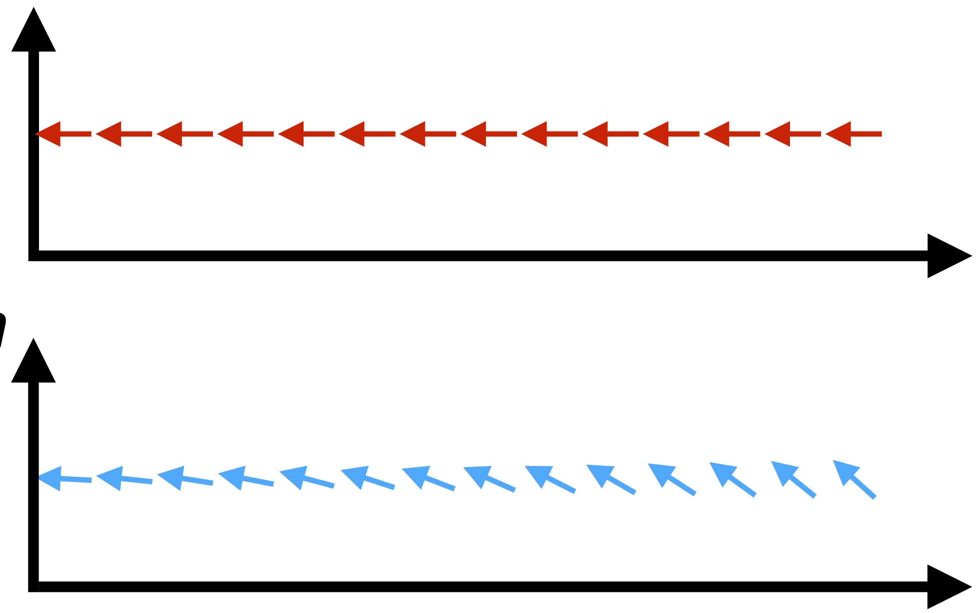

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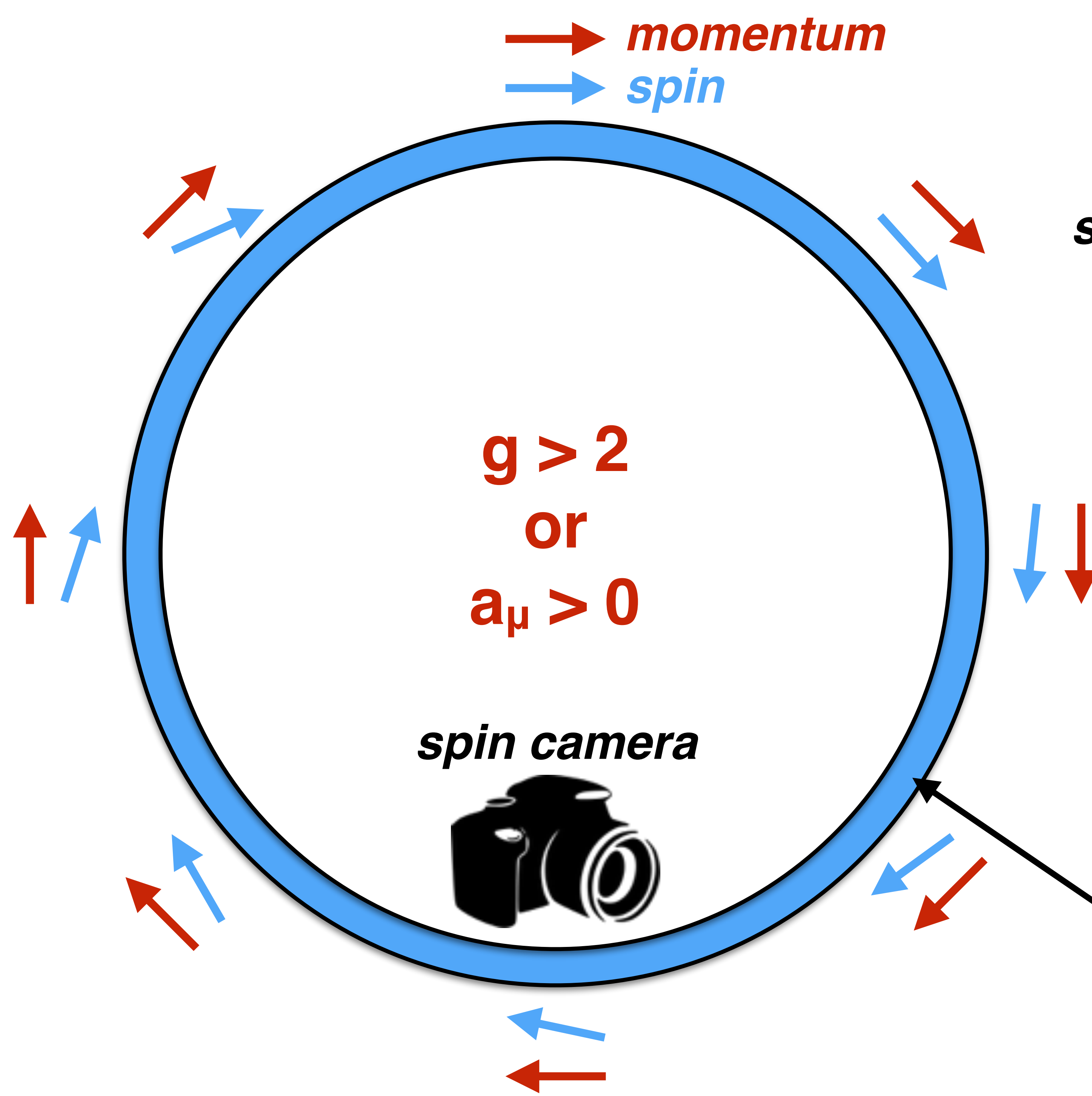
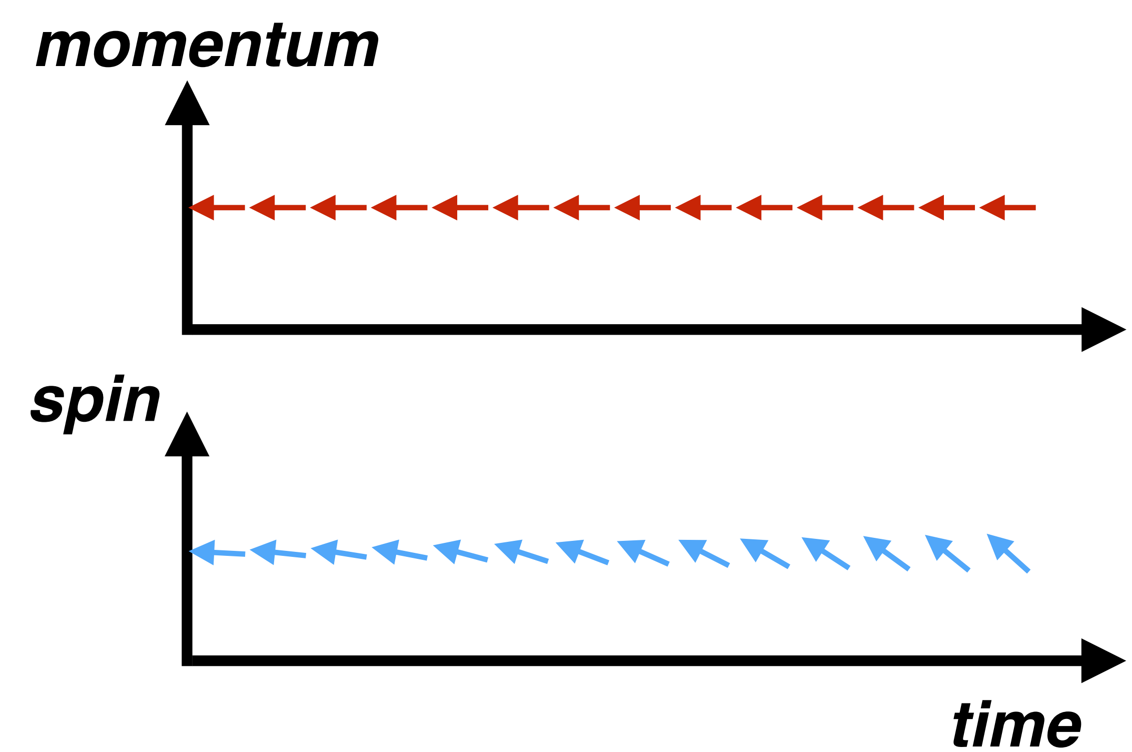


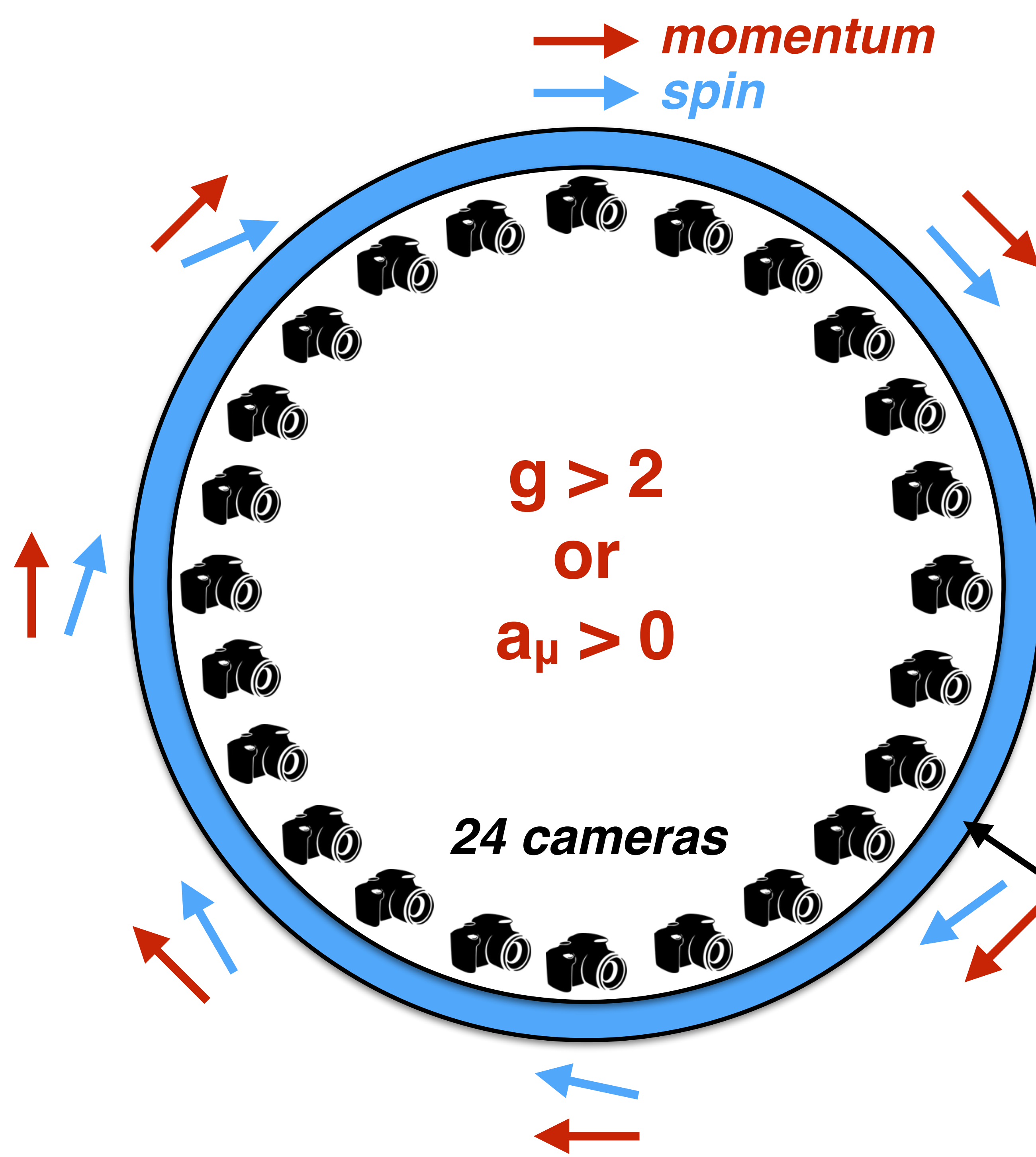


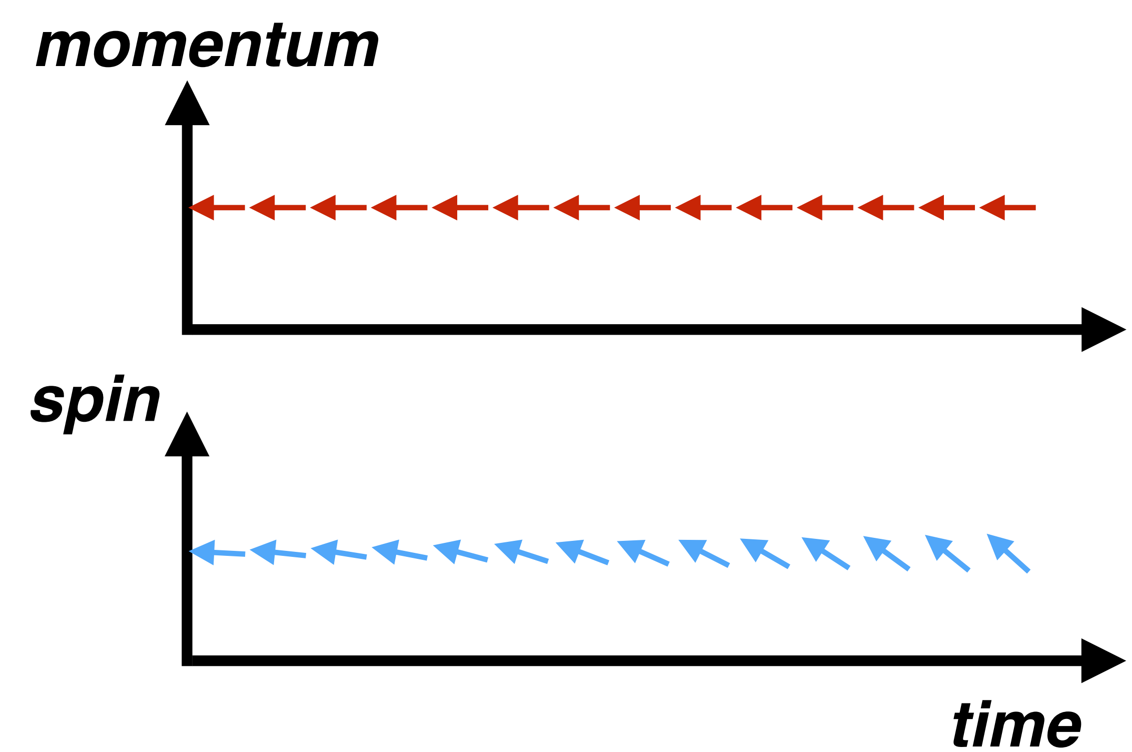
$$\omega_a = \omega_s - \omega_c$$

$$\omega_a = \left(\frac{e}{mc}\right) a_\mu B$$

Homogeneous vertical B-field

Measurement principles





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Measured using proton NMR probe

Magic momentum

- In practice, we need the E field (quadrupole) to vertically focus the beam

Magic momentum

- In practice, we need the E field (quadrupole) to vertically focus the beam

$$\vec{\omega}_a = \frac{e}{m_\mu c}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

Magic momentum

- In practice, we need the E field (quadrupole) to vertically focus the beam

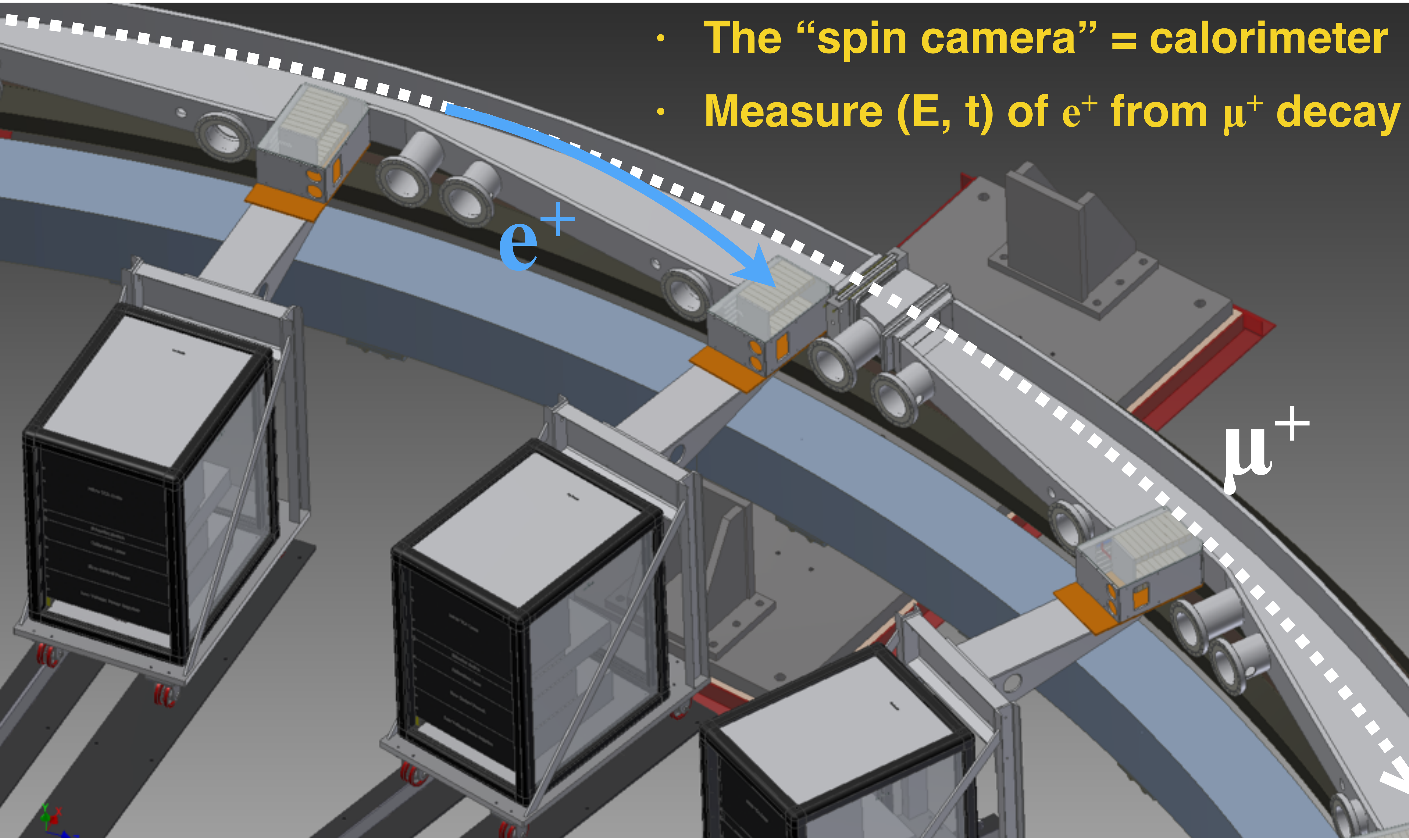
$$\vec{\omega}_a = \frac{e}{m_\mu c}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

- γ = 29.3 is chosen to eliminate E effect

- This corresponds to p = 3.094 GeV/c

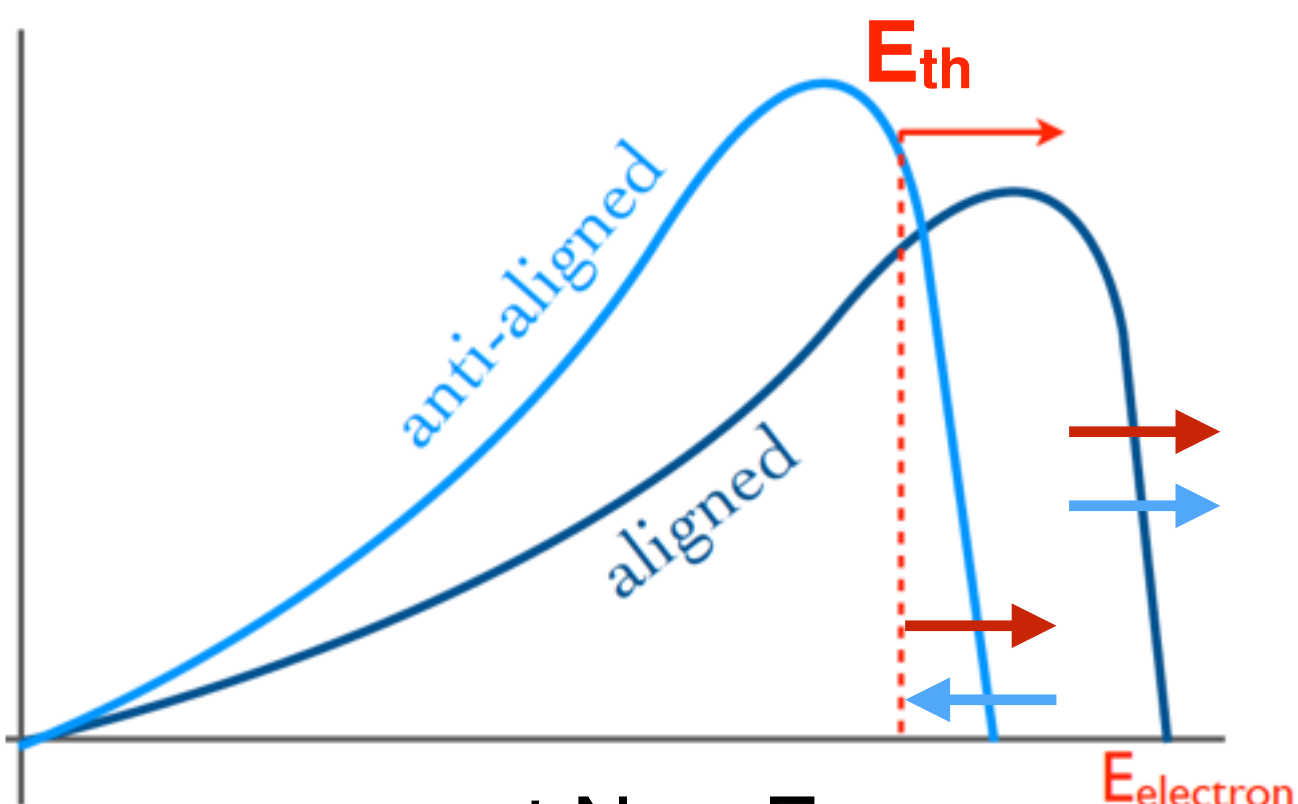
Measurement principles

- **The “spin camera” = calorimeter**
- **Measure (E, t) of e^+ from μ^+ decay**

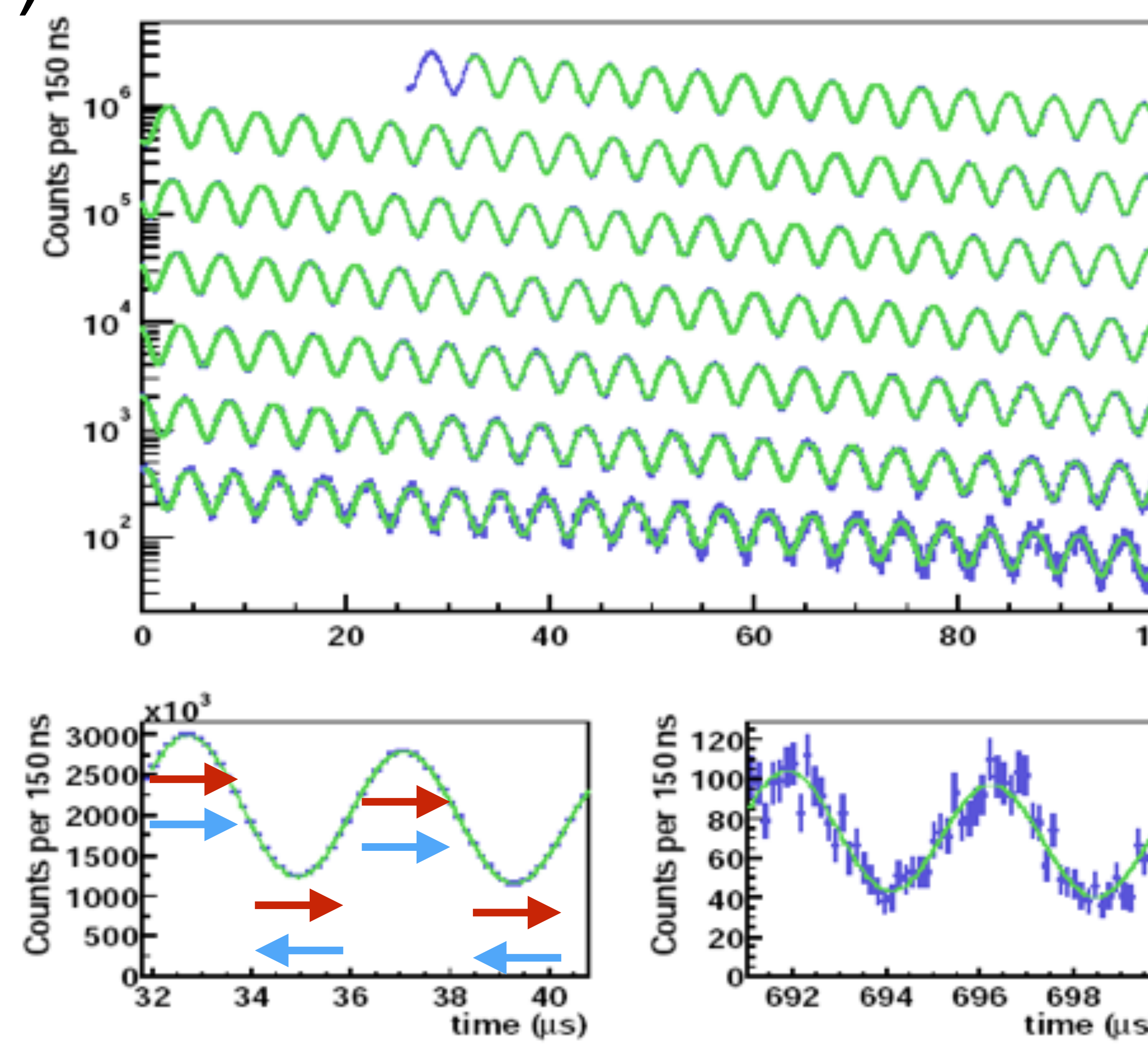


Measurement principles

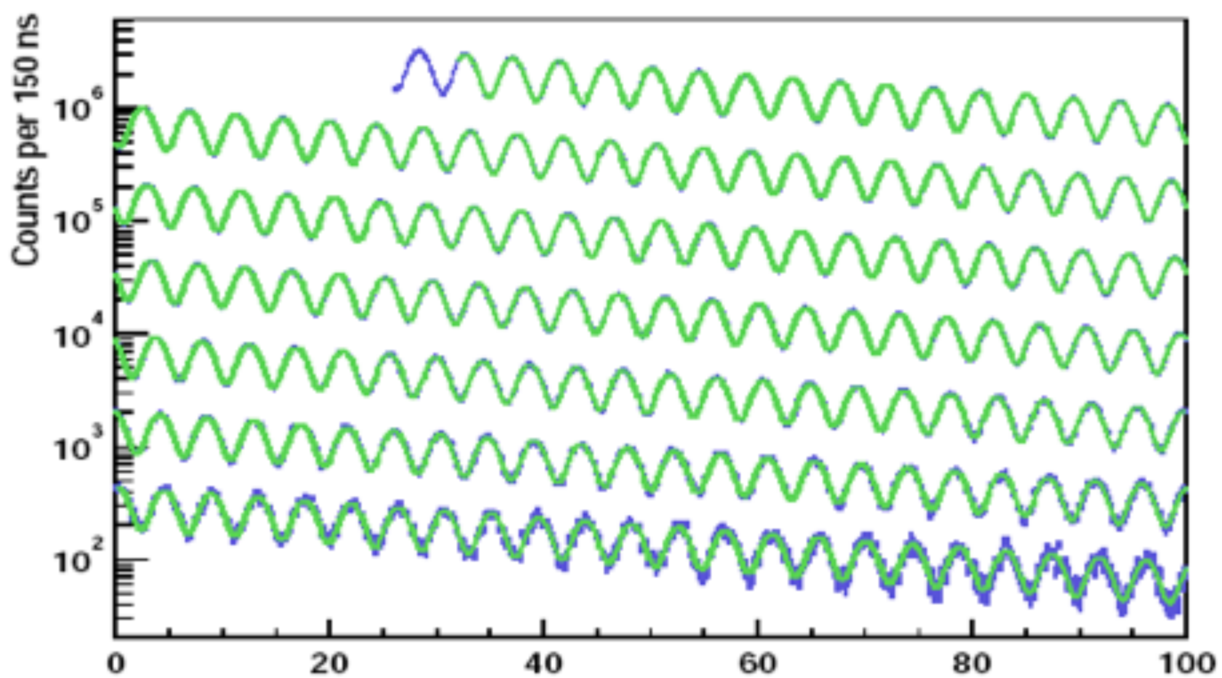
- Calorimeters measure (E, t) of e^+ from μ^+ decay
- (rest frame) e^+ prefers muon spin direction (P violation)
- (lab frame) Harder e^+ spectrum when spin and momentum are aligned (Boost)



count $N_e > E_{th}$



Fitting wiggle-plot



Need to carefully assess

- Pileup
- Gain stability (energy scale)
- Vertical Betatron Oscillation
- Coherent Betatron Oscillation
- Muon losses

$$N(t) = \frac{N_0}{\gamma\tau_\mu} e^{-t/\gamma\tau_\mu} \cdot \Lambda(t) \cdot V(t) \cdot B(t) \cdot C(t)$$
$$\cdot [1 - A(t)\cos(\omega_a t + \phi(t))]$$

with

$$\Lambda(t) = 1 - A_{\text{loss}} \int_0^t L(t') e^{-t'/\gamma\tau_\mu} dt'$$

$$V(t) = 1 - e^{-t/\tau_{\text{VW}}} A_{\text{VW}} \cos(\omega_{\text{VW}} t + \phi_{\text{VW}})$$

$$B(t) = 1 - A_{br} e^{-t/\tau_{br}}$$

$$C(t) = 1 - e^{-t/\tau_{\text{cbo}}} A_1 \cos(\omega_{\text{cbo}} t + \phi_1)$$

$$A(t) = A(1 - e^{-t/\tau_{\text{cbo}}} A_2 \cos(\omega_{\text{cbo}} t + \phi_2))$$

$$\phi(t) = \phi_0 + e^{-t/\tau_{\text{cbo}}} A_3 \cos(\omega_{\text{cbo}} t + \phi_3).$$

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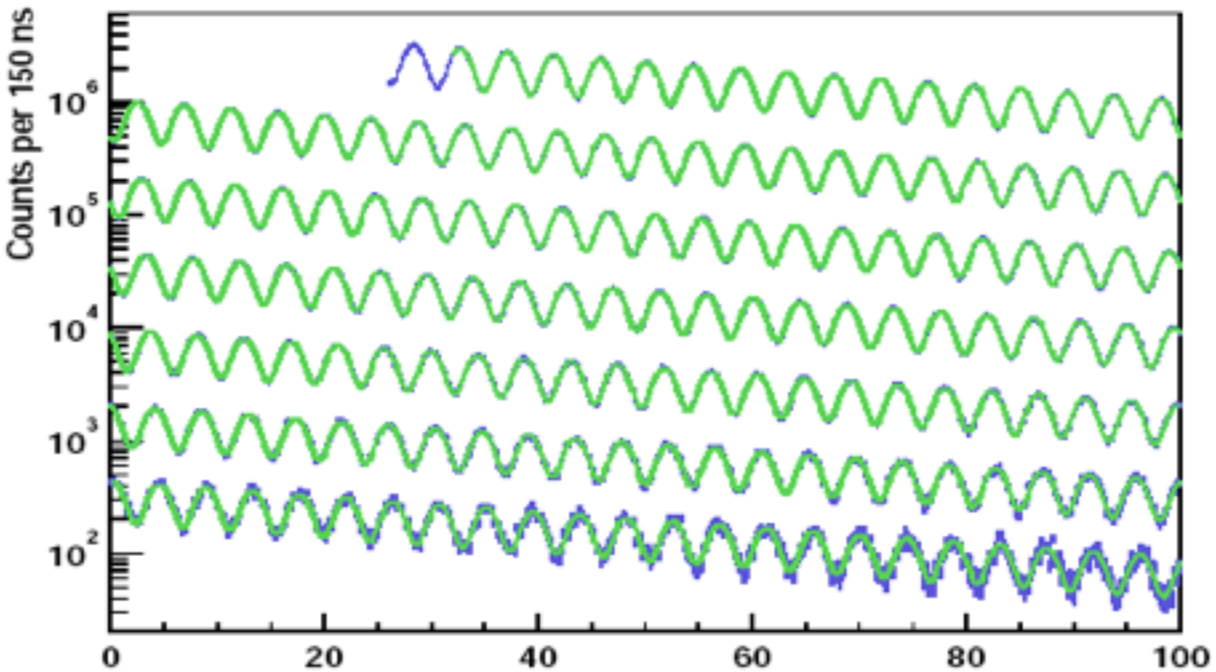

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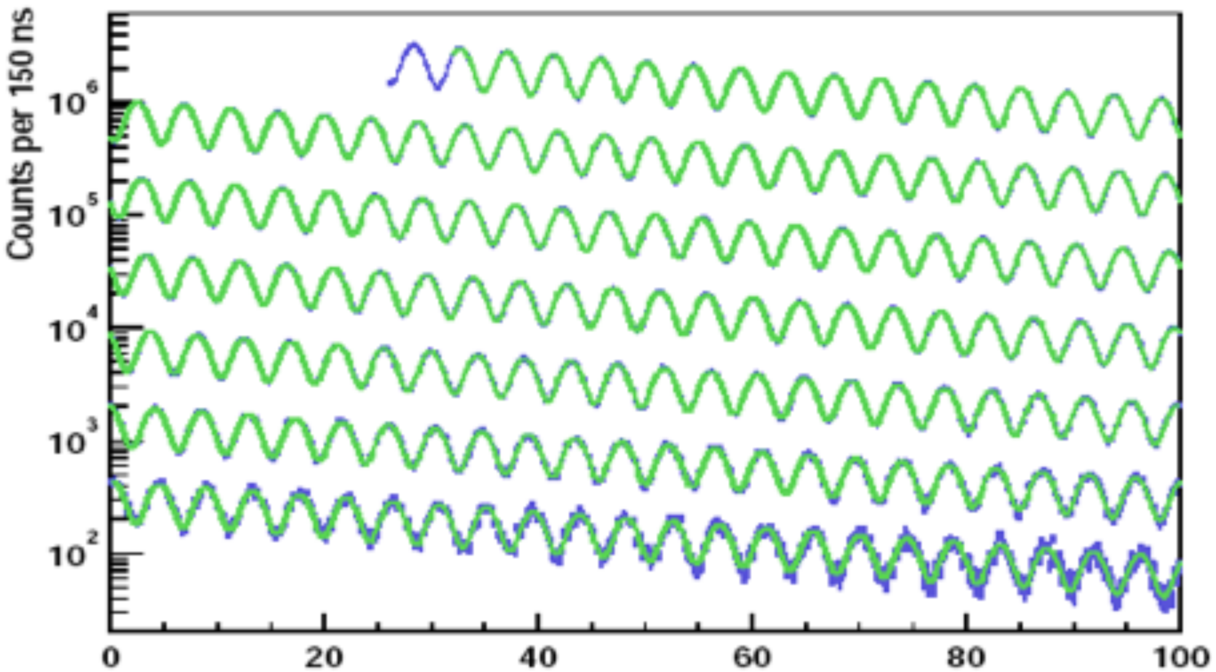

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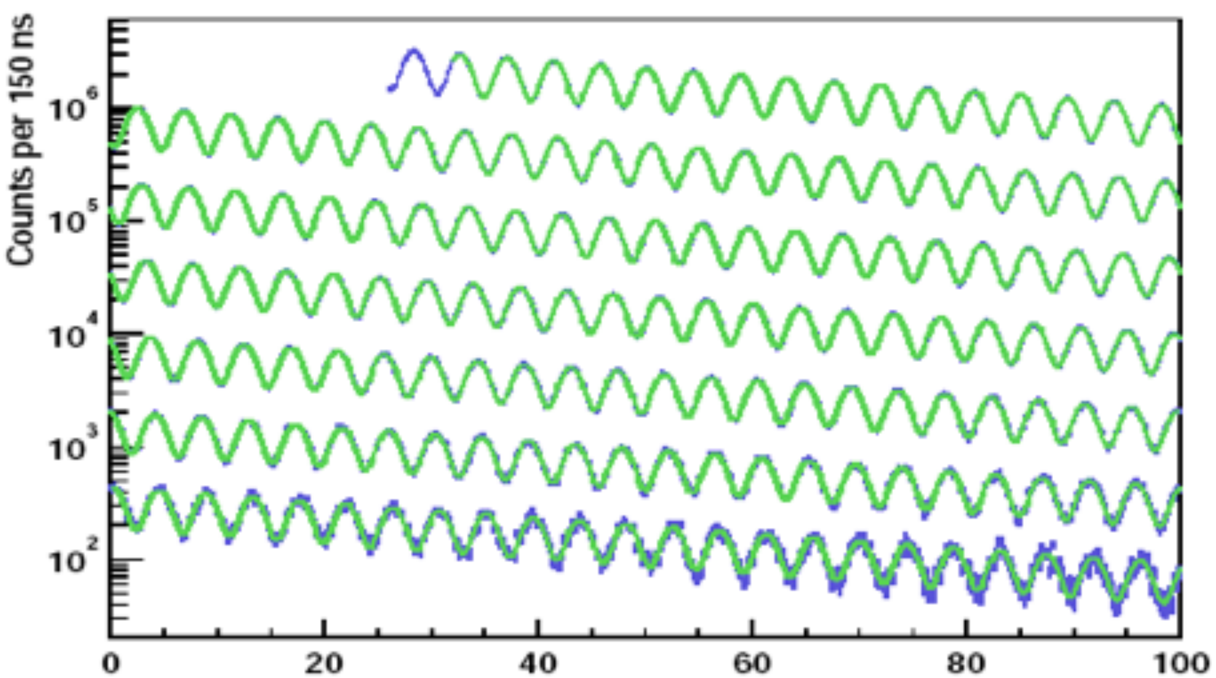

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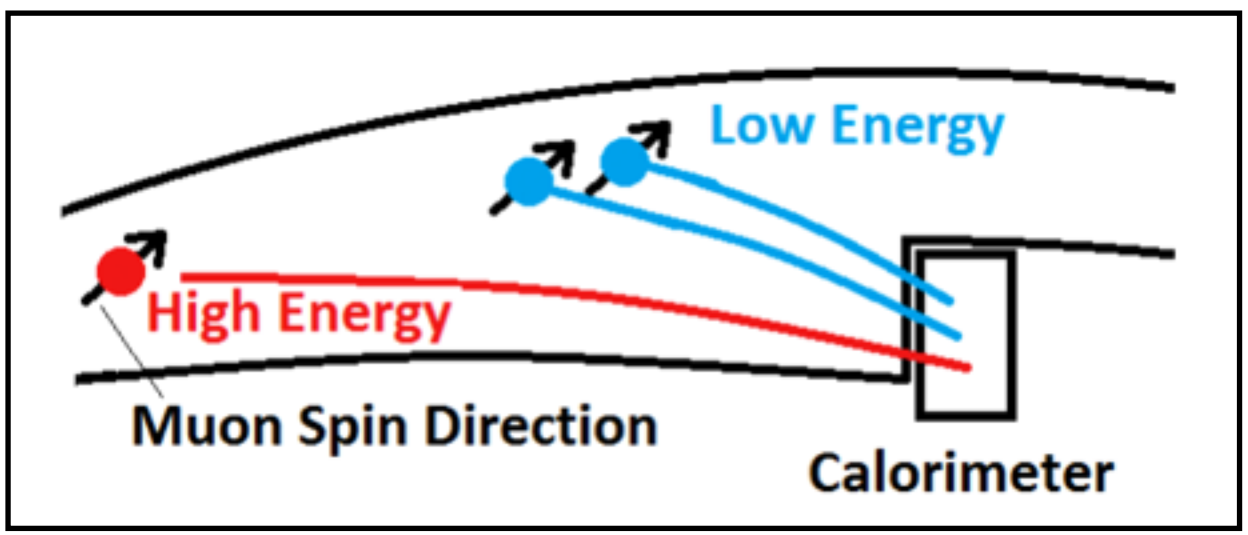
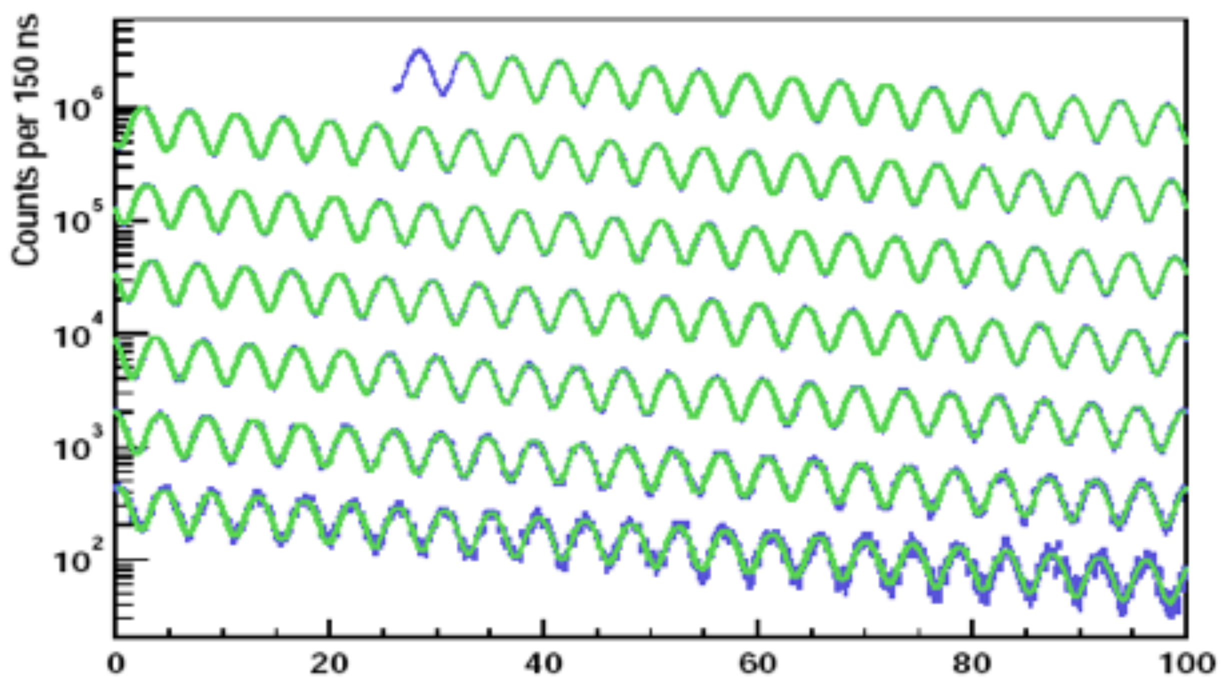


- Highly segmented calorimeter
- Fast calorimeter
- Template fit (need to know the pulse shape)
- Faster digitizer (800 MSPS)

Two low energy events interpreted as one (pileup) will pull fit parameters, pileup rate varies over time

$$[1 - A(t)\cos(\omega_a t + \phi(t))]$$

Fitting wiggle-plot



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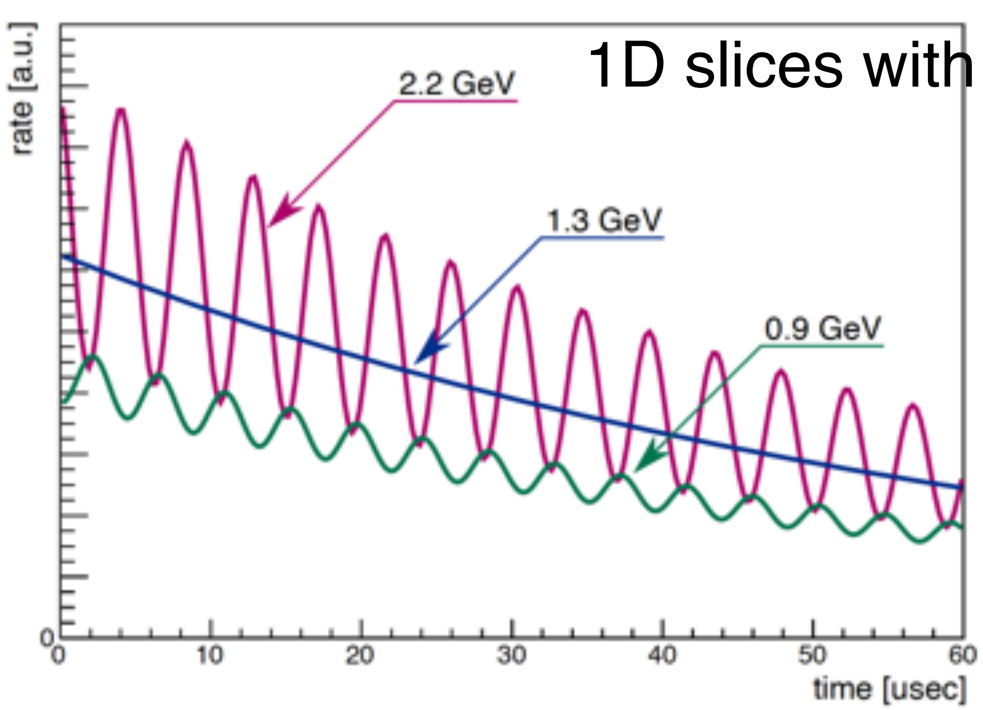
1D slices with fixed energy



$$A_1 \cos(\omega t + \phi_1) + A_2 \cos(\omega t + \phi_2) = A_3 \cos(\omega t + \phi_3)$$

Adding different slices over the time will modify the phase

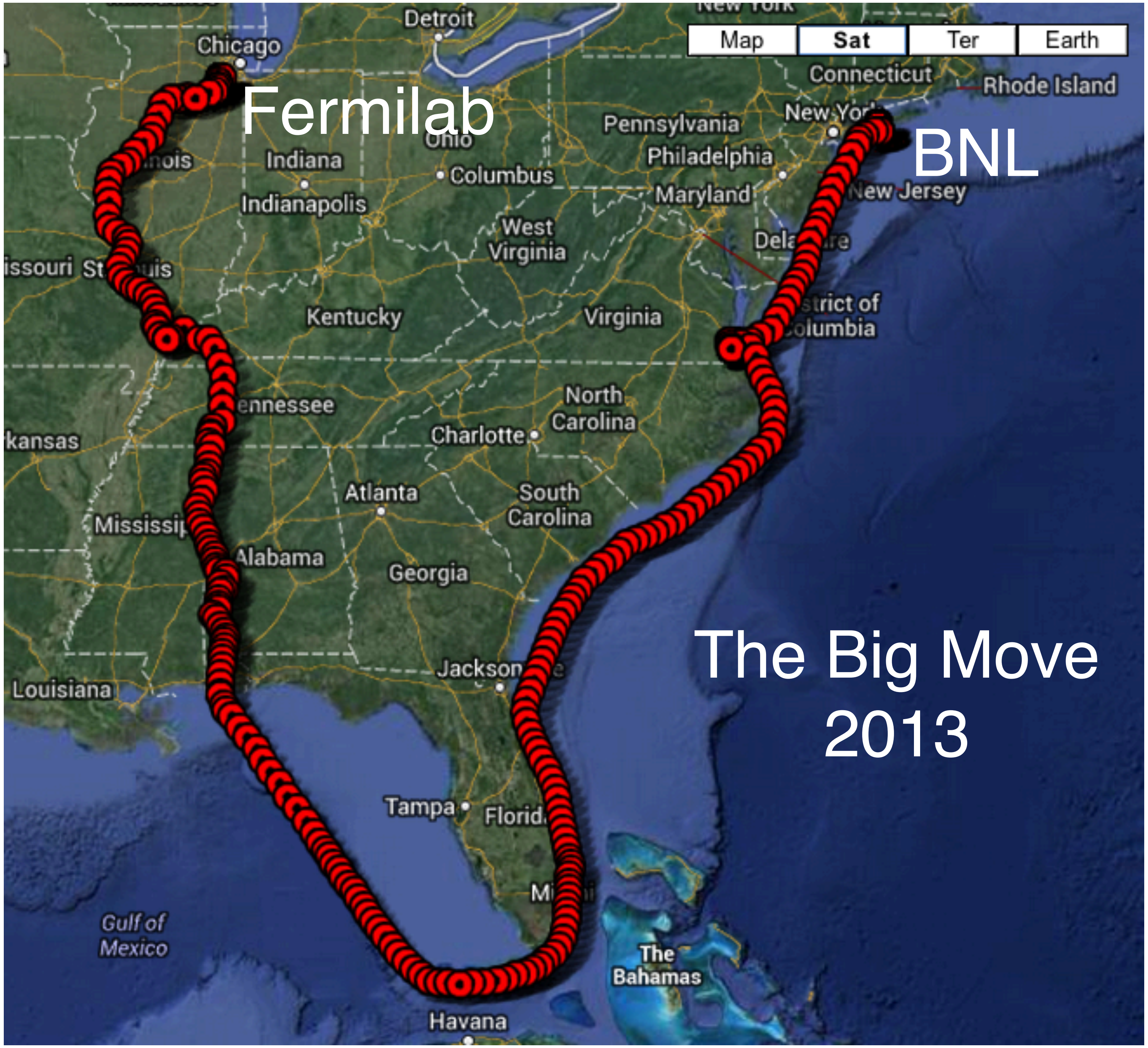
→

- Calorimeter with stable gain
- Plus gain monitoring system

Basic ingredients

- Highly homogenous magnet
- Polarized muons
- Muons at magic momentum
- Calorimeters
- pNMR probes

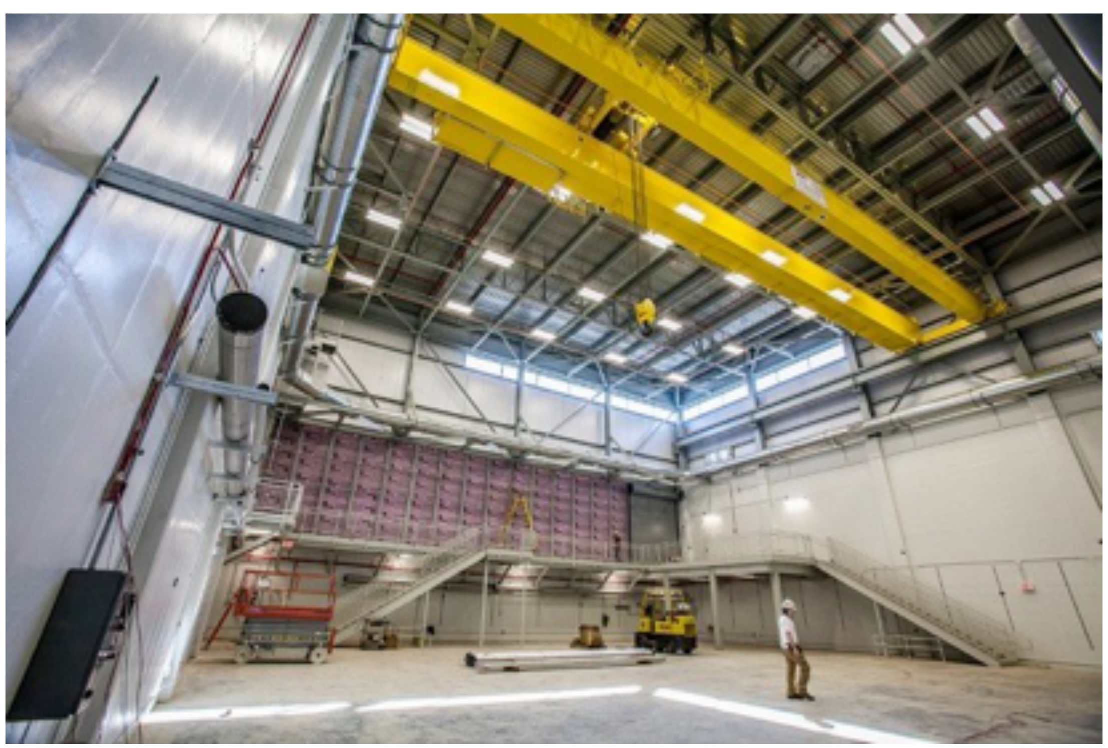
We transported the magnet from Brookhaven to Fermilab



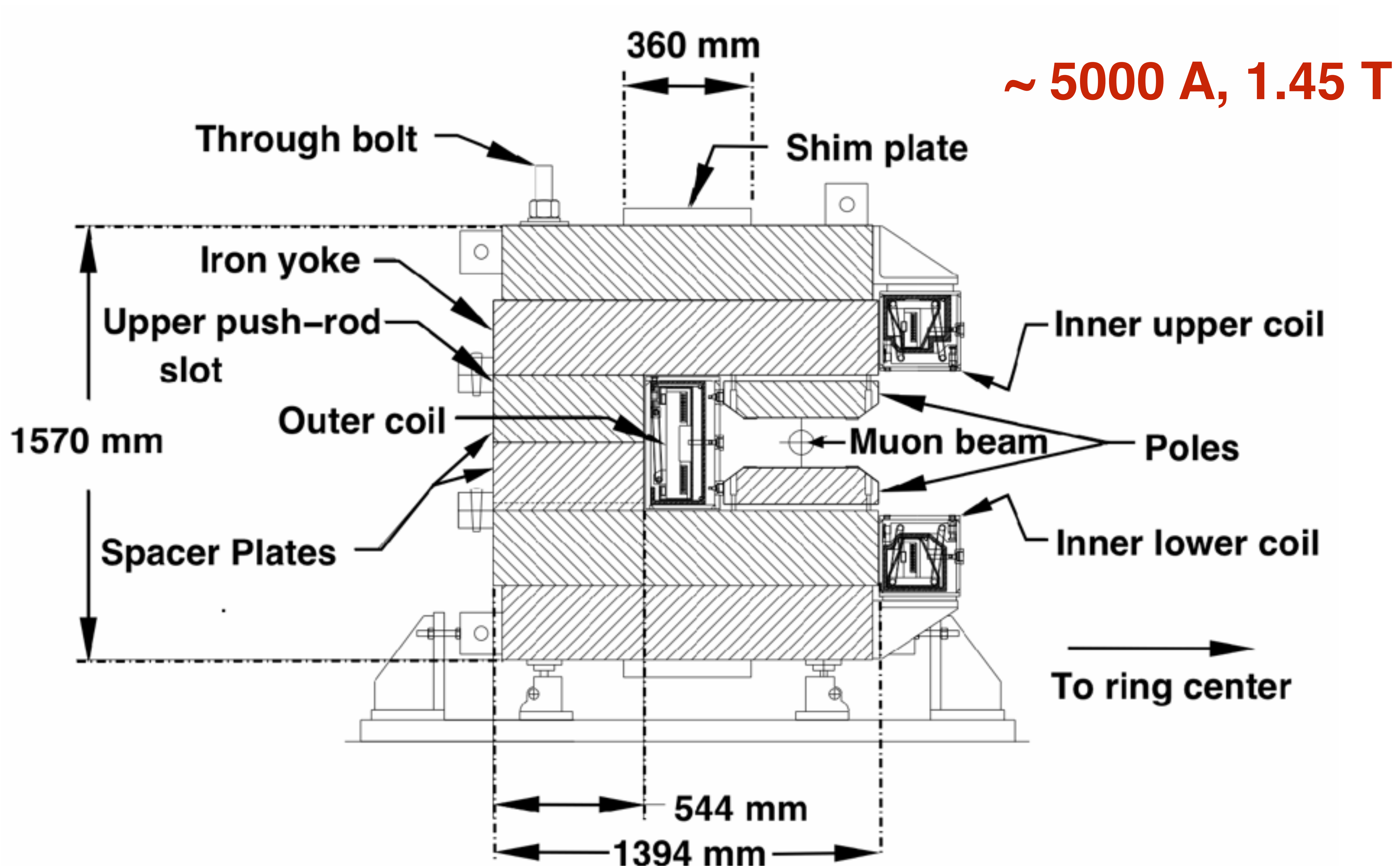
Moving 50 ft diameter ring without flexing by >1/8”

Closing two Interstates in Chicago

Finally arrived at FNAL



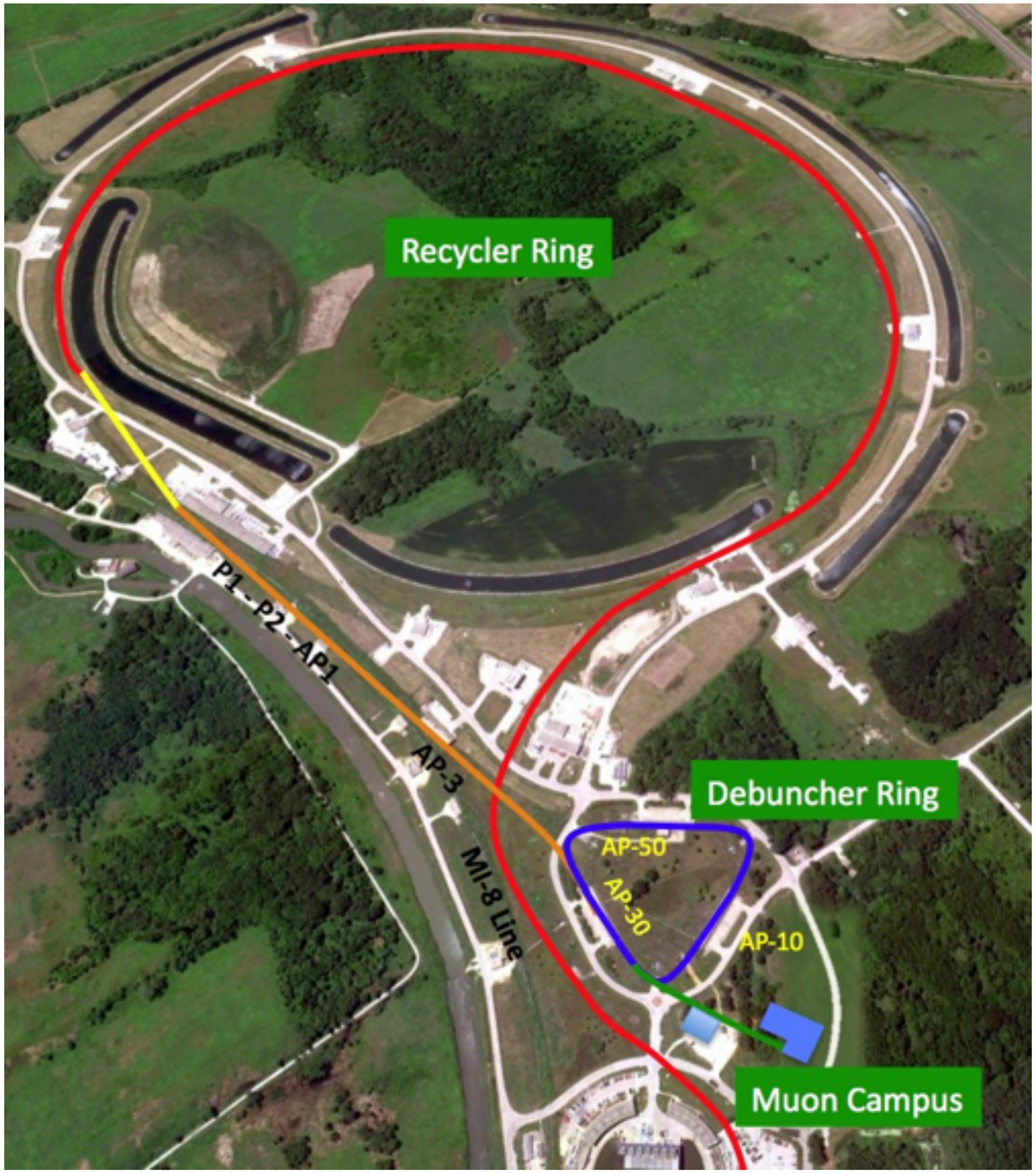
Superconducting magnet



Basic ingredients

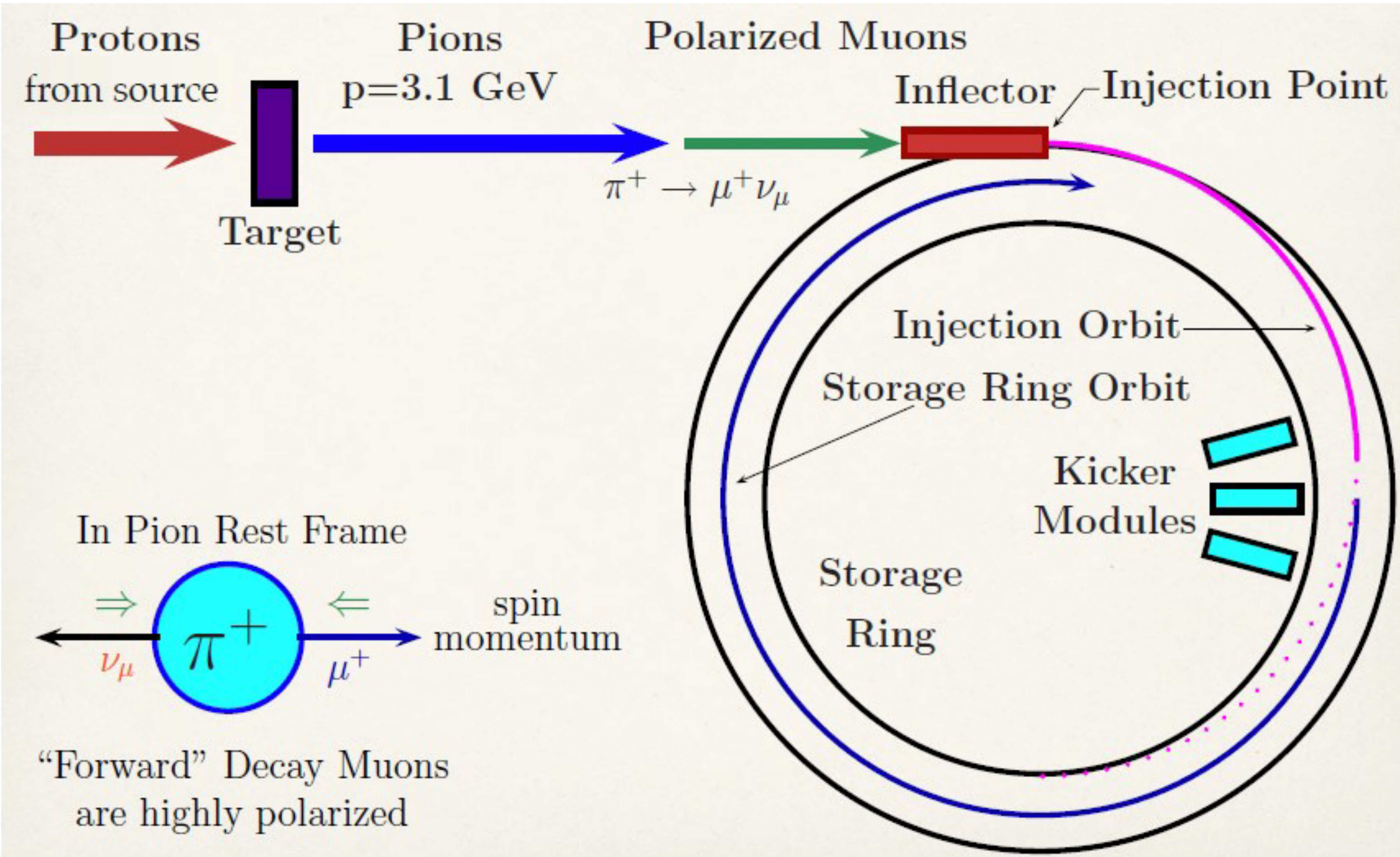
- Highly homogenous ~~magnet~~
- Polarized muons
- Muons at magic momentum
- Calorimeters
- pNMR probes

Fermilab Muon Campus



- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

Injection into the ring is a bit complicated



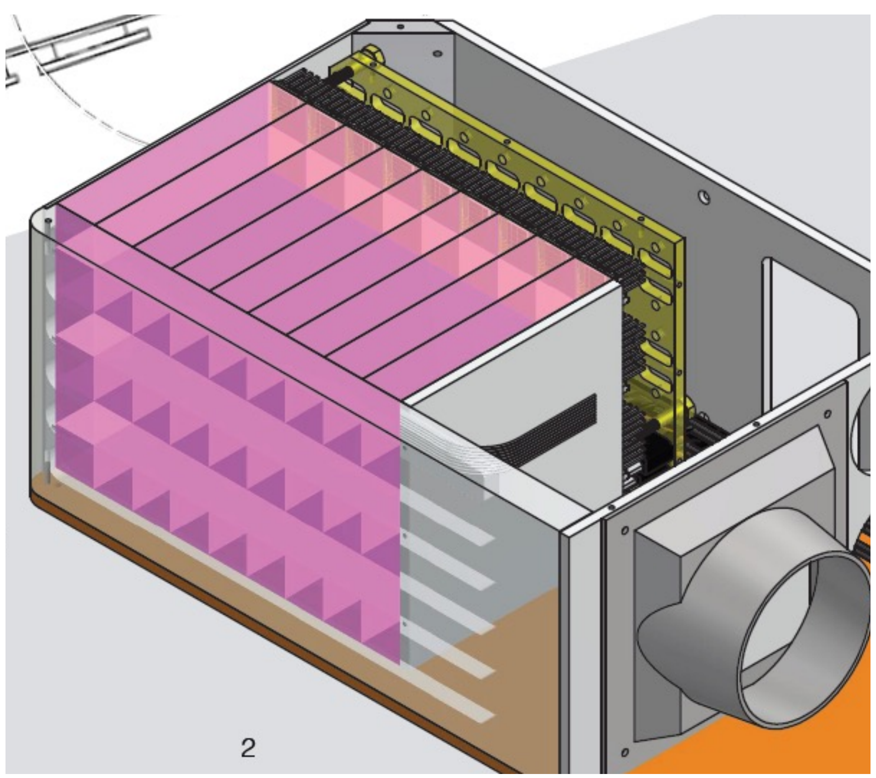
Basic ingredients

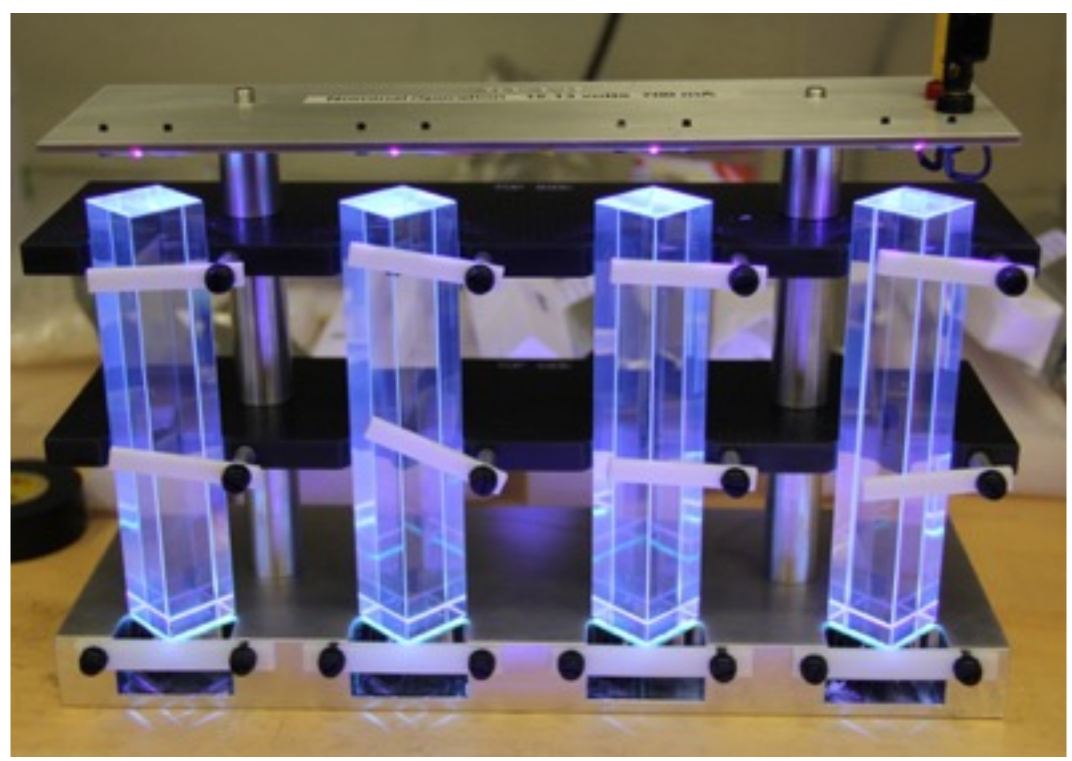
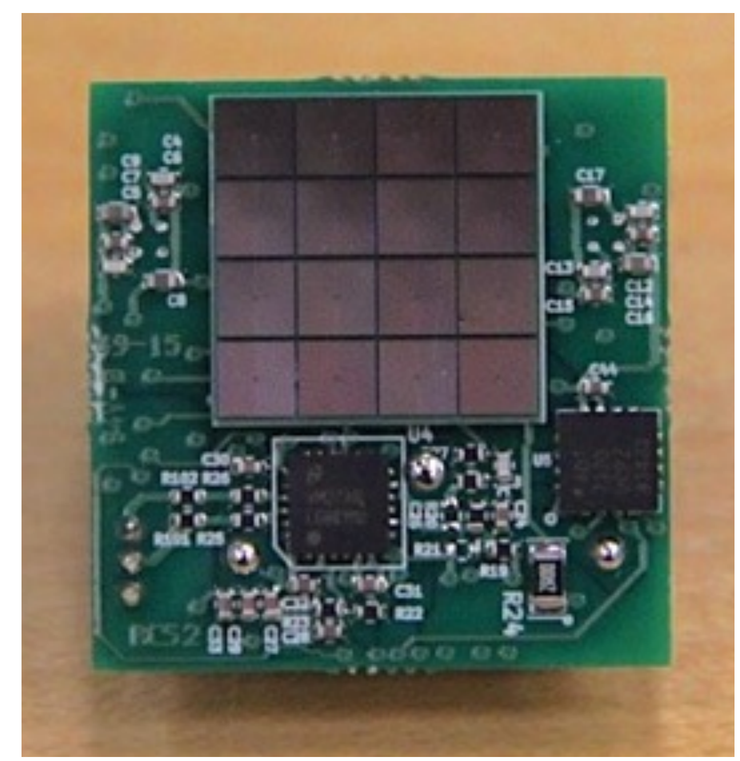
- Highly homogenous ~~magnet~~
- ~~Polarized muons~~
- ~~Muons at magic momentum~~
- Calorimeters
- pNMR probes

Calorimeters

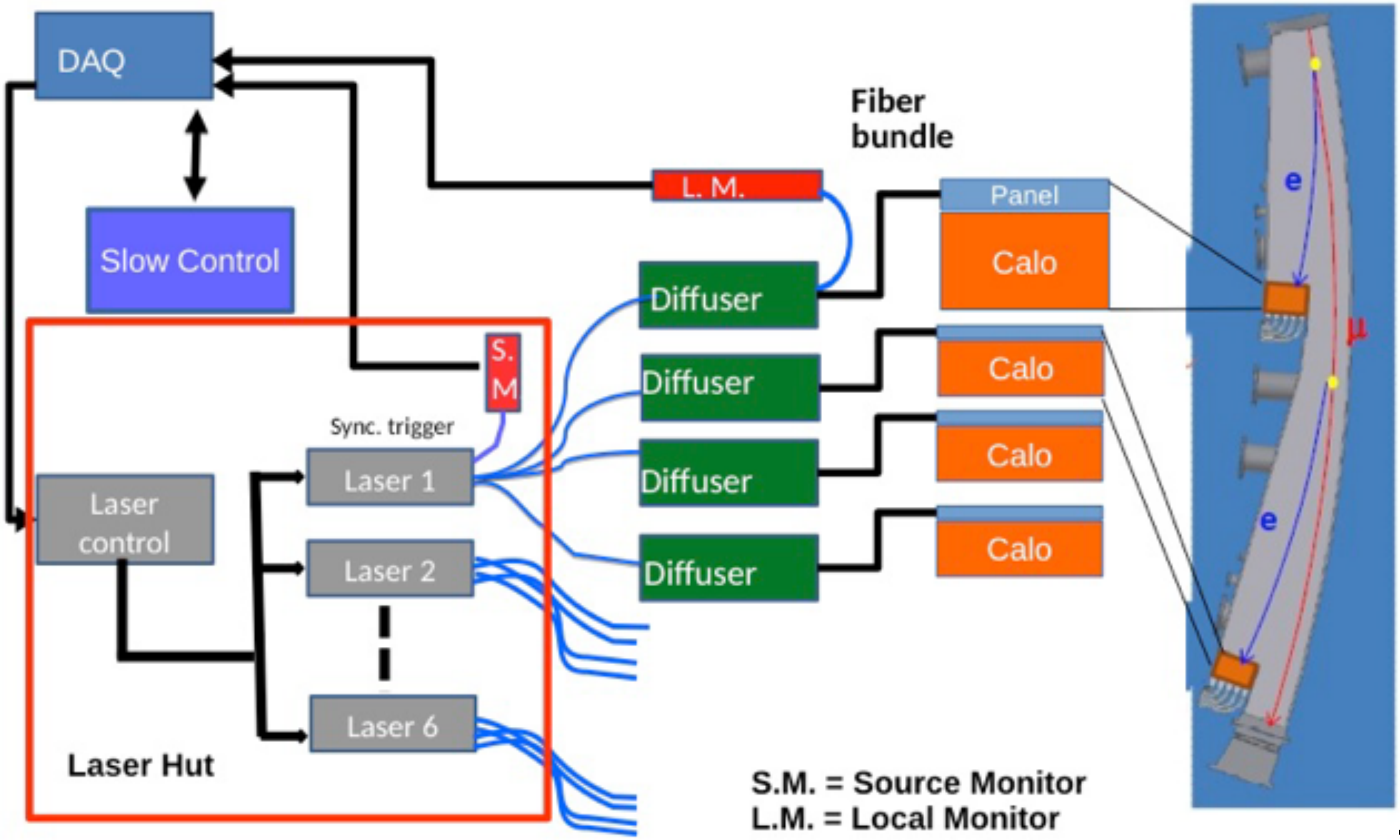
- Lead fluoride (PbF_2) crystals - pure Cherenkov-emitter
  good for temporal pileup separation
- Silicon photomultipliers (SiPM) - operation in B-field

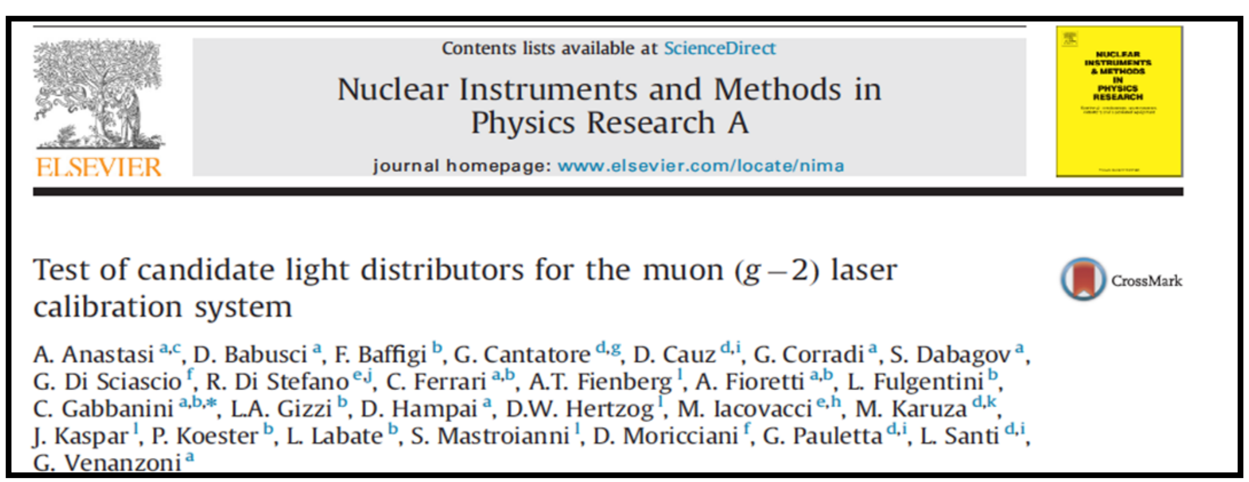
- 1 calorimeter = 9x6 segments of PbF_2 crystals
  good for spatial pileup separation



Laser monitoring and calibration system





Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

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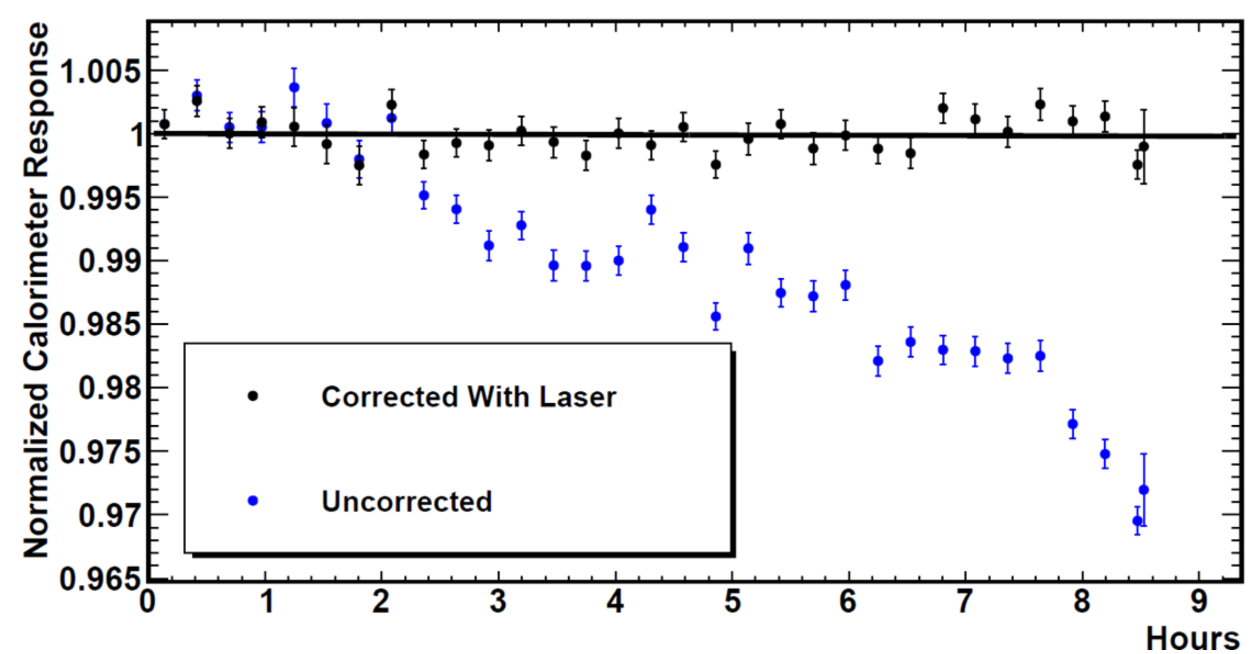
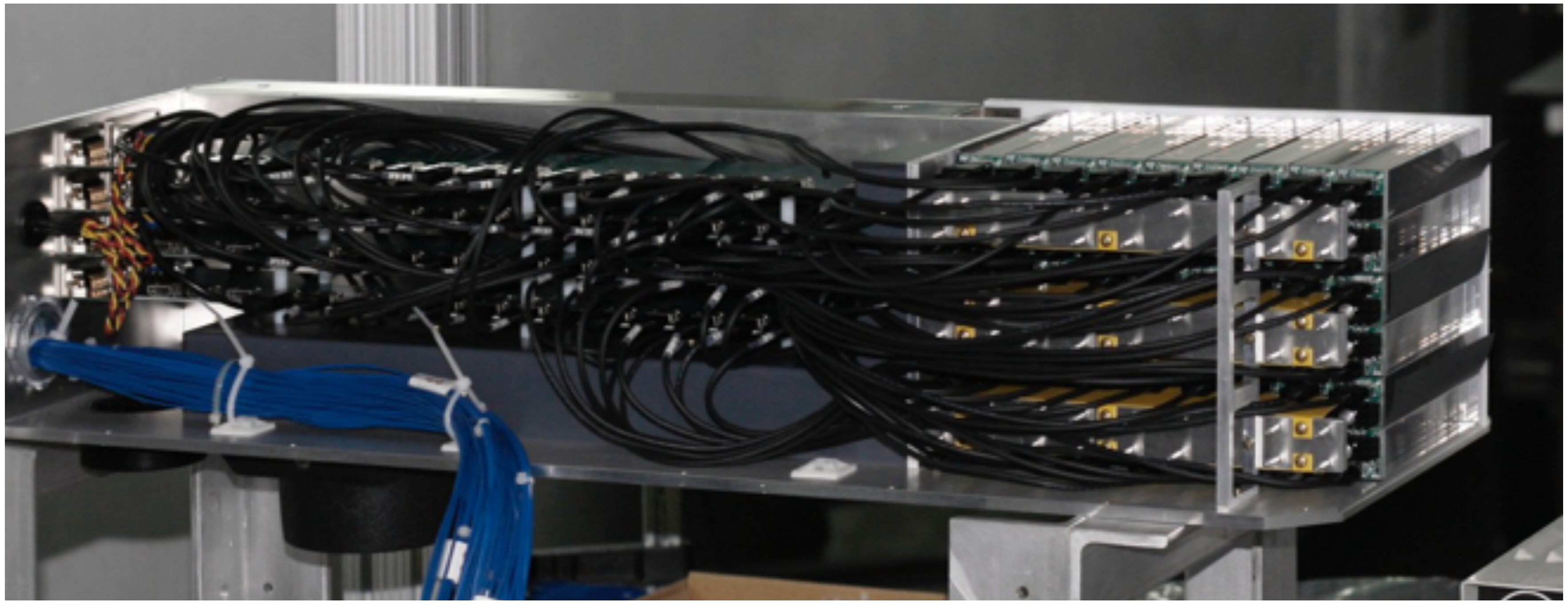
Test of candidate light distributors for the muon (g−2) laser calibration system

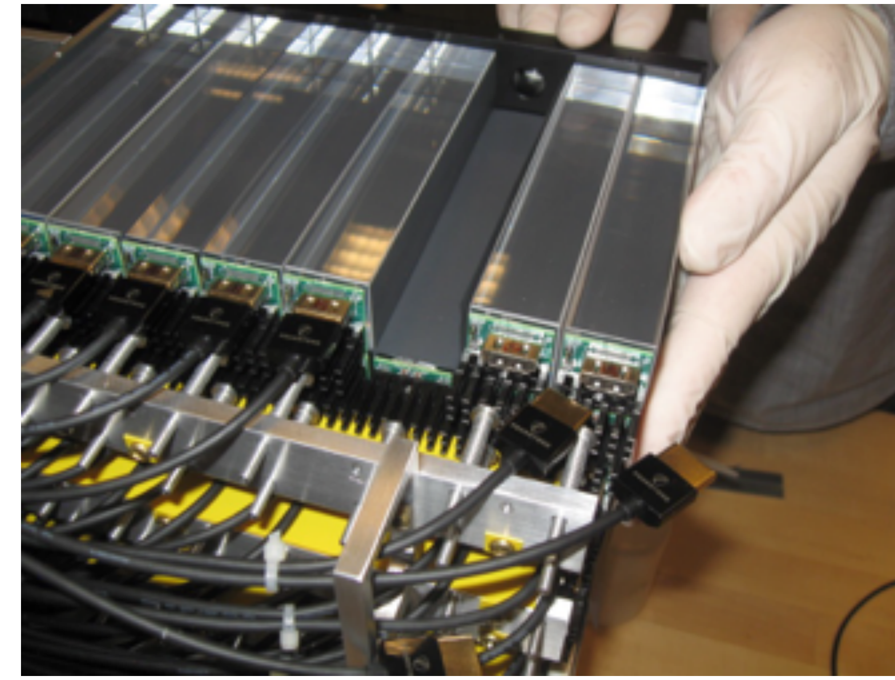
A. Anastasi [a,c], D. Babusci [a], F. Baffigi [b], G. Cantatore [d,g], D. Cauz [d,i], G. Corradi [a], S. Dabagov [a], G. Di Sciascio [f], R. Di Stefano [e,j], C. Ferrari [a,b], A.T. Fienberg [l], A. Fioretti [a,b], L. Fulgentini [b], C. Gabbanini [a,b,*], L.A. Gizzi [b], D. Hampai [a], D.W. Hertzog [l], M. Iacovacci [e,h], M. Karuza [d,k], J. Kaspar [l], P. Koester [b], L. Labate [b], S. Mastroianni [l], D. Moricciani [f], G. Pauletta [d,i], L. Santi [d,i], G. Venanzoni [a]

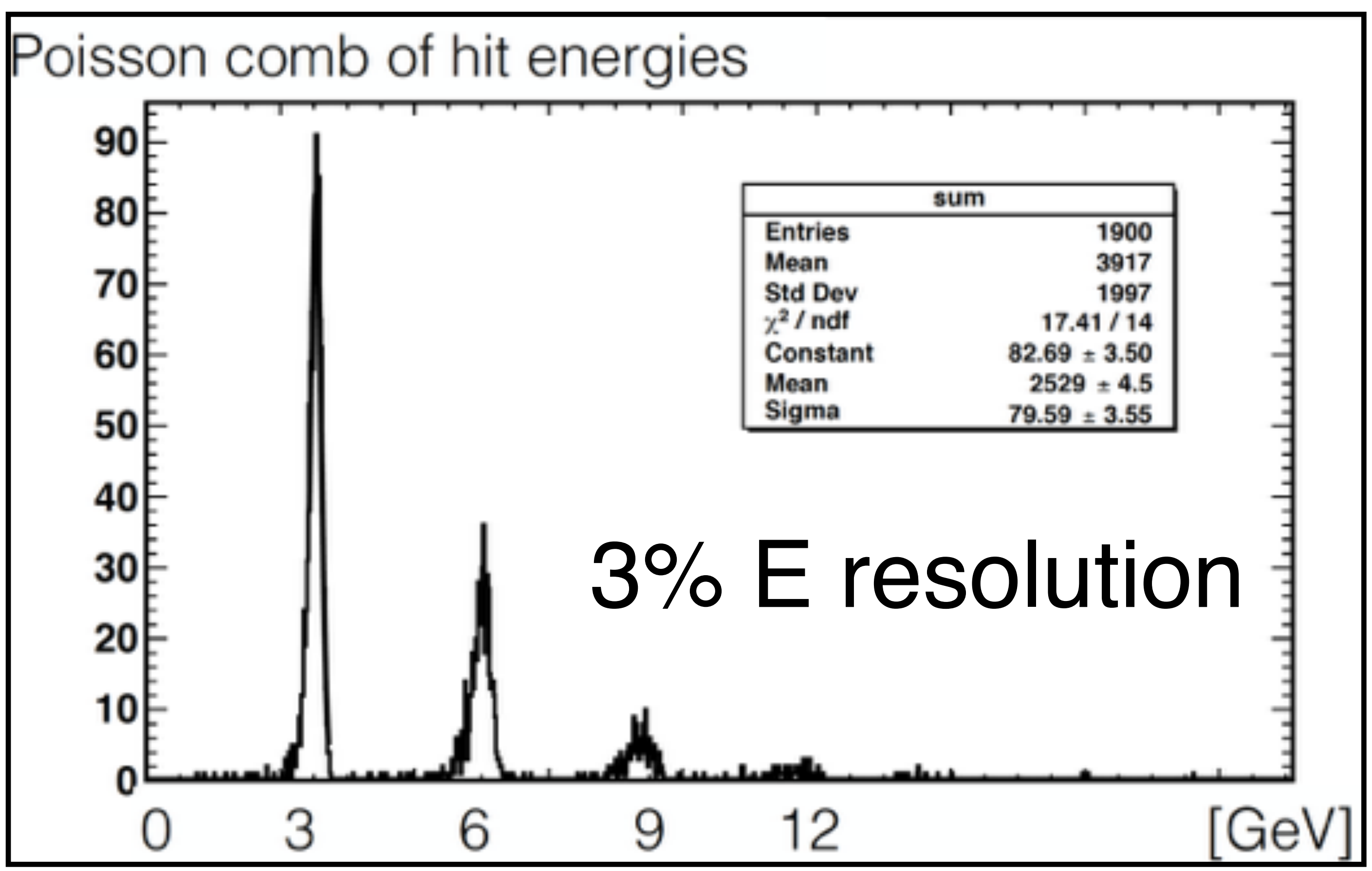
10^{-4}/hour demonstrated

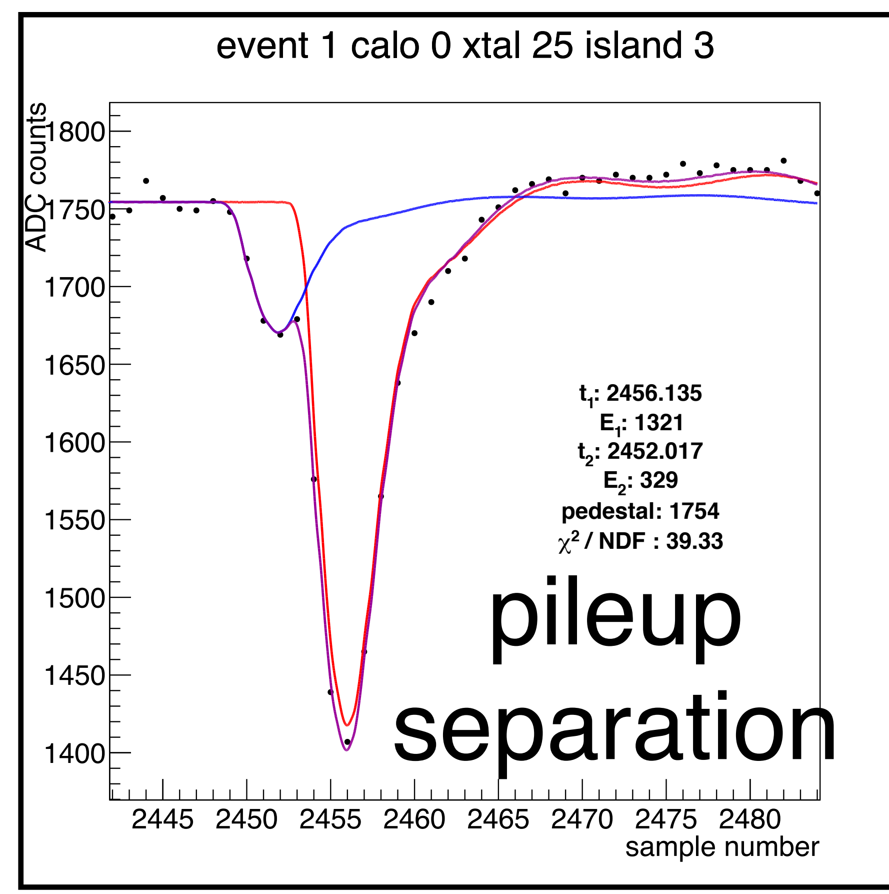


Testrun at SLAC, Jun 2016





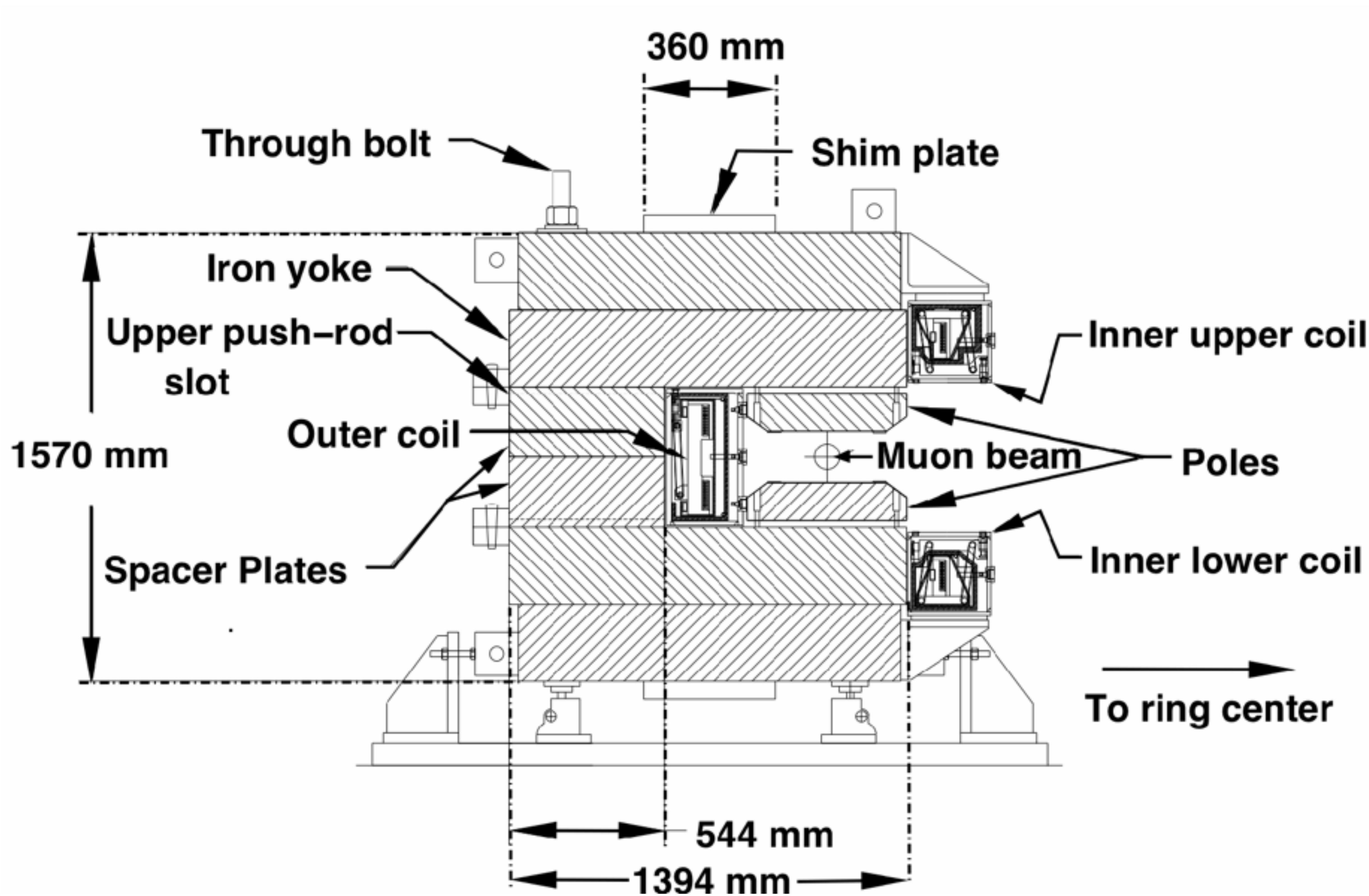




Basic ingredients

- Highly homogenous ~~magnet~~
- ~~Polarized muons~~
- ~~Muons at magic momentum~~
- ~~Calorimeters~~
- pNMR probes

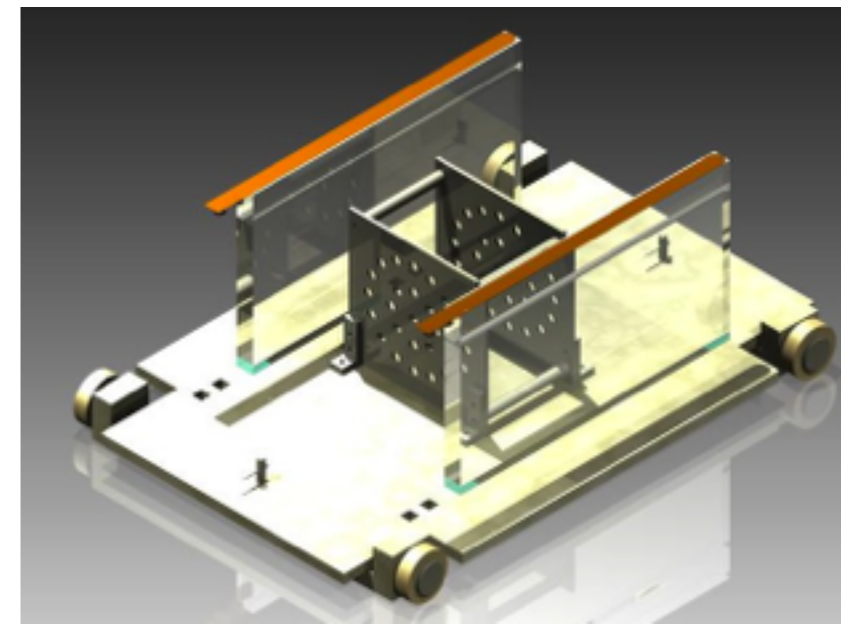
Superconducting magnet



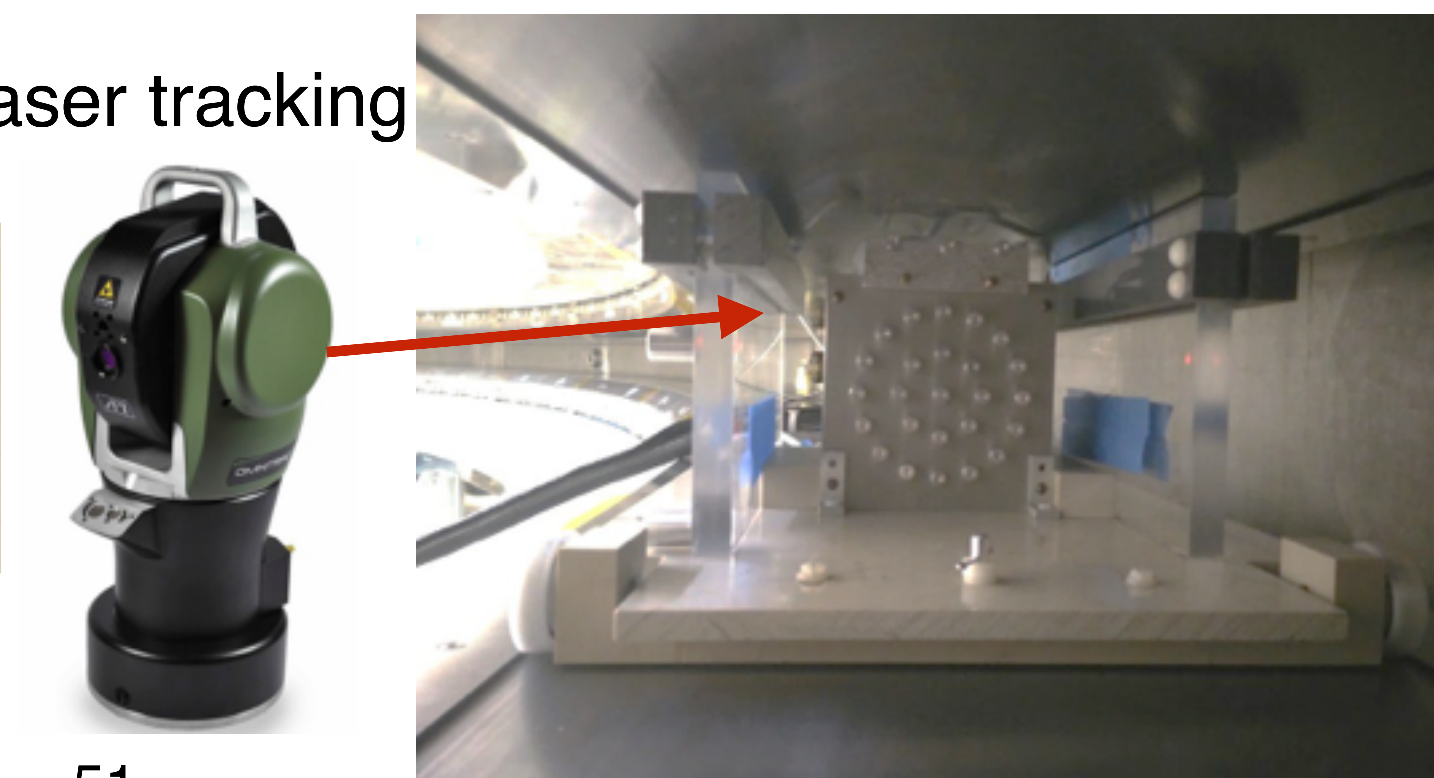
Cart for shimming

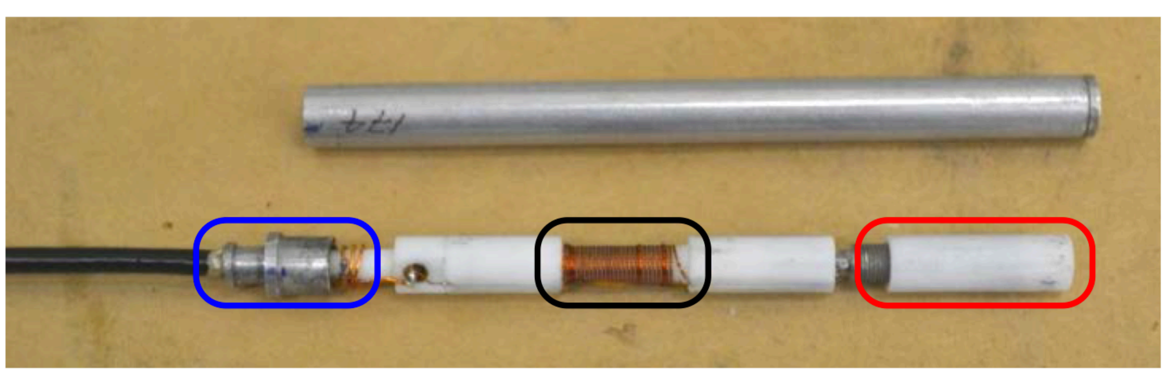
- A shim is a device used to adjust the homogeneity of a magnetic field

- A multipurpose instrument
  - 25 NMR probes for field measurement
  - 4 capacitive gap sensors
  - 4 position sensors (gives cart r,θ,z)



laser tracking





400 pNMR probes

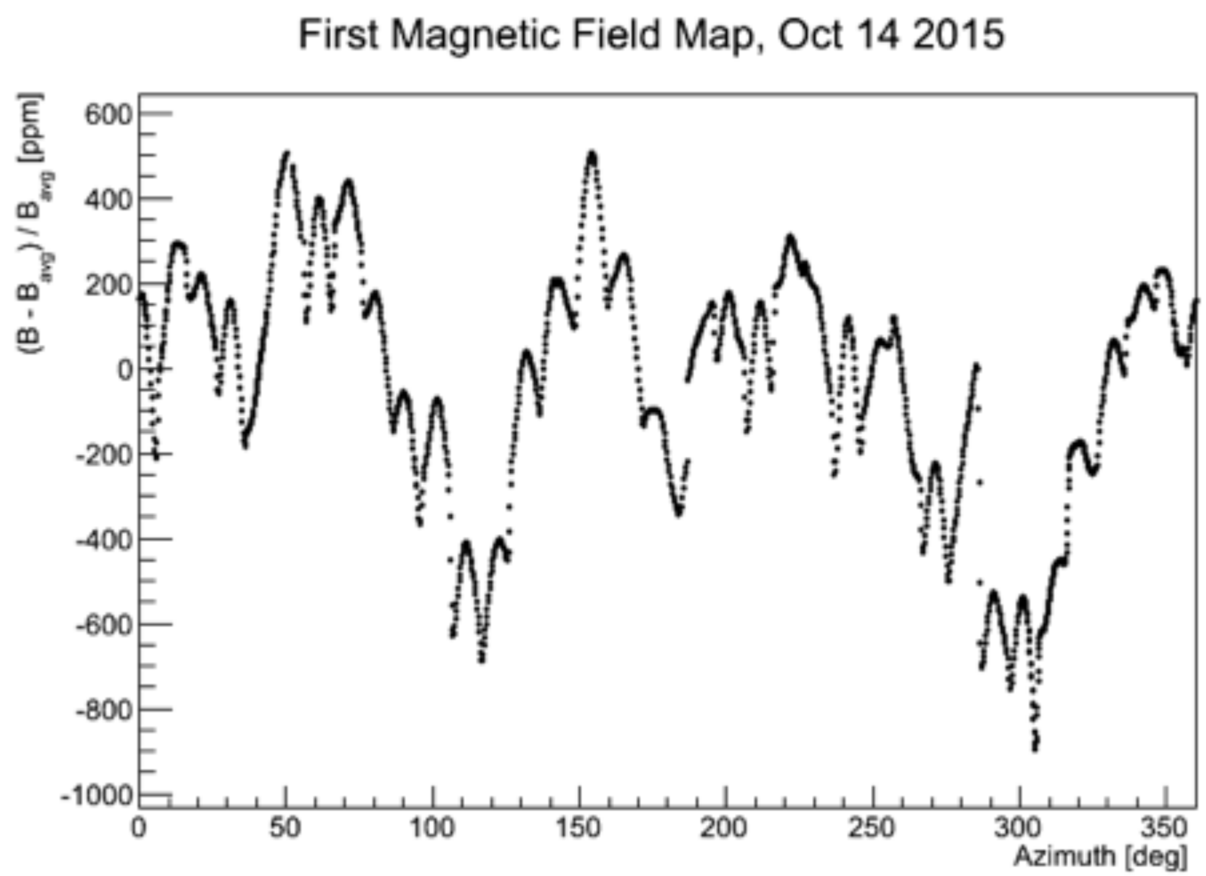
Basic ingredients

- Highly ~~homogenous magnet~~
- ~~Polarized muons~~
- ~~Muons at magic momentum~~
- ~~Calorimeters~~
- ~~pNMR probes~~

Initial field plots and goals

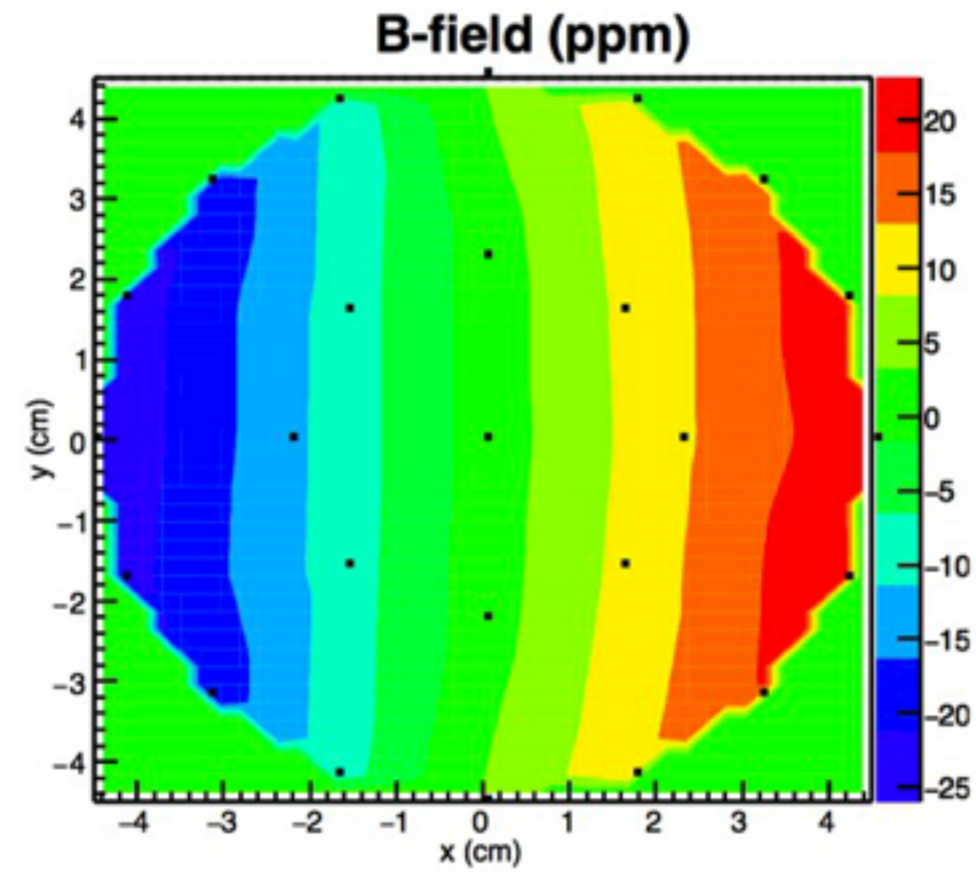
When we first turned on the magnet ……

Field vs Azimuth



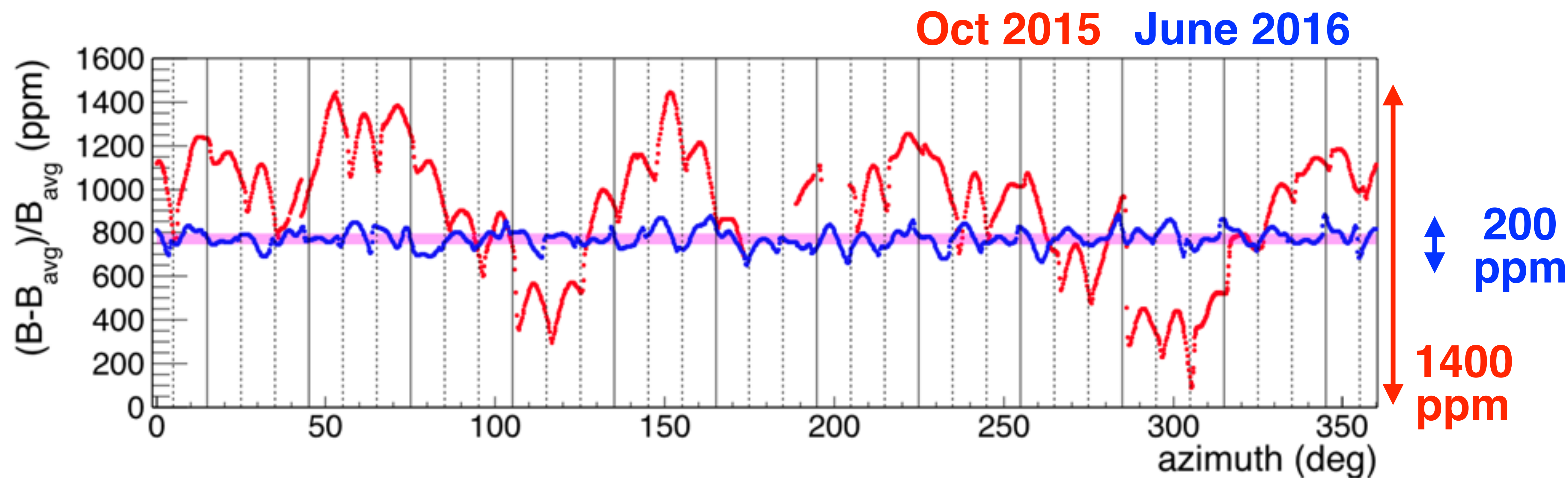
- Oct 2015: 700 ppm
- Goal: 25 ppm

Azimuthally averaged field

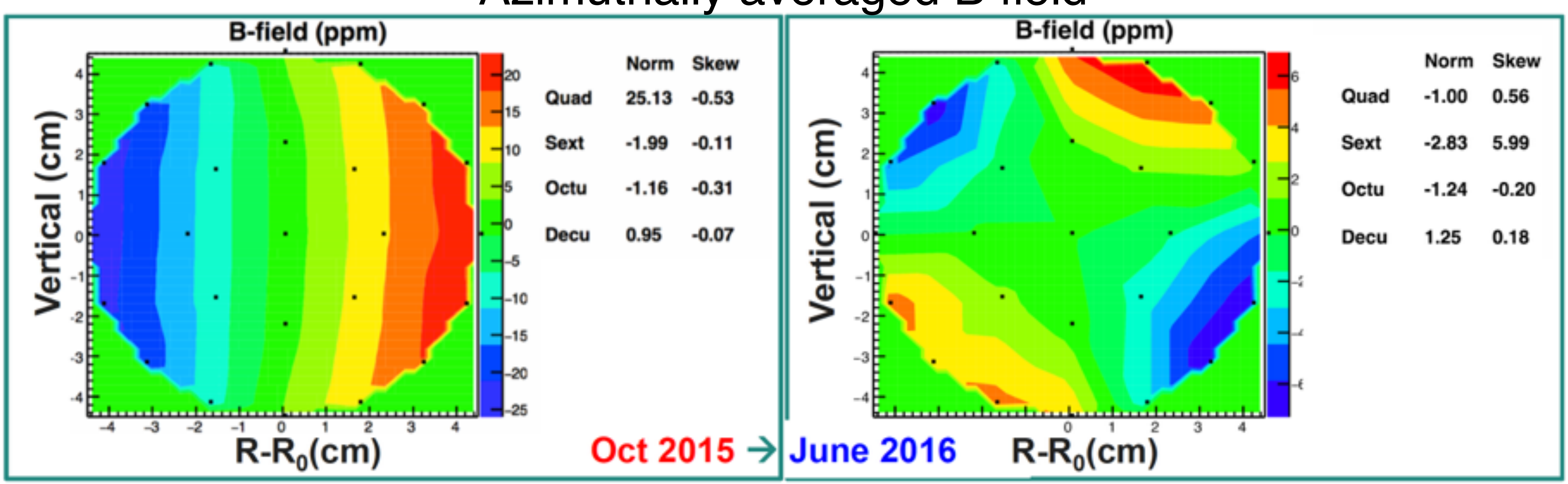


- Oct 2015: 25 ppm
- Goal: < 1 ppm

B field measurement



Azimuthally averaged B field



Summary

- Flagship experiment at the FNAL Muon Campus
- Lots of milestones achieved in 2016 especially at SLAC test run (calorimeter, DAQ, offline framework)
- Beam line construction, field shimming, final production of sub-systems (inflector, kicker, quad, detectors) progressing now
- On schedule for data taking in 2017
- Goal = 140 ppb on a_μ
- Huge progress on lattice QCD
- > 5 sigma could be realized
  (same central values, x2 improvement from theorists)