New Muon g-2 Experiment

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for E989 collaboration

BEACH2014 July 21-26, 2014
University of Birmingham, UK

Outline

- Motivation
- Experimental Technique
- New experiment at Fermilab

The Muon Anomalous Magnetic Moment

$$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)$$

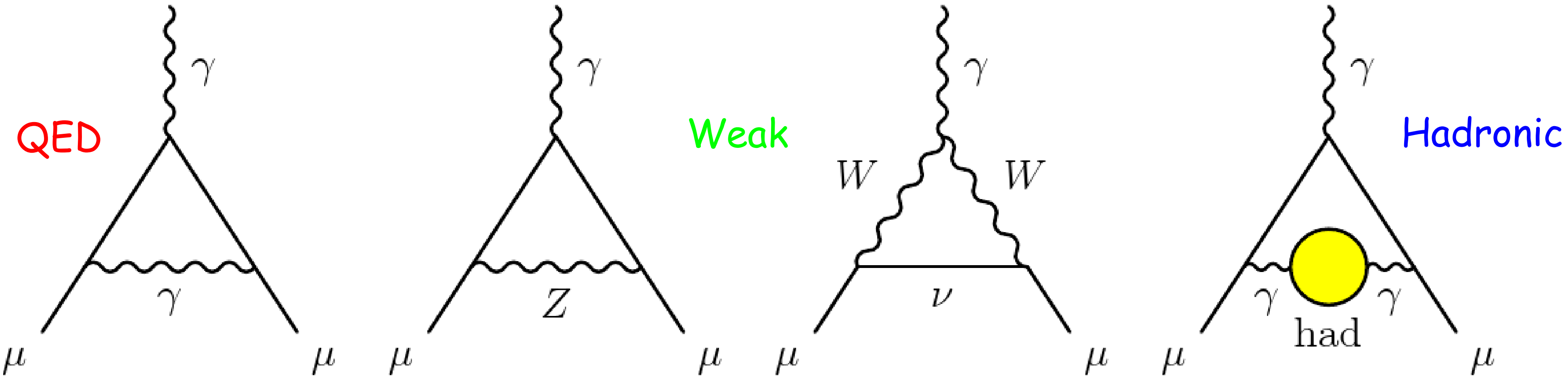
$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu}\vec{S}$$

$$g_\mu = 2$$

Quantum loop effects: $a_\mu \equiv \dfrac{g_\mu - 2}{2}$

a_μ - anomalous magnetic moment

SM prediction for a_μ



$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{Had}}$$

QED: photonic and leptonic (e,τ,μ) loops, $a_\mu^{\mathrm{QED}} = \sum_{i=1} C_i \left(\frac{\alpha}{\pi}\right)^i = 116\,584\,718.95(0.08) \times 10^{-11}$

Weak: loops involving W±, Z or Higgs

suppressed by at least a factor of $\frac{\alpha}{\pi}\frac{m_\mu^2}{m_W^2}$, $a_\mu^{\mathrm{W}} = 153.6(1.0) \times 10^{-11}$

Hadronic: quark and gluon loops.

at present not calculable from first principles

relies on a dispersion relation approach

$$a_\mu^{\mathrm{Had}}[\mathrm{LO}] = 6\,923(42)(3) \times 10^{-11}$$
$$a_\mu^{\mathrm{Had}}[\mathrm{NLO}] = 7(26) \times 10^{-11}$$

Total:

$$a_\mu^{\mathrm{SM}} = 116\,591\,803(1)(42)(26) \times 10^{-11}$$

-- PDG-2013

Comparison of Experiment and Theory

- Theory uncertainty: 0.42 ppm
- Experimental uncertainty: 0.54 ppm E821 @ BNL

PDG 2013

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 288(63)(49) \times 10^{-11} \qquad (3.6\sigma)$$

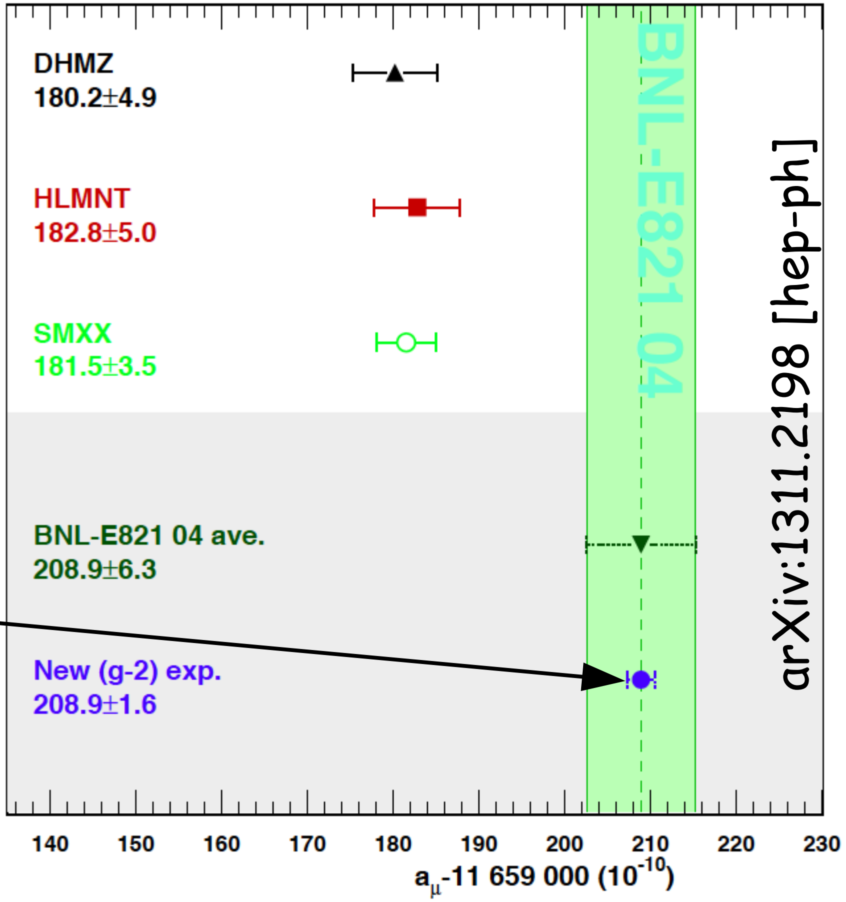
- "interesting but not yet conclusive discrepancy"
- new physics signal?

$$a_\mu^{\text{SUSY}} \simeq \text{sign}(\mu) \cdot 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{m_{\text{SUSY}}}\right) \tan(\beta)$$

A. Czarnecki and W.J. Marciano, PRD 64 (2001)

$$a_\mu^{\text{dark photon}} = \frac{\alpha}{2\pi}\varepsilon^2 F\left(\frac{m_V}{m_\mu}\right)$$

- Fermilab E989 goal: 0.14 ppm



arXiv:1311.2198 [hep-ph]

New g-2 Collaboration (E989)

Domestic Universities
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Massachusetts
  - Mississippi
  - Kentucky
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois University
  - Northwestern
  - Regis
  - Virginia
  - Washington
  - York College
- National Labs
  - Argonne
  - Brookhaven
  - Fermilab
- Consultants
  - Muons, Inc.

Italy
  - Frascati
  - Roma
  - Udine
  - Naples
  - Trieste

China:
  - Shanghai

The Netherlands:
  - Groningen

Germany:
  - Dresden

Japan:
  - Osaka

Russia:
  - Dubna
  - PNPI
  - Novosibirsk

England

University College London
Liverpool
Oxford
Rutherford Lab

Korea

KAIST

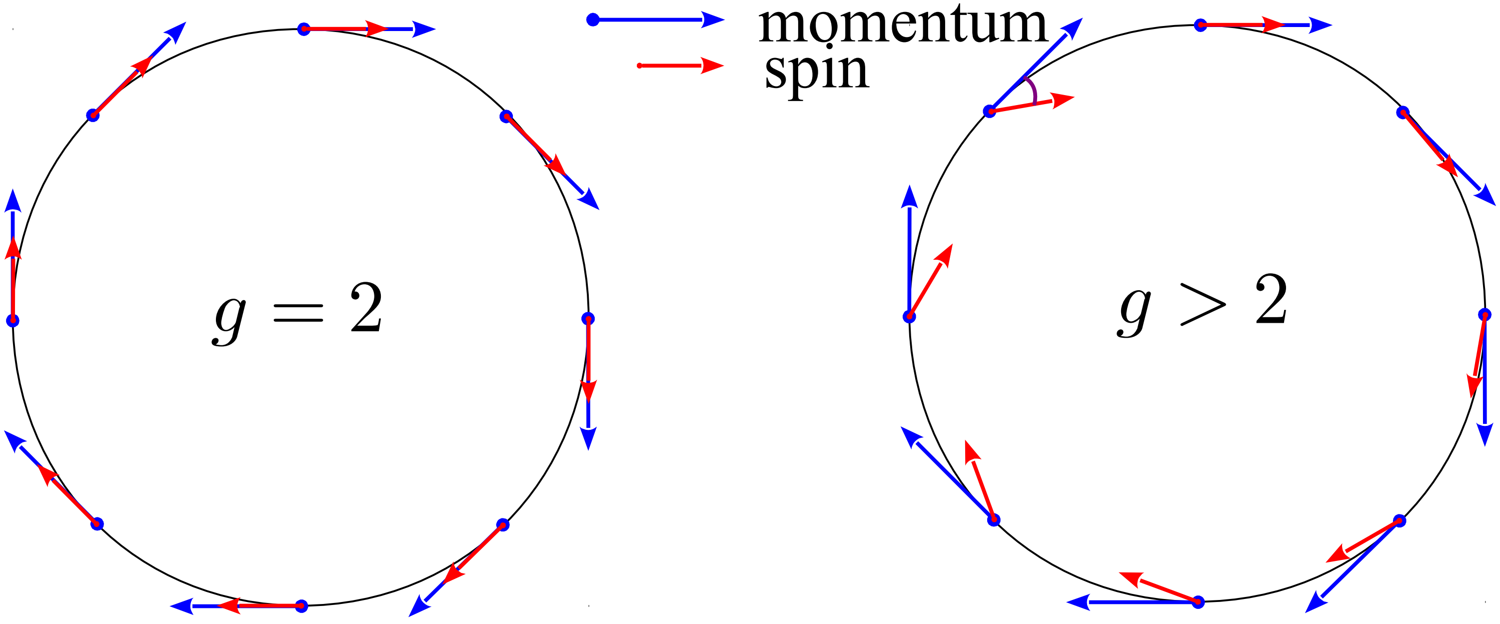
Co-spokespersons: David Hertzog, Lee Roberts
Project Manager: Chris Polly

Muon g-2 experiment in a nutshell

1) Take polarized muons (come naturally from pion decay)

2) Place muons into a uniform magnetic field

   - Momentum precession (cyclotron frequency) $\omega_c = \frac{e}{m\gamma}B$
   - Spin precession $\omega_s = \frac{e}{m\gamma}B(1+\gamma a_\mu)$



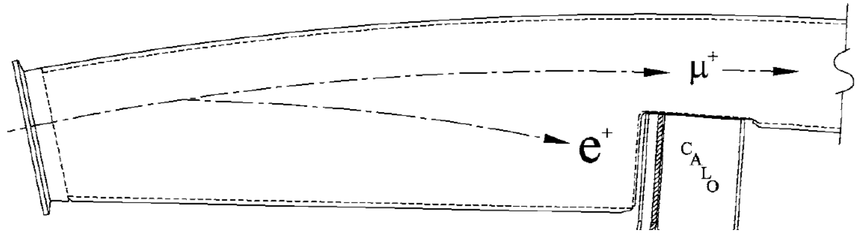
$$\omega_a = \omega_s - \omega_c = \frac{e}{m}a_\mu B$$

Muon g-2 experiment in a nutshell

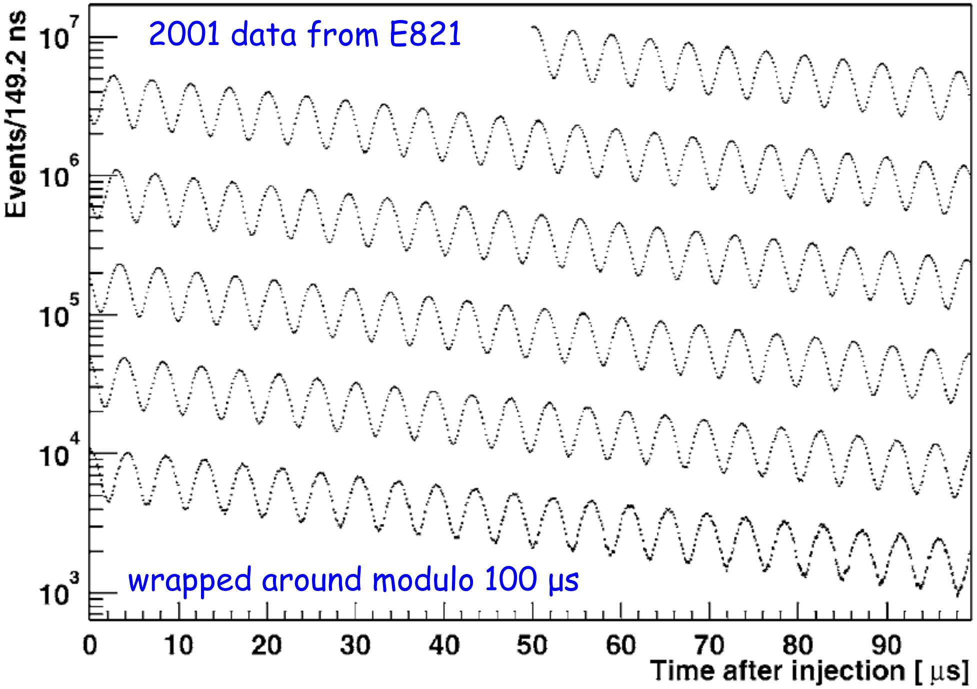
$$a_\mu = \frac{m}{e}\,\frac{\omega_a}{B}$$

Determining the anomalous magnetic moment requires measuring

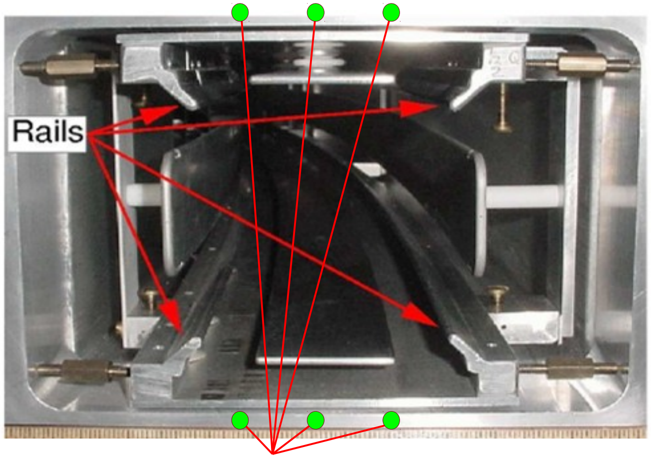
- The spin precession frequency ω_a



muon decay is self-analyzing: higher energy positrons are emitted preferentially in direction of muon spin

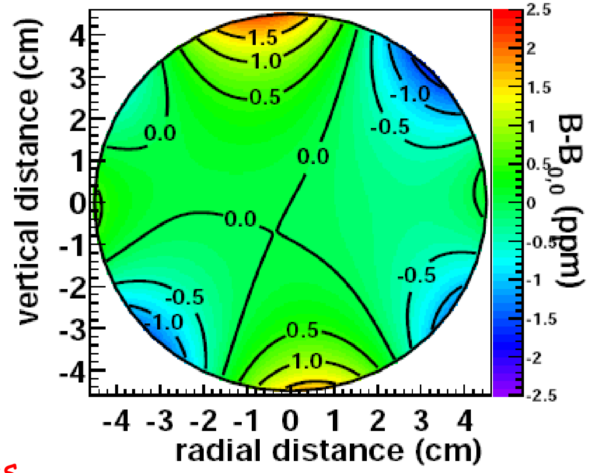


- The magnetic field B (ω_p)



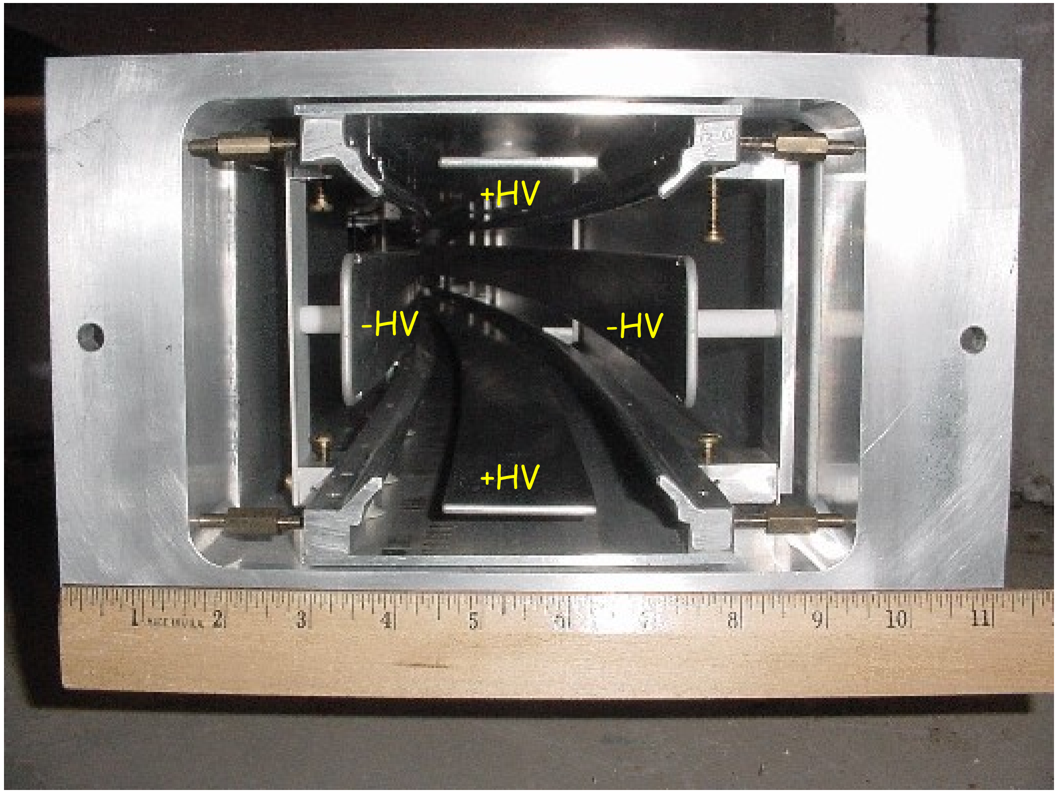
375 fixed NMR probes

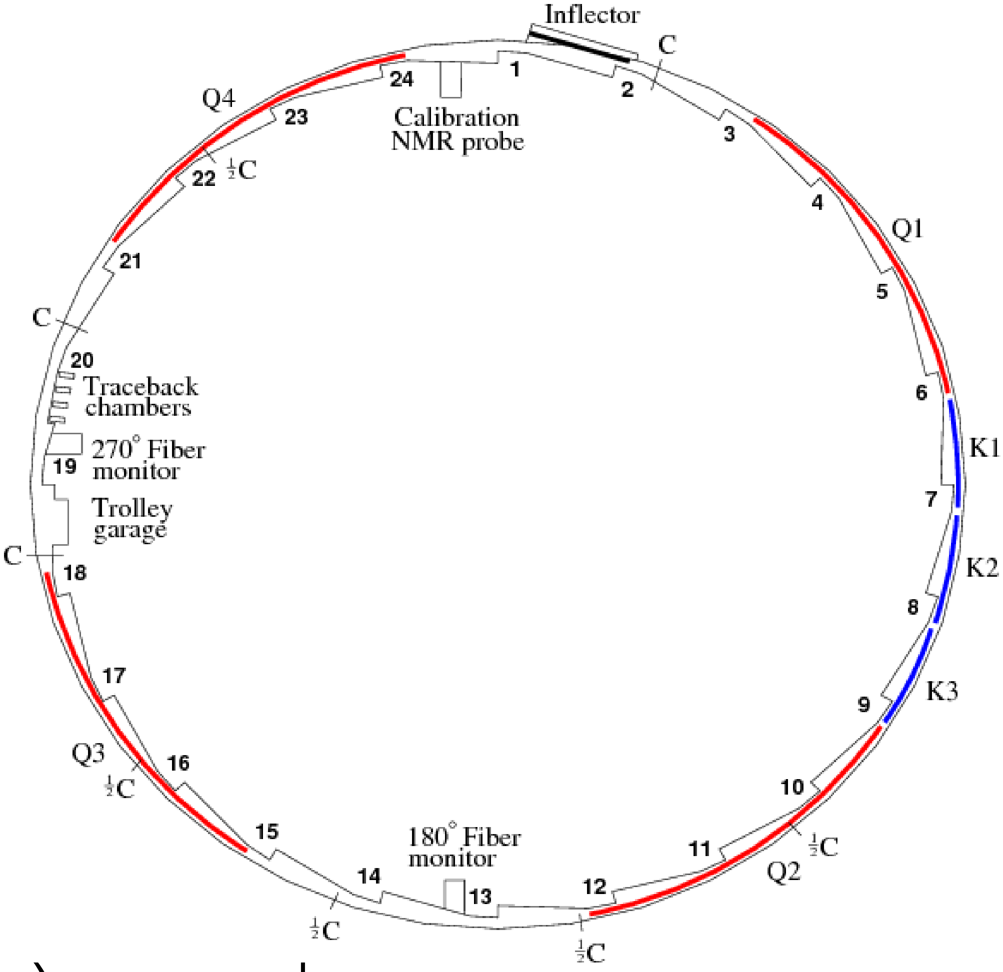
17 NMR trolley probes



$$a_\mu = \frac{\omega_a/\omega_p}{\underbrace{\omega_L/\omega_p}_{\text{from muonium hyperfine level structure measurements}} - \omega_a/\omega_p}$$

Electric quads to contain the beam vertically





$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{=0 \quad \text{for } \gamma = 29.3 \quad (p_\mu = 3.09\ \text{GeV/c})} \vec{\beta} \times \vec{E}\right]$$

E-field contribution vanishes

uncertainties in E821 and E989 goals

ω_p

D. Kawall, UMass

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

*Improvements in many of these categories will also follow from a more uniformly shimmed main magnetic field.

†Collective smaller effects in E821 from higher multipoles, trolley temperature uncertainty and its power supply voltage response, and eddy currents from the kicker.

uncertainties in E821 and E989 goals

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	
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

statistical goal: x20 more muons

pileup

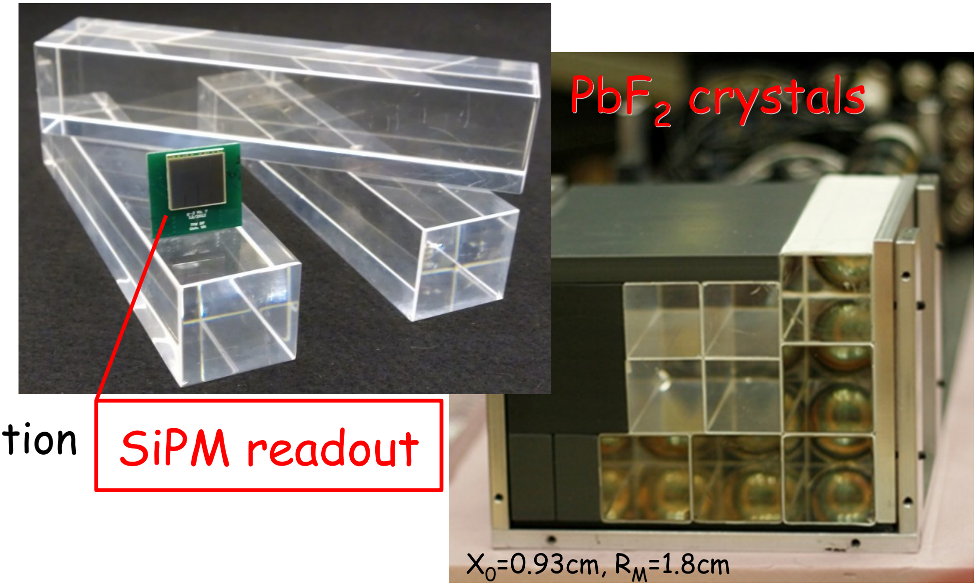
New calorimeters

D. Hertzog, UW

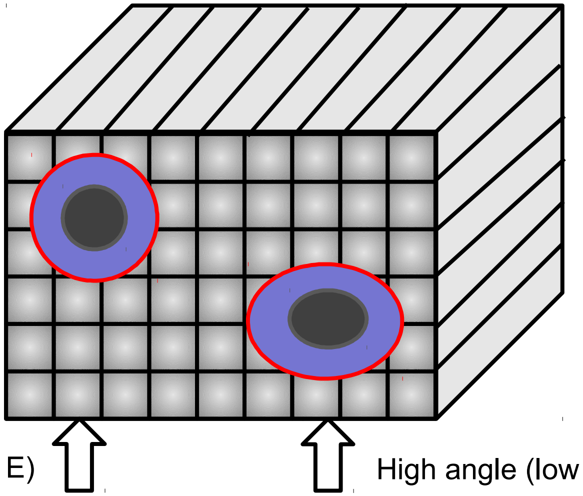
- **Compact** based on fixed space
- **Non-magnetic** to avoid field perturbations

- **Resolution** not too critical for dw$_a$
  - Useful for pileup, gain monitoring, shower partitioning and low thresholds
  - Goal <5% DE/E at 2 GeV (a soft requirement)

- **Gain stability** depends on electronics and calibration system
  - Goal: Short term < 0.1% DG/G in 600 ms
  - Goal: Longer term < 1% DG/G in 24 h
- **Pileup** depends on signal speed and shower separation
  - Subdivide calorimeter
  - Use Cherenkov
  - Goal: 2-pulse separation by space: 2 out of 3
  - Goal: 2-pulse separation by time: Dt > 5 ns

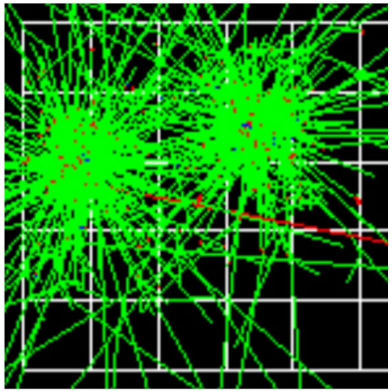


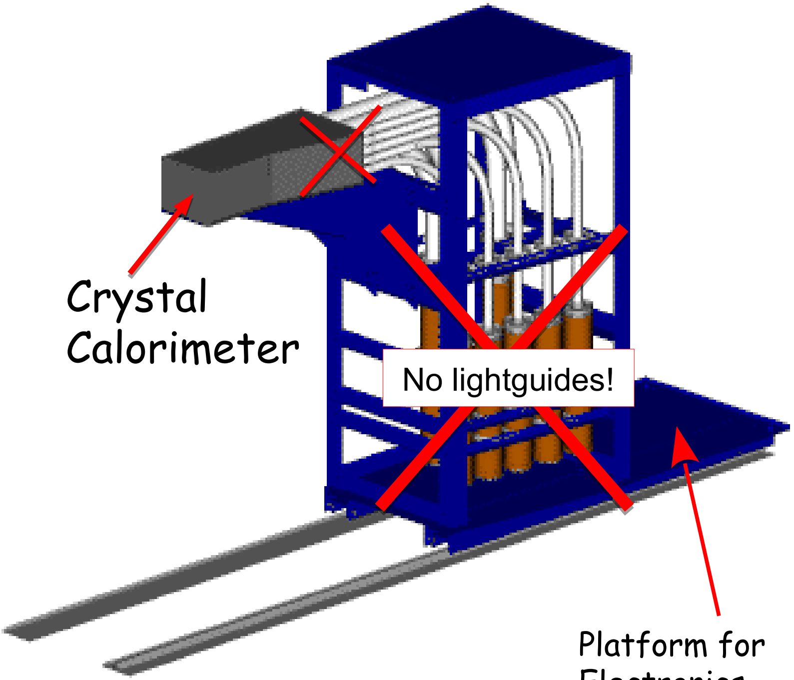
1 Moliere R
2 Moliere R



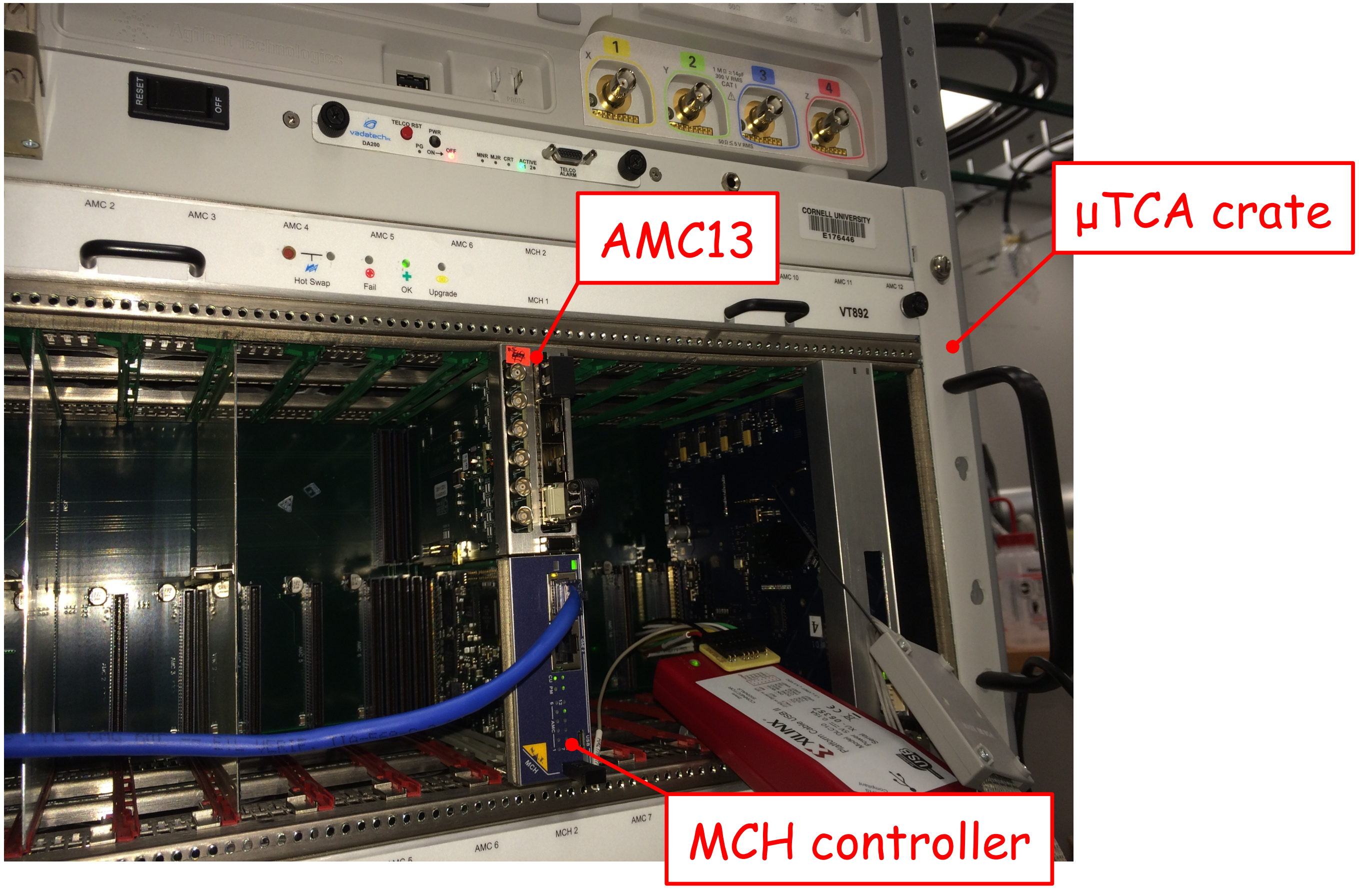
Head on (high E)

High angle (low E)





New electronics



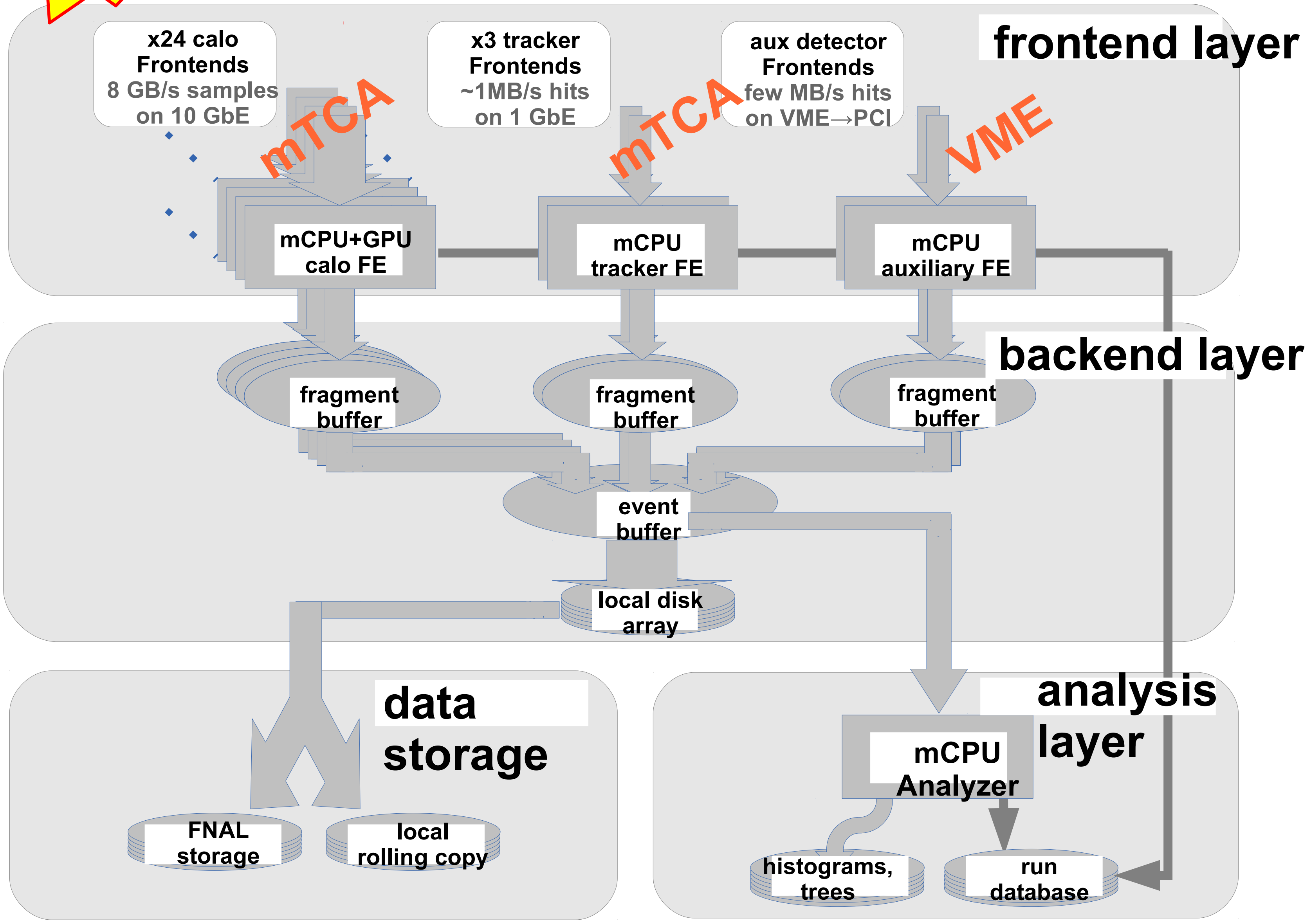
- 800 or 500 MSPS sampling rate
- continuous digitization over each 700-μs-long muon spill
- μTCA crate
- 10 Gb network for data readout based on AMC13 (designed by CMS)

BROOKHAVEN
NATIONAL LABORATORY

pileup + statistics

New DAQ

T. Gorringe, UKY



frontend layer

x24 calo Frontends
8 GB/s samples
on 10 GbE

x3 tracker Frontends
~1MB/s hits
on 1 GbE

aux detector Frontends
few MB/s hits
on VME→PCI

mTCA

mTCA

VME

mCPU+GPU
calo FE

mCPU
tracker FE

mCPU
auxiliary FE

backend layer

fragment buffer

fragment buffer

fragment buffer

event buffer

local disk array

data storage

FNAL storage

local rolling copy

analysis layer

mCPU Analyzer

histograms, trees

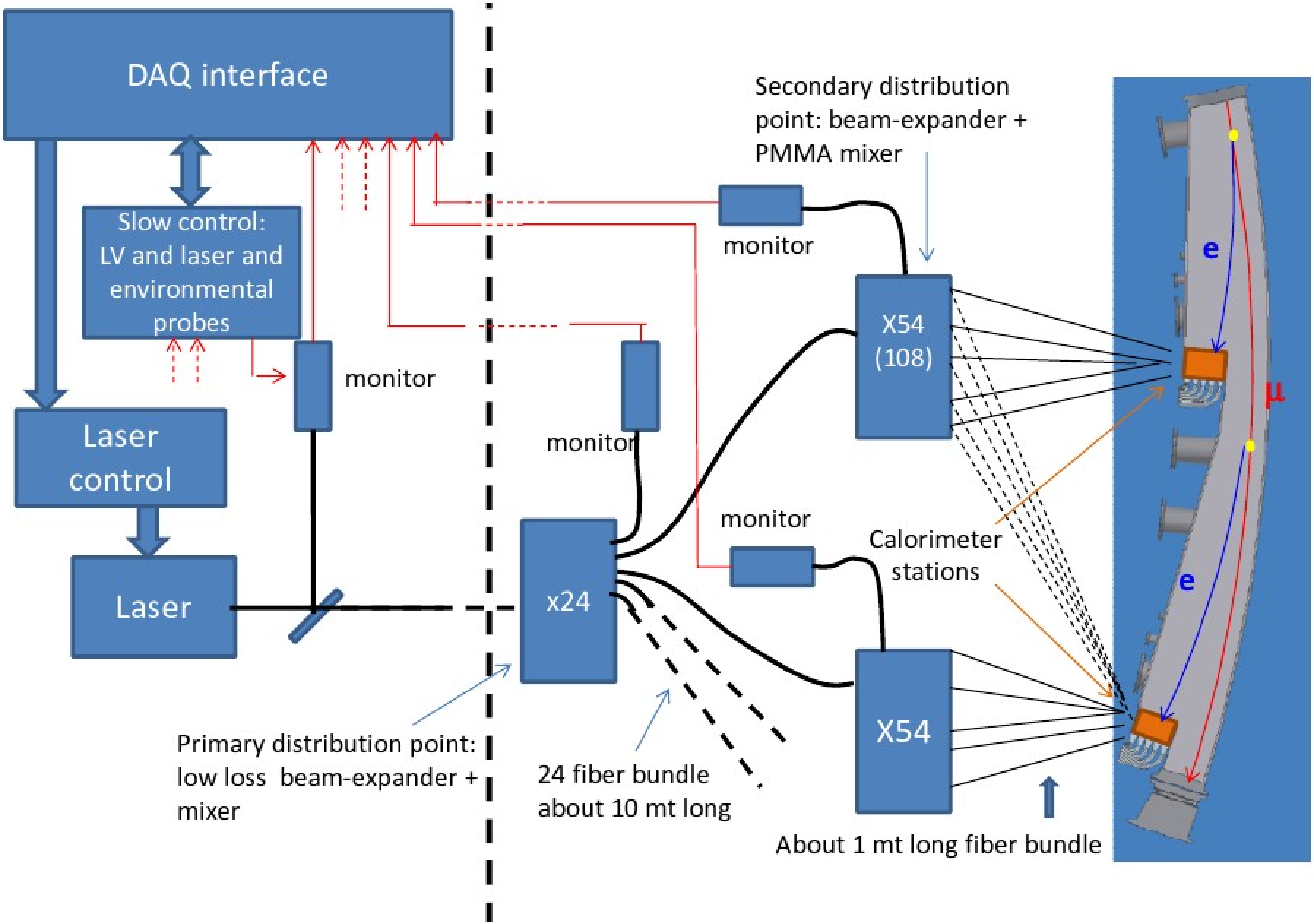
run database

using CUDA, MIDAS, ROOT packages

gain

Laser Calibration System

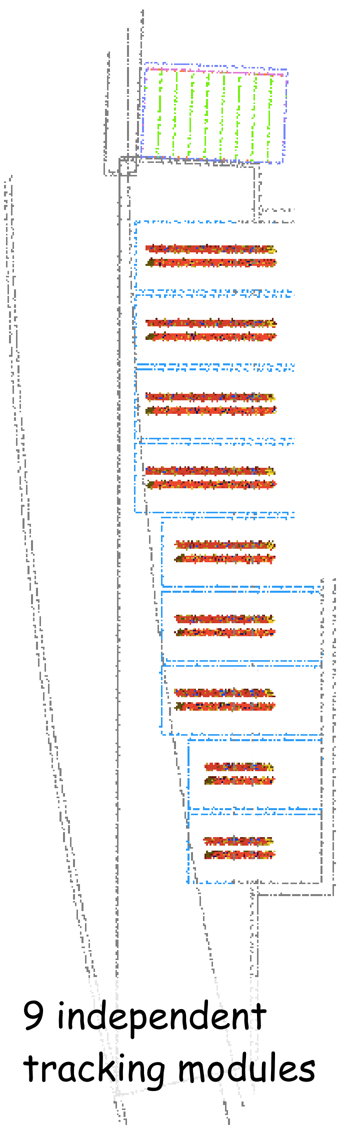
G. Venanzoni, Frascati

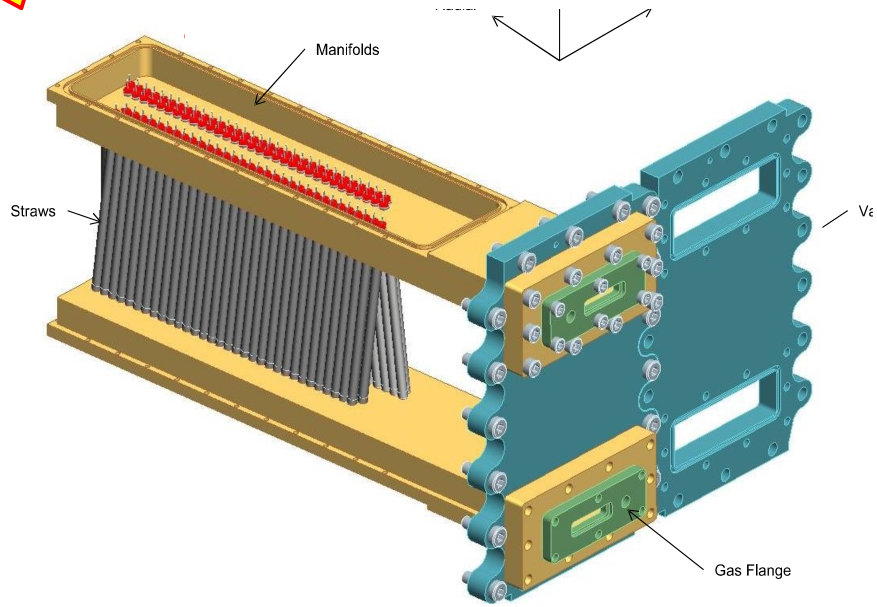


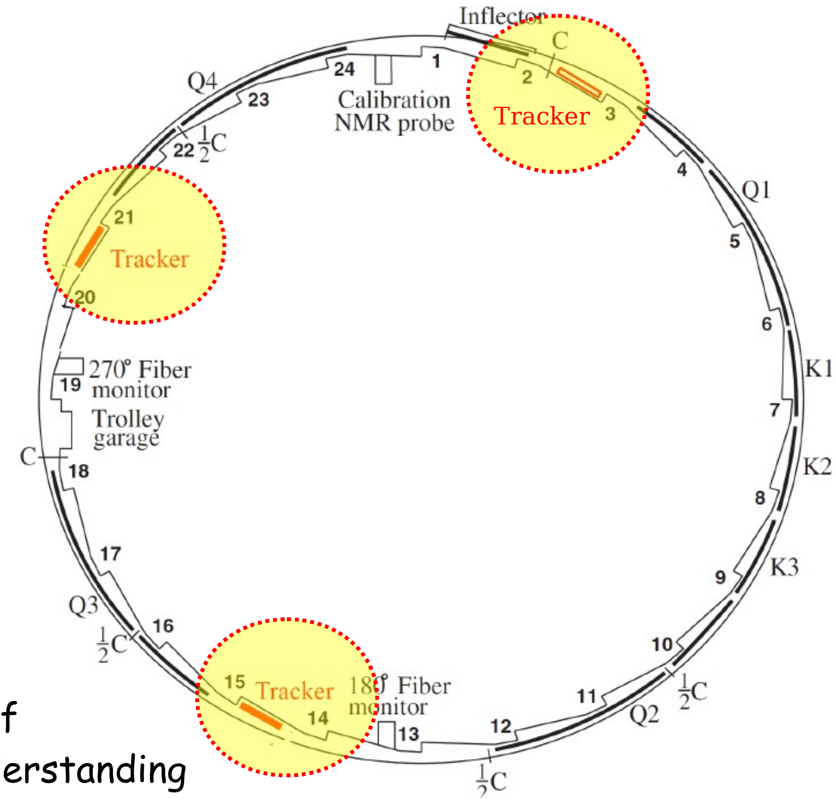
beam, EDM

New Tracker

B. Casey, FNAL


9 independent tracking modules





Purpose: measure the muon beam profile at multiple locations around the ring as a function of time throughout the muon fill. Is needed for understanding systematic uncertainties associated with with ω_a measurements (calorimeter pileup, calorimeter gain, muon loss, differential decay syst. uncertainty, etc). Will also be used to search for a tilt in the muon precession plane away from the vertical orientation (which would be indicative of an EDM of the muon).

Design: 5-mm-diameter 10-cm-long straw UV doublets at 7.5°.
straw walls: 6 μm Mylar
sense wires: 25 μm gold-plated tungsten at 1500 V
gas: 80:20 Argon:CO_2
readout: ASDQ chips

CBO

New Kicker

D. Rubin, Cornell

Kickers steer injected muons onto the closed orbit of the storage ring

Requirements:

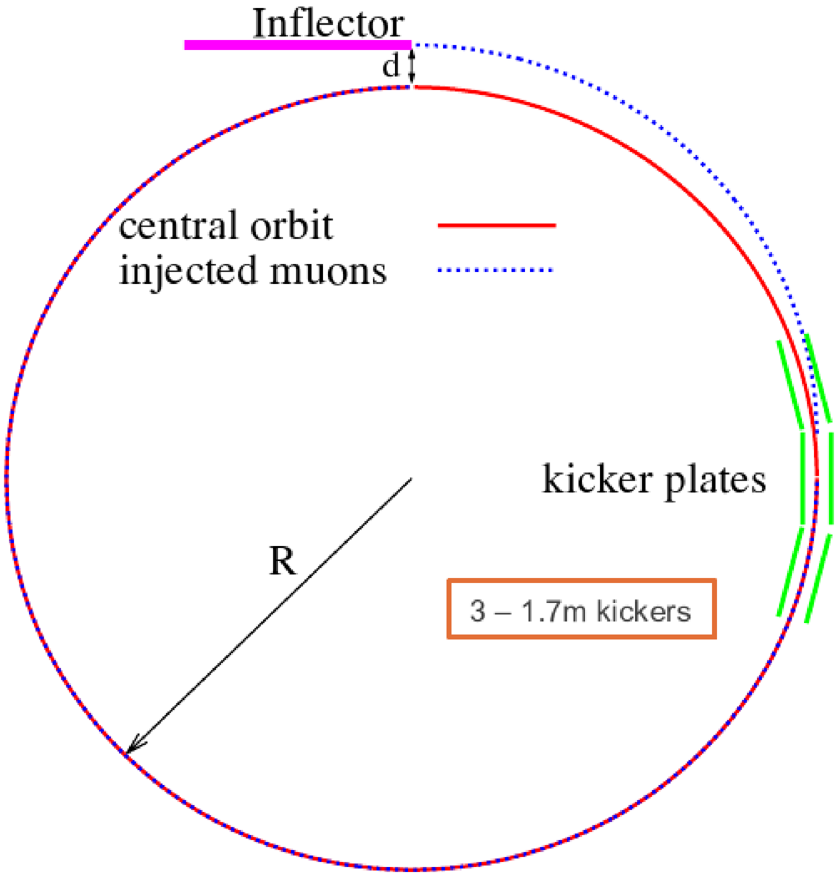
Kick angle ~ 10.8 to 12.1 mrad
Kicker B-field ~ 218 to 245 Gauss
Integrated B-field ~ 1.11 to 1.25 kG-m

Pulse width(τ_{wid})

$120\text{ns} < \tau_{wid} < 149\text{ns}$

Repetition rate

~100Hz peak, 12Hz average



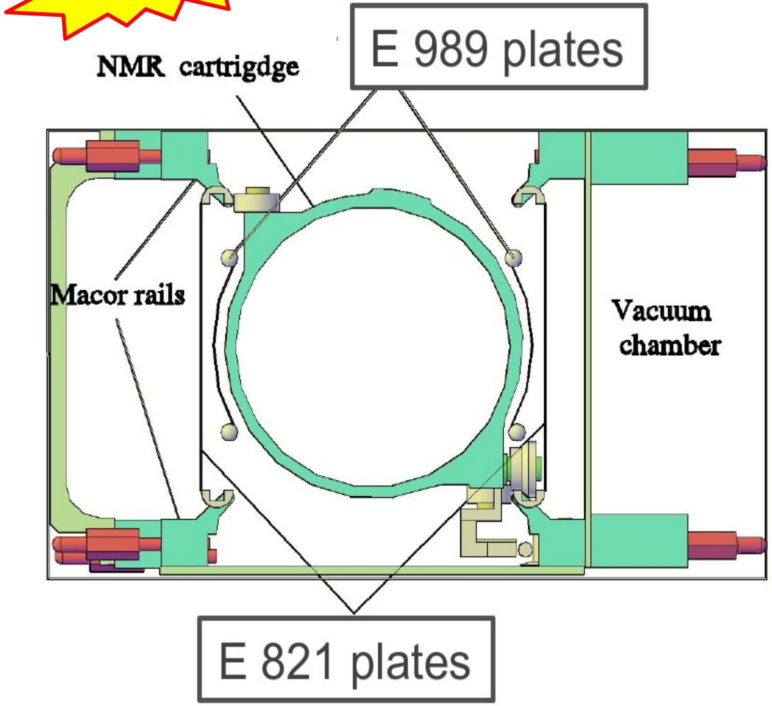
$\tau_{rev} = 149$ ns

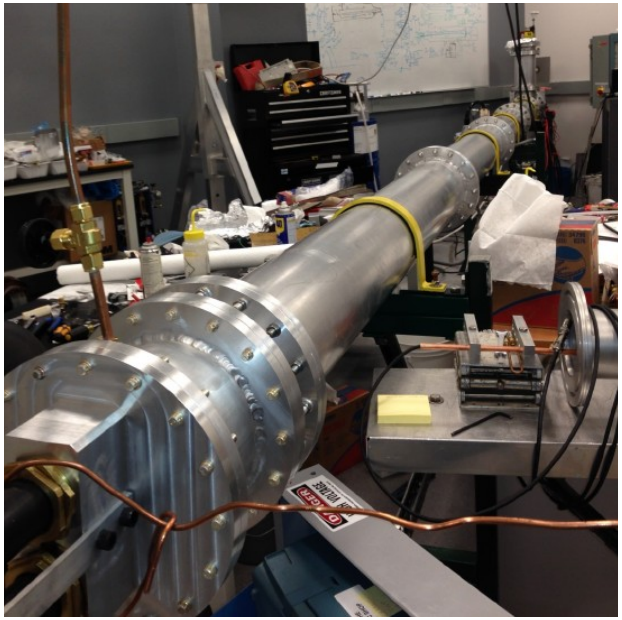
d = 77 mm, R=7112 mm
kick angle $\theta = d/R = 10.8$ mrad

CBO

New Kicker

D. Rubin, Cornell

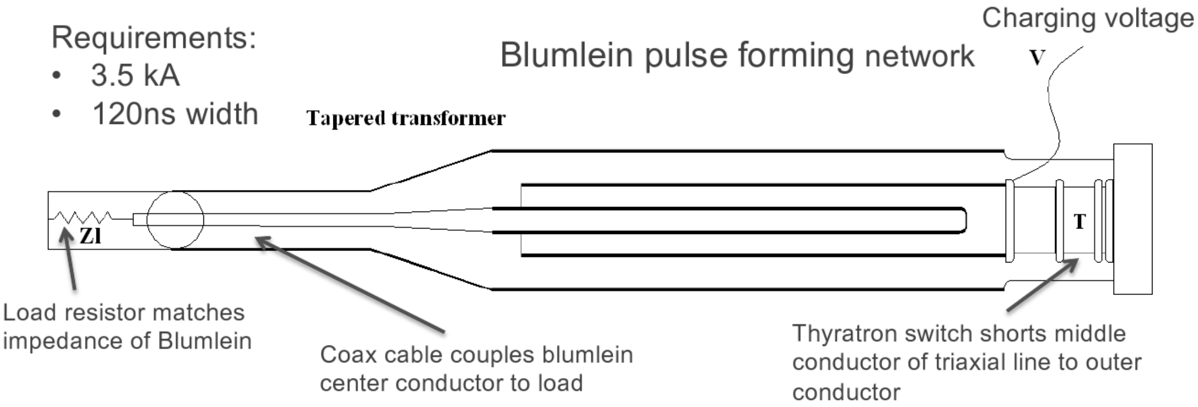




Requirements:

- 3.5 kA
- 120ns width

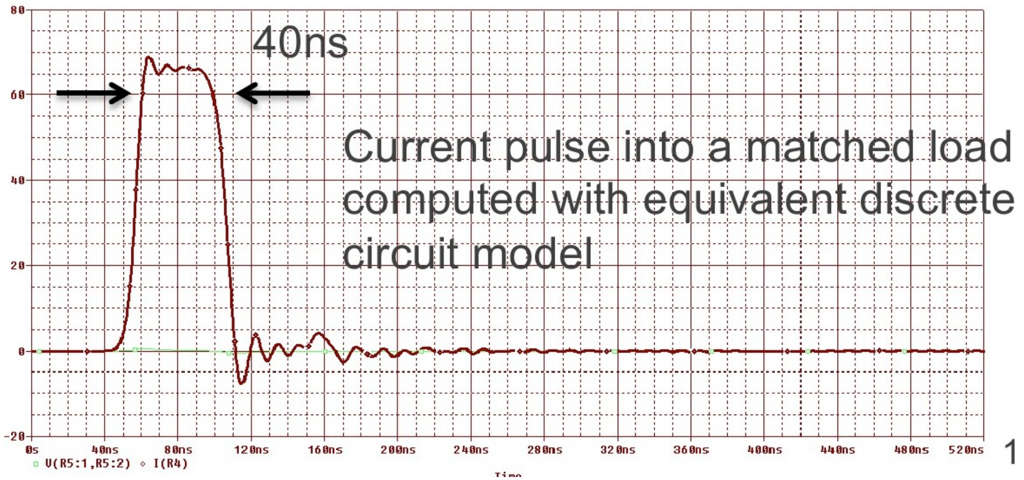
Blumlein pulse forming network



Load resistor matches impedance of Blumlein

Coax cable couples blumlein center conductor to load

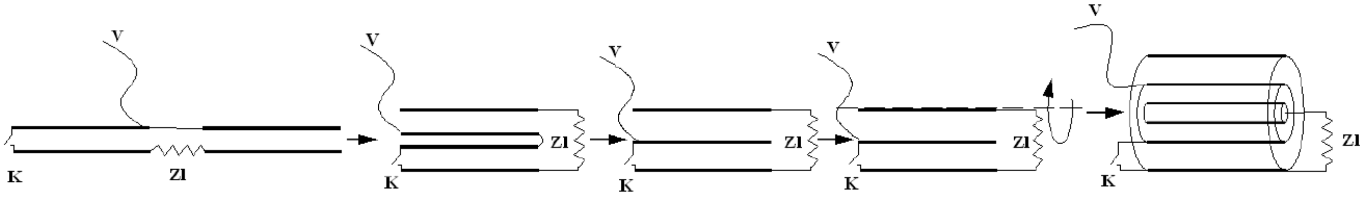
Thyratron switch shorts middle conductor of triaxial line to outer conductor



Current pulse into a matched load computed with equivalent discrete circuit model

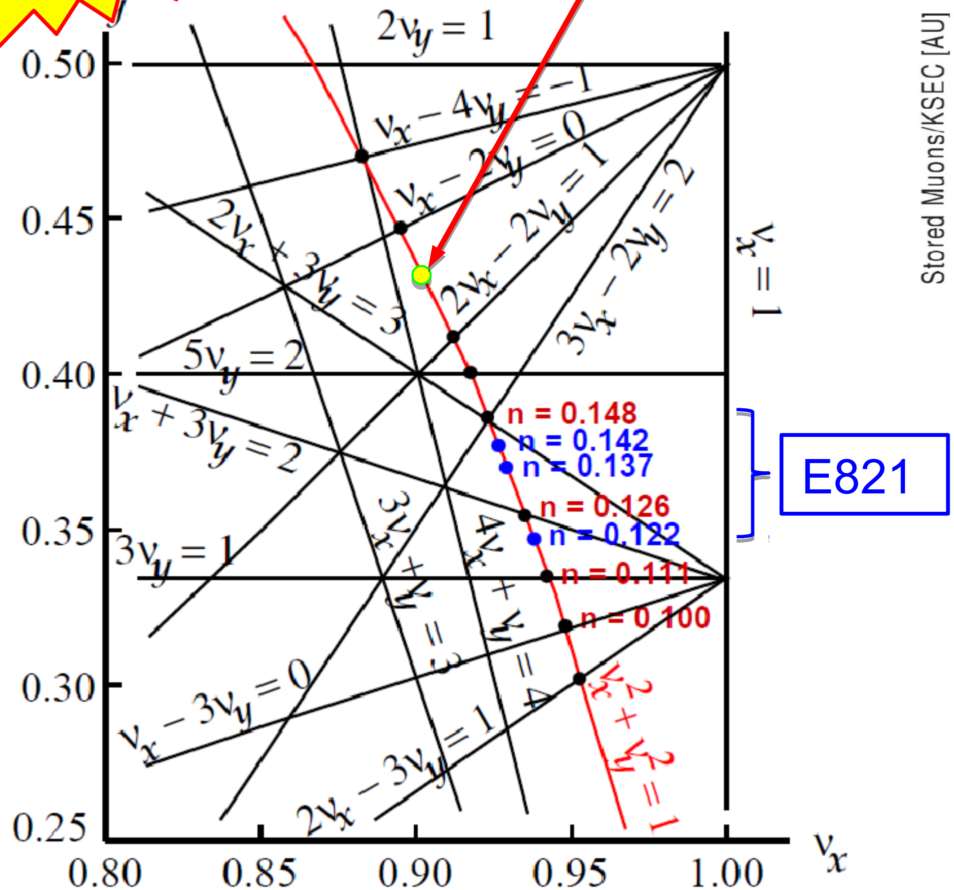
$$\tau = \frac{2L}{v}$$

width of pulse is proportional to length of blumlein



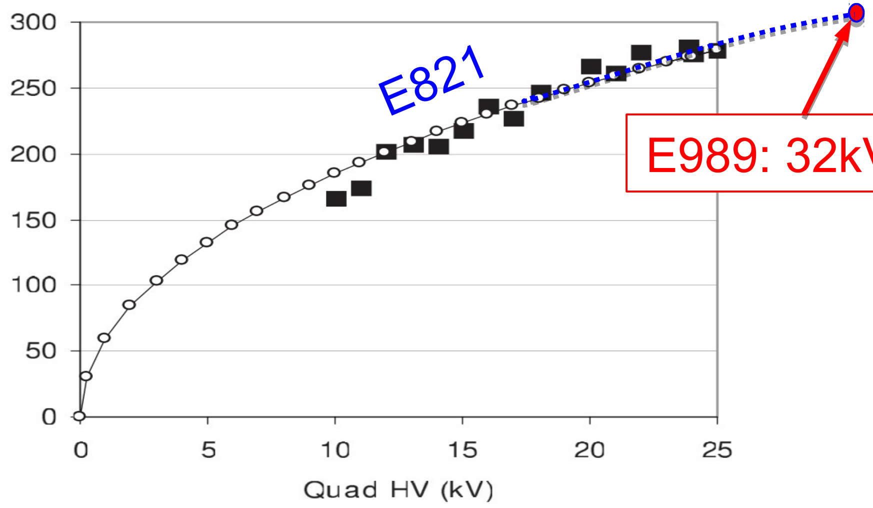
Upgrade of Quadrupoles to higher HV

CBO
Lost Muons

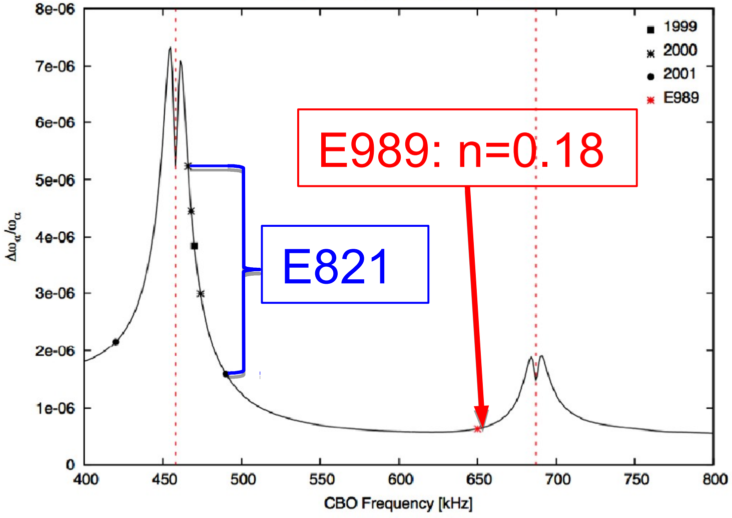


E989 goal

E821



E989: 32kV



E989: n=0.18

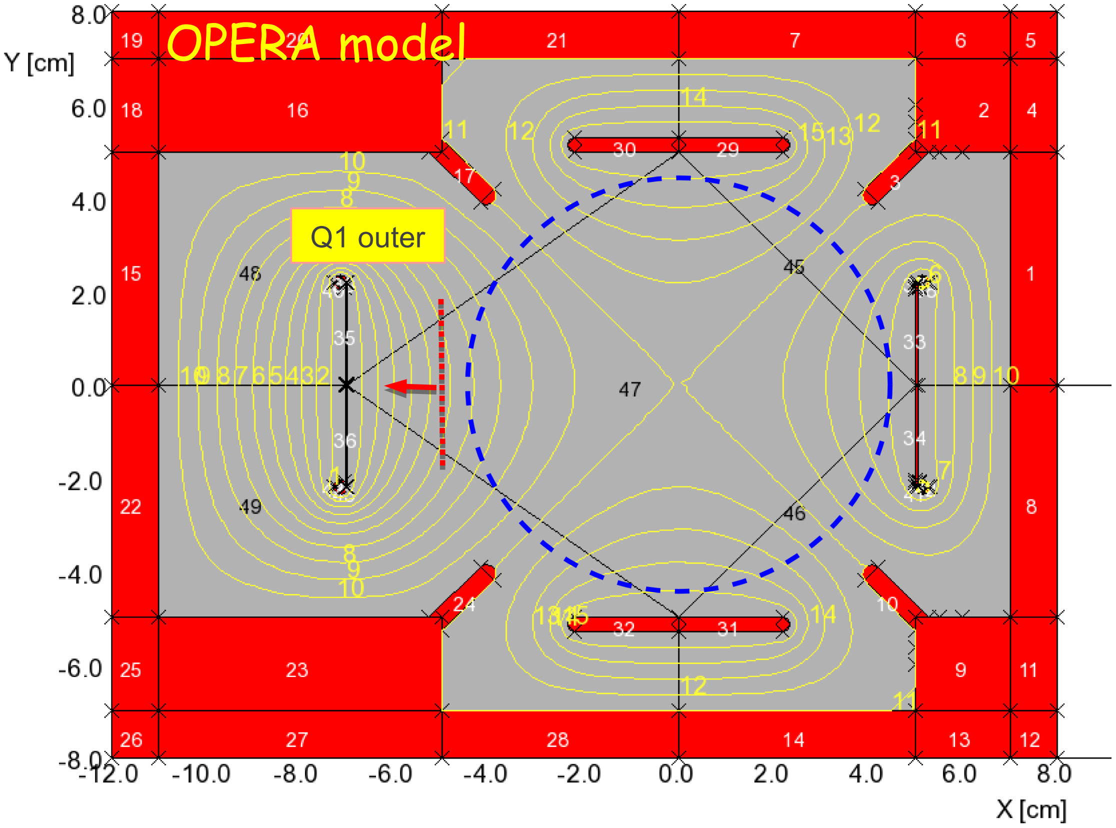
E821

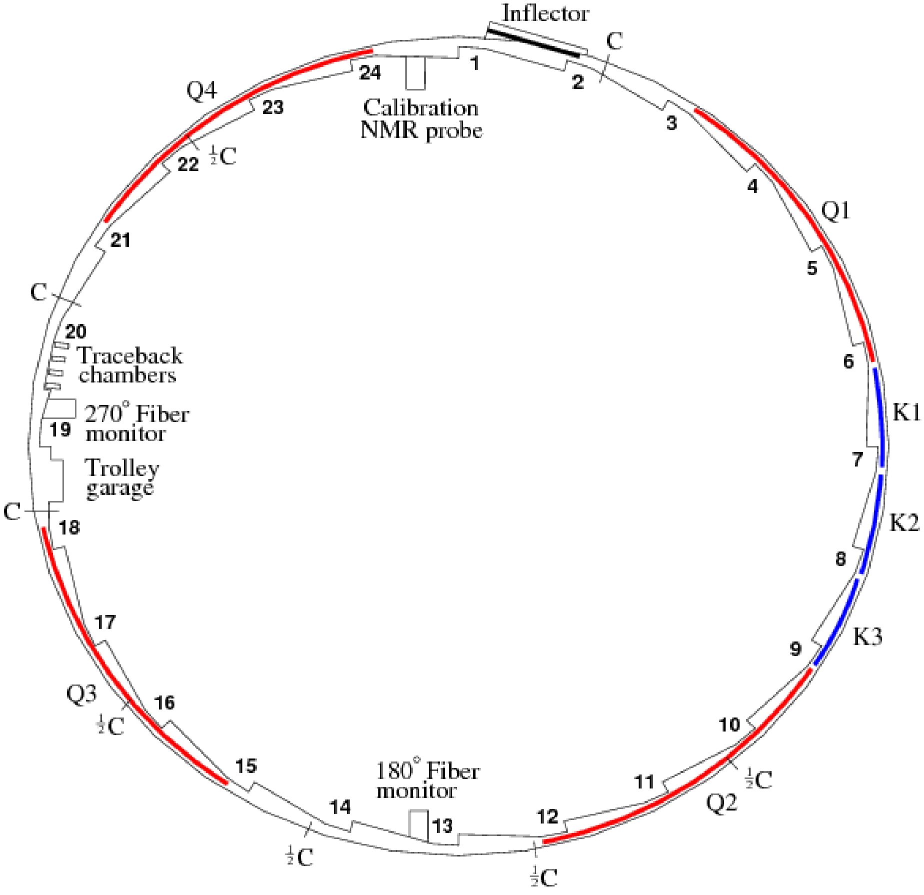
- Higher admittance of the (g-2) storage ring
- Lower CBO systematic error
- Lower muon loss systematic error

beam losses

Modify quadrupole Q1

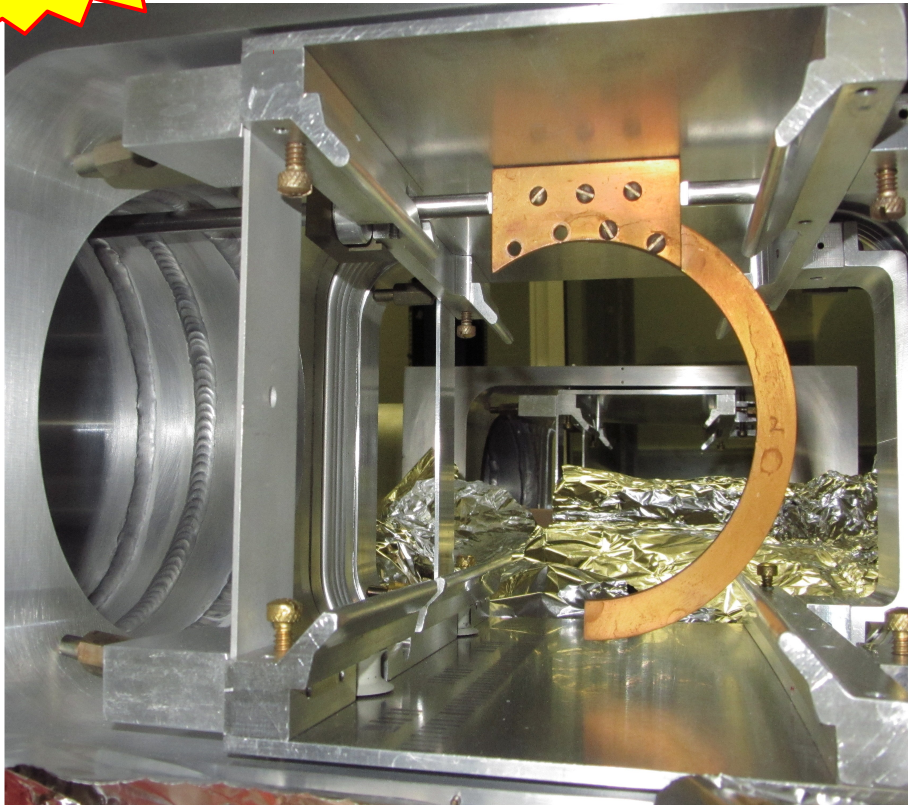
Goal: increase the number of stored muons (muon losses due to scattering in Q1 plate)
Baseline plan: Displace Q1 outer plate by ~2cm radially

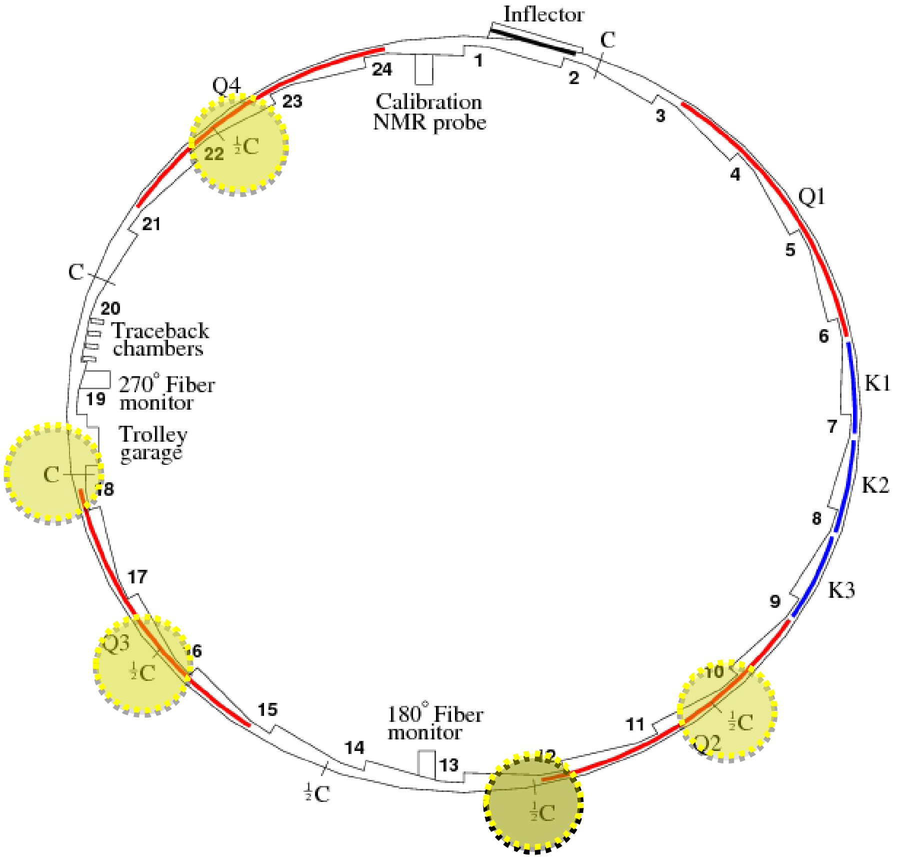




Lost Muons

New beam collimators

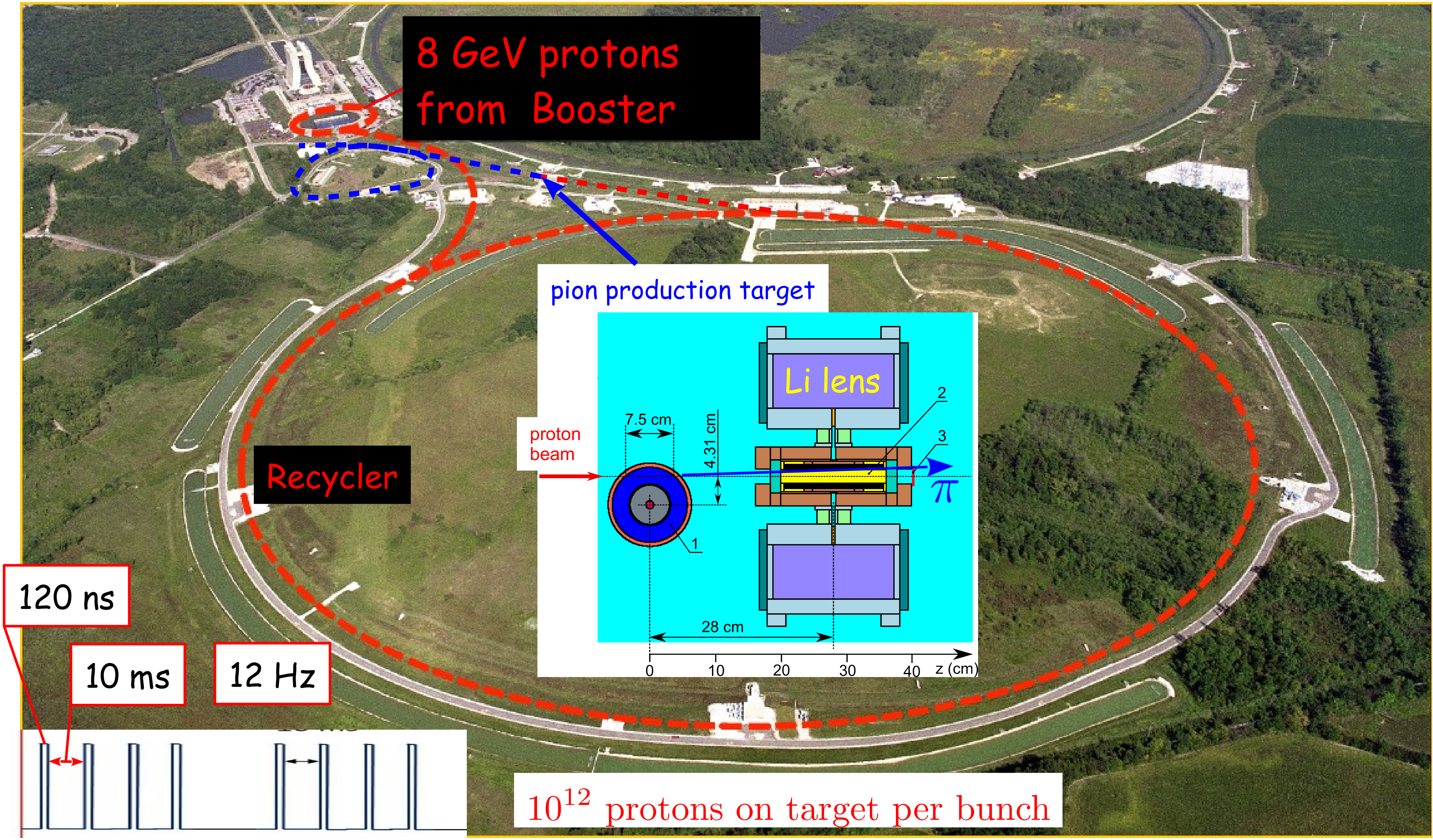




Baseline plan:

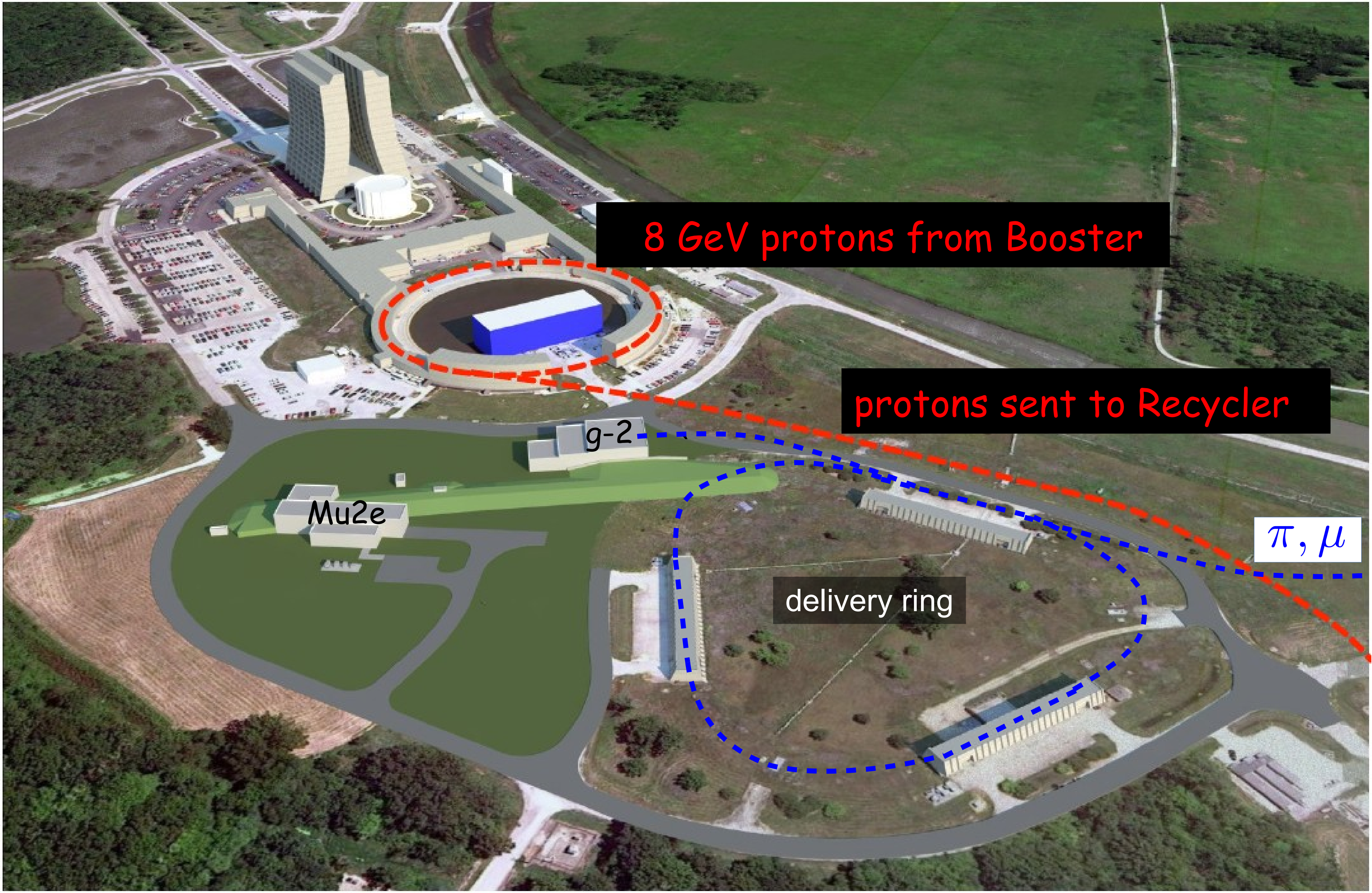
- Manufacture new collimators
- Elliptical profiles to match beta-functions of the g-2 storage ring
- Re-evaluate the thickness of collimators
- Replace $\frac{1}{2}$-collimators (see picture above) with full-collimators
- The number of collimators will be reduced due to conflicts with new tracking chambers
- Install sensors for in-beam/out-of-beam status monitoring

Muon Campus at Fermilab



10^{12} protons on target per bunch

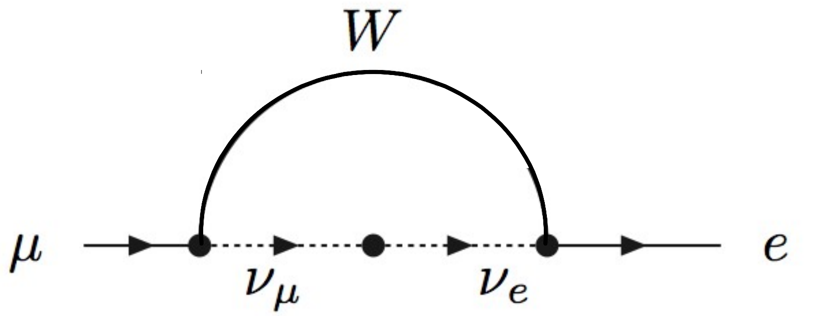
Muon Campus at Fermilab



Mu2e Physics

Goal: search for CLFV muon to electron conversion

SM



$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^{*}_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

Detection of charged lepton flavor violation will be an unambiguous signal of physics beyond the Standard Model.

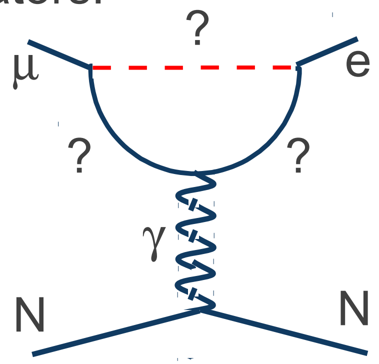
Mu2e Physics Reach

CLFV operators in SM Lagrangian.

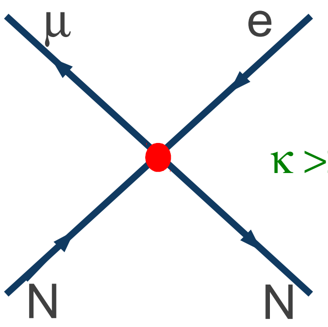
$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\sum_{q=u,d} \bar{q}_L \gamma^\mu q_L\right)$$

Λ is mass scale of new physics
κ controls relative contribution of two classes of operators:

$\kappa << 1$



Loops



$\kappa >> 1$

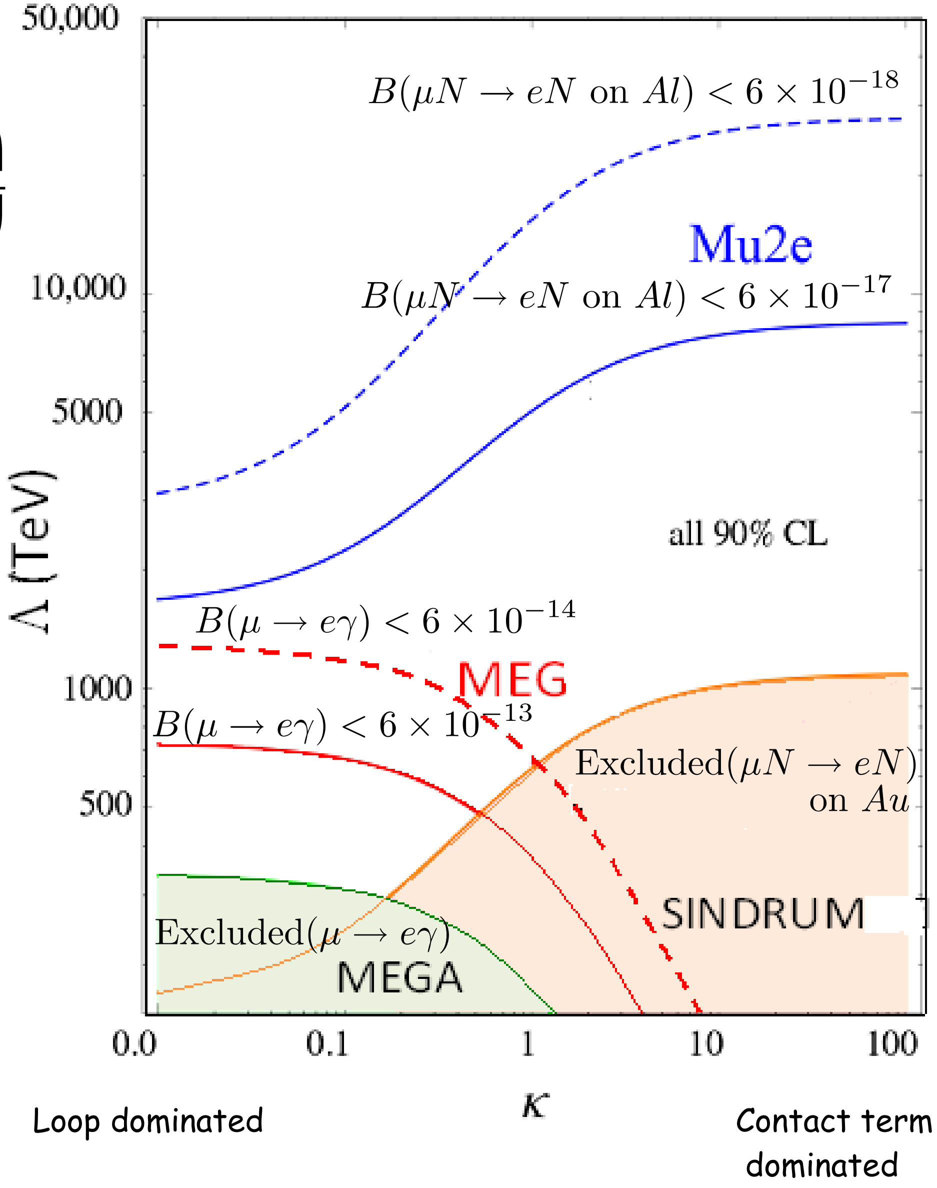
Contact Terms

Loops with photons contribute to μ –> eγ

Does not contribute to μ –>eγ

Both types of operators contribute to muon-to-electron conversion

A. de Gouvêa, P. Vogel, arXiv:1303.4097 [hep-ph]

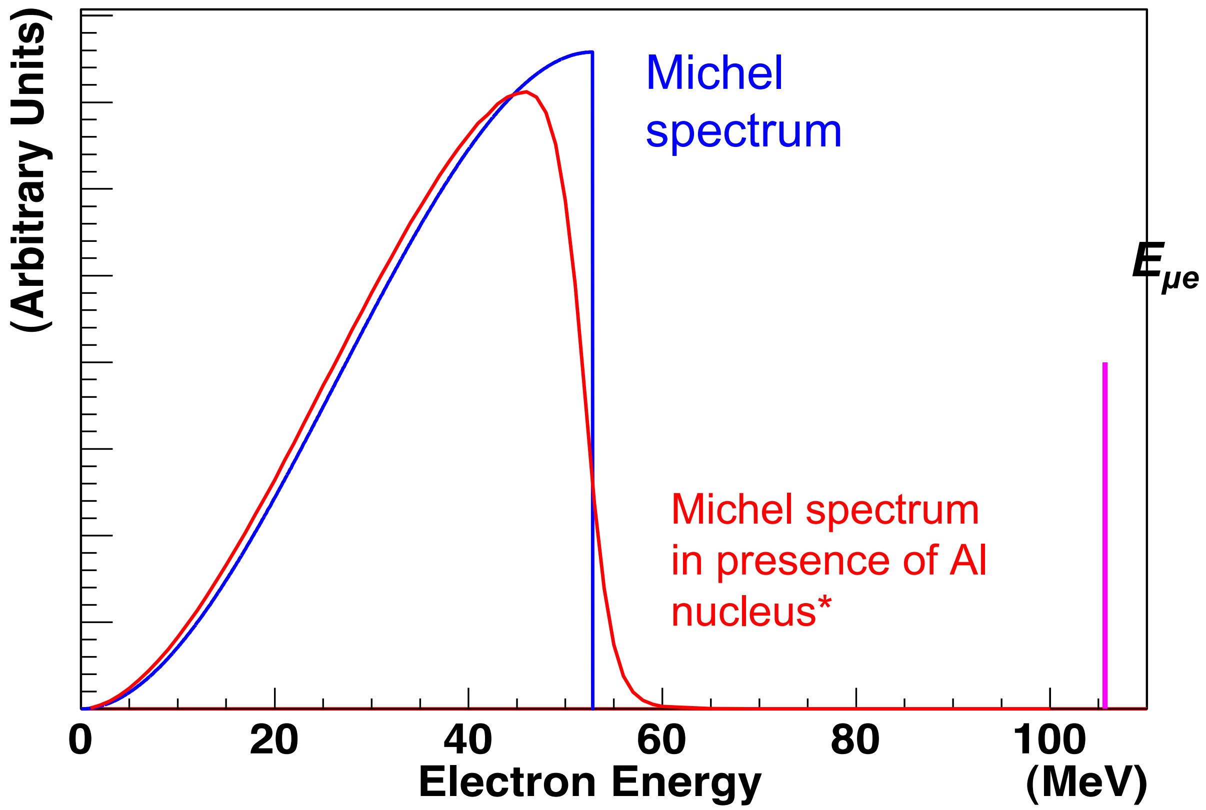


Mu2e Physics Signal

Coherent neutrinoless conversion of a muon to an electron in the field of a nucleus

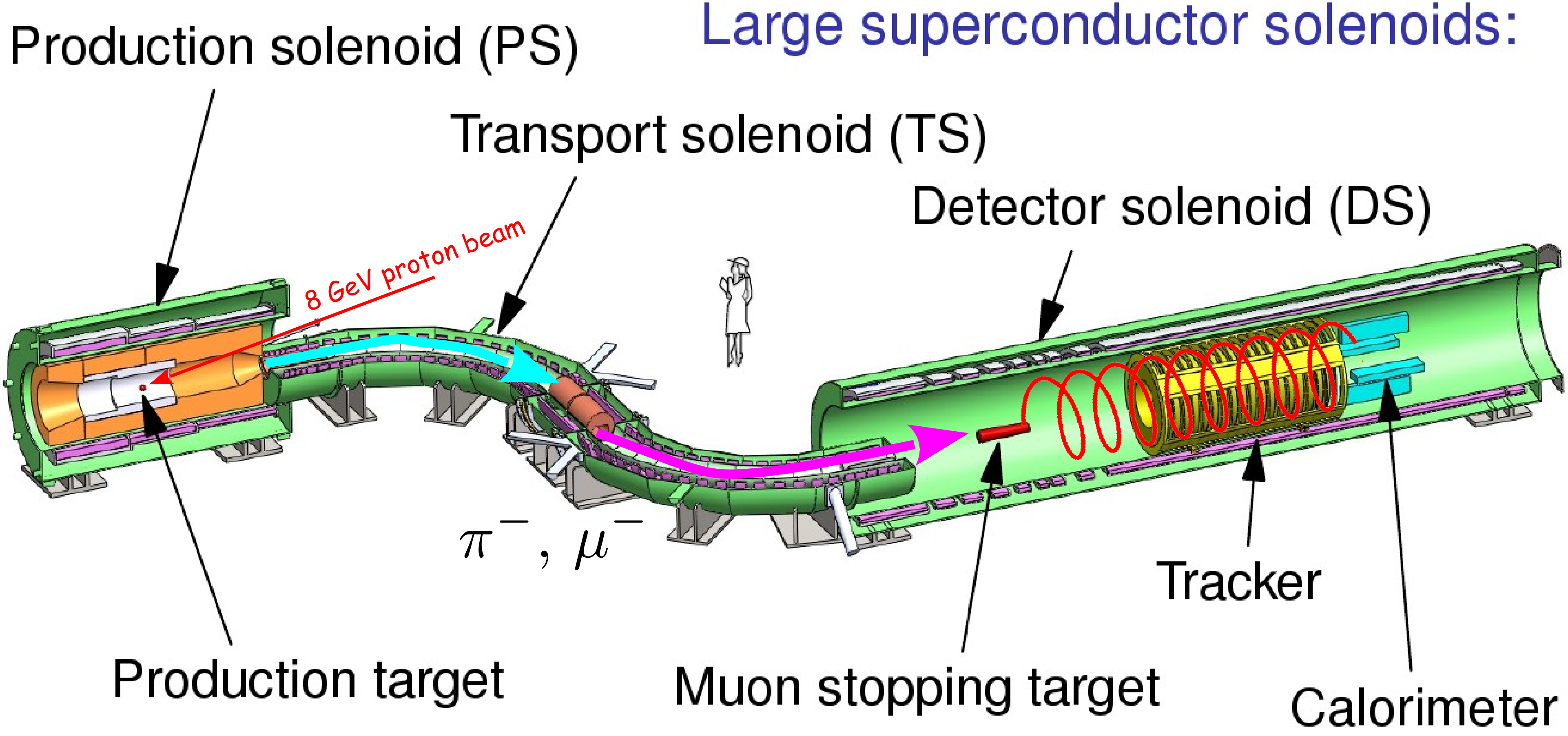
$$\mu^- N \rightarrow \; e^- N$$

$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\rm recoil} \\ &= 104.973 \text{ MeV} \quad (\text{for Al}) \end{aligned}$$



Mu2e Experiment

Large superconductor solenoids:



Not shown:

Cosmic ray veto, Extinction monitor, Stopping target monitor

MC1 (g-2) building


Photo: Brian Drendel, AD

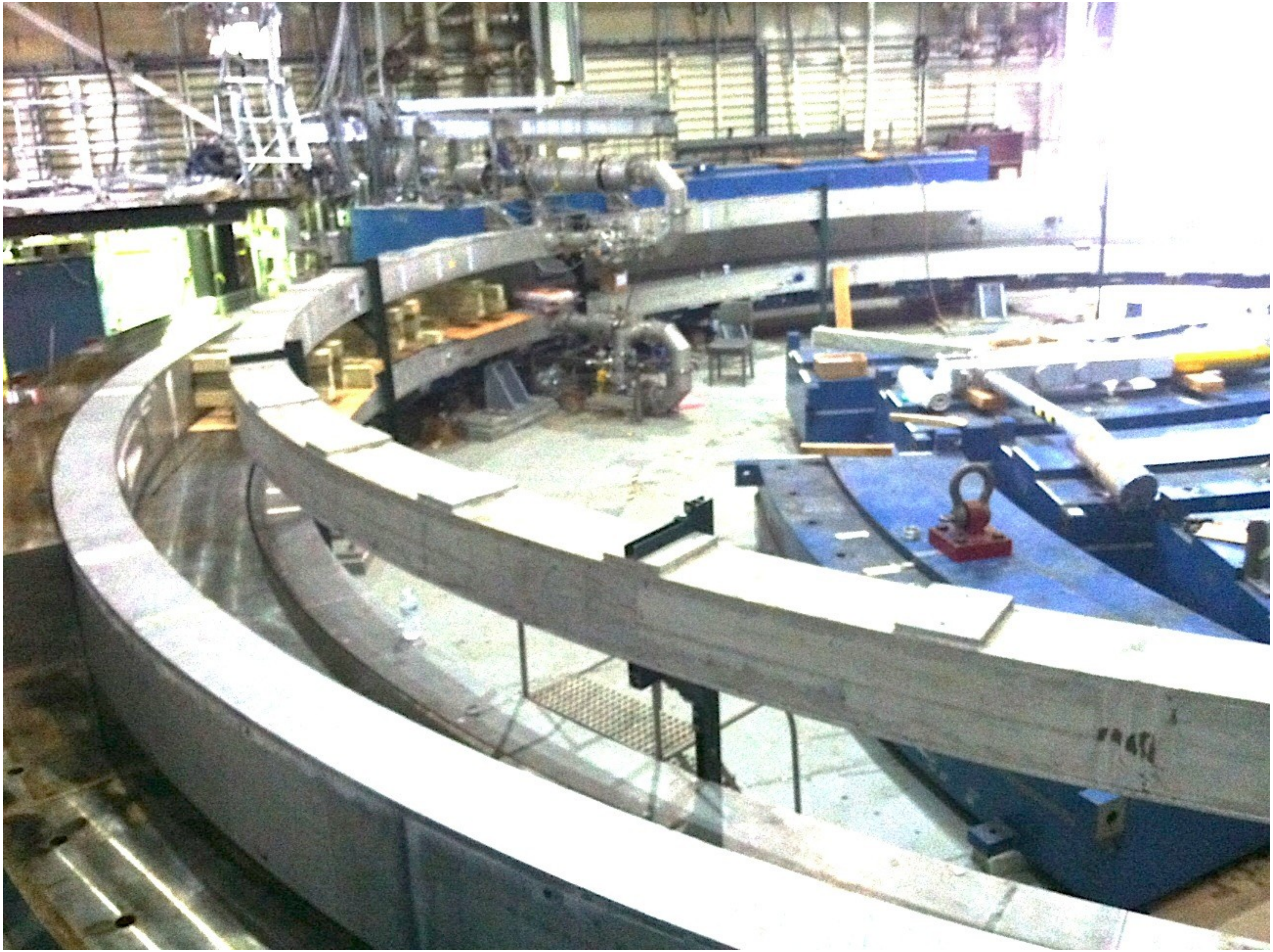
beneficial occupancy May 2014

- Hall temperature stability +/- 1°C
- Stable floor (reinforced concrete, 84-cm-thick)

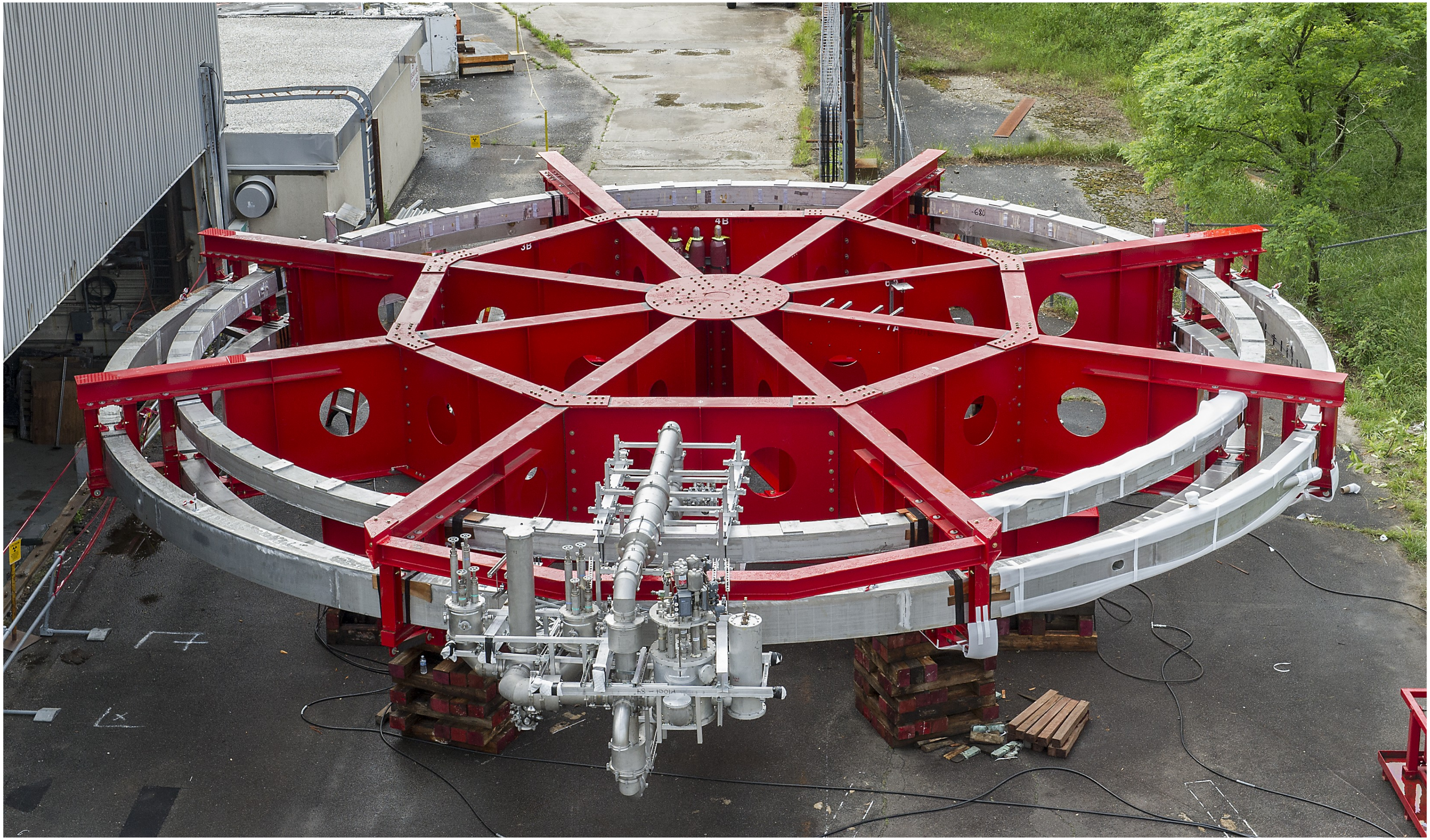
Storage ring at BNL in 2011 (E821)

September 2012: first yoke piece removed

30 September 2012



14 June 2013



The transport fixture and coils are outside Bldg. 919 at BNL. The superconducting coils are attached to the transport fixture.

22 June 2013

Moving from Bldg. 919 to BNL Lab. gate

24 June 2013


unloading...


Craning onto the barge


Leaving Smith Point Marina on Long Island

journey from NY to IL

more photos and info: http://muon-g-2.fnal.gov/bigmove

20 July 2013

Arriving Lemont, IL

At Fermilab

Ring reassembly at Fermilab

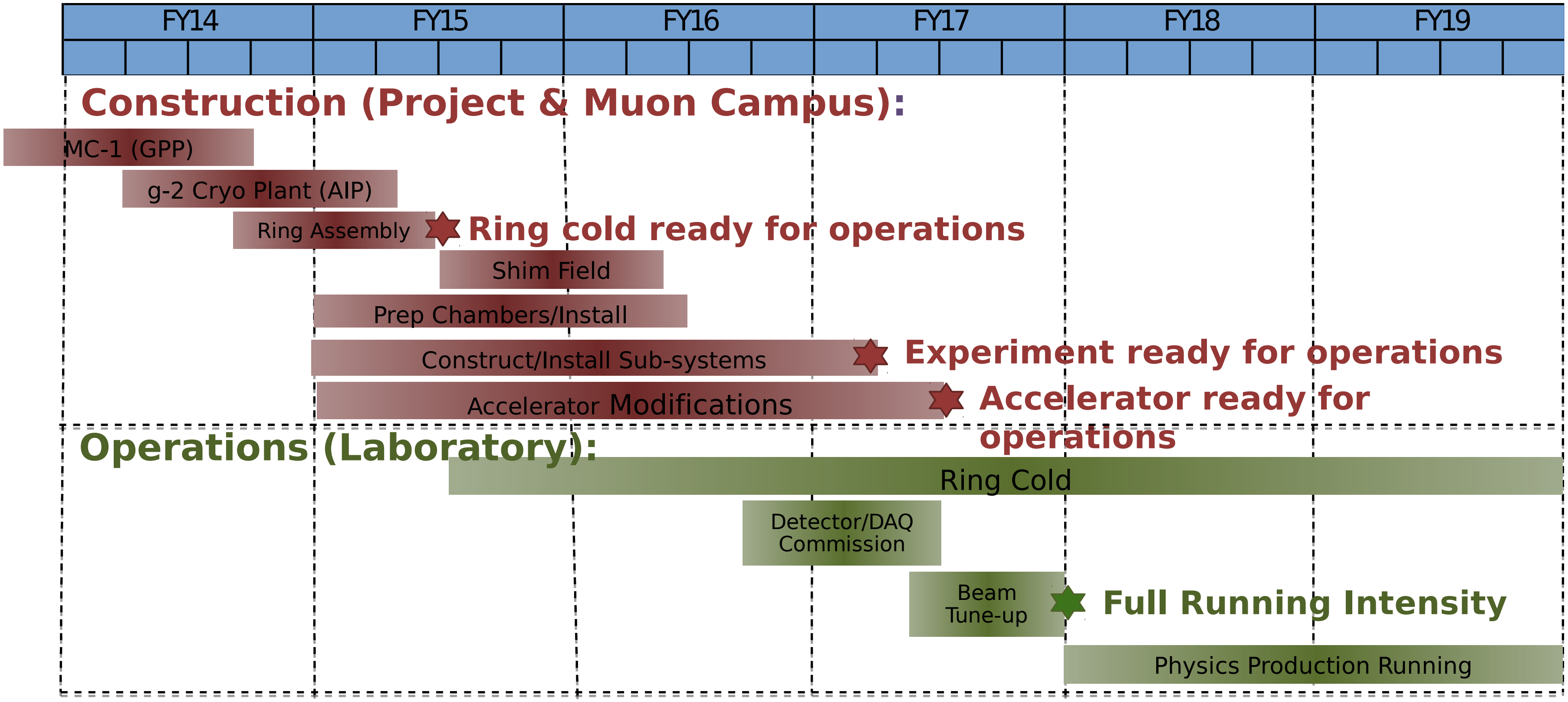
June 23, 2014. Bottom yoke. Reassembly progresses well. Superconducting coils will be moved into the experimental hall end of July 2014

Summary

- The new muon (g-2) experiment at Fermilab will reduce the experimental uncertainty by a factor of about four
- The experimental setup has been successfully moved from Brookhaven to Fermilab
- Reassembly of the g-2 storage ring progresses well
- R&D work on calorimeters, electronics, DAQ, kicker, quadrupoles, collimators, electron trackers, field measurement and instrumentation to reduce systematic uncertainties progresses well
- DOE CD2/3 review: Next week.

Backup Slides

Muon g-2 Schedule



FY14 FY15 FY16 FY17 FY18 FY19

Construction (Project & Muon Campus):

MC-1 (GPP)

g-2 Cryo Plant (AIP)

Ring Assembly

Ring cold ready for operations

Shim Field

Prep Chambers/Install

Construct/Install Sub-systems

Experiment ready for operations

Accelerator Modifications

Accelerator ready for operations

Operations (Laboratory):

Ring Cold

Detector/DAQ Commission

Beam Tune-up

Full Running Intensity

Physics Production Running