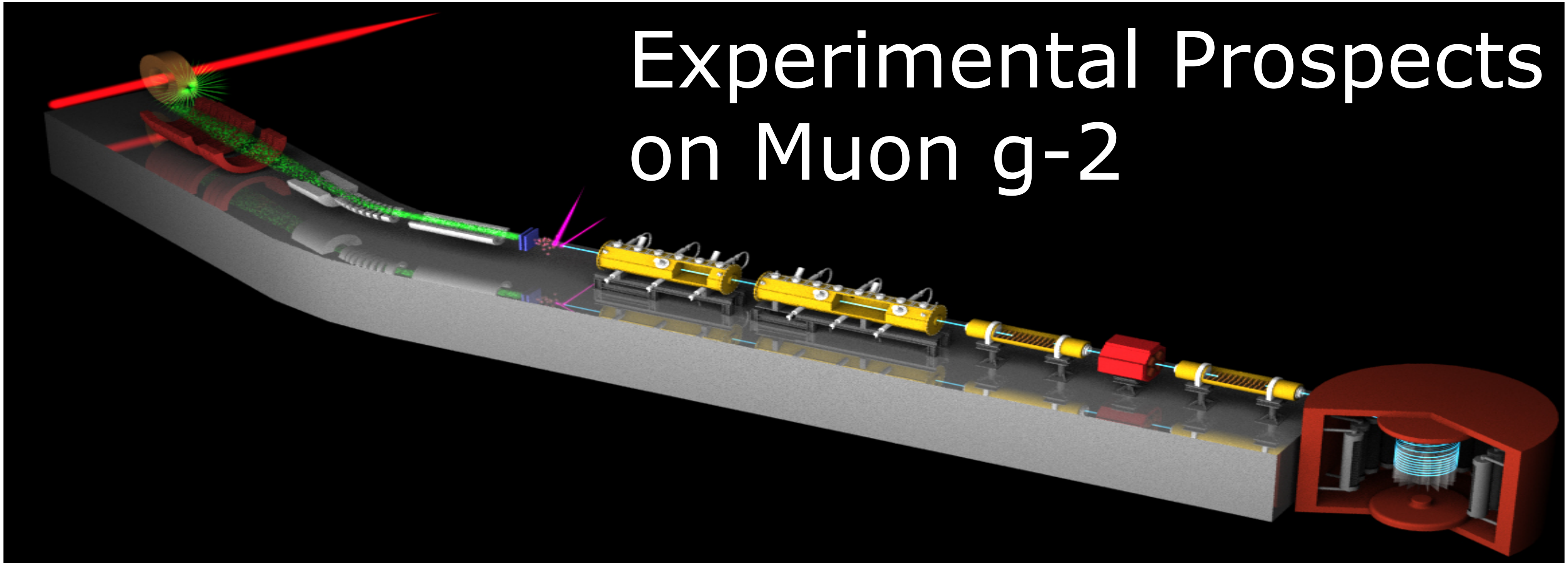
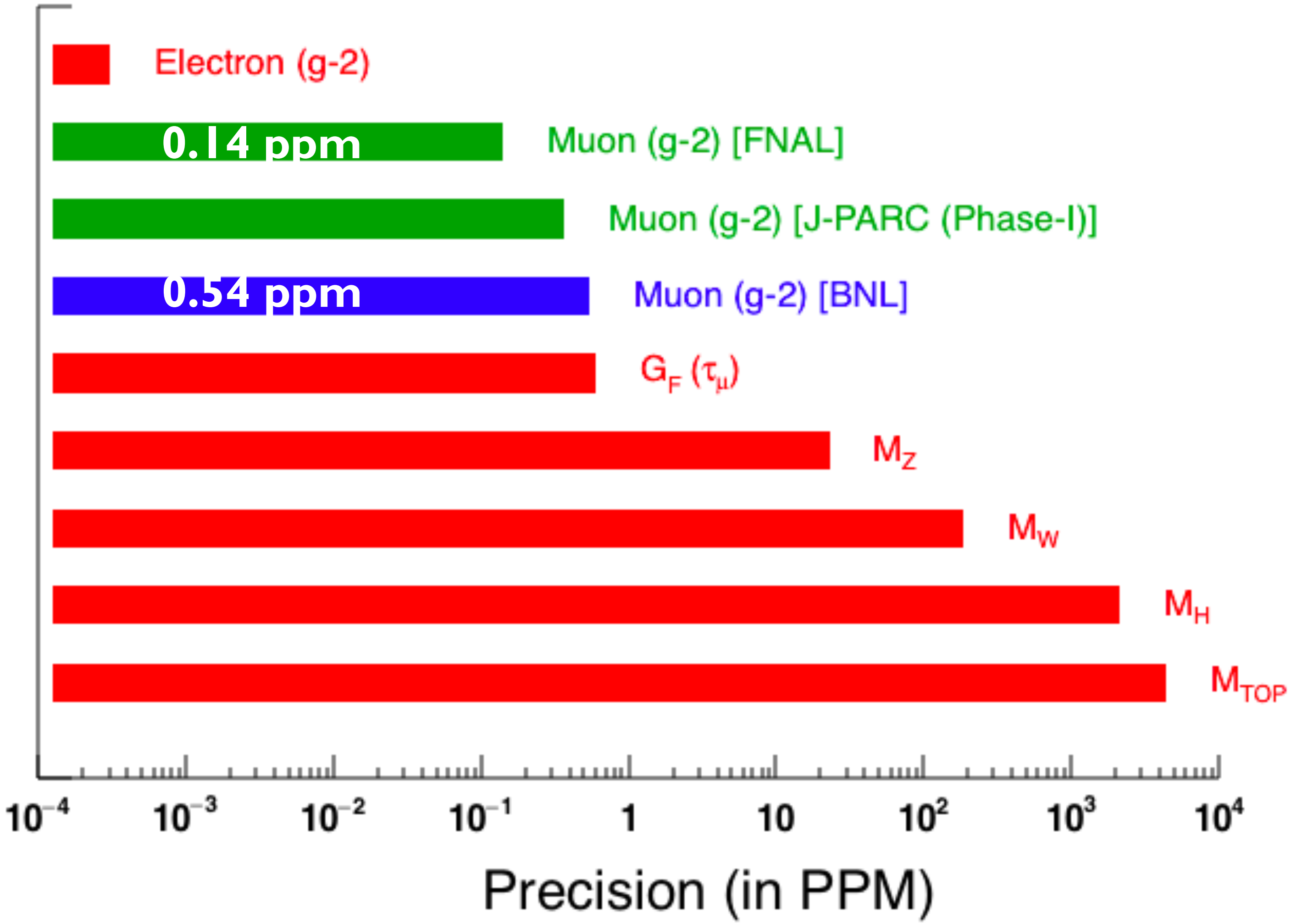
Experimental Prospects on Muon g-2



Mark Lancaster

University College London

Aim



Electron (g-2)
0.14 ppm
Muon (g-2) [FNAL]
Muon (g-2) [J-PARC (Phase-I)]
0.54 ppm
Muon (g-2) [BNL]
G_F (τ_μ)
M_Z
M_W
M_H
M_{TOP}
10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^2 10^3 10^4
Precision (in PPM)

How to achieve 0.1 ppm

“Never measure anything but frequency”

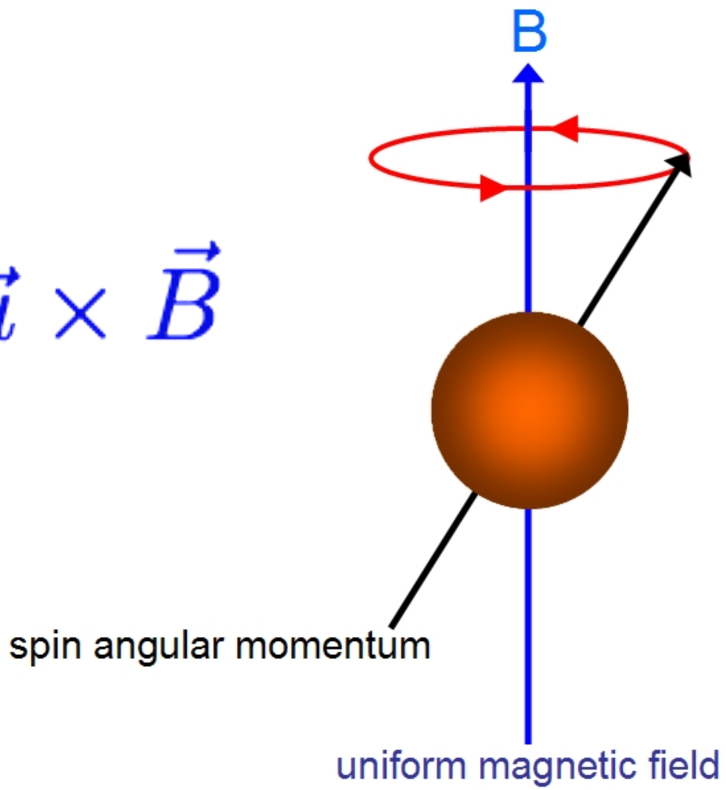
I. Rabi

g-2 basics

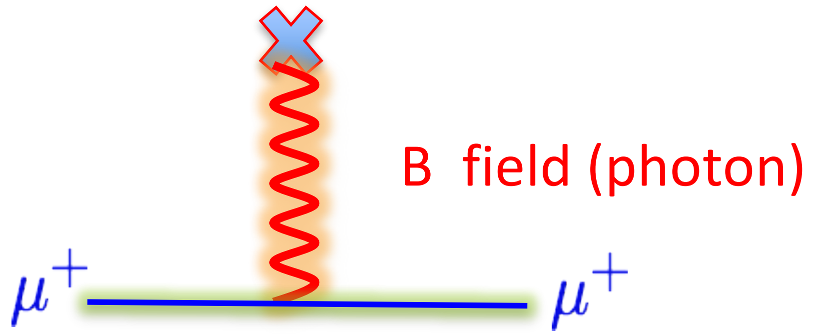
$$\vec{\mu} = g\frac{Qe}{2m}\vec{s}$$

Interaction between
magnetic moment (spin) with B-field.

$$\vec{\mu} \times \vec{B}$$



Spin **precesses** around B at
a frequency determined by "g"



Motion in B-field storage ring

Particle in a circular storage ring (B-field): two frequencies:

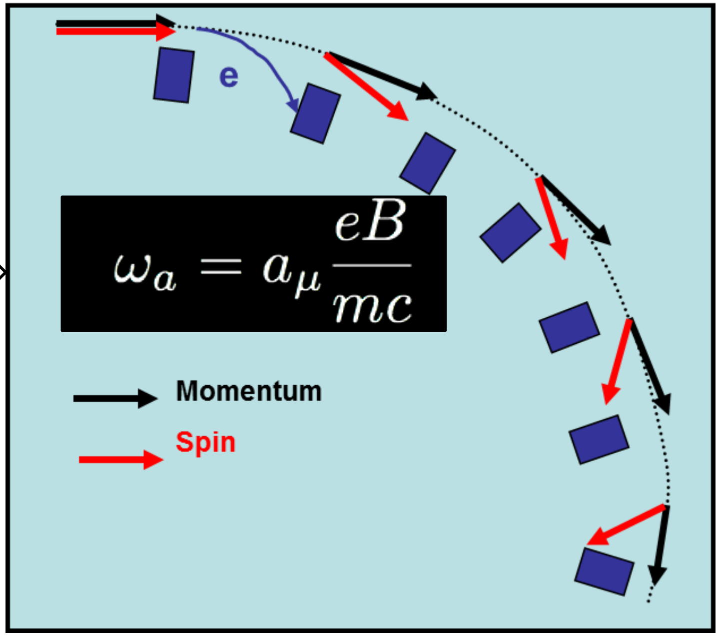
$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \qquad \omega_C = \frac{eB}{mc\gamma}$$

Spin vector of muon rotates slightly quicker than Momentum vector.

For a 1.5T field spin rotates in 144ns and momentum in 149ns.

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$

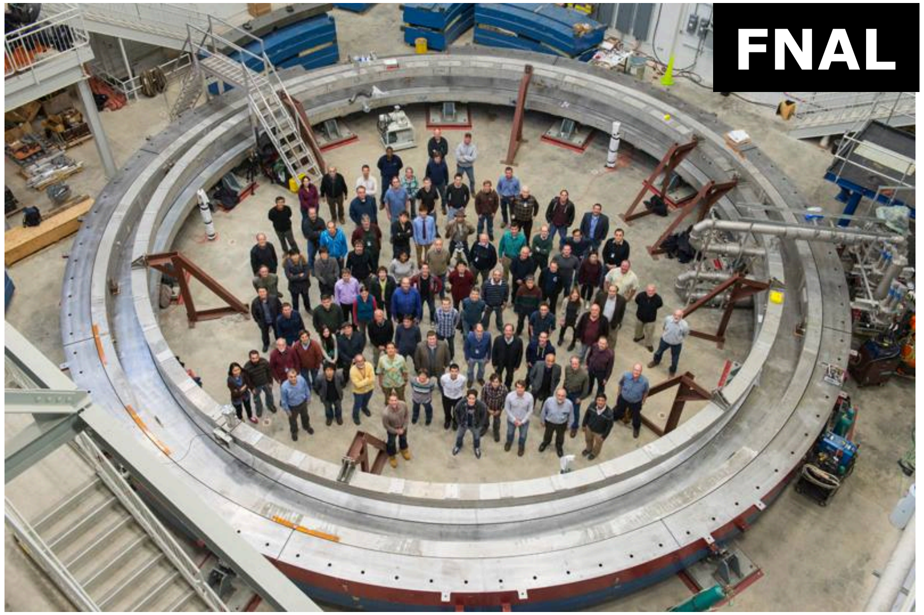
$$f_a = 228 \text{ kHz}$$

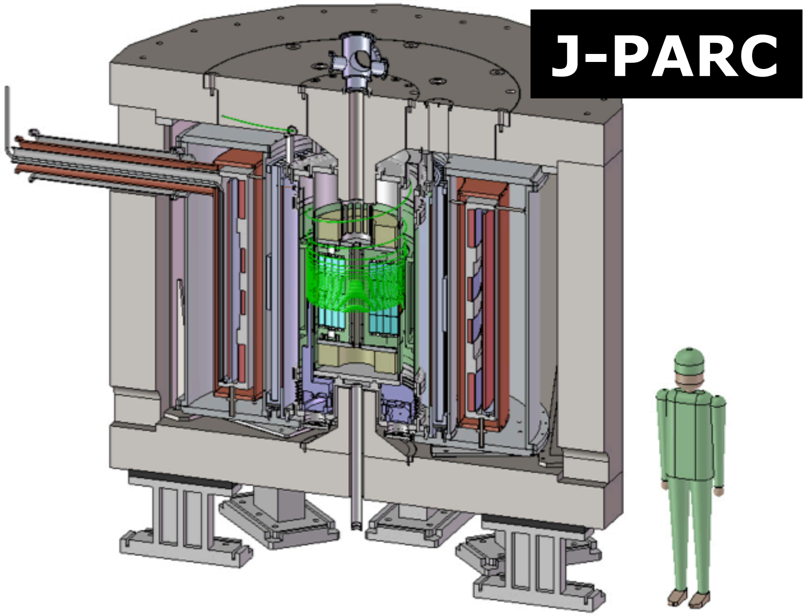


The real world

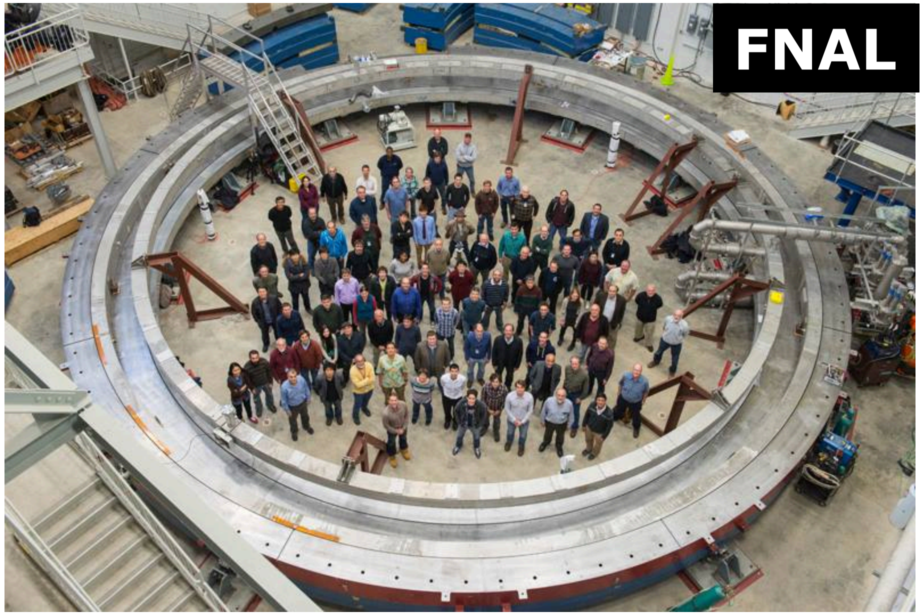
But real beams are not all on the same perfect circular orbit and can have a (small) transverse velocity component.
These imperfection causes beam to diverge vertically.

Two approaches:
- cancel the divergence with an electric quadrupole field (CERN,BNL, FNAL)
- minimise the divergence by reducing the beam p_T (J-PARC)

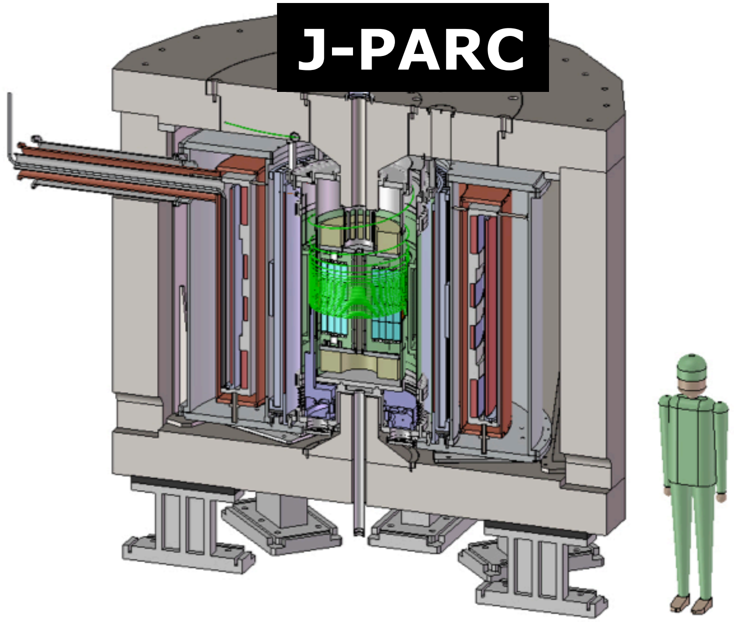




Two very different experiments



3.094 GeV muons
1.45 T, 14m bespoke magnet
Focussing quadrupoles
Kicker magnets
Emittance: 1000pimm



0.3 GeV muons
3T, 66cm MRI magnet
$\Delta p_T/p_T$ = 1e-5

Apparatus and hence systematics are very different

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

FNAL: MAKE ZERO BY CHOOSING "MAGIC" γ

J-PARC: MAKE ZERO BY HAVING E=0

$$a_\mu = \omega_a \frac{mB}{e}$$

Both expts need to measure two quantities
- B field
- ω_a

To better than 0.1 ppm

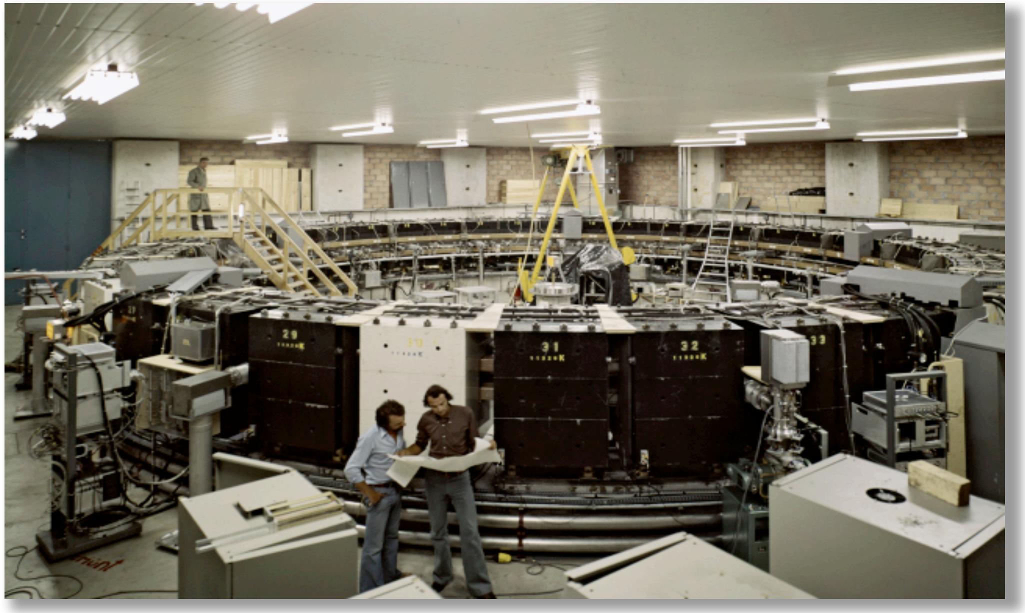
B is measured using NMR in terms of the proton Larmor frequency : ω_p

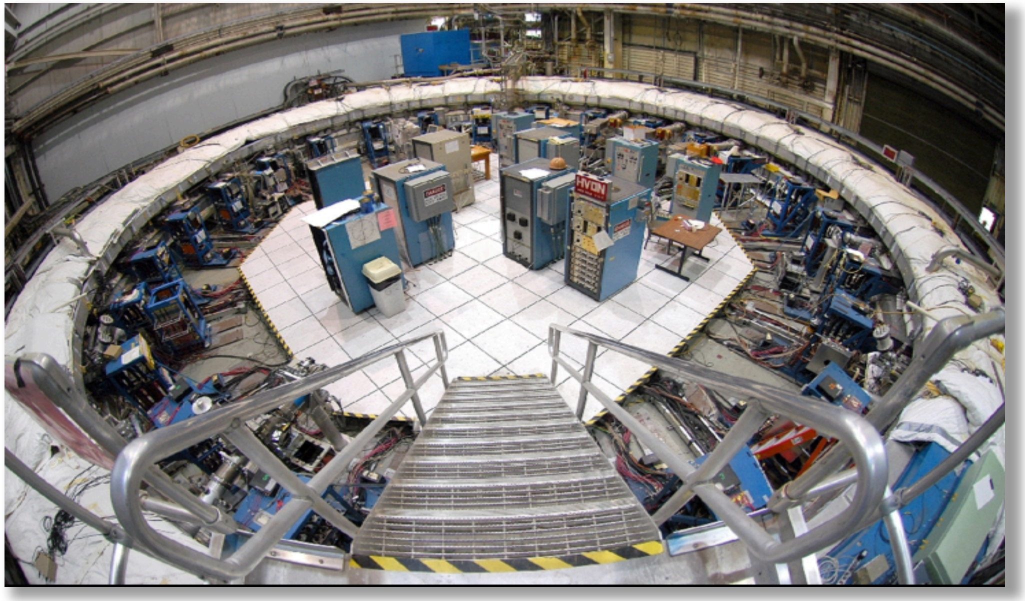
$$a_\mu = \frac{\omega_a/\omega_p}{\lambda_+ - \omega_a/\omega_p} \; ; \; \lambda_+ = \mu_{\mu^+}/\mu_p$$

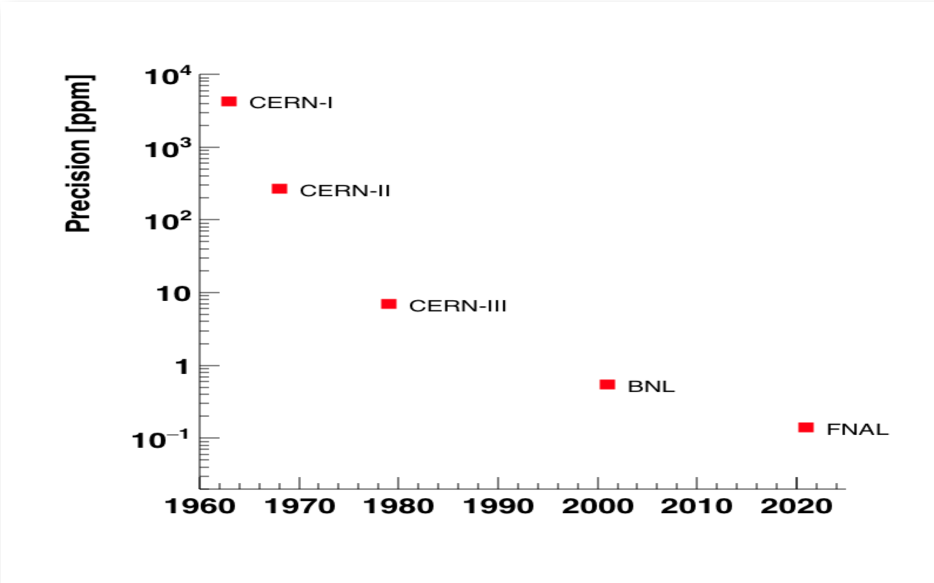
λ_+ measured from muonium hyperfine structure

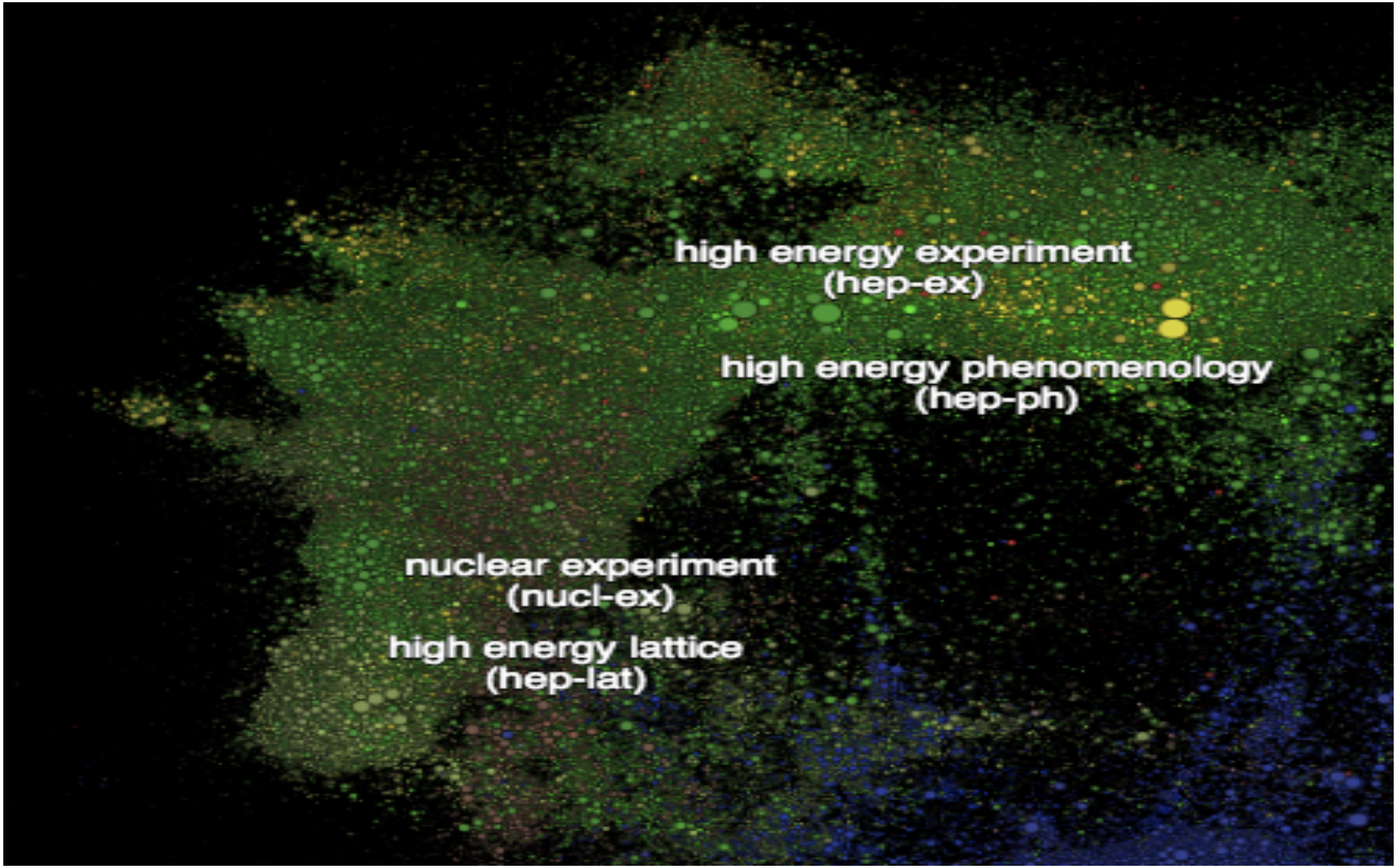
Uncertainty in a_μ determined by precision of ω_p and ω_a measurements

FNAL g-2 experiment

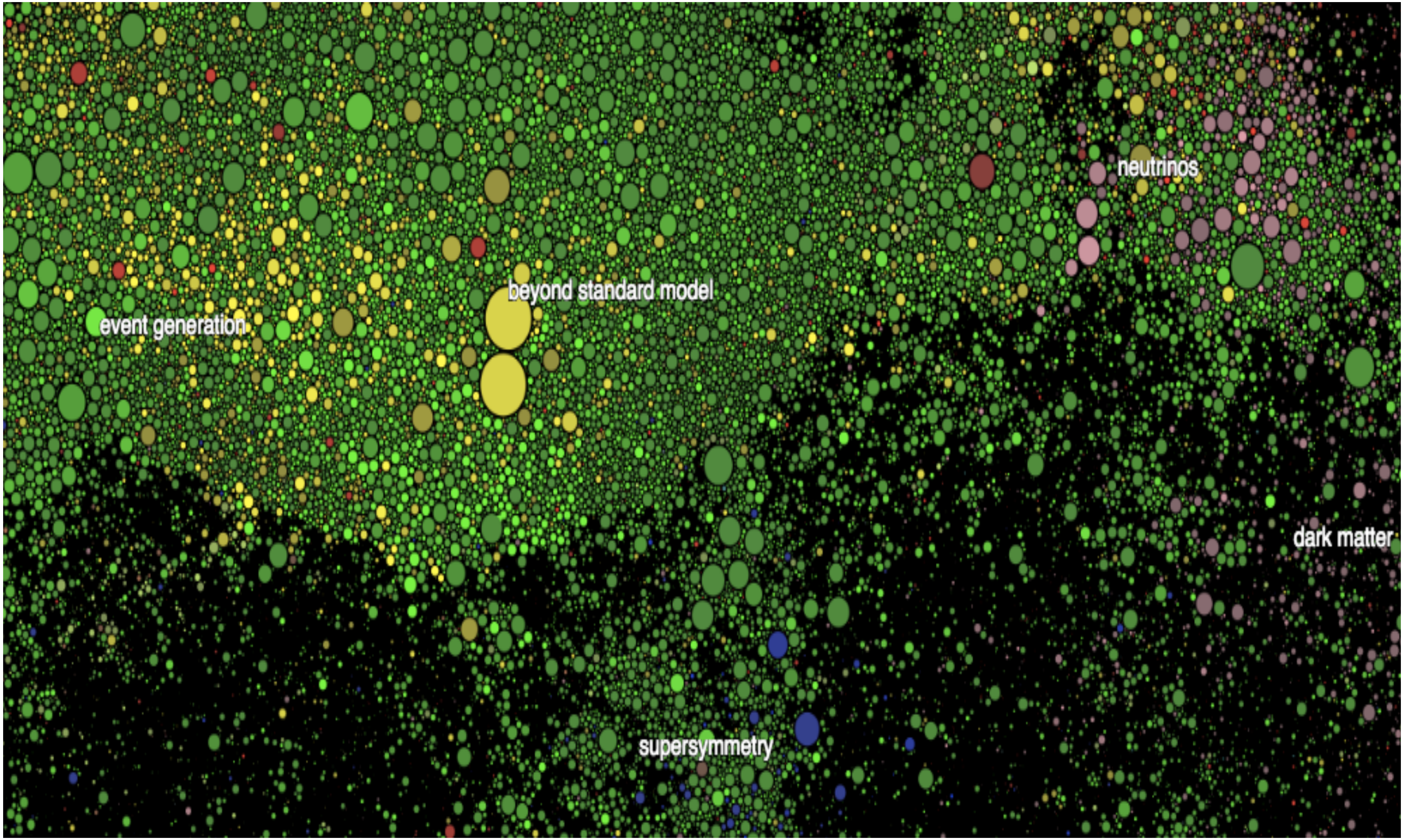


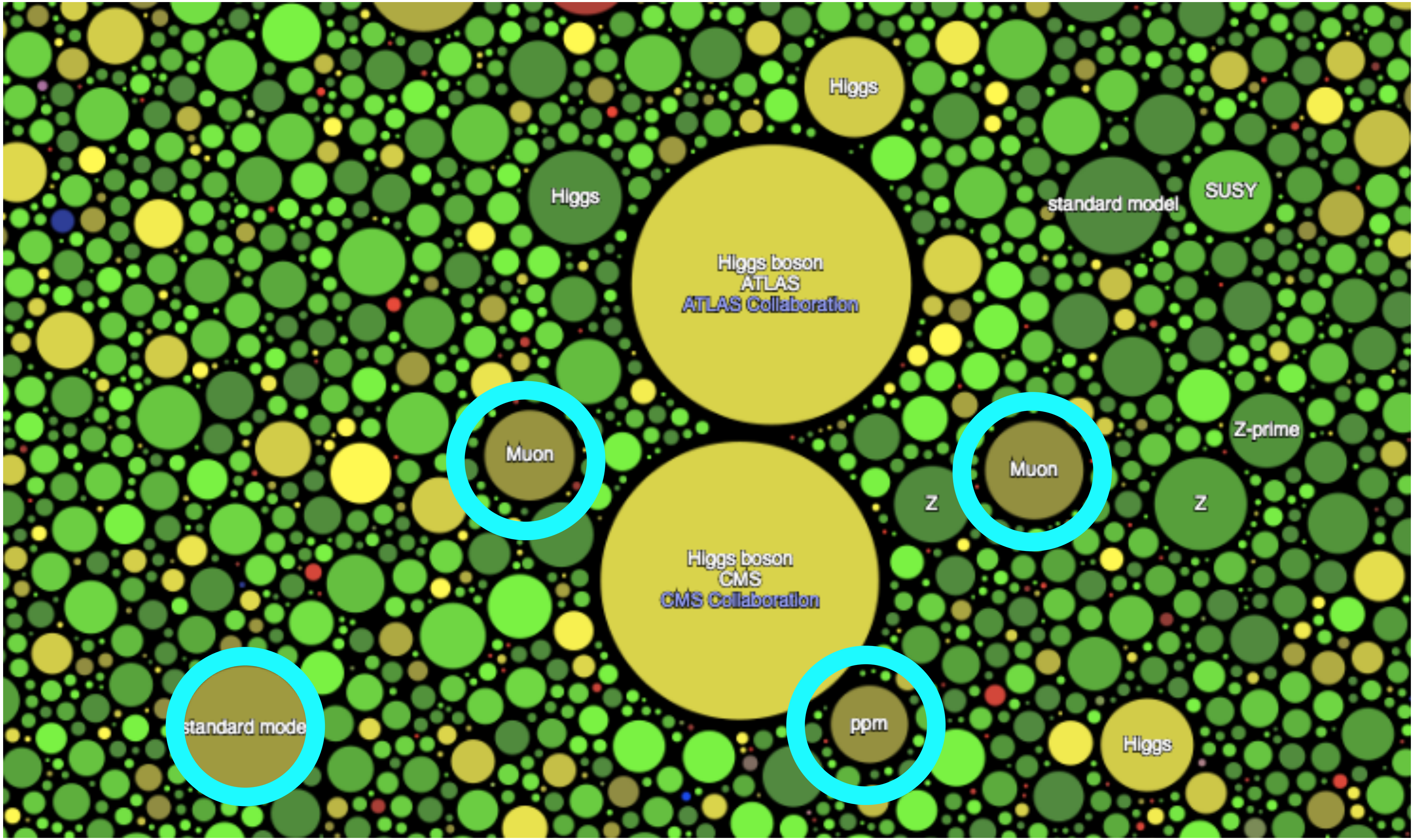





high energy experiment
(hep-ex)
high energy phenomenology
(hep-ph)
nuclear experiment
(nucl-ex)
high energy lattice
(hep-lat)

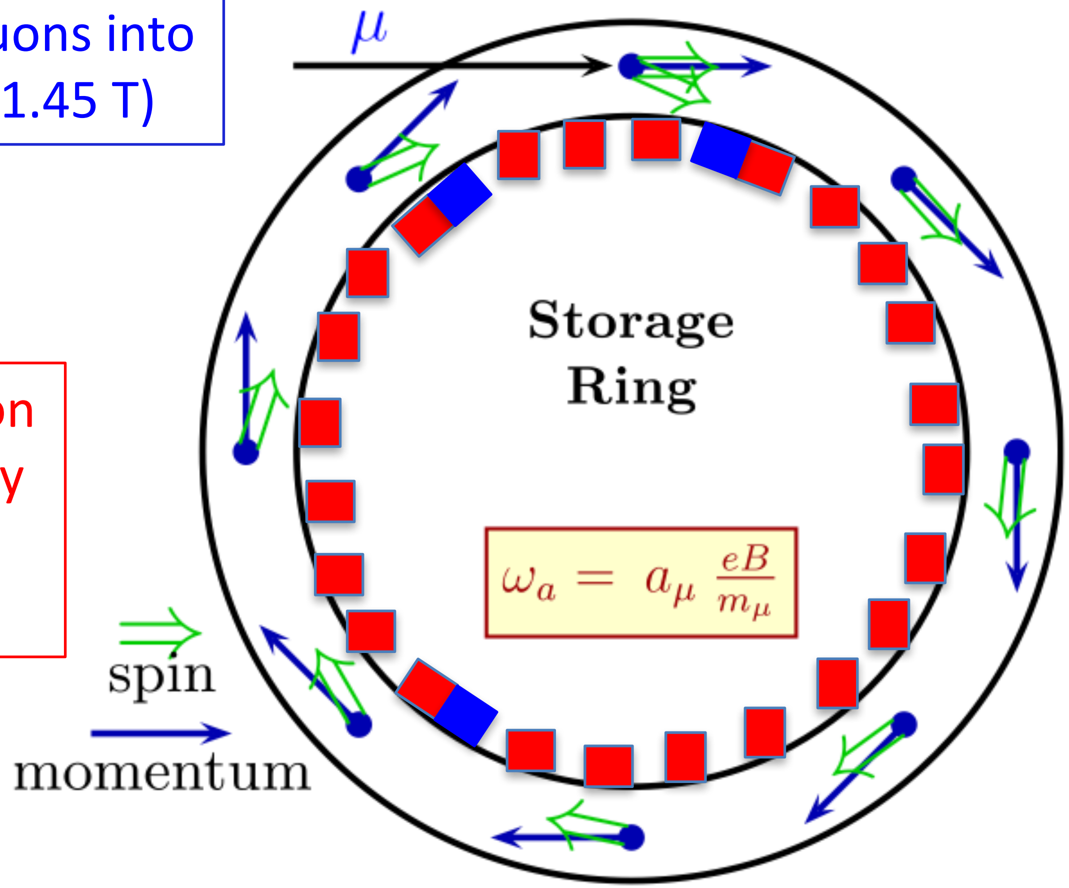
http://paperscape.org/




Higgs
Higgs
Higgs boson
ATLAS
ATLAS Collaboration
standard model
SUSY
Z-prime
Muon
Muon
Z
Z
Higgs boson
CMS
CMS Collaboration
standard mode
ppm
Higgs

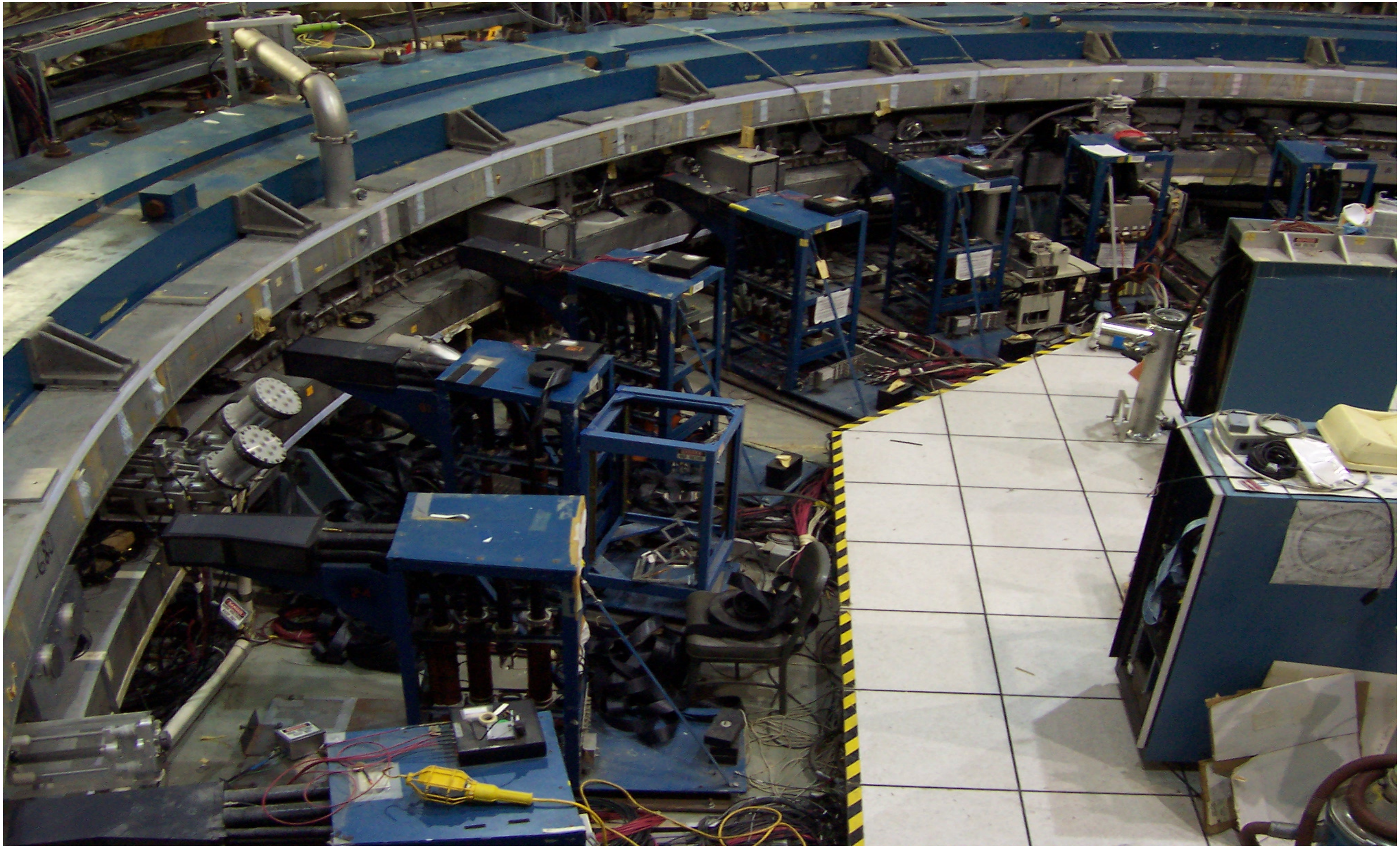
Inject 3.09 GeV muons into a storage ring (B = 1.45 T)

Exploit property that direction of e^+ from μ^+ decay is strongly correlated with μ^+ spin for highest energy e^+



24 calorimeters and 3 straw trackers measure e^+ for O(1 ms) for spills separated by 10ms.
16,000 stored 3.09 GeV muons from 10^{12} protons per spill.

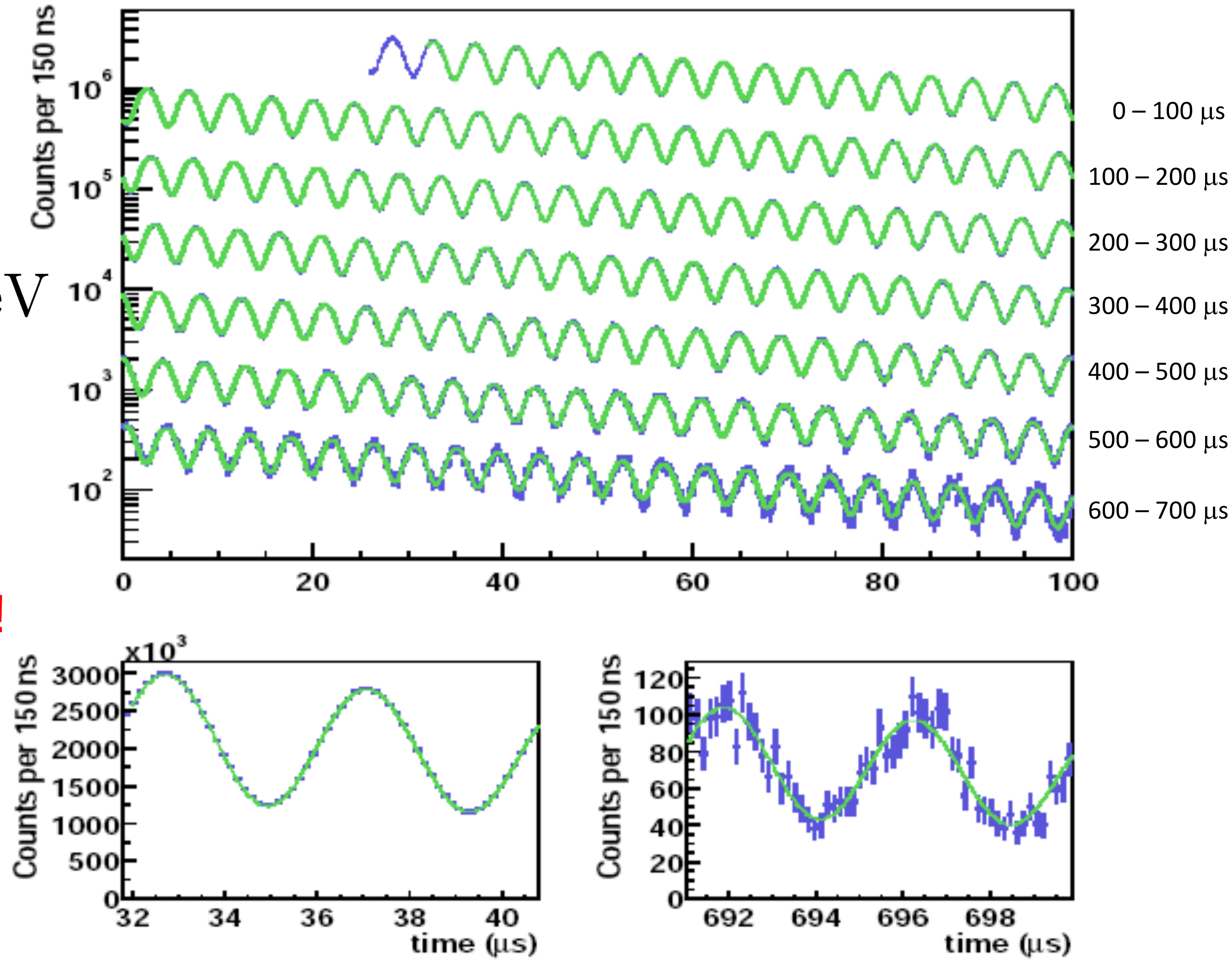
BNL calorimeters



The Wiggle Plot

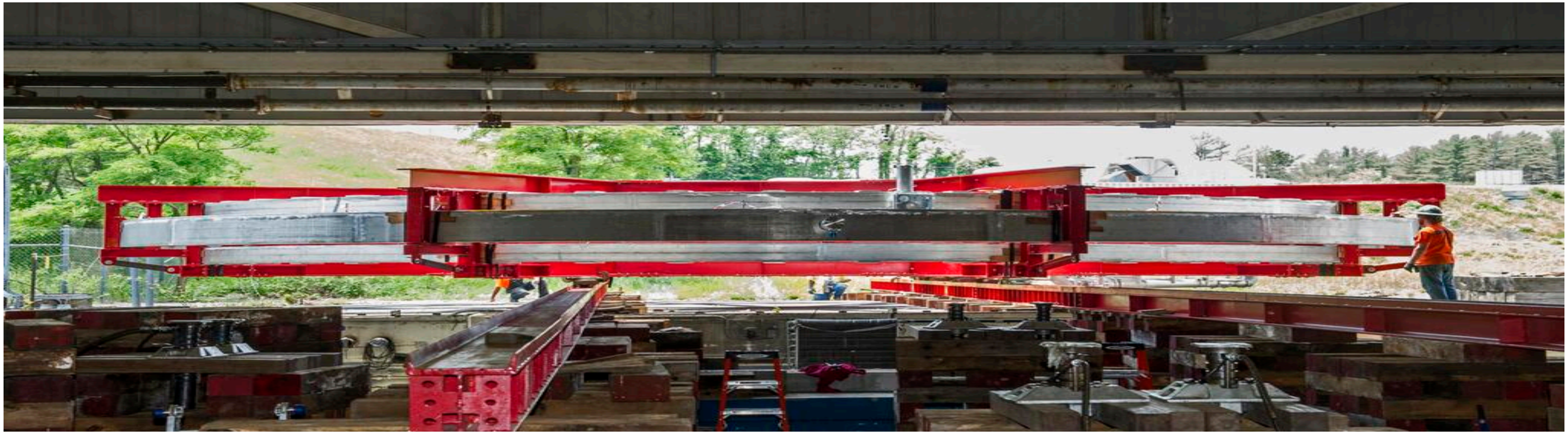
$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

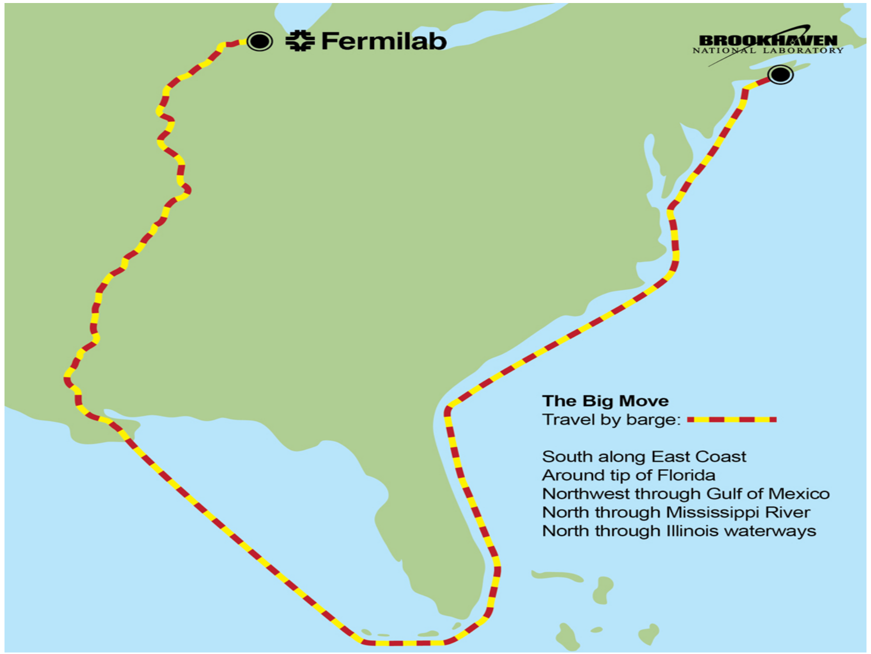
$E_{e^+} > 1.8$ GeV

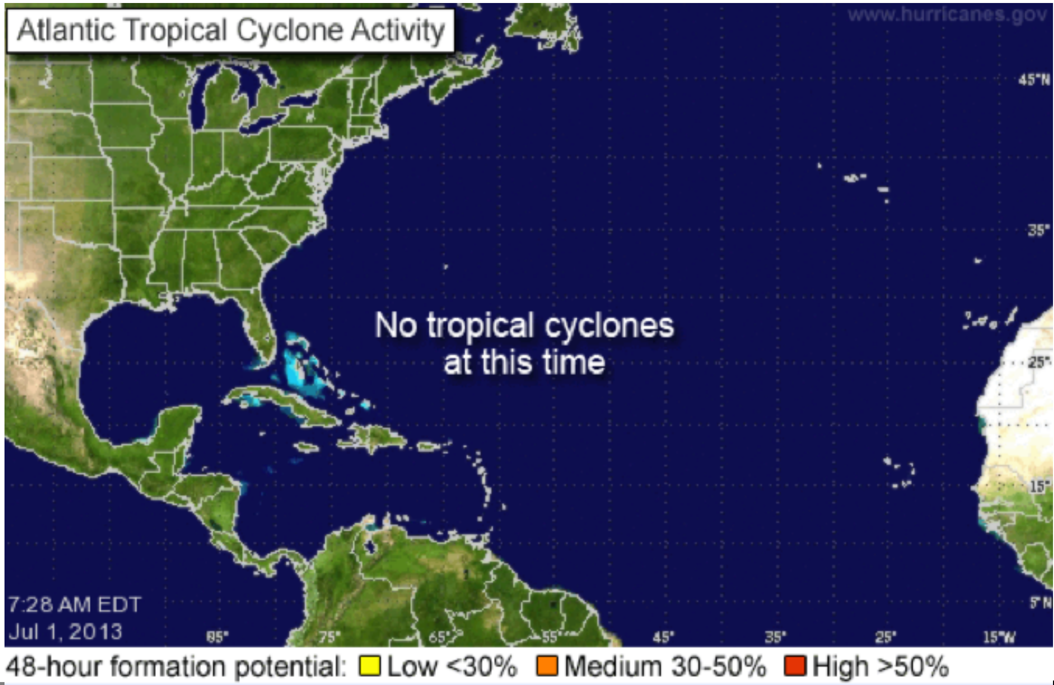


Need approx 100B muons !

The Move

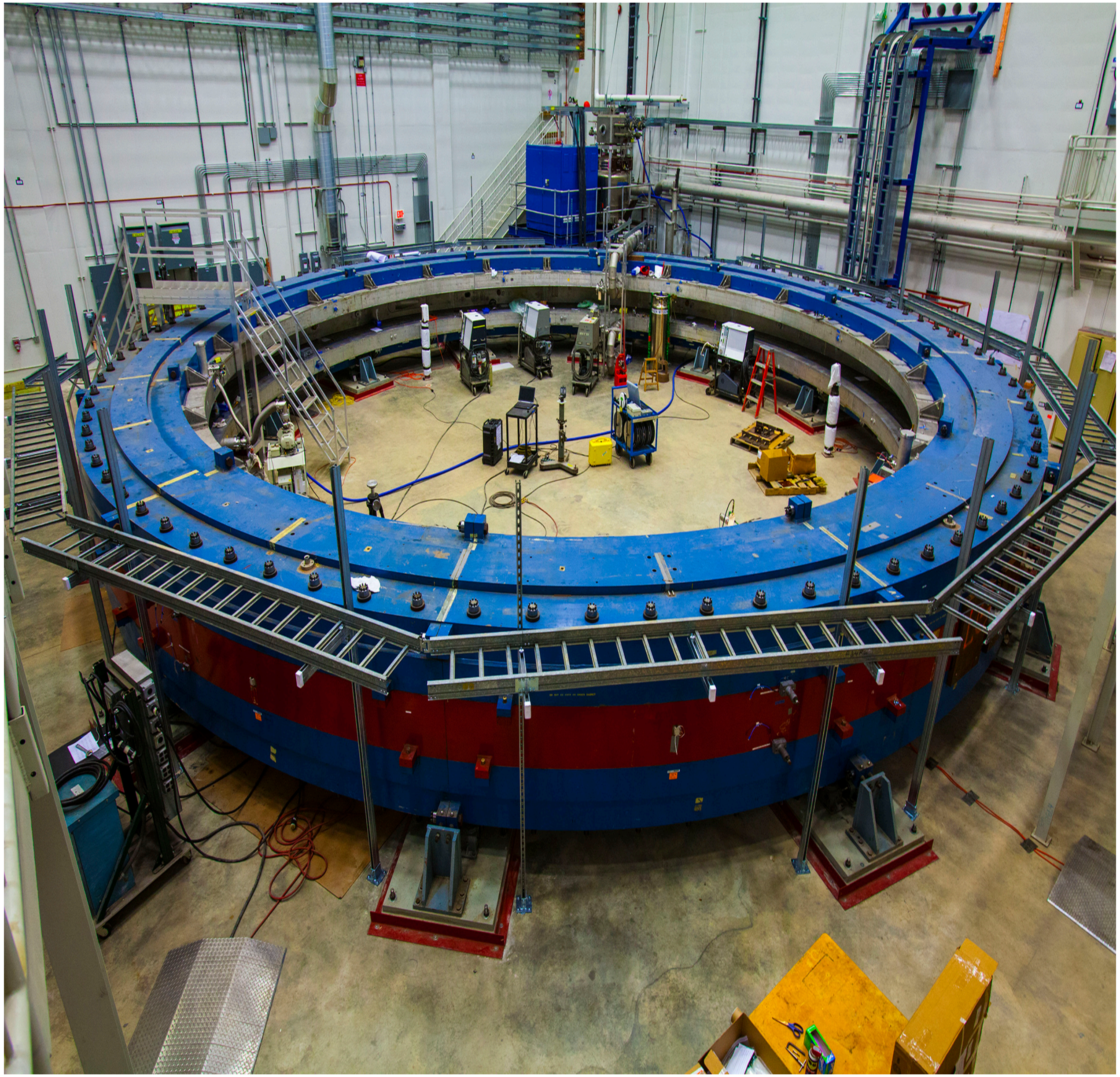



Fermilab
BROOKHAVEN NATIONAL LABORATORY
The Big Move
Travel by barge:
South along East Coast
Around tip of Florida
Northwest through Gulf of Mexico
North through Mississippi River
North through Illinois waterways


Atlantic Tropical Cyclone Activity
www.hurricanes.gov
No tropical cyclones at this time
7:28 AM EDT
Jul 1, 2013
48-hour formation potential: Low <30% Medium 30-50% High >50%

The Move

Long Live The Risk-Register




FARMSTEAD
BREWERY
NINJA

FNAL Improvements

More μ per proton | Lower inst. rate | Fewer pions

Unique capabilities of FNAL accelerators

Improved detectors

Improved stored muon beam dynamics

Improved field uniformity, field measurement & calibration

Improved modeling of beam & detectors

$$\mathrm{BNL} \rightarrow \mathrm{FNAL}$$

$$[54\ (\mathrm{stat.}) \oplus 33\ (\mathrm{syst.}) \rightarrow 11\ (\mathrm{stat.}) \oplus 11\ (\mathrm{syst.})] \times 10^{-11}$$

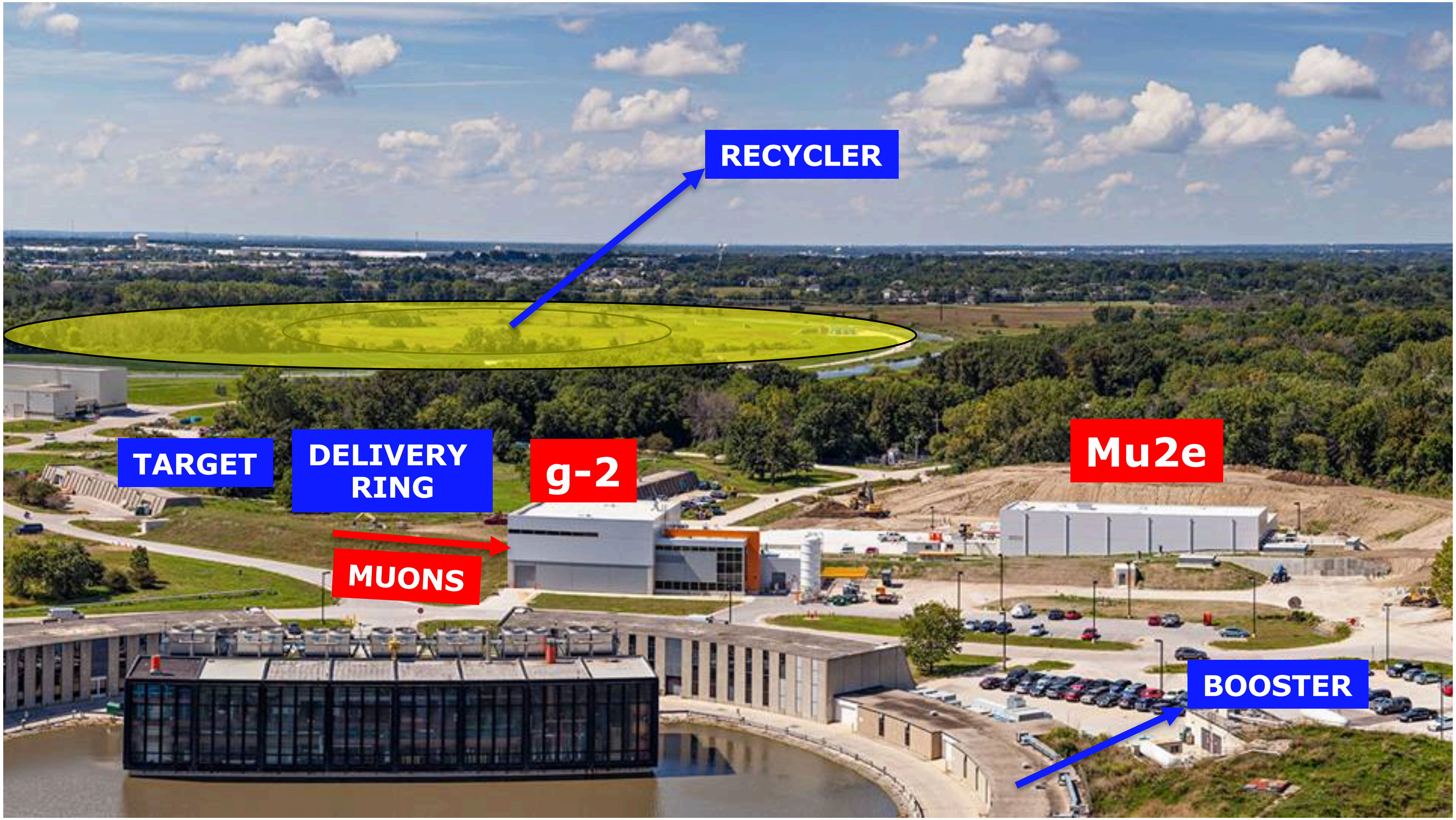
$$0.54\ \mathrm{ppm} \rightarrow 0.14\ \mathrm{ppm}$$

New / improved technologies

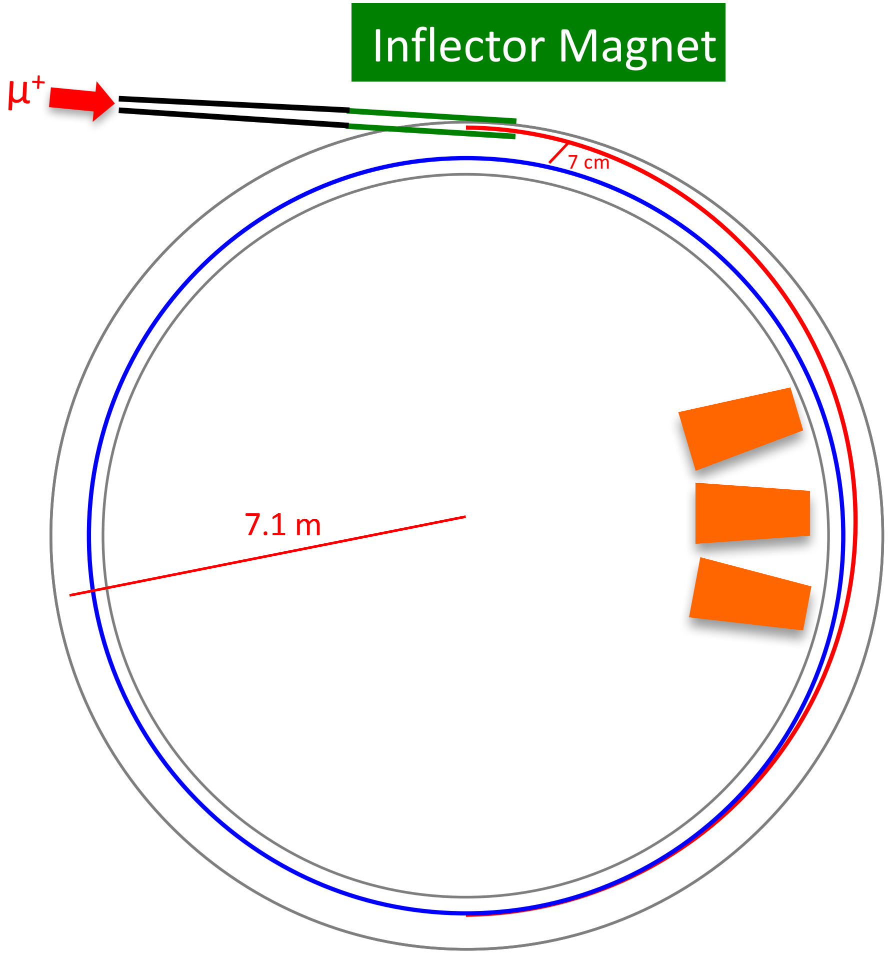
Additional collaborators

Building on wealth of experience from BNL E821 & other expts

Accelerator modifications mostly complete at FNAL

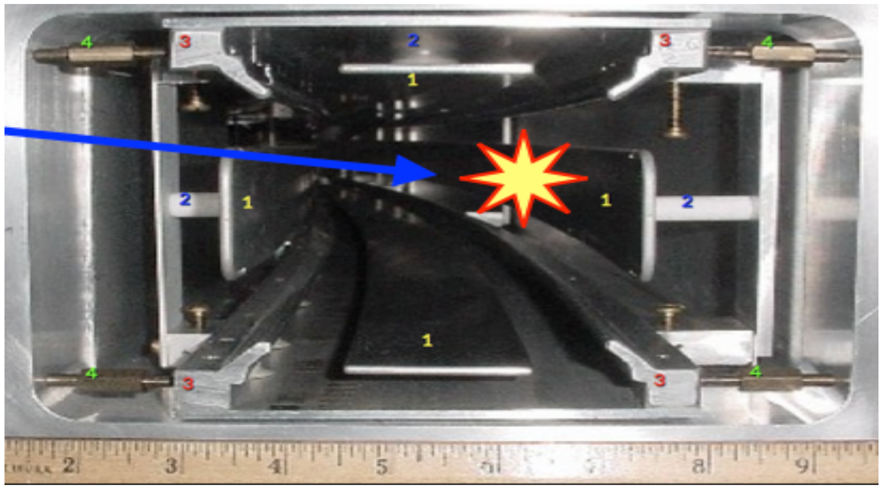


Beam infrastructure 90% complete
First beams (low muon intensity) from April 2017

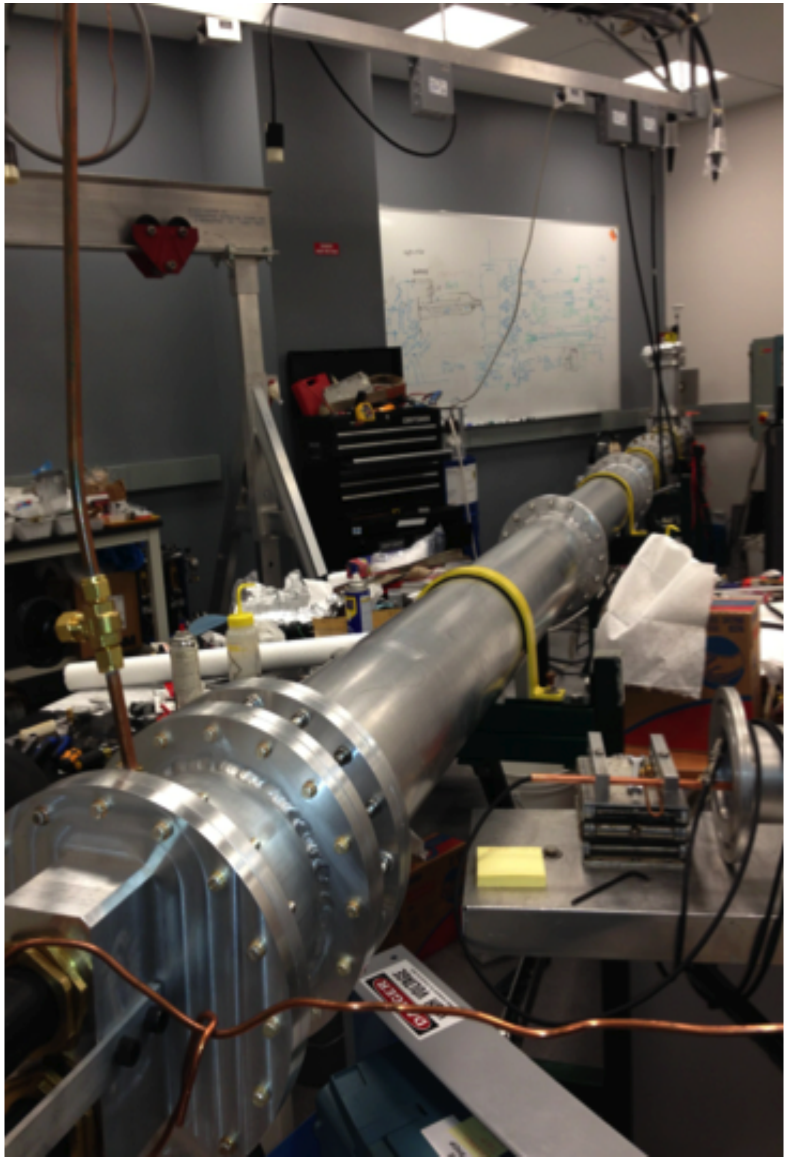


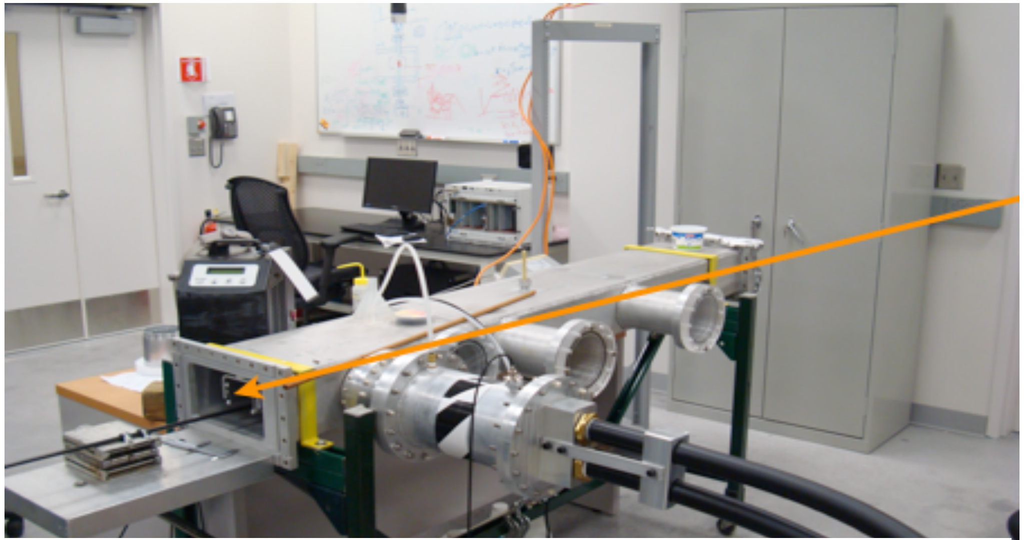
Beam doesn't enter on the correct orbit and needs a kick to get there !

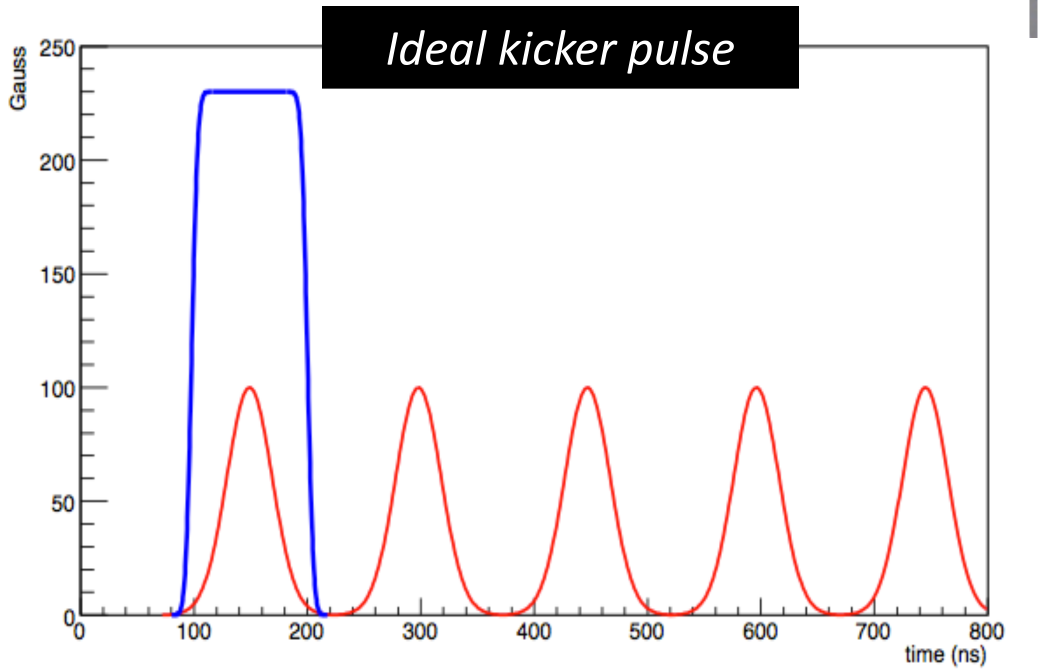
Kicker magnets



Kicker



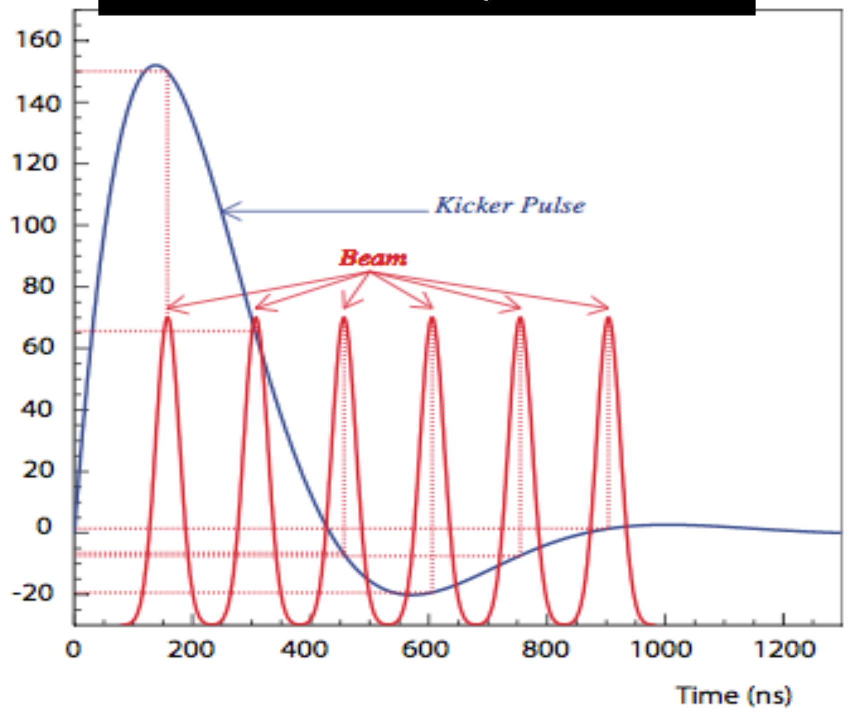




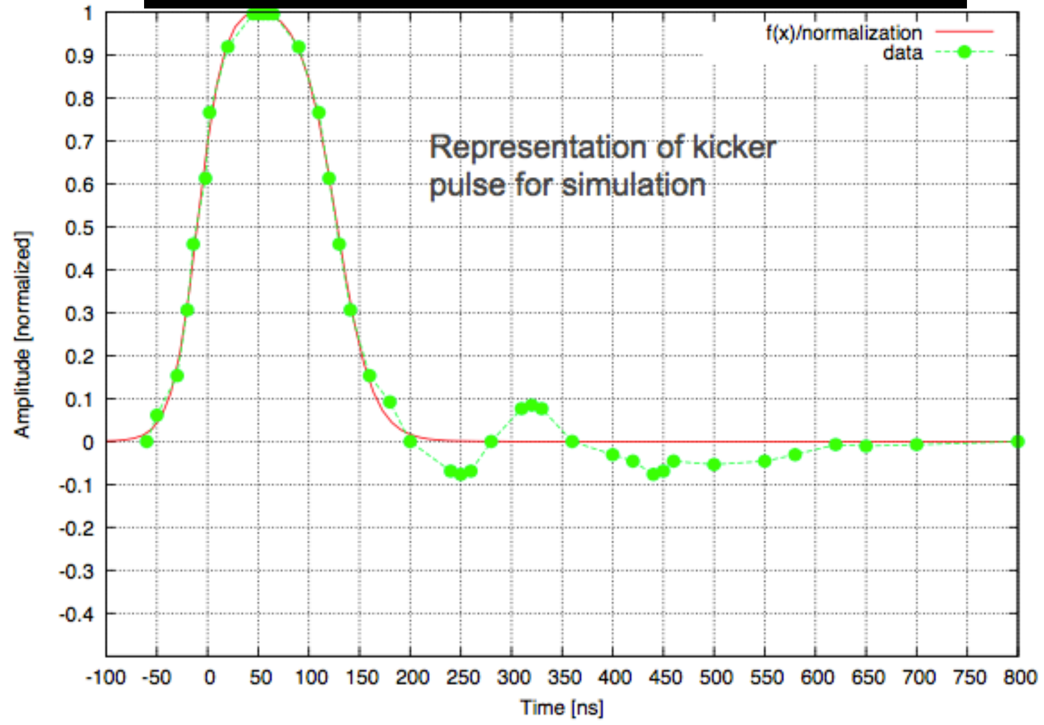
Ideal kicker pulse
Gauss
250
200
150
100
50
0
0
100
200
300
400
500
600
700
800
time (ns)

Kicker Pulse

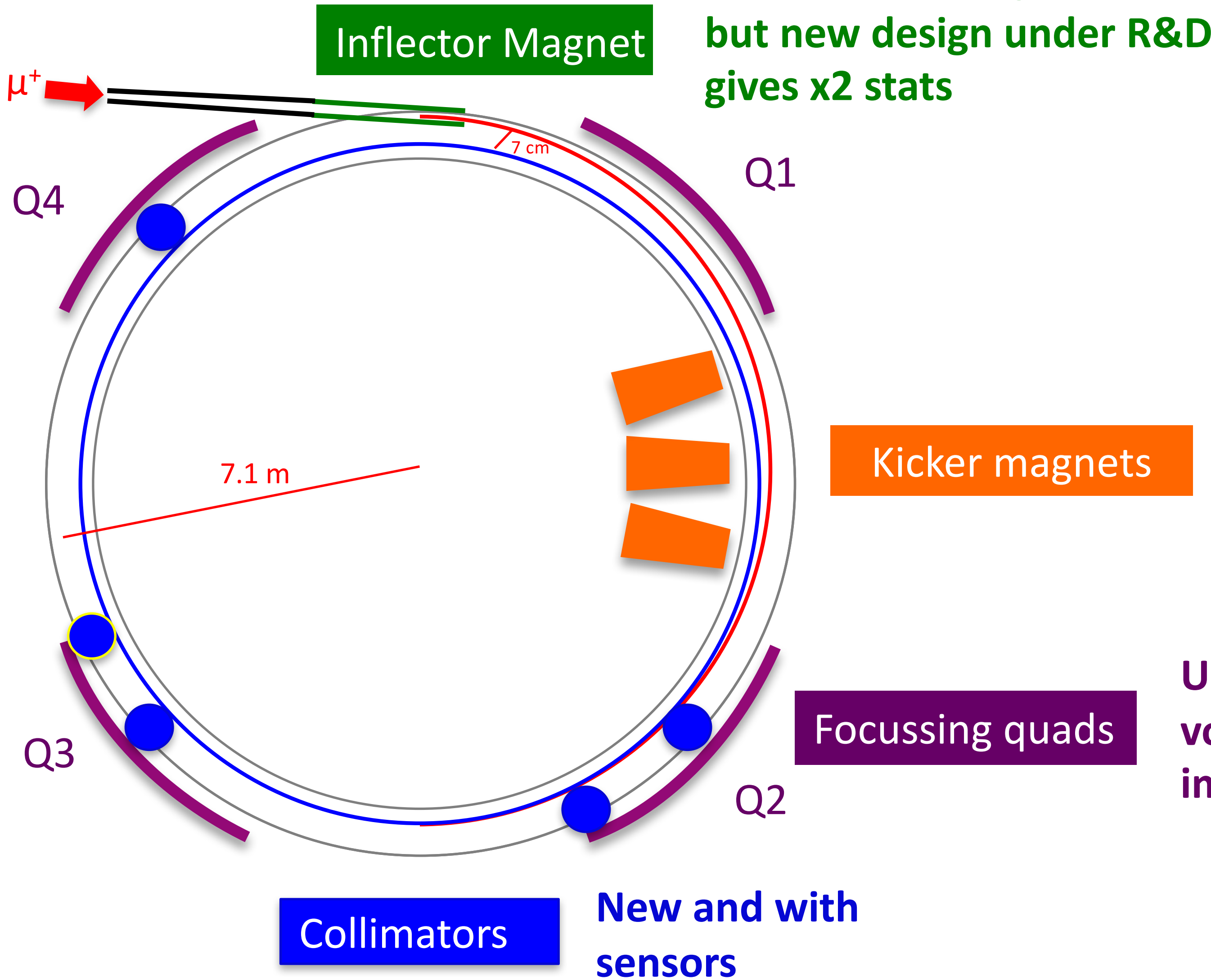
BNL kicker pulse



New FNAL (Cornell) kicker pulse



Improvements to injection system

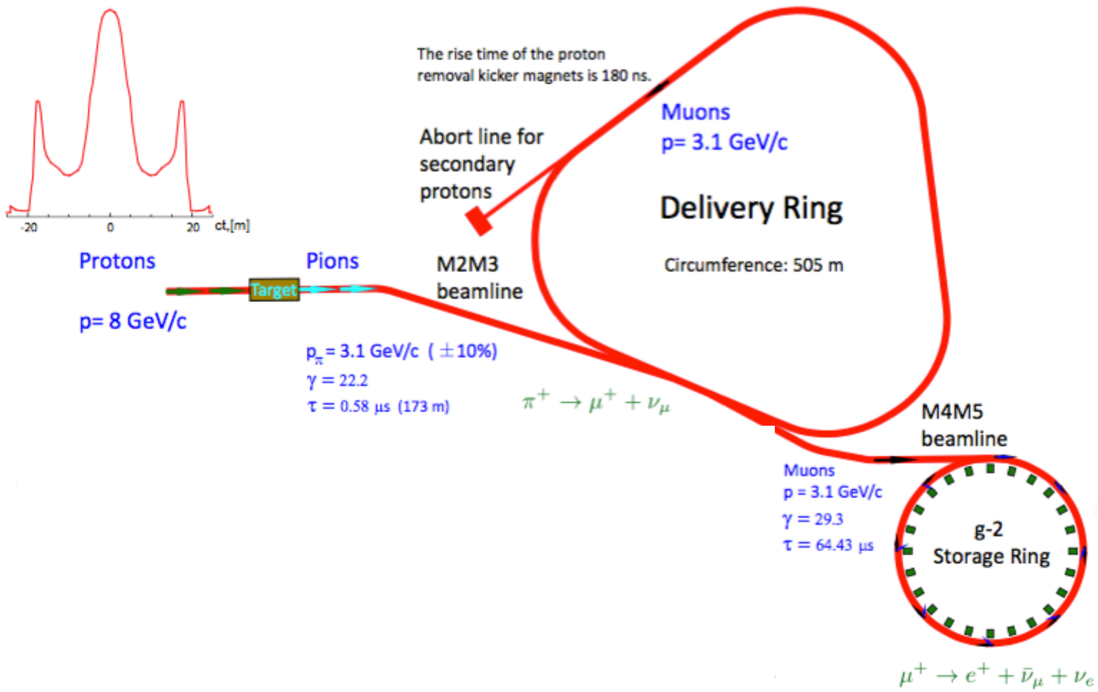


Baseline: existing BNL inflector but new design under R&D which gives x2 stats

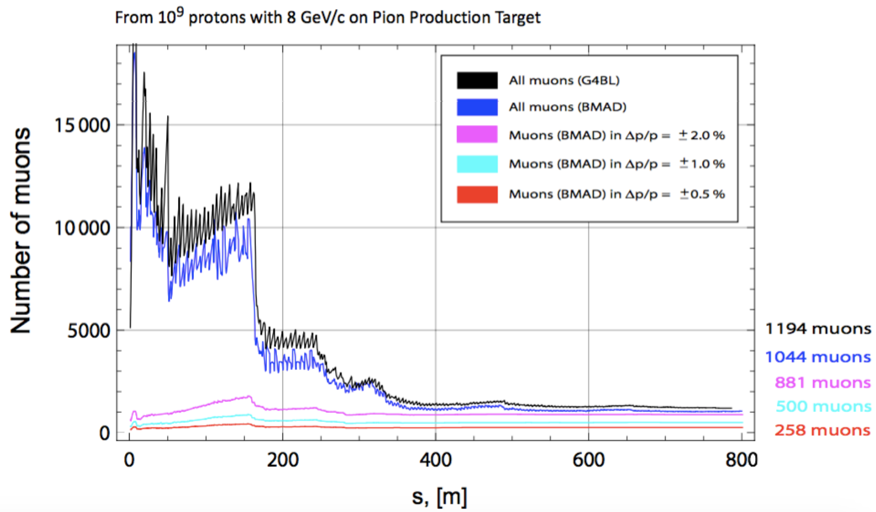
New with improved kick

Using higher voltage for improved tune

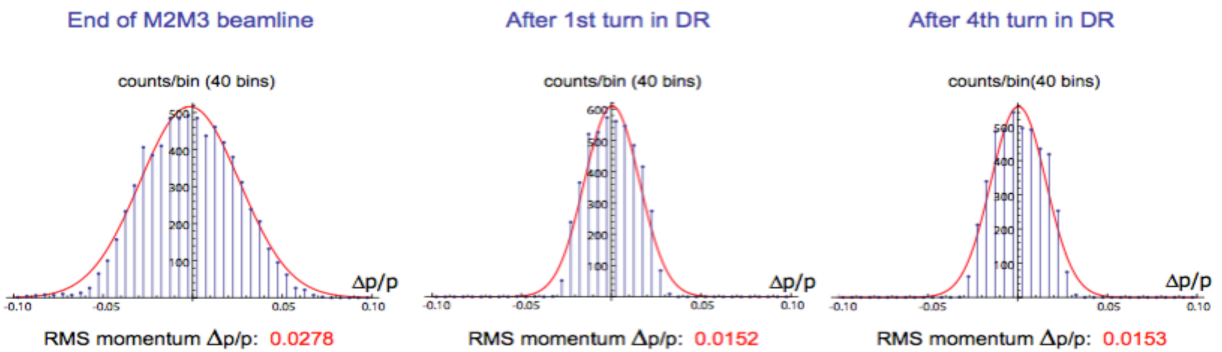
New and with sensors



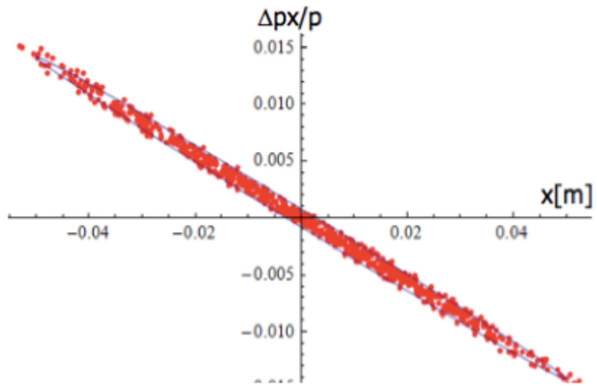
ct,[m]
Protons
p= 8 GeV/c
Target
Pions
p_π = 3.1 GeV/c (±10%)
γ = 22.2
τ = 0.58 μs (173 m)
$\pi^+ \rightarrow \mu^+ + \nu_\mu$
The rise time of the proton removal kicker magnets is 180 ns.
Abort line for secondary protons
M2M3 beamline
Muons
p= 3.1 GeV/c
Delivery Ring
Circumference: 505 m
M4M5 beamline
Muons
p = 3.1 GeV/c
γ = 29.3
τ = 64.43 μs
g-2 Storage Ring
$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$



From 10^9 protons with 8 GeV/c on Pion Production Target
Number of muons
s, [m]
All muons (G4BL)
All muons (BMAD)
Muons (BMAD) in Δp/p = ±2.0 %
Muons (BMAD) in Δp/p = ±1.0 %
Muons (BMAD) in Δp/p = ±0.5 %
1194 muons
1044 muons
881 muons
500 muons
258 muons



End of M2M3 beamline
counts/bin (40 bins)
Δp/p
RMS momentum Δp/p: 0.0278
After 1st turn in DR
counts/bin (40 bins)
Δp/p
RMS momentum Δp/p: 0.0152
After 4th turn in DR
counts/bin(40 bins)
Δp/p
RMS momentum Δp/p: 0.0153



Δpx/p
x[m]

g-2 Magnet

72 pole pieces

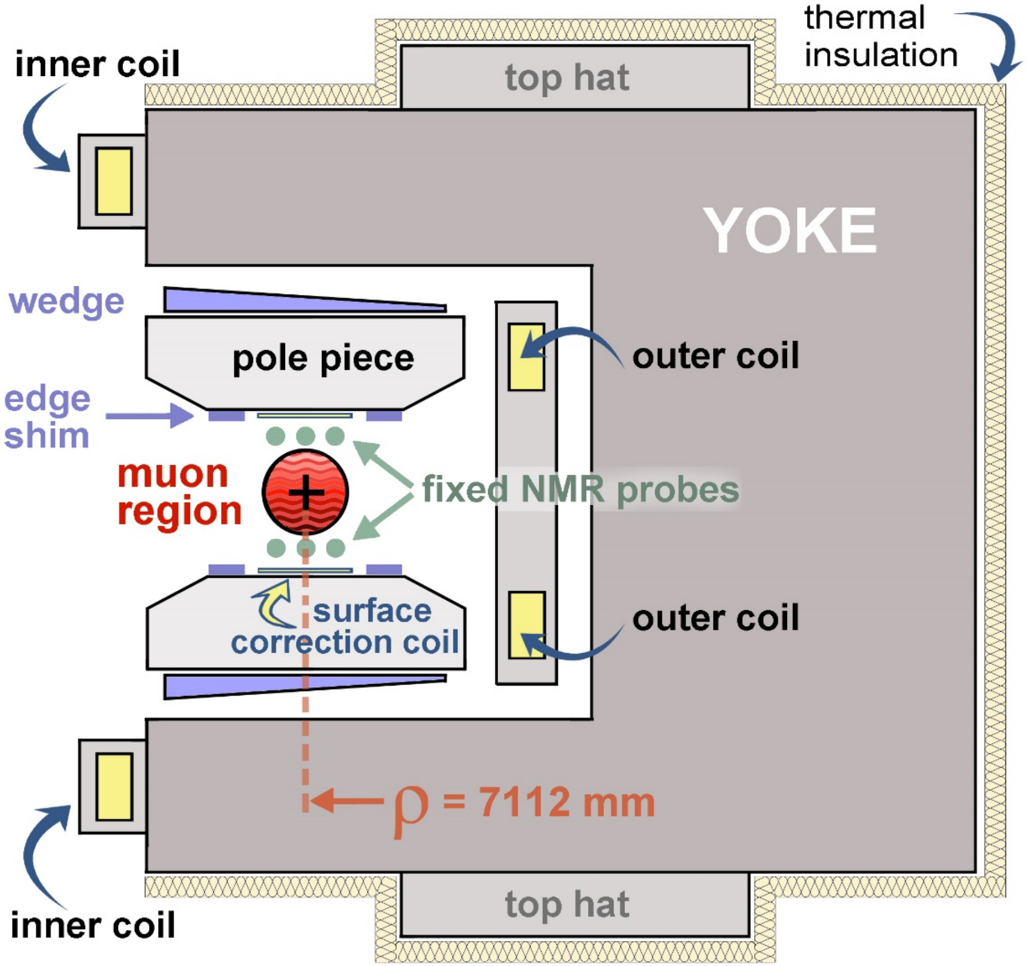
864 wedges

48 iron “top hats”

144 edge shims

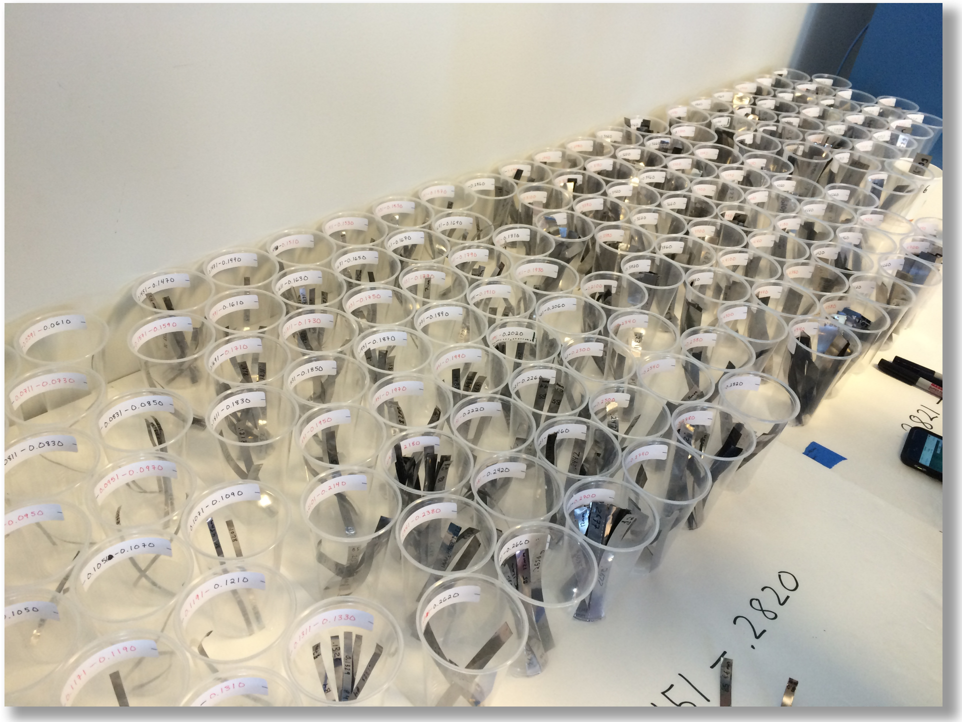
8000 surface iron foils

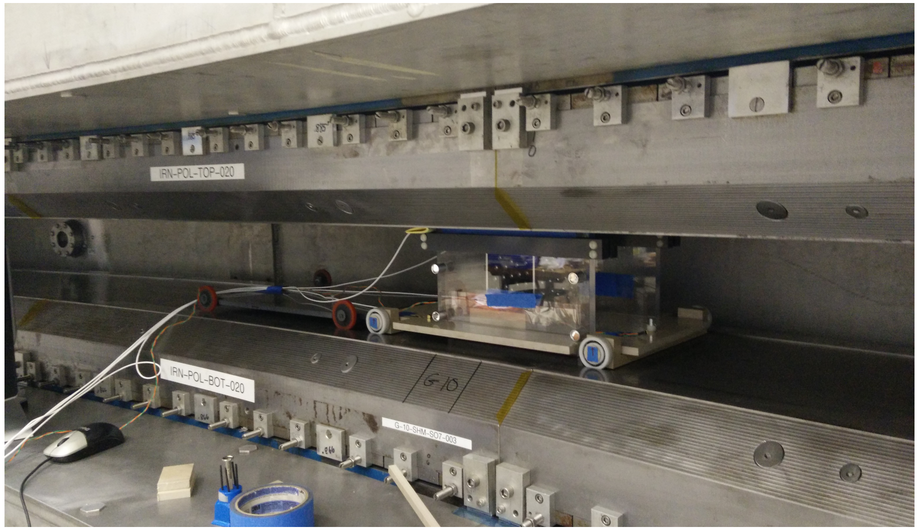
100 active surface coils

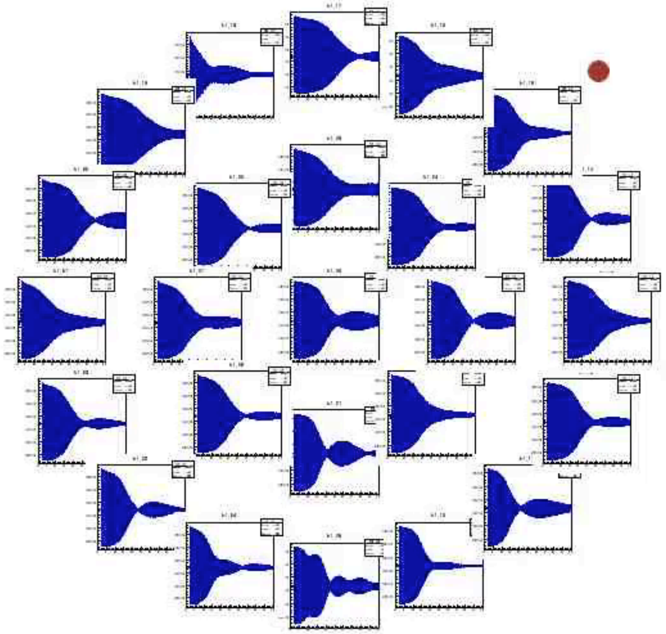


Yoke : 26 tons to 125 microns….

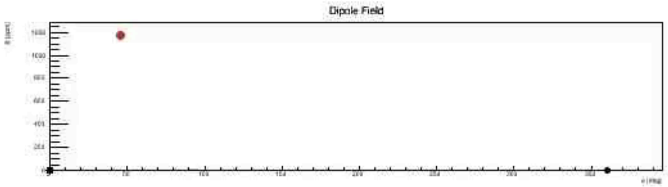
The laminators !

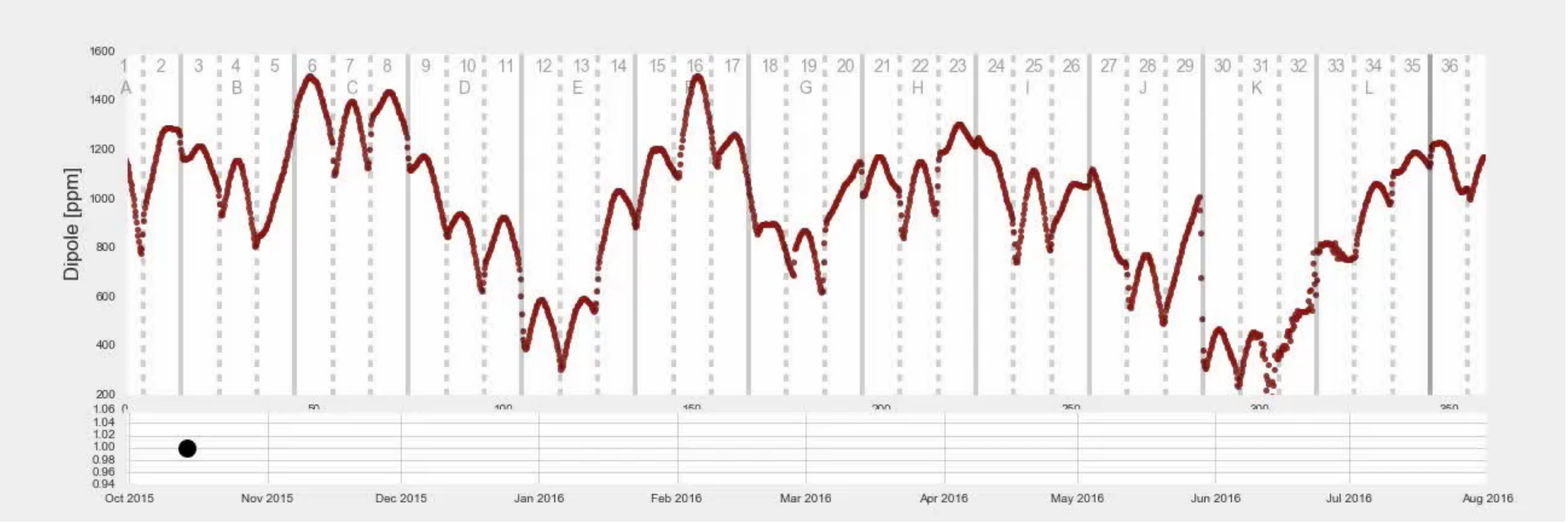


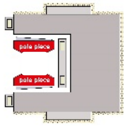

IRN-POL-TOP-020
IRN-POL-BOT-020
G 10



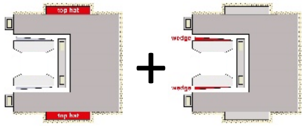

METROLAB PRECISION NMR TESLAMETER PT 2025
1.4500706


Dipole Field

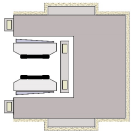




Poles

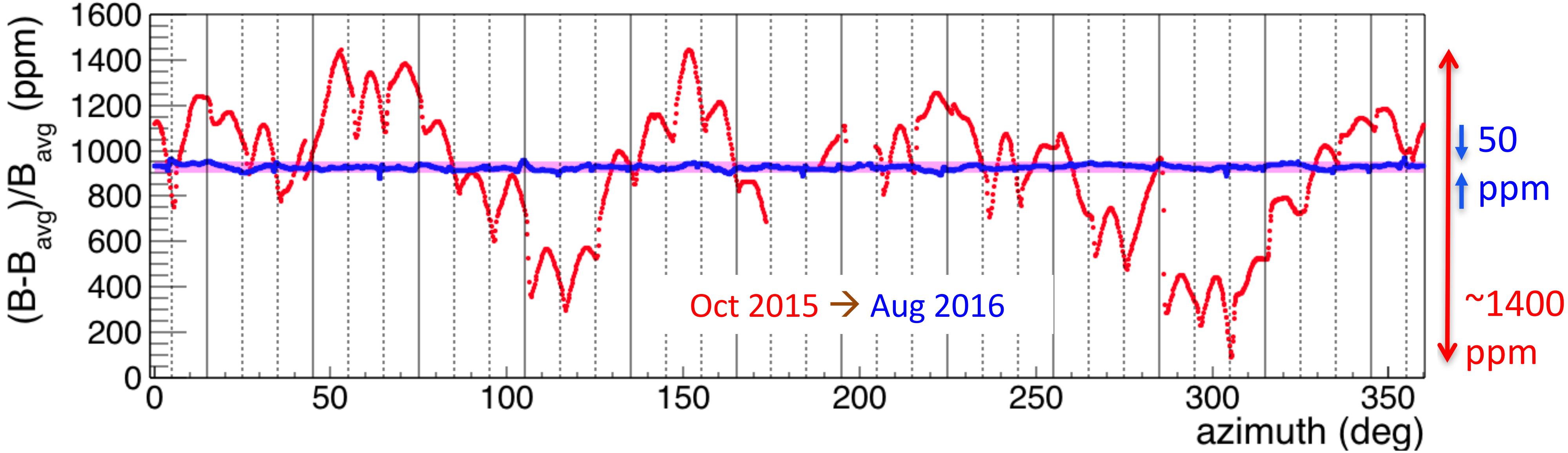


Top hats & wedges

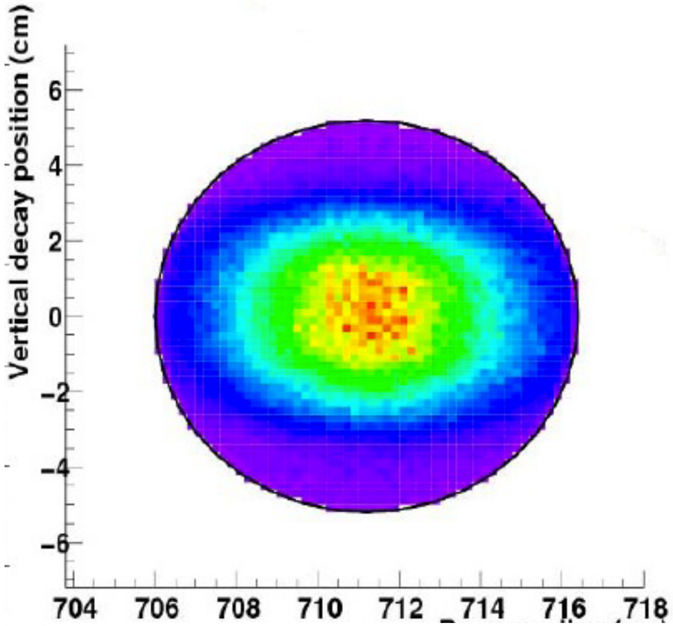


Surface foils

Field uniformity x30 improved in a year and now x4 better than achieved at BNL after first shimming round.



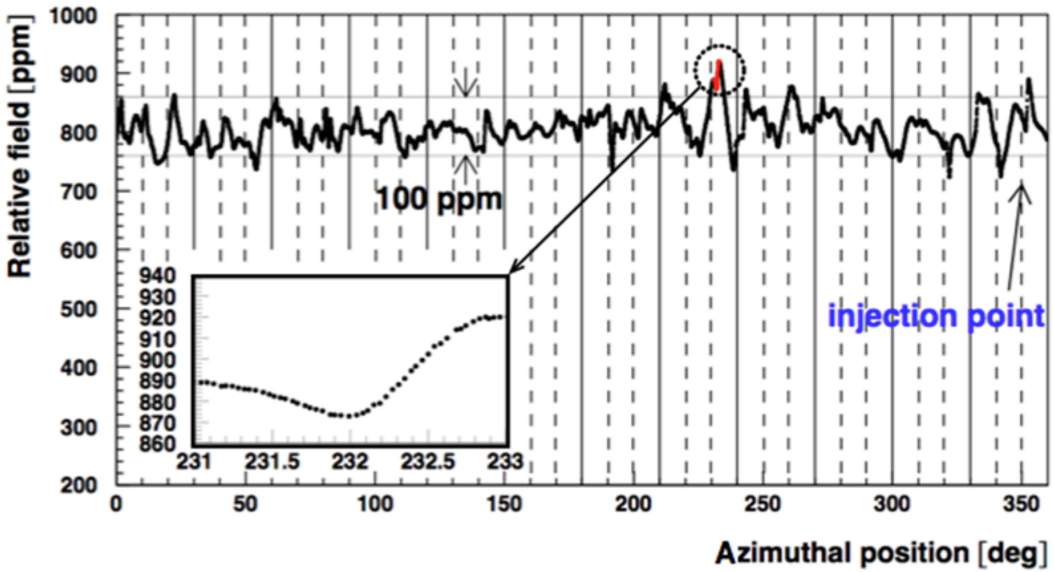
B-field map

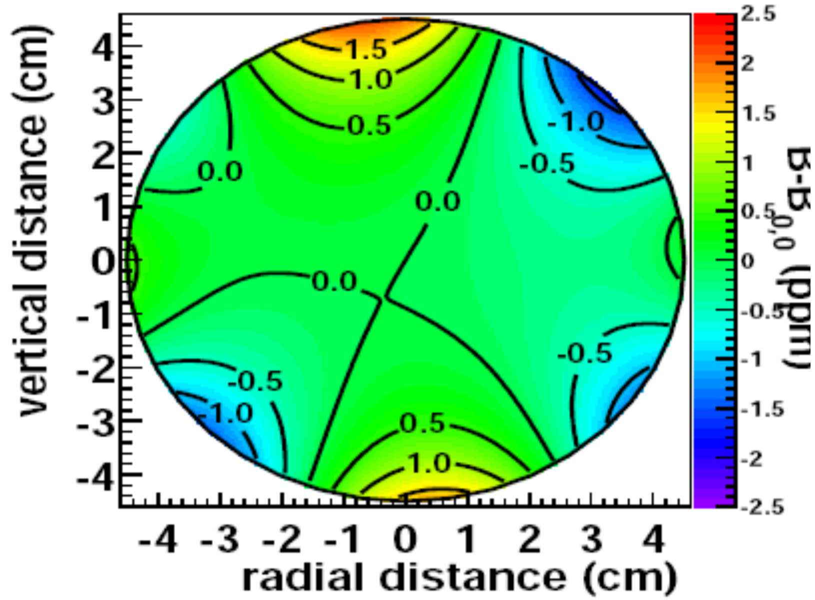


Muons are distributed over storage volume

B-field is not uniform over this volume

Need to convolute the two.



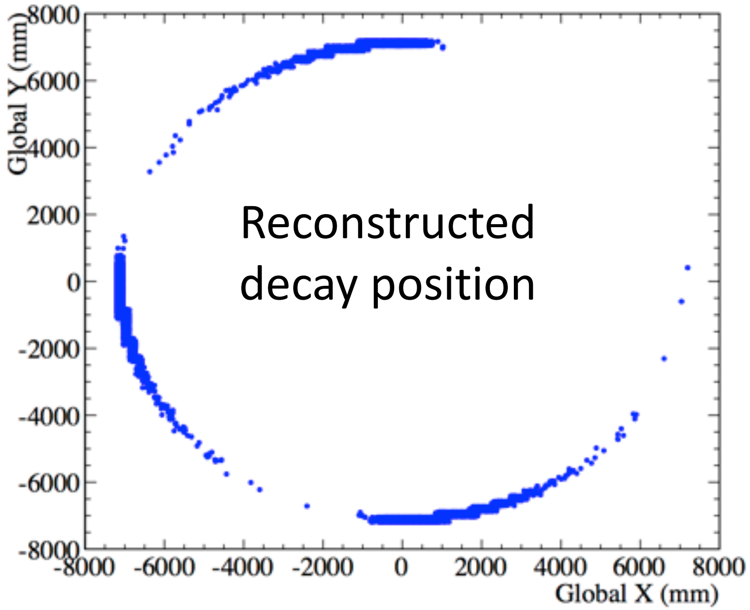


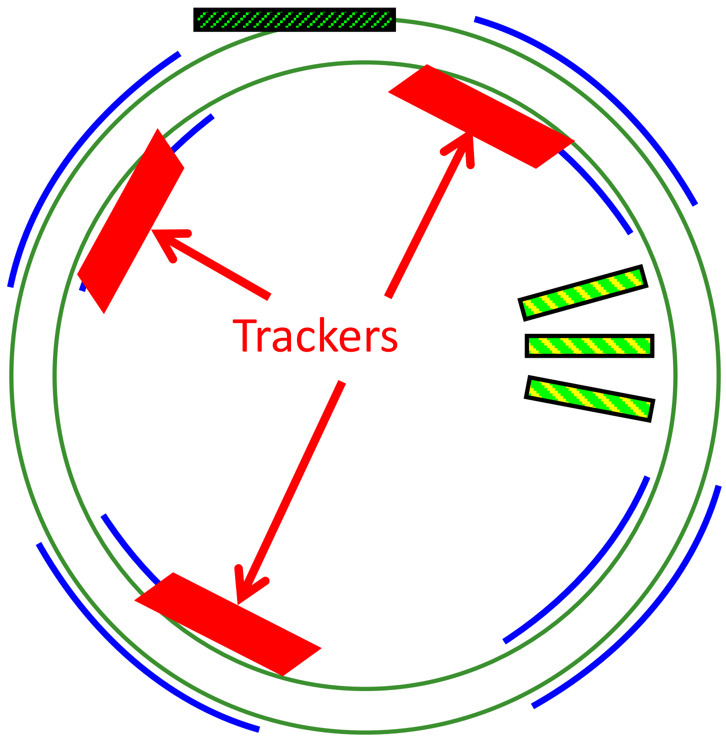
Straw tracking detectors

Measure beam profile

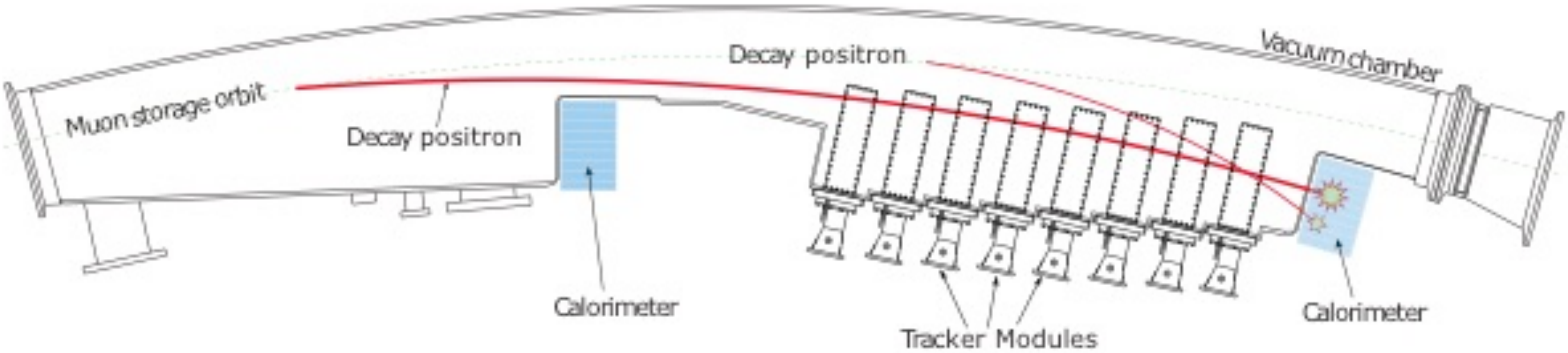
Identify pileup and muons lost from beam

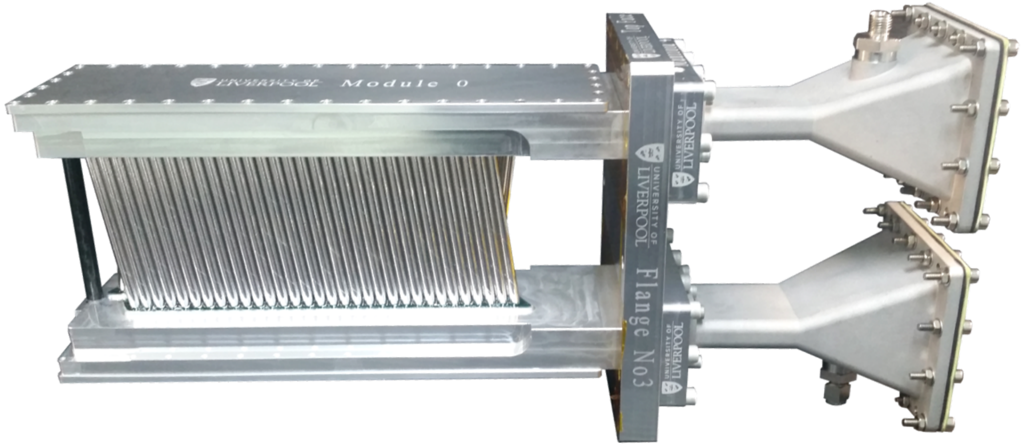
Measure EDM

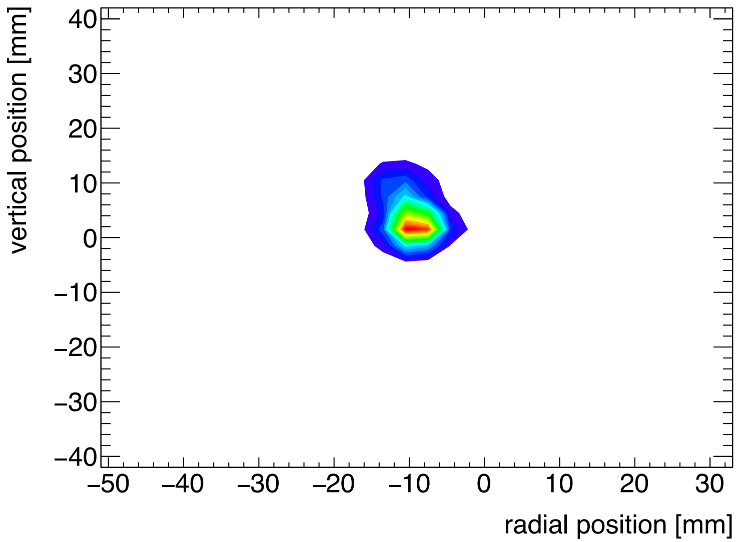


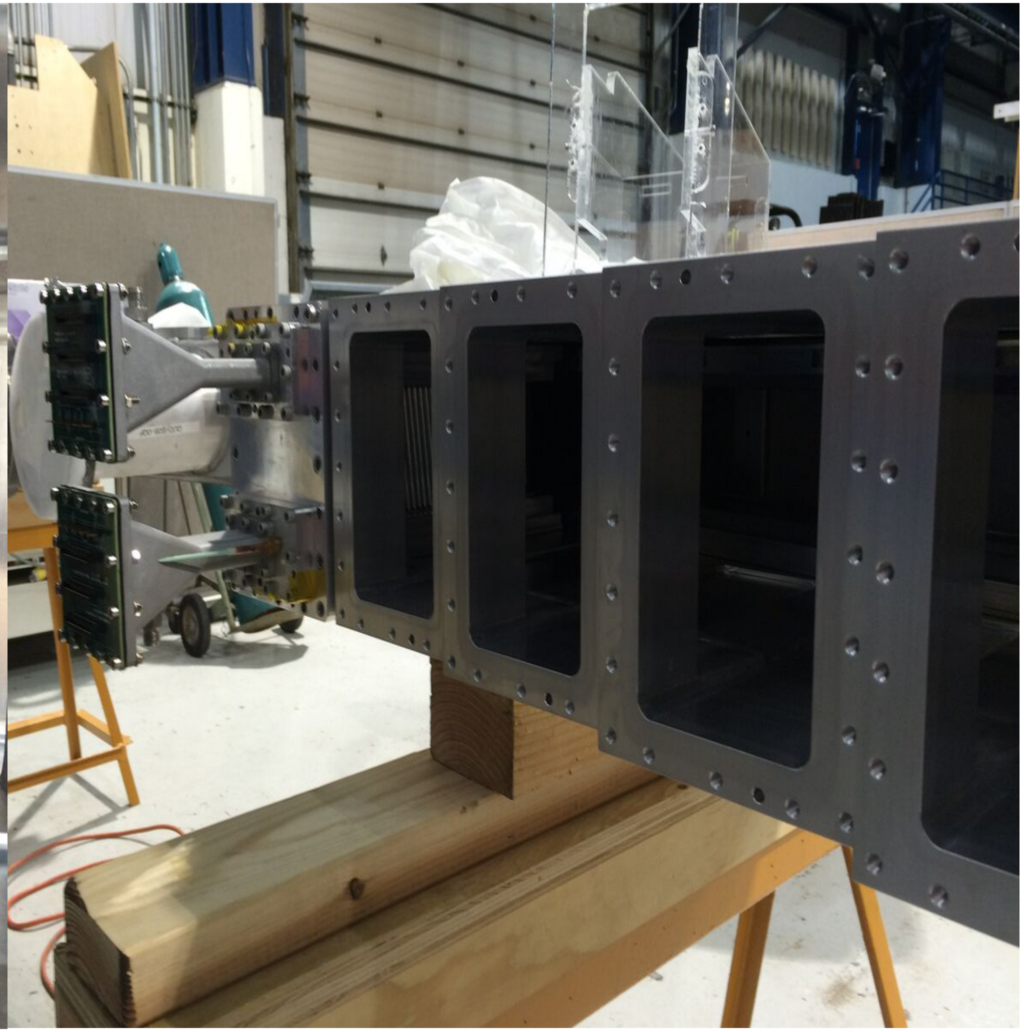


Straw tracking detectors

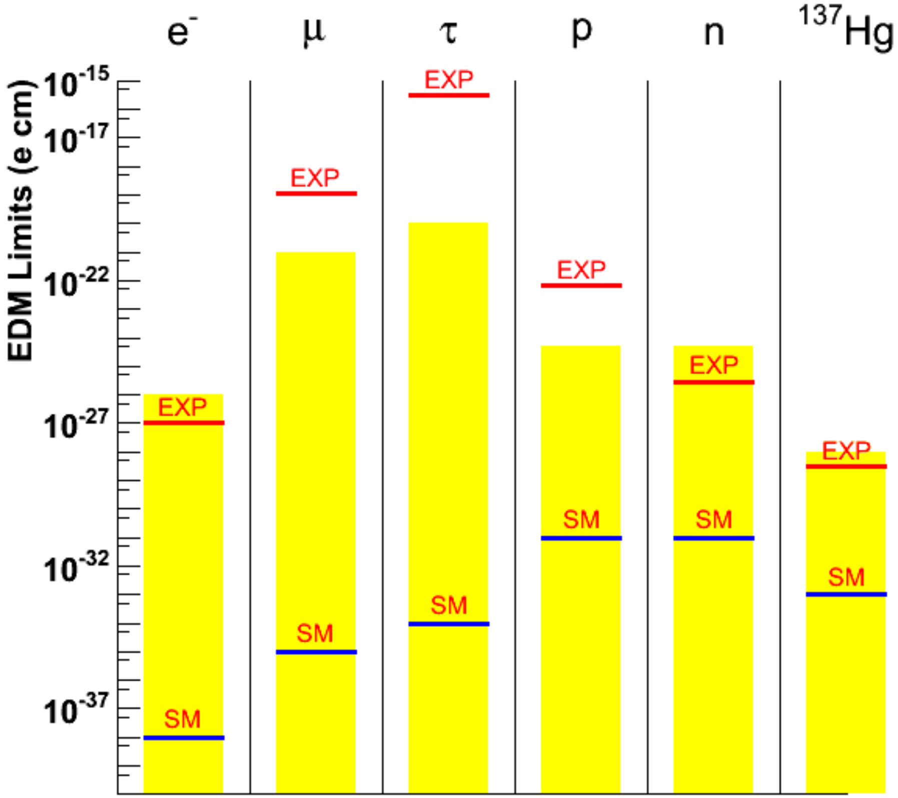


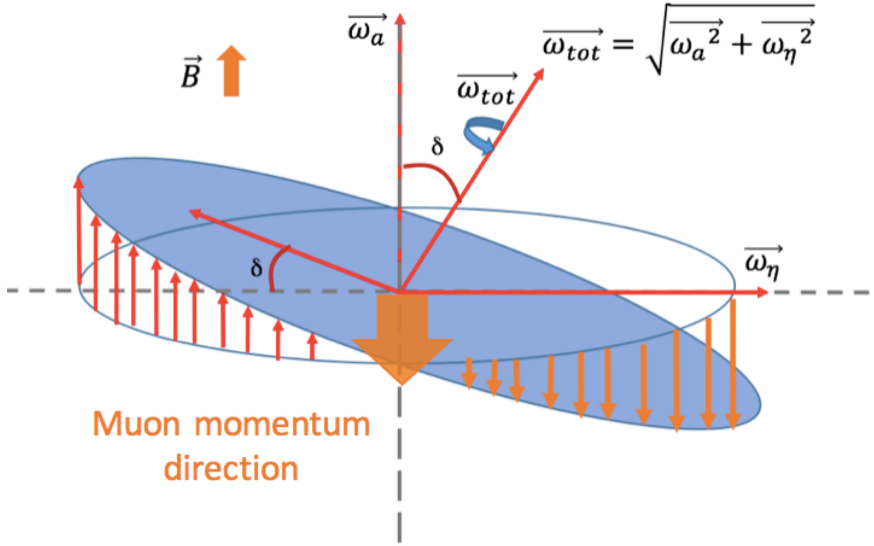






Essentially zero in SM : any observation is new physics



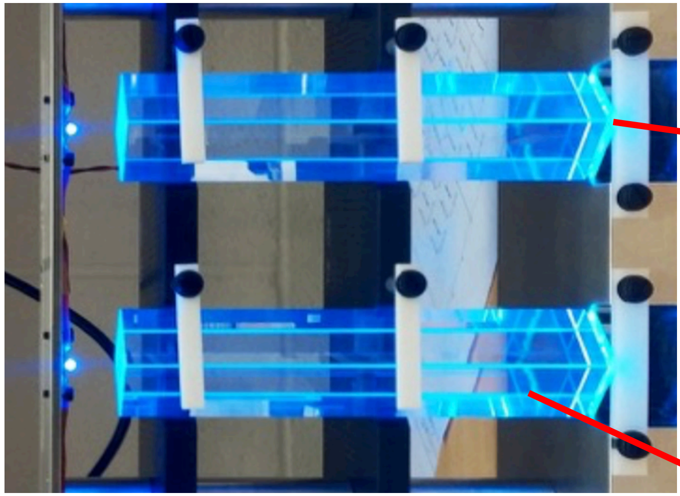


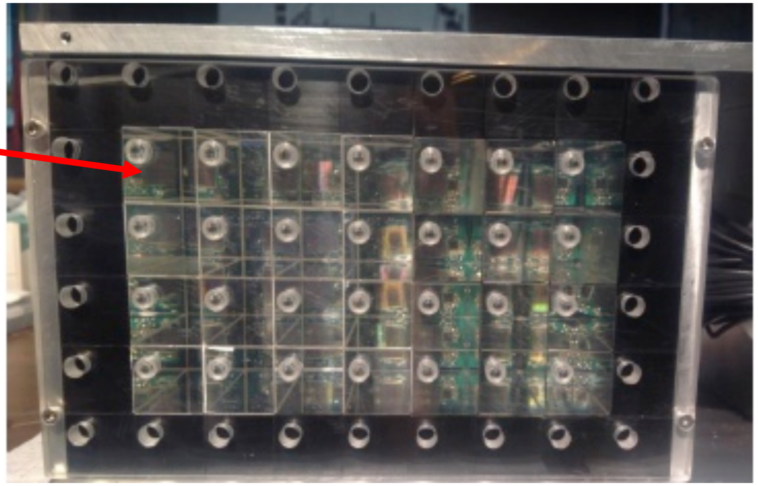
Expect several billion events in the trackers and so reach 10-21 vs 2×10^{-19} at BNL

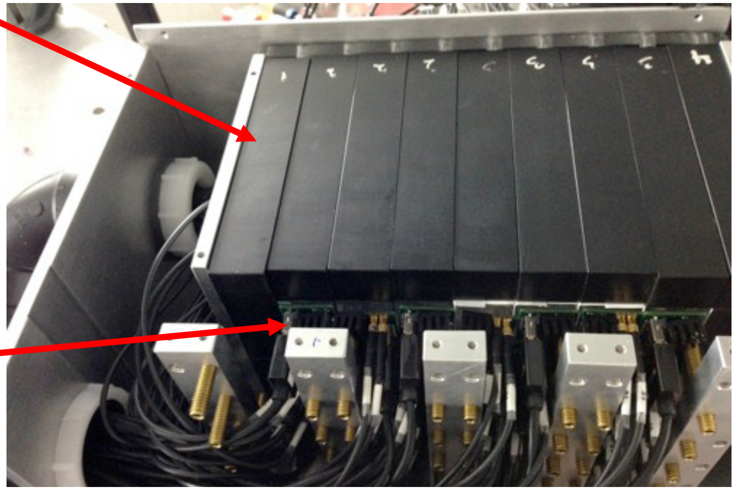
Needs non mass-scaling BSM effects to be in expt's reach given e- EDM limit

PbF_2 calorimeter

50 MeV resolution at 2 GeV and pulse separation < 5ns.



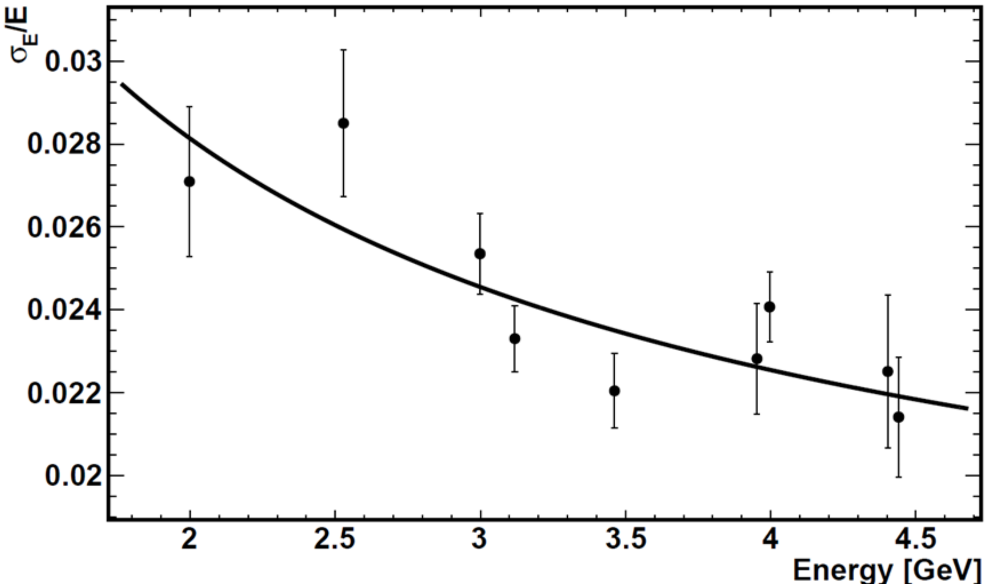




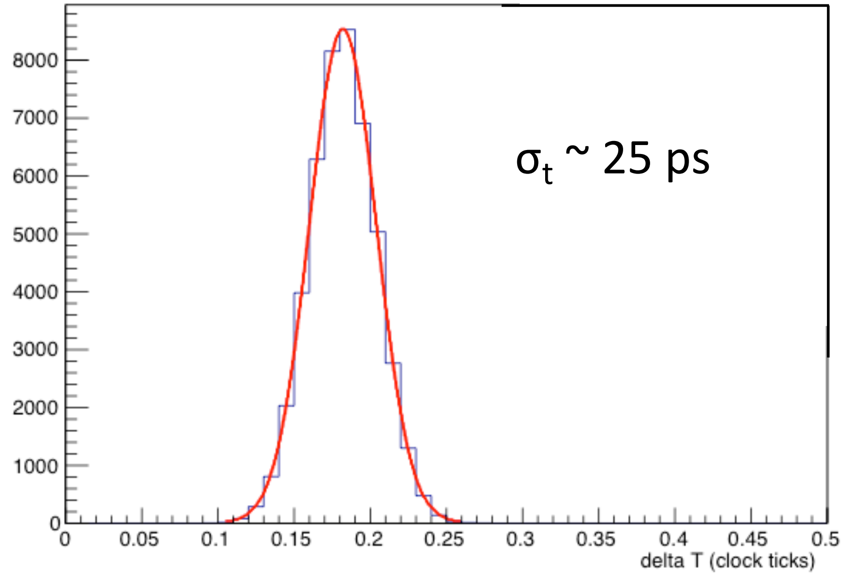
Calorimeter testbeam results

[NIM A 783 (2015),]

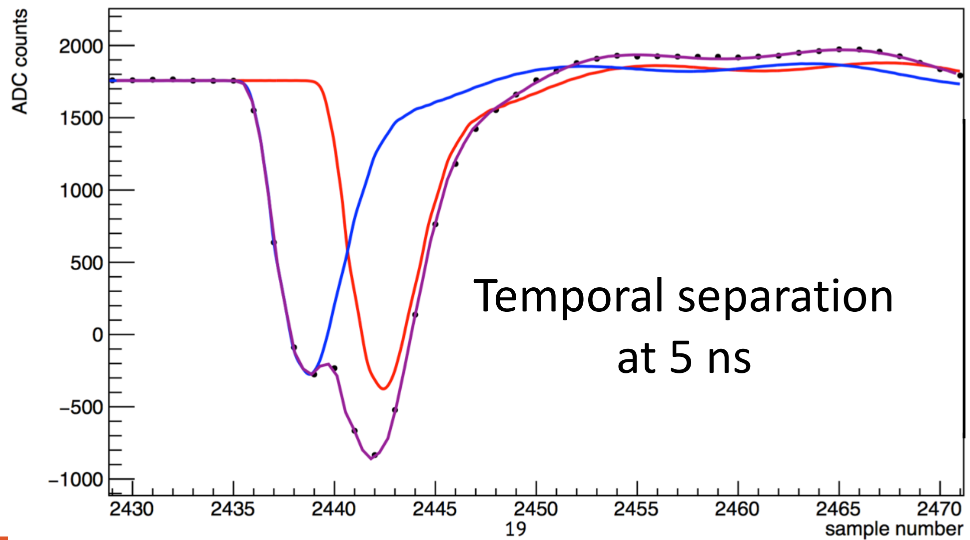
Energy Resolution



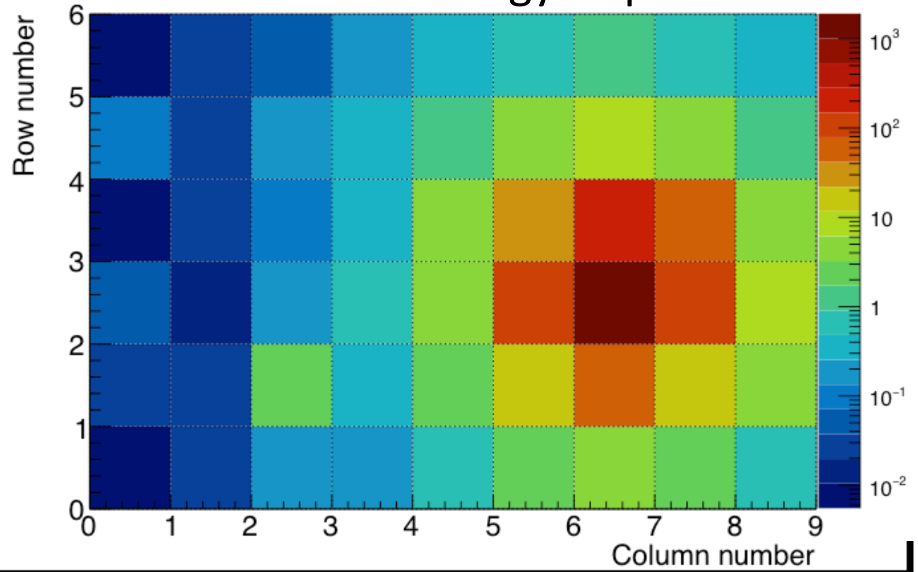
Timing Resolution



Electron pile-up



Position from Energy Deposit

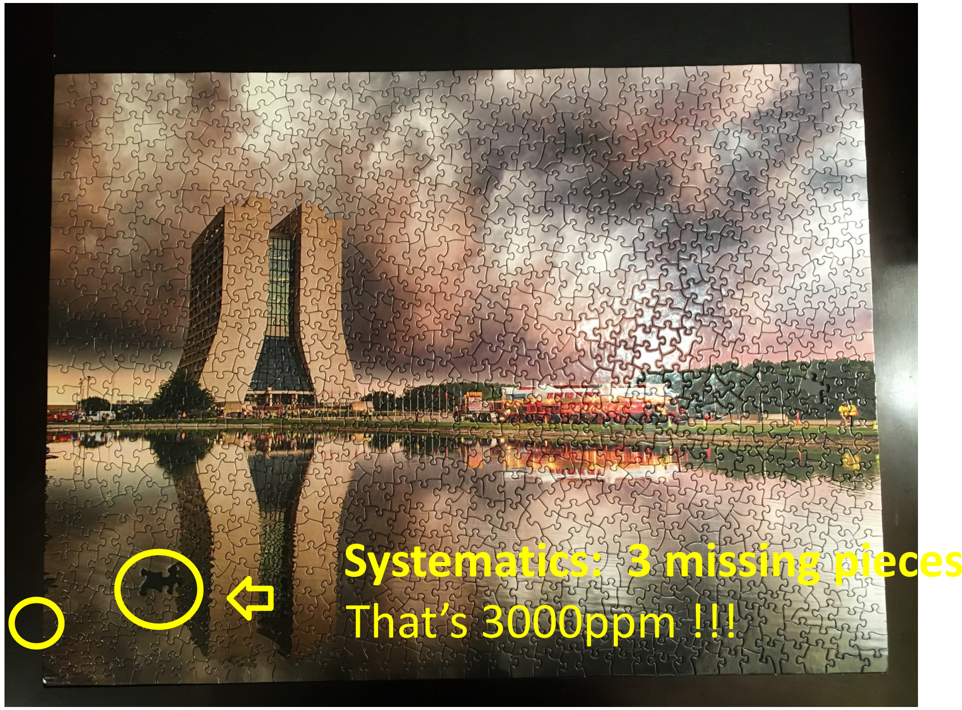


Status

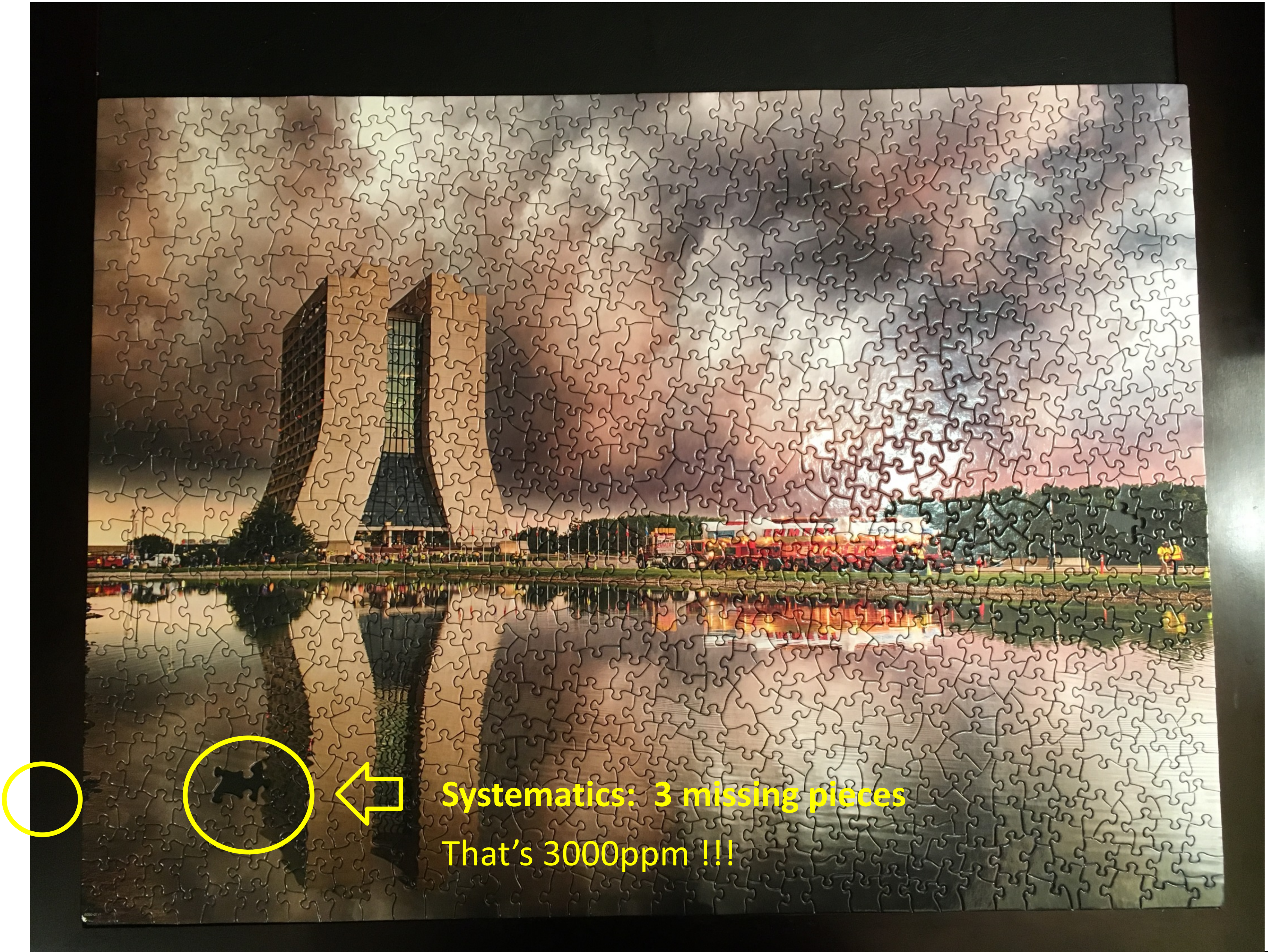
1st beam is expected in April with first muon data to be accumulated towards the end of 2017.

BNL-level statistics by mid-2018 and by 2020 x20 the statistics

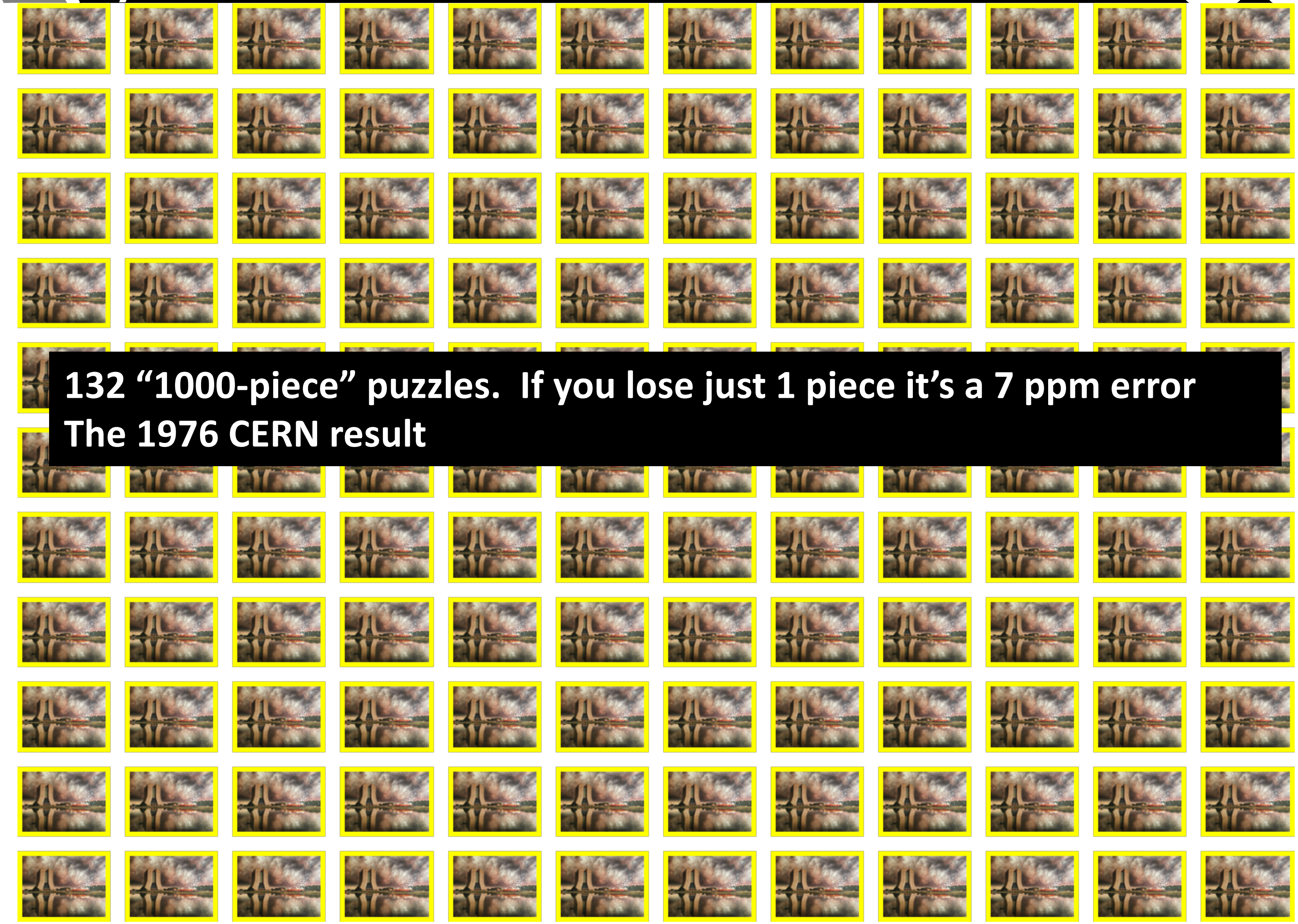
Expectation is to publish 3 results with 100%, 50% and 25% of BNL precision



Systematics x 1/3



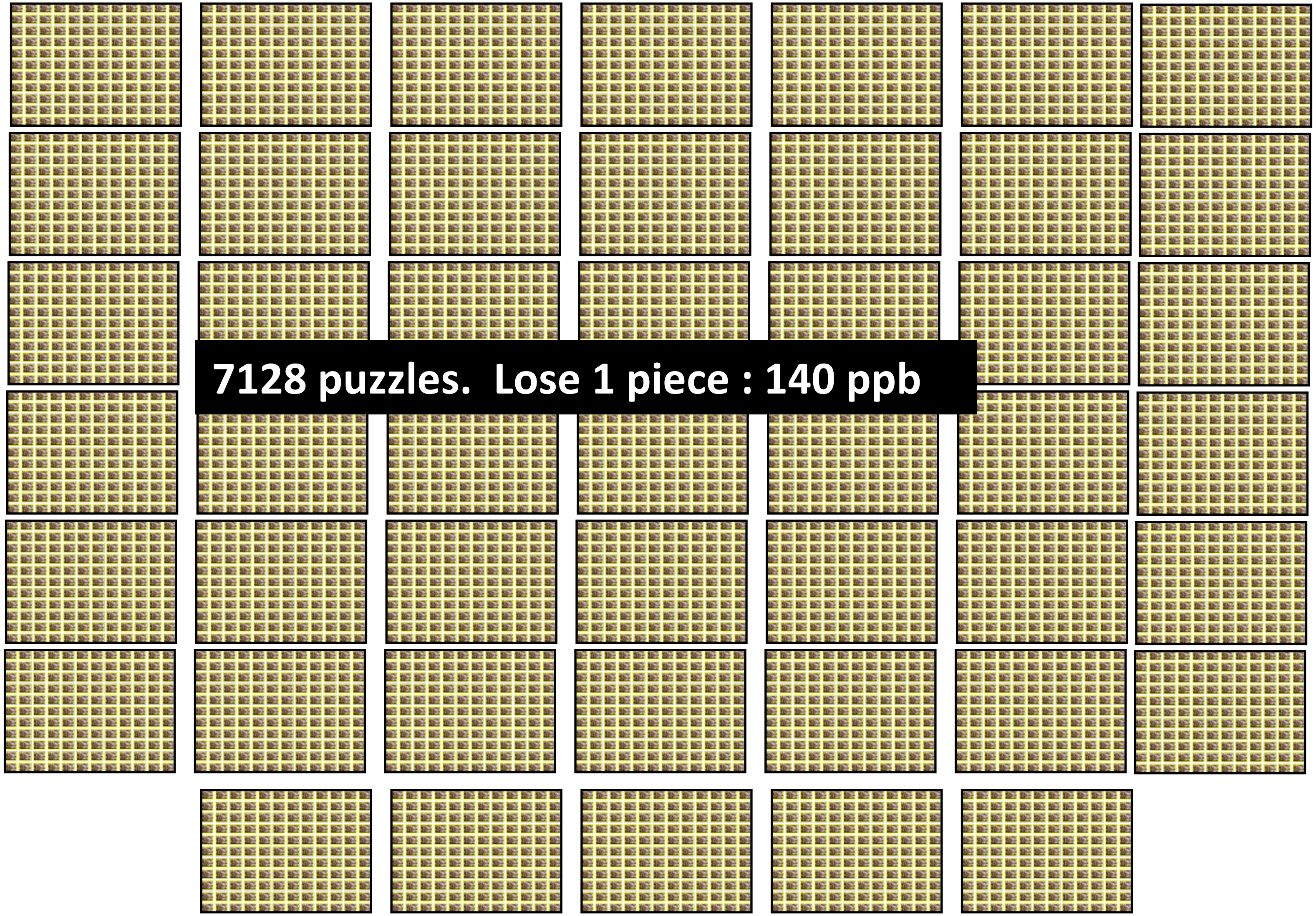
Systematics x 1/3



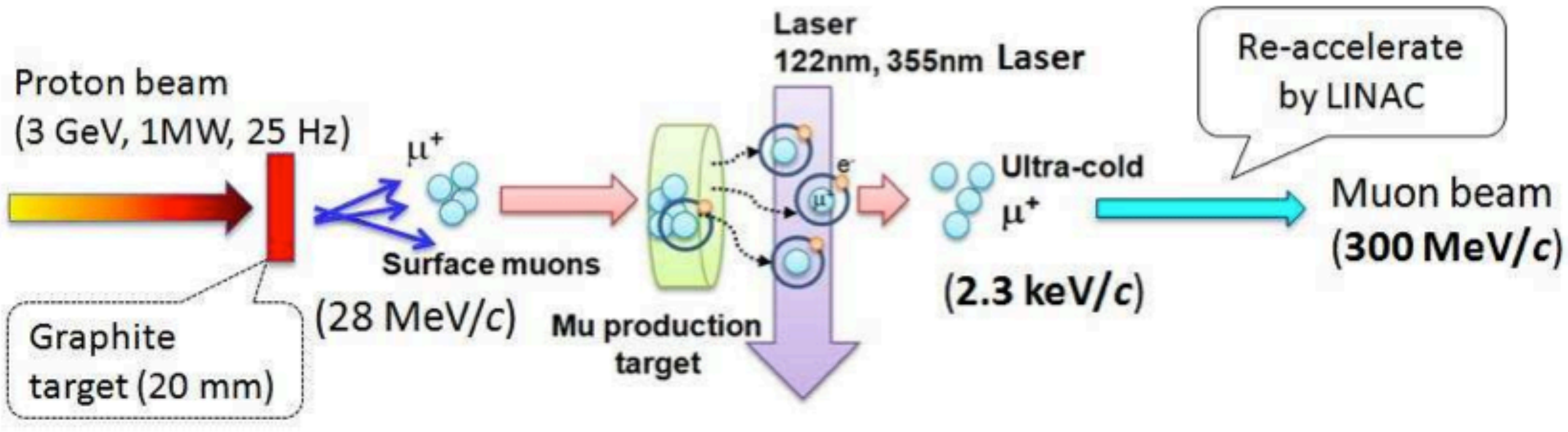
132 “1000-piece” puzzles. If you lose just 1 piece it’s a 7 ppm error

The 1976 CERN result

Systematics x 1/3



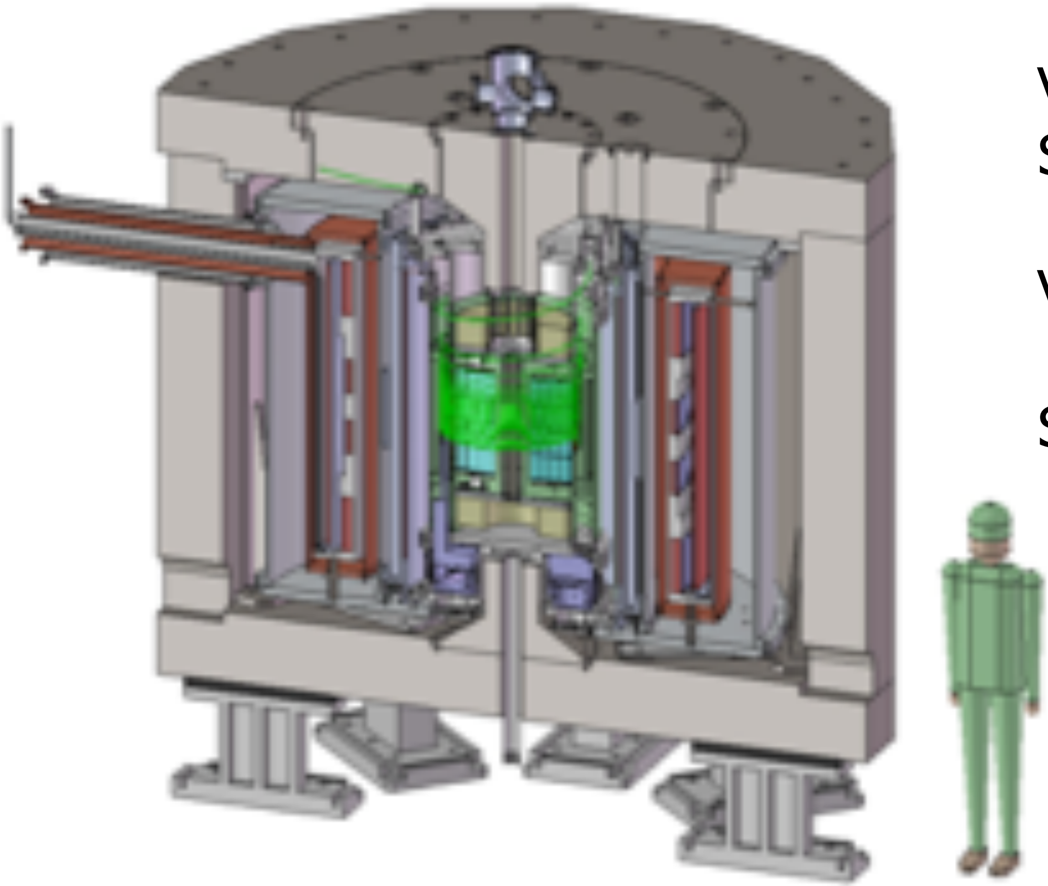
J-PARC g-2 Experiment



Requires several innovations to achieve 10^6 muons/sec

- production of sufficient muonium using special materials
- pulsed 100 μJ VUV lasers to ionise muonium
- muon linac keeping $\Delta p_T/p_T < 1e\text{-}5$: world's 1st muon accelerator !

MRI magnet and Si detectors



Very precise tracking using
Si detectors

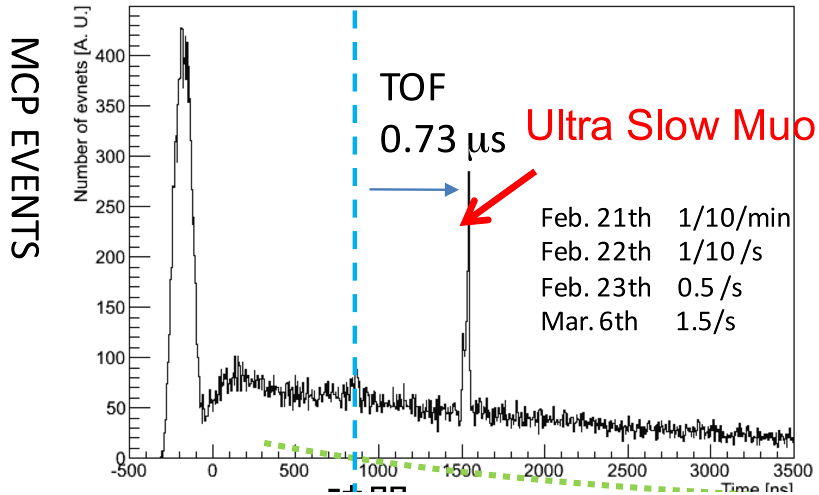
Very uniform field (MRI magnet)

Spiral 3D beam injection !

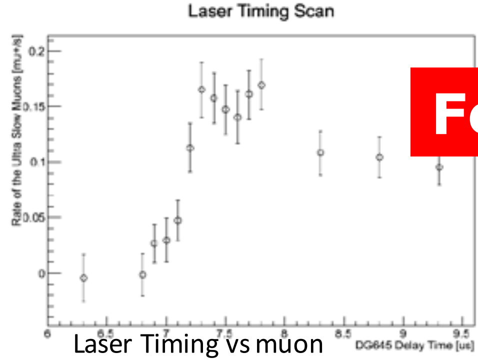
Observation of Ultra Slow Muons @U-Line

ULTRASLOW MUON MICROSCOPE

Events of the MCP

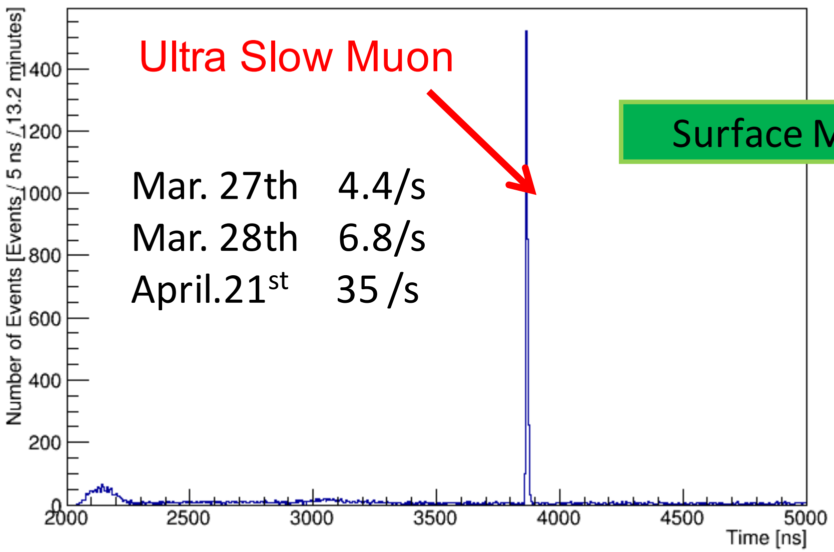


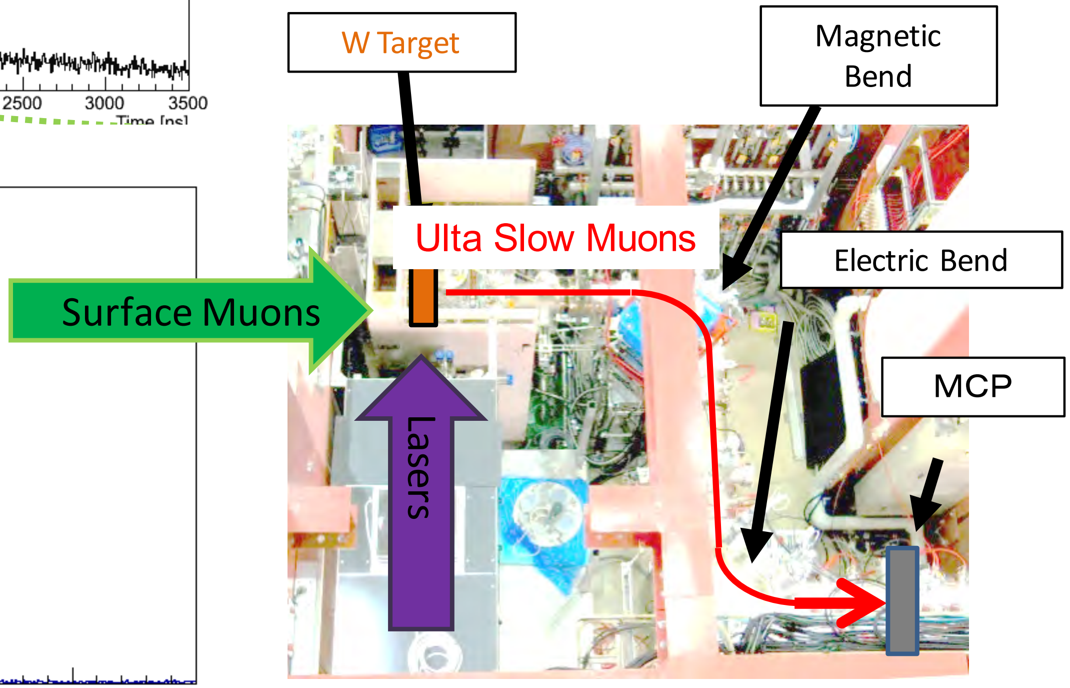
2016 3/7 23:04:31



Laser Timing vs muon

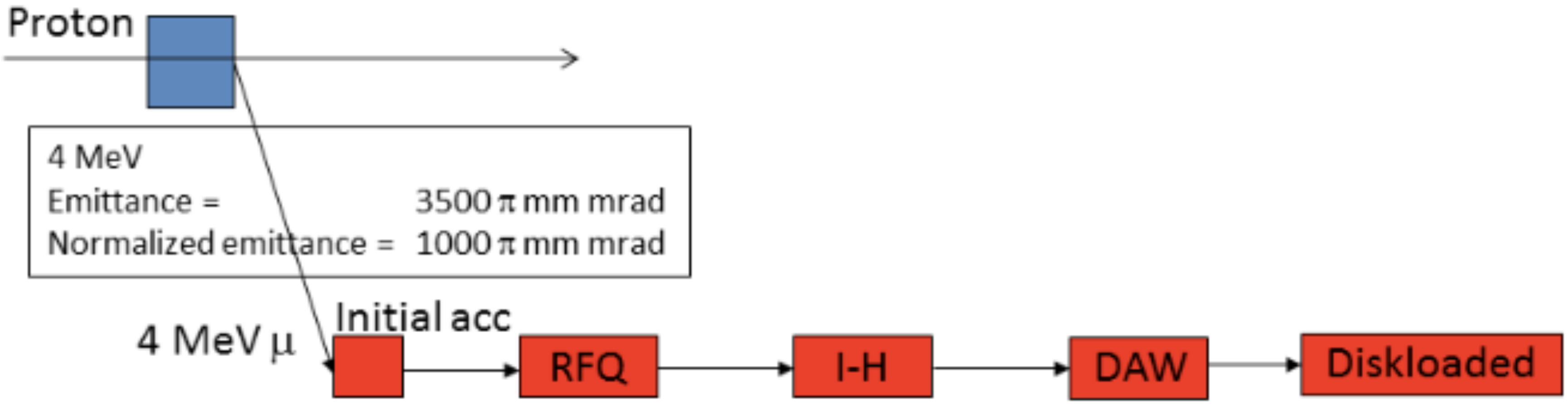
Feb 2016





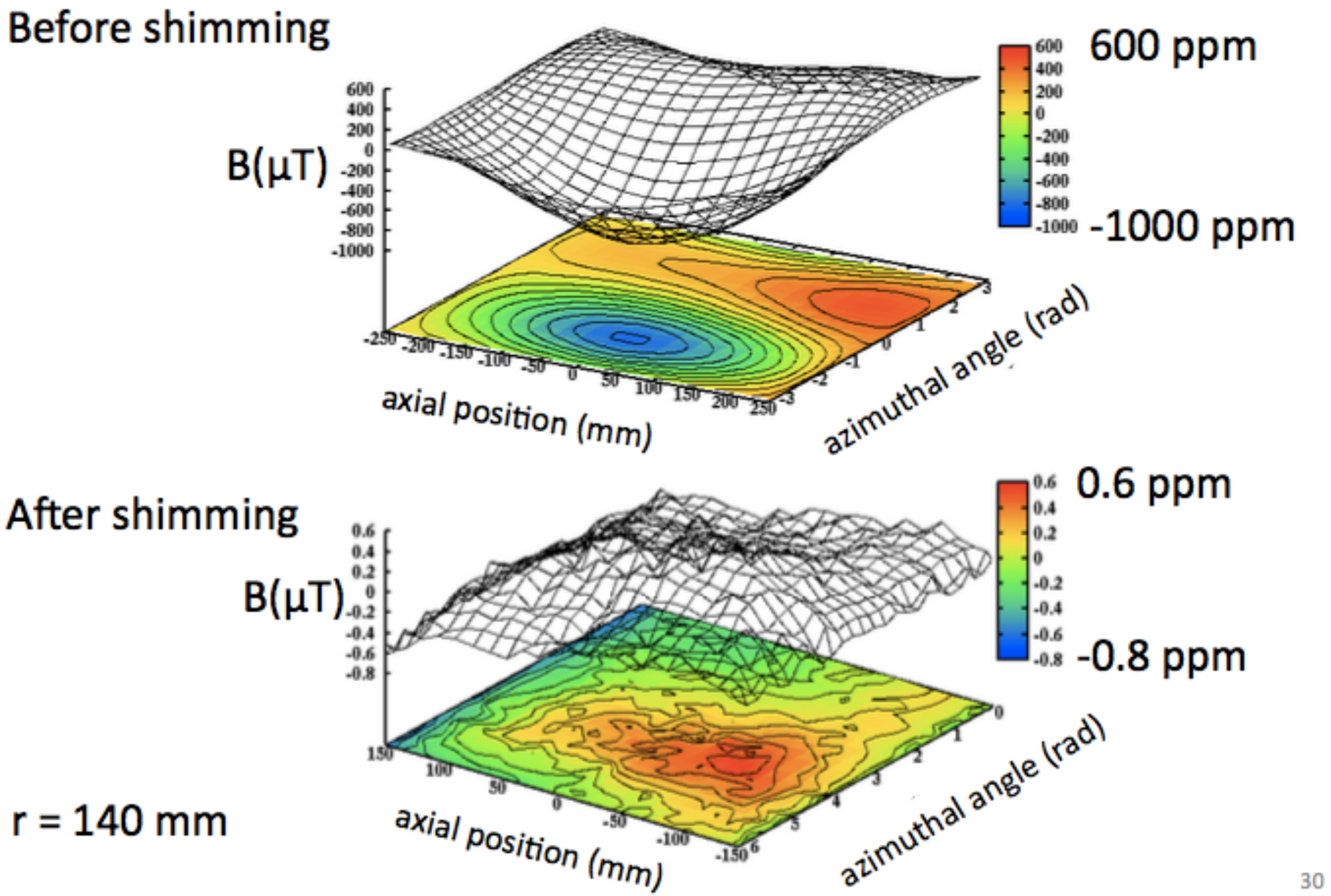
Topview of U-Line

Acceleration progress



	5.7keV	340 keV	4 MeV	50MeV	200 MeV
βγ	0.01	0.08	0.278	0.98	2.71
Emittance(mm mrad)	150	19	5.4	1.5	0.55
Normalized emittance	1.5	1.5	1.5	1.5	1.5

Tests of 1st two acceleration stages completed.


Before shimming
B(μT)
600 ppm
-1000 ppm
axial position (mm)
azimuthal angle (rad)
After shimming
B(μT)
0.6 ppm
-0.8 ppm
r = 140 mm
axial position (mm)
azimuthal angle (rad)
30

R&D phase being completed in next year

Funds for most of construction are secured.

Expect data taking to begin after FNAL g-2 i.e. 2020.

Initial sensitivity at 0.37 ppm (stat) reducing to 0.1 ppm (stat)
i.e. similar to FNAL 0.1 ppm (stat) [0.1 ppm (syst)]

This will provide a crucial measurement with completely different systematic effects compared to the FNAL measurement.

"If you enjoy doing difficult experiments, you can do them, but it is a waste of time and effort because the result is already known" : Pauli

"No experiment is so dumb, that it should not be tried" : Gerlach

FNAL B-field / ω_p systematics

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

FNAL ω_a systematics

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07