The Muon g-2 Experiment at Fermilab

Kevin Lynch

For the Muon g-2 Collaboration

NuFact 2015

Centro Brasileiro de Pesquisas Físicas

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YORK College

THE CITY UNIVERSITY OF NEW YORK

μ g-2

Muon g-2 holds a prominent place in the near term US HEP program

Building for Discovery

Strategic Plan for U.S. Particle Physics in the Global Context

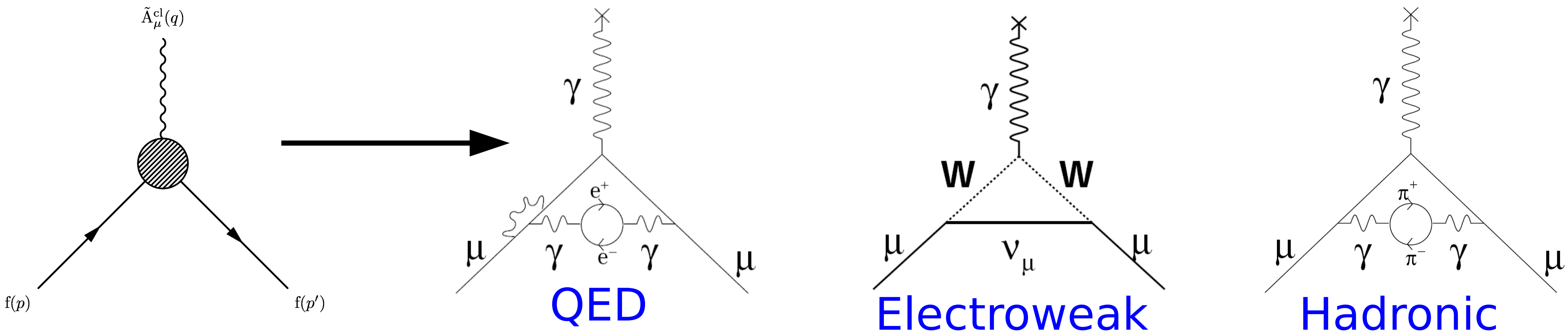
P5 Report Recommendation 22: Complete the Mu2e and Muon g-2 projects.

Why this emphasis on muon physics?

*P5 = Particle Physics Project Prioritization Panel

http://www.usparticlephysics.org/p5/

Muon g-2 is interesting precisely because theorists can calculate it!



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(\mathrm{NP})$$

	Value $(\times 10^{-11})$ units
QED $(\gamma + \ell)$	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)**	-98.4 ± 0.7
H-LBL†	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

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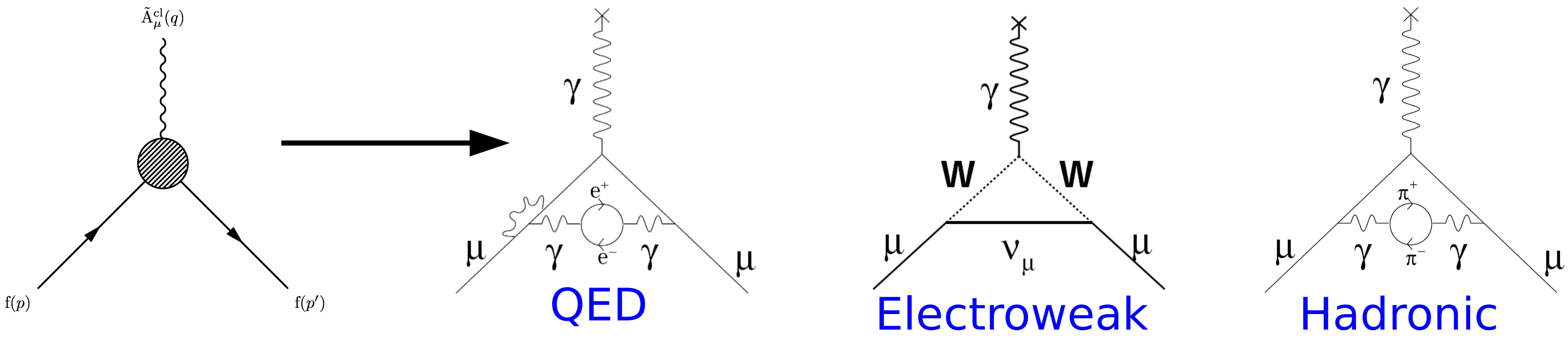

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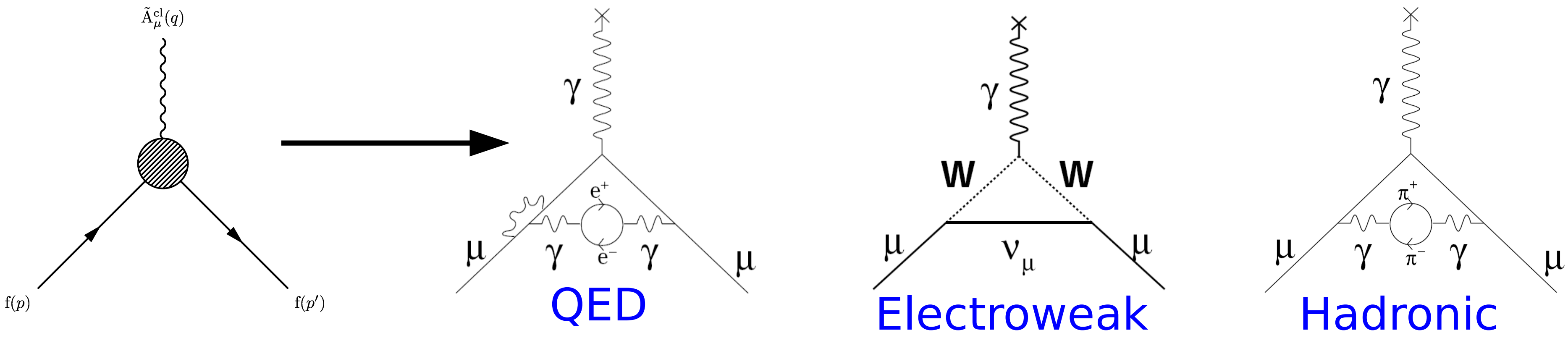

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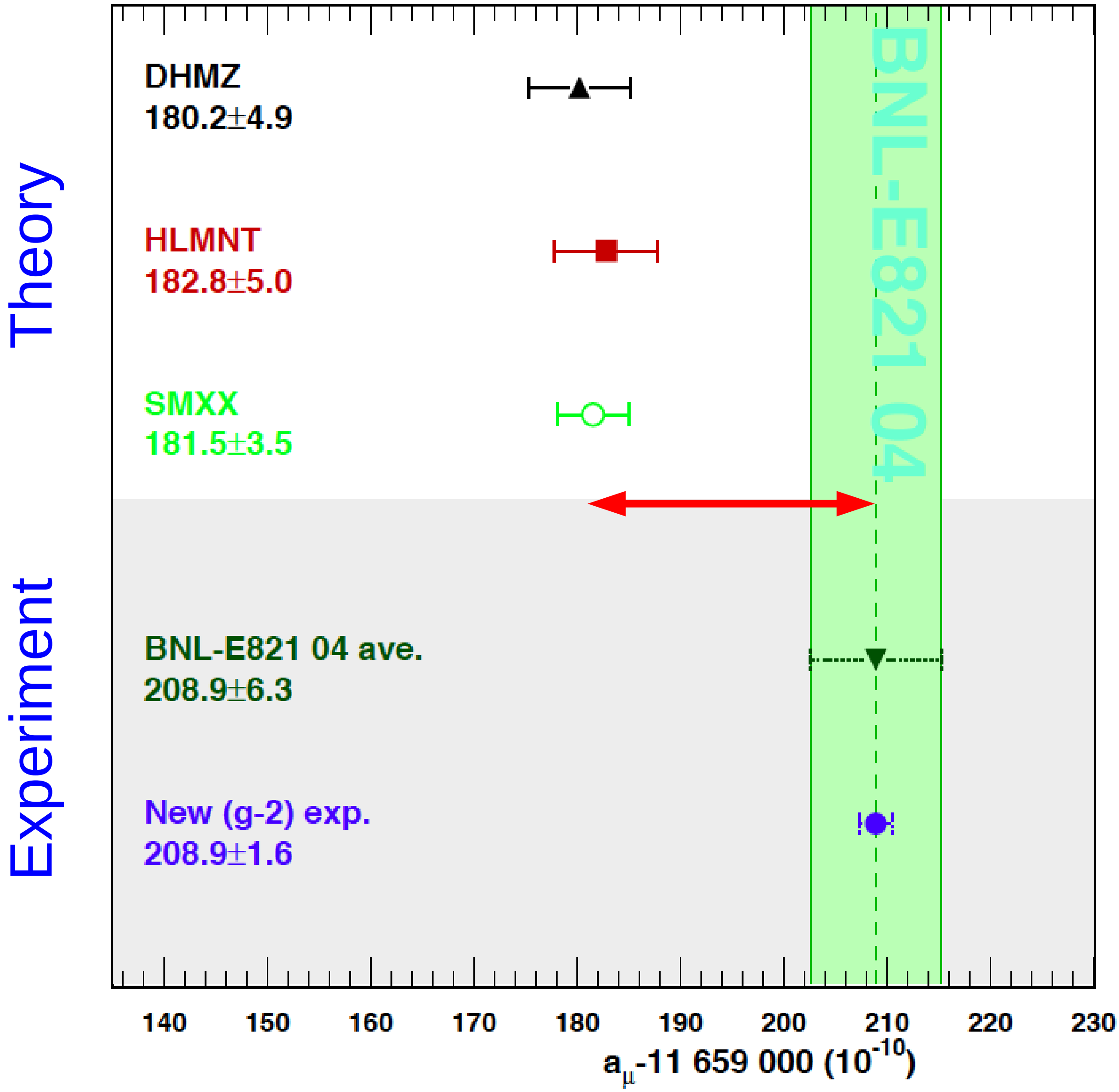
QED dominates the value

But hadrons dominate the uncertainty

Muon g-2 can both be calculated and measured to fabulously high precision



These error bars are all smaller than 1ppm

The theory/experiment discrepancy currently sits at 3.6σ

We achieve this experimental precision because we measure frequencies

If we put a point charged fermion into motion in a plane transverse to a pure magnetic dipole field, both the momentum and the spin precess

Momentum precession – cyclotron motion:

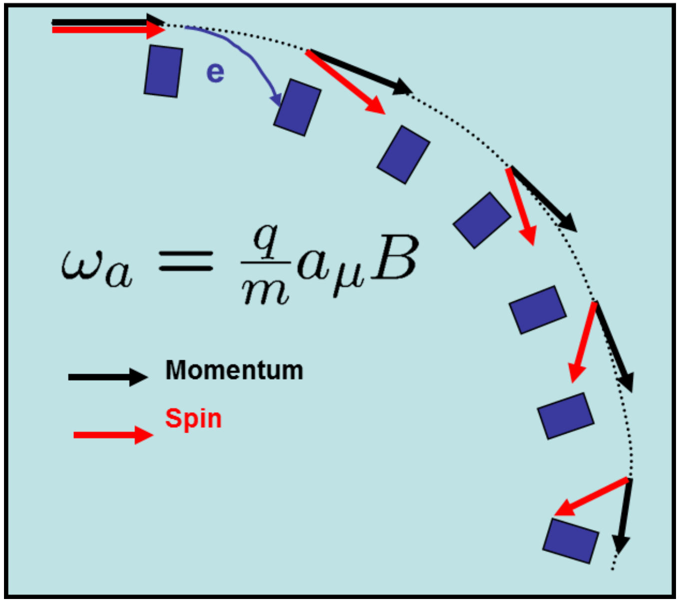
$$\frac{\mathrm{d}\vec{p}}{\mathrm{d}t} = e\vec{v} \times \vec{B} \longrightarrow \omega_C = \frac{eB}{\gamma mc}$$

Spin precession – Larmor plus Thomas motion:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\mu} \times \vec{B} \longrightarrow \omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

We achieve this experimental precision because we measure frequencies

The difference between these two comes from an *anomalous magnetic moment* not predicted by pure Dirac theory



$$\omega_a = \omega_C - \omega_s = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a_\mu \frac{eB}{mc}$$

If we're a little more careful and include other moments and fields, the frequency to be measured becomes more complicated

$$\vec{\omega}_a = \frac{e}{mc}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta}\right)$$

We can address these additional terms by careful experimental design

$$\vec{\omega}_a = \frac{e}{mc}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E} - a_\mu \frac{\gamma}{\gamma + 1}(\vec{\beta} \cdot \vec{B})\vec{\beta}\right)$$

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Make motion
transverse to the field

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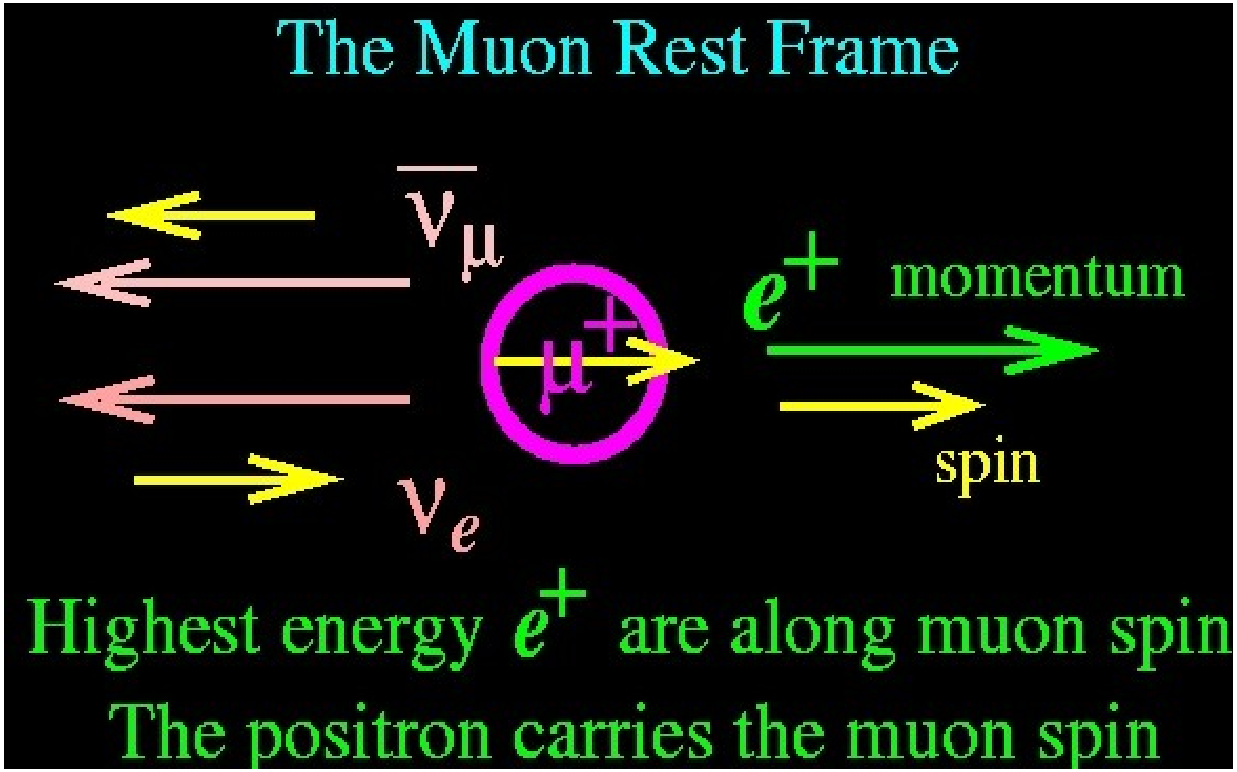
Make motion transverse to the field

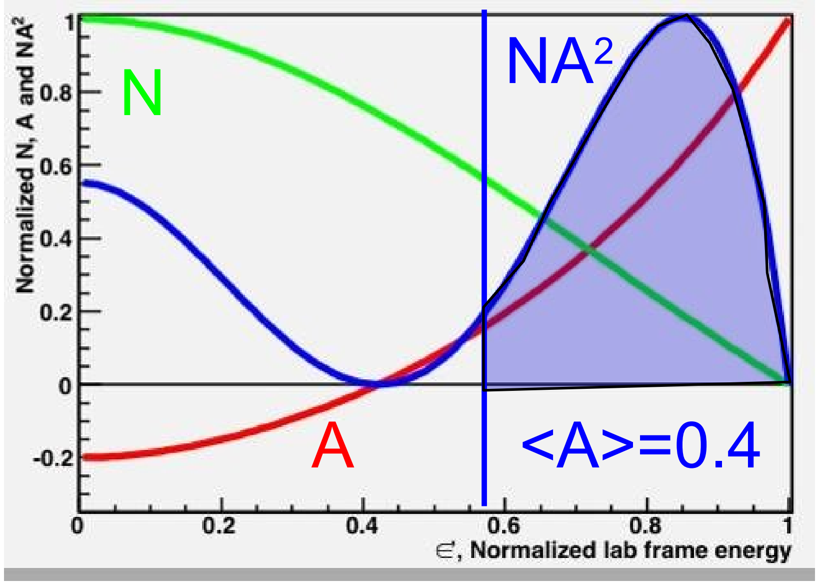
There are, of course, small corrections that must be applied for deviations from these ideals, but they are small, well understood, and well controlled.

Muon decays are self-analyzing for the spin orientation

The same chirality violating SM weak physics that produces polarized muon beams in pion decay imprints the muon spin on the electron momentum

$$\frac{\mathrm{d}^2\Gamma^{\pm}_{\mu}}{\mathrm{d}y\,\mathrm{d}\Omega} = n(y)\,(1 \mp a(y)\cos\theta)$$





Experimental Technique

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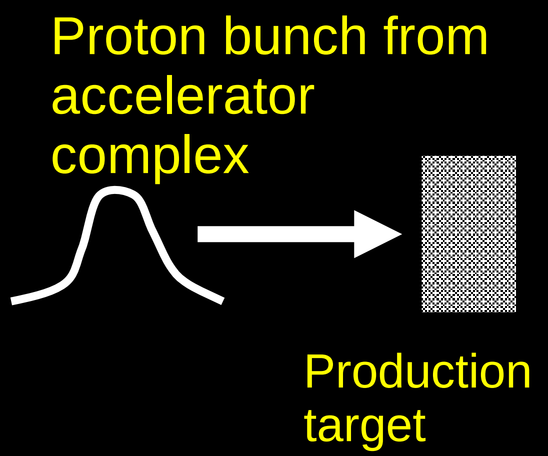

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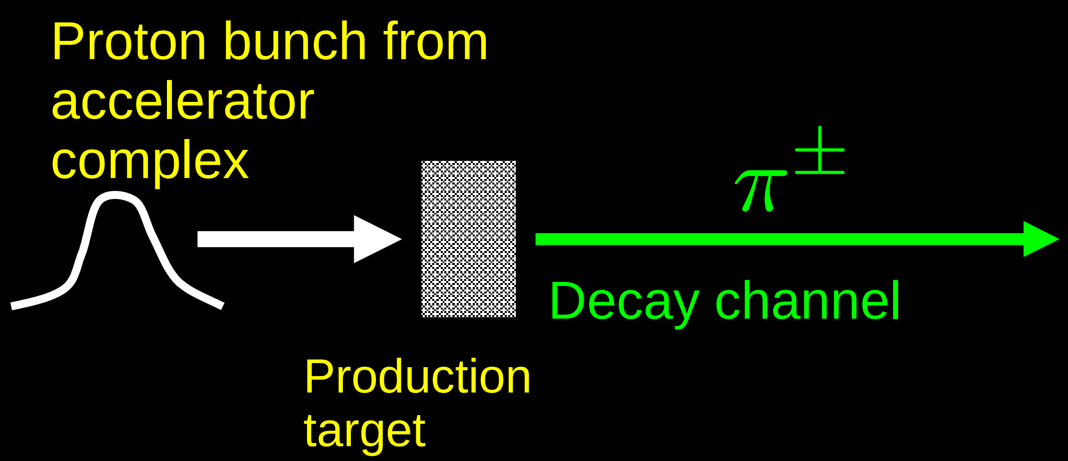

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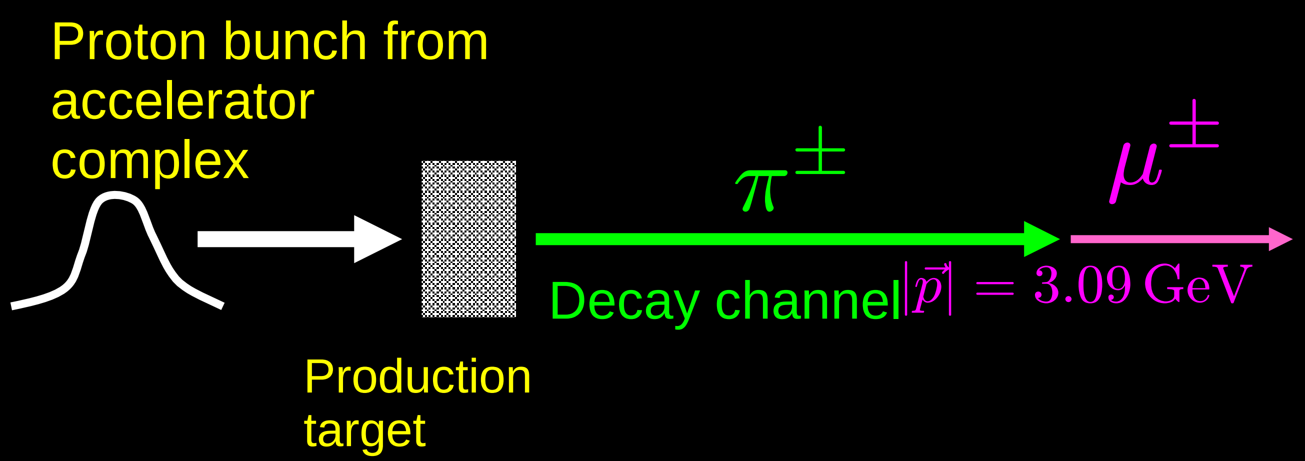

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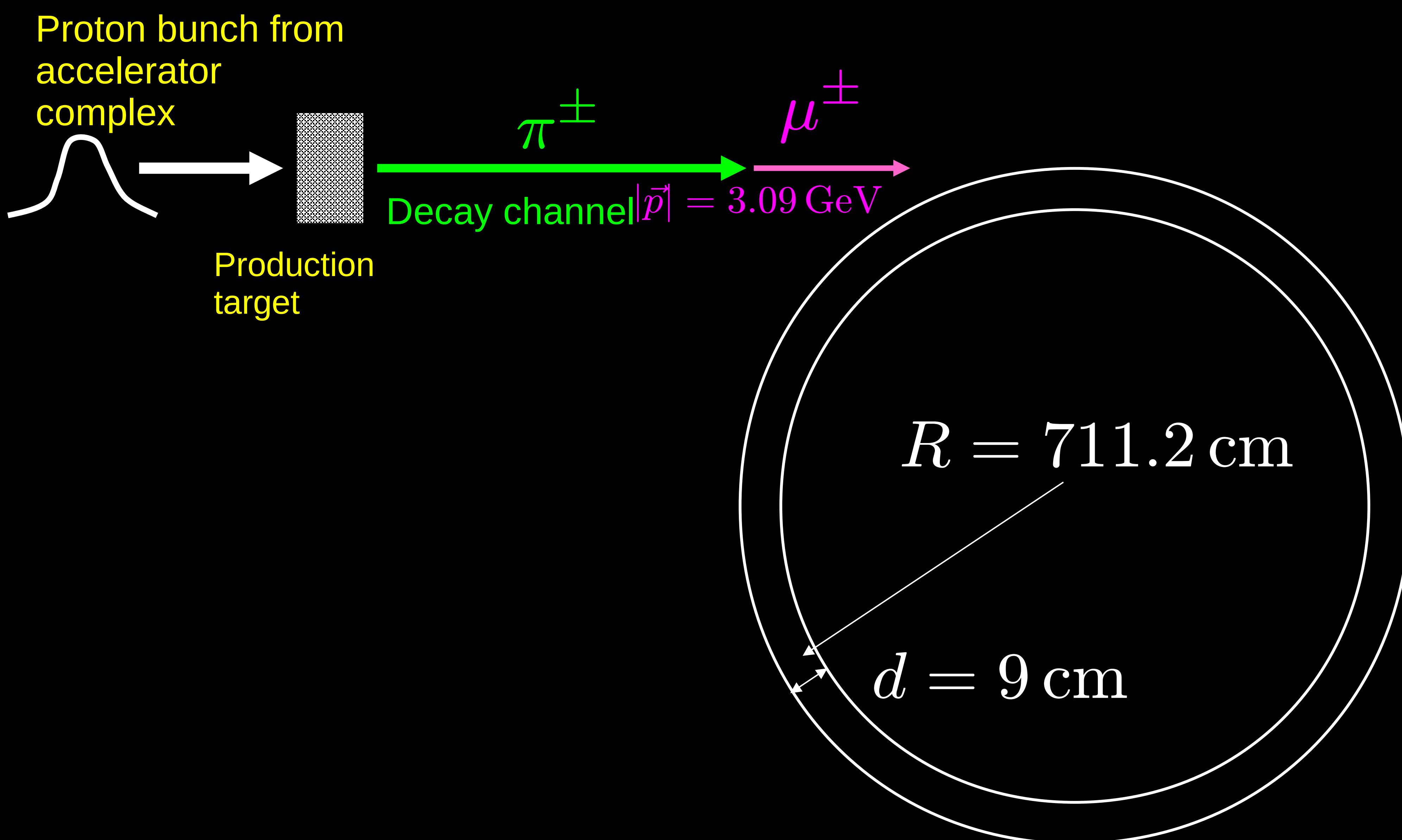

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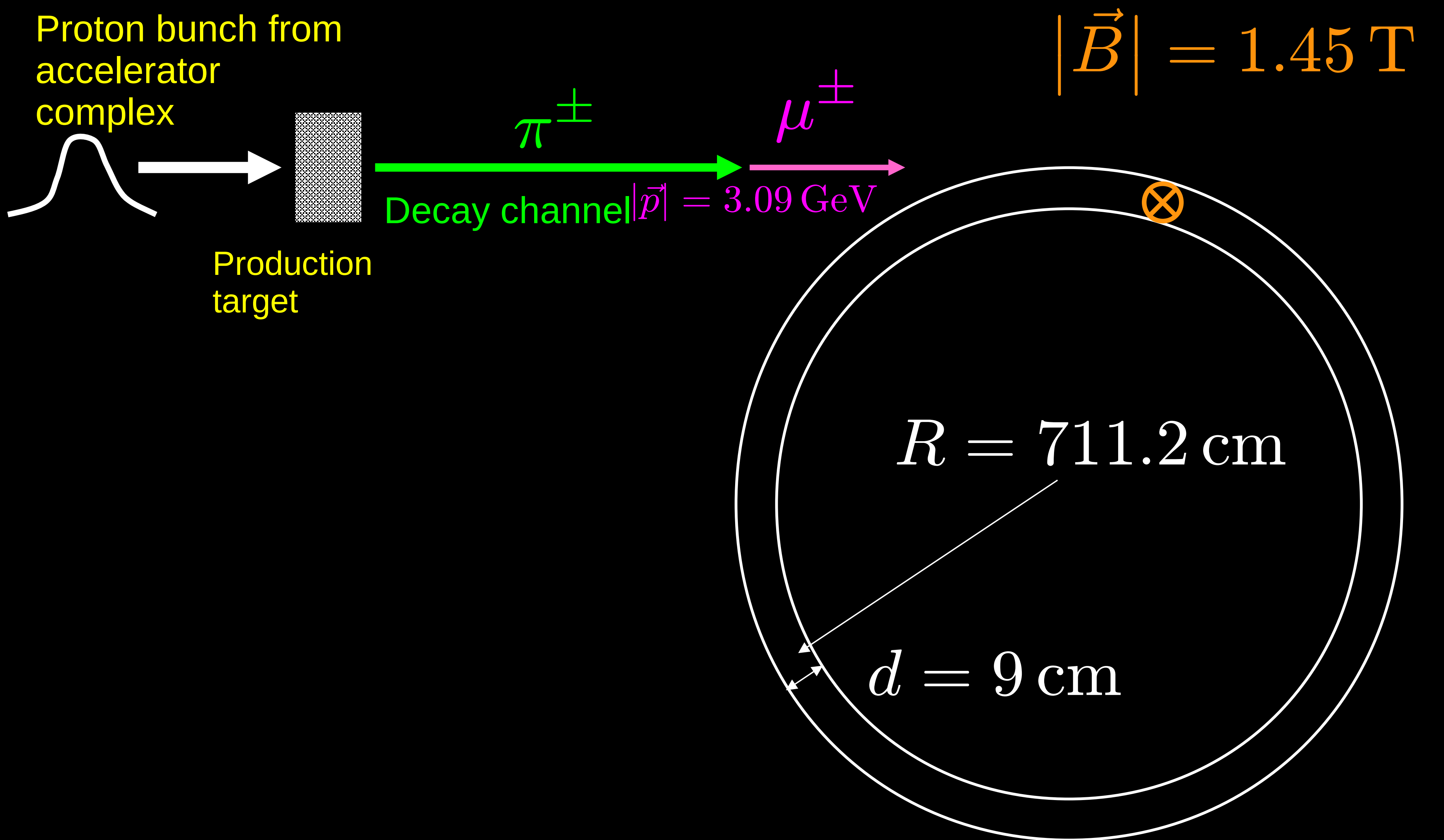

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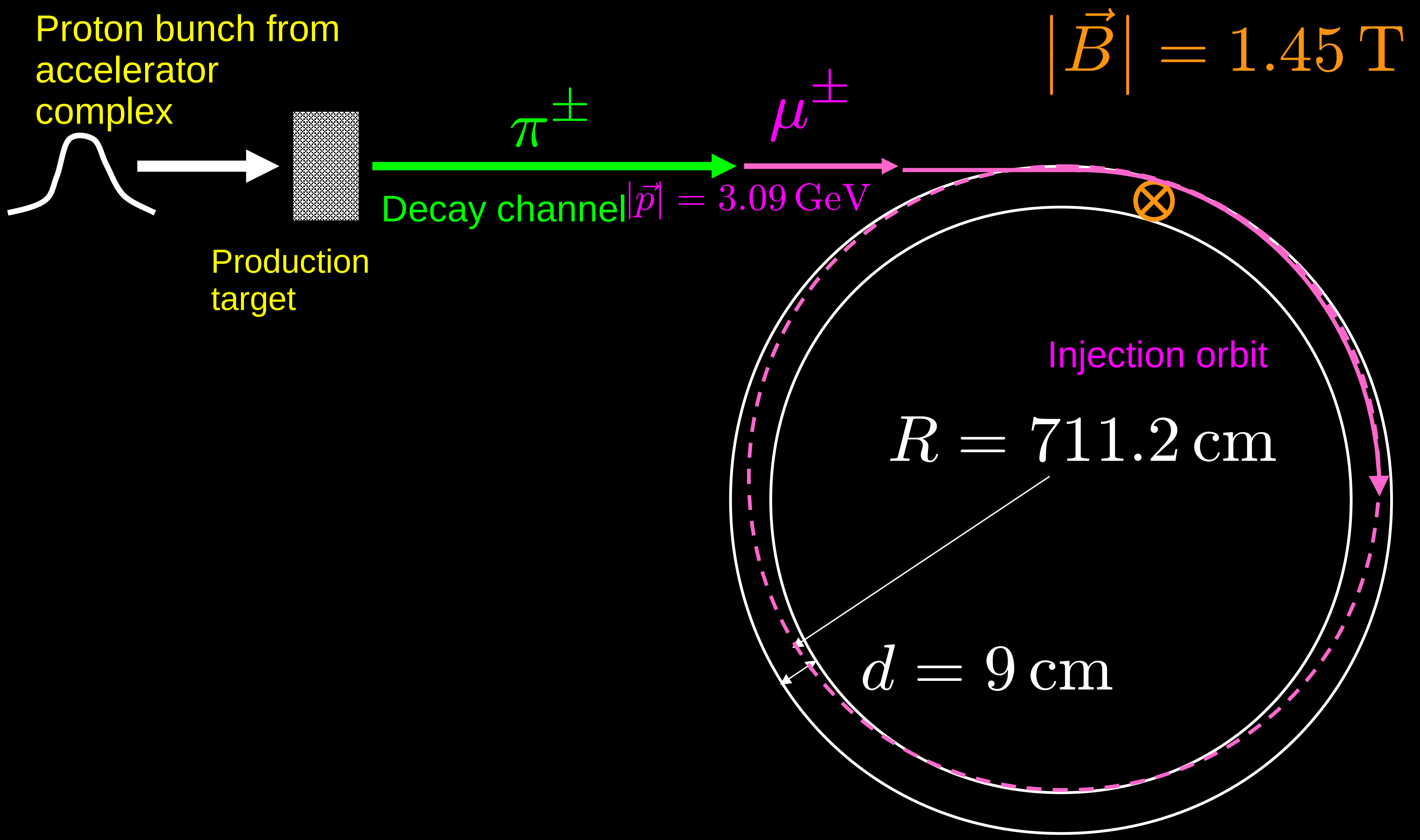

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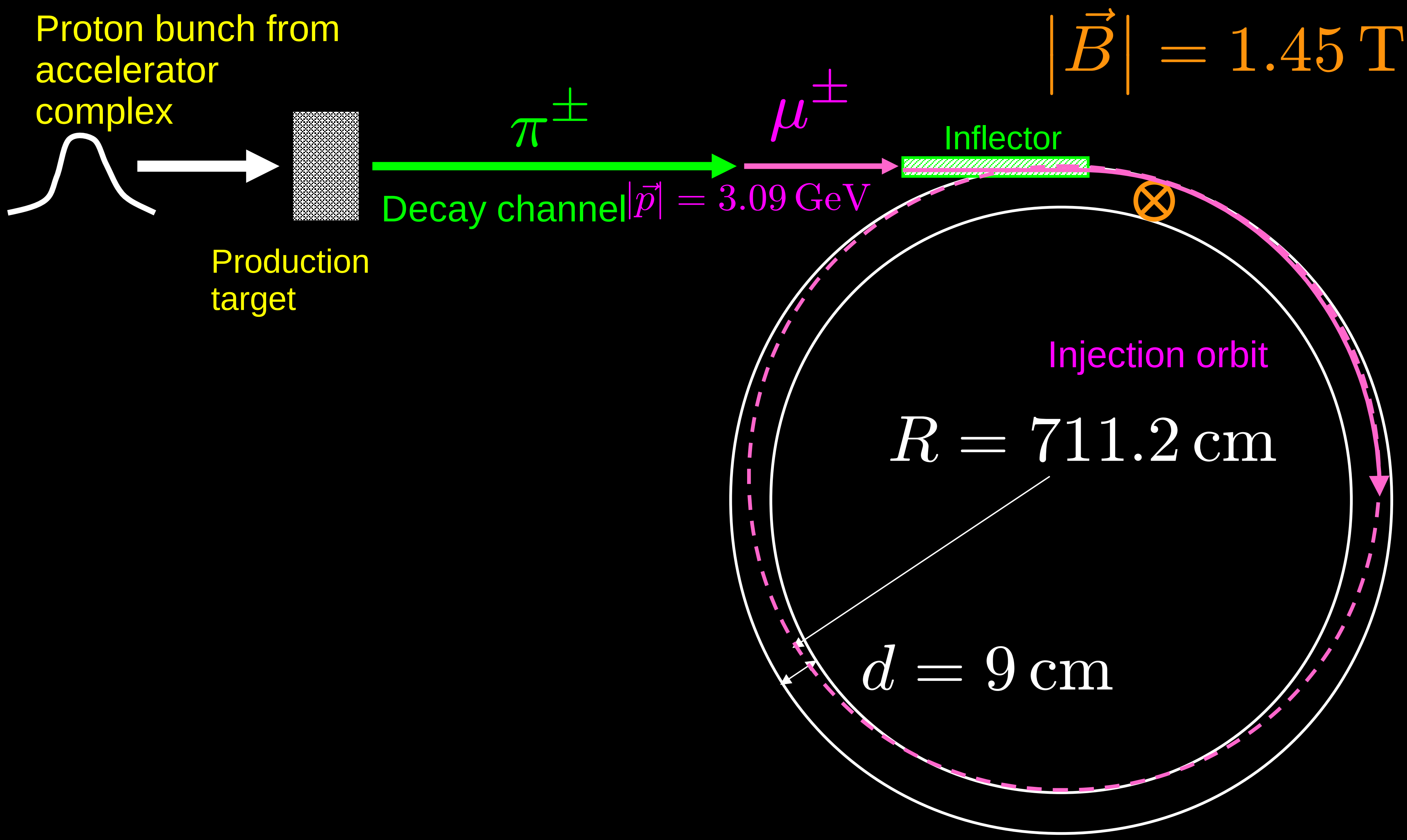

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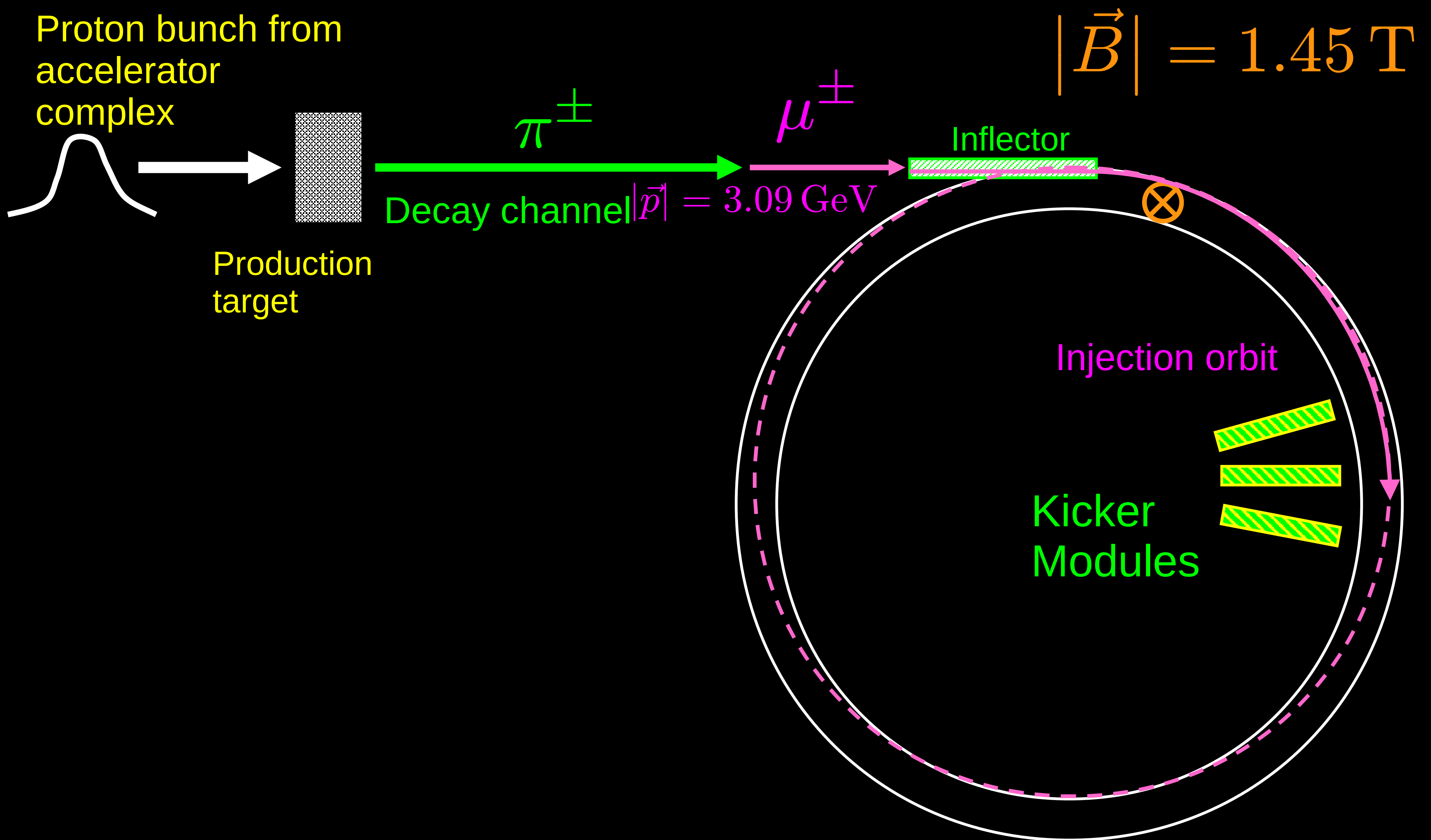

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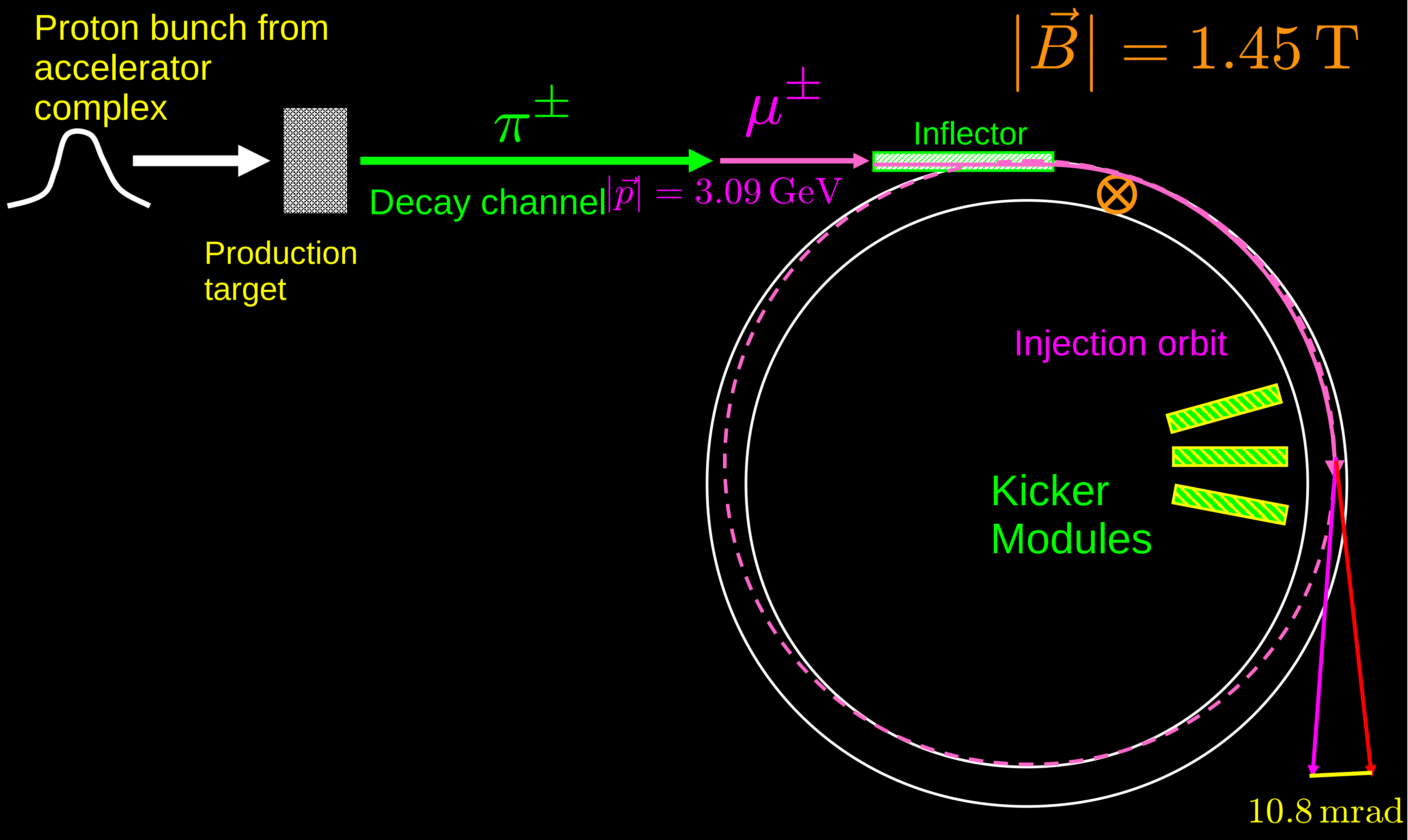

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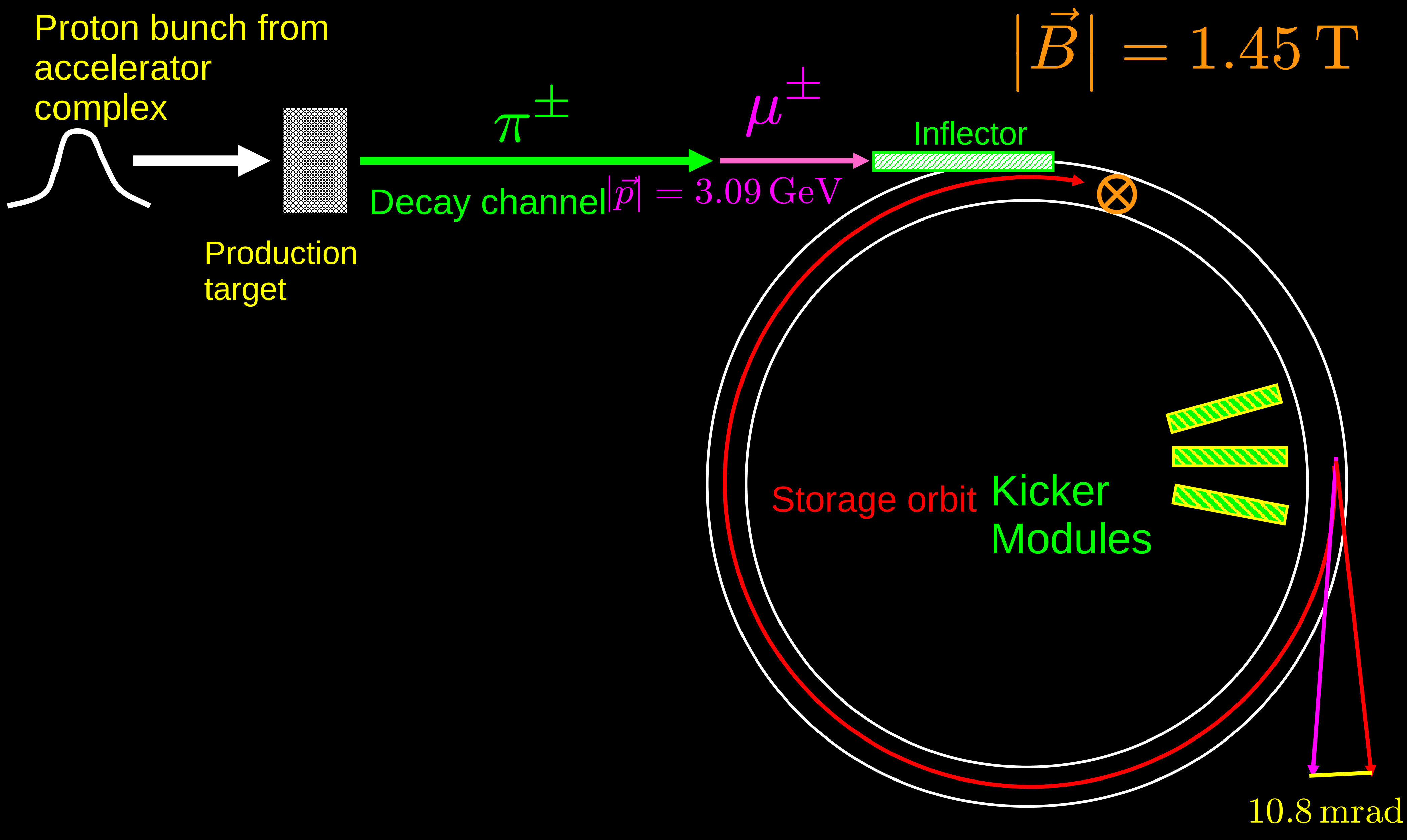

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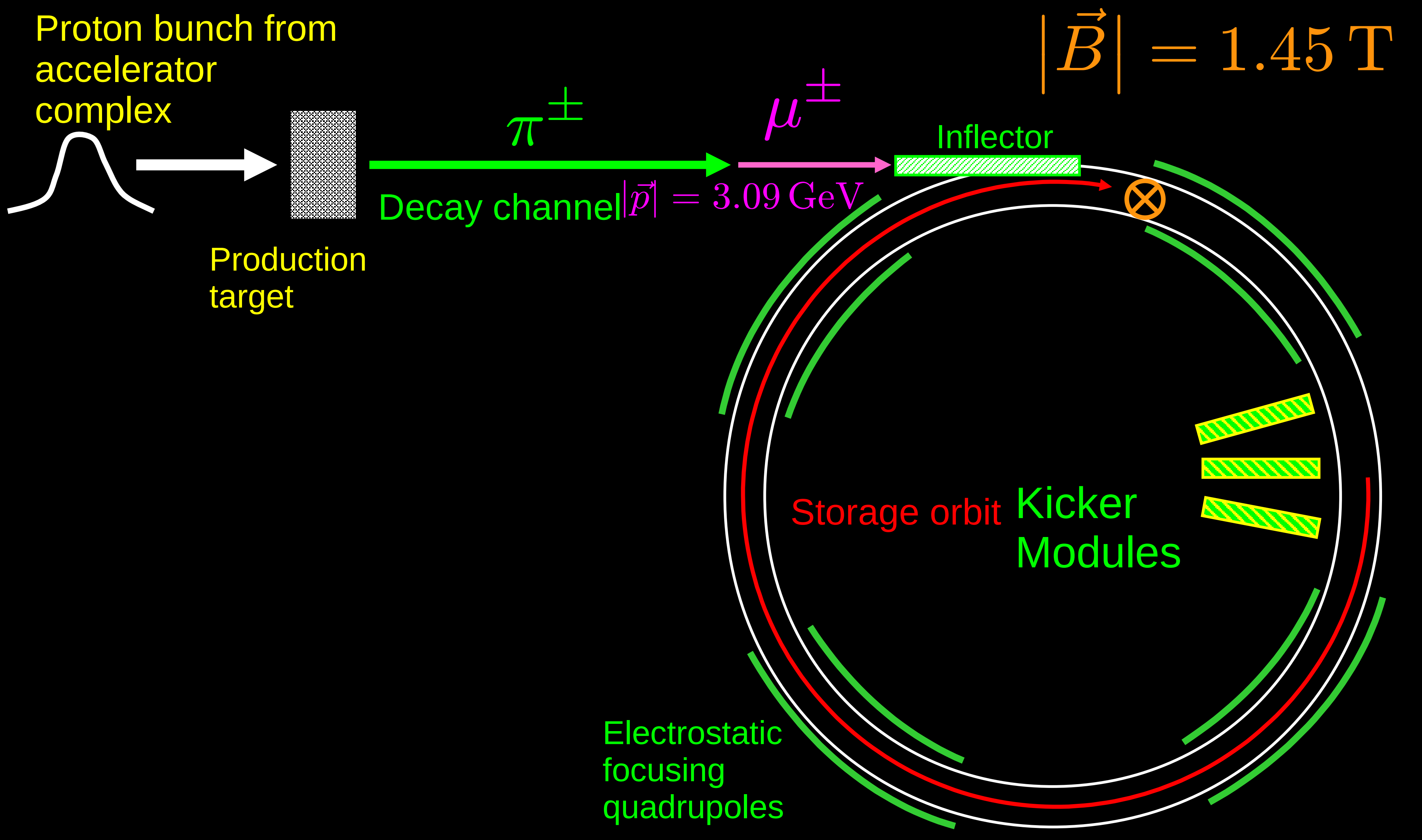

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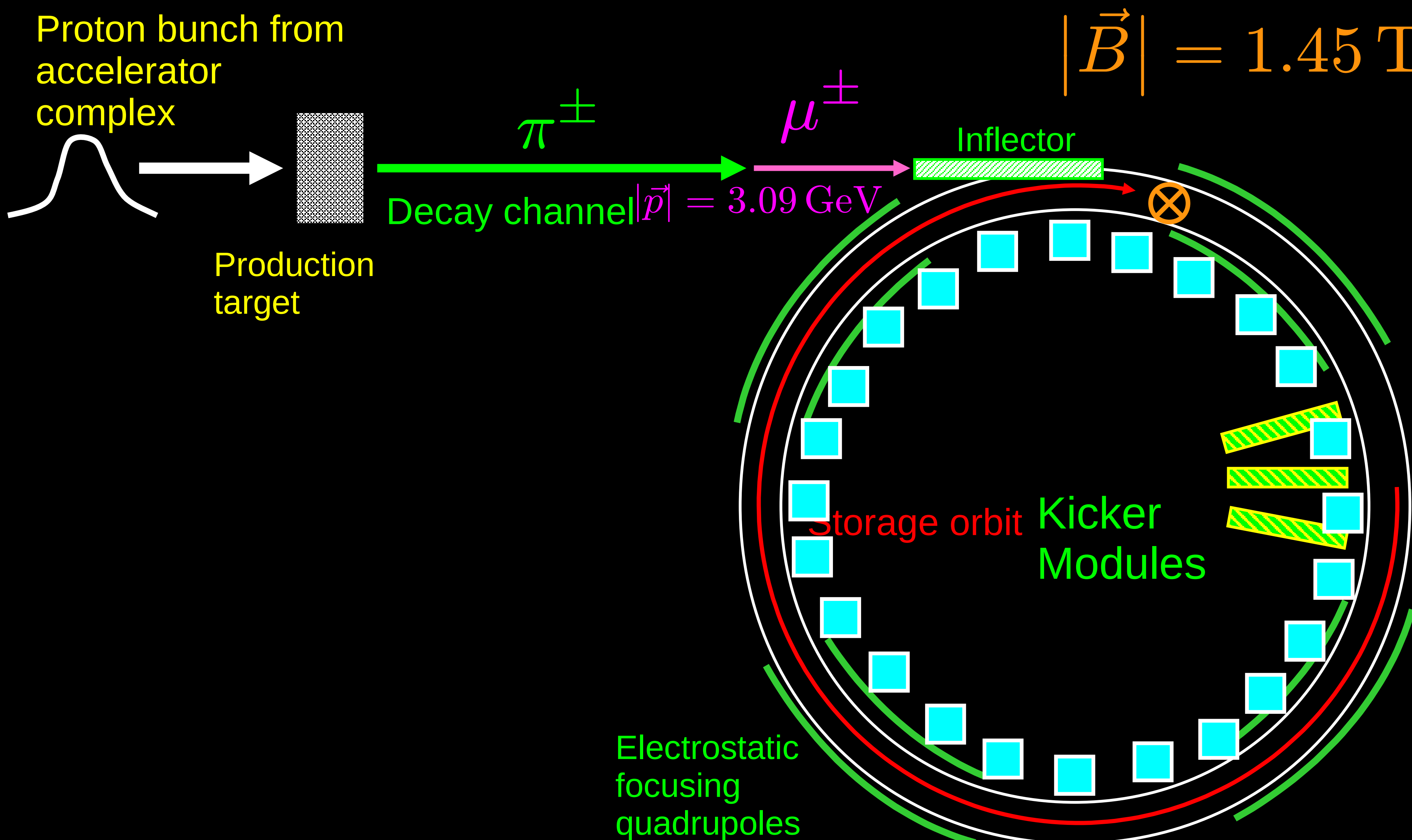
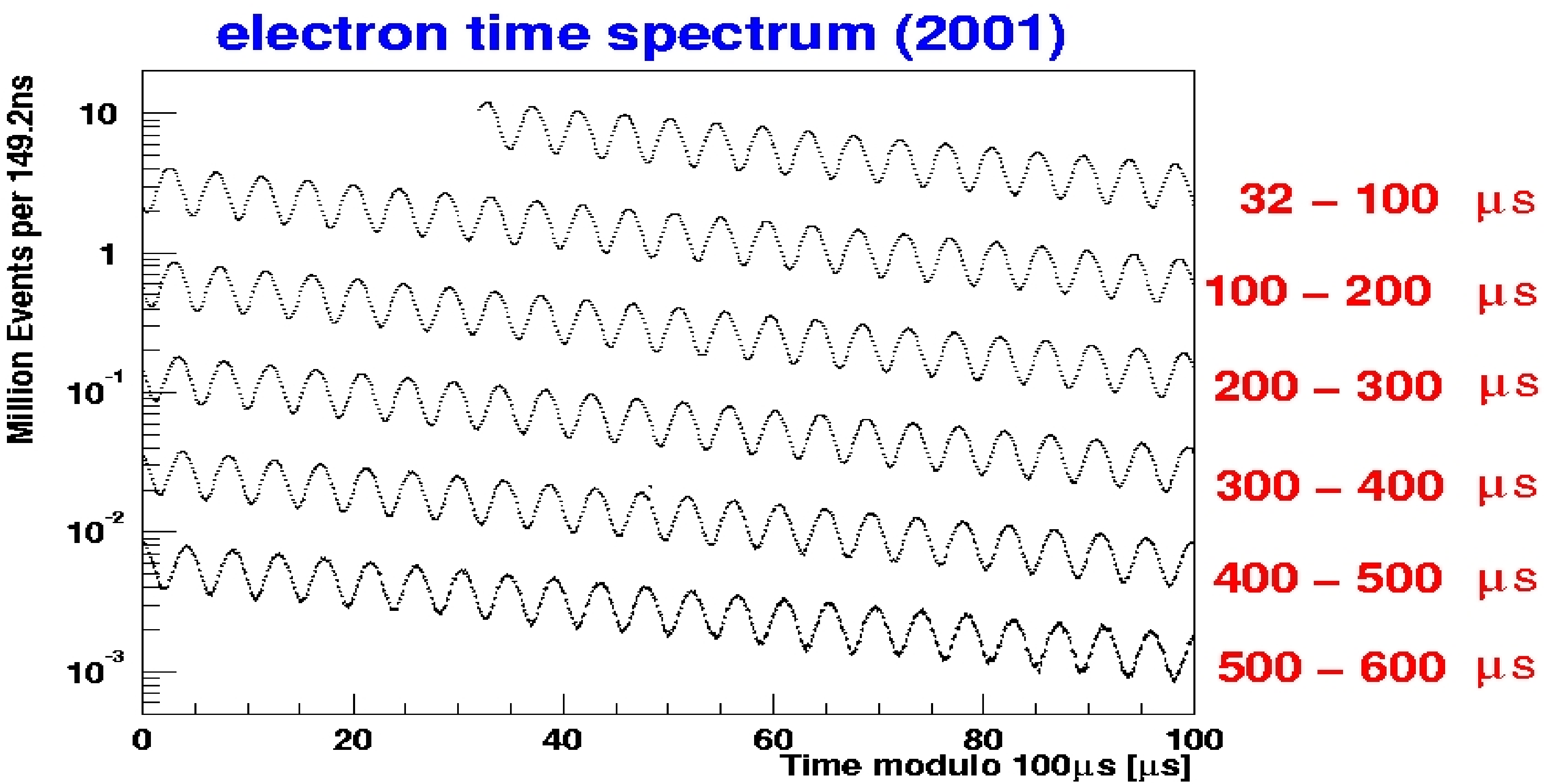


We measure the electron energies, choose a cutoff, and fit for ω_a ...

$$f(t) = N_0(E)e^{-t/\tau}\left[1 + A(E)\cos(\omega_a t + \phi)\right]$$



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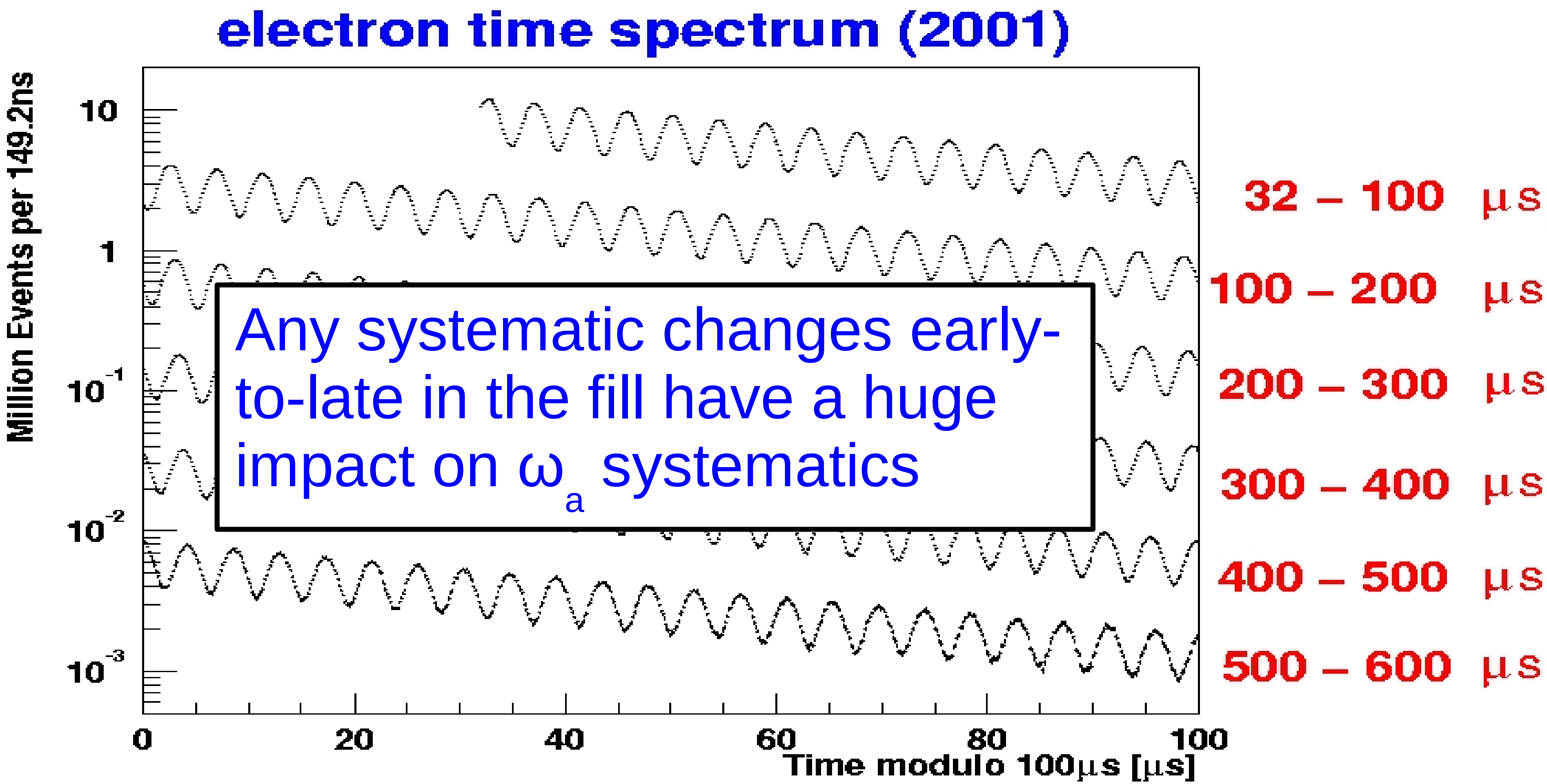
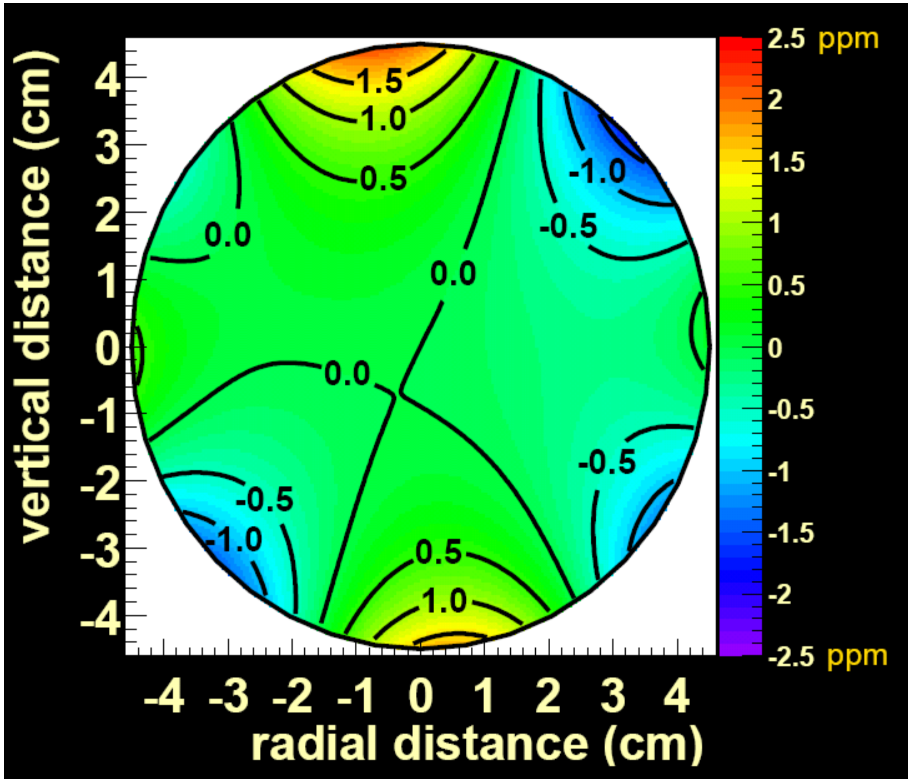


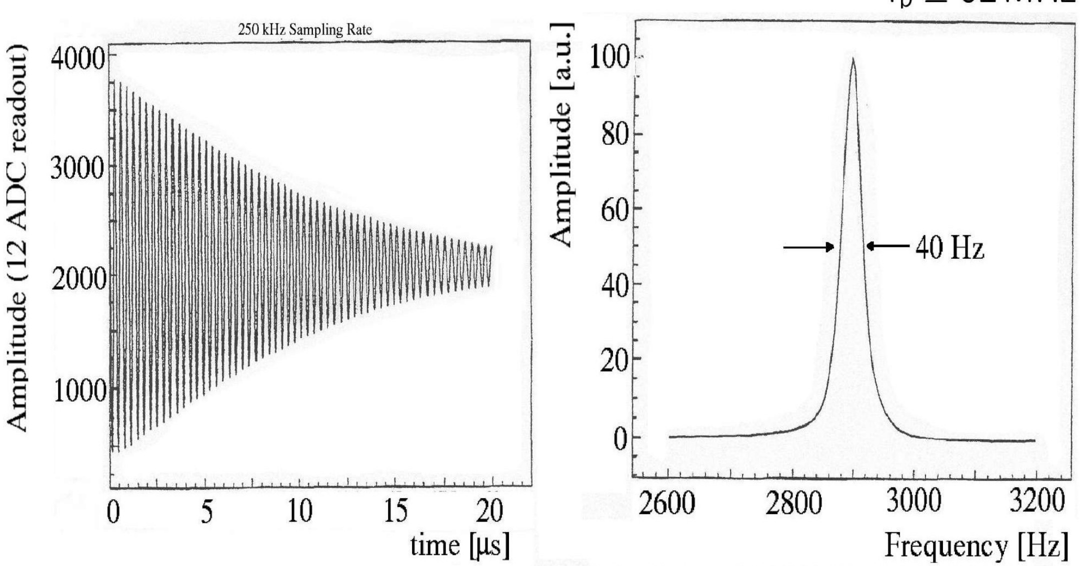
We simultaneously find the magnetic field with a frequency measurement

Pulsed NMR and FID of protons with mobile and fixed probes measure the Larmor frequency, ω_p, in the storage field.



Free induction decay signals:

$f_p \simeq 62\,\mathrm{MHz}$



The B-field at E821 was uniform at the 1ppm level with uncertainty on <B> is less than 0.03ppm

Finally, combine the omegas to get a result

$$\omega_a = \left(\frac{eB}{m_\mu}\right)\frac{g_\mu - 2}{2} \qquad \omega_p = \left(\frac{eB}{2m_p}\right)g_p$$

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$$\sigma_{\mathrm{BNL}} = \left\{ \begin{array}{c} 0.46\,\mathrm{ppm\ statistical} \\ 0.28\,\mathrm{ppm\ systematic} \end{array} \right\} = 0.54\,\mathrm{ppm}$$

To do better using this technique, requires many small improvements in a lot of areas

Field Systematics:

Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	5
Others †	150	100	100	30
Total systematic error on ω_p	400	240	170	70
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

- †Higher multipoles, trolley temperature (≤ 50 ppb/$^\circ$C) and power supply voltage response (400 ppb/V, ΔV=50 mV), and eddy currents from the kicker.

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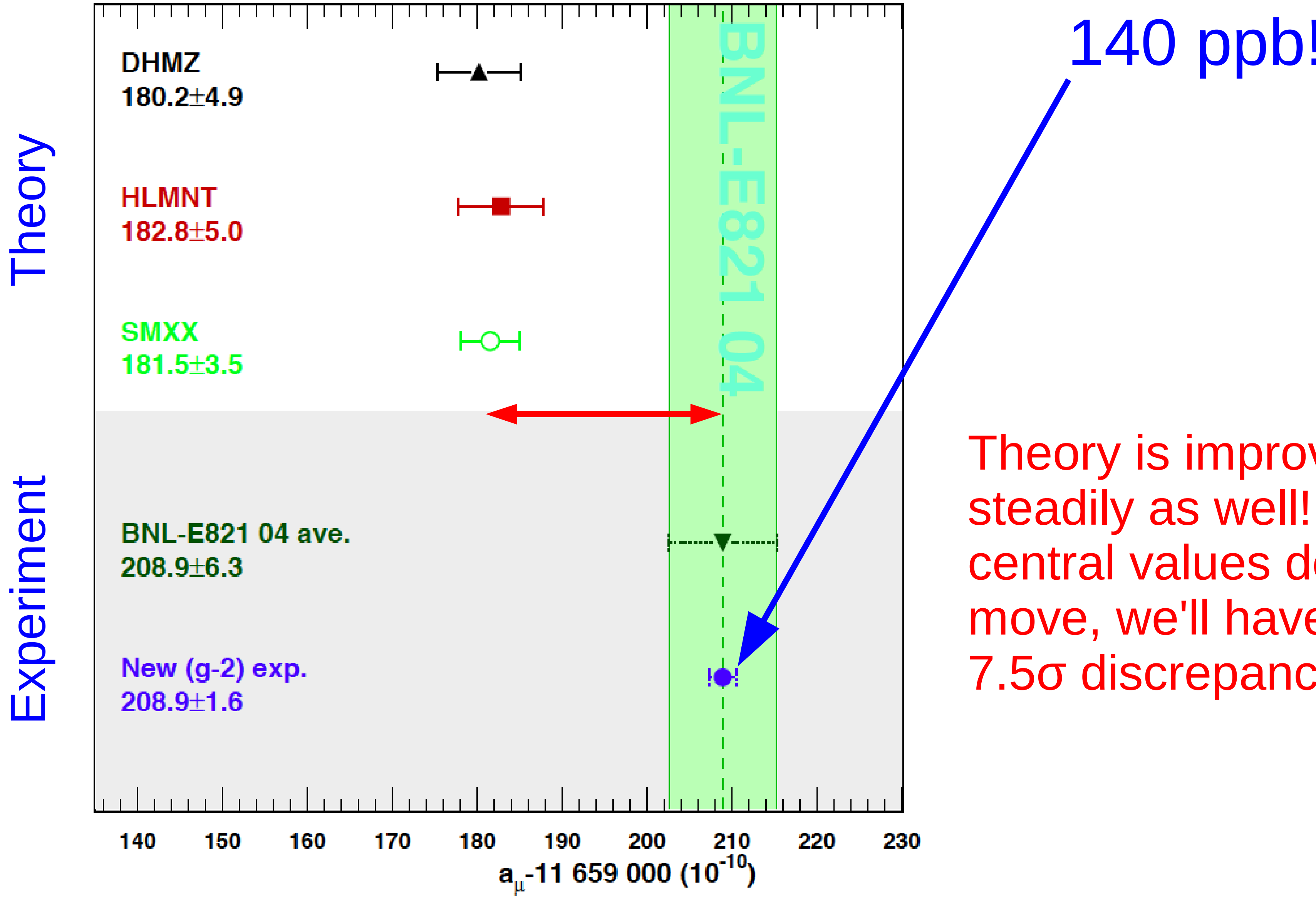
Precession Systematics:

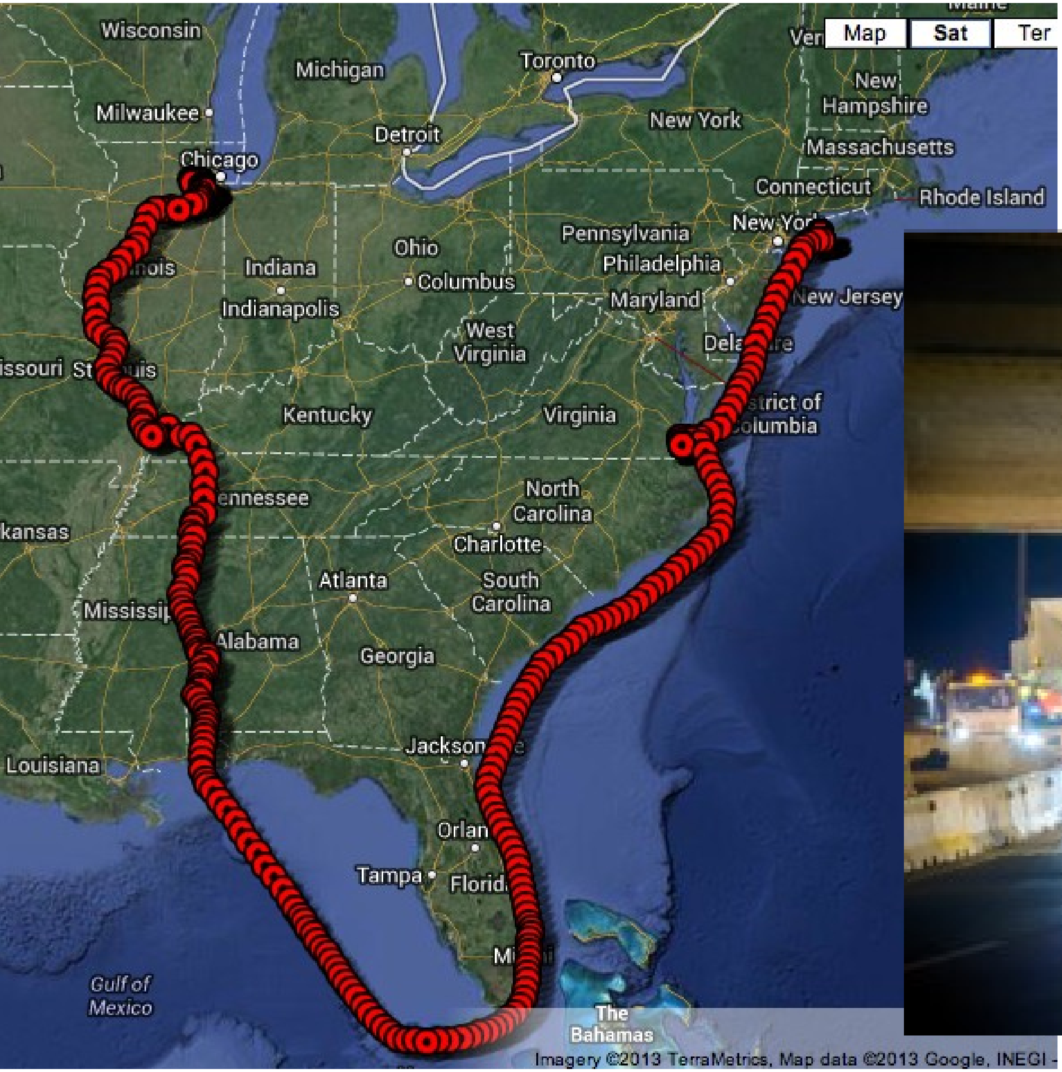
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

Along with the additional statistics, the total uncertainty will improve by a factor of 5



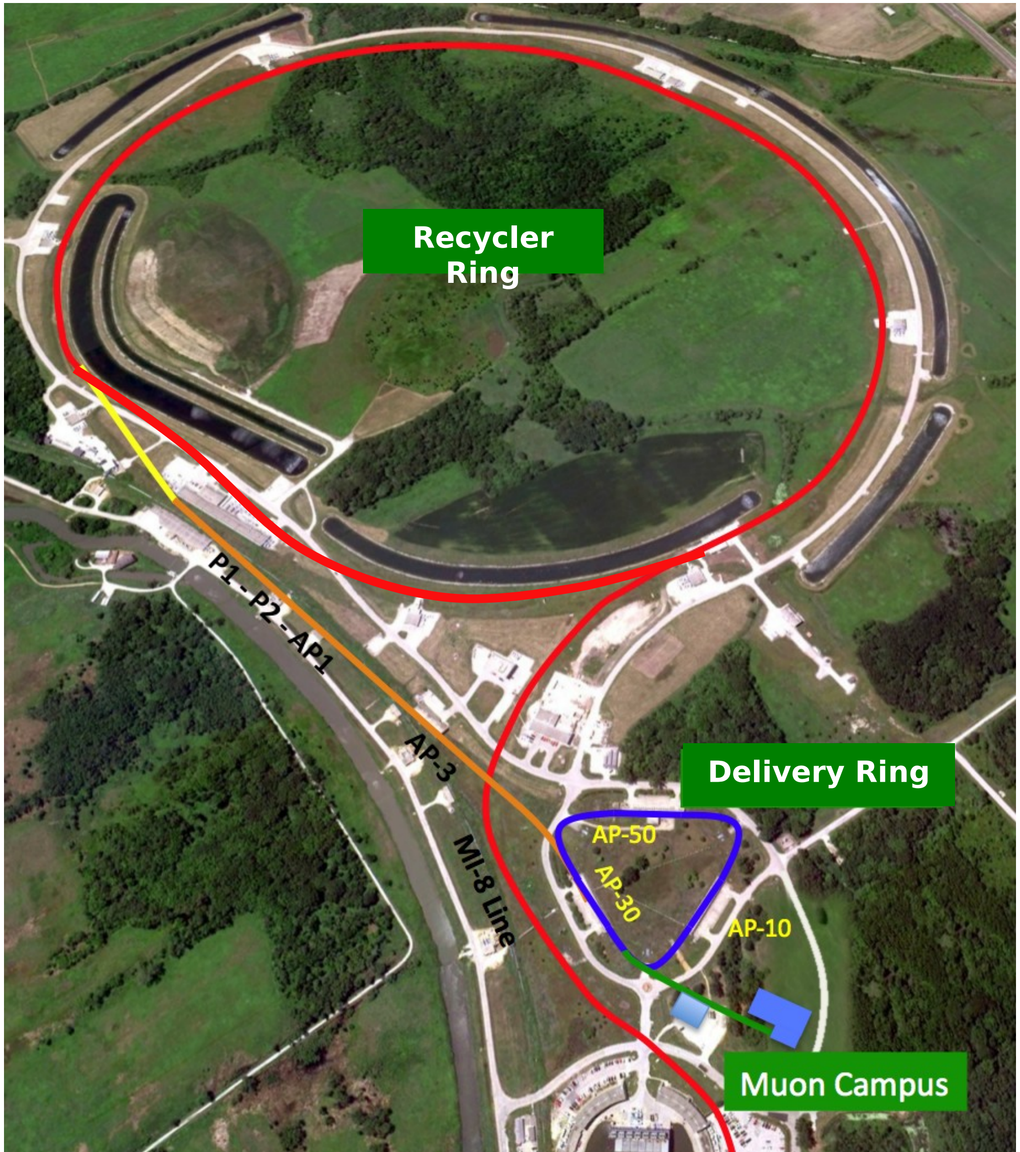
Theory is improving steadily as well! If the central values don't move, we'll have a 7.5σ discrepancy

The first step was moving the ring from BNL to FNAL ...



… and giving it a new home

We need a new, highly polarized muon source



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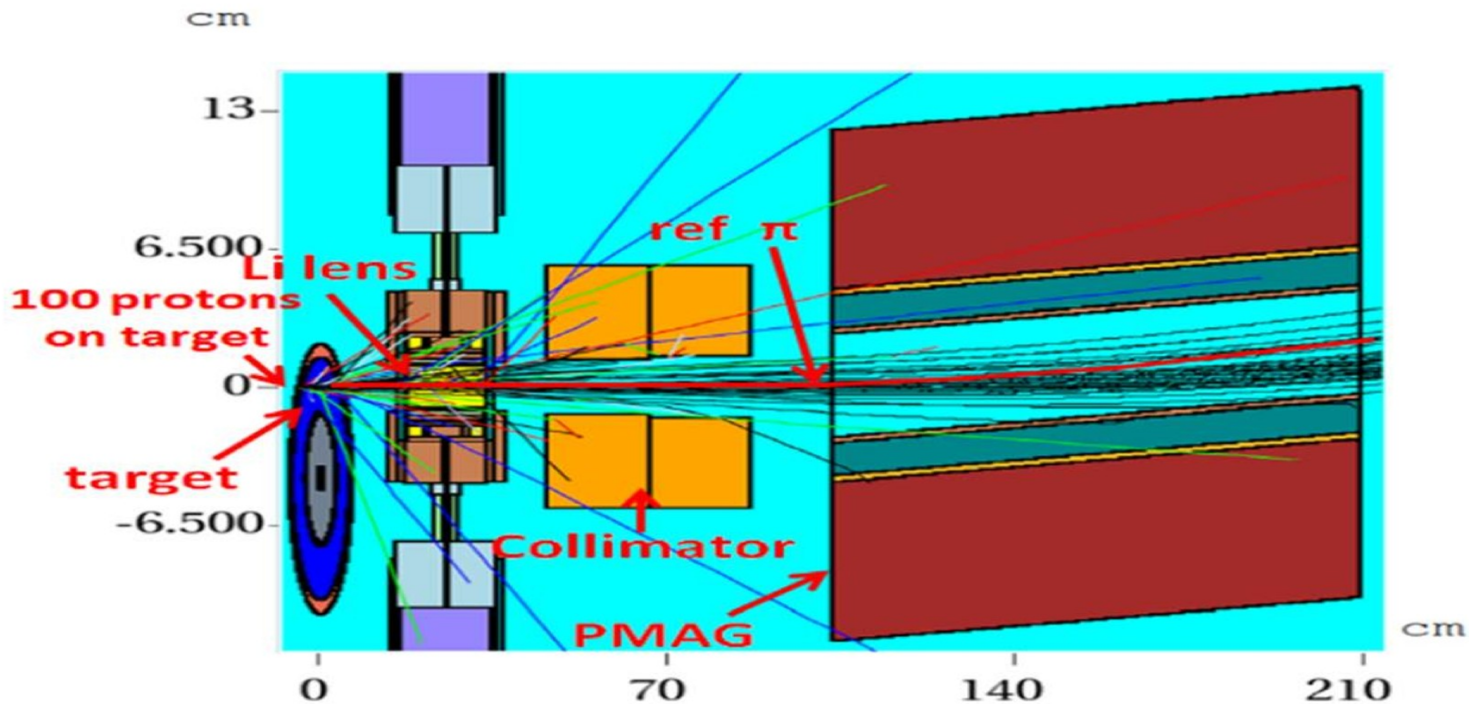
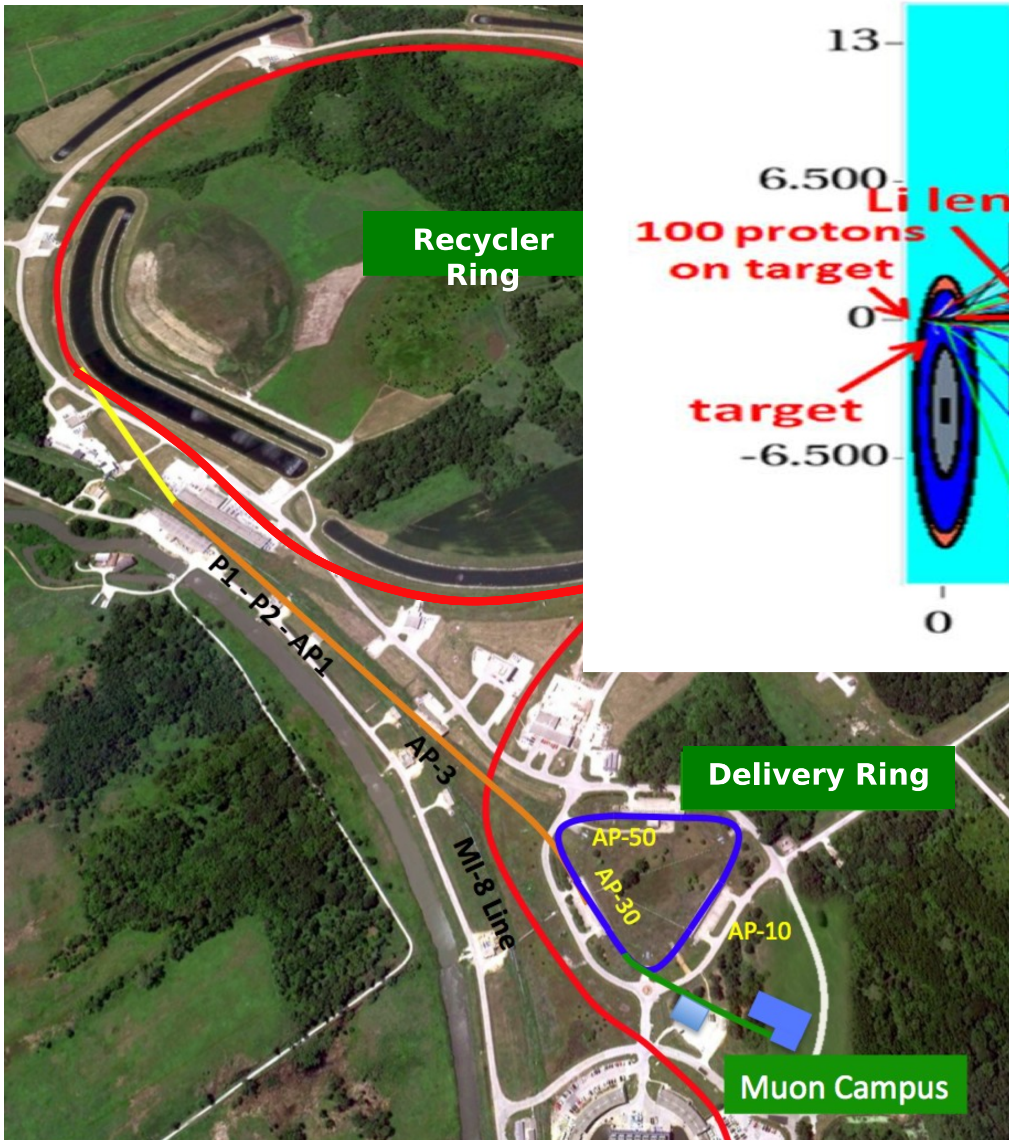
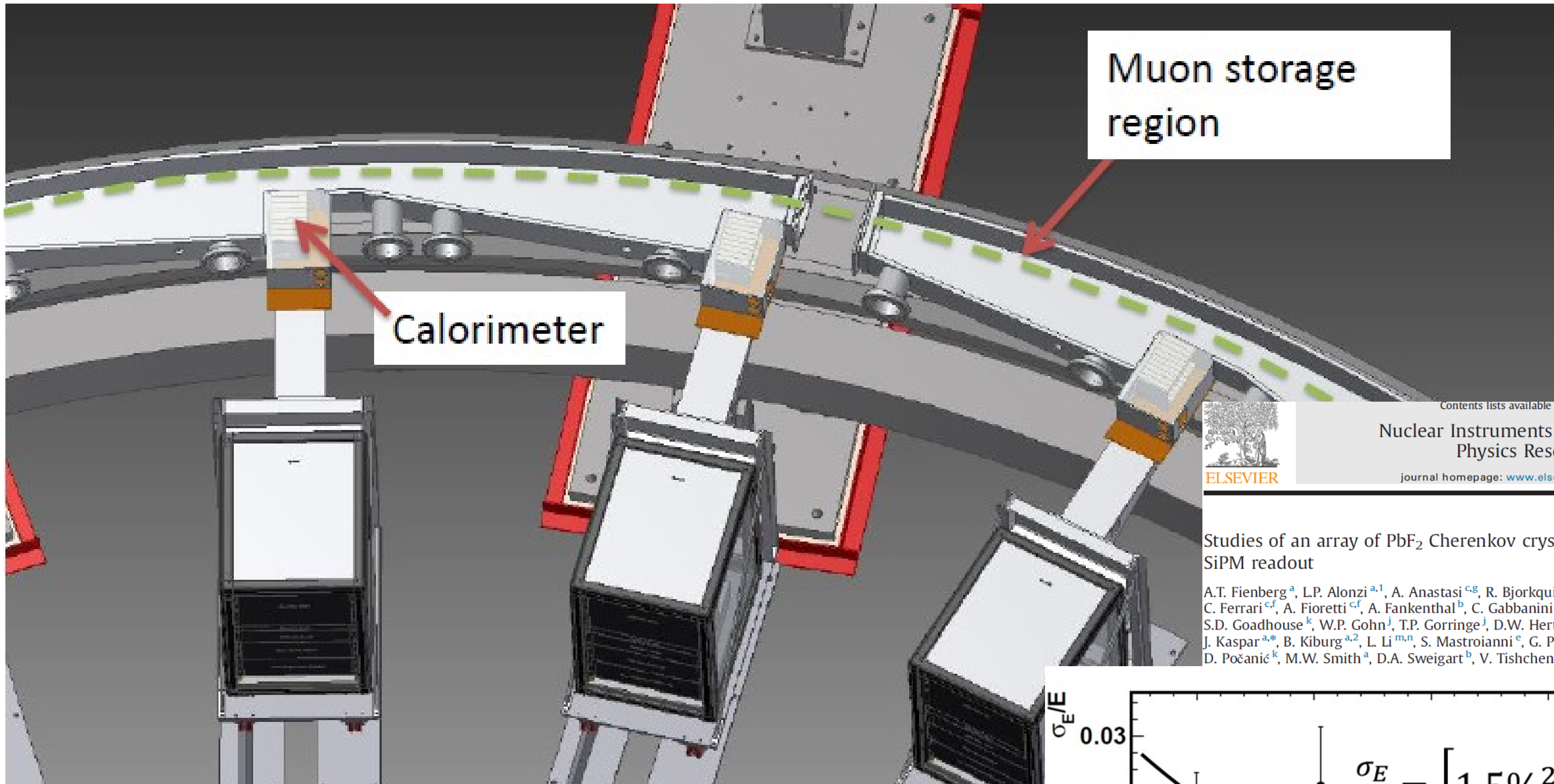




The original antiproton source becomes the g-2 pion production target station, while the delivery ring acts as a pion decay channel

The detector systems will be all new



24 segmented PbF_2 with SiPM readout optimized to behave like short pulse duration PMTs to minimize pileup and excellent resolution

Contents lists available at ScienceDirect
Nuclear Instruments and Methods in Physics Research A
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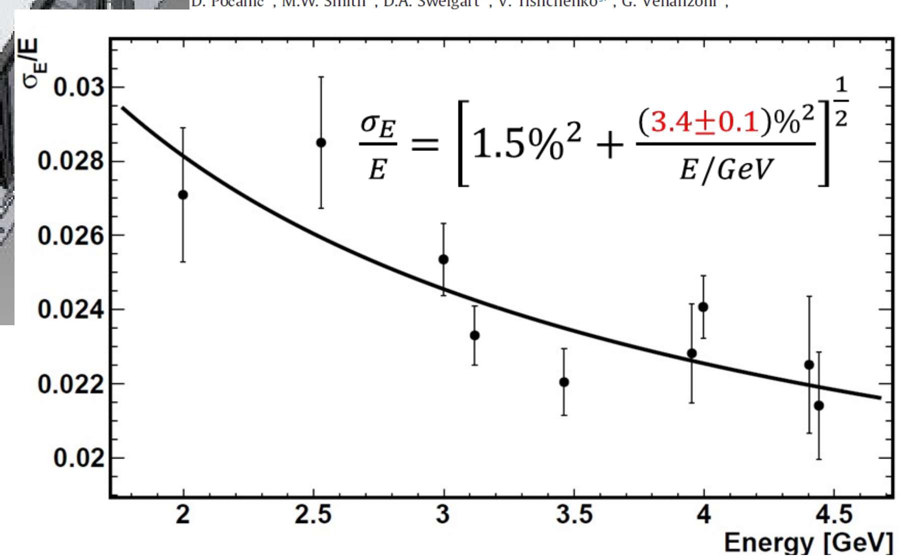
Studies of an array of PbF_2 Cherenkov crystals with large-area SiPM readout

A.T. Fienberg[a], L.P. Alonzi[a,1], A. Anastasi[c,g], R. Bjorkquist[b], D. Cauz[d,i], R. Fatemi[j], C. Ferrari[c,f], A. Fioretti[c,f], A. Fankenthal[b], C. Gabbanini[c,f], L.K. Gibbons[b], K. Giovanetti[l], S.D. Goadhouse[k], W.P. Gohn[j], T.P. Gorringe[j], D.W. Hertzog[a], M. Iacovacci[e,h], P. Kammel[a], J. Kaspar[a,*], B. Kiburg[a,2], L. Li[m,n], S. Mastroianni[e], G. Pauletta[d,i], D.A. Peterson[a], D. Počanić[k], M.W. Smith[a], D.A. Sweigart[b], V. Tishchenko[j,3], G. Venanzoni[c],



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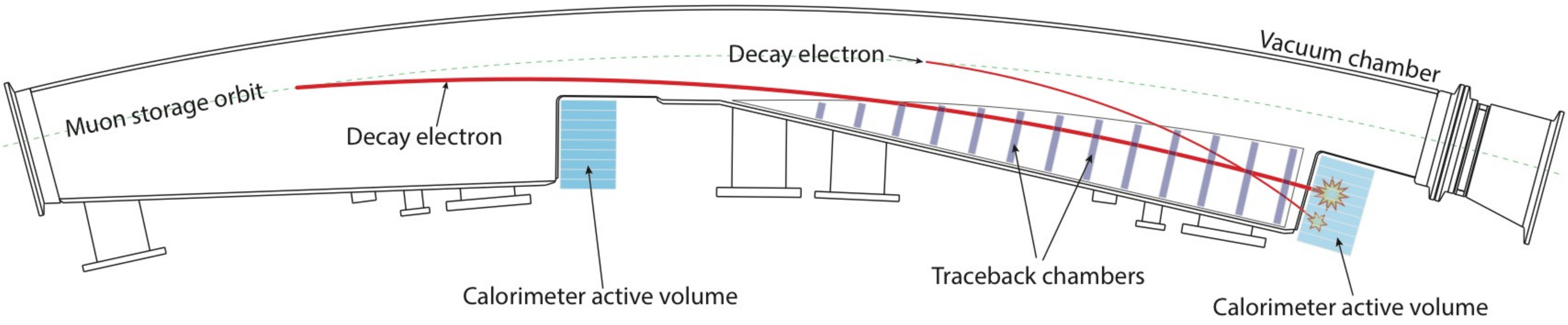
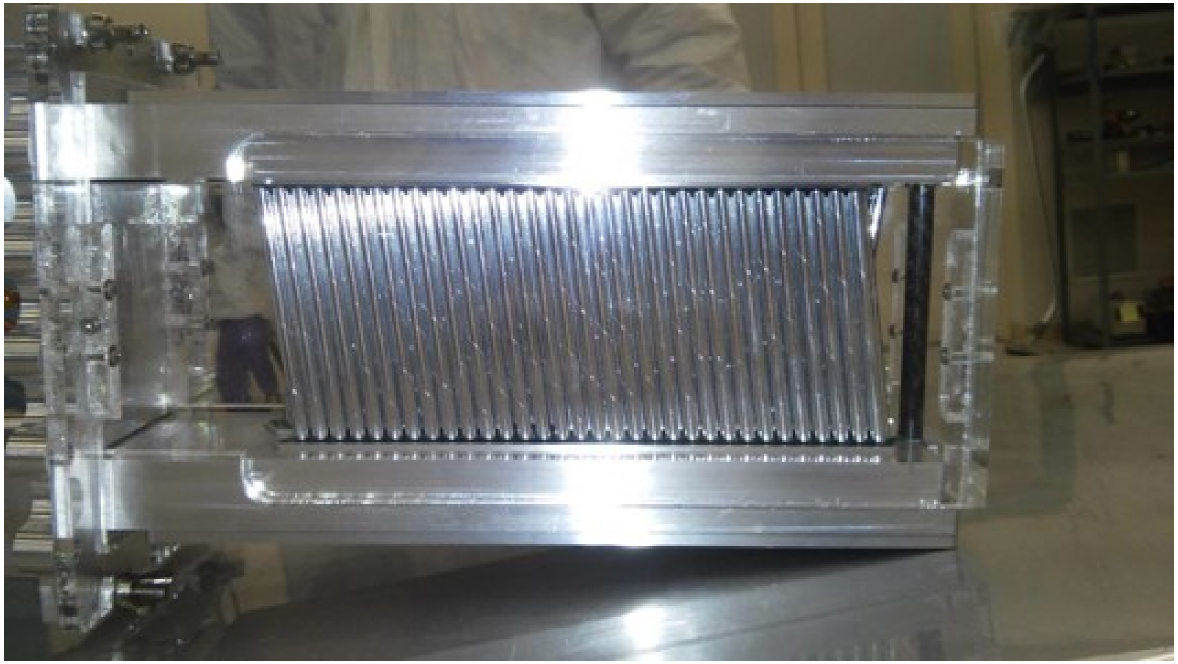
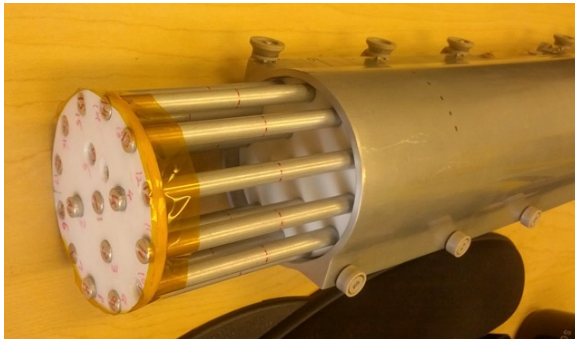




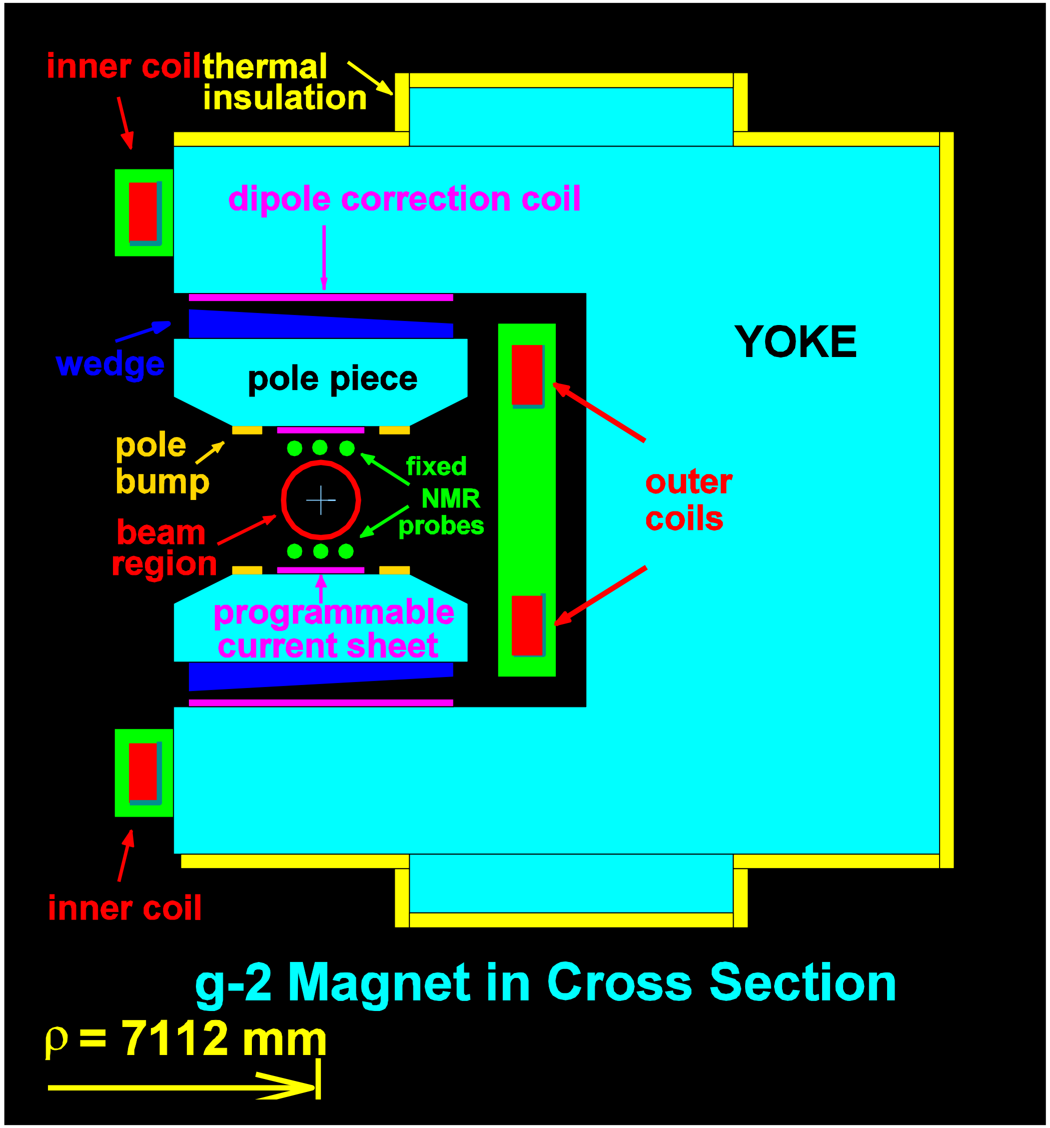
Three multiplane straw tracker systems will reconstruct the time-dependent muon decay position within the ring

There are numerous improvements to both the field and field measurements



New fixed and mobile field mapping probes

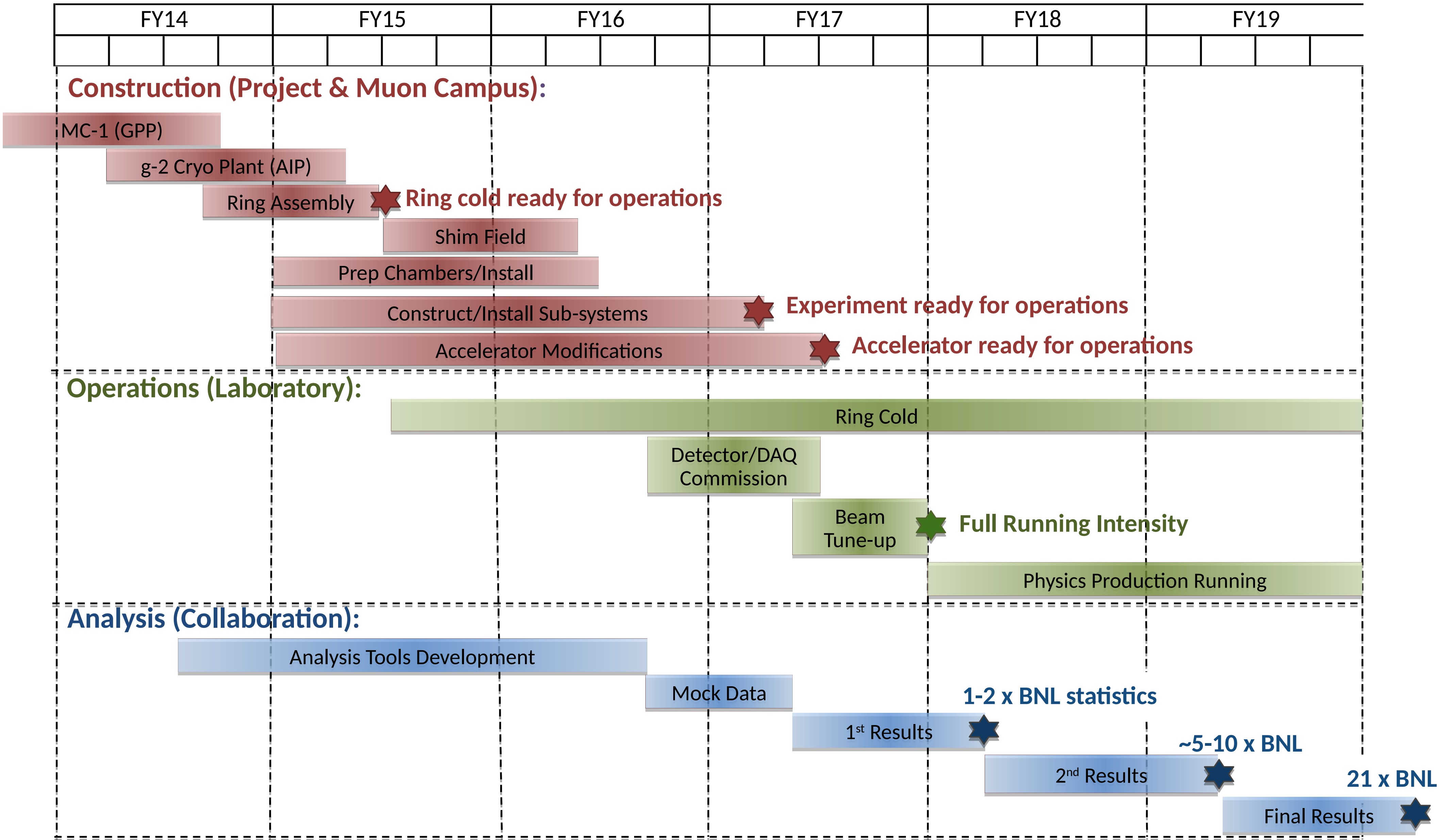
Improved temperature control, passive shimming, and active low order multipole correction



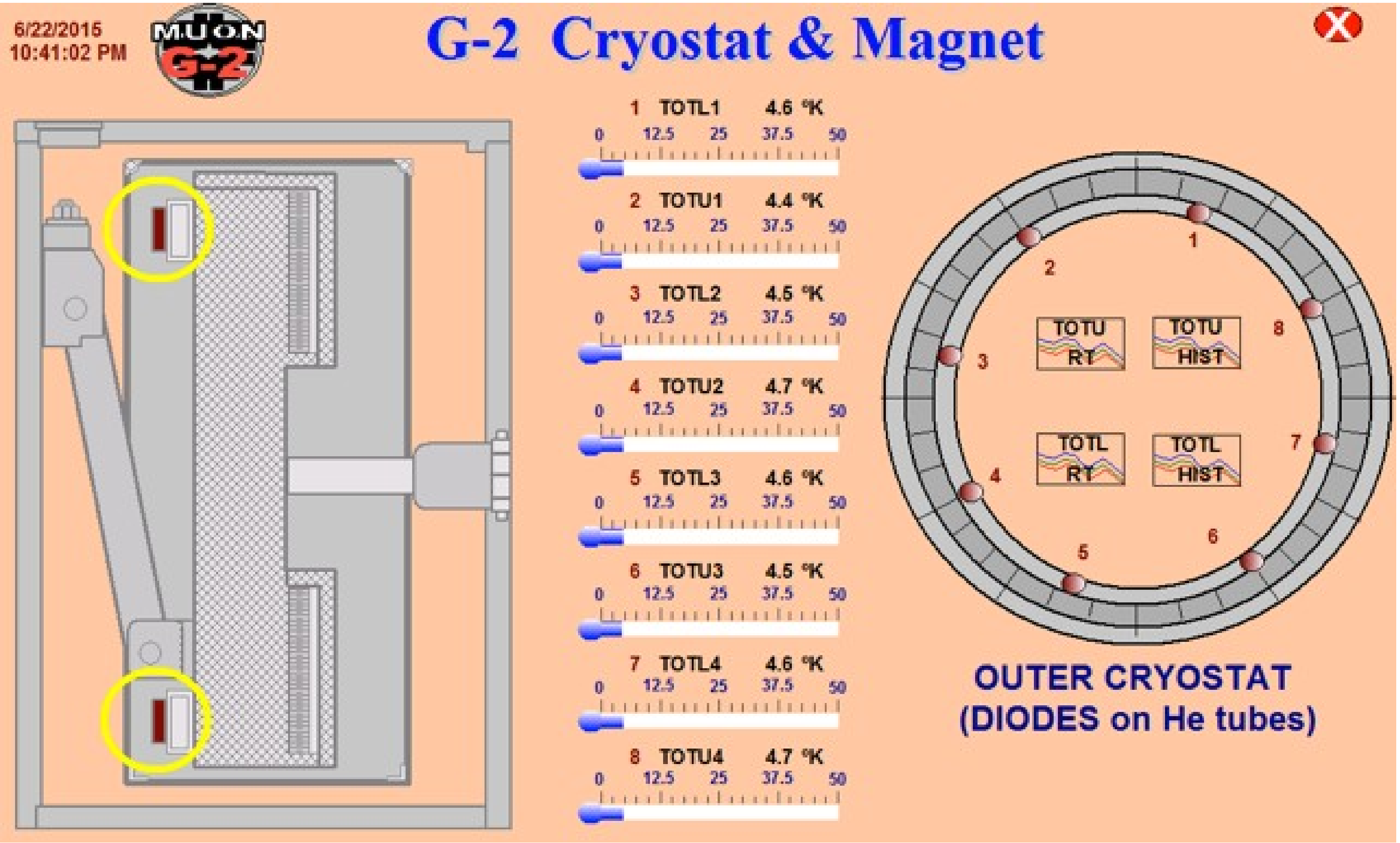
Compared to E821, there are a whole host of other improvements too numerous to discuss

- New quadrupoles
- New kicker modules
- New absolute field calibration
- New trolley field calibration system
- New detectors to measure beam profiles
- New analysis algorithms
- More complete simulation framework
- New data acquisition hardware
- New data acquisition software
- New laser gain stabilization system

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
Analysis (Collaboration):
Analysis Tools Development
Mock Data
1-2 x BNL statistics
1st Results
~5-10 x BNL
2nd Results
21 x BNL
Final Results

Recent significant progress



After 14 years, the ring has been cooled to superconducting temperatures and partially energized; some inevitable teething problems have been fixed, and the cooling should begin again on Monday

We can do other muon physics in parallel:EDMs, Lorentz Violation searches

$$\vec{\omega}_e = -\frac{\eta e}{2mc}\left(\vec{E} + \vec{\beta} \times \vec{B} - \frac{\gamma}{\gamma + 1}(\vec{\beta} \cdot \vec{E})\vec{\beta}\right)$$

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Causes an out of plane rotation that is in phase with the g-2 precession!

We can do other muon physics in parallel:EDMs, Lorentz Violation searches

$$\vec{\omega}_e = -\frac{\eta e}{2mc}\left(\vec{E} + \vec{\beta}\times\vec{B} - \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{E})\vec{\beta}\right)$$

Causes an out of plane rotation that is in phase with the g-2 precession!

The trackers are designed to enable a measurement of this rotation; we expect a 100 fold improvement over the E821 value using the same method due to greater statistics.

Thanks for your continuing interest!