FERMILAB-SLIDES-20-011-AD

Northern Illinois University

Understanding Particle Loss Rates in the Muon g-2 Experiment Storage Ring

Mike Syphers

Northern Illinois University

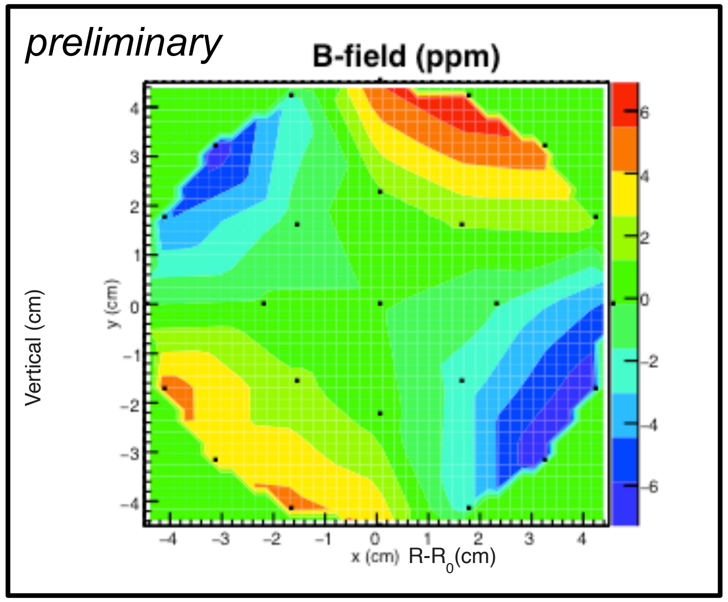
Fermi National Accelerator Laboratory

Work supported by Northern Illinois University and by the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. DOE- OHEP.

April Meeting of the American Physical Society
20 April 2020

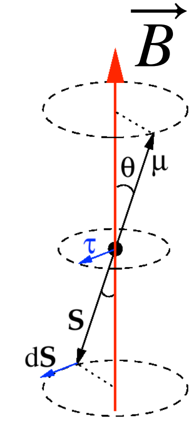
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

The Muon g-2 Experiment



highly uniform *B field*

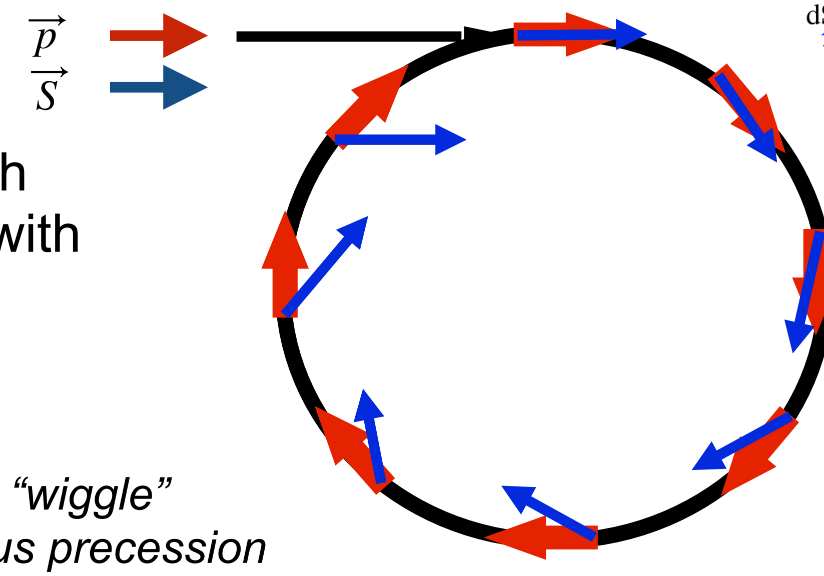
inject muons



Northern Illinois University

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

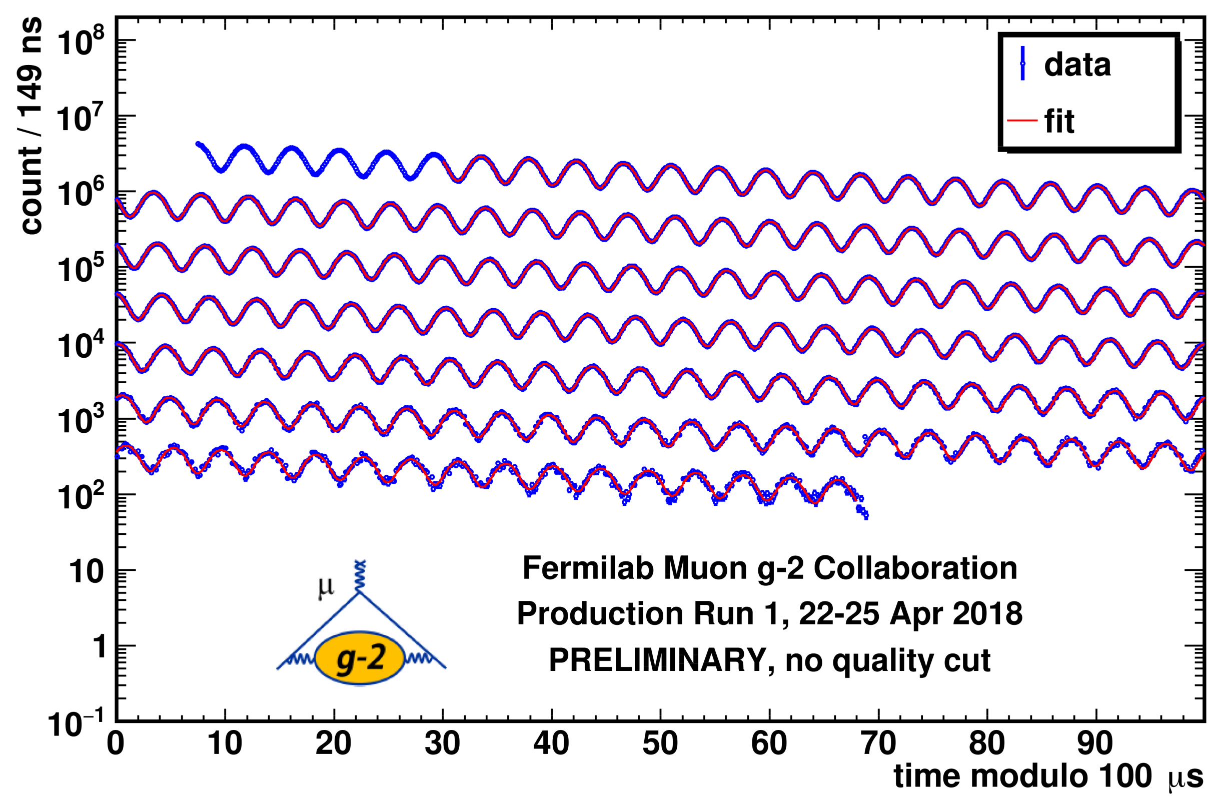
magnetic moment

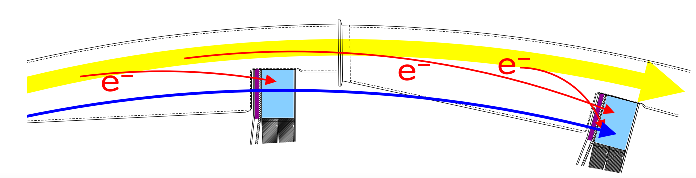


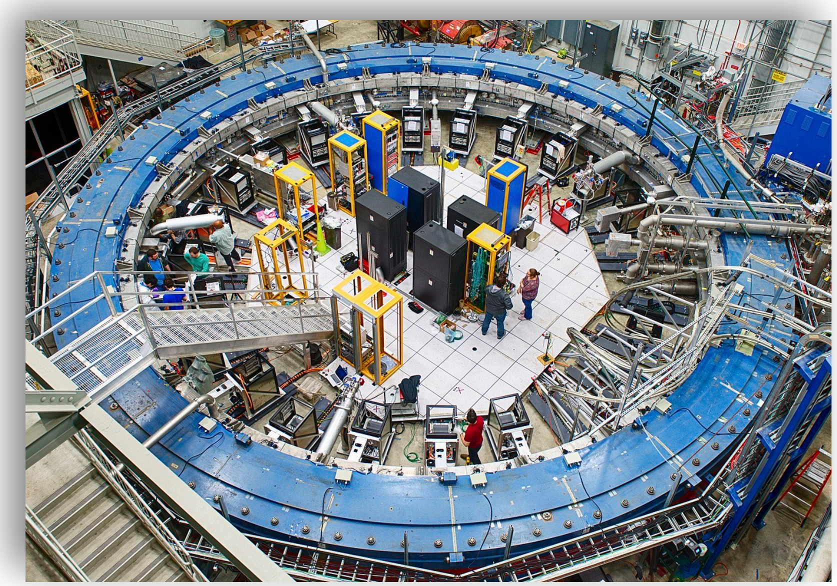
ideal: highly polarized, with spin aligned with momentum

detector rates will "wiggle" with the anomalous precession frequency $\propto\ g-2$

detect positrons from muon decay; high energy e⁺ direction aligned with muon spin







$$N(t) = N_0 e^{-t/\tau_\mu}\left[1 + A\cos(\omega_a t + \phi_0)\right]$$

Observed Loss Rates

- Following the initial injection losses (first 10-20 turns), and factoring out the muon decay process, a slow loss of muons *prior to decay* continues to persist, and exponentially reduces during the measurement
  - » a “triple coincidence” in adjacent calorimeters indicates a direct muon hit
  - » observed in BNL version of the experiment, as well as at FNAL

BNL — PRD 73, 072003 (2006)

FINAL REPORT OF THE E821 MUON ANOMALOUS . . .

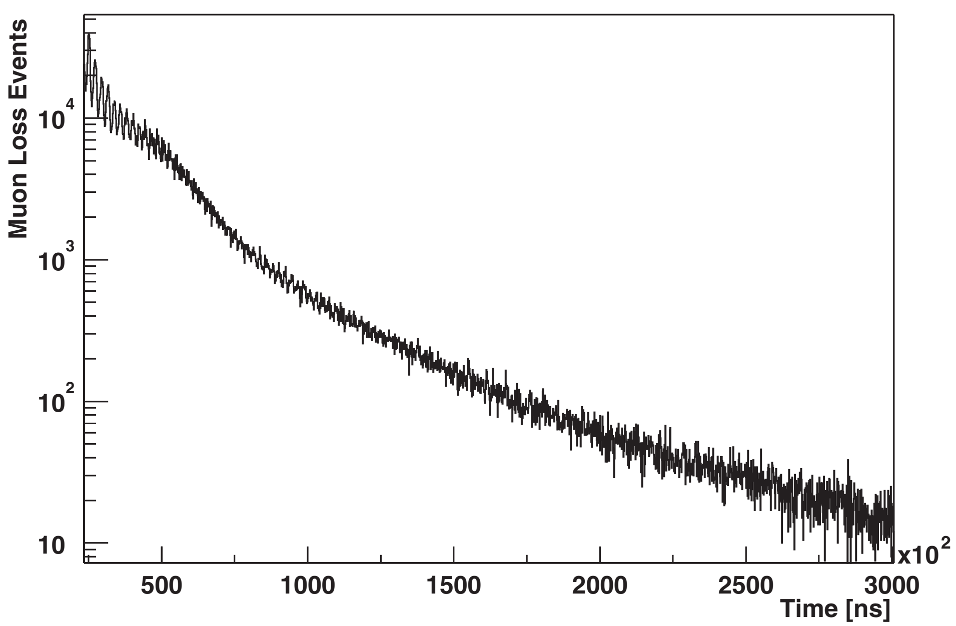
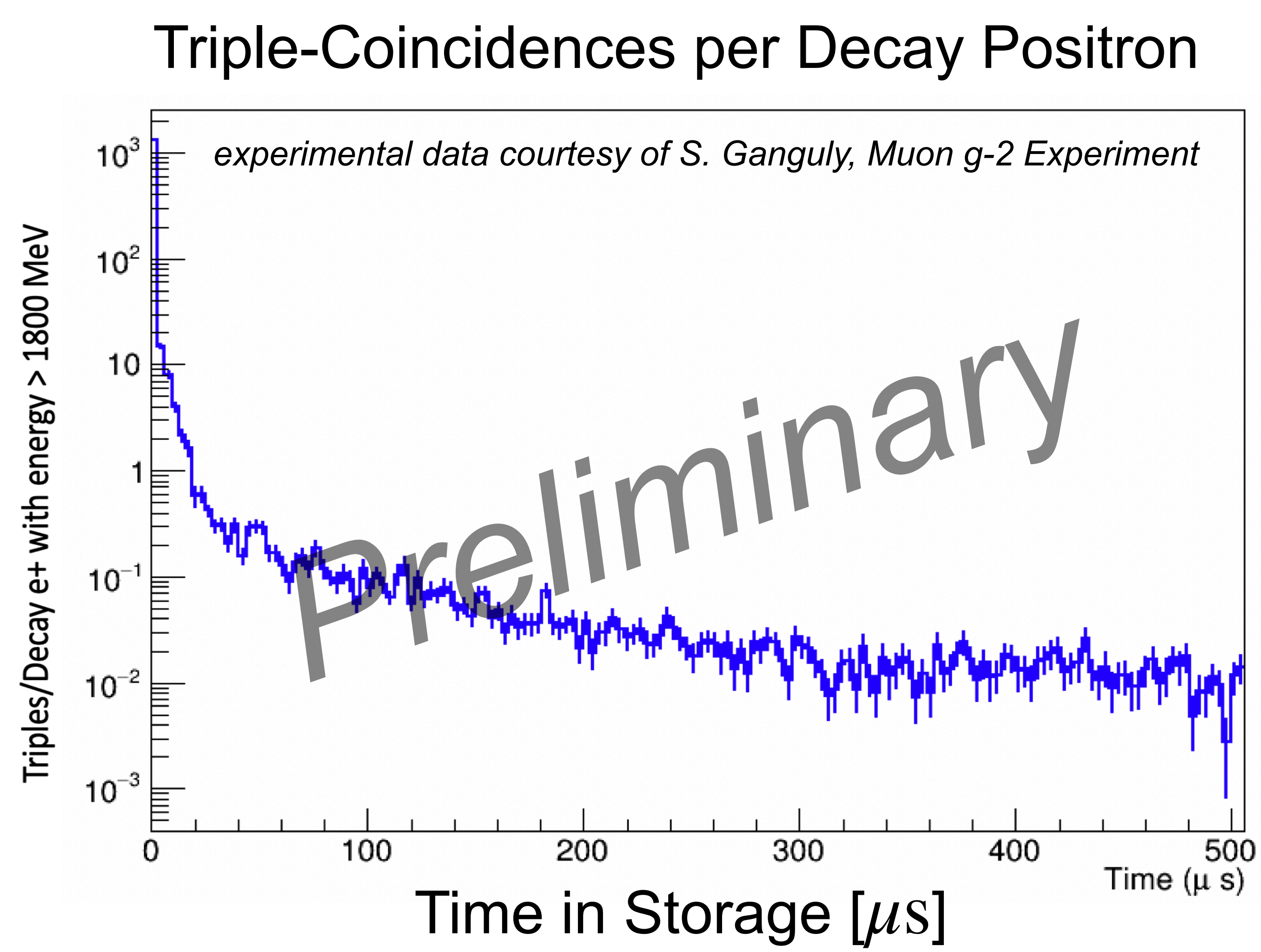


FIG. 35. Muon-loss rate vs time from the R00 period. Three consecutive and coincident FSD station signals form the muon-loss signal. The loss function $L(t)$ is proportional to this raw data plot.

the Monte Carlo simulation. With an estimated acceptance of a few percent, results from the fits indicate an approximate fractional loss rate of 10^{-3} per lifetime.

FNAL — sample from recent running



Why the Concern?

- Not a *radiation* concern; very low intensity, by storage ring standards; rather, it is important to understand in the final analysis of the experimental data
- wiggle plot and multi-parameter fit

goal ↓

$$N(t) = N_0 e^{-t/\tau_\mu}\left[1 + A\cos(\omega_a t + \phi_0)\right]$$

  - if the contributions to the determination of the average initial phase evolves during the measurement, can give a systematic error on the actual precession frequency being sought
- Suppose muons which can reach the collimator (halo) have a different spin distribution than those of the central core:

$$\langle\phi\rangle = \frac{N_c\langle\phi_c\rangle + N_h\langle\phi_h\rangle}{N_c + N_h}$$

  » then, since only the halo particles get lost,

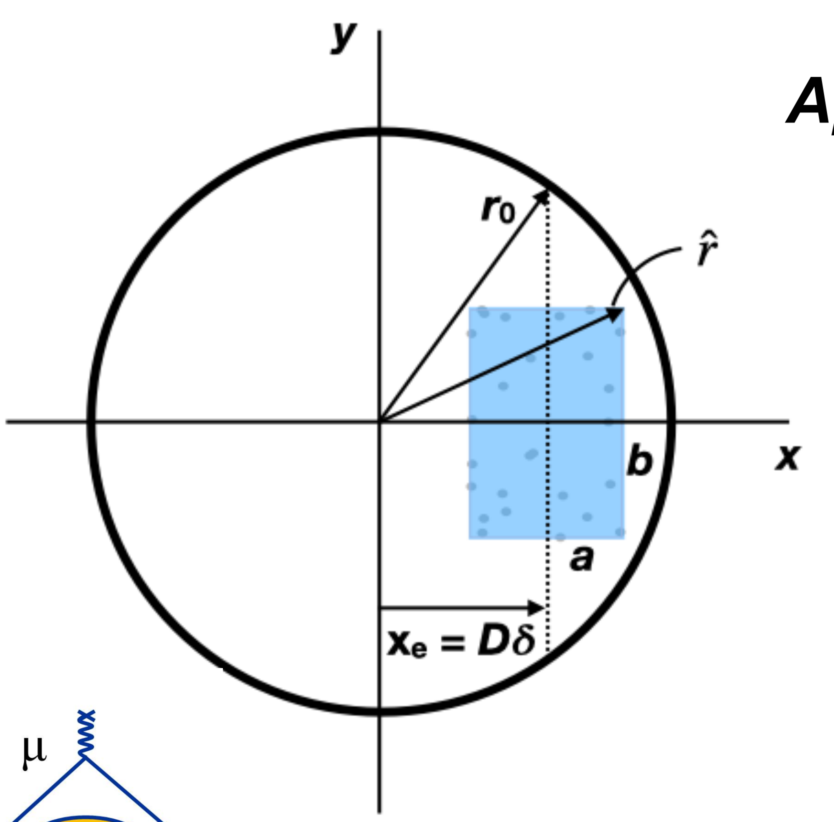
can yield an ***apparent*** *precession:*

$$\Delta\omega_a = \frac{d\langle\phi\rangle}{dt} = \left(\frac{N_c}{N_c + N_h}\right)\left(\frac{\dot{N}_h}{N_c + N_h}\right)\left[\langle\phi_h\rangle - \langle\phi_c\rangle\right]$$

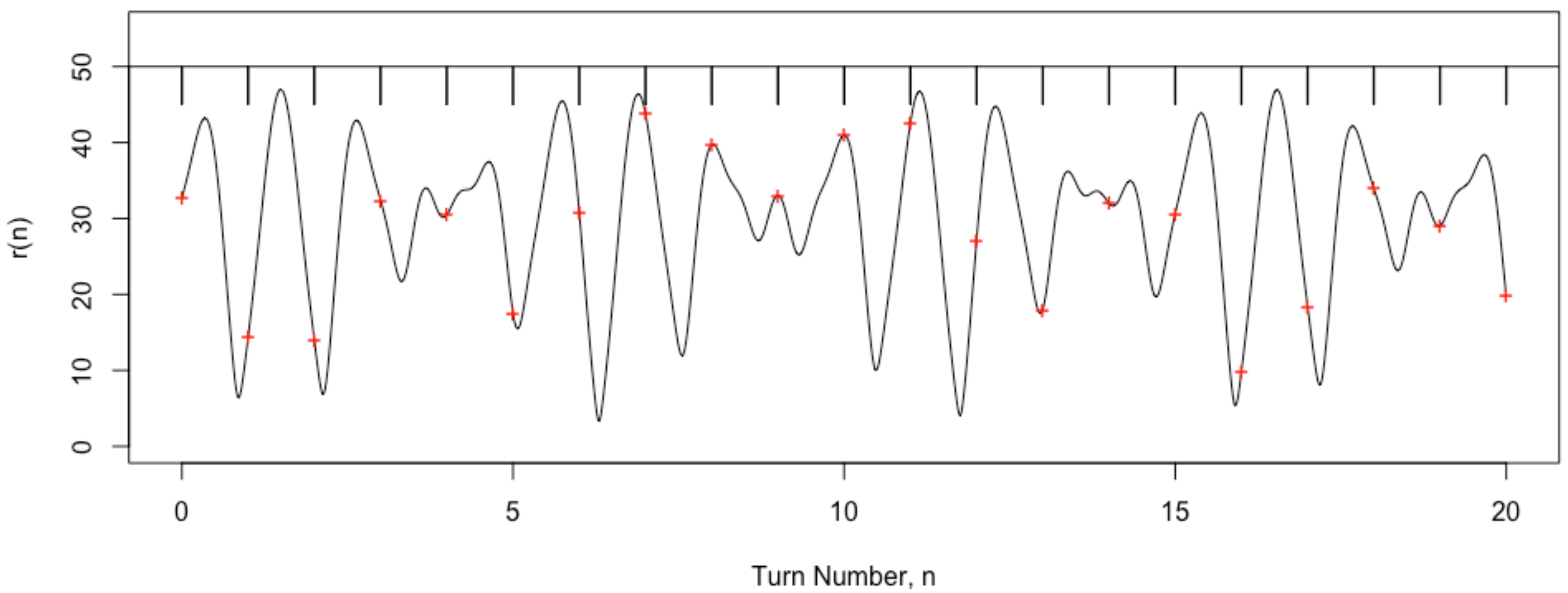
fraction in the core loss rate distr. diff.

Sources of Long-Term Particle Loss

- Beam-gas scattering **X**
  - particles are in the ring for only ~0.5 ms; vacuum $\lesssim 0.5\ \mu$torr
  - loss rate computed to be 10x less than observable rate; no variation with vacuum pressure observed
- Nonlinear fields and resonances **X**
  - all major resonances mapped out, avoided during operation
  - high field quality ($\Delta B/B \lesssim 0.1$ ppm) ensures linear behavior to high accuracy
- Can it just take time for particles to reach the aperture limit? ***check…***



Aperture defined by collimator(s) at just a few locations in ring



Simple (but Detailed) Investigation

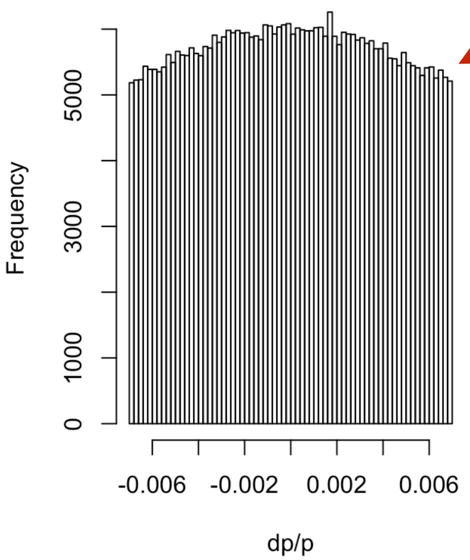
- Consider this third loss mechanism — how long might it take ***some*** particles to finally encounter the collimator?

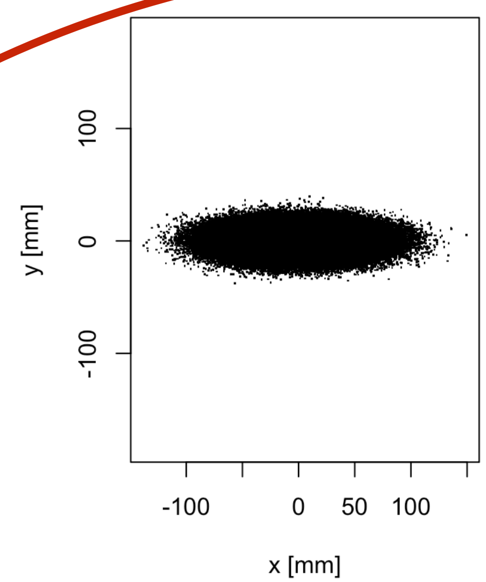
- Highly uniform fields in ring — basic linear theory describes motion well

- So, model injection; *freeze* phase space conditions, write to data frame
- Without tracking, perform this simple analysis:
  - for each particle, calculate *departure time* and *transverse position* when lost
  - from this information, create plot of intensity *vs* time; look at loss rates
  - for particles lost during the measurement period, examine loss positions, momentum distributions, etc.
  - compare computed loss rate and its evolution with time to actual data
  - use 2-distribution model to understand level of the systematic effect

Model the Injection Process

incoming from beam line: general characteristics confirmed by measurements

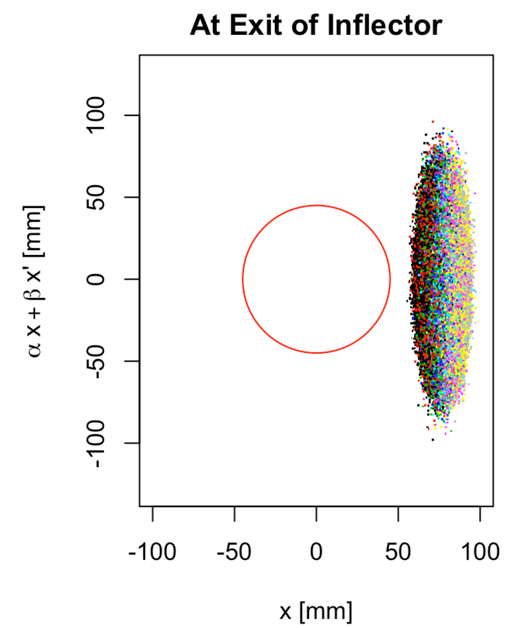


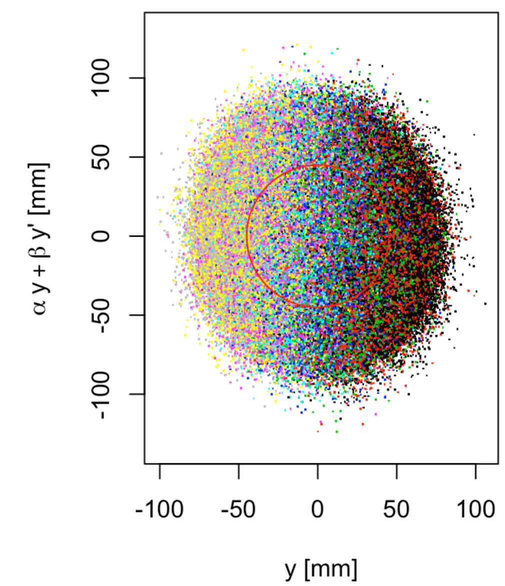


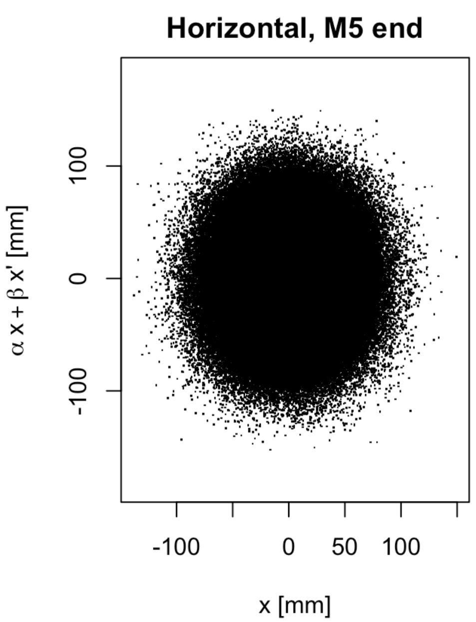
momentum spread of incoming beam is ~10 times larger than ring acceptance

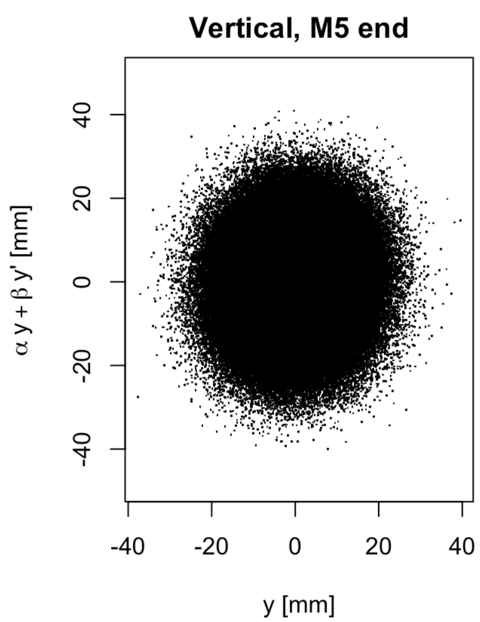
x phase space

y phase space

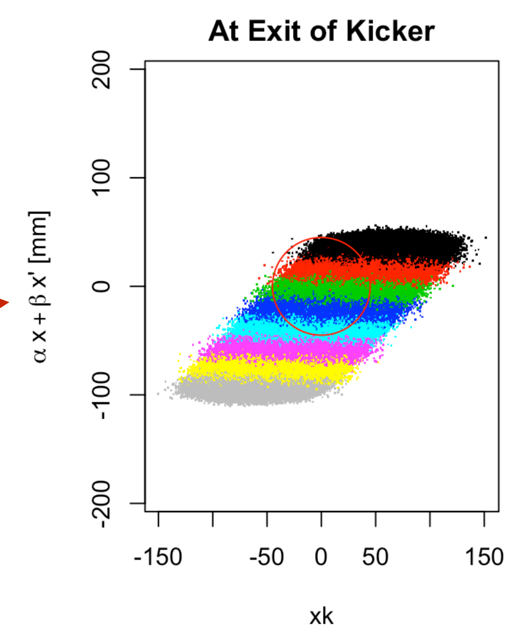


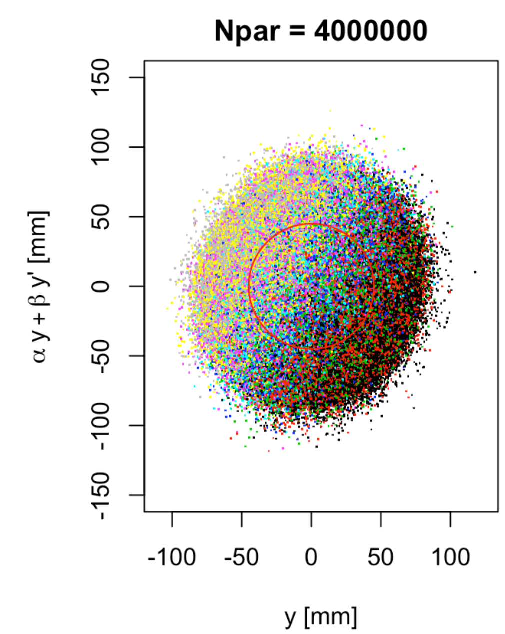






spreads out due to large dispersion mismatch

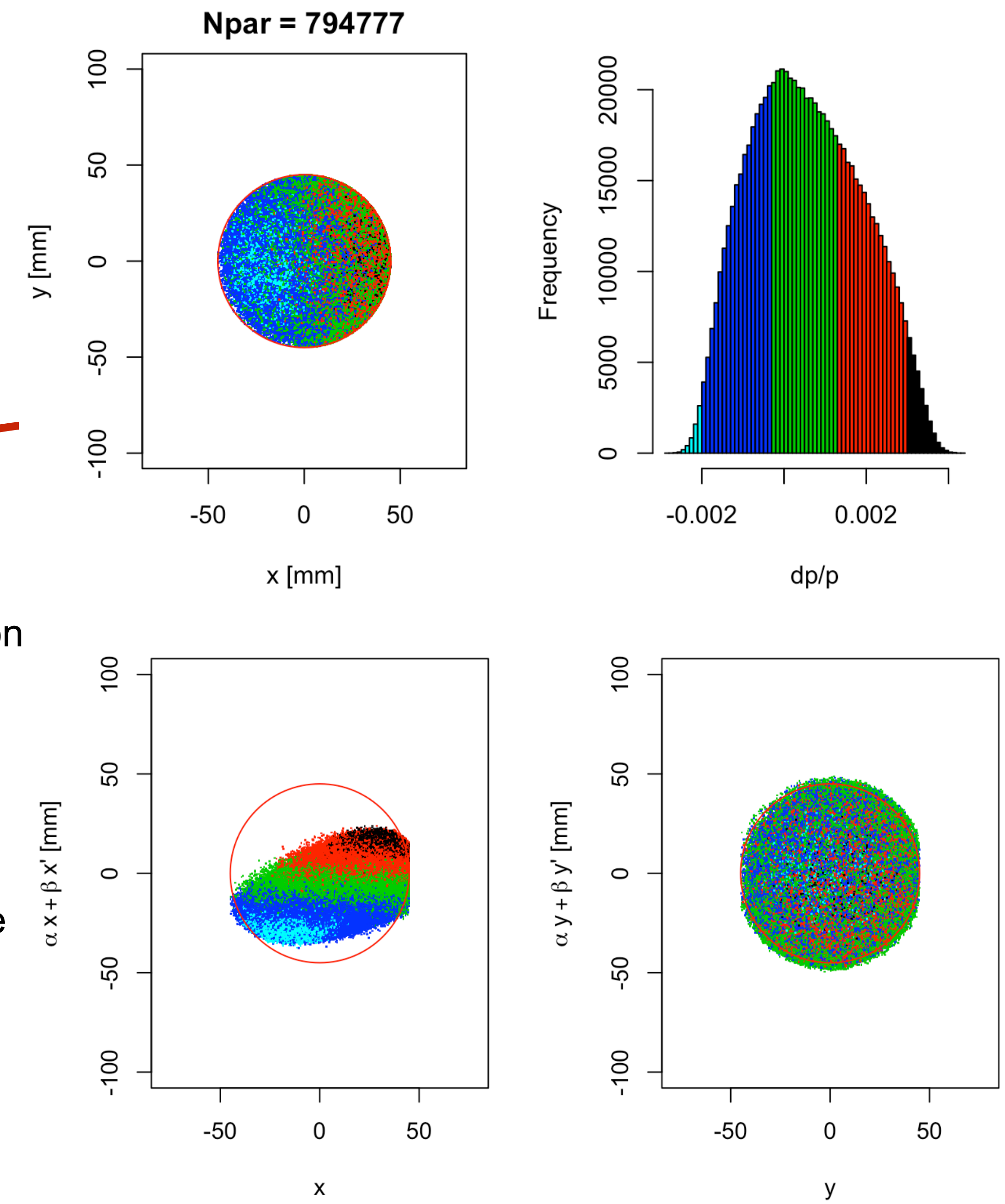




dp/p: -0.004 0.004

Particle Storage

- After modeling the injection kick, "freeze" the distribution at n=0
  - » Top/Left: x,y for all particles within r=45 mm
  - » Top/Right: momentum distribution
  - » Bottom/Left: x-phase space
  - » Bottom/Right: y-phase space



compute amplitudes, initial betatron phases

$$
\begin{aligned}
x &= D\cdot\delta + a\cos(2\pi\nu_x n + \phi_x)\\
\beta_x x' + \alpha_x x &= -a\sin(2\pi\nu_x n + \phi_x)\\
y &= b\cos(2\pi\nu_y n + \phi_y)\\
\beta_y y' + \alpha_y y &= -b\sin(2\pi\nu_y n + \phi_y)
\end{aligned}
$$

compile data frame of info for each particle

	x	Px	y	Py	del	ax	ay	phix	phiy
1	6.689066	-72.42946	-16.711137	18.62327	-0.006698057	94.65789	25.02175	-0.8713067	2.302132
2	17.712190	-25.46969	-10.846479	14.95387	-0.001279813	37.90932	18.47334	-0.7367146	2.198320
3	5.610937	-49.93999	-31.715068	-37.71116	-0.003976070	62.64292	49.27451	-0.9226708	4.013143

⋮

Times of Departure

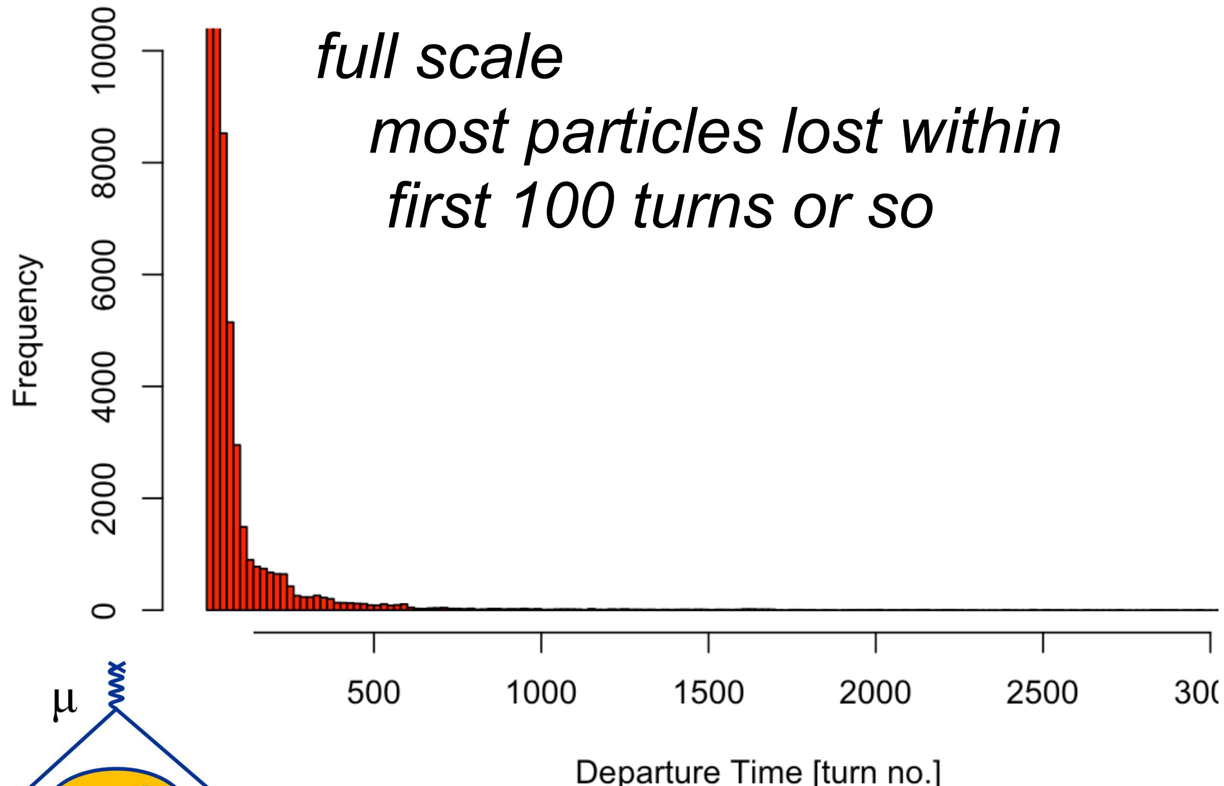
- For each particle, determine if its betatron amplitudes are such that the particle can reach the collimator:

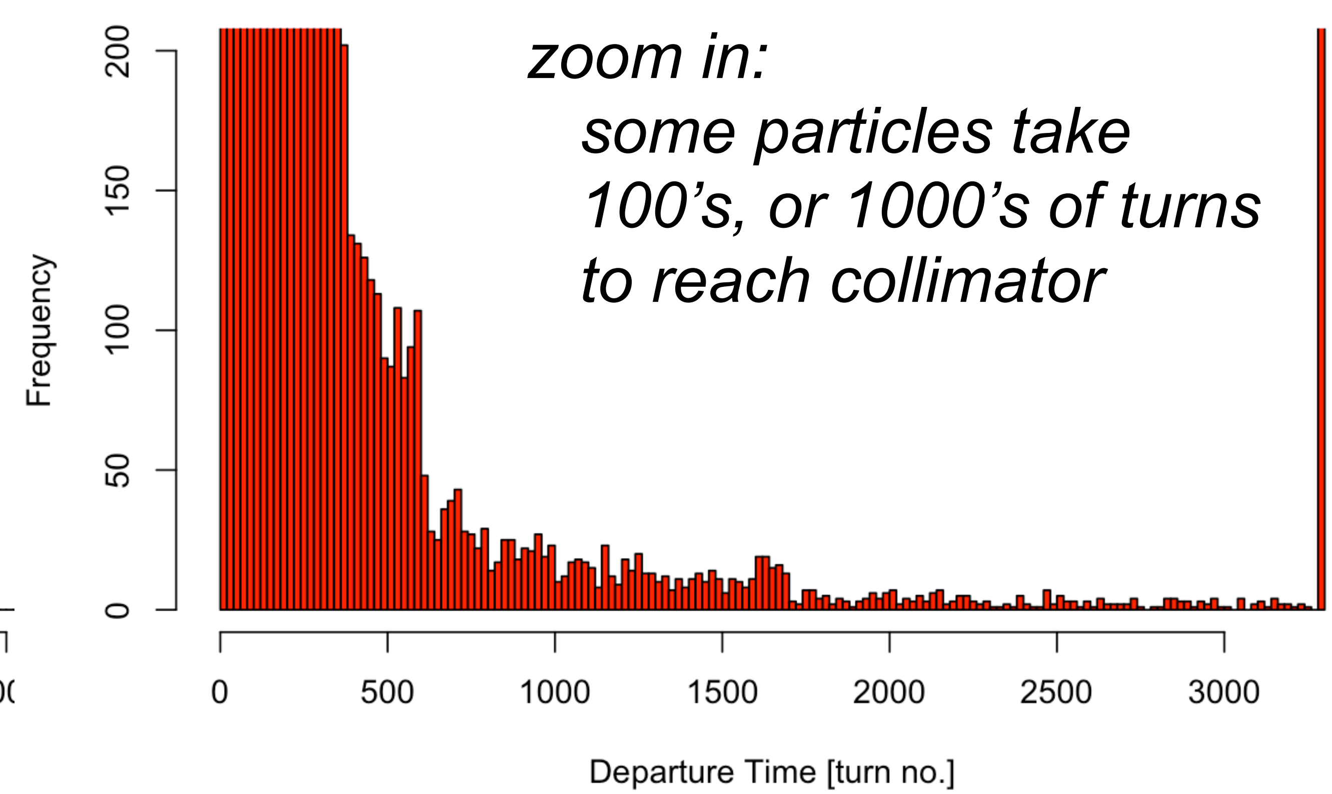
$$r^2(n) = [D\delta + a\cos(2\pi\nu_x n + \phi_x)]^2 + [b\cos(2\pi\nu_y n + \phi_y)]^2$$

  » if not, then "Core" particle $(\hat{r} < 45 \text{ mm})$
  » if it can, then "Edge" particle $(\hat{r} \geq 45 \text{ mm})$

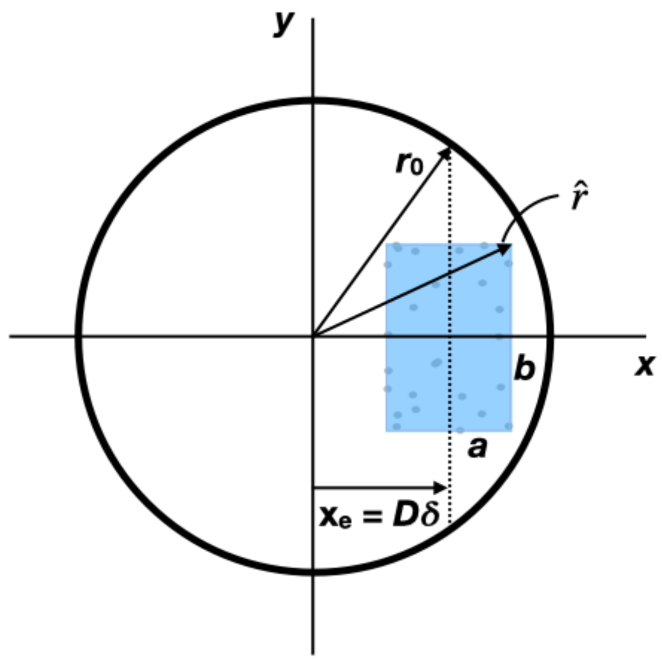
- For every Edge particle, compute at what value of *n* will it reach the collimator and $(x,y)_{lost}$, and add these values to the particle data frame

Results:

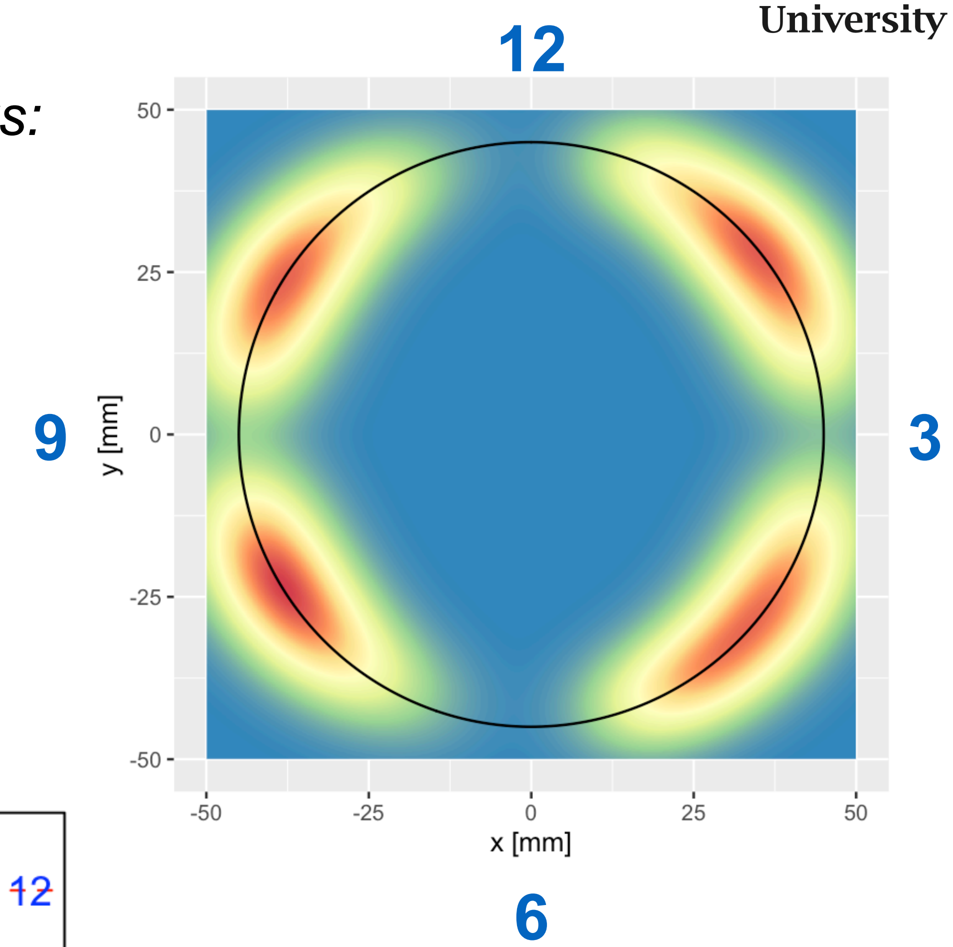


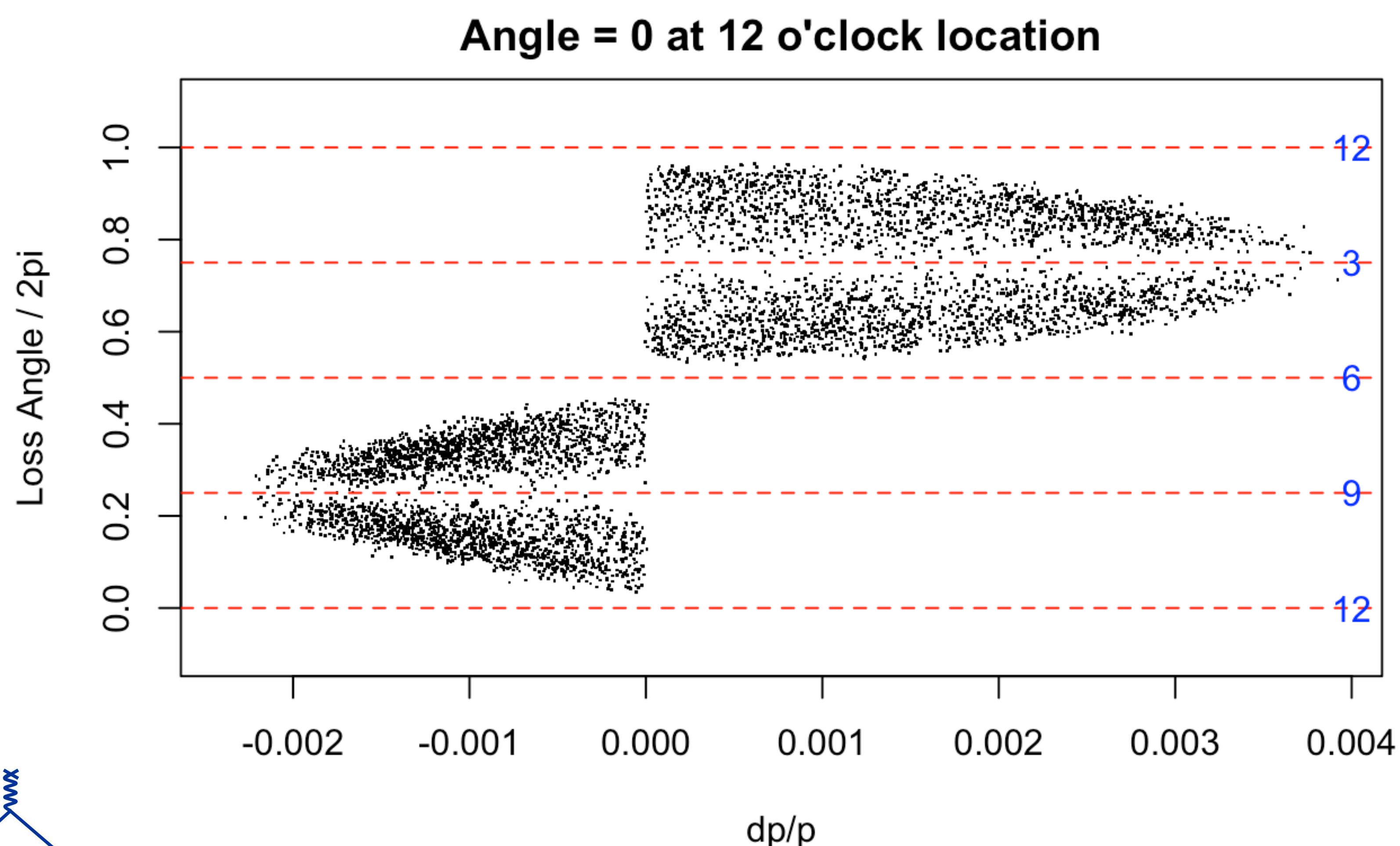


Loss Patterns and Rates



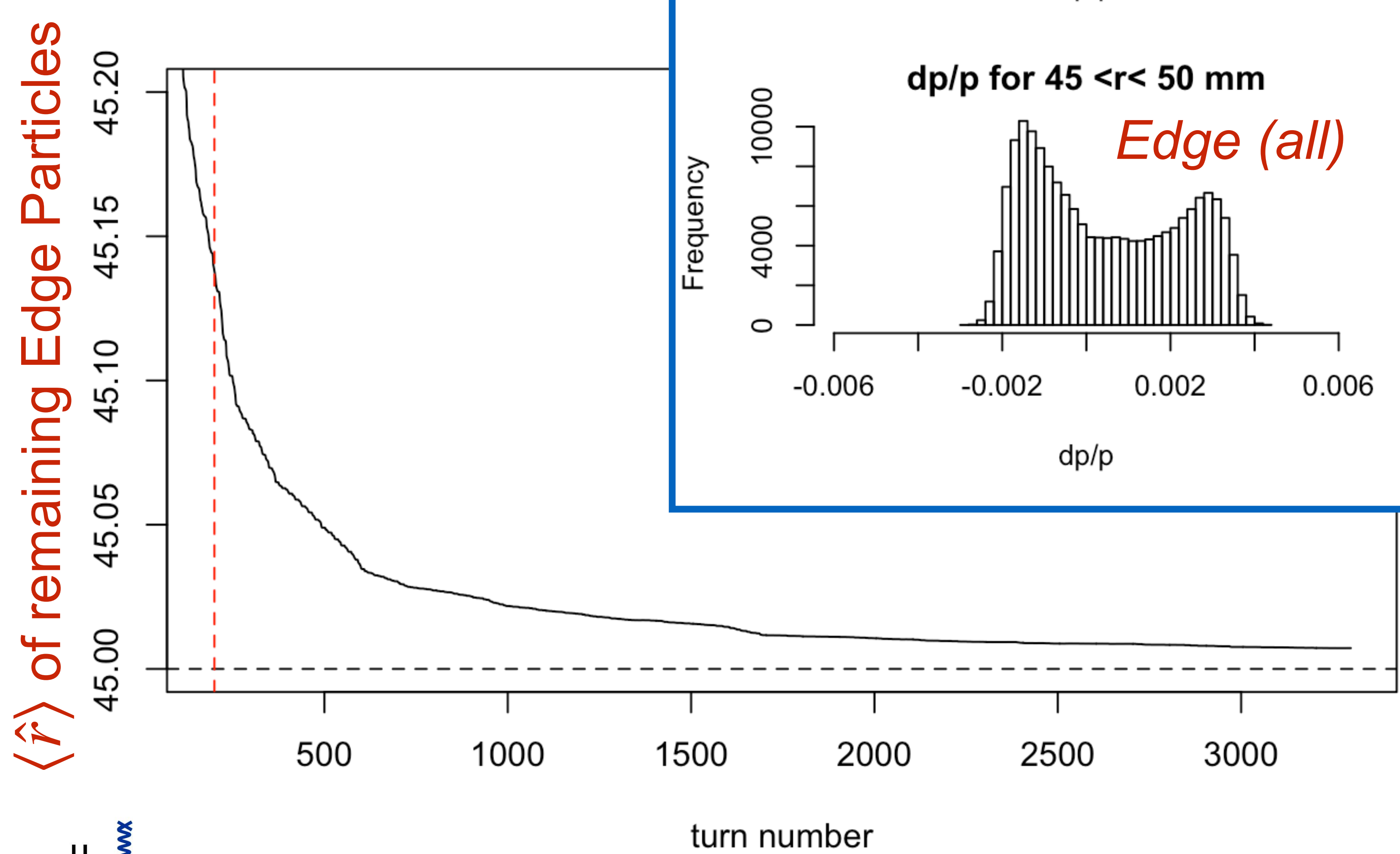
Computed loss points:

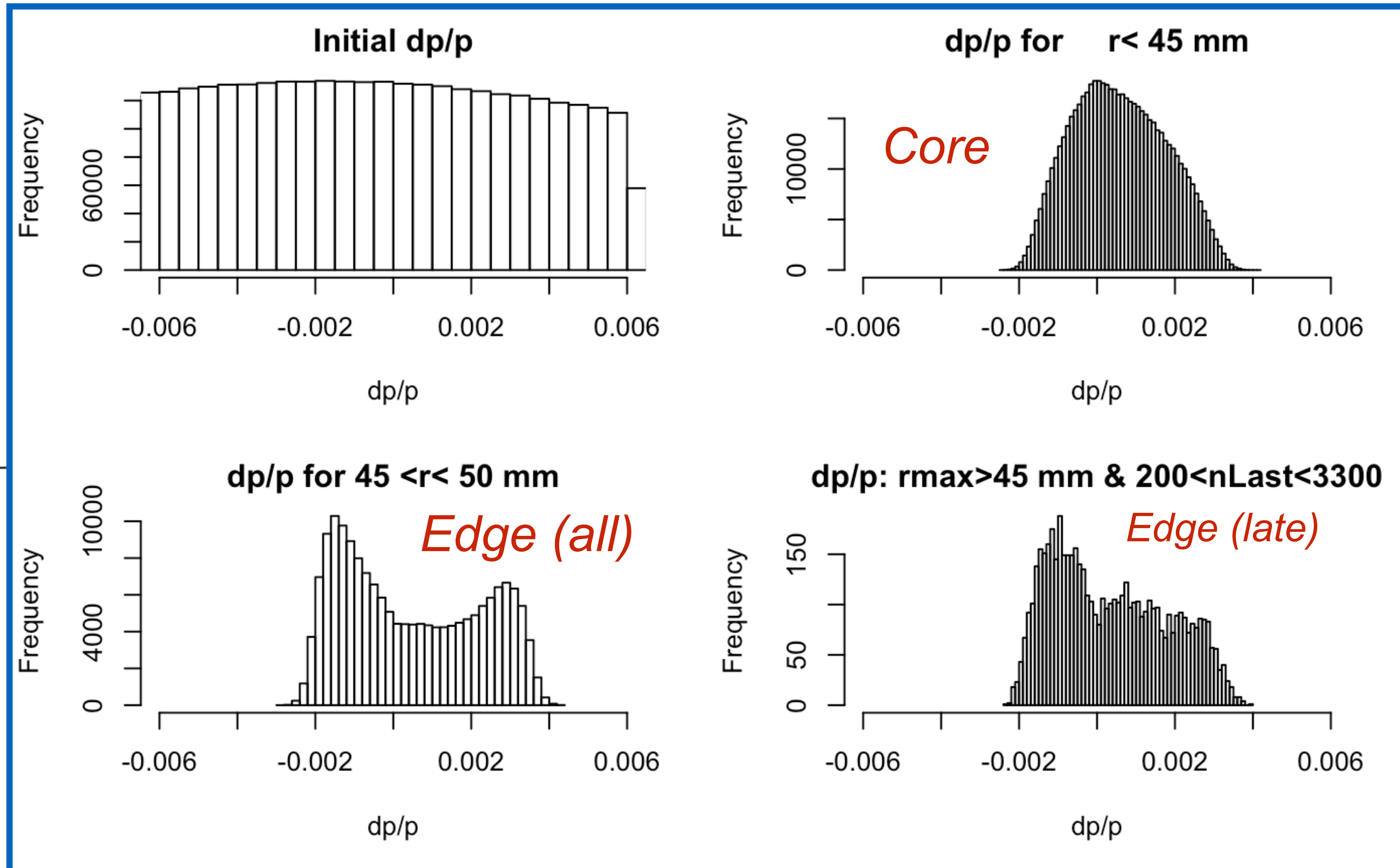




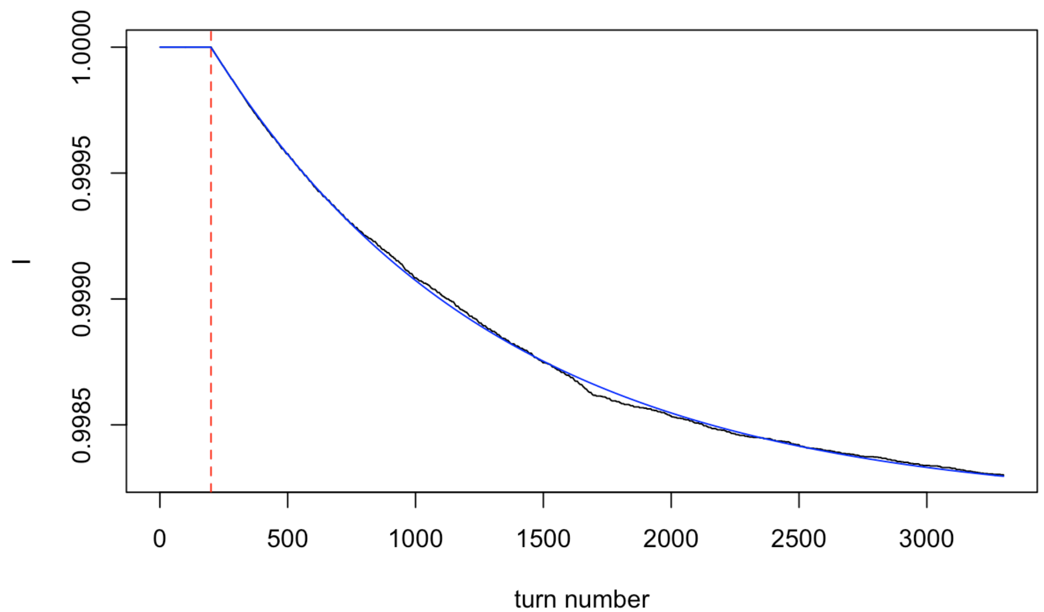
high momentum lost on right, low momentum lost on left

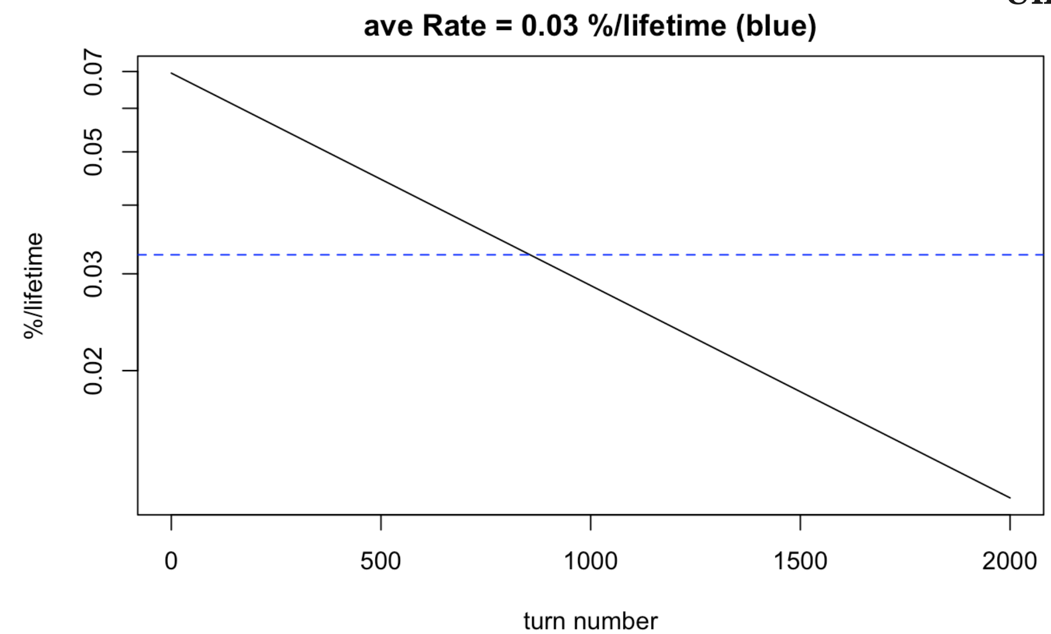
Loss Distributions on the Edge

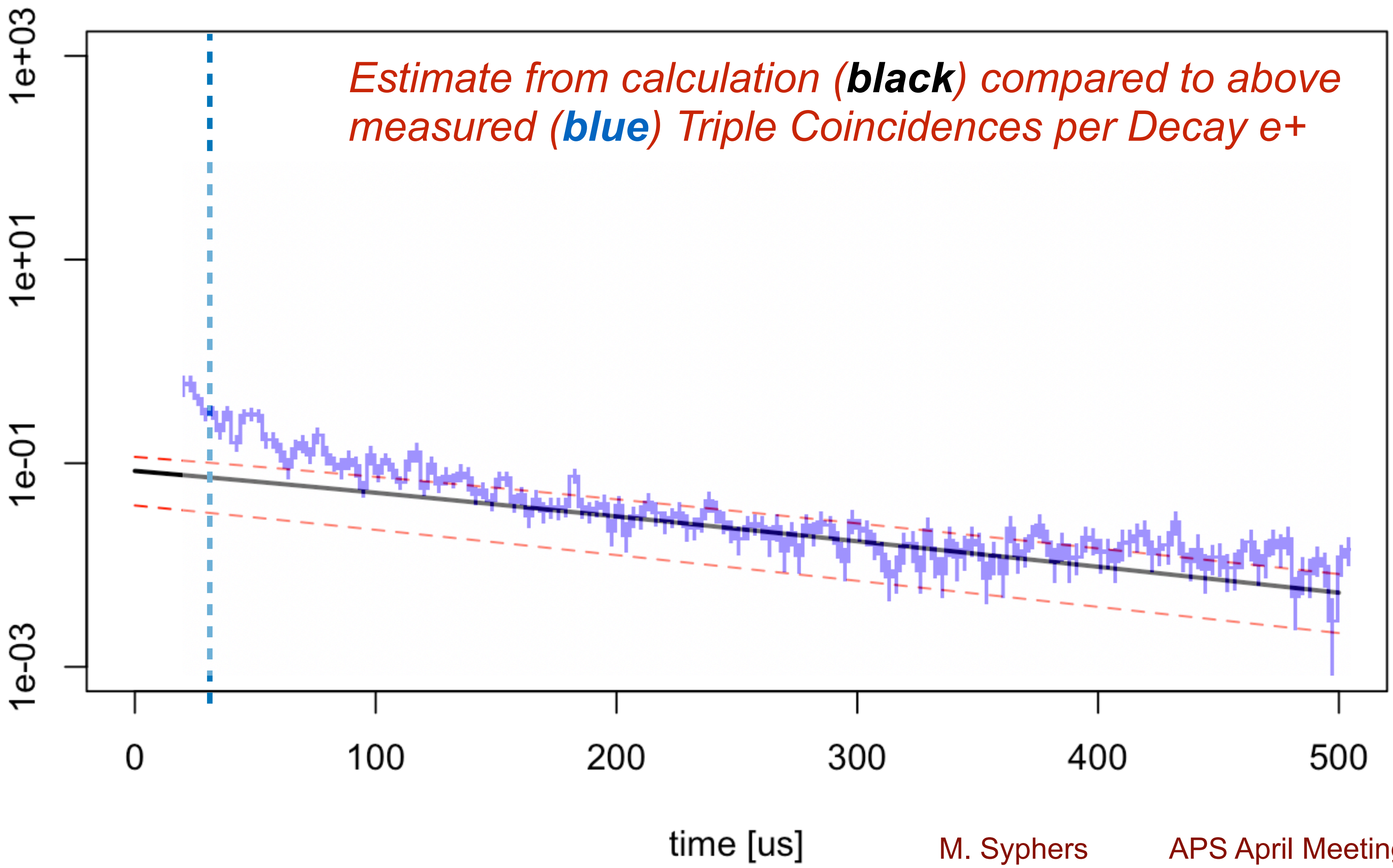




Loss Rate, its Evolution, and Comparison with Measurement







Concluding Remarks

- Data-frame-approach analysis; no standard-style particle tracking was involved. Expedient calculations from realistic phase space information
- Identified primary long-term loss mechanism
  - incoming distribution "fills" available phase space
  - two distinct distributions: Core particles and Edge particles
  - some Edge particles may survive hundreds or thousands of revolutions
- Horizontal/vertical betatron oscillations yield largest transverse displacement when particle reaches appropriate "corner"; hence, most losses occur at the 45° points on collimator perimeter
- Loss rates should be on the order of 0.01-0.1% per muon lifetime, and decrease exponentially with a time constant on the scale of ~100-200 μs
  - both level and the exponential time constant are in line with observations
- Core/Edge distributions have different forms, but central values are similar and the loss rate is low enough that error on measurement of ω_a should be ~10-20 ppb level.

- Special thanks to H. Binney, J. Crnkovic, N. Froemming, S. Ganguly, D. Hertzog, and W. Morse for their help providing data, insightful comments, questions, and suggestions