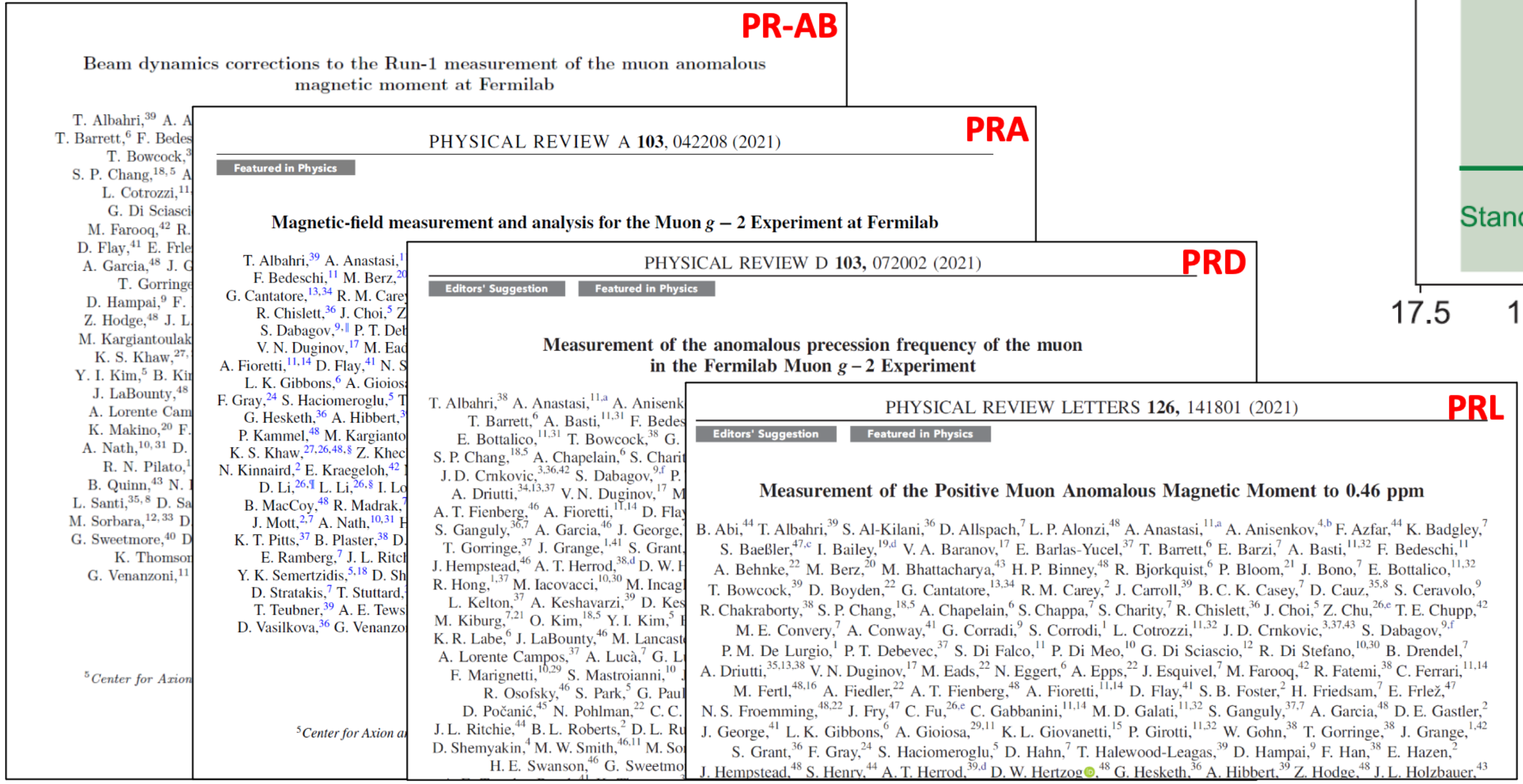
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

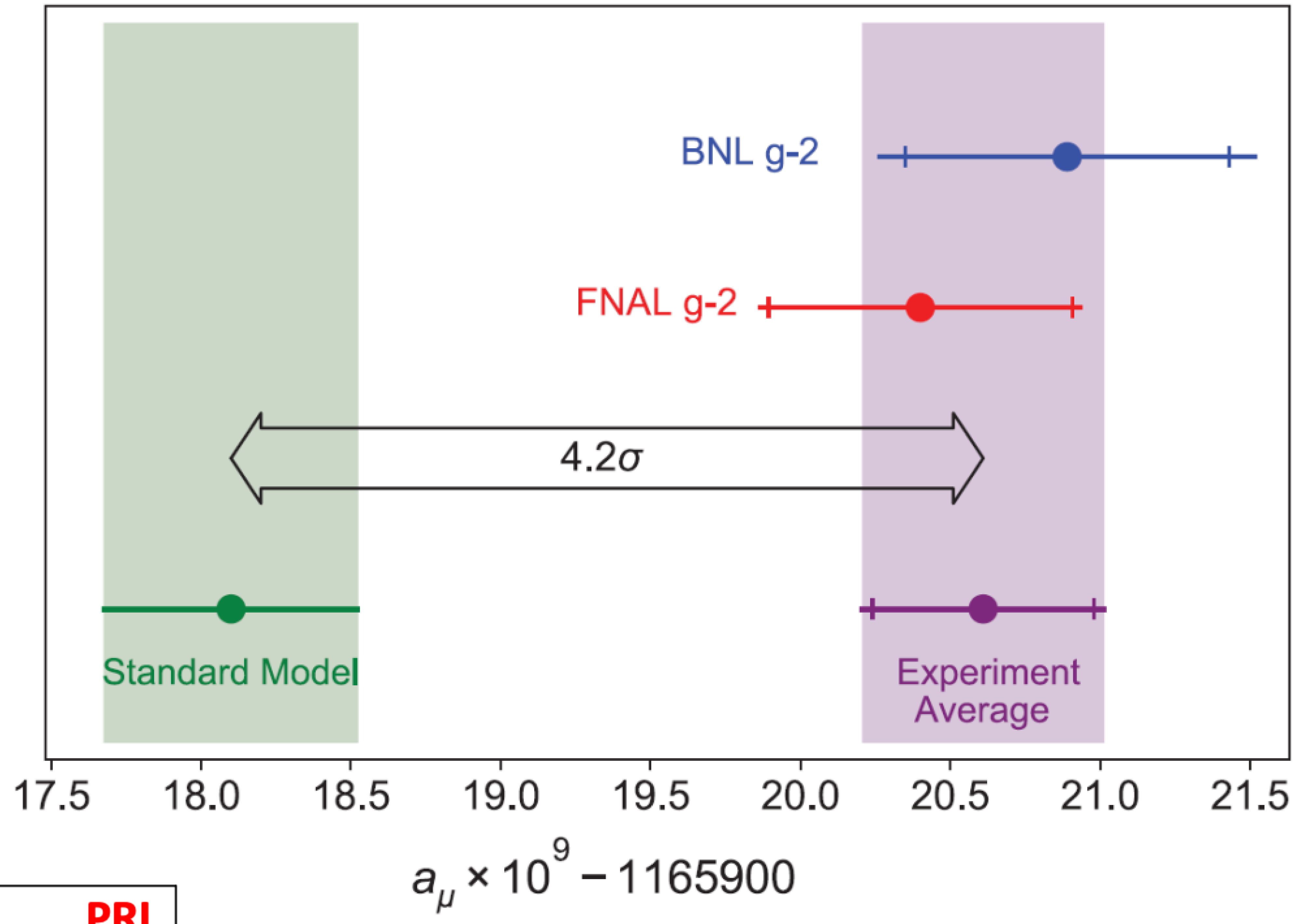
Muon g-2 experiment: first results and future prospects

Hannah Binney
Rising Stars in Experimental Physics
September 22, 2021

The big result!

- Four papers published April 2021 with results of Run-1 of data taking
- Verified old Brookhaven result to similar precision
- Combined result disagrees with current standard model calculation to 4.2 σ





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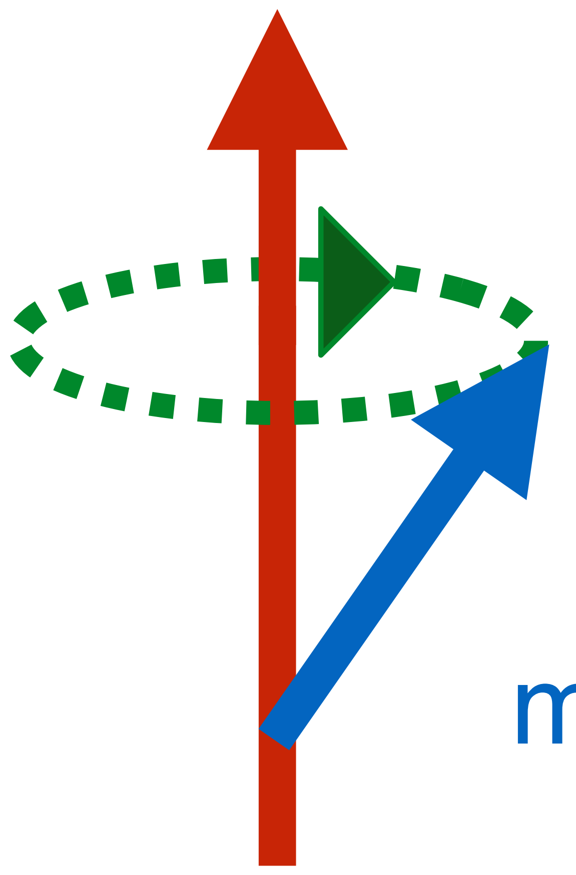
Anomalous magnetic moments

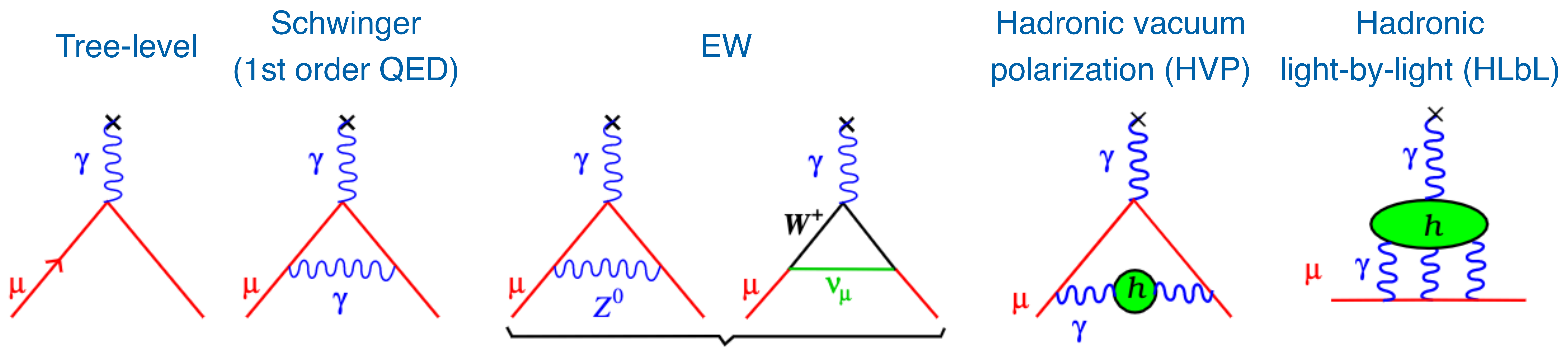
- A charged particle with intrinsic spin has a magnetic dipole moment
  $\vec{\mu} = g\frac{q}{2m}\vec{S}$
- In a magnetic field, it precesses at the frequency
  $\omega = g\frac{qB}{2m}$
- Dirac equation predicts $g = 2$ for pointlike spin 1/2 particles
- Virtual particles result in corrections to $g = 2$
- $a \equiv \frac{g-2}{2}$, the anomalous magnetic moment



A test of the standard model

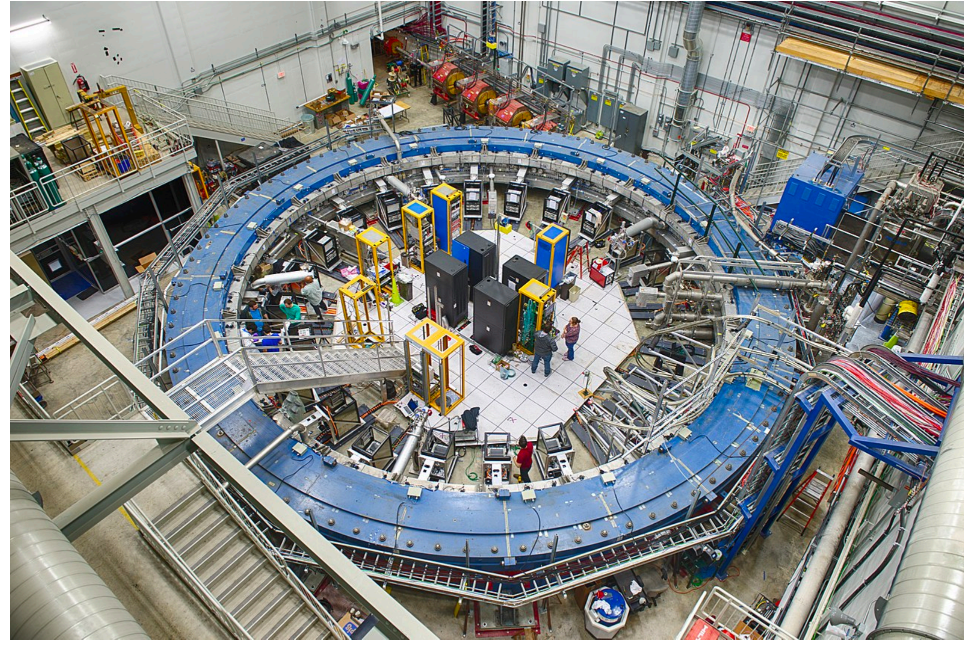
- Schwinger calculated first order QED correction
  - $a \rightarrow \frac{\alpha}{2\pi}$
- Higher order QED
- Weak
- Hadronic
  - Highest uncertainty for hadronic terms

Source	Value (x 10^{-11}) [1]	Error
QED	116,584,718.93	0.10
EW	153.6	1.0
HVP	6845	40
HLbL	92	18



[1] T. Aoyama et. al. The anomalous magnetic moment of the muon in the Standard Model (2020).

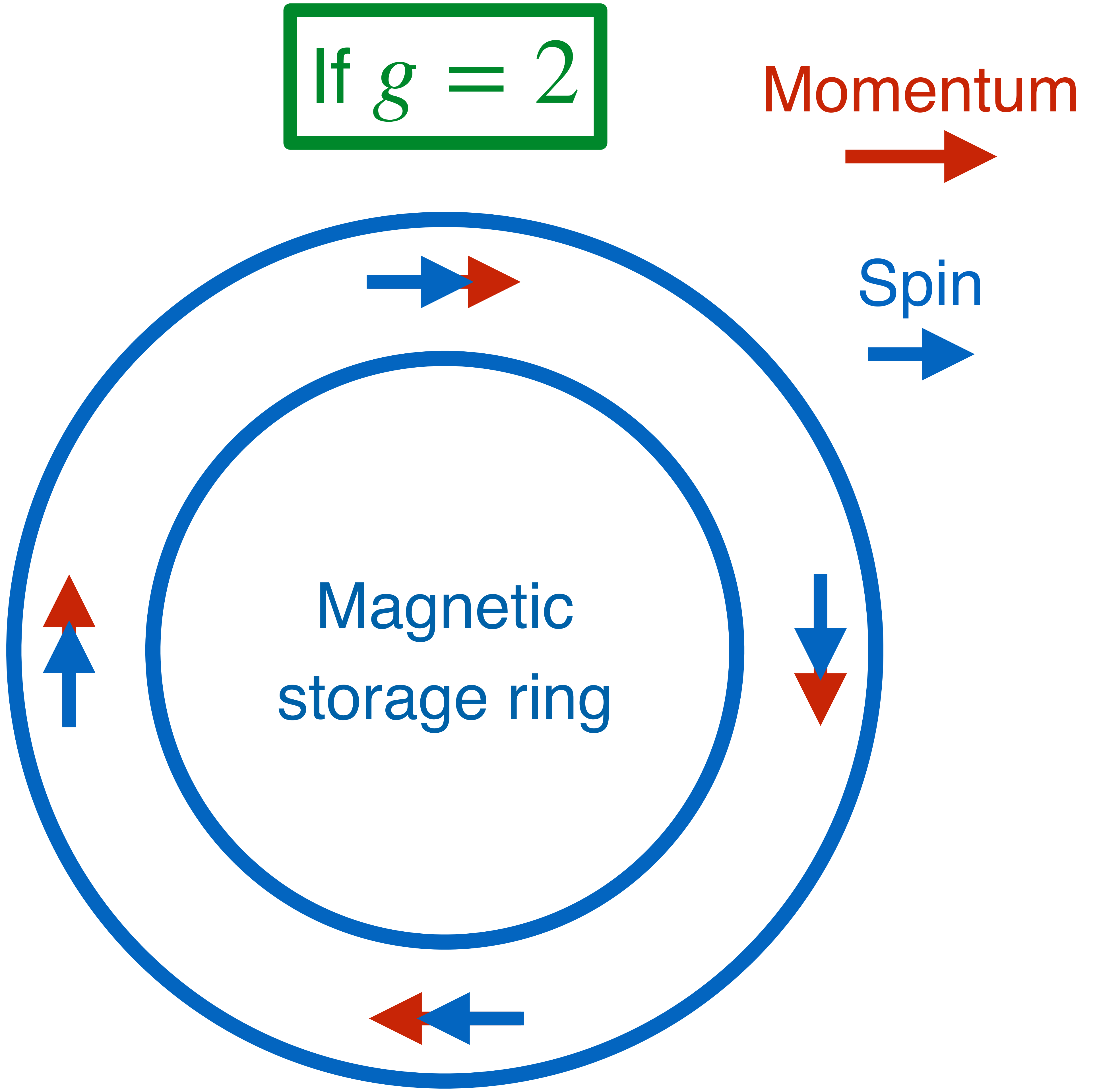
Measuring a_μ: cyclotron and spin frequency



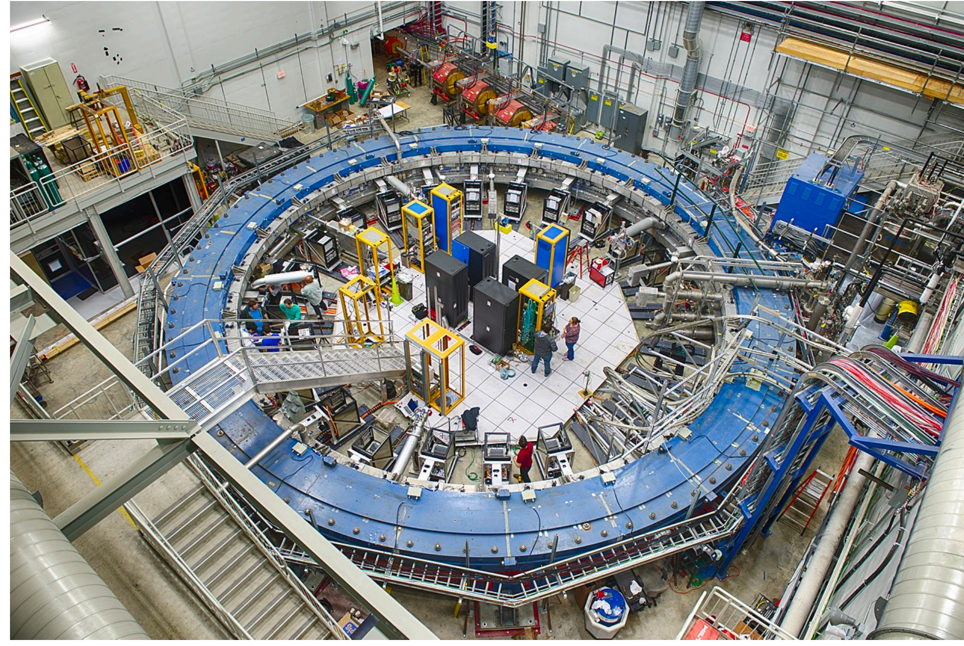
In the absence of an electric field, for a muon orbiting horizontally in a perpendicular magnetic field:

a_μ (the anomalous magnetic moment)

$$\omega_a \equiv \omega_s - \omega_c = -\left(\frac{g-2}{2}\right)\frac{eB}{m}$$



Measuring a_μ: cyclotron and spin frequency



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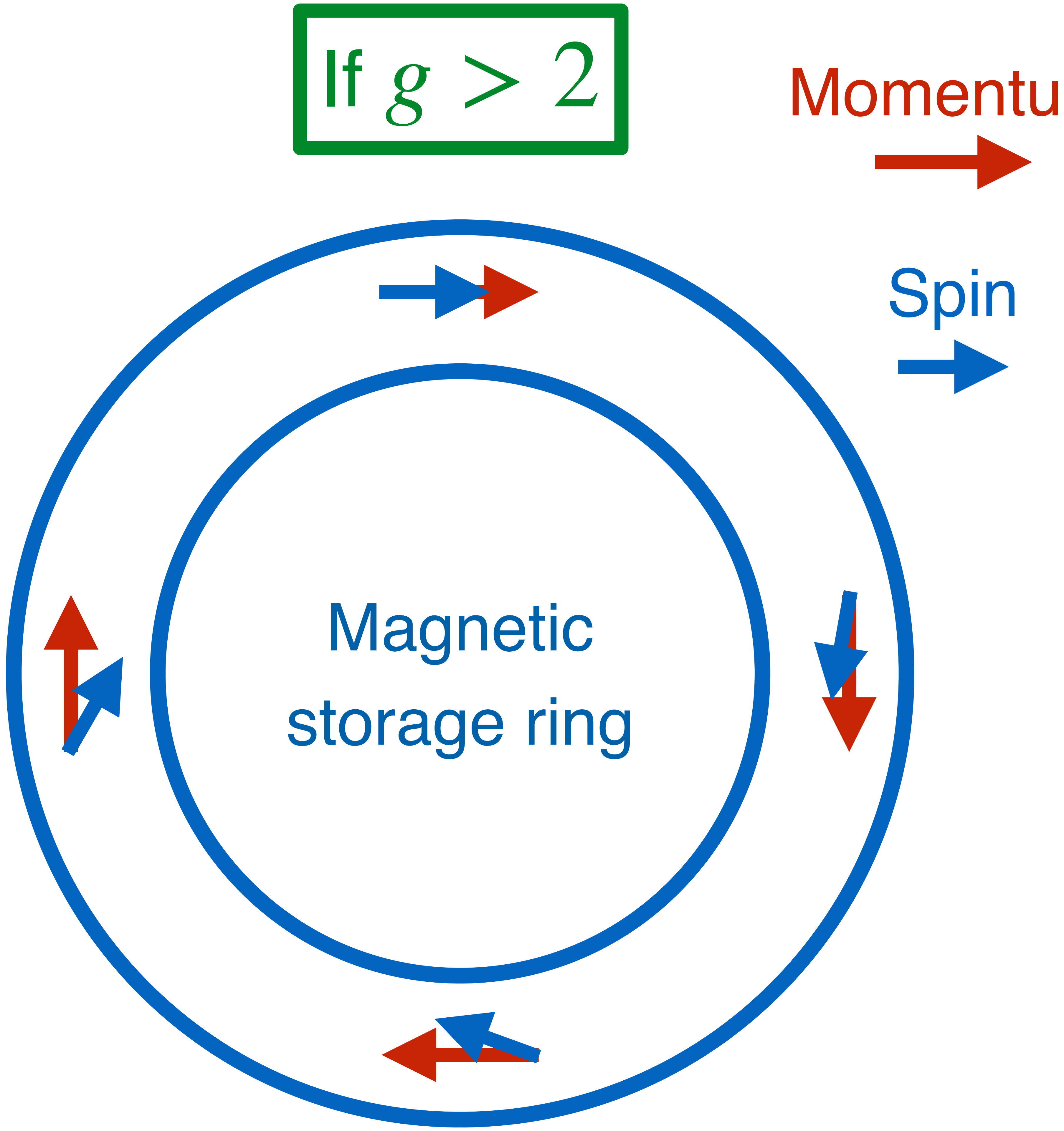
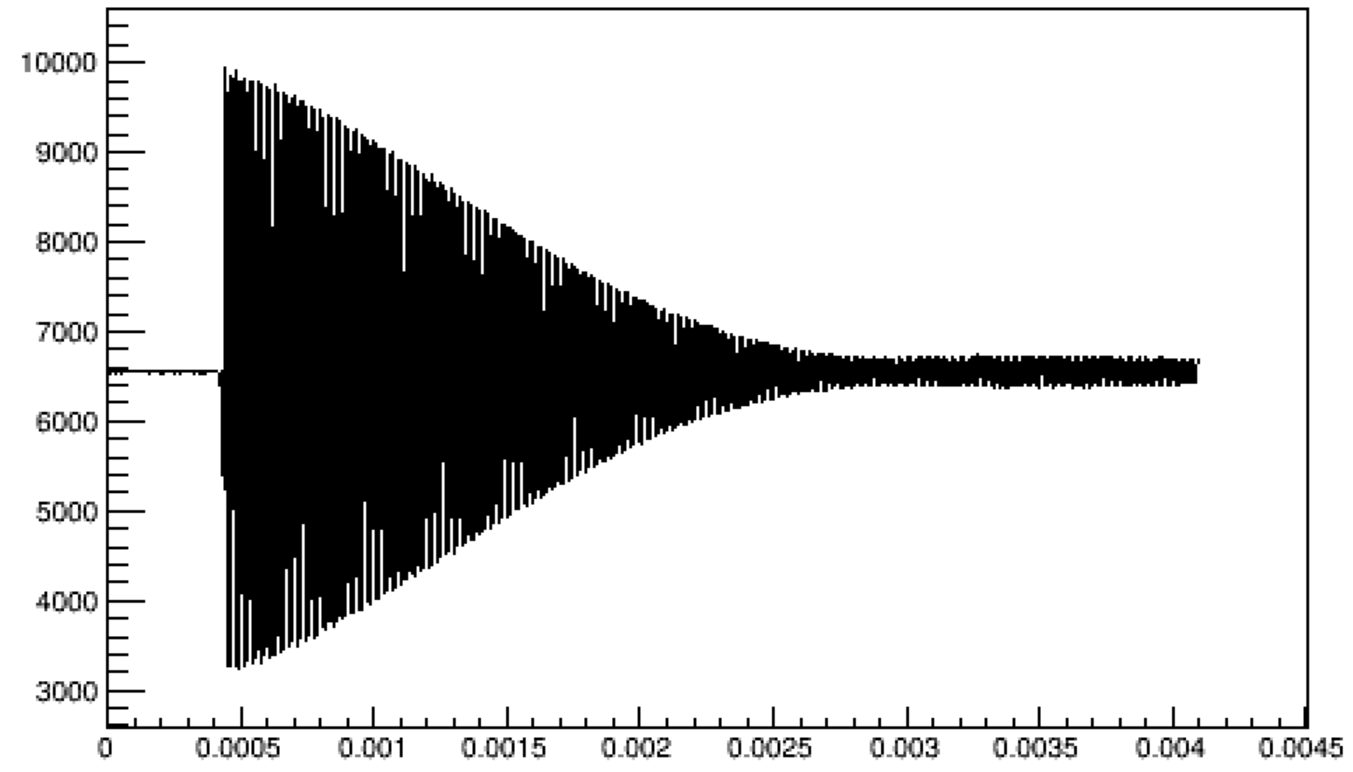
Quantities to measure

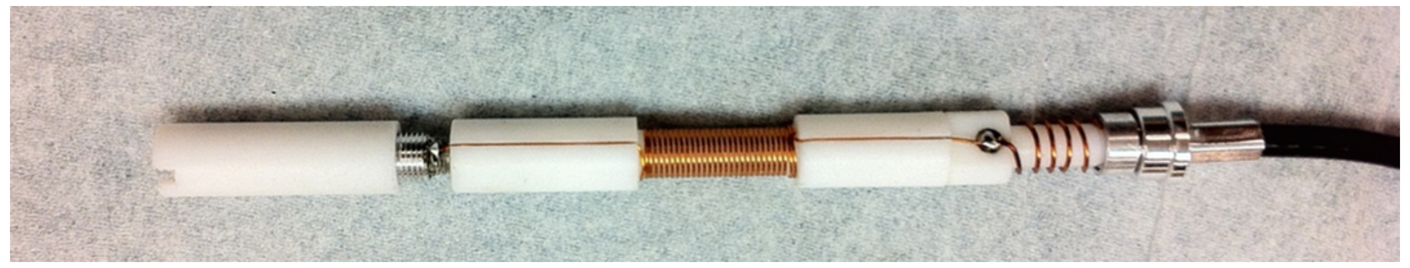


Measuring $\tilde{\omega}_p$

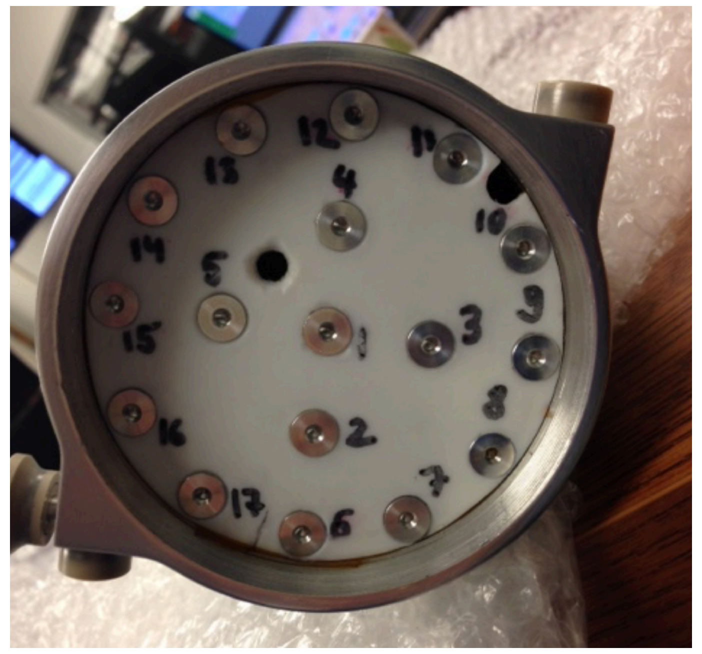
Free induction decay signal



NMR probe



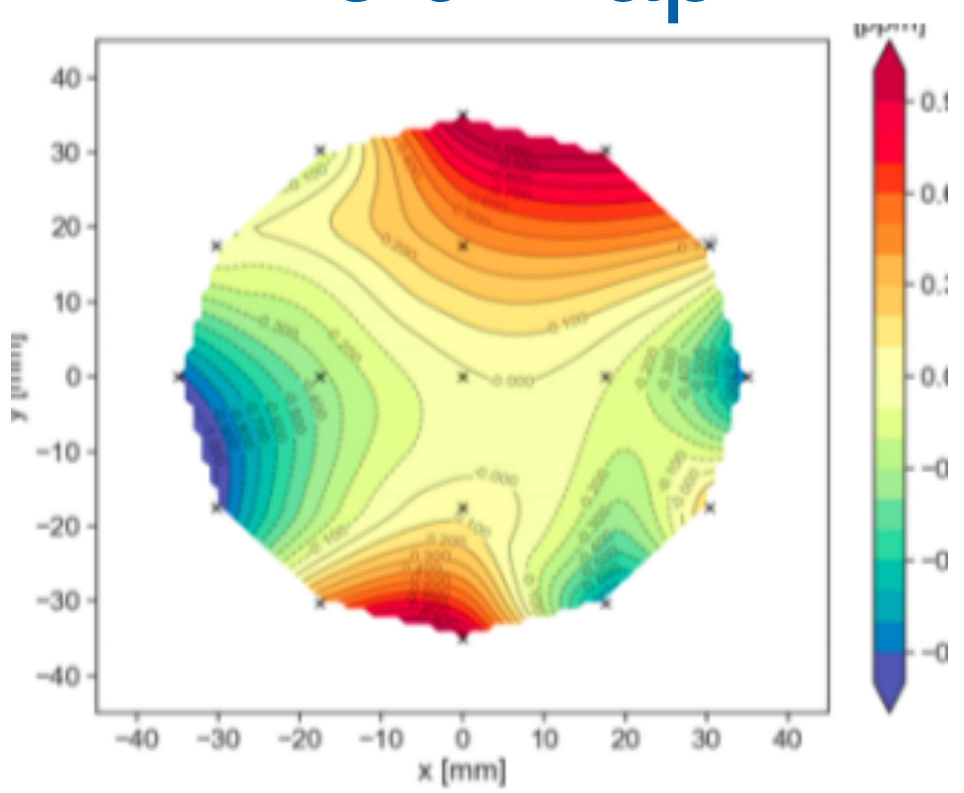
Trolley



- The magnetic field B is measured using the Larmor precession frequency of free protons, ω_p
- Nuclear magnetic resonance (NMR) probes measure ω_p
- Trolley with 17 probes periodically measures field in storage region
- Fixed probes are used to interpolate the field between trolley runs
- Beam distribution measured by straw tracking detectors

$$\tilde{\omega}_p = \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$$

Field map



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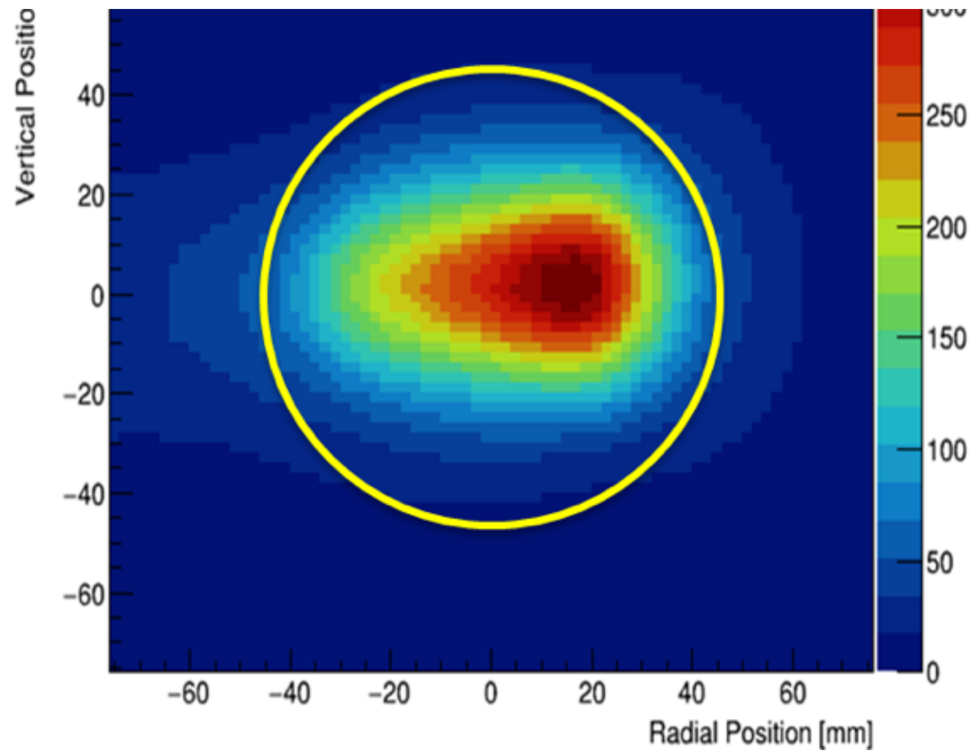
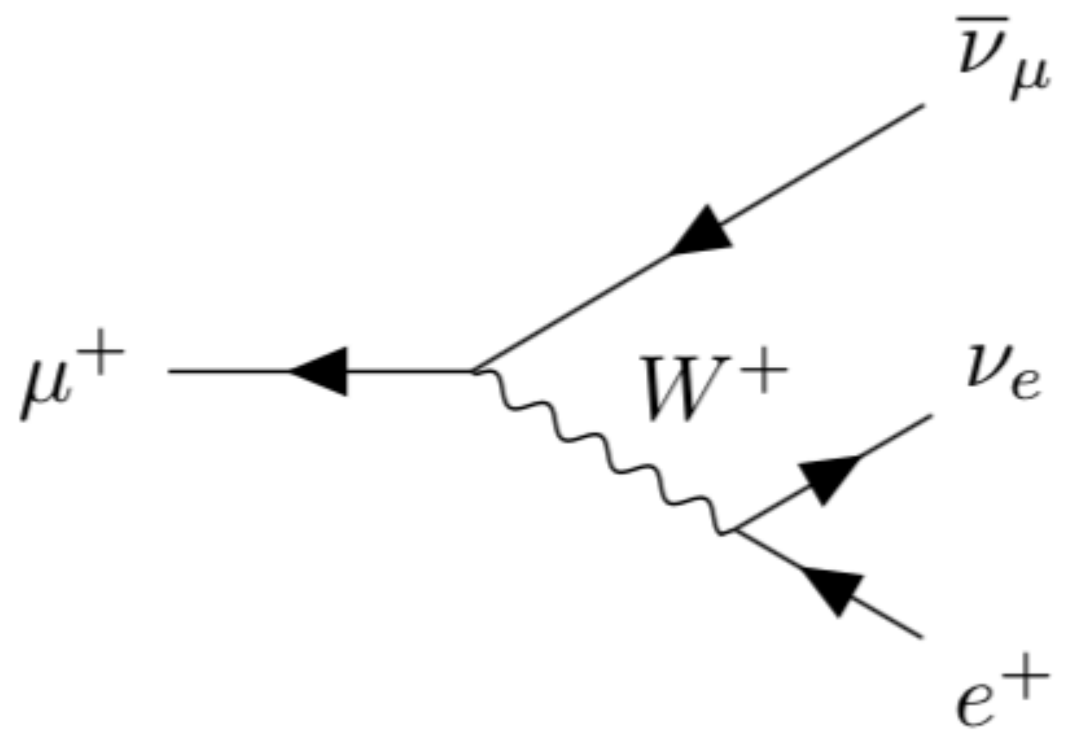
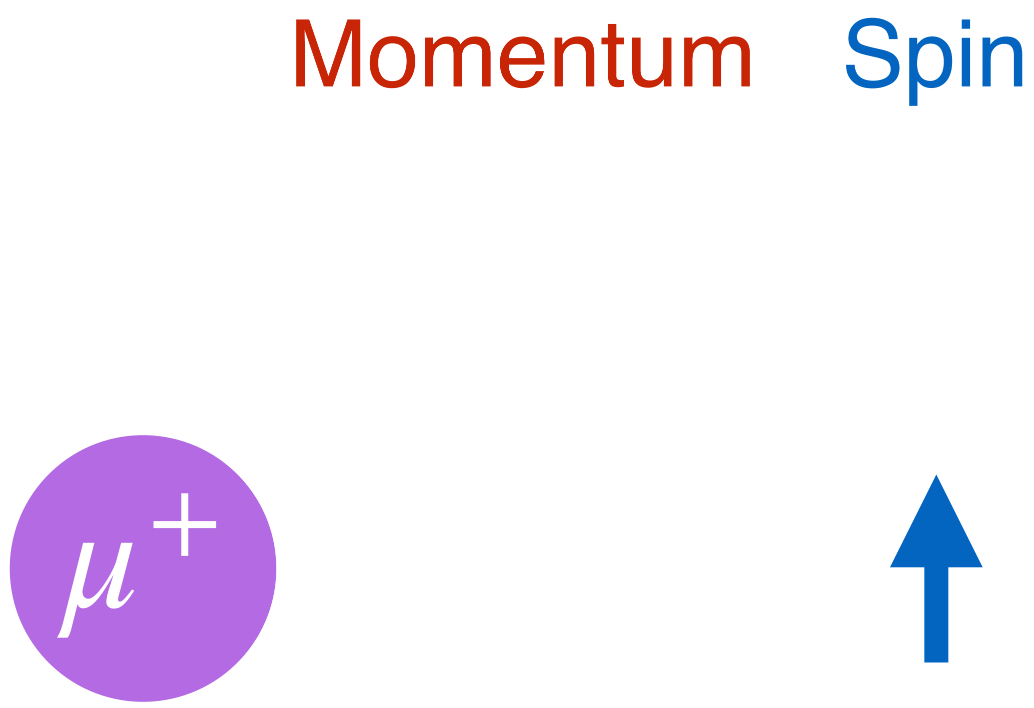
Beam map



Measuring ω_a: parity violation in the weak decay

- Muons decay into electrons through the weak interaction, exhibiting parity violation
- Highest energy positrons emitted preferentially in direction of muon spin





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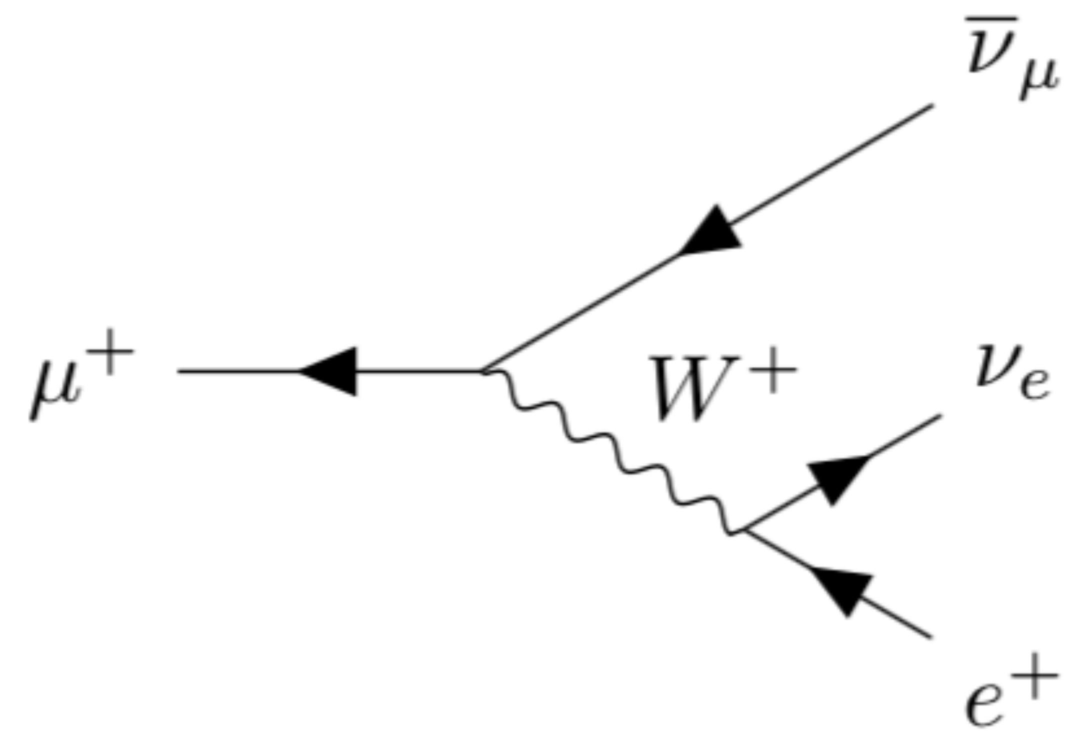
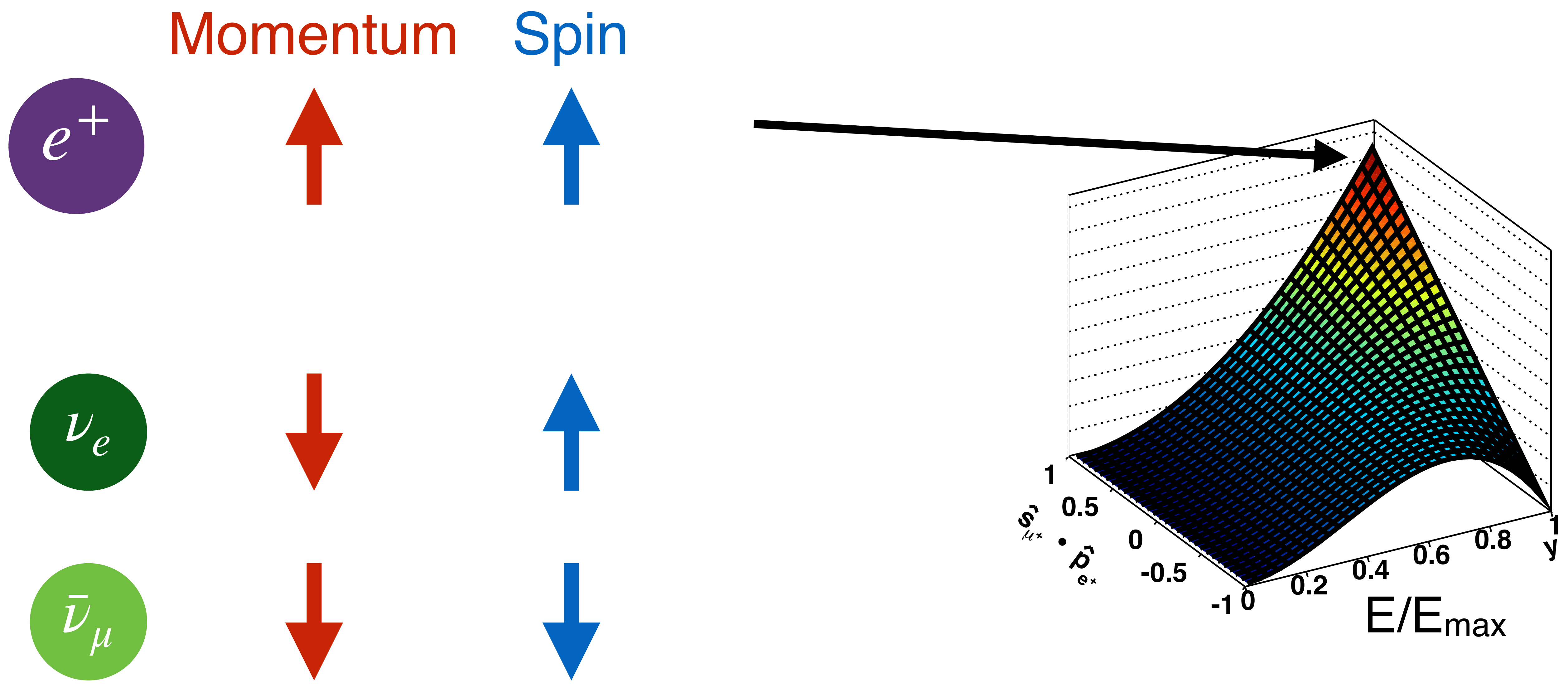


Highest e^+ energy configuration



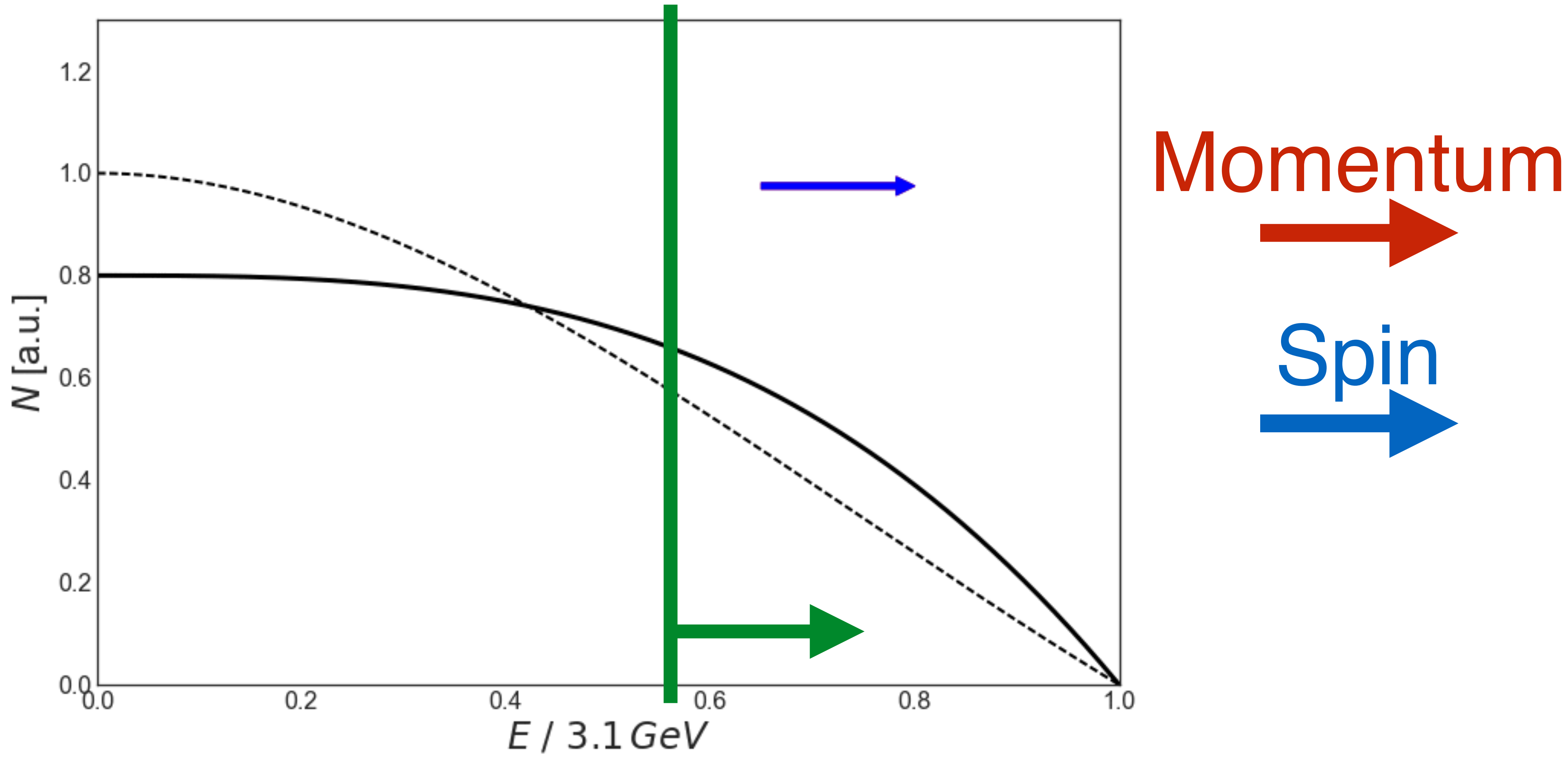
Measuring ω_a: parity violation in the weak decay

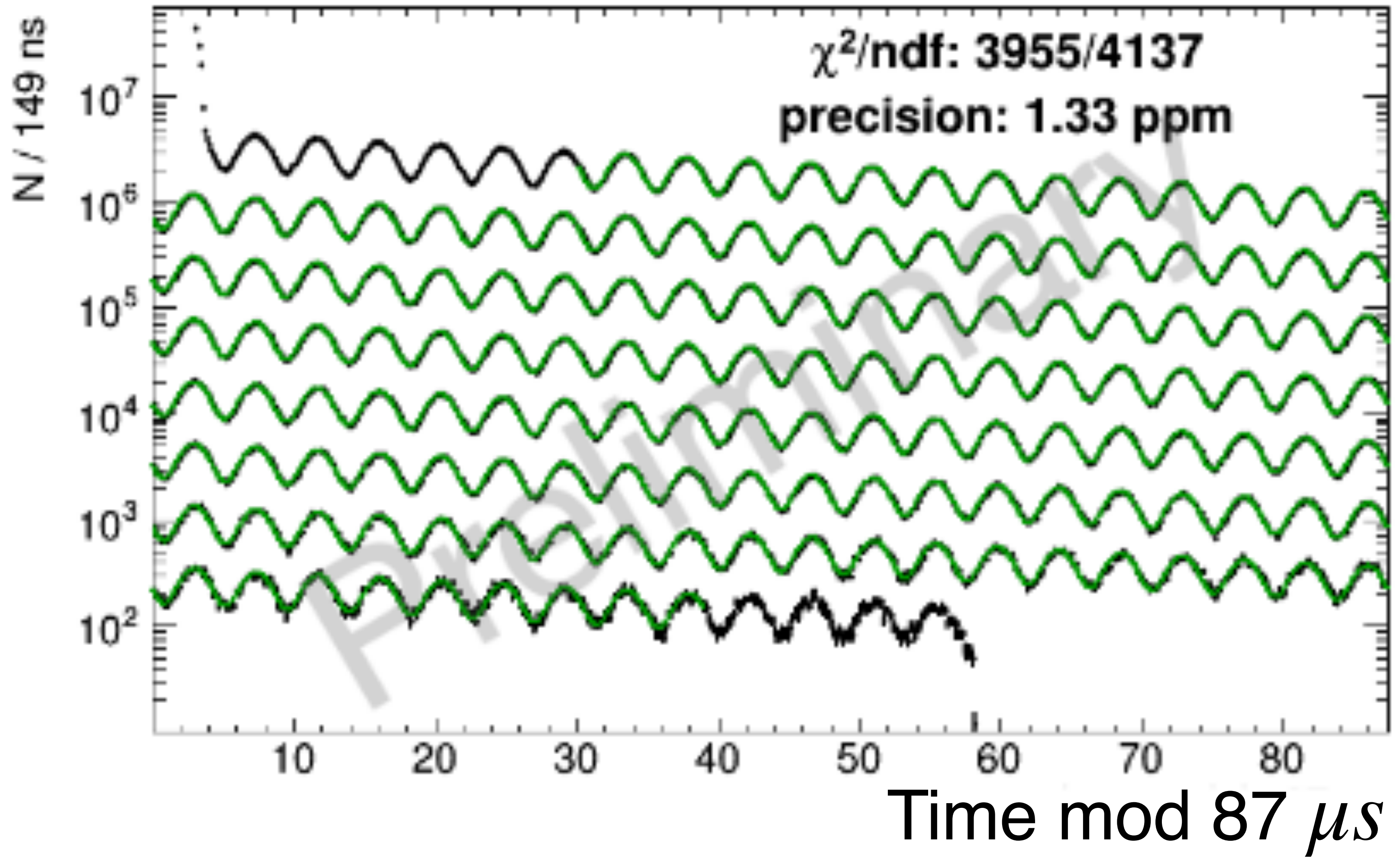
- ω_a encoded in number of decay positrons above a certain energy threshold

- 5 parameter fit function:

$$N(t) = N_0 e^{-t/\tau}[1 - A\cos(\omega_a t - \phi)]$$

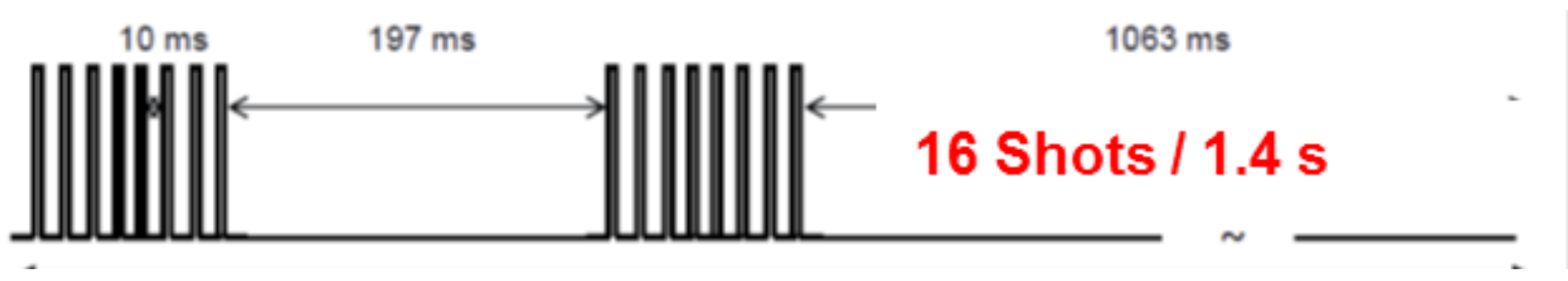
Time dilated muon lifetime (τ) · Asymmetry (A) · Frequency (physics quantity) (ω_a) · Spin phase at injection (ϕ)

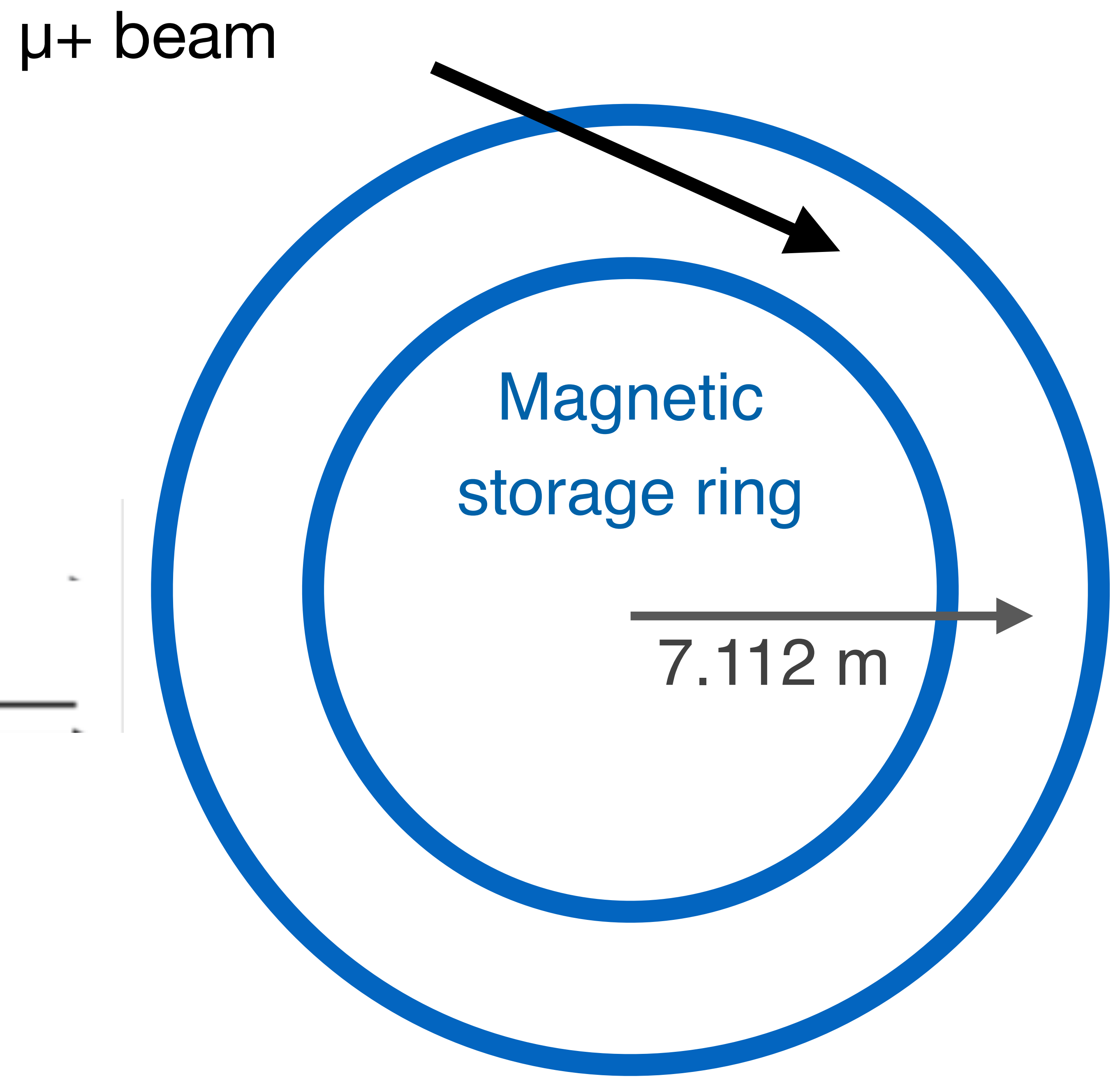




Beam injection

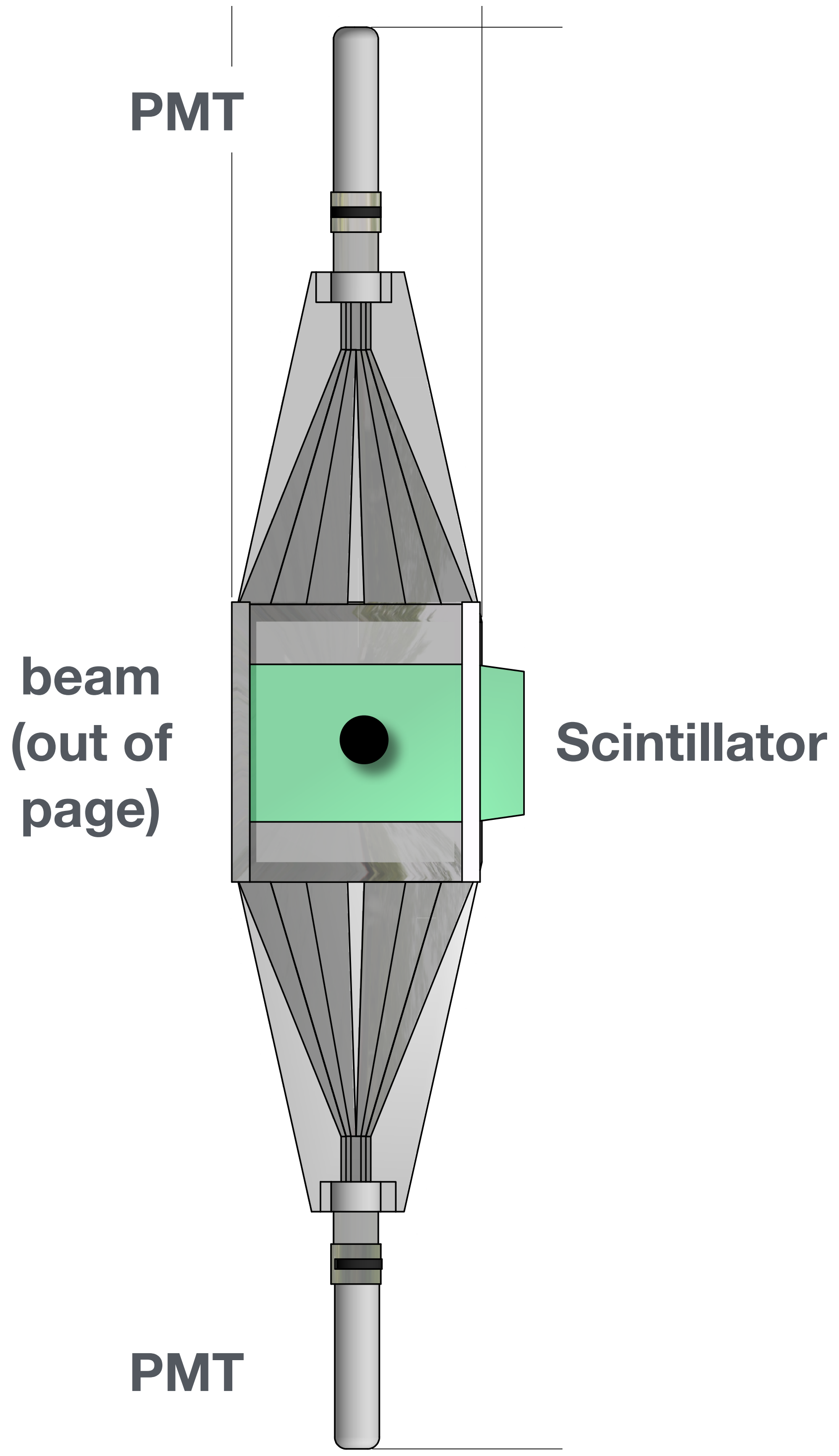
- A polarized muon beam is injected into a magnetic storage ring



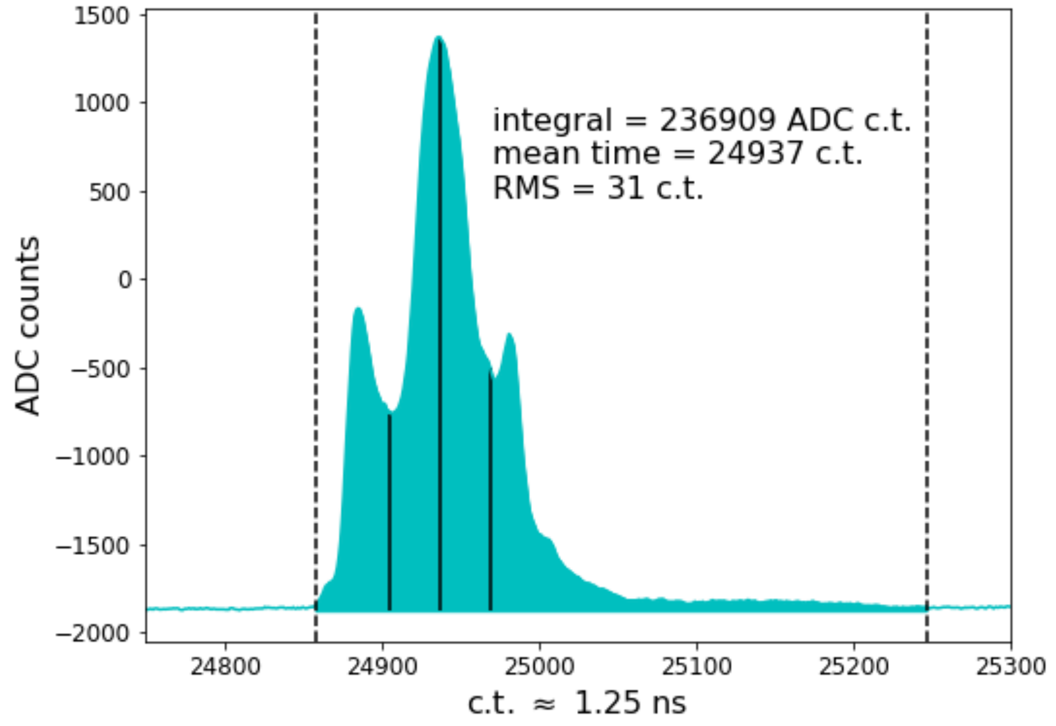


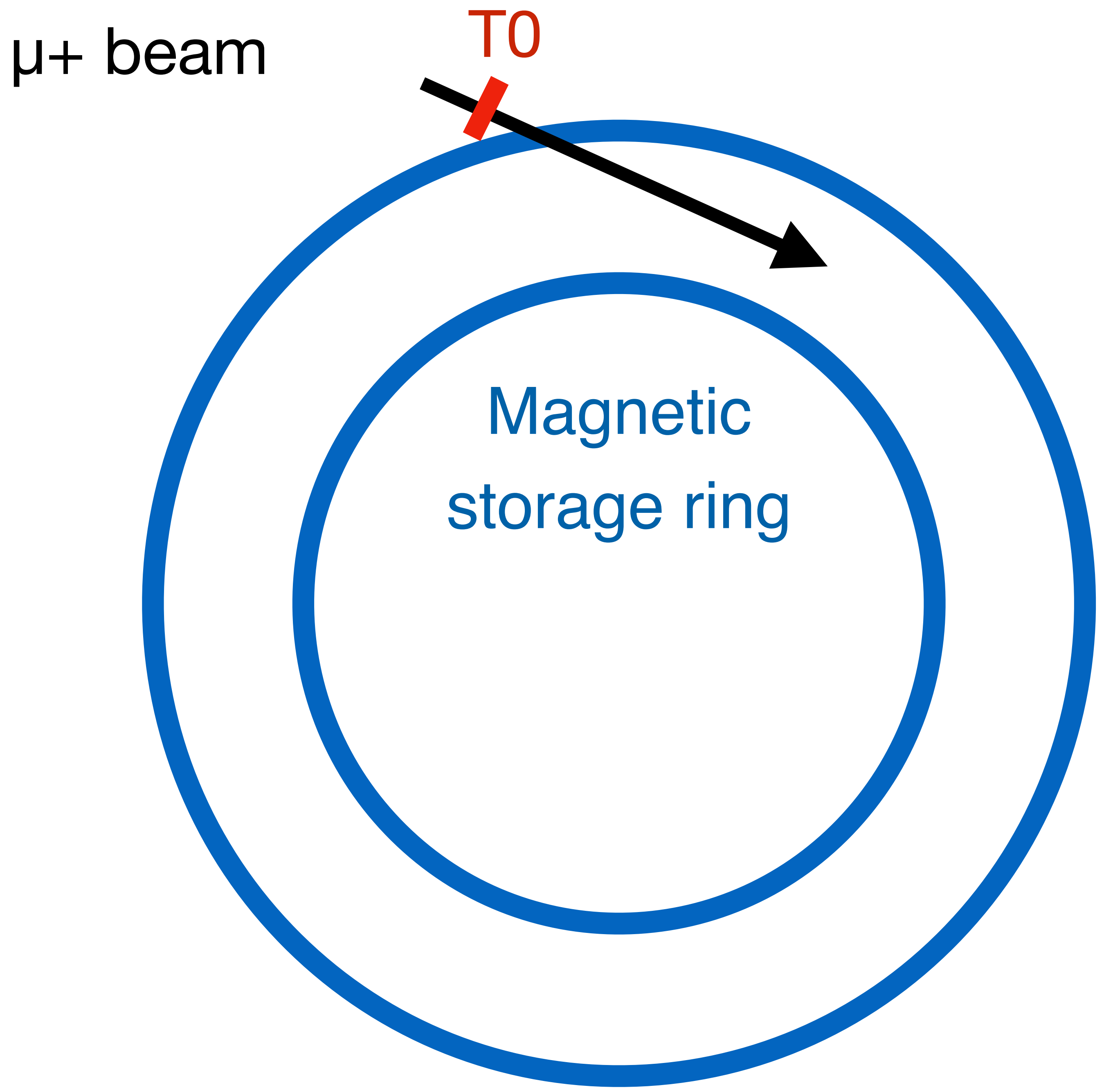
Beam injection

T0 detector



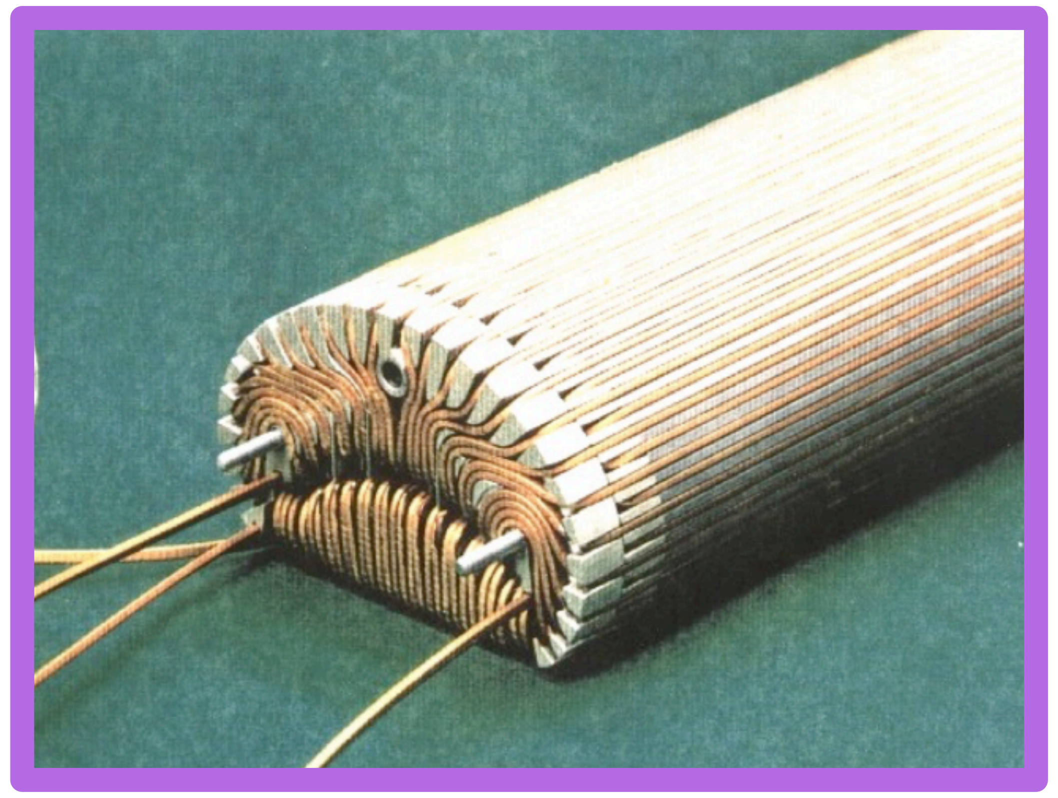
T0 time profile

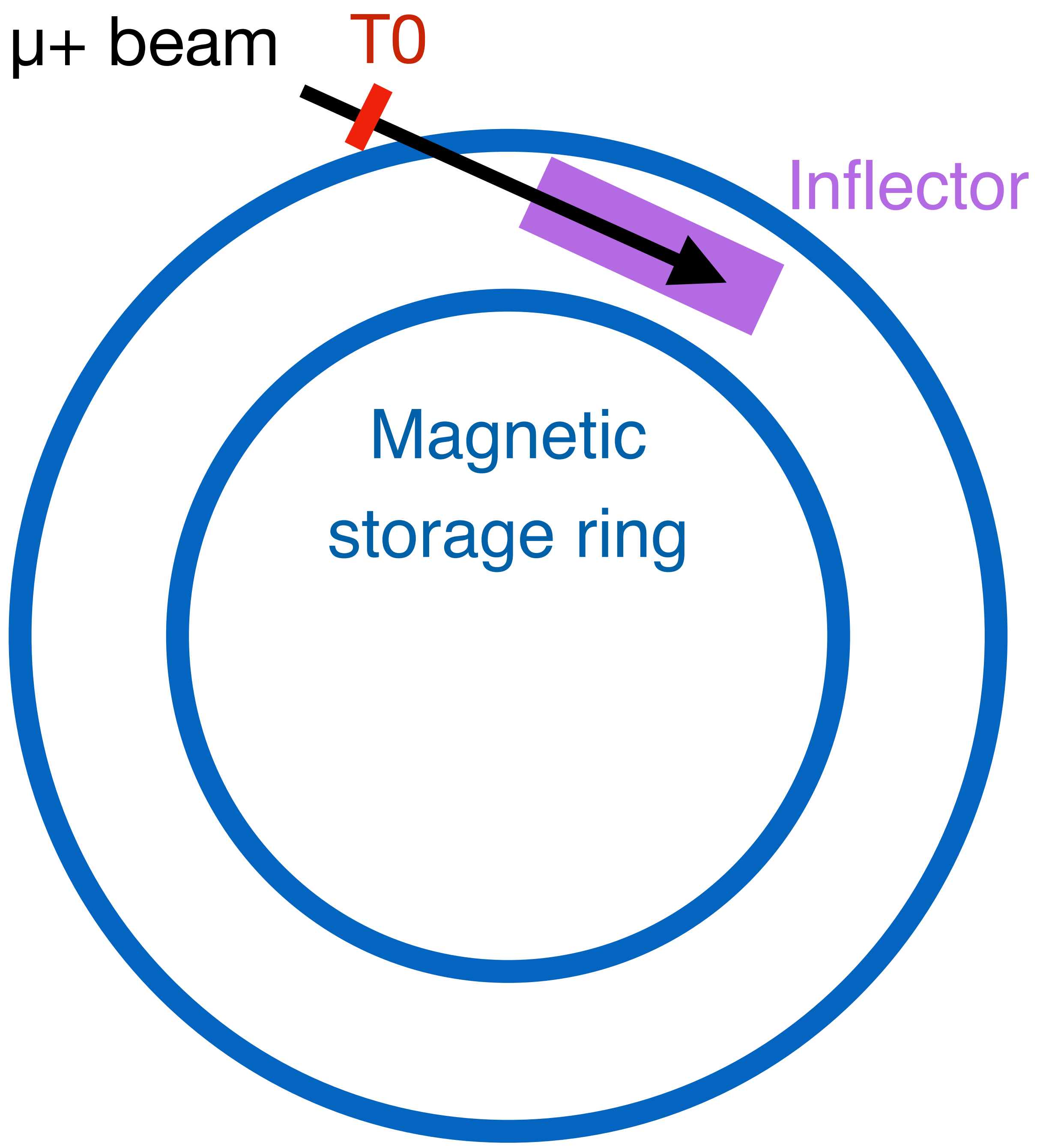




Beam injection

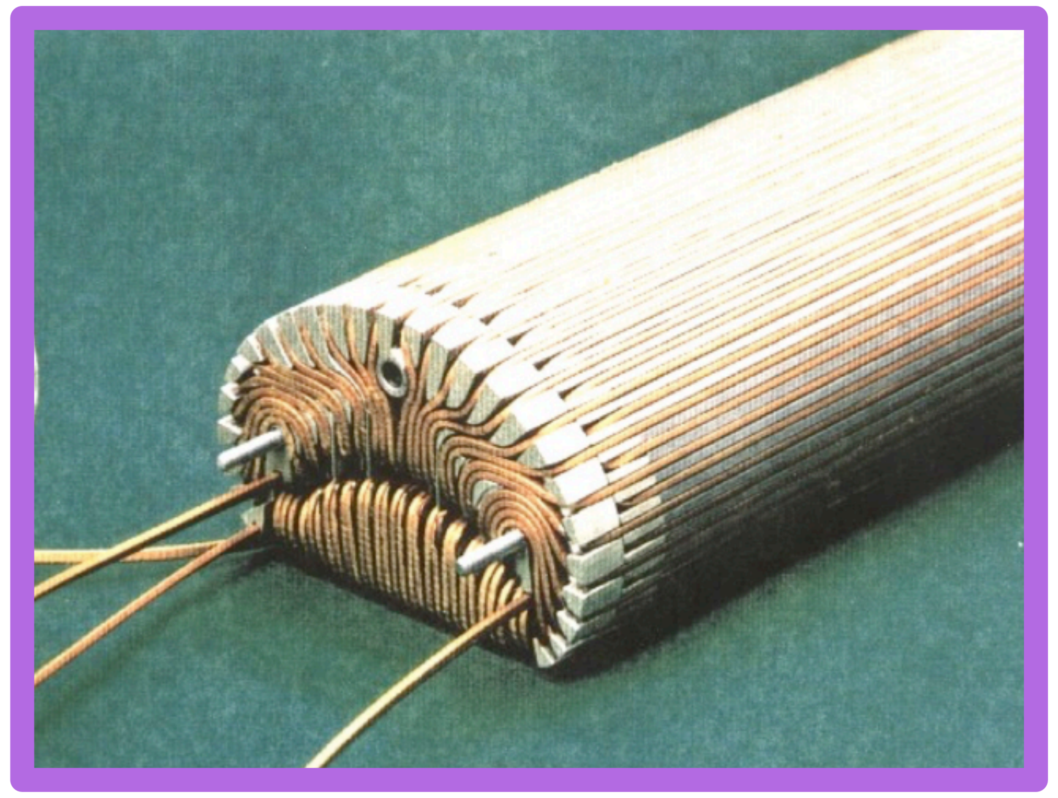
- Superconducting inflector creates a field-free region so the muons can enter the storage ring

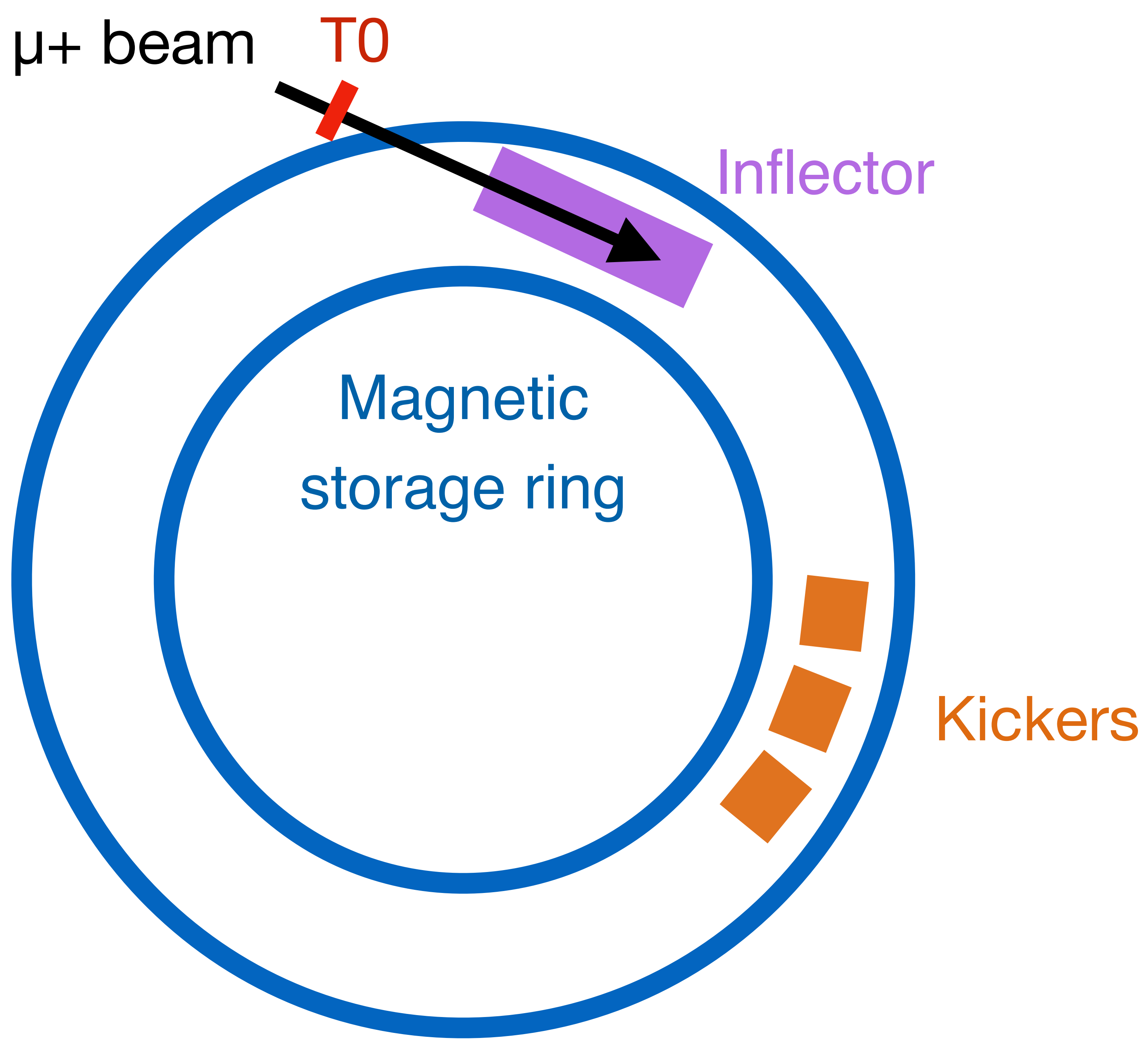


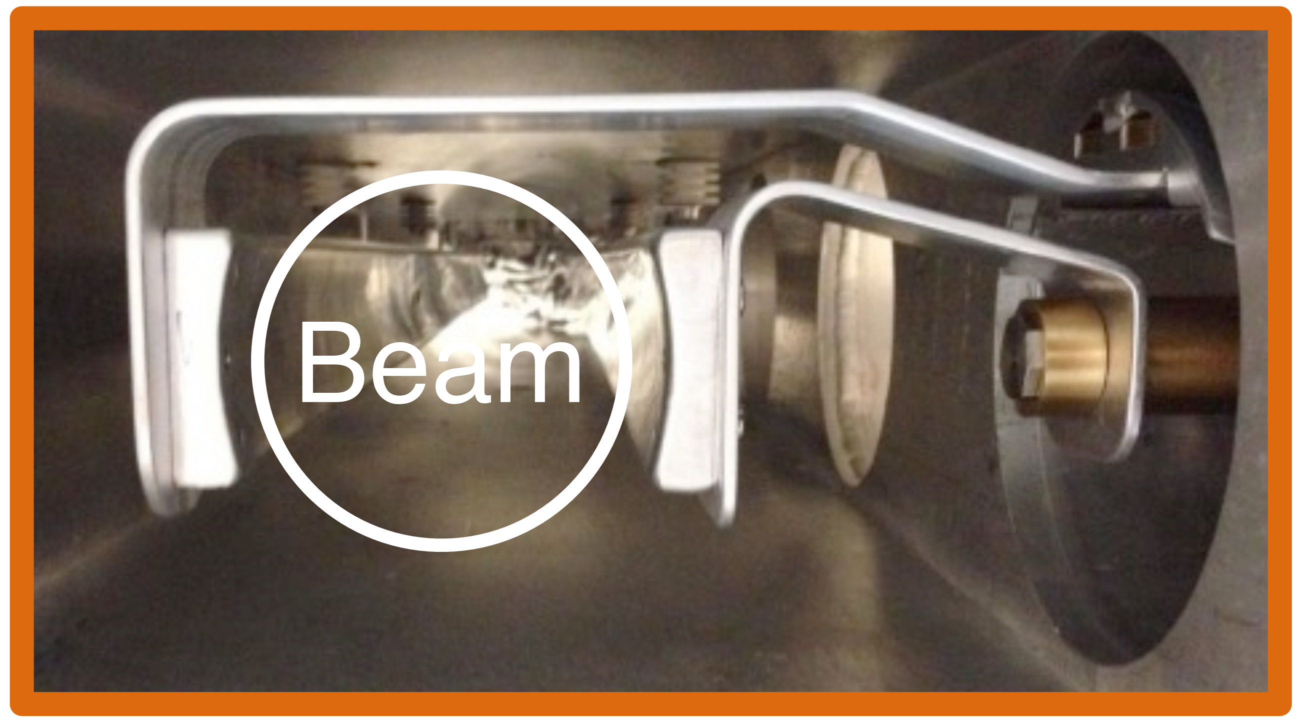


Beam storage

- Superconducting inflector creates a field-free region so the muons can enter the storage ring
- Three magnetic kickers deflect muons onto their proper orbit

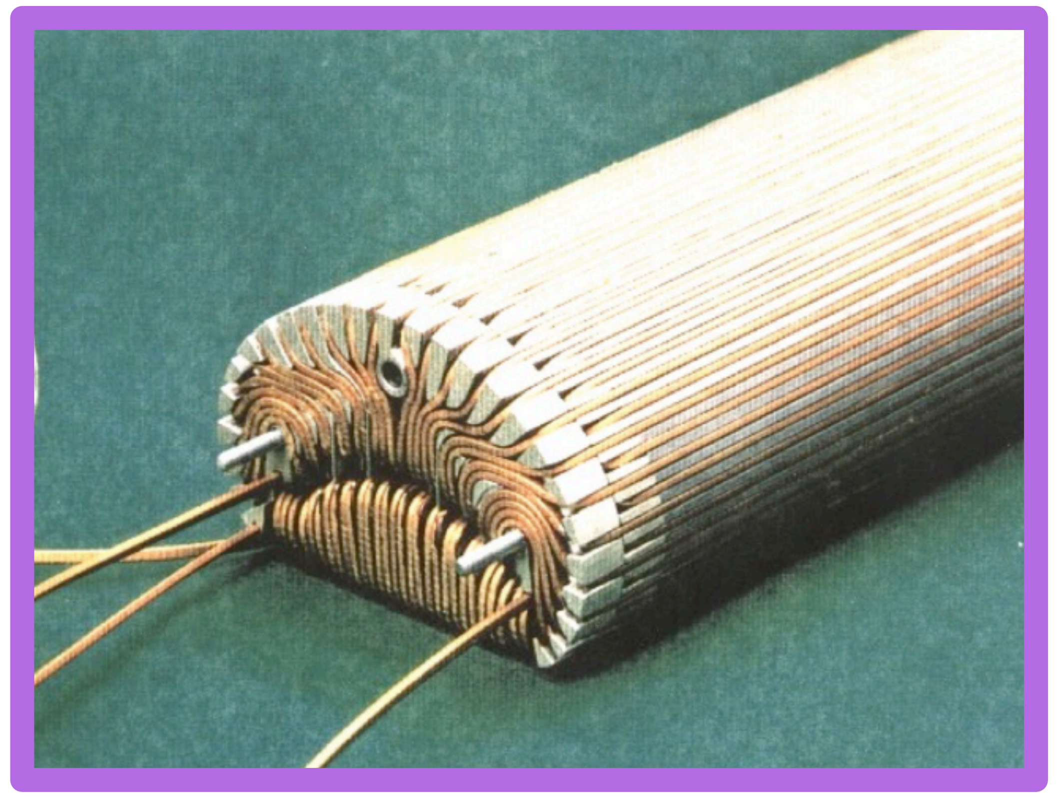


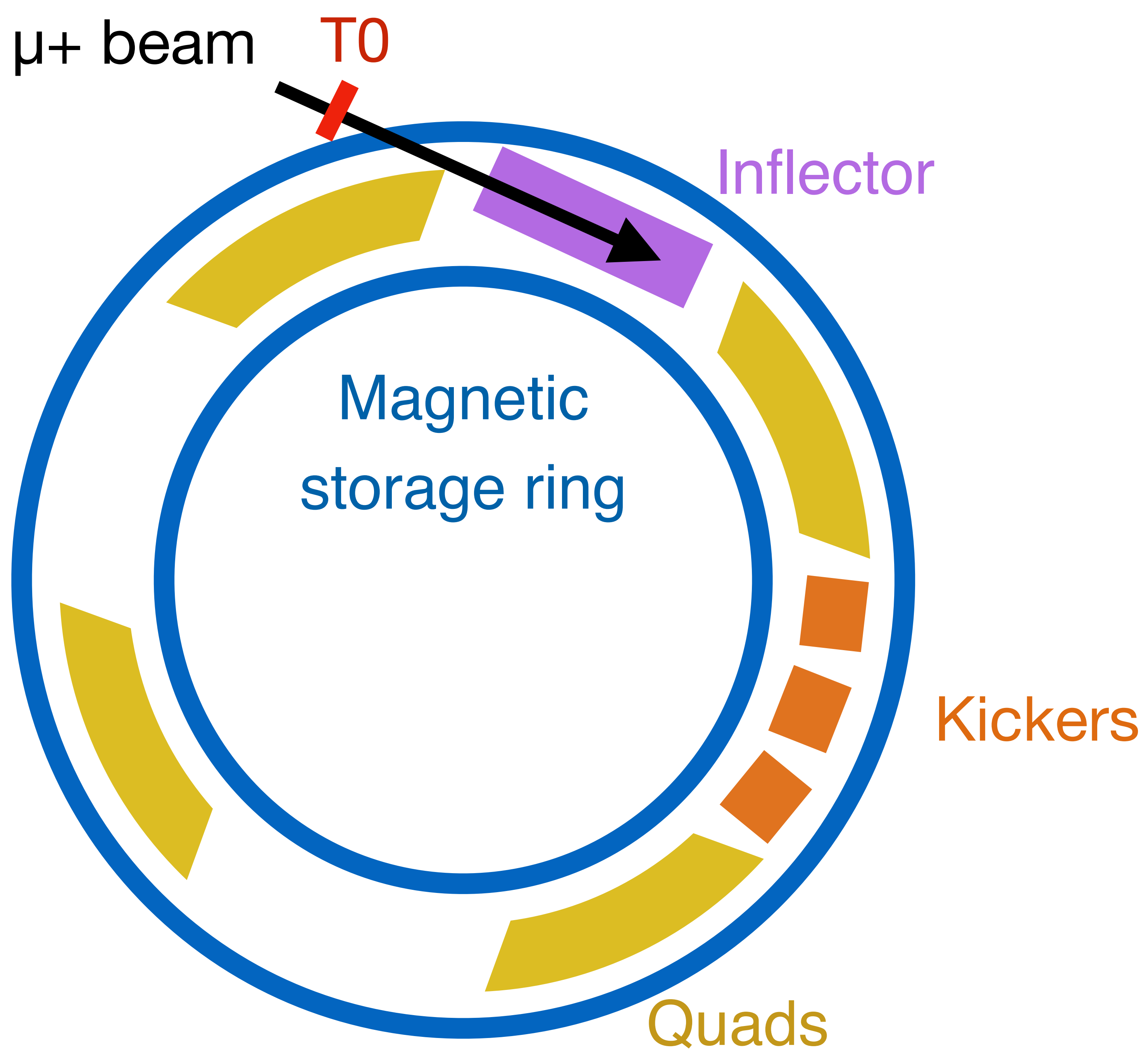


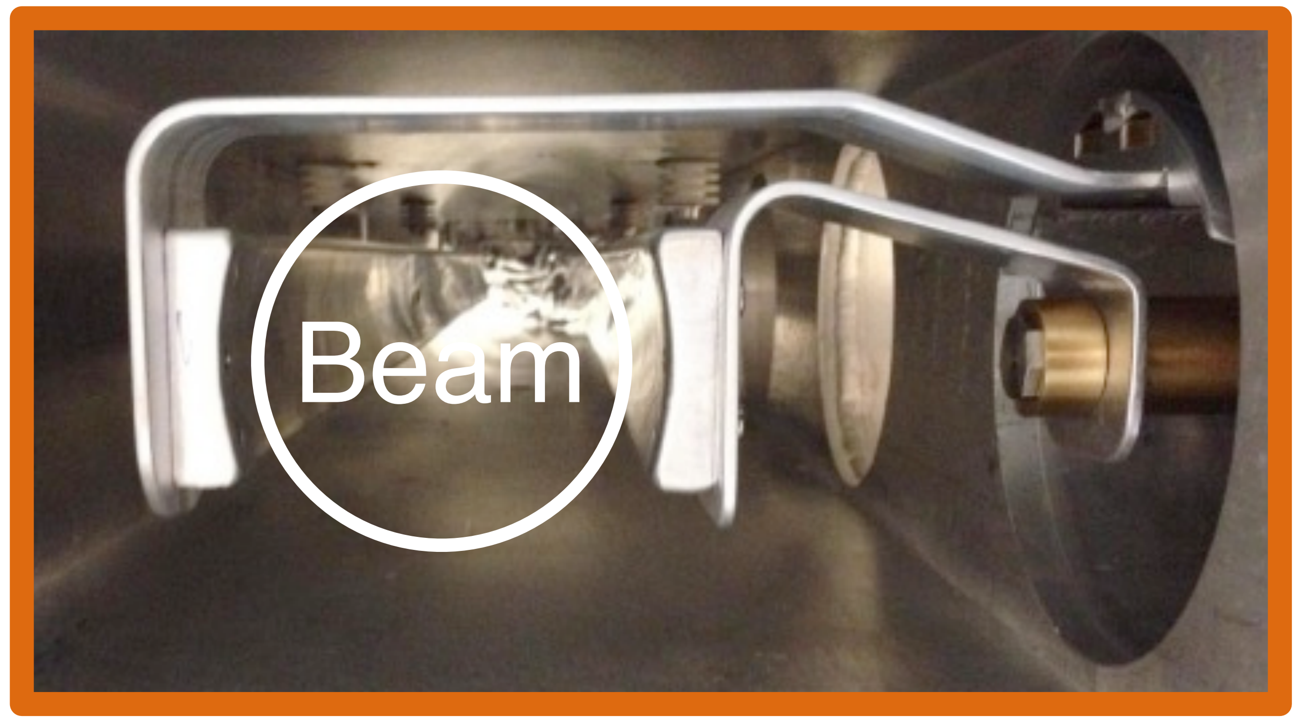


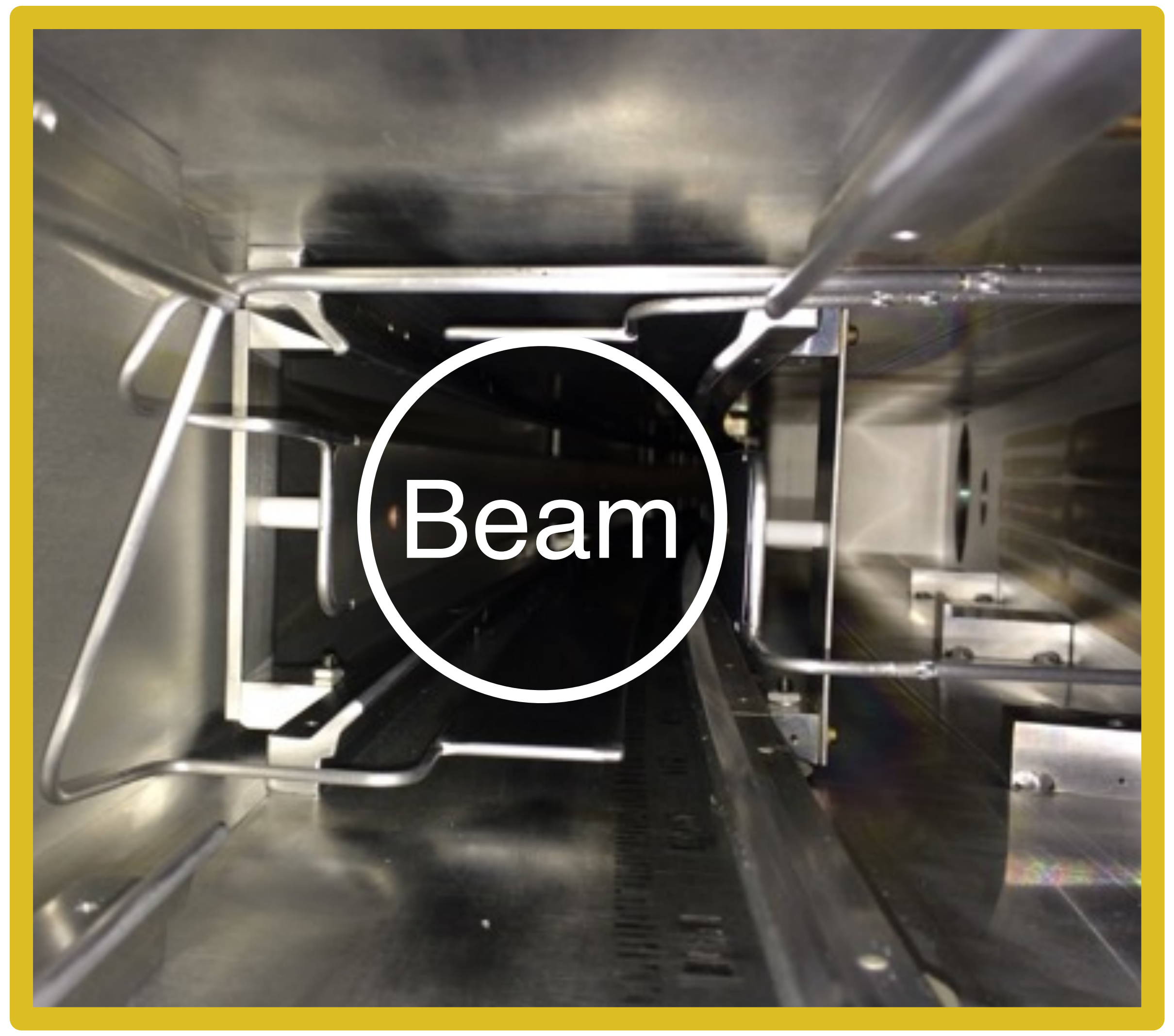
Beam storage

- Superconducting inflector creates a field-free region so the muons can enter the storage ring
- Three magnetic kickers deflect muons onto their proper orbit
- Electrostatic quadrupoles provide vertical focusing



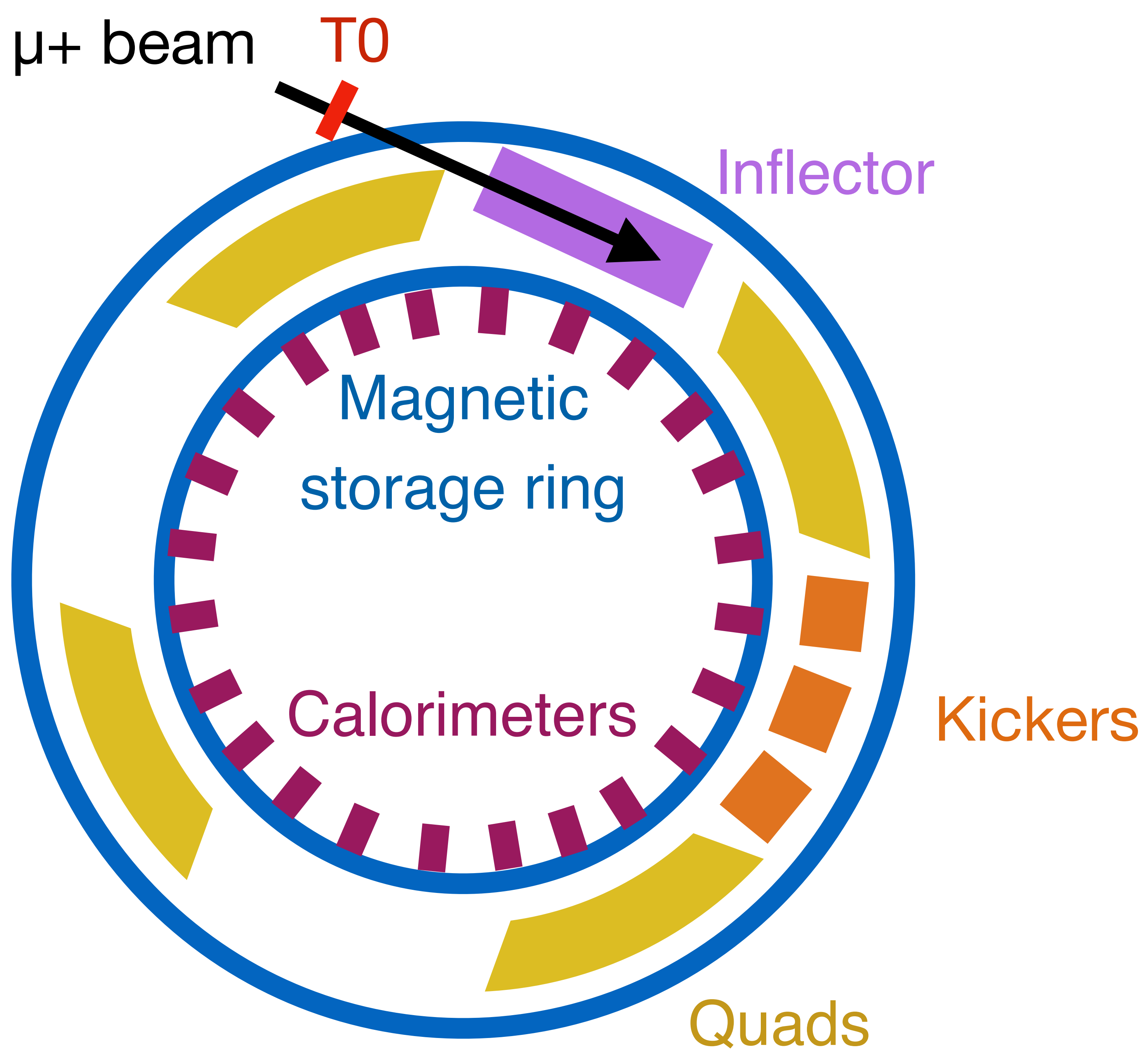


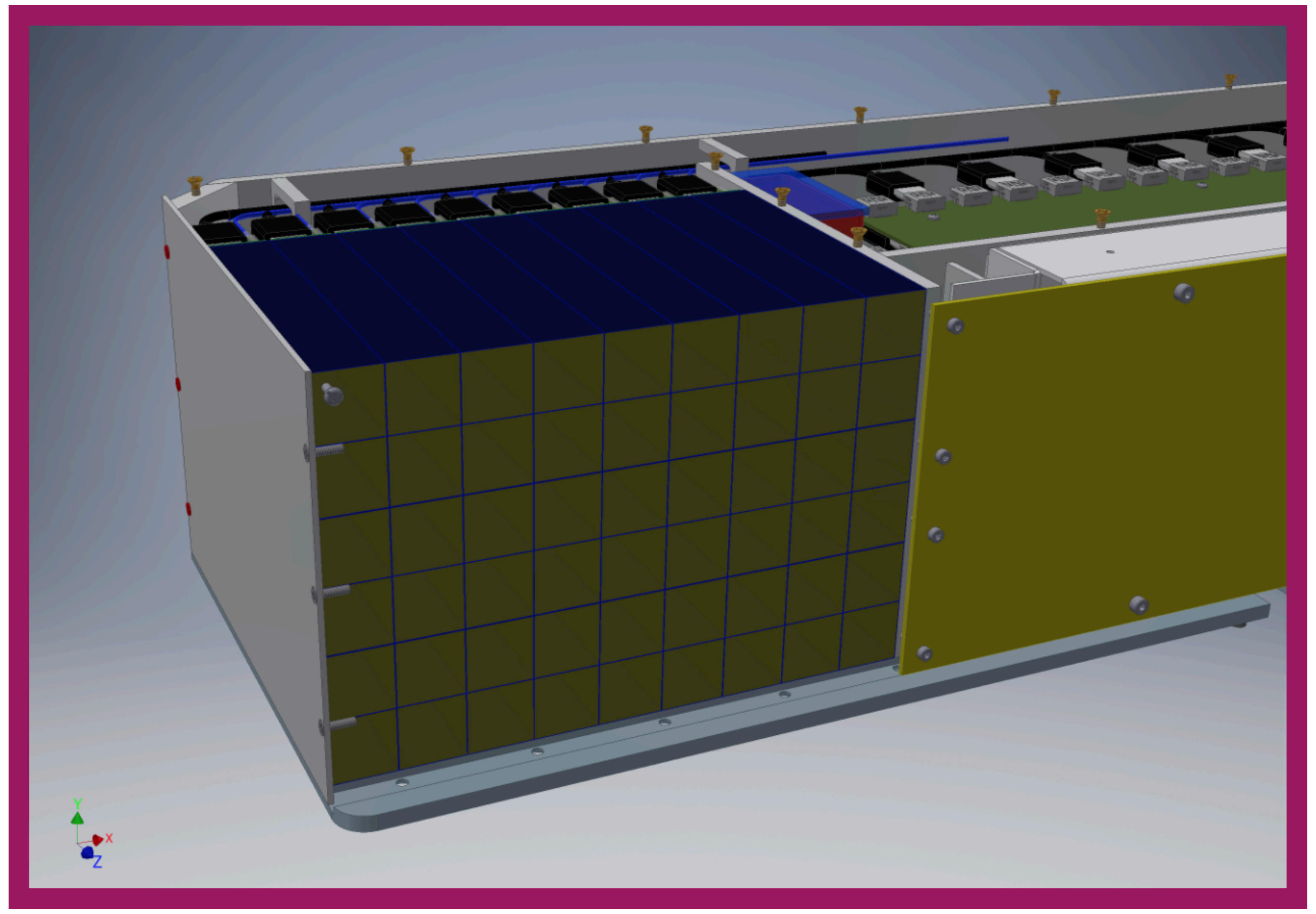


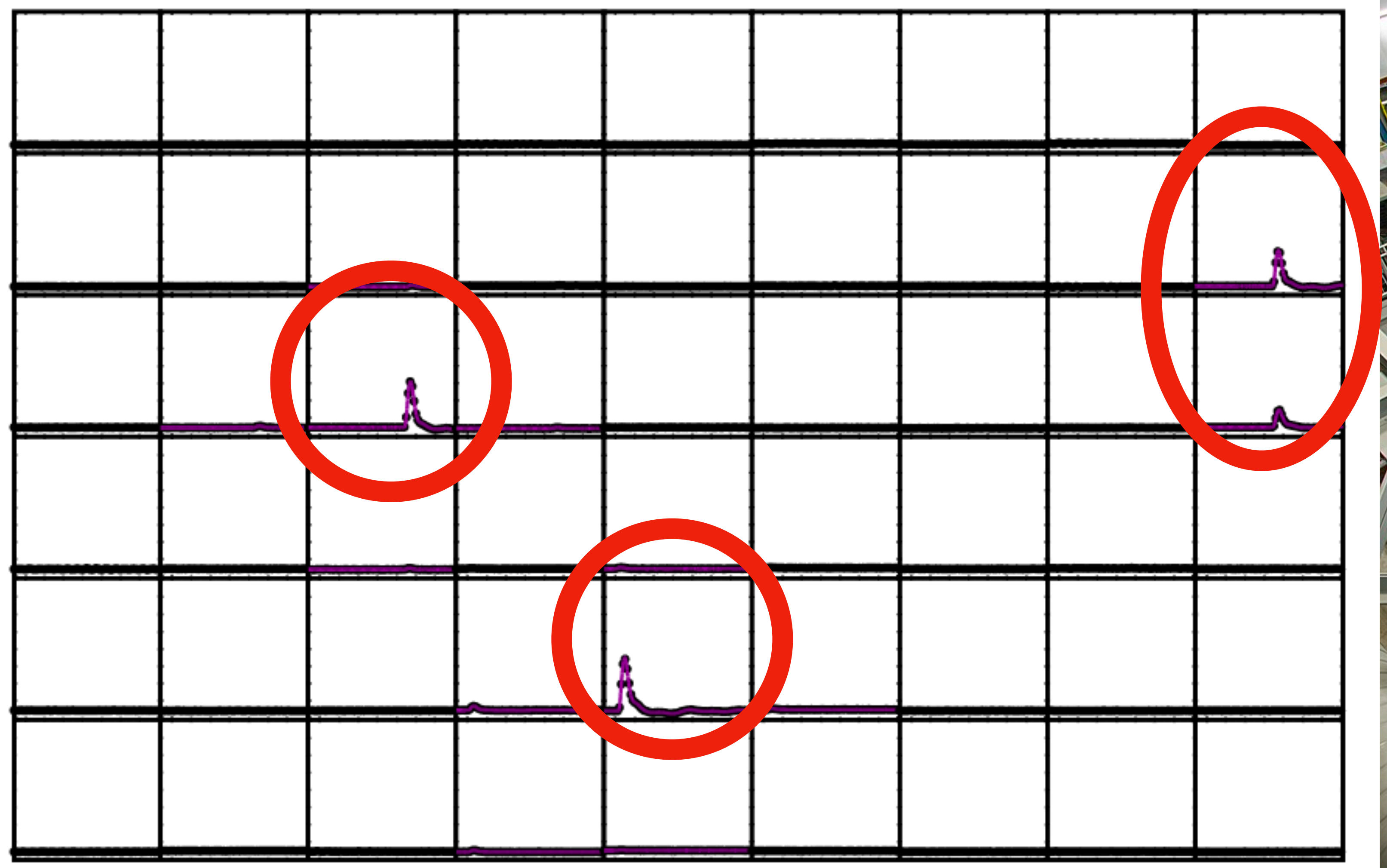


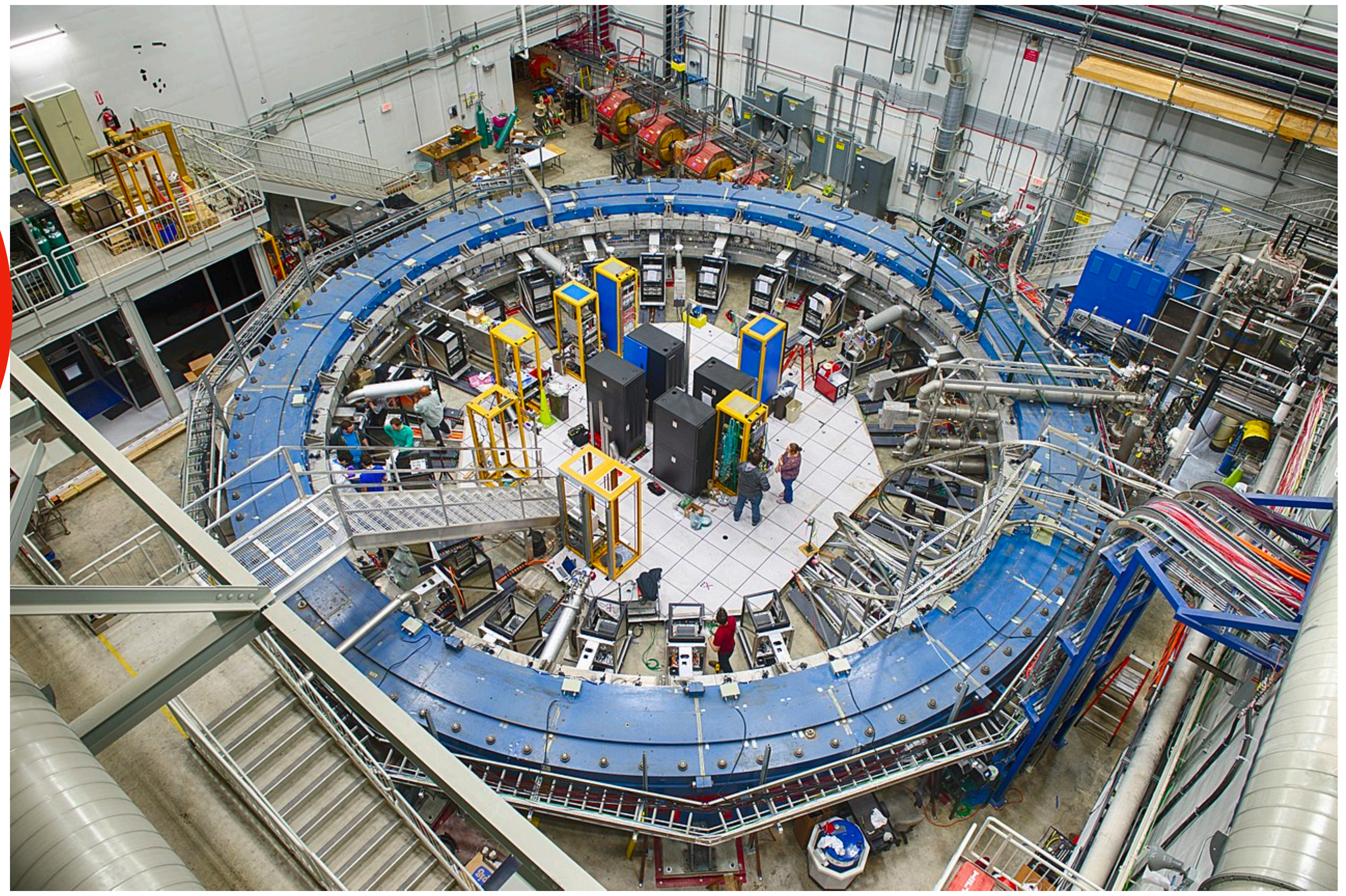
Calorimeters

- Decay positrons have lower momentum than muons, curl inward
- (time, energy) of positrons detected in 24 calorimeters
  - Composed of 54 PbF_2 Cherenkov crystals attached to silicon photomultipliers

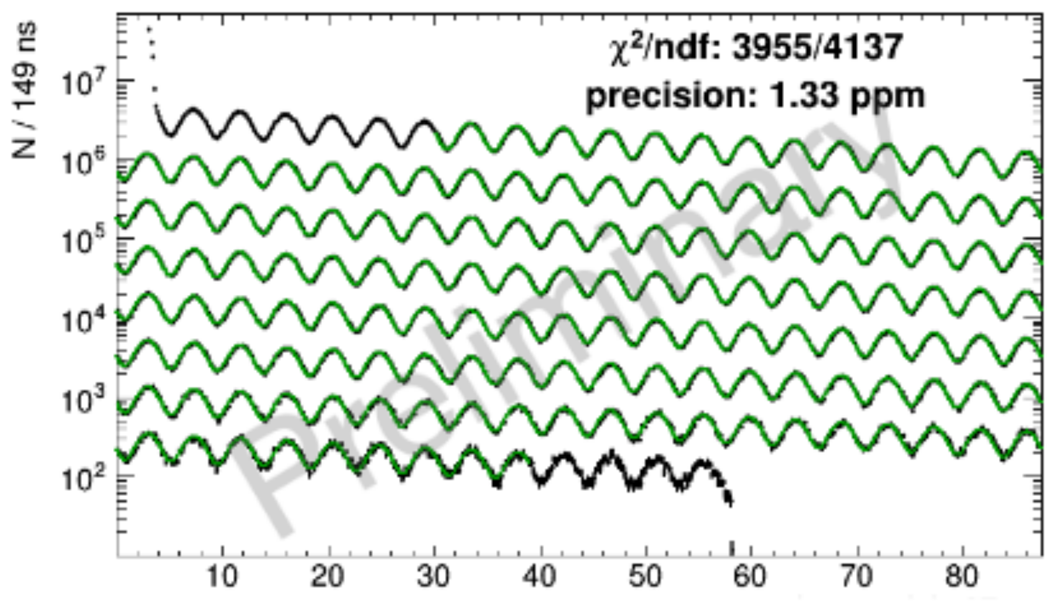








The Run1 analysis



Blinded clock

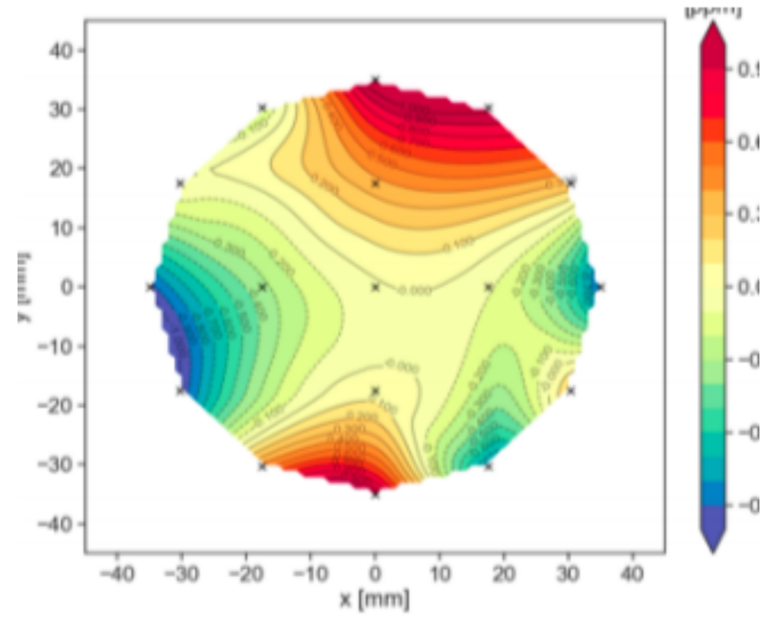
Beam dynamics corrections

My Run1 contribution
Muon loss correction

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\,\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle\,(1 + B_k + B_q)}$$

Absolute calibration

Transient field corrections



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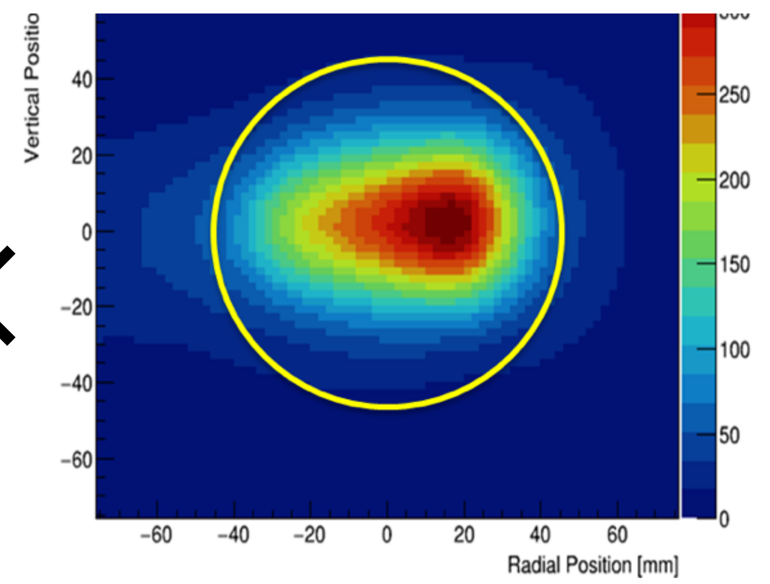
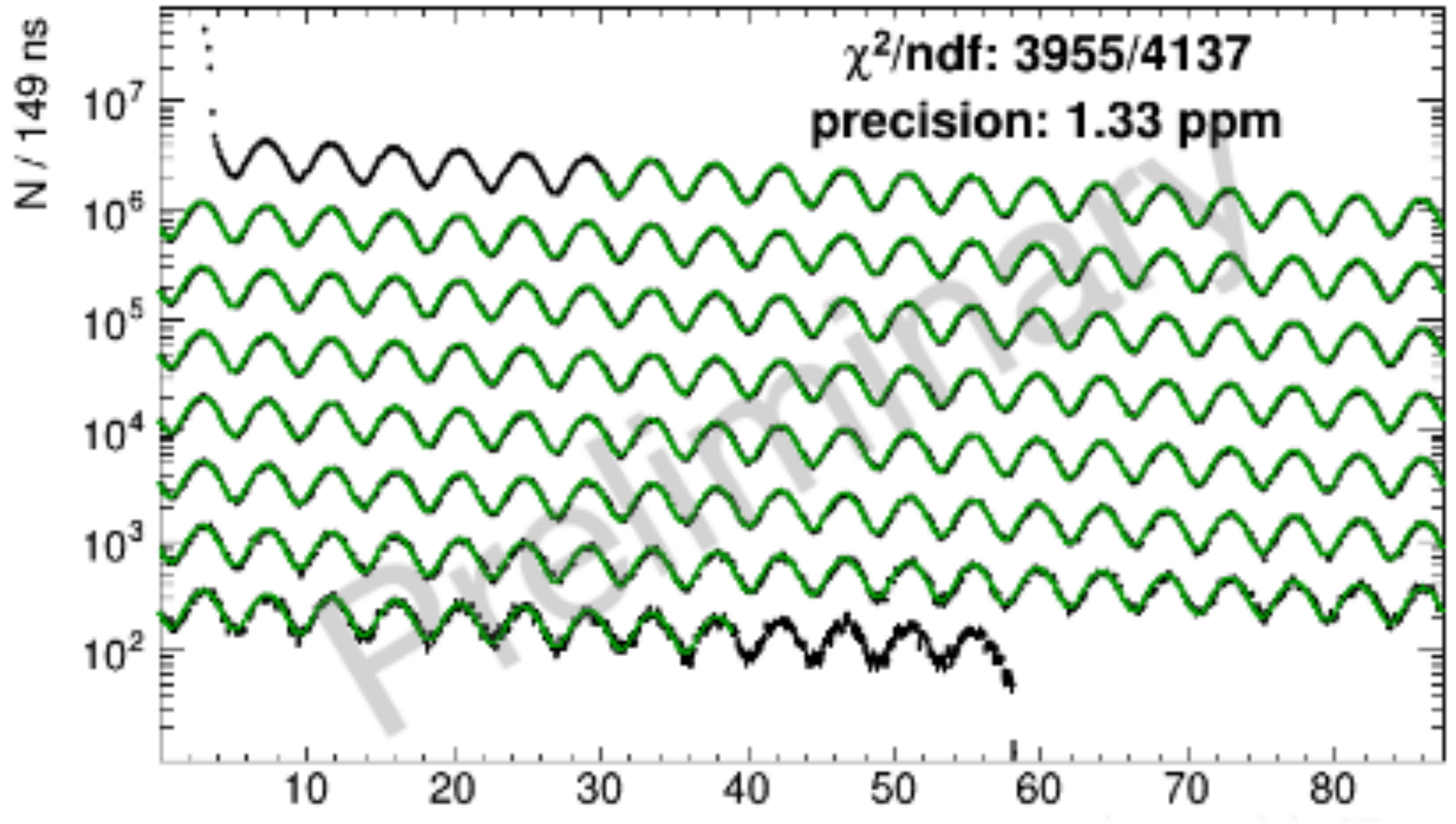


ω_a systematics: Effect of a changing spin phase

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

$$N(t) = N_0 e^{-t/\tau}[1 - A\cos(\omega_a t - \phi)]$$

- τ: Time dilated muon lifetime
- A: Asymmetry
- ω_a: Frequency (physics quantity)
- ϕ: Spin phase at injection

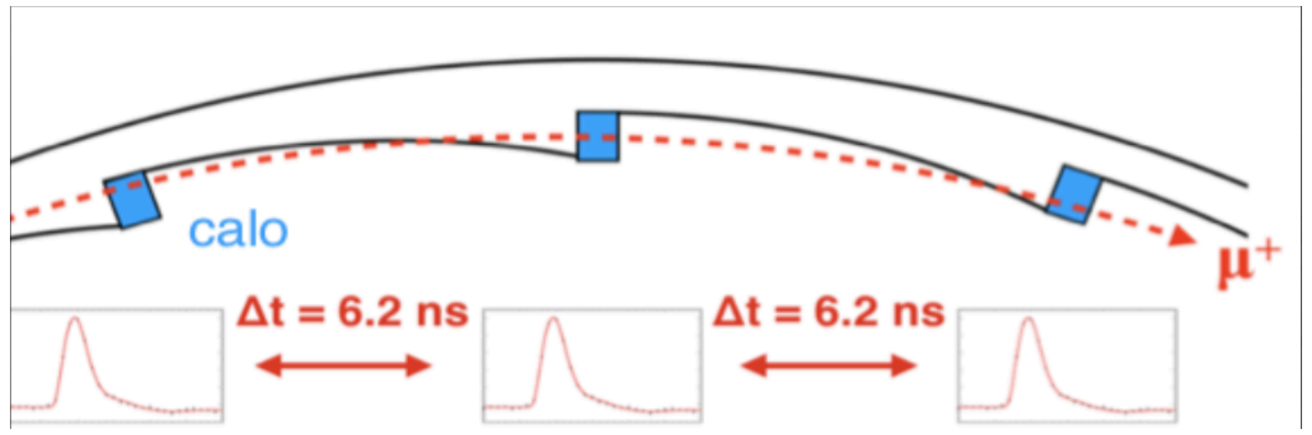


- If $\phi(t) = \phi_0 + \frac{d\phi}{dt}t + \frac{d^2\phi}{dt^2}t^2 \ldots$
- Then $\Delta\omega_a = \frac{d\phi}{dt}$

Muon loss correction

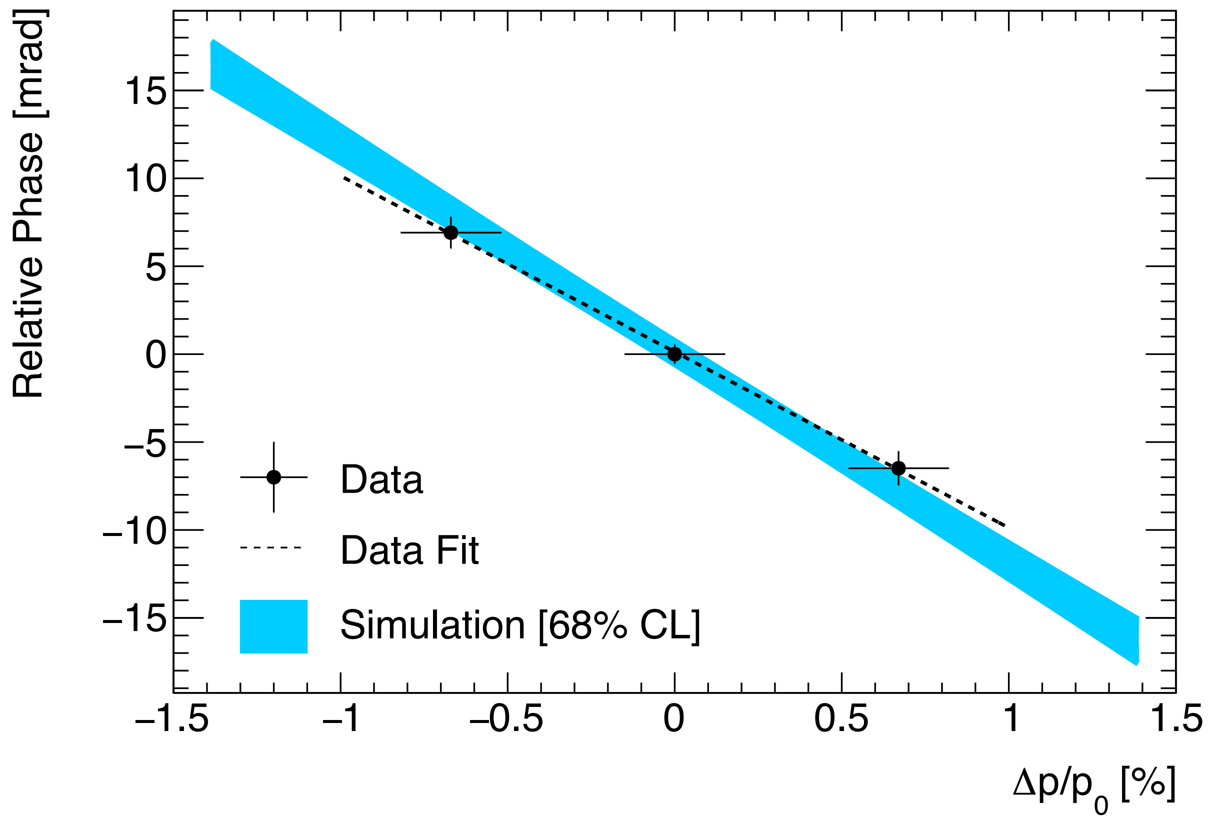
$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

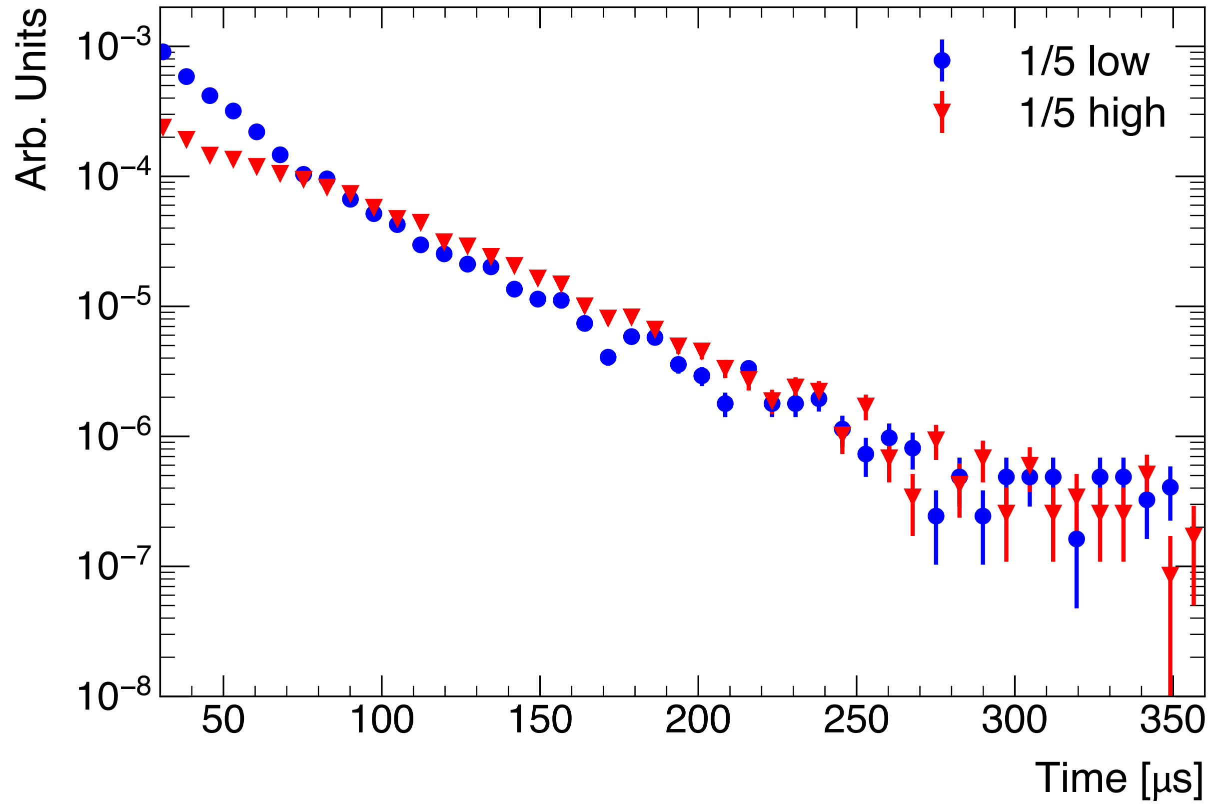
- Some muons are lost from the storage ring before decaying into positrons
- They can bias ω_a if they have different average phases than the stored muons



Several dedicated systematic studies showed that:

1. Muon phase and momentum is correlated
2. Low momentum muons are more likely to be lost





Phase is changing with time

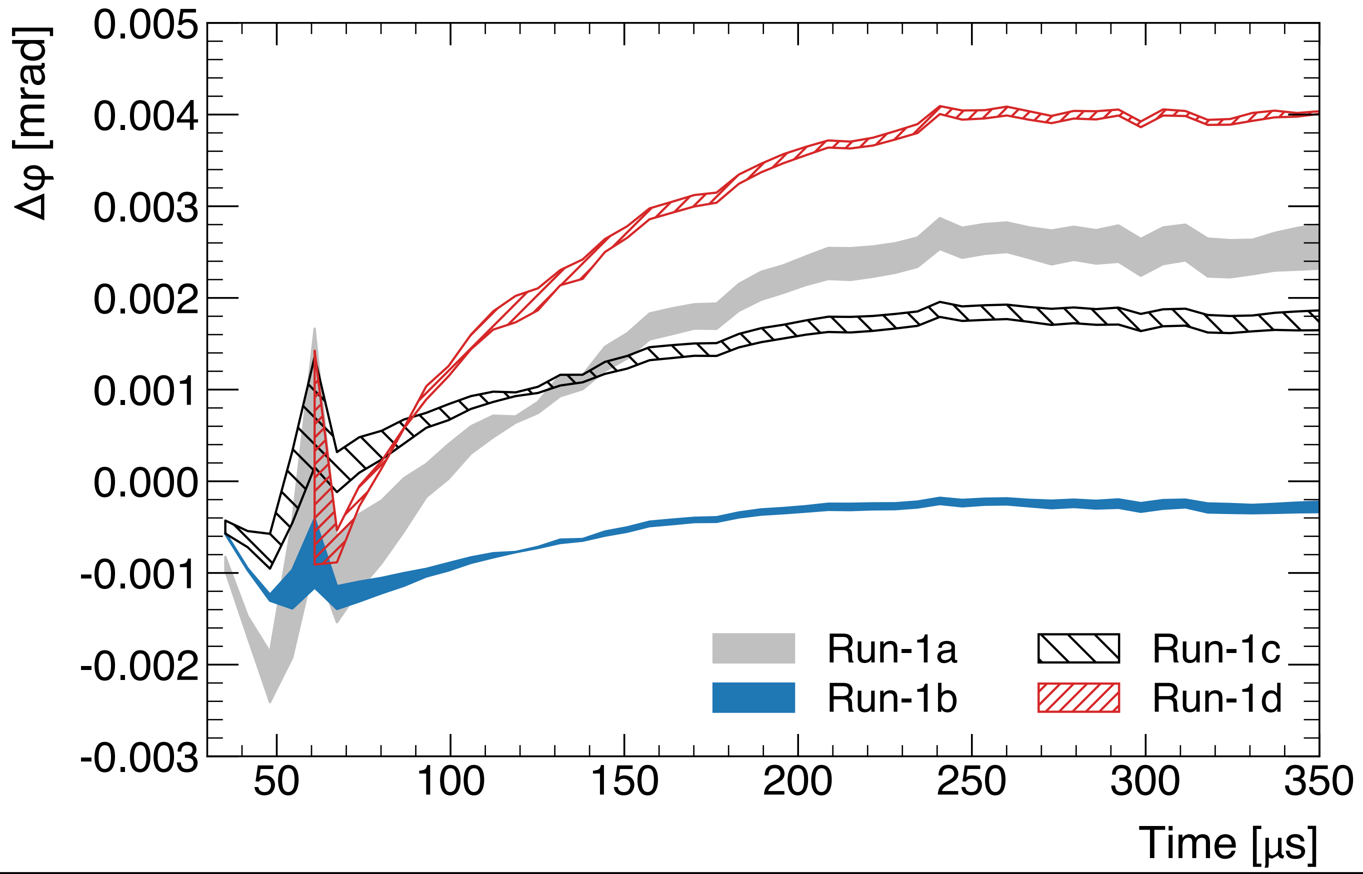


TABLE VII. Muon loss correction C_{ml} (ppb) with three sources of uncertainty contributing to $\sigma_{C_{ml}}$ (ppb).

Dataset	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	−14	−3	−7	−17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6

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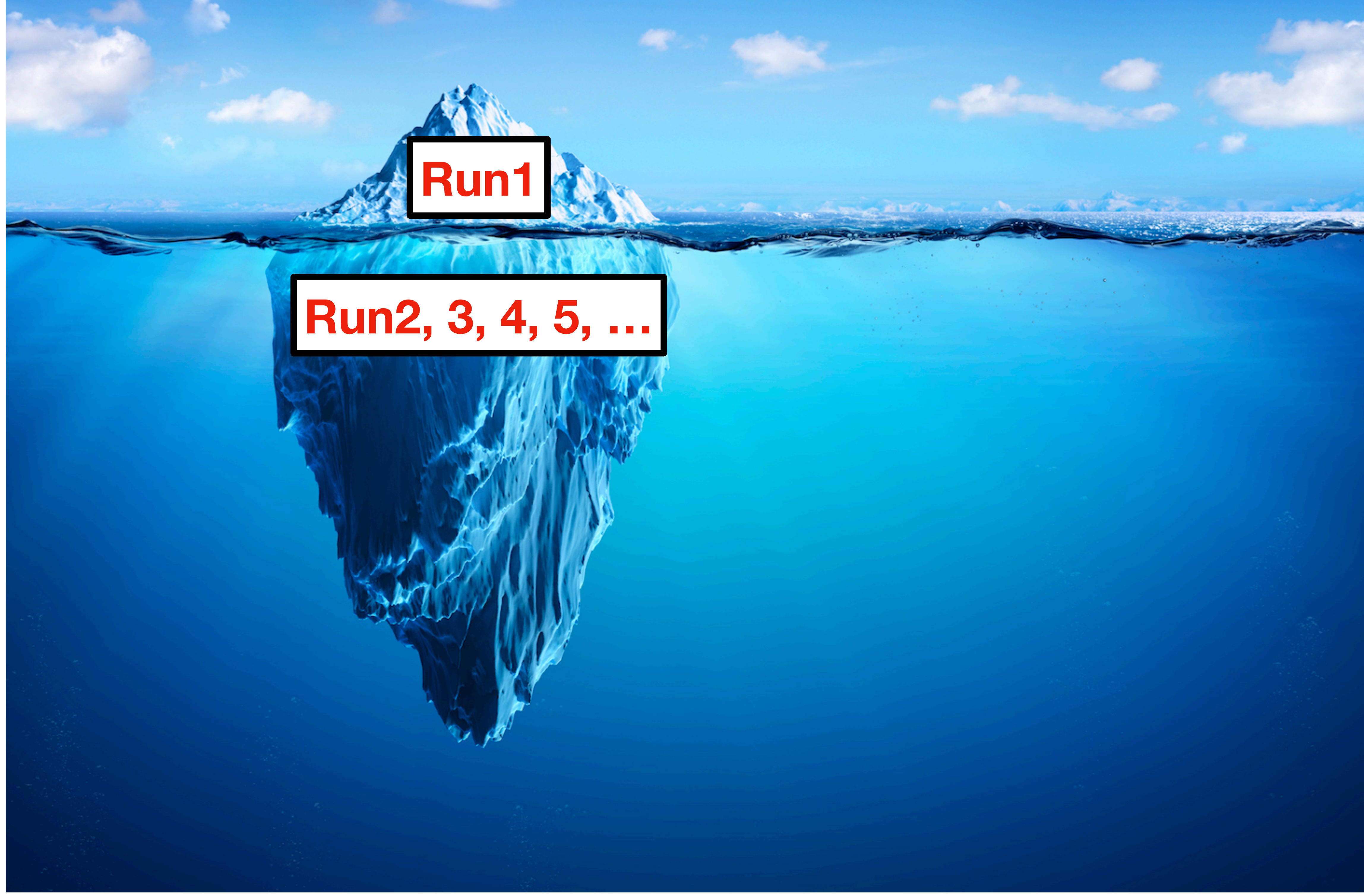
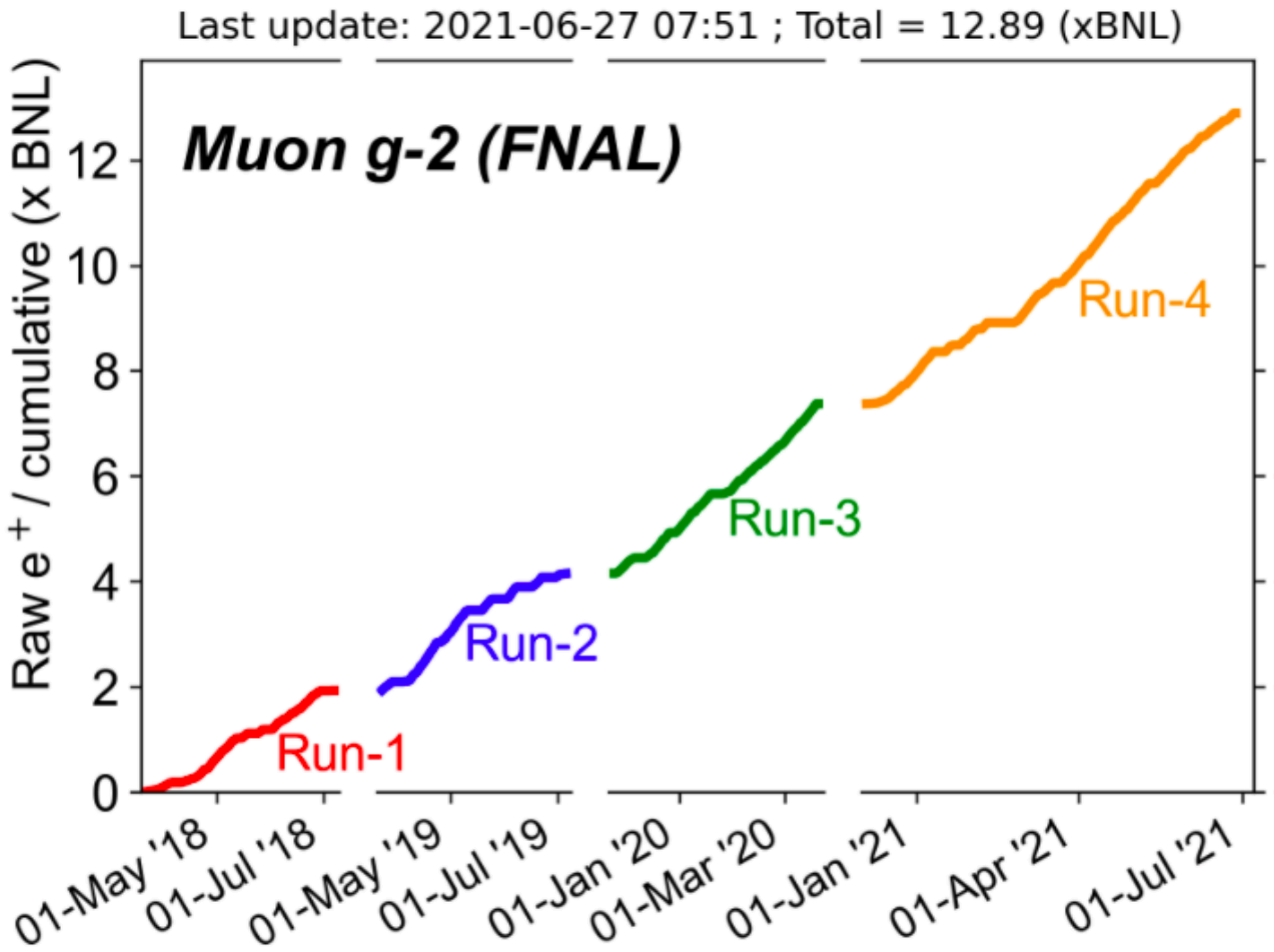
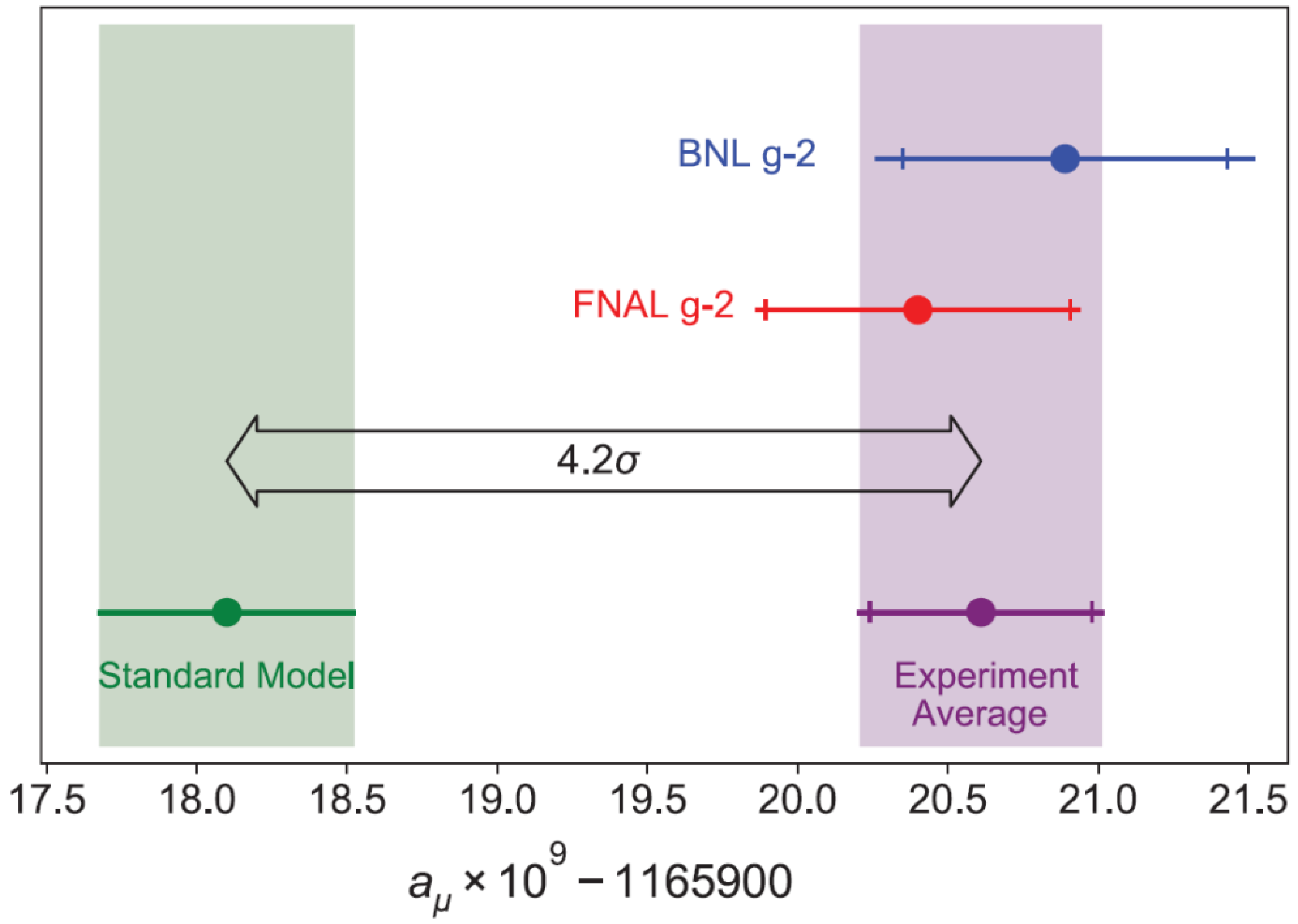
Run1 results: the tip of the iceberg

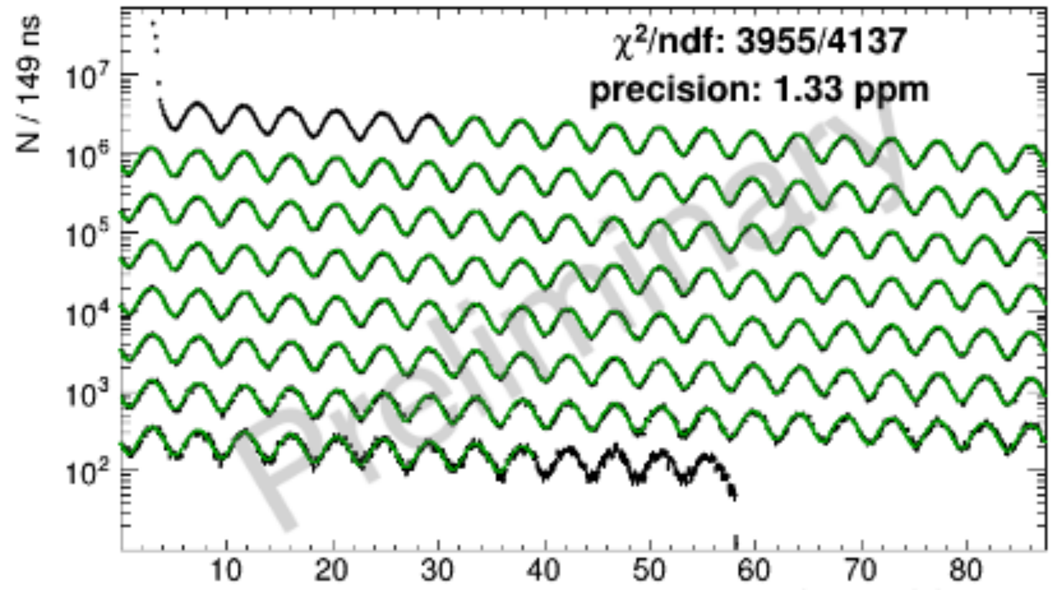
- BNL and FNAL results have similar uncertainties
- So far we have only analyzed ~10% of data we have taken and ~5% of data we expect to take
- Uncertainty in Run1 was statistics-dominated, but we will be pushing that uncertainty lower
  - Want to improve some of the larger sources of systematic uncertainty







Run2 and beyond



Blinded clock

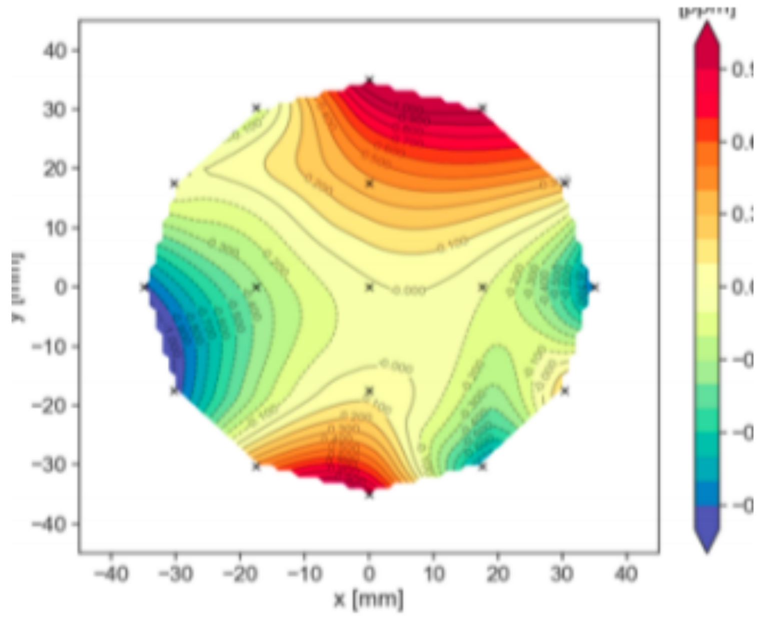
Beam dynamics corrections

My Run2 contribution
ω_a fitting and analysis

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle \omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

Absolute calibration

Transient field corrections



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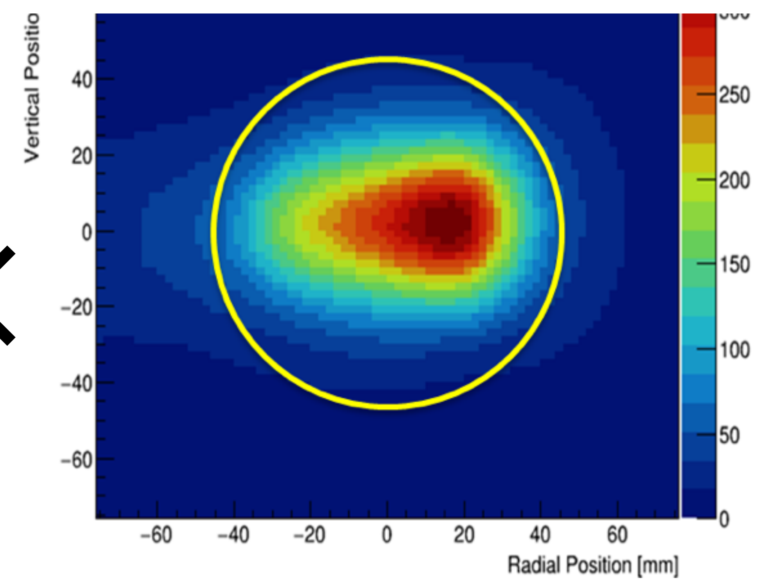
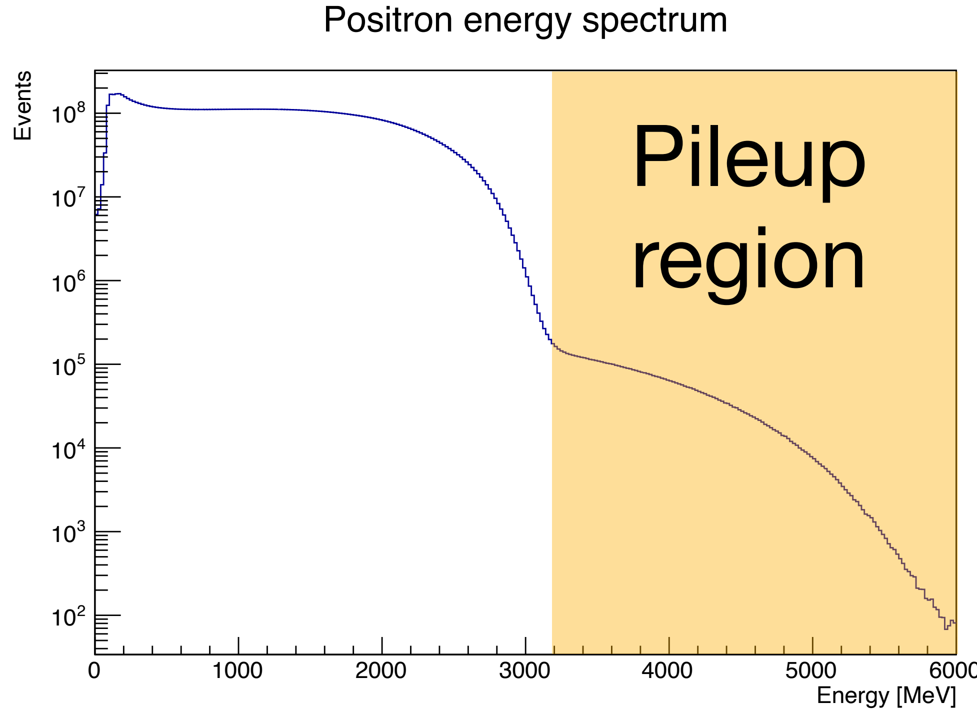


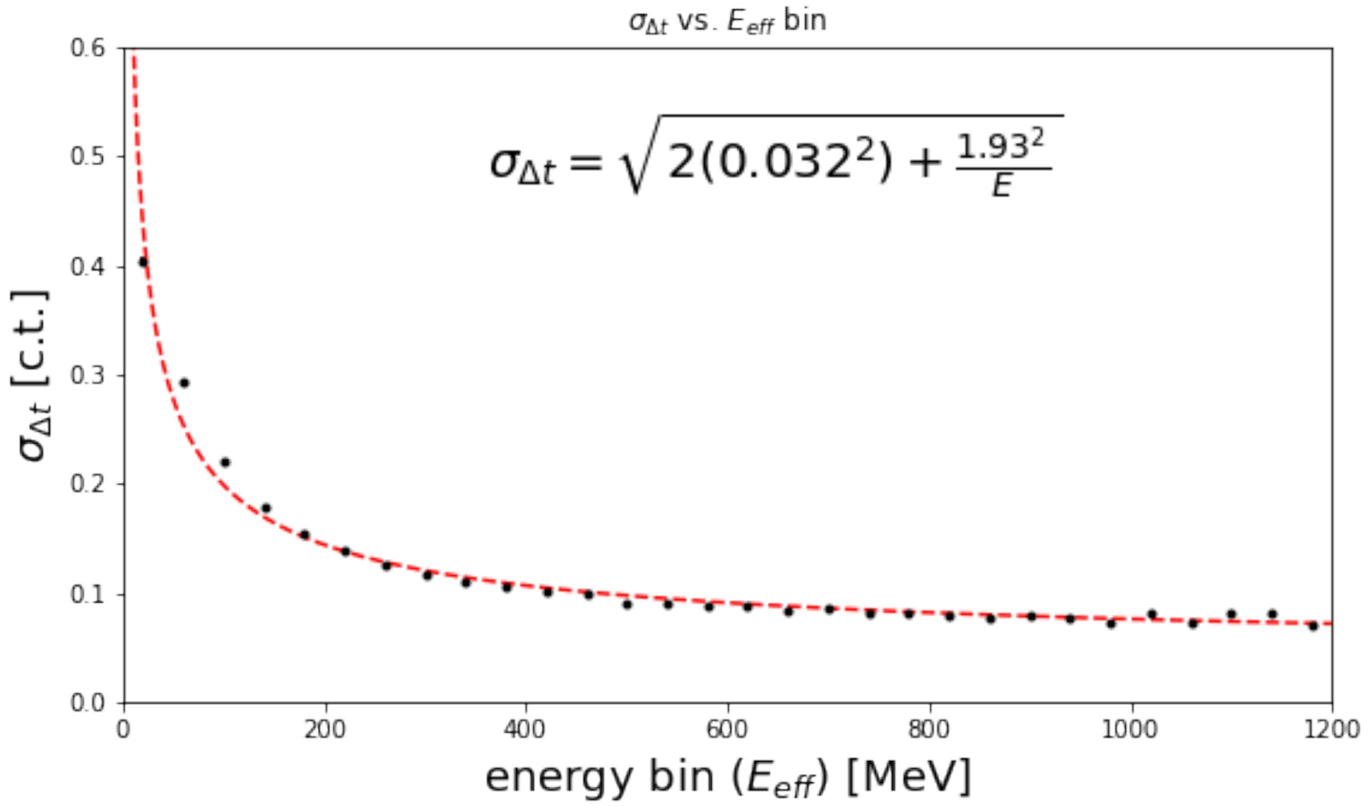
Improving pileup systematic

$$a_\mu \propto \frac{f_{\text{clock}}\,\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

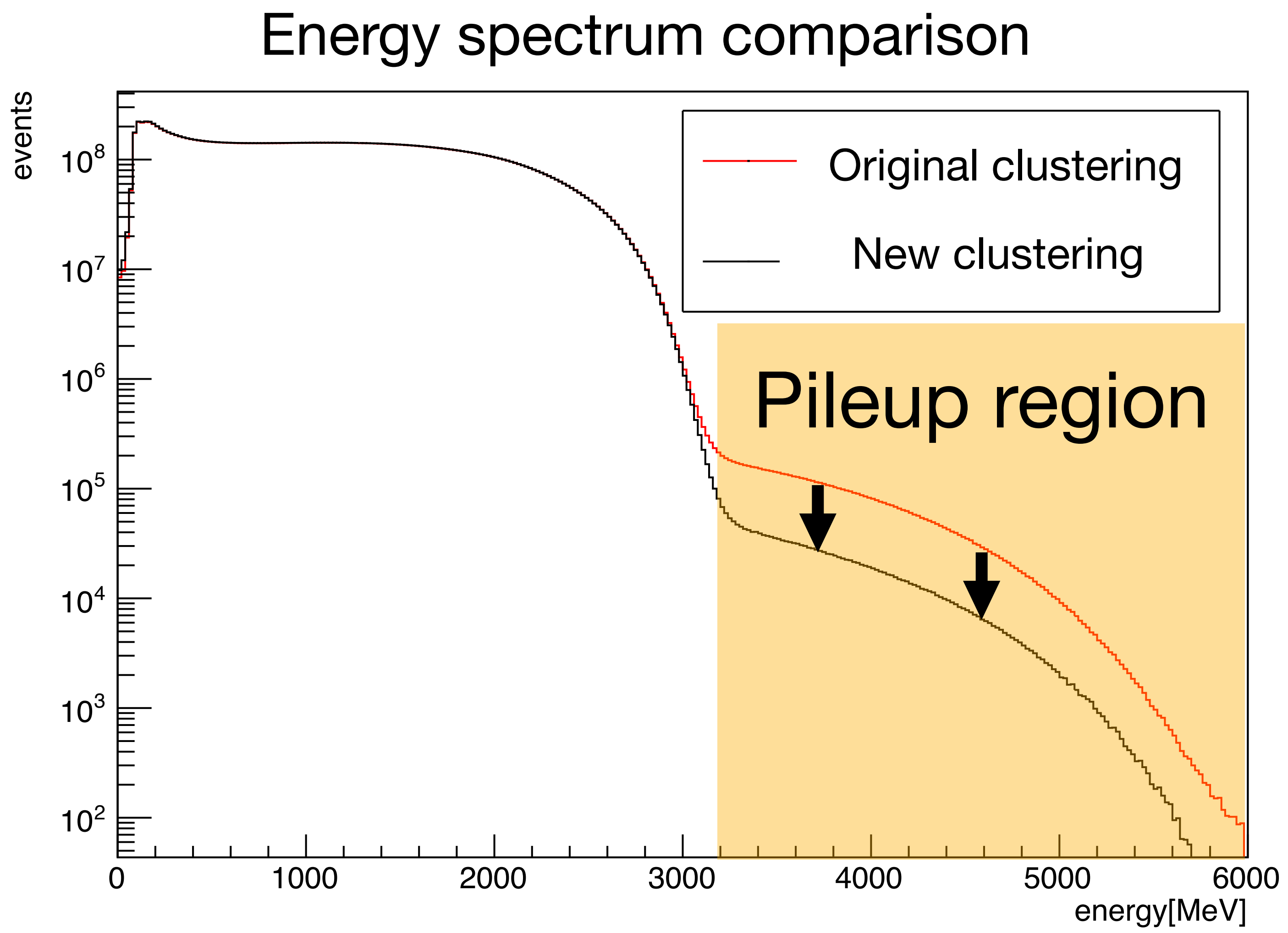
- Two positron hits can be measured by the calorimeters as a single event
- One event with E1+E2 has different phase and asymmetry than two events with E1, E2
- A pileup correction is applied to avoid bias to ω_a
  - One of the largest Run1 systematic errors on ω_a

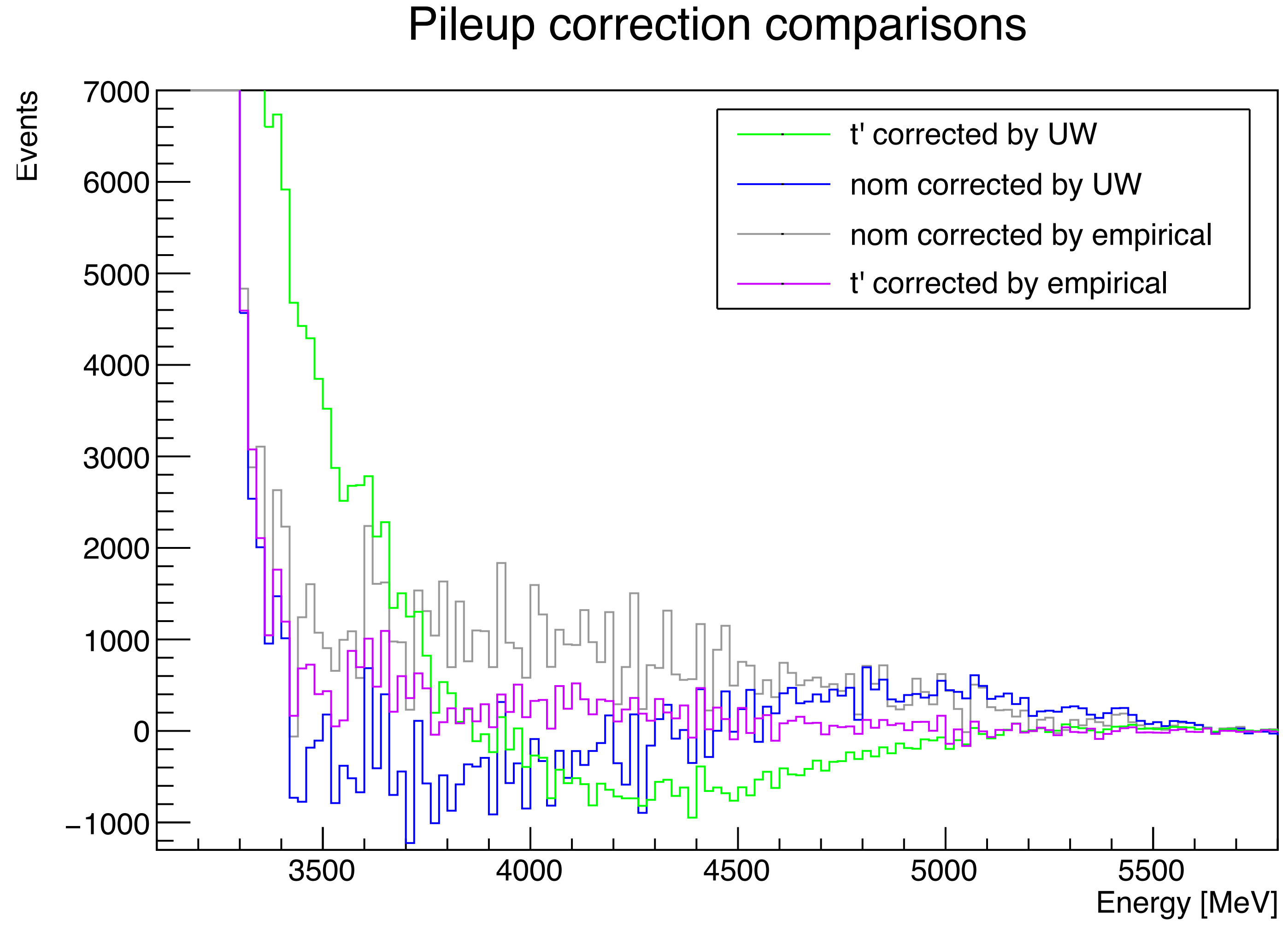


- Crystal hits have a known energy-dependent time resolution
- Info incorporated to improve discrimination of positron events arriving close in time



- Reduction of 4x in pileup region
- Implemented new pileup correction with very successful results (in purple)
- Should decrease pileup uncertainty in Run2/3





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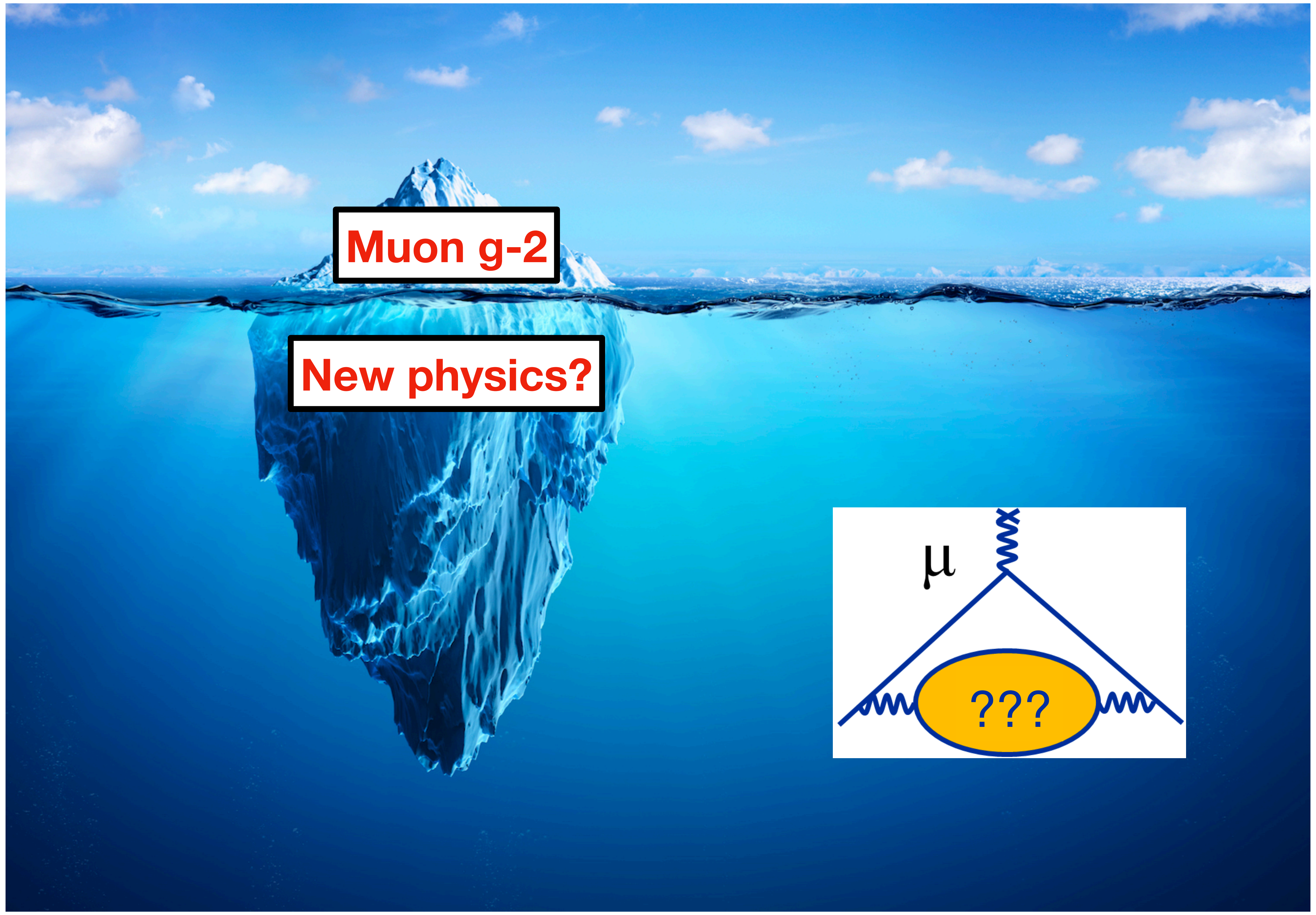
Muon g-2: the tip of the iceberg?

- Motivation…
  - To achieve our full precision goal
  - For precision muon experiments
  - For precision tests of the standard model
  - For improvements and updates to the theory

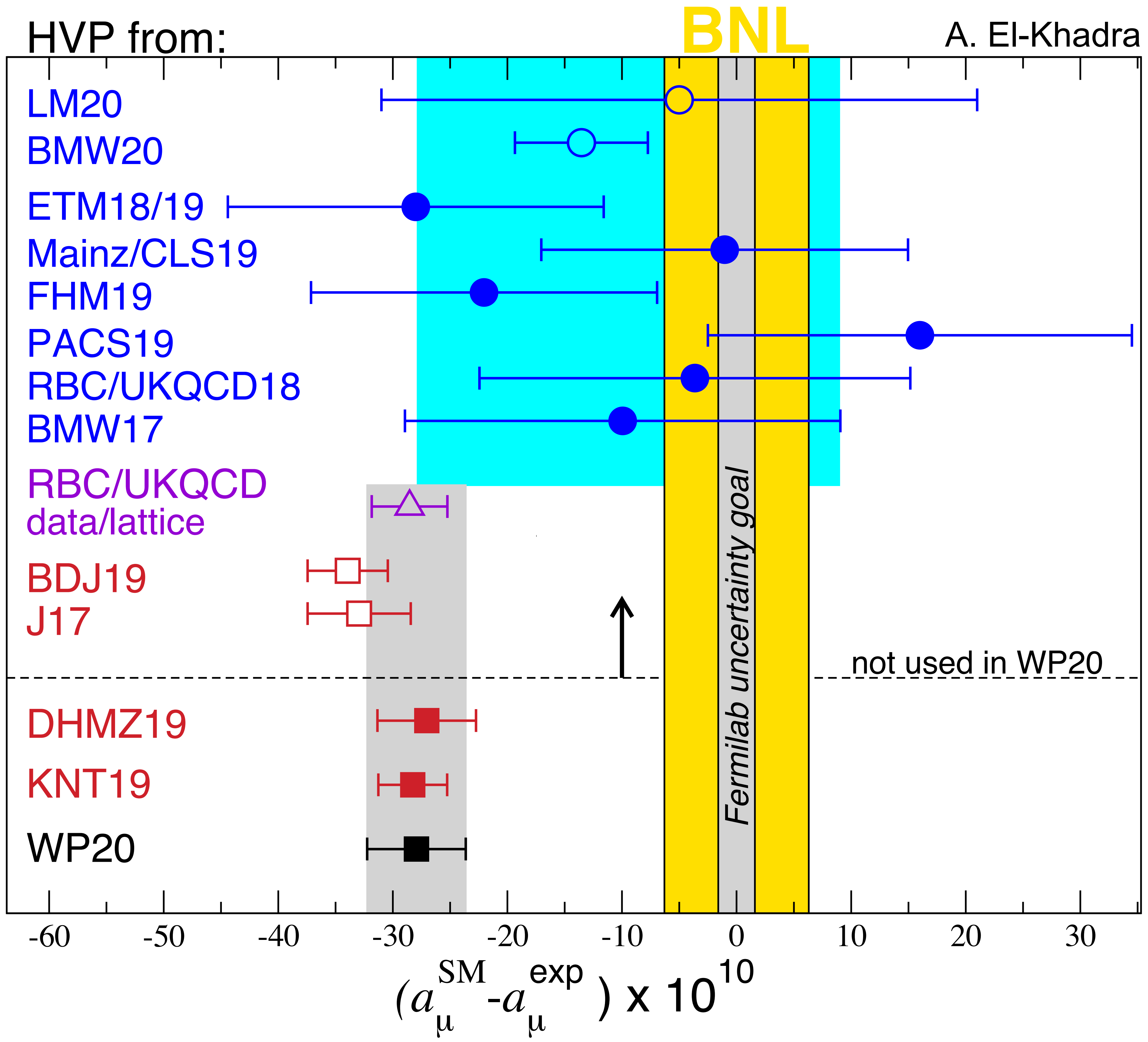


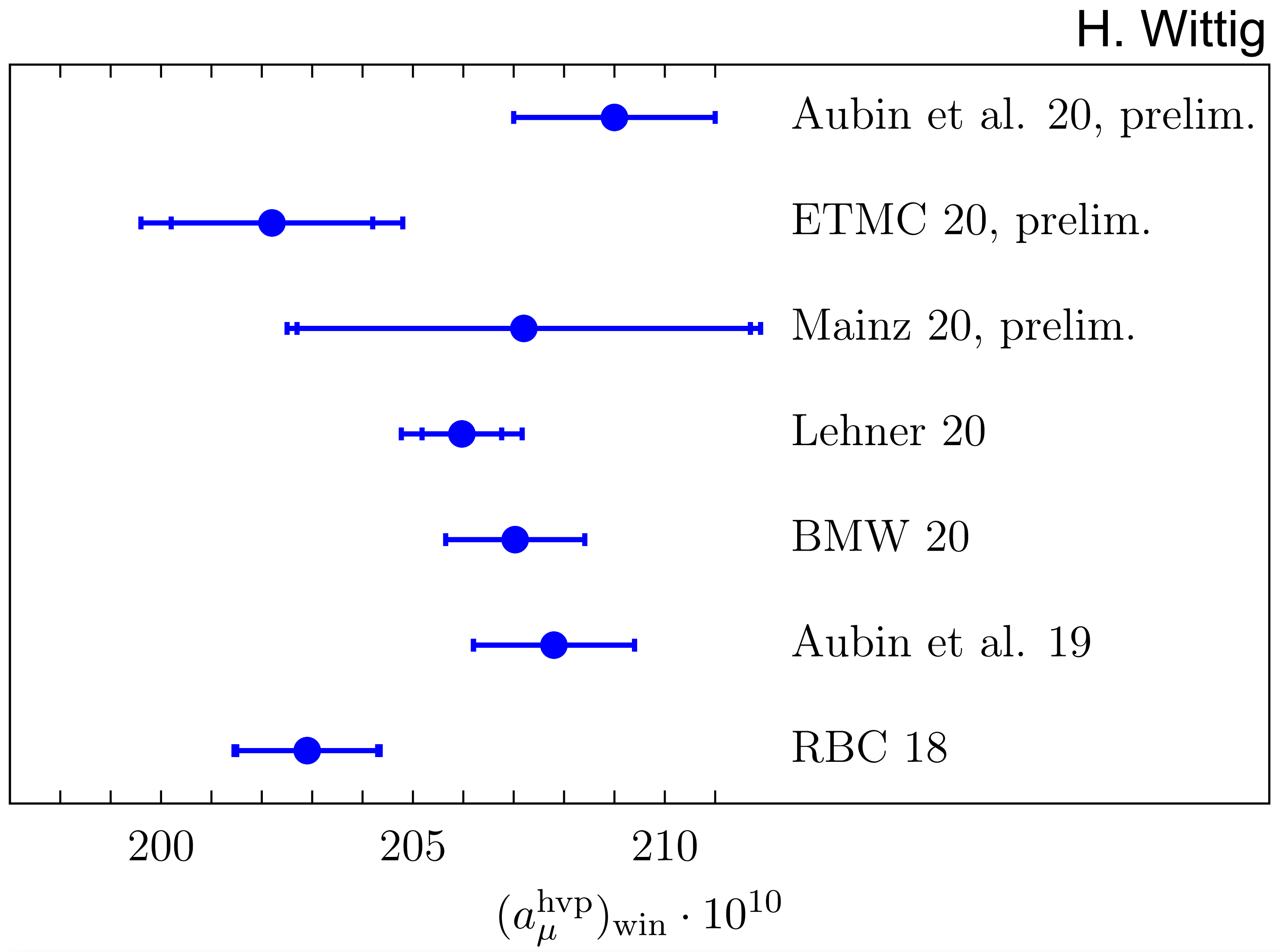
Questions?

Backup

The current spin on a_μ

Muon g-2 theory initiative





$a_\mu^{SM} = 116591810(43) \times 10^{-11}$
T. Aoyama, *et al.*, Physics Reports (2020), https://doi.org/10.1016/j.physrep.2020.07.006.

$a_\mu^{BNL} = 116592080(63) \times 10^{-11}$
Phys.Rev.D, 73 (2006) 072003

3.5 standard deviation discrepancy

Components of a_μ measurement

- Need to measure both ω_a and B to high precision
- B measured using Larmor precession frequency of the free proton, ω_p

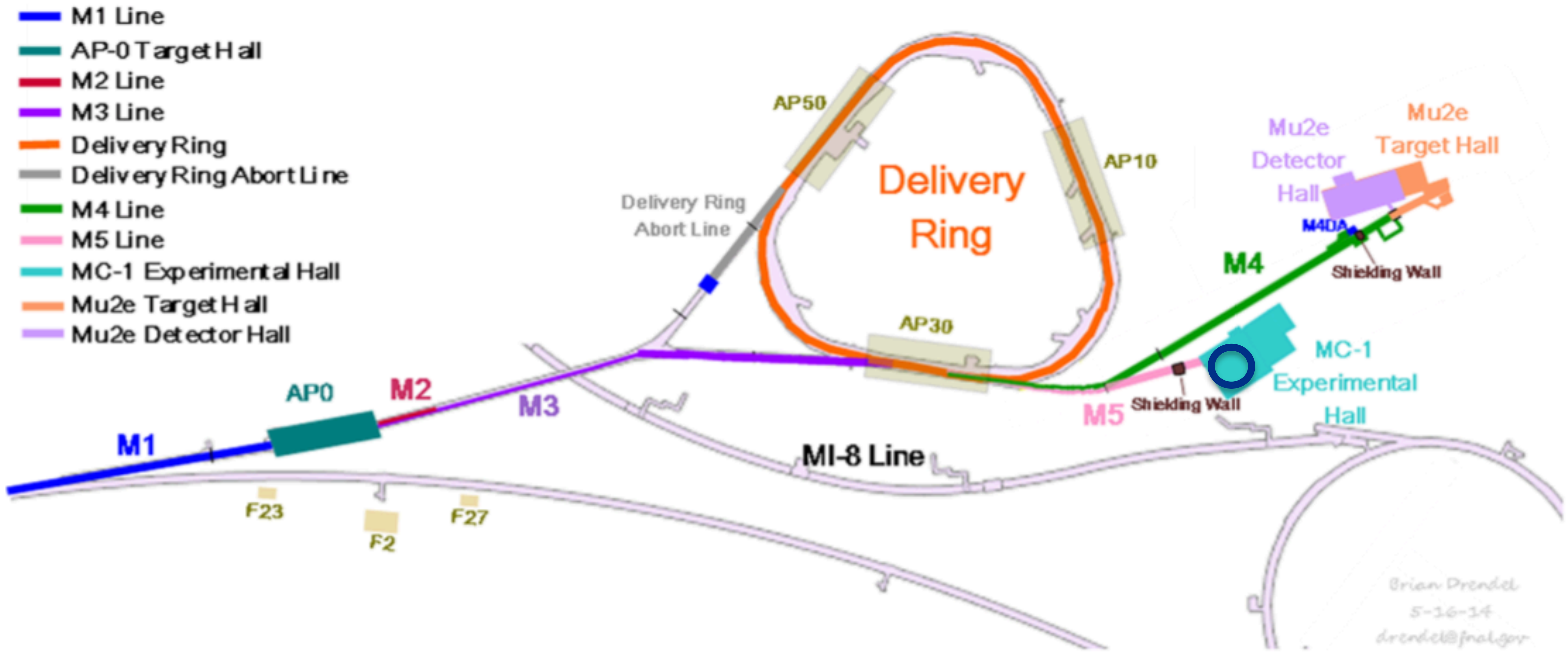
$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p} \frac{g_e}{2} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e}$$

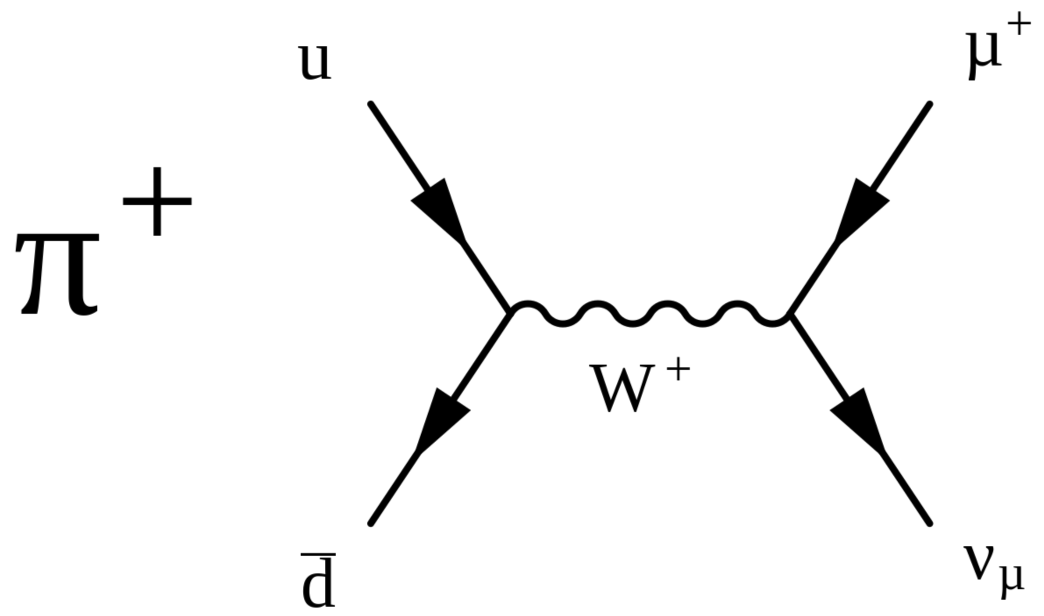
To measure! Known from other experiments

	Relative error (ppb)	Experiment
g_e	0.000 26	Quantum electron cyclotron. Hanneke et al. 2008.
μ_e/μ_p	3.0	Hydrogen spectroscopy. Winkler et al. 1972.
m_μ/m_e	22	Muonium hyperfine splitting. Liu et al. 1999.
$\omega_a/\tilde{\omega}_p$	140	Fermilab $g-2$

Fermilab beamline

- 8 GeV protons hit target, producing pions
- Pions near 3.11 GeV selected
- Pions decay into muons
- Muons near maximum pion energy (3.094 GeV) selected to create polarized muon beam (M2/M3)
- Muons separated from protons in delivery ring
- Muon beam arrives in g-2 storage ring





Precession in a real storage ring

Vertical confinement (focusing)

- Electrostatic quadrupoles

Finite momentum spread

Desired precession term, but also…

Vertical beam motion

"E field correction"

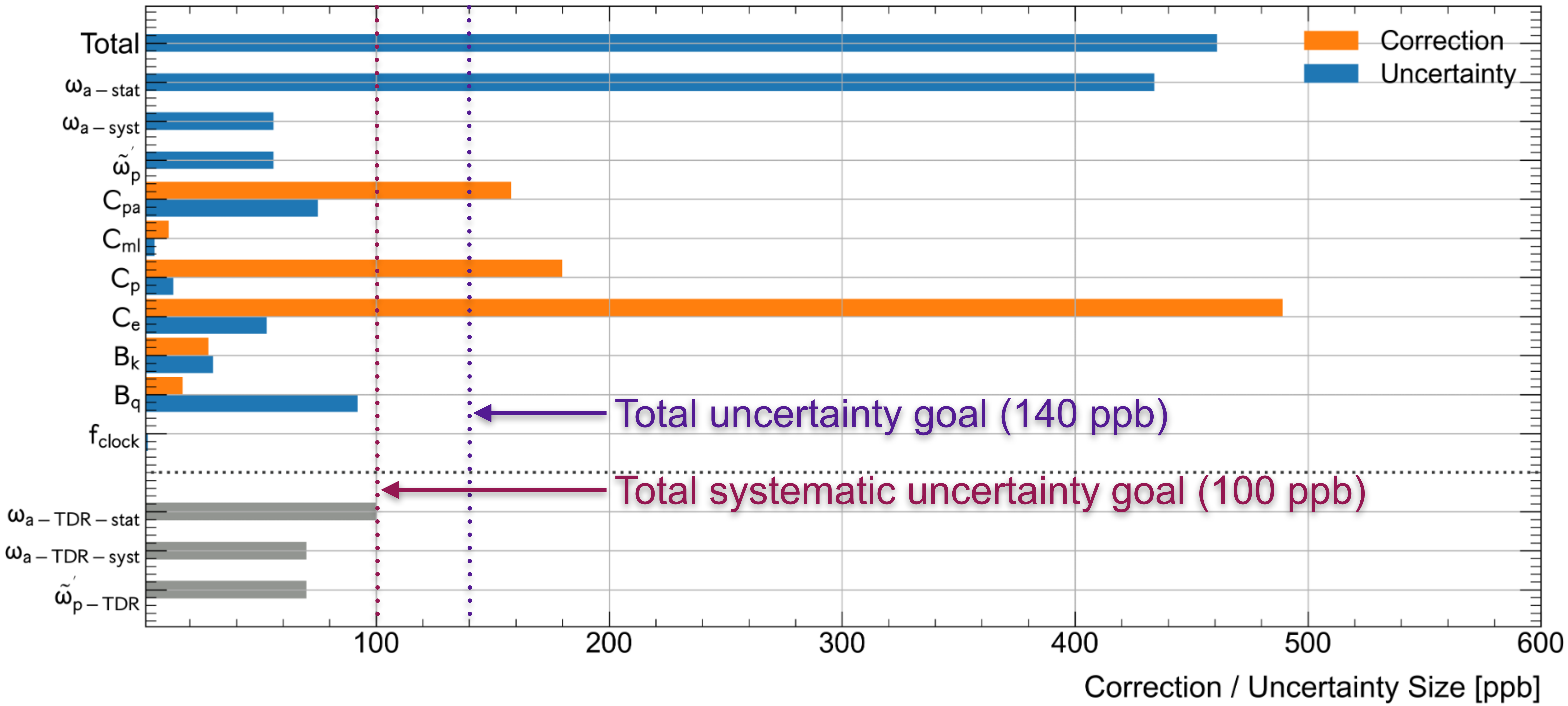
"pitch correction"

$$\frac{d(\hat{\beta} \cdot \mathbf{S})}{dt} = -\frac{e}{m}\mathbf{S}_\perp \cdot \left[a_\mu \hat{\beta} \times \mathbf{B} + \beta \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\mathbf{E}}{c}\right]$$

"Magic" momentum to cancel:
$\gamma \sim 29.3$ ($p_\mu \sim 3.094$ GeV)

Combining it all…

$$a_\mu^{(\mathrm{FNAL})} = 116\,592\,040\,(51)_{\mathrm{stat}}(18)_{\mathrm{sys}}(3)_{\mathrm{external}} \quad (462\ \mathrm{ppb})$$

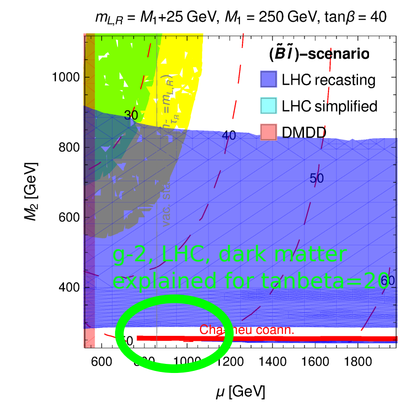


Implications

Which models can still accommodate large deviation?

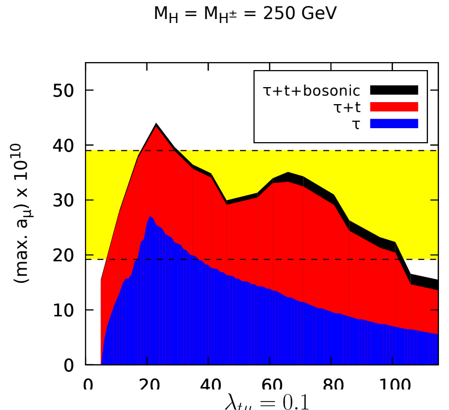
SUSY: MSSM, MRSSM

- MSugra. . . many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns



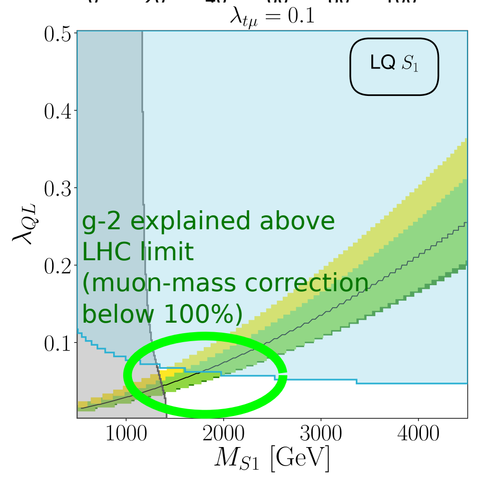
Two-Higgs doublet model

- Type I, II, Y, Type X(lepton-specific), flavour-aligned



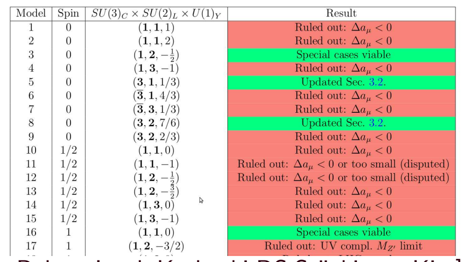
Lepto-quarks, vector-like leptons

- scenarios with muon-specific couplings to μ_L and μ_R



Simple models (one or two new fields)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)



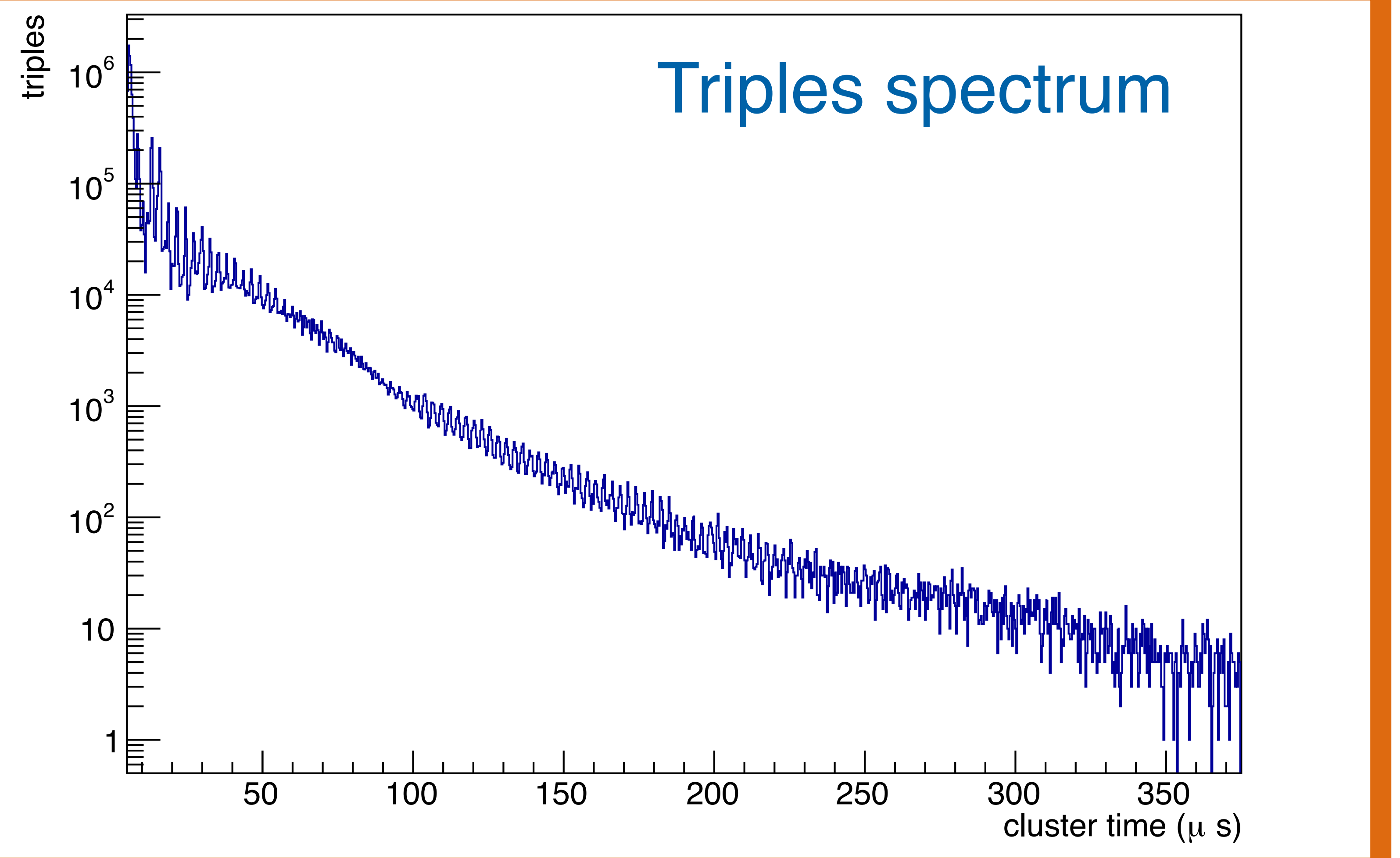
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim]

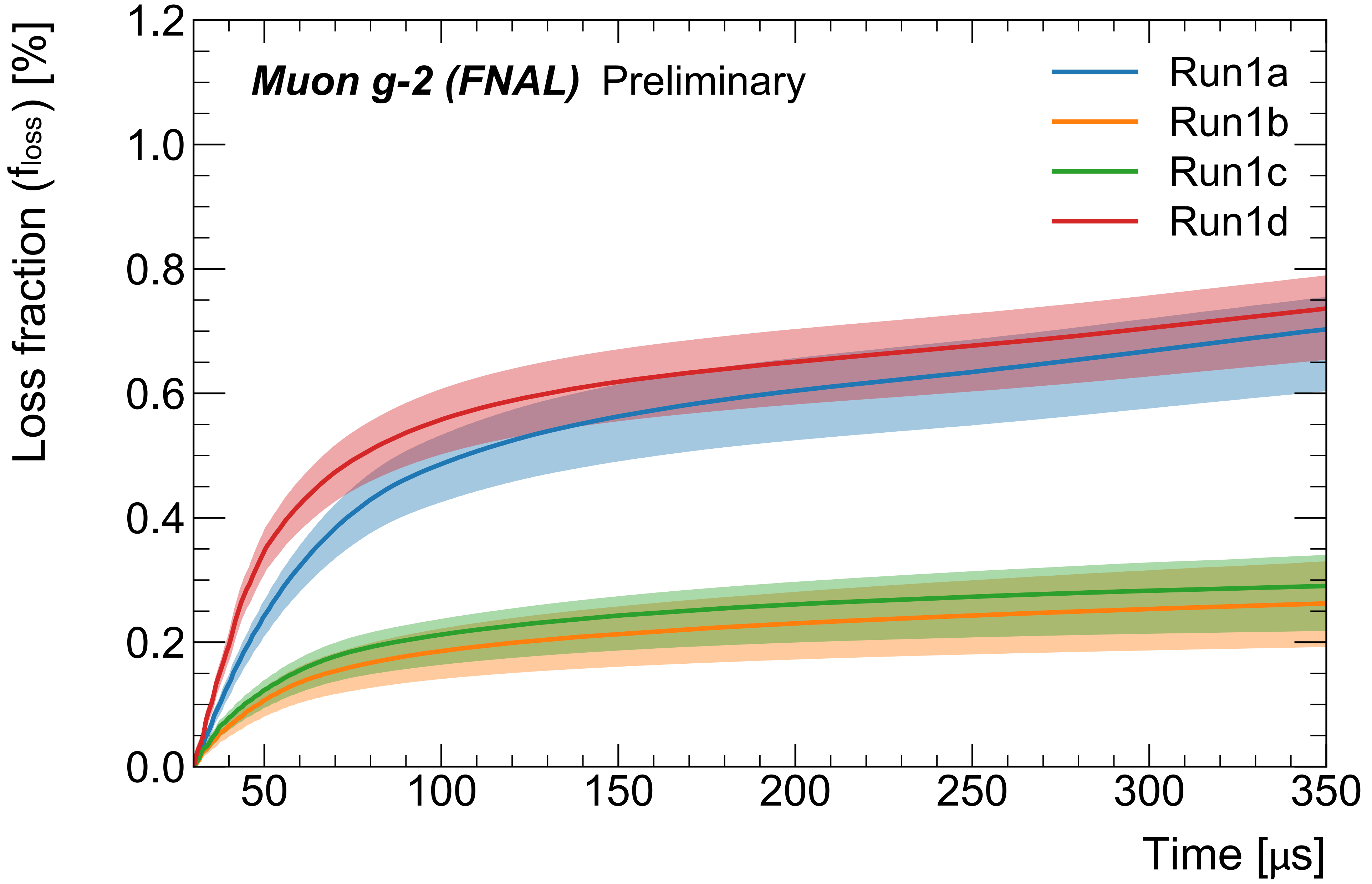
D. Stöckinger, April 2021 APS meeting, https://…

Lost muons in the ω_a fit

$$N_0 \rightarrow N_0 \left(1 - K_{loss} \int_{t_s}^{t} \exp(t'/\tau) L(t') dt' \right)$$

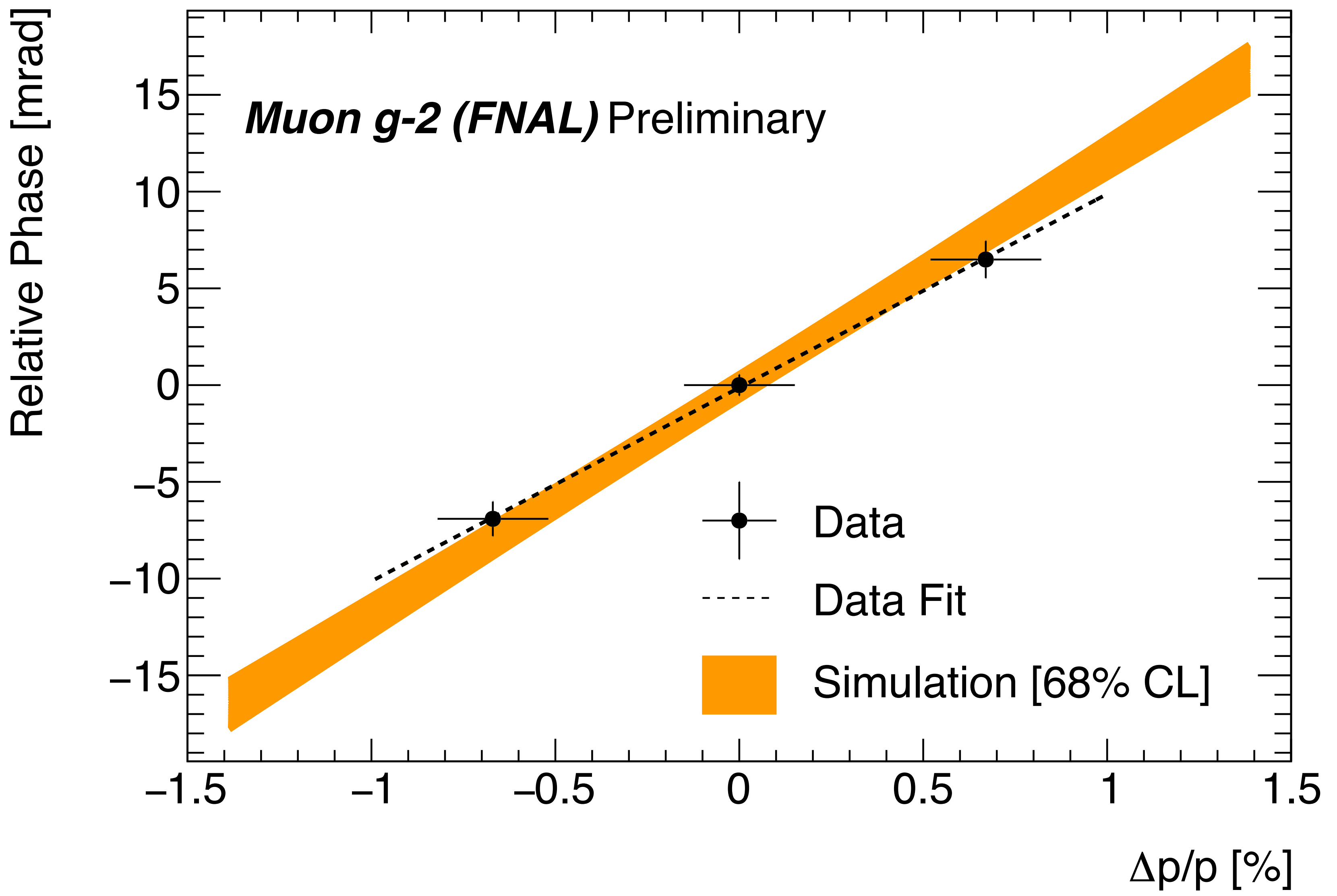
Scale parameter (from fit)

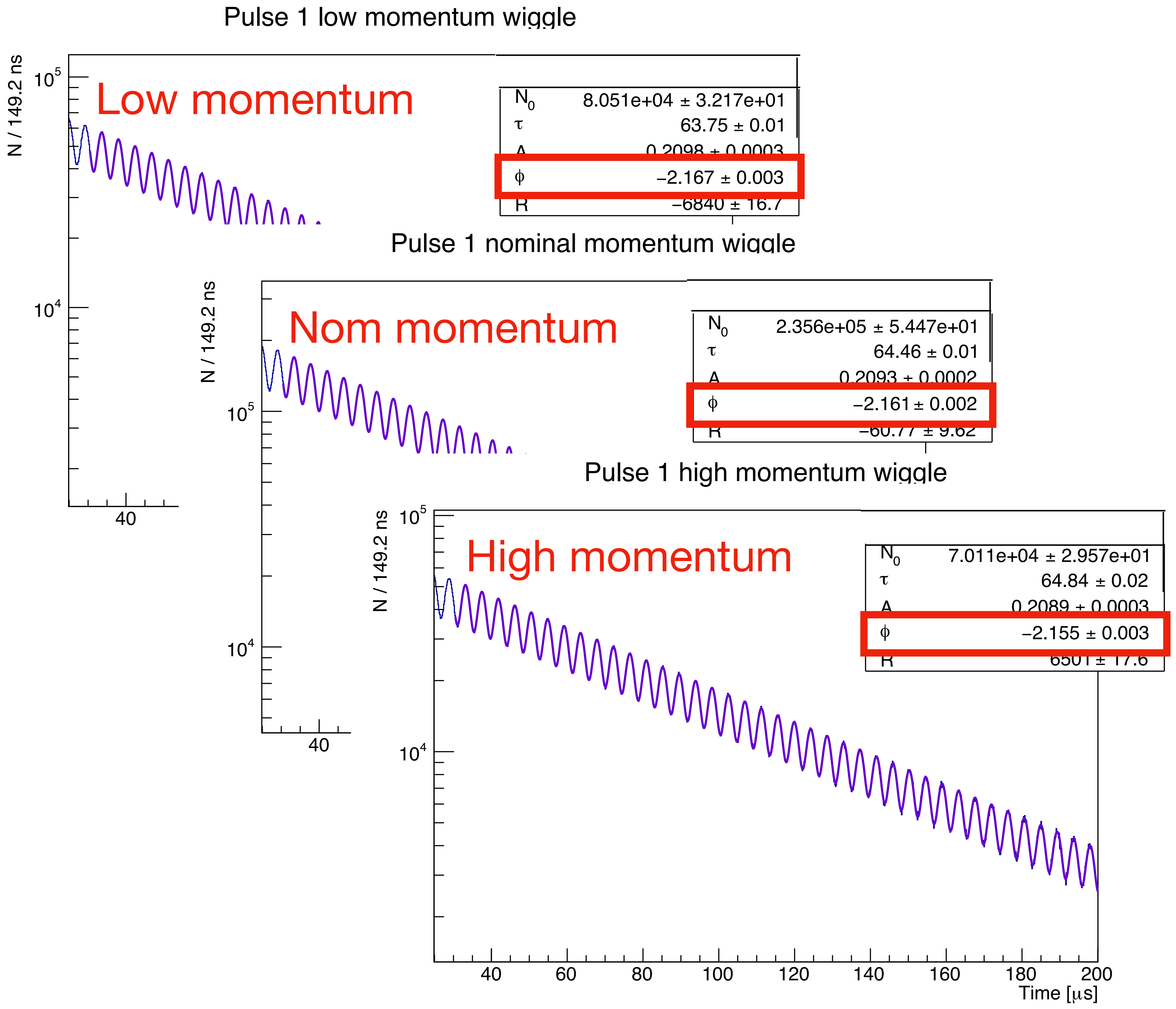




Measuring the phase-momentum correlation

- Perform fit on each dataset to extract the phase
- Measurements show a correlation between phase and momentum of $10 \pm 1.6 \frac{\text{mrad}}{\% \, dp/p}$, in line with simulation
- $\frac{d\langle\phi\rangle}{d\langle p\rangle} \neq 0$! there is a correlation between phase and momentum





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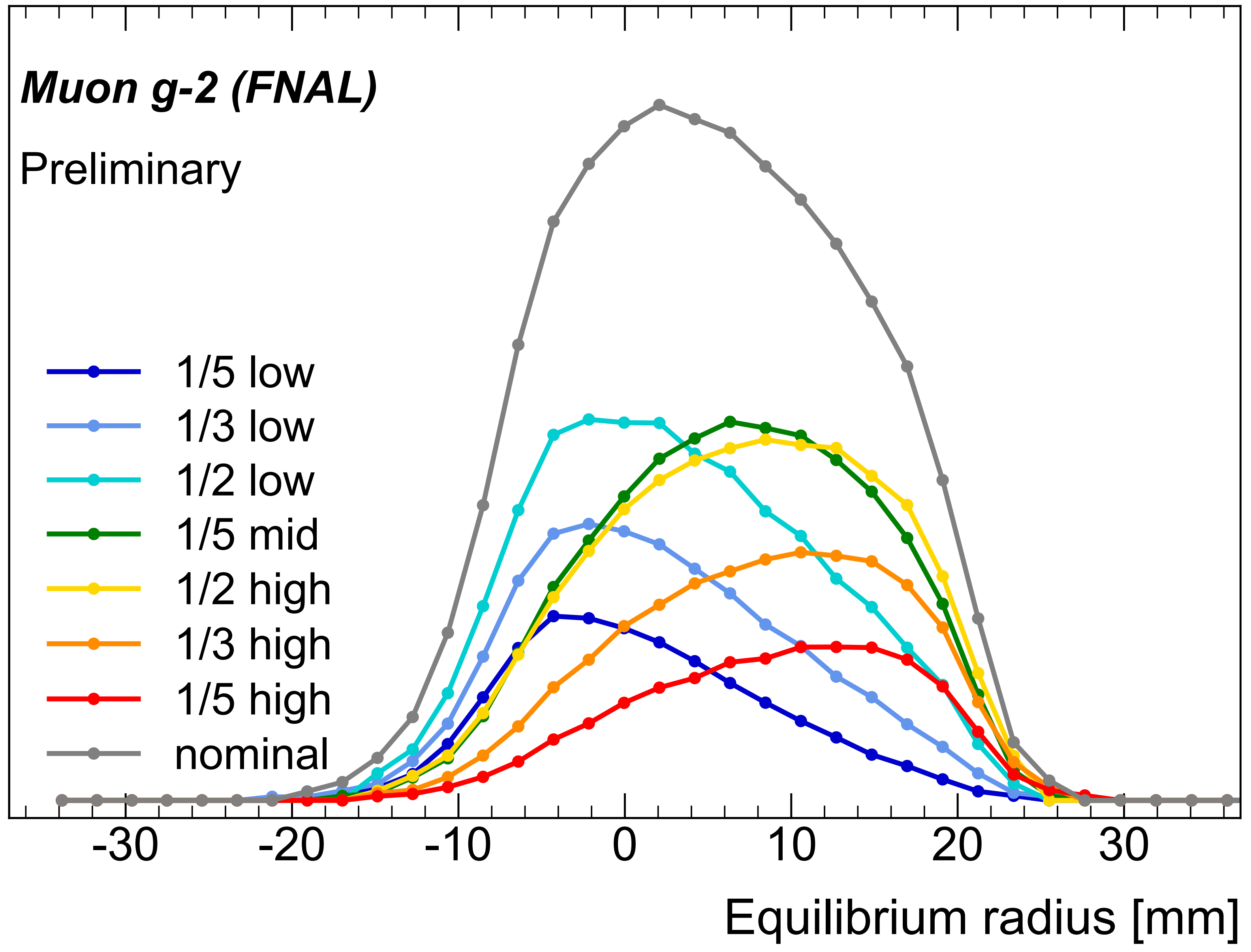
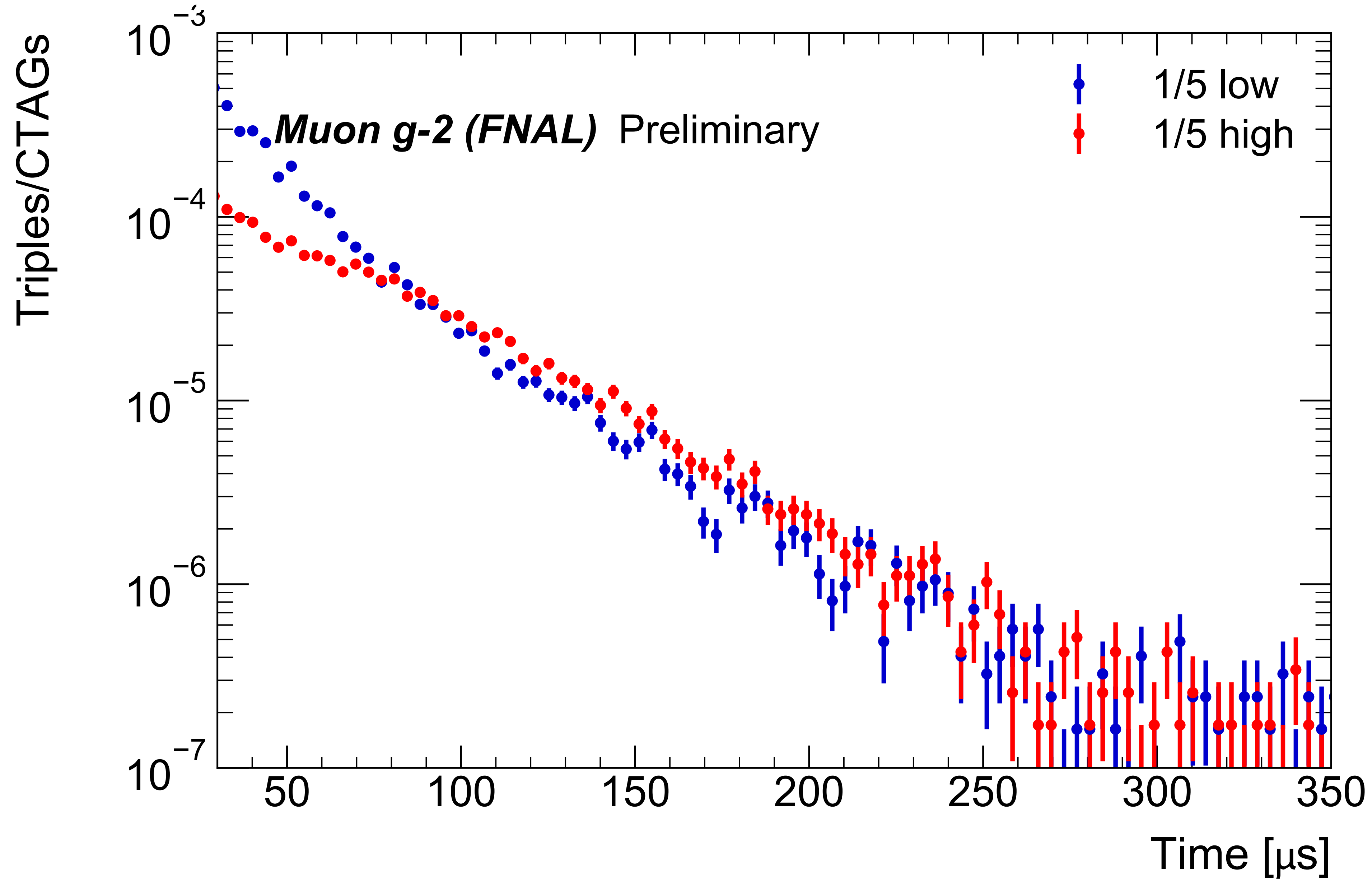
Measuring the momentum change

- Goal: measure whether high or low momentum muons are preferentially lost
- Use upstream collimators to bias the momentum distribution in the ring
  - Measure stored momentum distribution
  - Measured loss spectrum for each momentum distribution





Building a loss function

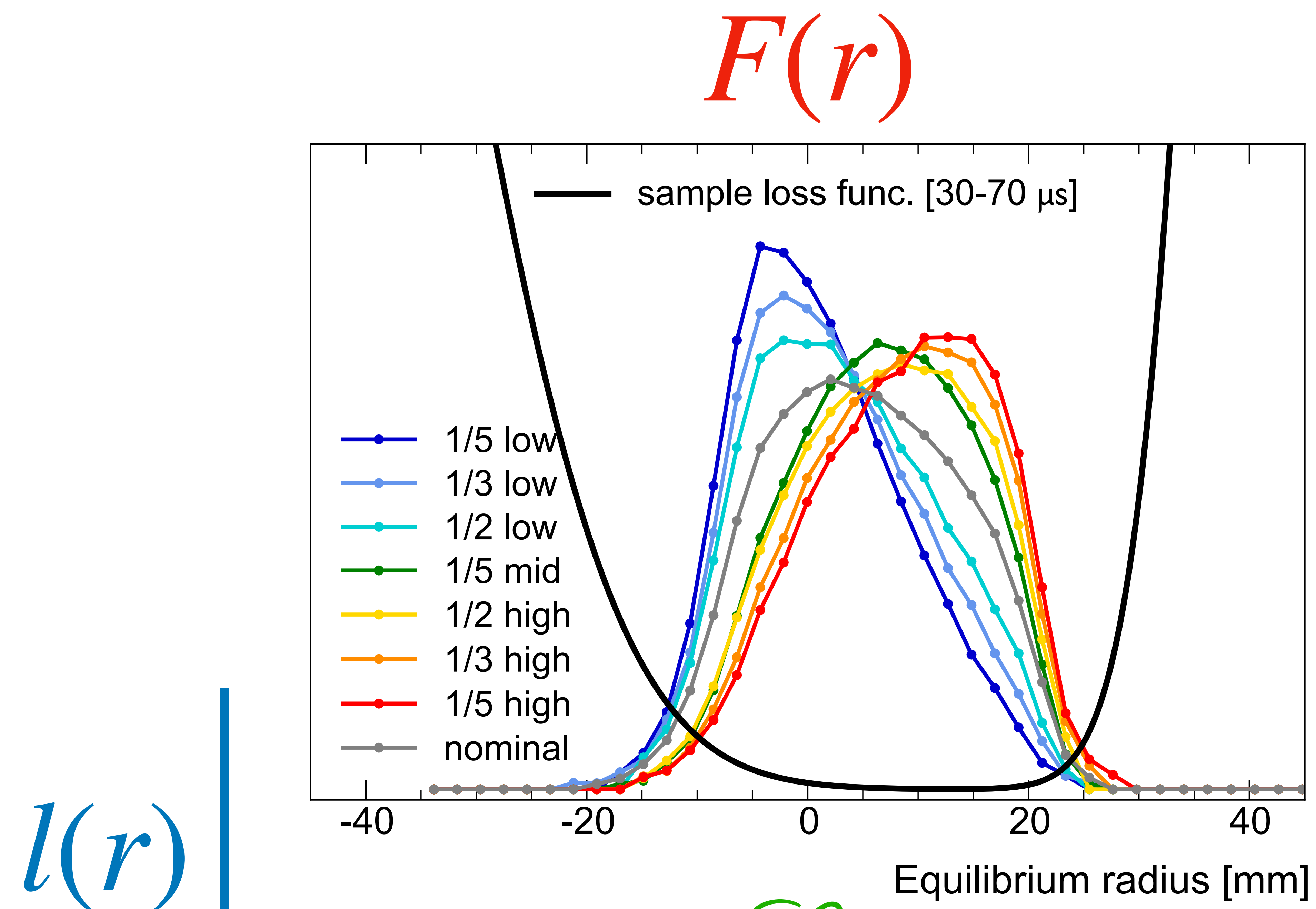
- Perform a fit using a set of equations, one per systematic run
- Loss function maps a momentum distribution to a measured number of lost muons
    - Assume analytical form of loss function

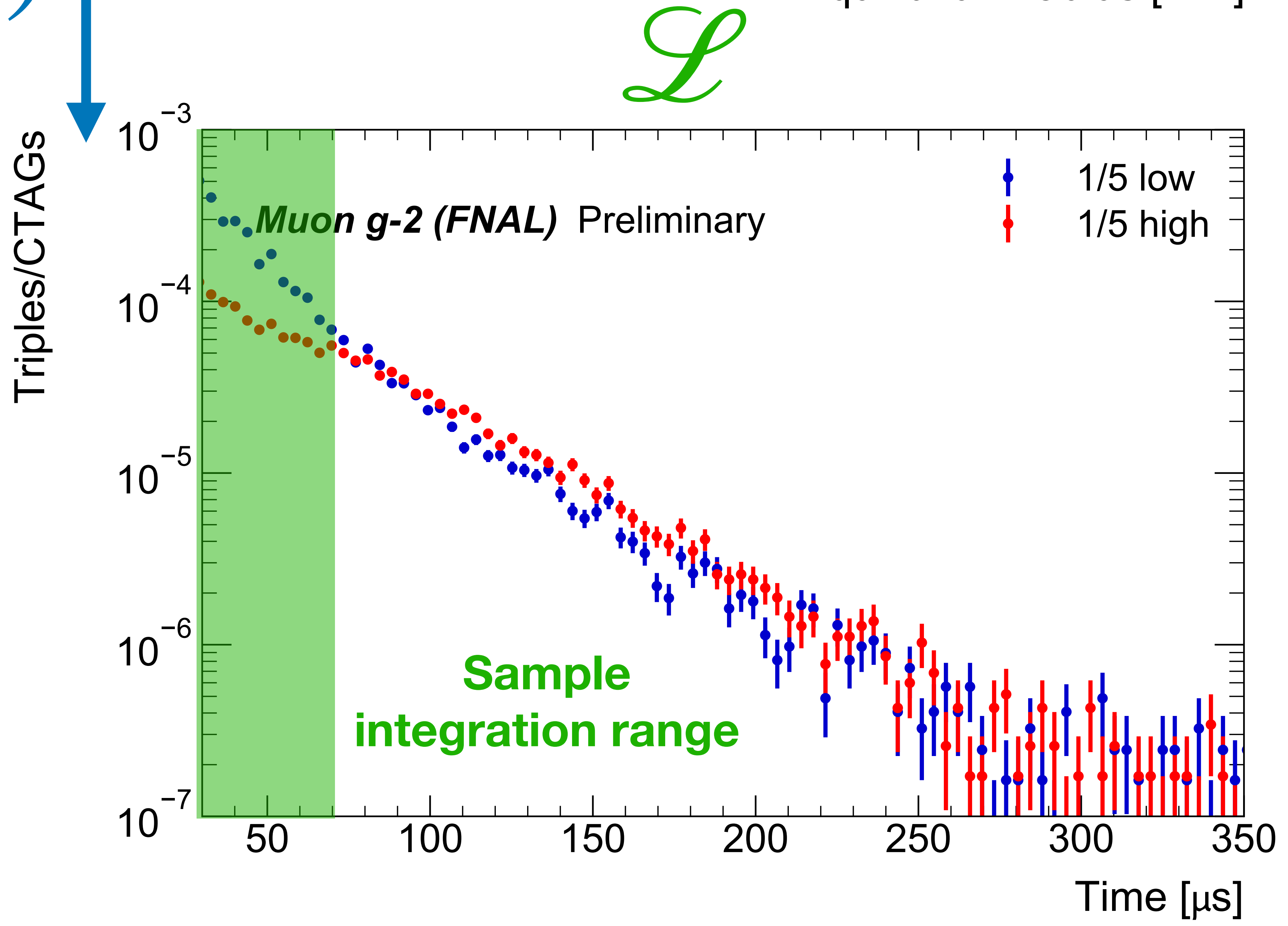
$$\int_{R_{min}}^{R_{max}} F(r)\, l(r)\, dr = \mathscr{L}$$

$F(r)$: Momentum distributions (measured)

$l(r)$: Loss function (fit)

$\mathscr{L}$: Integrated losses (measured)

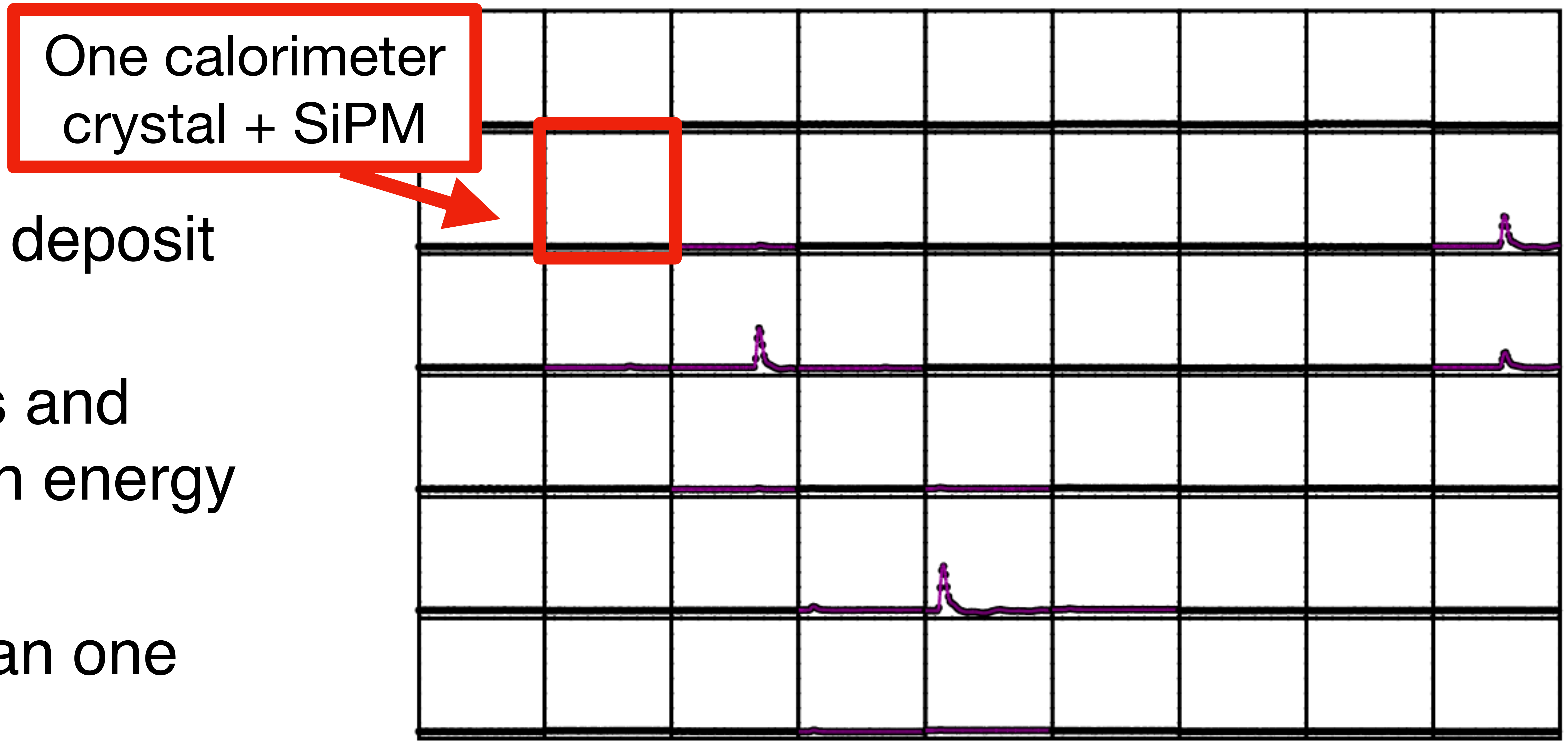


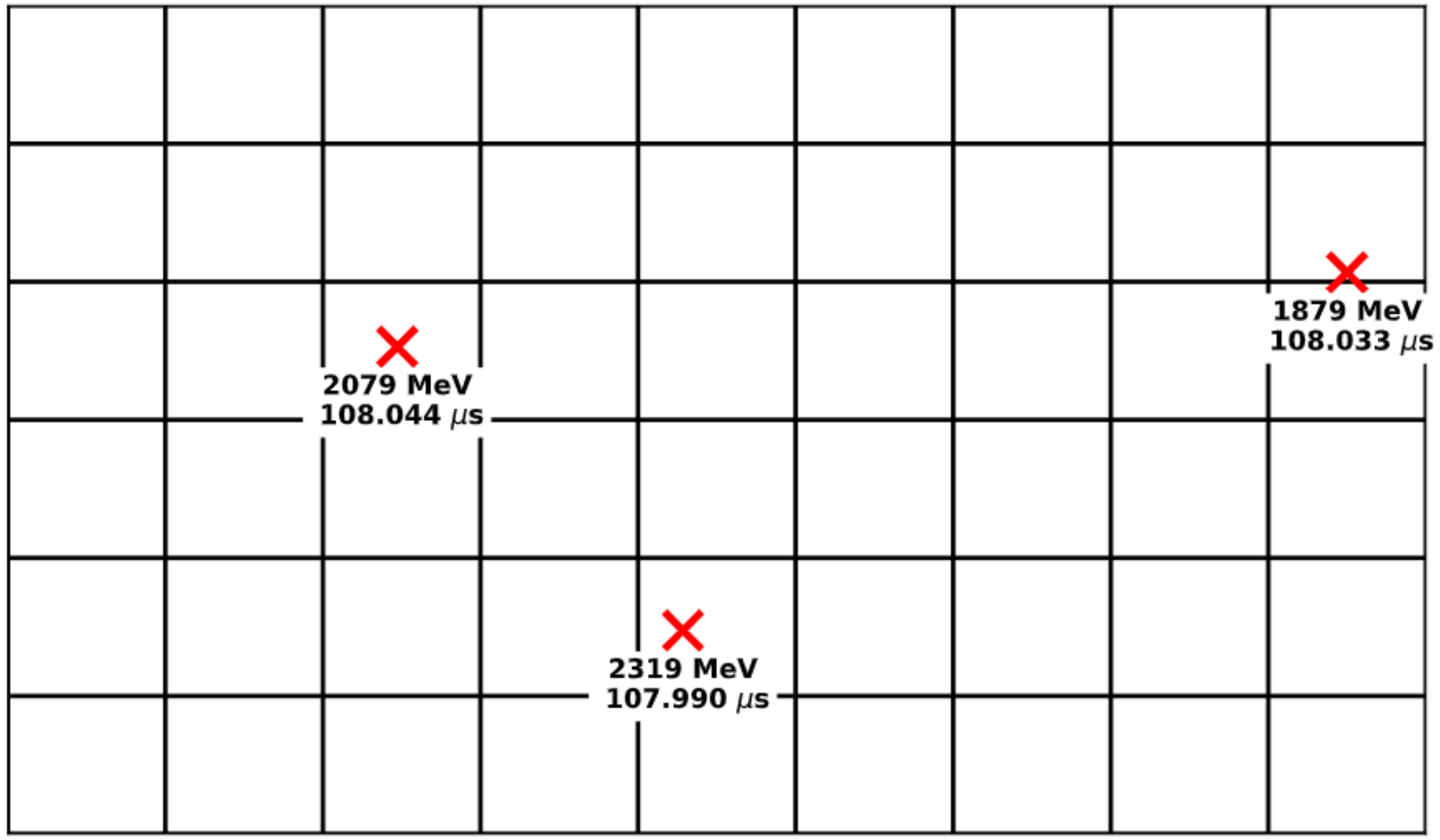


What is clustering?

- A positron hitting a calorimeter may deposit energy in multiple crystals
- Clustering gathers these crystal hits and sums the energy to give the positron energy
- Ideally: one cluster = one positron
- Pileup event: one cluster = more than one positron

- Less pileup to begin with means less pileup to subtract means lower pileup uncertainty
  - **Strategy: improve clustering to reduce pileup**





A. Fienberg thesis

Clustering improvement strategies: Improving time discrimination

- Calo channels have a known energy-dependent time resolution
  - Timing of high-energy pulses known more precisely

- This information has not yet been incorporated into clustering algorithm … an opportunity for improvement

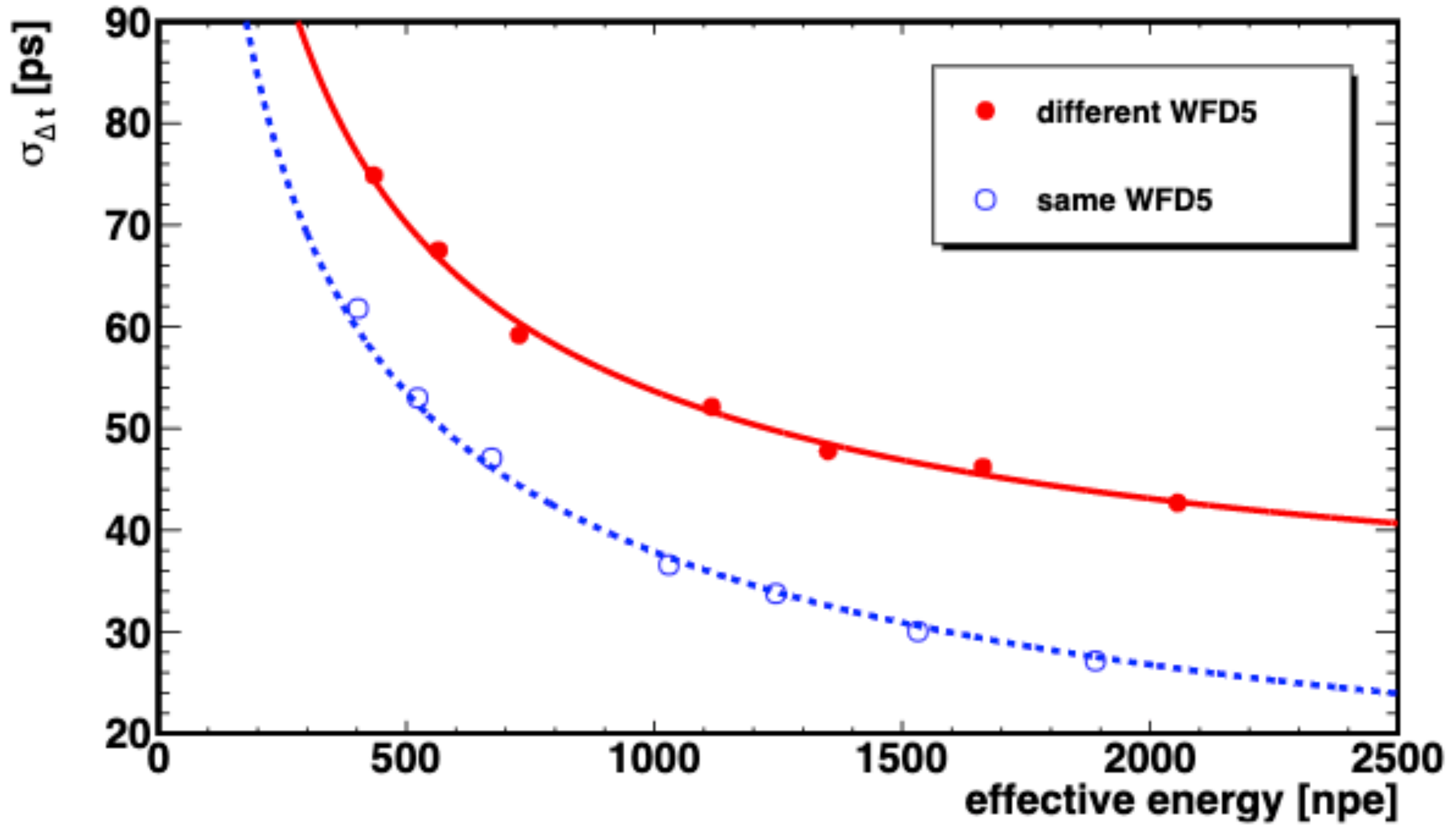
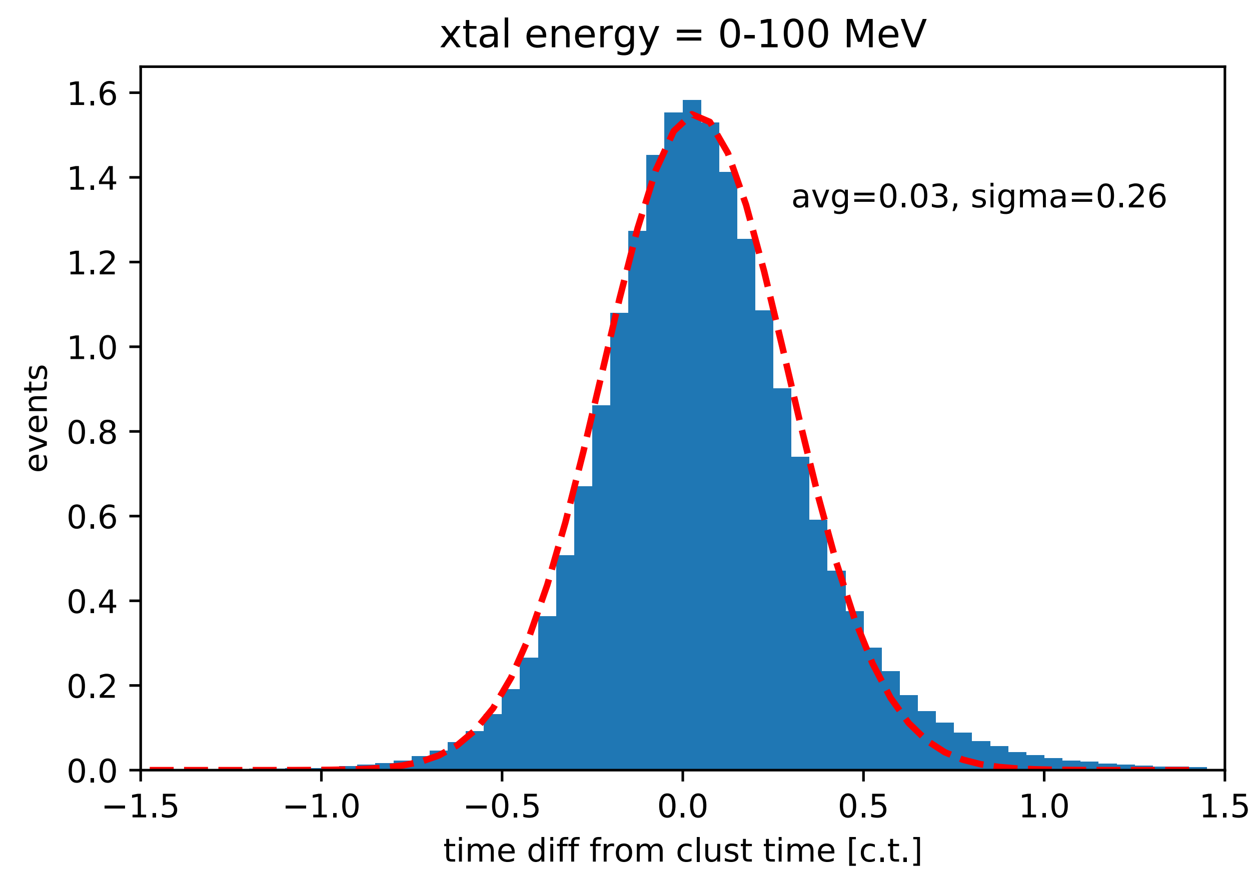


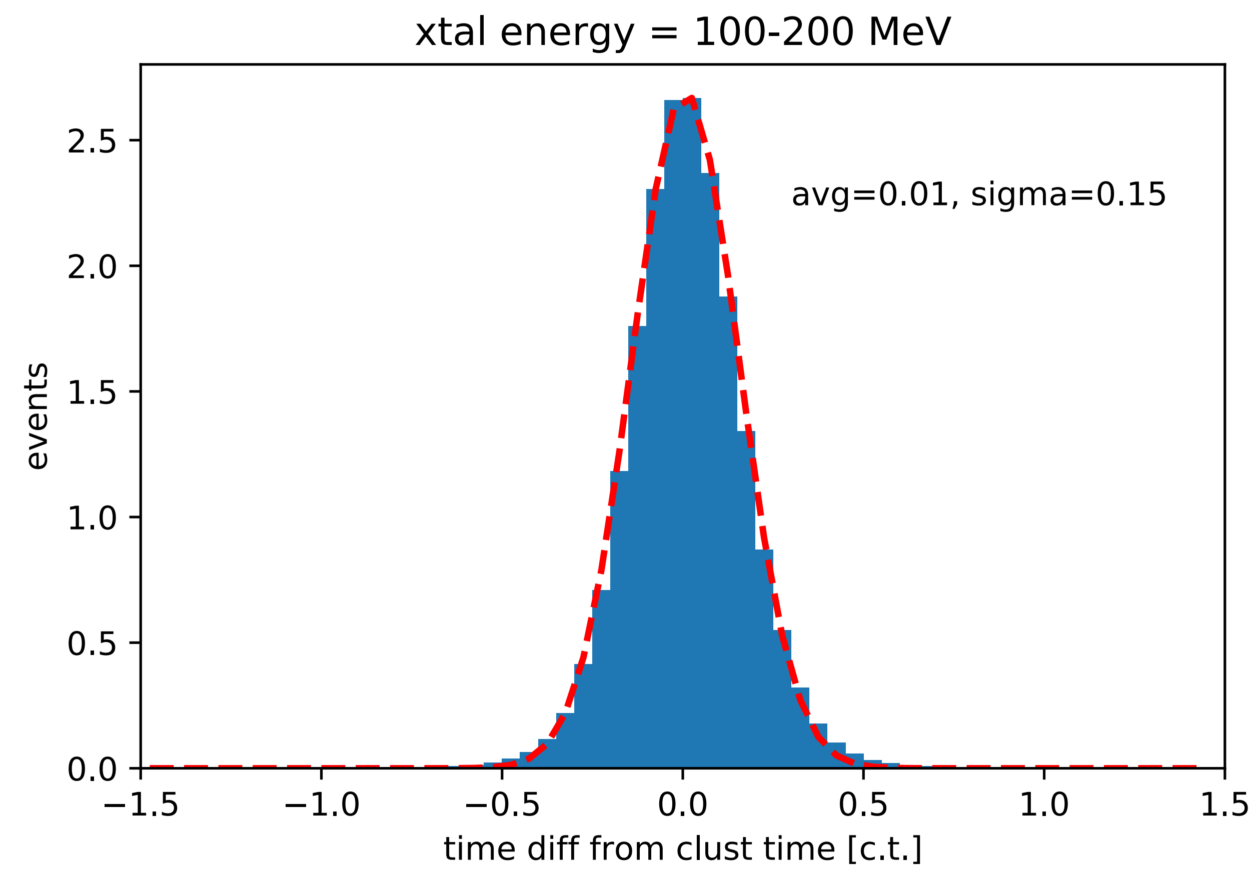
Figure 16: Standard deviation of the time difference distribution versus effective energy for laser events read out by the same, or different, WFD5s. A single channel resolution can be obtained by using the dotted line and scaling the vertical axis by $1/\sqrt{2}$.

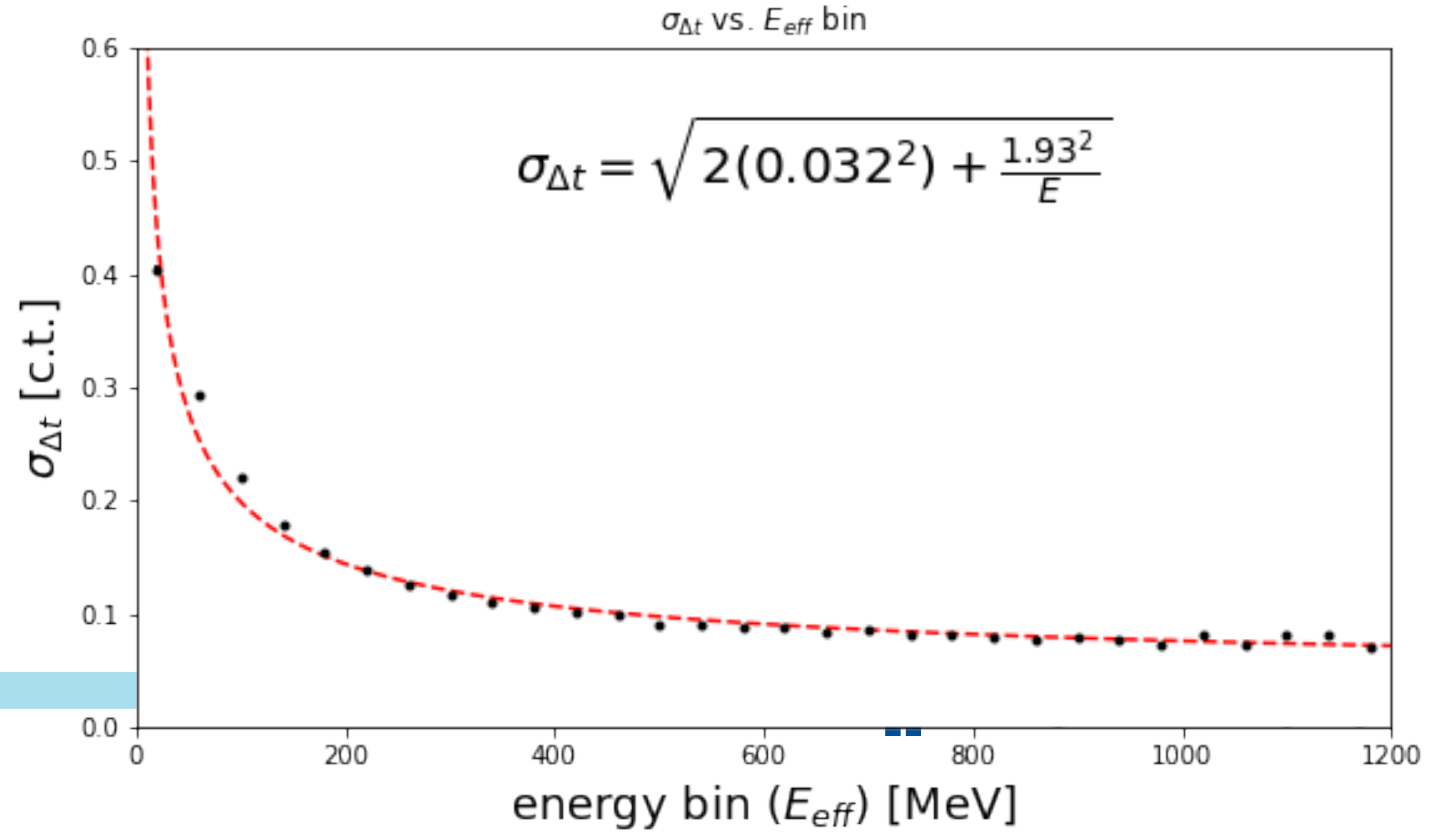
Performance of the Muon g-2 calorimeter and readout systems measured with test beam data (K.S. Khaw et. al.)

Measurement of $\sigma_{\Delta t}(E_{eff})$ for clusters

- Construct analogous time resolution function for existing clusters
  - Incorporates timing resolution information and physics-based width of shower
- For each cluster, calculate the time difference of each crystal hit from the cluster time
- Bin as a function of effective energy $E_{eff} \equiv \dfrac{E_1 E_2}{\sqrt{(E_1^2 + E_2^2)/2}}$
- Fit to $\sigma_{\Delta t} = \sqrt{2(A^2) + B^2/E_{eff}}$



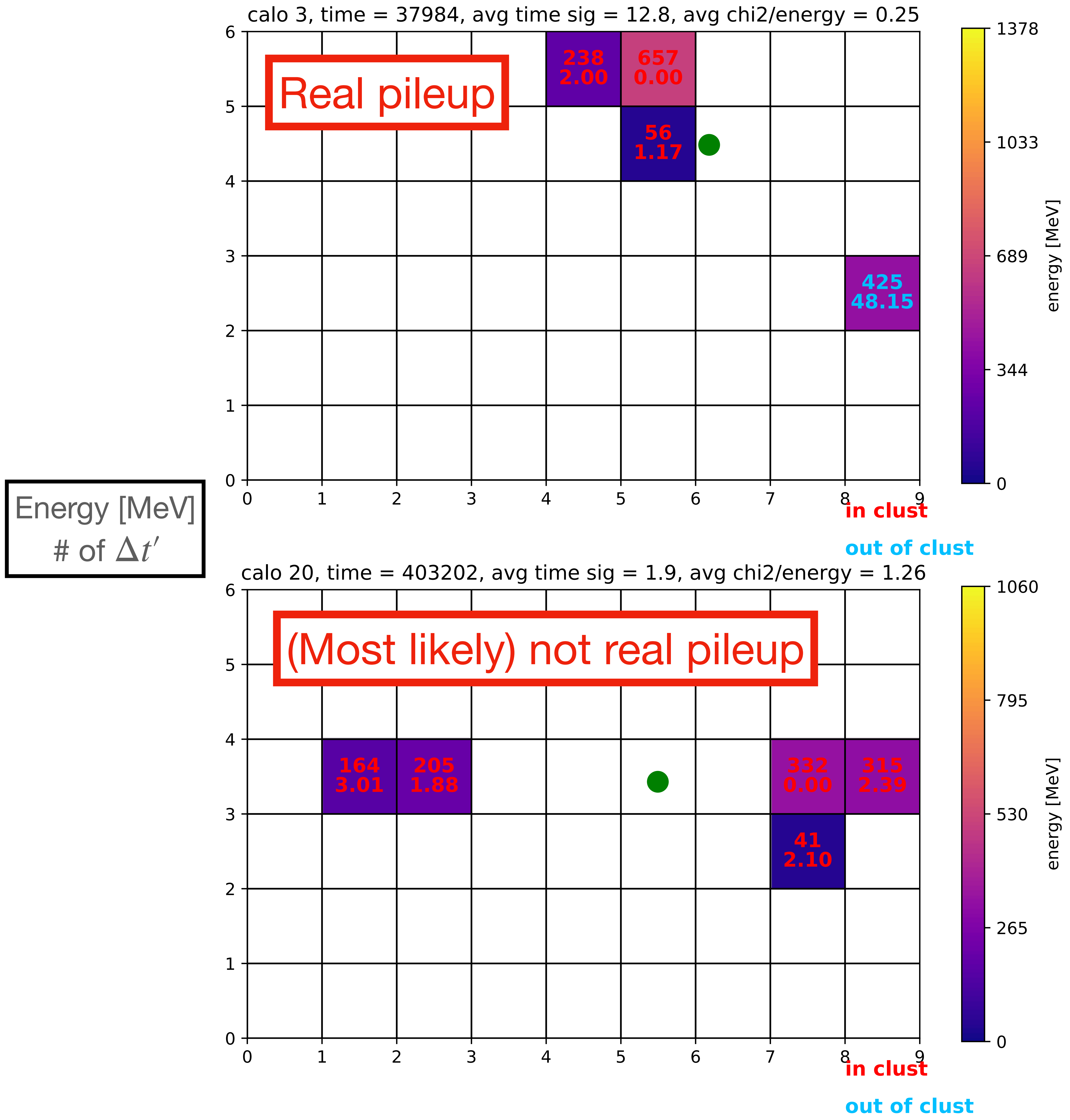




Implementation

- Replace Δt discriminator in algorithm with $\Delta t'$, which is weighted by time resolution
  - $$\Delta t'(E_{eff}) \equiv \frac{\Delta t}{\sigma_{\Delta t}(E_{eff})} = \frac{t_x - t_c}{\sigma_{\Delta t}(E_{eff})}$$
    - t_x: time of hit in cluster
    - t_c: cluster time

Events that would have originally been clustered together



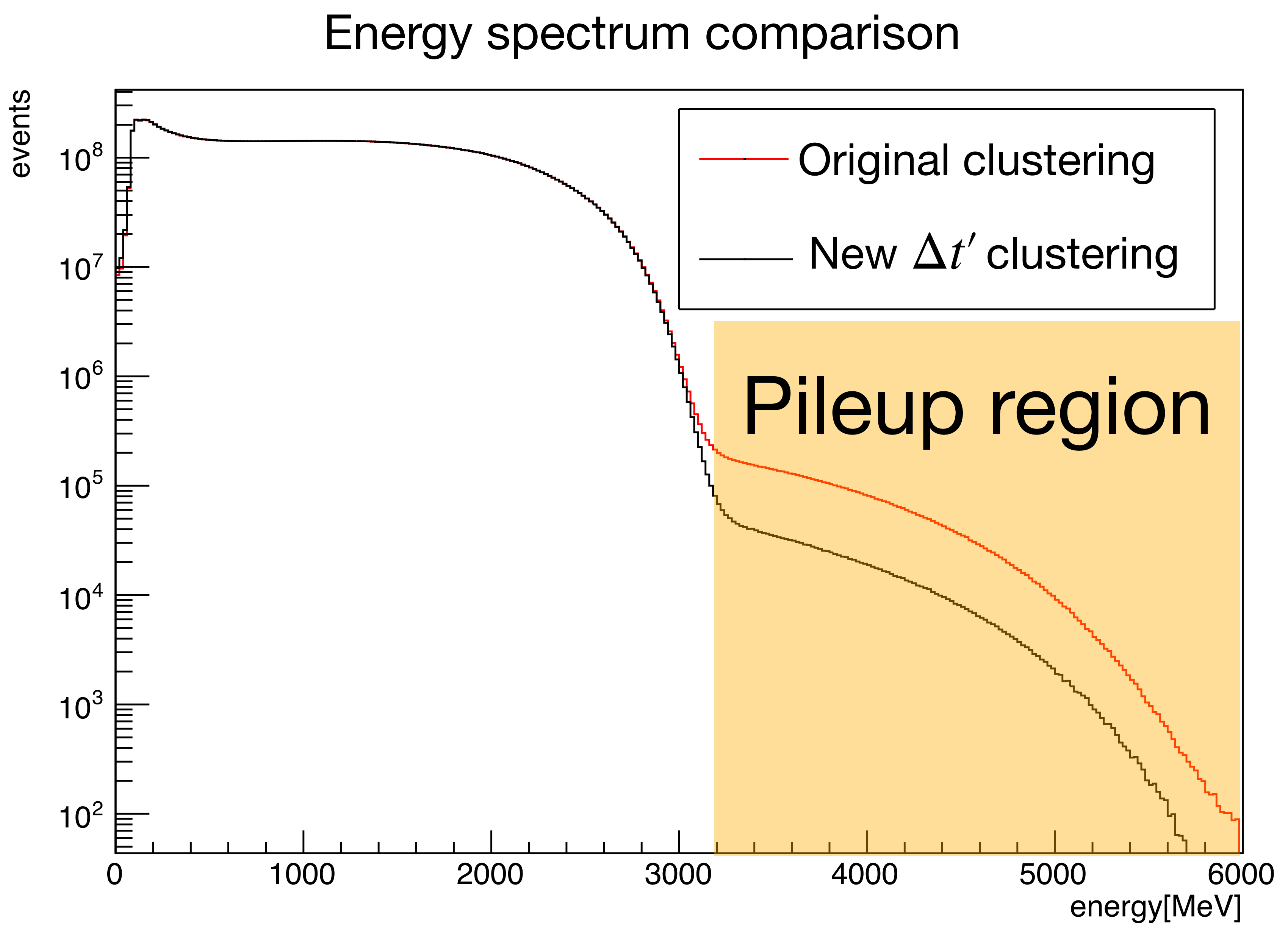
Effect on energy spectrum

- Tested different $\Delta t'$ windows to see effect on energy spectrum
- Chose 6-8 $\Delta t'$ window based on limited distortion to energy spectrum
- This new clustering successfully reduces pileup by ~4x in the pileup region!

Ratio of $\Delta t'$ clusters to Δt (nominal) clusters

Ratio

Energy [MeV]



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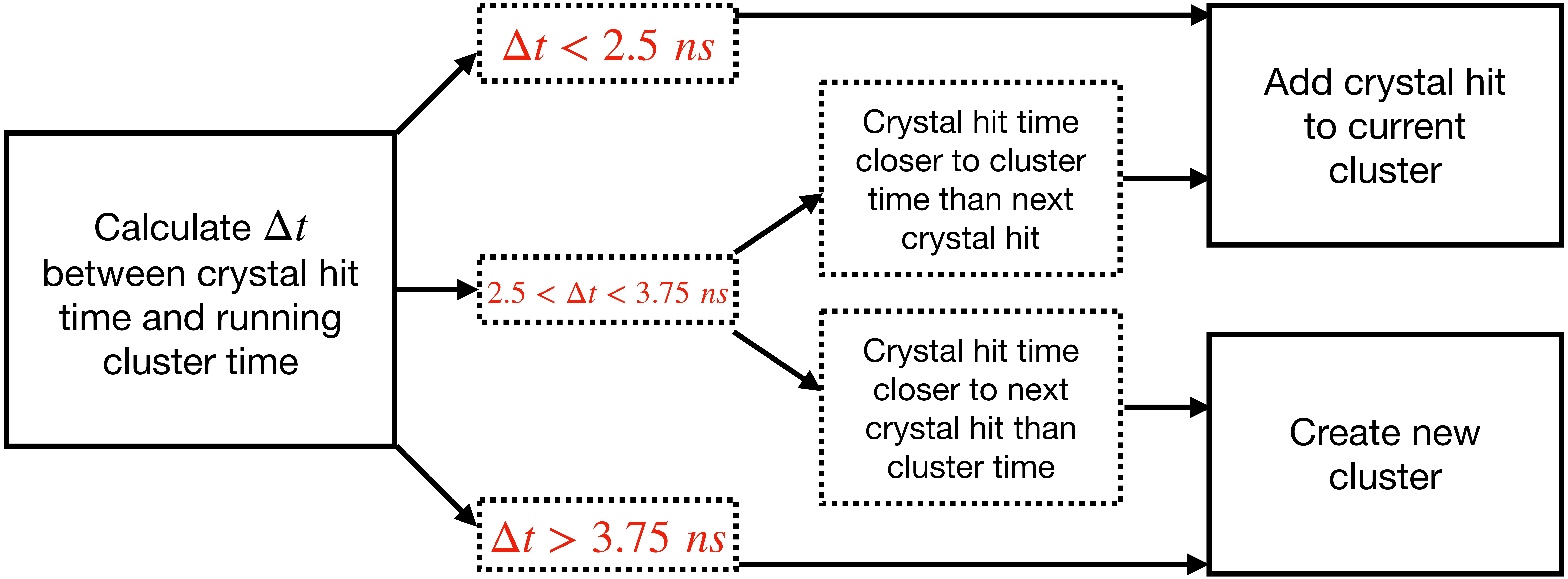
Current clustering method

- Clustering method used in the UW analysis uses time separation only



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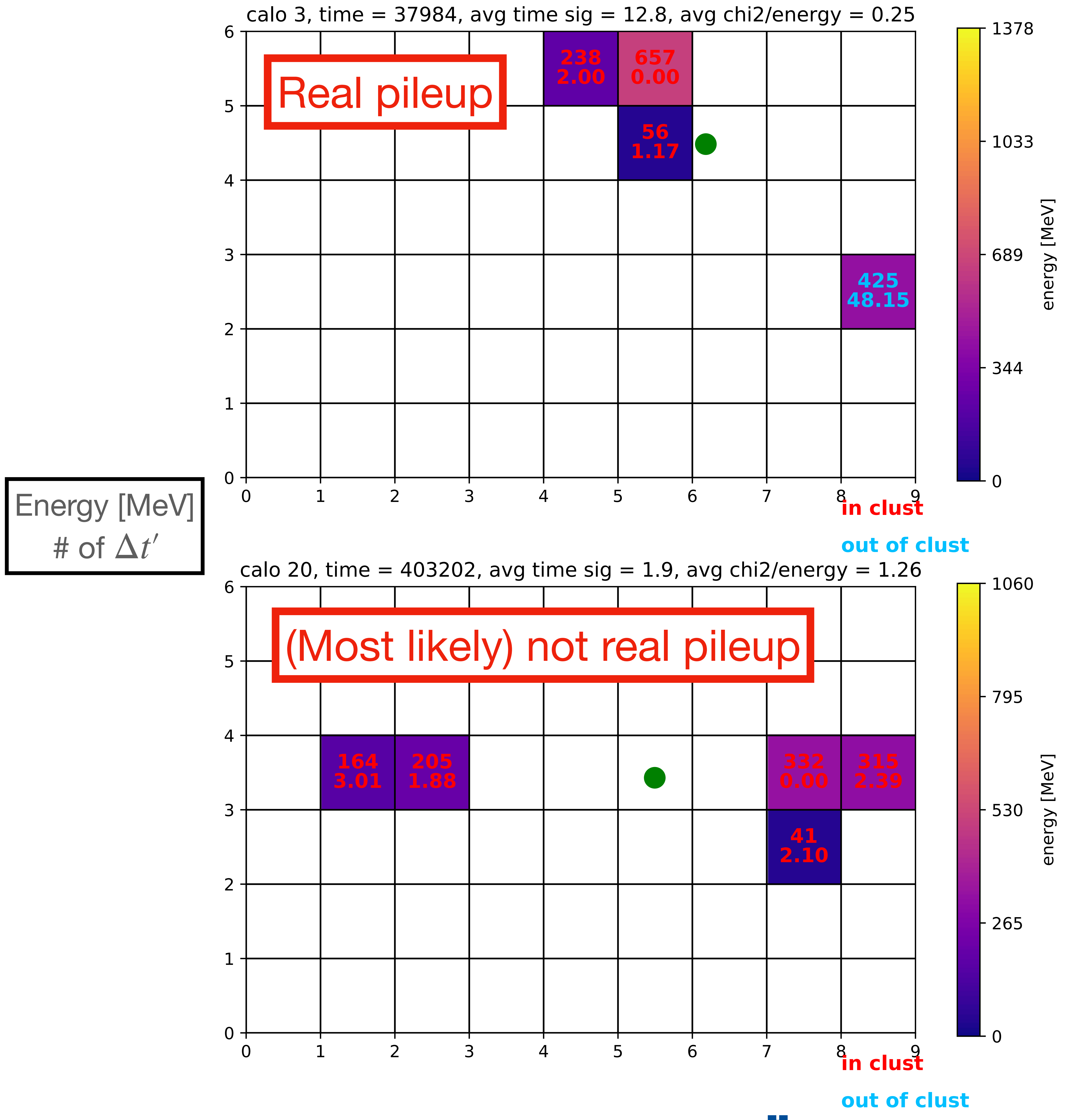

If it's real, what are general take-home remarks (D. Stockinger)

- The deviation is larger than the SM EW contributions and hence "large" and not obviously easy to explain in BSM

- a_μ is a loop-induced, CP- and flavor-conserving, and chirality-flipping
  - (an inclusive probe of essentially all particles/interactions)
  - The chirality flip implies interesting correlations to the muon mass
    - fundamental questions like Higgs/electroweak symmetry breaking and Yukawa couplings/connection to flavor structure/origin of three generations

- Many BSM scenarios *can give* large contributions, but
  - they either involve a chirality flip enhancement (connections to deep physical properties)
  - or rather light, neutral new particles (dark matter?)
  - In virtually all cases there are strong parameter constraints from LHC, dark matter, LEP, flavor experiments etc.

- Typically one is forced into *non-traditional parameter regions*.

What might this mean ?   (first “in general”)

- For us: strong motivation to push Run 3/4/4 analysis and obtain the full statistics goal.
  - We have almost met our systematics goal already
- For other precision muon physics experiments: You might be onto something good!
  - Mu2e, MEG III, Mu3e, COMET, J-PARC g-2,
- For precision physics: Sensitive experiment can really probe SM; go for it
  - B_K, LFUV, beta decays, MOLLER, EDMs, etc
- For theorists: (no need to motivate them …)

- 41 Citations to the PRL as of last night… A bit hard to briefly summarize ☹

D. Hertzog