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A measurement of muon anomalous magnetic moment at Fermilab

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for the Muon $g-2$ Collaboration

Quy Nhon, Vietnam

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The Muon campus at Fermilab

Outline

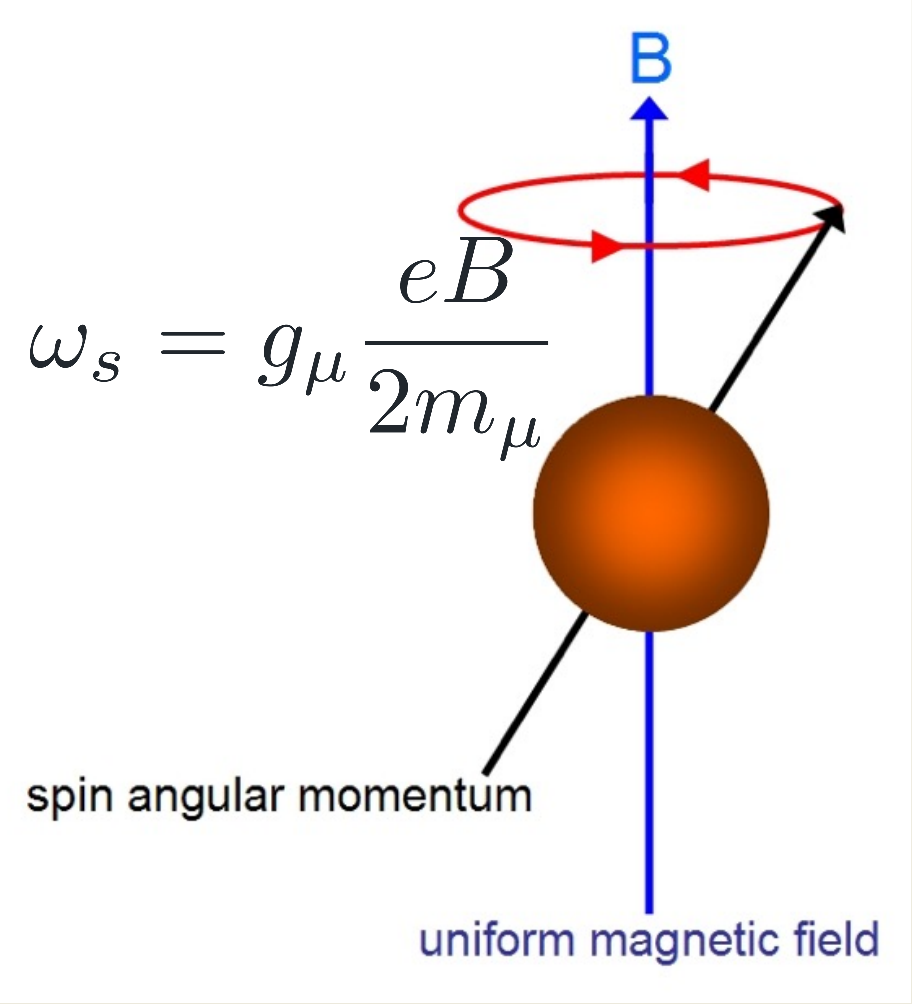
- Overview
- Experimental techniques
- Status of the experiment
- Summary

Muon magnetic moment and the anomaly

- The muon has an intrinsic magnetic moment:

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

- Precesses in an external magnetic field with a frequency determined by the gyromagnetic ratio g_μ
- $g_\mu = 2$ from Dirac equation for a spin-1/2 charged particle



- In reality: $g_\mu > 2$, i.e. there is an anomalous magnetic moment.
- The anomaly: $a_\mu = \frac{g_\mu - 2}{2}$

a_μ in the Standard Model

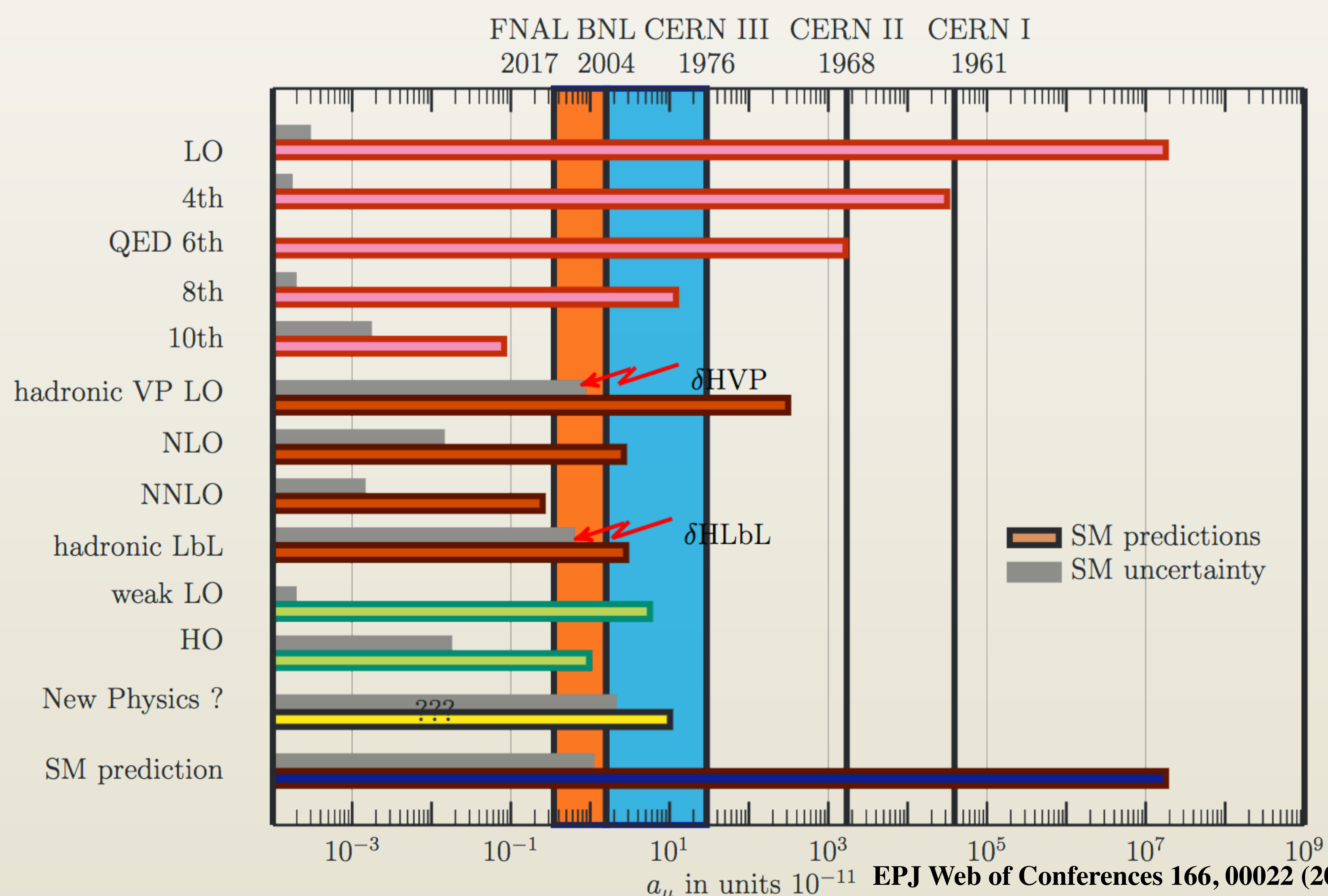
- Uncertainty dominated by hadron corrections:

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{had}}$$

PDG, Phys. Rev. D 98, 030001 (2018)

$$= 116\,591\,823(1)(34)(26) \times 10^{-11}$$

EW — **had LO** — **had HO**



EPJ Web of Conferences 166, 00022 (2018)
https://doi.org/10.1051/epjconf/201816600022

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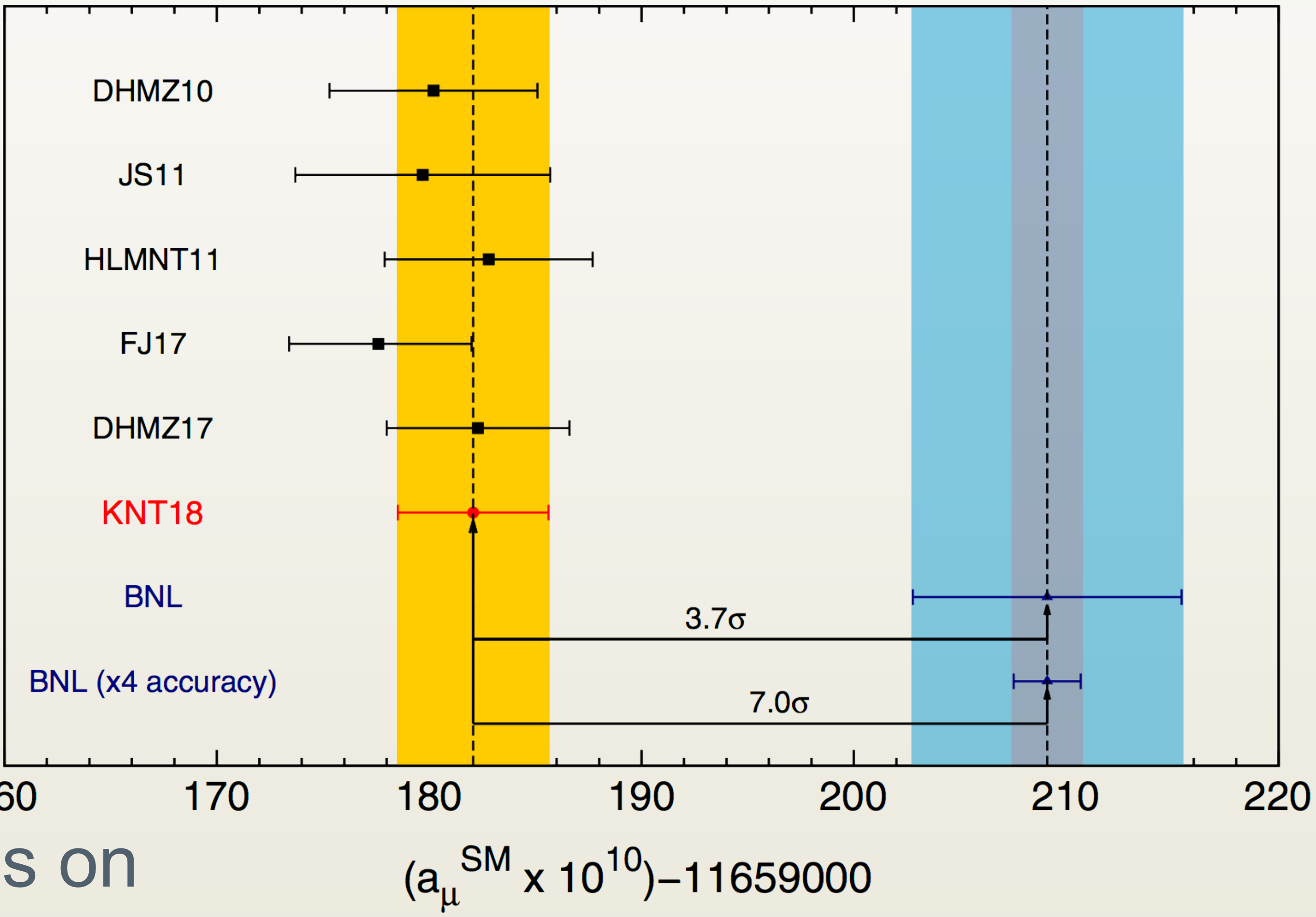
Experimental vs theoretical values

- Best measurement: BNL E821 from 1999 to 2001,
  - uncertainty: 540 ppb
  - 3 - 4 σ difference from SM predictions
- Inspired new efforts from theorists: Muon $g-2$ Theory Initiative
  - focus on reducing uncertainties on HVP and HLbL contributions
  - 4 workshops taken place
  - would publish 1st report in Sep 2018

Phys. Rev. D 97 (2018) 114025



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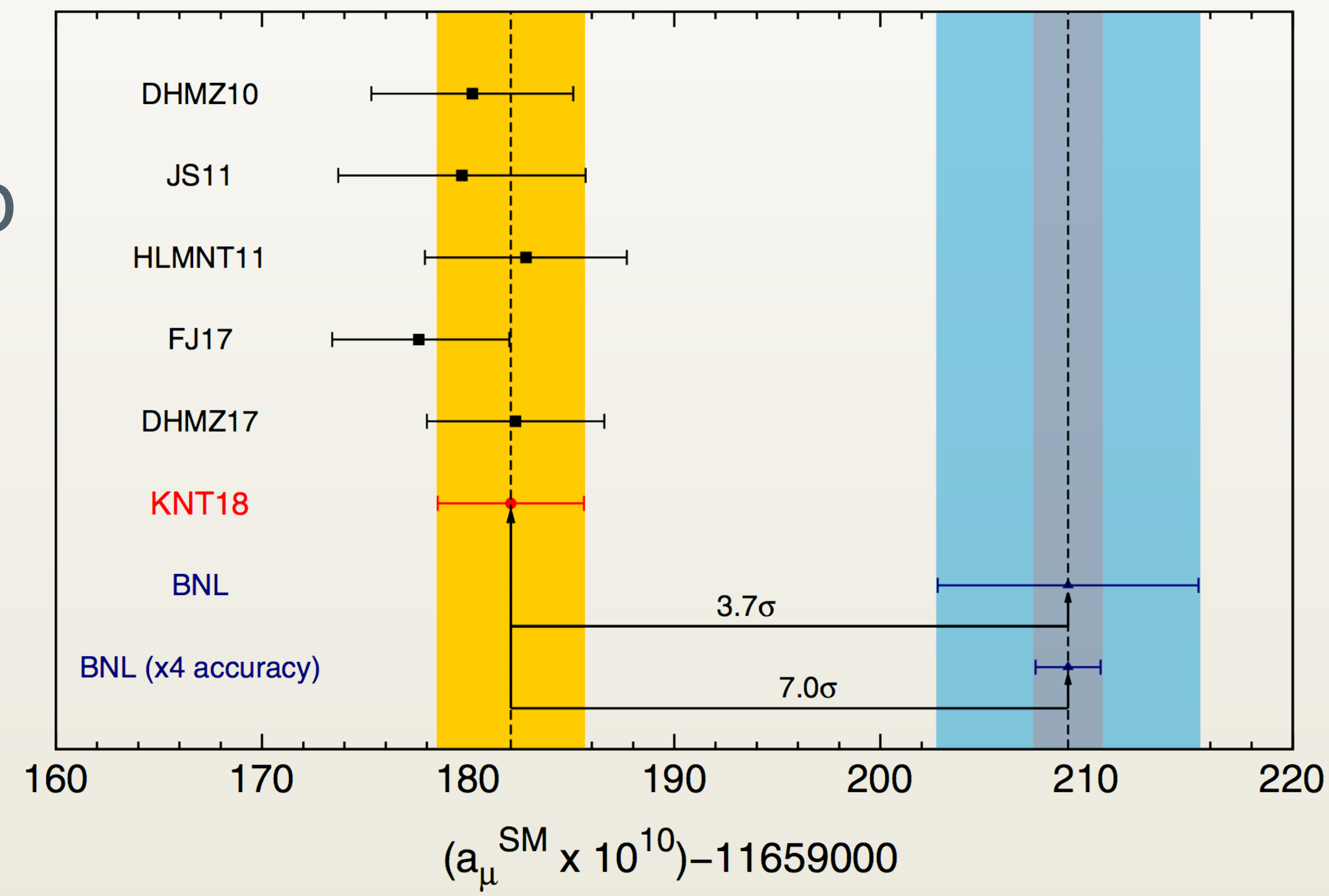
New Muon g-2 experiment at Fermilab

- Goal: 4 times improvement in precision, i.e. to 140 ppb
  - increased statistics: 21 times number of events recorded in BNL E821 (2×10^{11} events, 480 ppb $\rightarrow$ 100 ppb)
  - reduced systematics: 2.5 times better (248 ppb $\rightarrow$ 100 ppb)

Phys. Rev. D 97 (2018) 114025



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How do we measure a_μ?

- Store longitudinally polarized muons in a ring, with uniform dipole magnetic field B
- Consider difference between spin and cyclotron frequencies:

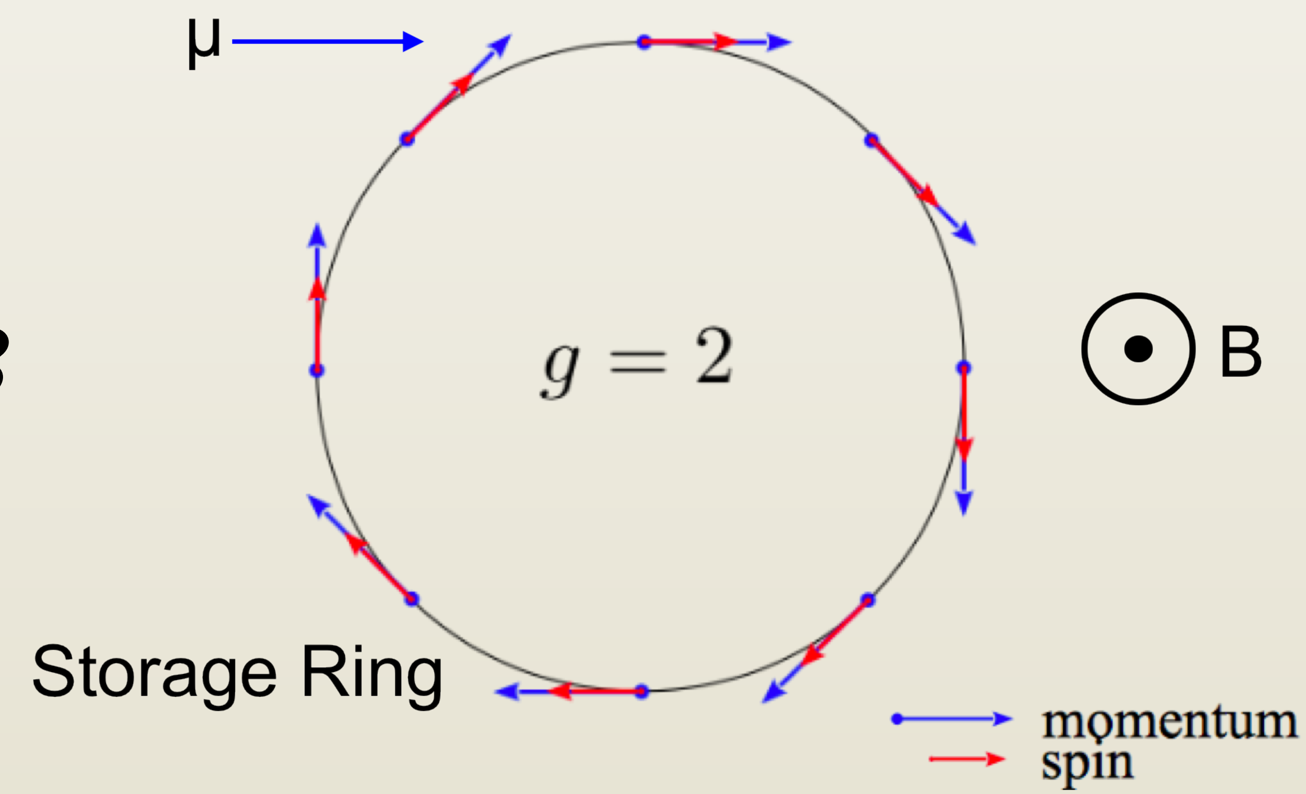
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_c = \frac{eB}{\gamma mc}$$

$$\omega_a = \omega_s - \omega_c = \frac{g-2}{2}\frac{e}{m}B$$

$$\omega_a = a\frac{e}{m}B$$

- If $g_\mu = 2$: spin always aligns with momentum



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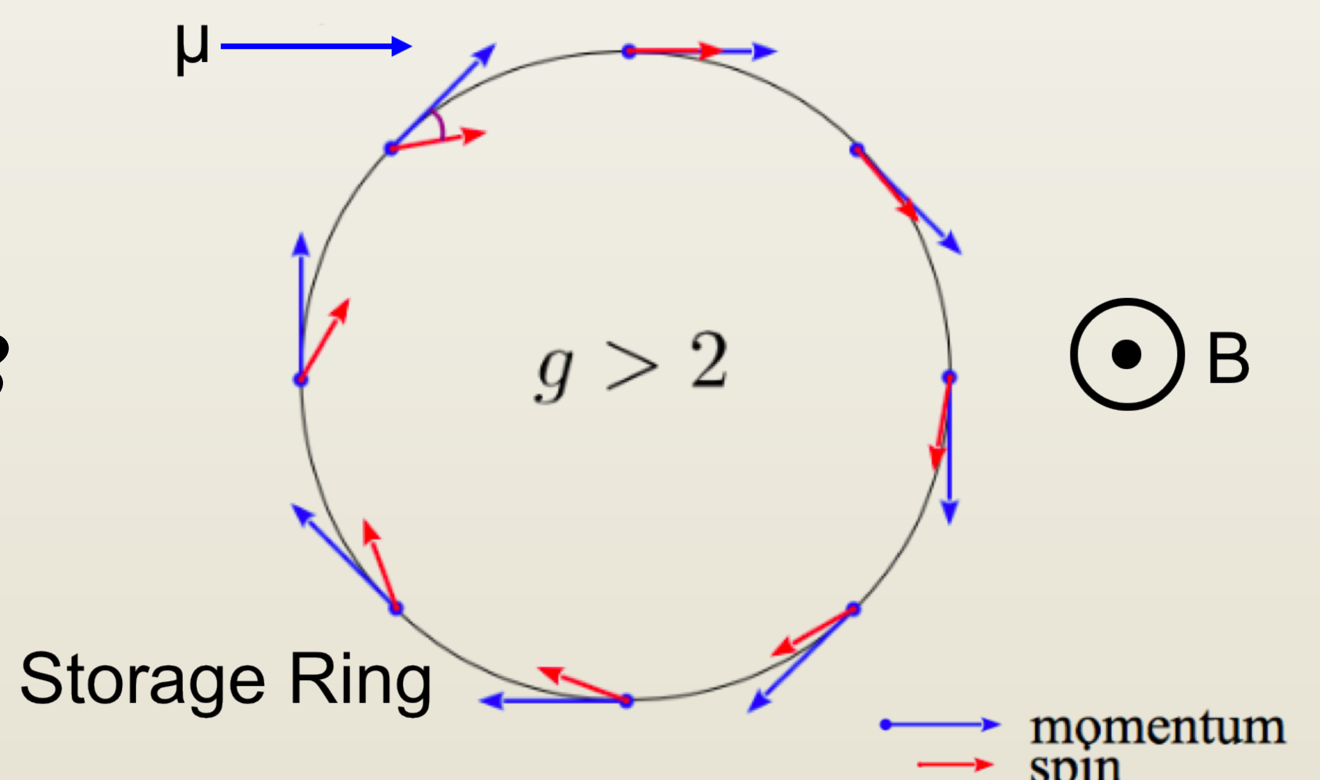

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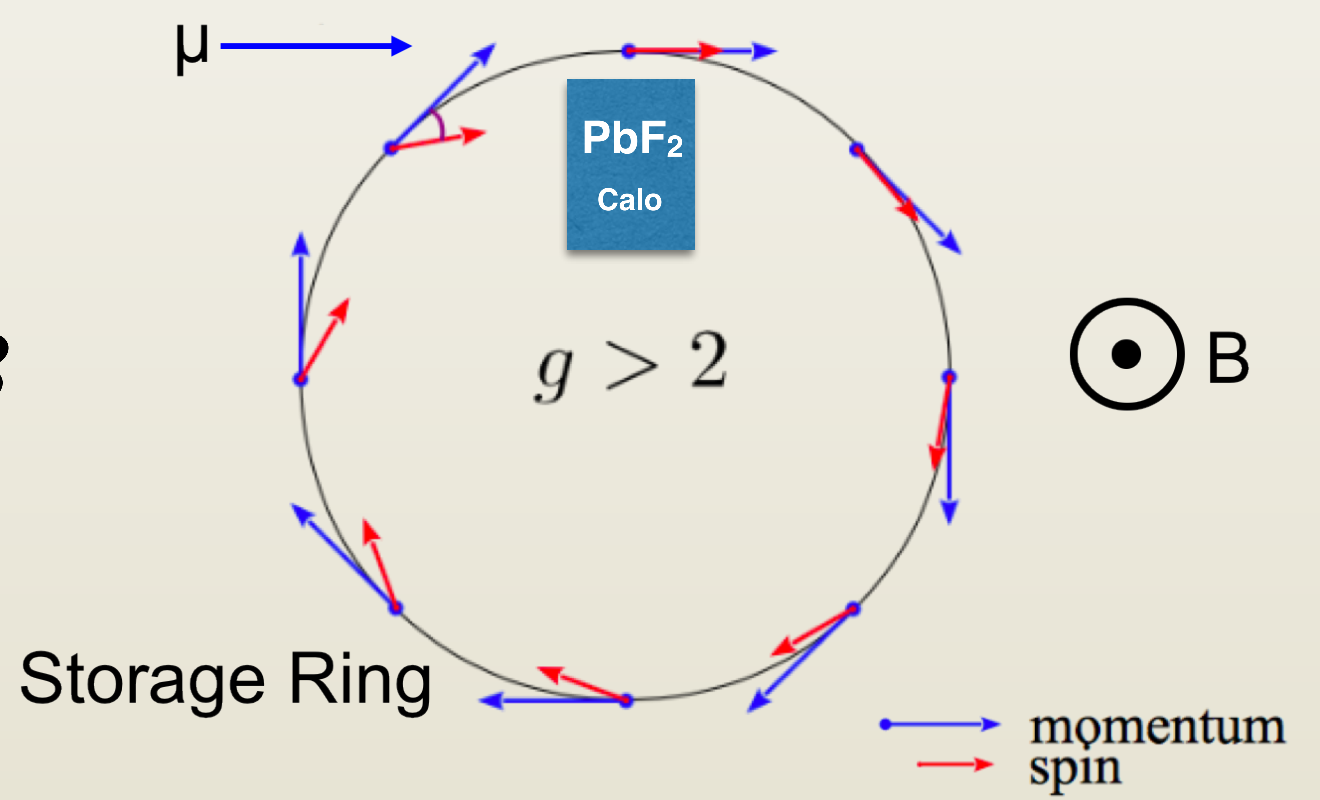

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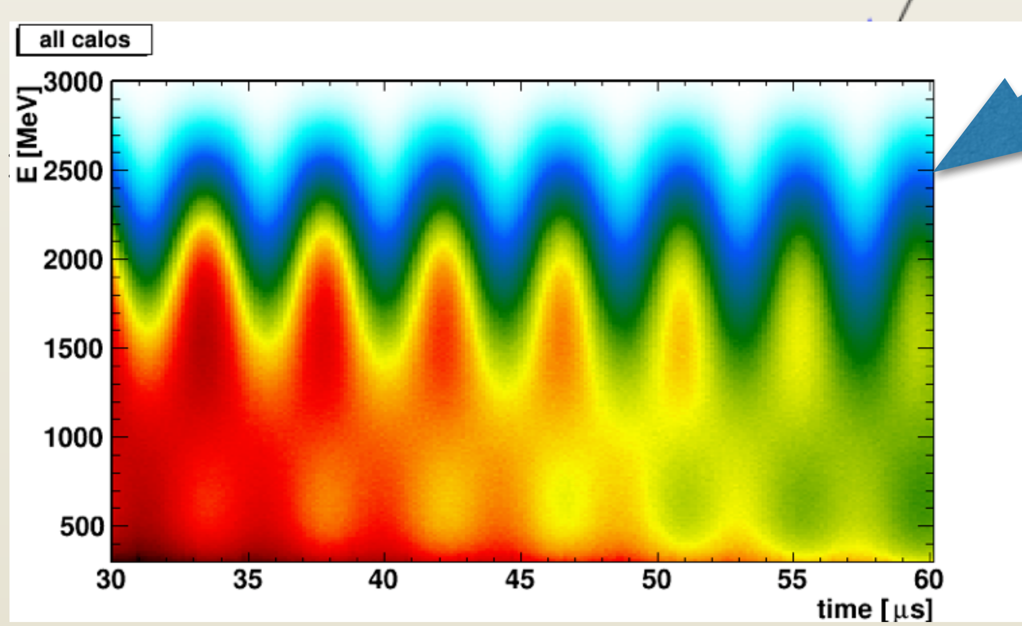

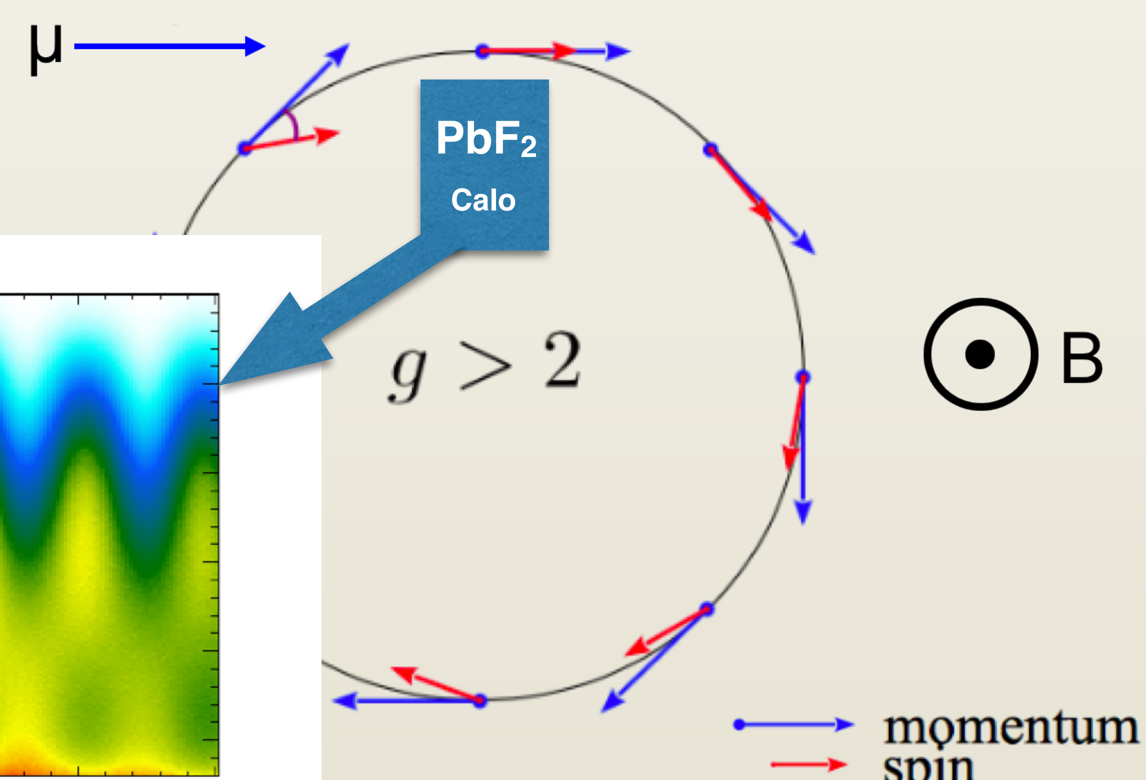

How do we measure a_μ?

- Actual extraction of a_μ:

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

- $\tilde{\omega}_p$ is weighted average of Lamor precession frequency of a free proton in the magnetic field
  - measured using NMR probes and an absolute calibration probe

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- Actual extraction of a_μ:

$$\delta\left(\frac{m_\mu}{m_e}\right) \sim 25\,\text{ppb}$$

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

$$\delta\left(\frac{\mu_e}{\mu_p}\right) \sim 8\,\text{ppb} \qquad \delta\left(\frac{g_e}{2}\right) \sim 0.3\,\text{ppt}$$

***Uncertainties are taken from CODATA**

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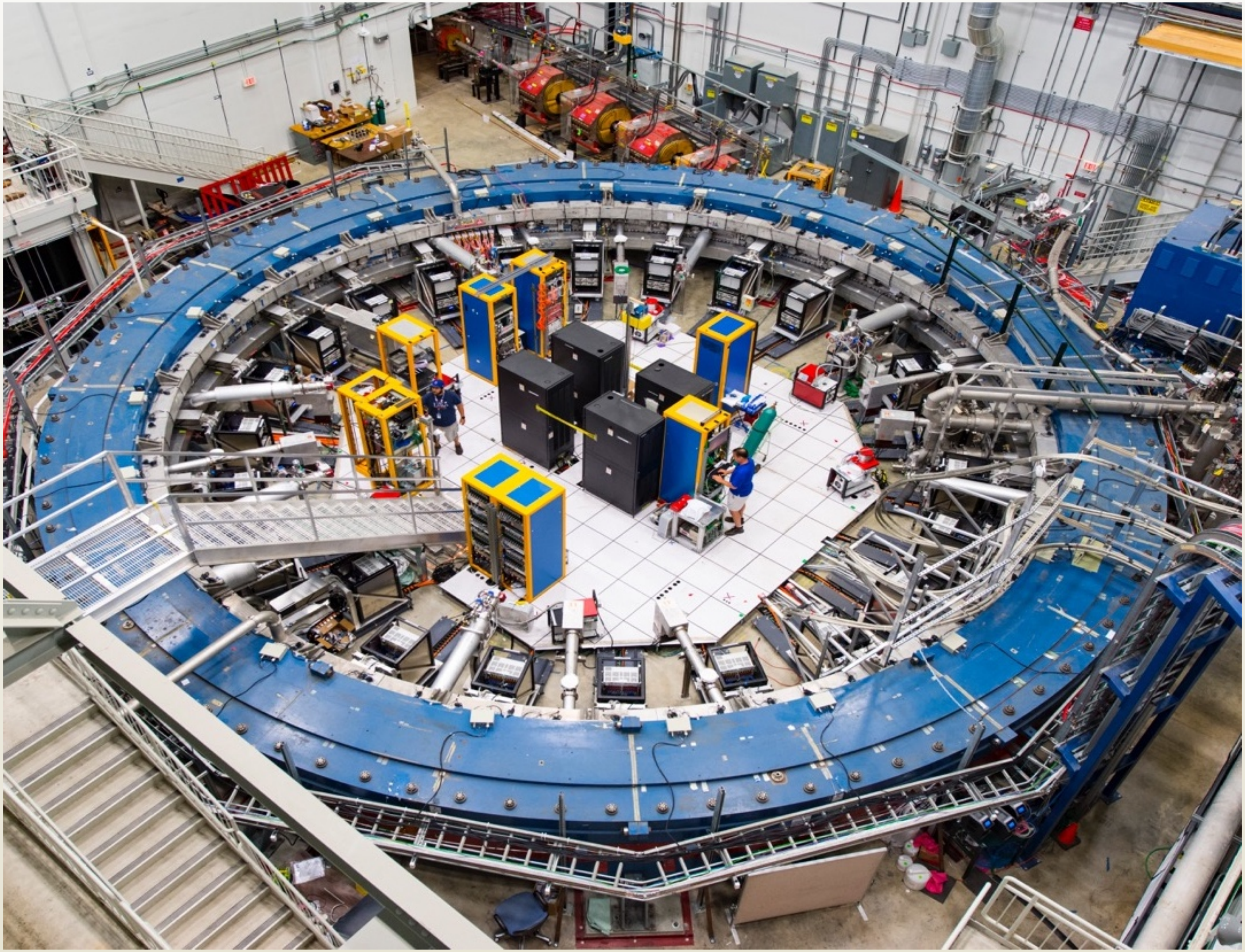
The Ring



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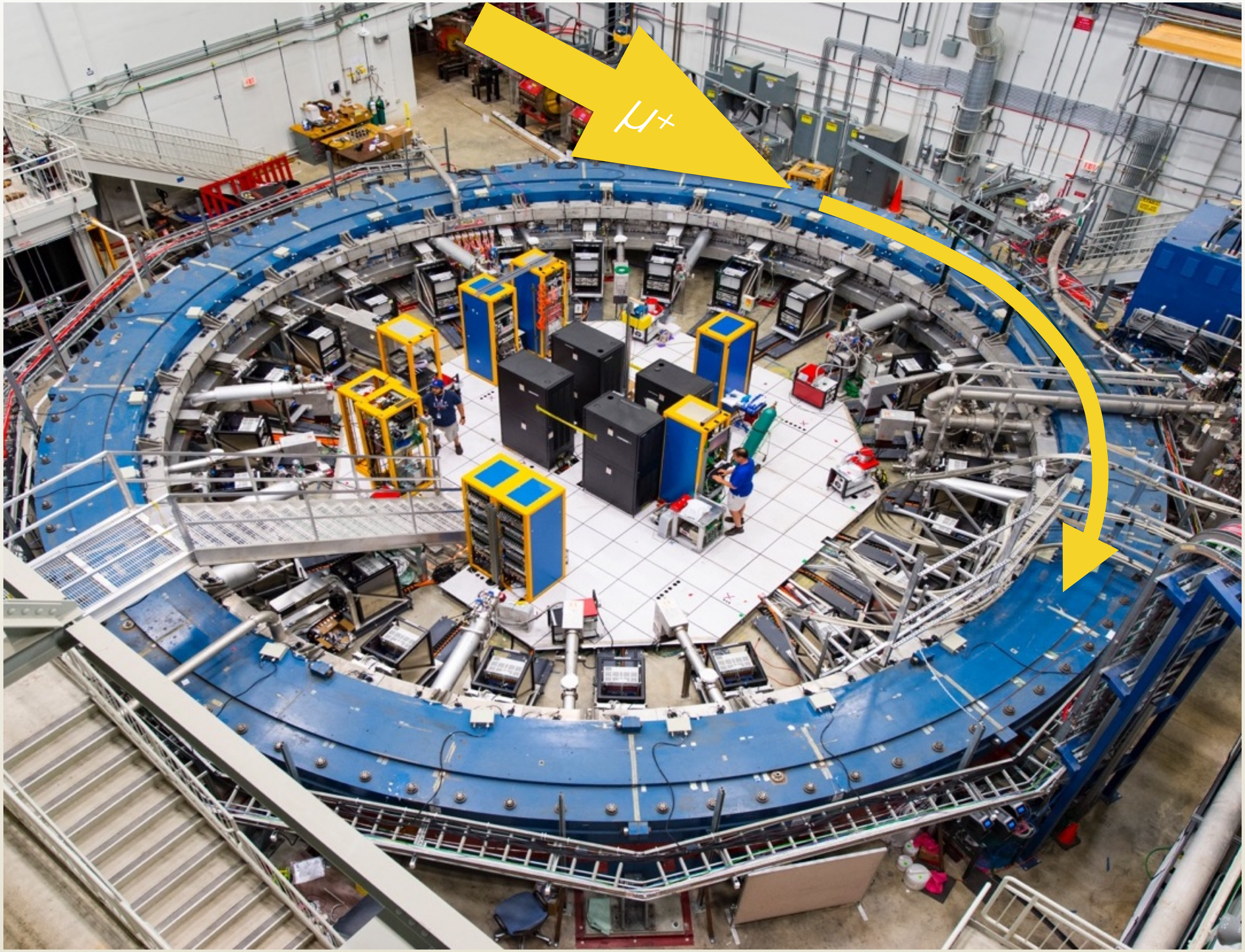

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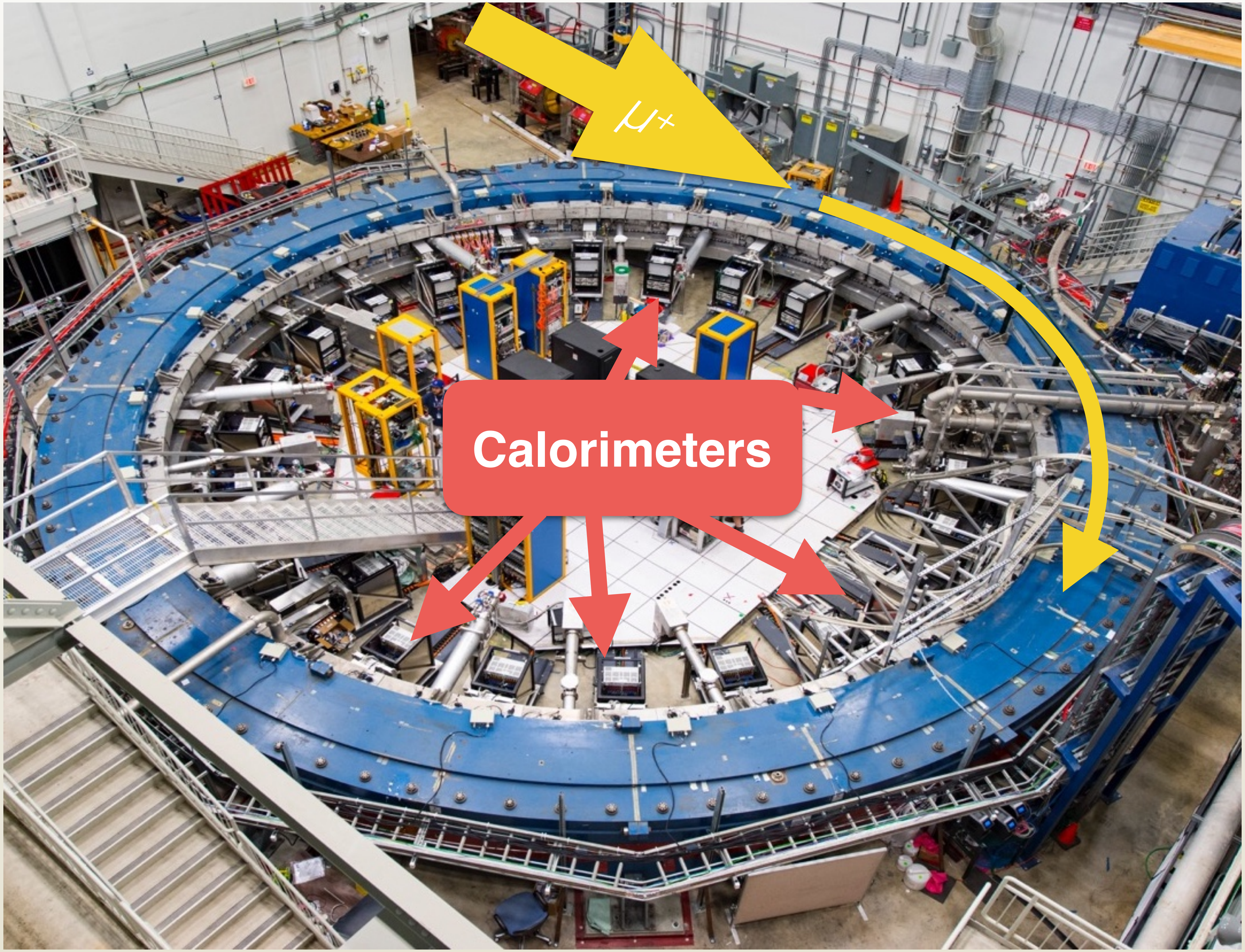

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Real world considerations

- Real muon beam has a small vertical component
- Need vertical electric field to focus the beam

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

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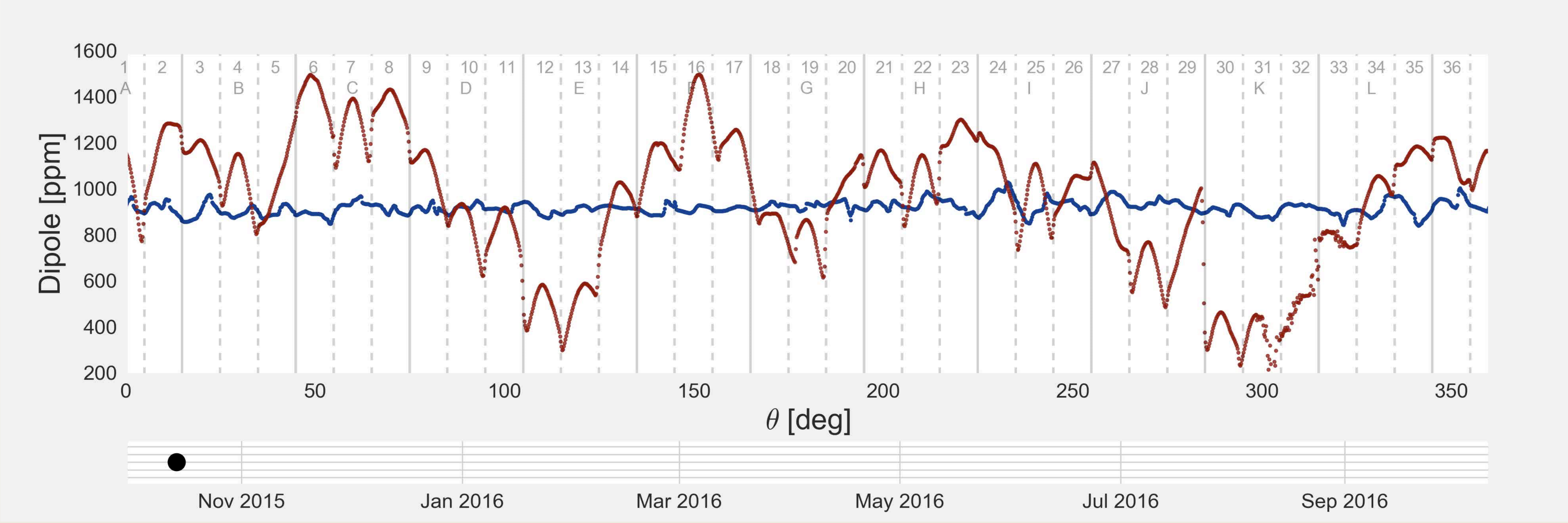
- Choose γ = 29.304 (p = 3.09 GeV, a.k.a magic momentum)
  - but not all muons are at magic momentum (Δp = 0.5 %), i.e. the term is not completely vanished
- Vertical motion of the beam can be corrected for by measuring beam profile
  - using scintillating fiber tracker (destructive), and straw tube trackers (non-destructive)

Magnetic field uniformity

- Shimming 1.45 T field



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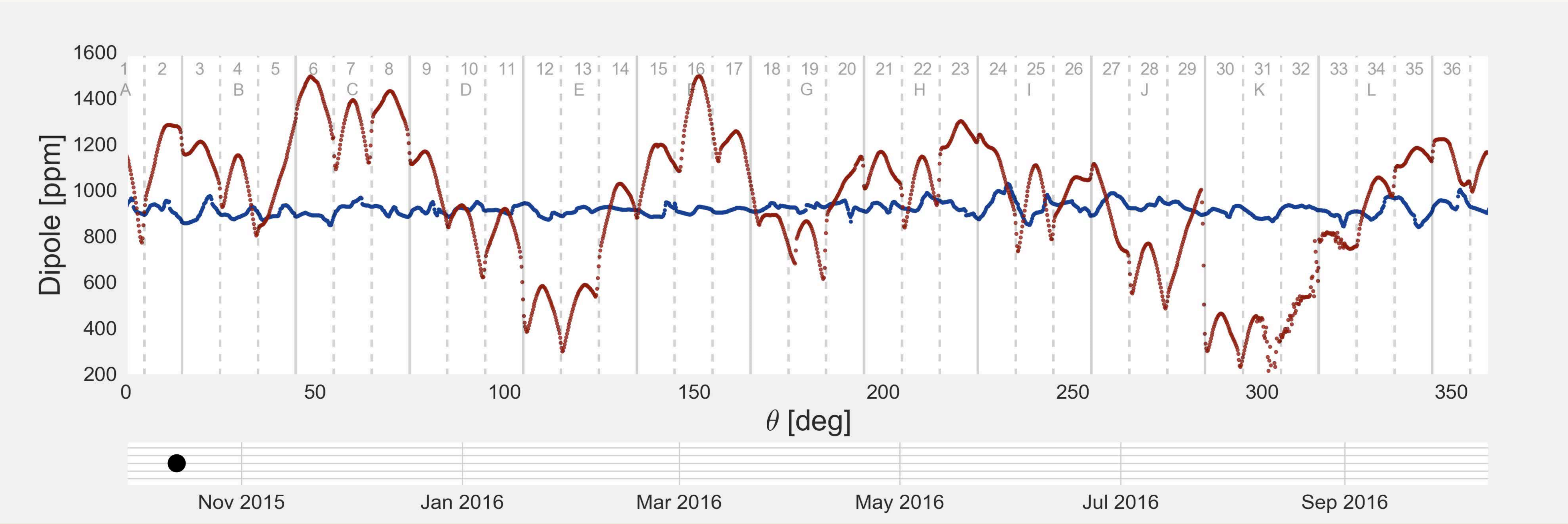

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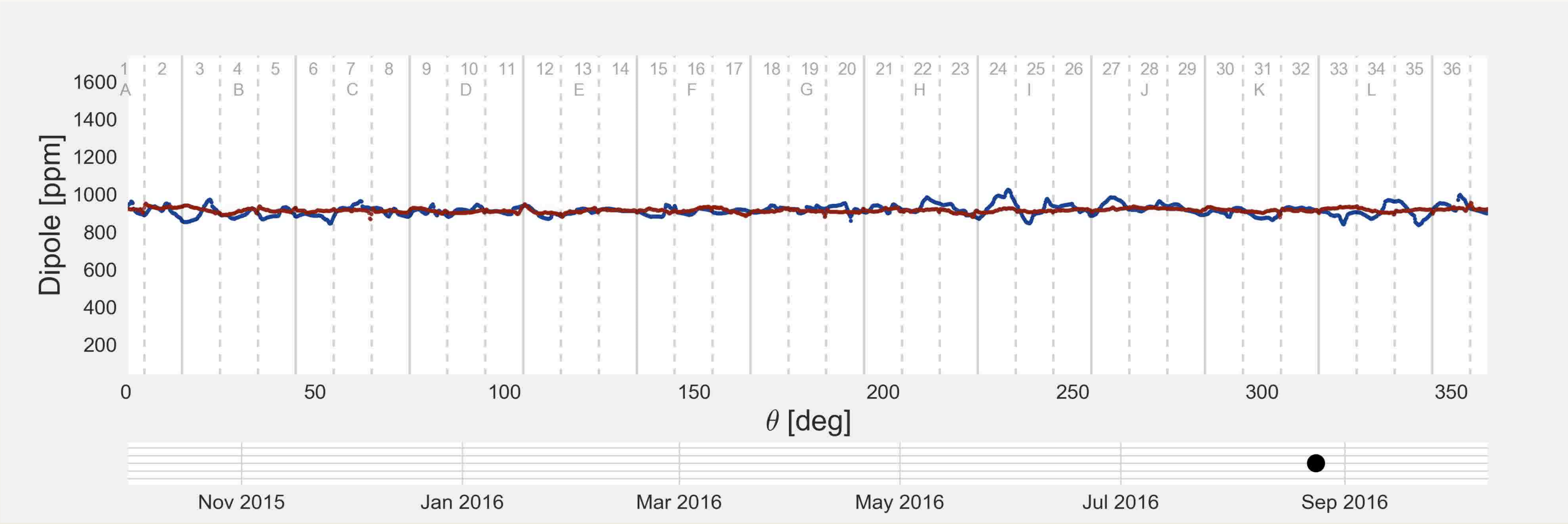

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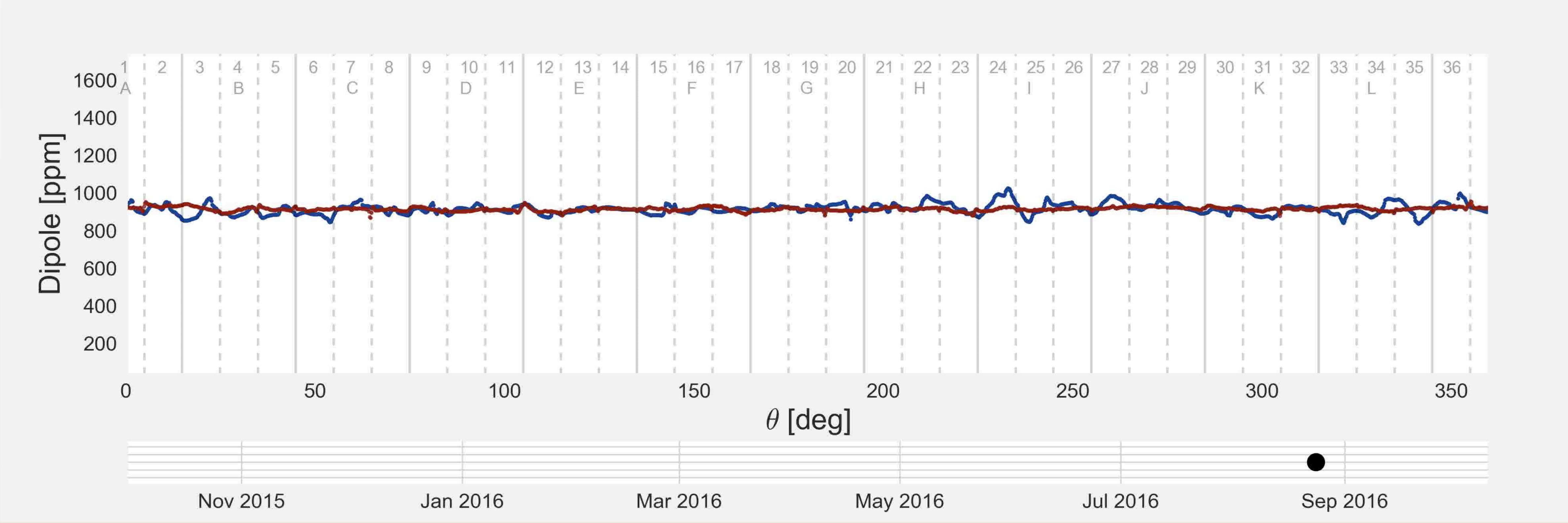

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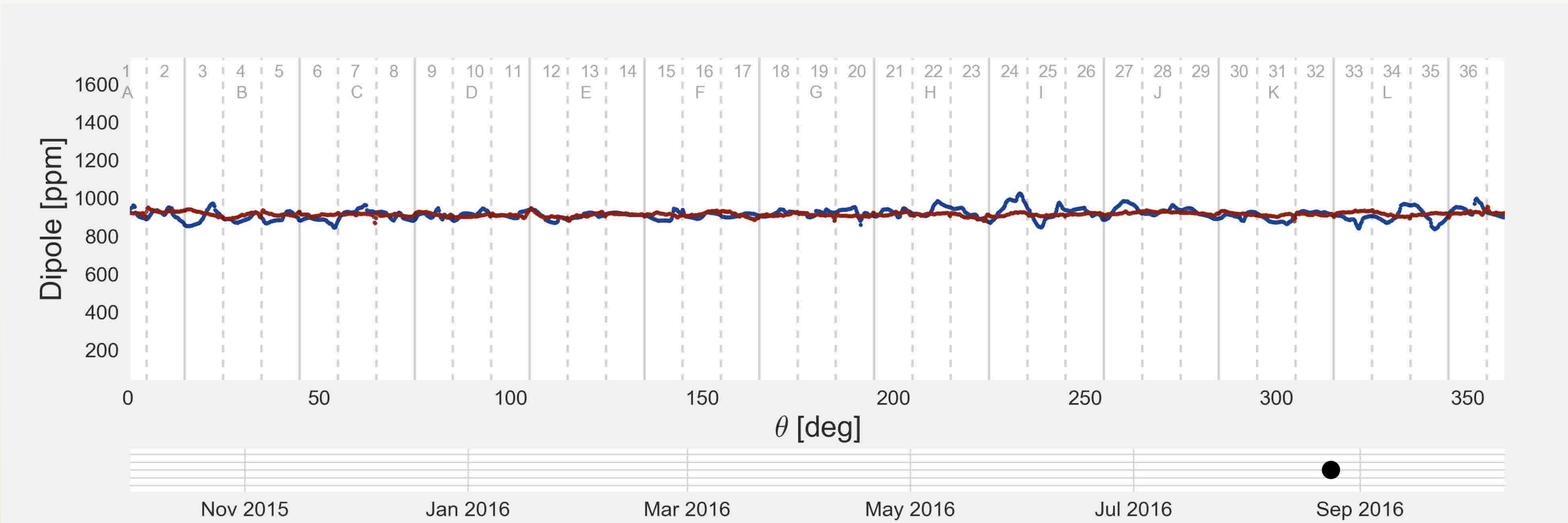

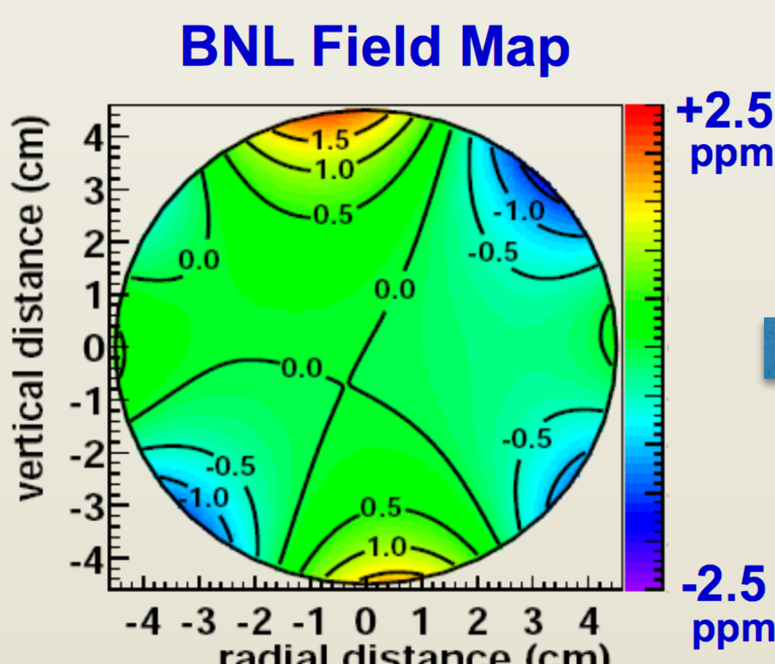

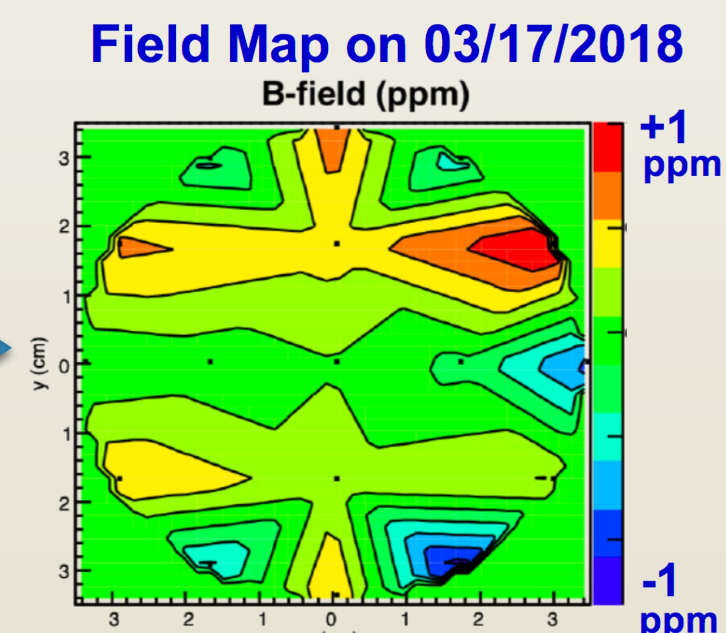

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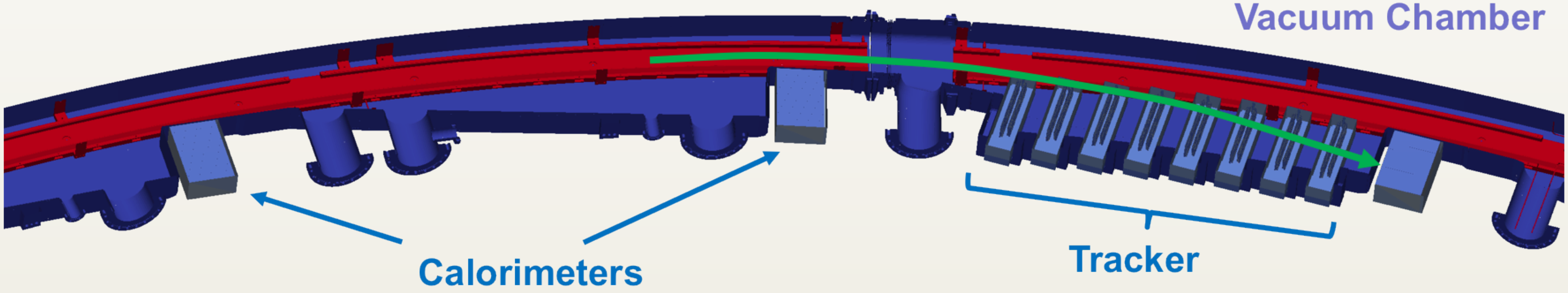
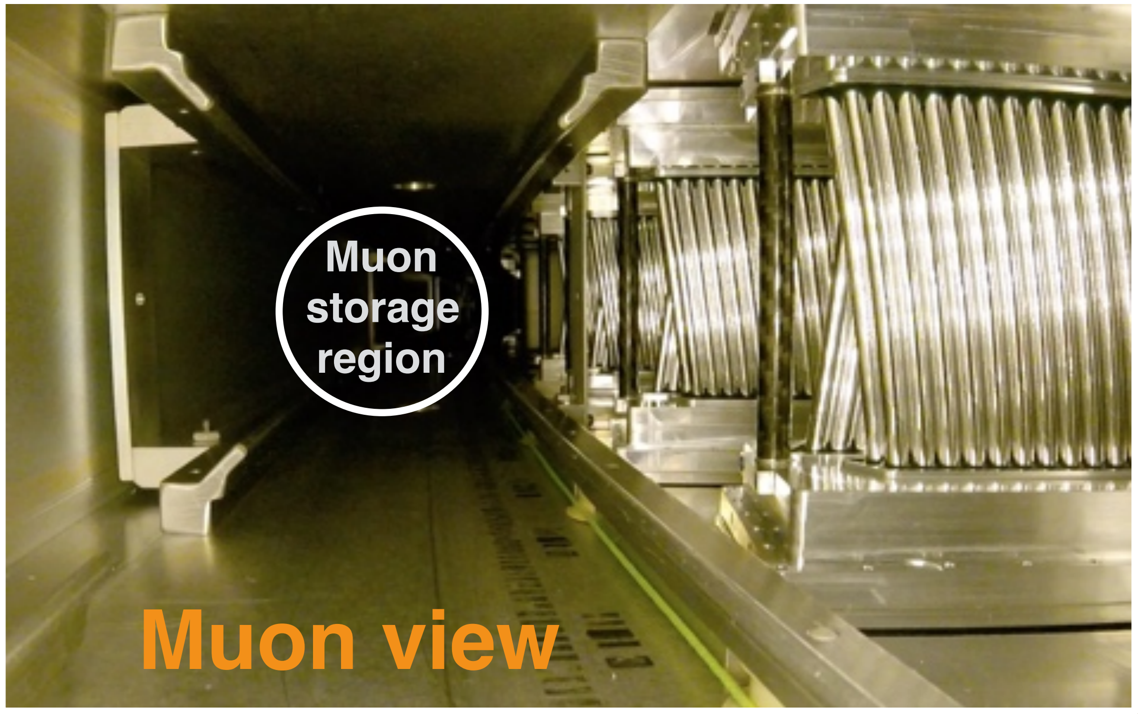
Beam profile measurement

- Two tracker stations for monitoring





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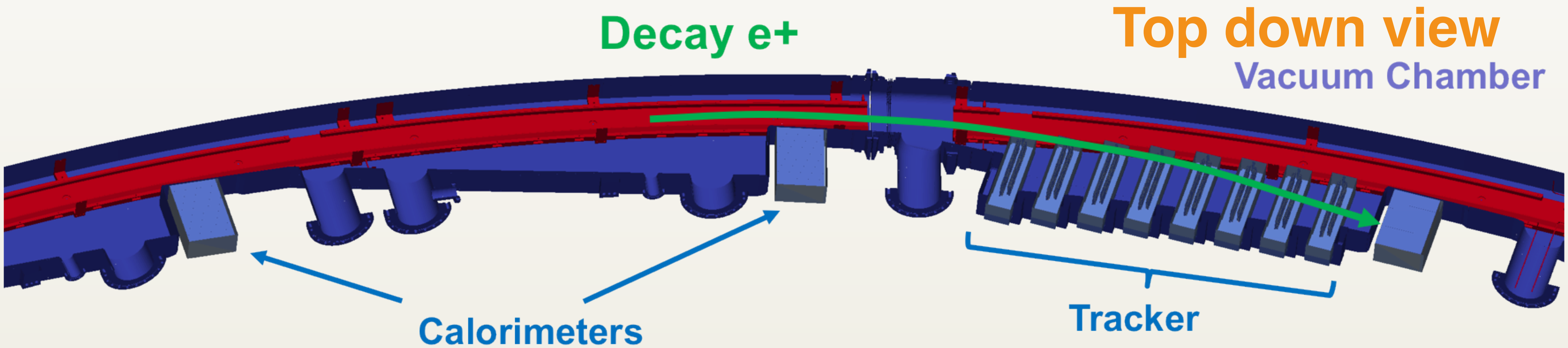
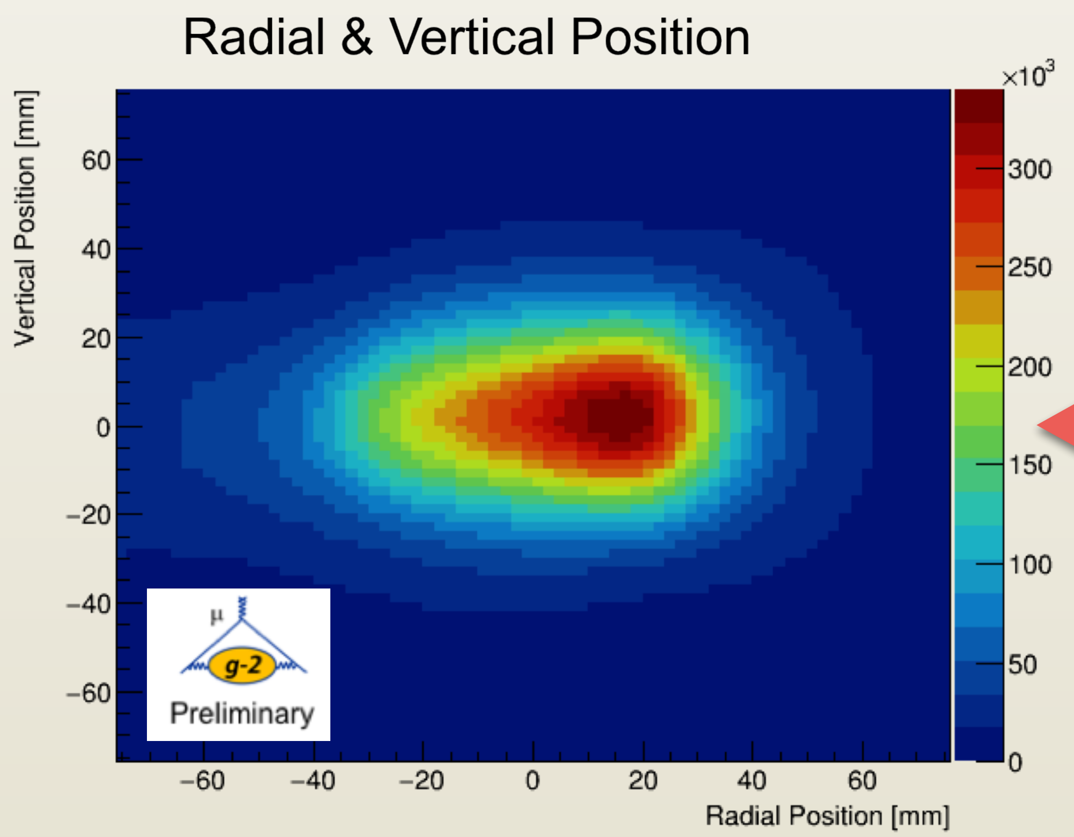
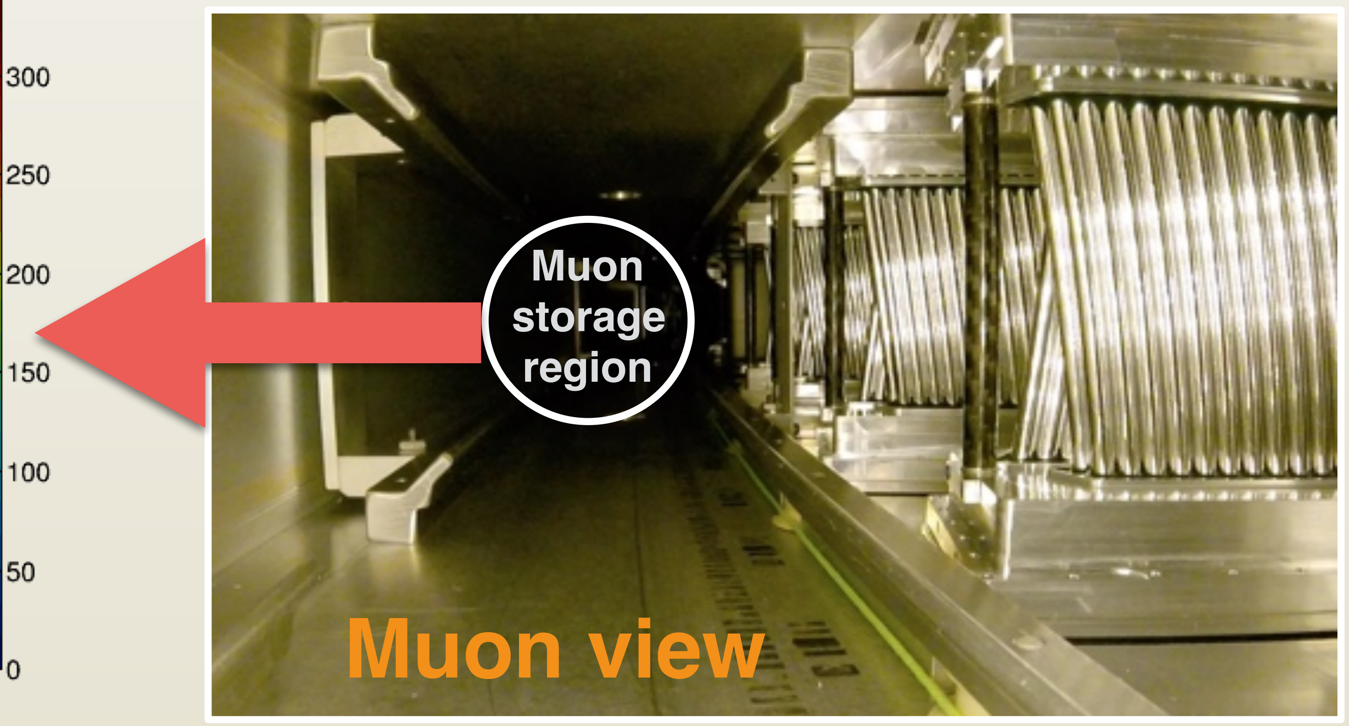


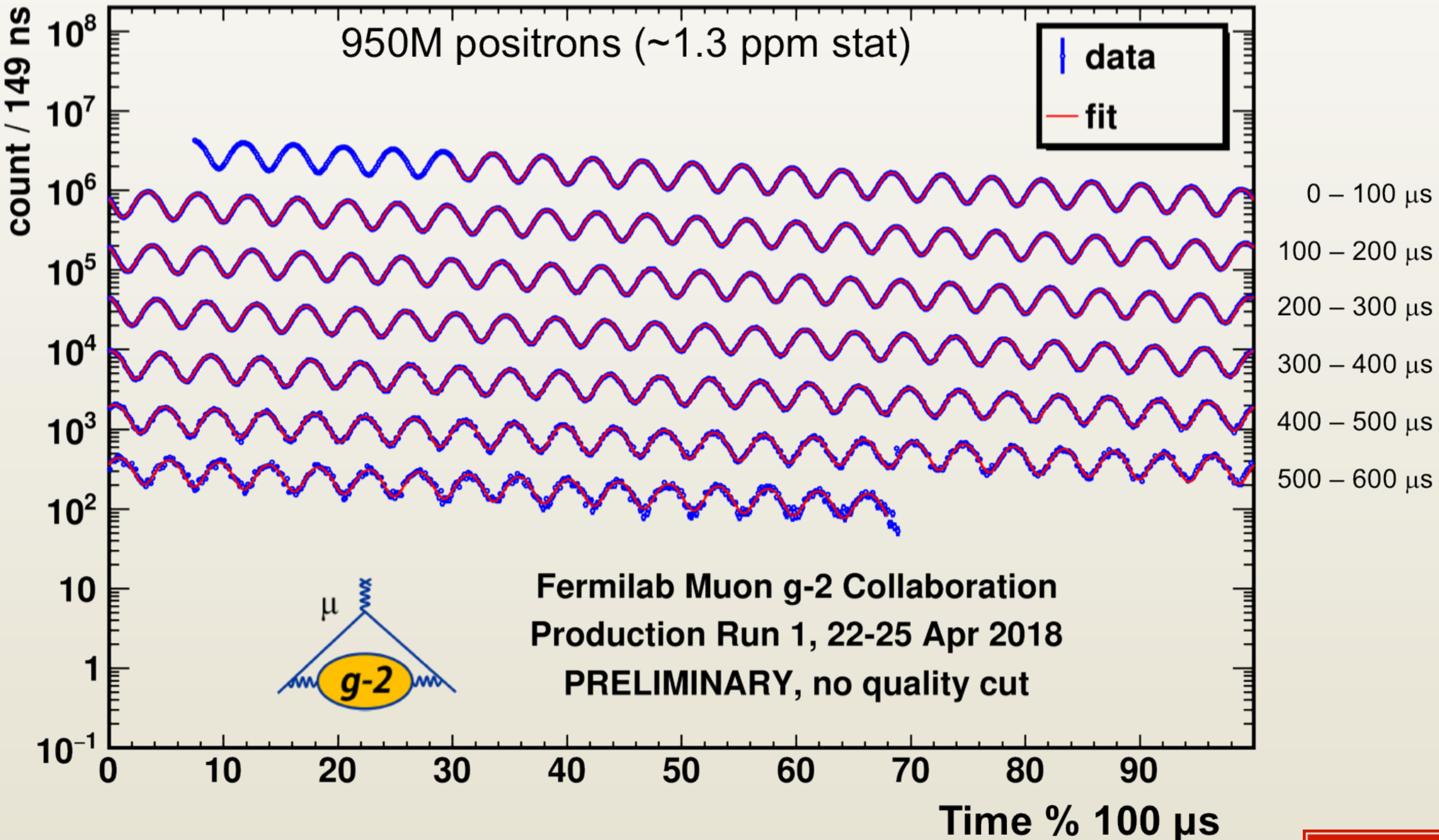




Preliminary data: ω_a oscillation

- Number of positrons (E > 1.8 GeV) as function of time:

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



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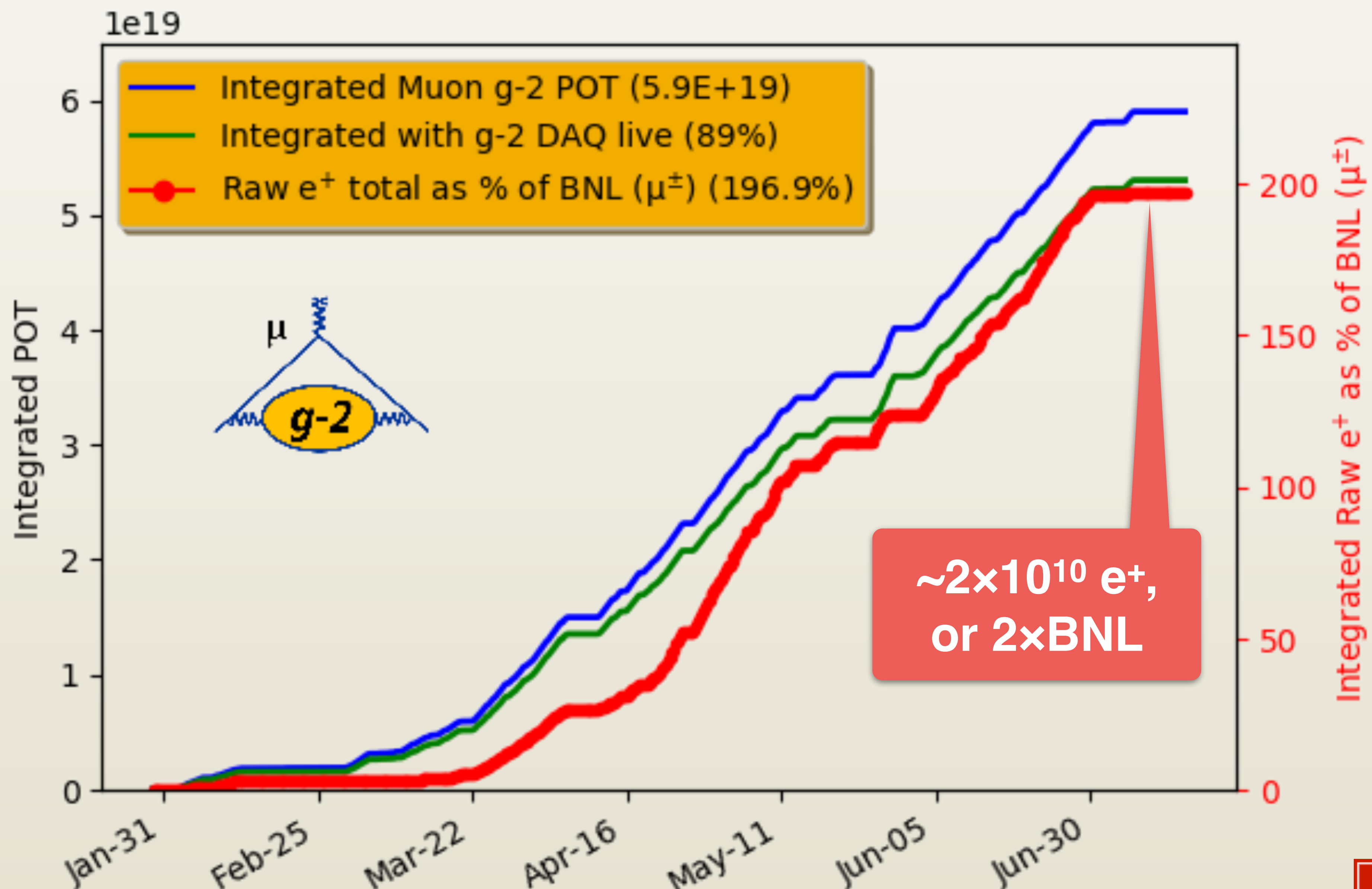
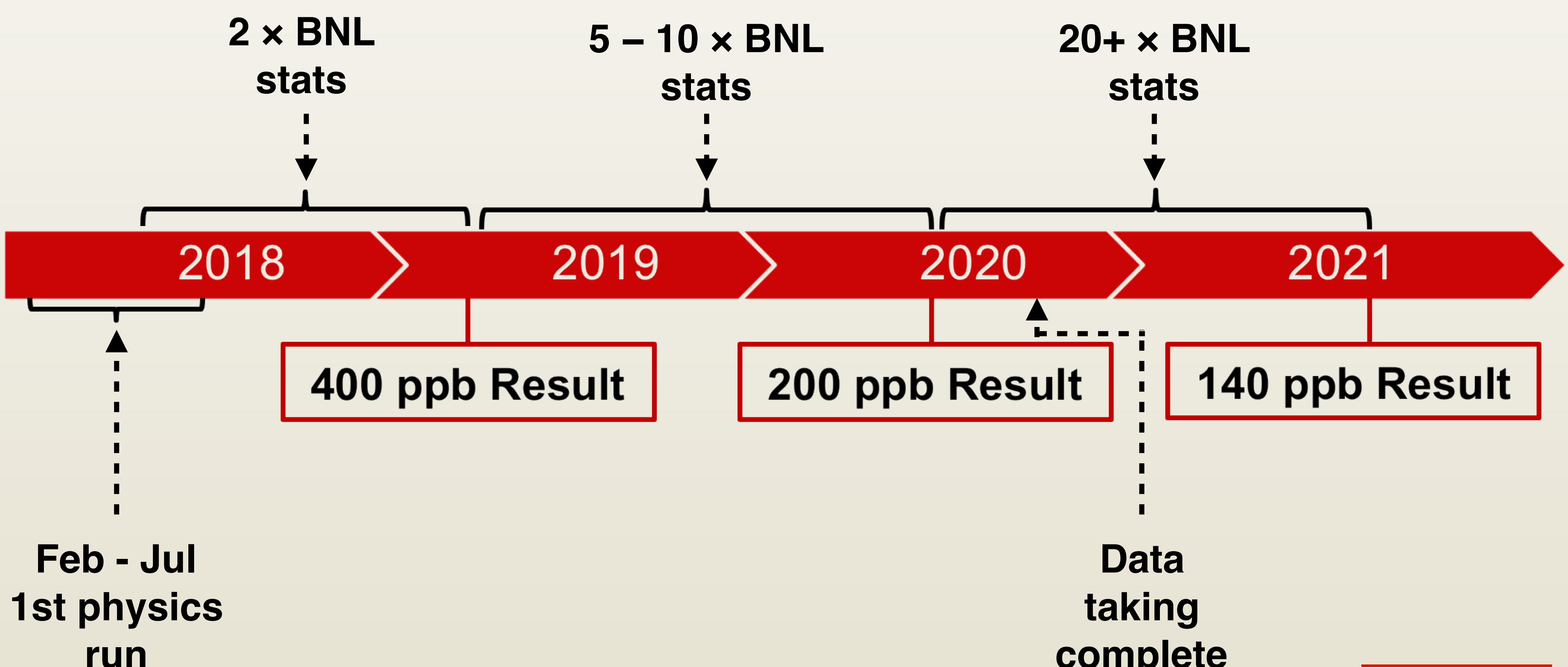
Accumulated statistics

- First physics run from Feb. to early Jul. 2018: 1/10 of targeted number of positrons collected



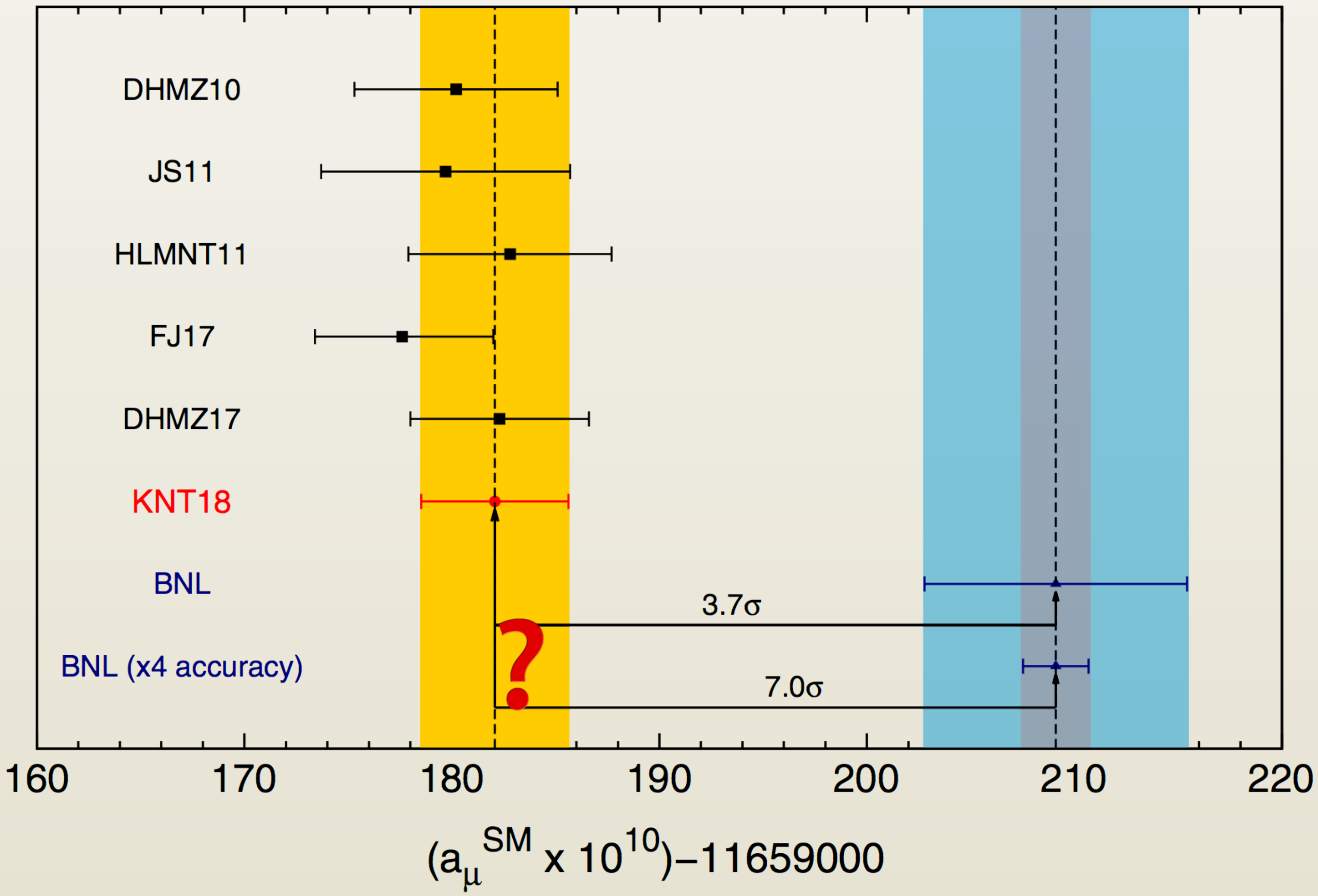
Outlook

- Just finished the first physics run
- Upgrading elements of the storage system
- Analysis of the first dataset in progress
- 3 papers on a_μ planned



Summary

- It is an interesting time for muon g-2!
  - lots of progress from the Theory Initiative
  - production data taking has been started
- Detectors performed well, analysis tool chain is ready
- First result from $2{\times}10^{10}$ e^{+} is scheduled for early 2019



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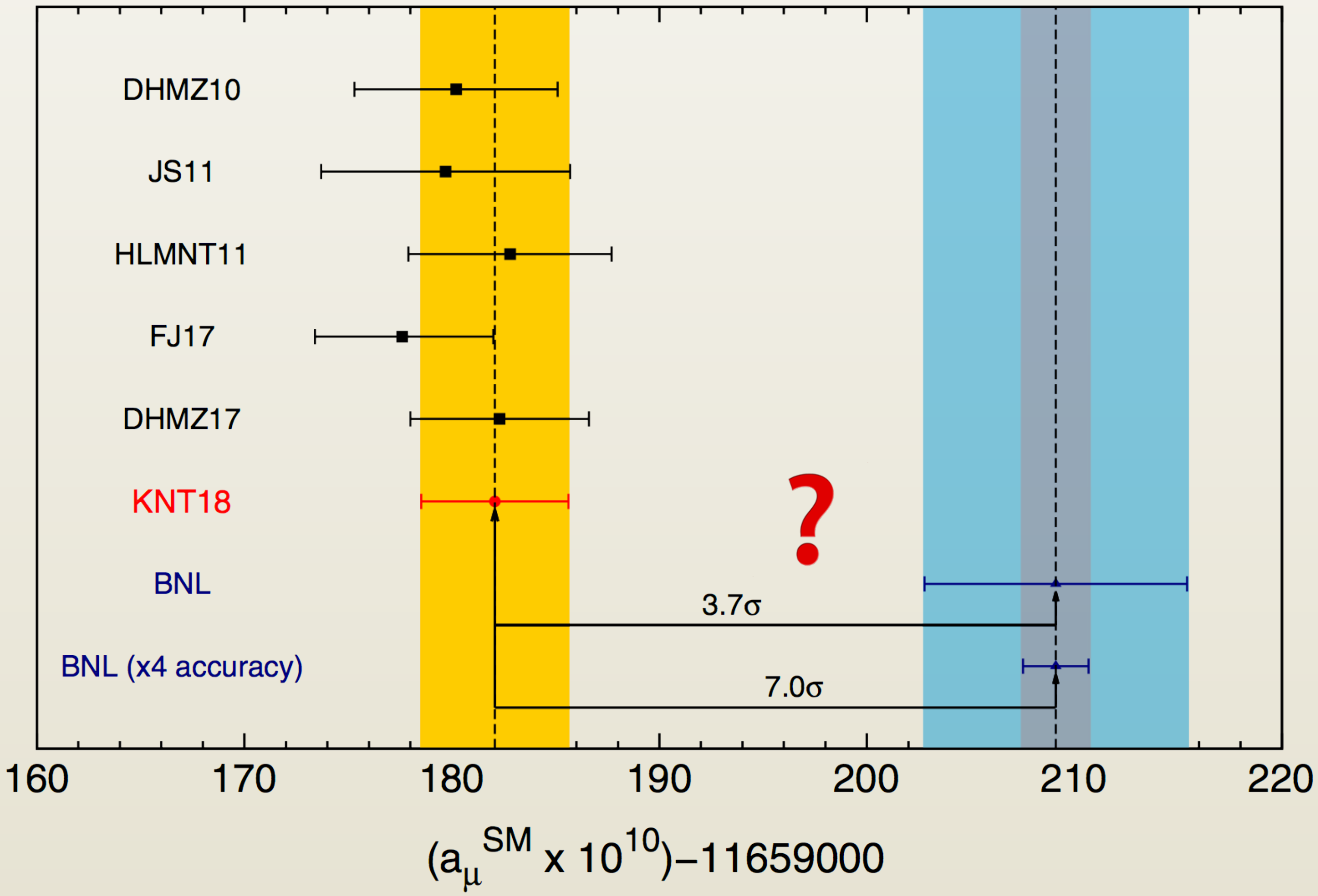

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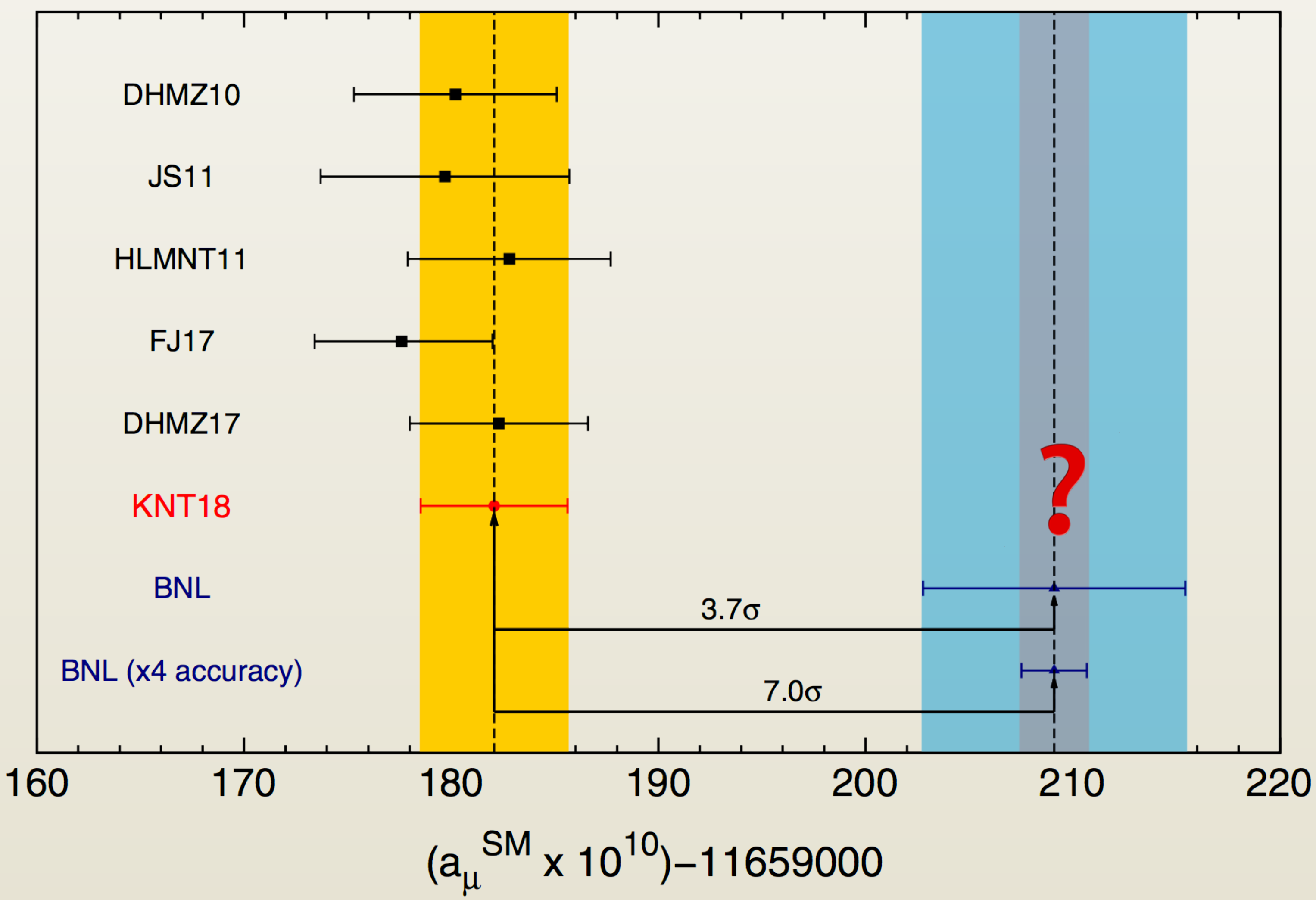

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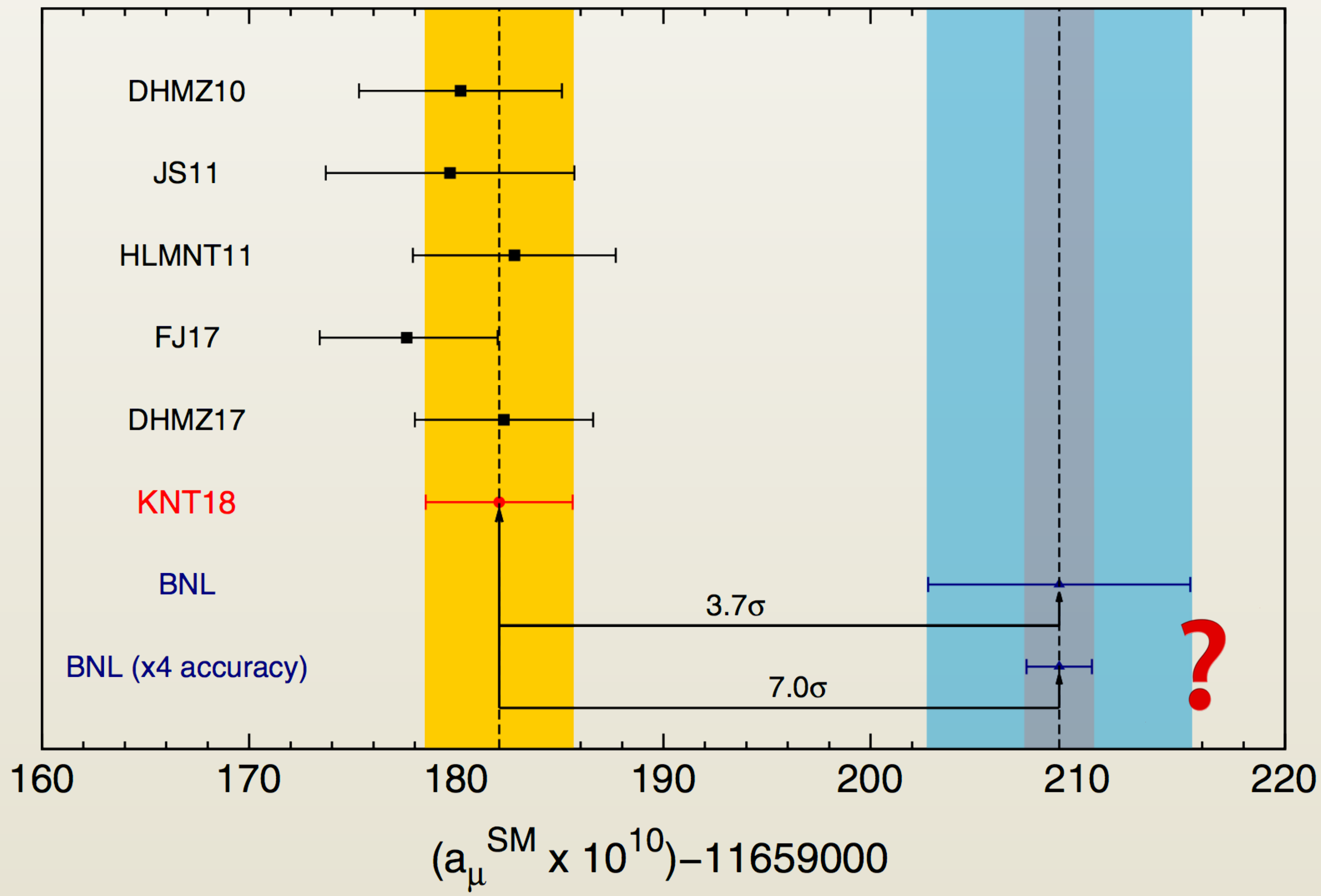

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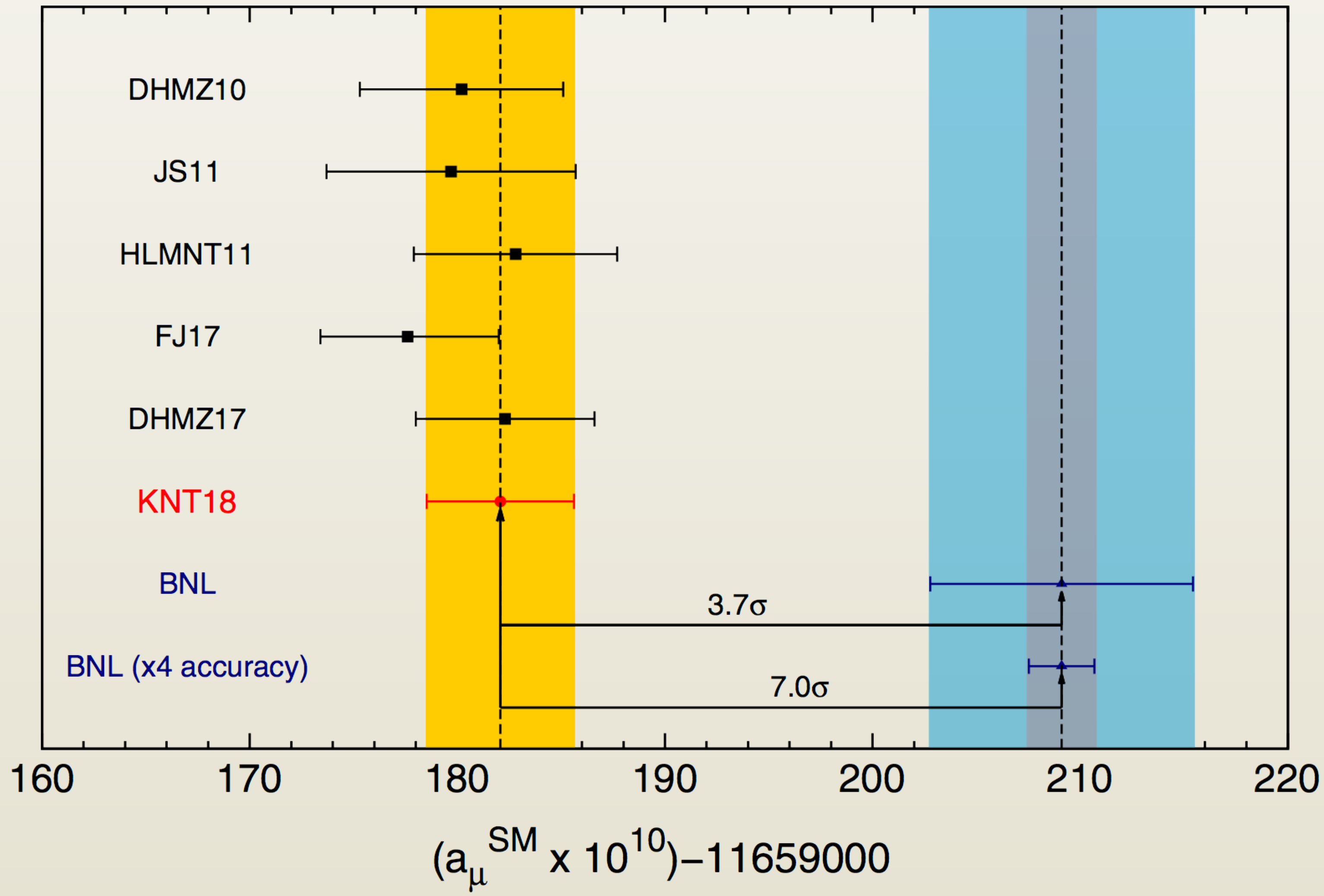

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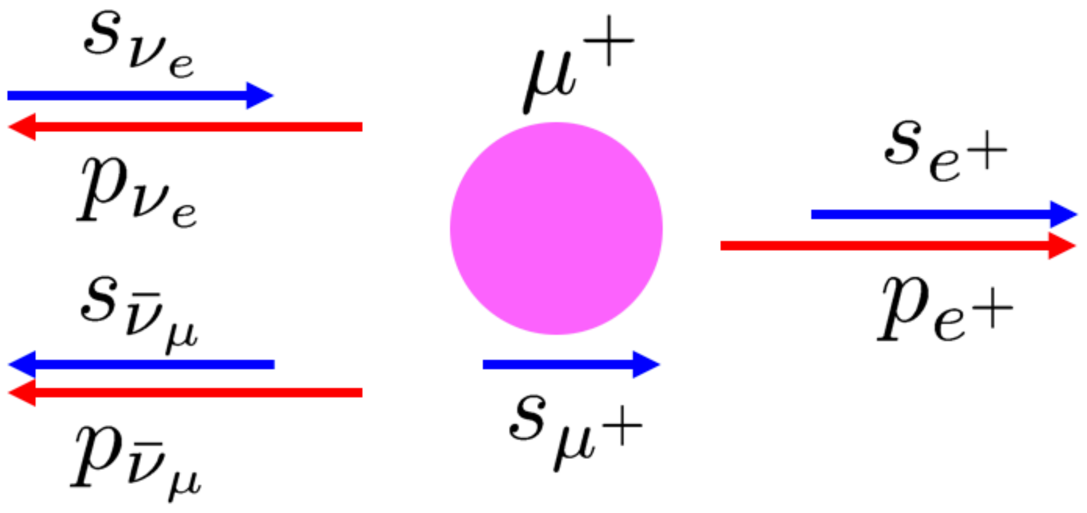
Backup

ω_a measurement

- Highest energy positrons are correlated with the muon spin



- As the μ^+ spin precesses towards and away from the calorimeters the number of high energy e^+ is modulated

- The muons pass the calorimeters at cyclotron frequency ω_c, so the modulation occurs at the difference freq, ω_a

Why a_μ and not a_e

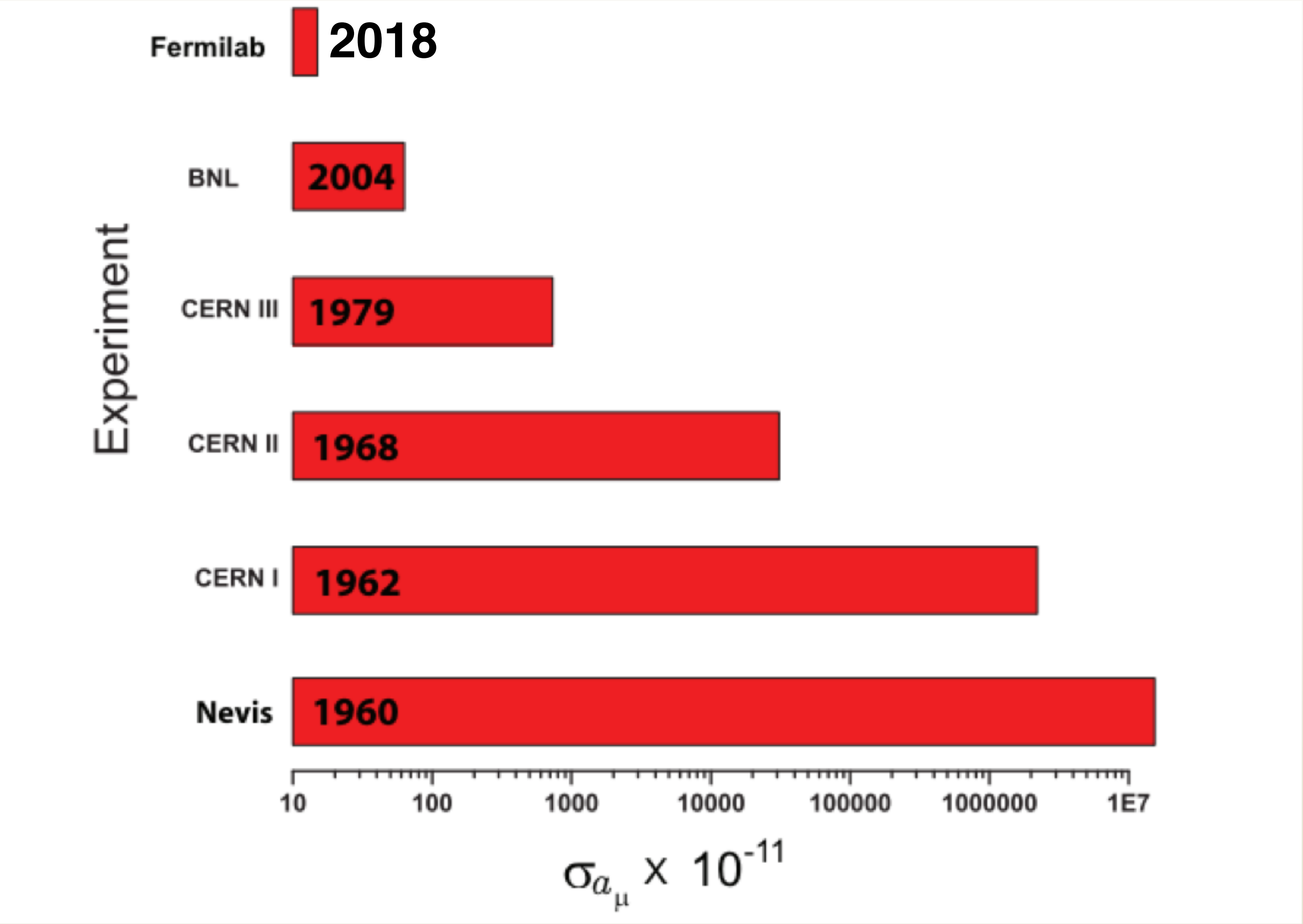
- Coupling of virtual loops goes as m^2
- Therefore, while a_μ is measured much less precisely than the a_e, it has better sensitivity to heavy physics scales:

$$\left(\frac{m_\mu}{m_e}\right)^2 \simeq 43,000$$

- E.g. lowest-order hadronic contribution to a_e is

  $a^{had,LO} = (1.875 \pm 0.017) \times 10^{-12}$ (1.5 ppb of a_e)
- By comparison, for the muon the hadronic contribution is ~60 ppm.

Muon g-2 measurement uncertainties



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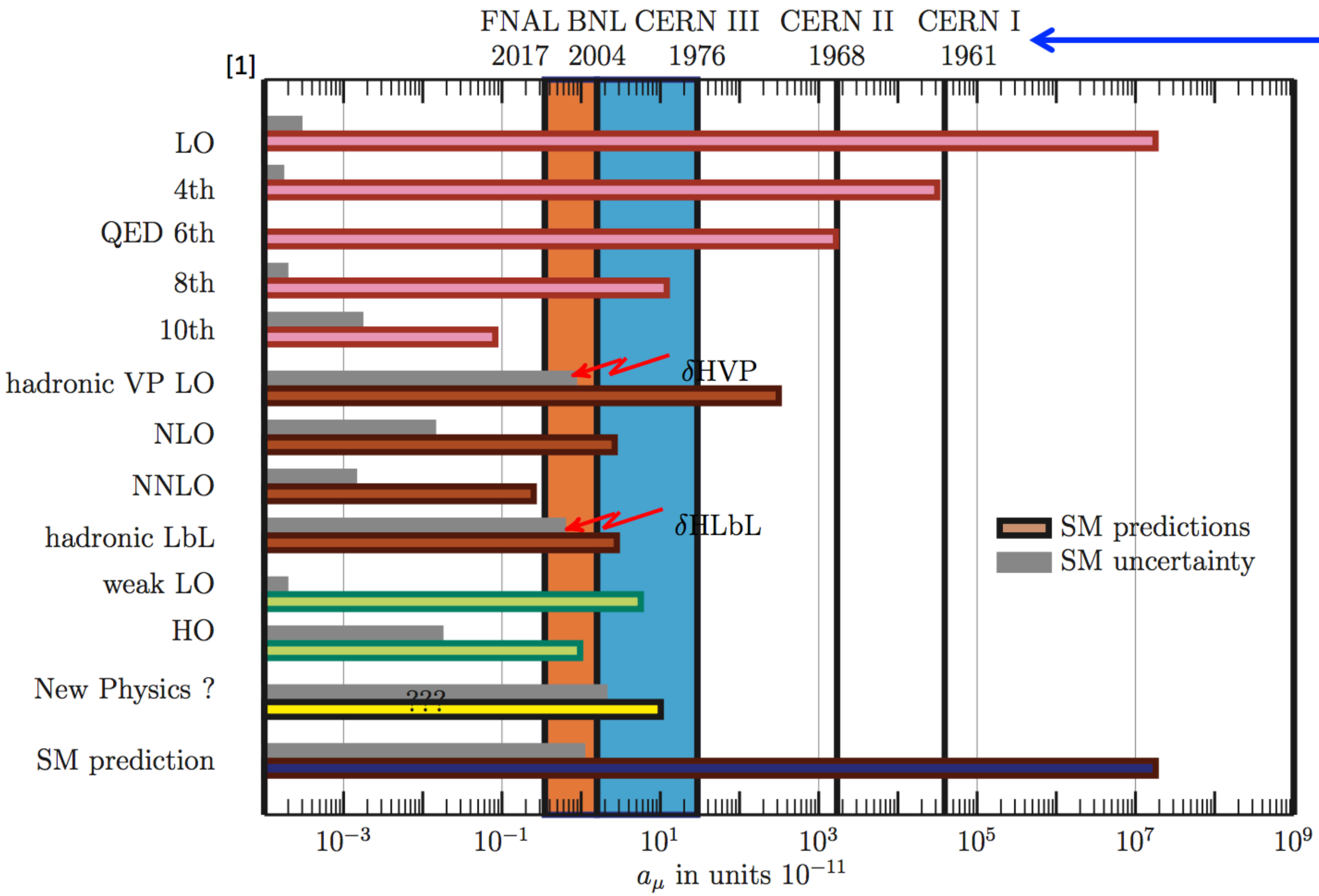


Measurement precision achieved by different experiments

LO = Leading Order
QED = Quantum Electrodynamics
VP = Vacuum Polarization
NLO = Next To Leading Order
NNLO = Next To Next To Leading Order
LbL = Light-by-Light
HO = Higher Order
SM = Standard Model

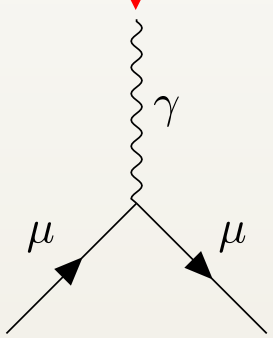
3

[1] F. Jegerlehner, EPJ Web Conf. **166**, 00022 (2018) doi:10.1051/epjconf/201816600022 [arXiv:1705.00263 [hep-ph]].

a_μ in the Standard Model

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had, VP}} + a_\mu^{\text{had, LbL}}$$

$$= 0.001\,165\,918\,23(43)$$



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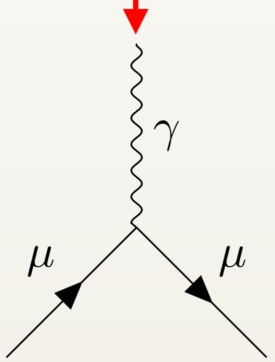

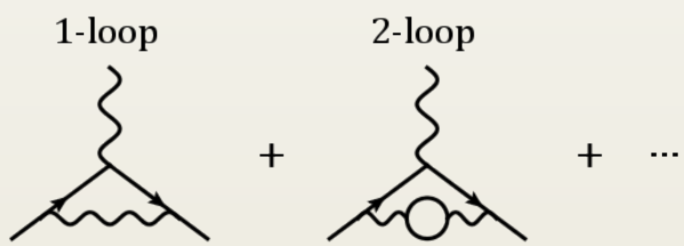

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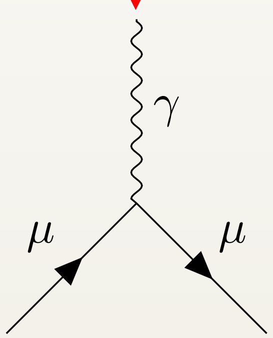

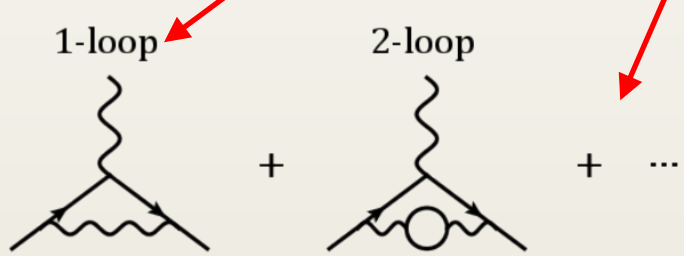

- QED:
  - known to 5-loop
  - 99.99% of a_μ^{SM}
  - ~0.001% of $\delta a_\mu^{\mathrm{SM}}$

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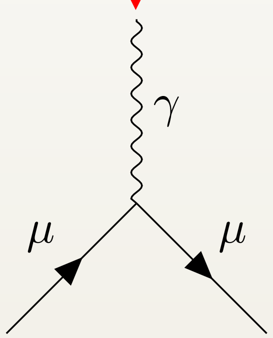

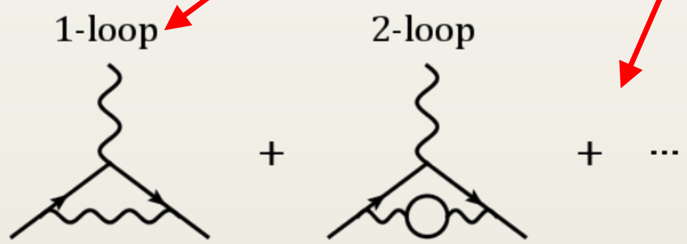

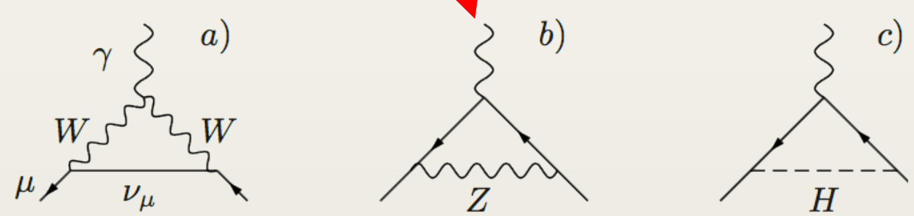

- QED:
  - known to 5-loop
  - 99.99% of a_μ^{SM}
  - ~0.001% of δa_μ^{SM}
- EW:
  - known to 2-loop
  - 0.0001% of a_μ^{SM}
  - 0.2% of δa_μ^{SM}

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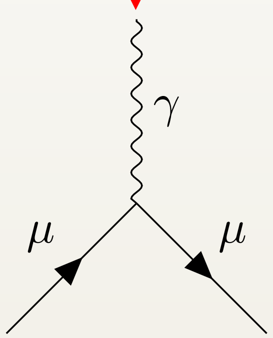
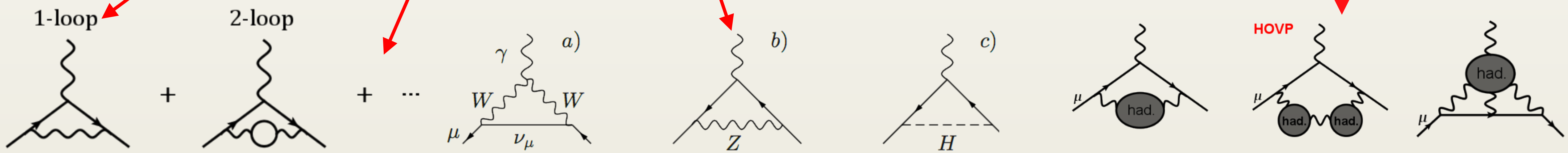
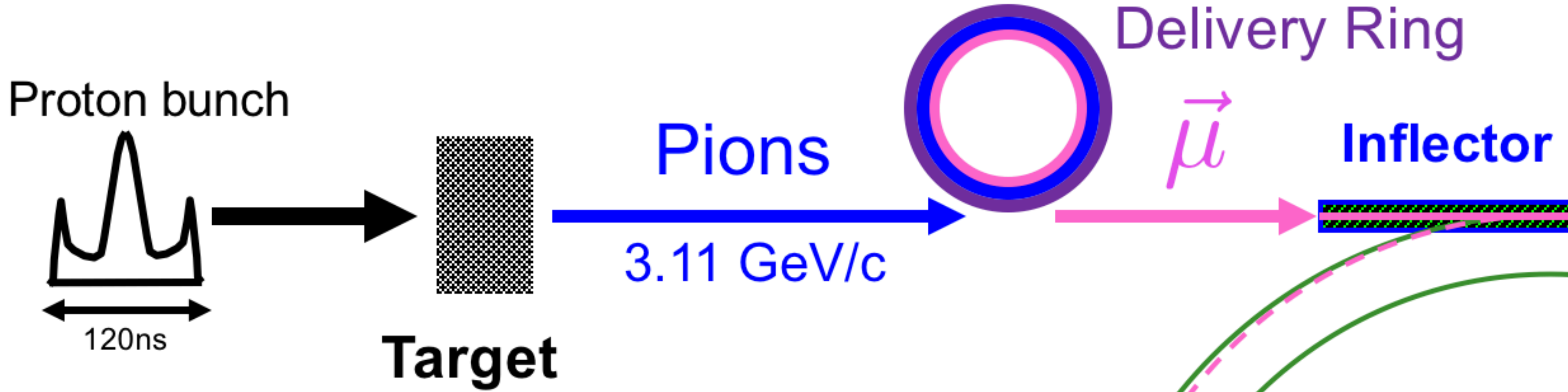
$$= 0.001\,165\,918\,23(43)$$

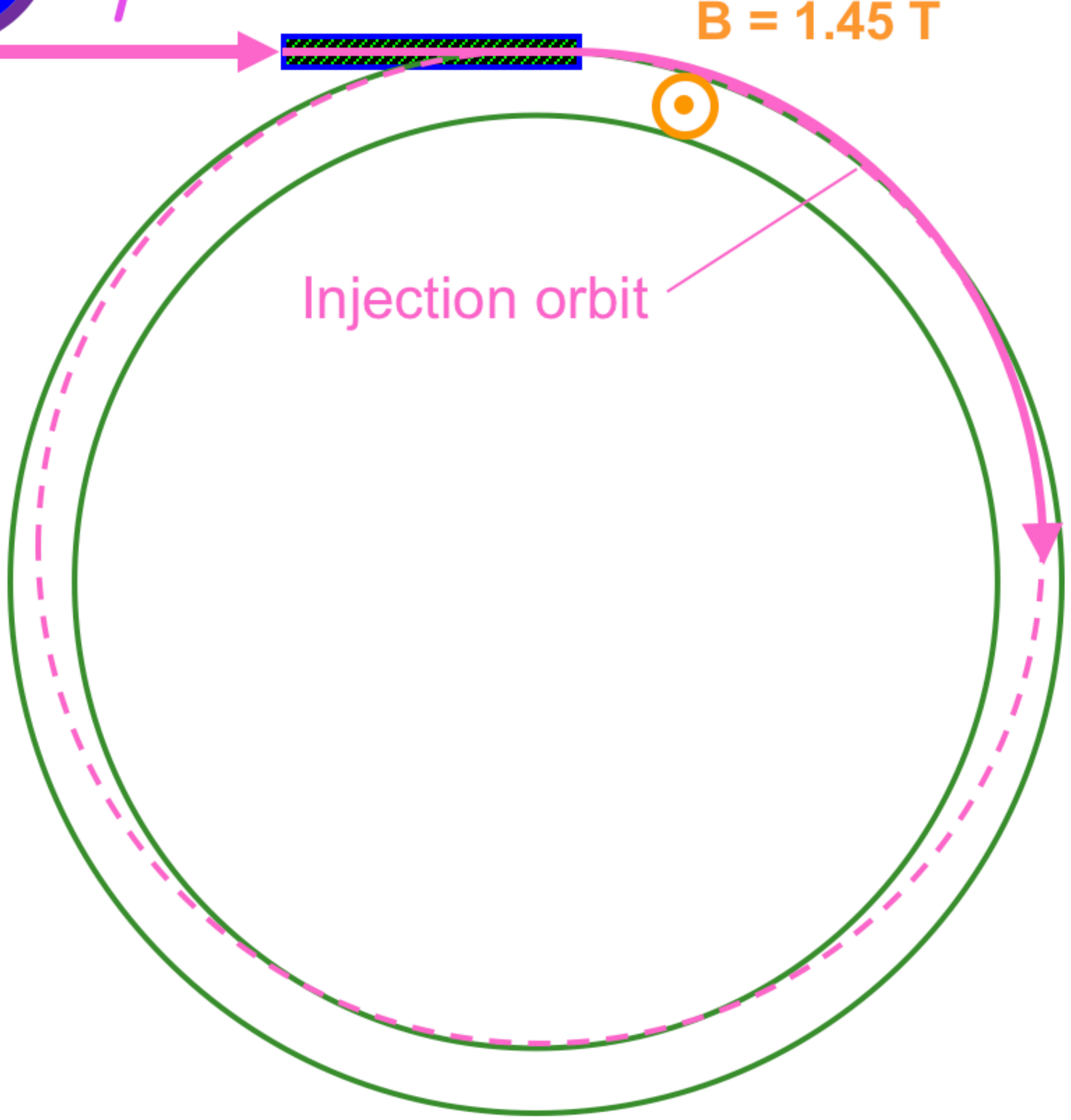


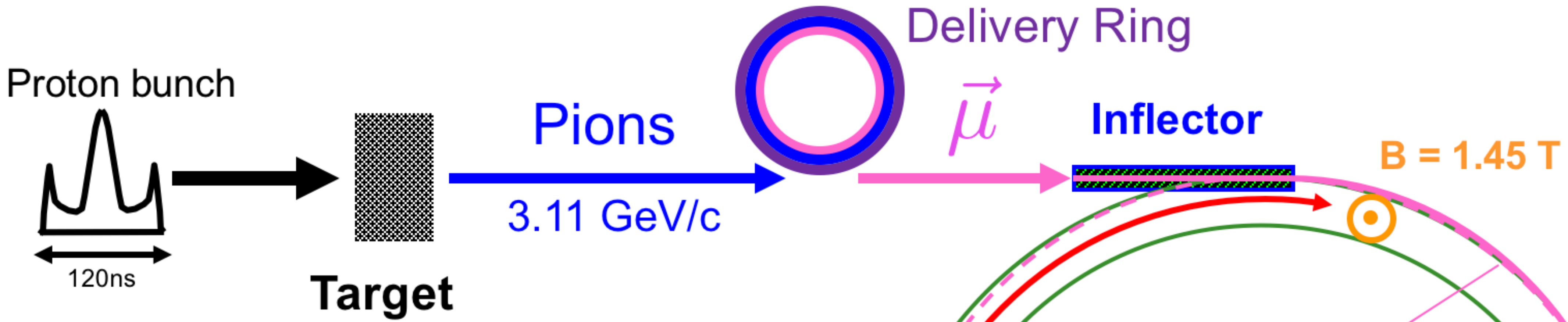


- QED:
  - known to 5-loop
  - 99.99% of $a_\mu^{\rm SM}$
  - ~0.001% of $\delta a_\mu^{\rm SM}$
- EW:
  - known to 2-loop
  - 0.0001% of $a_\mu^{\rm SM}$
  - 0.2% of $\delta a_\mu^{\rm SM}$
- Hadron:
  - 0.006% of $a_\mu^{\rm SM}$
  - ~99.8% of $\delta a_\mu^{\rm SM}$

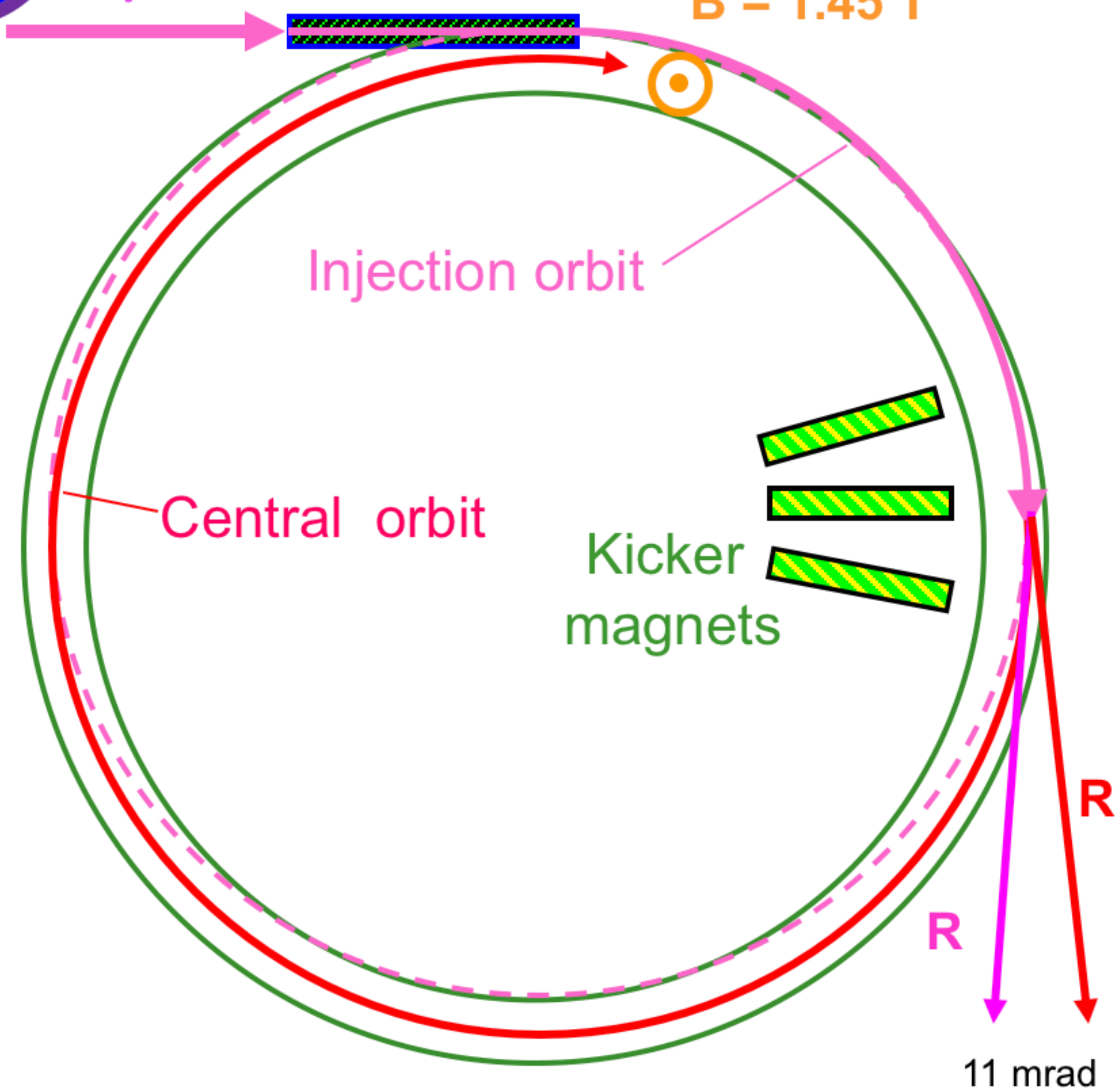


- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit





- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Magnetic kicker moves the orbit to the centre of the storage ring



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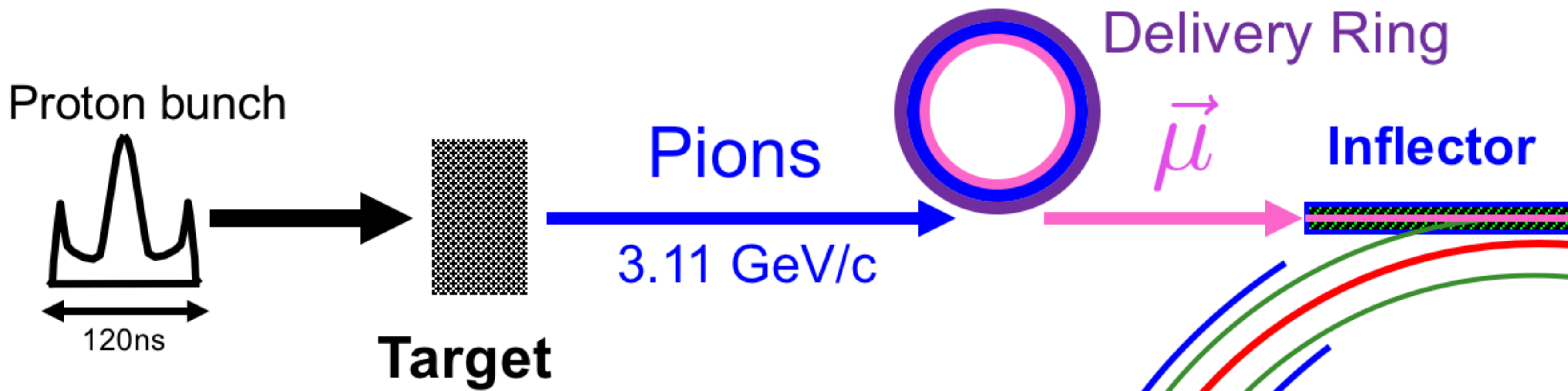
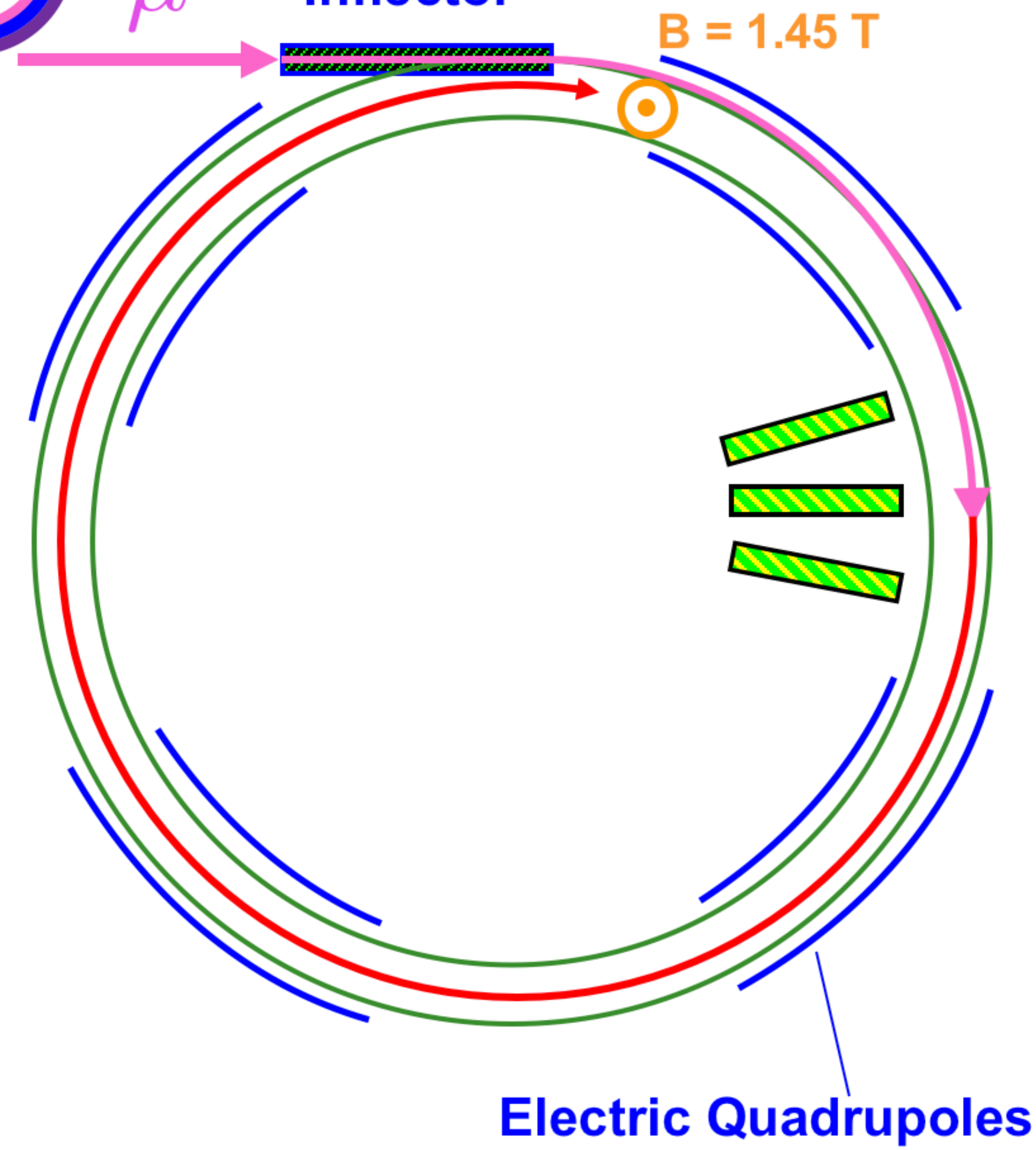


- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Magnetic kicker moves the orbit to the centre of the storage ring
- Muons focussed vertically with electrostatic quadrupoles



Muon EDM search

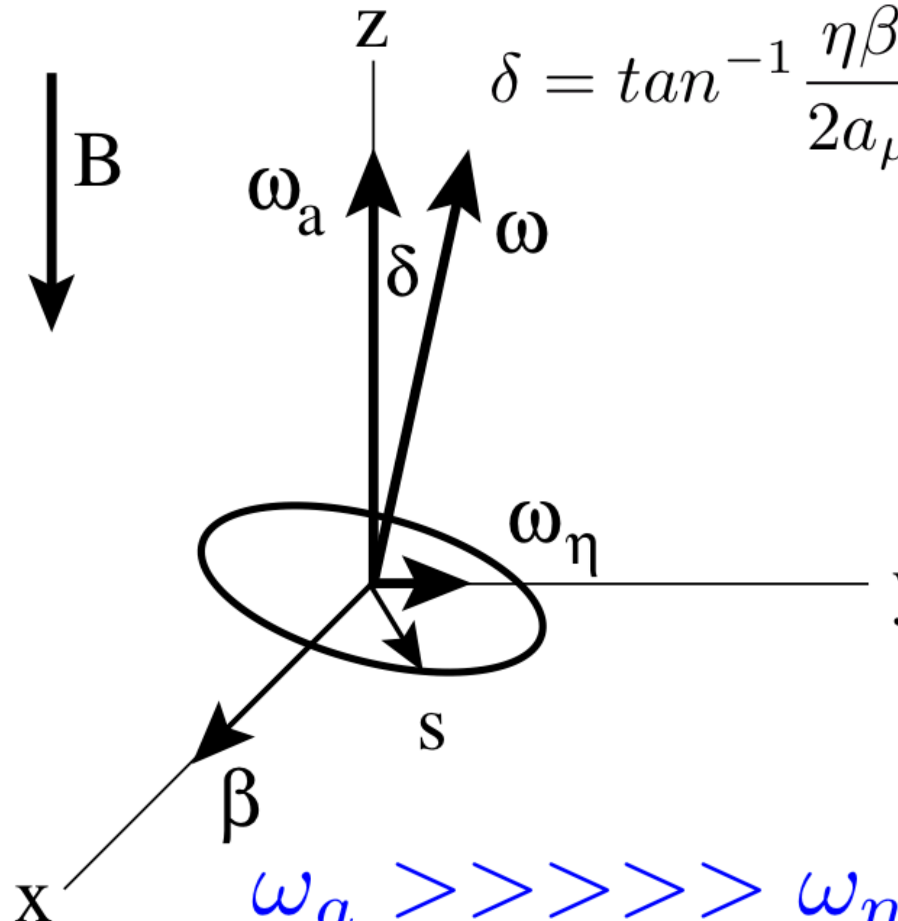
- A non-zero muon EDM would modify the spin equation

$$\vec{\omega}_{a\eta} = -\frac{Qe}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \eta\frac{Qe}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right]$$

- $\vec{\beta}\times\vec{B}$ dominates, so precession plane is tilted.

$$\delta = tan^{-1}\frac{\eta\beta}{2a_\mu}$$

$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2} = \sqrt{\omega_a^2 + \left(\frac{e\eta\beta B}{2m}\right)^2}$$



- Search for an up-down oscillation, out of phase with ω_a.

$$\omega_a >>>>> \omega_\eta$$

$$
\begin{aligned}
\boldsymbol{\Omega}_{\mathrm{a}}^{\mathrm{eff}} &= \boldsymbol{\Omega}_{\mathrm{s}}^{\mathrm{eff}} - \boldsymbol{\Omega}_{\mathrm{c}}^{\mathrm{eff}} \\
&= -\frac{e}{m}\Bigg(\left(1 + 3\epsilon^2\phi\right) a_\mu \mathbf{B} \\
&\qquad - \left[a_\mu - \frac{1}{\gamma^2 - 1} - \epsilon^2\phi\left(4 + a_\mu + \frac{3}{\gamma^2 - 1}\right)\right] \boldsymbol{\beta} \times \mathbf{E} \\
&\qquad - a_\mu \frac{\gamma}{\gamma + 1}\left(1 - \epsilon^2\phi(2\gamma - 1)\right)(\boldsymbol{\beta}\cdot\mathbf{B})\,\boldsymbol{\beta}\Bigg). \qquad (73)
\end{aligned}
$$

2.8×10^{-9} exactly cancel the 3.6σ discrepancy

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The GR paper, and why it was wrong (?)

$$\left[\left(a_\mu - \frac{1}{\gamma^2-1}\right) \pm \xi\right] \frac{\vec{\beta}\times\vec{E}}{c}$$

$$= \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right) \frac{\vec{\beta}\times\vec{E}}{c}}_{\text{radial } E\text{-field correction}} \pm \xi \frac{\vec{\beta}\times\vec{E}}{c}$$

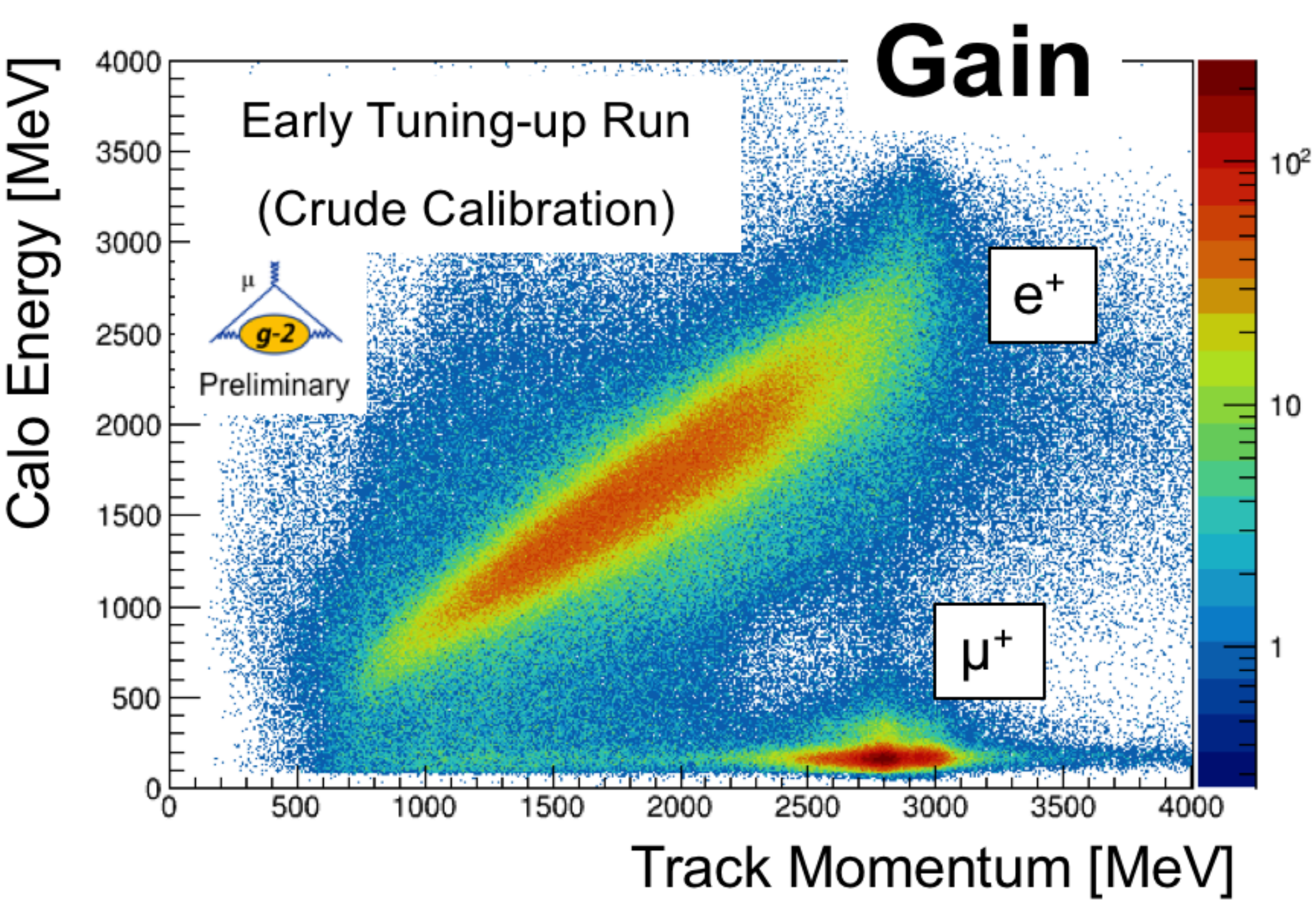
$$\frac{\Delta a_\mu}{a_\mu} = \frac{\xi \times \beta \times (E_r)_{avg}}{cBa_\mu} \tag{26}$$

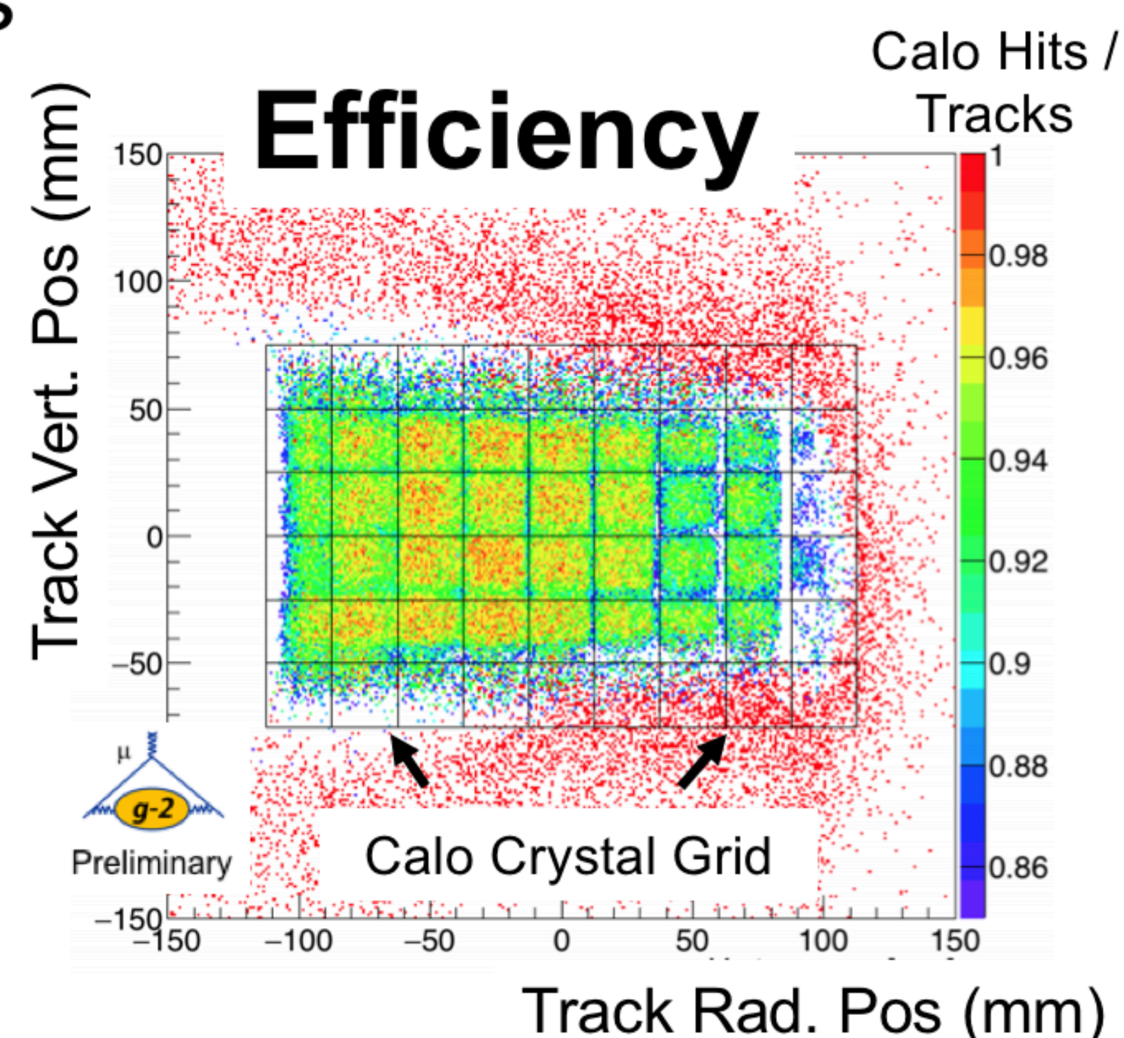
To calculate a numerical value, we use $B = 1.45$ T, $\beta = 0.9994$, $a_\mu = 1.1659 \times 10^{-3}$. Using these values and $\xi = 2.8 \times 10^{-9}$ one gets:

$$\frac{\Delta a_\mu}{a_\mu} = 1.4 \times 10^{-10}, \tag{27}$$

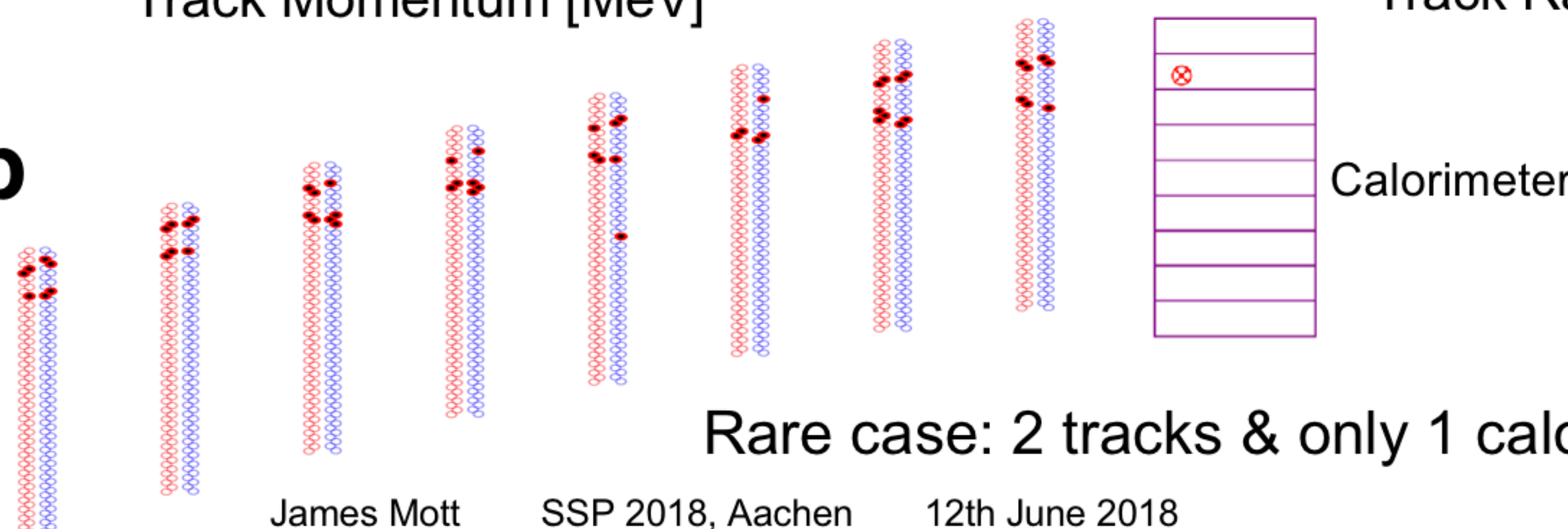
Tracker-Calorimeter Cross-checks

- Independent measurement of e^+ momentum, time and position for calo systematic checks





Pile-up



Rare case: 2 tracks & only 1 calo cluster