Talking: Mark Owen

Dipole moments and CLFV

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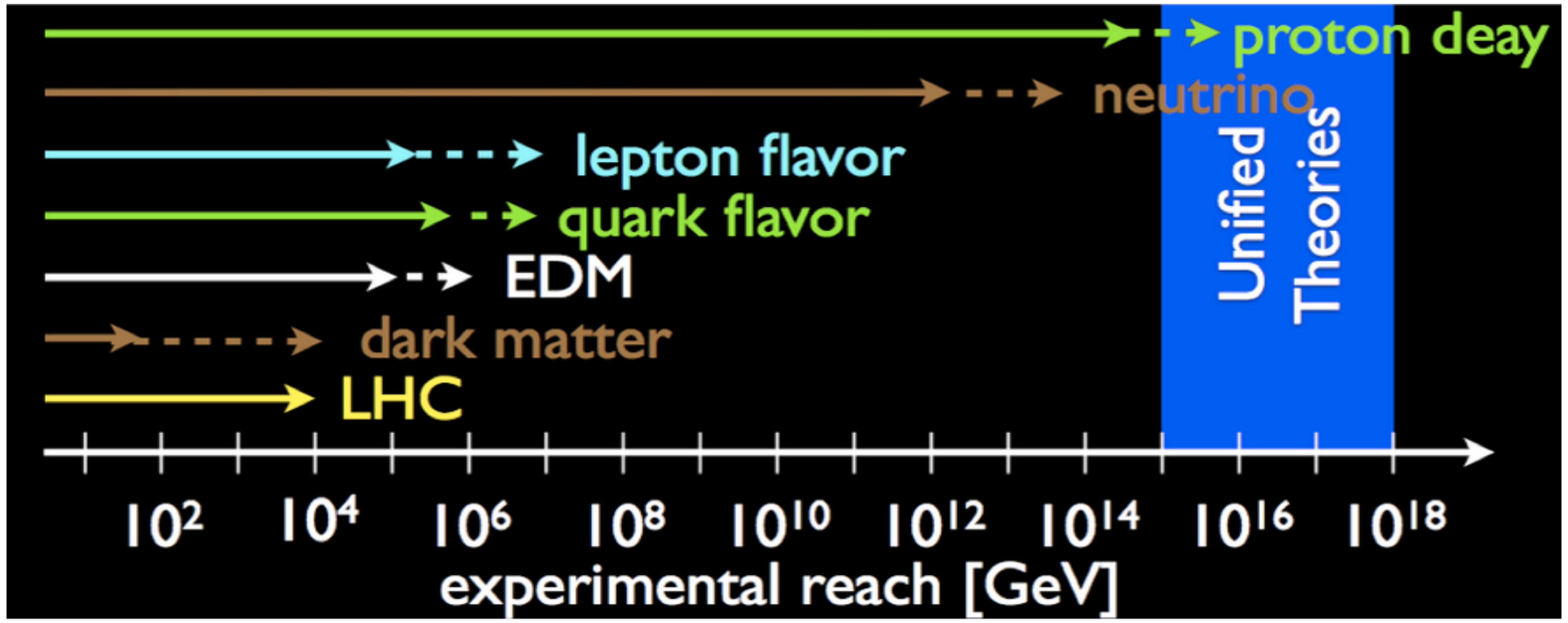
PPAP

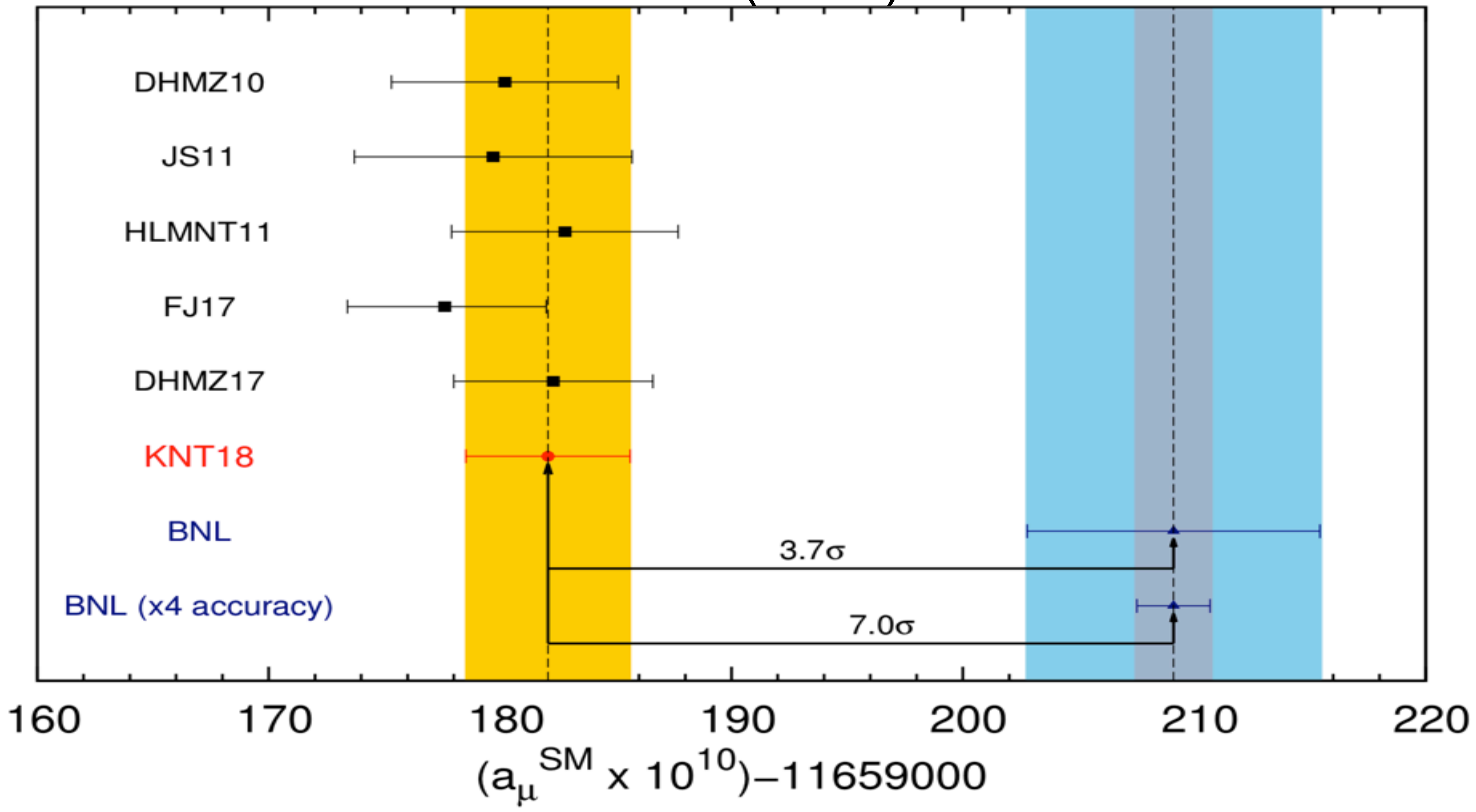
November 20th, 2020

Motivation

- High intensity muon beams herald new era of precision measurements to probe SM
- MDM, EDMs and CLFV offer new avenues for BSM models



PRD **97** 114025 (2018)



Fermilab: g-2, Mu2e

JPARC: COMET, g-2

PSI: Mu3e

UK involvement in all 3

g-2 experiment at FNAL

MDM: Measurement Principle

- Inject polarized muon beam into magnetic storage ring
- Measure **difference** between spin precession and cyclotron frequencies
- If g = 2, $\omega_a = 0$
- g ≠ 2, $\omega_a \cong (e/m_\mu)a_\mu B$

Spin precession freq.

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

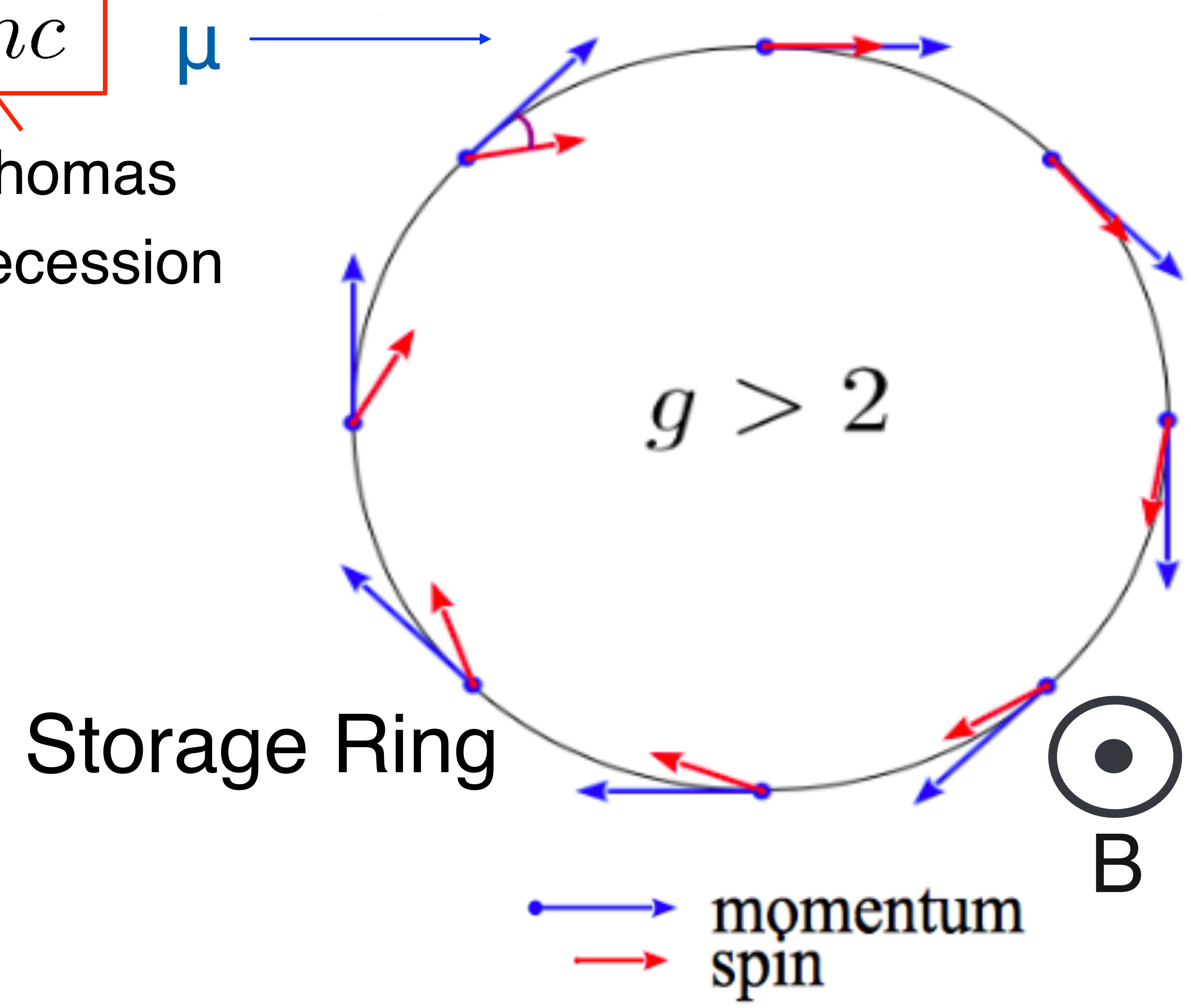
Larmor precession

Thomas precession

Cyclotron freq.

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

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

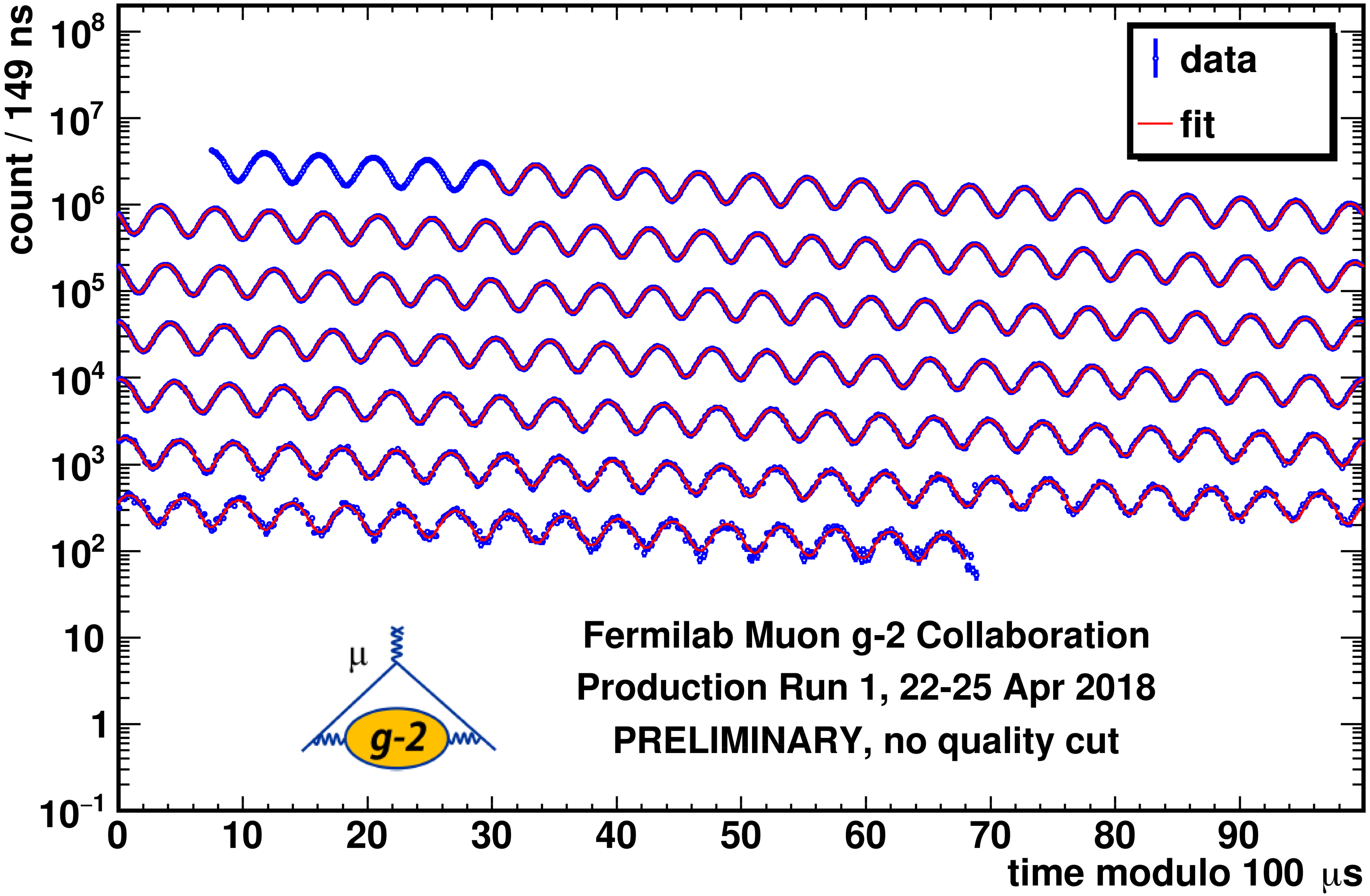


$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\underset{\underset{\text{3 ppb}}{\uparrow}}{\mu_e}}\frac{m_\mu}{\underset{\underset{\text{22 ppb}}{\uparrow}}{m_e}}\frac{g_e}{\underset{\underset{\text{0.3 ppt}}{\uparrow}}{2}}$$

Rev. Mod. Phys. **88**, 035009 (2016)

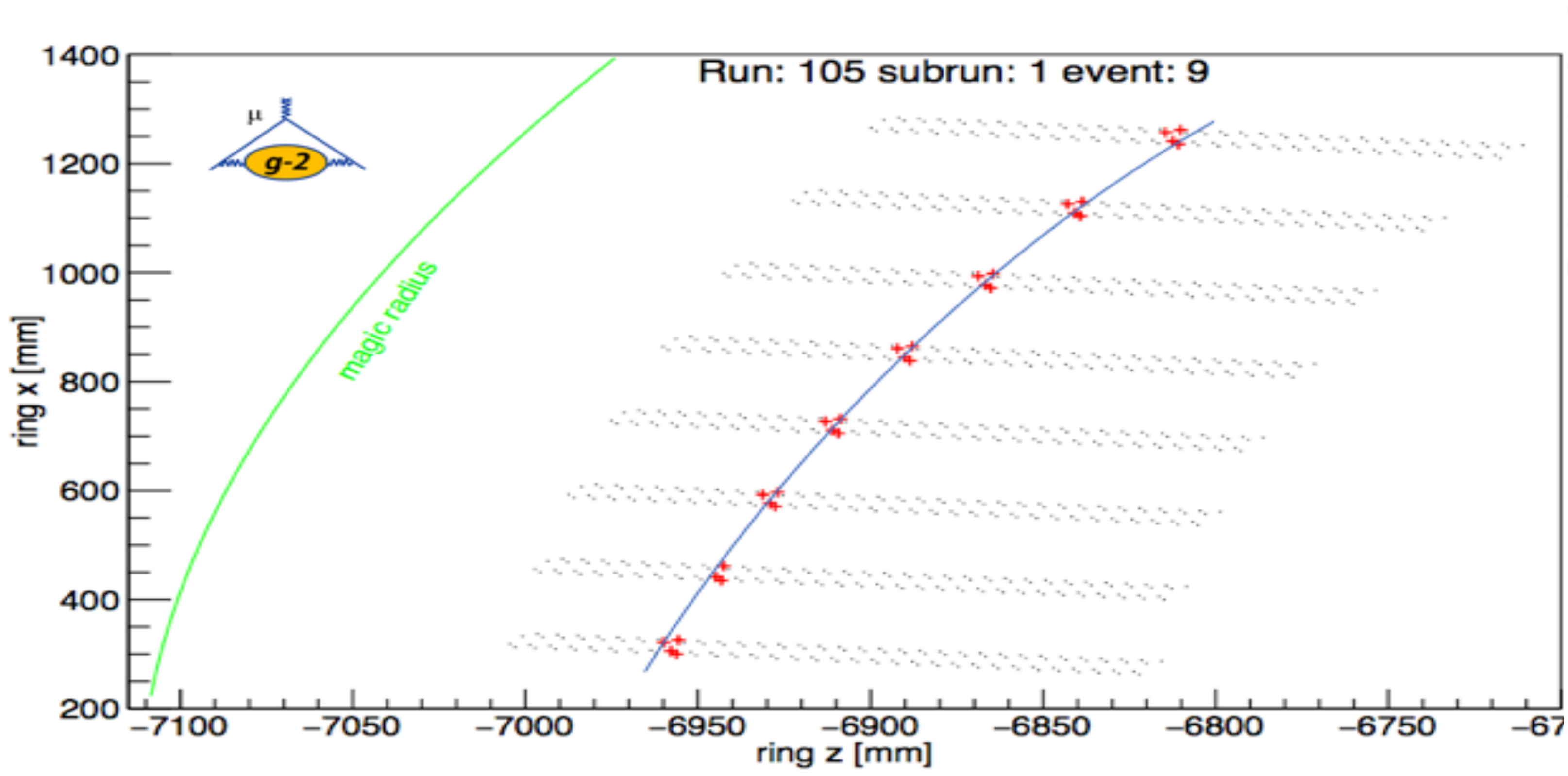
- We measure **ω_a** and **ω_p** separately
- Aiming for 70 ppb precision on each (systematic)
- **Target: δa_μ(syst) = 140 ppb; factor of 4 improvement over BNL**

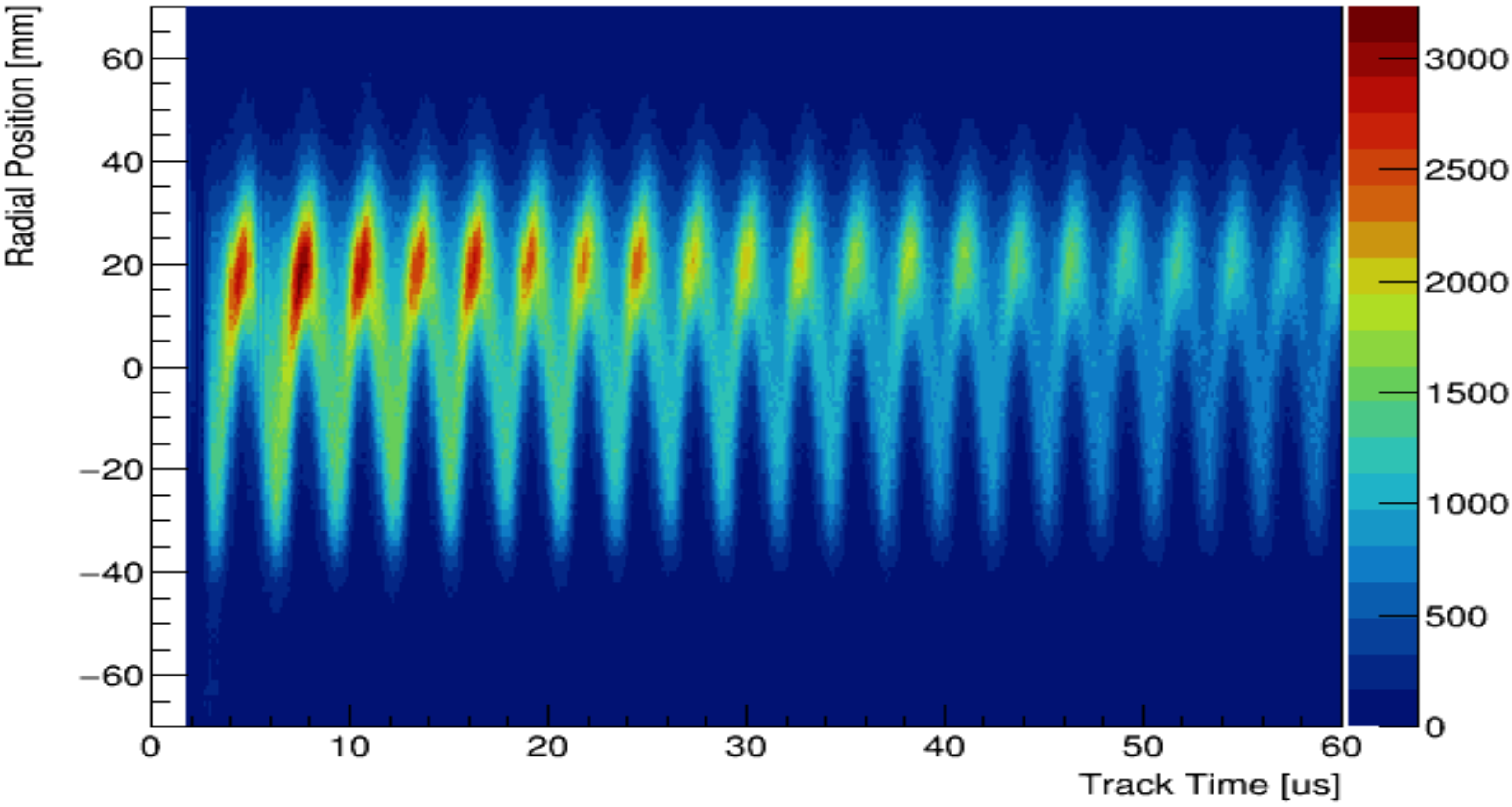
Precession plot



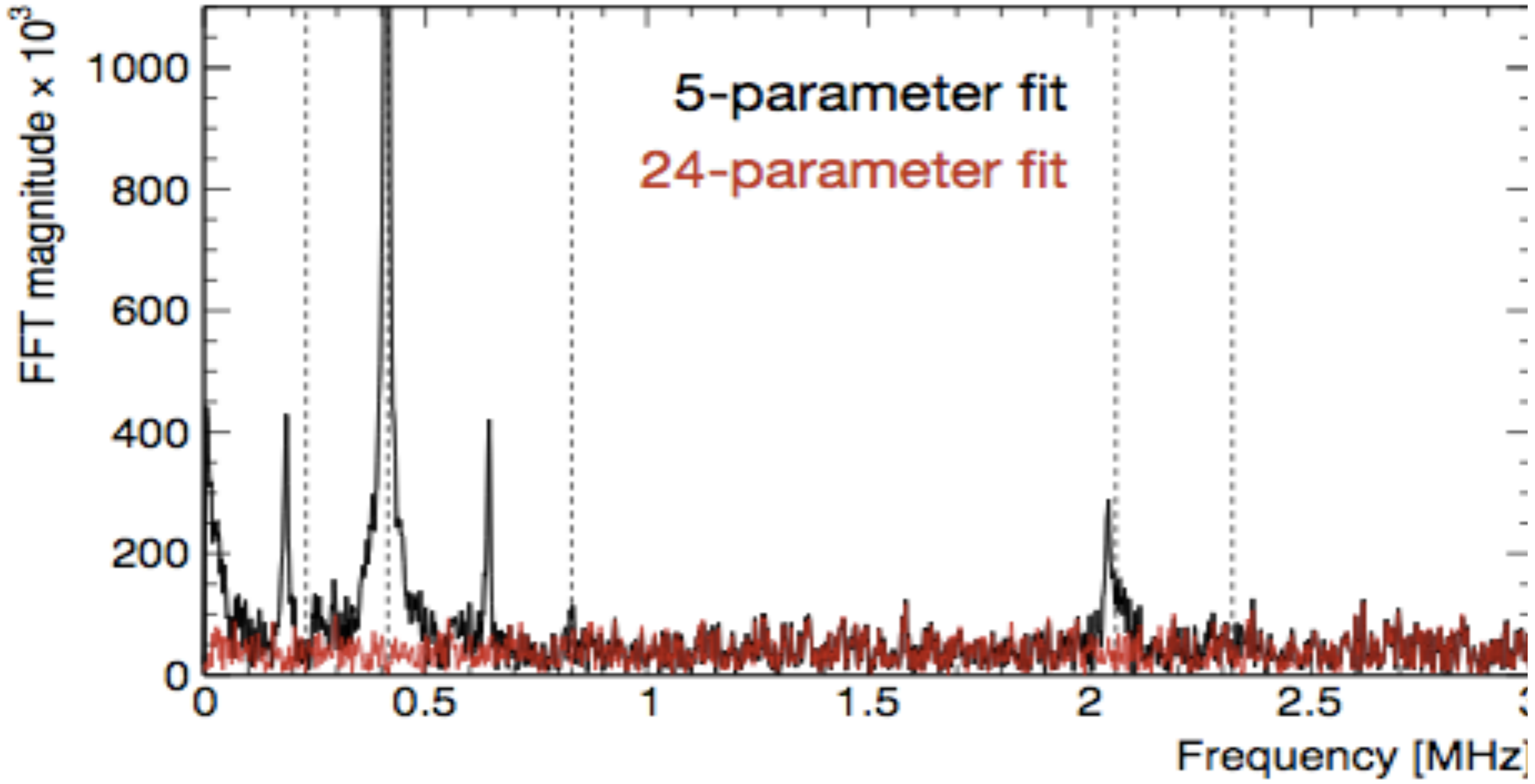
- Data from subset of run 1
- ~1 billion positrons
- 24 parameter fit
- Includes terms that account for beam oscillations…

Tracking detectors



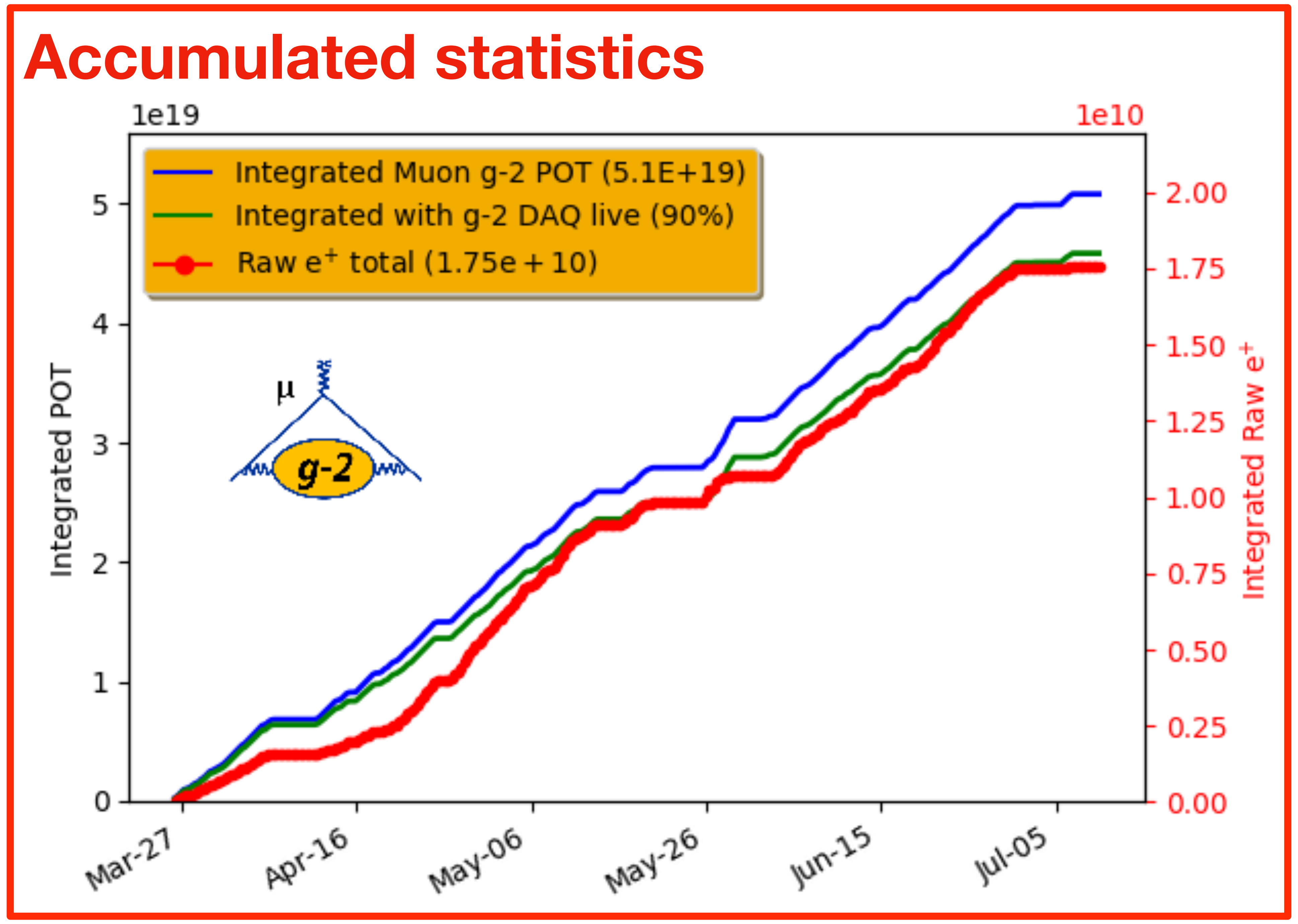


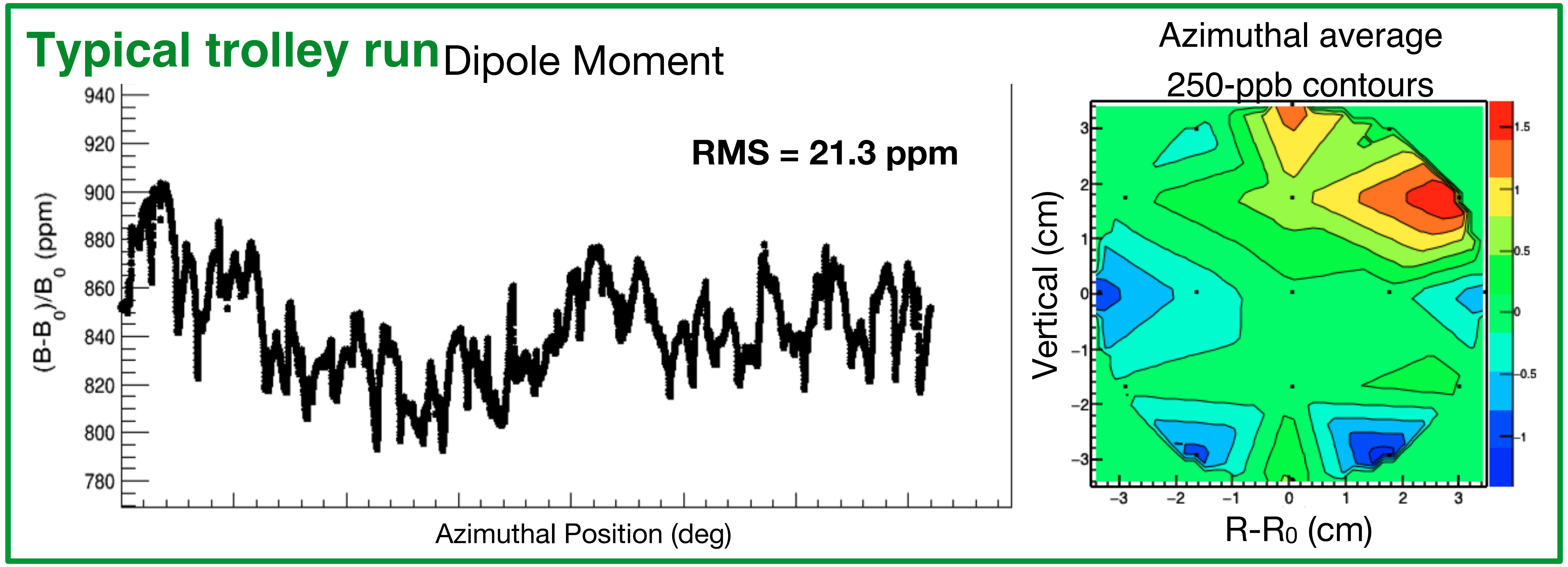
- Tracking detectors (UK built) major improvement w.r.t. BNL
- Precise measurement of beam
- Beam oscillation frequencies can be removed from fit for more accurate measurement



Run 1 Overview

- Data taking period: April—July 2018
- Accumulated ~ 1.1 x BNL statistics (after data quality cuts) — **δω$_a$(stat) ~ 450 ppb**
- Field uniformity ~ 2x better than BNL

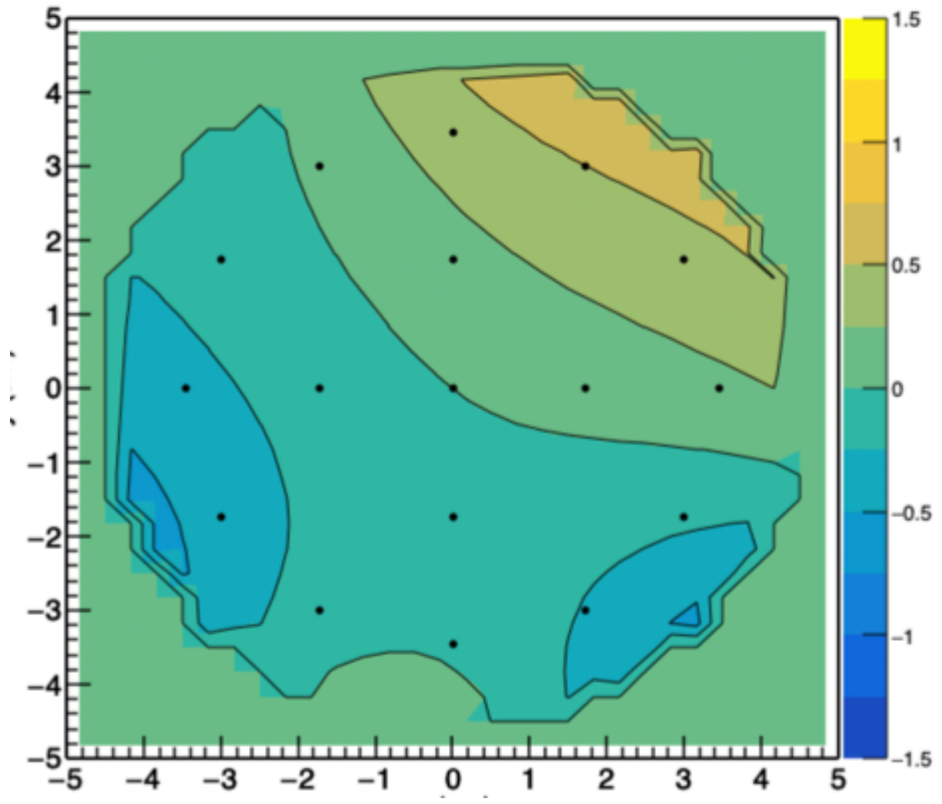

Accumulated statistics


Typical trolley run

- New result imminent based on run 1 data
- Accuracy comparable to BNL
- See if discrepancy between theory and experiment holds…

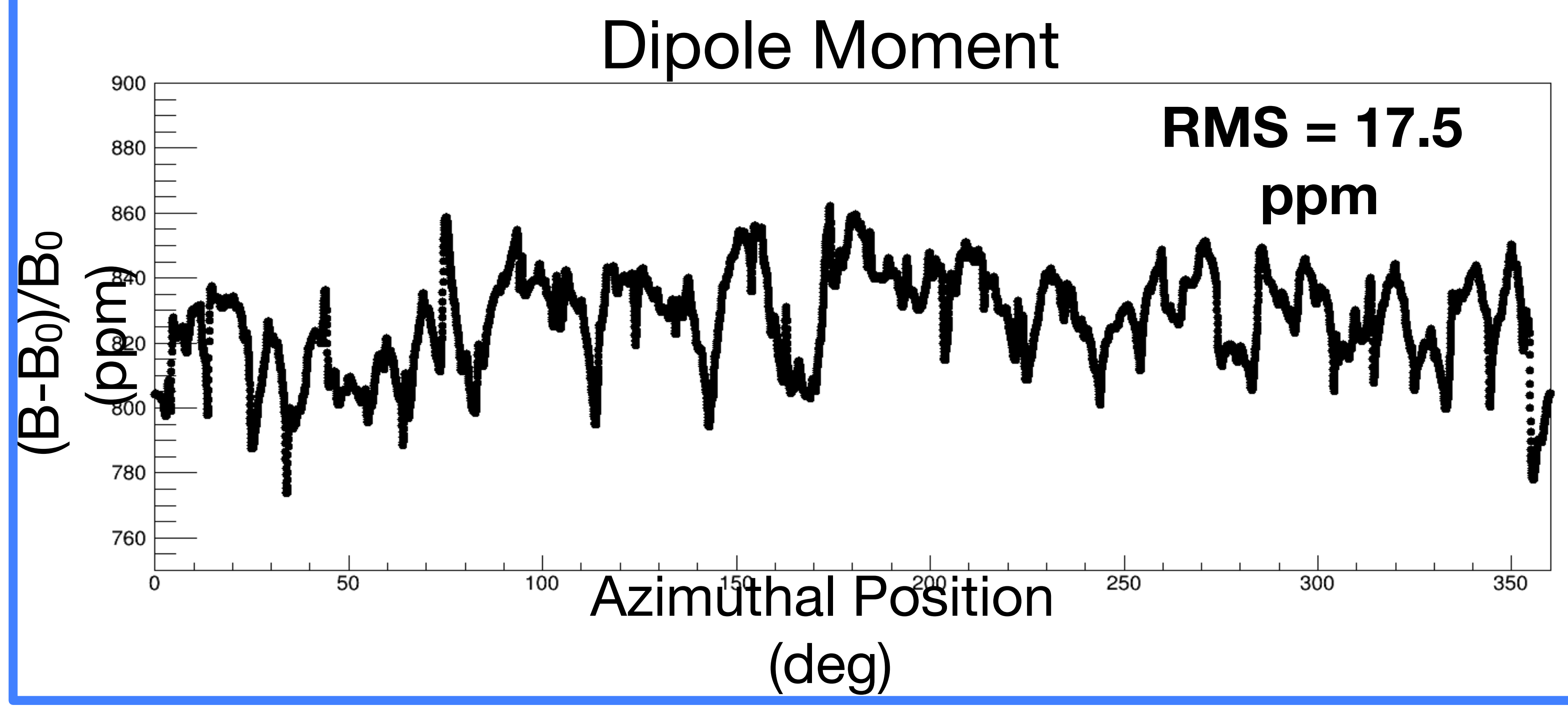
Run 2 and 3 Overview

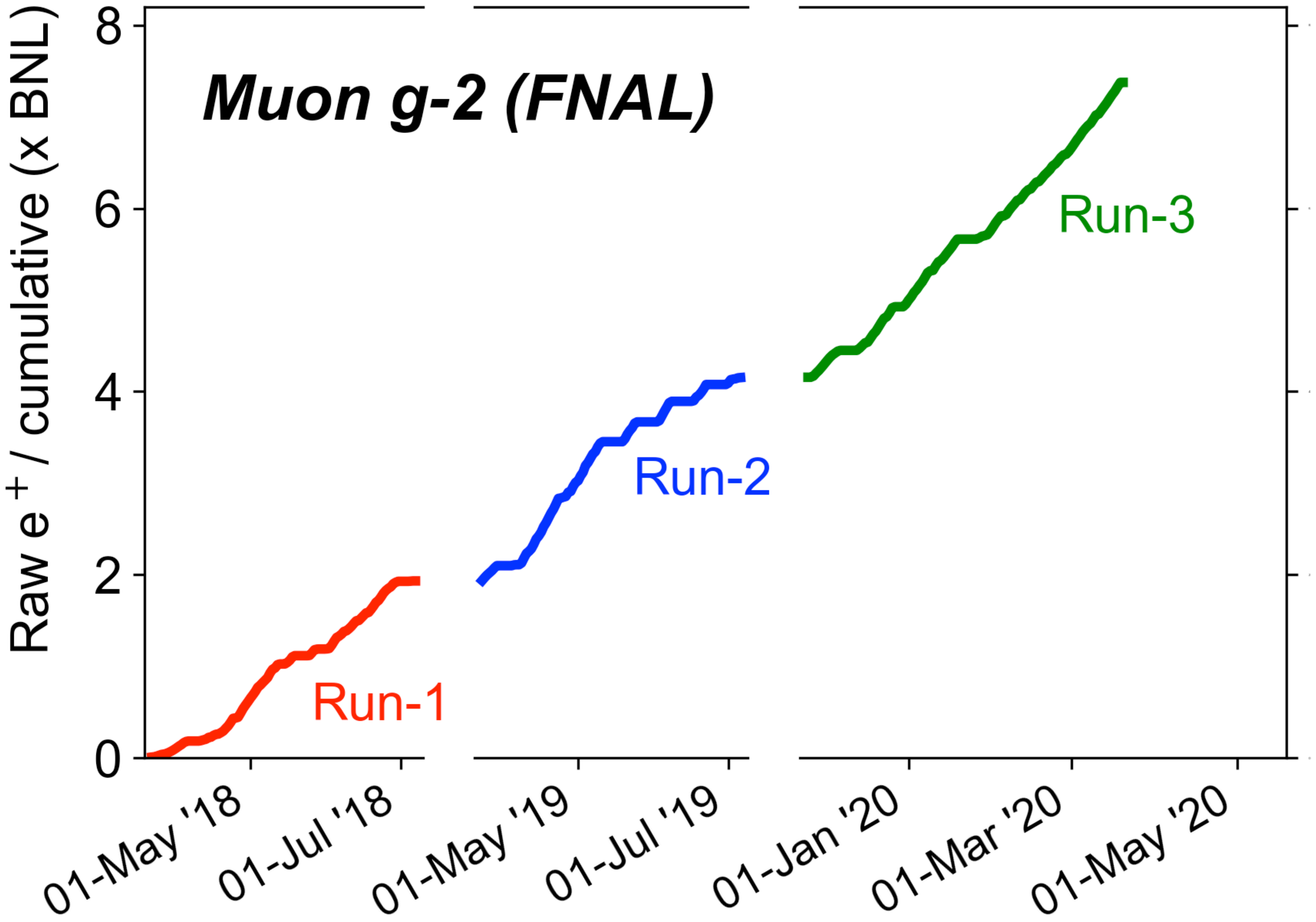
- More data taken during ‘19,’20
- Field uniformity expected to be similar to run 1



Azimuthal average
250-ppb contours

Run 2 Magnetic field measurement





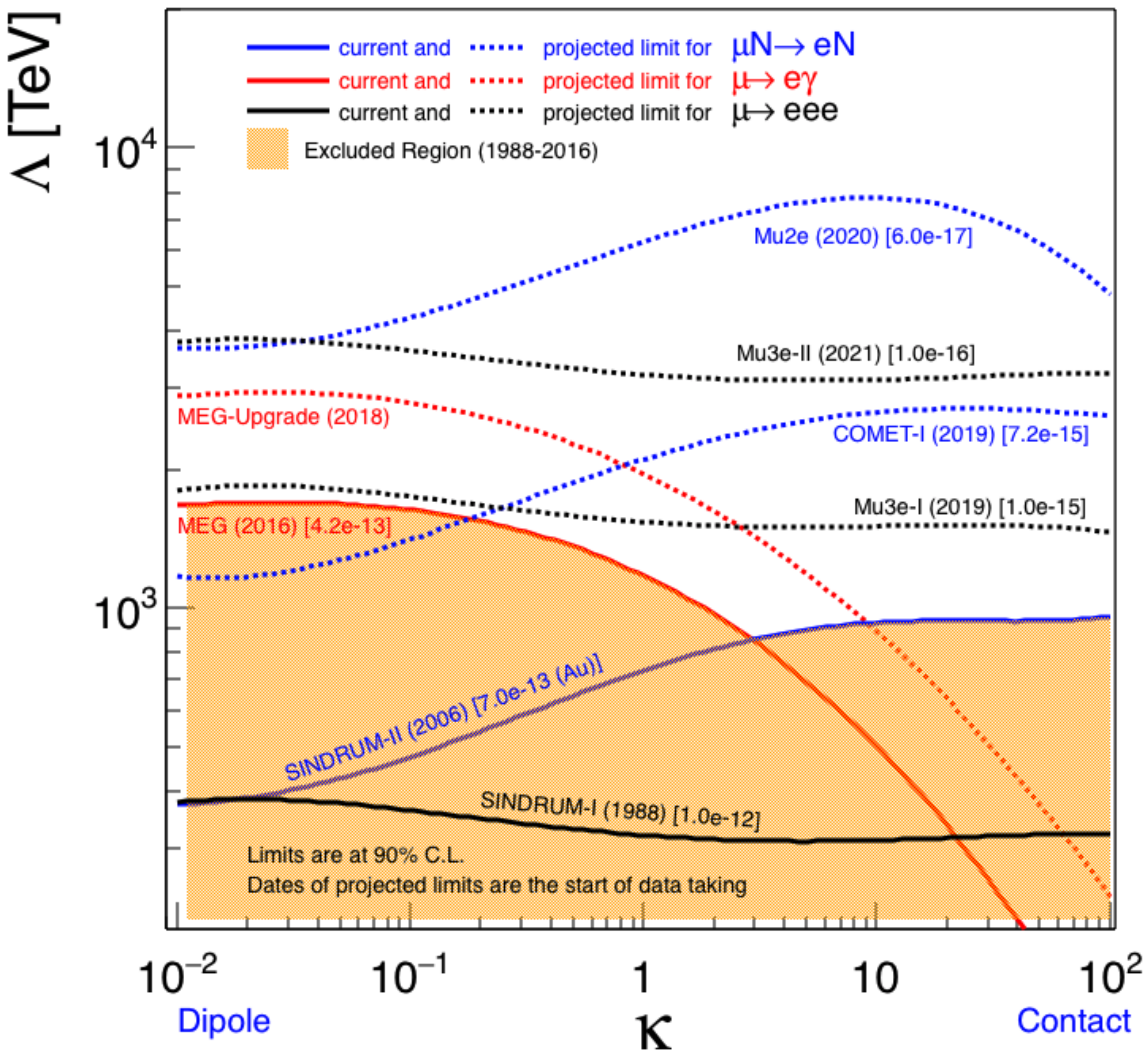
Can take 5% of a BNL per day!

Runs 4 and 5 approved for 21xBNL target

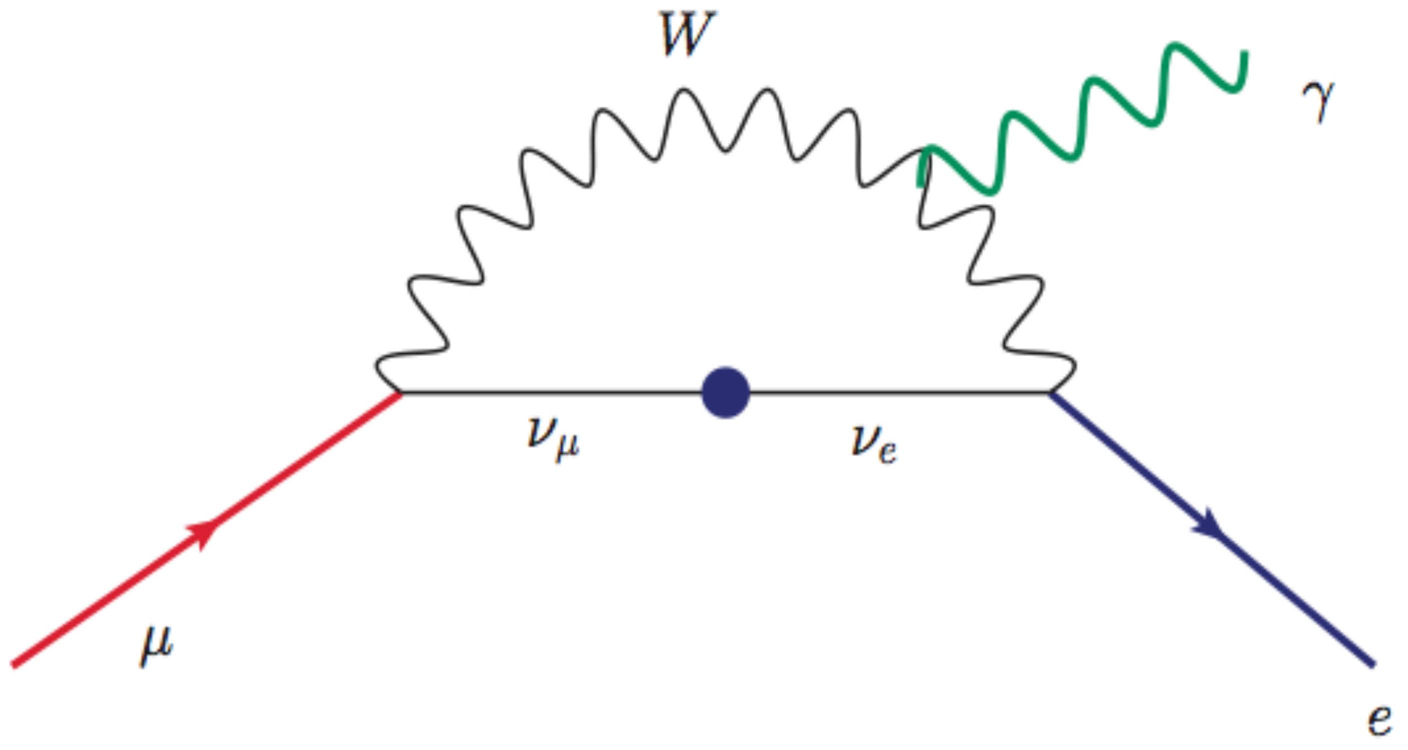
Charged Lepton Flavour Violation (CLFV)

CLFV: motivation

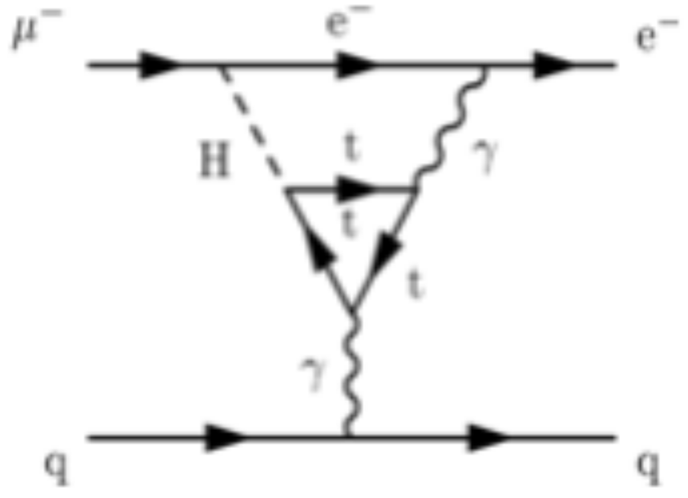
arxiv 1303.4097



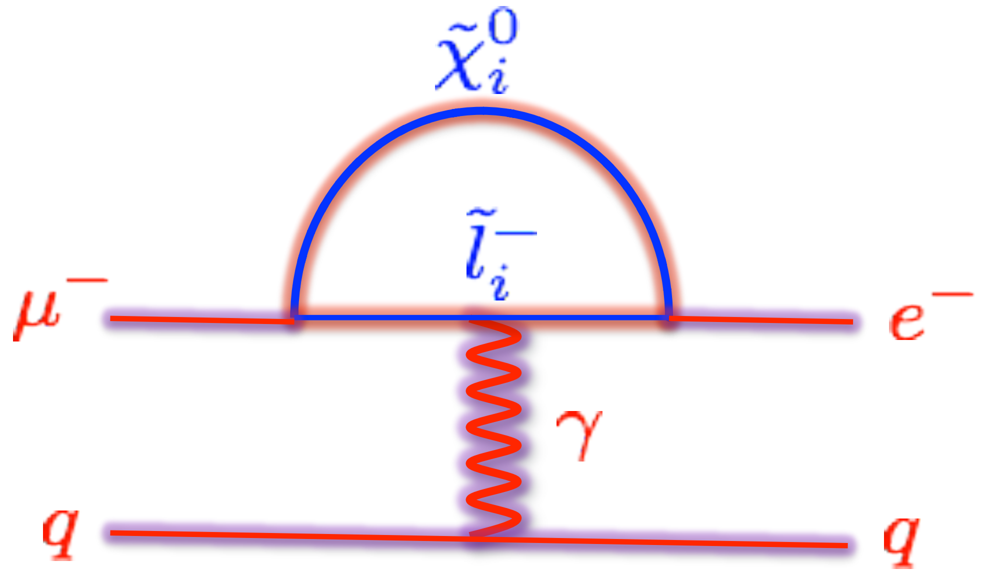
Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

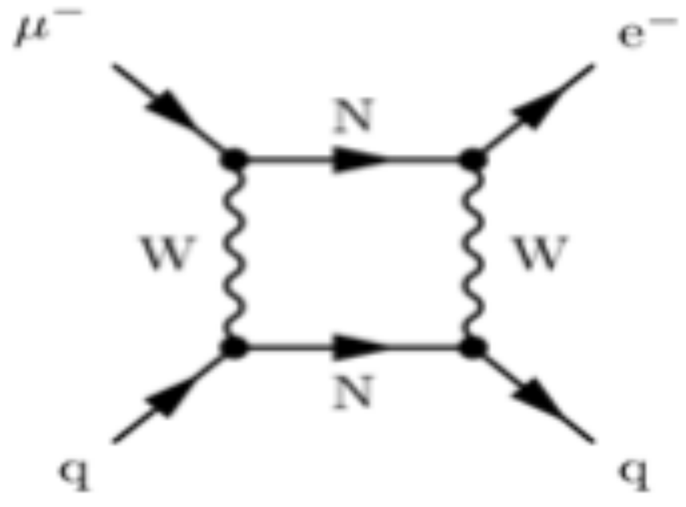


- SM contribution O(10^{-50})
- Any signal is a sign of new physics

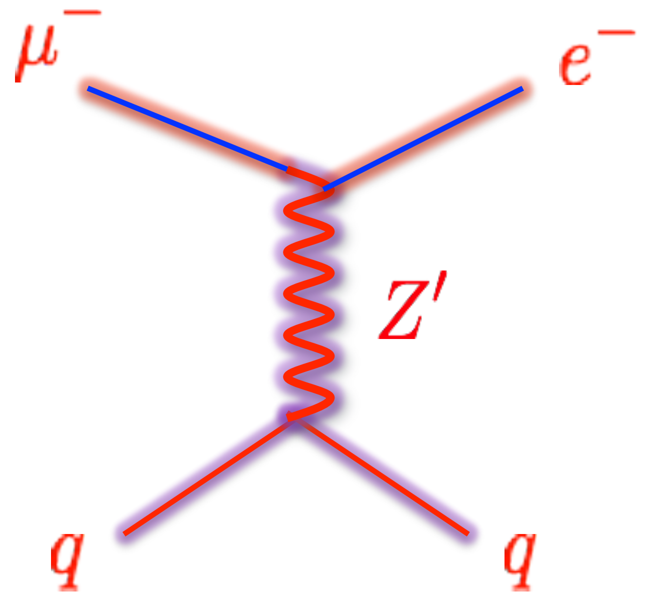


Second Higgs Doublet



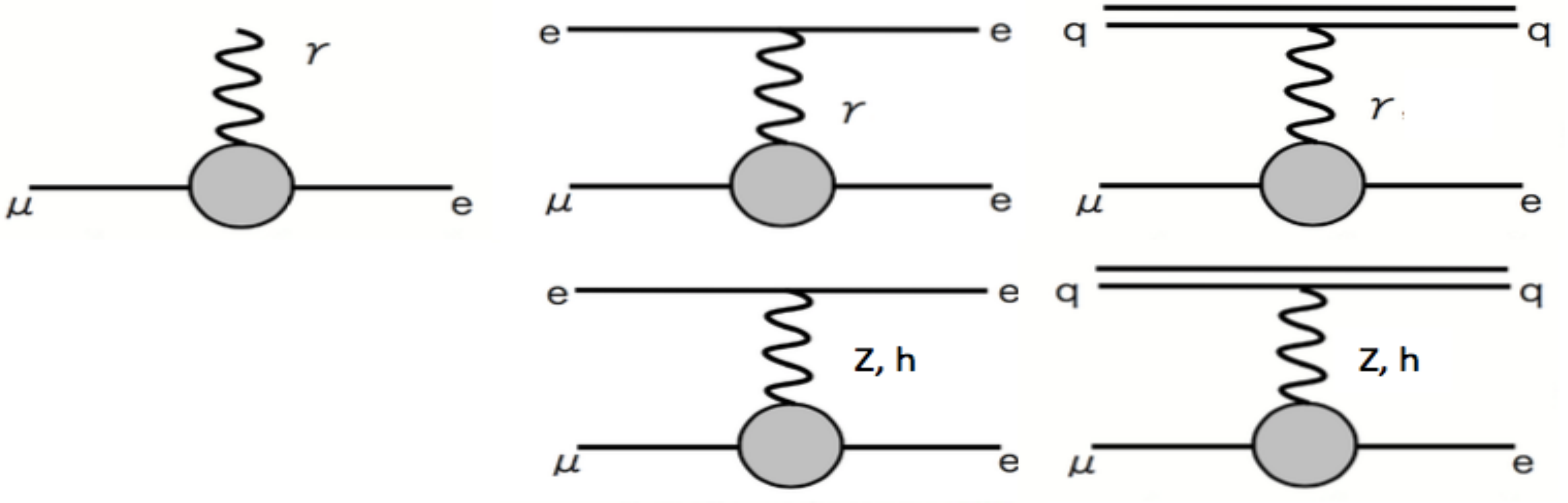


Heavy Neutrinos



CLFV: channels

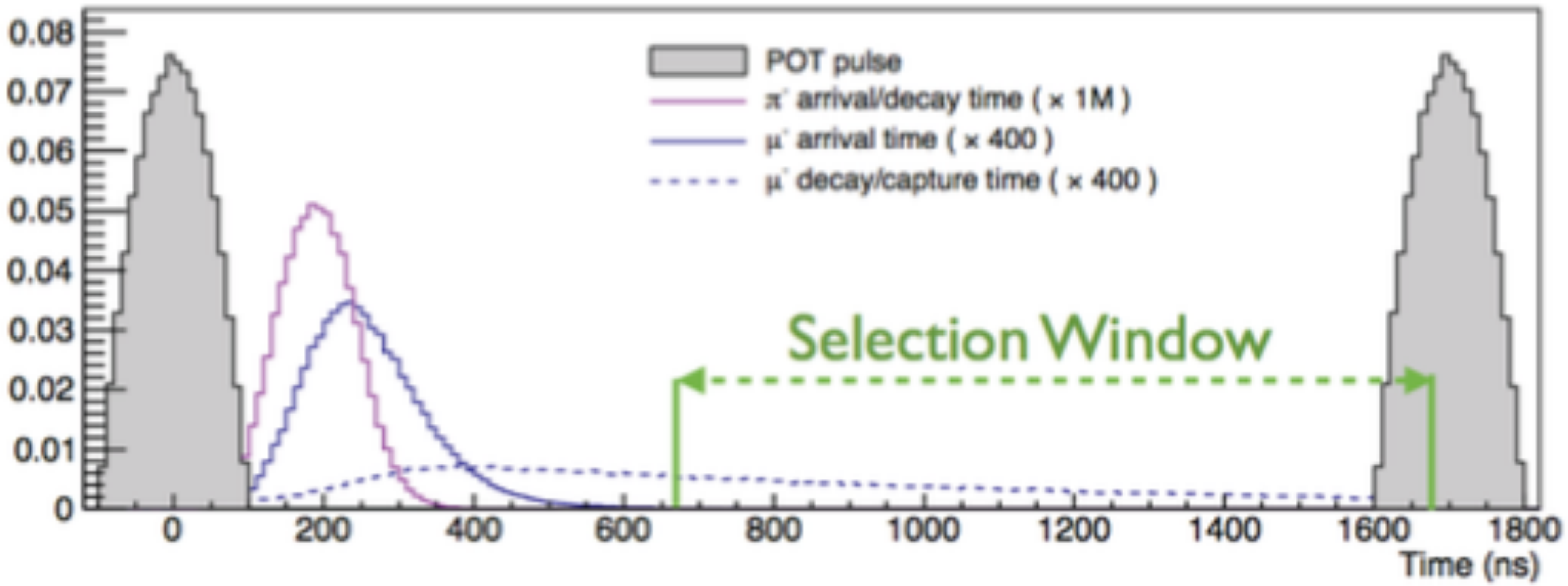
$\mu \to e\gamma$ $\mu \to eee$ $\mu N \to eN$

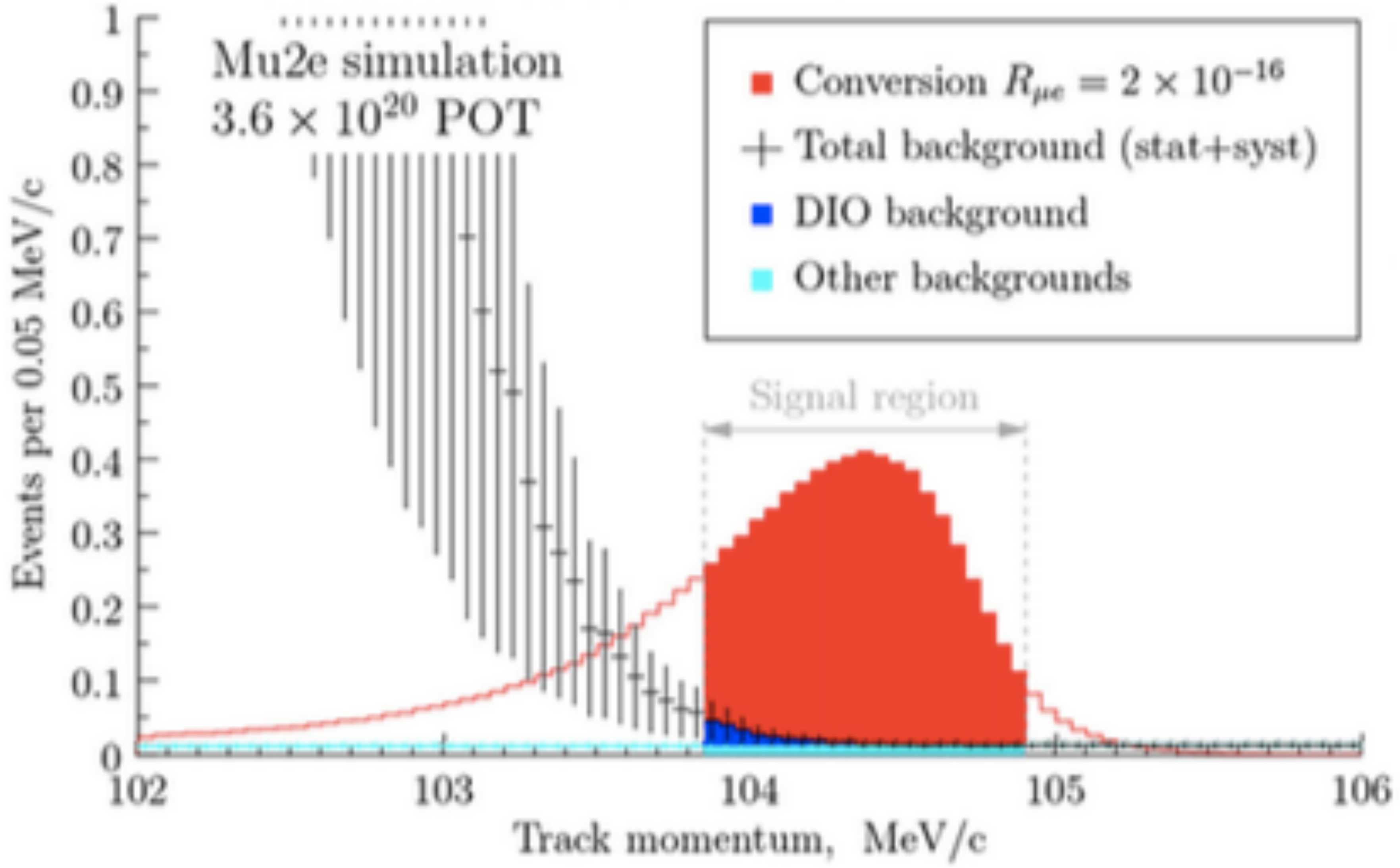


- Can use high intensity muon beams to look for charge lepton flavour violation
- Require muons p < 50MeV and stopping target (thickness ~1mm)
- Look for $\mu \to e$ in 3 channels, UK involvement in 2

Mu2e and COMET $\mu^- N \to e^- N$

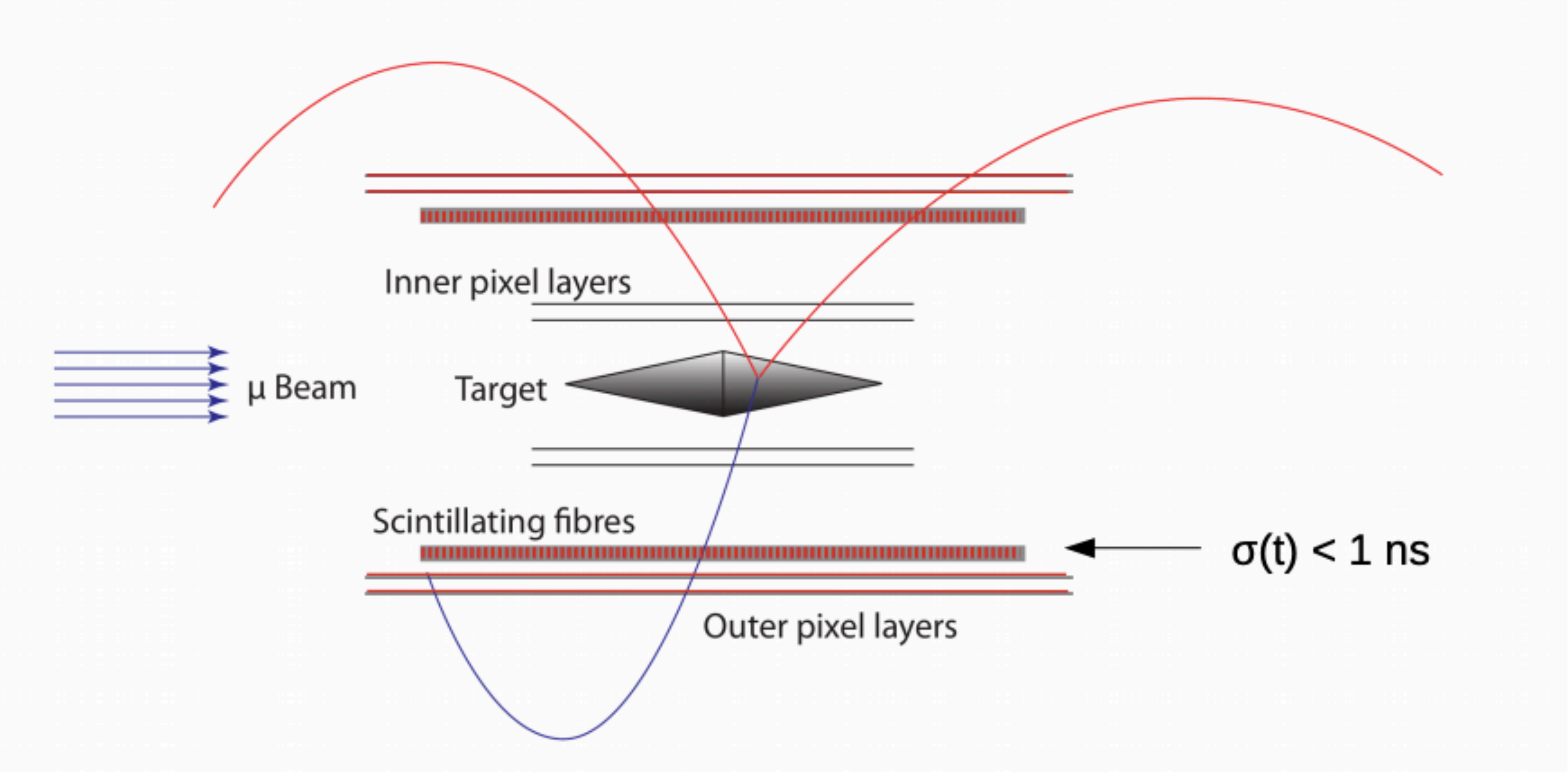
- Enhancement in sensitivity to CLFV due to small orbital radius of trapped μ
- Measure rate of conversions to nuclear muon capture ($R_{\mu e}$(Al))
- Signal: monoenergetic electron at E_e = 104.394 MeV/c
- COMET Phase I will improve current limit by 2 orders of magnitude
- Mu2e and COMET Phase II will both get to $\boxed{R_{\mu e}(\text{Al}) = 7 \times 10^{-17} \text{ (@90\% CL)}}$

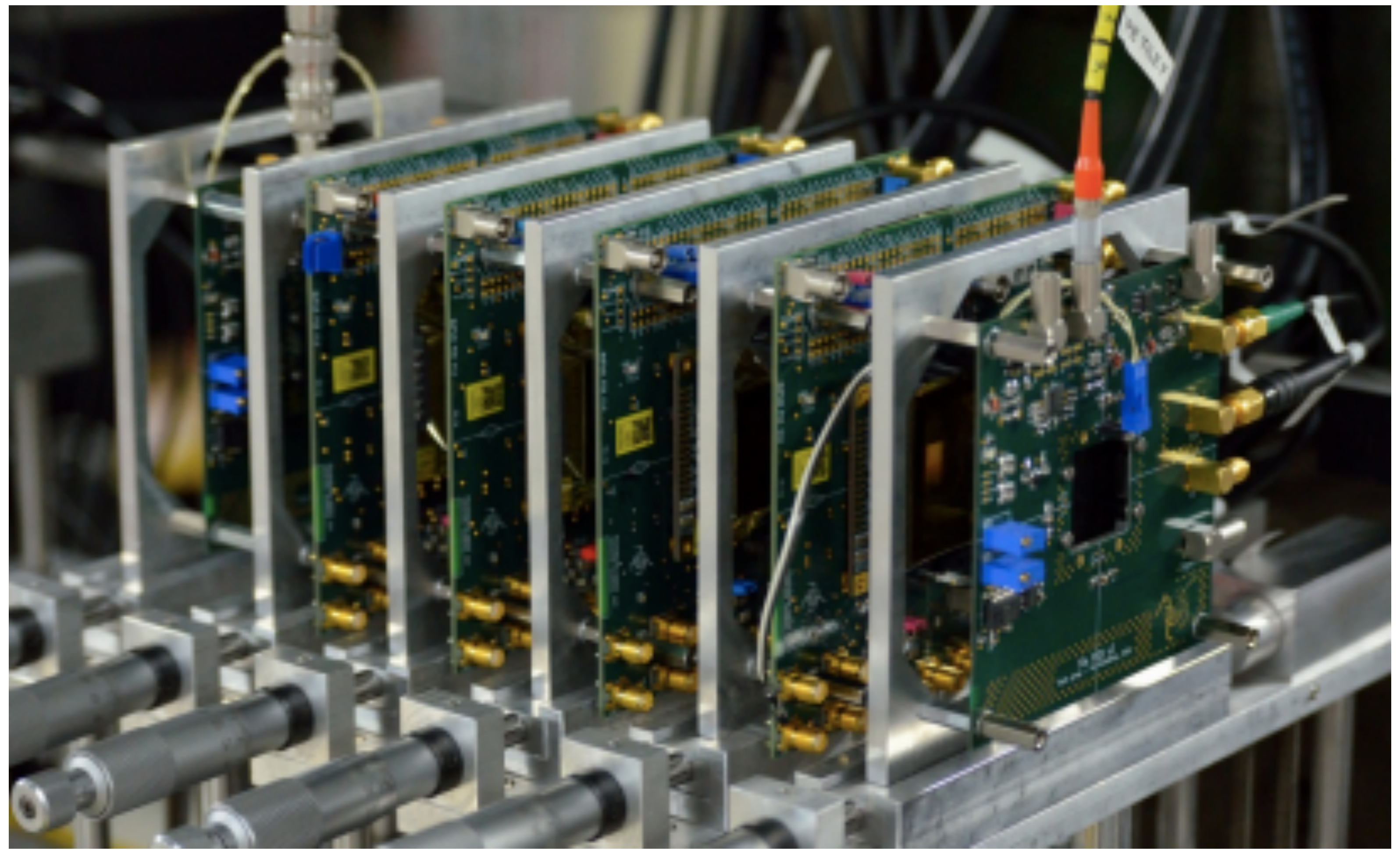




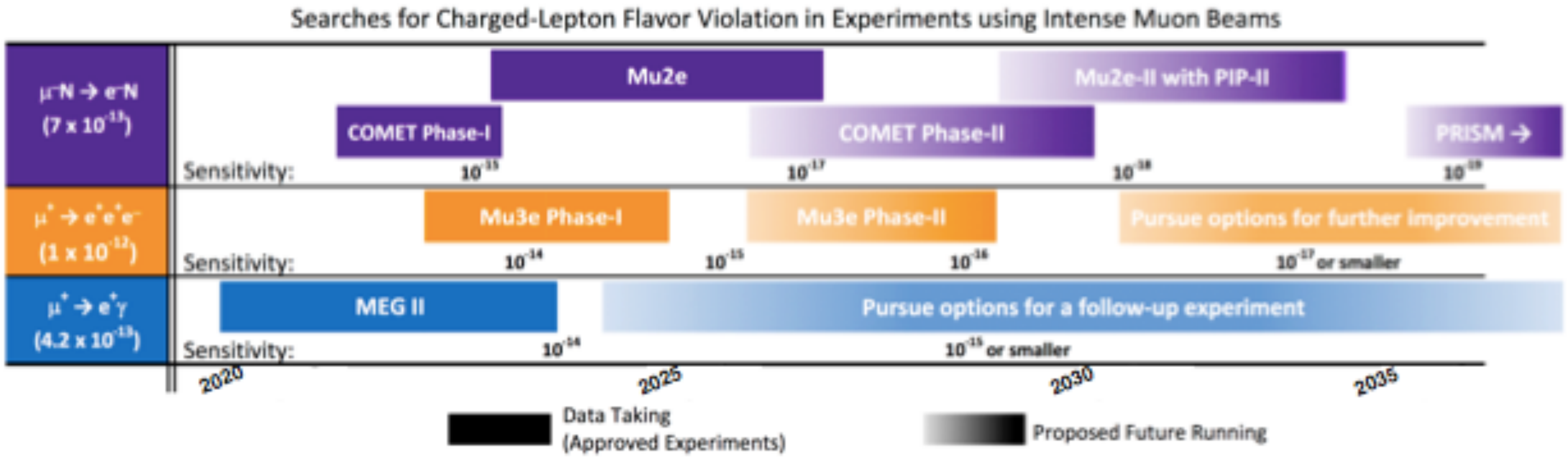
Mu3e $\mu^+ \to e^+e^+e^-$

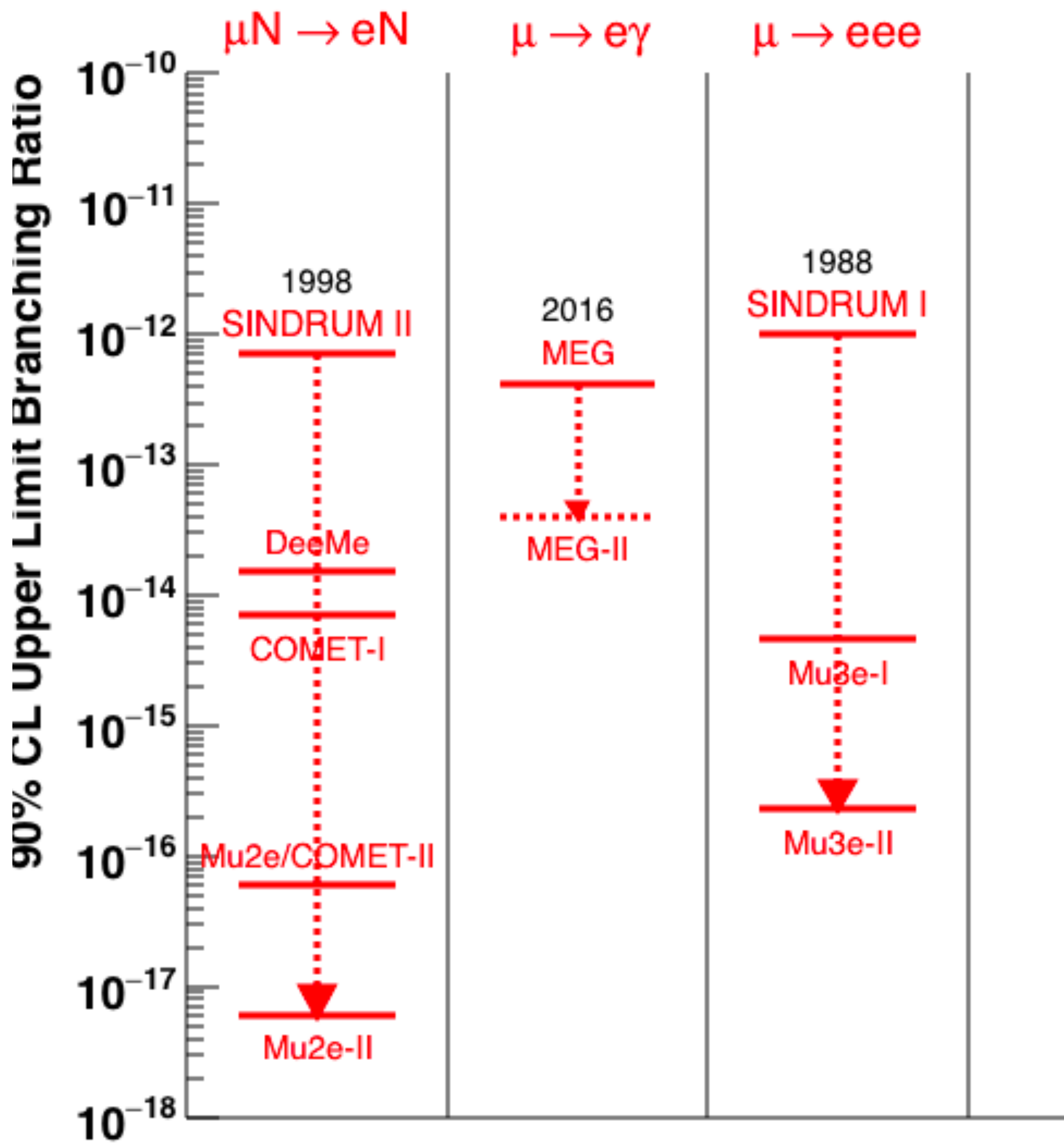
- Located at PSI
- Signal: 3 simultaneous e (1MeV < E < $m_\mu/2$), same vertex
- Accidental and can be kept down with energy and vertex resolution
- Aiming for $\boxed{\text{BR}(\mu^+ \to e^+e^+e^-) < 5 \times 10^{-15} \text{ (@90\% CL)}}$ in Phase I





CLFV: Timescale and Physics Reach



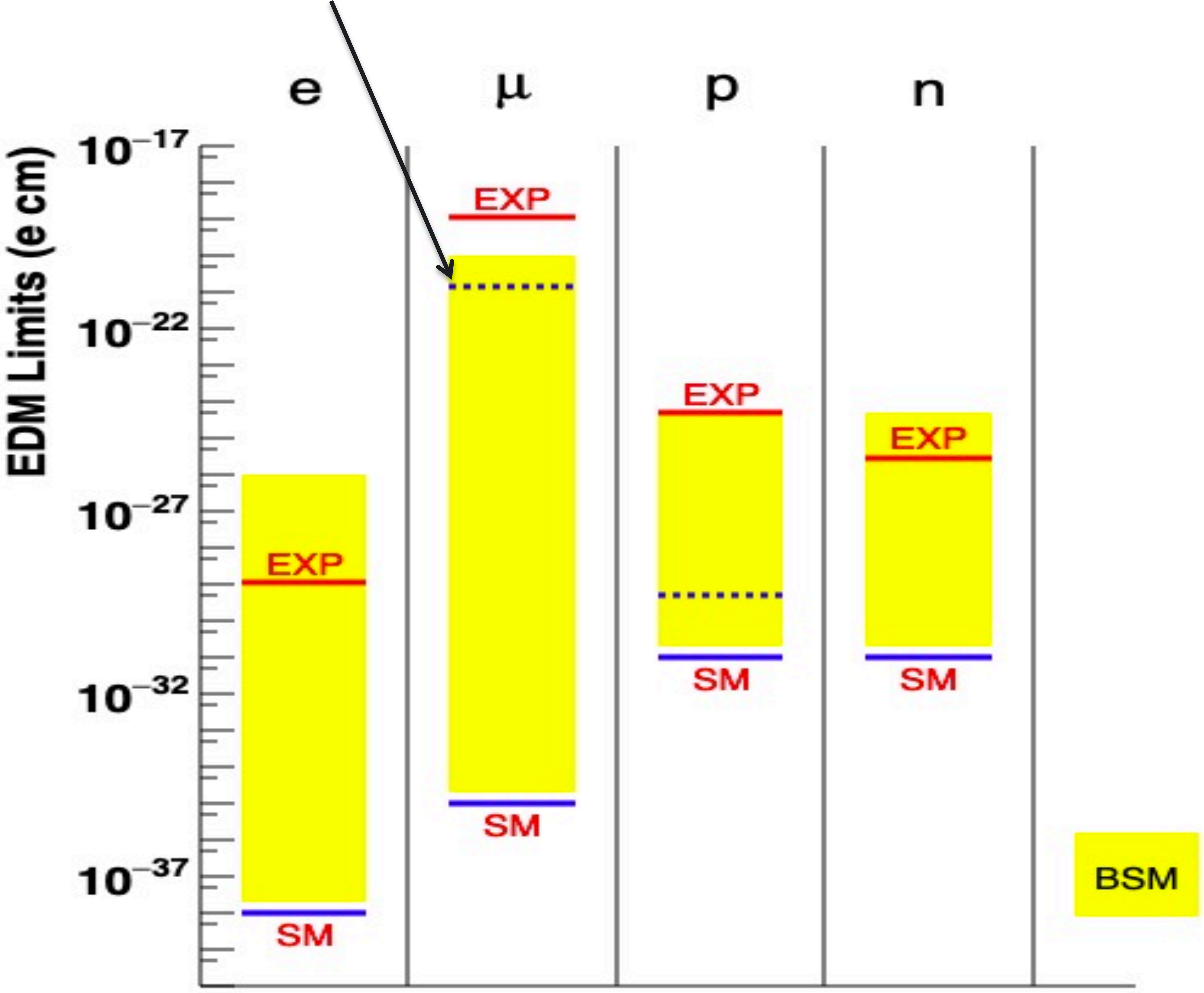


- 10 - 10^4 improvement in current limits in all 3 channels within 10 years
- Physics program extends beyond the next 10 years with COMET and Mu2e upgrades, and possible tau flavour violating experiments

EDM Measurements

- EDMs offer a source of CP violation
- Search for a μEDM underway at FNAL (g-2), publish first results after MDM measurement
- UK involvement in EDM:
  - Liverpool/Manchester/UCL: **muon**
  - Imperial: **electron**
  - Sussex/RAL: **neutron**
  - Future proton storage ring measurement?
- New EDM-UK group meeting set up to explore common goals and complimentary techniques

$|d_\mu| < 10^{-21}$e.cm expected with full statistics!



Summary

The Fermilab Muon g-2 Experiment

- Completed Run 1: result planned for 2021. Statistic ~1.1 x BNL
- Run 2 and 3 completed March 2020 — another ~4 x BNL, Run 4 begins next month
- Aiming for >5σ result (if central value remains the same as BNL) in 2021

μ EDM search ~100 x improvement

Charged Lepton Flavour Violation

- **COMET**: beam in Feb 2021, full Phase-I running Spring 2023
- **Mu2e**: commissioning beam 2023 (after g-2 has ended)

10^4 sensitivity improvement

- **Mu3e**: Test beam in April combining UK-trackers and with Scintillators
  - Operation with complete phase-I detector expected in 2023

10^2 - 10^3 sensitivity improvement

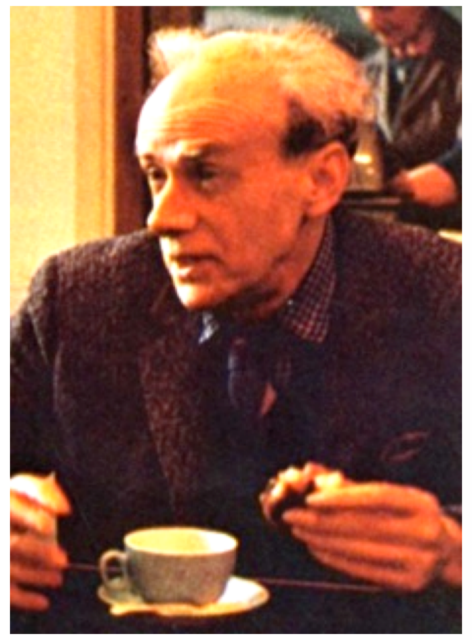
- COMET upgrade (PRISM) and Mu2e upgrade (Mu2e-II) to push sensitivity by > factor of 10
- Mu3e-II reaches 10^4 sensitivity, factor of 20 improvement on Phase-I

Thank you!

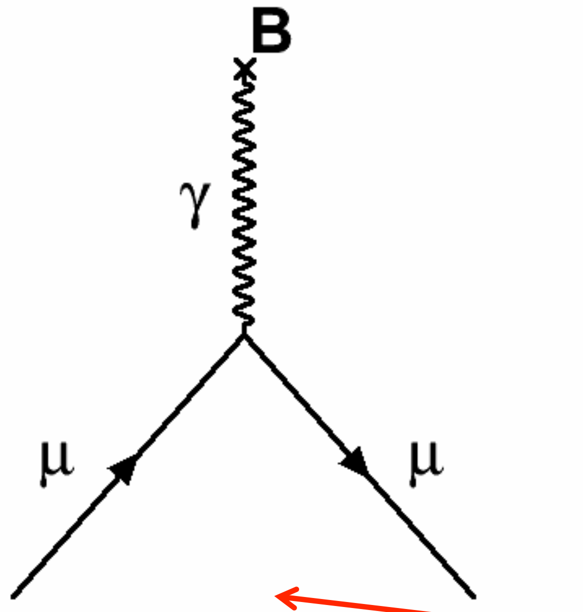
Backup

Standard Model Components of muon g-2

Dirac

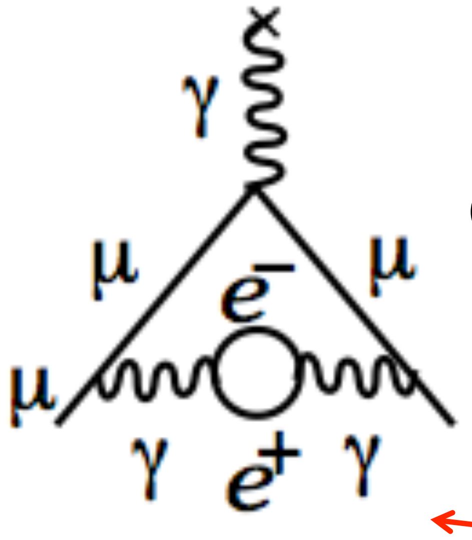


Charged,
spin ½ particle

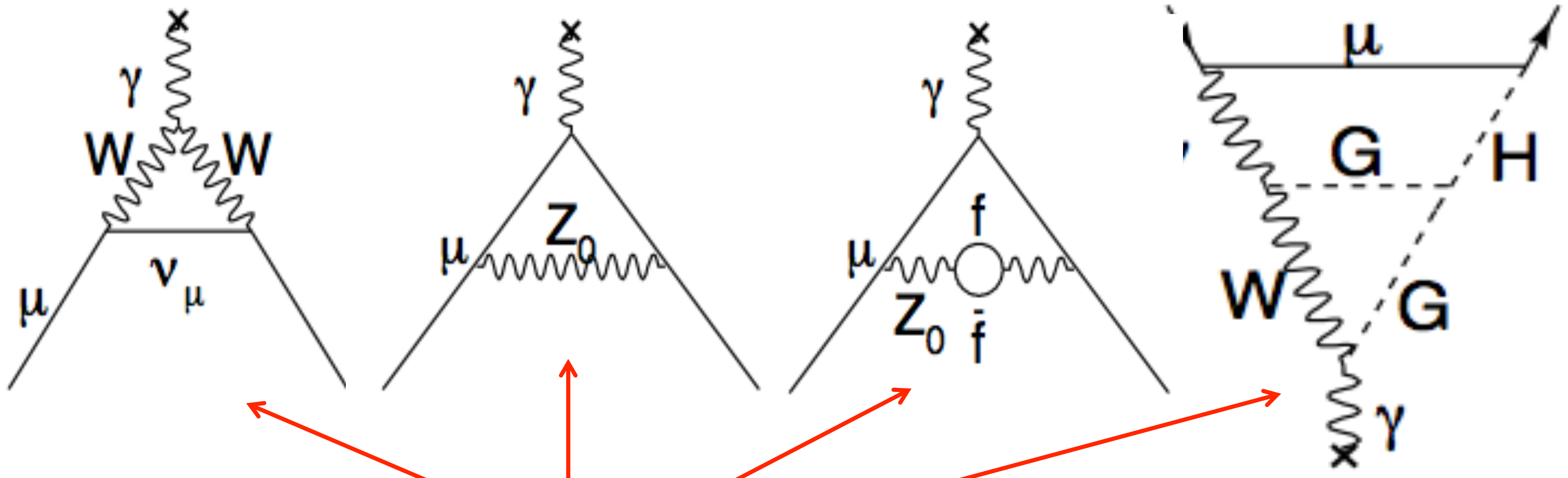


Kinoshita

Up to 10th
Order QED



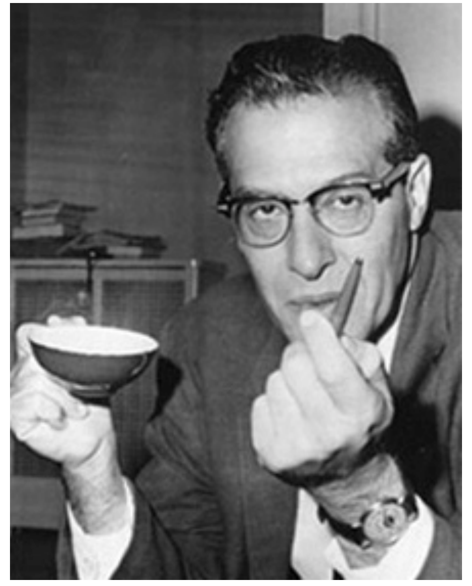
+12671
diagrams

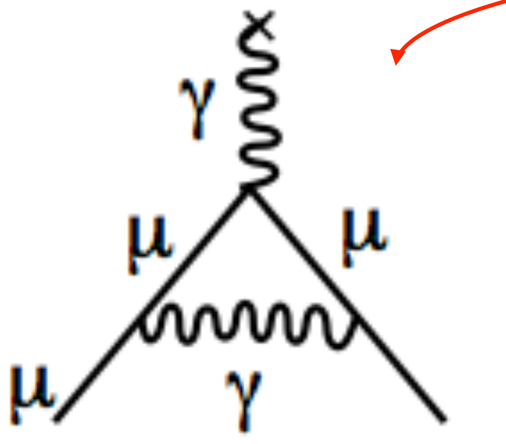


Electroweak

$$g_\mu = 2.00233183636(86)$$

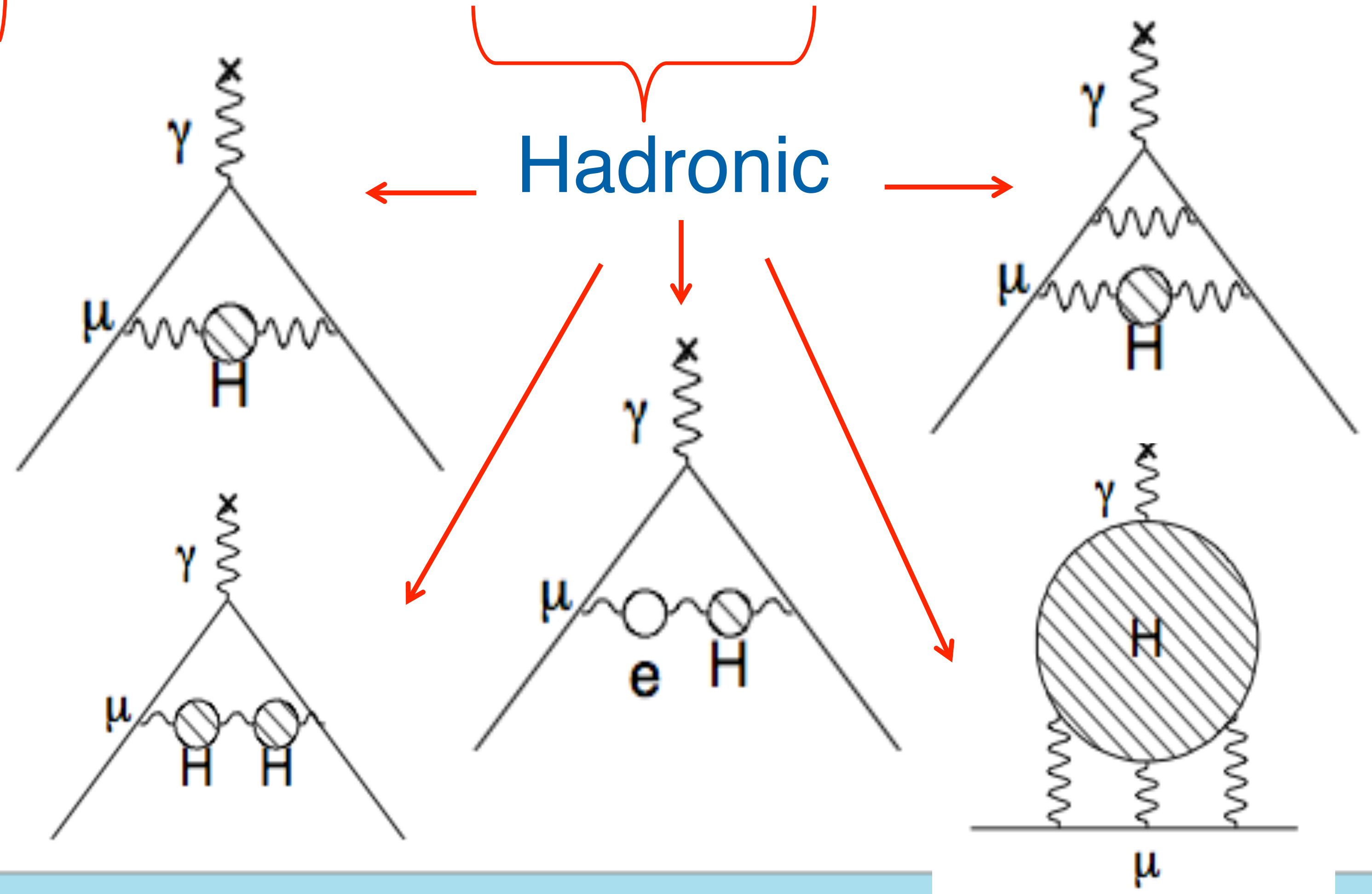
Schwinger





1st Order QED

$$\frac{\alpha}{2\pi} = 0.00232$$

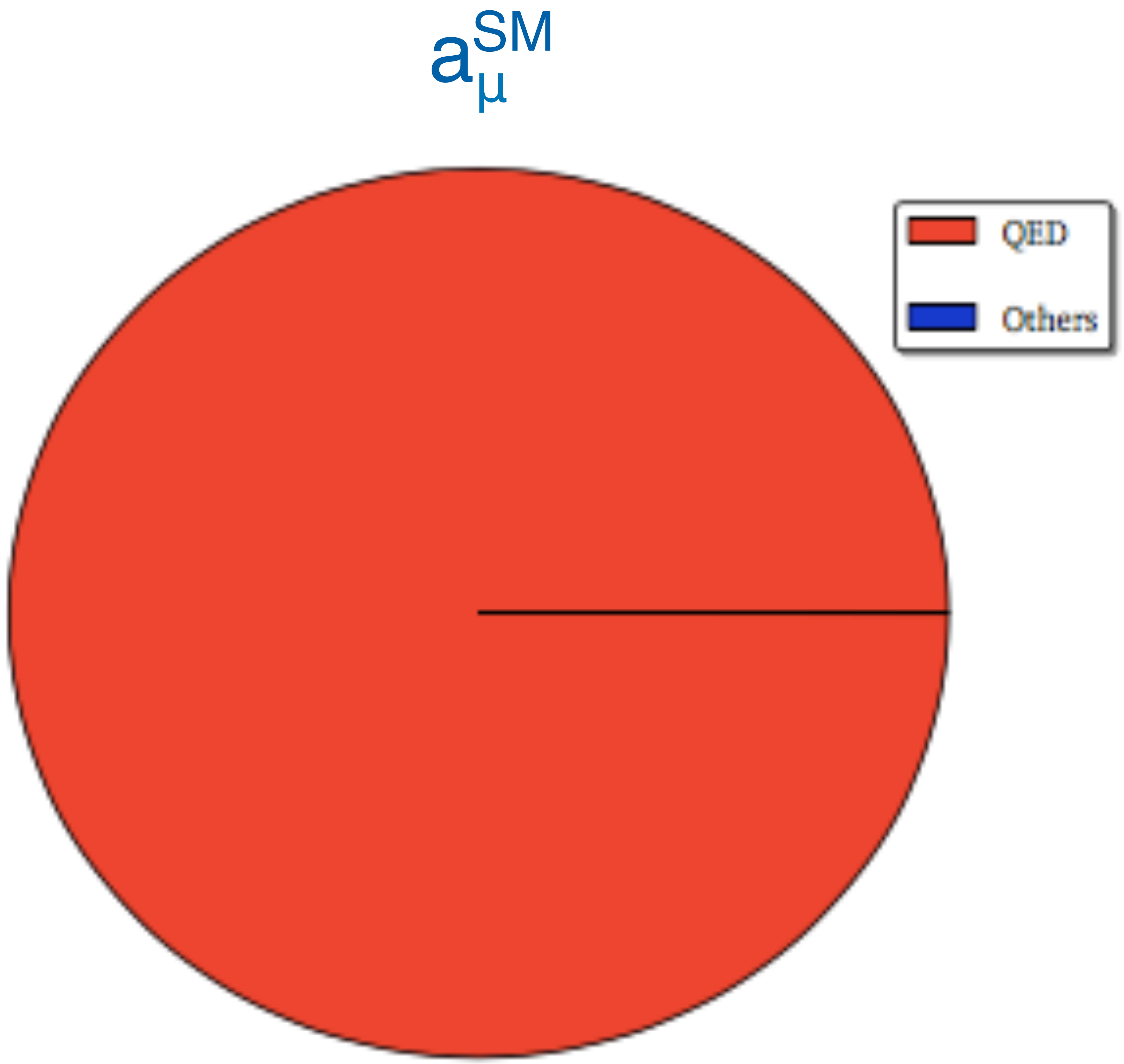


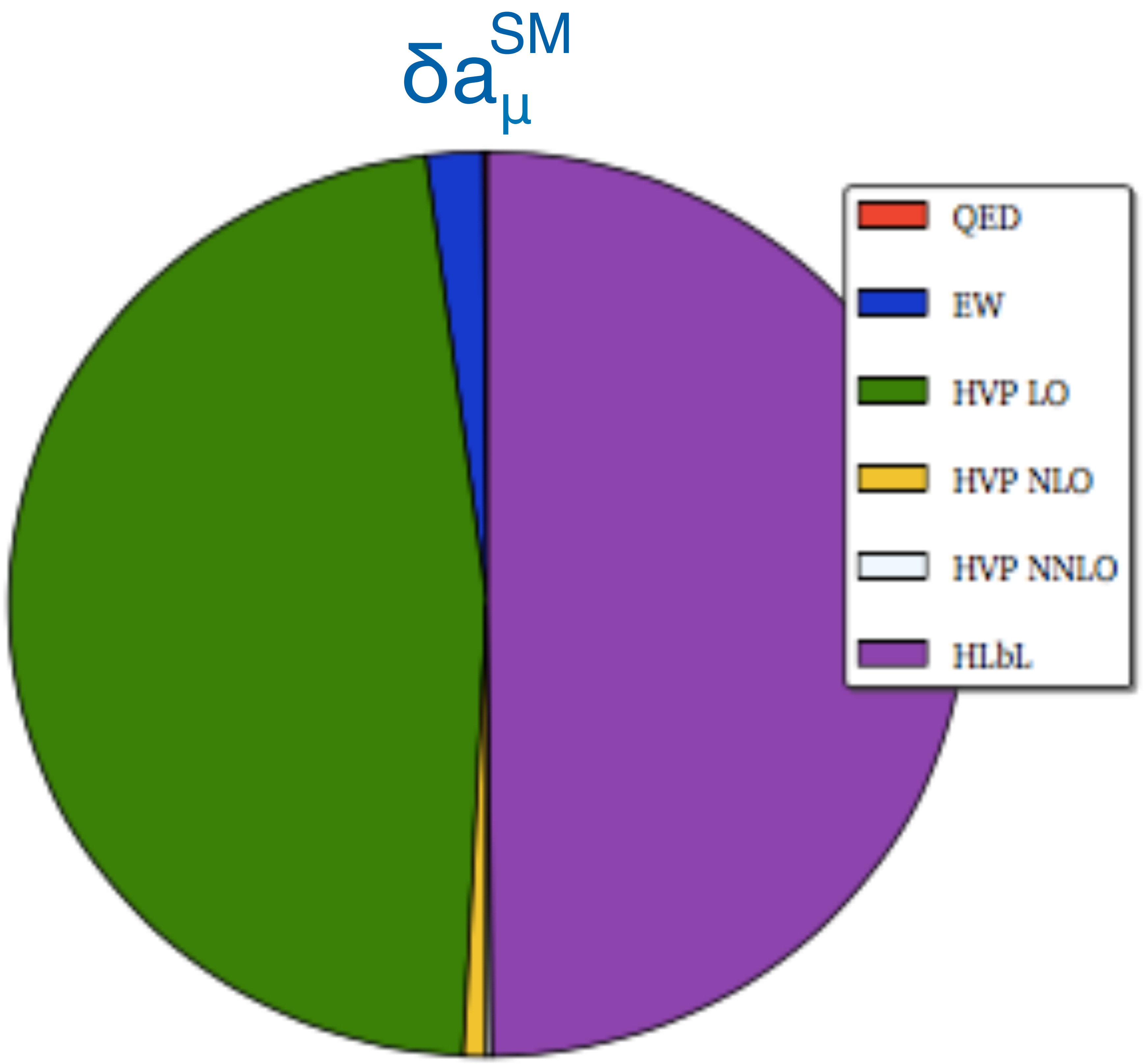
Hadronic

SM
uncertainty

Standard Model Uncertainties

$$a_\mu = \frac{g_\mu - 2}{2}$$





- The SM value of a_μ is dominated by QED
- But its uncertainty is dominated by Hadronic contributions
- Split into Hadronic Vacuum Polarisation (HVP) & Hadronic Light by Light (HLbL)

a_μ Theoretical Status

New *ab initio* approaches [PRD **98** 094503 (2018)] finding consistent result of (-93 ± 13) x 10^{-11} — **lattice making big strides**

		12)
		13)
		7)
H O)	**6933 ± 25**	PRD **97** 114025 (2018)
HVP (NLO)	**-98.7 ± 0.7**	EPJ C **77** 827 (2017)
HVP (NLO)	**-98.2 ± 0.4**	PRD **97** 114025 (2018)
HVP (NNLO)	12.4 ± 0.1	PLB 734 144 (2014)
HLbL (LO + NLO)	101 ± 26	PLB 735 90 (2014), EPJ Web Conf 118 01016 (2016)
	91 818 ± 43	
	91 821 ± 36	

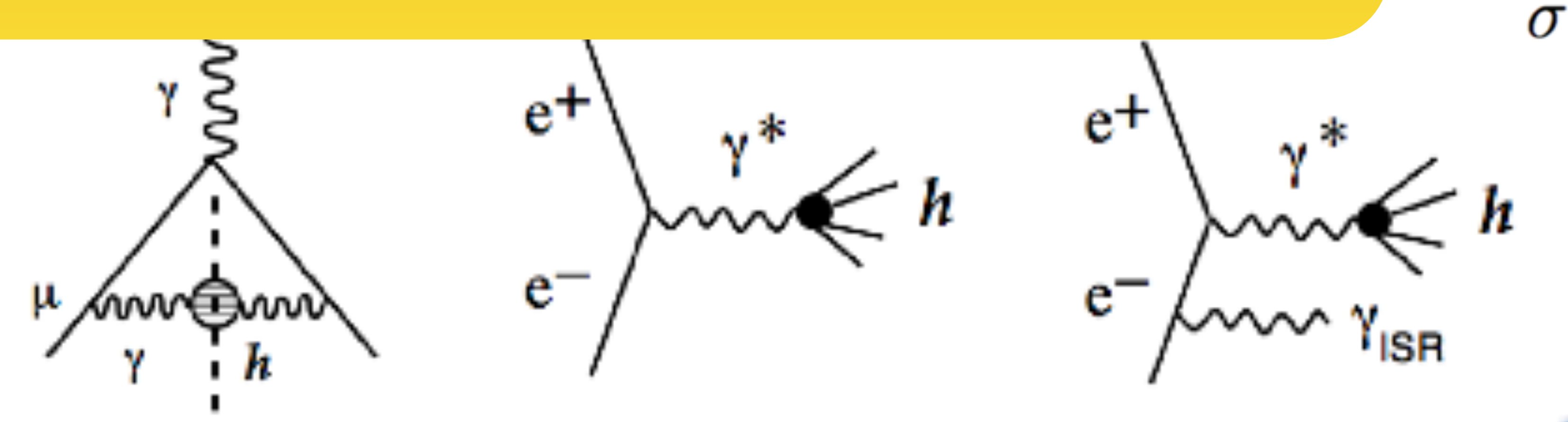
Builds confidence in HLbL term

HVP (LO): Lowest-Order Hadro

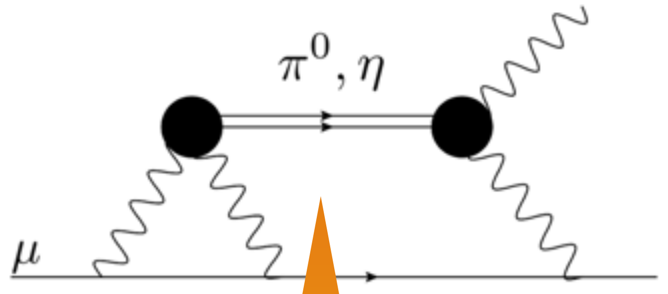
- **Critical input** from e^+e^- colliders (data BaBar, KLOE, Belle, BESIII), δa_μ^{HVP} ~ 0 program in place to reduce δa_μ^{HVP} to ~ 0.3% in coming years
- **Progress on the lattice**: Calculations at physical π mass; goal: δa_μ^{HVP} ~ 1—2% in a few years (cross-check with e^+e^- data)

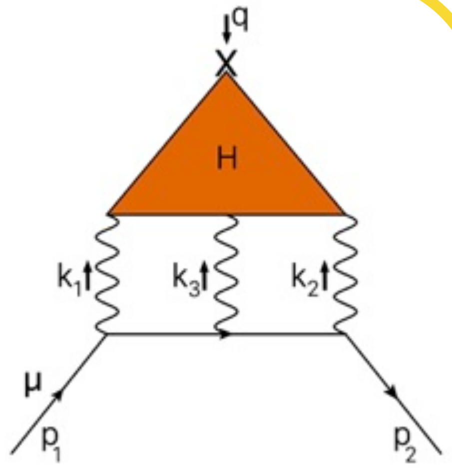
Recent data-driven calculation [PRL **121** 112002 (2018)] for $a_\mu^{\pi^0-\text{pole}}$ is consistent with earlier vector-, lowest-meson dominance calcs [PRD **65** 073034 (2002), PRD **94** 053006 (2016), EJC **75** 586 (2015)]

$$R(s) \equiv \frac{\sigma_{\text{tot}}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



HLbL: Hadronic Light-by-Light

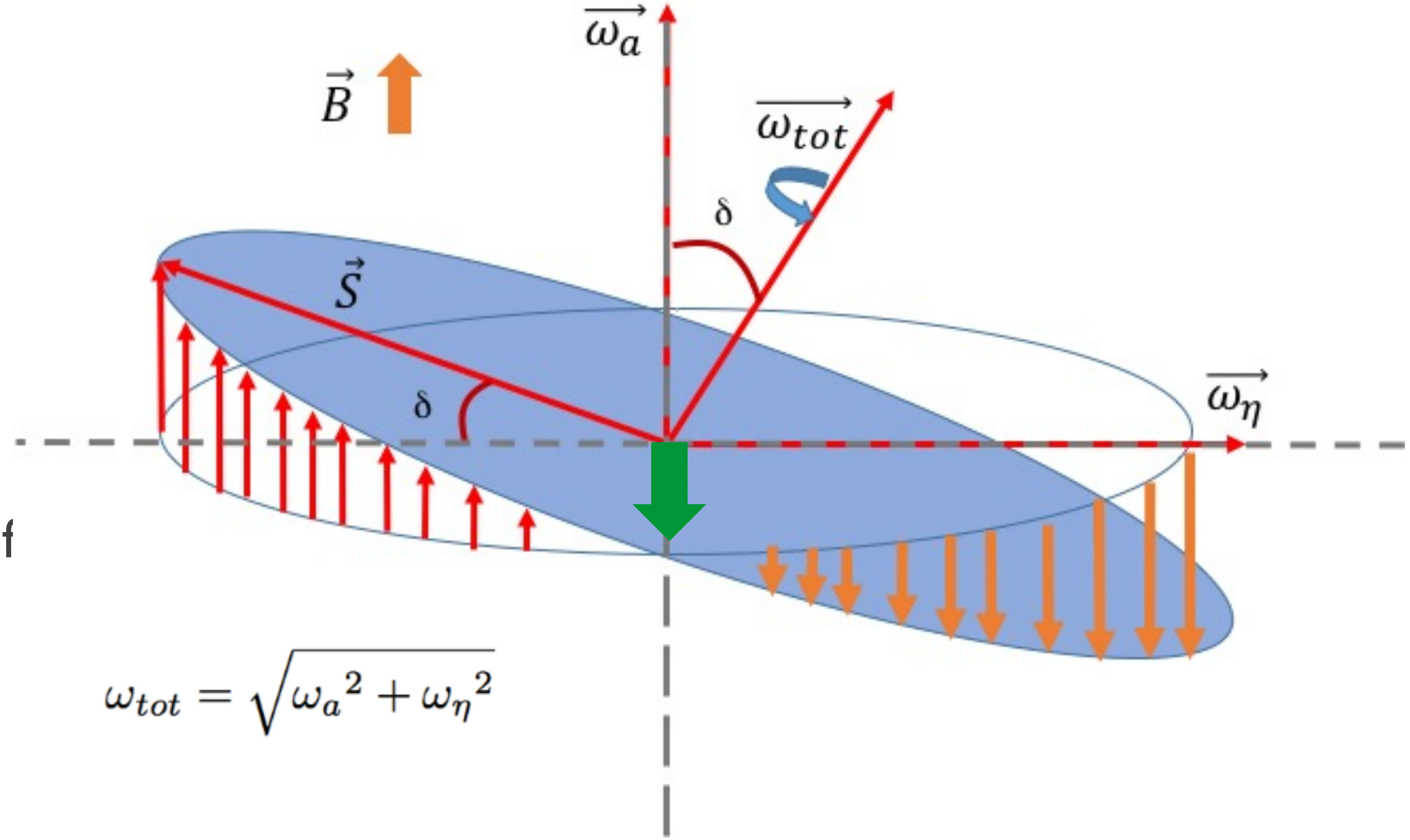




- Model depende : based on χPT + short-distance constraints (op tor product expansion)
- Difficult to rela data like HVP (LO); γ* physics, π^0 data (BESIII, KLOE ortant for constraining models
- **Theory Prog** lew dispersive calculation approach; extend the l ite volume, disconnected diagrams); gress

EDM measurements at muon storage rings

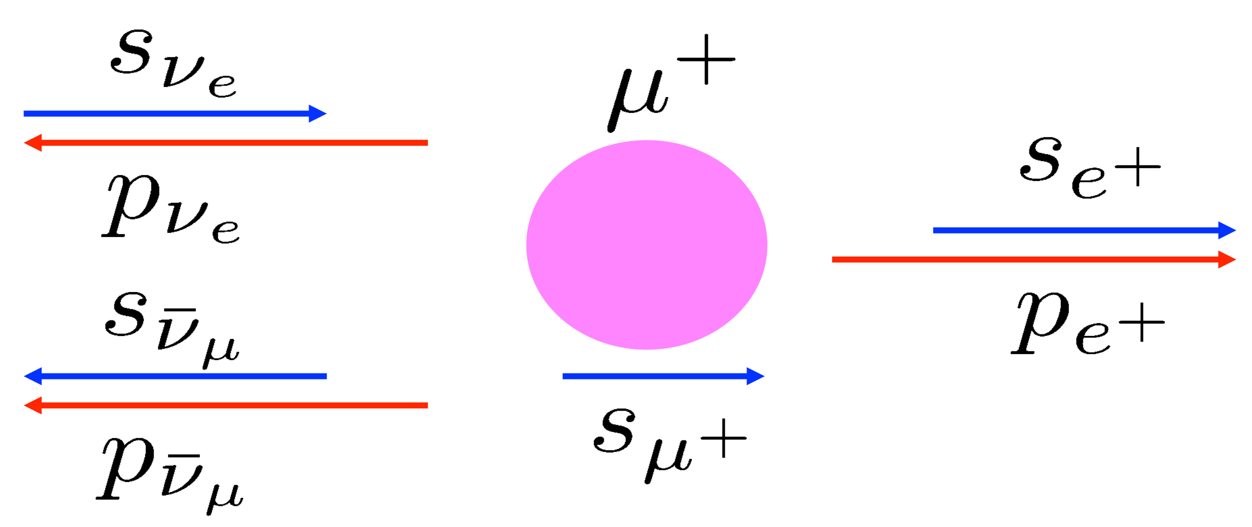
- Precession plane tilts towards center of ring
- Causes an increase in muon precession frequency
- Oscillation is 90° out of phase with the a_μ oscillation

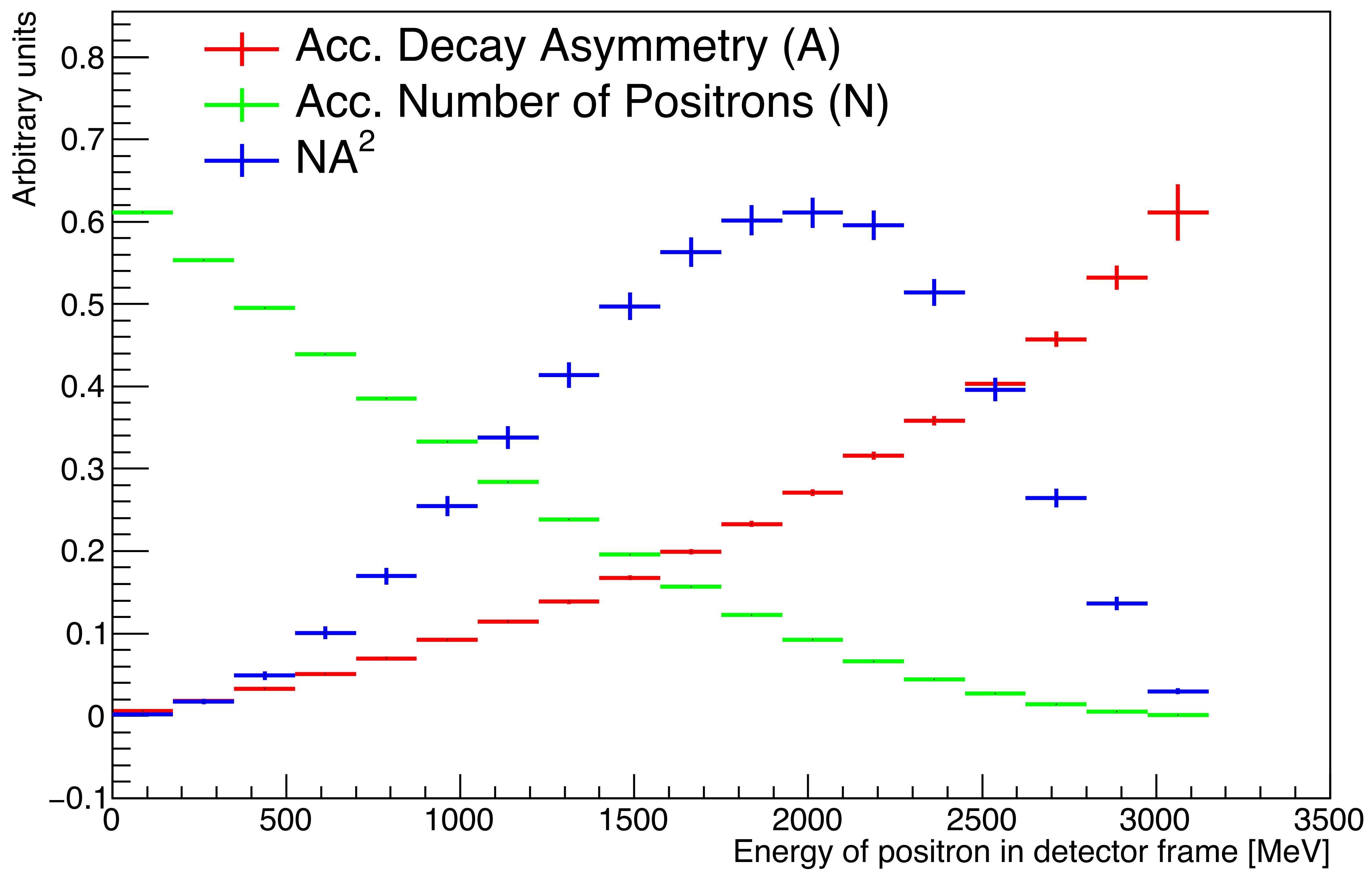


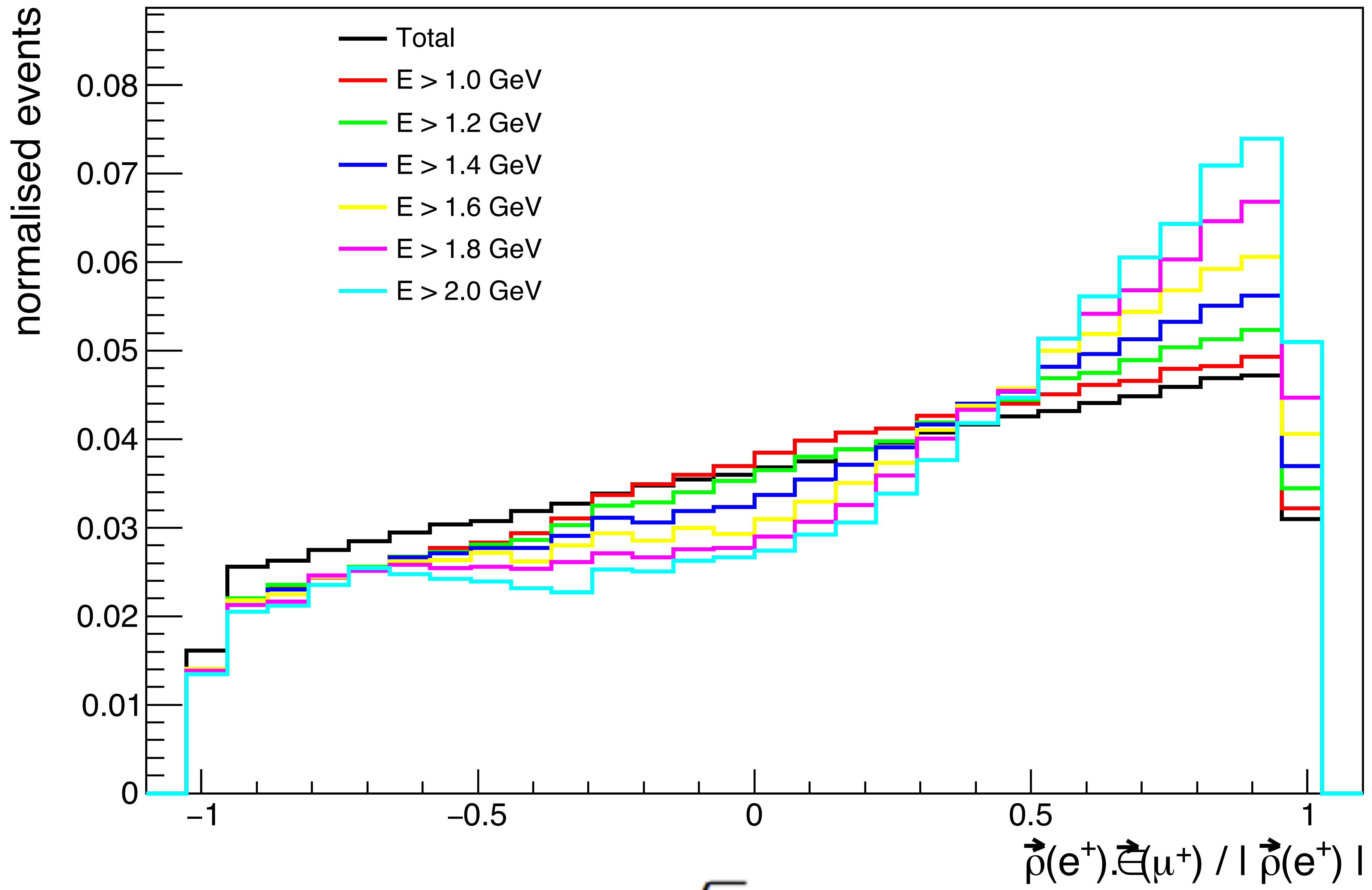
- 10 x improvement to current limit expected at FNAL - trackers improved since BNL
- JPARC g-2/EDM is more sensitive - possible 100 x improvement

Measuring the muon spin…

- e⁺ preferentially emitted in direction of muon spin



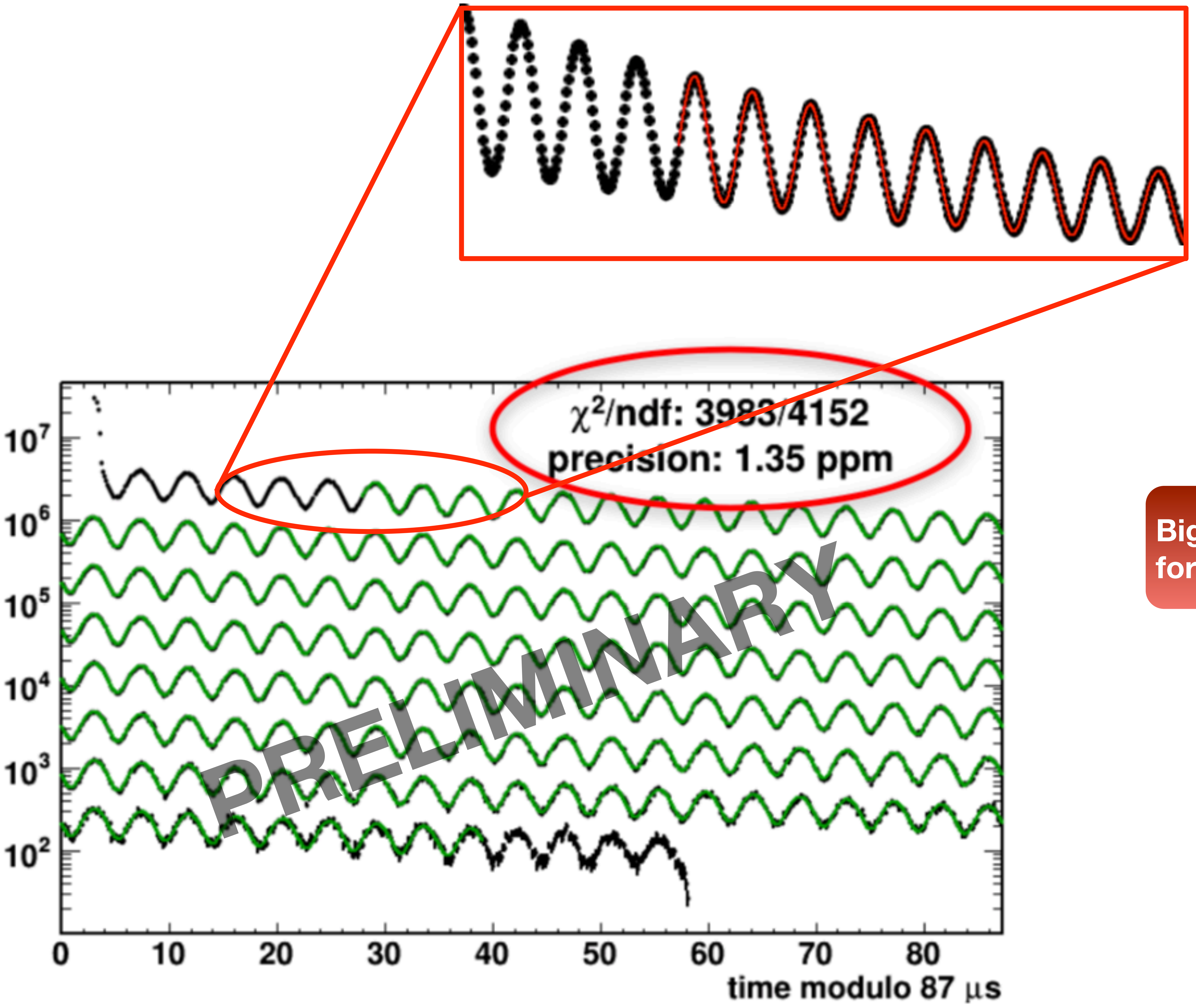




$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu \sqrt{NA^2}}$$

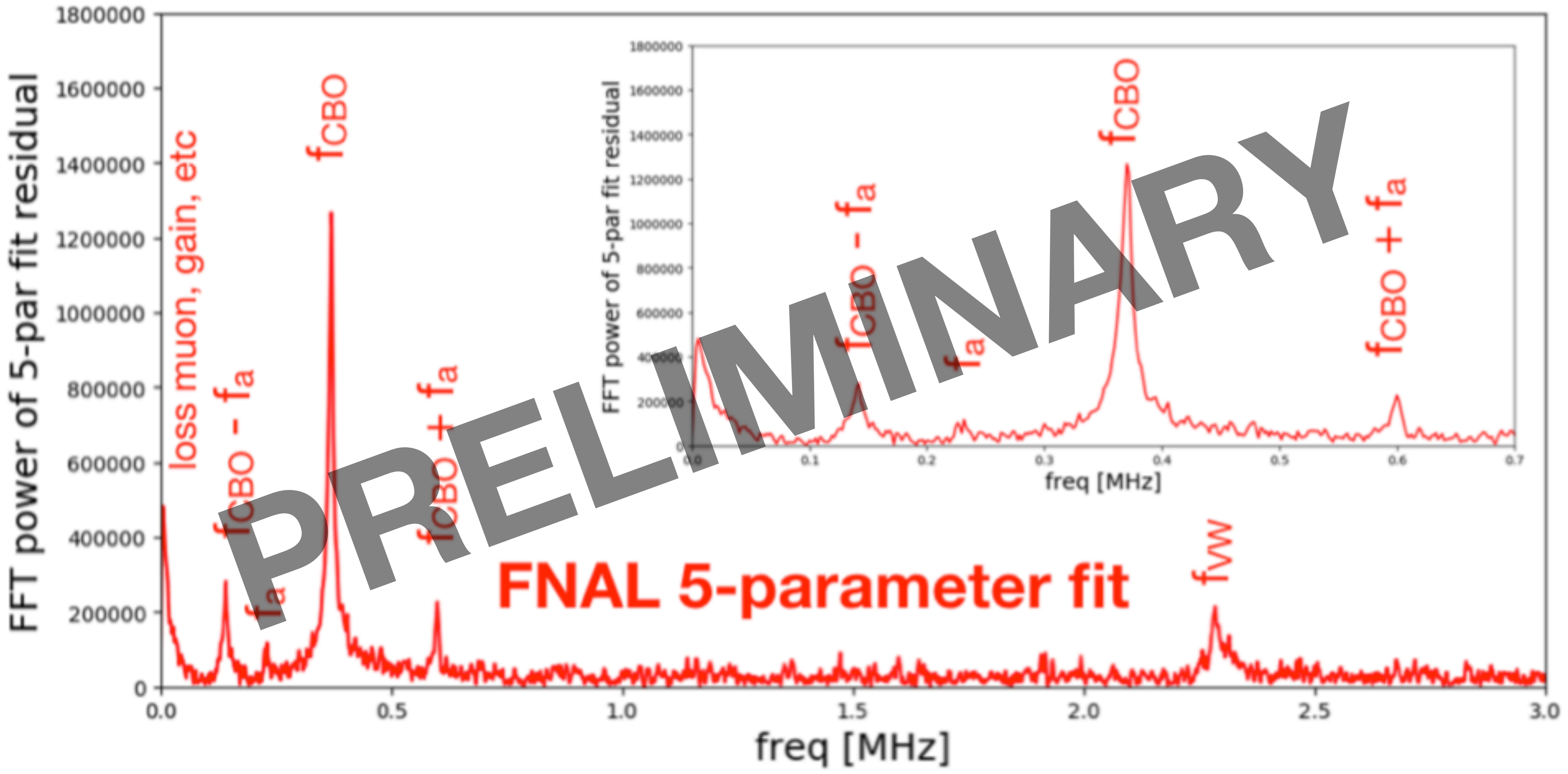
- Asymmetry is larger for high momentum e+
- Optimal cut at E~1.8 GeV

Run 1 Analysis Status: ω_a

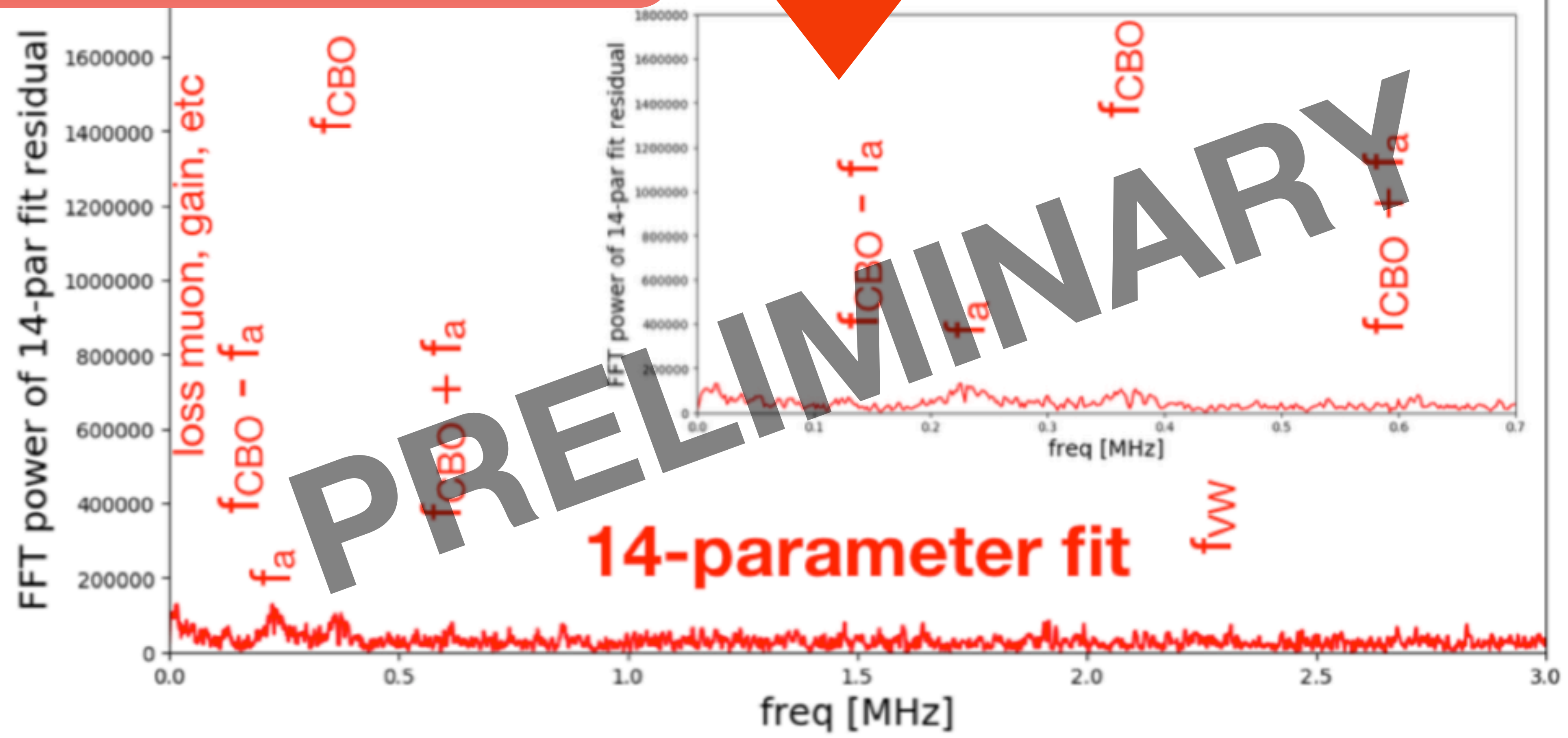


Simple five-parameter fit

FFT of fit residuals

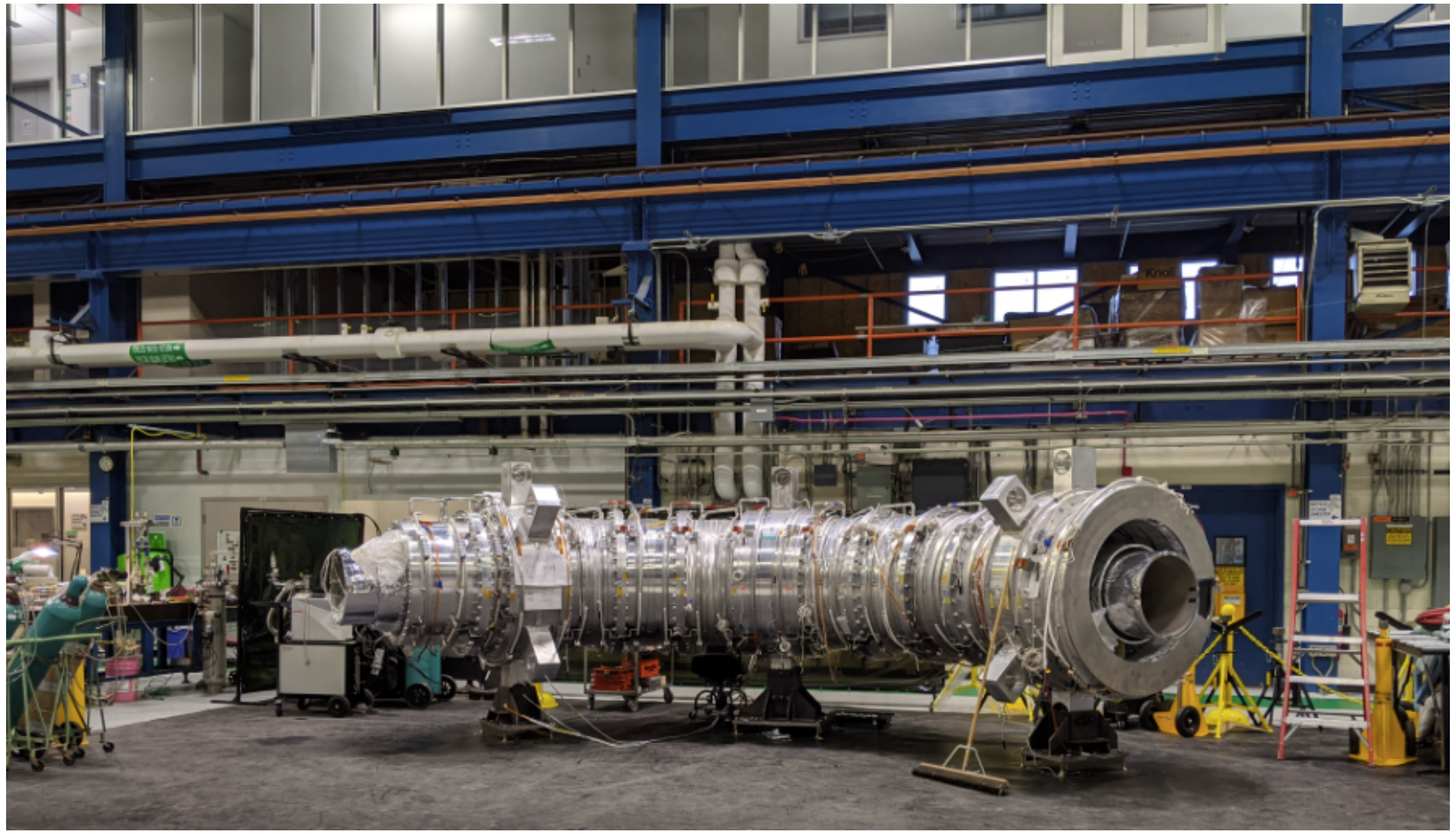


Big improvements when accounting for CBO, lost muons,…



Mu2e

- Mu2e Solenoid completed (assembled in old CDF hall)

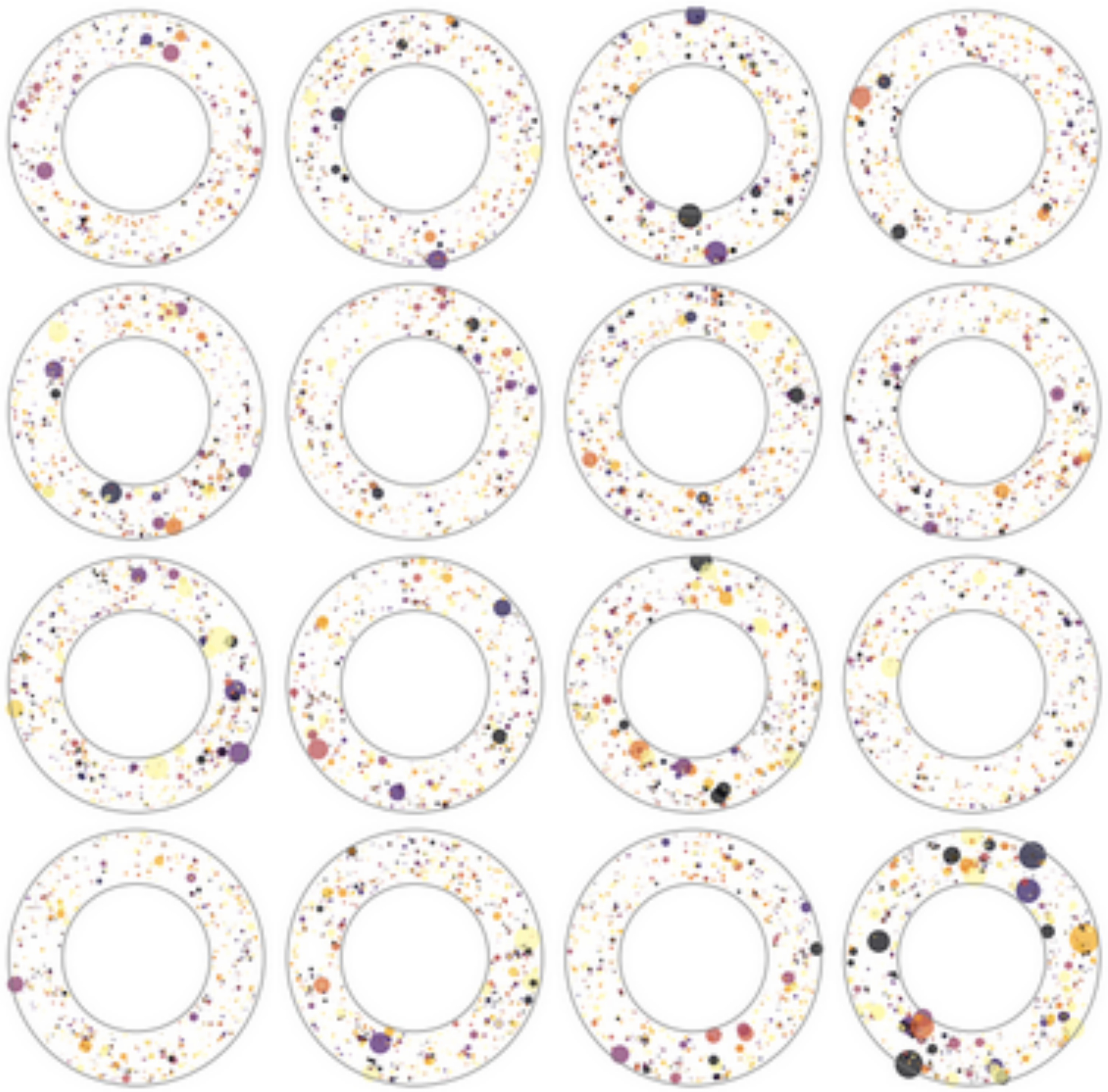


COMET timeline

- **Early 2020:** Proton beam line to COMET area completed
  February 2021: 8 GeV-running tests and inter-bunch extinction measurements
  Mid 2021-Mid 2022: Long shutdown for COMET construction and Main Ring upgrades
  Autumn 2022: "Phase-α" running with full proton beam line, target, muon transport solenoid etc.
  Spring 2023: Phase-I data-taking
- Phase-II on KEK Roadmap 2021
  Development of Phase-II sensitivity improvements to approximately a factor 10 better than original design goal to $O(10^{-18\text{-}19})$

COMET UK

- Significant roles in planning all data-taking campaigns; intend to be directly involved in all, including February 2021 runs
- Leads software and computing effort for collaboration
- Pioneering incorporation of machine-learning techniques into simulation, reconstruction and DAQ designs and firmware
- Working closely with several Malaysian groups on all of the above via Newton Fund
- UK Collaboration Board Chair since 2013



Background events in main Phase-I detector produced using a Generative Adversarial Network (M. Dubouchet)