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cLFV/g-2/EDM Experiment

Satoshi MIHARA
(KEK-IPNS/J-PARC/Sokendai)

Congratulations FNAL g-2 !

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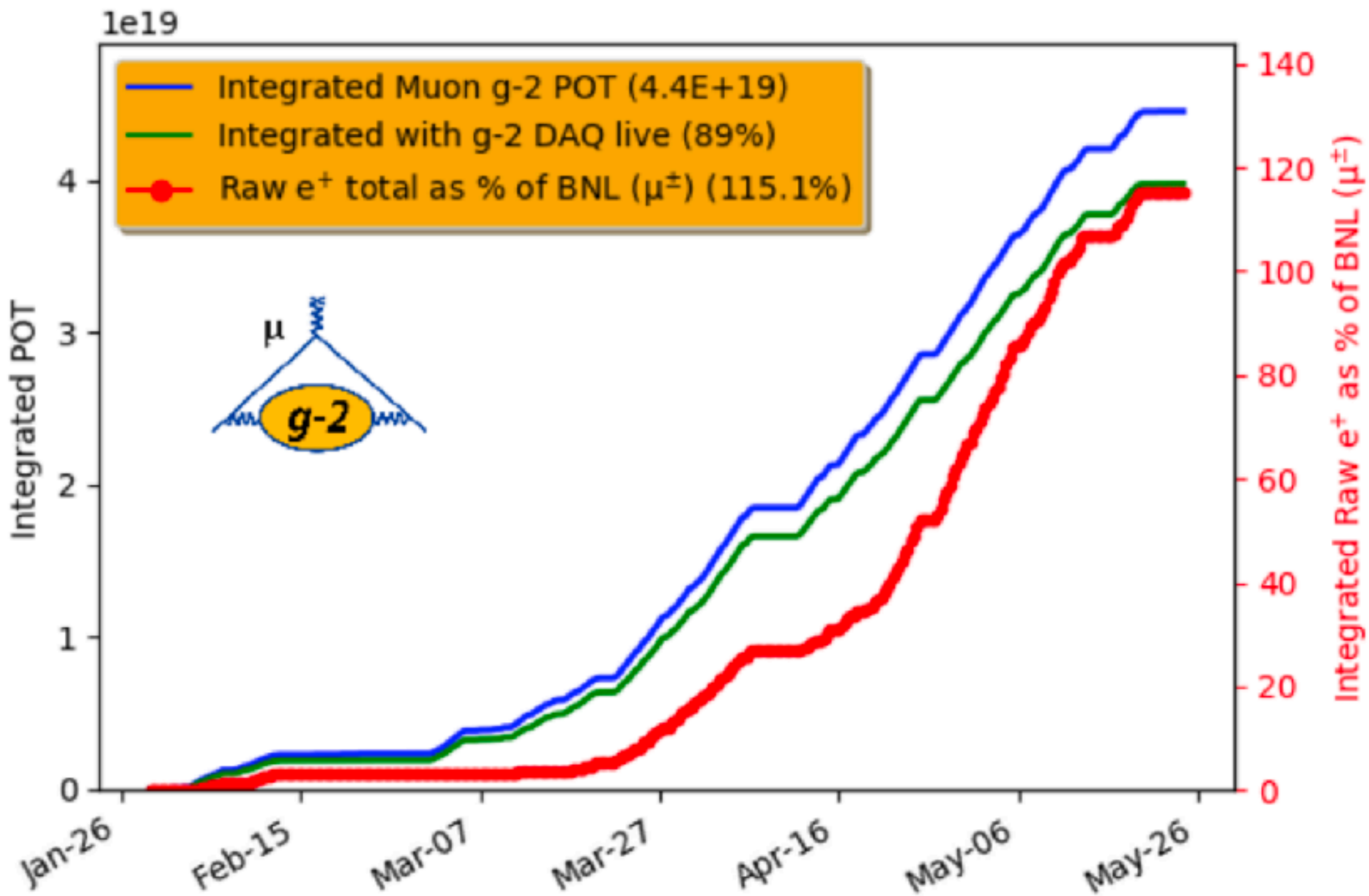


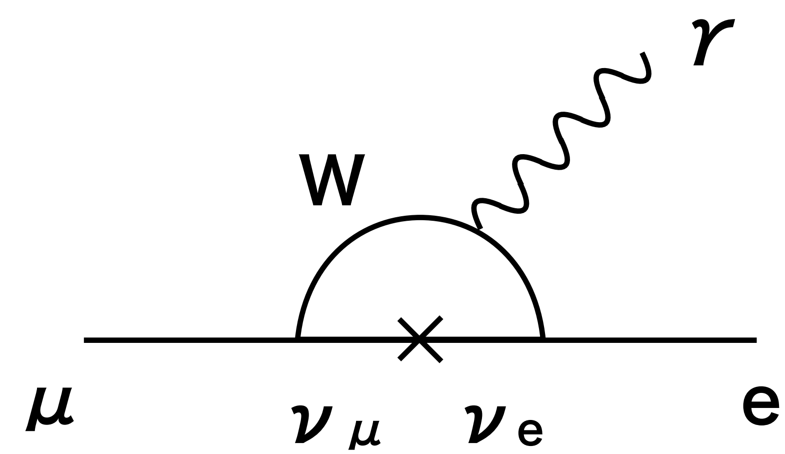
S. Haciomeroglu 5/Jul

Outline

- Introduction
- Muon cLFV experiments
  - MEG & MEG II, COMET, Mu2e, and Mu3e
- Muon g-2/EDM experiments
- Tau cLFV experiments
- Summary and Outlook

Charged Lepton Flavor Violation

- cLFV rate in the Standard Model with non-zero neutrino mass is too small to be observed in experiments; O(BR) $< 10^{-50}$
  - No SM Physics Background
  - Observation = clear evidence of NP
- Motivated by many kinds of new physics models BSM



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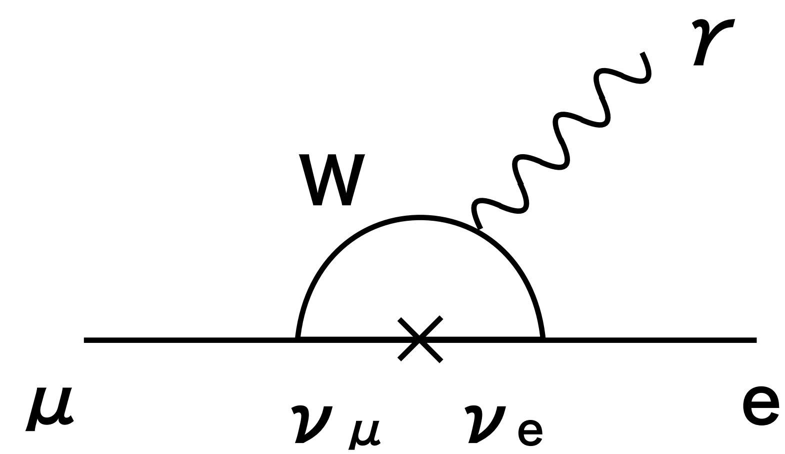

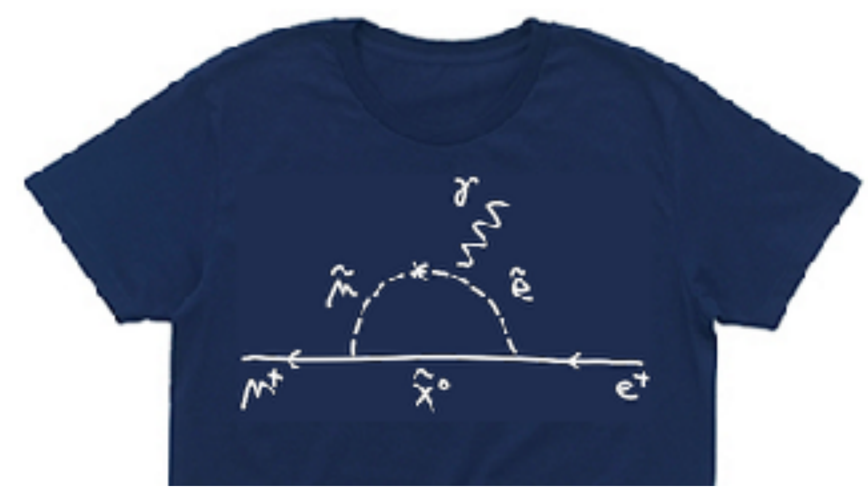

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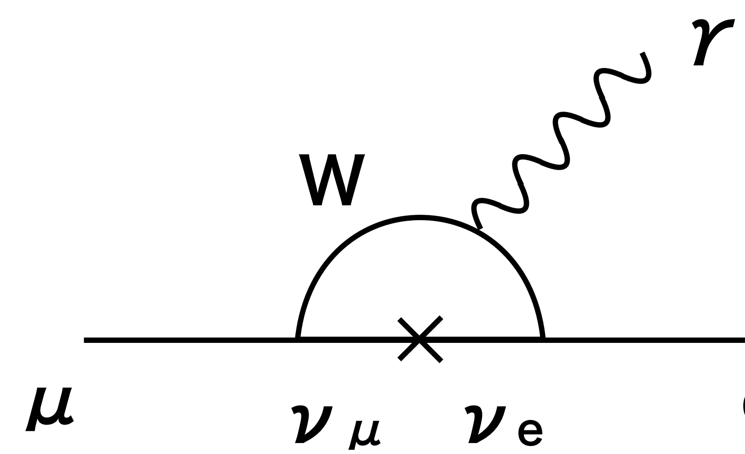
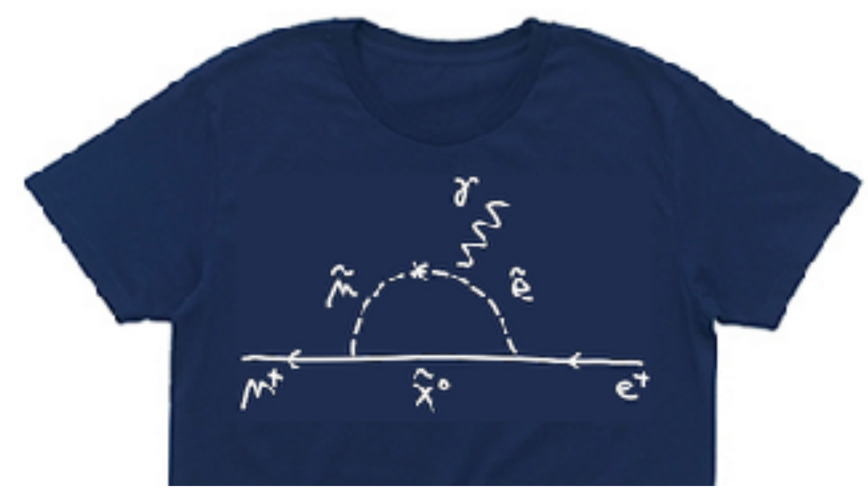
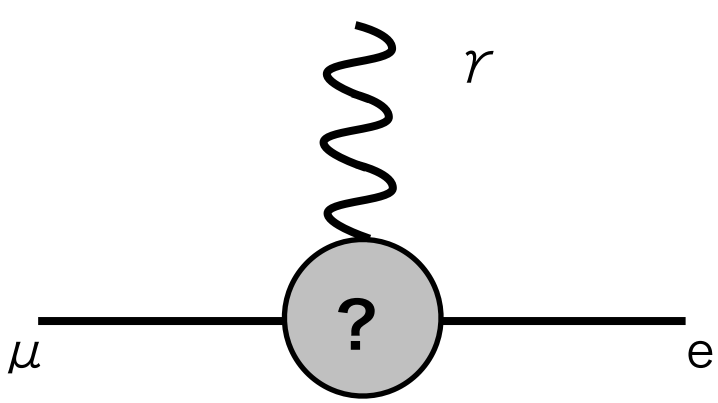




$\mu \rightarrow e\gamma$



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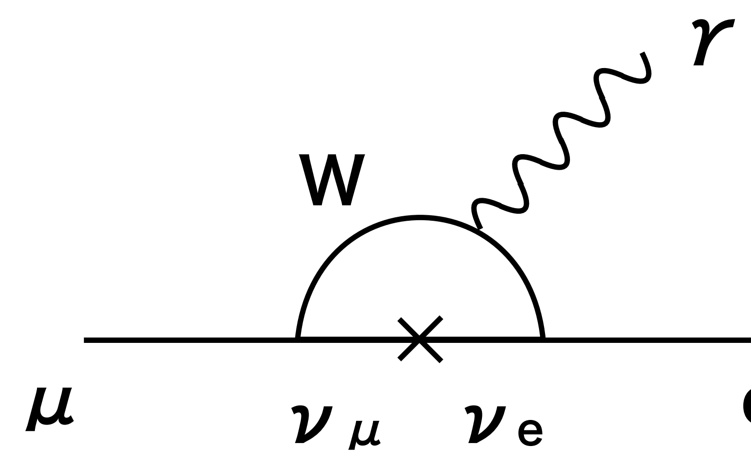

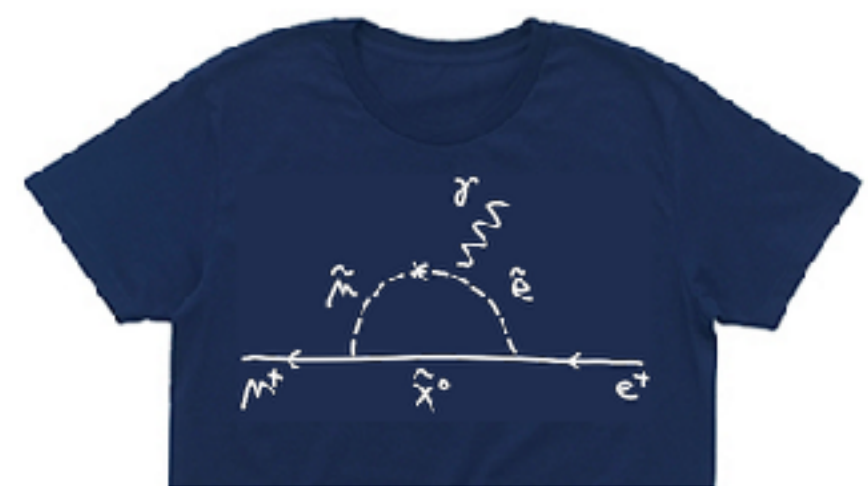

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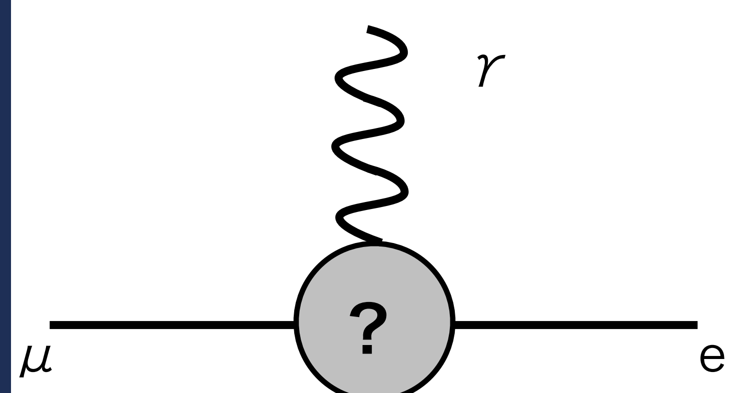
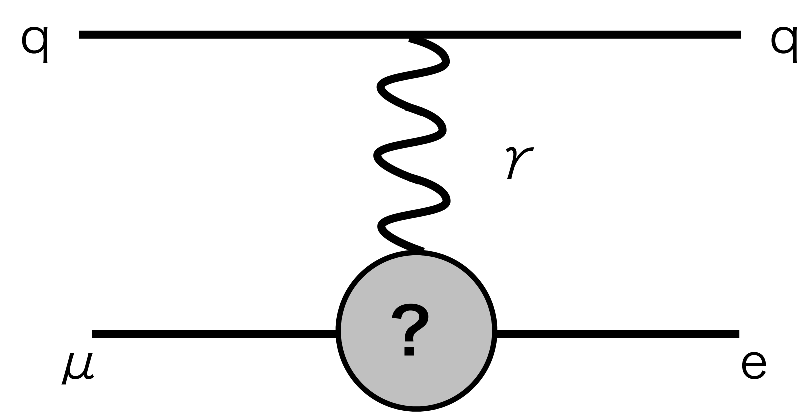


μ-e conv.



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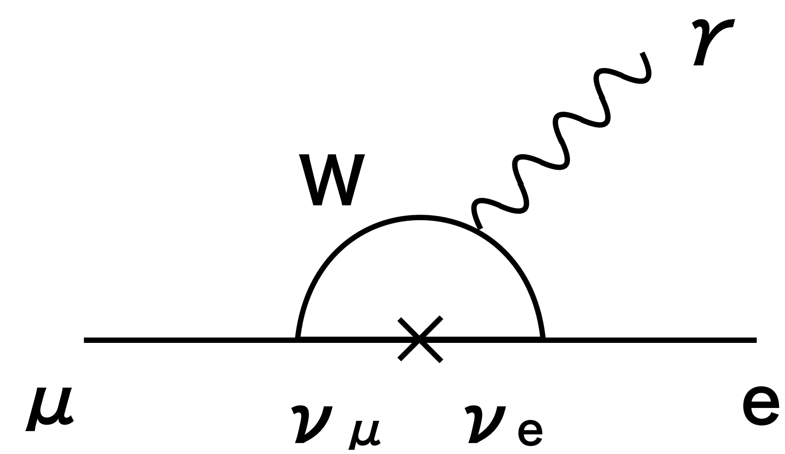

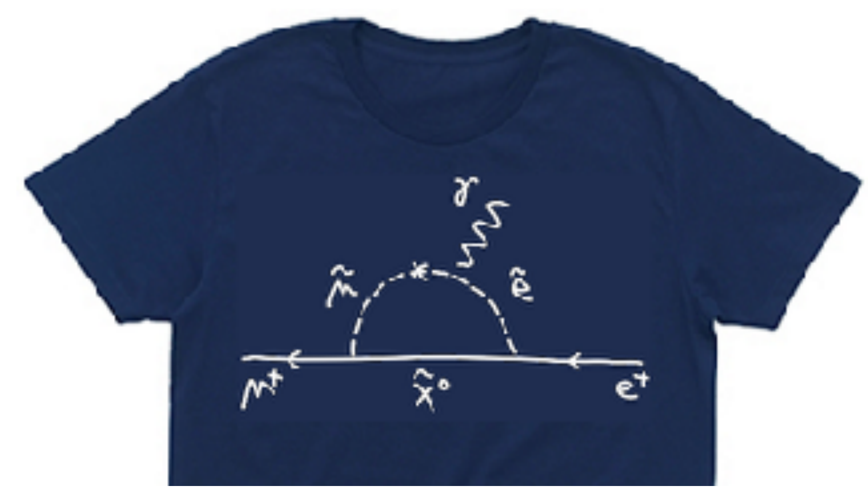

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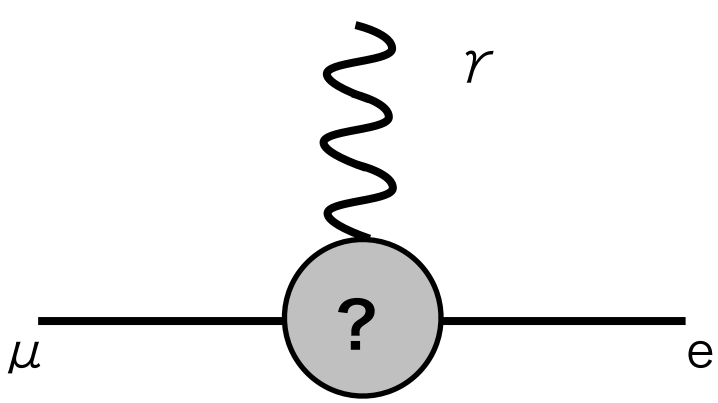

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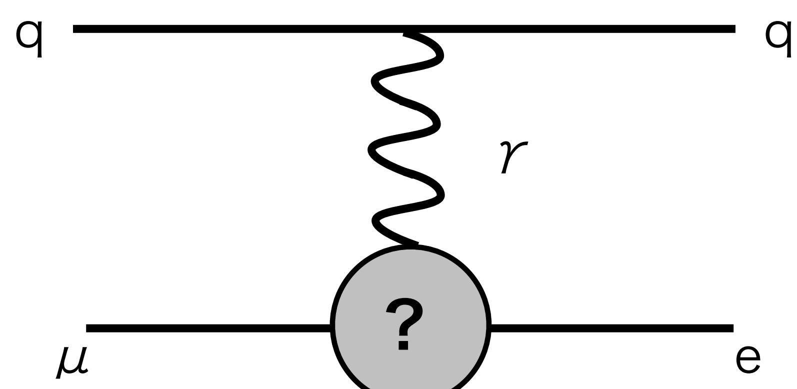

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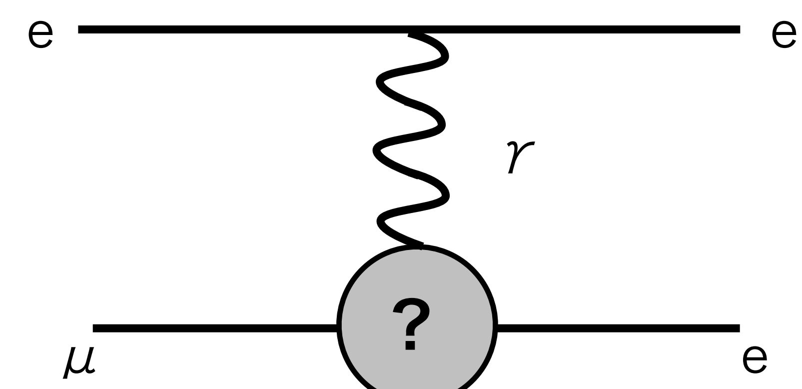

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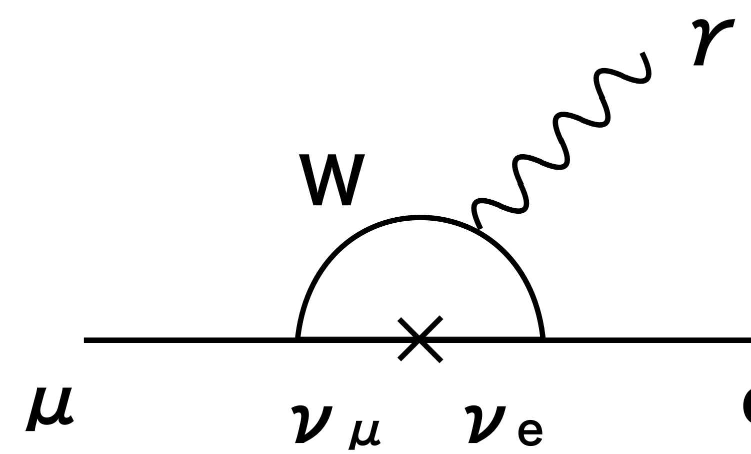

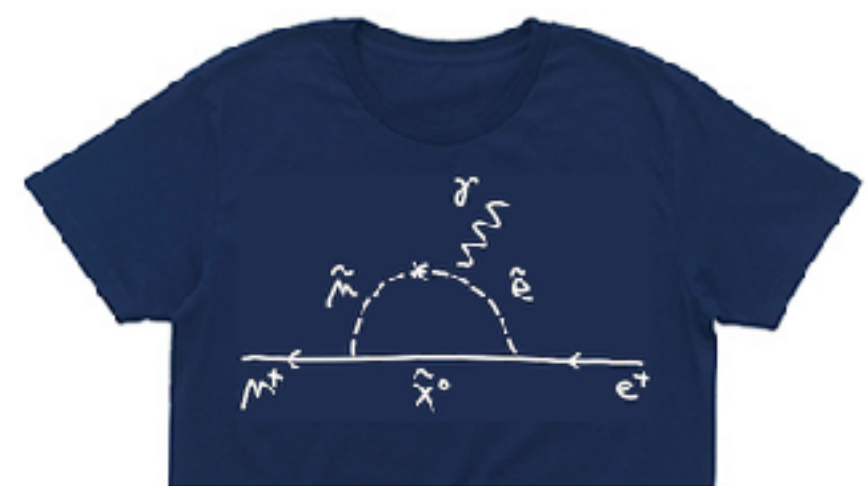

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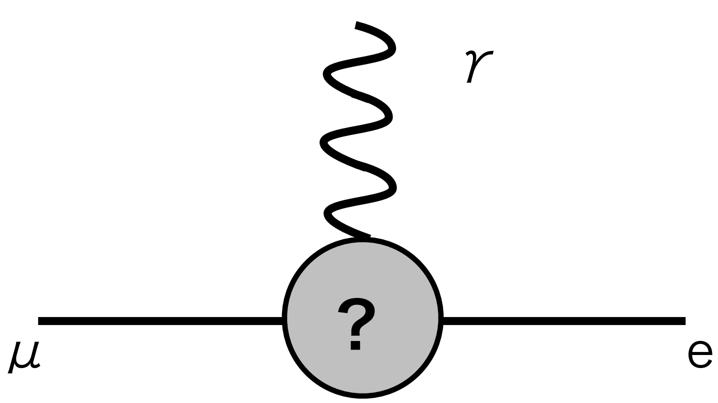

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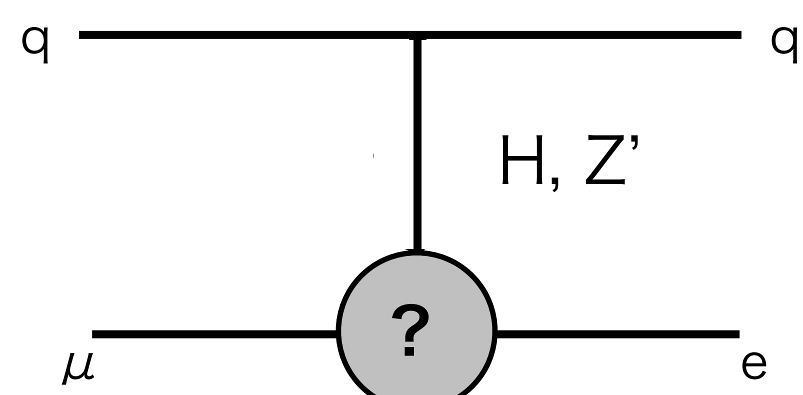

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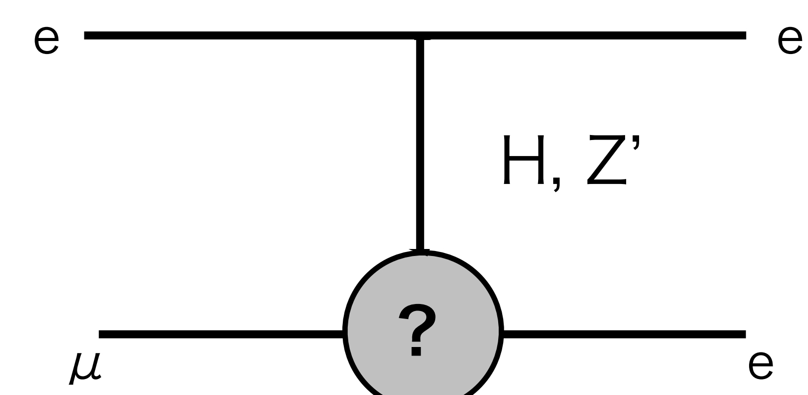

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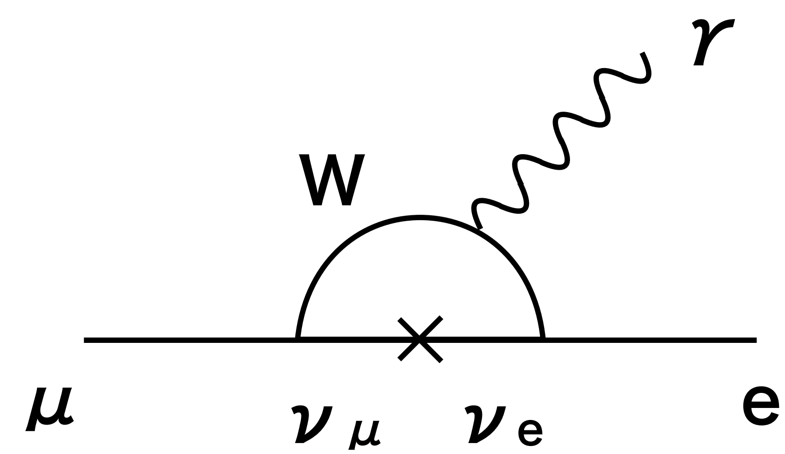

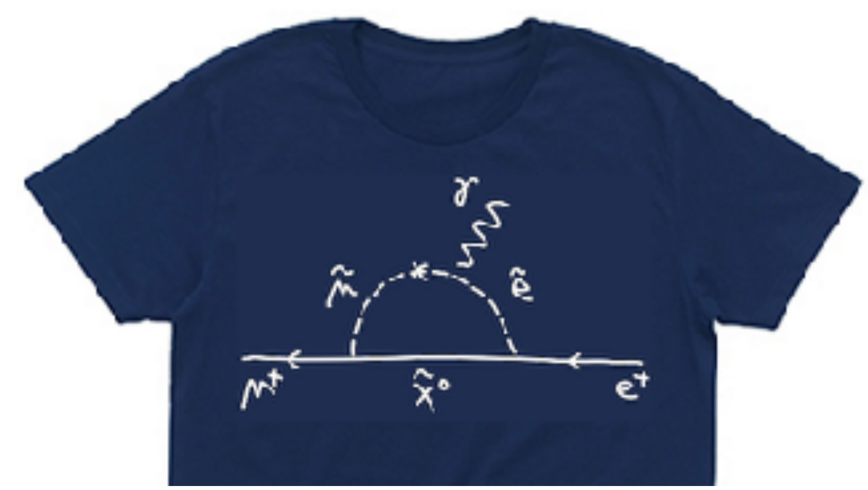

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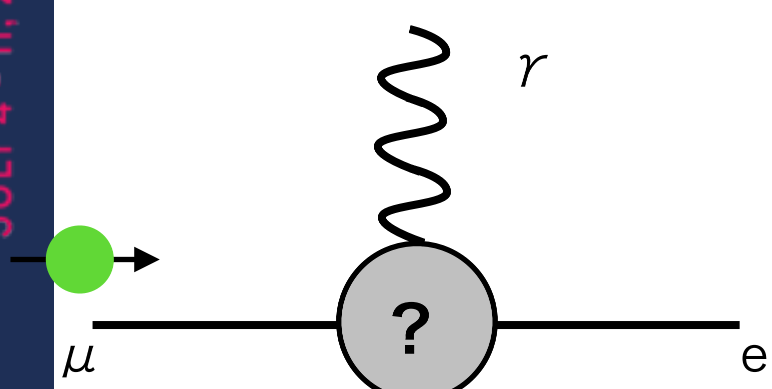

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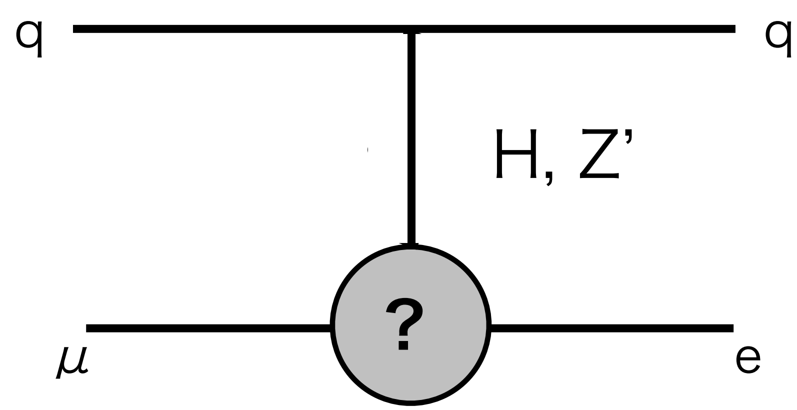

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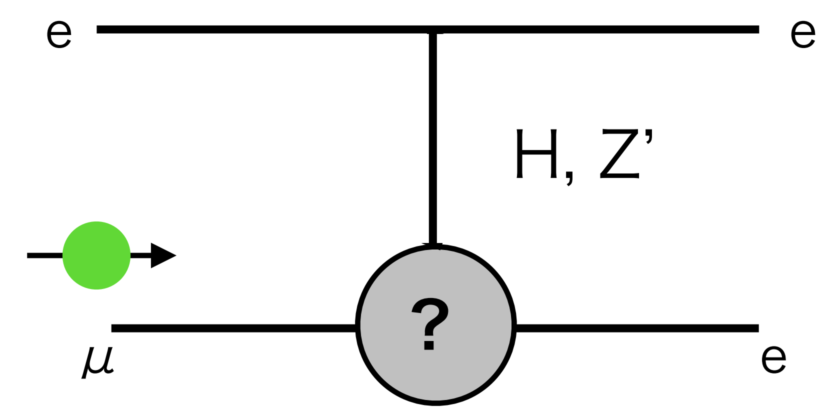
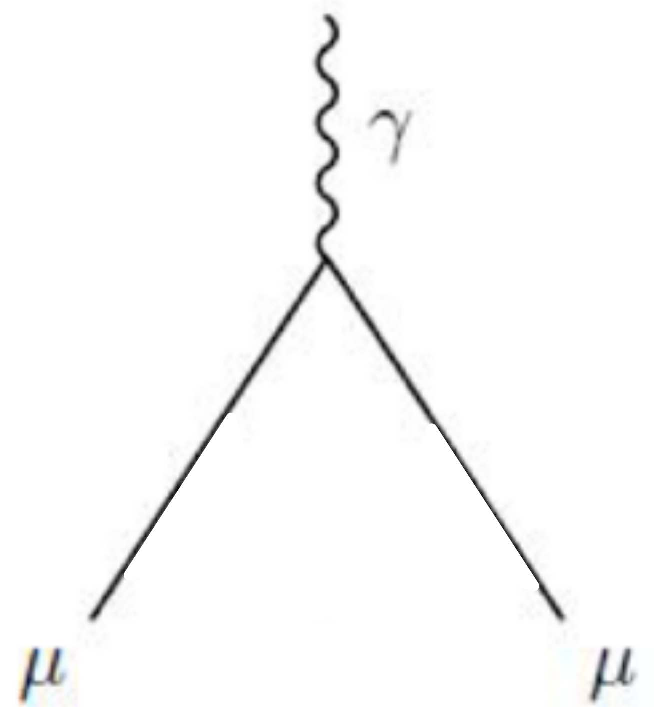
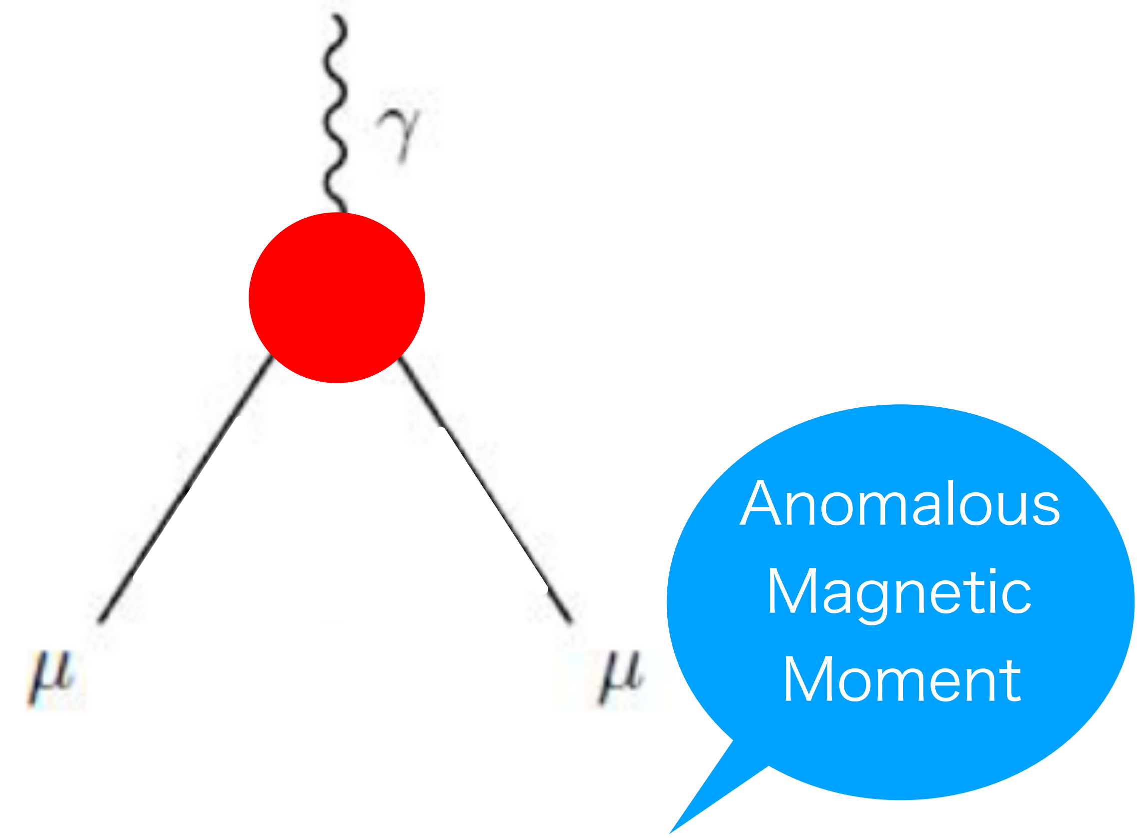


...and muon g-2

- The Lande's *g* factor is 2 in tree level (Dirac equation)



- In quantum field theory, *g* factor gets corrections:



$$g = 2\,(\,1 + a_\mu)$$

$$a_\mu = a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

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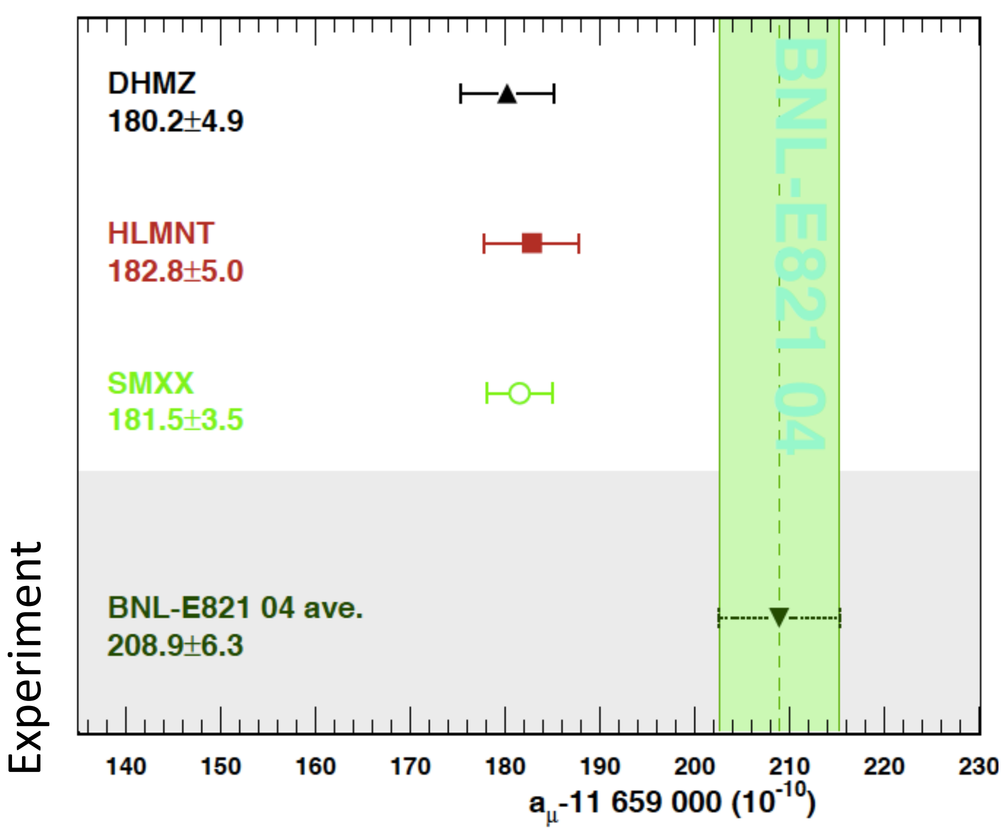
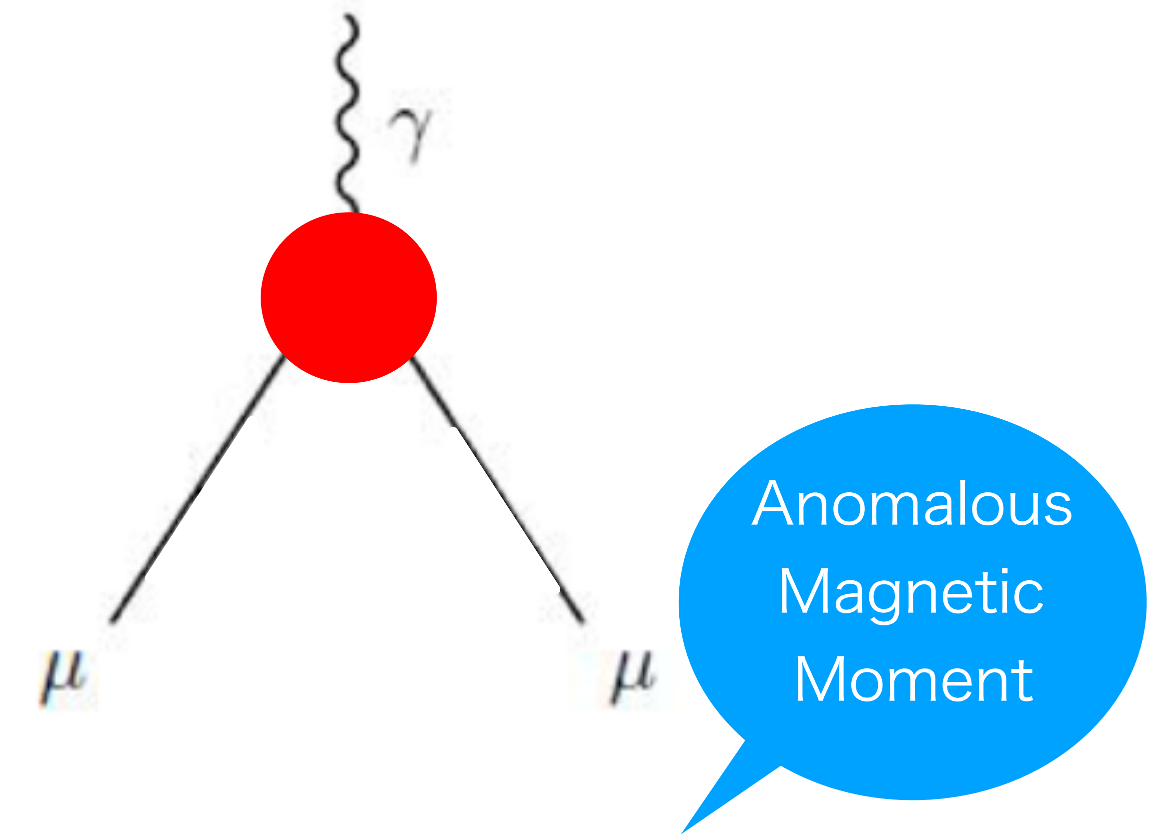




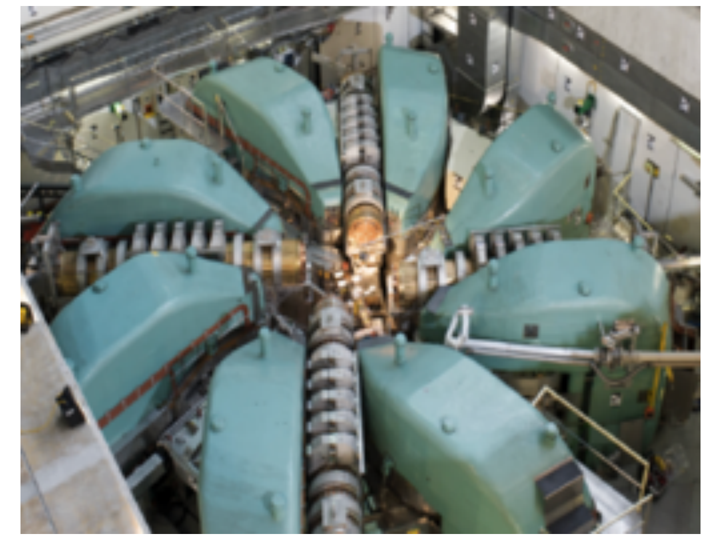
$$g = 2\,(1 + a_\mu)$$

$$a_\mu(QED) + a_\mu(had) + a_\mu(weak) + a_\mu(BSM)$$

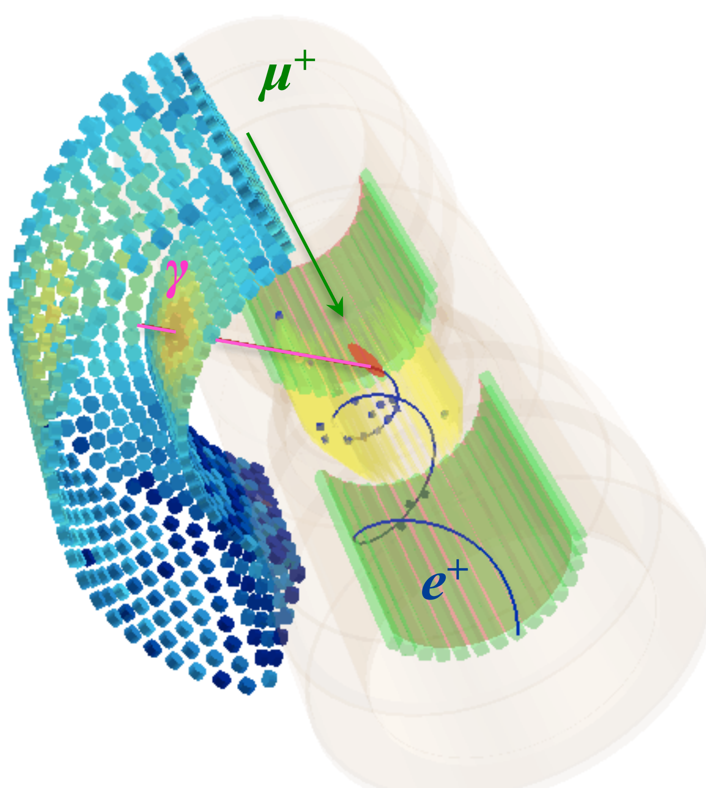
MEG & MEG II

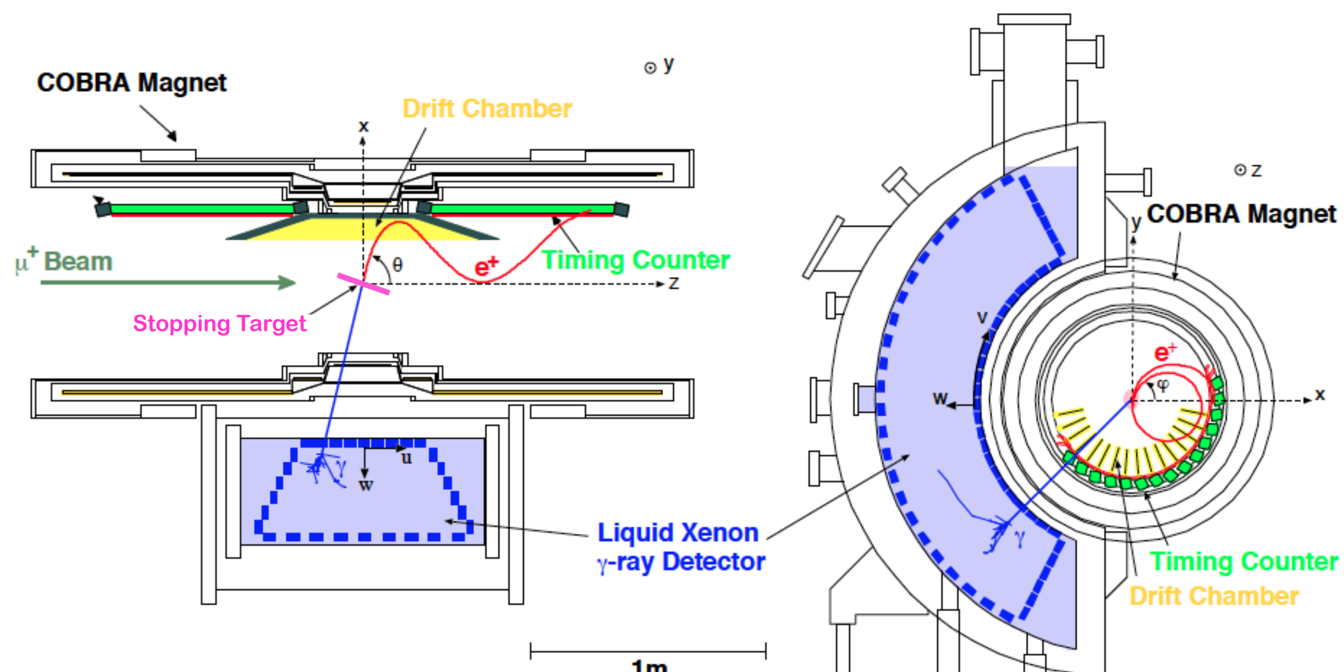
Search for $\mu^+ \to e^+ \gamma$ at Paul Scherrer Institute

- World's most intense DC muon beam at PSI
- MEG, MEG II (and Mu3e) require
  - Low momentum (surface muon at 29MeV/c)
  - High intensity continuous beam as they observe multi-particles in the final state



PSI Ring Cyclotron
590MeV, 1.4MW

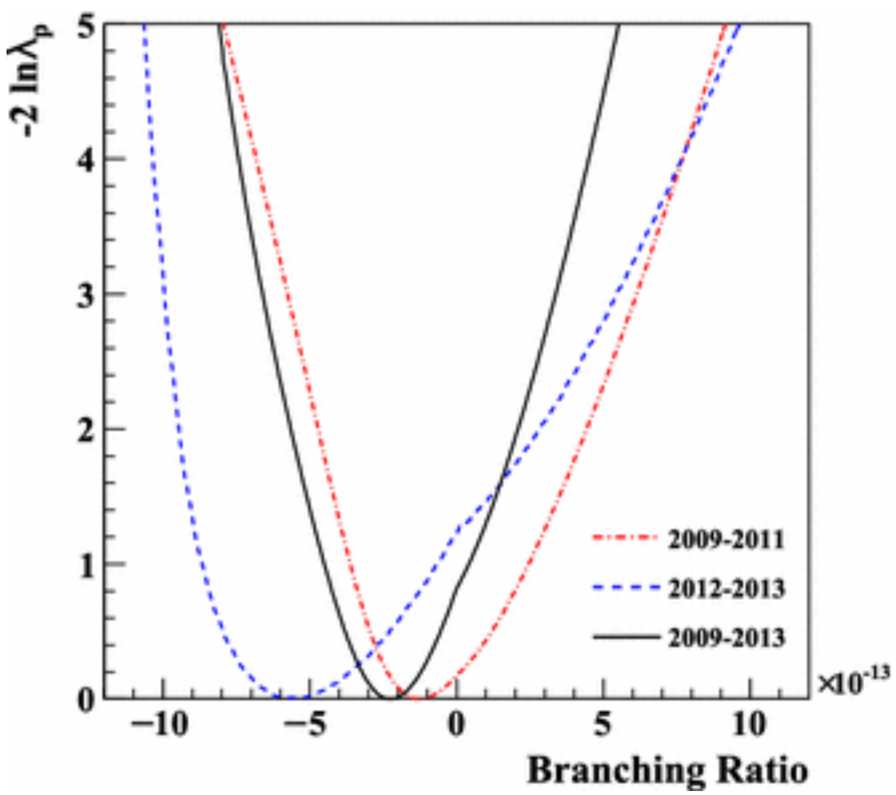


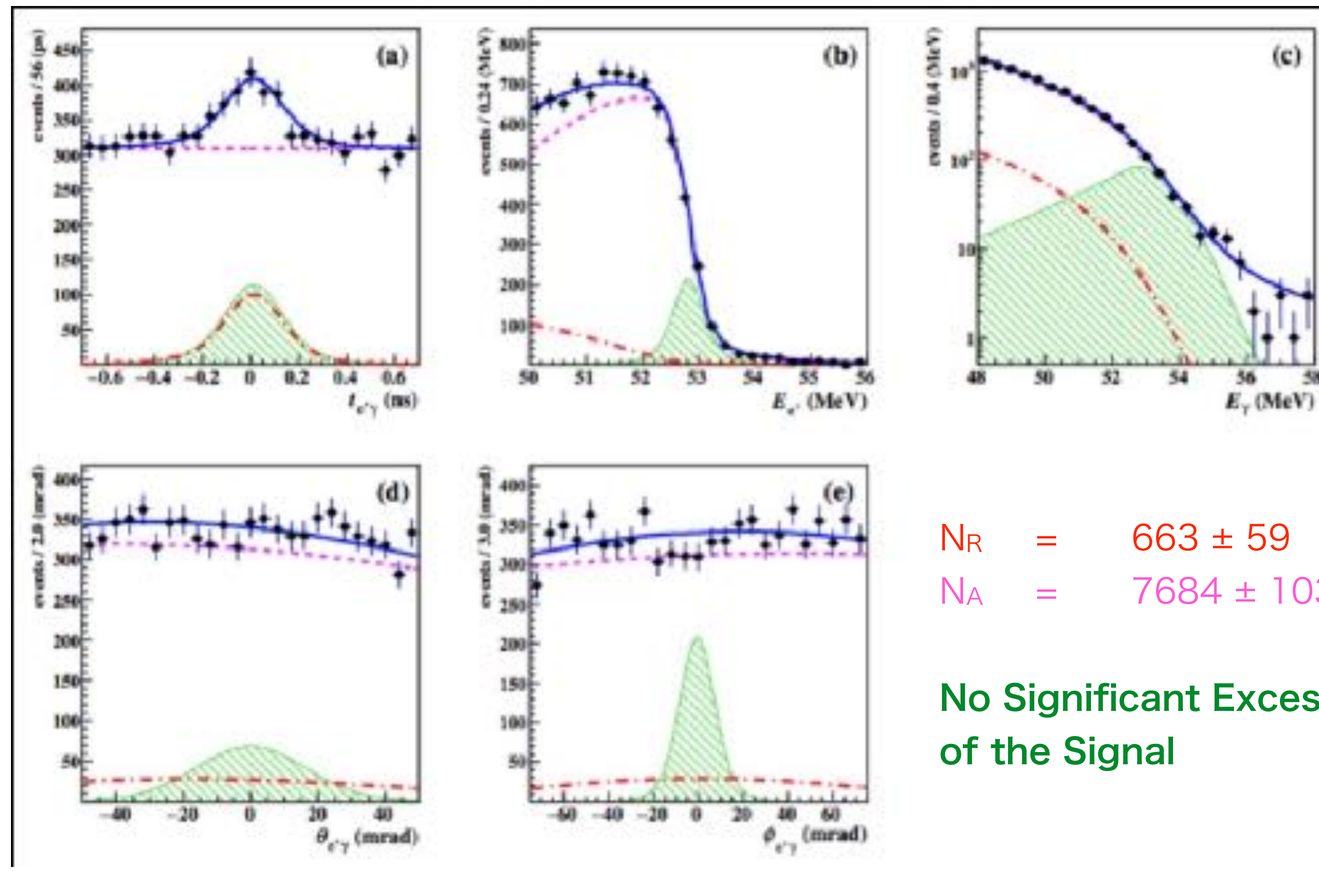


EPJ C 73 (2013) 2365

EPJ C 76 (2016) 434

MEG Result





N_R = 663 ± 59

N_A = 7684 ± 103

No Significant Excess of the Signal

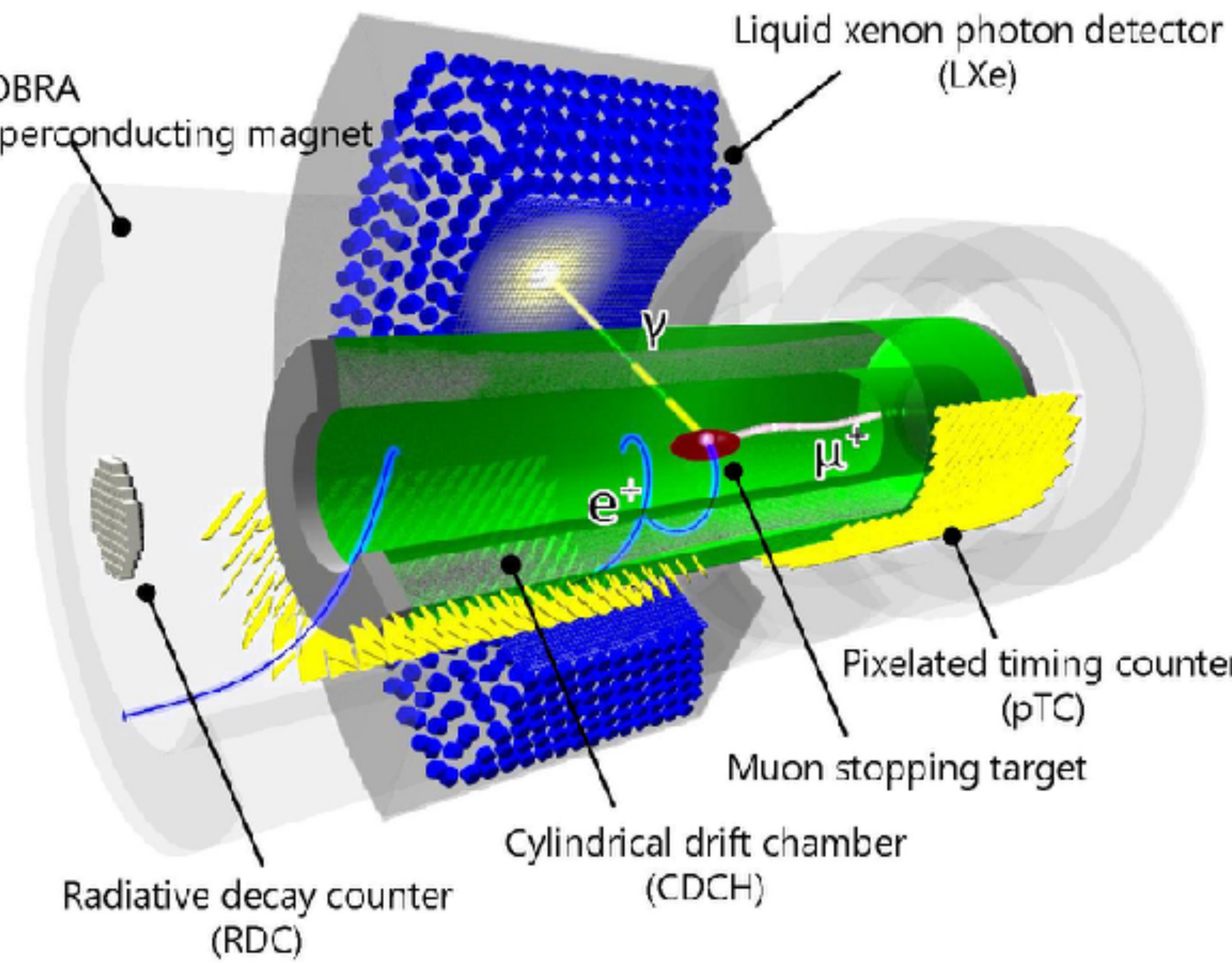
- Confidence interval calculation by following the Feldman-Cousins approach with the profile-likelihood ratio ordering.
- Profile-likelihood ratios all consistent with a null-signal hypothesis.

$Br(\mu \rightarrow e\gamma) < 4.2\times10^{-13}$ @ 90% C.L.

A. Papa 7/Jul
S. Ogawa 7/Jul

Detector Upgrade: MEG II

- Twice better resolutions in all components
- Double the muon beam rate
  - 7×10^7 muon stops/s
- New detector to tag the radiative muon decay event
- New calibration method



Target Sensitivity : 6×10^{-14} in 3 years running

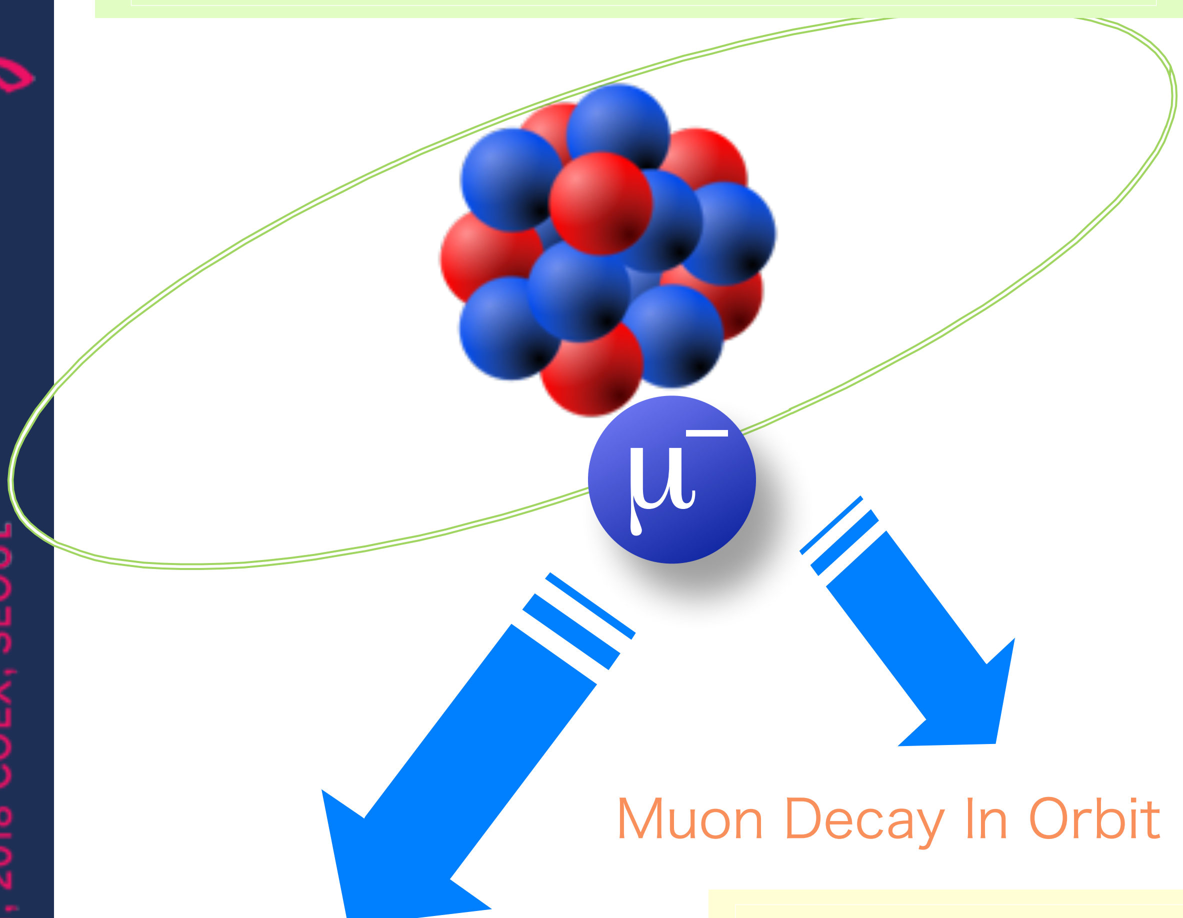
COMET & Mu2e

μ-e conversion searches

μ-e Conversion Search

μ-e conversion

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$



Muon Decay In Orbit (39%)

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture (61%)

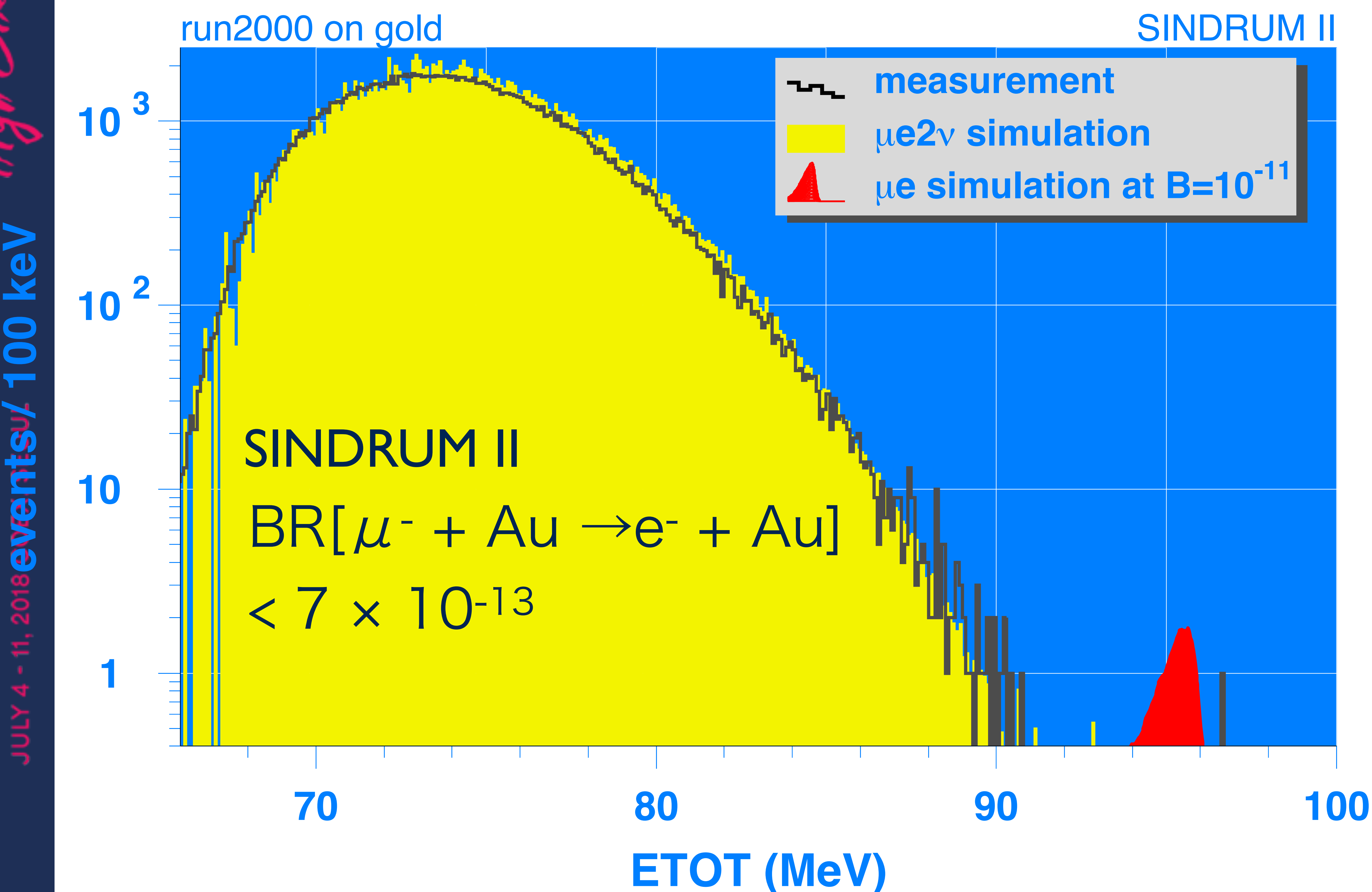
$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

- **Atomic capture of μ^-**
  - Decay in orbit (DIO)
    - electron gets recoil energy
  - Capture by nucleus
    - resultant nucleus is different
  - $\tau_\mu^N < \tau_\mu^{free}$ (τ_μ^{Al} = 860 nsec)
- **μ-e conversion**

- $E_{\mu e}(Al) \sim m_\mu - B_\mu - E_{rec}$=104.97MeV
  - B_μ: binding energy of the 1s muonic atom

μ-e Conversion

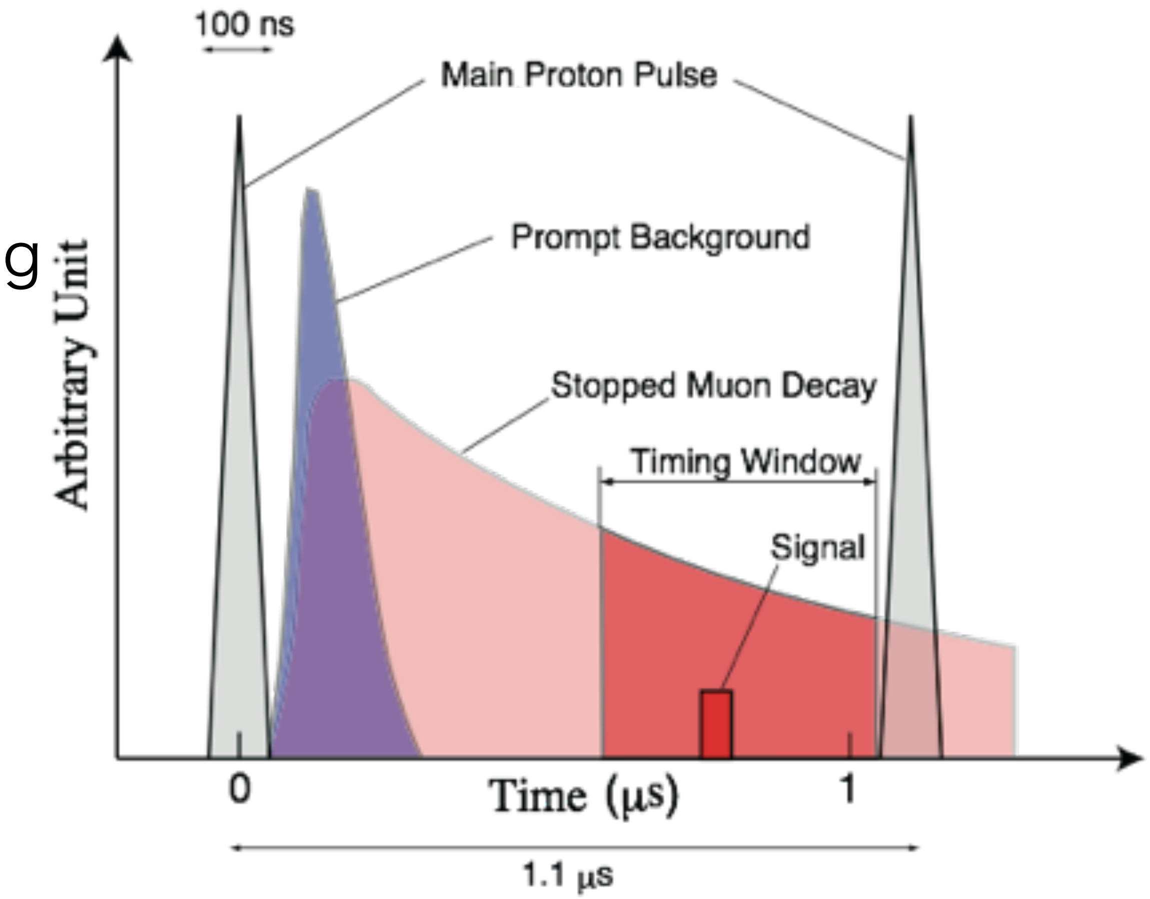
Electron Energy Spectrum



μ-e Conversion

Signal and Background

- Signal
  - Electron from the muon stopping target with a characteristic energy with a delayed timing
- Background
  - Decay in Orbit Electron
  - Radiative muon capture
  - Cosmic-ray
  - and others



Tiny leakage of protons in between consecutive pulses can cause a background through Beam Pion Capture process:

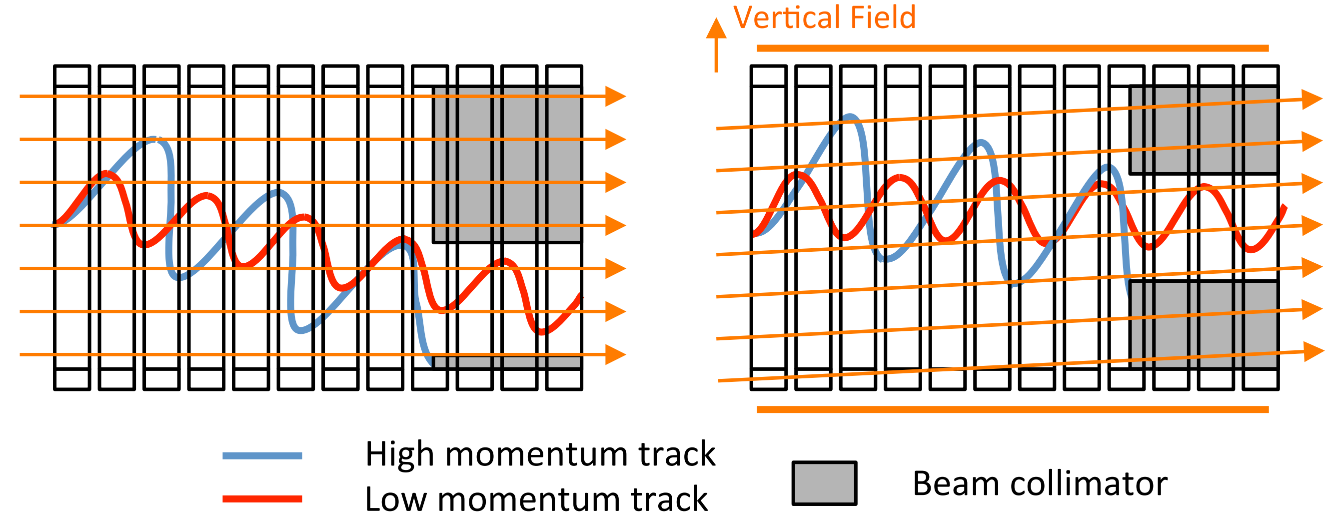
- $\pi^- + (A,Z) \rightarrow (A,Z\text{-}1)^* \rightarrow \gamma + (A,Z\text{-}1)$
  $\gamma \rightarrow e^+ e^-$

$$R_{ext} = \frac{\text{Number of protons between pulses}}{\text{Number of protons in a pulse}}$$

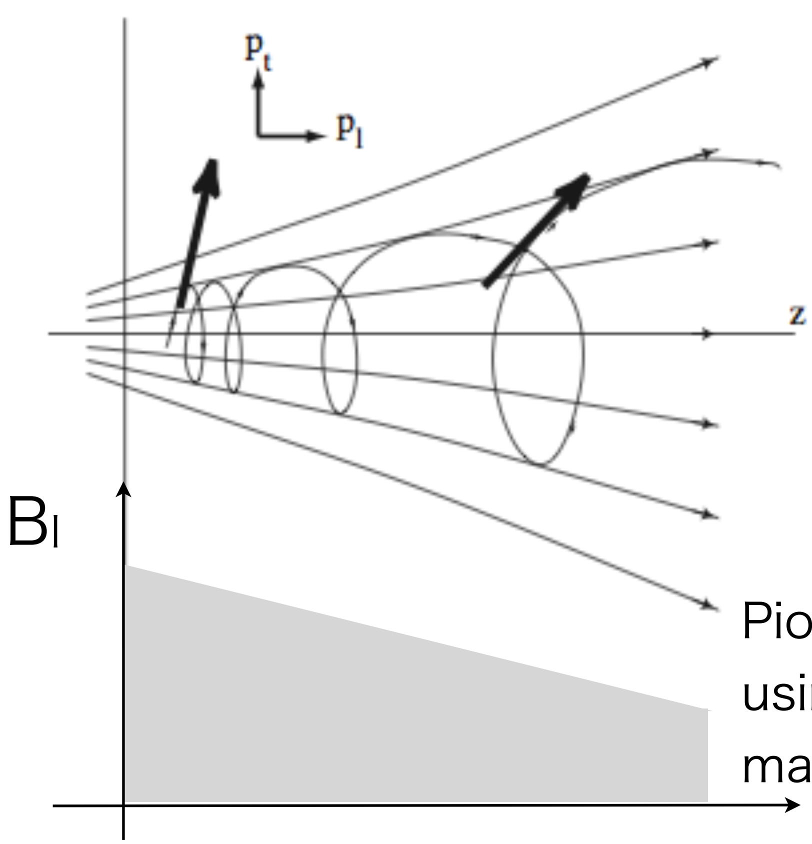
More Muons

- Pion production in magnetic field
- Pion/muon collection using gradient magnetic field
- Beam transport with curved solenoid magnets

Curved Solenoid Beam Transport

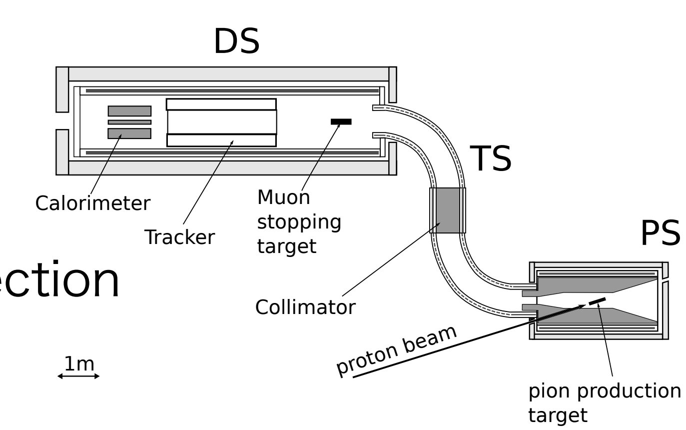


- Momentum and charge separation
- Same scheme used in COMET Phase-II electron spectrometer

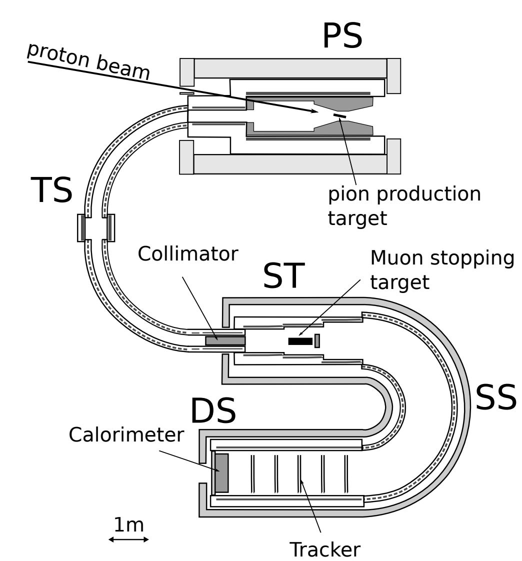


Pion/muon collection using gradient magnetic field

Mu2e

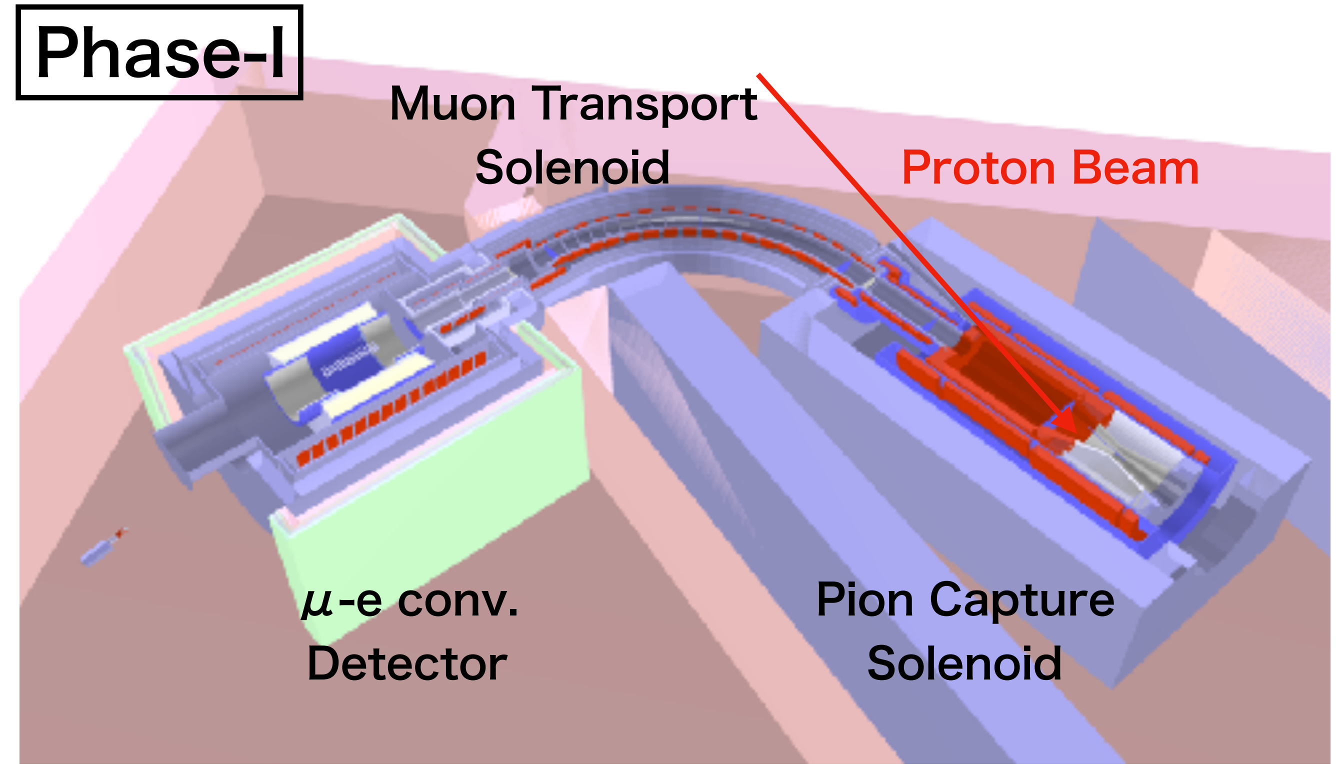


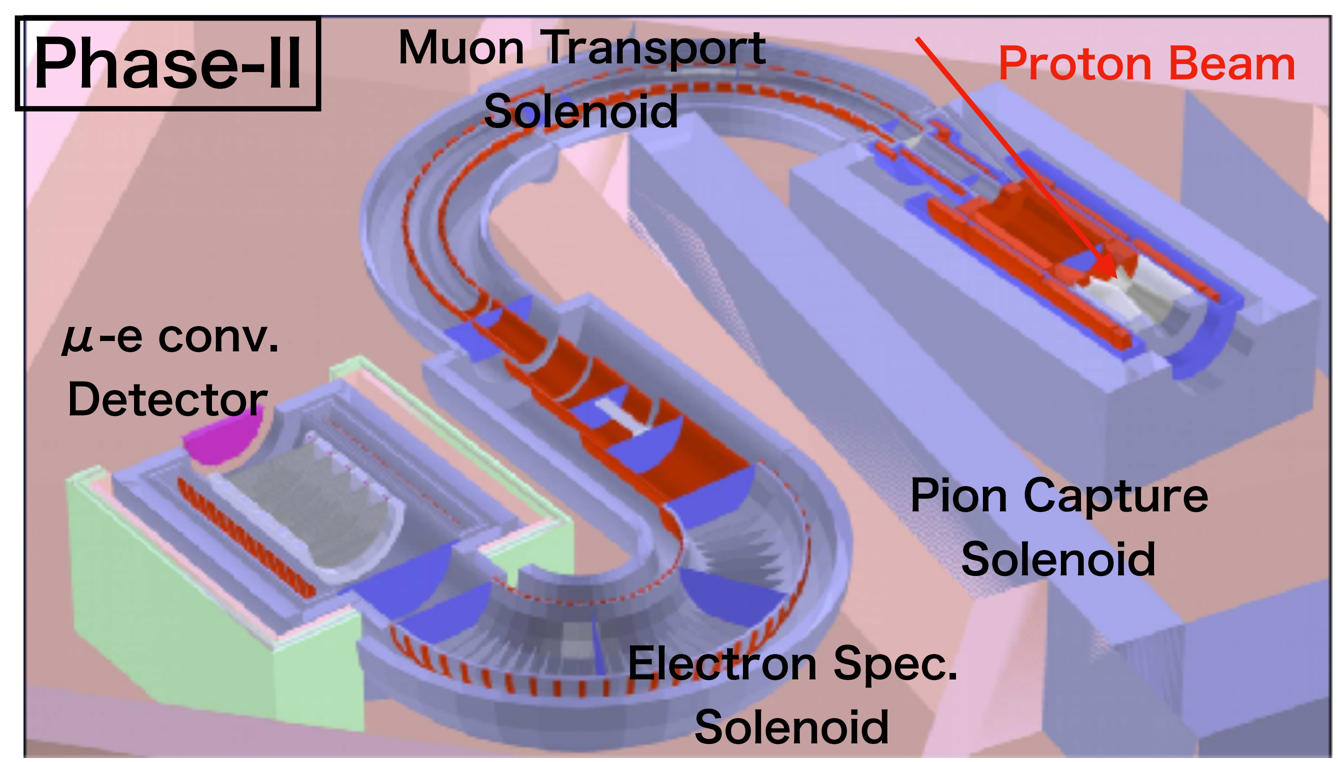
COMET



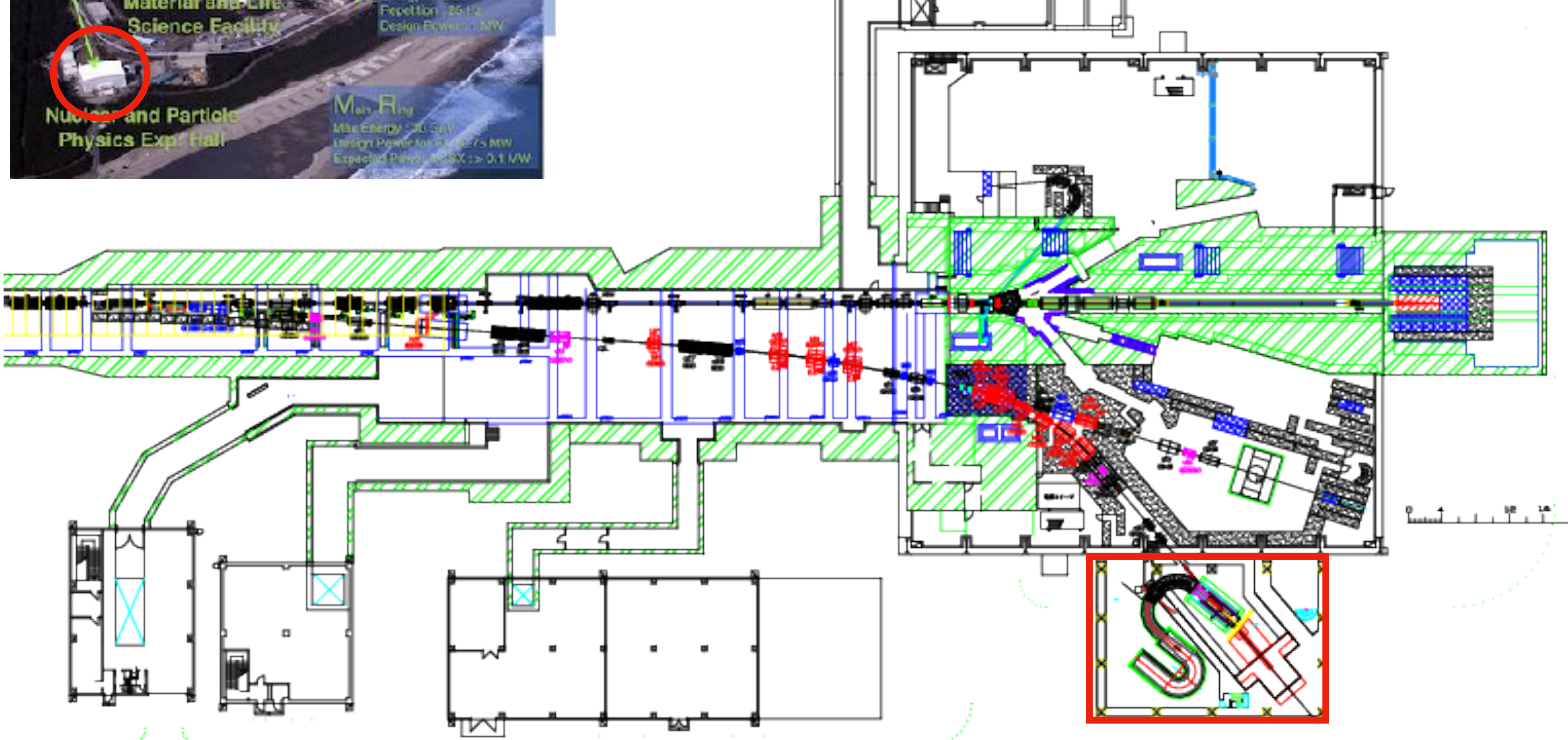
COMET at J-PARC

- **Target S.E.S. 2.6×10^{-17}**
- **8GeV Pulsed proton beam at J-PARC**
  - Insert empty buckets for necessary pulse-pulse width
  - bunched-slow extraction
- **pion production target in a solenoid magnet**
- **Muon transport & electron momentum analysis using C-shape solenoids**
  - smaller detector hit rate
  - need compensating vertical field
- **Tracker and calorimeter to measure electrons**
- COMET decided to take a staging approach to realize this. The collaboration is making an effort to start physics DAQ as early as possible under this.
  - **Phase-I 8GeV-3.2kW, < 10^{-14}**
  - **Phase-II 8GeV-56kW, < 10^{-16}**



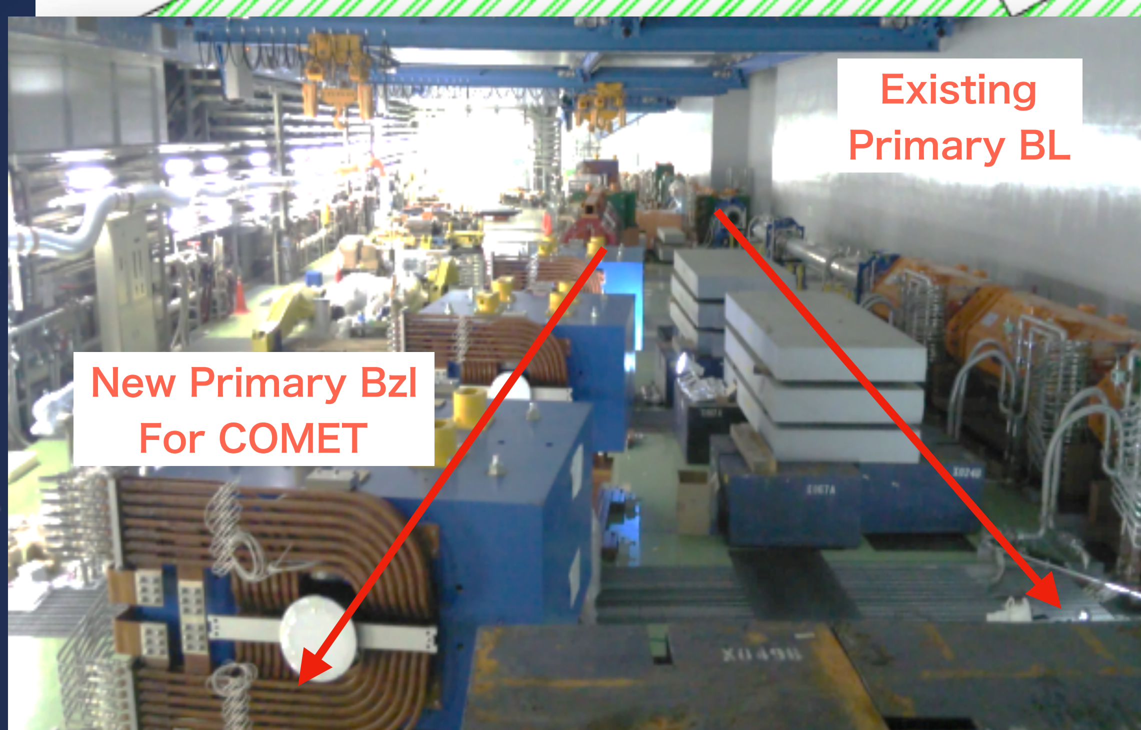


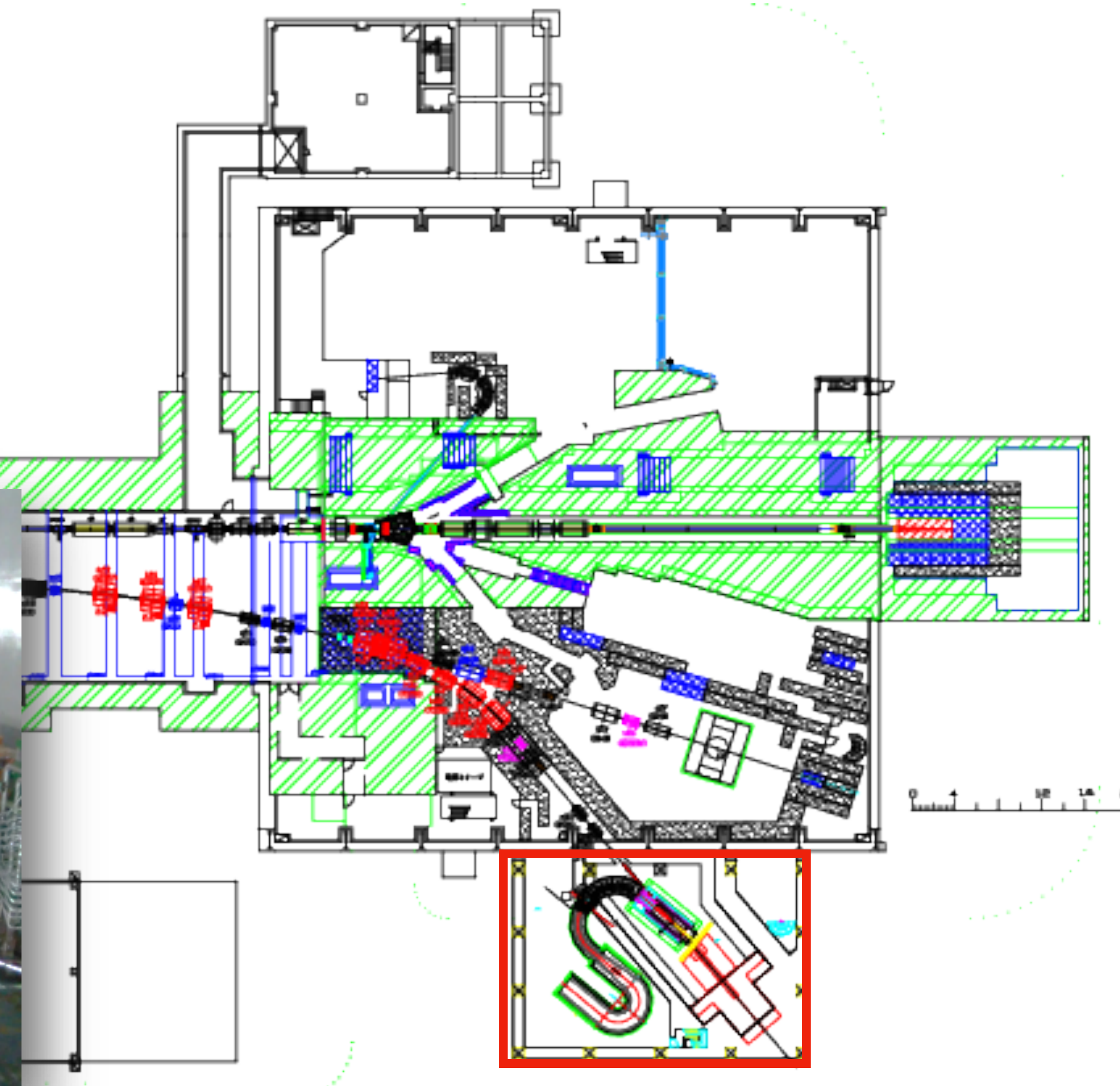
COMET Facility Construction Status



COMET Experiment Hall

COMET Facility Construction Status





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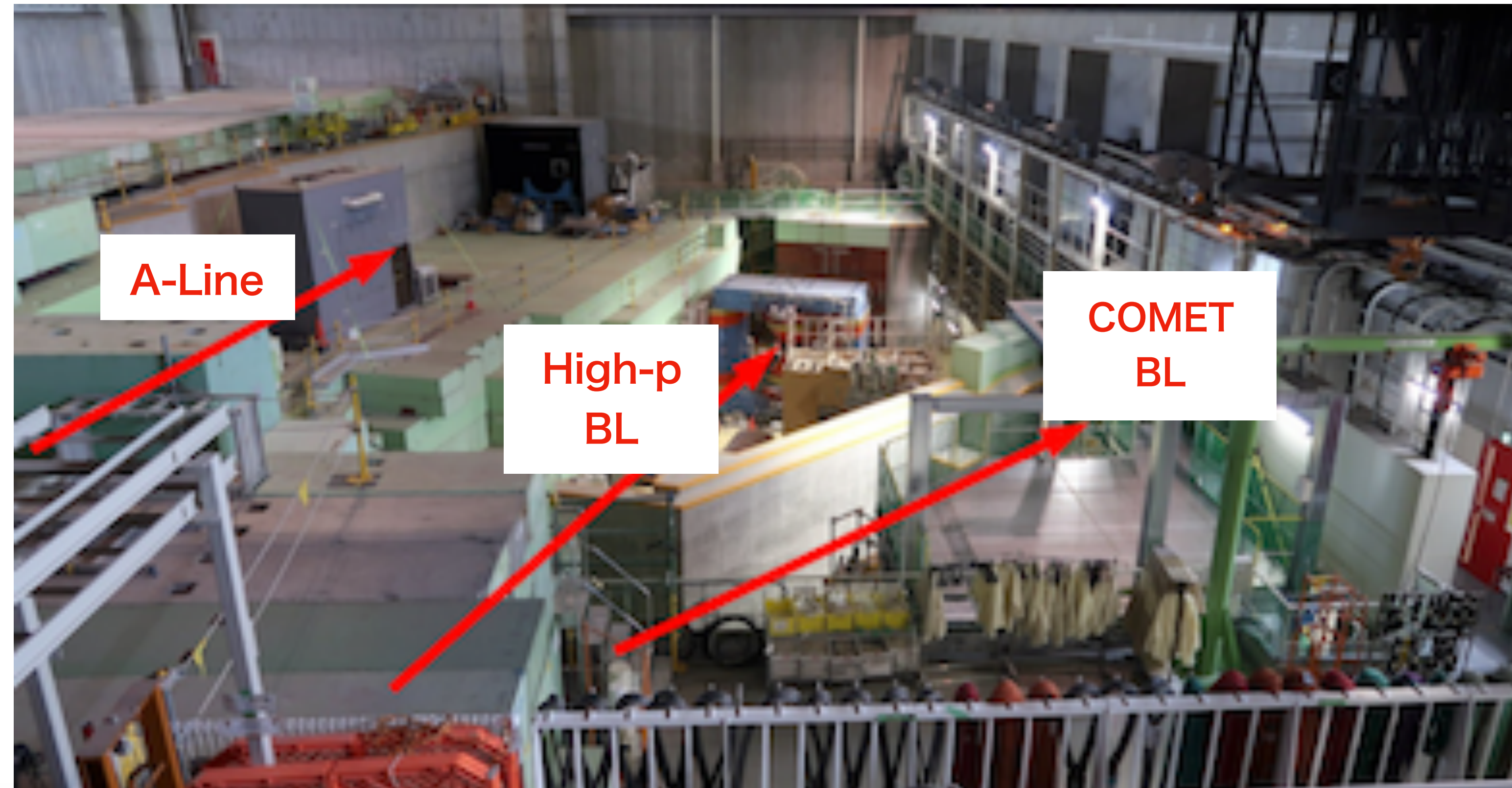

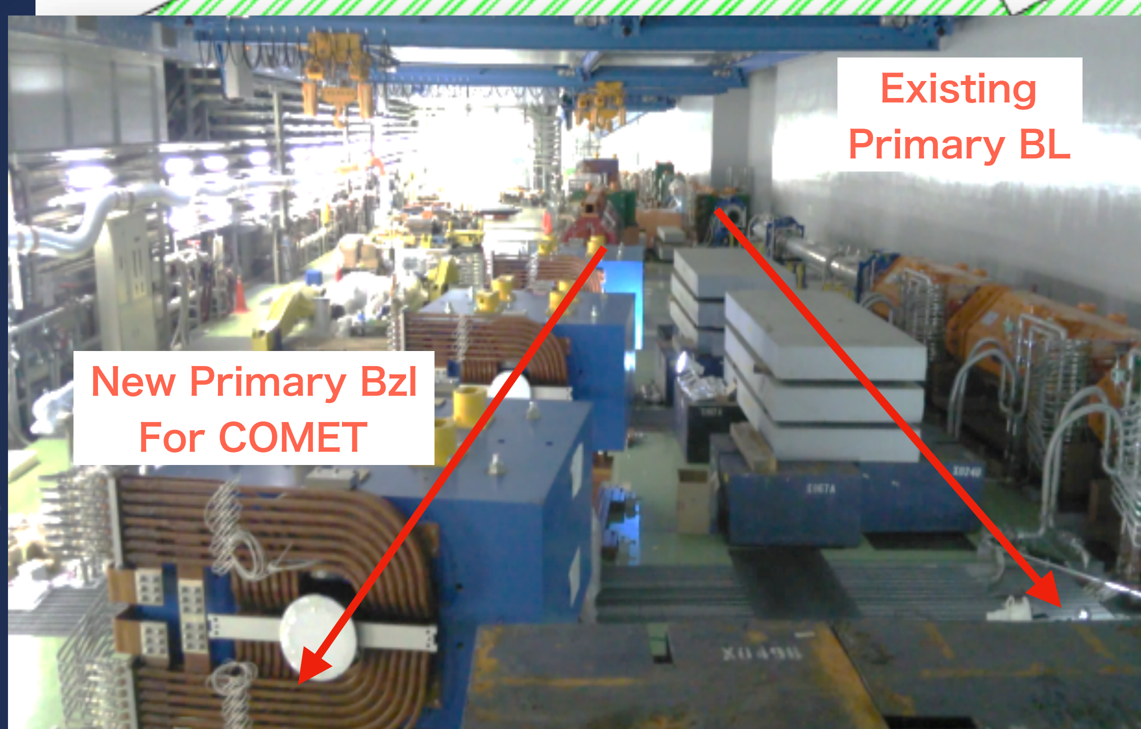

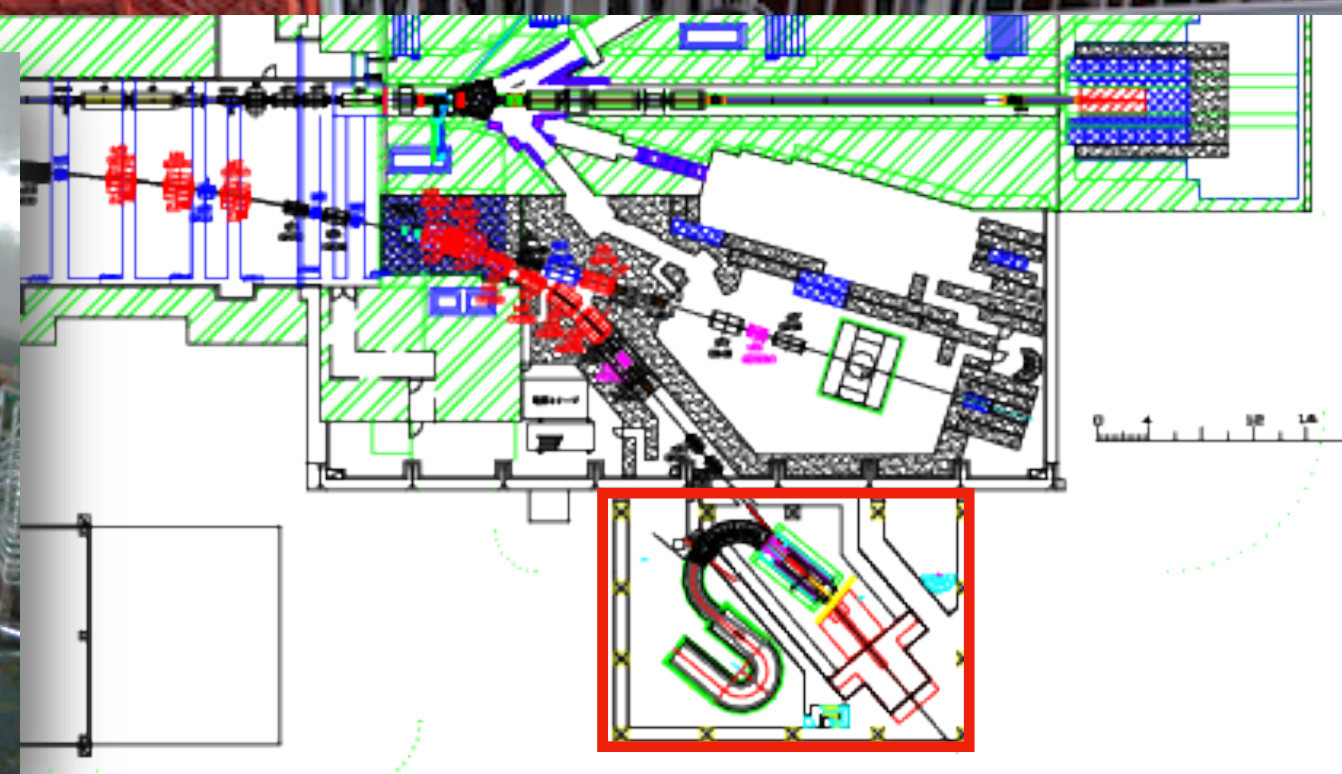

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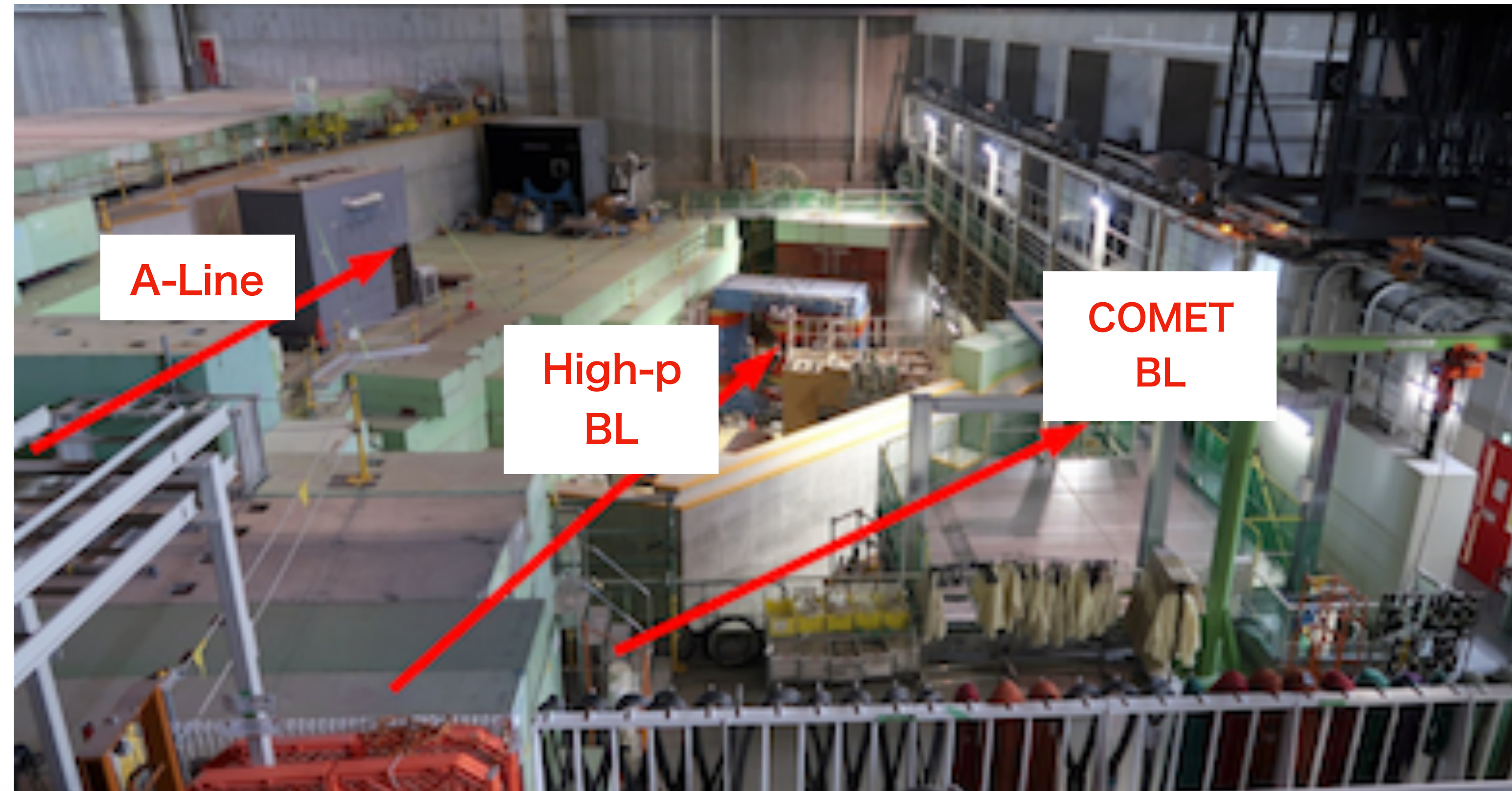
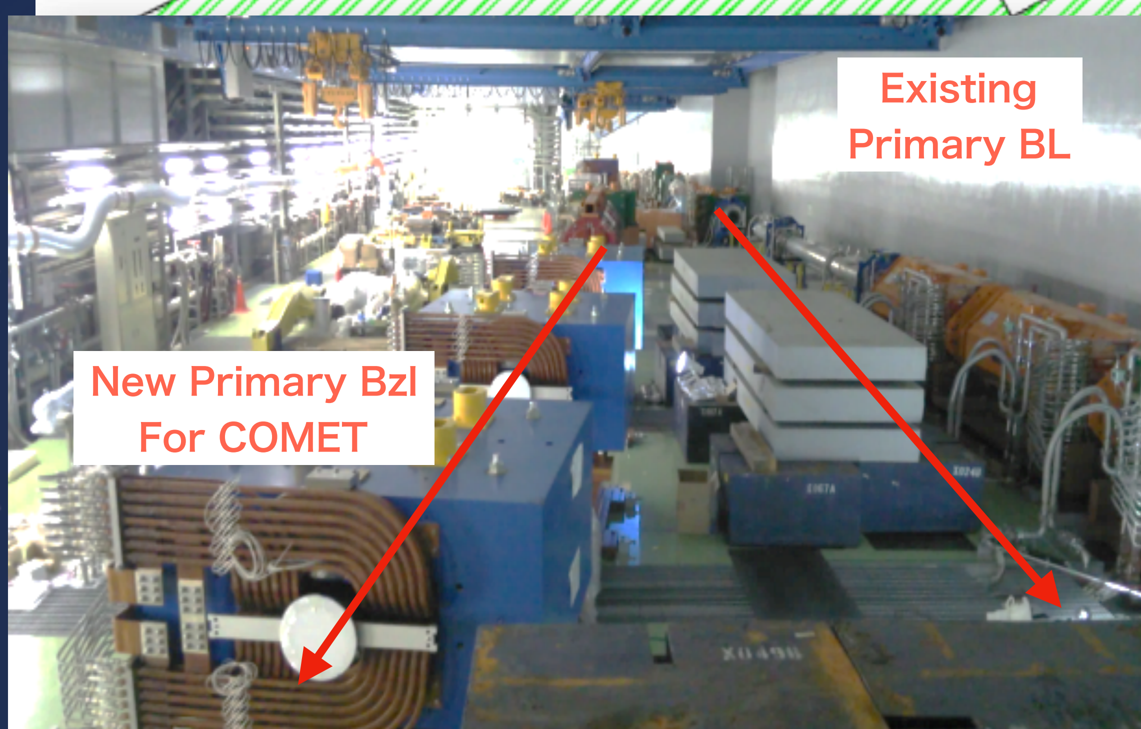
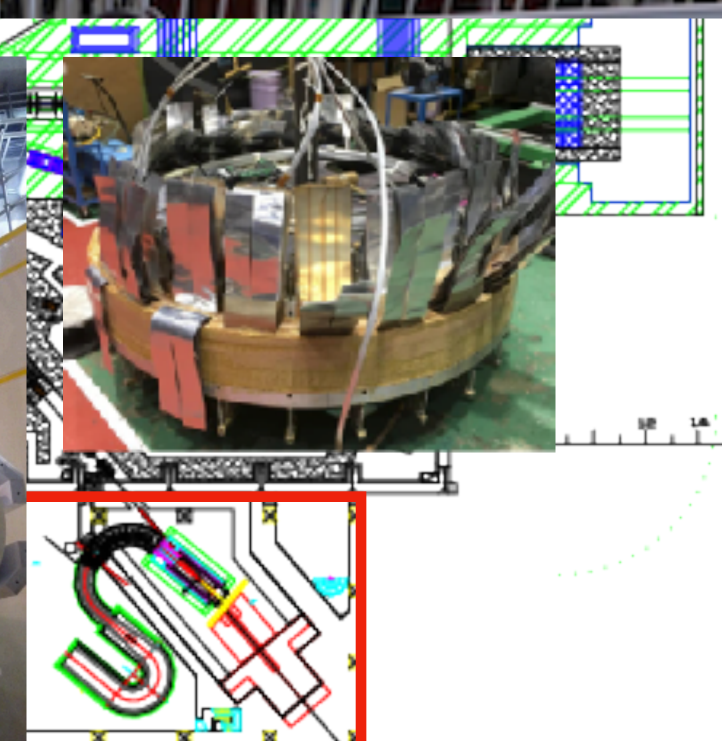




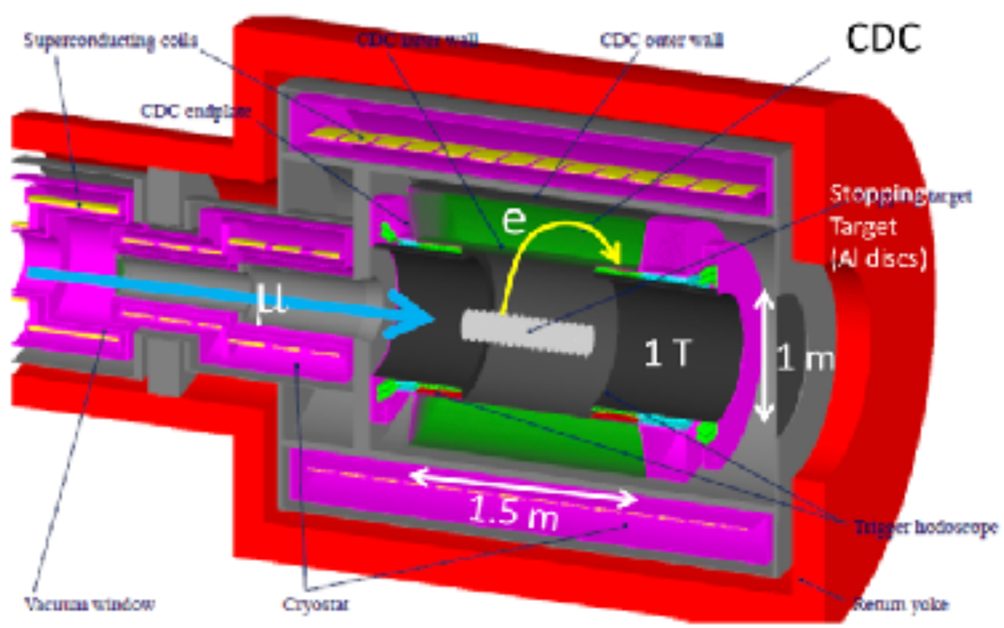


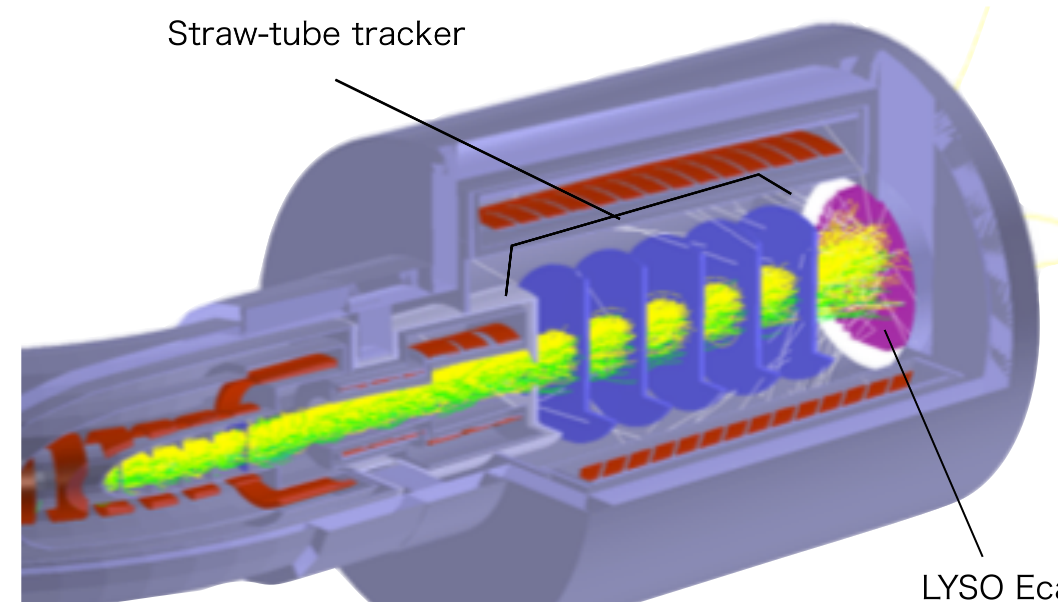
COMET Experiment Hall

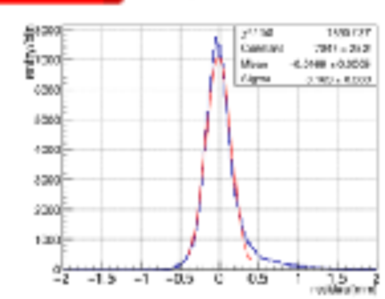
M. Moritsu 7/Jul
B. Yeo 6/Jul, M. Lee 6/Jul

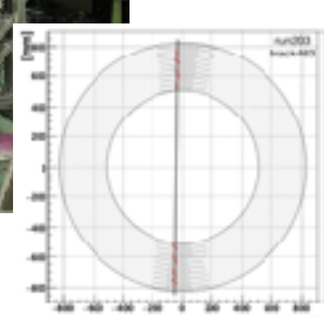
COMET Phase-I Status

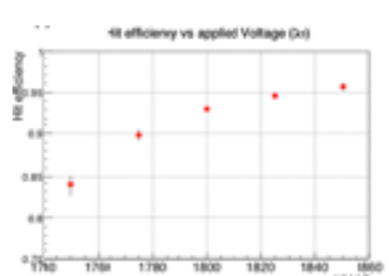
- Physics Detector
  - CDC and trigger counters
  - Optimized for Phase-I physics
- Beam measurement Detector
  - Straw-tube tracker and LYSO Ecal
  - Prototype of Phase-II detector

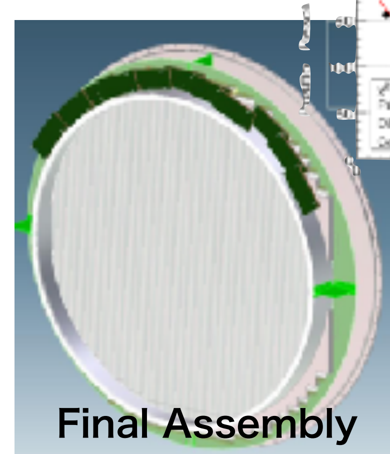


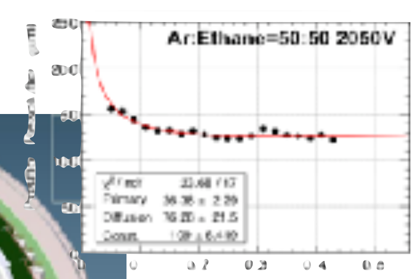


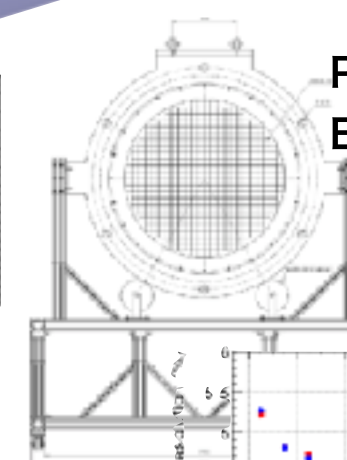


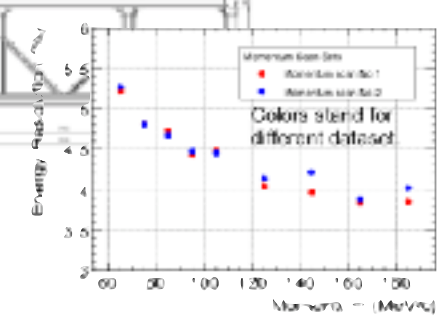






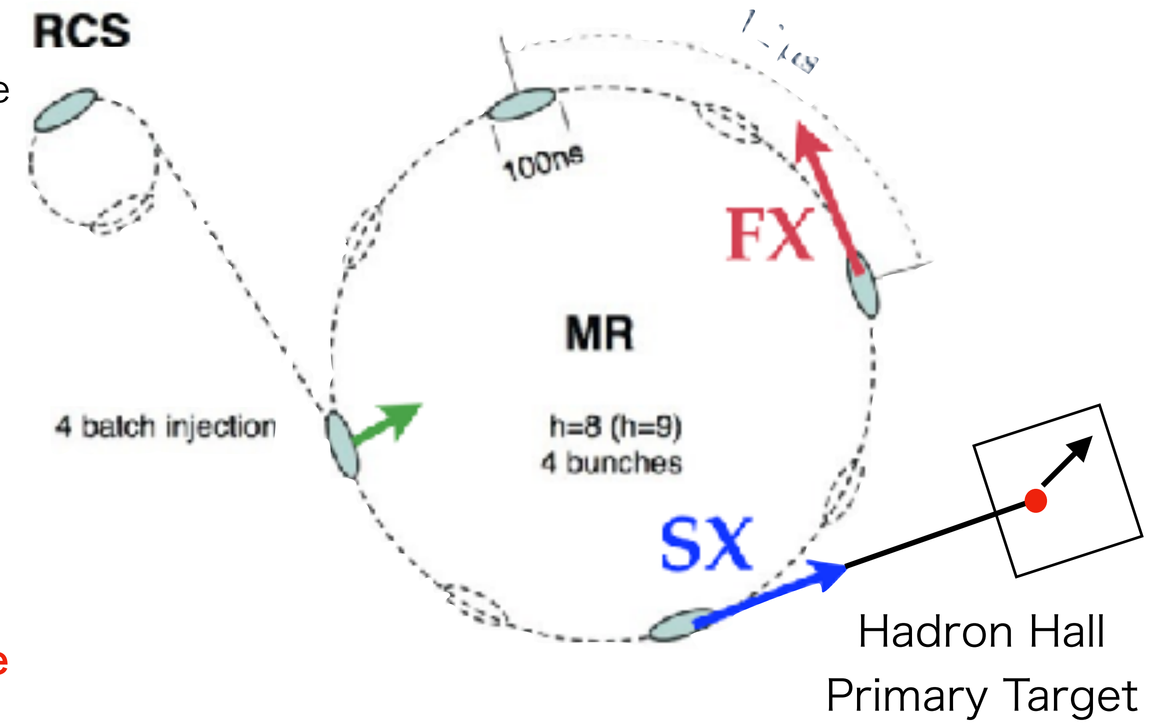



Phase I Ecal Design

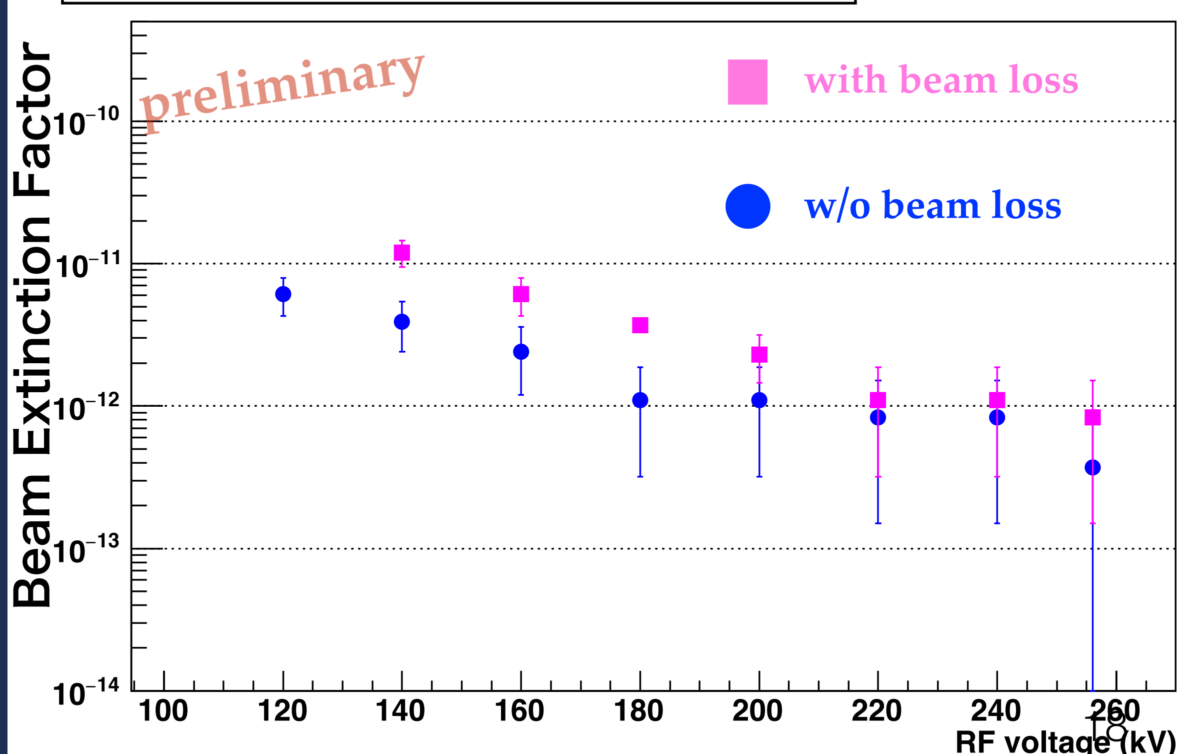


8GeV Acceleration Test and Extinction Factor Measurement

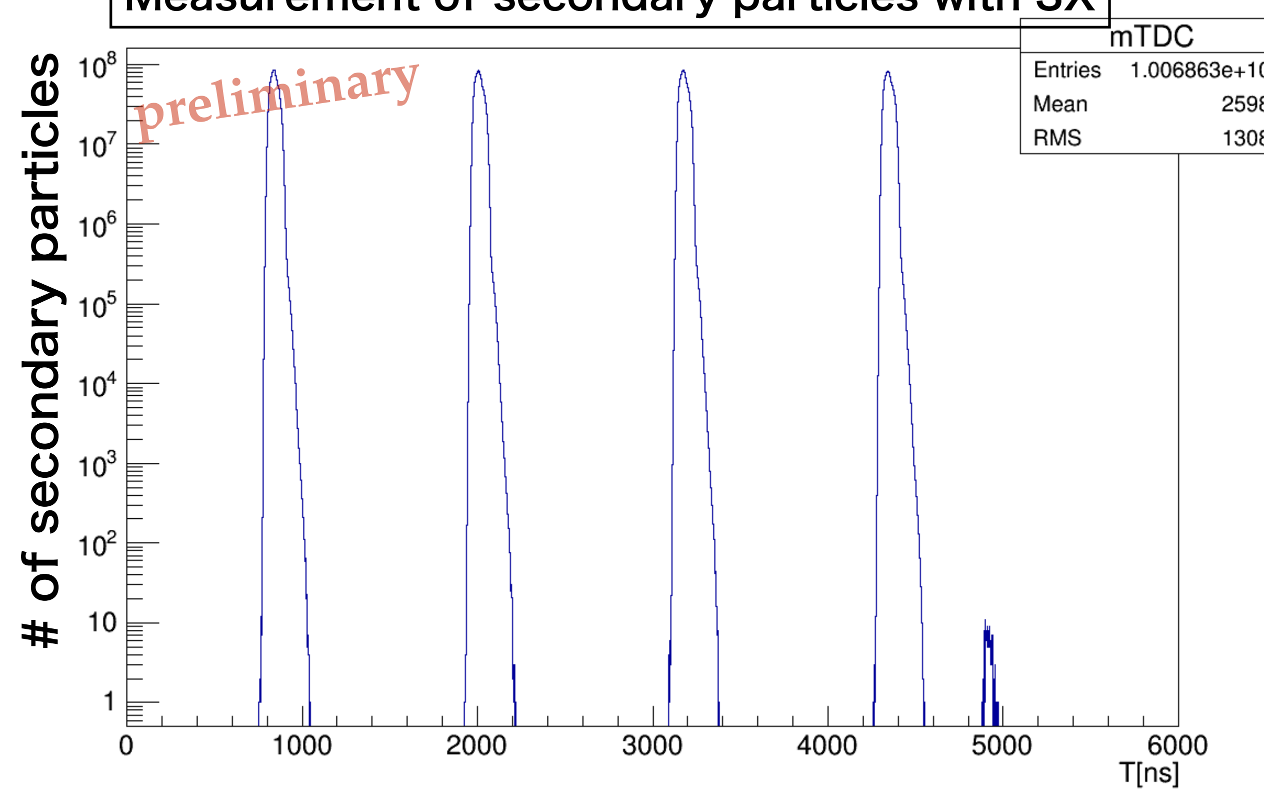
- 8GeV acceleration and extraction to the abort line (FX) and Hadron Hall (SX)
  - 4 bunches out of 9 bunches are filled with protons to realize the COMET beam time structure
    - Same number of protons per bunch with that of Phase-I beam
  - Injection kicker timing is shifted to kick in only the filled bunch
  - SX with RF HV on to keep the bunched time structure
- $R_{ext} = 10^{-11\sim-12}$ in FX and < 6×10^{-11} in SX, possible to improve even further with more accelerator study time in future



Measurement at Abort Line with FX



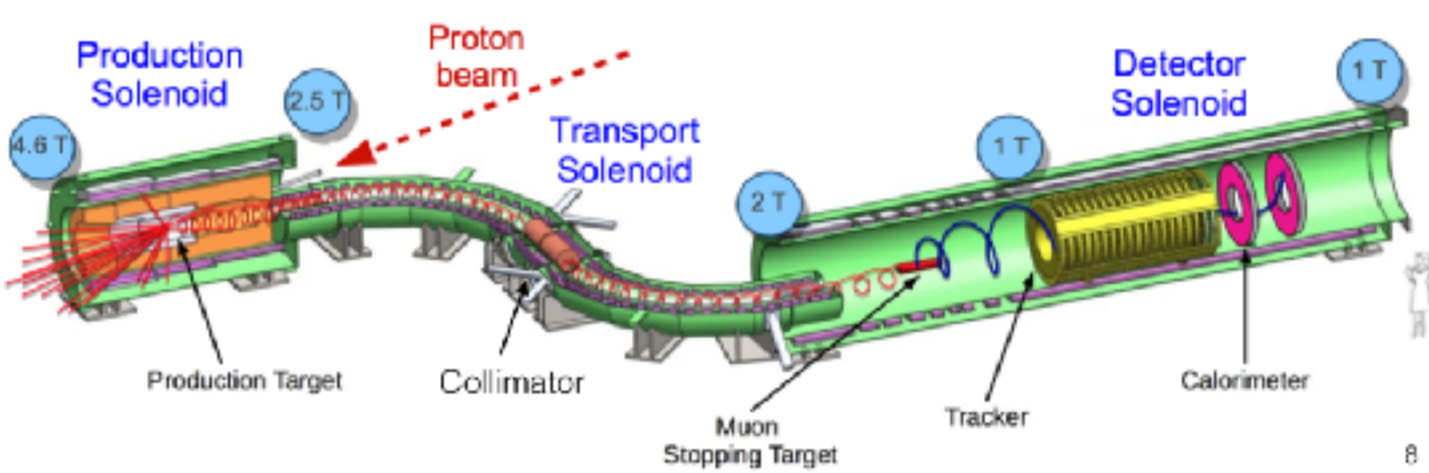
Measurement of secondary particles with SX



G. Pezzullo 7/Jul

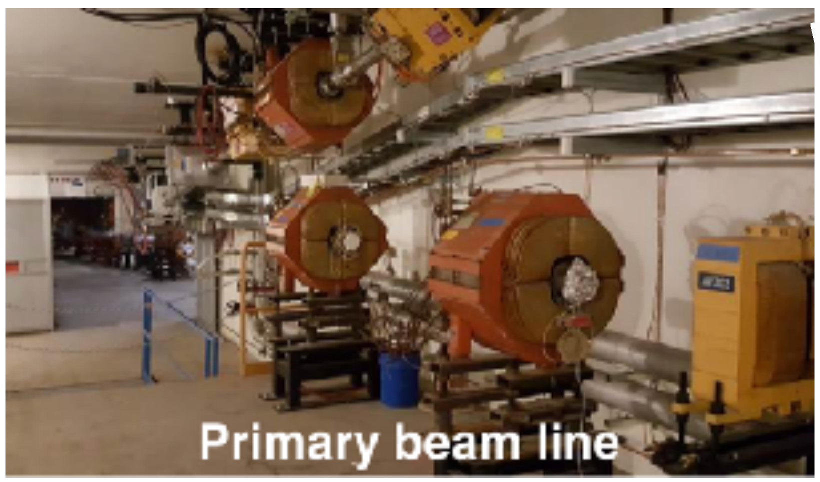
Mu2e at FNAL

- 8GeV protons from FNAL accelerator complex
- Re-bunching in the Delivery Ring
- Injected onto the tungsten target located in Capture Solenoid magnet
- Single event sensitivity: 3×10^{-17}
- DAQ starts in 2022, 1 yr commissions and 3 yrs running.



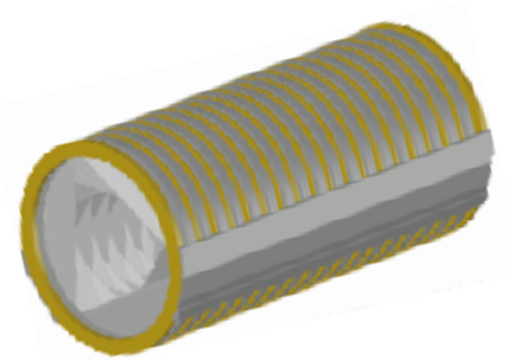
Mu2e Status

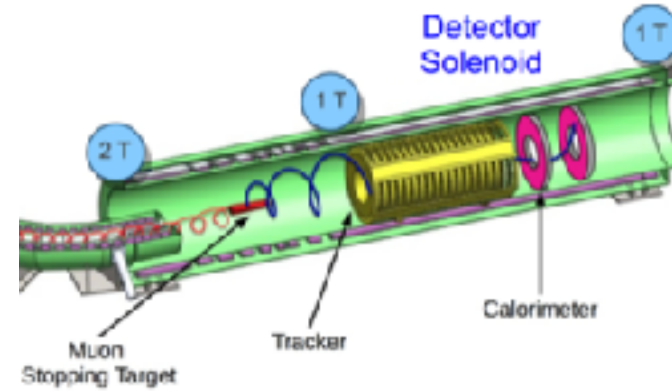
Facility Construction



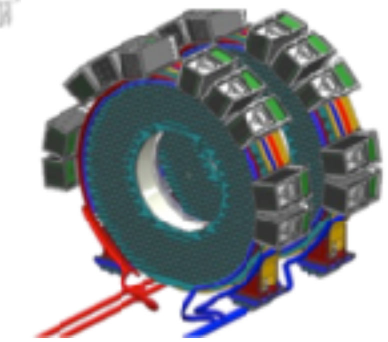
Detector Building

Straw Tube Tracker

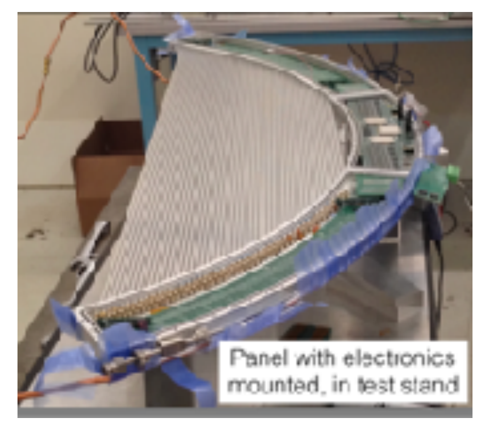




CsI Calorimeter

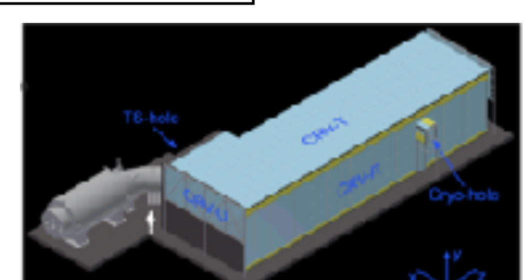


2 disks, each disk contains 674 undoped CsI crystals of $20x3.4x3.4cm^3$

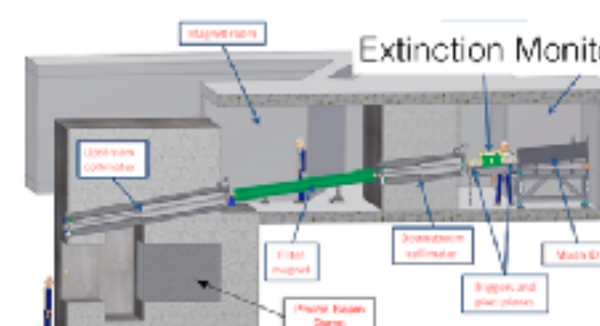


Other essential components

Target remote handling



CR Veto

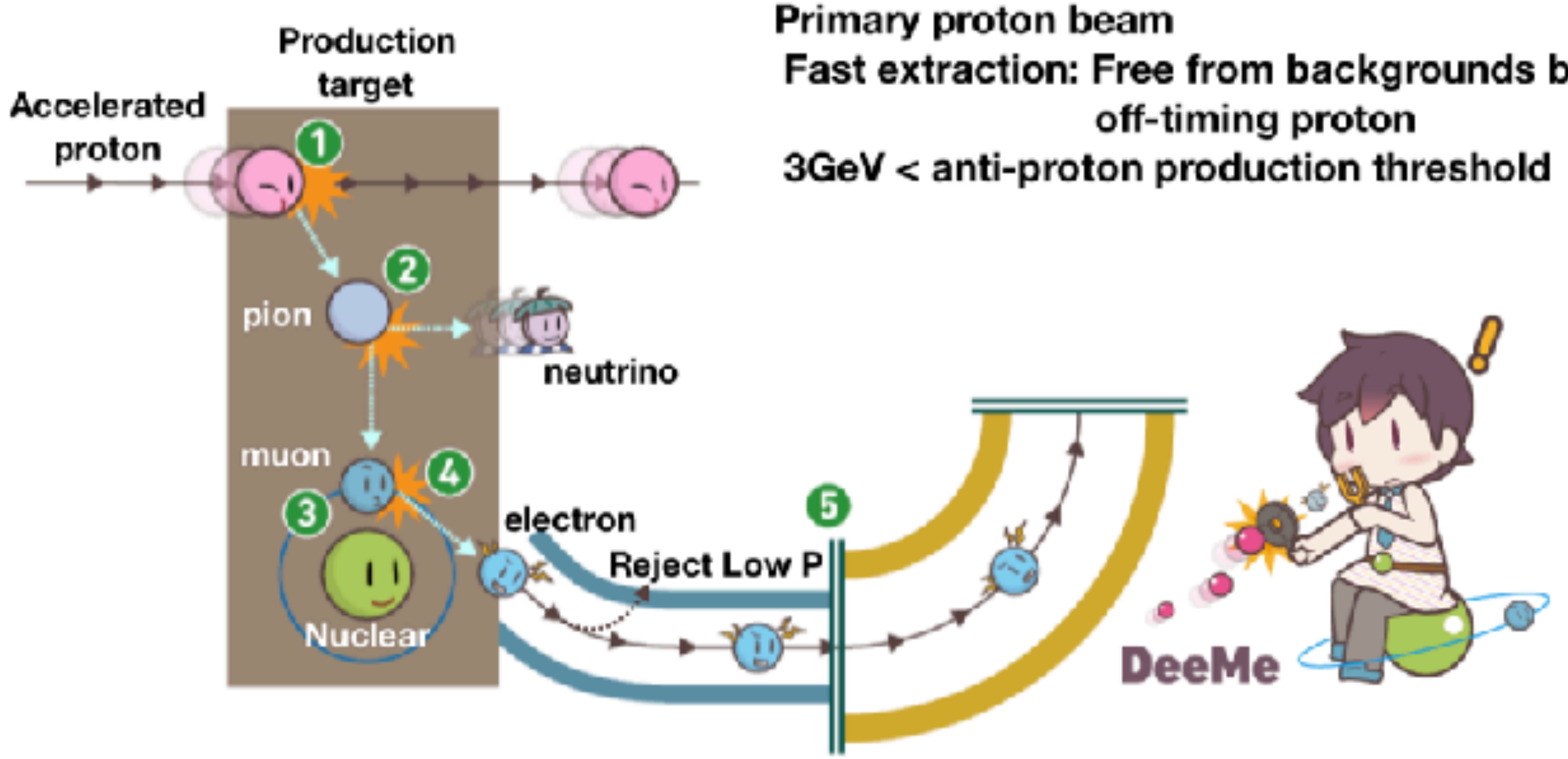


Extinction monitor

Yet Another μ-e Conversion Search at J-PARC

Design of DeeMe

Primary proton beam
Fast extraction: Free from backgrounds by off-timing proton
3GeV < anti-proton production threshold

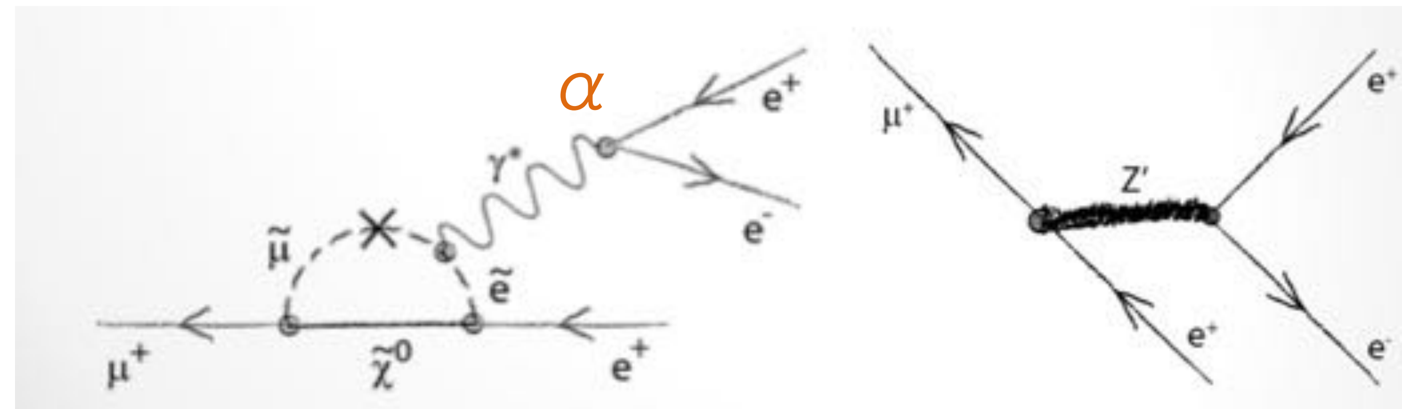


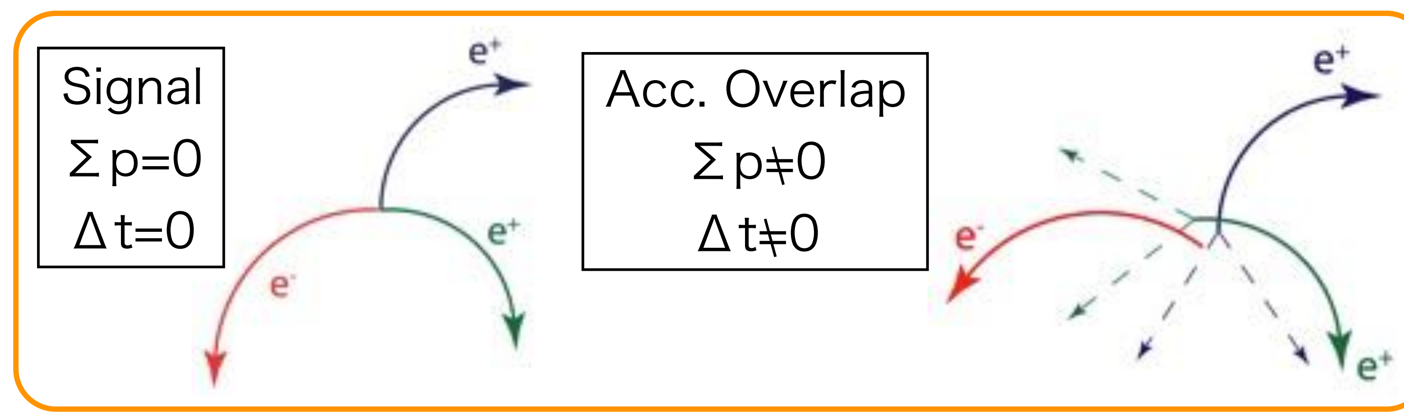
1. Pion production by accelerated proton hits on target
2. $\pi^- \rightarrow \mu^- + \nu_\mu$
3. μ^- trapped by a nuclear. Muonic atom formation
4. Particles emitted from muonic atom
5. Extract electron via secondary beam line and measure the momentum

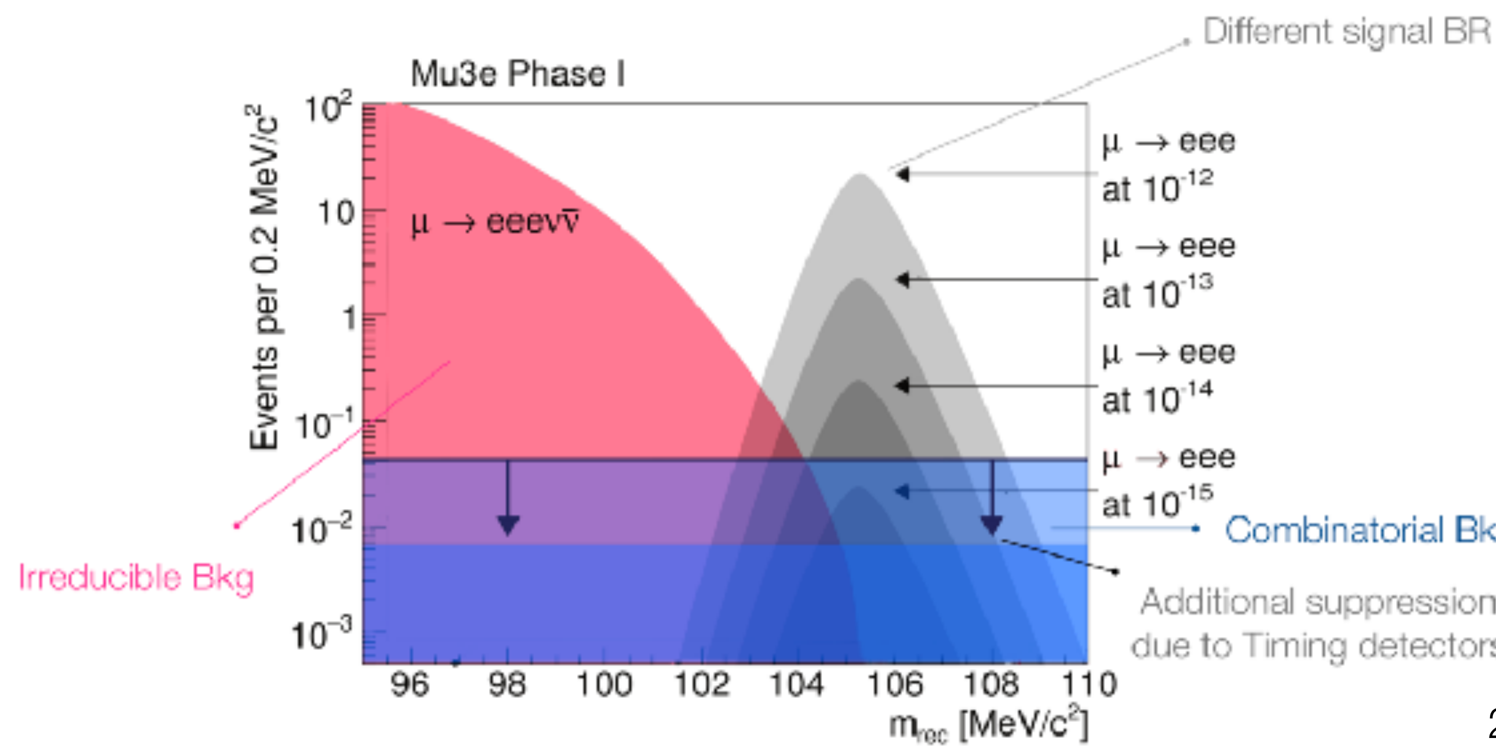
Mu3e

$\mu \to eee$ Search using DC Muon Beam

- Another channel sensitive to cLFV with DC muon beam
  - 1.0×10^{-12} (90% C.L.) by SINDRUM
  - **Goal : 10^{-16} in 2 steps**
- Measure all electron tracks with extreme precision
- Background source
  - $\mu^+ \to e^+ \underline{e^+} e^- \nu \nu$
  - Accidental overlap
- Beamline is shared with MEG

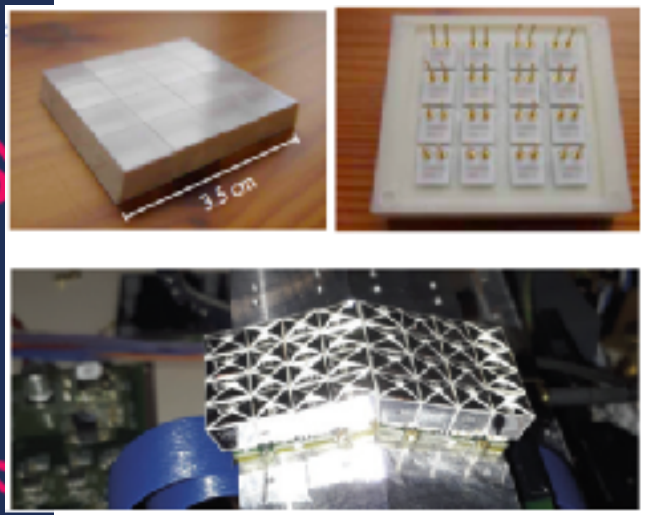




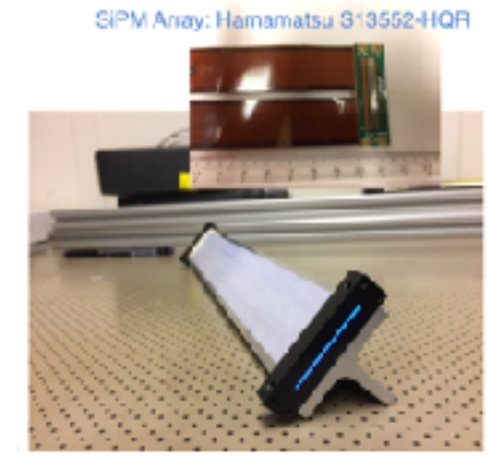


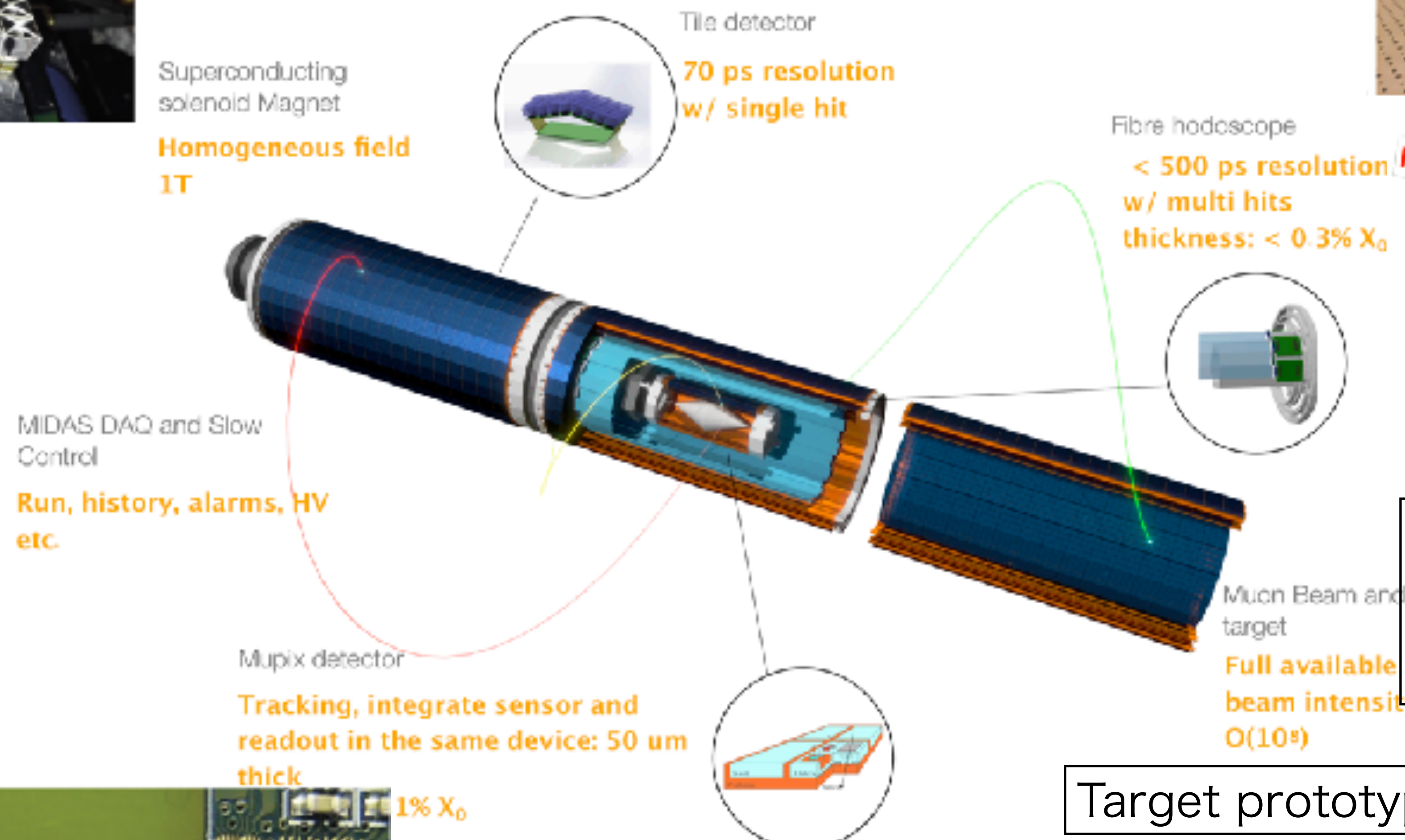
ICHEP2018 SEOUL
XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS
JULY 4 - 11, 2018 COEX, SEOUL

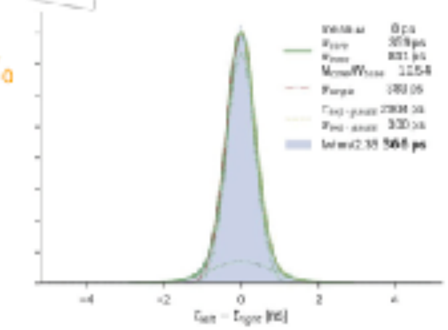
Detector Preparation



Tile detector prototype
Good enough σ_t

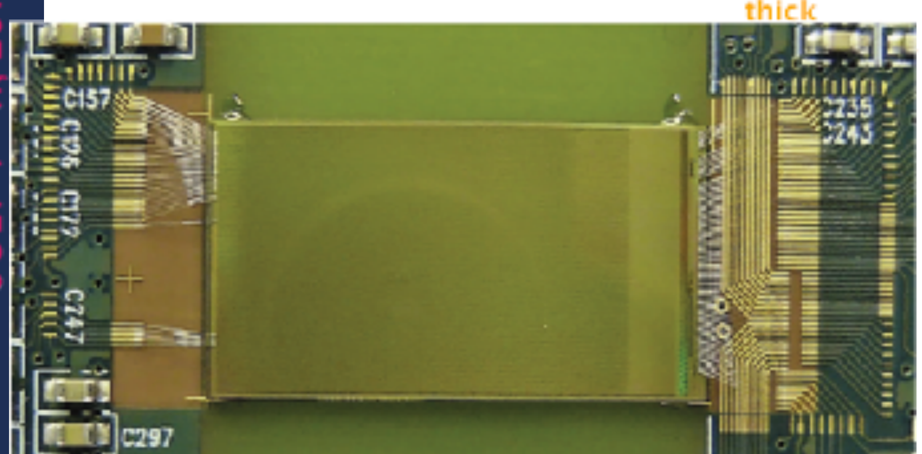


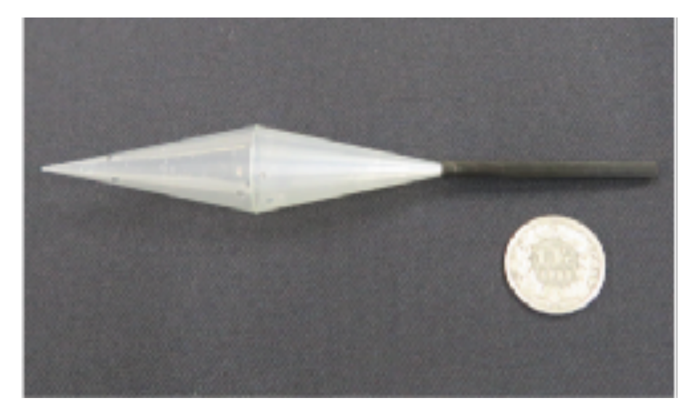




Fiber hodoscope
prototype
Good enough σ_t

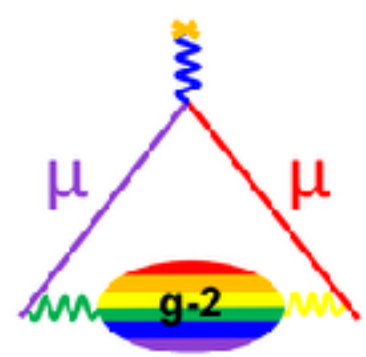
Target prototype





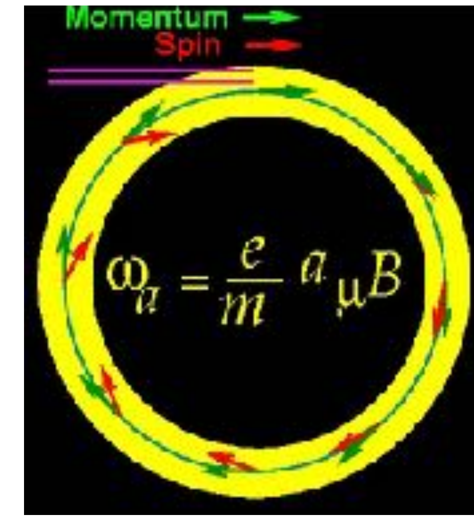
1st large-area prototype
MuPix8 is being tested
MuPix9 & MuPix10 follow

Muon g-2 & EDM



Muon g-2/EDM Measurements

- In uniform magnetic field, muon spin rotates ahead of momentum due to g-2≠0



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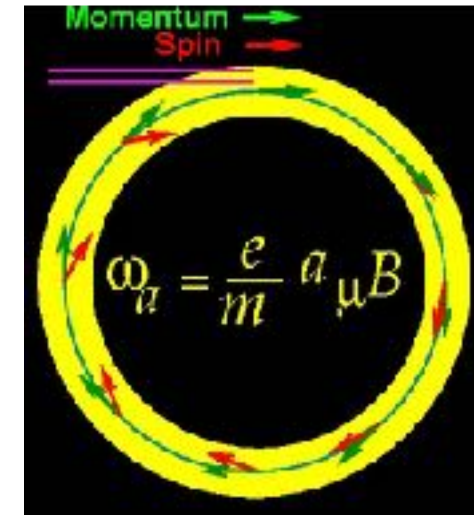

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BNL/FNAL approach
γ=29.3 (P=3.09 GeV/c)

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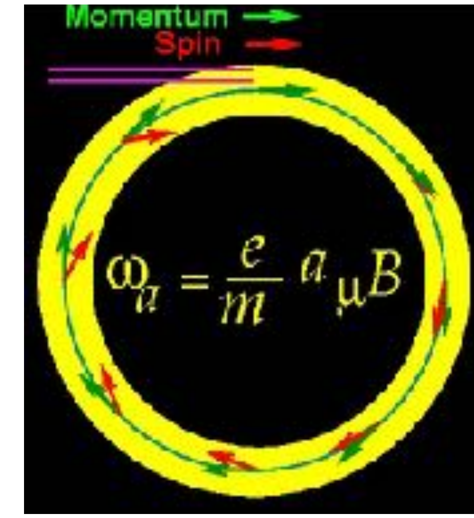

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(the term $\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}$ is crossed out)

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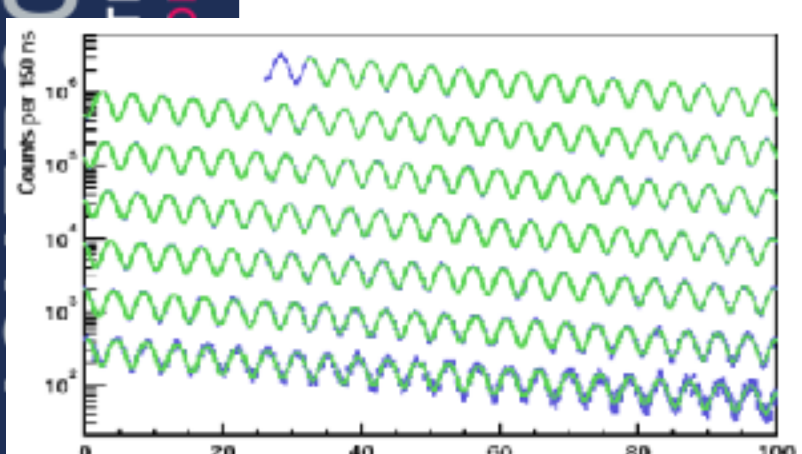
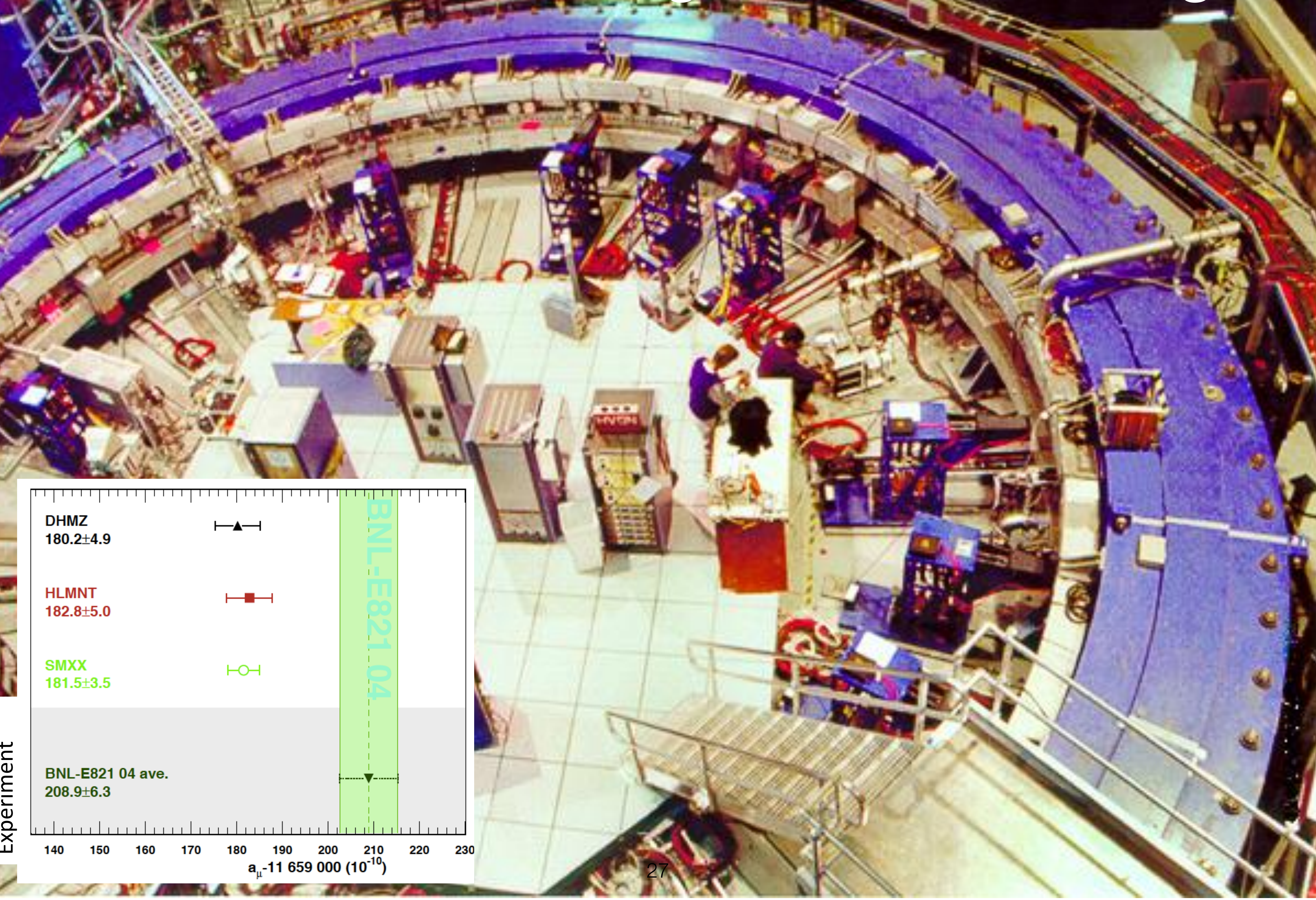


$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Continuation at FNAL with 0.1ppm precision

Muon anomalous magnetic moment (g-2)



Muon anomalous magnetic moment (g-2)

PR D97, 114025 (2018)

Editors' Suggestion | Featured in Physics

Muon $g-2$ and $\alpha(M_Z^2)$: A new data-based analysis

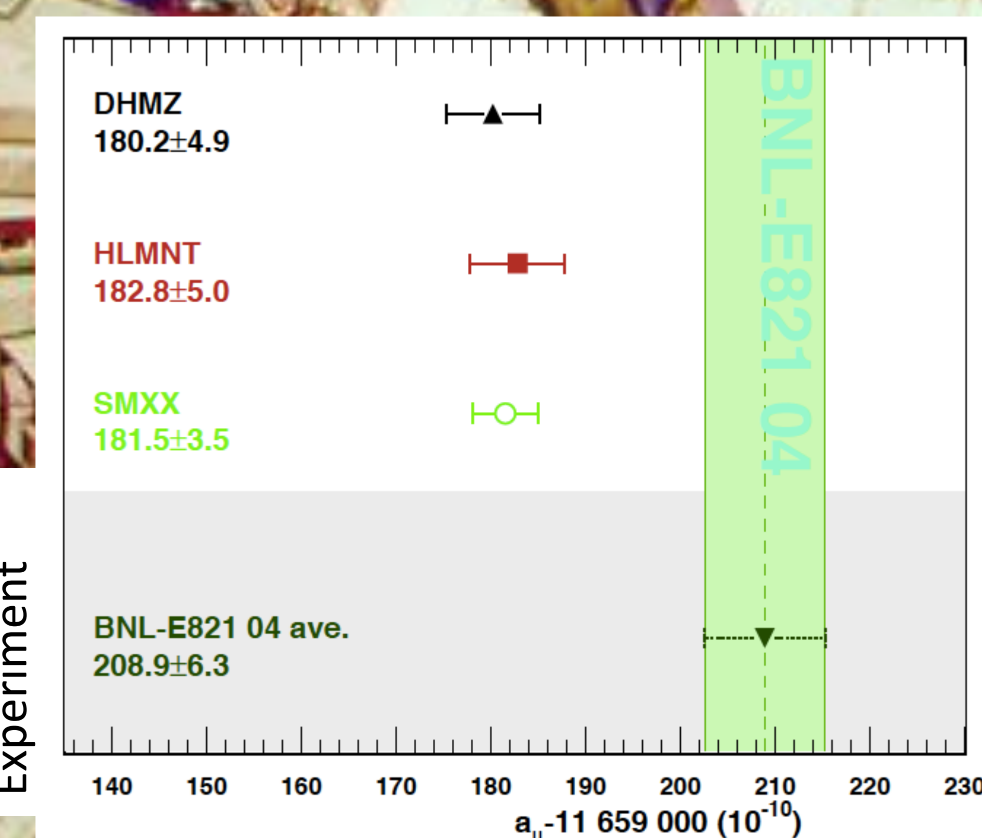
Alexander Keshavarzi,[1,*] Daisuke Nomura,[2,3,†] and Thomas Teubner[1,‡]
[1]Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom
[2]KEK Theory Center, Tsukuba, Ibaraki 305-0801, Japan
[3]Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

(Received 6 April 2018; published 25 June 2018)

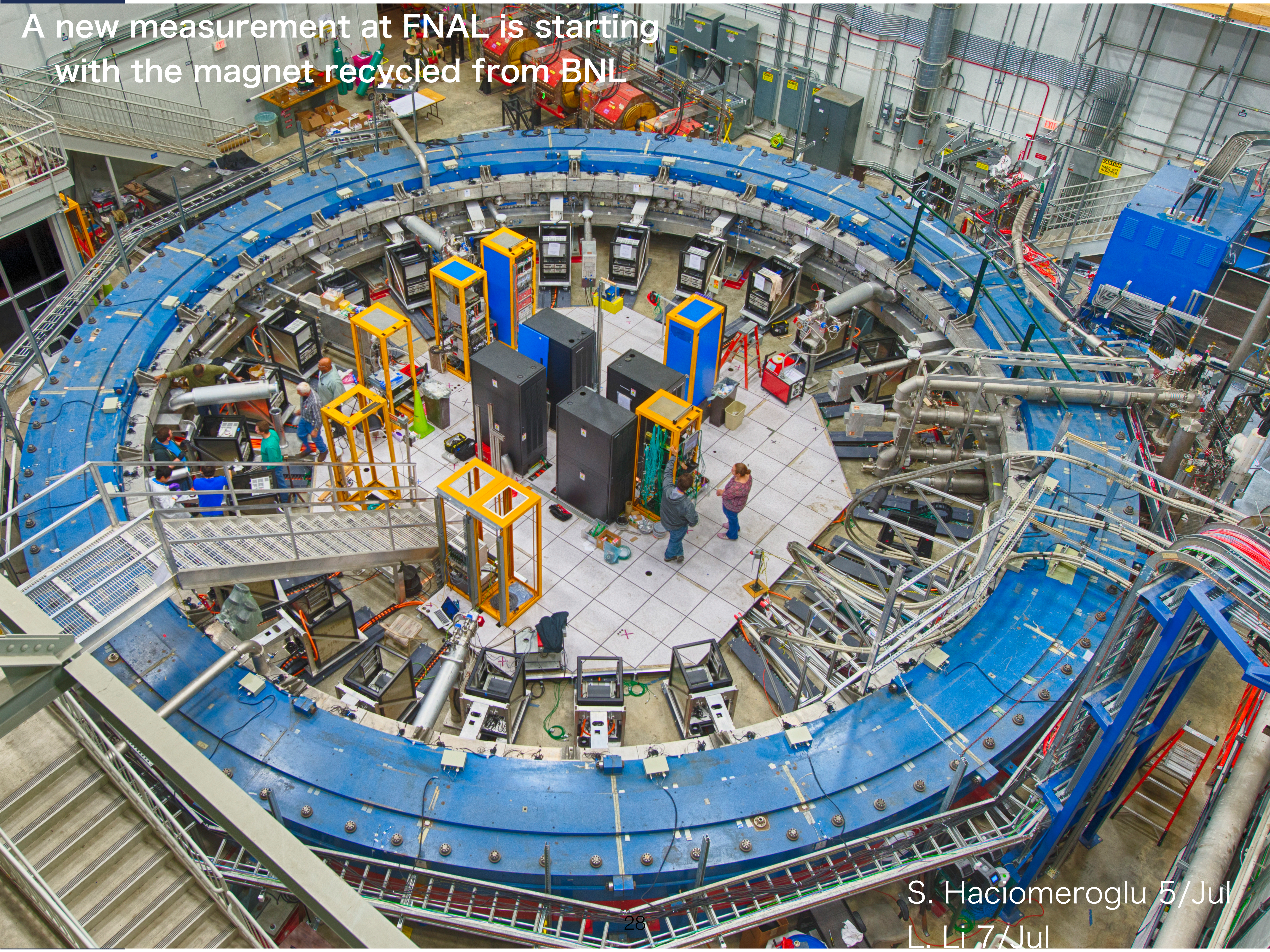
This work presents a complete reevaluation of the hadronic vacuum polarization contributions to the anomalous magnetic moment of the muon, $a_\mu^{\rm had,VP}$, and the hadronic contributions to the effective QED coupling at the mass of the Z boson, $\Delta\alpha_{\rm had}(M_Z^2)$, from the combination of $e^+e^- \to$ hadrons cross section data. Focus has been placed on the development of a new data combination method, which fully incorporates all correlated statistical and systematic uncertainties in a bias free approach. All available $e^+e^- \to$ hadrons cross section data have been analyzed and included, where the new data compilation has yielded the full hadronic R-ratio and its covariance matrix in the energy range $m_\pi \le \sqrt{s} \le 11.2$ GeV. Using these combined data and perturbative QCD above that range results in estimates of the hadronic vacuum polarization contributions to $g-2$ of the muon of $a_\mu^{\rm had,LO\,VP} = (693.26 \pm 2.46) \times 10^{-10}$ and $a_\mu^{\rm had,NLO\,VP} = (-9.82 \pm 0.04) \times 10^{-10}$. The new estimate for the Standard Model prediction is found to be $a_\mu^{\rm SM} = (11659182.04 \pm 3.56) \times 10^{-10}$, which is 3.7σ below the current experimental measurement. The prediction for the five-flavor hadronic contribution to the QED coupling at the Z boson mass is $\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = (276.11 \pm 1.11) \times 10^{-4}$, resulting in $\alpha^{-1}(M_Z^2) = 128.946 \pm 0.015$. Detailed comparisons with results from similar related works are given.

DOI: 10.1103/PhysRevD.97.114025

3.7σ



A new measurement at FNAL is starting with the magnet recycled from BNL



S. Haciomeroglu 5/Jul
L. Li 7/Jul

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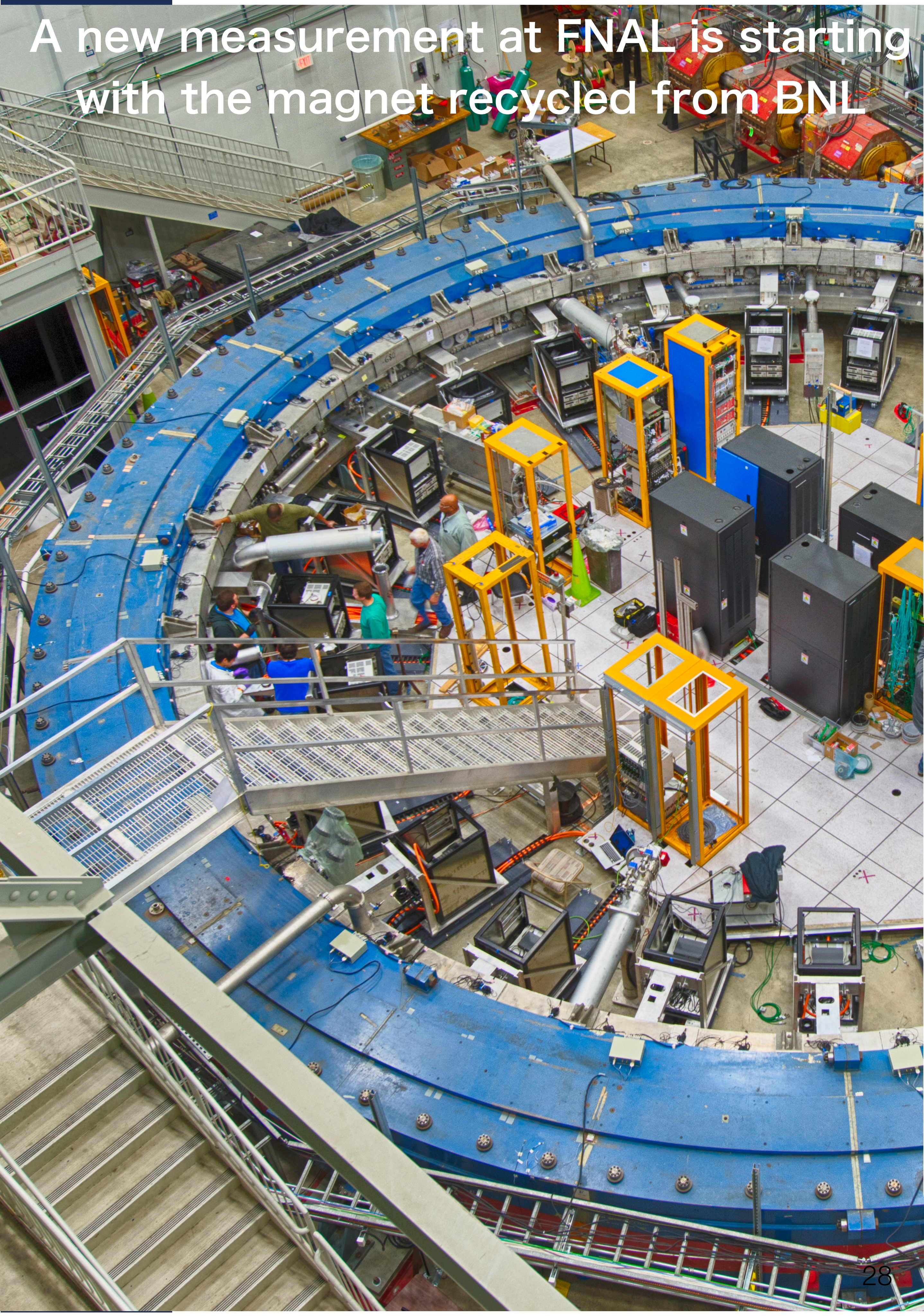

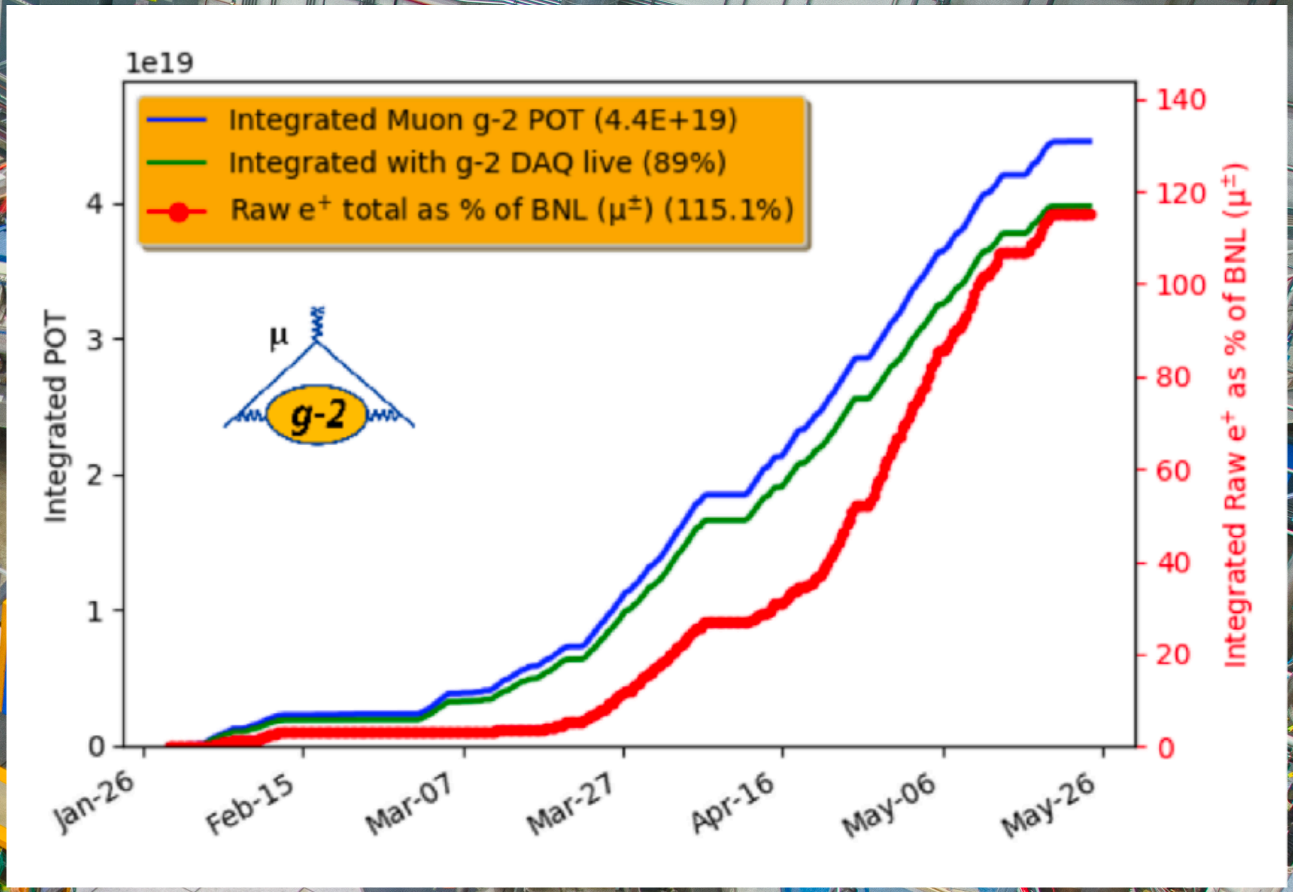

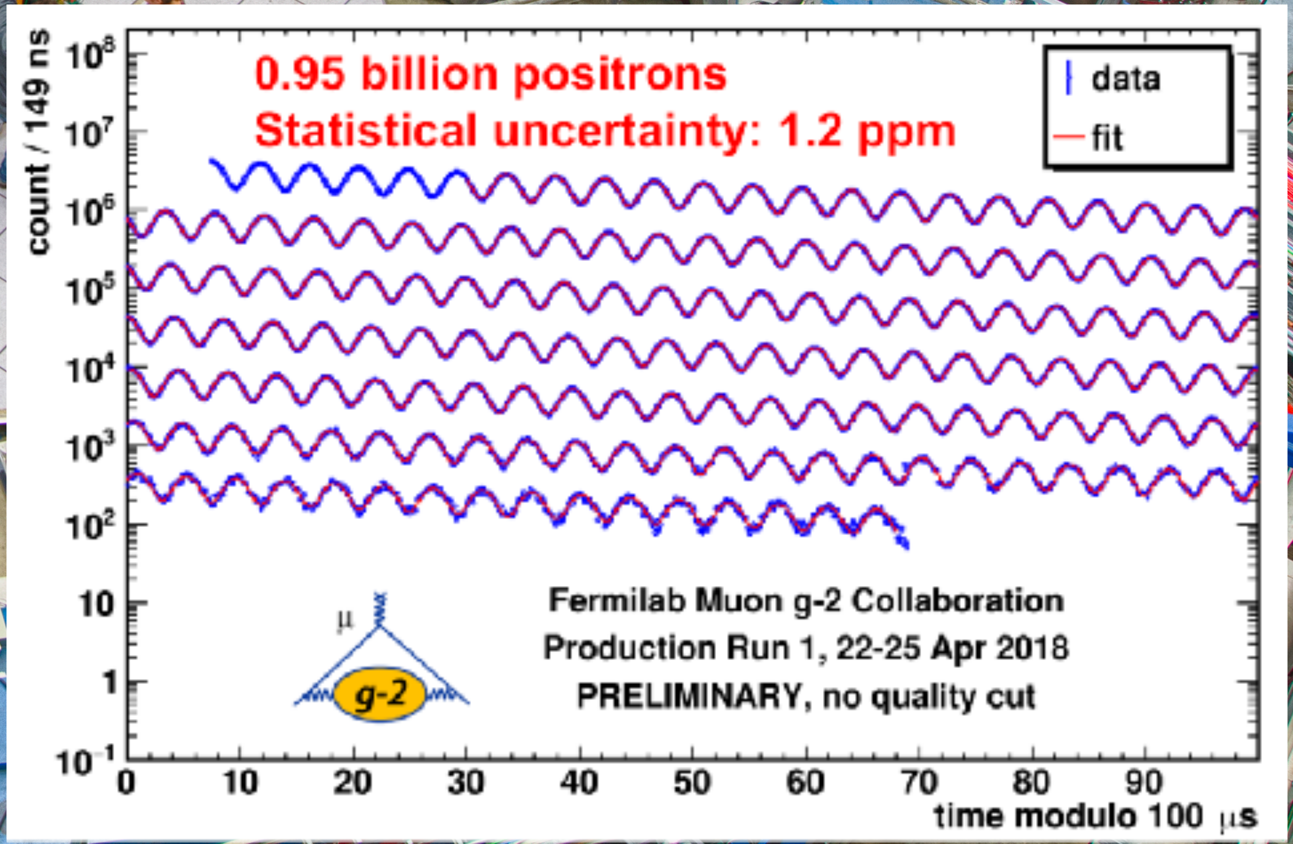

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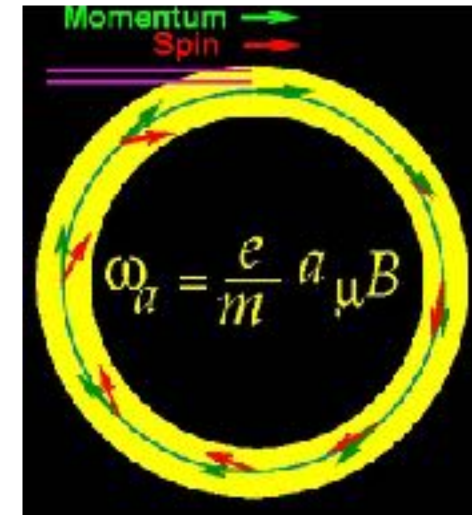

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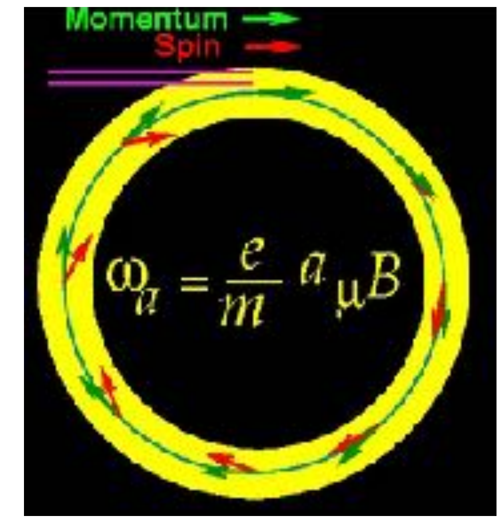

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J-PARC approach
E = 0 at any γ

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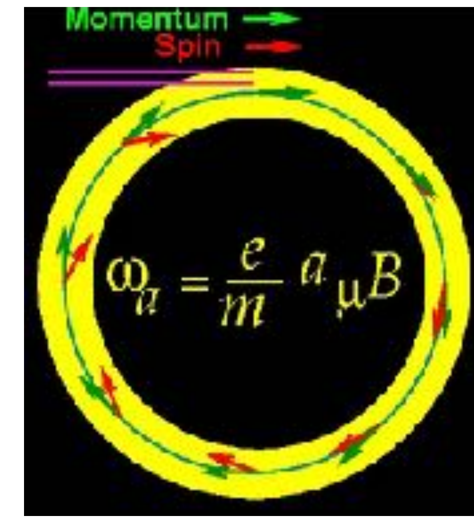

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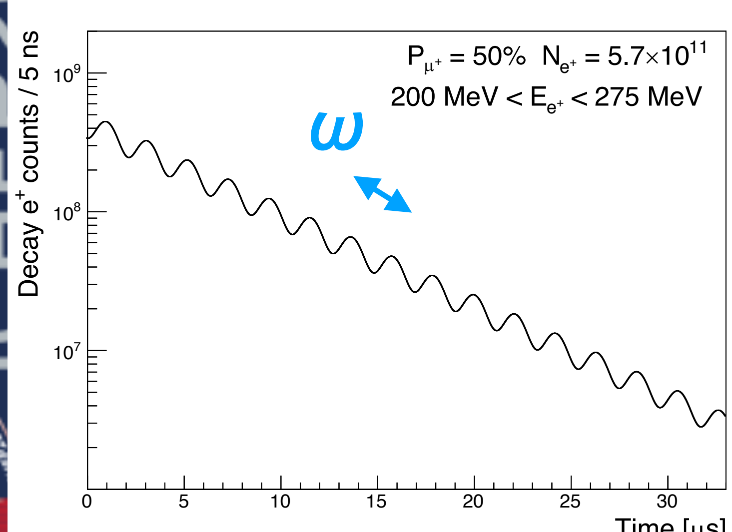

J-PARC g-2/EDM measurement

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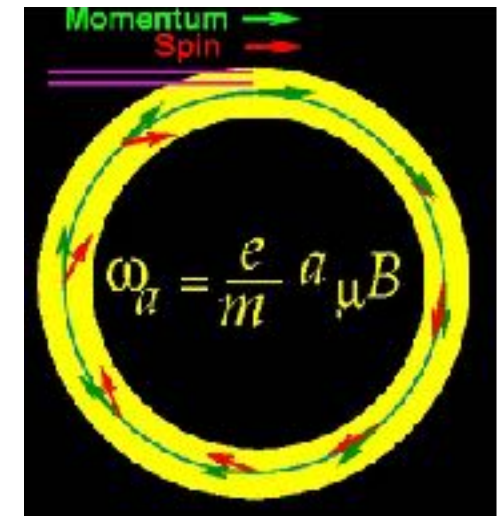

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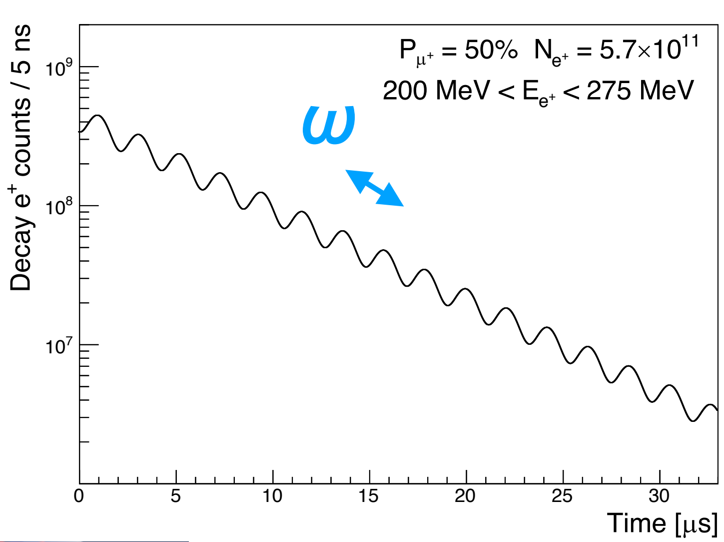
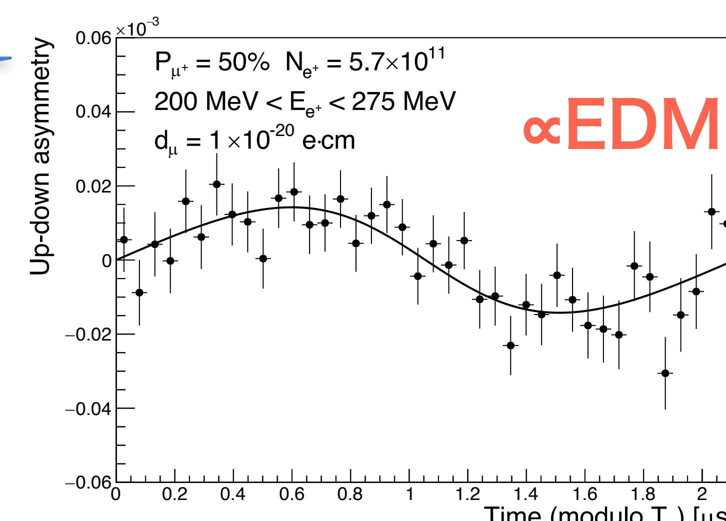
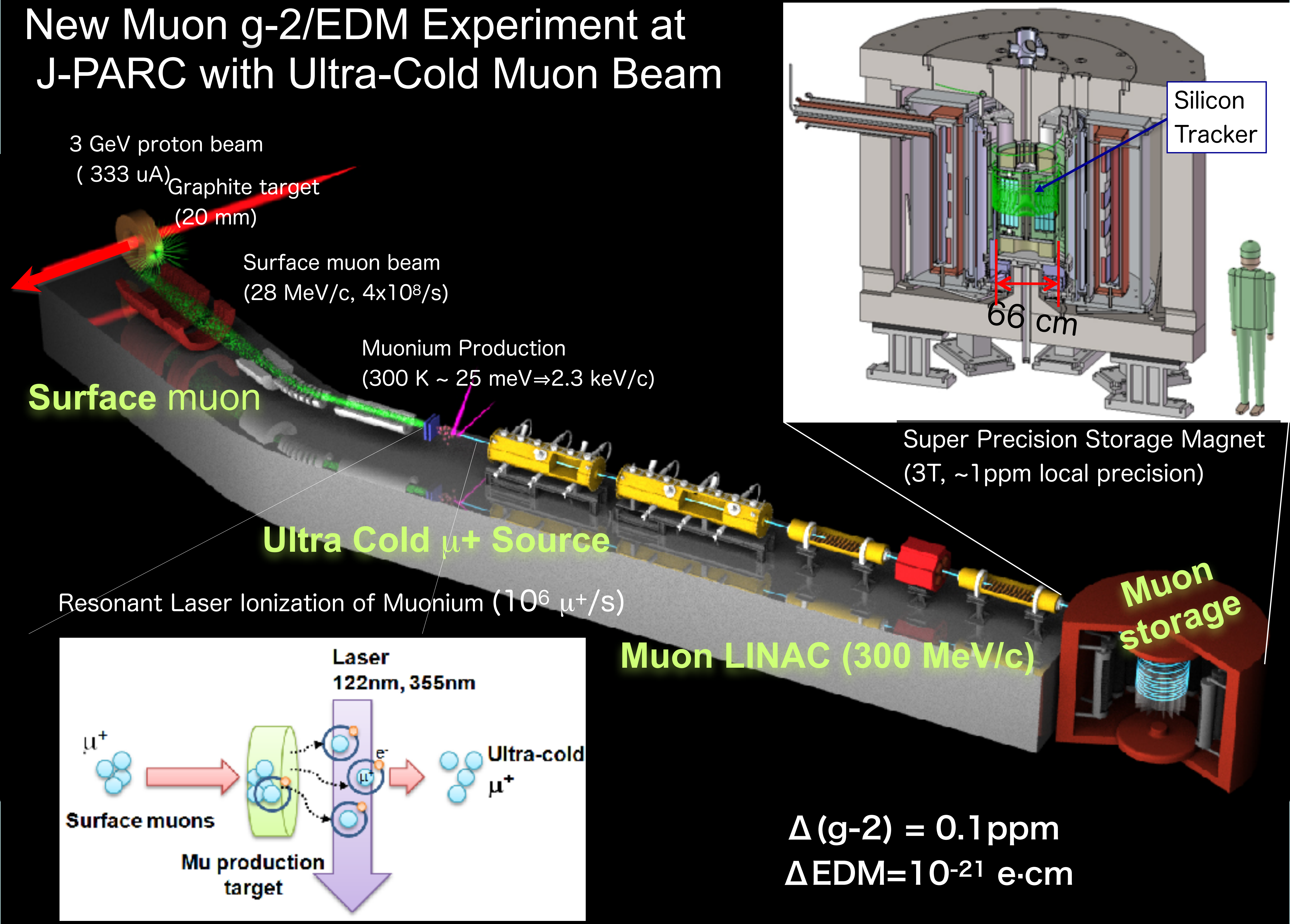




J-PARC g-2/EDM measurement

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam



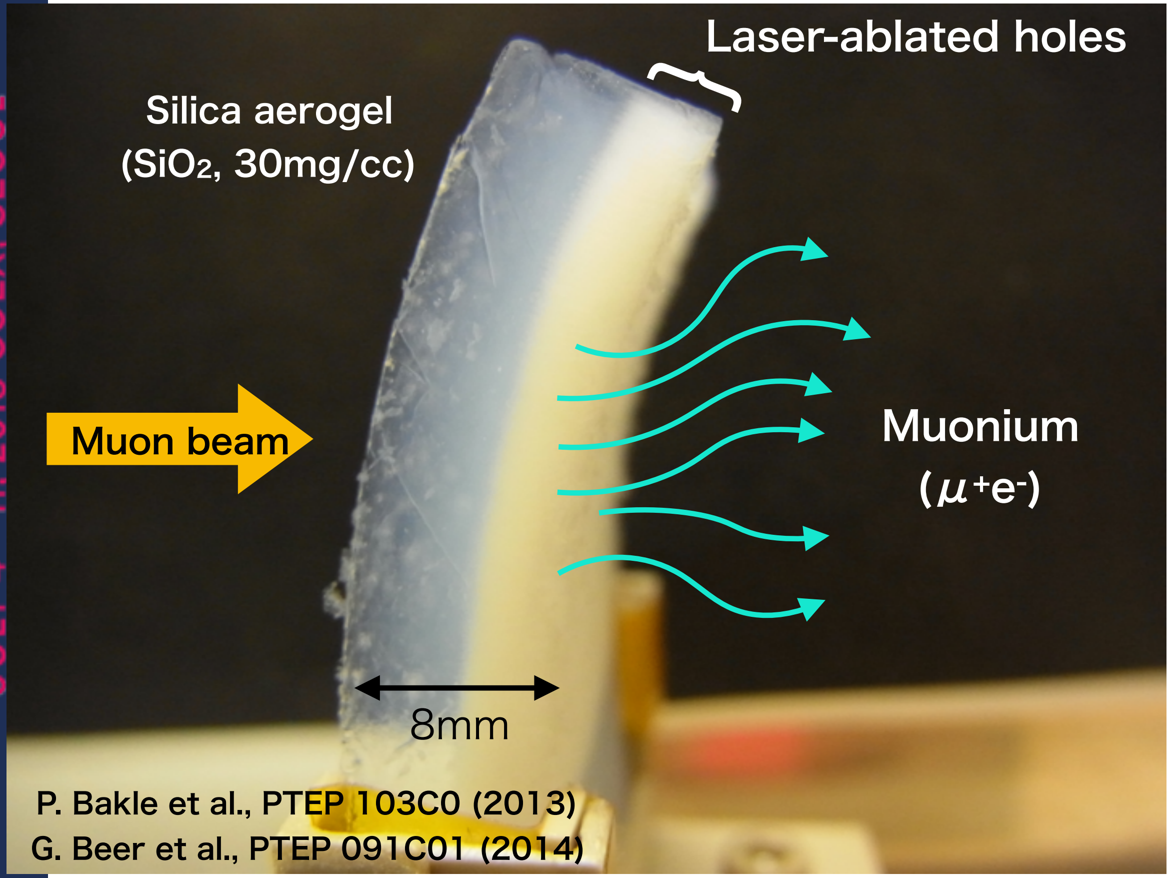
Δ(g-2) = 0.1ppm

ΔEDM=10^{-21} e·cm

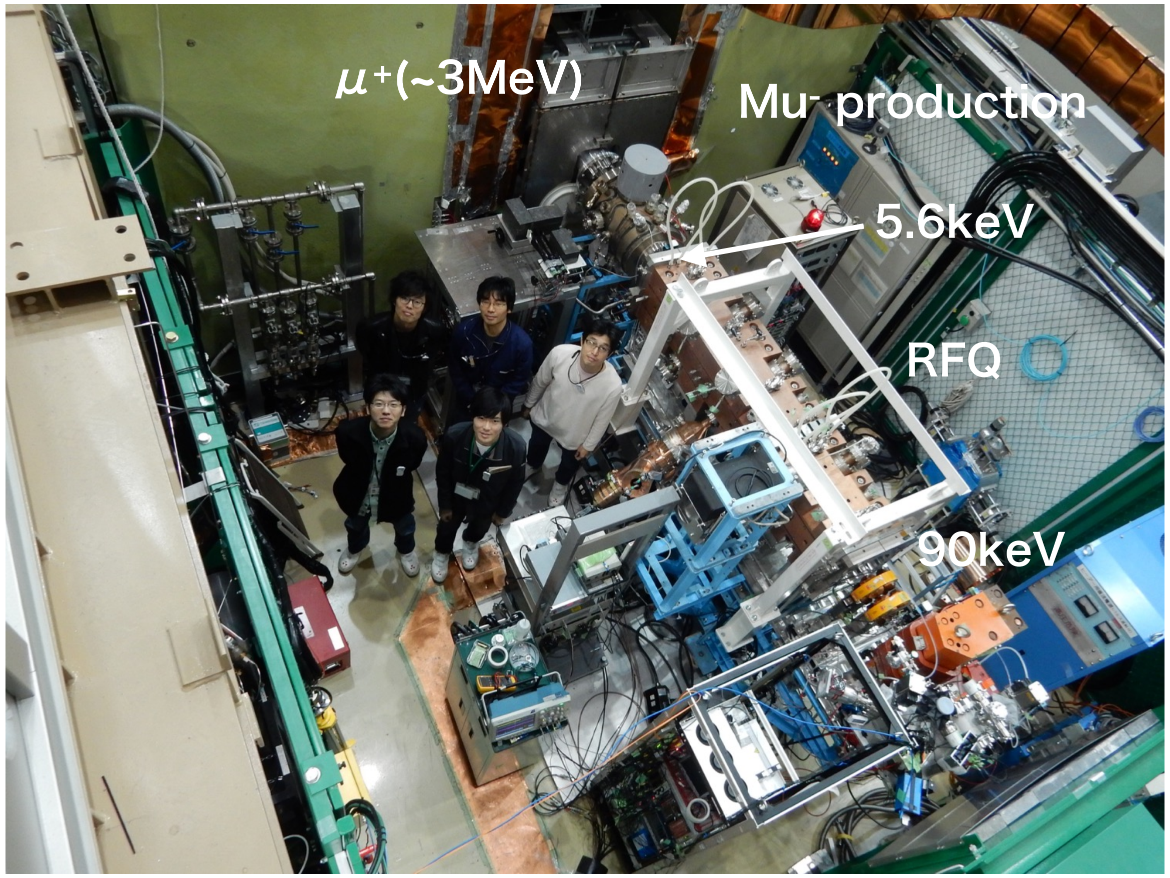
J-PARC Muon g-2/EDM

Muon source R&D and Acceleration

- Muonium production with aerogel samples with different sizes of holes
- Acceleration of negative muonium atoms (Mu$^-$) by static electric field and RFQ



P. Bakle et al., PTEP 103C0 (2013)
G. Beer et al., PTEP 091C01 (2014)



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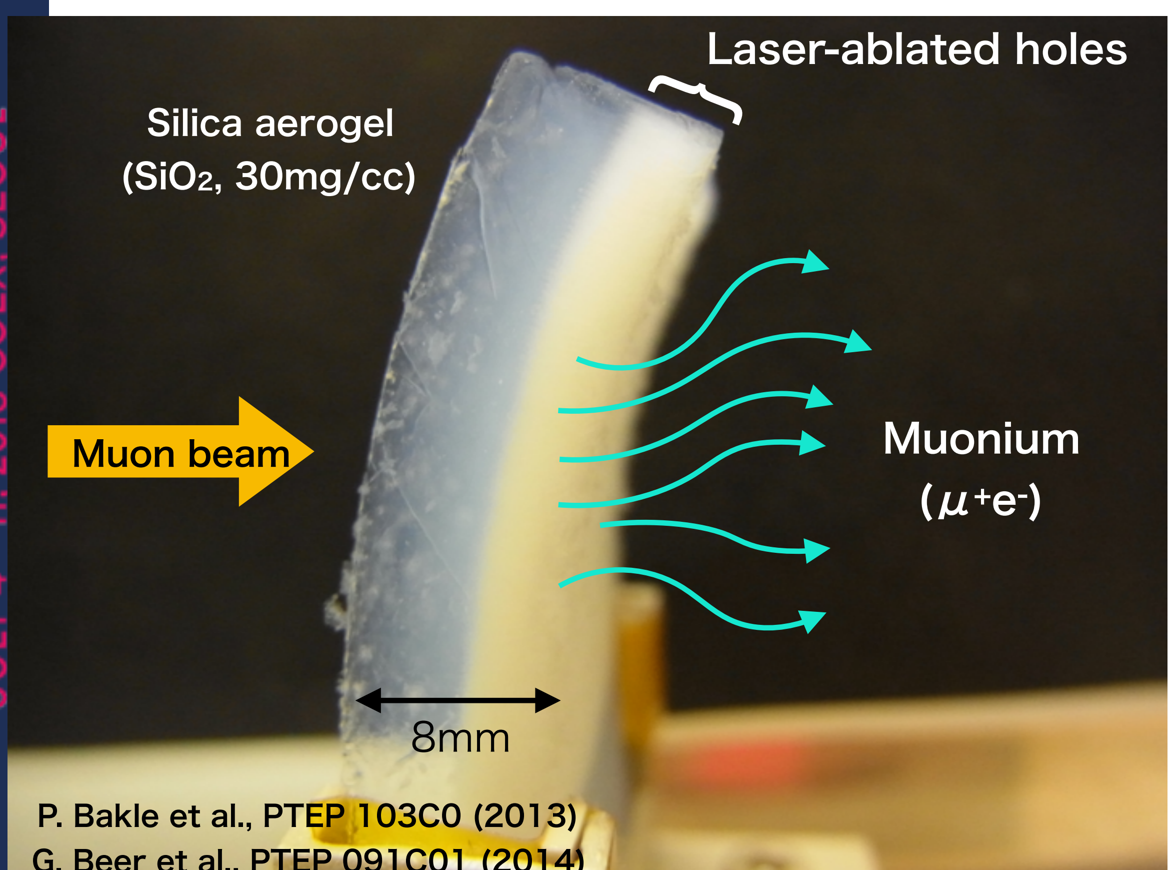
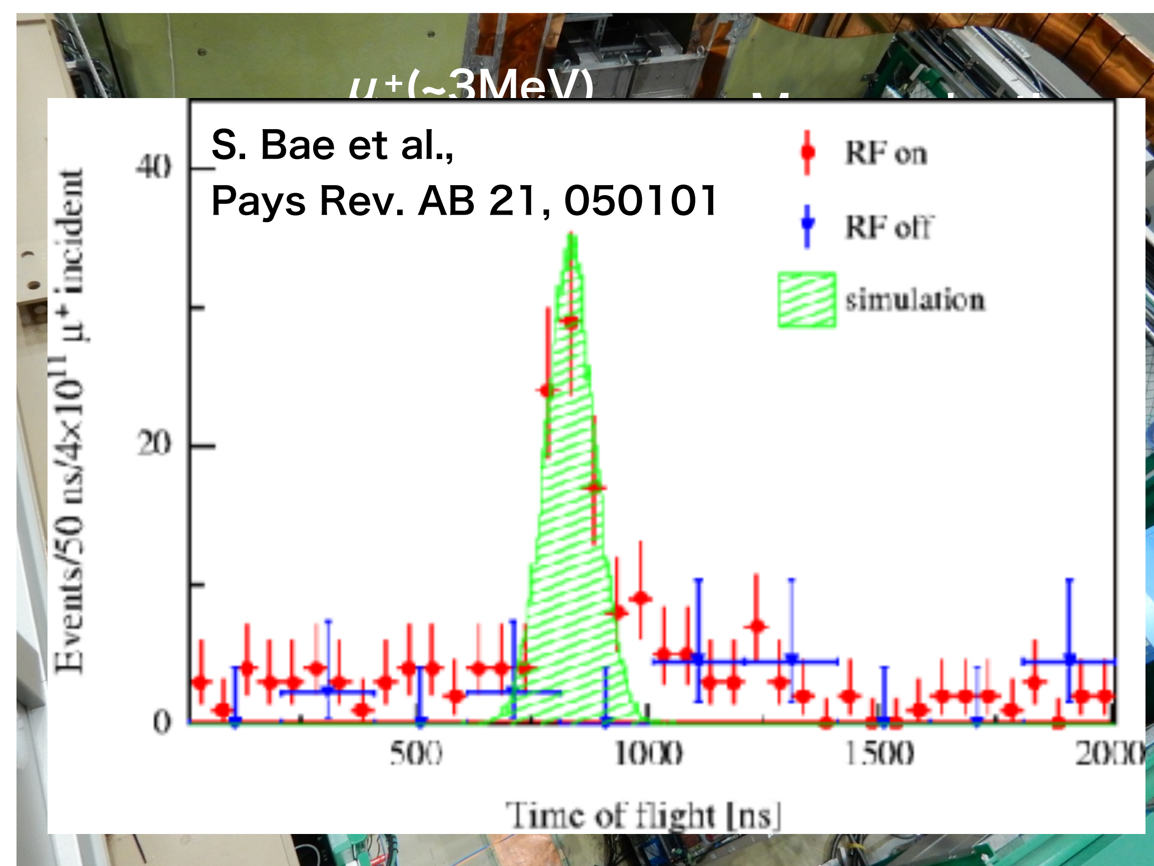
- Muonium production with aerogel samples with different sizes of holes
- Acceleration of negative muonium atoms (Mu^-) by static electric field and RFQ

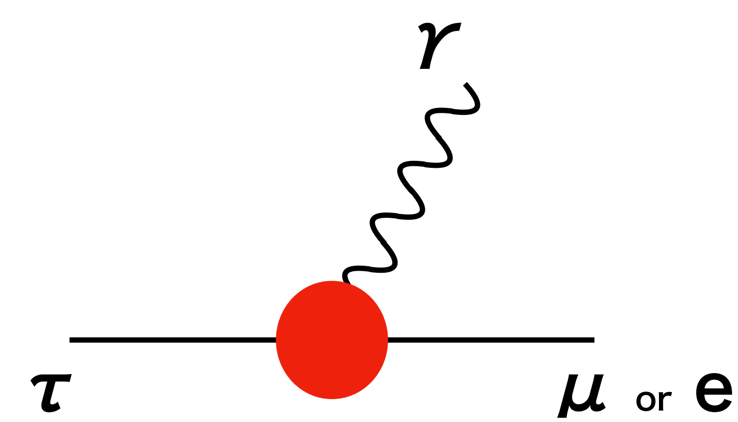


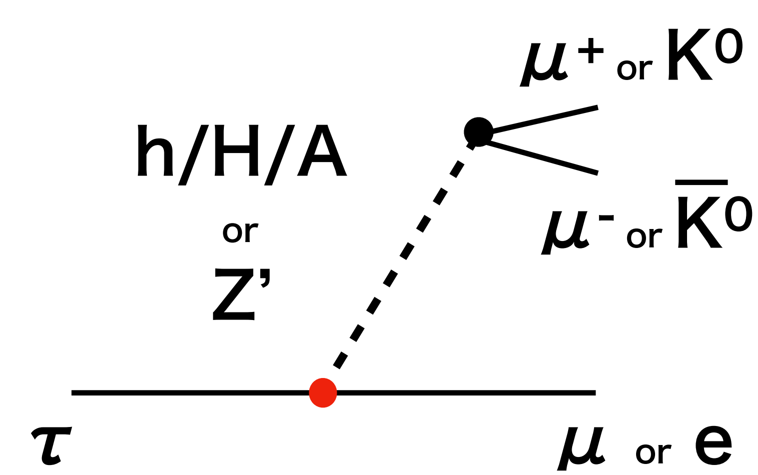


Tau cLFV

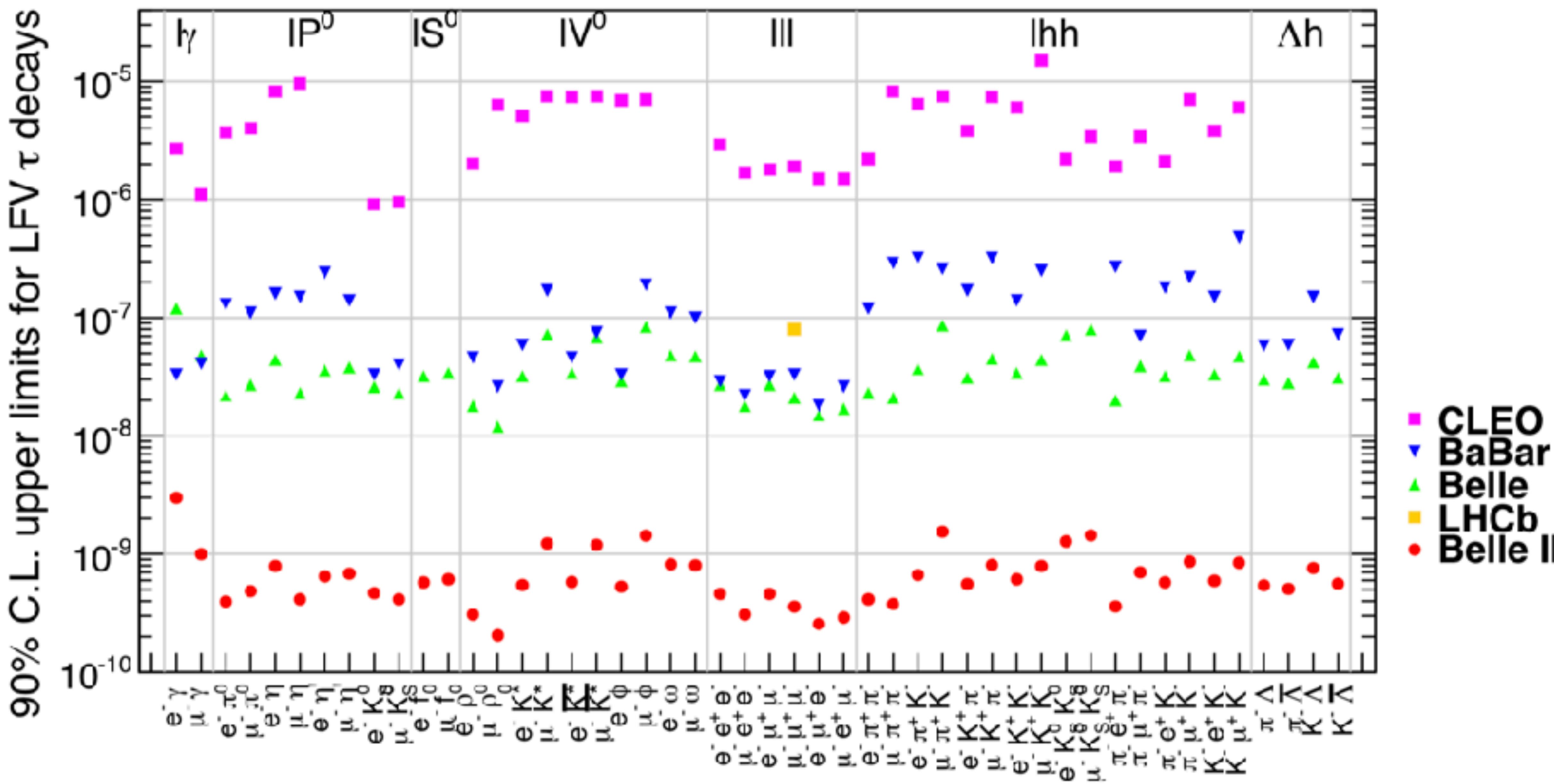
New Physics Searches with τ Leptons

- Same physics motivation with muon cLFV searches
- m_τ heavier than m_μ
    - Different, perhaps larger, coupling expected to new physics
    - More final state types
- Large τ statistics in collider experiments including LHCb





τ LFV searches summary and prospects



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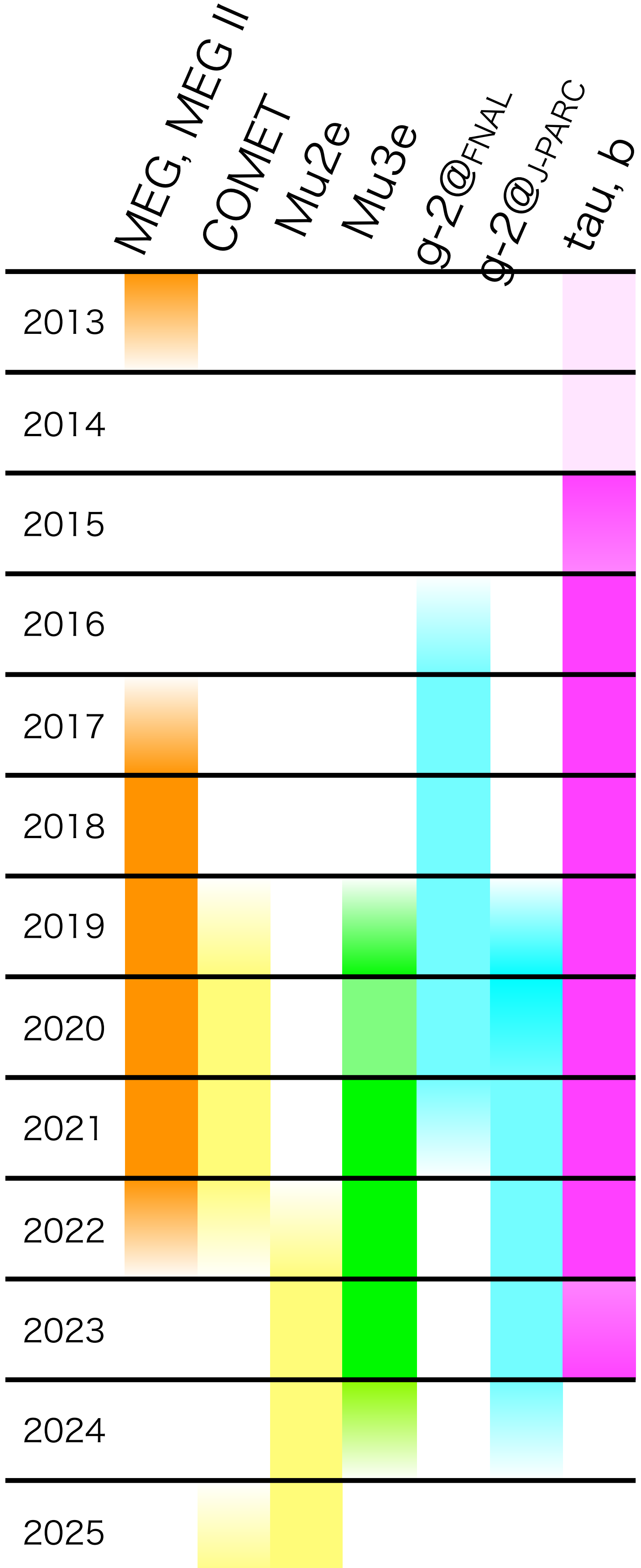
Summary and Outlook



- > 3σ deviation of muon g-2 in BNL E821 experiment
  - **FNAL g-2 started physics DAQ!**
  - J-PARC g-2/EDM succeeded initial test of muon acceleration
- MEG limit: Br($\mu \to e \gamma$) < 4.2×10^{-13}
  - MEG II engineering run, followed by physics DAQ
- COMET, Mu2e & Mu3e in 2019-202x
- More tau data from Belle II