Flavor and Precision Physics Experiments Overview

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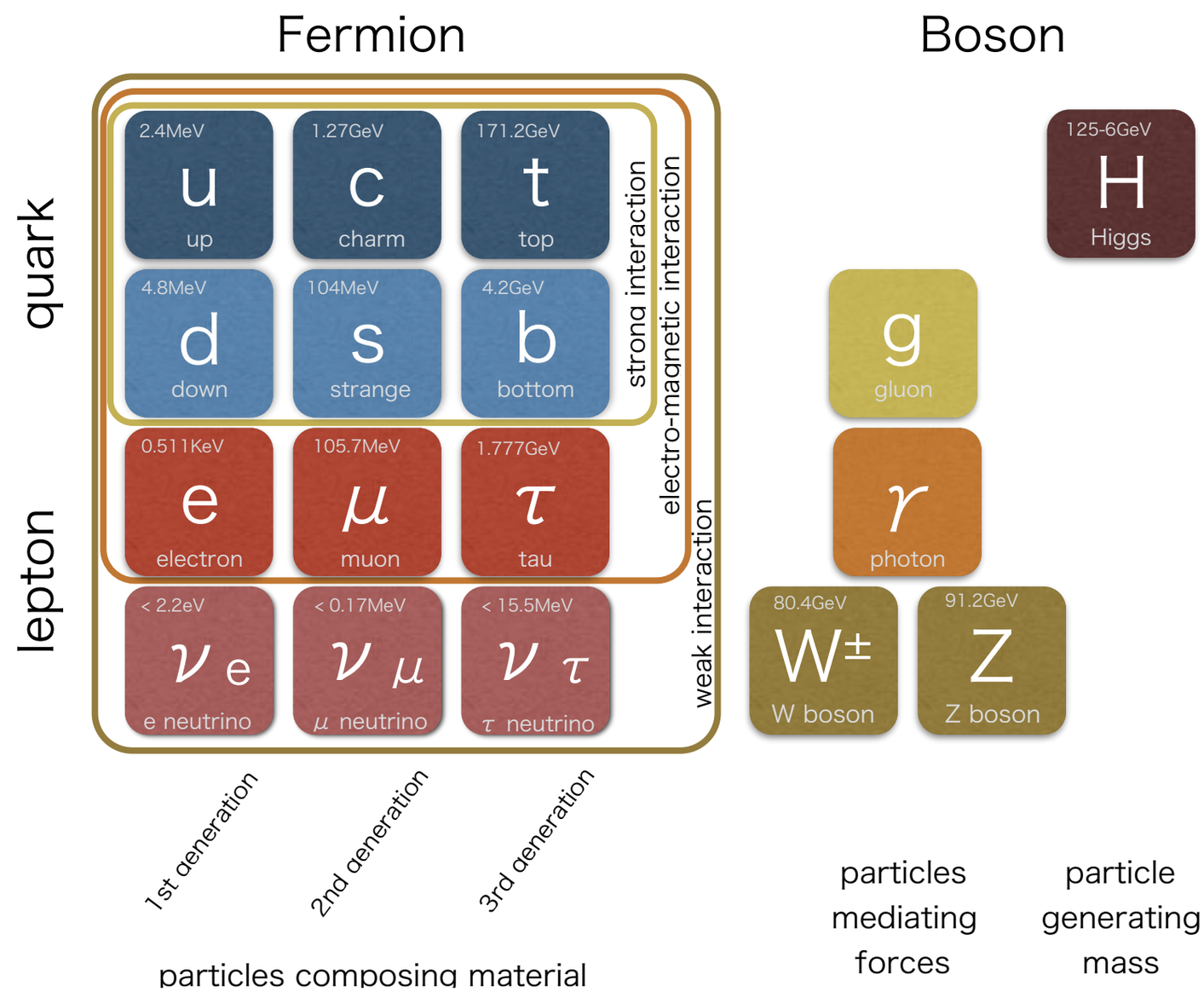
Contents

Flavor Physics

- Precise measurement of flavor structure
- Establishment of SM
- Indication of BSM?
  - muon g-2, proton radius, B leptonic decay …



Flavor Physics with Muons

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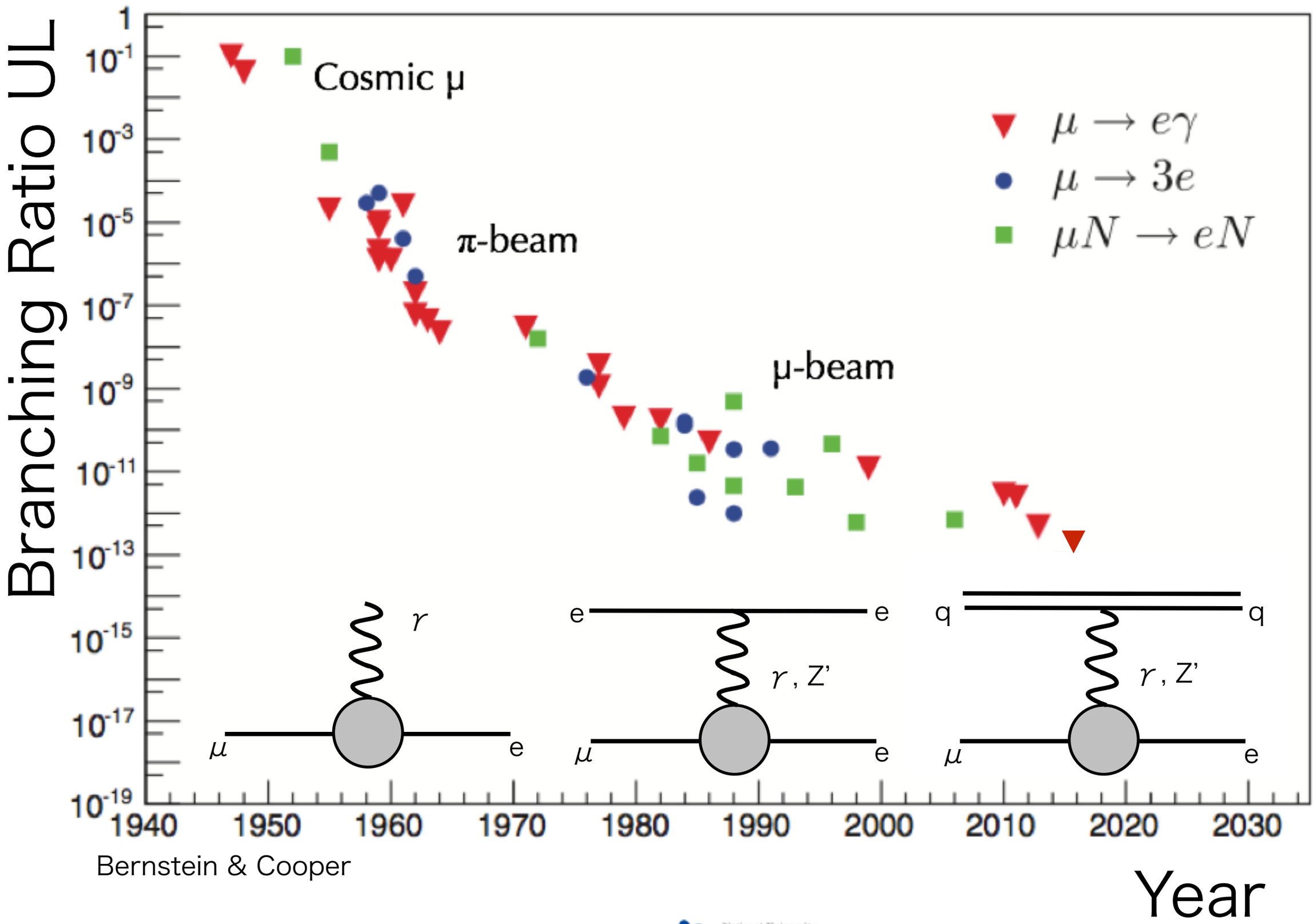
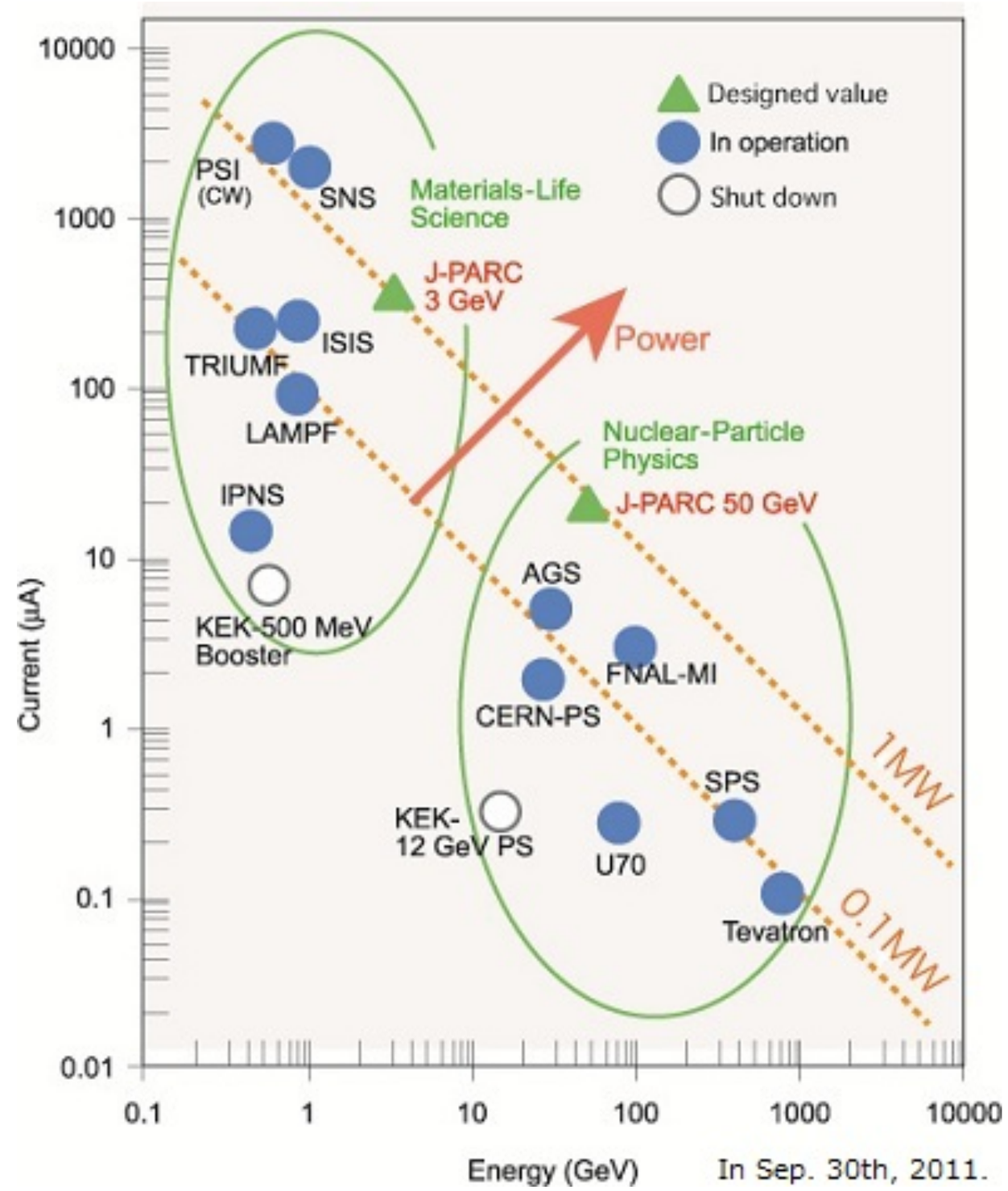


Bernstein & Cooper

More Muons!

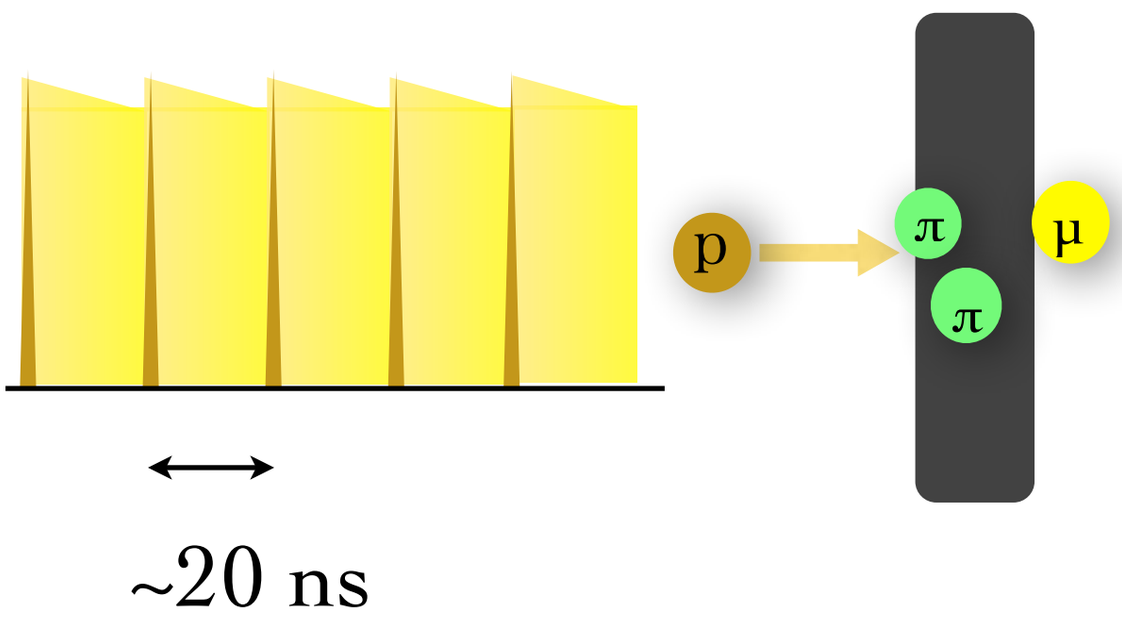
- Muons are produced from pion decays
- More muons produced in more pion decays
- Pion production yield depends on the power the proton driver
  - High-Power machine rather than High-Energy machine
  - Proton current

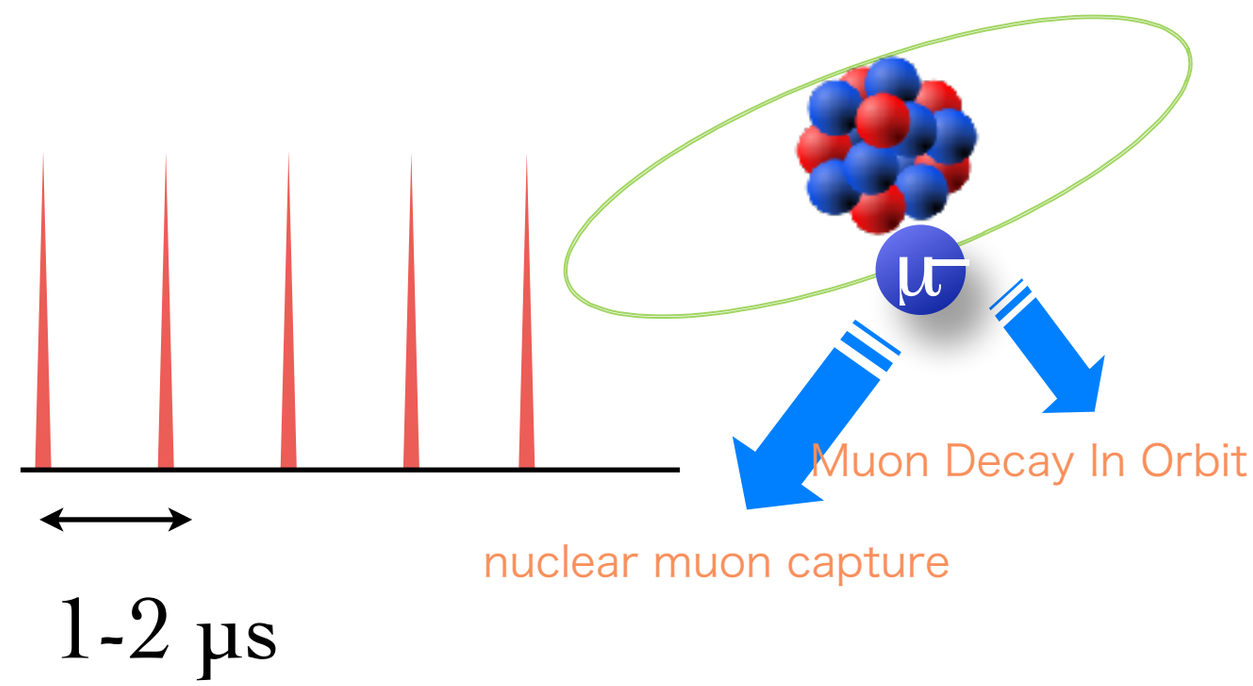


DC or Pulse?

- DC beam for coincidence experiments
  - utilize the lifetime difference between pions and muons
  - $\mu \to e\gamma$, $\mu \to e\,e\,e$

- Pulse beam for non-coincidence experiments
  - Optimize the proton beam pulse structure
  - μ-e conversion





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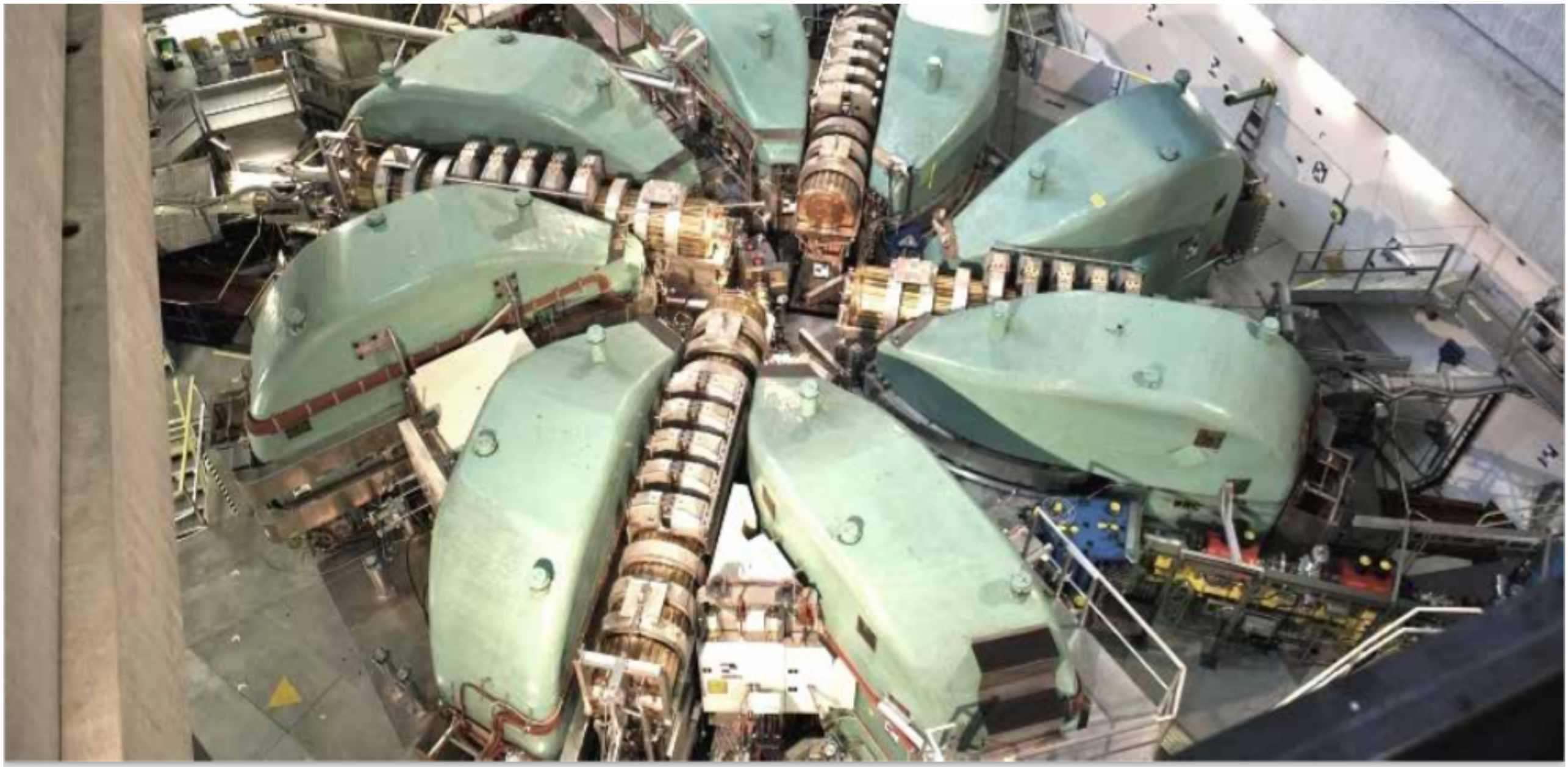
PSI Cyclotron (DC Muon)

- 2.2mA at 590 MeV: 1.3MW beam power



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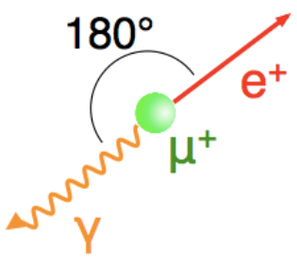
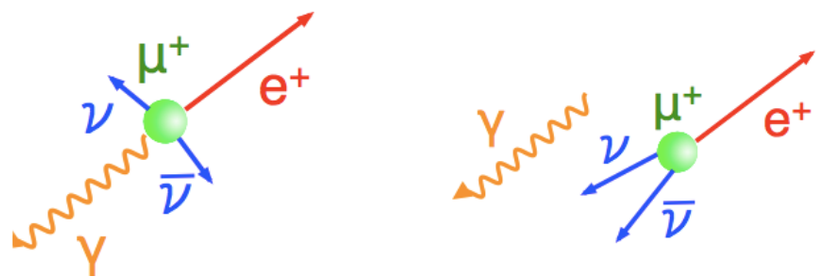
MEG & MEG II

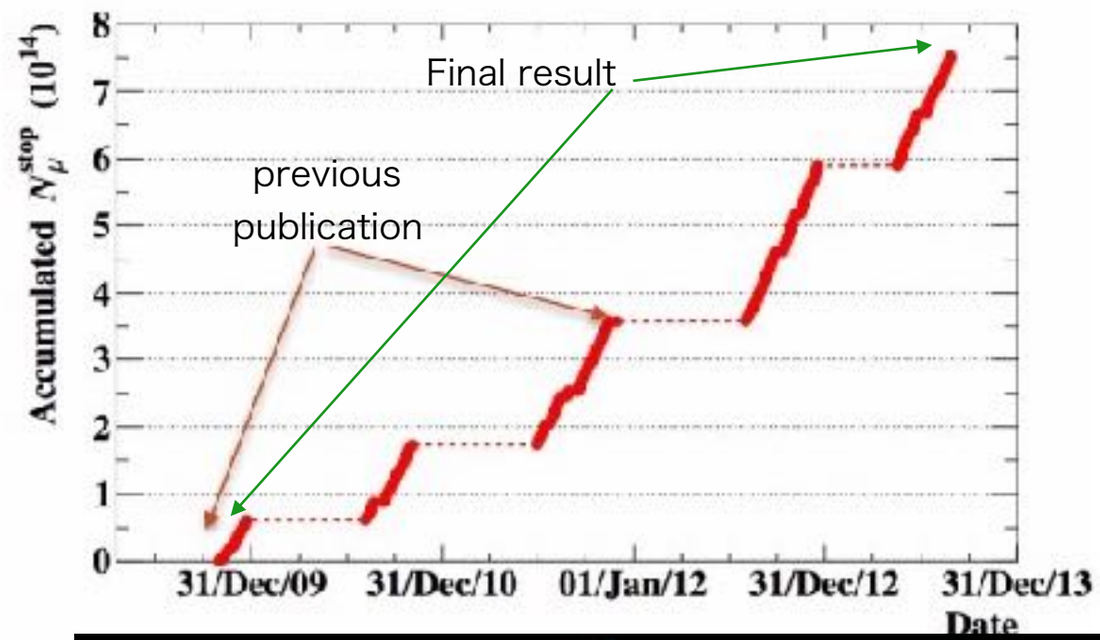
Signal



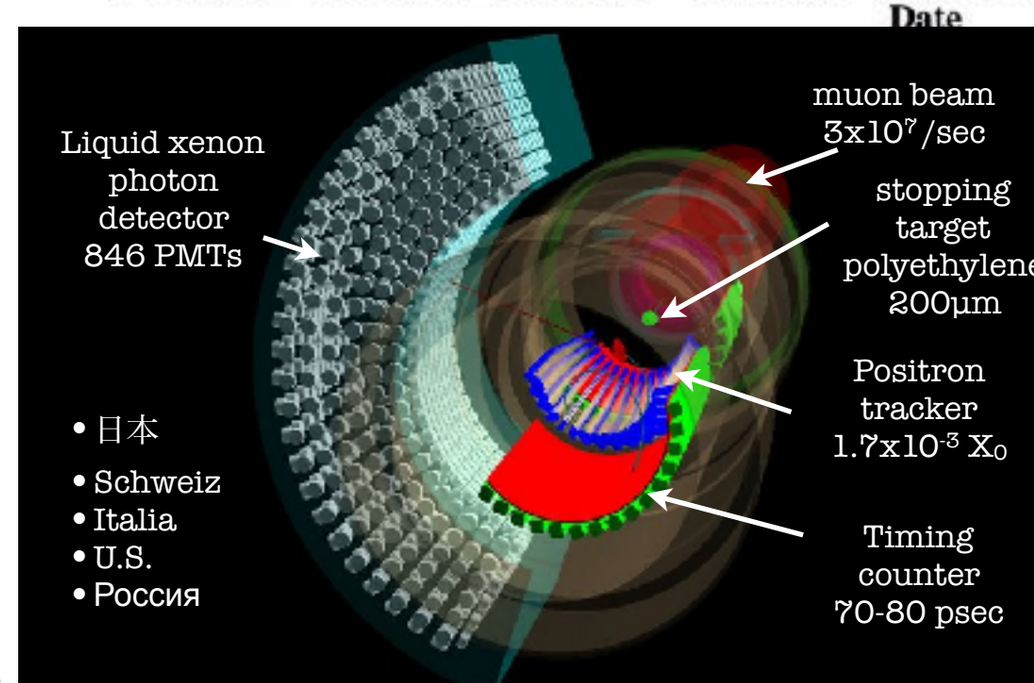
Background



MEG Muon Statistics

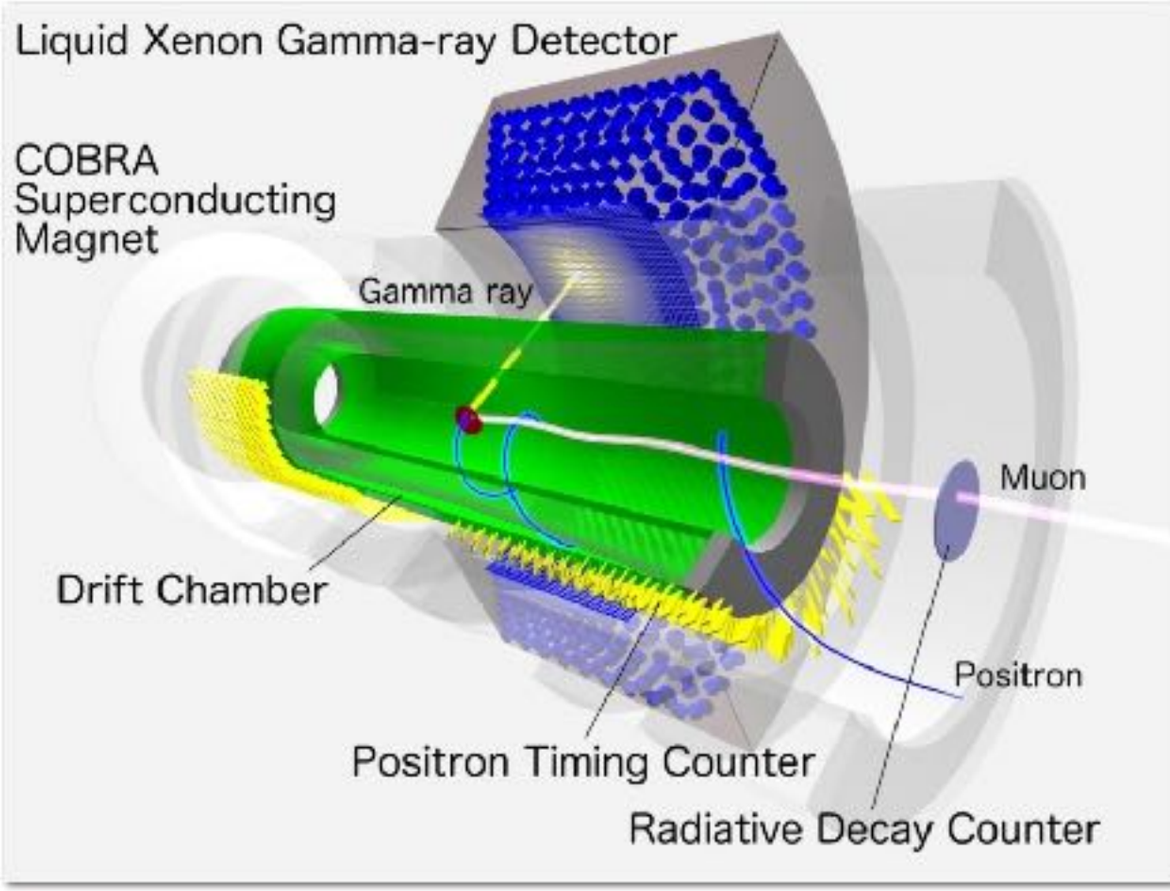


- MEG@PSI
  - Search for $\mu^+ \to e^+ \gamma$ using 3×10^7Hz muon beam
  - Liquid Xe photon detector & COBRA positron spectrome...
  - DAQ in 2008-2013
  - **Final upper limit result published: 4.2×10^{-13} @ 90% C.L.**
  - European Physical Journal C, 76(8), 1-30
- Detector upgrade to achieve 10 times better sensitivity : MEG II



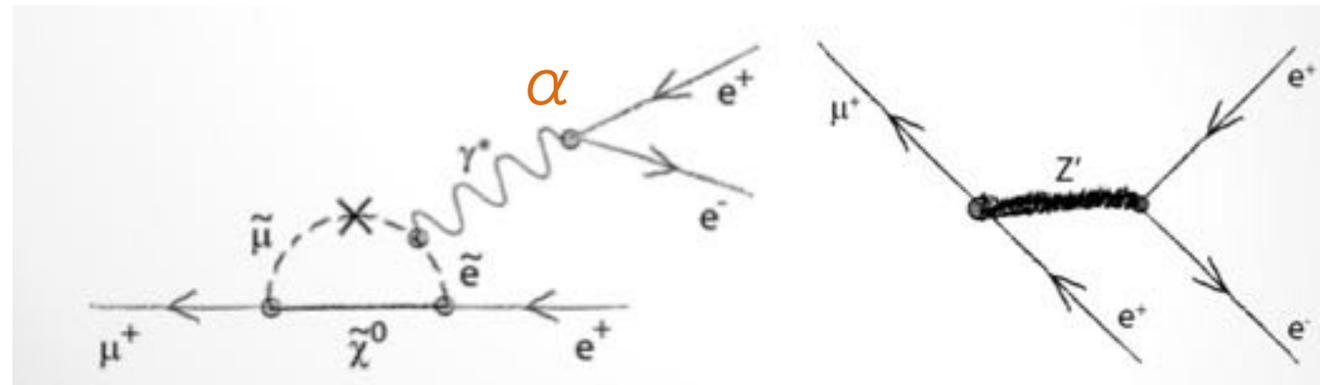
MEG II

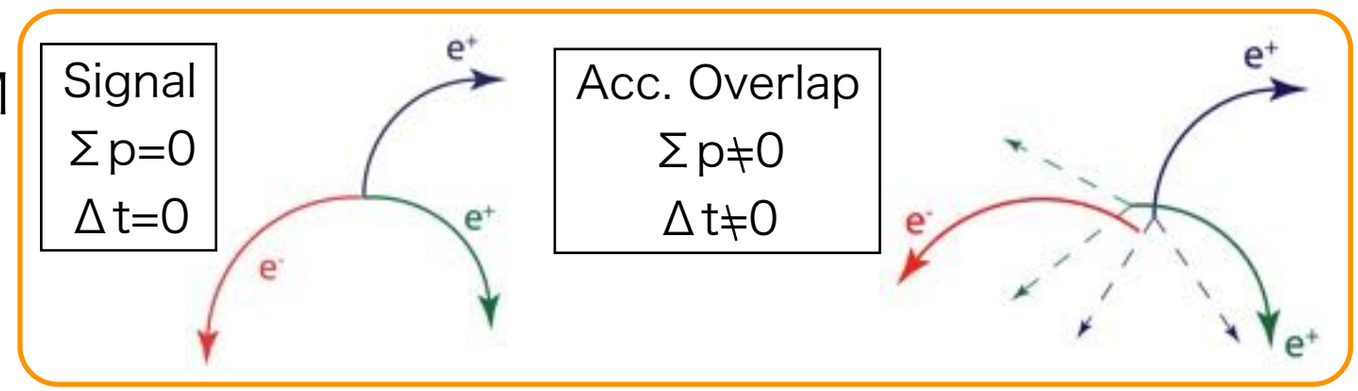
- Improve resolutions by about factor 2 everywhere
- μ beam rate of 7×10^7 Hz to reach **the sensitivity of 4×10^{-14}**
- Engineering run in 2016

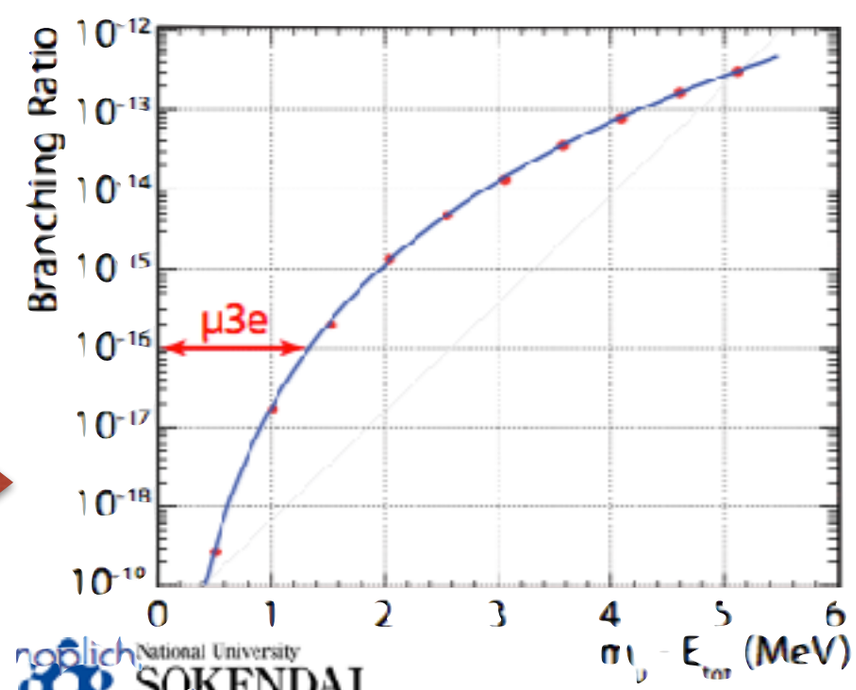


$\mu \to eee$ Search using DC Muon Beam

- Another channel sensitive to cLFV with DC muon beam
  - 1.0×10^{-12} (90% C.L.) by SINDRUM
  - **Goal : 10^{-16} in 3 steps**
- Measure all electron tracks precisely
- most severe BG
  - $\mu^+ \to e^+ e^+ e^- \bar{\nu} \nu$

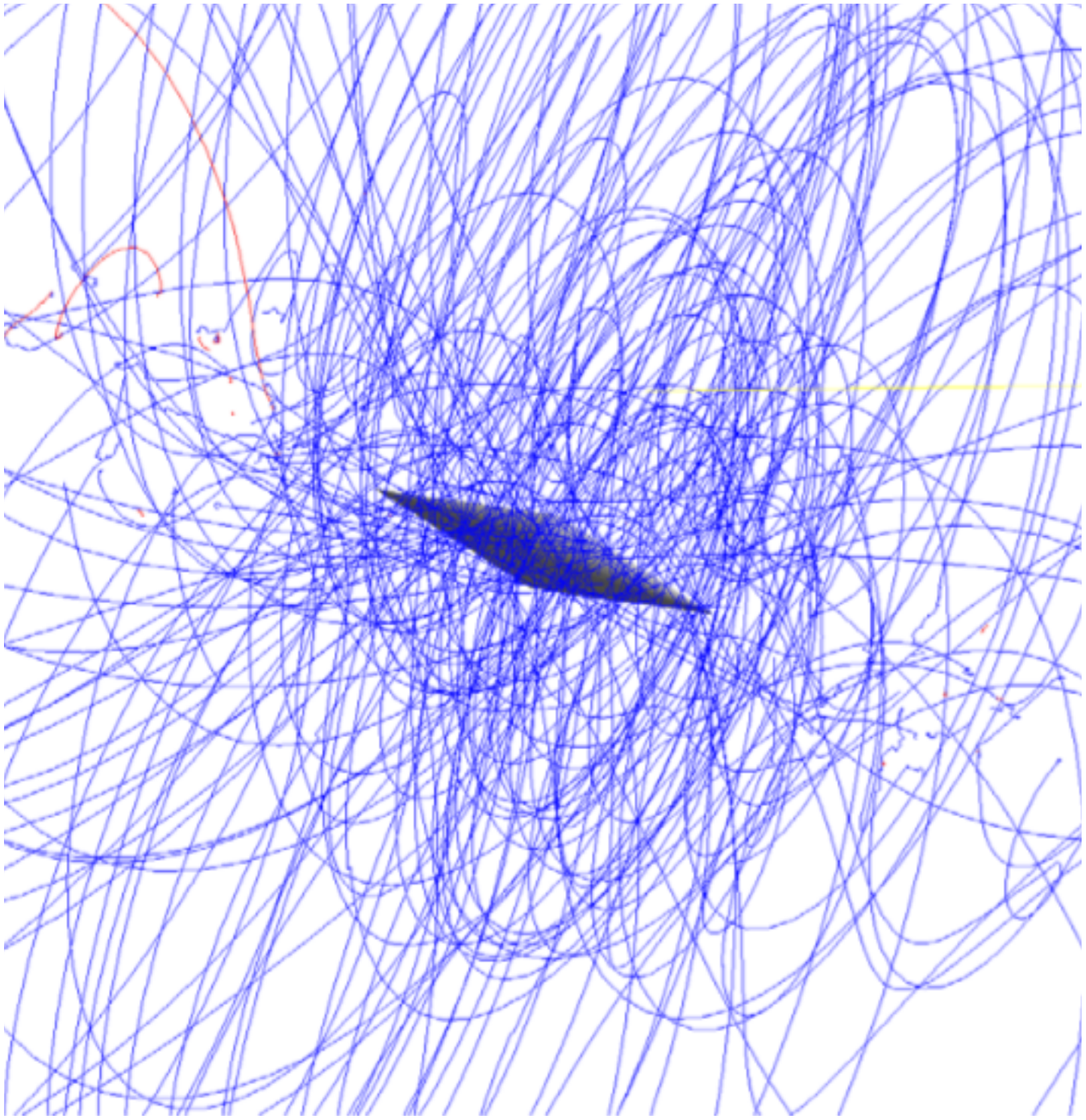






Suppress BG by more than **16 orders of magnitudes**

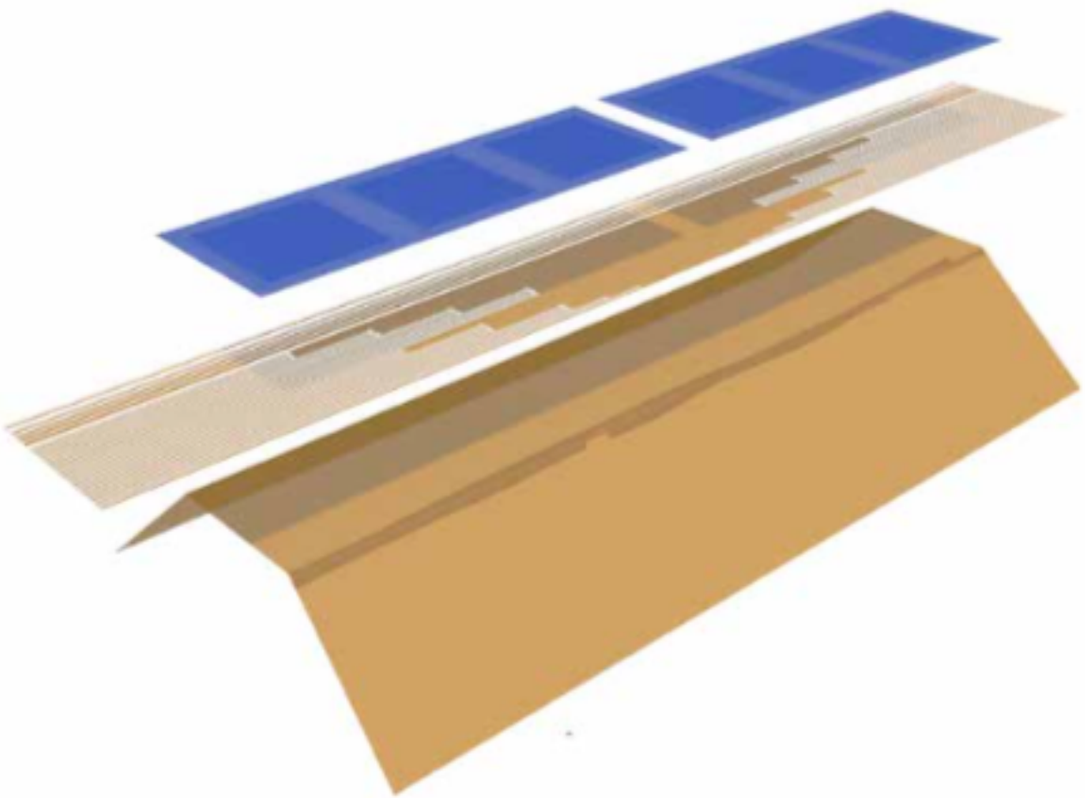
Detector Technology



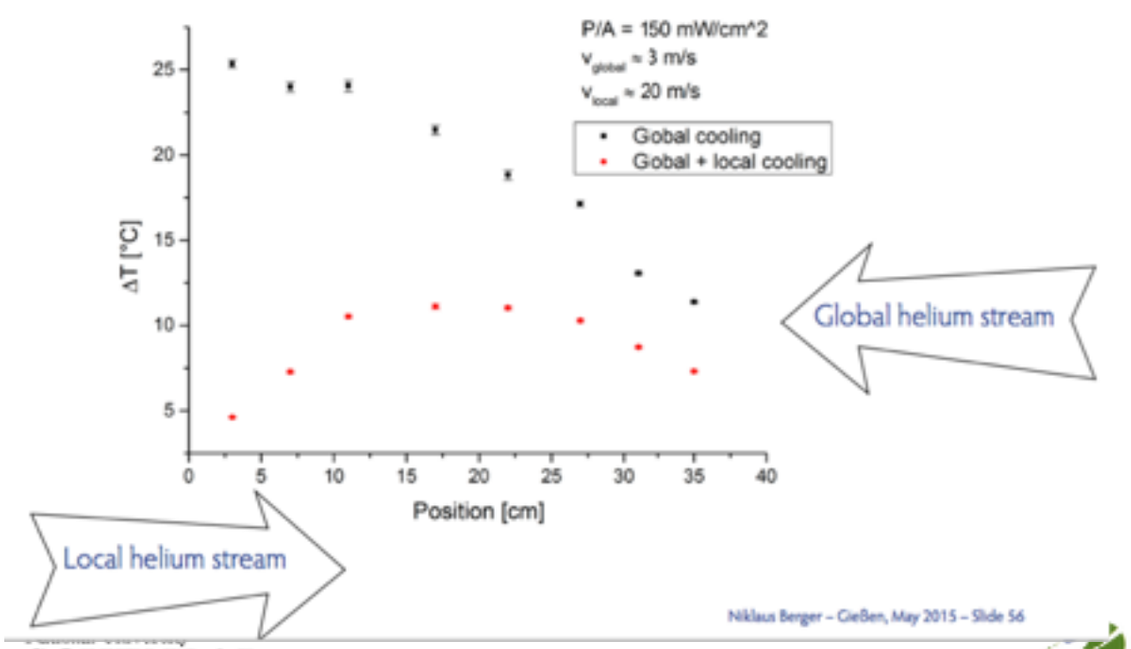
50 nsec, 1Tesla

- High granularity (occupancy)
- Close to target (vertex resolution)
- 3D space points (reconstruction)
- Minimum material (momenta below 53 MeV/c)
- Gas detectors do not work (space charge, aging, 3D)
- Silicon strips do not work (material budget, 3D)
- Hybrid pixels (as in LHC) do not work (material budget)

Detector Building



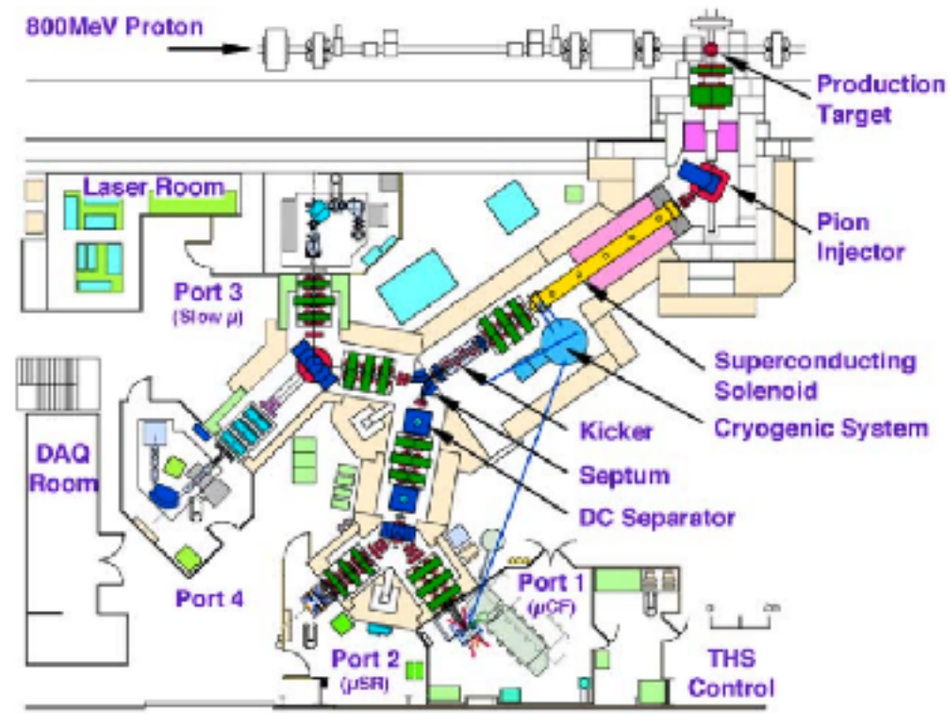
- 50 μm silicon
- 25 μm Kapton™ flexprint with Al traces
- 25 μm Kapton™ frame
- Less than 1% R.L. per layer
- He cooling for 2kW heat generation from the chips



Pulsed Muon Beam Facility

(in Operation)

- **RIKEN-RAL muon facility**
  - 800MeV-300μA, 50Hz
  - Surface mu: 1.5x10^6 /sec
- **J-PARC MLF**
  - 3GeV, 1MW (goal), 25Hz
  - Surface mu: > 3x10^7 /sec (from MLF Web site as of 2016 Jan)



Layout of the RIKEN-RAL Muon Facilty

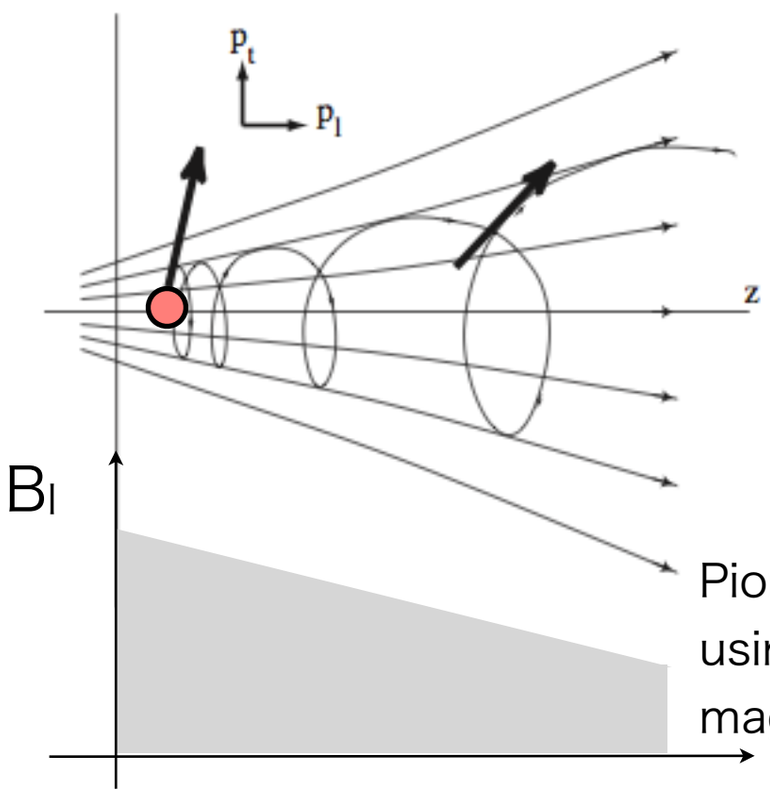
J-PARC MLF H-Line

Pulsed Muon Beam Facility

(in construction)

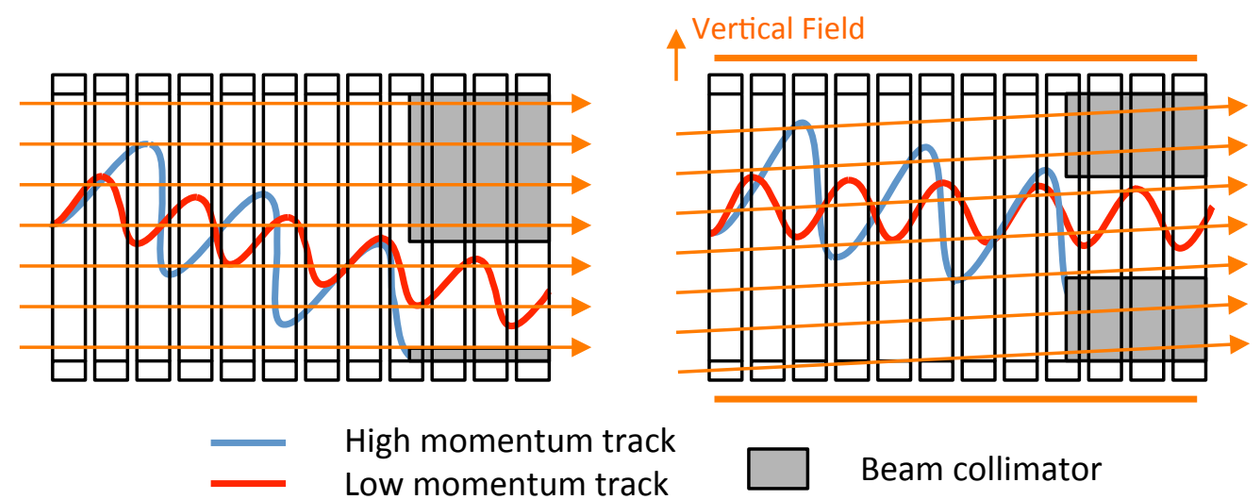
- MLF H-Line @ J-PARC MLF
- **COMET**
- **Mu2e**

> 10^9 μstops/sec

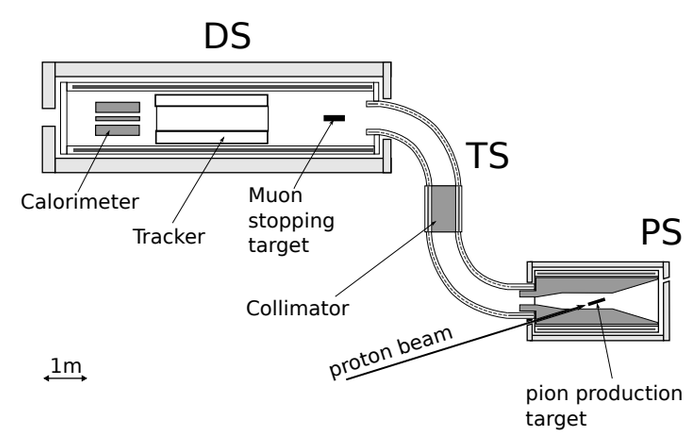


Pion/muon collection using gradient magnetic field

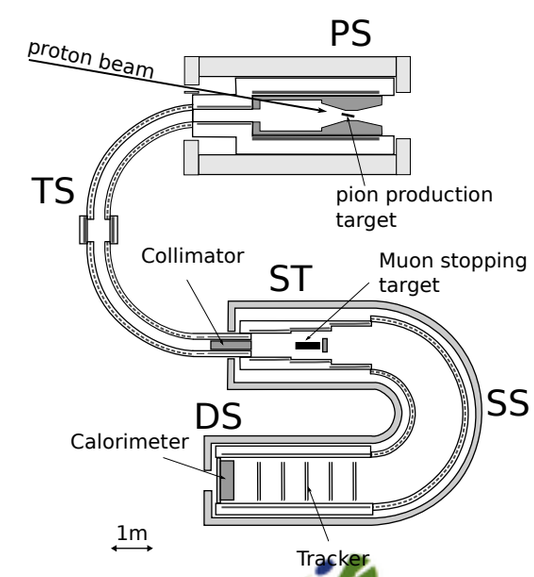
Muon transport with large momentum acceptance and momentum selection



Mu2e

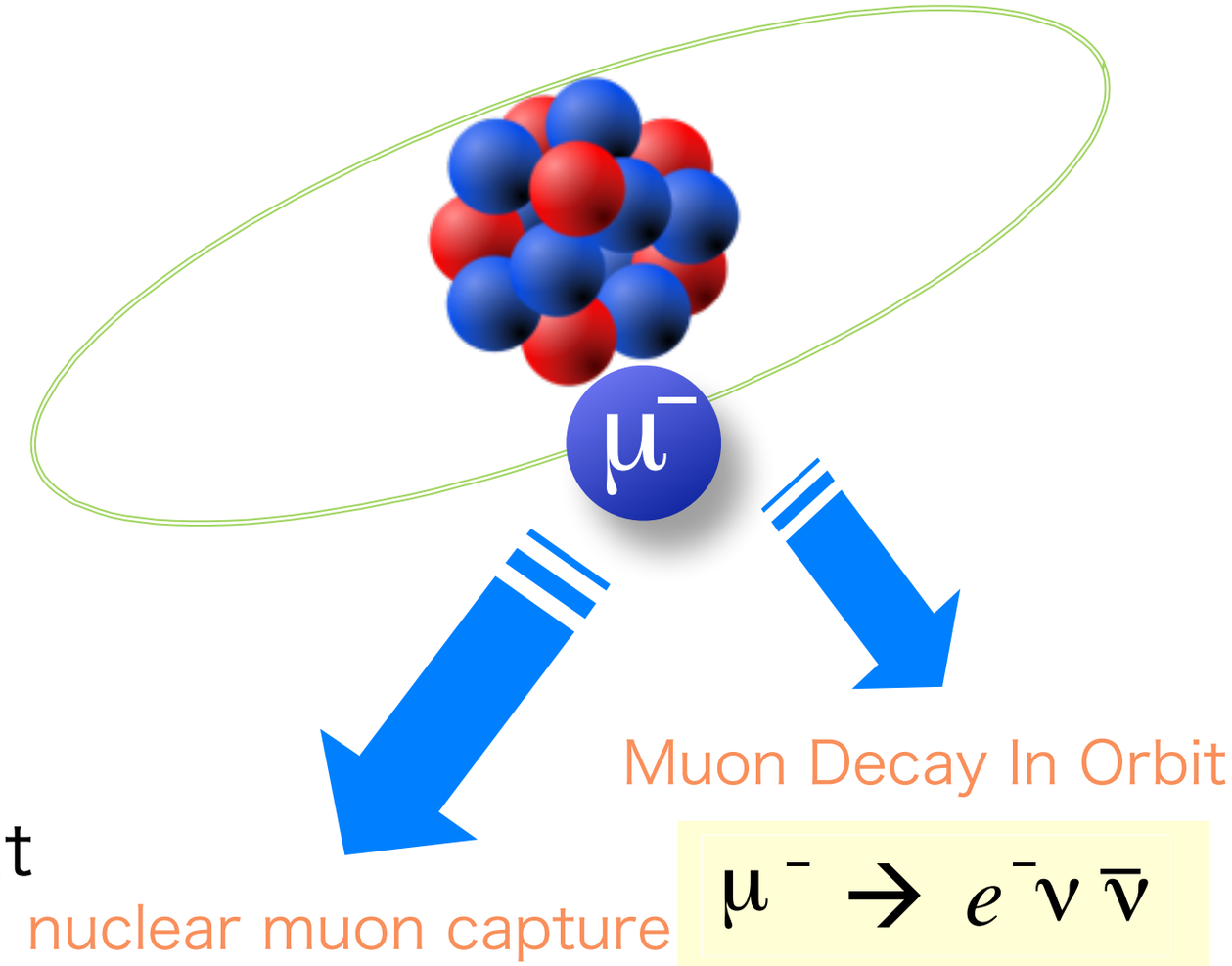


COMET



μ-e conversion search

- **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} = 800 nsec)



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

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

- $E_{\mu e}(Al) \sim m_\mu - B_\mu = 105MeV$
  - B_μ: binding energy of the 1s muonic atom

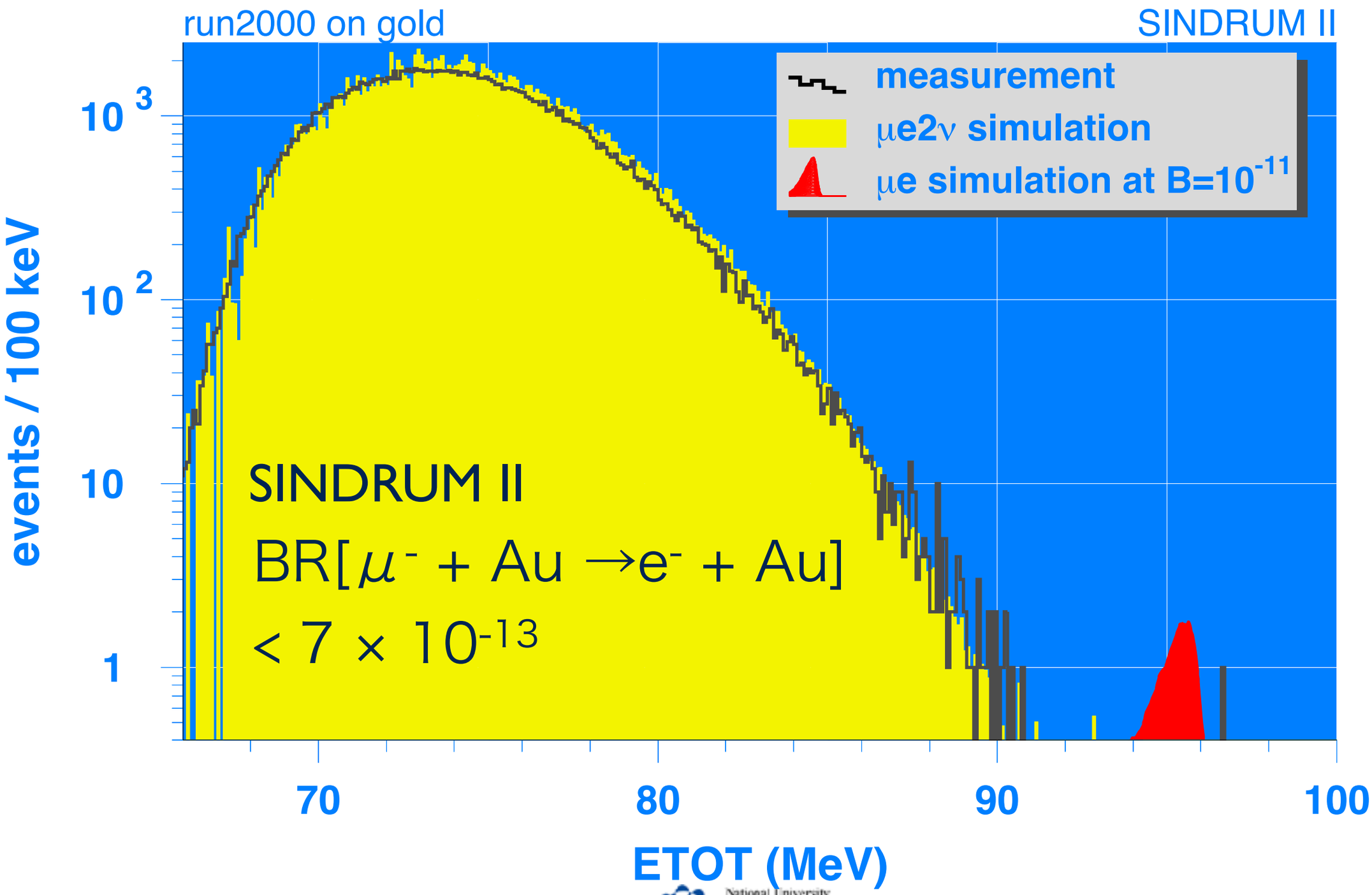
μ-e conversion

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

- **μ-e conversion**

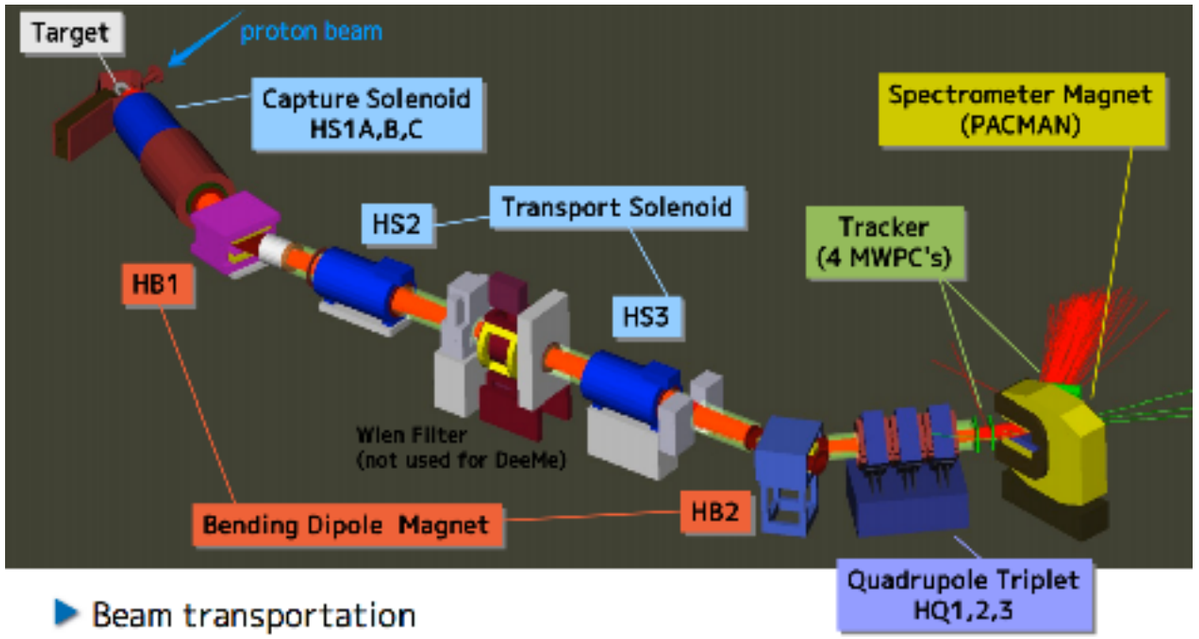
Mu-e Conversion

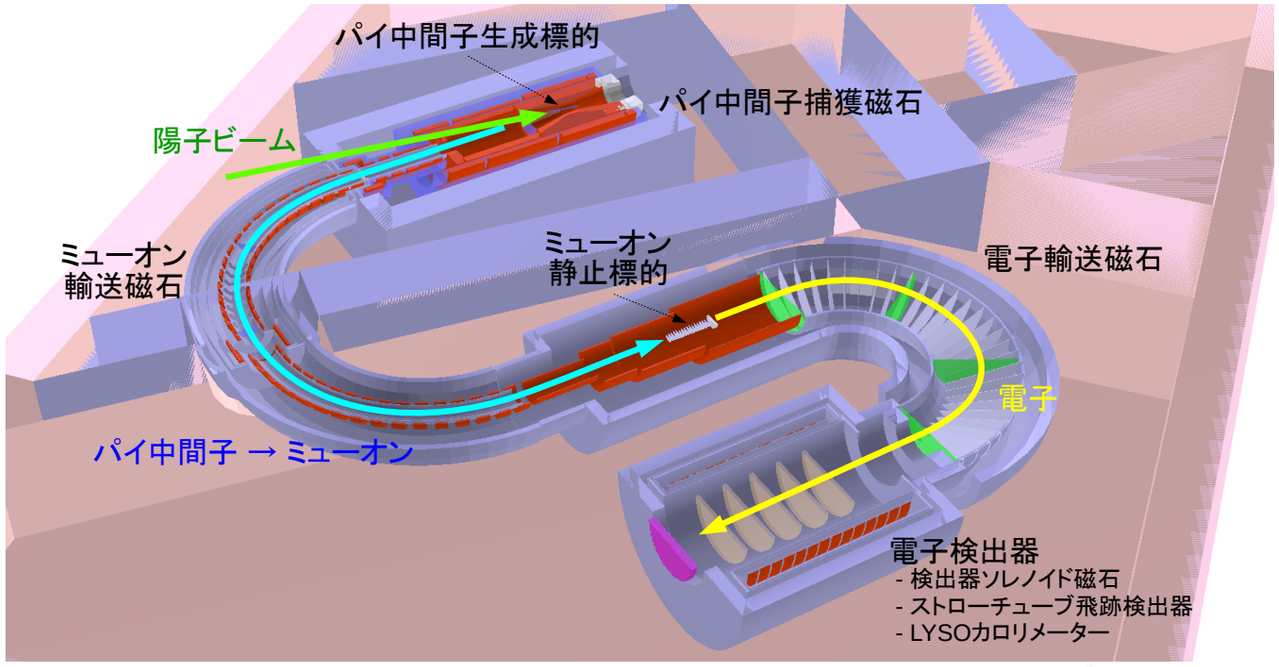
Electron Energy Spectrum



Mu-e Conversion Search Experiments

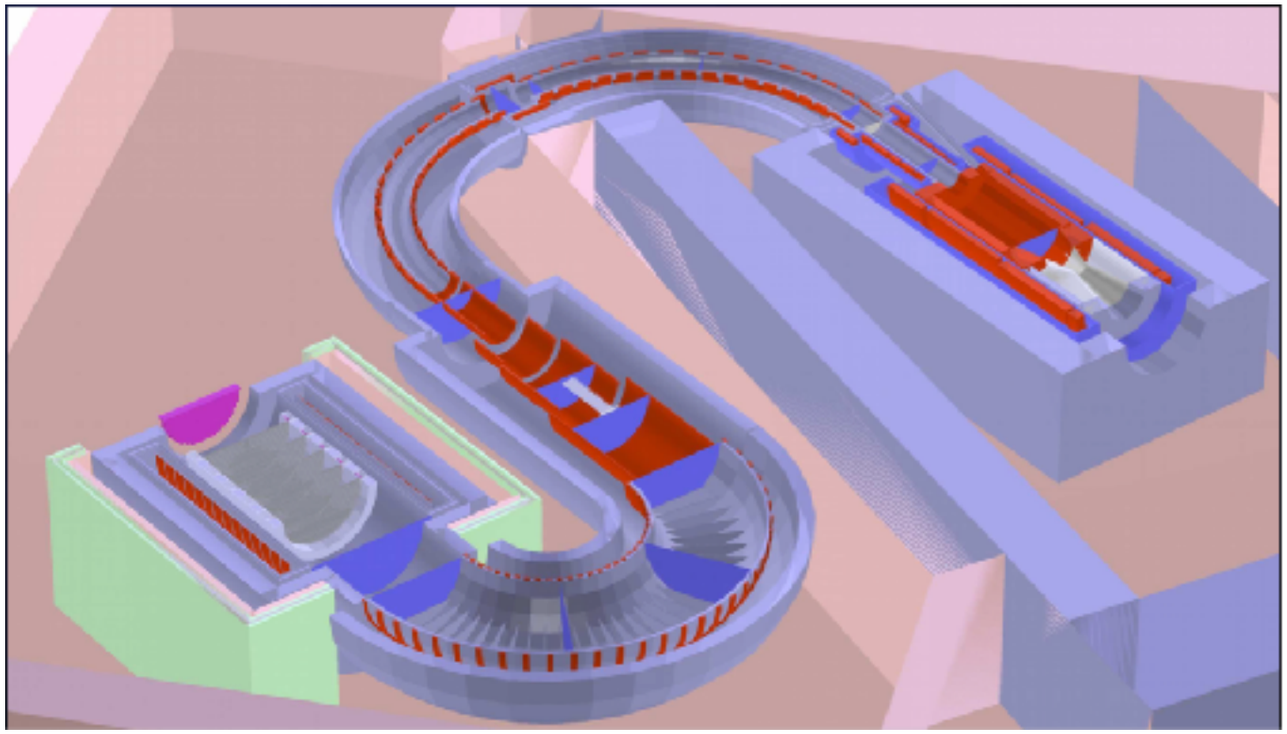
- **DeeMe**
  - ~$10^{-13\text{-}14}$ using C or SiC for muonic atom formation
- **COMET Phase-I & II**
  - Al target to reach the 10^{-14} sensitivity in Phase-I and 10^{-16} in Phase-II
- **Mu2e**
  - Al target to reach the 10^{-16} sensitivity

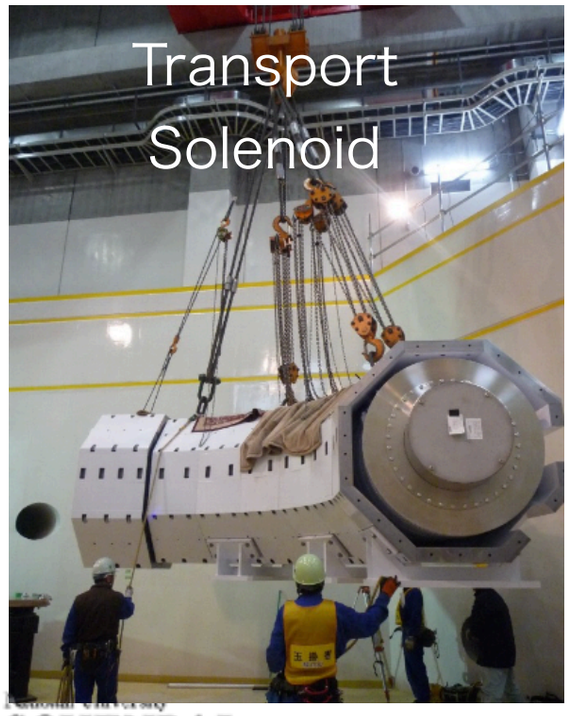


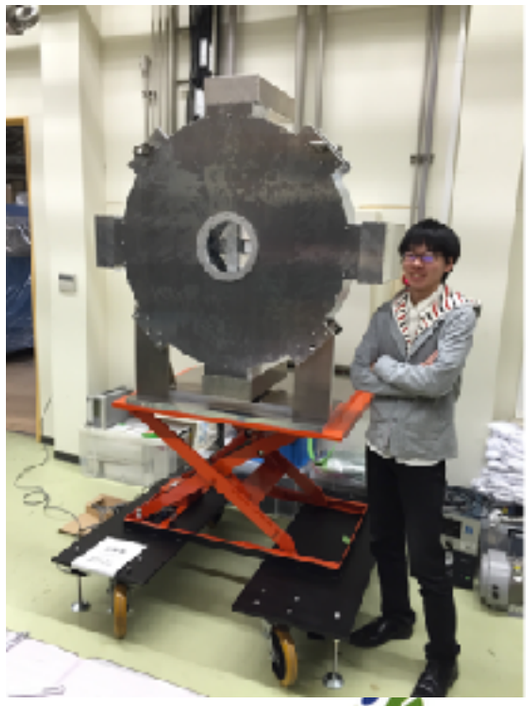


COMET at J-PARC

- **Target S.E.S. 2.6×10^{-17}**
- 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
- Recently staging plan showed up. 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}**







Mu2e at FNAL

- **Target S.E.S. 2×10^{-17}**

- uses the antiproton accumulator/debuncher rings to manipulate proton beam bunches

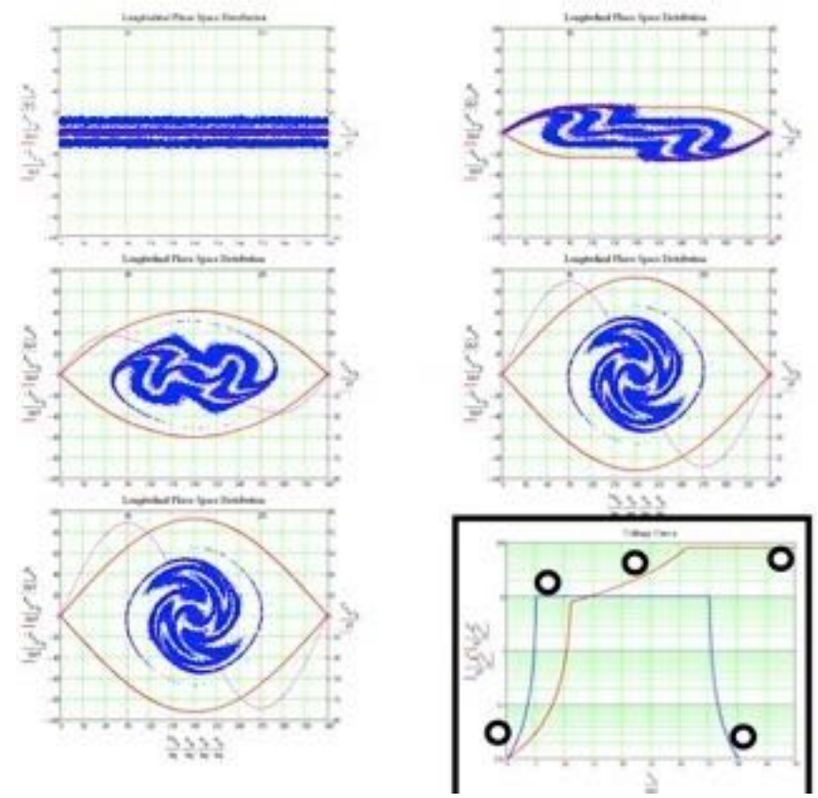
- No interference with NOvA experiment

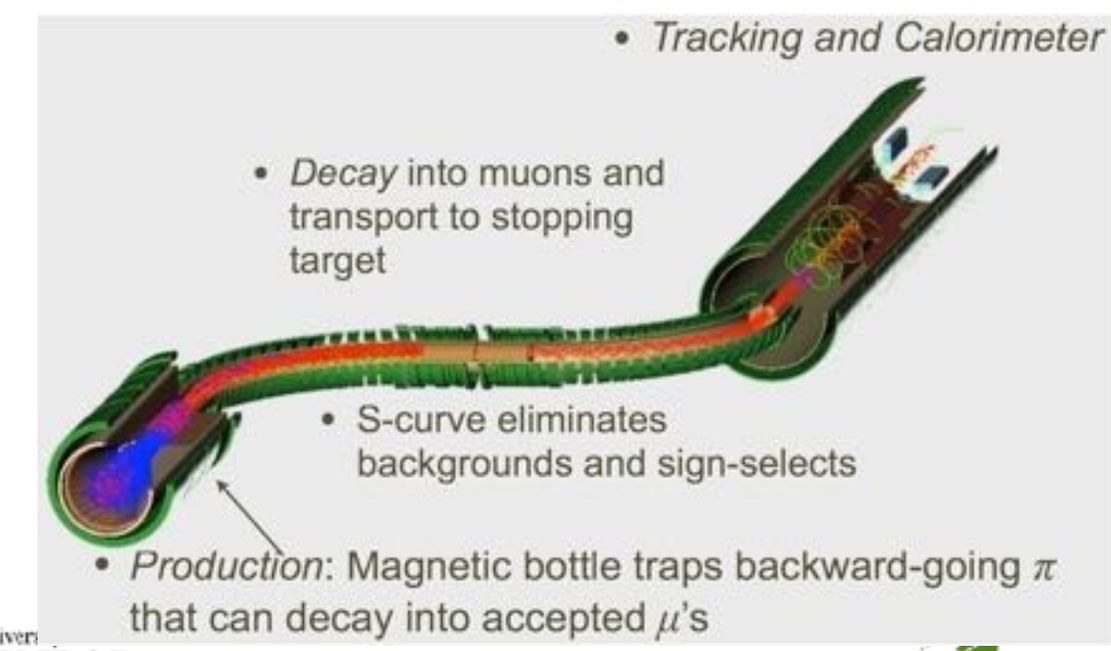
  - Mu2e uses beam NOvA can't

- pion production target in a solenoid magnet

- S-shape muon transport to eliminate BG and sign-select

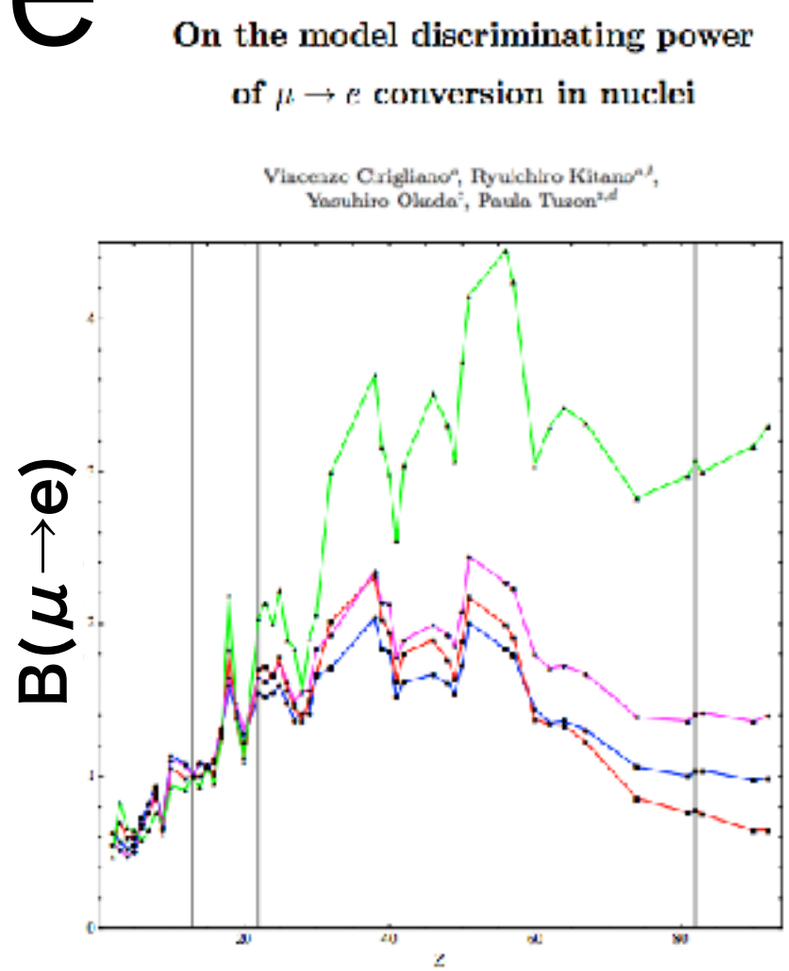
- Tracker and calorimeter to measure electrons





Muon Stopping Target Dependence

- Different target material contains different quark contents
  - May be possible to see the target dependence on the mu-e conversion rate
  - Discriminate the principal interaction of the mu-e conversion?
- Possible taget
  - DeeMe: C (& Si)
  - COMET & Mu2e: Al (& Ti in future? & Pb in far future ??)



	Al	Ti
lifetime	864 ns	330 ns
time window	0.3	0.2
signal	1	1.5
net	0.3	0.3

Muon Precision Physics
muon g-2/EDM
&
Proton radius

muon g-2/EDM measurements

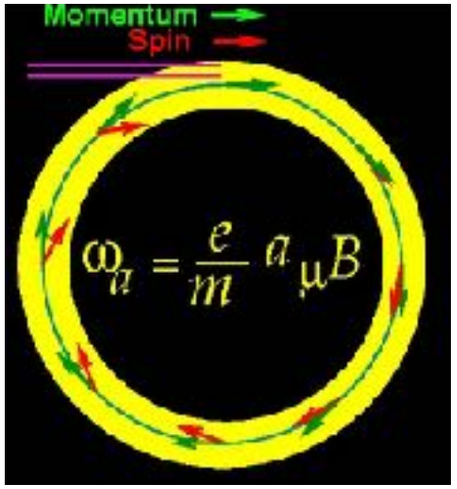
Anomalous magnetic moment (g-2)

$a_\mu = (g-2)/2 = 11\,659\,208.9\,(6.3) \times 10^{-10}$ (BNL E821 exp) **0.5 ppm**

$11\,659\,182.8\,(4.9) \times 10^{-10}$ (standard model)

$\Delta a_\mu = \text{Exp} - \text{SM} = 26.1\,(8.0) \times 10^{-10}$ **3σ anomaly**

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



general form of spin precession vector:

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

BNL E821 approach
γ=30 (P=3 GeV/c)

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

J-PARC approach
E = 0 at any γ

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

Continuation at FNAL with 0.1ppm precision

Proposed at J-PARC with 0.1ppm precision

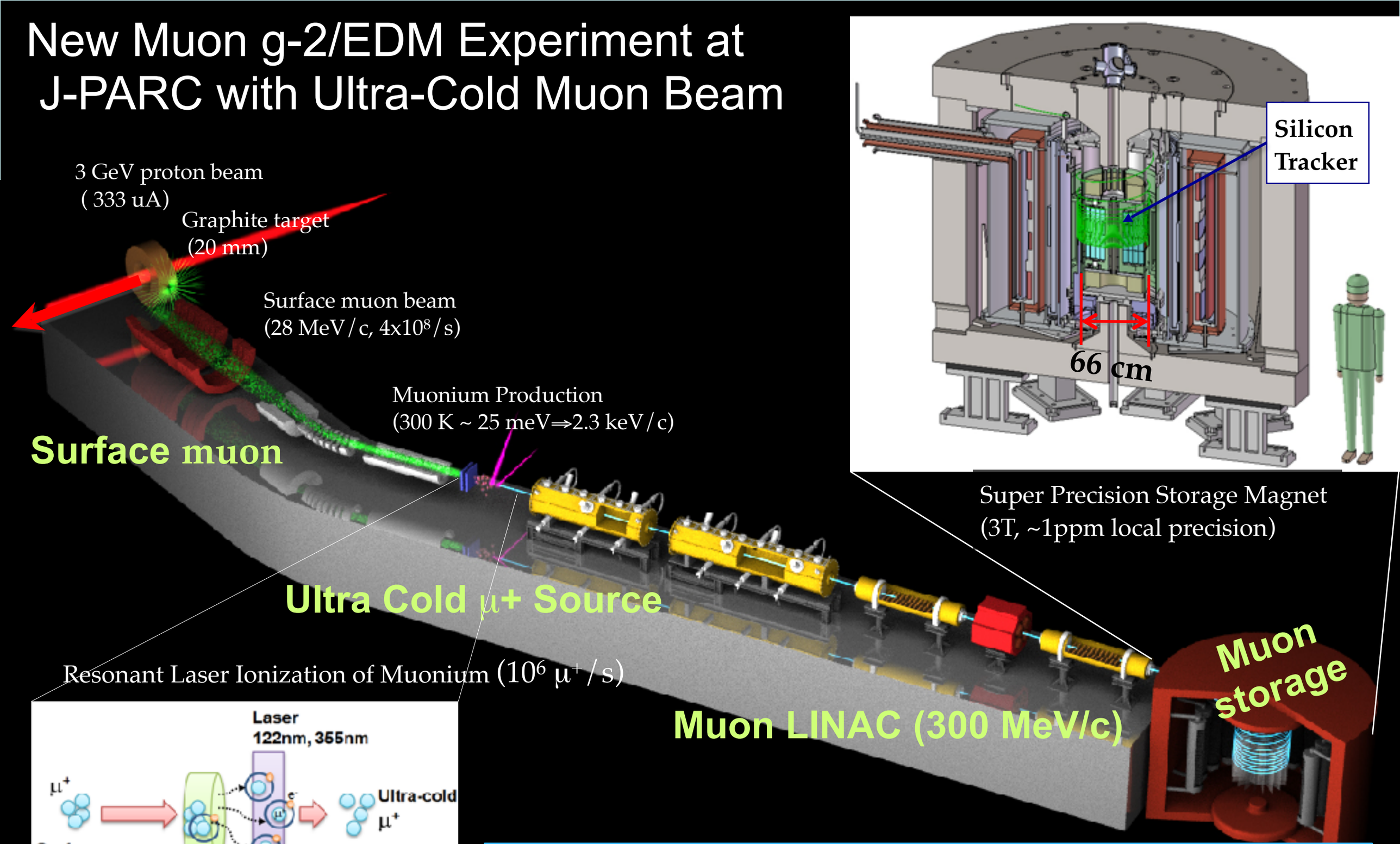
Fermilab E989

- **Goal:**

$$\delta a_\mu \leq \pm 16 \times 10^{-11} \text{ (.14 ppm)}$$

- 1.8×10^{11} detected high energy decays
  - systematic errors ω_a, ω_p ±0.07 ppm each

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

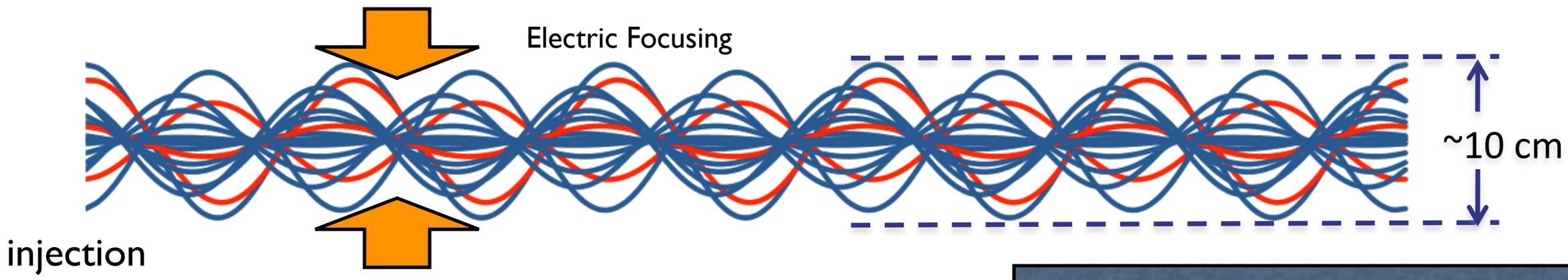


1. Ultra-cold μ^+ beam is injected to storage magnet.
2. Pulse kicker stops muons in storage area
3. Positron tracker measures e+ from $\mu^+ \rightarrow e^+\nu\nu$ decay for the period of 33μs (5 x lifetime)

What's different?

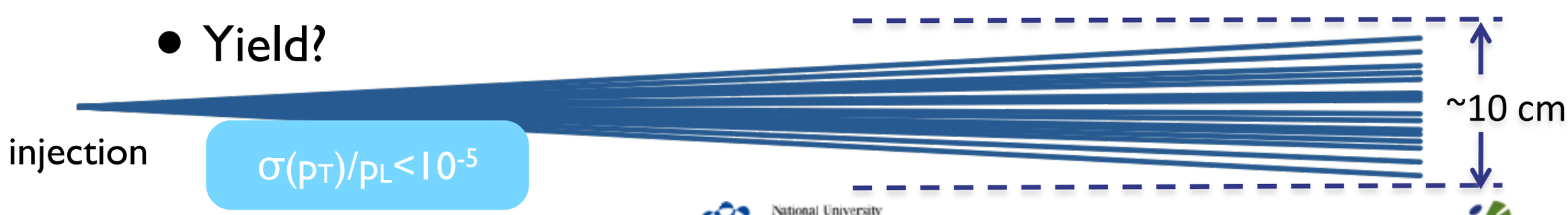
- Tertiary Muon Beam
  - Widely spread over phase space
  - Contamination of pions

Electric focusing
⇒ Magic momentum



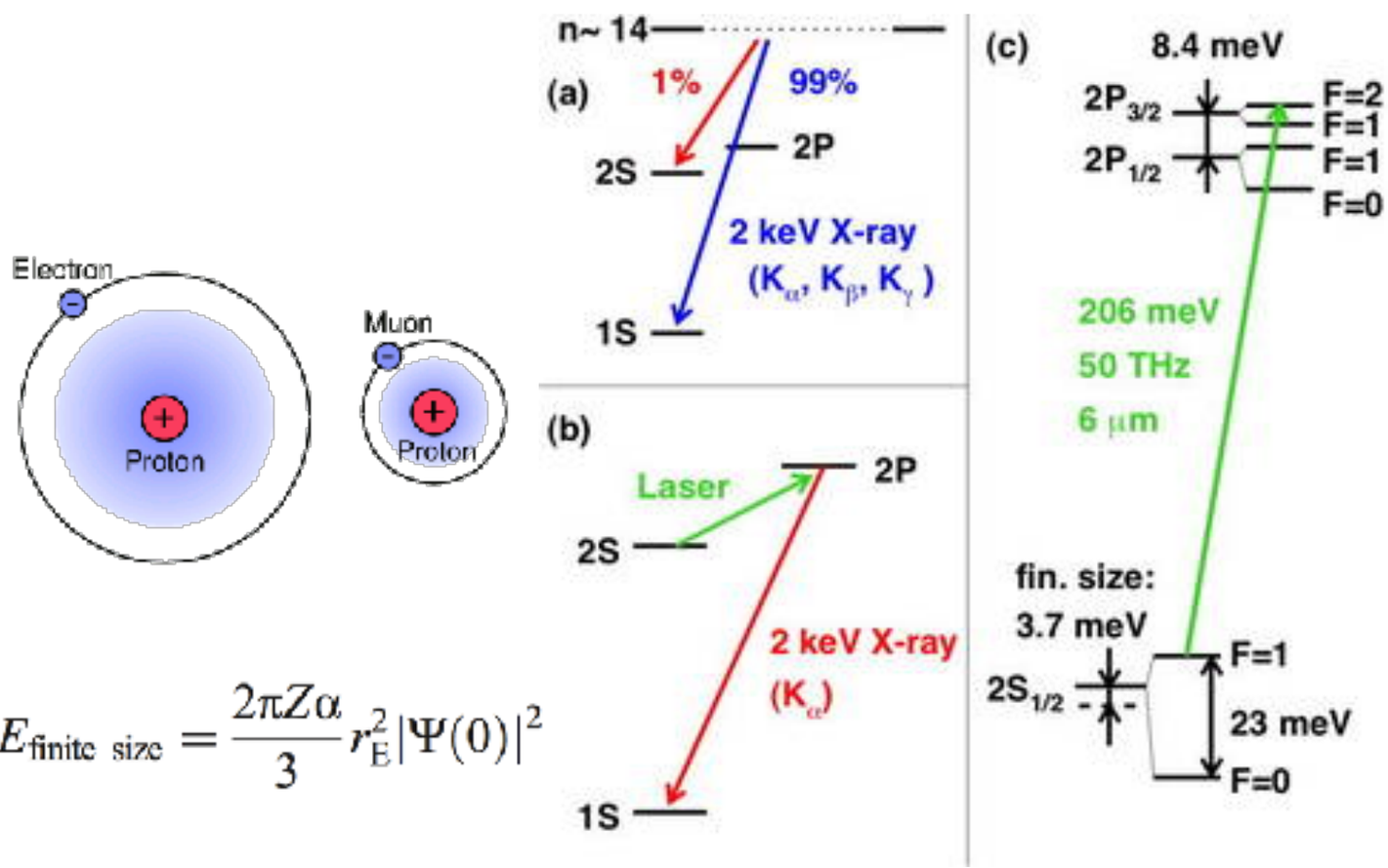
No focusing
⇒ Any momentum

- Ultra-Cold Muon Beam
  - Can be contained in the detection volume w/o focusing
  - Yield?



Muonic Hydrogen

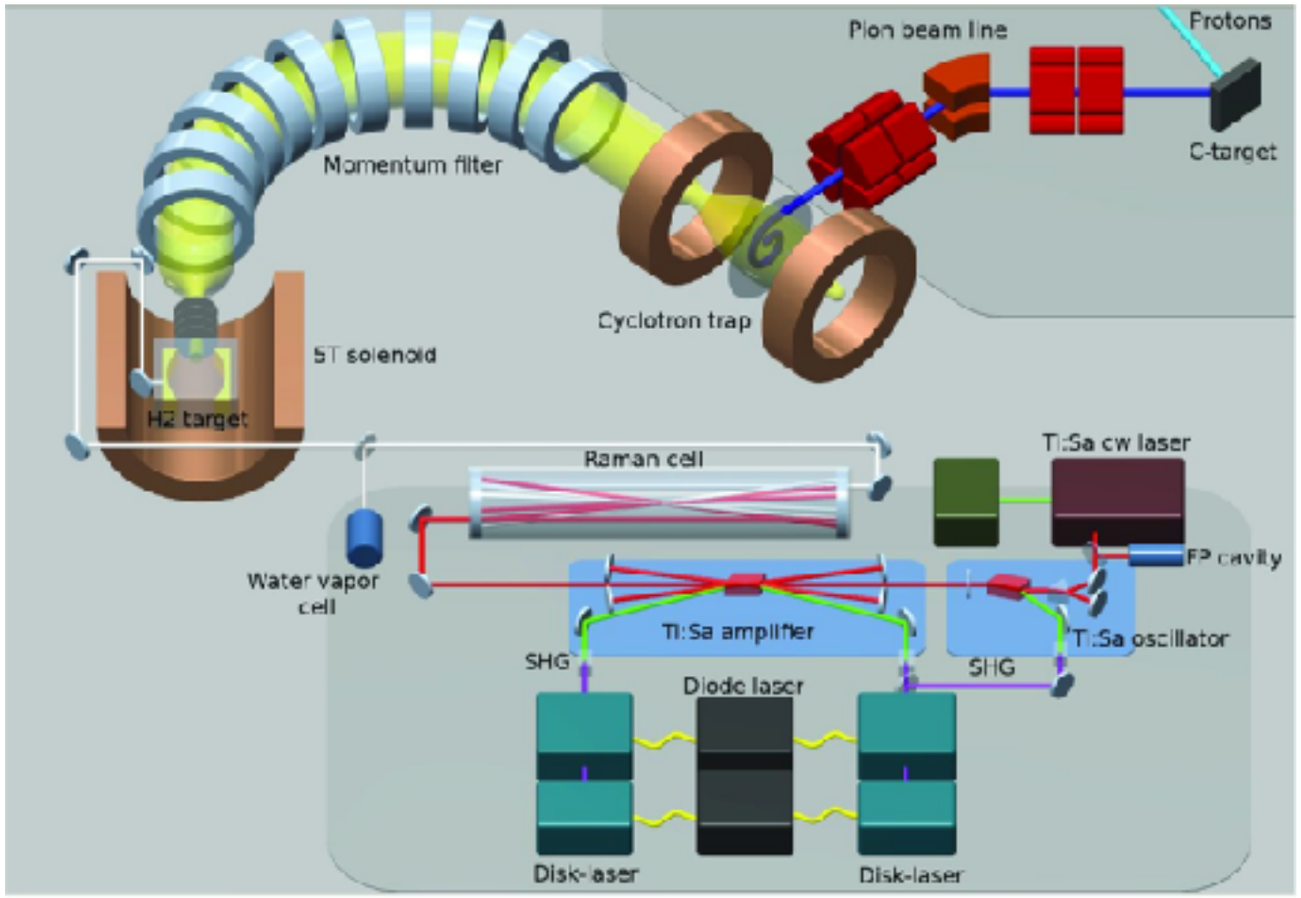
- Formation of μp (highly excited state)
- Laser excitation (2S-2P) after subsequent cascade

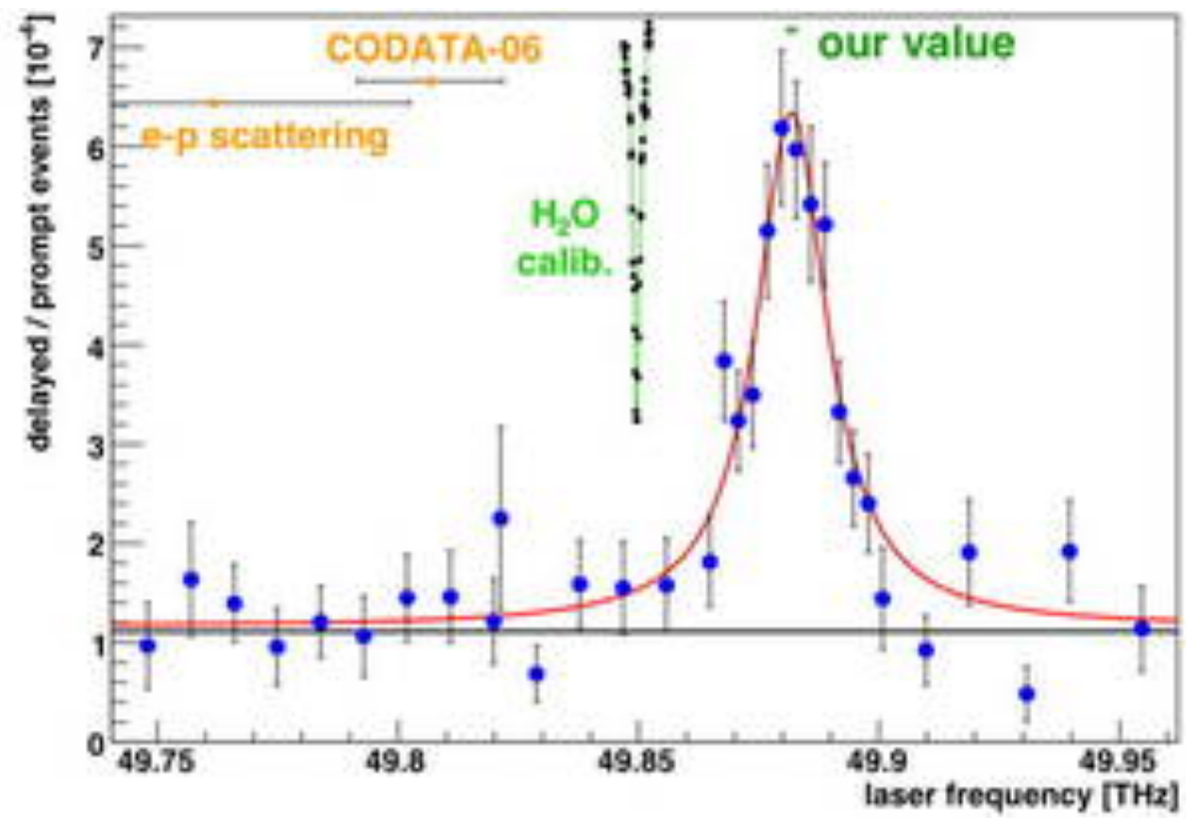


$$\Delta E_{\text{finite size}} = \frac{2\pi Z\alpha}{3} r_E^2 |\Psi(0)|^2$$

Hydrogen Charge Radius

Antognini et al, Science 2013





- ~7σ discrepancy!
  - r_p=0.84037(39) fm (muonic hydrogen lamb shift)
  - r_p=0.8775(51) fm (electron scattering, spectroscopy)

Flavor Physics with B, tau, H, and Z

KEK 大学共同利用機関法人 高エネルギー加速器研究機構
National University SOKENDAI The Graduate University for Advanced Studies
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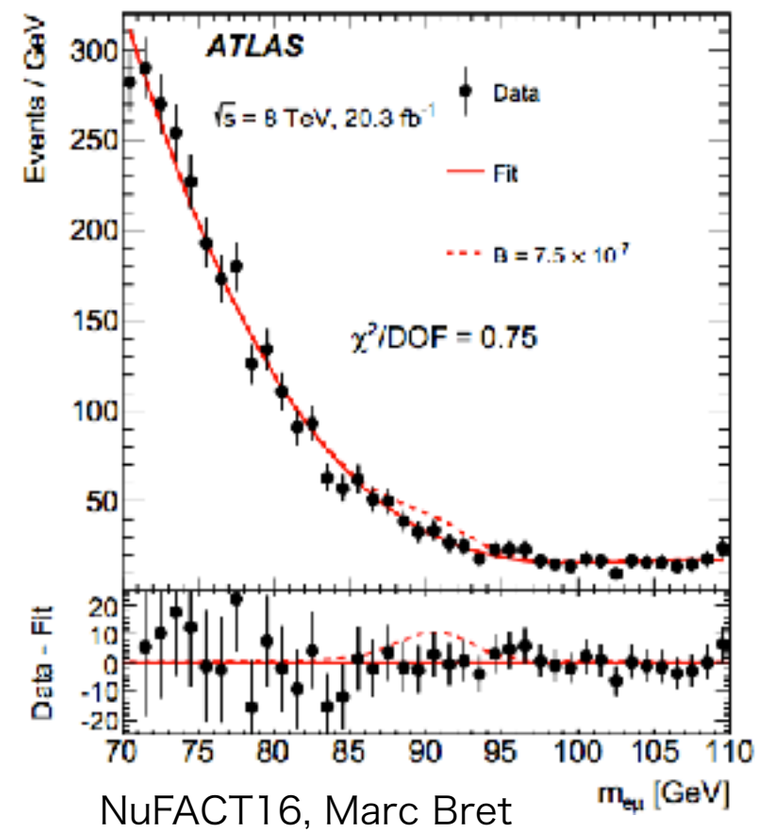
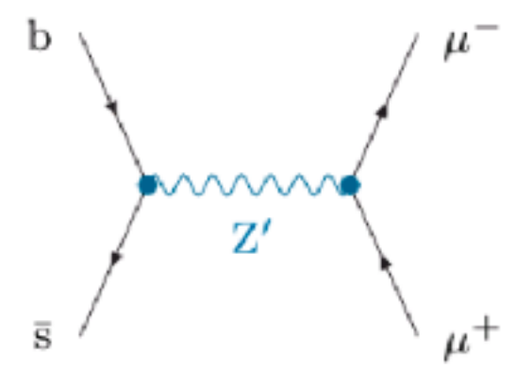
cLFV Searches and Lepton Universality Tests at Colliders

- cLFV searches
  - H/Z boson decays to e/μ,τ at LHC
  - tau lepton decays at LHC, BES III & Belle (and Belle II soon!)
- Tensions in B-Physics
  - $B^0 \to D^{(*)} \tau \nu_\tau / l \nu_l$ 3.9σ : LHCb + BaBar + Belle
  - $B^+ \to K^+ \mu\mu$ / ee 2.6σ : LHCb
  - Anomalies b → sll , esp. P'5 in B → K*$\mu\mu$ @ LHCb 3.4σ & Belle 2.1σ
    - New physics effect or long distance charm loop?



NuFACT16, Marc Bret

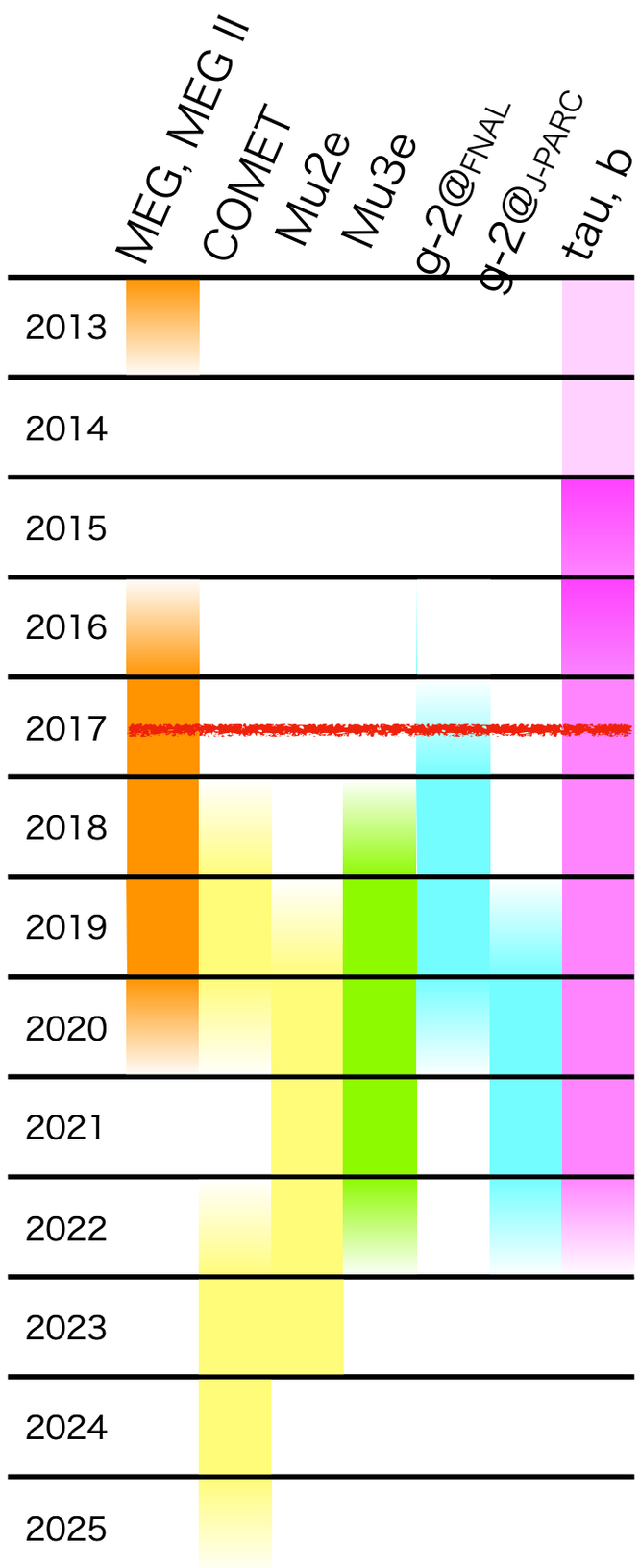


arXiv:1604.08221

Z' models

Buras et al;
Altmannshofer,Gori,Pospelov,Yavin;
Crivellin,D'Ambrosio,Heeck; ...

Summary



- Flavor & precise physics experiments
  - Complementary approach to High-Energy Frontier Experiments
- cLFV experiments using muons.
  - New experiments (MEG II, Mu3e, COMET, Mu2e, DeeMe) are in preparation
- Precise measurements using muons
  - FNAL g-2, J-PARC g-2/EDM
  - Proton radius
- New results from LHC experiments and BES III & Belle