Lepton Flavor Physics with muon beam

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Outline

- Charged Lepton (Flavor) in the Standard Model
- New physics in Charged Lepton Flavor Violating (cLFV) processes
- cLFV searches using muons (and taus)
- muon g-2/EDM measurements
- Summary

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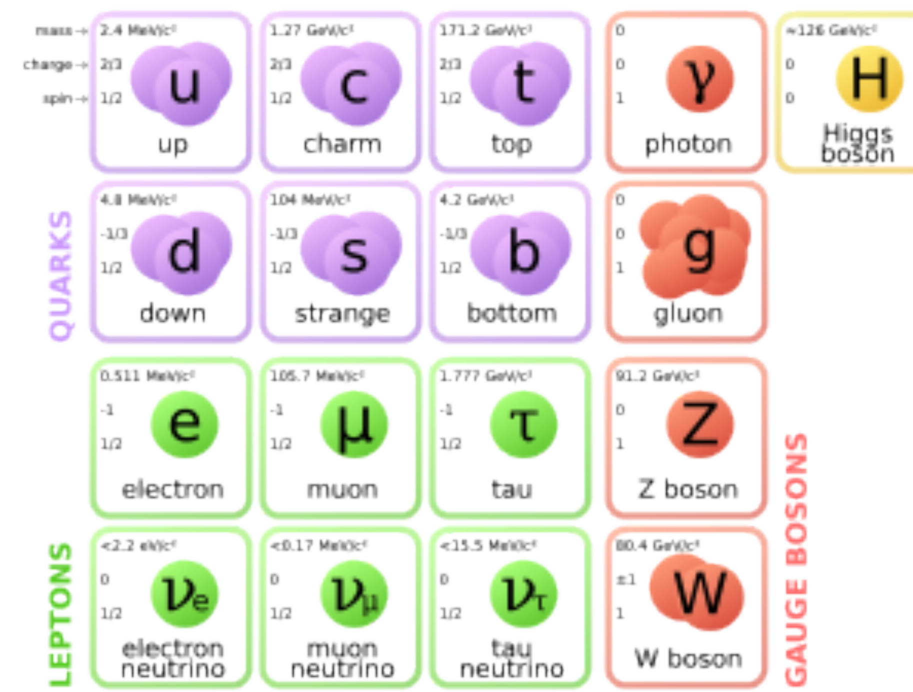
1st Conference on Charged Lepton Flavor Violation in Lecce 6-8/May/2013

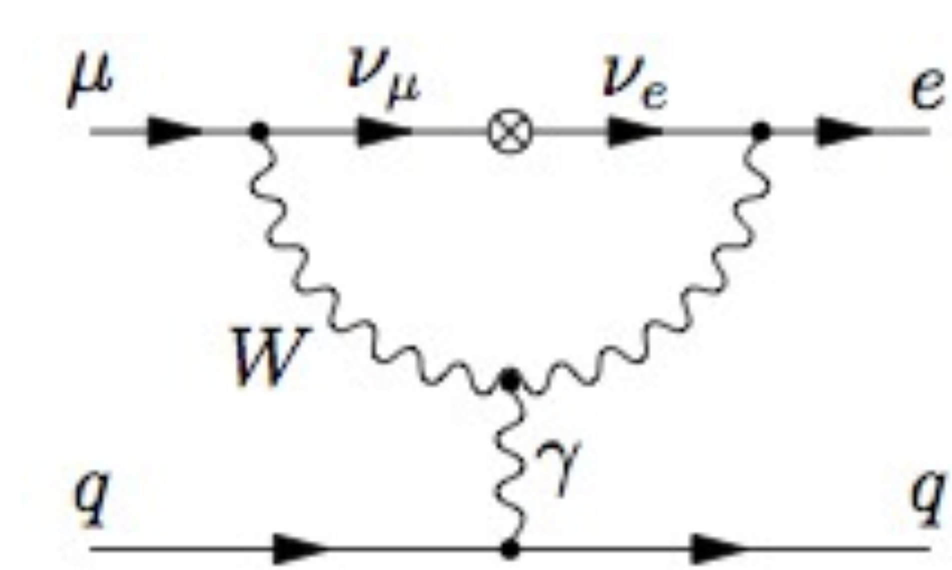
http://clfv2013.le.infn.it/

Charged Lepton Flavor in SM

- Precise measurement of charged lepton behavior contributed to establish the SM
- No observation of "exotic decay mode"
  - Concept of Generation (Flavor)
- Lepton flavor transition is strictly forbidden
- Neutrino Oscillation has been observed
  - ν oscillation + SM

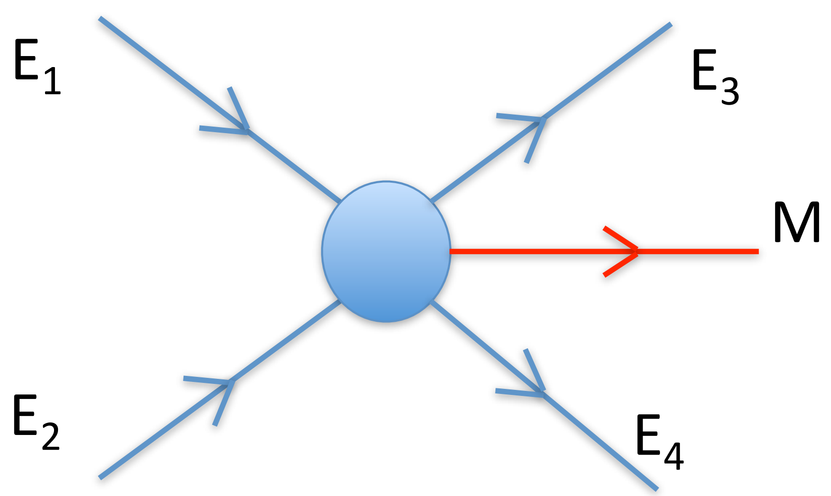


wiki



Role of low-energy charged lepton physics in LHC/ILC era

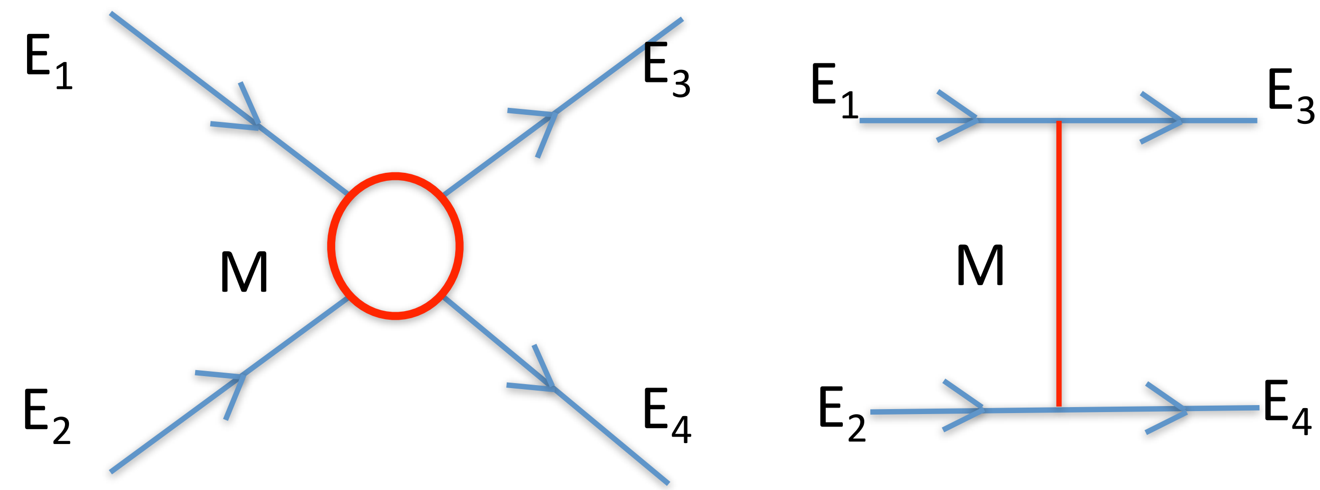
- Direct search
  (Energy Frontier)



$E_1+E_2 > M$~$O(>100GeV)$

- LHC, ILC
  - Higher energy for heavier new particle

- Indirect search
  (Intensity Frontier)



$E_1+E_2=E_3+E_4 <M$

- Charged LFV/g_μ-2
  $L = L_{SM} + L_{BSM}$
  "Slight" difference from SM prediction

Charged Lepton Tools to investigate beyond SM

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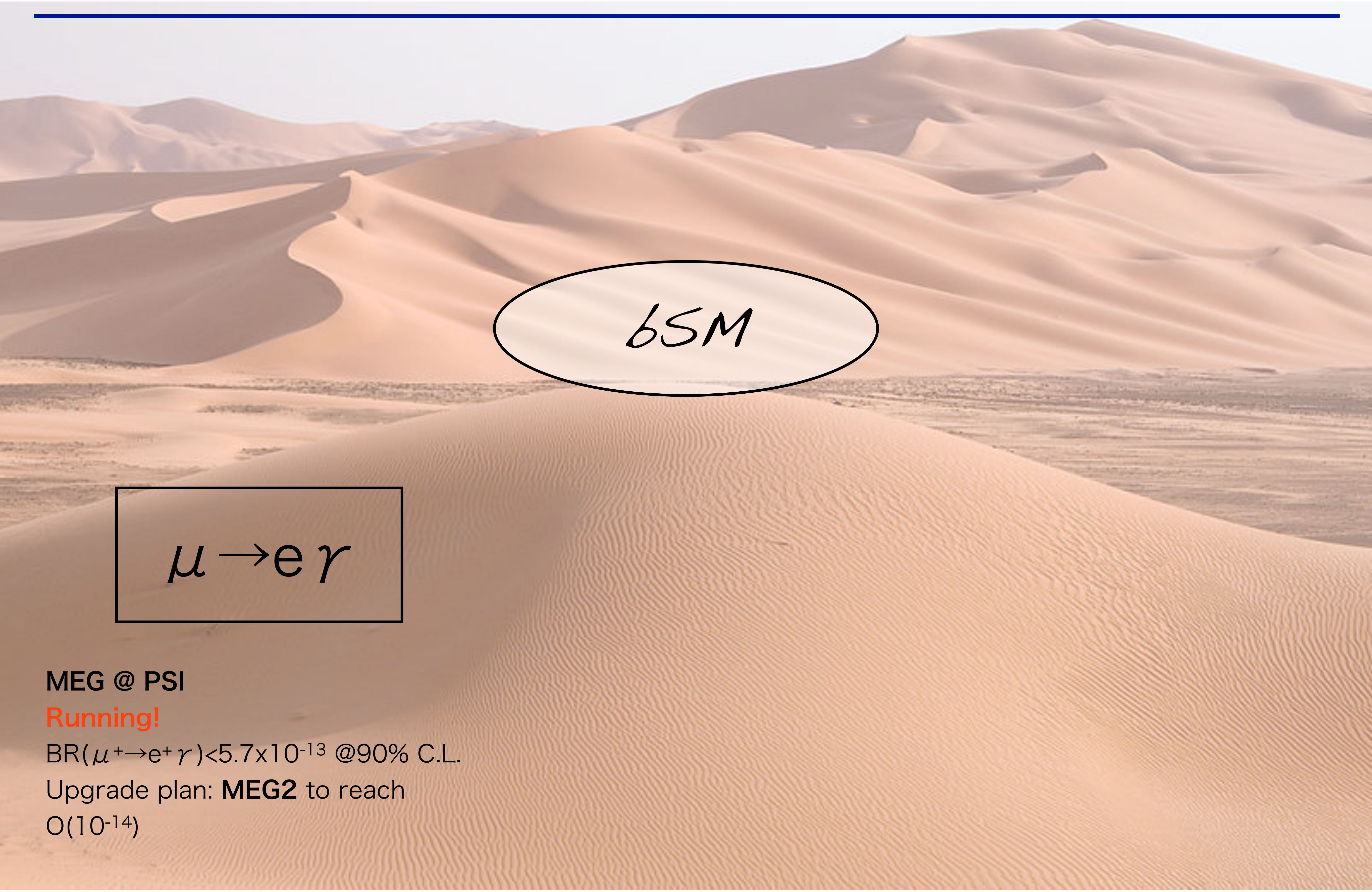

MEG @ PSI

Running!

BR($\mu^+ \rightarrow e^+ \gamma$)<$5.7 \times 10^{-13}$ @90% C.L.

Upgrade plan: **MEG2** to reach $O(10^{-14})$

Charged Lepton Tools to investigate beyond SM

bSM

$\mu \rightarrow e \gamma$

$\mu \rightarrow e$ conversion

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SINDRUM II @ PSI

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COMET Phase I&II @ J-PARC, O(10^{-14}) & O(10^{-16})

Mu2e @ FNAL O(10^{-16})

DeeMe @ J-PARC O(10^{-14})

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BR($\mu^+ \rightarrow e^+e^+e^-$)<10^{-12} @90% C.L.
mu3e IA / IB @ PSI**,** O(10^{-15})
II @ PSI O(10^{-16})

Charged Lepton Tools to investigate beyond SM

$\tau \to \mu \gamma$

$\tau \to e \gamma$

BaBar
BR($\tau \to \mu \gamma$)<4.4×10^{-8} @90% C.L.
BR($\tau \to e \gamma$)<3.3×10^{-8}@90%C.L.
Belle analysis in progress
Belle II, O(10^{-9})
(BR($\tau \to \mu\mu\mu$) ~O(10^{-10}))

bSM

$\mu \to e \gamma$

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(BR($\tau \to \mu \mu \mu$) ~O(10^{-10}))

bSM

g_μ-2

and EDM

E821 @ BNL

a_μ^{exp} -a_μ^{SM} = +3.3 σ

d_μ < 2.7×10^{-19} ecm (90%C.L.)

g-2/EDM@J-PARC

0.1 ppm for g-2 / O(10^{-21}) for EDM

g-2 @ FNAL

20 times statistics, 4 times better uncertainty

$\mu \to e \gamma$

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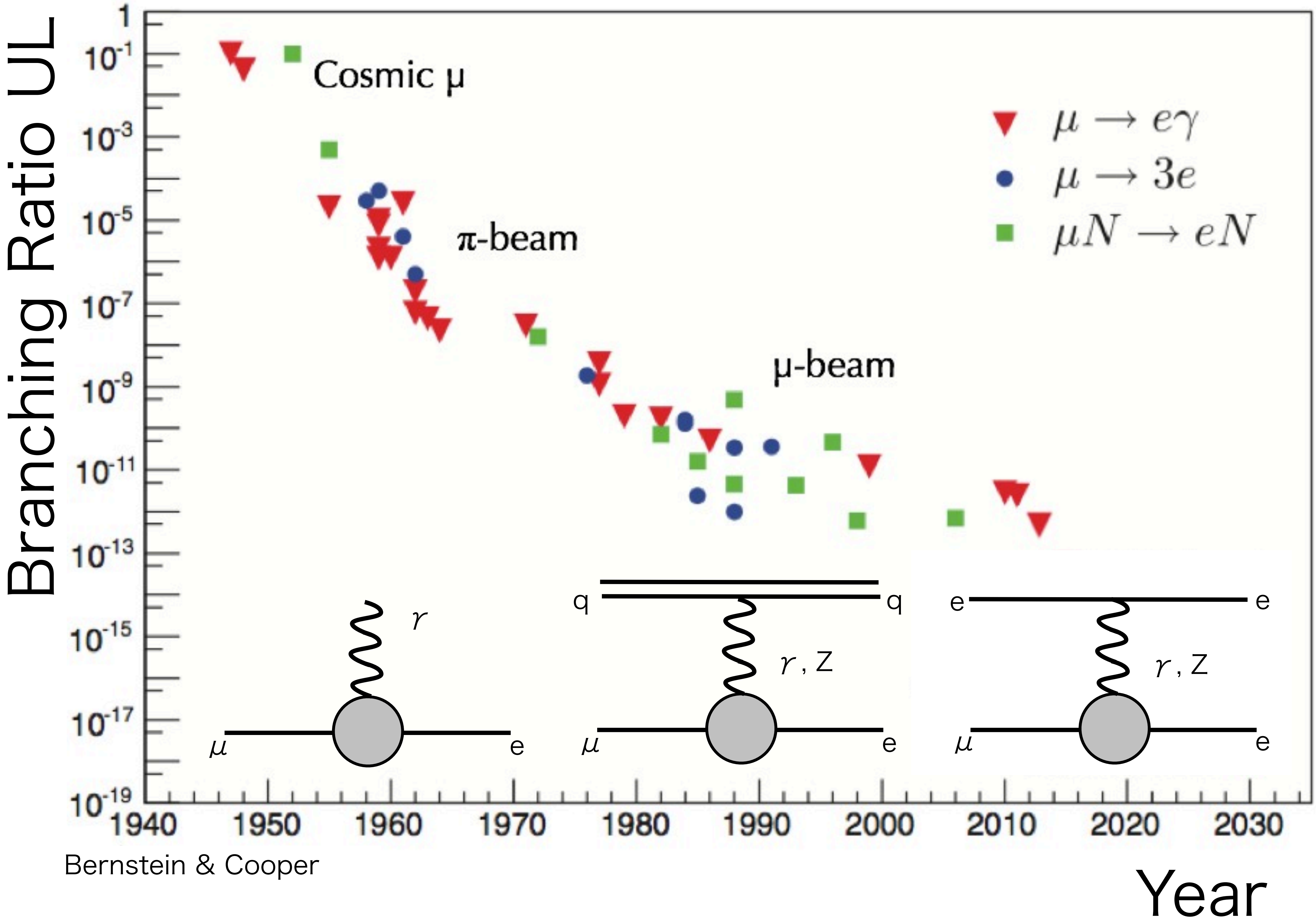
II @ PSI O(10^{-16})

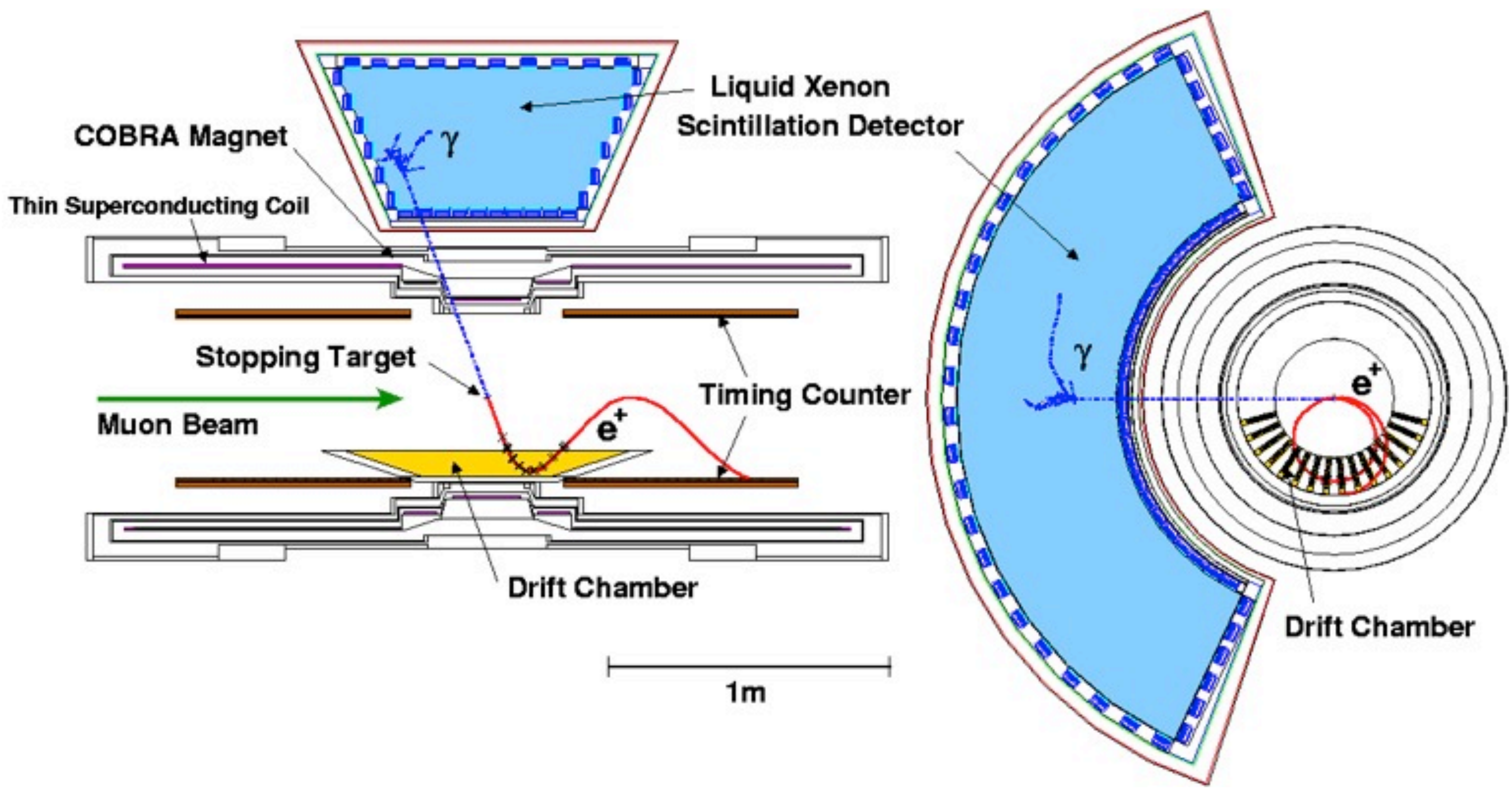
cLFV searches using muons



Bernstein & Cooper

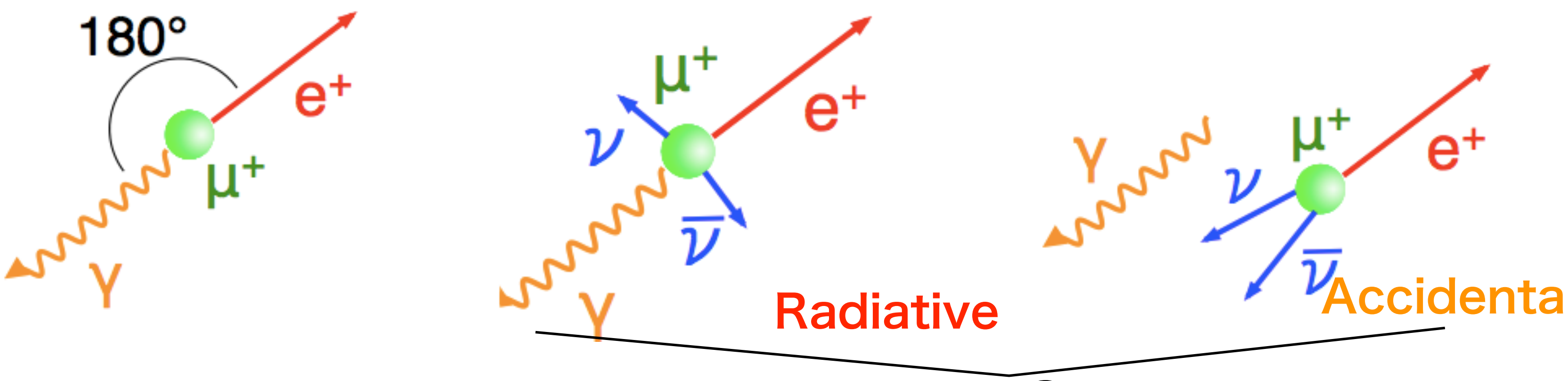
MEG at PSI

- Only running cLFV search experiment using muons
- $\mu \to e\gamma$ search with a target sensitivity of 10^{-13}
- PSI DC muon beam ($<10^8 \mu^+$/sec)
- Liquid Xe photon detector
- COBRA positron spectrometer



MEG collaboration, PRL 110(2013)201801

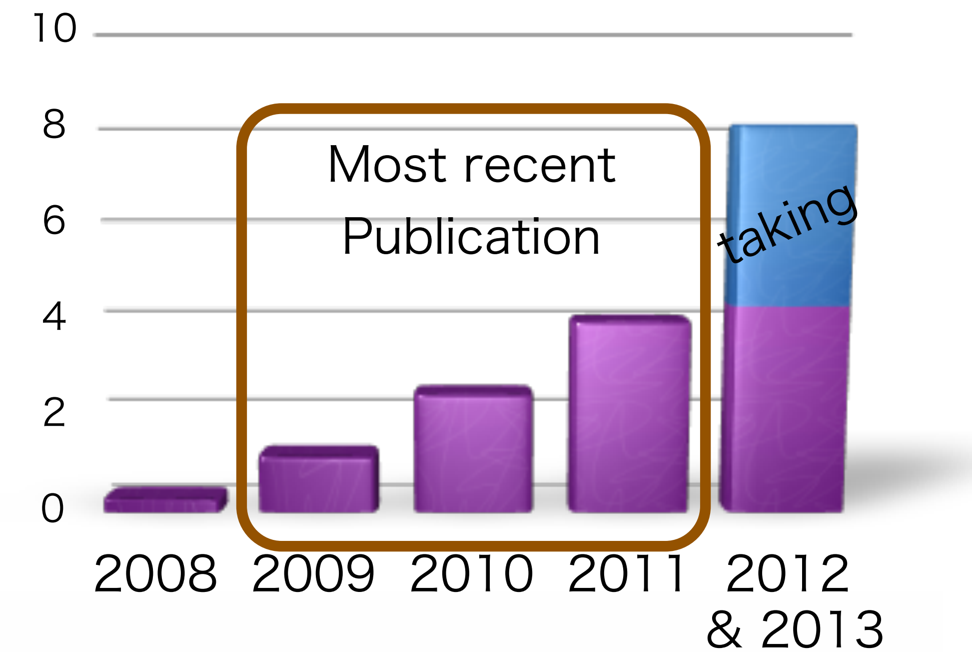
MEG Result



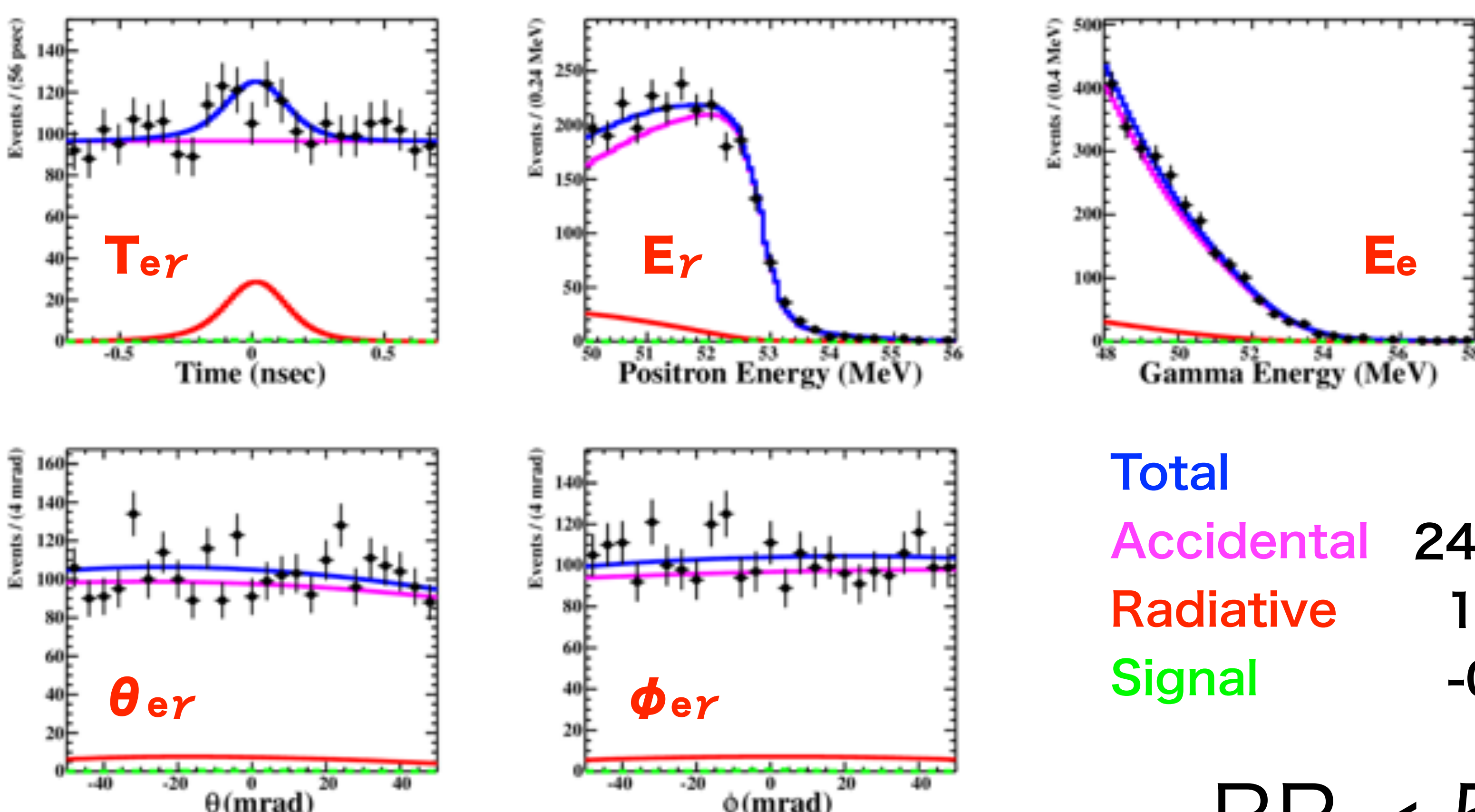
signal

BG

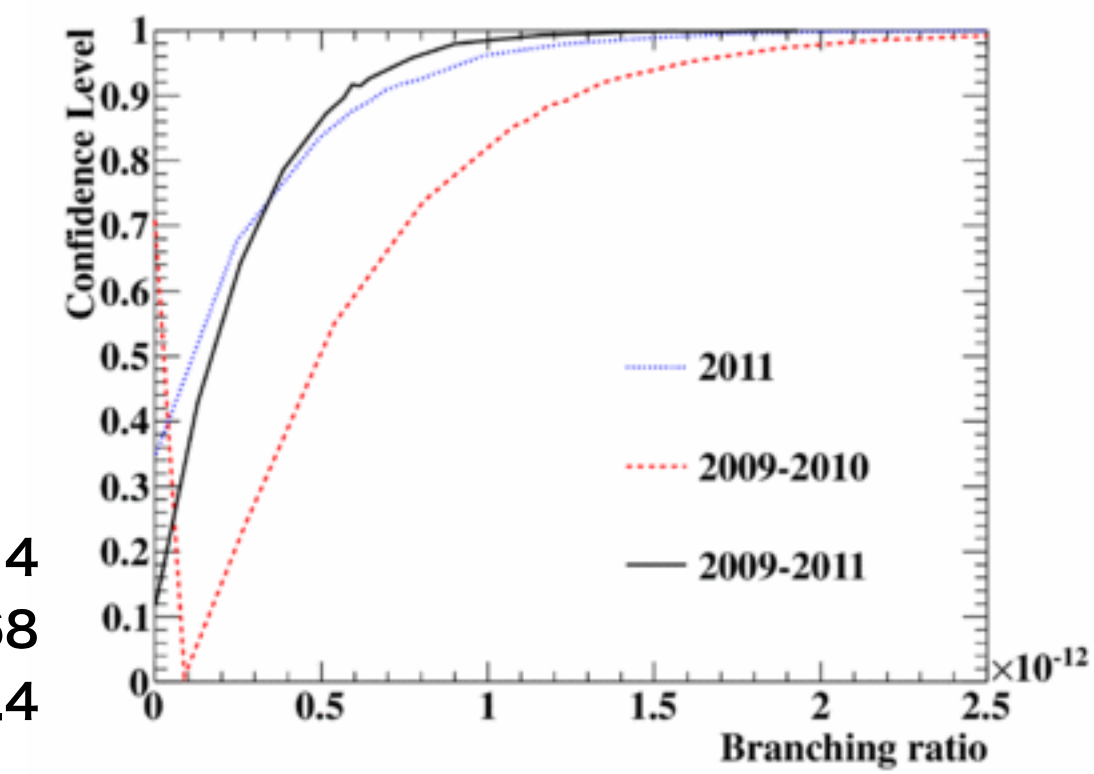
k factor=SES^{-1}(x10^{12})



2009-2011 combined data

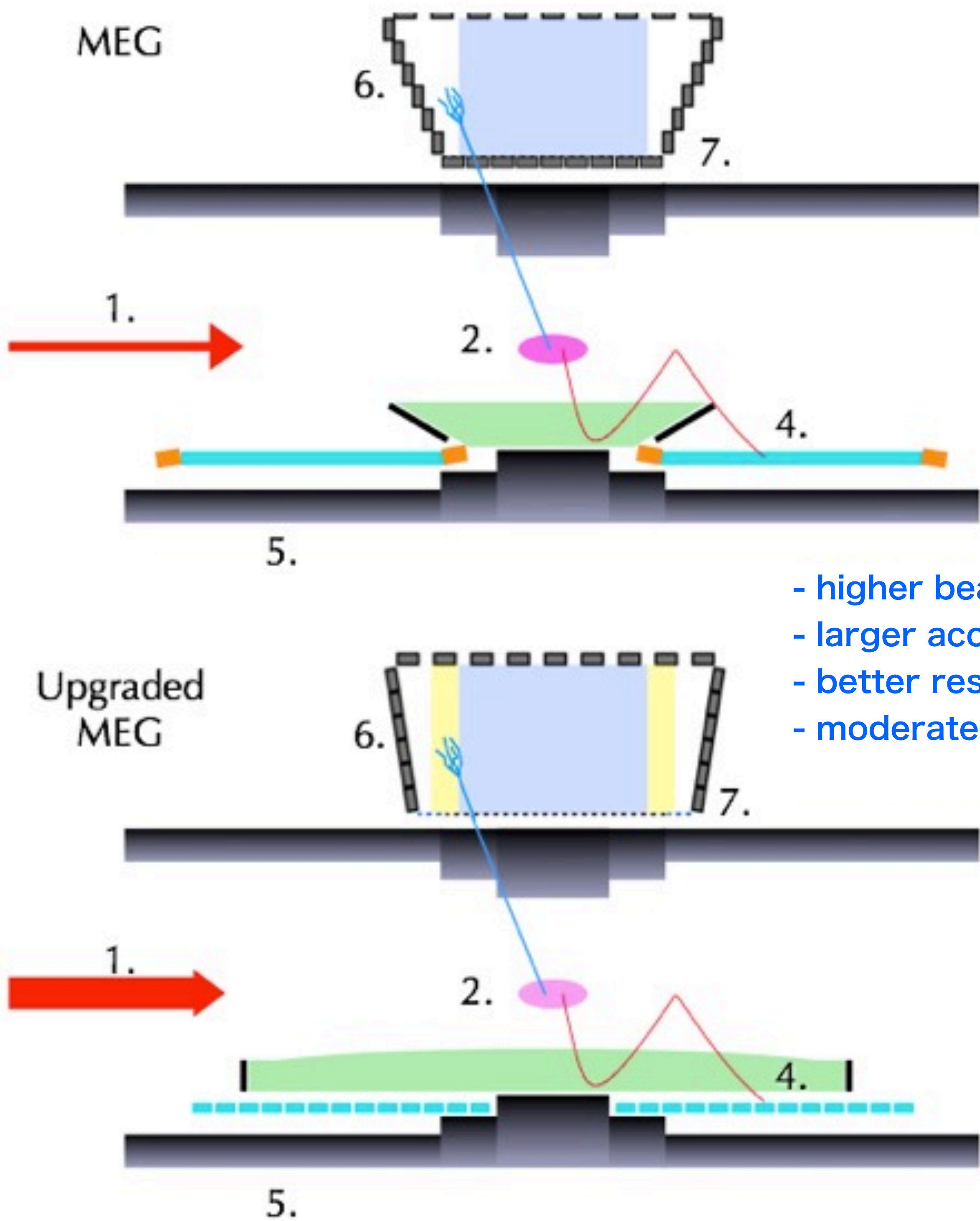


Total	
Accidental	2414
Radiative	168
Signal	-0.4

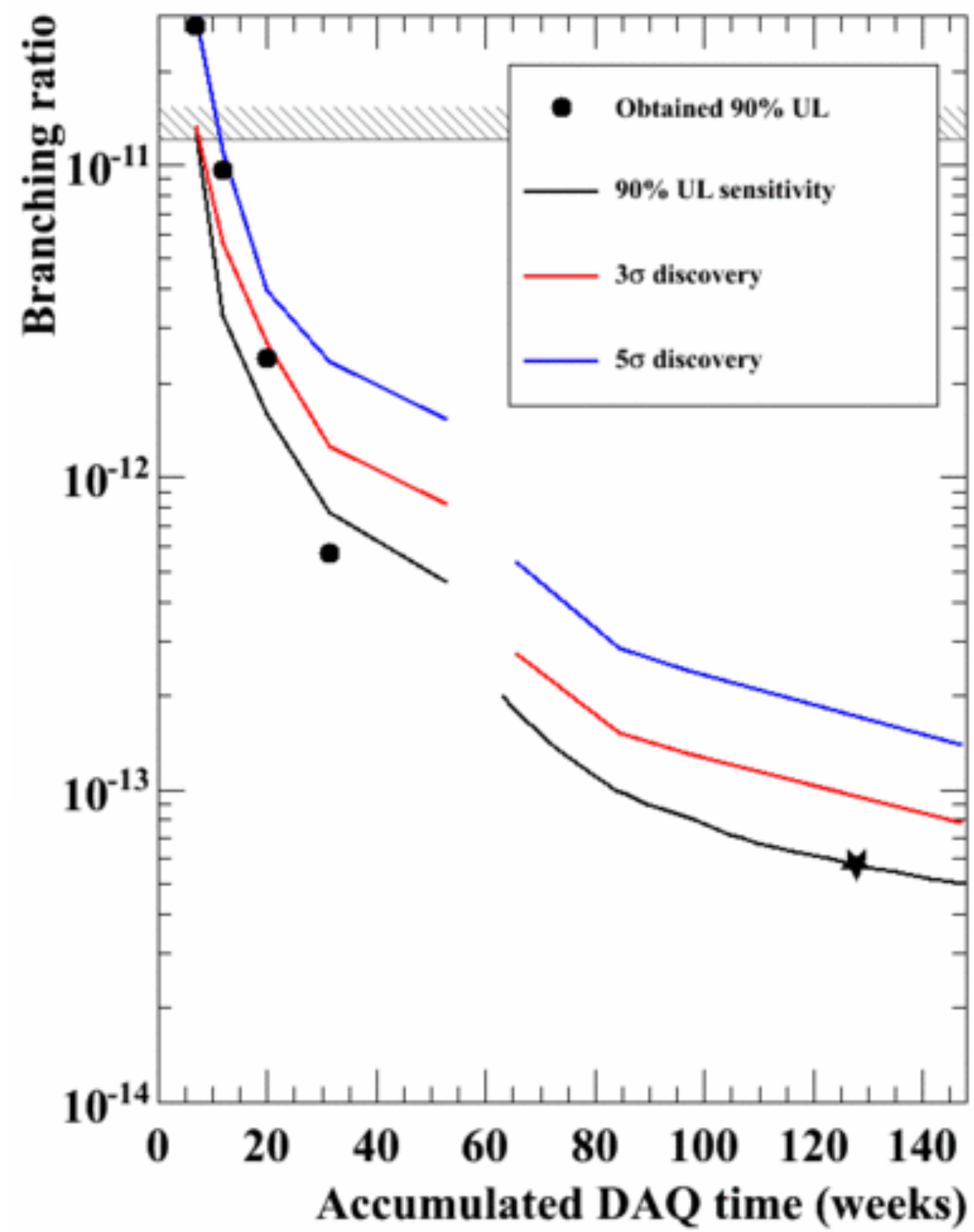


BR < 5.7x10^{-13} 90% C.L.

MEG Upgrade Plan



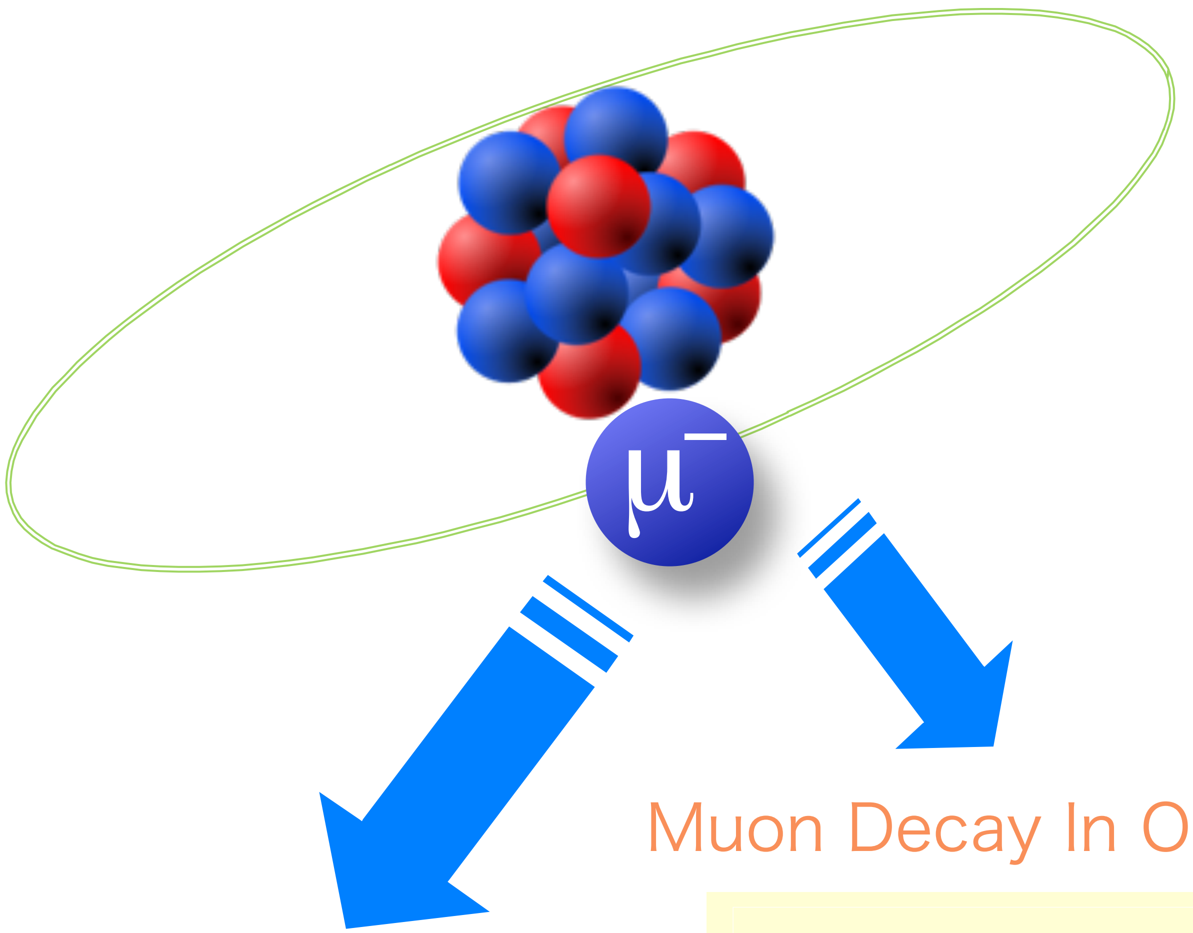
- higher beam rate
- larger acceptance
- better resolutions
- moderate cost



mu-e conversion

COMET
mu2e
DeeMe

$\mu \rightarrow$e search using pulsed muon beam



Muon Decay In Orbit

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

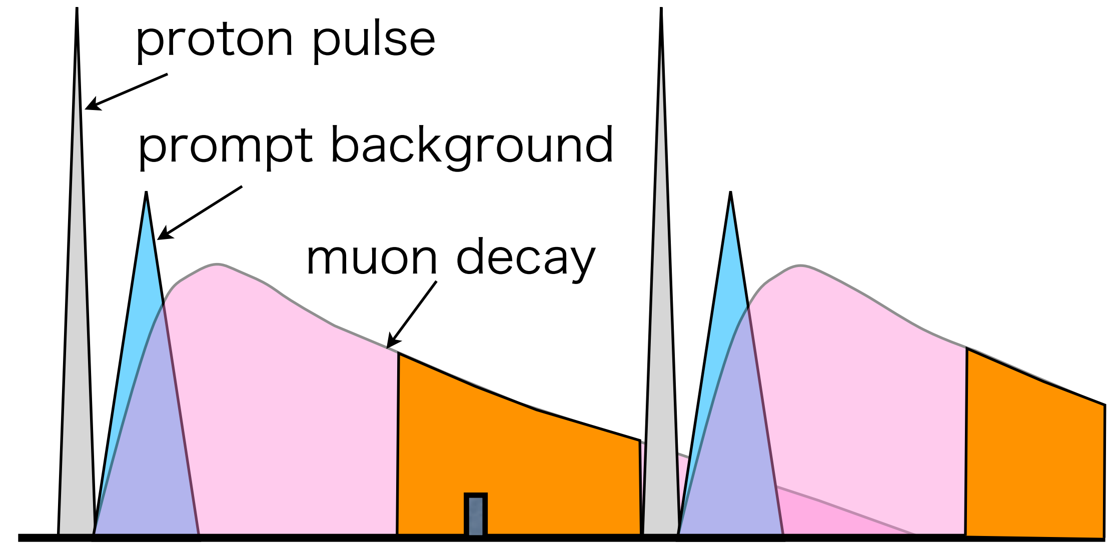
nuclear muon capture

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

μ-e conversion

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

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



π^-+(A,Z)→(A,Z-1)*, (A,Z-1)* → γ+(A,Z-1), γ→e^+e^-

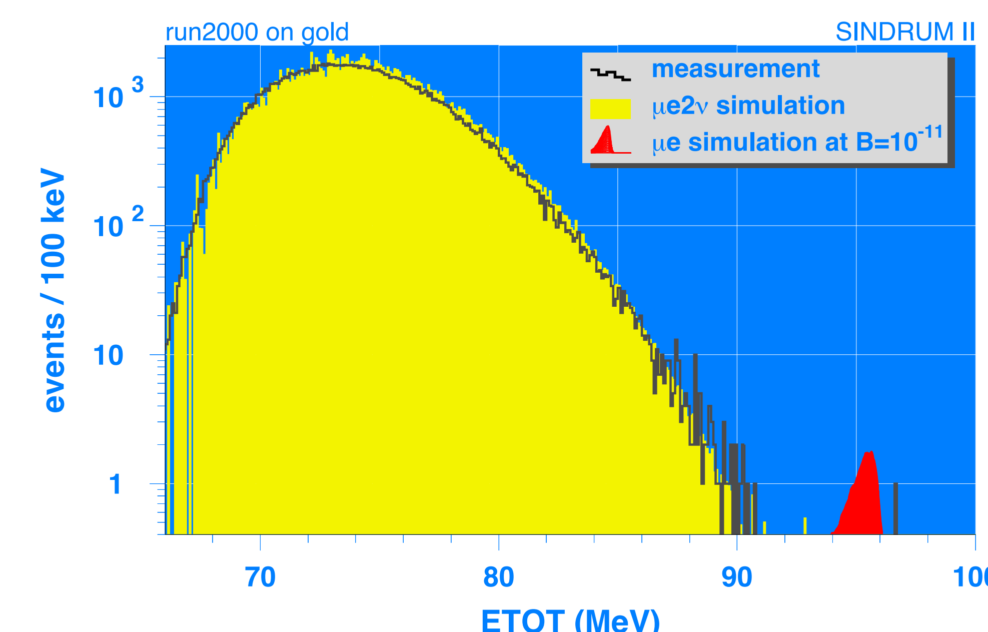
Prompt timing

Other sources

μ^- decay-in-flight, e^- scattering, neutron streaming

$$R_{ext} = \frac{\text{number of proton between pulses}}{\text{number of proton in a pulse}}$$

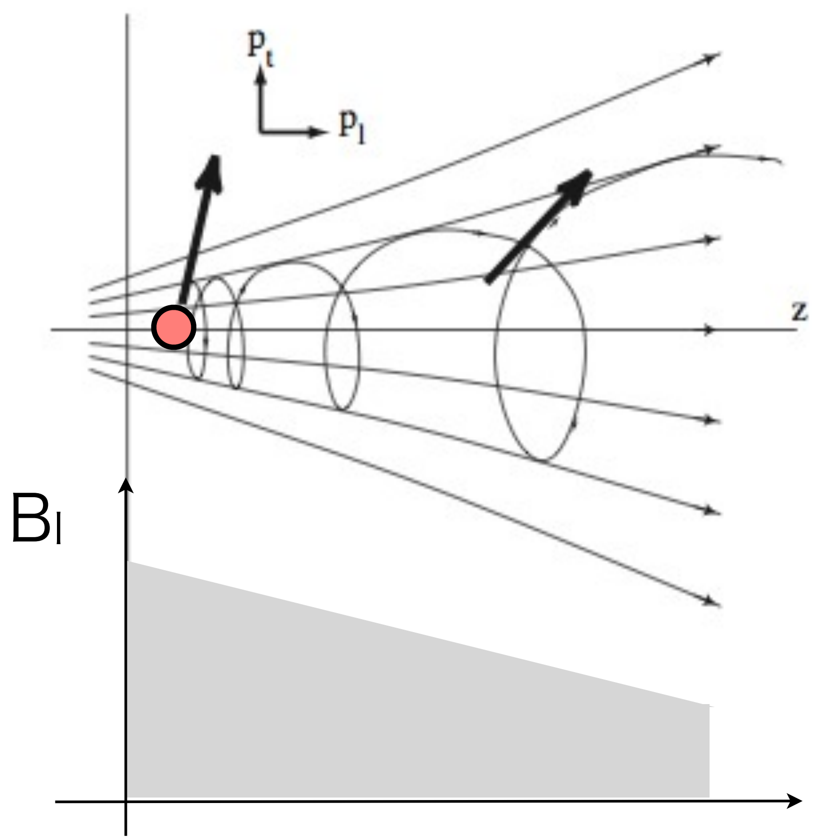
SINDRUM II BR[μ^- + Au →e^- + Au] < 7 × 10^{-13}

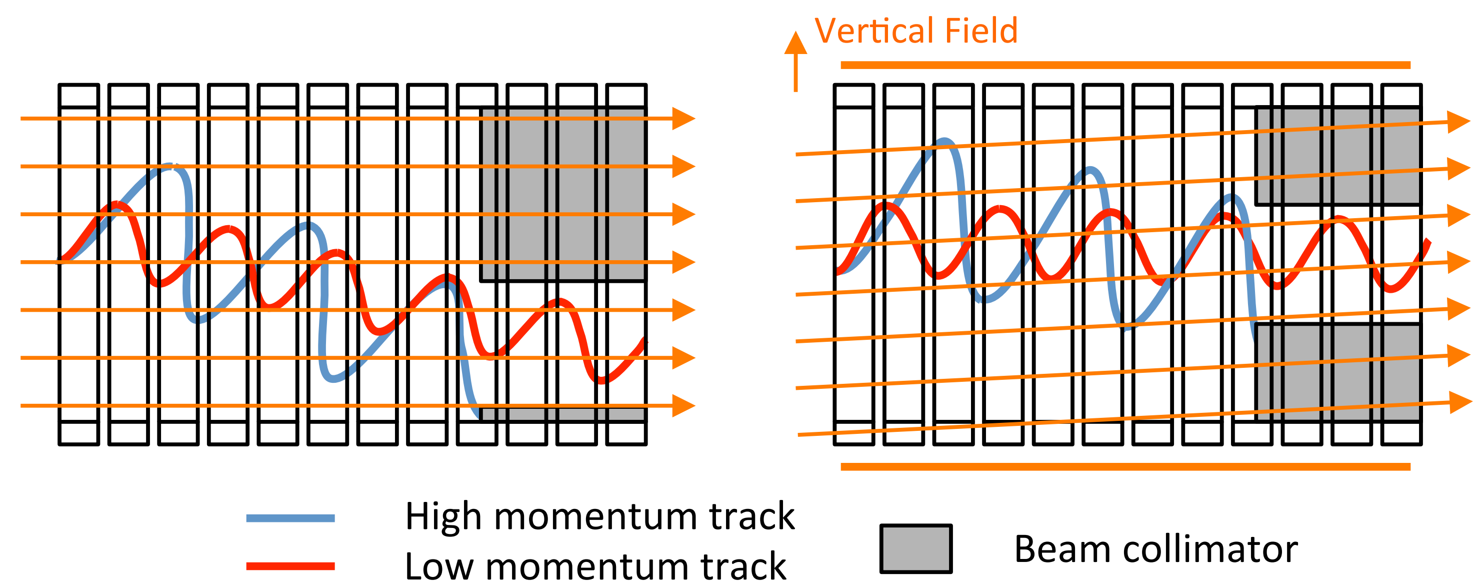


As many muons as possible!

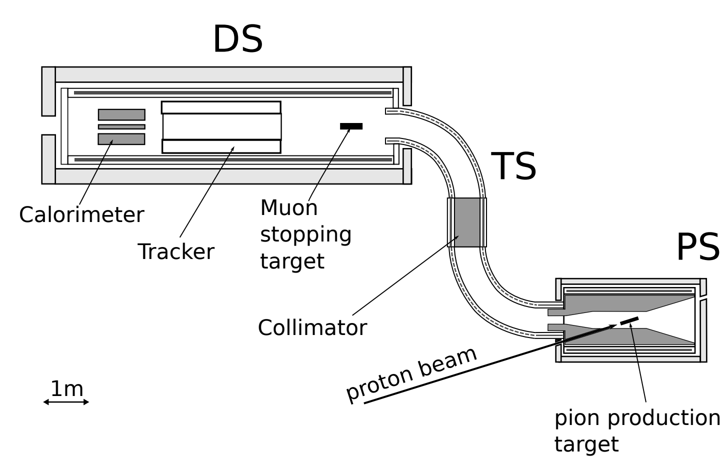
Pion/muon collection using gradient magnetic field

Muon transport with large momentum acceptance and momentum selection

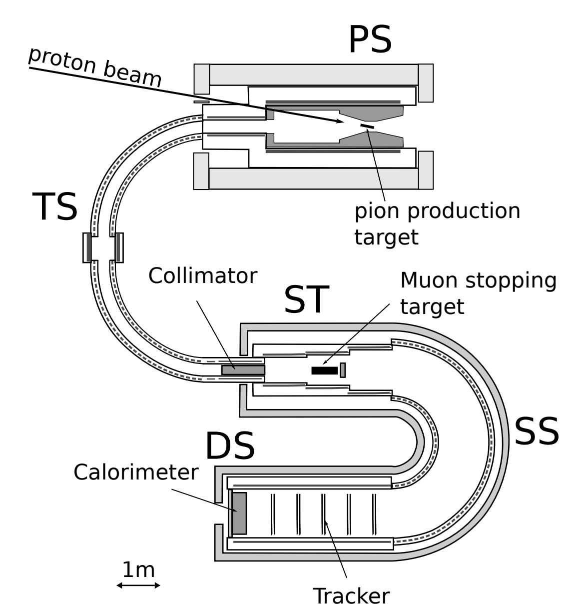




Mu2e

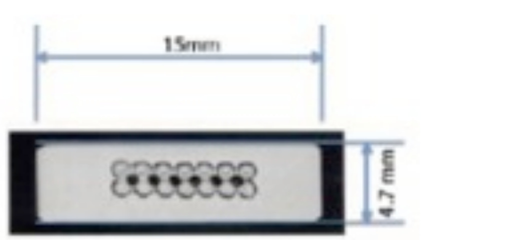


COMET



Strong Magnetic field in high radiation environment

Aluminum stabilized SC
Collaborative R&D between COMET & Mu2e

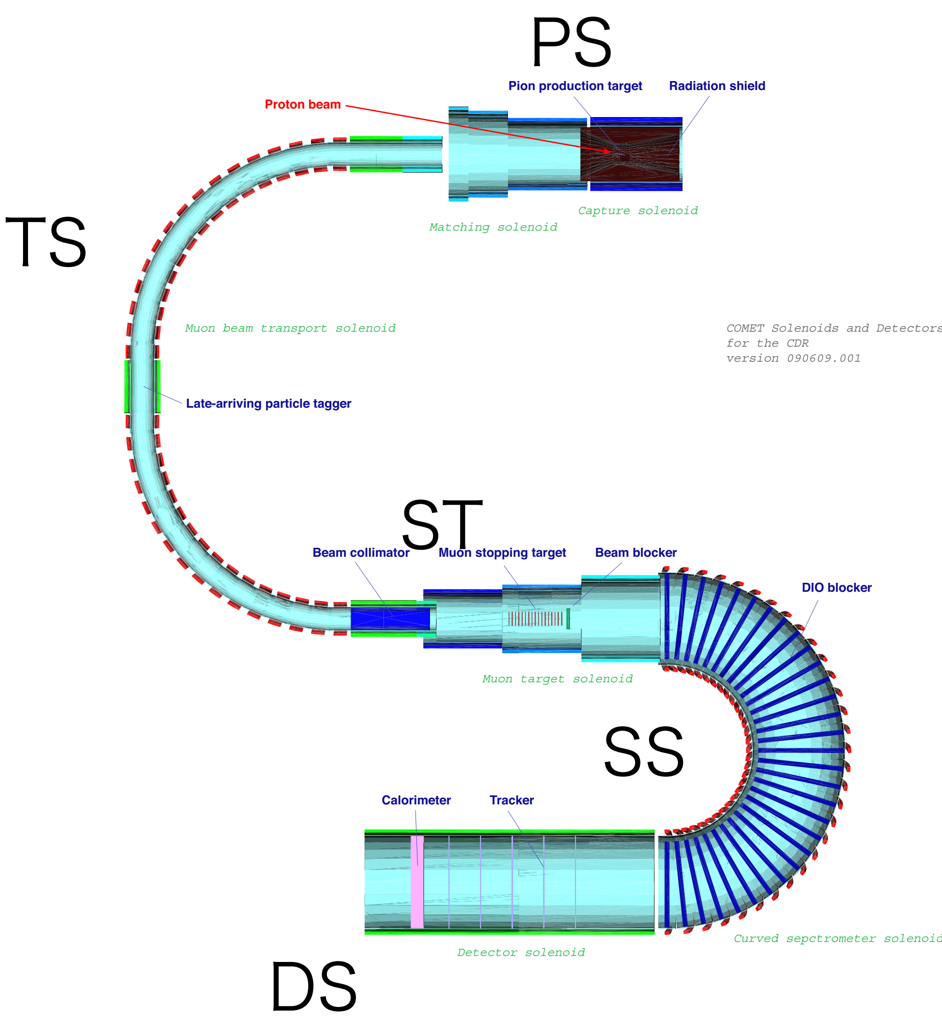


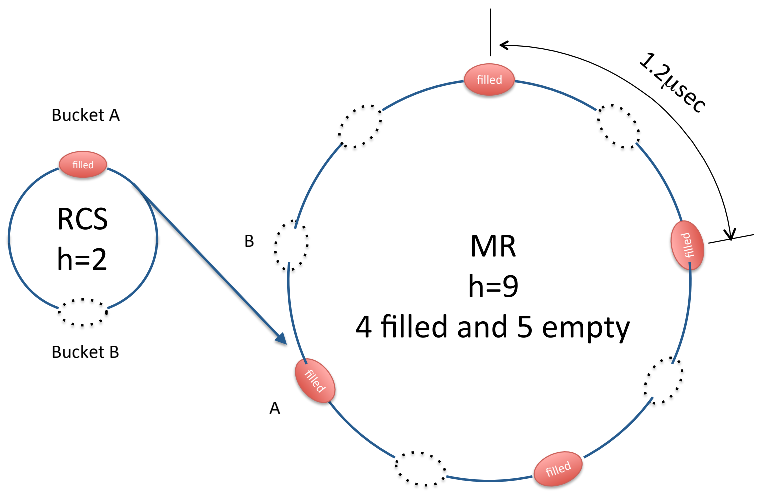
Al/Cu/NbTi : 7.3/0.9/1.0

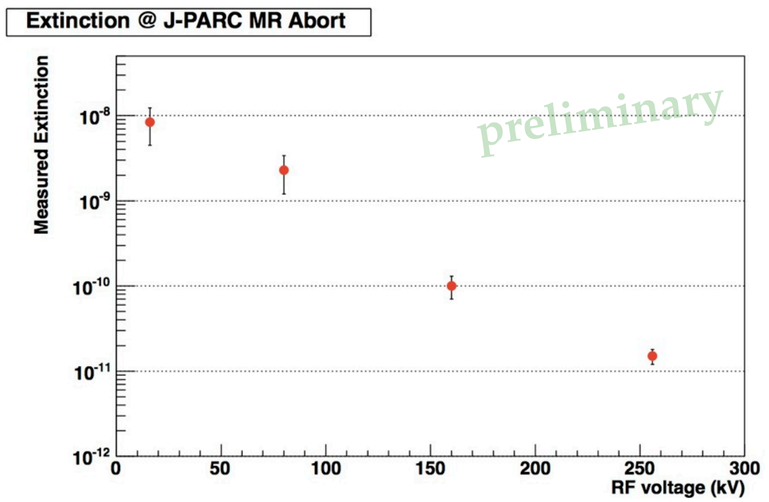
Y. Yuan WG4

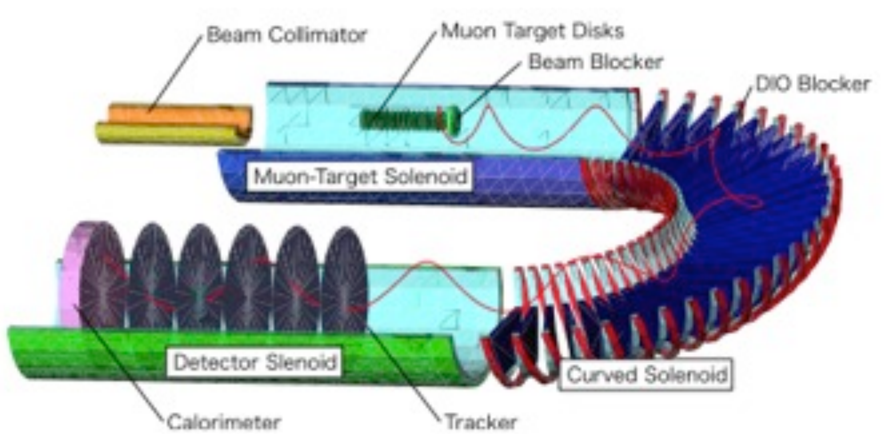
COMET at J-PARC

- J-PARC pulsed proton beam to produce pulsed muon beam
  - 8GeV, 3kW-56kW
  - Beam extinction factor study
    - 30GeV w/o extraction, $R_{ext} < 1.5\times10^{-11}$
- 32m long chain of SC solenoid magnets
  - pion collection (PS)
  - muon transport (TS)
  - muon focusing on the stopping target (ST)
  - electron momentum selection (SS)
  - electron spectrometer (DS)
- Electron spectrometer
  - 1T solenoidal field, Multi-layer straw tube tracker, crystal calorimeter



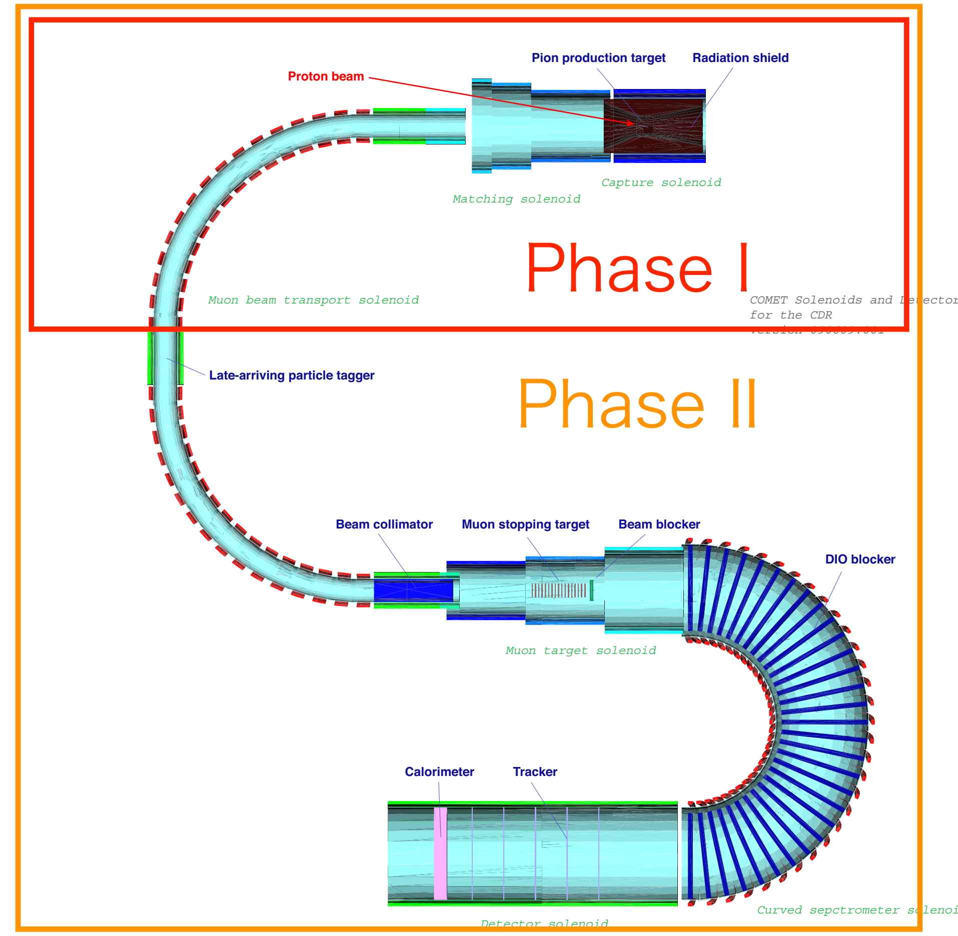




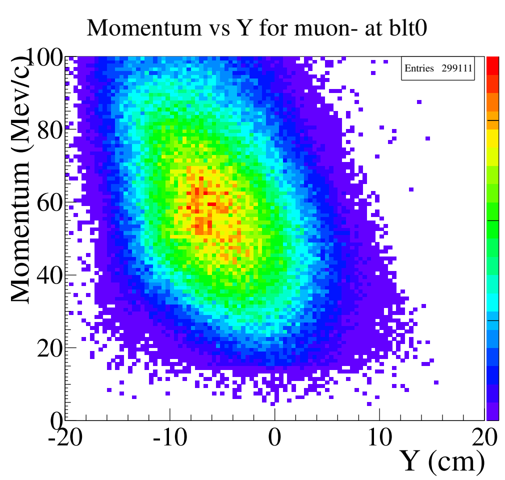


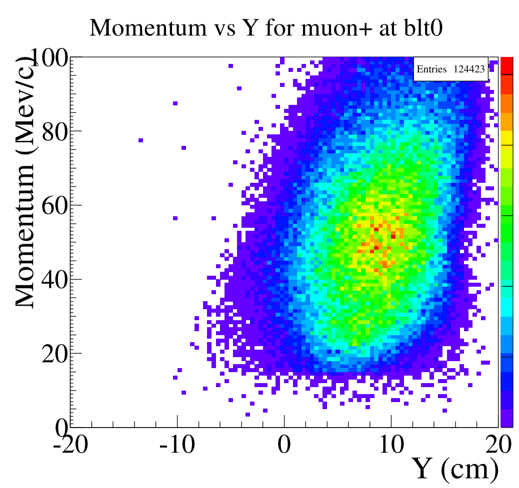
COMET Phase I & II

- Phase I
  - Beam background study and achieving an intermediate sensitivity of $<10^{-14}$
    - 8GeV, ~3.2kW, ~3 weeks of DAQ
- Phase II
  - 8GeV, ~56 kW, 1 year DAQ to achieve the COMET final goal of $< 10^{-16}$ sensitivity



μ^-

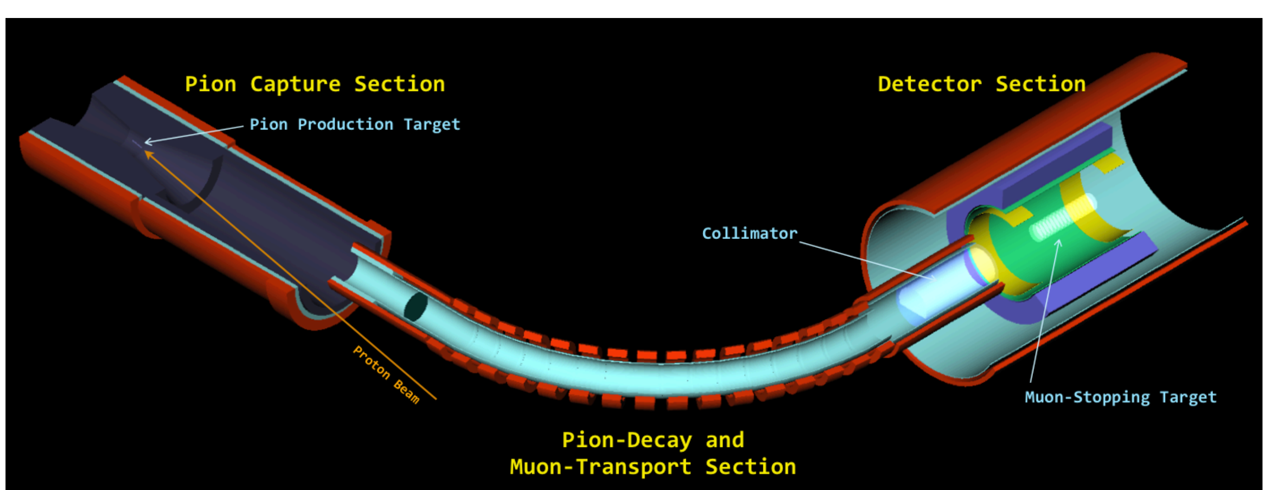


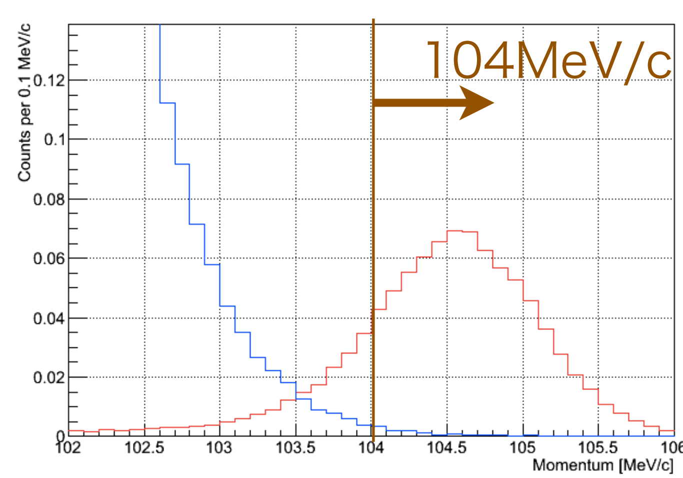


μ^+

Phase I

0.03 BG expected in 1.5×10^6 sec running time

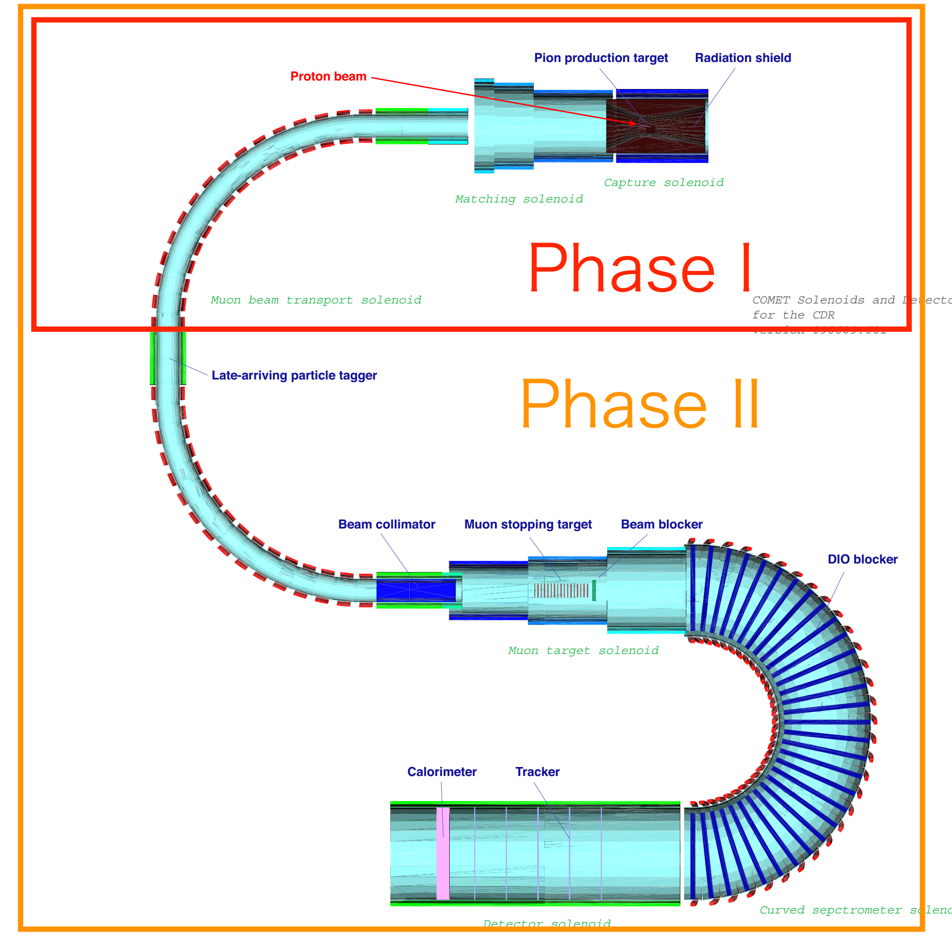


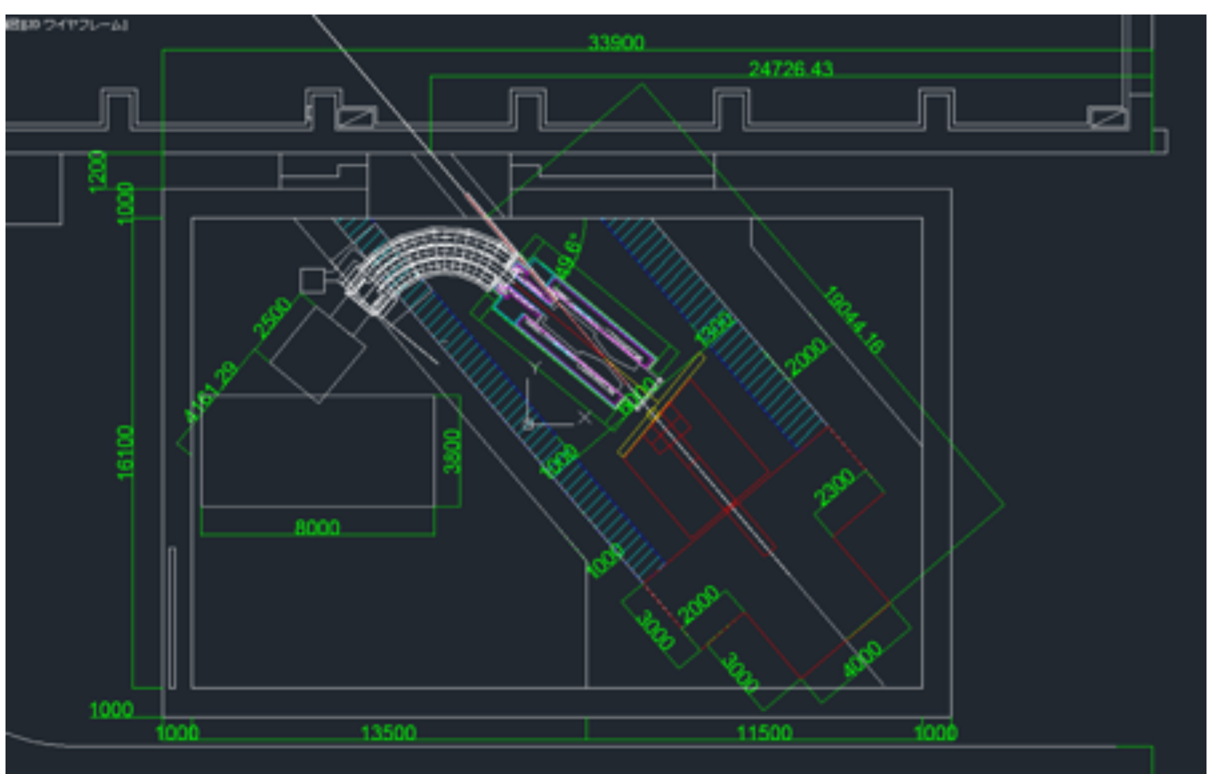


Phase I
2013-2015
Facility construction
2013-2016
Magnet construction & installation
2016
Eng. run & Physics run
Phase II
Eng. run in 2020(?)

COMET Phase I Status

- Facility construction started in 2013
  - JFY 2012 supplementary budget approved for
    - beam line & beam dump
    - (Part of) Phase I solenoid system
    - Building
- Detector R&D and design work in progress
  - JSPS funding in Osaka Univ.
  - IHEP as well !
  - Discussion in UK and other countries





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Eng. run in 2020(?)

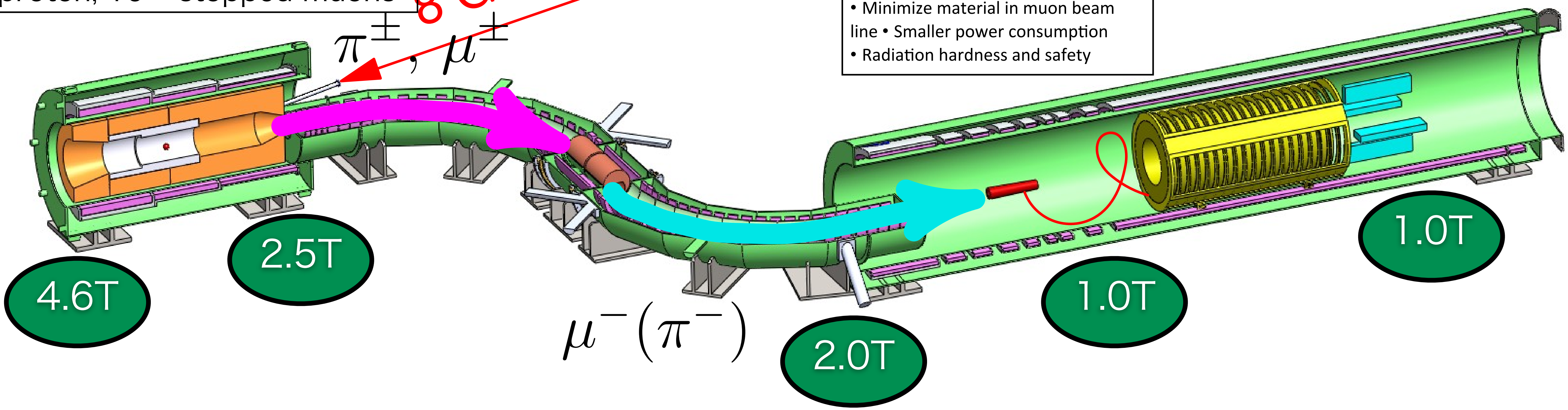
Z. You WG4

Mu2e at FNAL

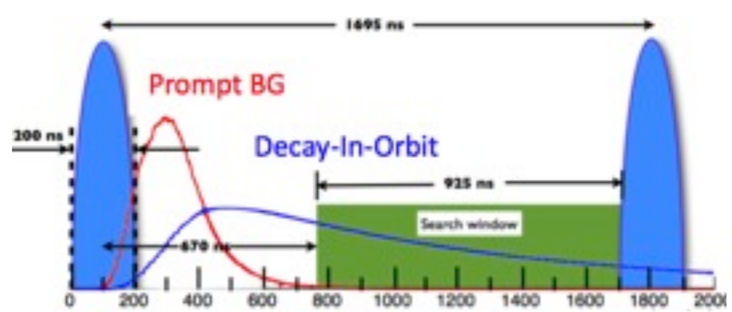
- 8GeV-8kW proton beam
- 3 years running, 4×10^{20} proton, 10^{18} stopped muons

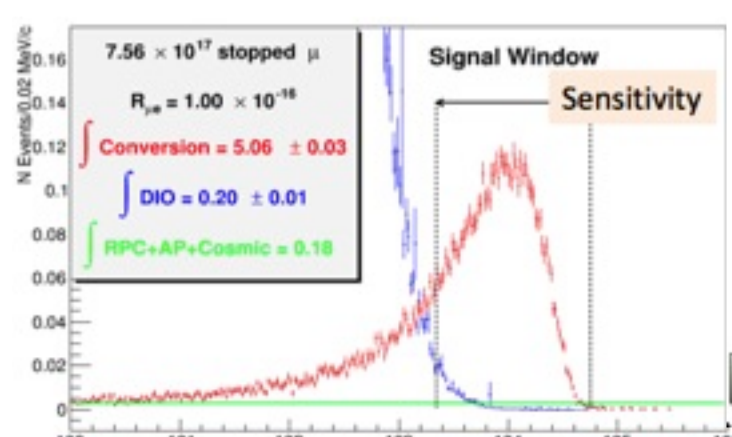
Mu2 challenges

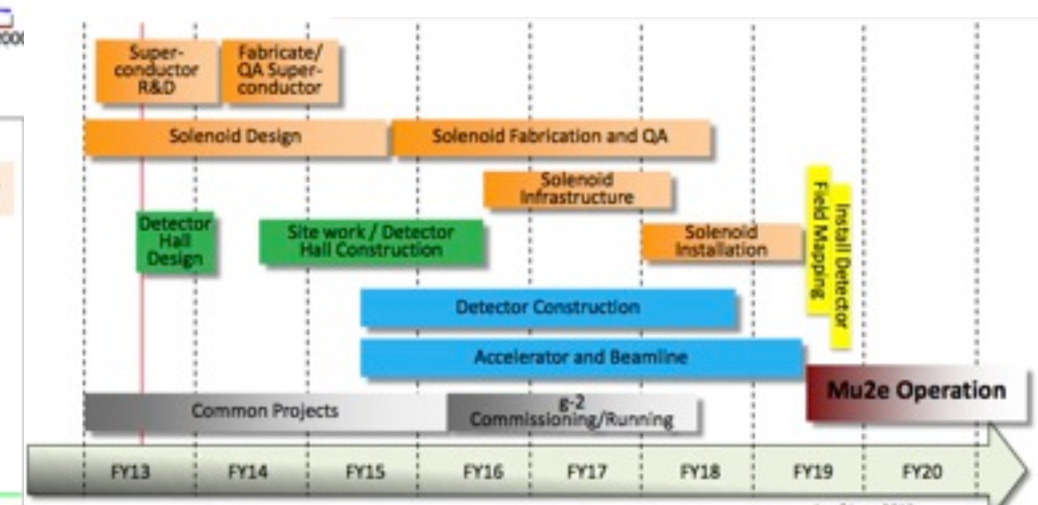
- Momentum resolution $\Delta p/p$ ~0.2%
- Beam Extinction factor 10^{-10}
- Total proton 3.6×10^{20}
- Minimize material in muon beam line • Smaller power consumption
- Radiation hardness and safety



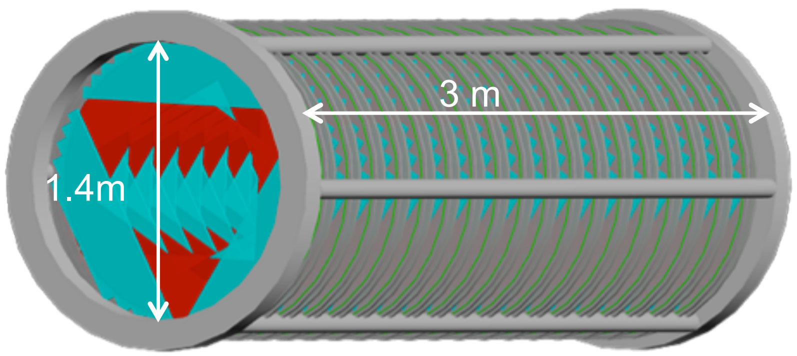
Mu2e operation starts in 2019, data is expected in 2022, SES~2×10^{-17}, and Project X ...





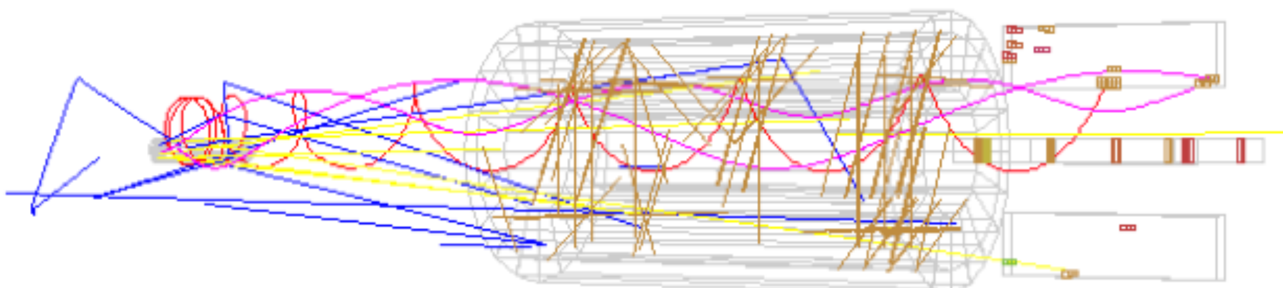


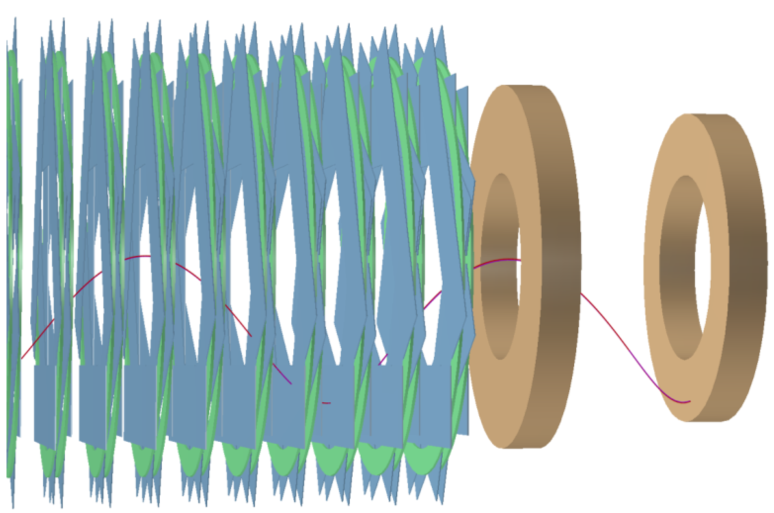
Mu2e Detector R&D



Straw tube tracker

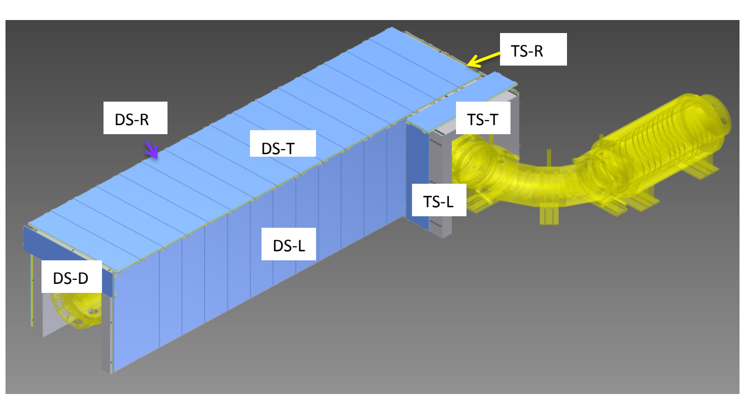
3 m long, 1.4 m diameter, in a uniform 1 T magnetic field
Made of 21,600 straw drift tubes, 18 stations, 2 planes/station
Each straw 5 mm diameter, 25 μm sense wire, 15 μm mylar walls
Custom ASIC for Time Division Readout, Δt resolution < 50 ps
ADC for dE/dx capability to separate highly ionizing protons.





Calorimeter

Provides independent energy, time and position measurements
Helps to eliminate backgrounds and provides a cross check to verify the validity of signal events.
Disk structure is selected from two designs: Vane / Disk
Two disks composed of hexagonal LYSO crystals
Charge symmetric, can measure $\mu^- N \rightarrow e^+ N'$

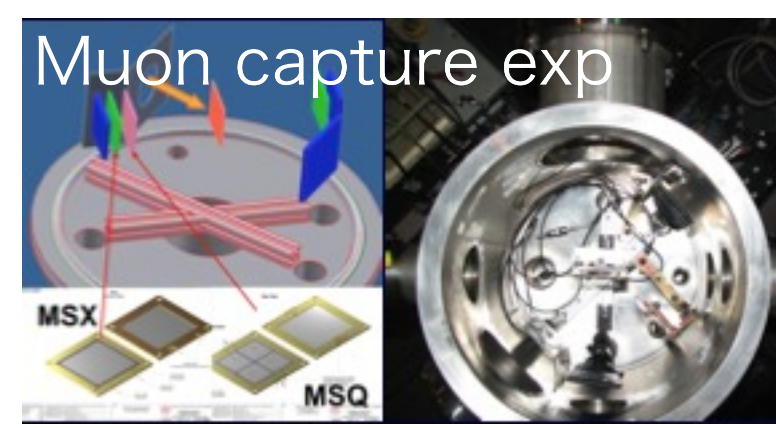


Cosmic Ray Veto

Cosmic rays is a major sources of background
- Muons hitting stopping target or DS materials, generating delta rays
- Muons decay into electrons

CRV are composed of 3 layers overlapping scintillators, placed around DS and part of TS area
Requires 0.9999 efficiency to achieve proposed background rejection

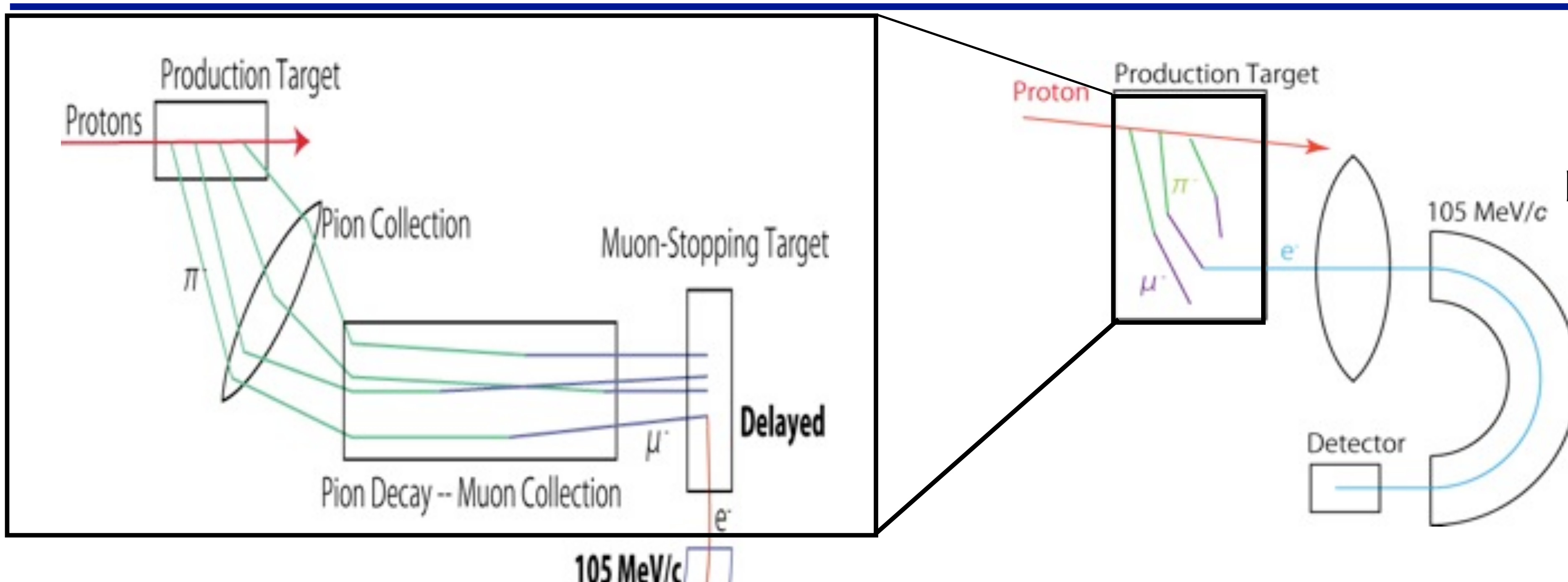
Collaborative work by COMET & Mu2e

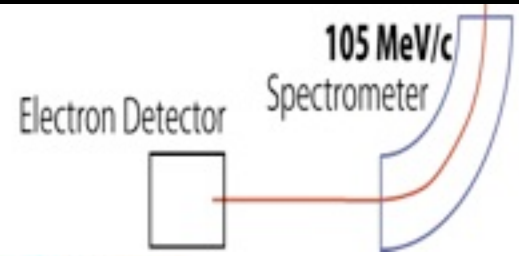


Y. Kuno WG4

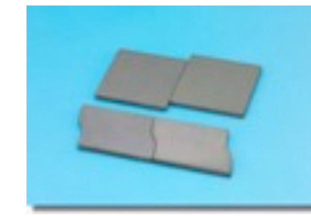
Y. Nakatsugawa WG4

DeeMe at J-PARC





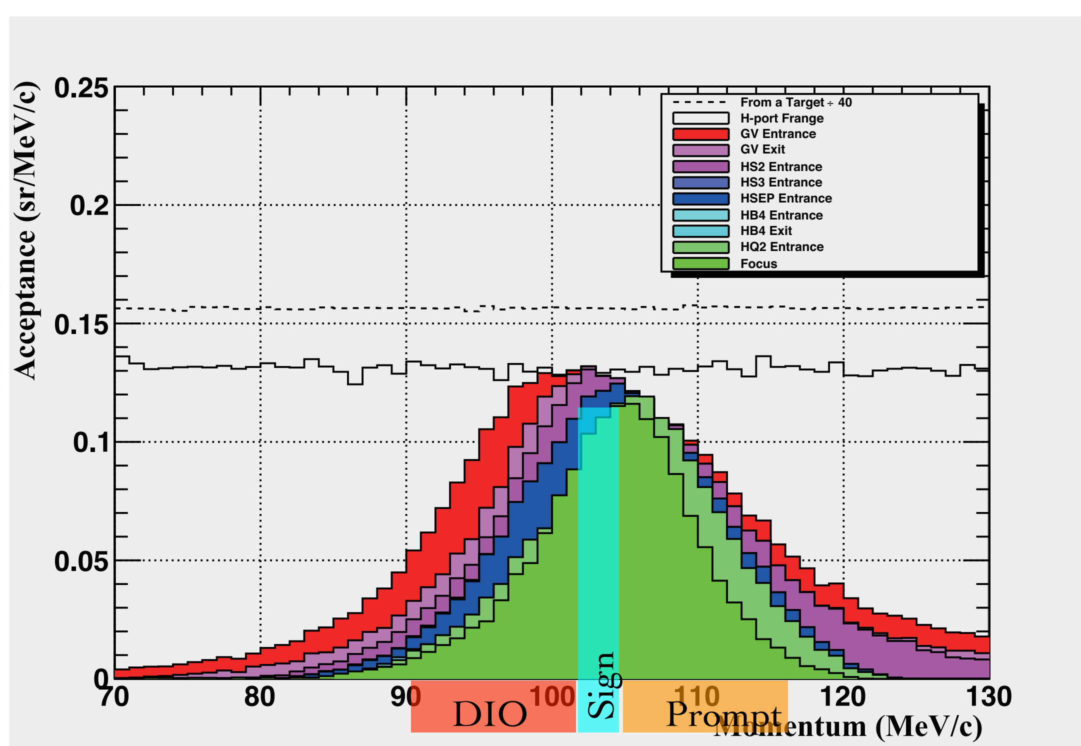
SiC
Rotating target
R&D in progress



target material	$f_C \times f_{MC}$
Graphite	0.08
Silica-carbide (SiC)	0.46

- An electron analogue of the surface muon.
- Experiment could be very simple, quick and low-cost.

PACMAN magnet
from TRIUMF



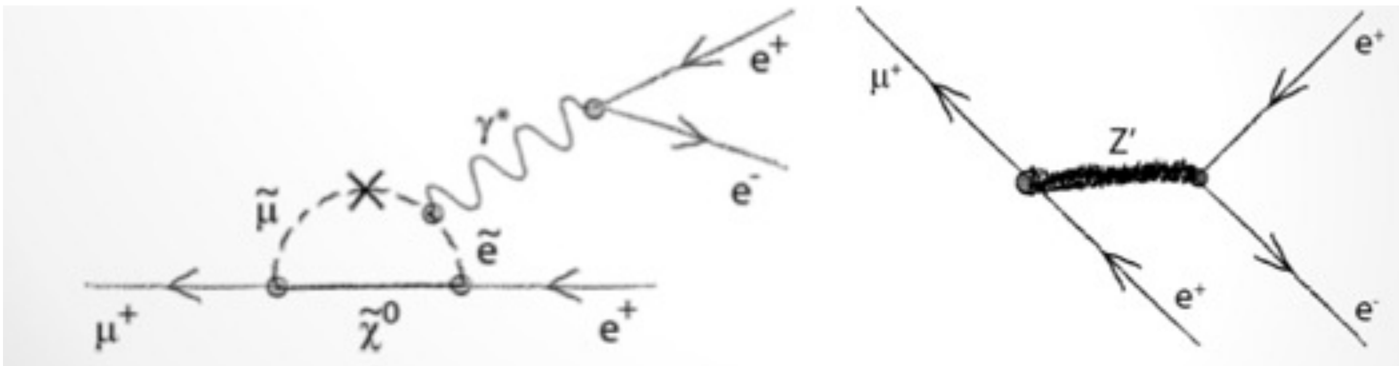
- S.E.S. ~10^{-14}
- Stage 1 approval
- DAQ in 2015

$$\mu \to e\, e\, e$$

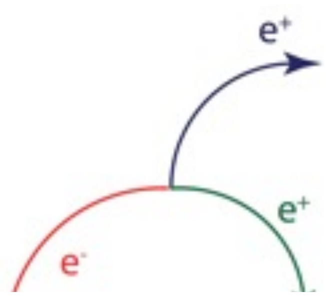
A. Bravar WG4

$\mu^+ \to e^+e^+e^-$ search using DC muon beam

- **SINDRUM @ PSI** BR($\mu^+ \to e^+e^+e^-$)<10^{-12} @90% C.L.
- New collaboration at PSI Mu3e



Signal
Σp=0
Δt=0

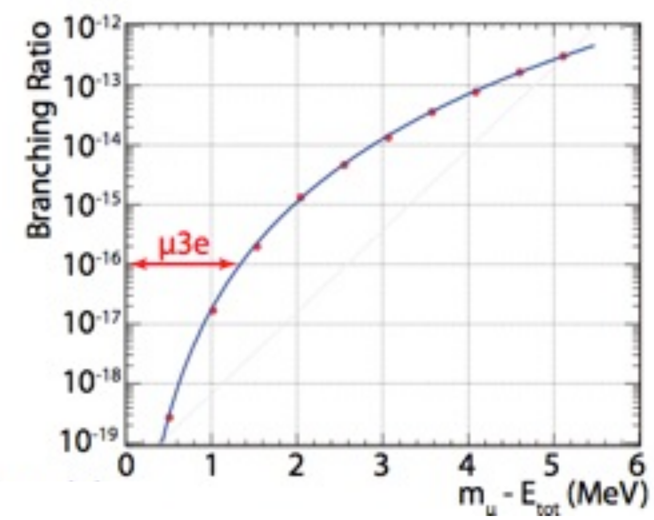


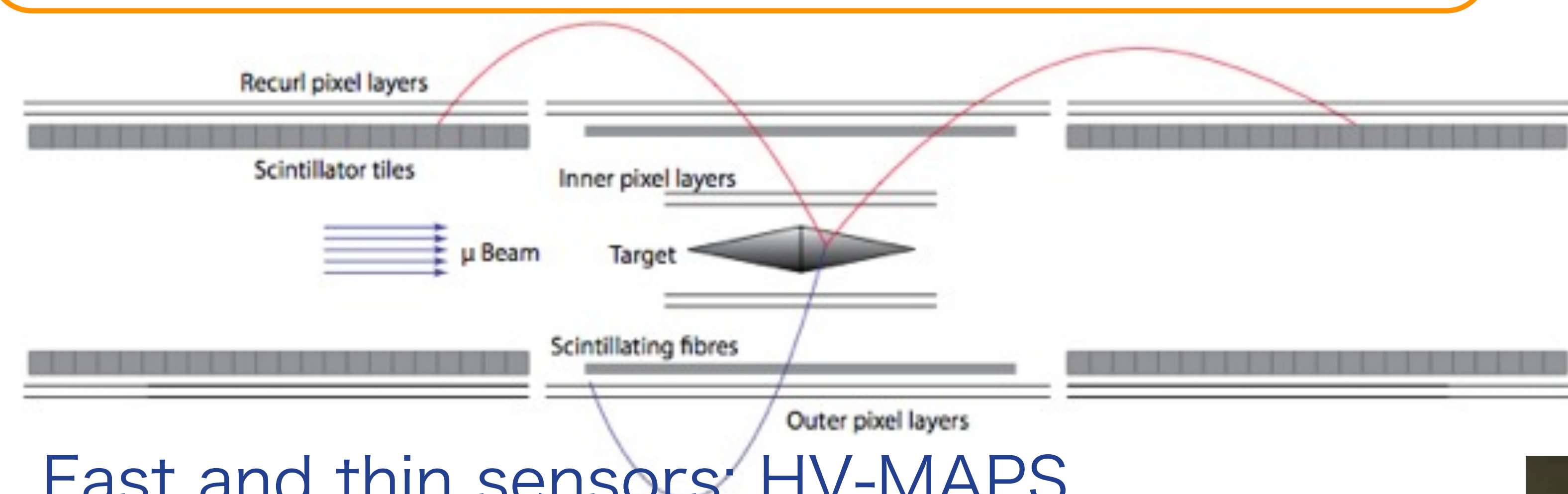
Acc. Overlap
Σp≠0
Δt≠0

- Allowed radiative decay with internal conversion:

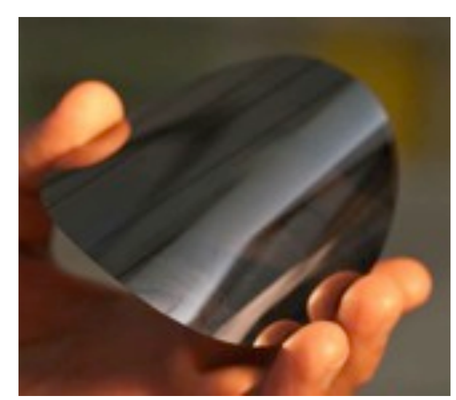
$$\mu^+ \to e^+e^-e^+\nu\bar{\nu}$$

- Only distinguishing feature: Missing momentum carried by neutrinos





Fiber/tile counters to measure t



Fast and thin sensors: HV-MAPS

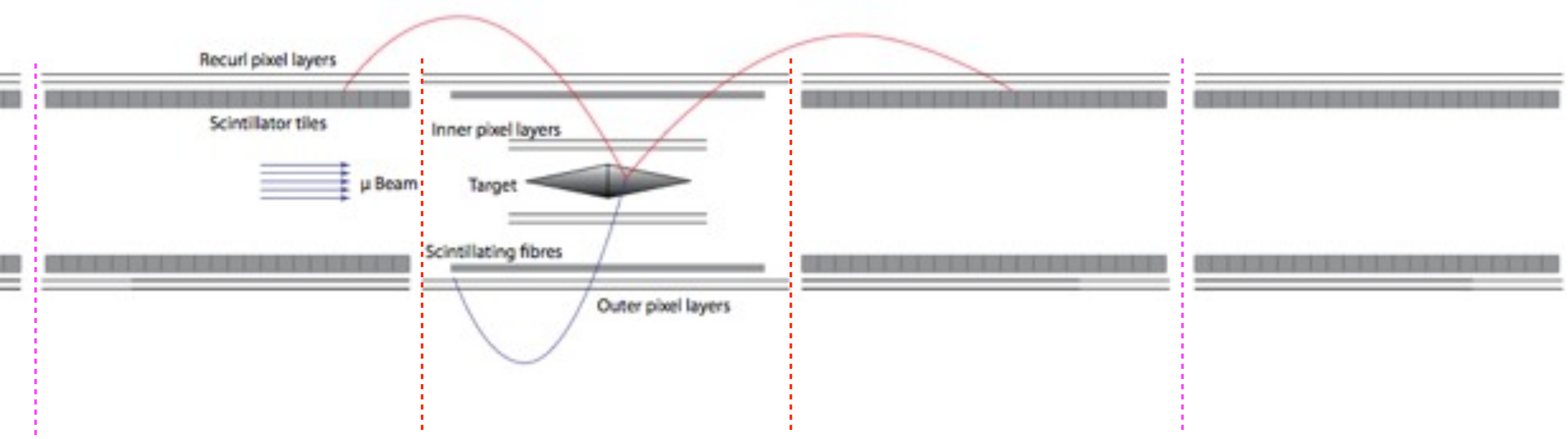
50 μm silicon

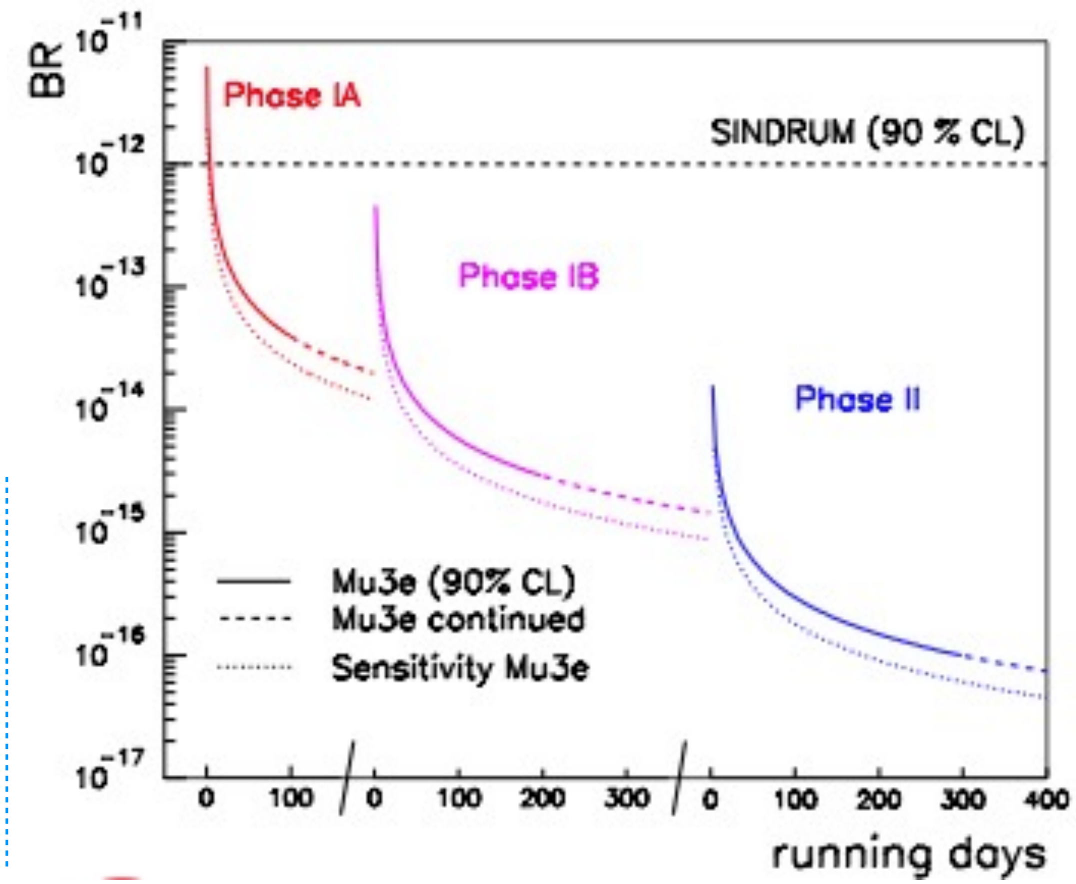
- 25 μm KaptonTM flexprint with aluminium traces
- 25 μm KaptonTM frame as support
- Less than 1‰ of a radiation length per layer

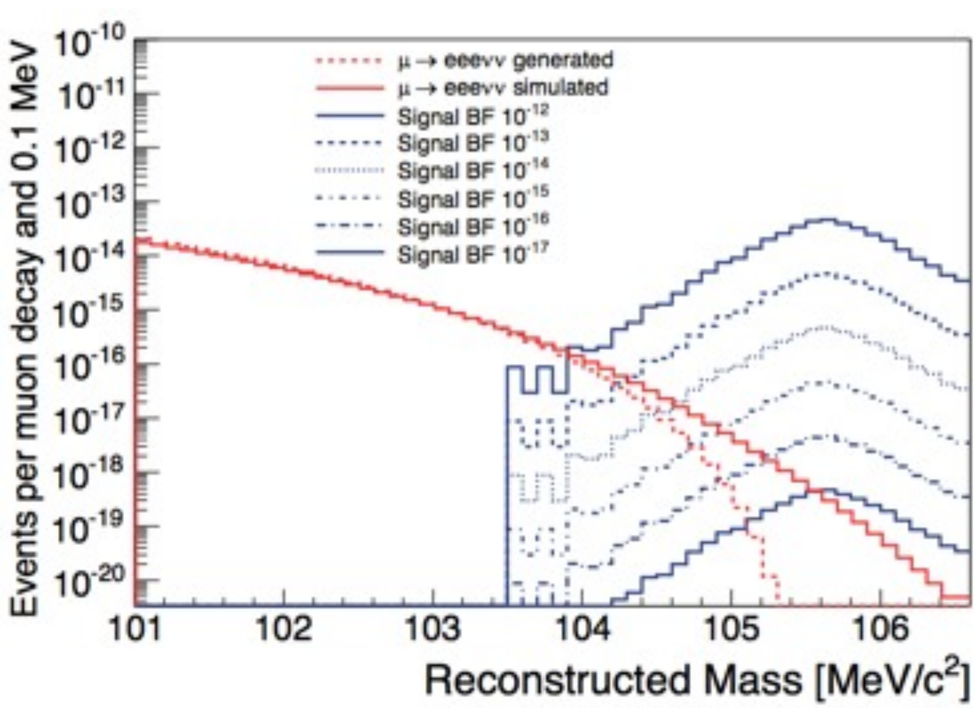
NIM A 582 (2007) 876

Mu3e

- Mu3e staging approach
  - Phase IA 2015 (PiE5 beam line)
  - Phase IB 2016-2017 (PiE5 beam line)
  - Phase II 2018+ (new beam line)

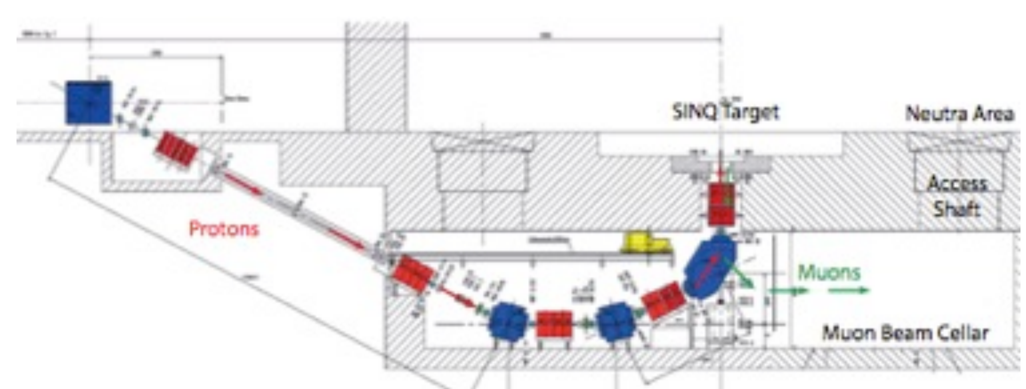


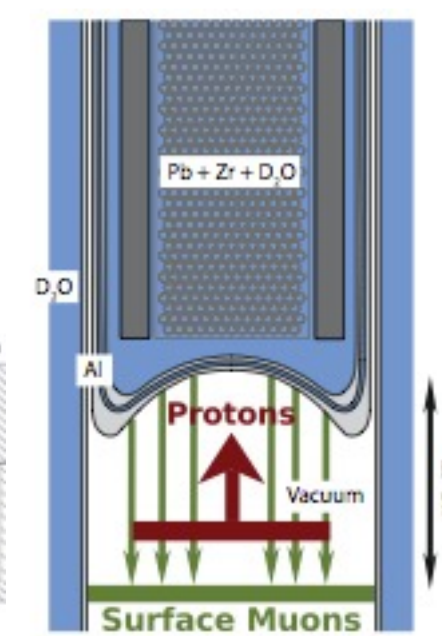




Muon beam

- 10^8 muons/sec for Phase I
- $2x10^9$ muons/s for Phase II

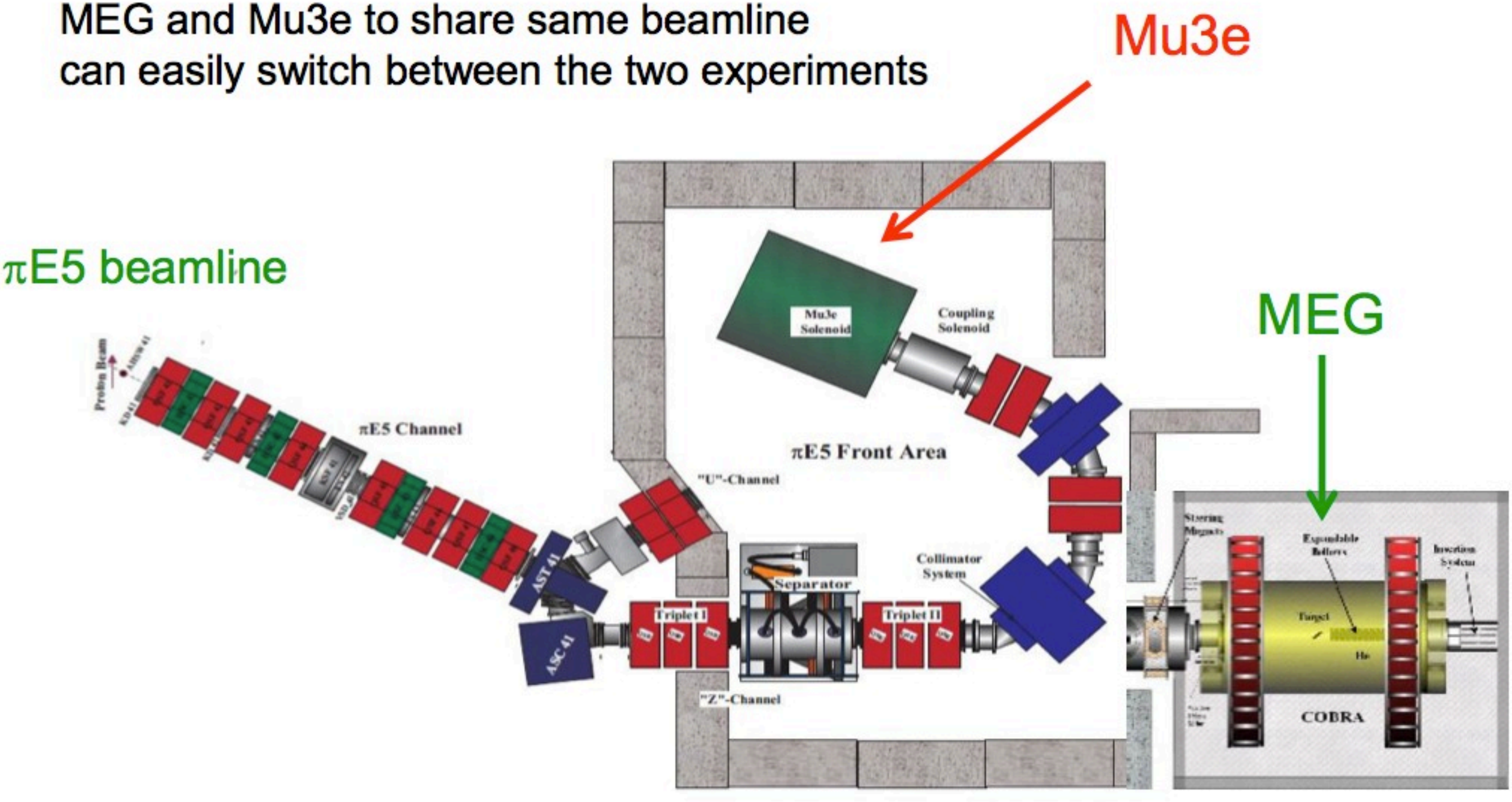


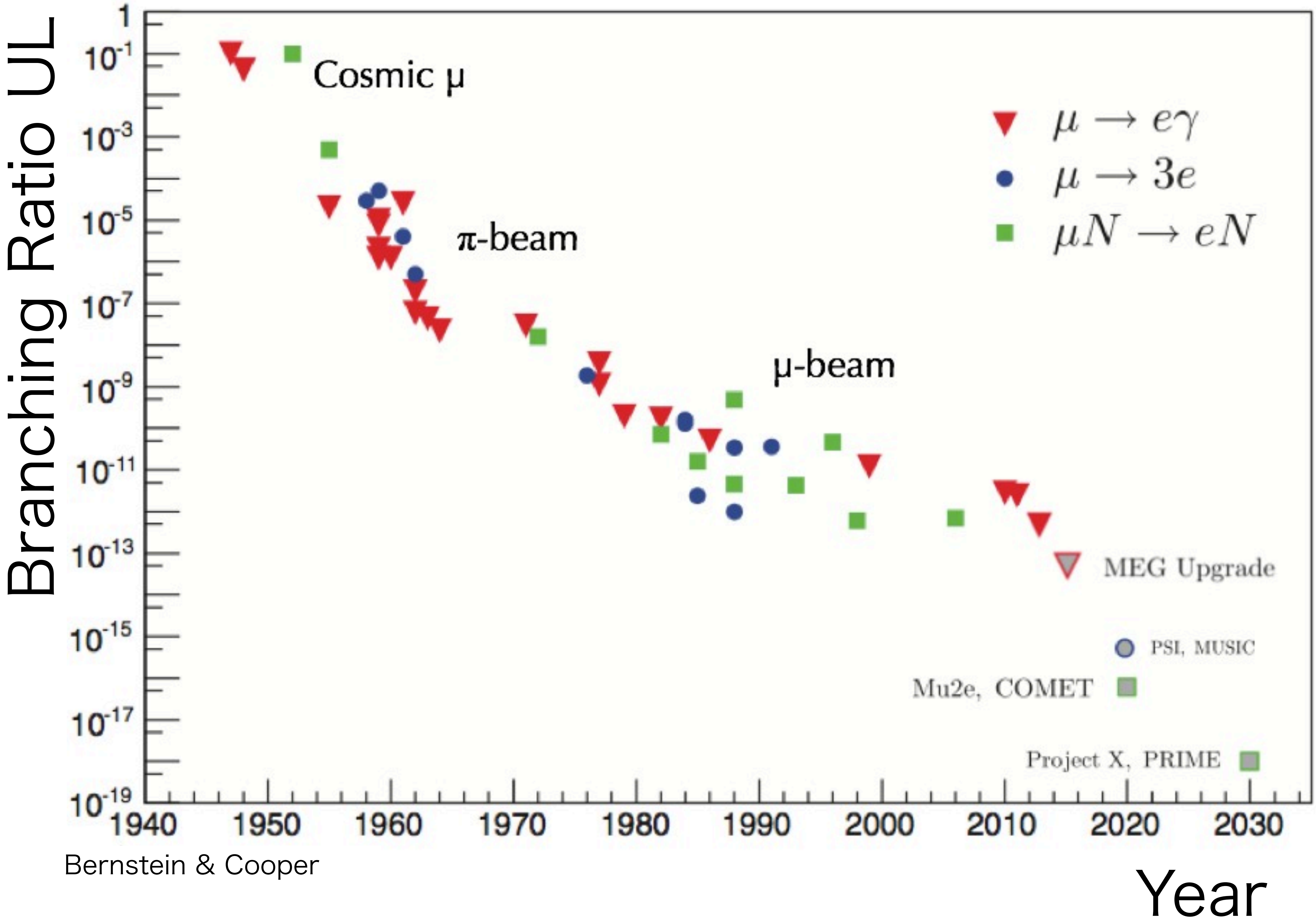


PSI new muon beam line (not before 2017)

Mu3e Phase I beam

MEG and Mu3e to share same beamline
can easily switch between the two experiments

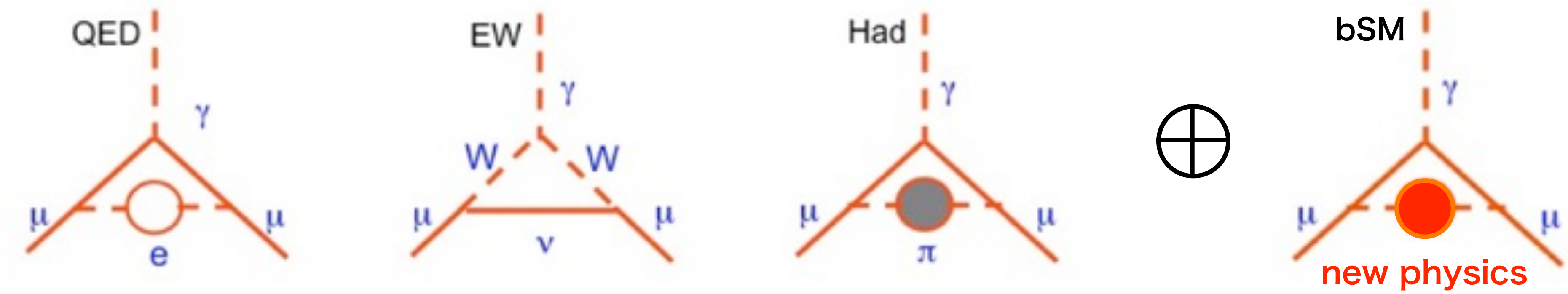




Bernstein & Cooper

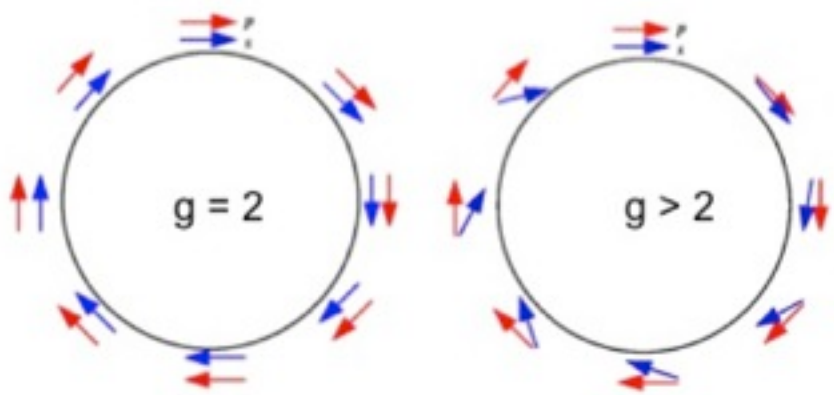
$g_\mu - 2$

g_μ-2

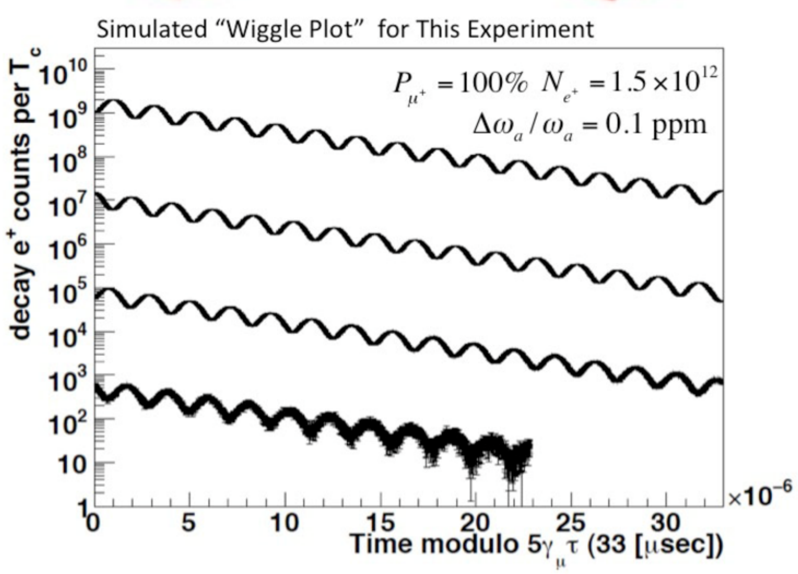


$a_\mu=(g_\mu-2)/2=11\ 659\ 208\ (6)\ \times 10^{-10}$ (0.5ppm)

Physical Review Letters 92; 1618102 (2004)

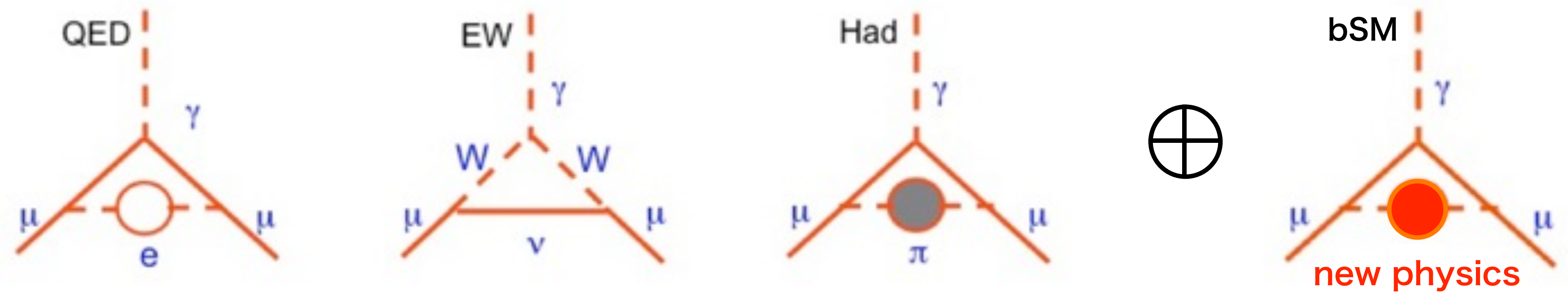


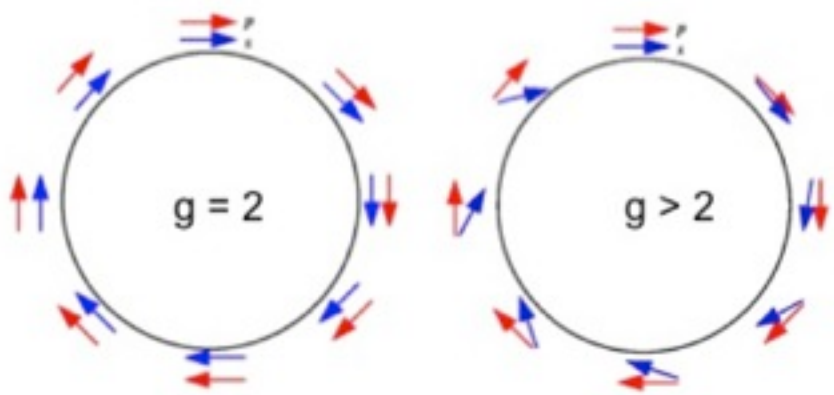
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$



continuation at FNAL toward 0.1ppm precision

g_μ-2





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Physical Review Letters 92; 1618102 (2004)

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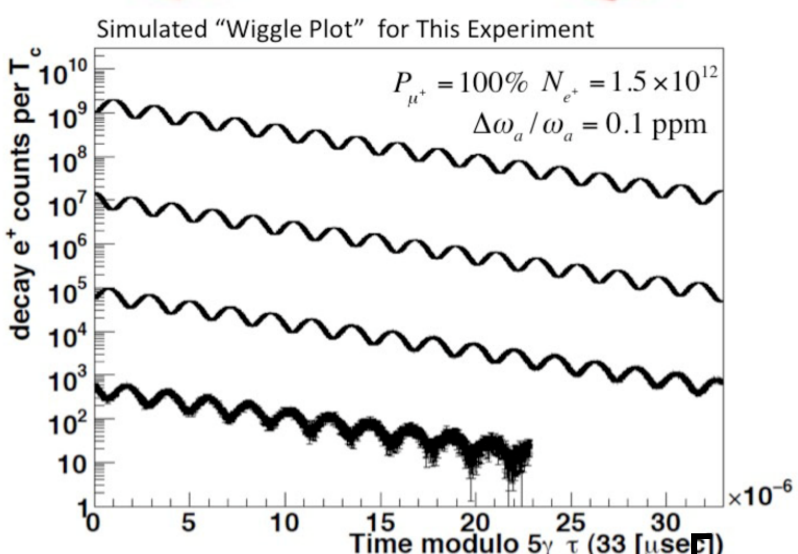
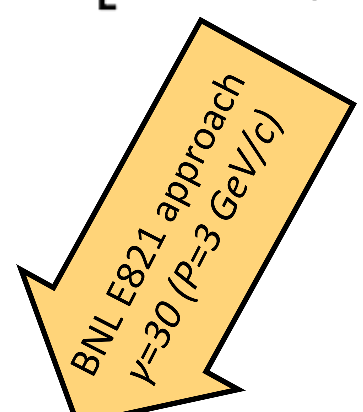
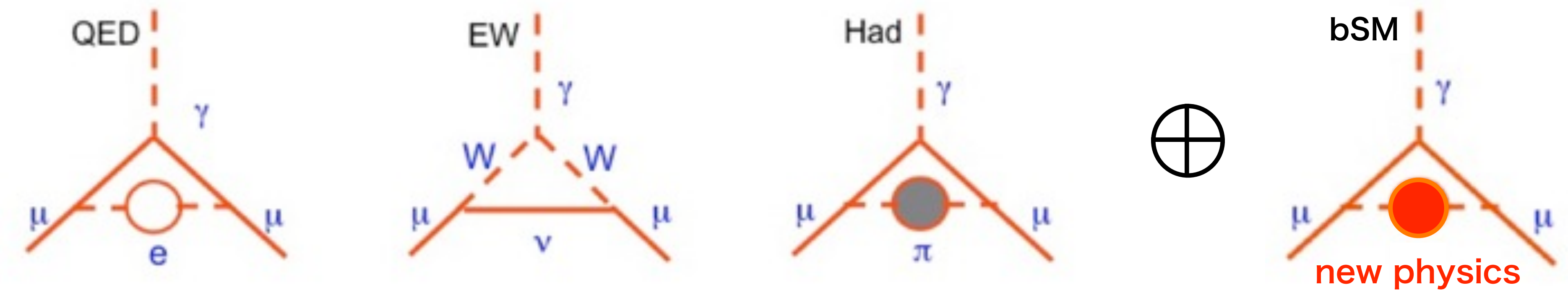


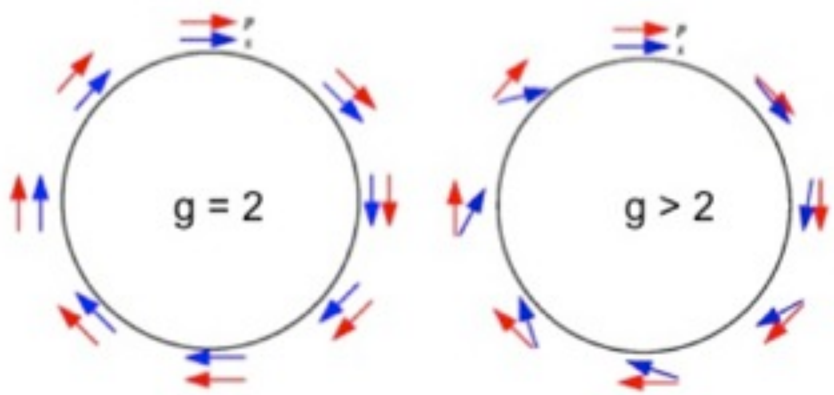


$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

continuation at FNAL toward 0.1ppm precision

gμ-2





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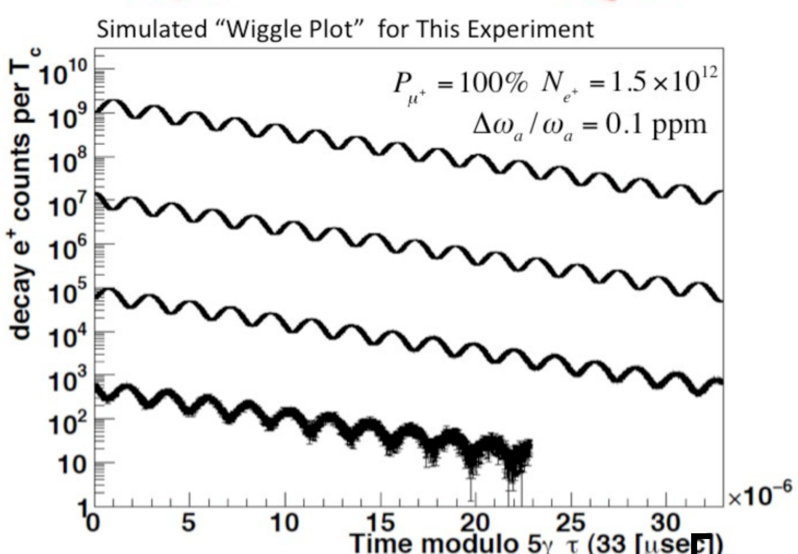
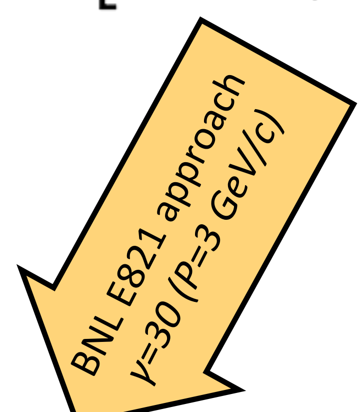
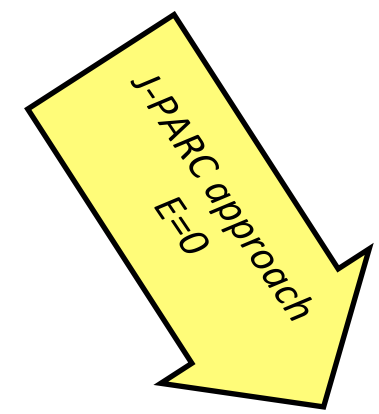


$$\vec{\omega}=-\frac{e}{m}\left[a_\mu\vec{B}-\left(a_\mu-\frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}+\frac{\eta}{2}\left(\vec{\beta}\times\vec{B}+\frac{\vec{E}}{c}\right)\right]$$



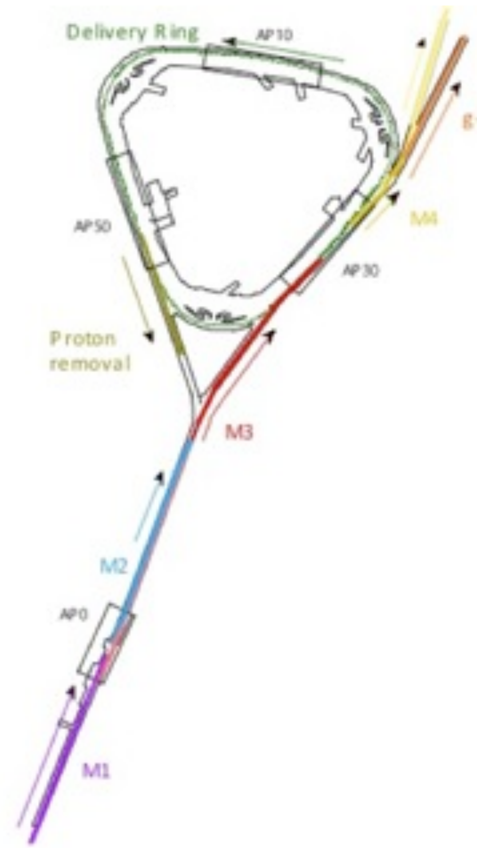


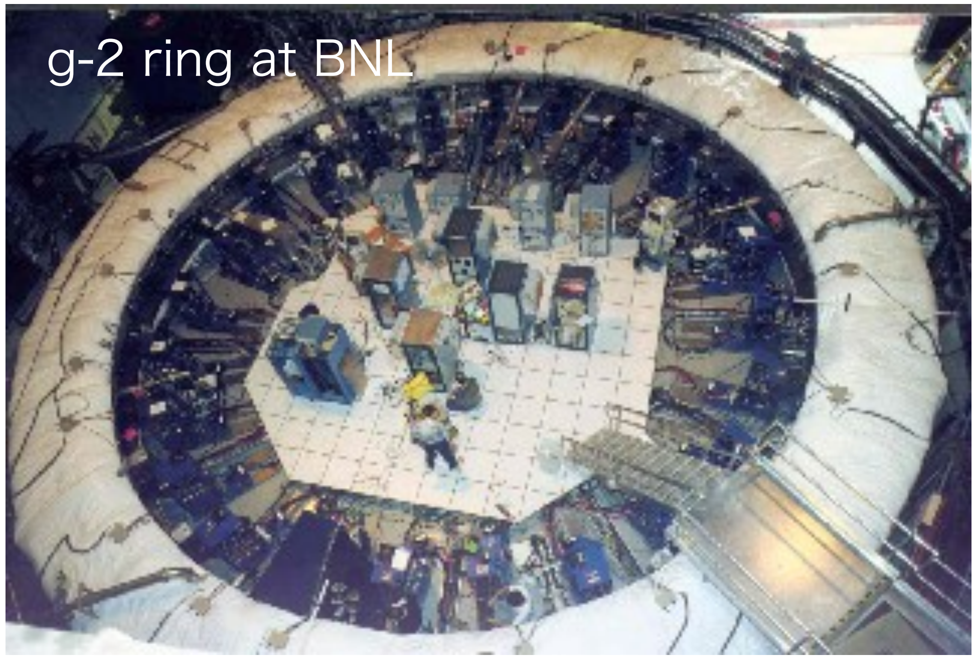
$$\vec{\omega}=-\frac{e}{m}\left[a_\mu\vec{B}+\frac{\eta}{2}\left(\vec{\beta}\times\vec{B}+\frac{\vec{E}}{c}\right)\right]$$

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

continuation at FNAL toward 0.1ppm precision

g-2 at FNAL



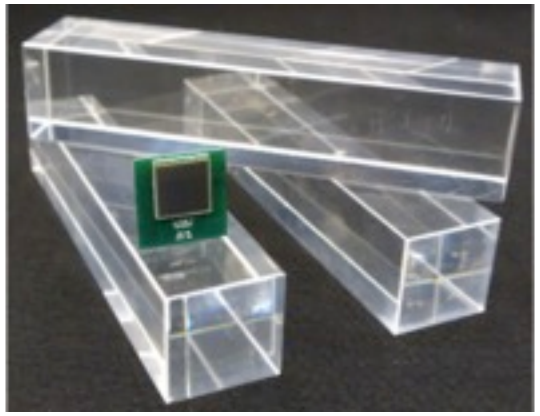


Improvements in detector technology will reduce the two largest systematic uncertainties on the ω_a measurement.

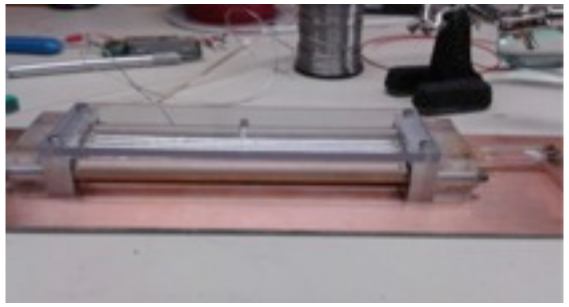
1 Pileup: 0.08 ppm reduced to 0.02 ppm

2 Gain: 0.12 ppm reduced to 0.02 ppm

fine calorimeter segmentation for better pile-up identification



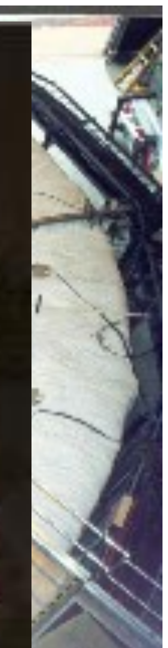
straw in-vacuum tracking detector



DAQ will start in 2016

TBA WG4

g-2 at FNAL



Improven
reduce th
uncertair

1 Pileu

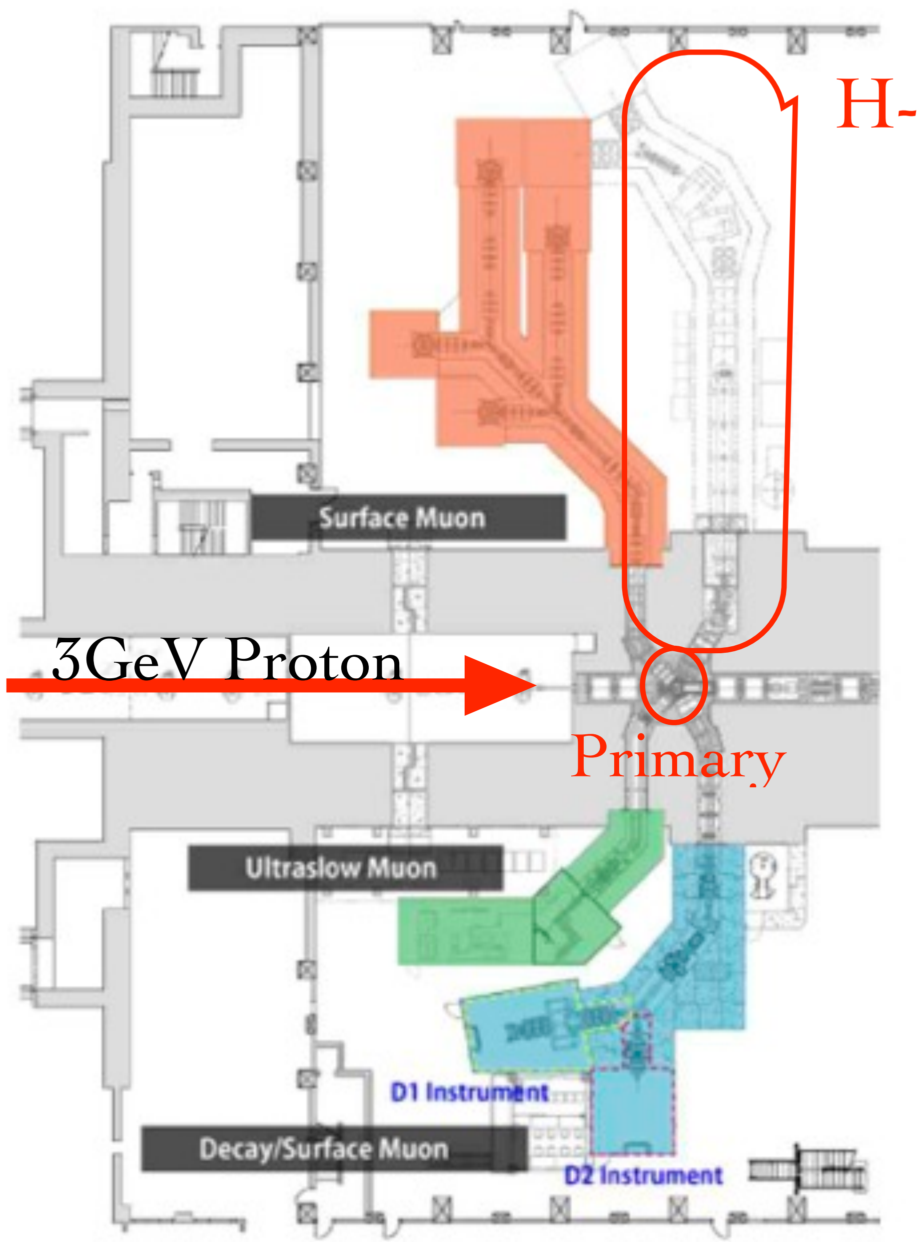
2 Gain:

fine calc
for bett

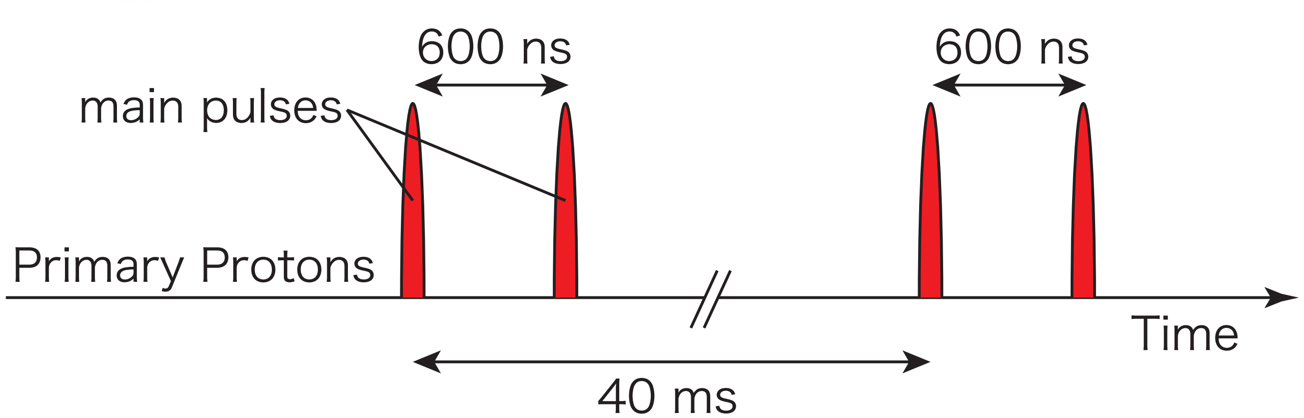
DAQ will start in 2016

K. Shiomura WG4

J-PARC MLF H-Line for muon Programs

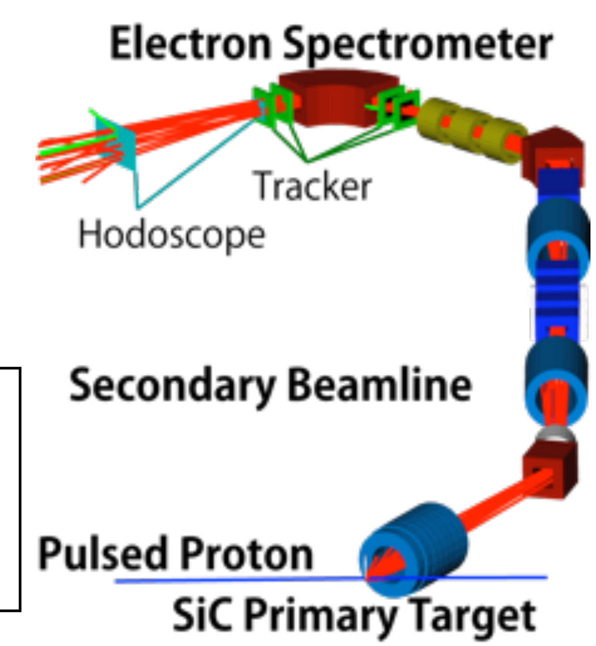


- Multi-purpose beam line for particle physics experiments
- Large momentum range <30MeV/c - 120 MeV/c
- 1×10^8 muons/sec
- Construction of the front part completed
- Wien filter & fast kicker



muon g-2/EDM

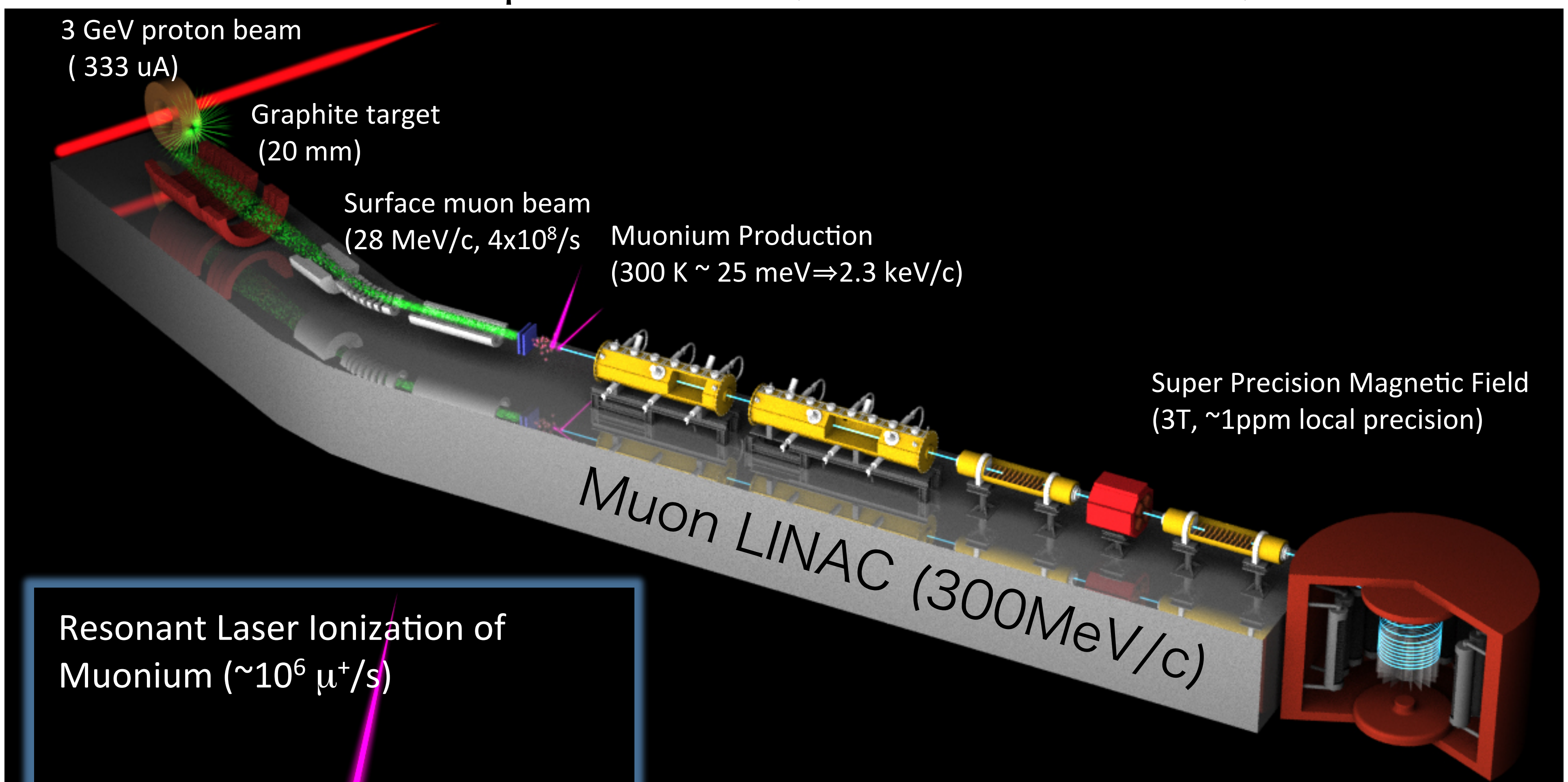
DeeMe
(another mu-e conversion search at J-PARC)

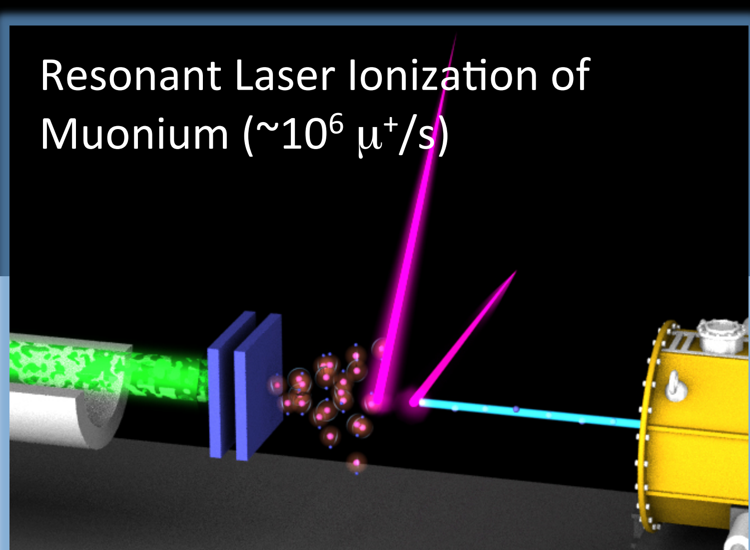


T. Mibe WG4

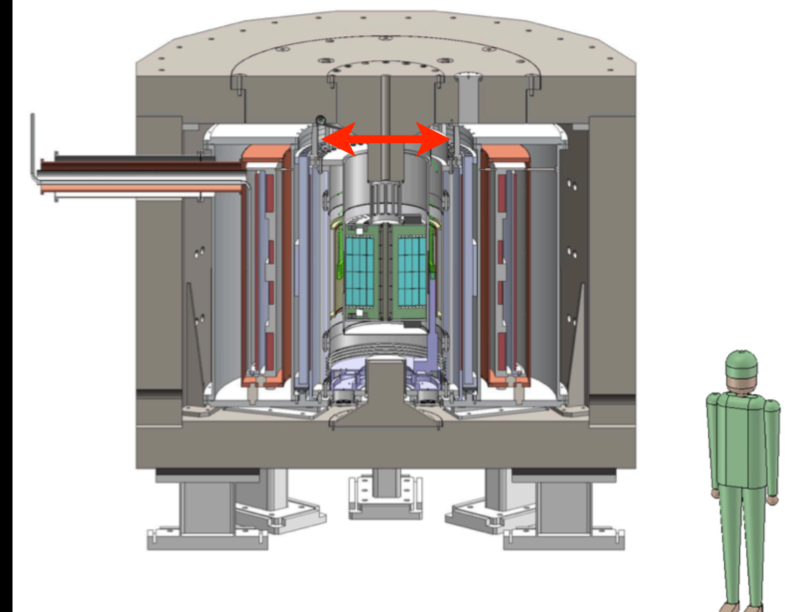
J-PARC g-2/EDM

- Muon g-2/EDM experiment at J-PaRC with Ultra-Cold Muon Beam
    - Muonium production, Laser Ionization, and muon acceleration





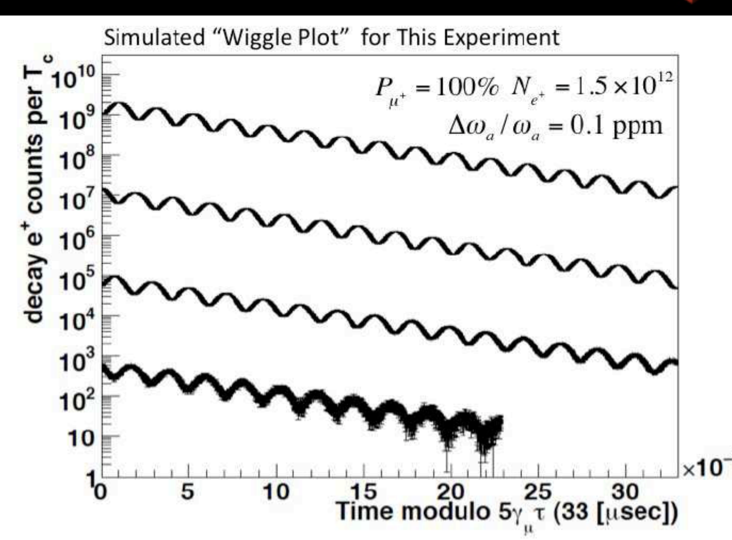
66cm diameter

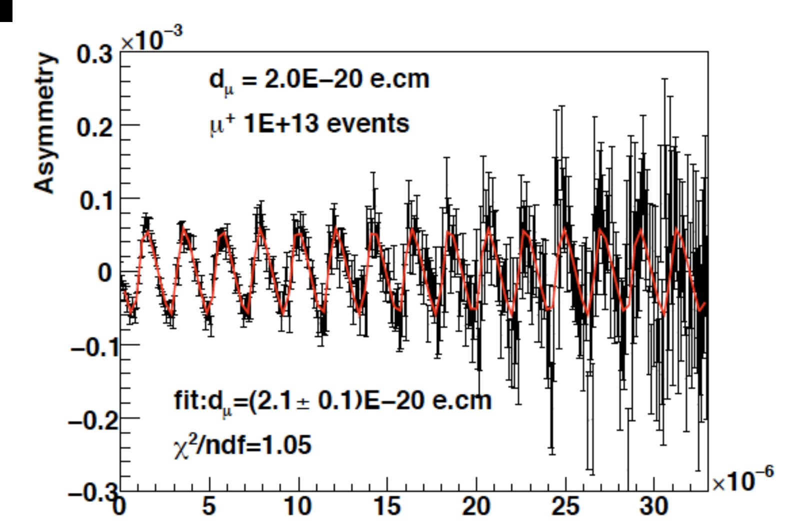


Silicon detector for electron tracking

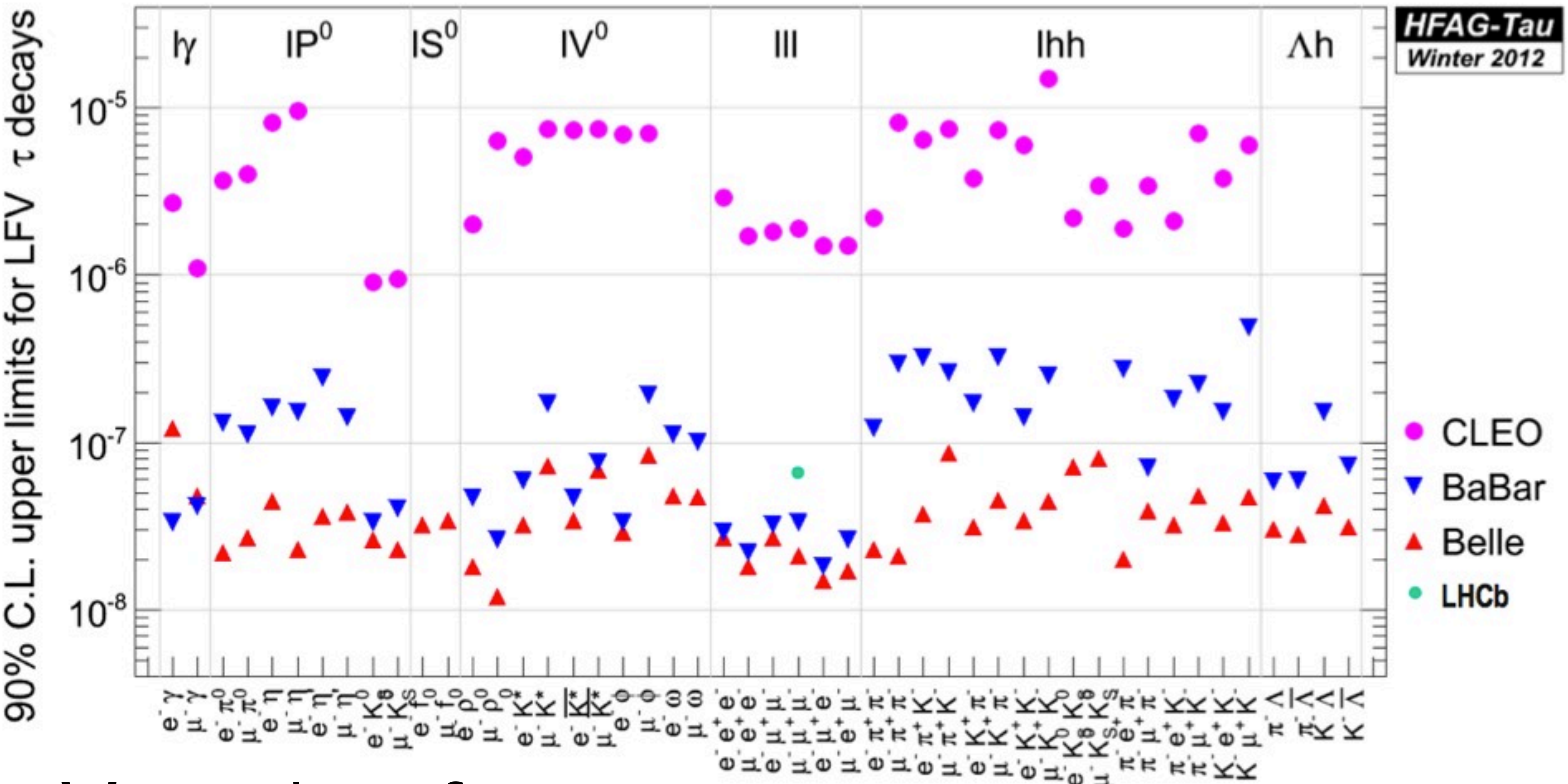
DAQ start in 2016 (?)

- Technically driven schedule
- Budget





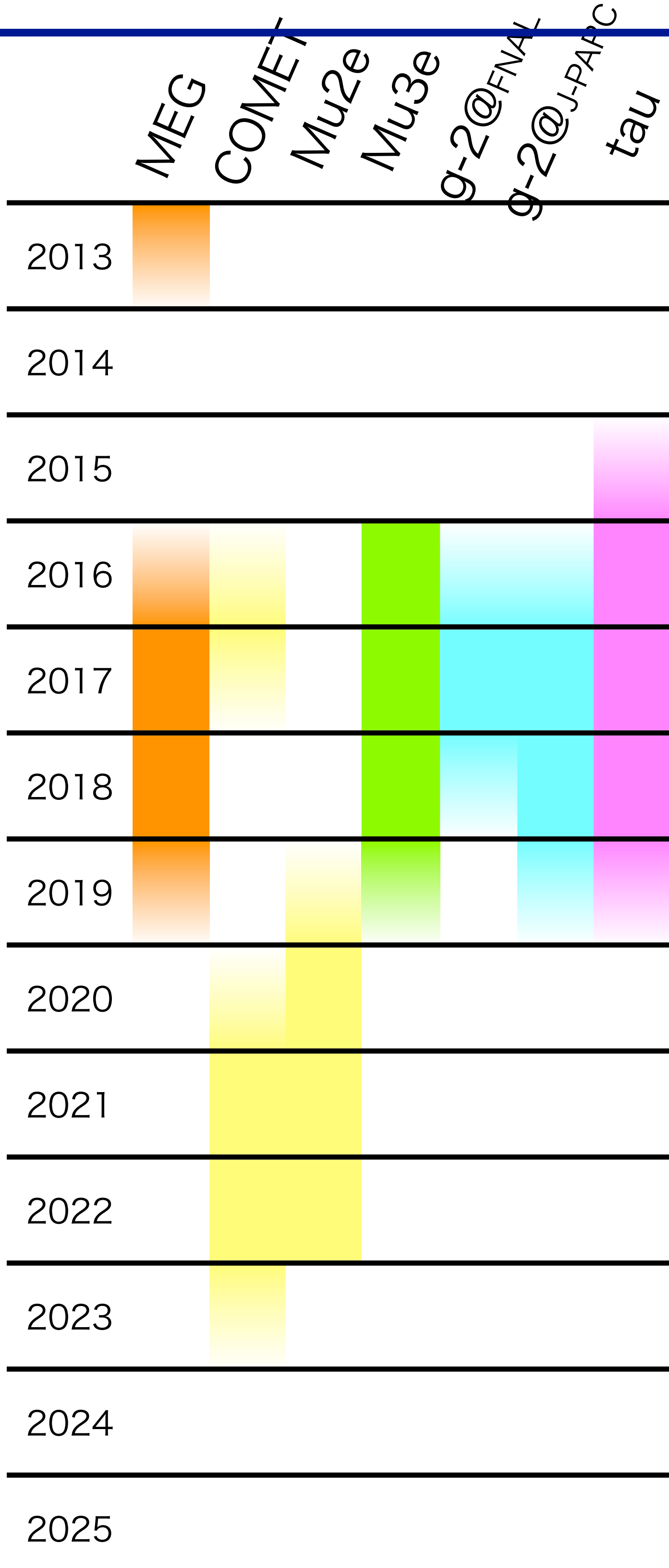
τ cLFV searches



More data from

Belle II at SuperKEKB & LHCb upgrade !

Conclusion



- cLFV search as a tool to investigate bSM
  - complementary approach to energy frontier
- MEG: $\mathrm{Br}(\mu \to e\gamma) < 5.7\times10^{-13}$
- New experiments are in preparation
  - $\mu \to e\gamma$: MEG2
  - $\mu \to e$ conversion:

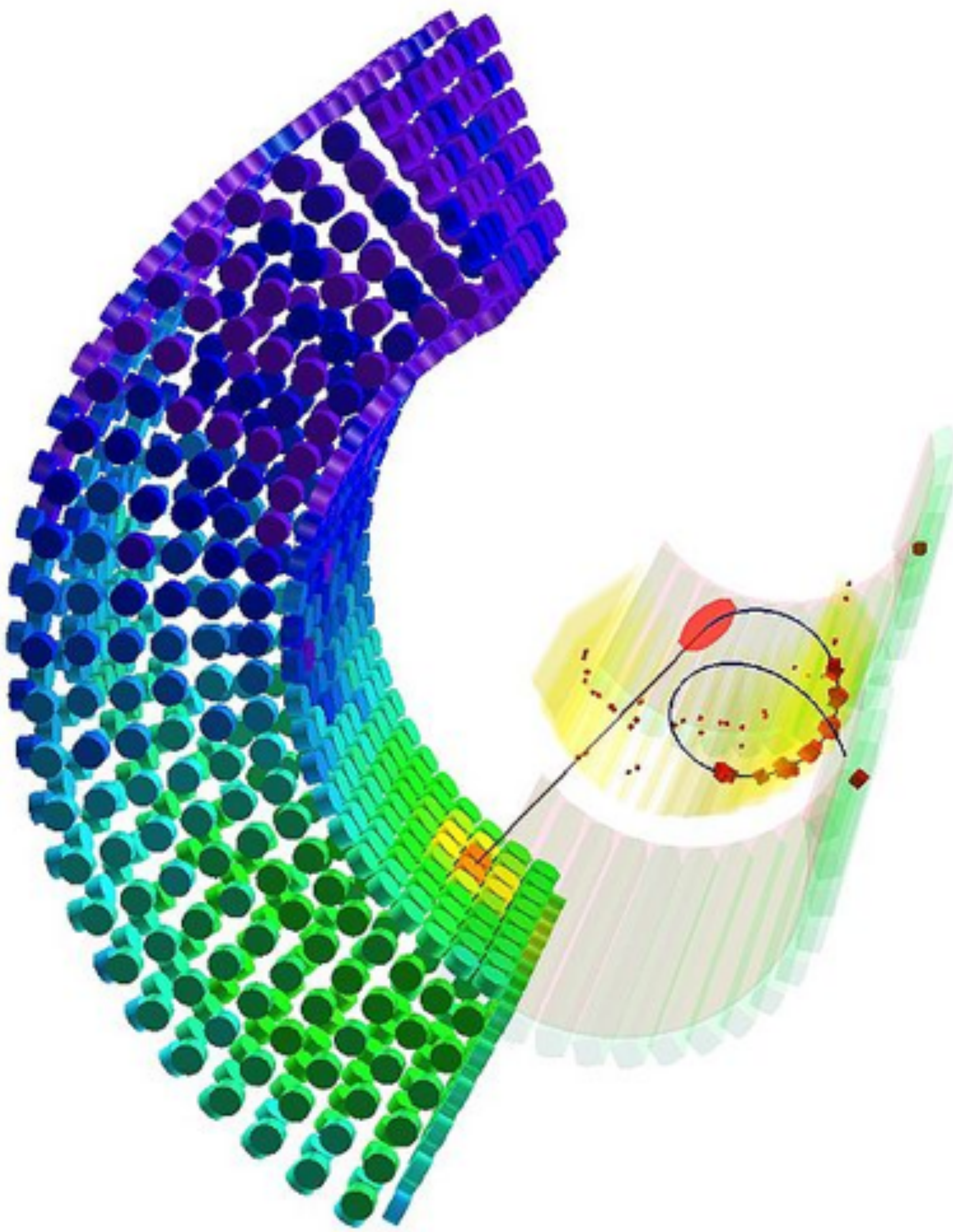
    COMET, Mu2e (& DeeMe)
  - $\mu \to eee$: Mu3e
- Verification of BNL E821 g_μ-2 measurement with better precision
  - FNAL g_μ-2, J-PARC g_μ-2 (muon EDM as well)
- (more tau lepton data in future B-factory experiments)

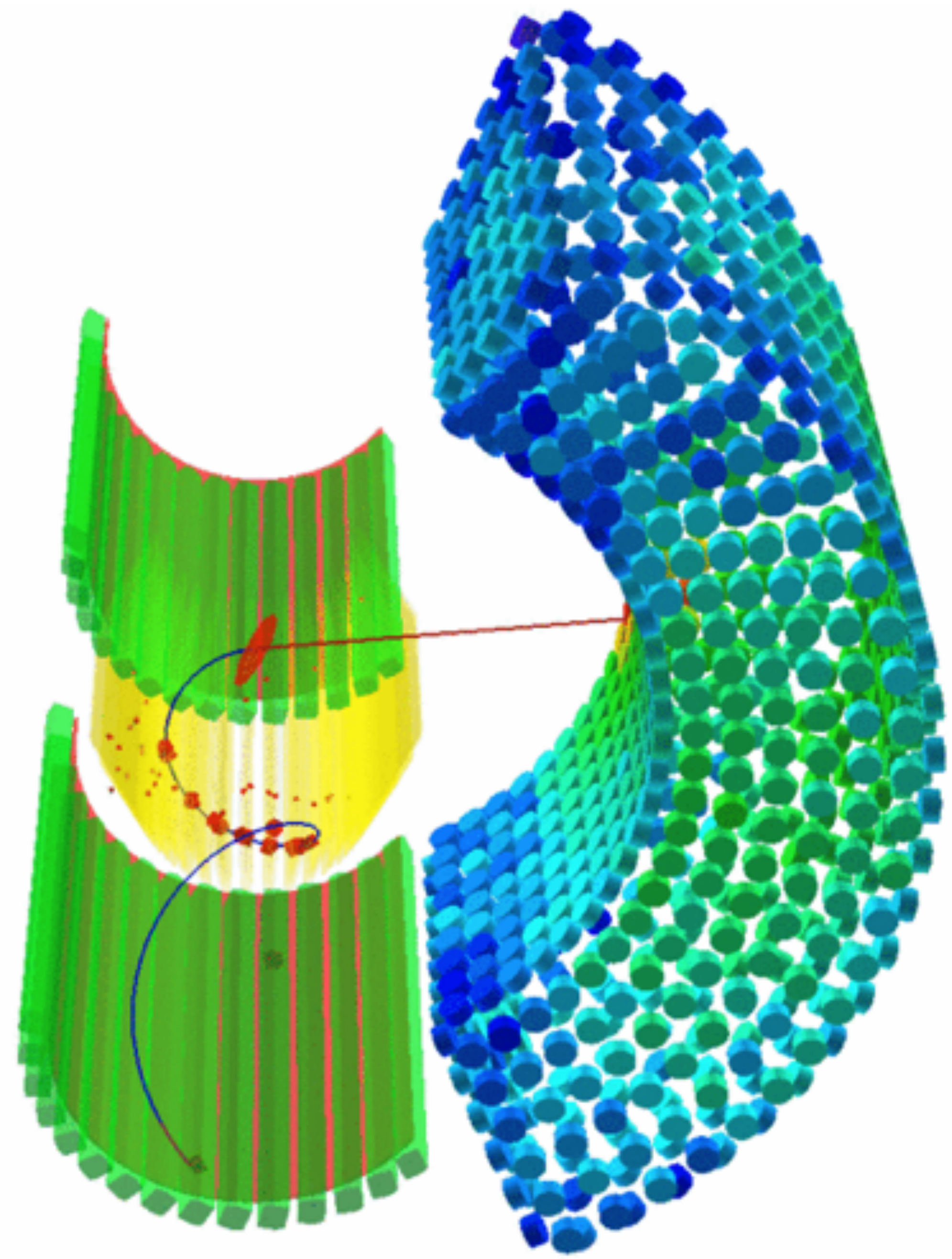
- Many thanks to
  - MEG, COMET, DeeMe, and J-PRAC g-2/EDM collaborations
  - Angela Papa, Nik Berger & Alessandro Bravar
  - Zhengyun You

Backup

MEG

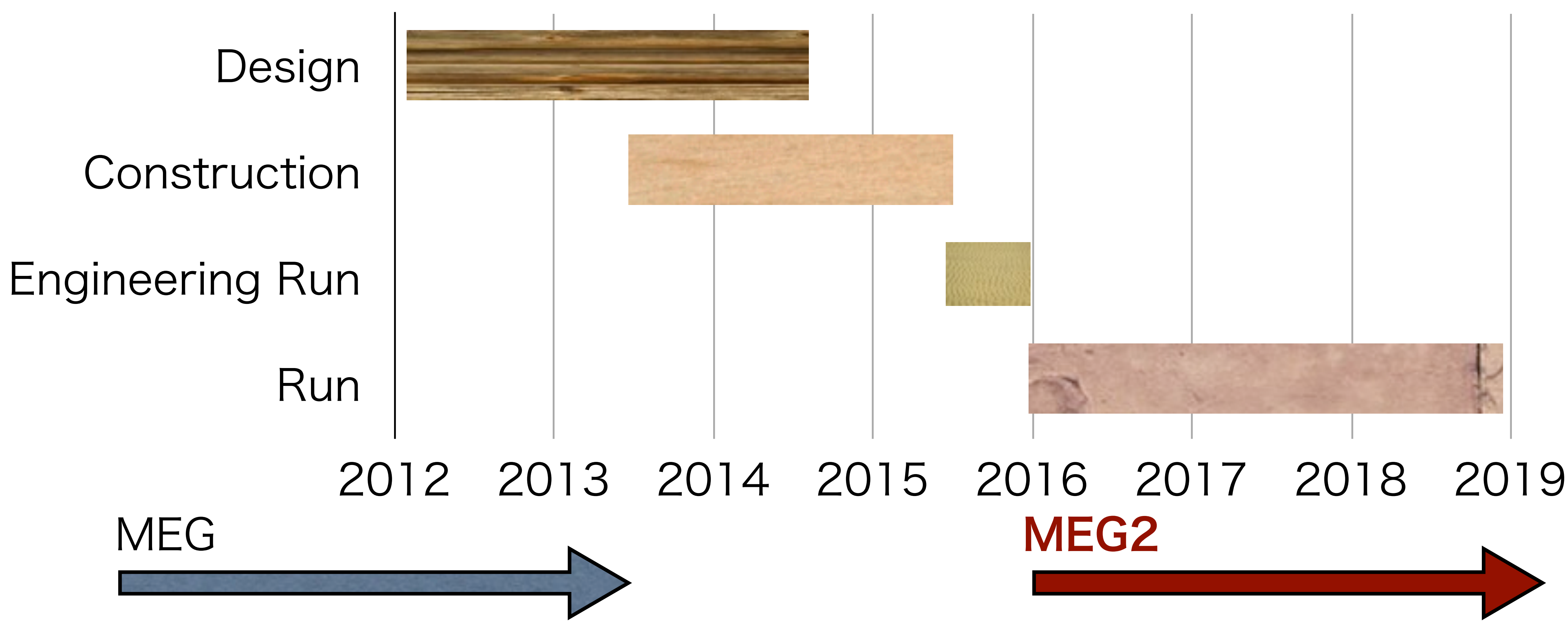
MEG Event Examples





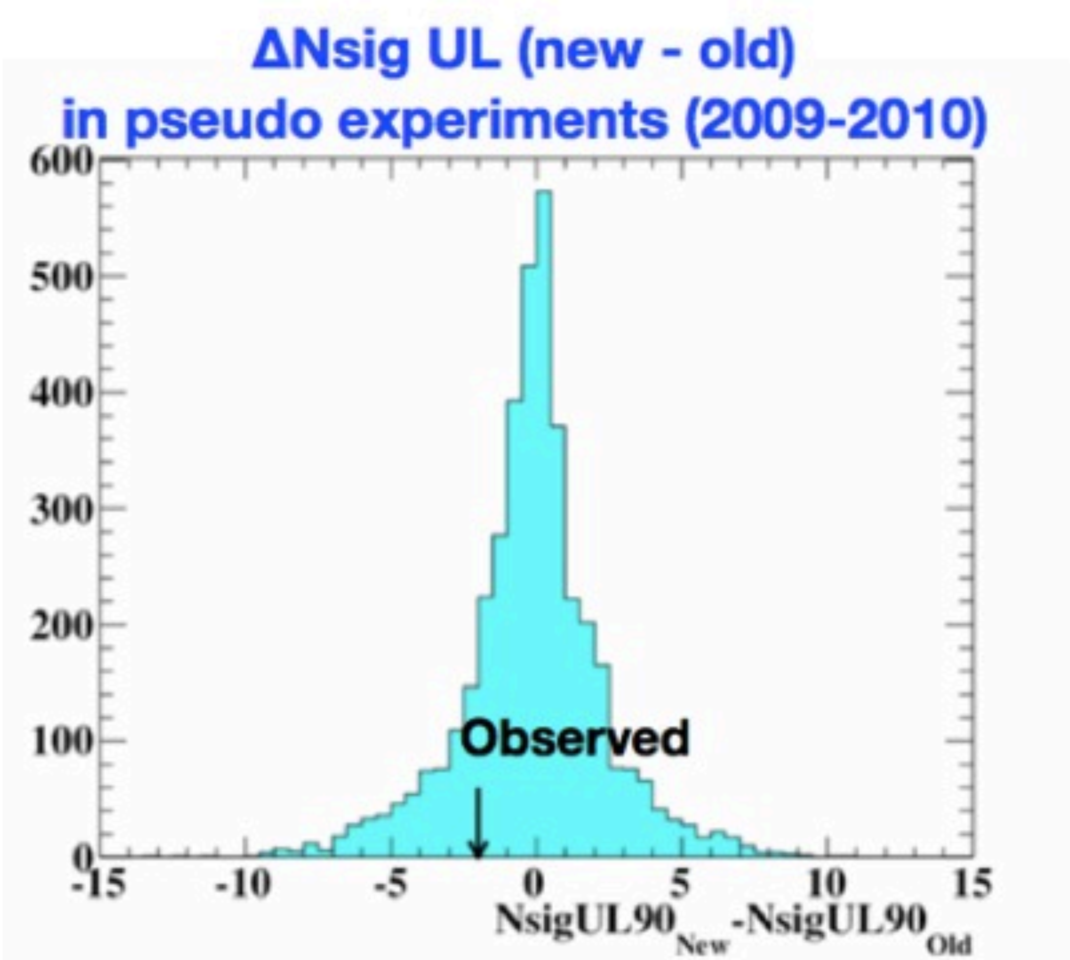
MEG Upgrade Schedule

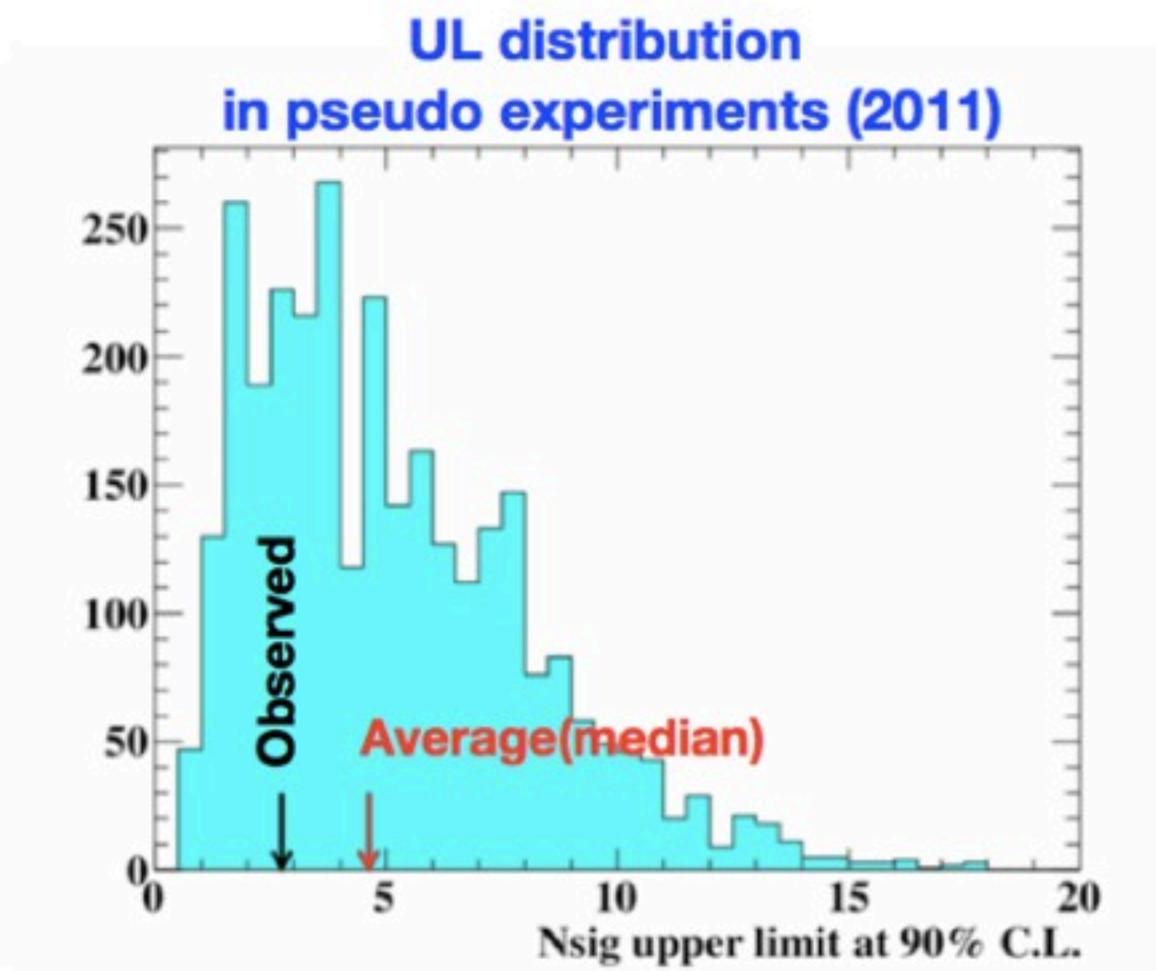
- Upgrade proposal was submitted to PSI in December 2012
- Approved by PSI committee in January 2013



Consistency Check

- Compatibility bw new/old analysis
- UL distribution

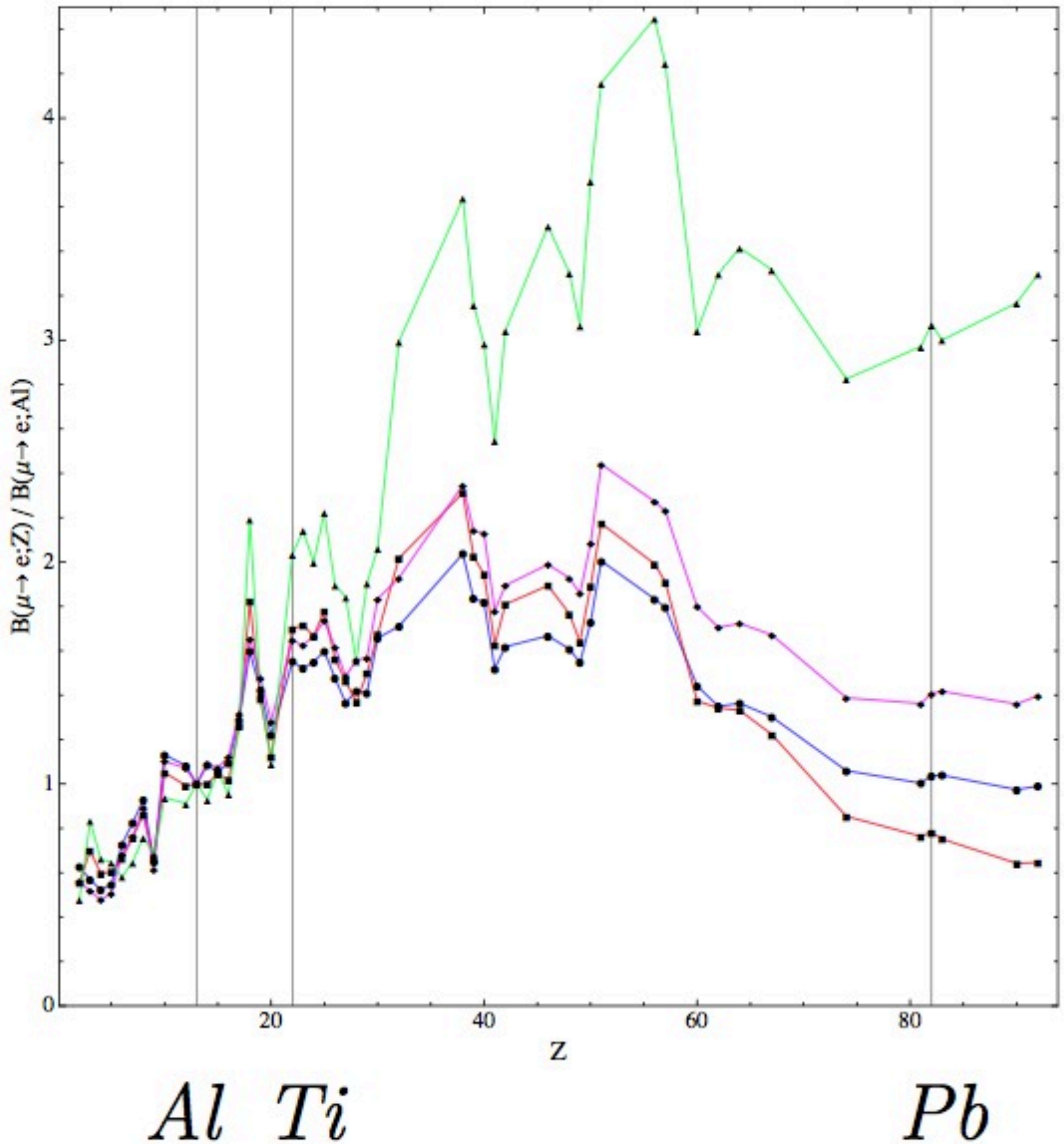




Backup

COMET/Mu2e/DeeMe

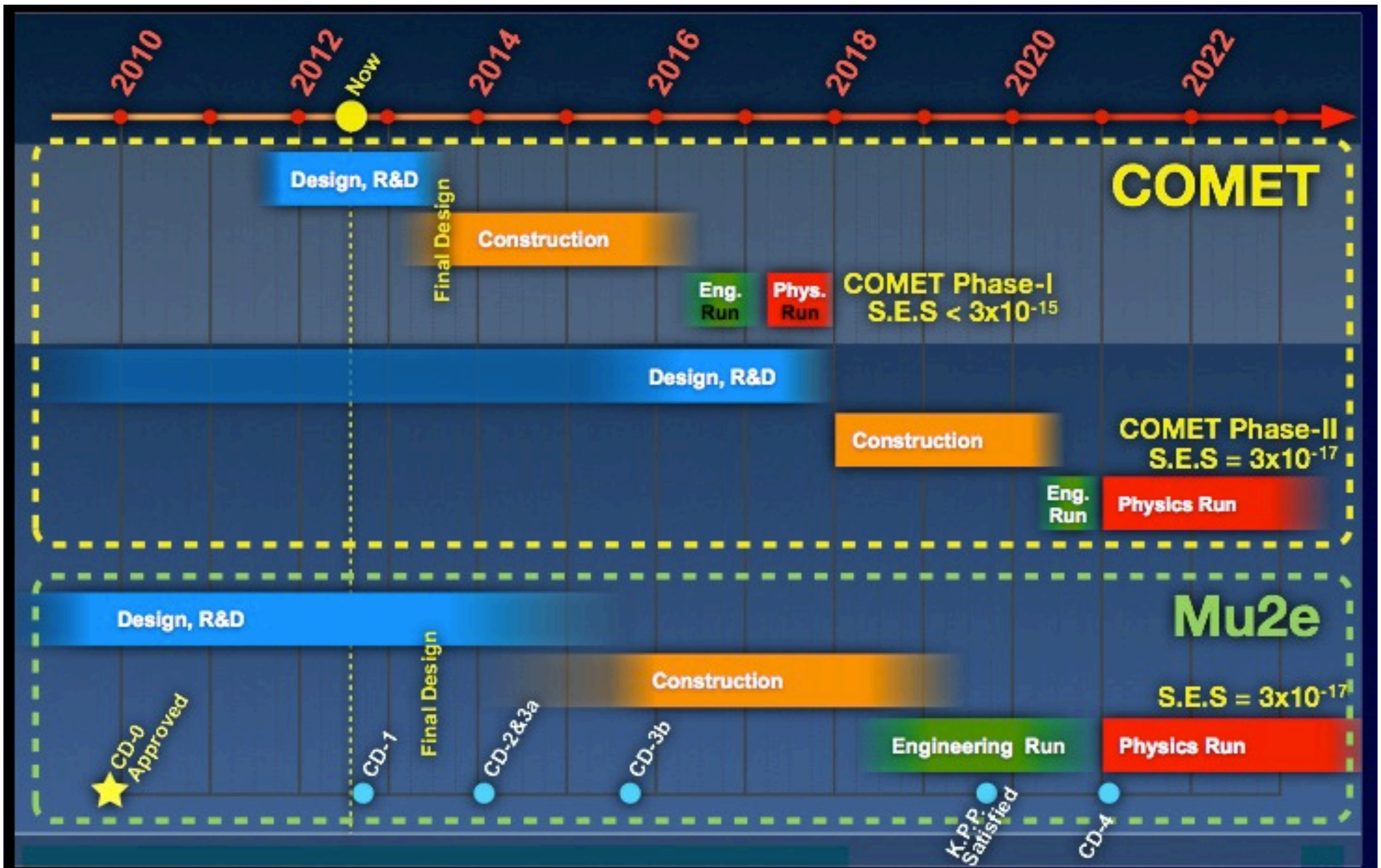
Cirigliano, Kitano, Okada, Tuzon, 2009



COMET vs Mu2e

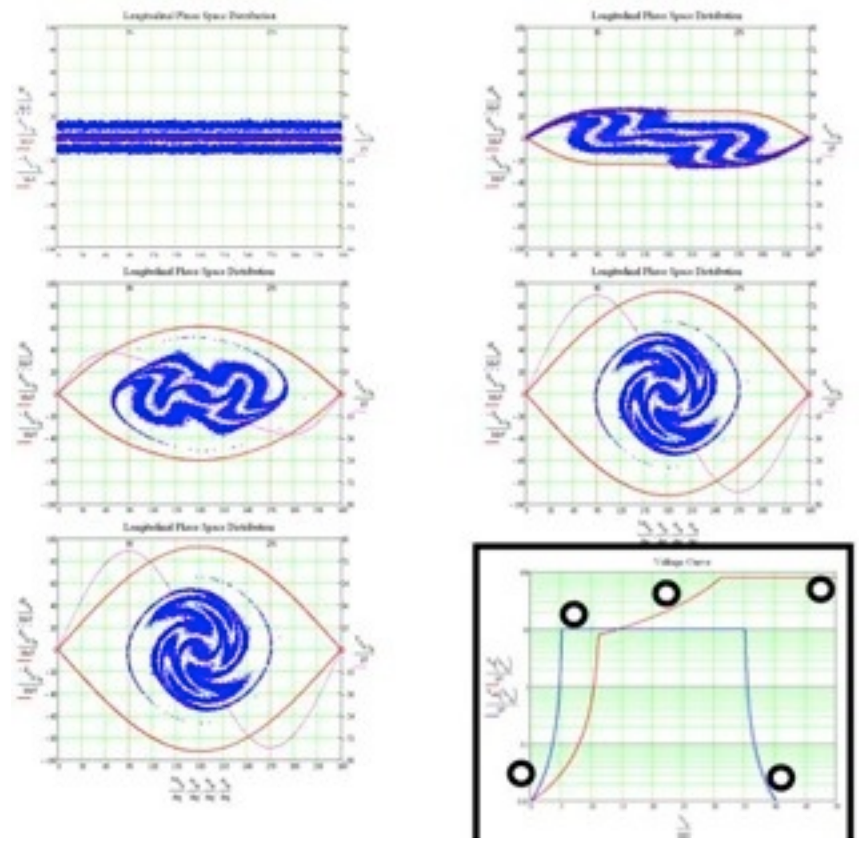
	S.E. sensitivity	BG events at aimed sensitivity	running time (sec)	Year	Comments
COMET Phase-I	$3x10^{-15}$	0.03	$1.5x10^{6}$	~2016	Proposal (2012)
COMET Phase-II	$3x10^{-17}$	0.34	$2x10^{7}$	~2019	CDR (2009)
Mu2e	$3x10^{-17}$	0.4	$3x (2x10^{7})$	~2019	J. Miller's talk at SSP2012

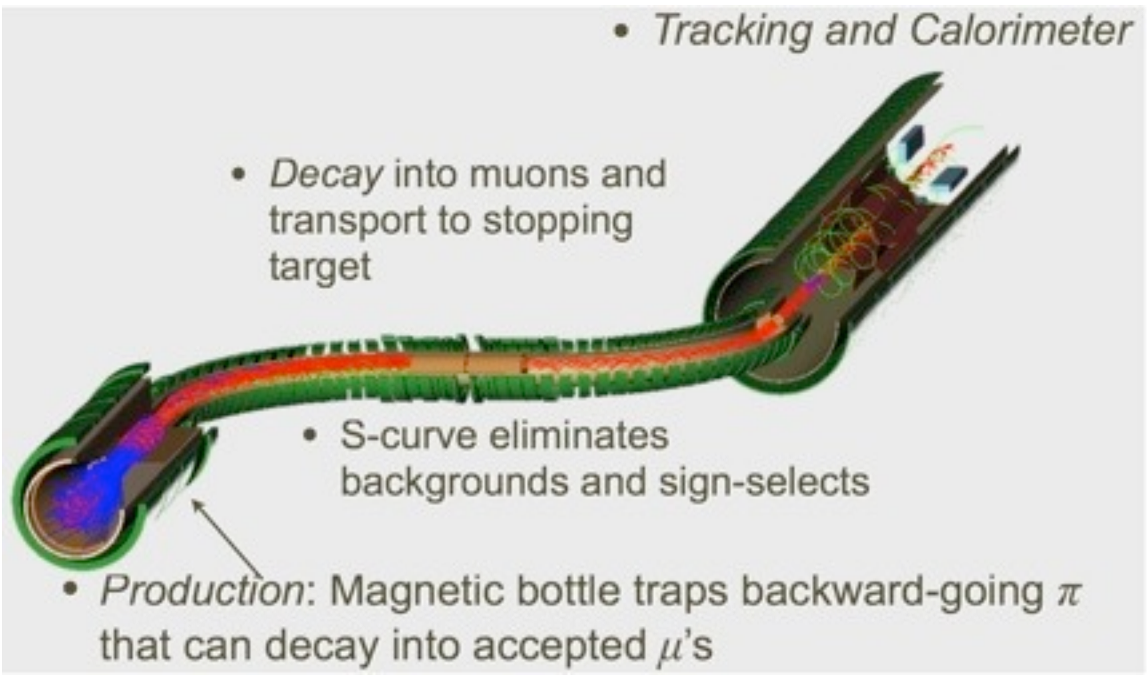
COMET & Mu2e Schedule



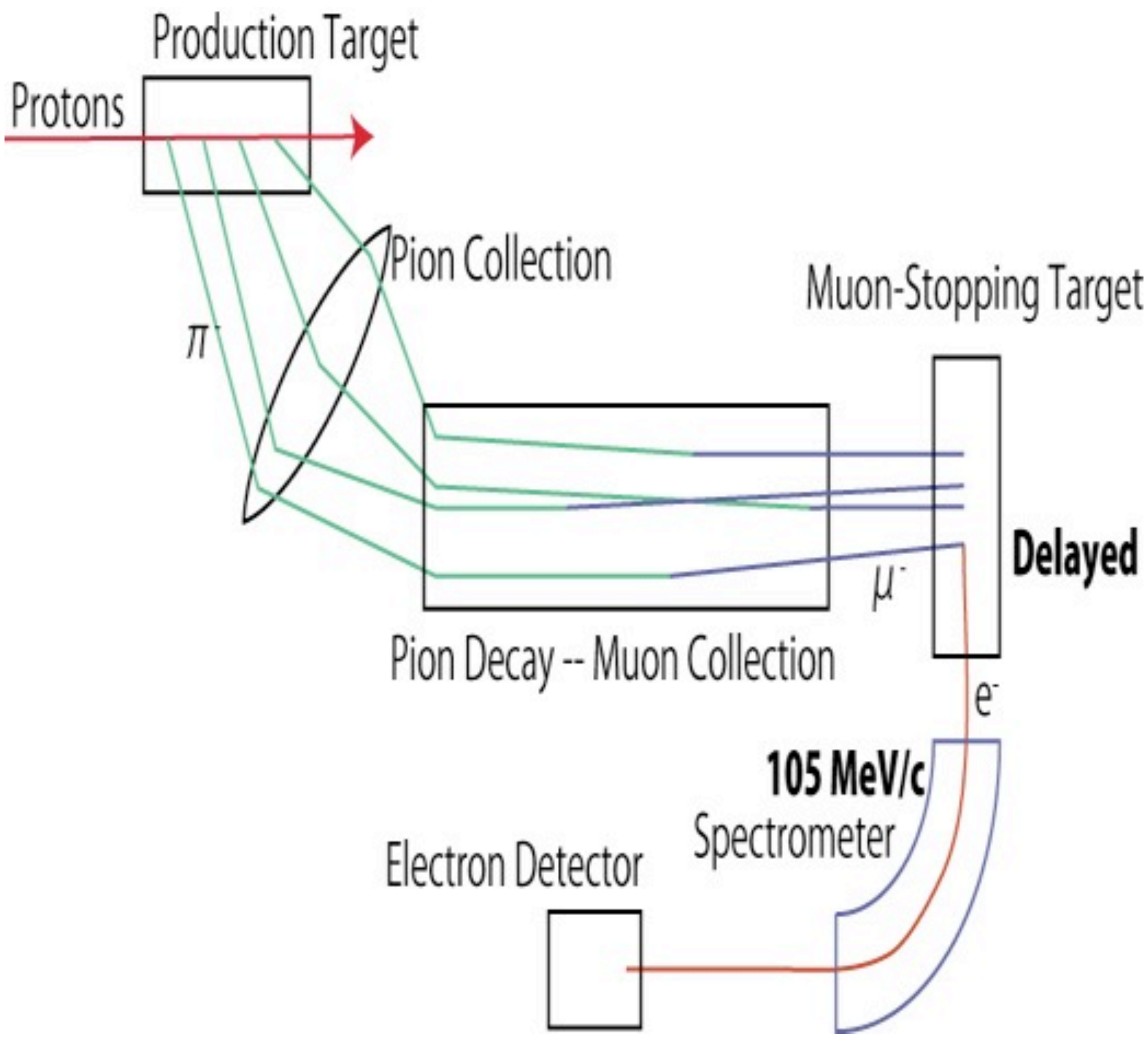
Mu2e Experiment at FNAL

- 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



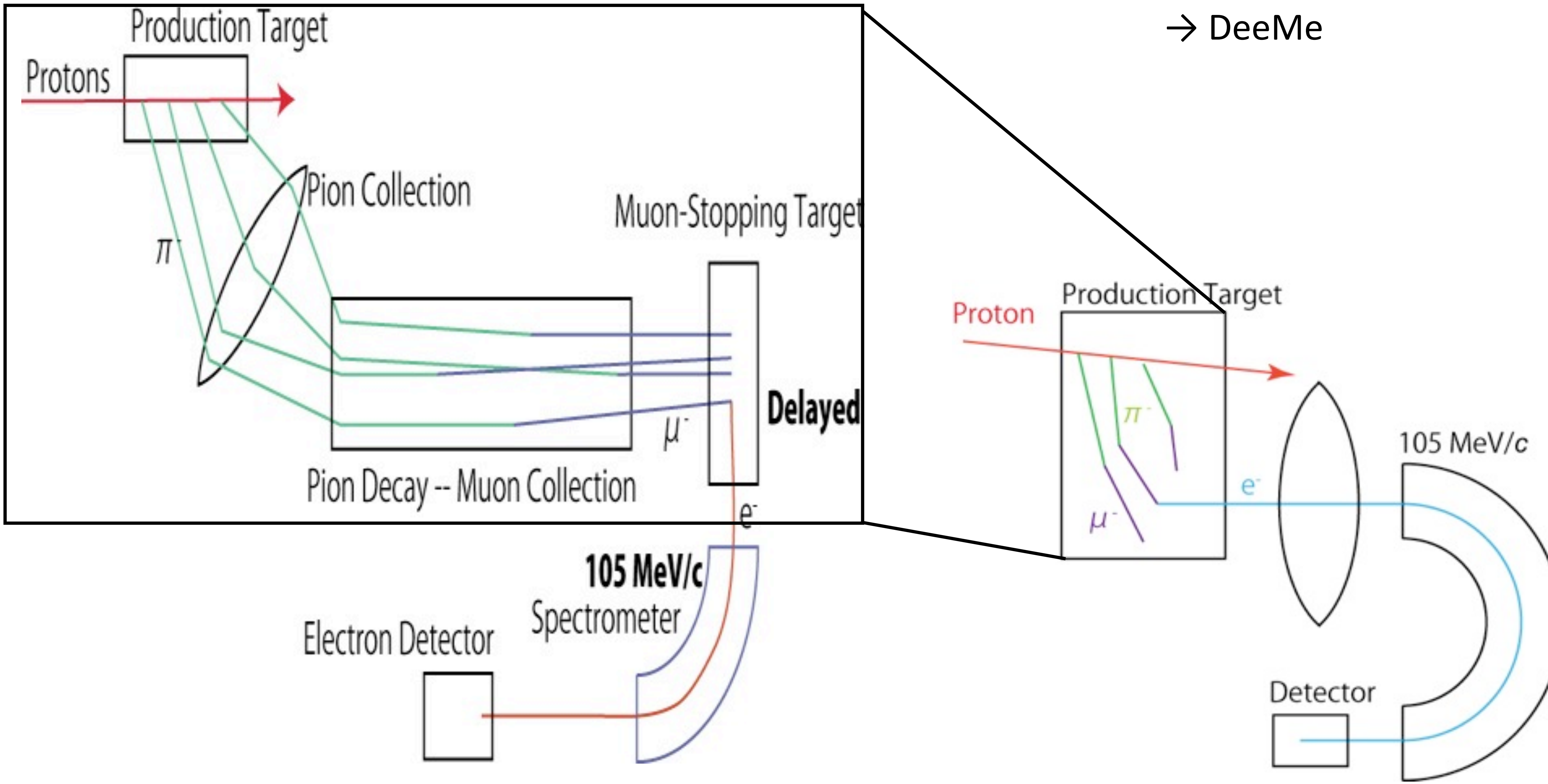


DeeMe at J-PARC MLF



- An electron analogue of the surface muon.
- Experiment could be very simple, quick and low-cost.

DeeMe at J-PARC MLF

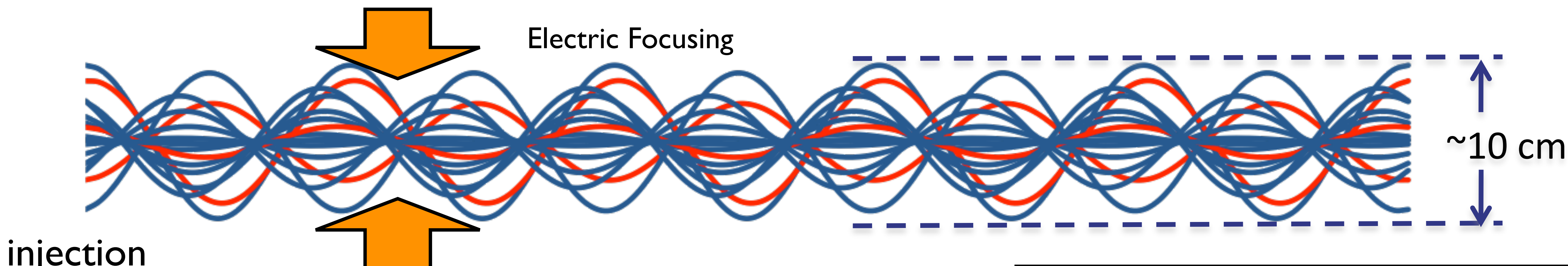


- An electron analogue of the surface muon.
- Experiment could be very simple, quick and low-cost.

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?