Muon Conversion Experiments: COMET/Mu2e and future

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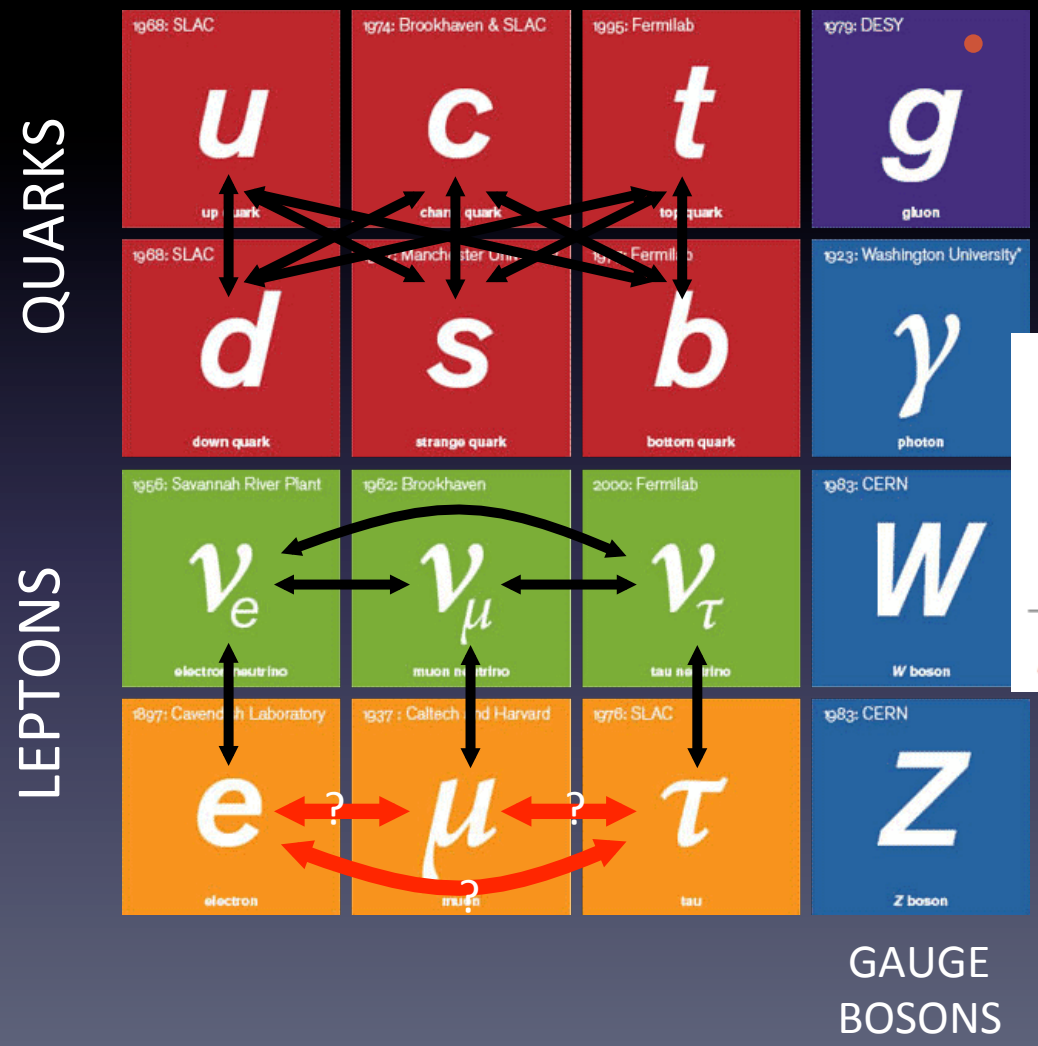
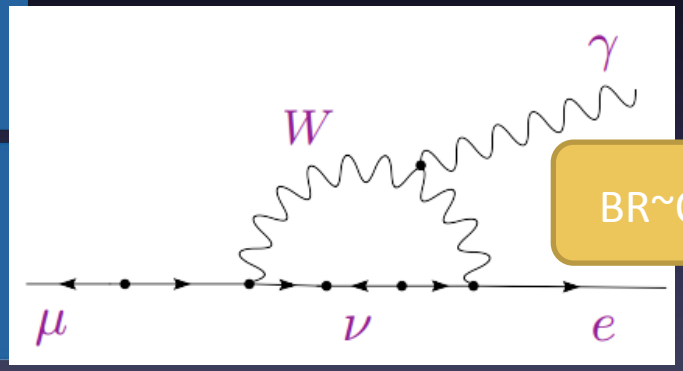
HINT 2015

Lepton Flavor Violation (LFV)



Charged Lepton mixing NOT observed

- Very small possibility in SM



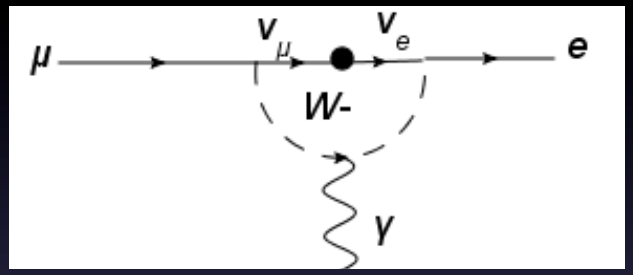
BR~O(10^{-54})

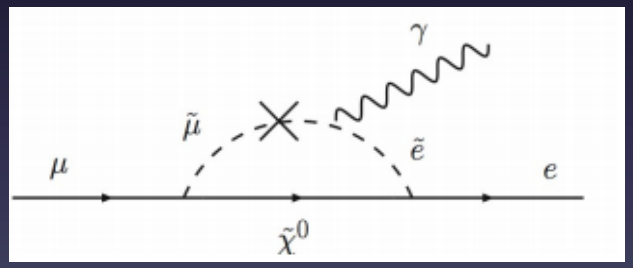
- **LFV = New physics in BSM**

Muon LFV

Note : $\mu \to e \nu_e \nu_\mu$

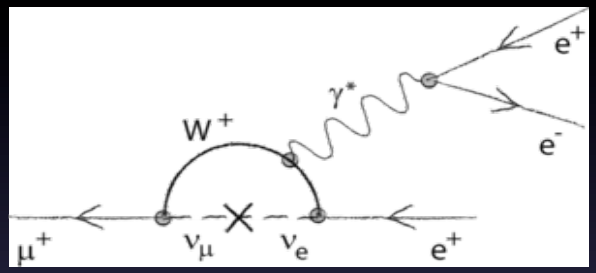
$\mu \to eY$

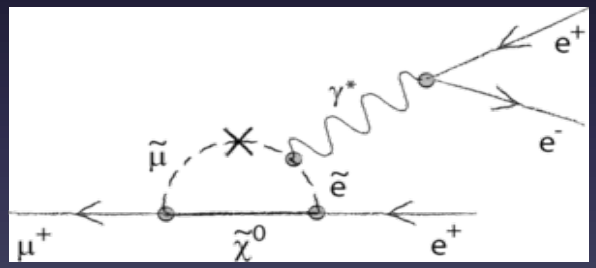




- MEG (PSI)
- MEG upgrade (planned)

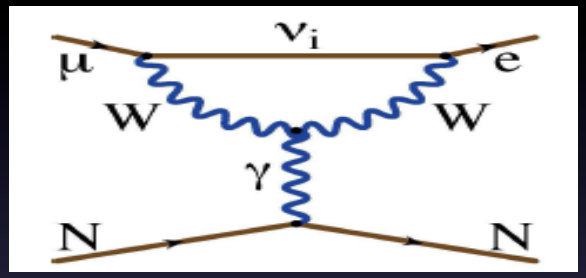
$\mu \to 3e$

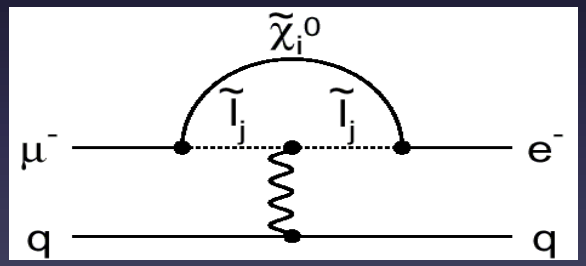




- Mu3e (PSI, planned)

$\mu N \to eN$

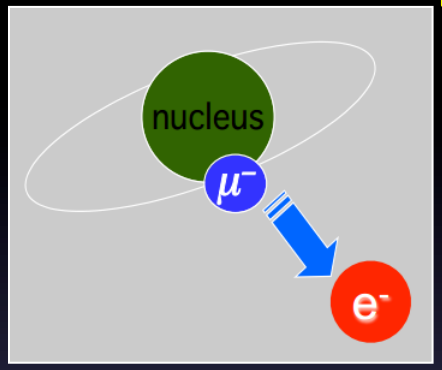


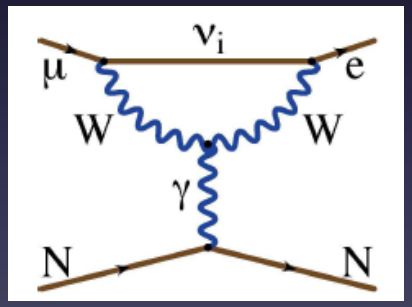


- Mu2e (FNAL)
- **COMET** (J-PARC)

Muon conversion experiment

$\mu^- N \rightarrow e^- N$

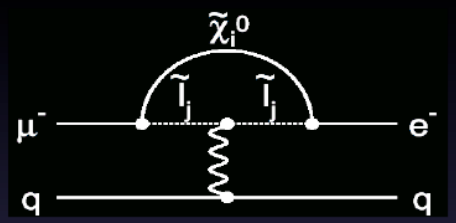


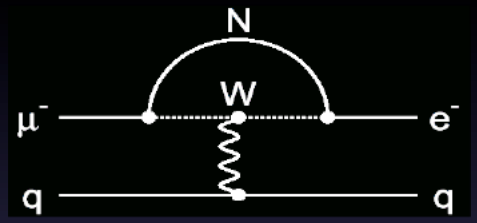


Standard model Muon conversion : $R \approx 10^{-54}$

$$R_{\mu e} = \frac{\text{Muon to Electron conversion rate}}{\text{Ordinary muon capture rate}}$$

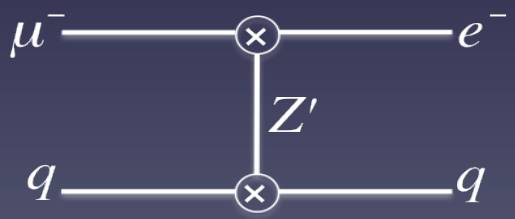
Beyond Standard Model





Supersymmetry : $R \leq 10^{-13}$ Heavy neutrino

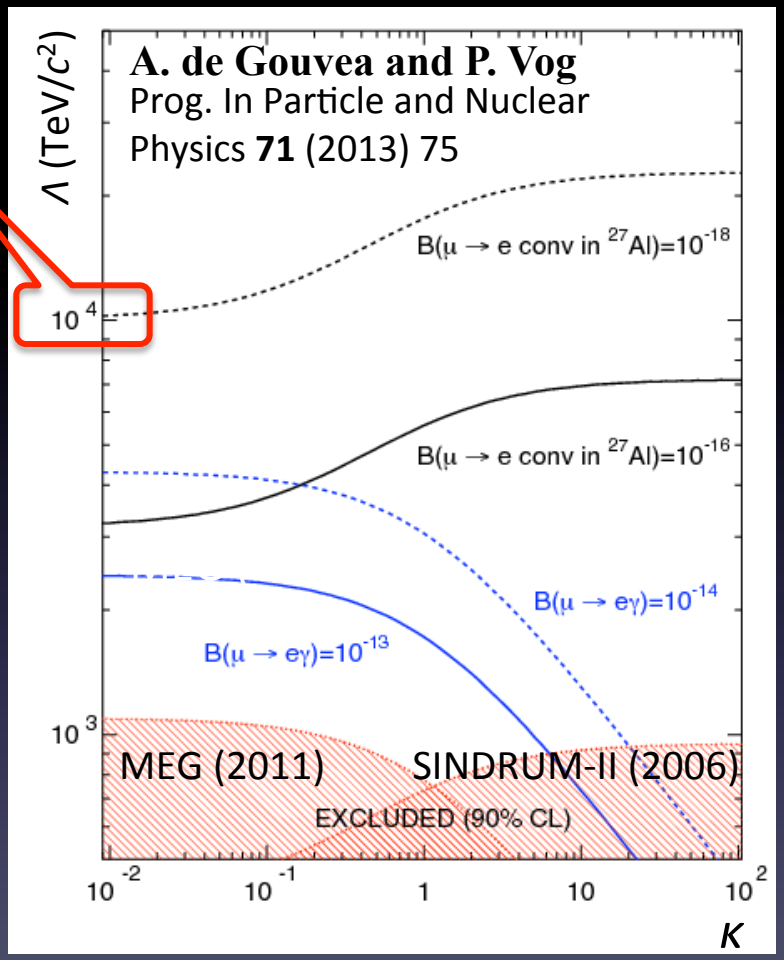
Only COMET/Mu2e sensitive

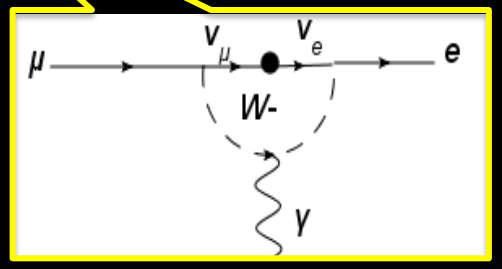


μN→eN vs μ→eγ

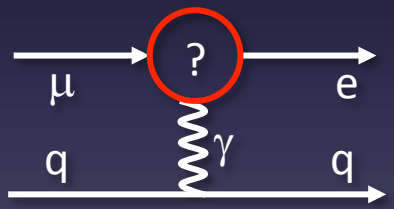
Probing O(10^4) TeV mass scale,

➔ Much higher energy scale than LHC





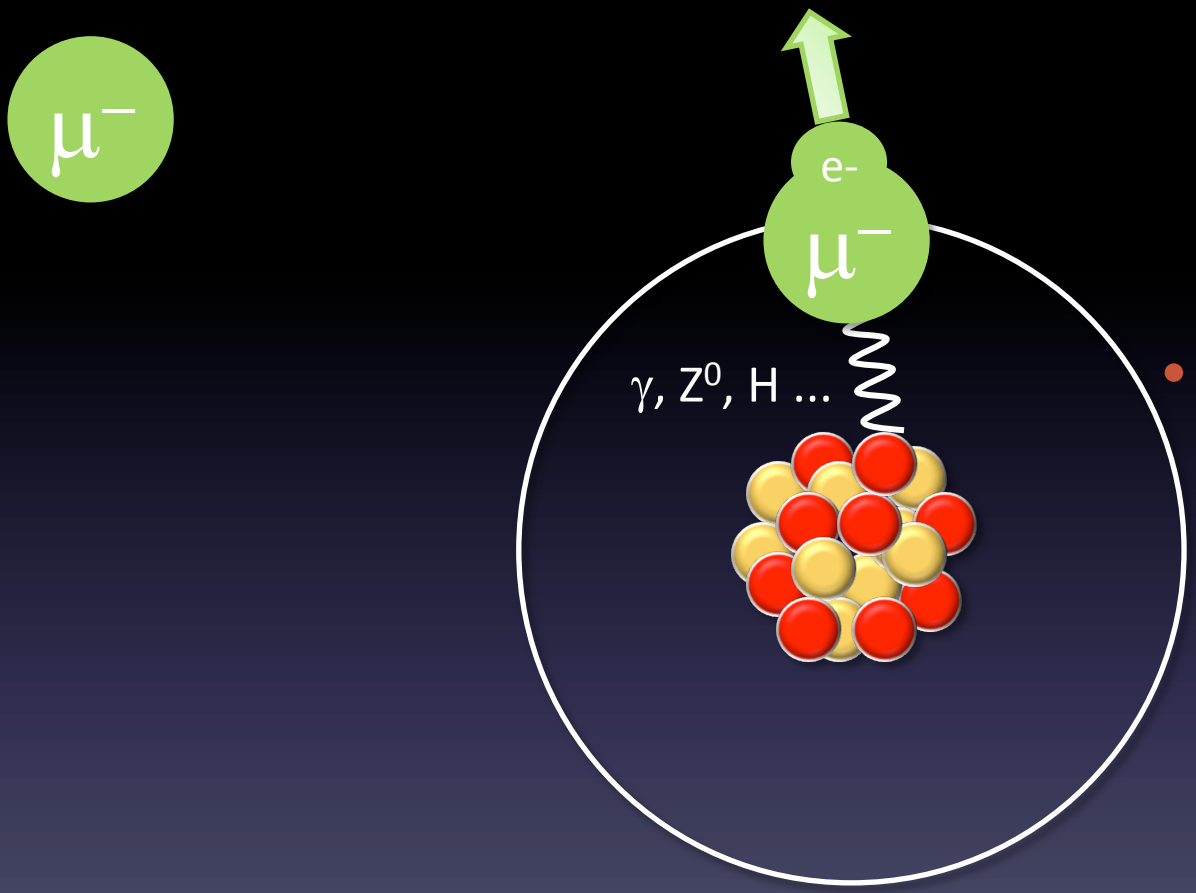
Dipole Interaction



Contact interaction

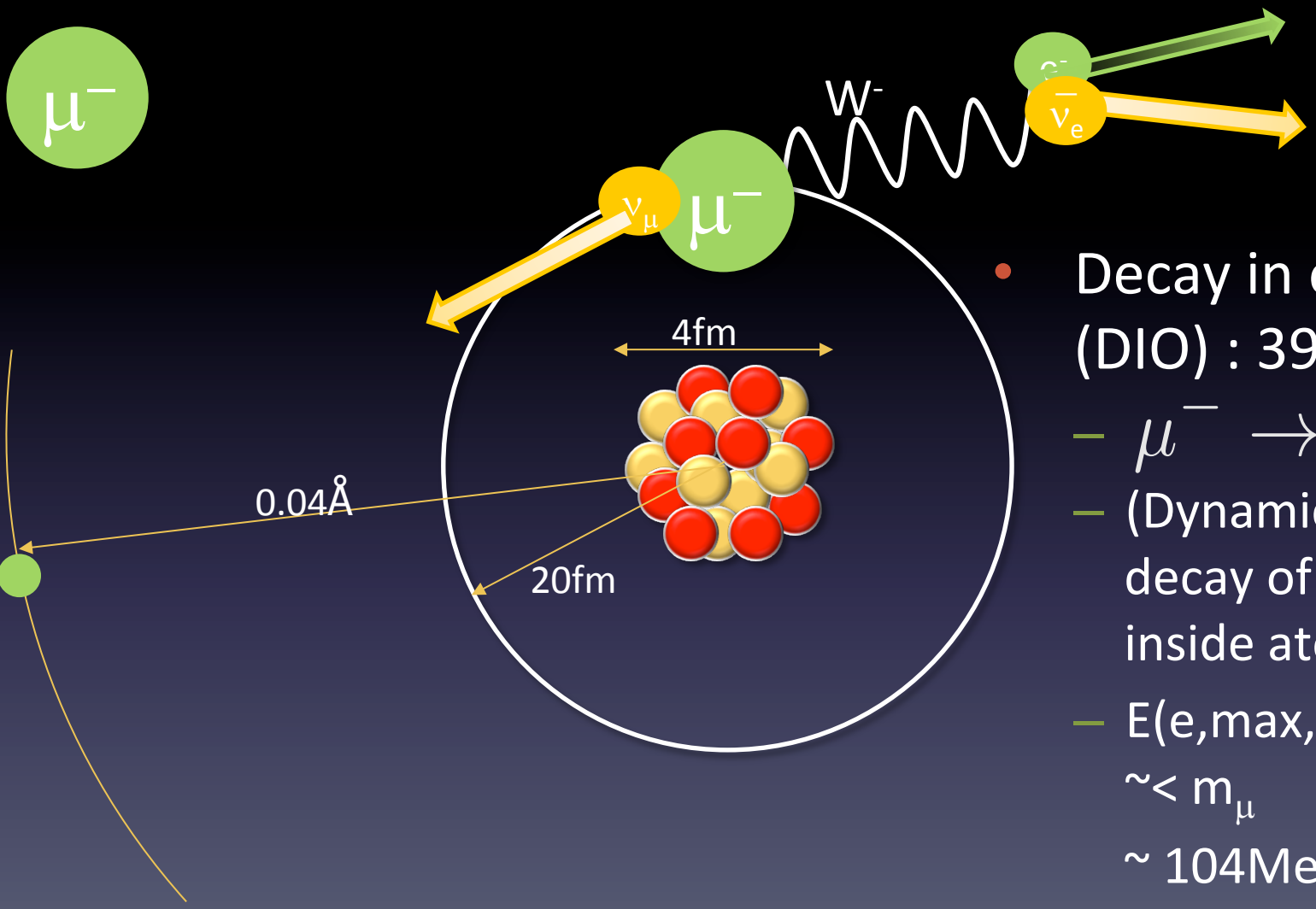
$$L_{CLFV} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\Big(\sum_{q=u,d}\bar{q}_L\gamma_\mu q_L\Big)$$

Stopped μ- in matter: Conversion



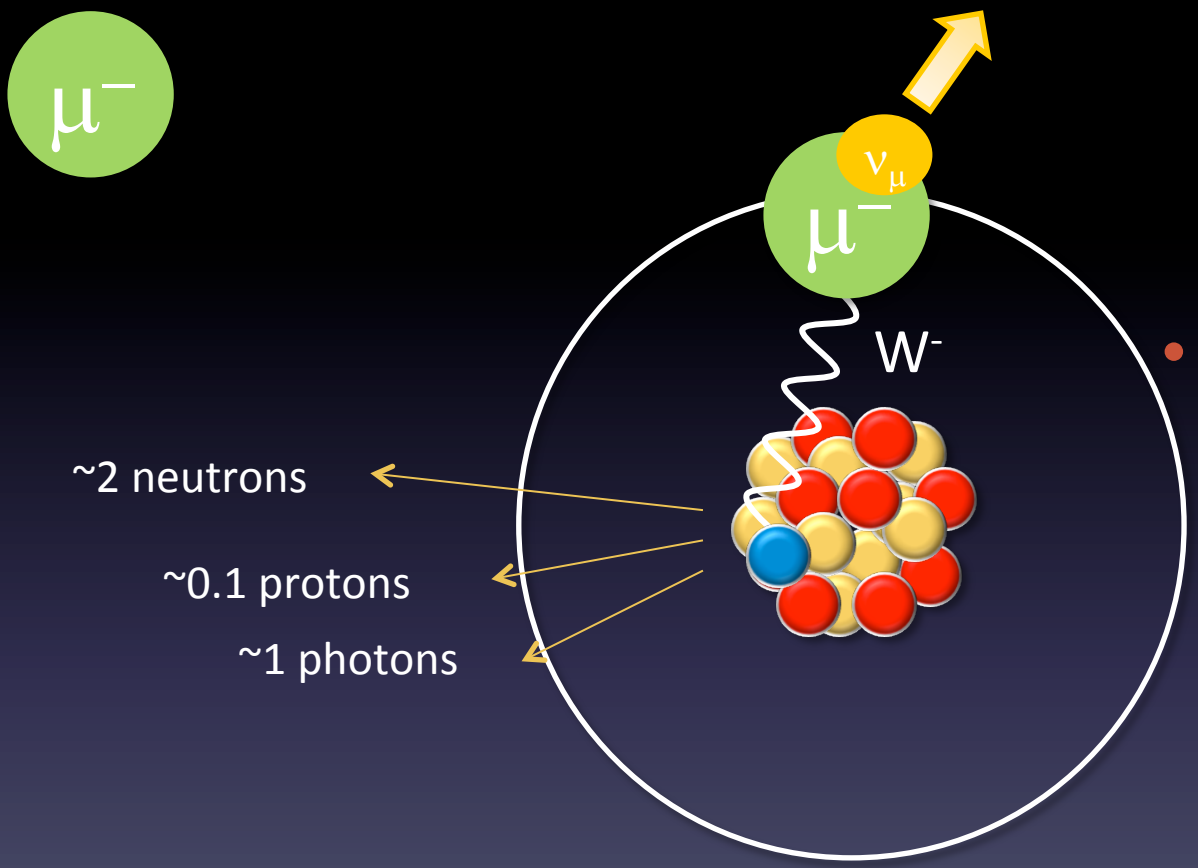
- Muon converion
  - $\mu^- + N \rightarrow e^- + N$
  - Muon conversion coherently with nucleus

Stopped μ- in matter: DIO



- Decay in orbit (DIO) : 39% (Al)
  - $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$
  - (Dynamically) free decay of muon inside atom
  - E(e,max,Al) ~< m_μ ~ 104MeV (peak at 50 MeV)

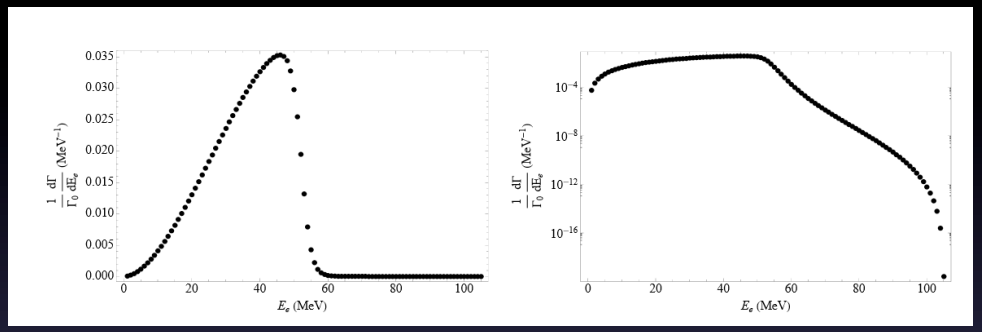
Stopped μ- in matter: Capture



- Muon capture : 61% (Al)
  - $\mu^- + p \rightarrow \nu_\mu + n$
  - Muon decay coherently with nucleus
  - Source of background hits

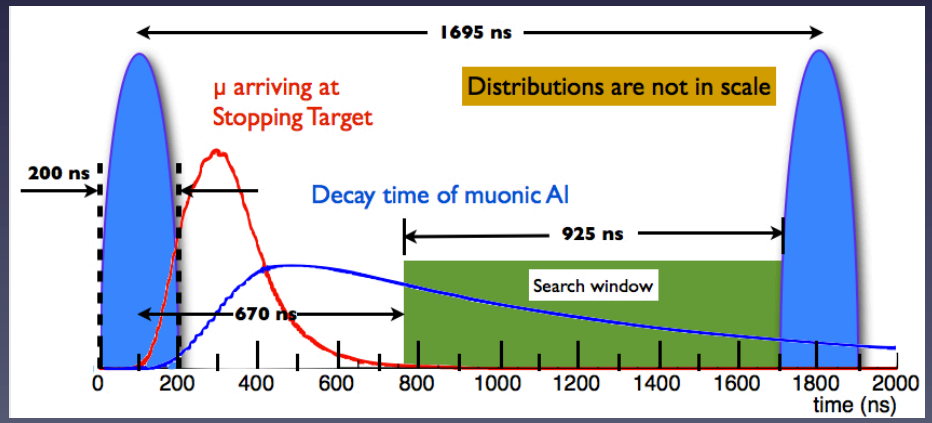
Backgrounds

- Decay-In-Orbit (DIO) : dominant BG
  - Not always BG but one way to calibrate detector



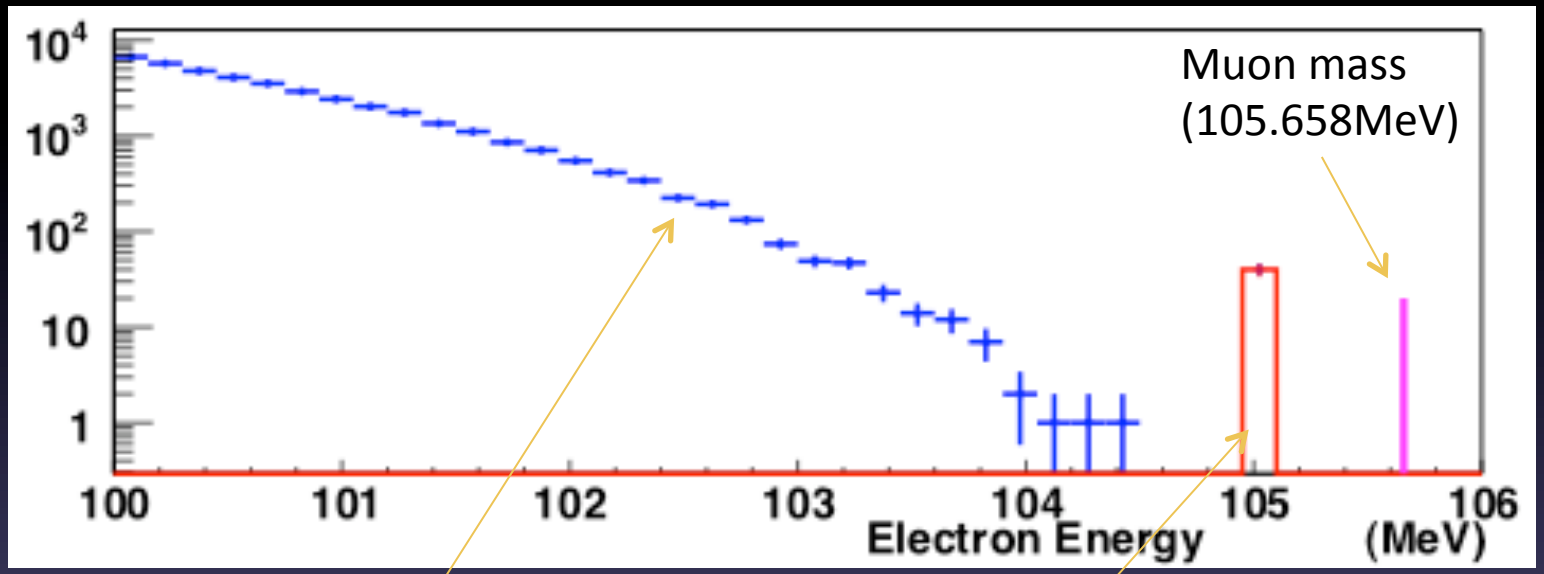
- Prompt background (to beam arrival)
  - By beam π/n/e, muon/pion decay in flight
  - Ex) πN→γX; γ→e+e-, E(e-)~105MeV mimics signal
  - "Pulsed beam" with "high extinction" required
    - 10^{-10} extinction required, achieved 10^{-10} - 10^{-12} at COMET

(Mu2e beam spill profile)

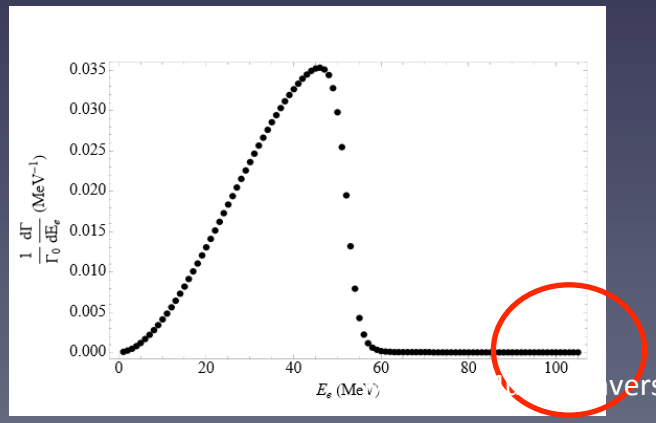


Muon Conversion Signal

(Ideal detector)



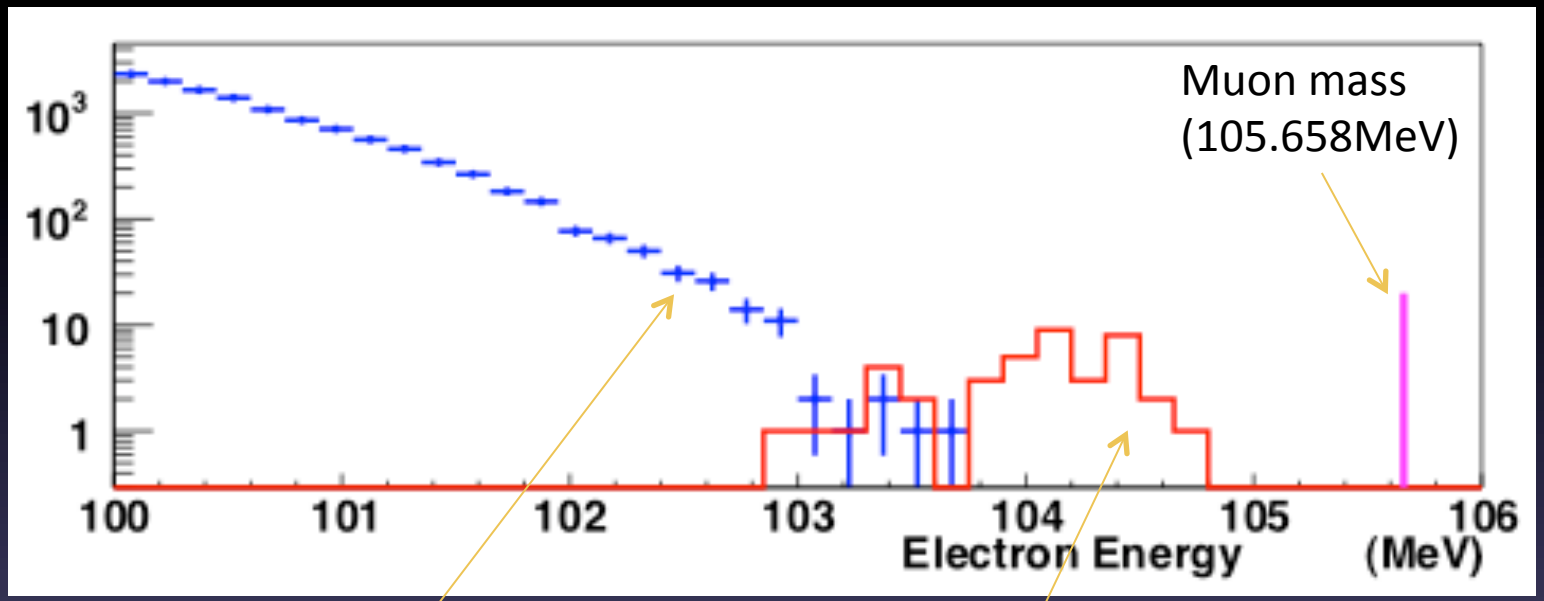
Muon Decay-In-Orbit



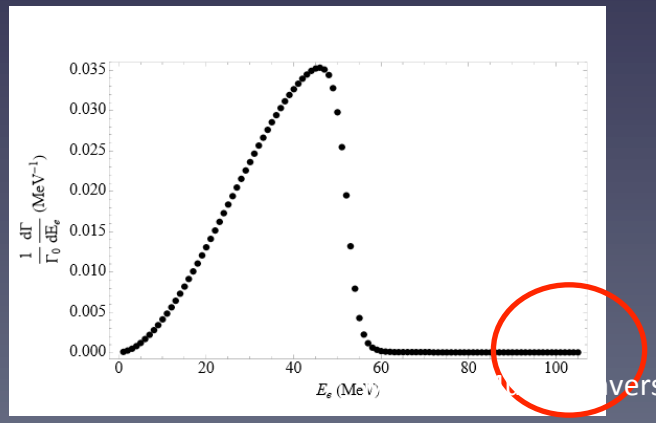
Signal : ~105MeV monoenergetic electron $= m_\mu - E_{rec} - E_B$

Muon Conversion Signal

(Real detector)

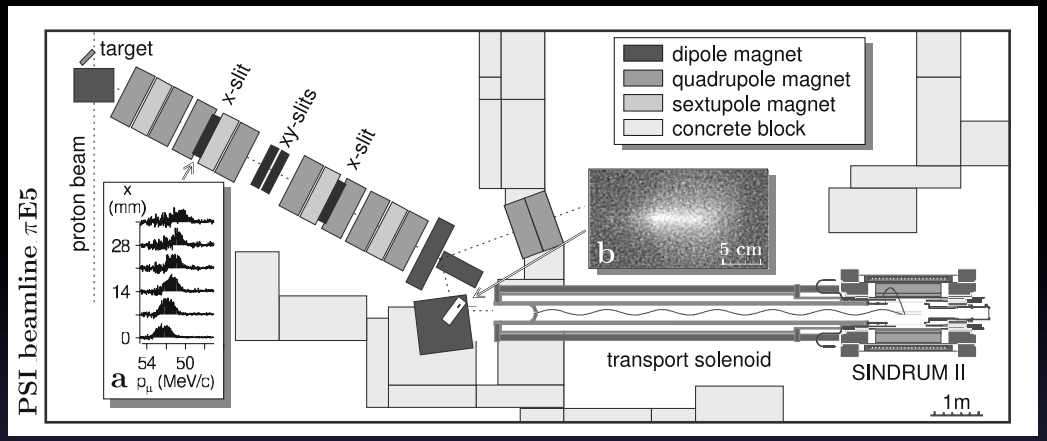


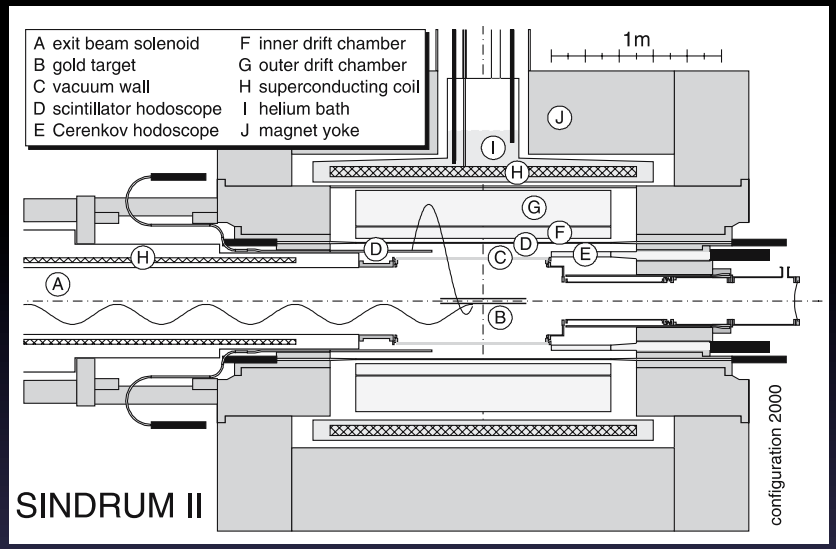
Muon Decay-In-Orbit

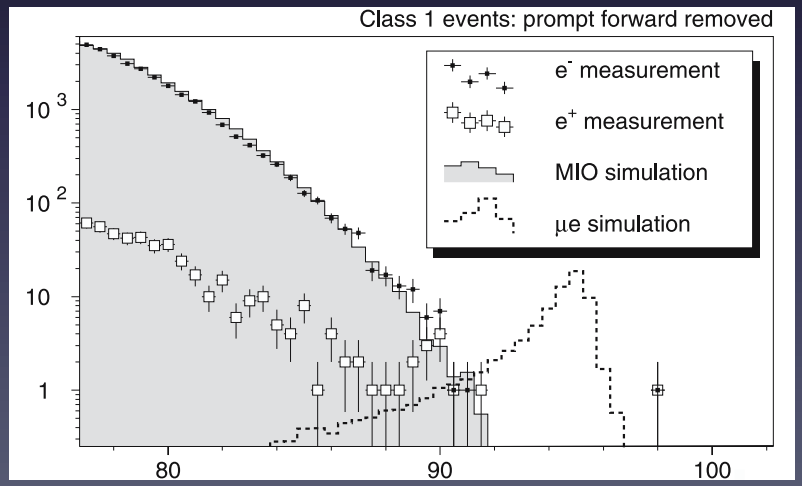


Signal : ~105MeV monoenergetic electron $= m_\mu - E_{rec} - E_B$

A precursor : SINDRUM-II (@PSI)







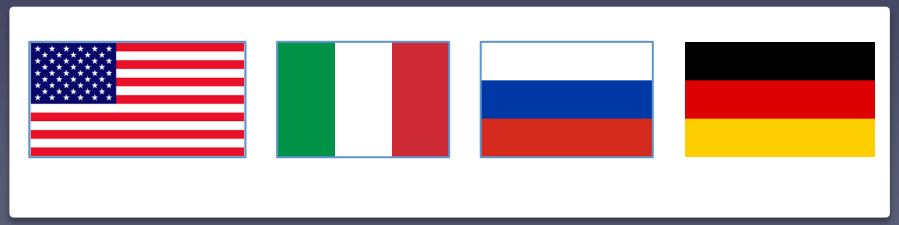
$$B_{\mu e}^{\mathrm{Au}} < 7 \times 10^{-13} \quad 90\%\, C.L.$$

Eur. Phys. J. C 47, 337–346 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2006-02582-x

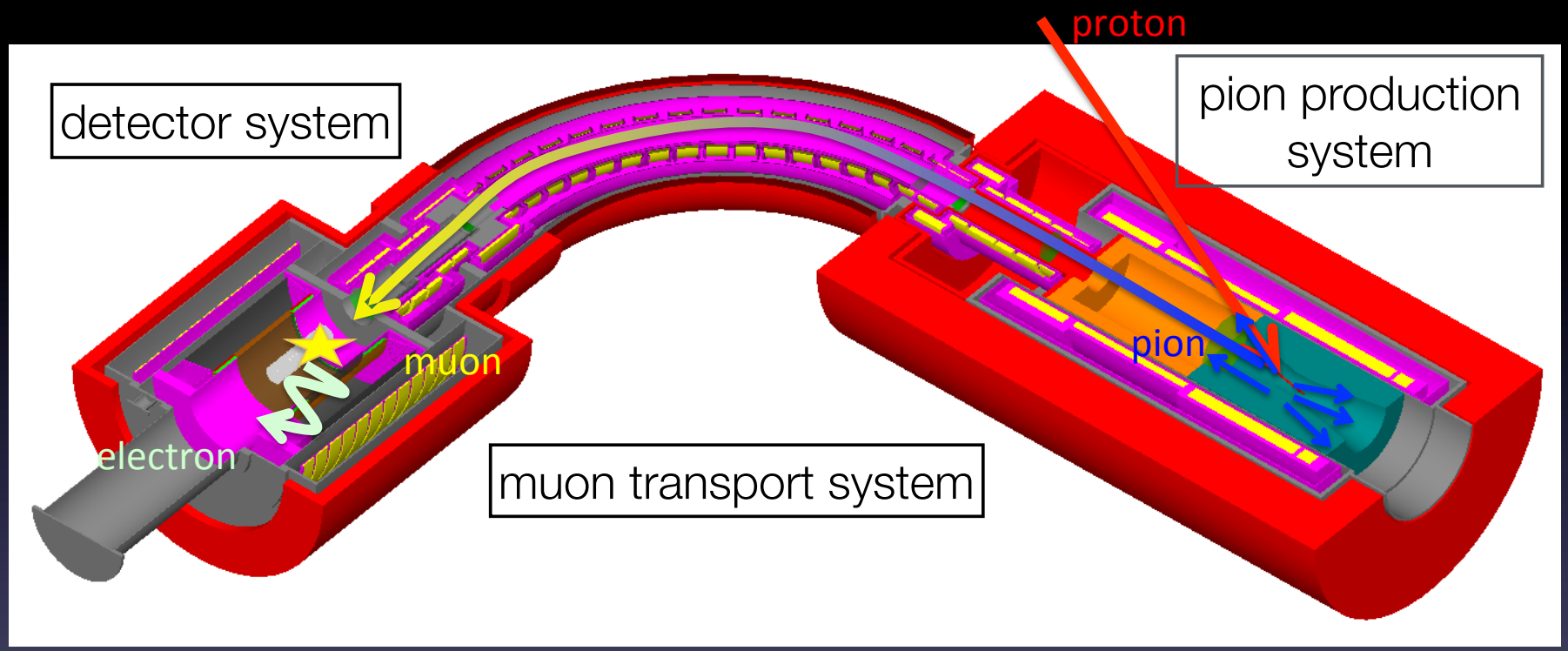
COMET (J-PARC) / Mu2e (FNAL)

177 collaborators,
32 institutes
(as of July 2015)

193 collaborators
33 institutions
(as of June 2015)

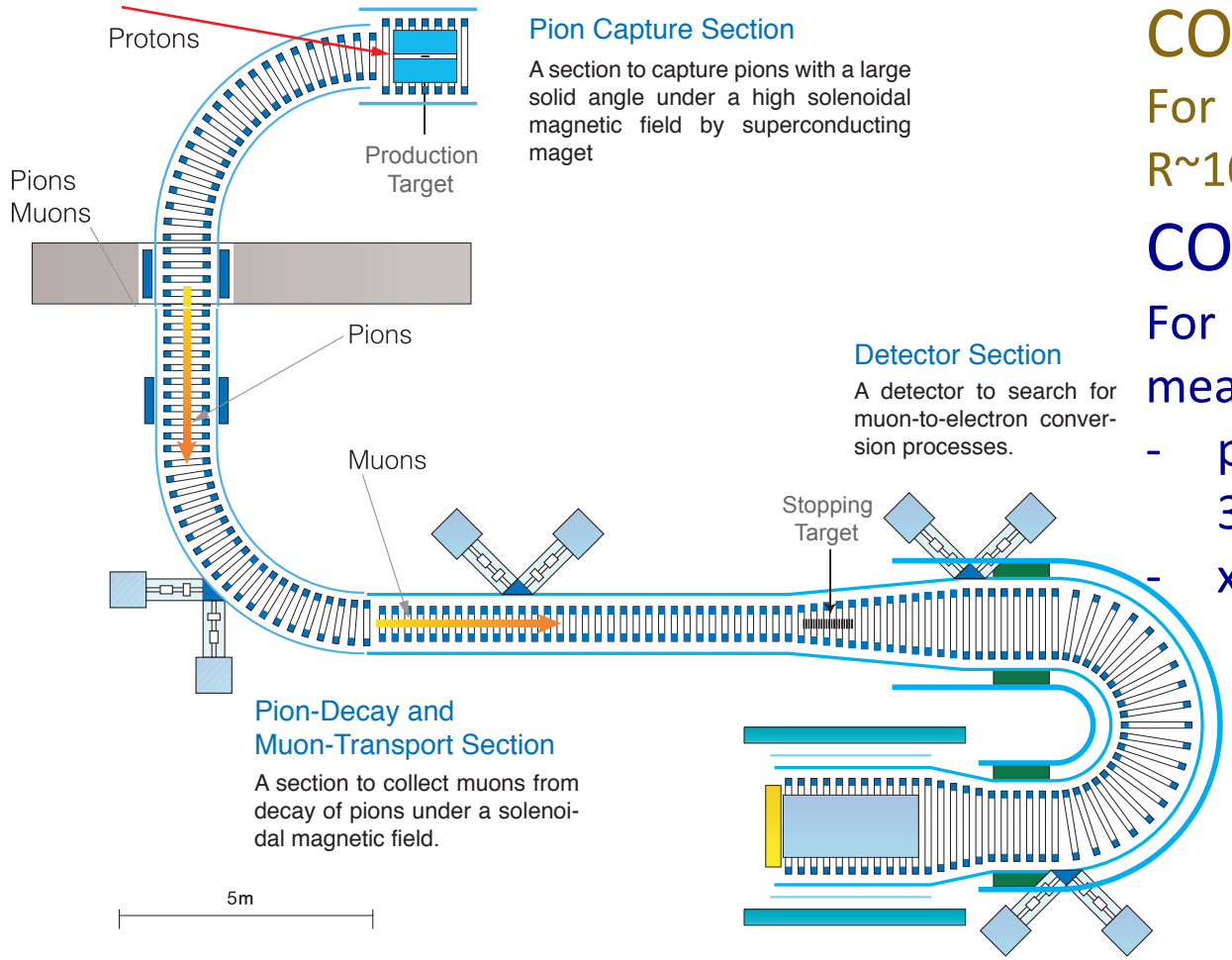


COMET Phase-I experiment



1. Proton hits target and generates pions
2. Negative pions are collected, decays to muon and transported through solenoid
3. Muon stops at target, captured and decays
4. Secondary electrons are detected at detector

COMET Phase-II experiment



COMET-Phase-I

For BG measurement, R~10^{-15} muon conversion

COMET Phase-II

For R~10^{-17} muon conversion measurement

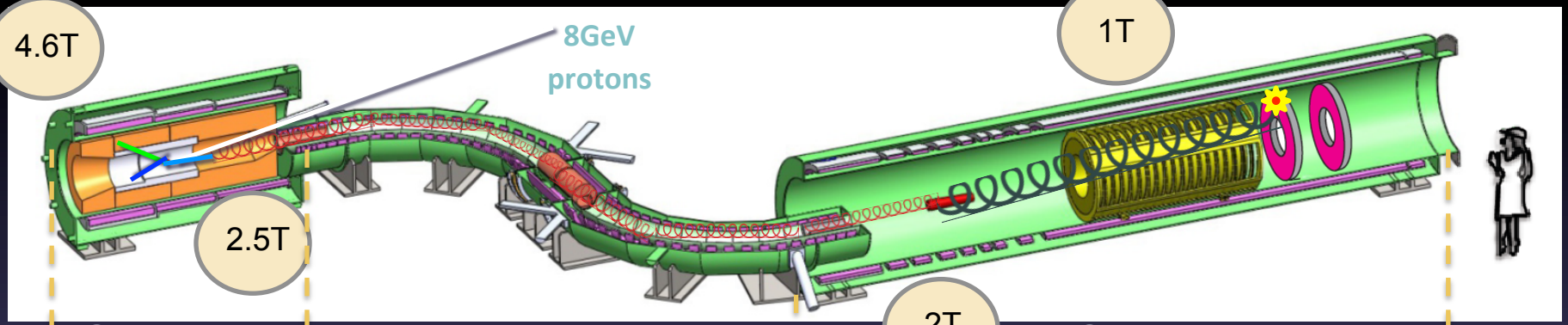
- proton beam power 3kW→56kW
- x2 DAQ time

Mu2e experiment

❶ Proton beam bunches with high extinction rate are provided to Mu2e.

❹ Muons reach Stopping Target , absorbed and decays coherently.

❻ Daughter electron finally hits calorimeters and provide energy and trigger information.



❷ Protons hit Production Target to generate pion.

❸ Pions are transported along solenoid system, and decay to muon.

❺ Daughter electron makes tracker straw hits. They are read out to measure the momentum precisely.

Production solenoid

: Gradient field to collect pions

Transport solenoid

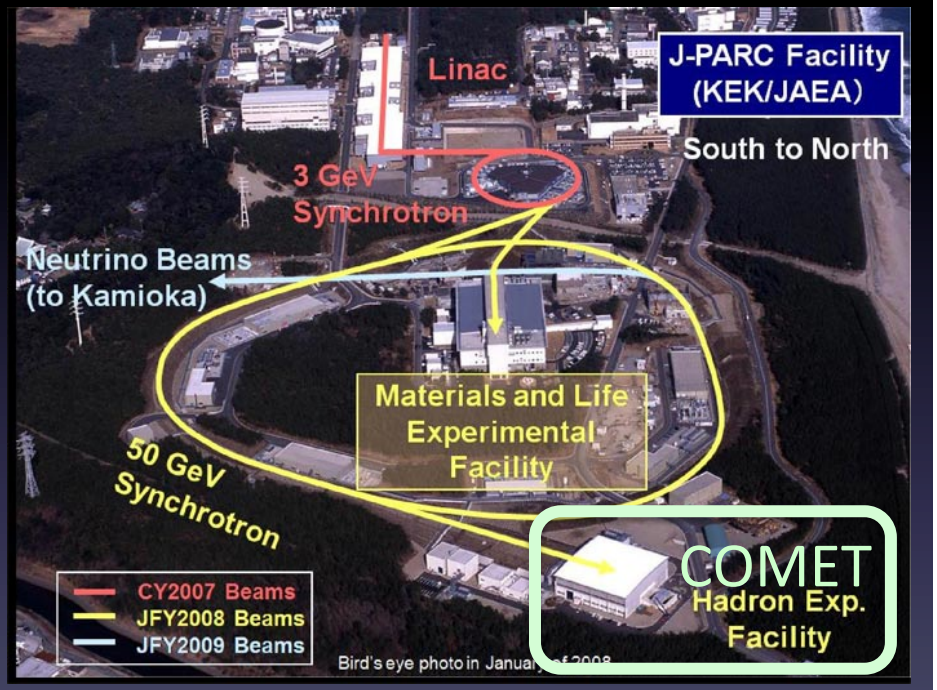
: Momentum and charge selection, S-shape to remove line-of sight neutron

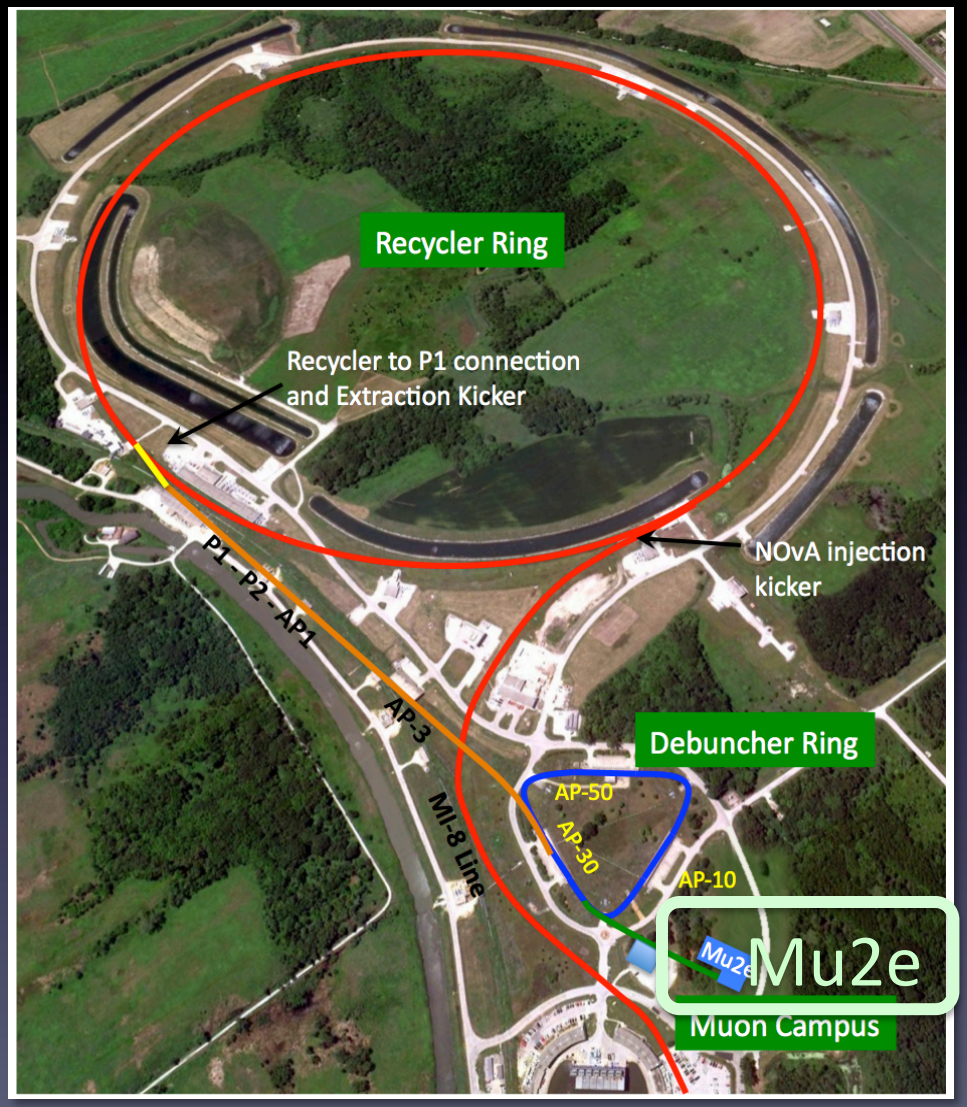
Detector solenoid

: Gradient field at upstream to collect electrons Constant field at downstream for tracking

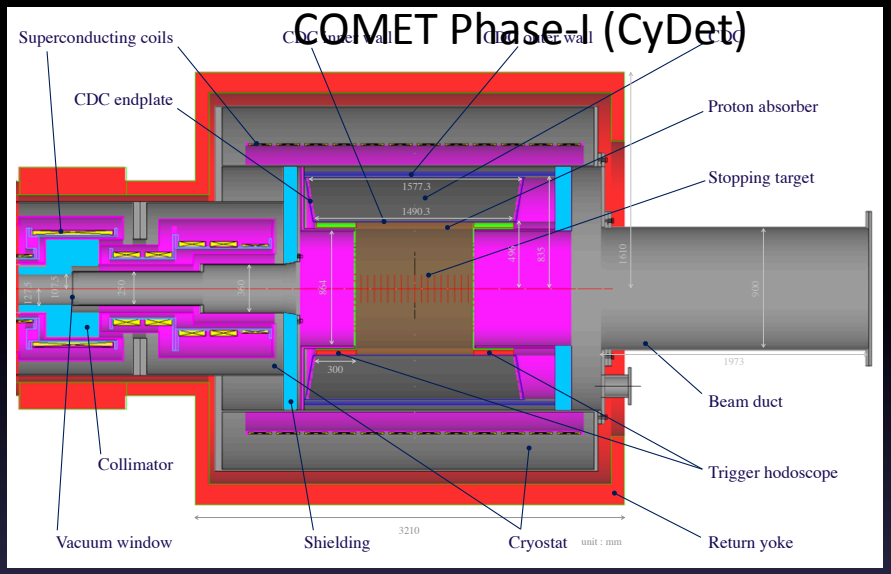
* Not shown : Cosmic ray veto, Muon beam dump, Proton/neutron absorber, Extinction monitor

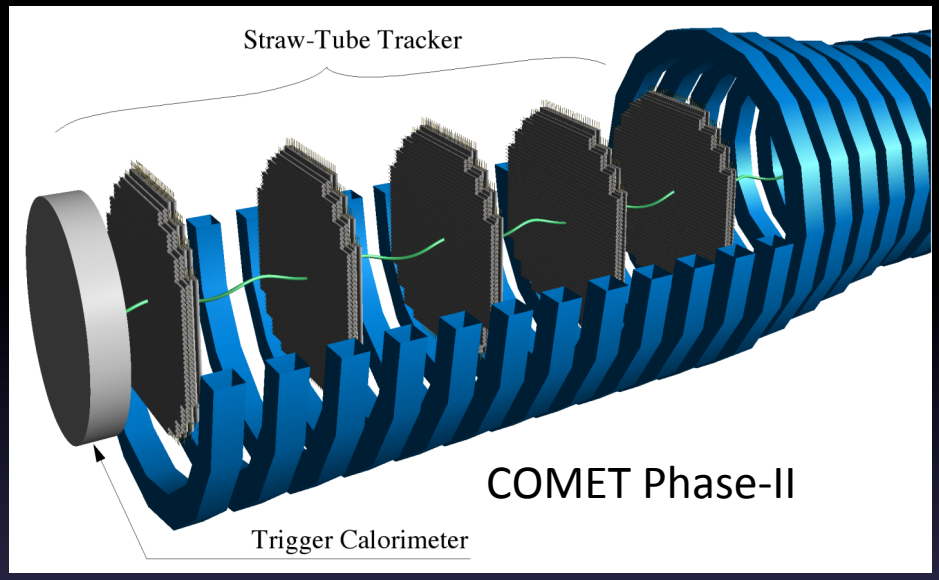
J-PARC / Fermilab facility

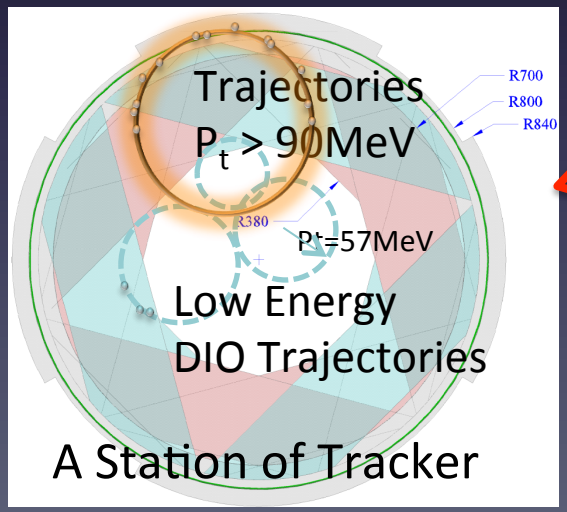


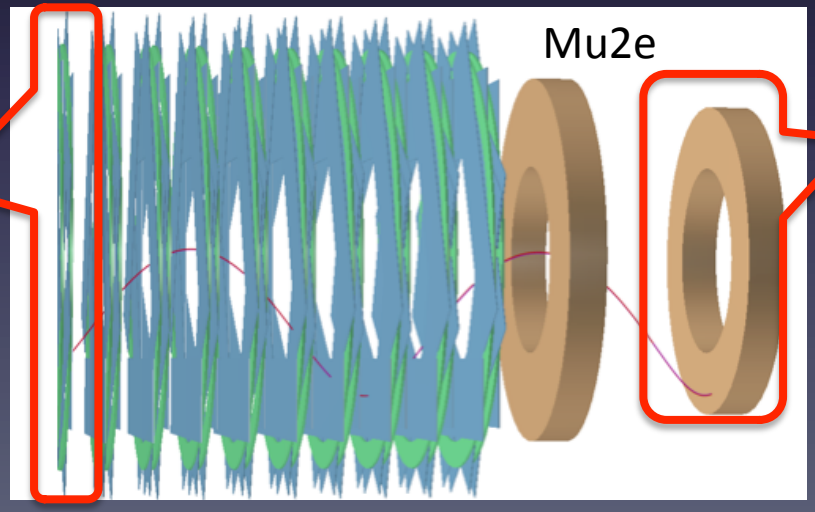


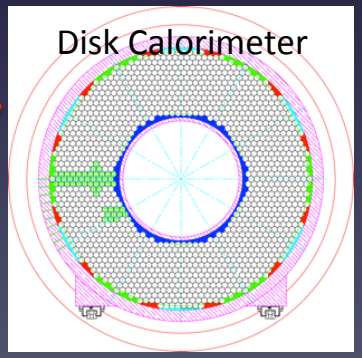
Detectors


COMET Phase-I (CyDet)
Superconducting coils
CDC endplate
Proton absorber
Stopping target
Beam duct
Collimator
Trigger hodoscope
Vacuum window
Shielding
Cryostat
Return yoke


Straw-Tube Tracker
COMET Phase-II
Trigger Calorimeter

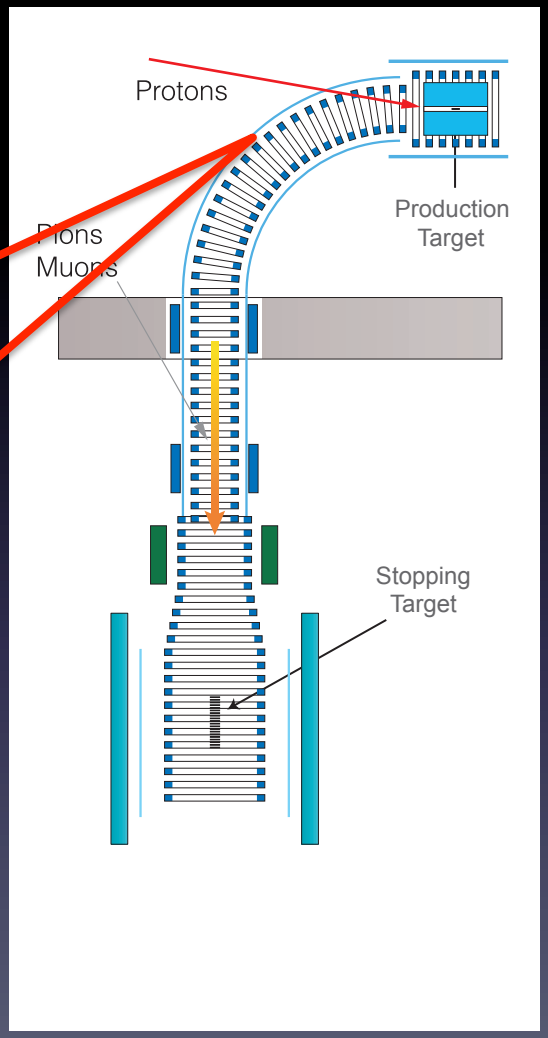

Trajectories
P_t > 90MeV
R700
R800
R840
R380
Pt=57MeV
Low Energy
DIO Trajectories
A Station of Tracker


Mu2e

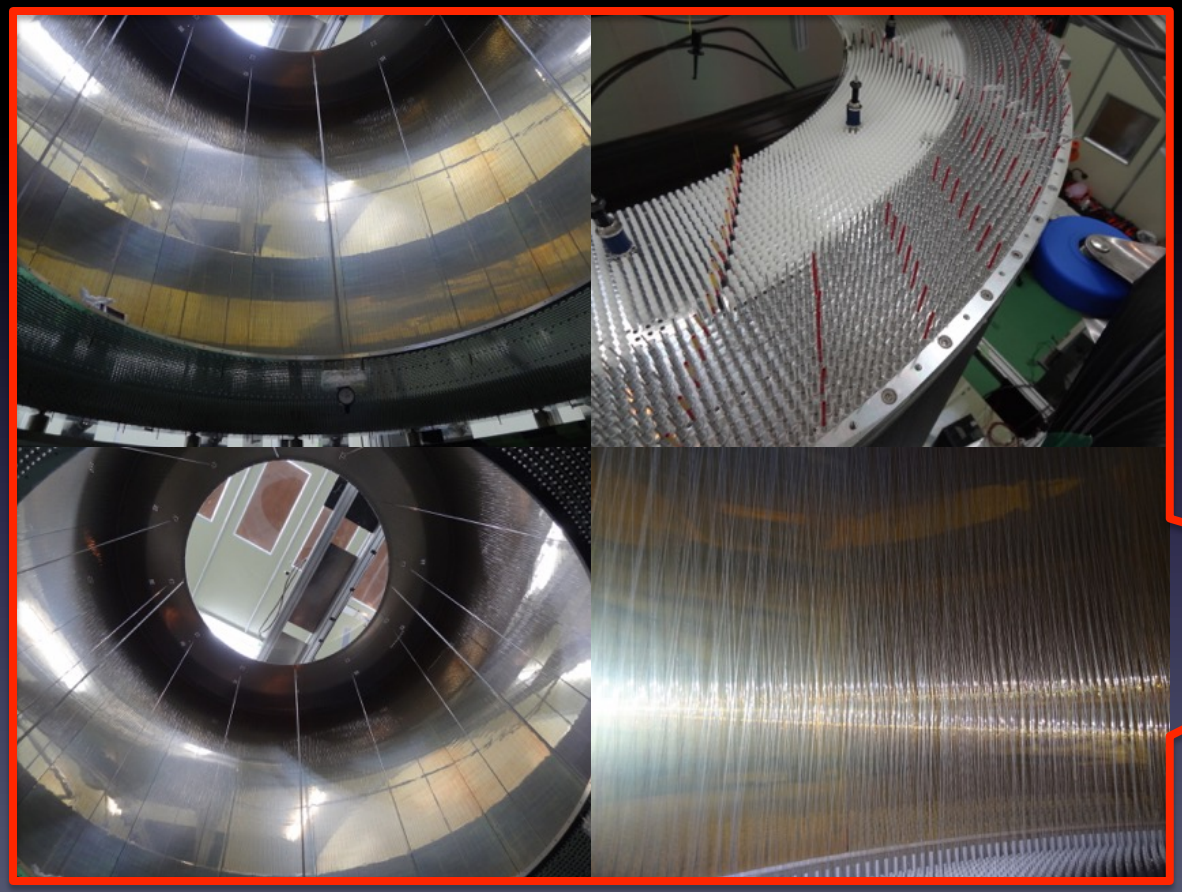

Disk Calorimeter

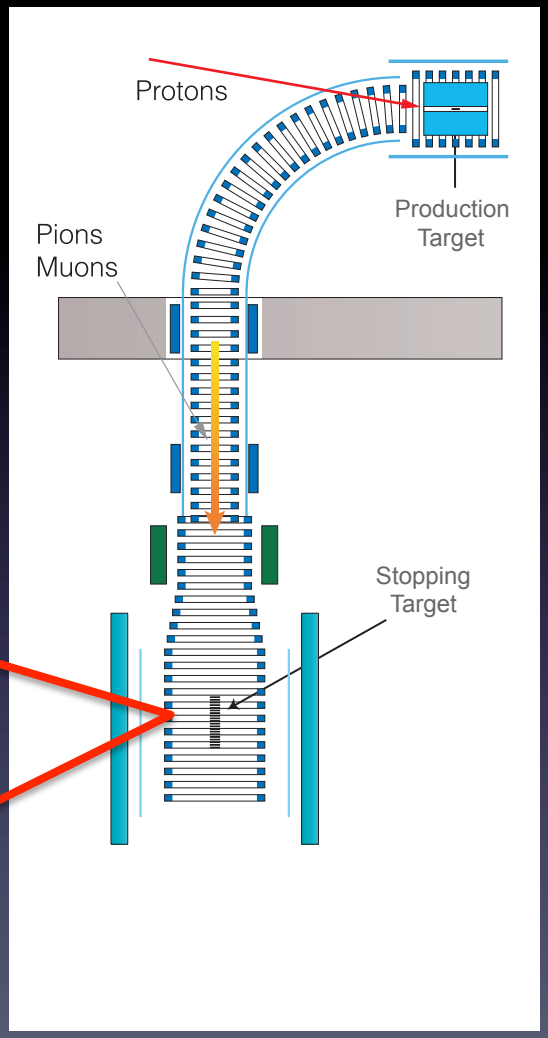
COMET Building Construction

COMET Transport Solenoid



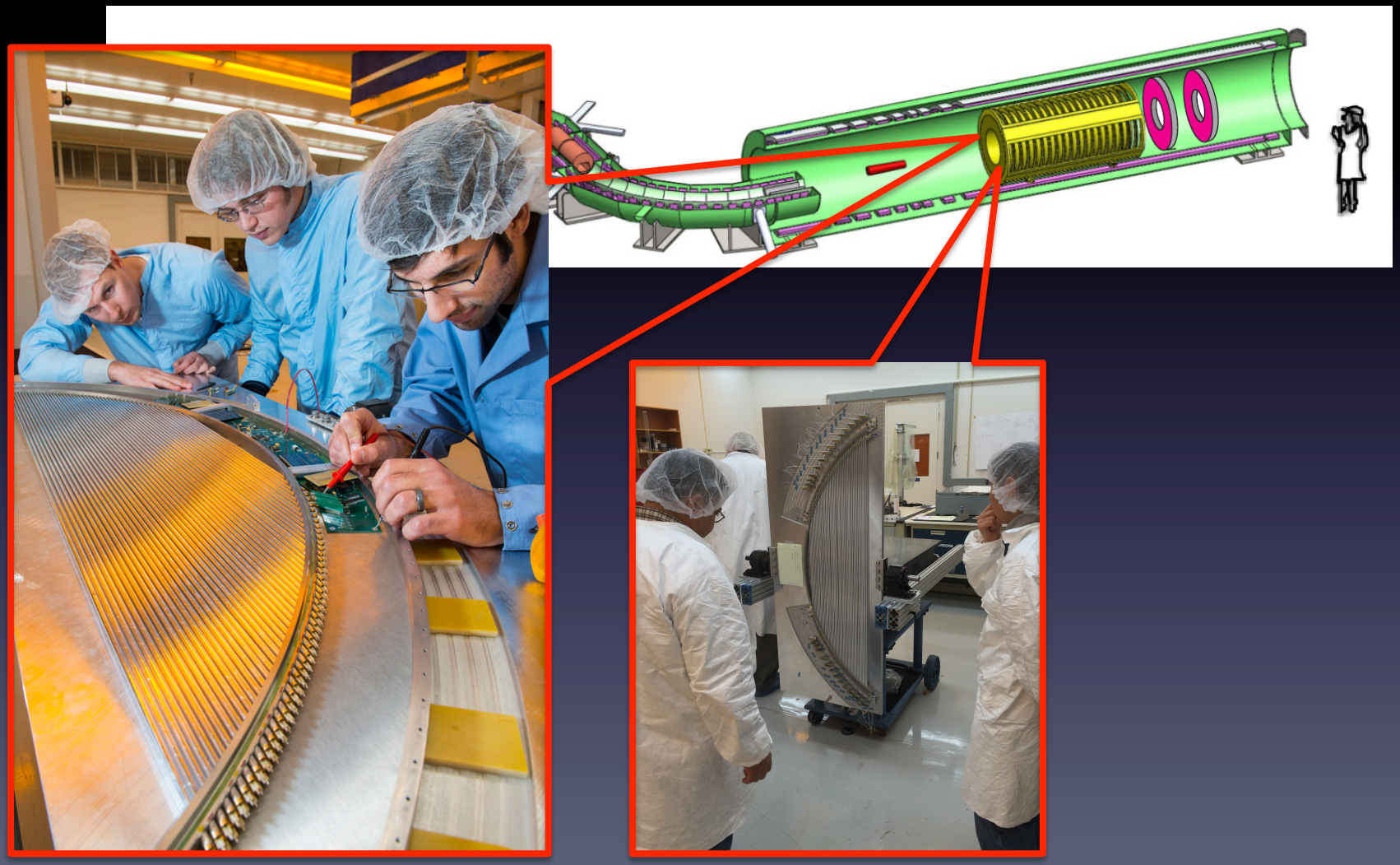
COMET Phase-I CyDet Detector



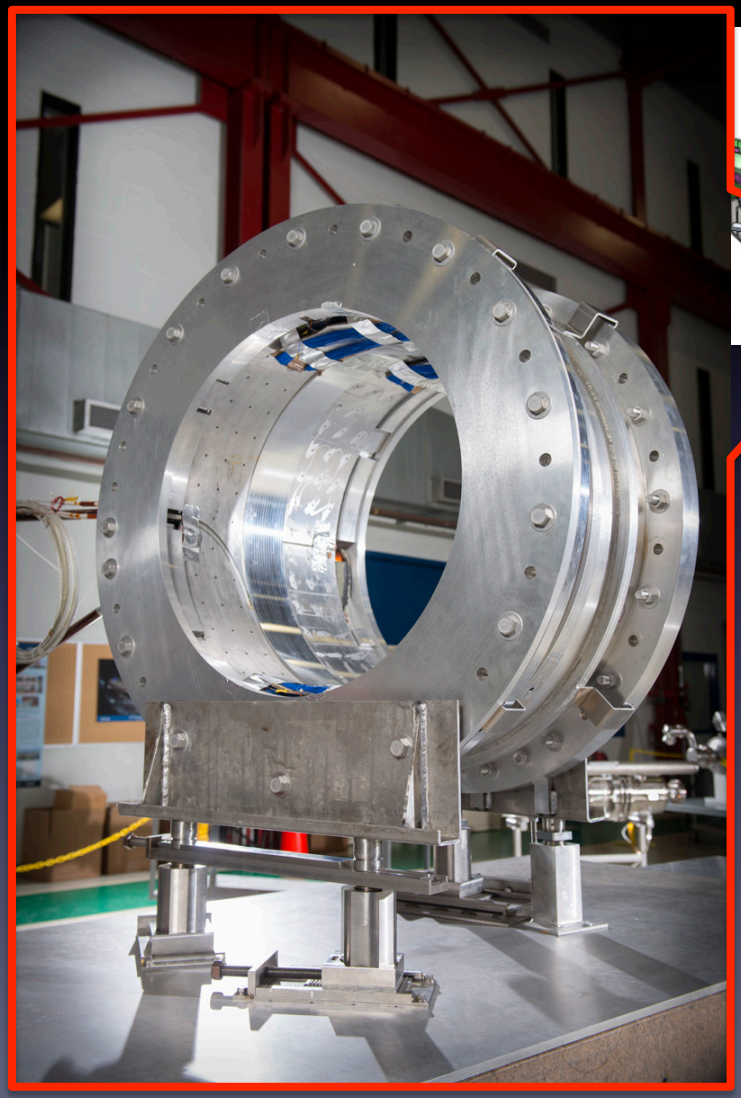


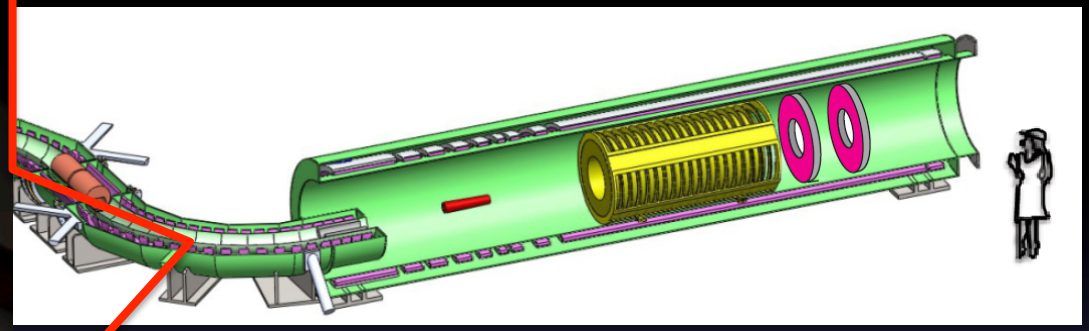
Mu2e Building Construction

Mu2e Tracker (straw detectors)



Mu2e Transport Solenoid



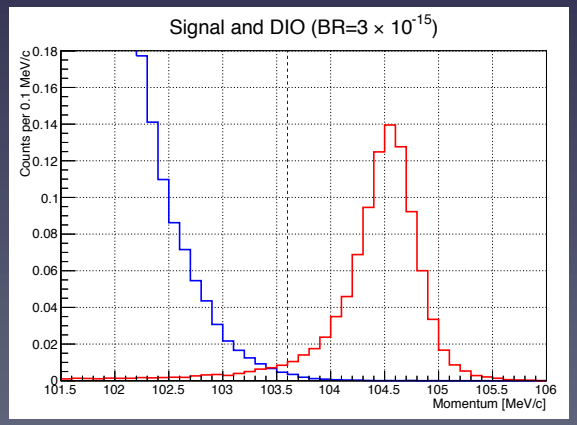


Prototype transport solenoid successfully tested (Aug 2015)

Acceptance/Background/Sensitivity

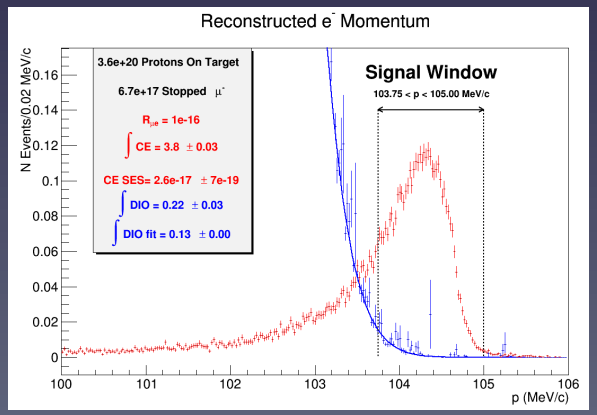
COMET Phase-I

- Net acceptance = 4.3%
  - Geometric acceptance 37%
  - Other detector accep. 64%
  - Reconstruction 15%
- Background = 0.25
  - RPC ~ 0.24
  - DIO ~ 0.01
- SES(Phase-I) ~ 3.1×10^{-15}
- SES(Phase-II) ~ 2.5×10^{-17}



Mu2e

- Net acceptance = 8.5%
  - Detector acceptance 96%
  - Reconstruction 9.3%
- Background = 0.37
  - DIO ~0.20
  - RPC ~0.02
  - Anti proton ~0.05
- SES ~2.6×10^{-17}



Schedules

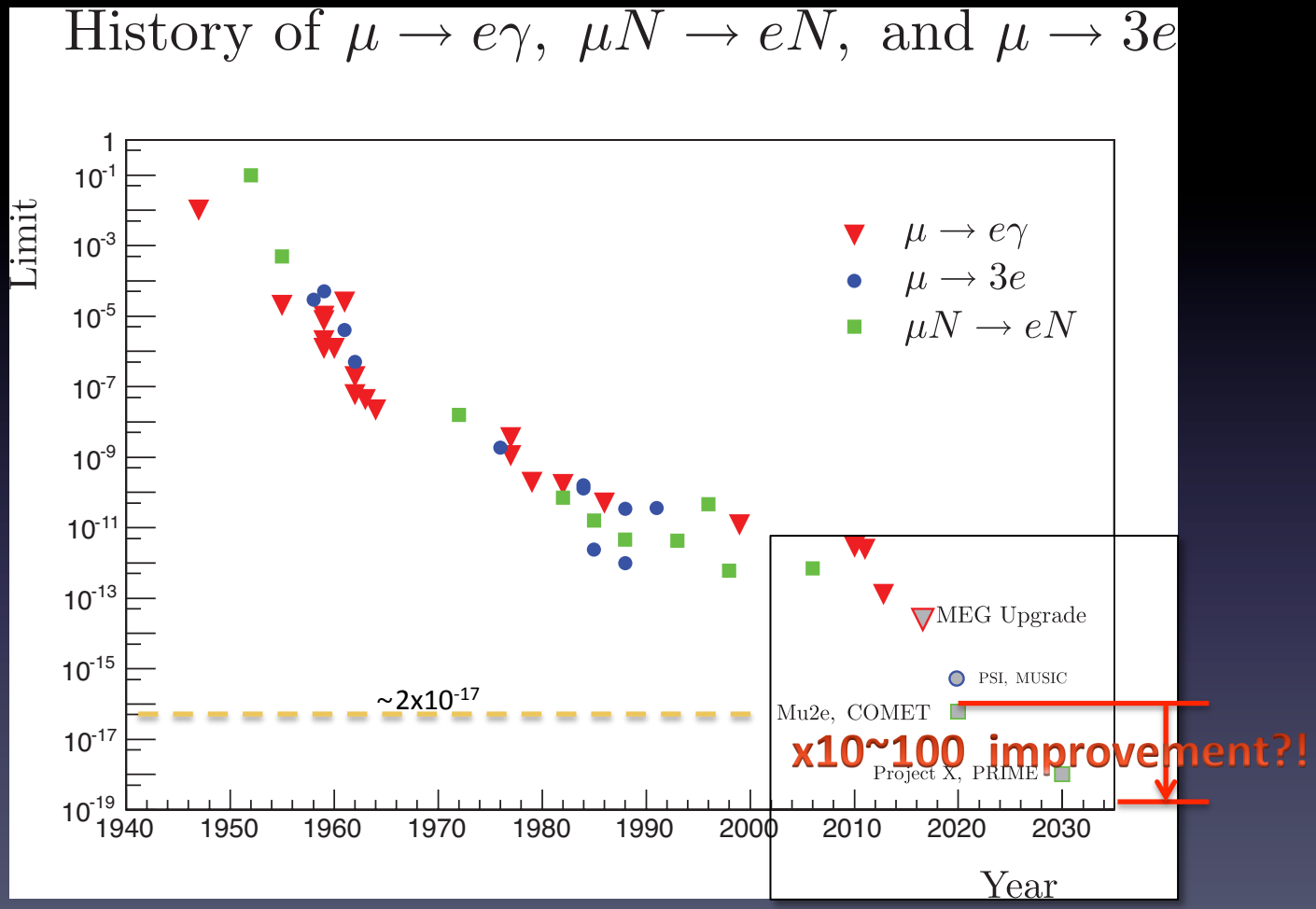
COMET

- Proton beam line construction complete in 2017
- Phase-I physics data taking in 2018 or 2019, depending on budget situation
  - Was 2017 or 2018 in original schedule
- Phase-II R&D in parallel with Phase-I R&D and data taking
- Phase-II physics data taking in **2021**
- ~ 1 year data taking

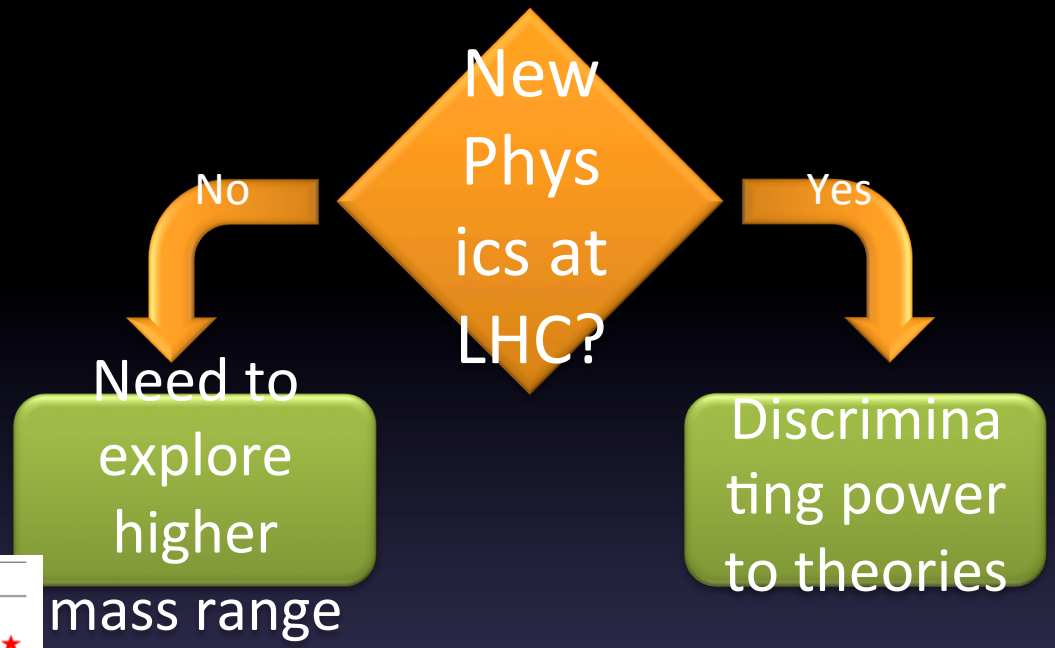
Mu2e

- Strong support by P5 in 2014
- CD (Critical Decision) -3c for approval start of construction in FY2016 2/4
  - CD-3a (long lead procurement) at FY2014 ¾
  - CD-2 (baseline) / 3b (phased construction) at FY2015 ¼
- Beamline ready at FY2020 4/4
- DAQ start in FY 2021 ¼
- ~3 years data taking

Sensitivity



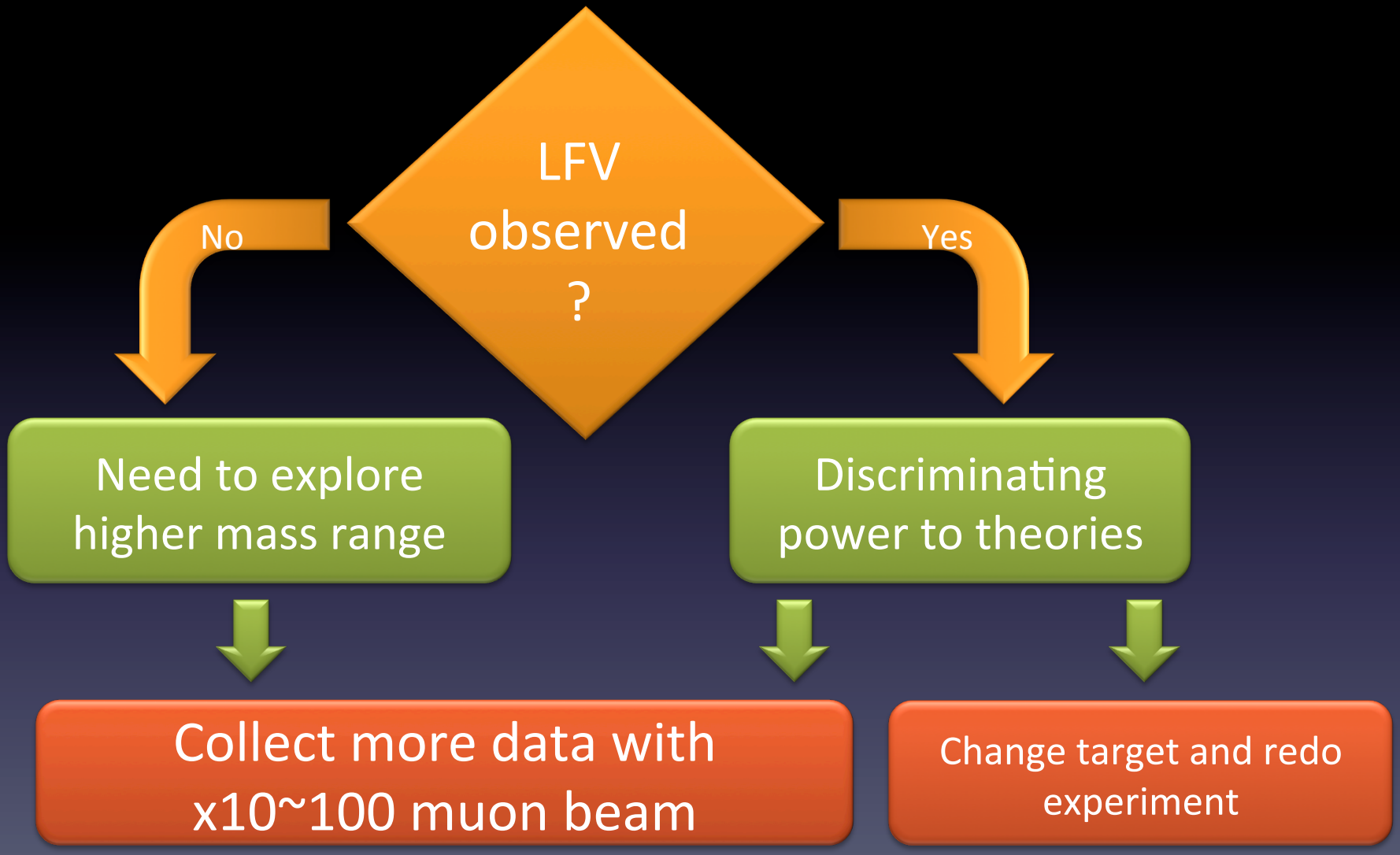
Do we need x100 improvement?



	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

W. Altmannshofer et al., Nuclear Physics B 830, pp17-94 (May 2010)

Do we need x100 improvement?



Future projects

- Need >x10 times intense muon beam, >10^{12} muons/sec
  - Stronger proton beam for more muons
- Keep the current background rate (<1 BG) even in the increased muon rate
  - Note : x10 beam does not mean x10 BG

- Mu2e-II
  - Increase proton beam intensity x10
  - Use Mu2e detector (with minor modification)
- PRISM/PRIME
  - Intense muon beam using storage ring muon cooling

Mu2e-II

- Originally studied for Project-X (arXiv:1307.1168)
- Target SES ~ 2×10^{-18} (x10 improvement), BG<1 event
- Minor modification on detector
  - Such as readout electronics, DAQ
  - To reduce cost
  - However, requires careful redesign on pion production solenoid
- x100 improvement should be "Mu2e-III"
  - Major detector modification

- Can Mu2e-II survive from background?

Mu2e-II @ Project-X

	Mu2e	Mu2e-II @ Project-X	
Proton beam energy	8 GeV	3 GeV	1 GeV
Beam power	8 kW	Up to MW	
Beam width	200 ns	100ns	
Required Proton on Target (POT) (*)	3.6×10^{20}	8.7×10^{21}	4.0×10^{22}
Duty factor	0.32	0.90	
Extinction	$< 10^{-10}$	?	
Muon stops / POT	1.7×10^{-3}	6.7×10^{-4}	1.4×10^{-4}
Muon stops / kW	7.6×10^{16}	8.0×10^{16}	5.2×10^{16}
Required beam power		72 kW	112 kW
Total muon stops	6.1×10^{17} (**)	5.8×10^{18}	
Background (DIO dominated)	0.41	2.34 / 0.79 (***)	

(*) Assuming the same beam time
(**) 9×10^{17} at TDR, depending on simulation setup
(***) Aluminum / Titanium
Ref: arXiv:1307.1168

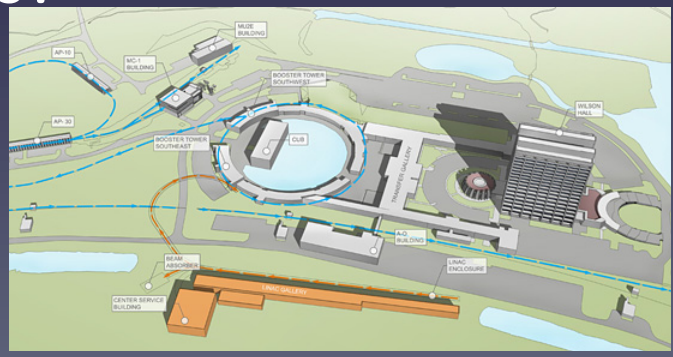
Mu2e-II @ PIP-II

	Mu2e	Mu2e-II @ PIP-II
Proton beam energy	8 GeV	800 MeV
Beam power	8 kW	8 – 100 kW
Beam width	200 ns	(< 200 ns)
Proton on Target (POT) (*)	3.6×10^{20}	$3.6 \times 10^{21} – 4.5 \times 10^{22}$
Duty factor	0.32	0.90
Extinction	$< 10^{-10}$	$<10^{-12}$?
Muon stops / POT	1.7×10^{-3}	1.0×10^{-4}
Muon stops / kW	7.6×10^{16}	4.7×10^{16}
Total muon stops	6.1×10^{17} (**)	4.7×10^{18} @100kW

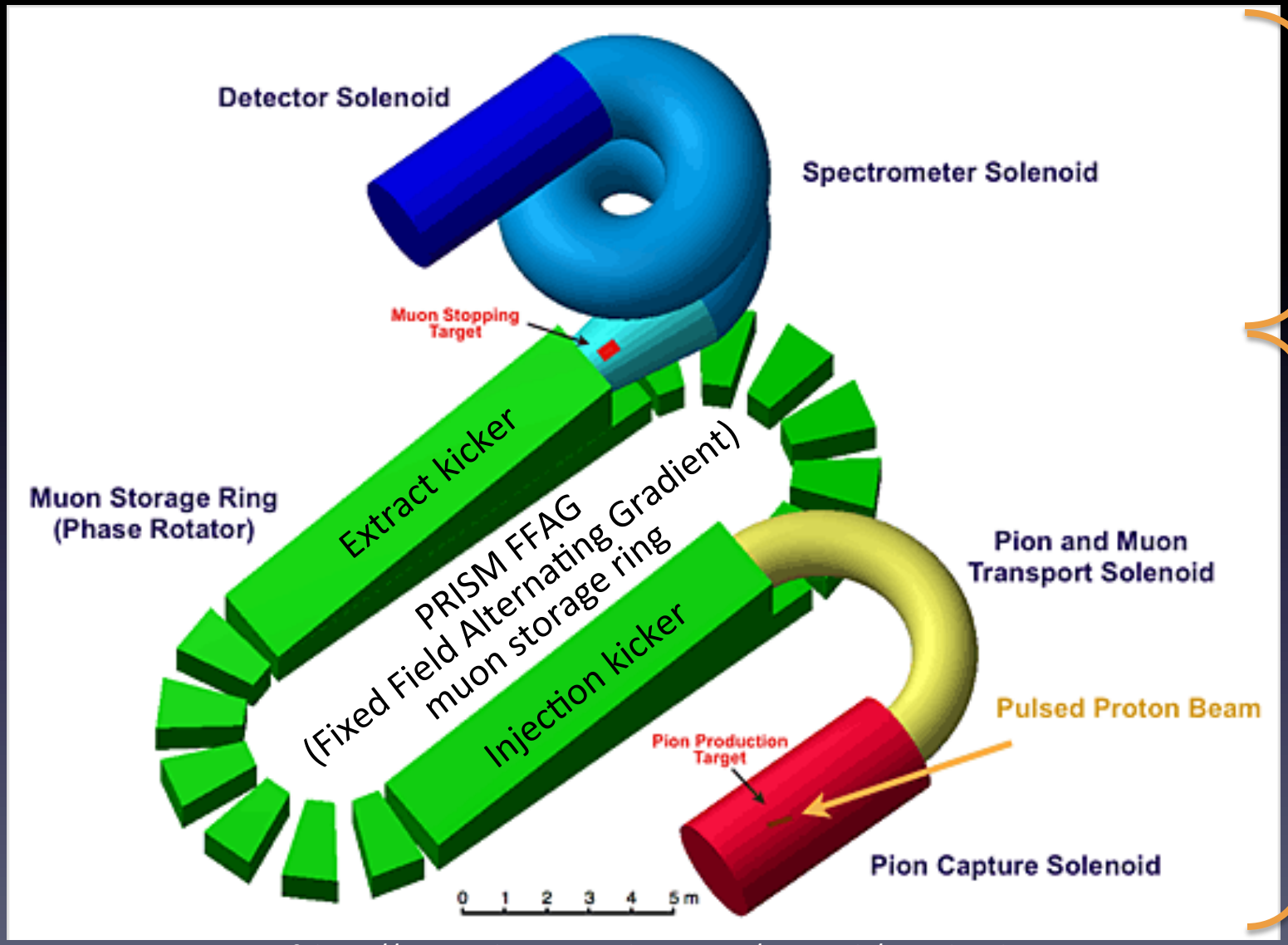
(*) Assuming the same beam time
(**) 9×10^{17} at TDR, depending on simulation setup
Ref : https://indico.fnal.gov/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=10235

Mu2e-II @ PIP-II

- 7.7 times more muons possible for Mu2e-II
  - Not that higher number, detector may survive
- Less beam background because of lower beam energy
  - Ex. no anti-proton background
  - Less radiation effect at pion production
- Background (after reconstruction), detector/electronics occupancy requires careful check
- Driving LINAC beam to muon campus?
  - Not PIP-II original plan



PRISM/PRIME



PRIME

PRISM
Muon to
Electron
conversion

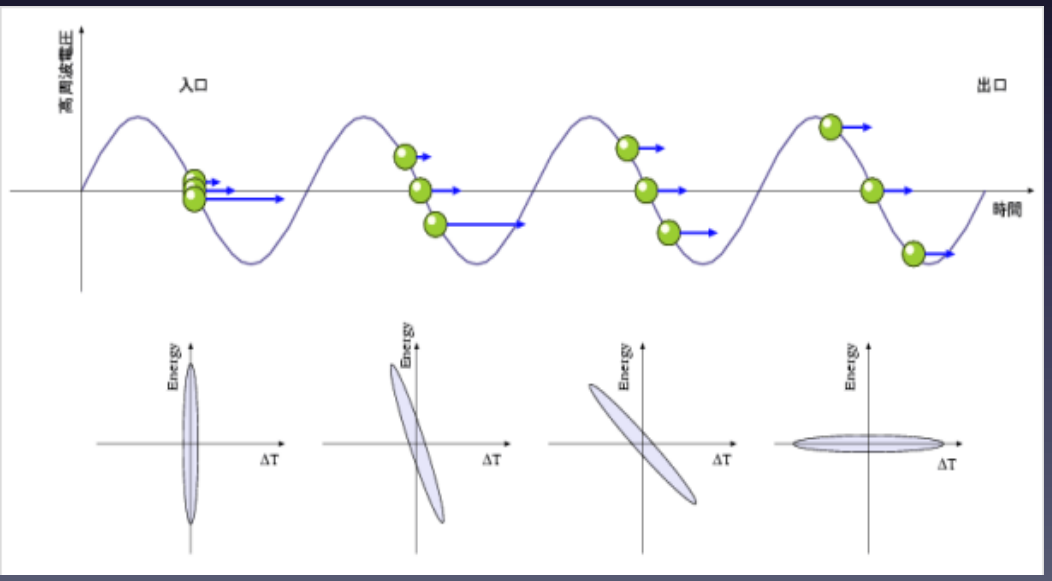
PRISM

Phase
Rotated
Intense
Slow
Muon
source

Ref: http://prism.phys.sci.osaka-u.ac.jp/research/r003.html

FFAG Muon Storage Ring

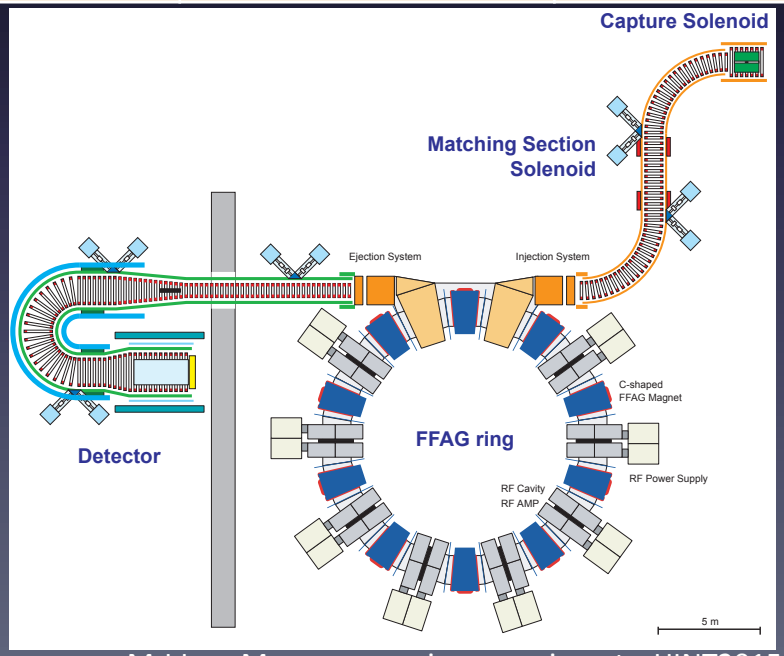
- To get more intense, monochromatic, pure (from pion) muon beam
- Use Altenating electric field
  - Faster muon lose energy, slow muon get energy
- Storage ring
  - Pion decays away



Ref: http://prism.phys.sci.osaka-u.ac.jp/research/r003.html

COMET vs PRISM/PRIME

Specification	COMET	PRISM/PRIME	Comments on PRISM/PRIME
Muon intensity	~10^{11} muons/sec	10^{11} – 10^{12} muons/sec	~10^{11} muons/sec
Muon momentum	0-140MeV (70MeV peak)	68 ± 2 MeV/c	3% spread (Enhanced from 30% by phase rotation) Less than 70MeV to suppress DIF
Beam repetition	~1 MHz	100-1000Hz	Due to kicker Better to reject cosmic ray origin BG



Ref: Y.Kuno, Mu2e workshop (2016)

How to get x100 improvement?

Ref: Private communication, Y.Kuno @ Osaka

- x(1/2) from reduced beam acceptance from solenoid to FFAG
- x3 from removing detection time window (no pion)
- x3 from pion capture improvement
- x20 from 56 kW→1MW

Multi MW proton source is critical!

Instead of Summary: Much less chance than "needle in haystack"

Courtesy to B.Bernstein @ FNAL

- Or, handful of grains out of earth beach
  - Earth coastline length = ~800,000km
  - Assuming width = 50m, depth = 1m, grain/cm3 ~ 8000
  - Total grains in earth beach ~ 3×10^{20}
- SES~10^{-19} is a few finger tips out of earth beach
- MW proton source is critical to explore O(10^4) TeV energy scale