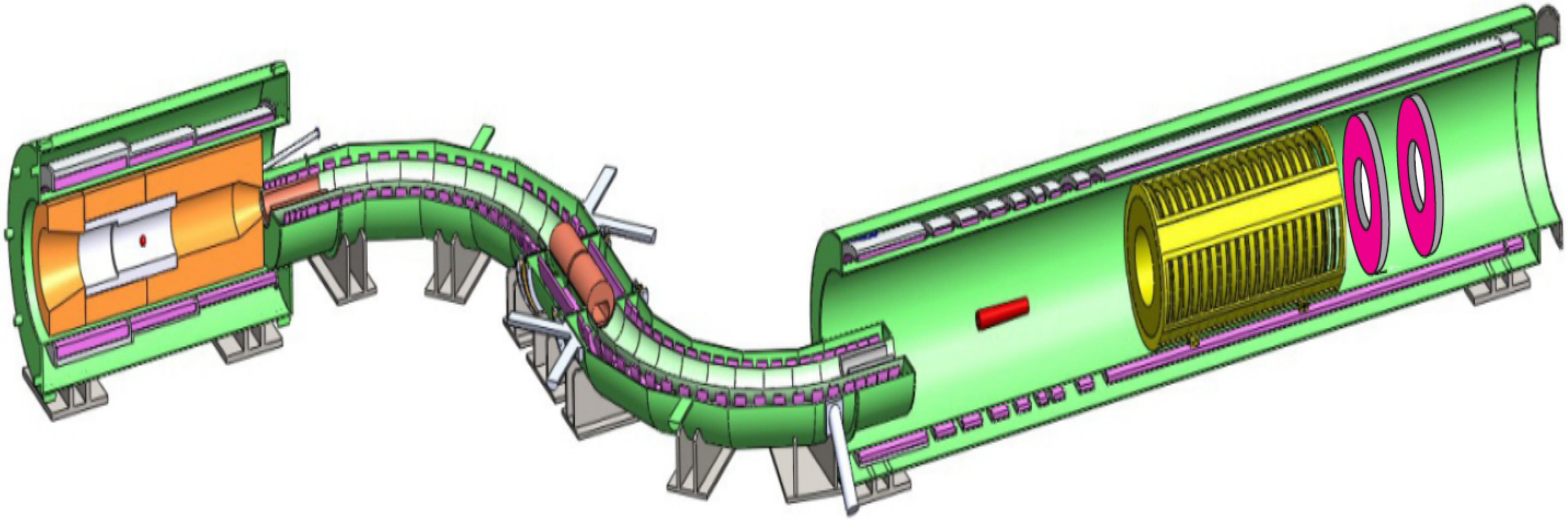
Mu2e-doc-3227-v4

The Mu2e Experiment at Fermilab



http://mu2e.fnal.gov

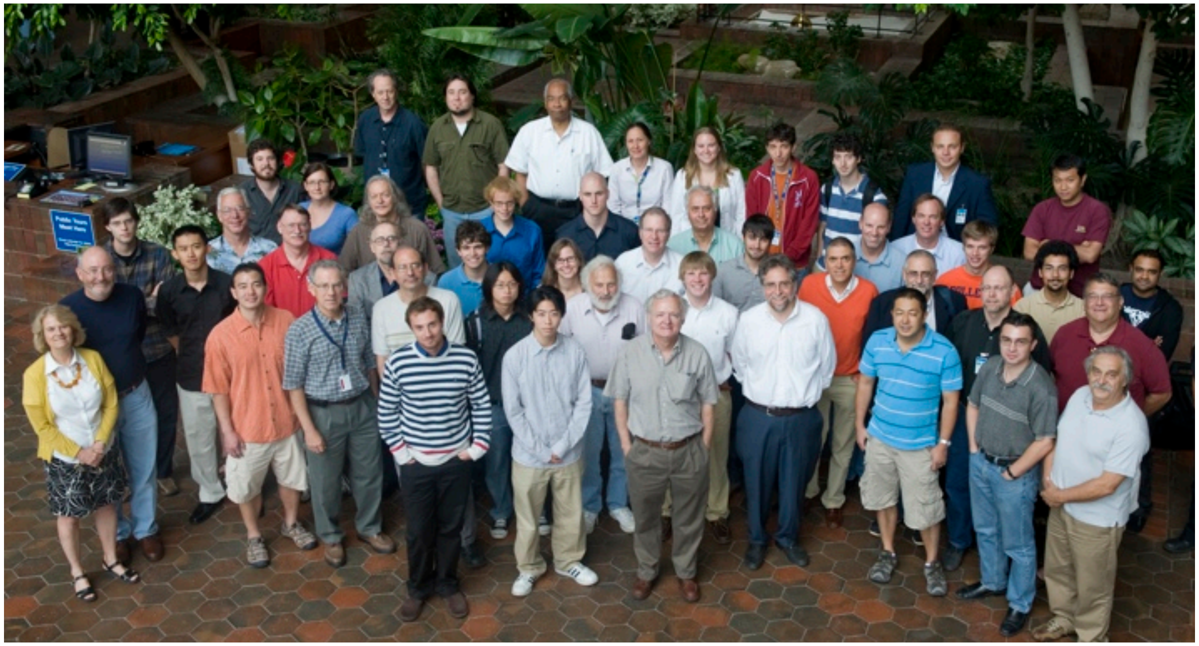
Rob Kutschke, Fermilab

Presented at DPF 2013

August 16, 2013

The Mu2e Collaboration ~130 Members

Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermilab
University of Houston
University of Illinois, Urbana-Champaign
University of Massachusetts, Amherst
Lawrence Berkeley National Laboratory
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of Virginia
University of Washington, Seattle

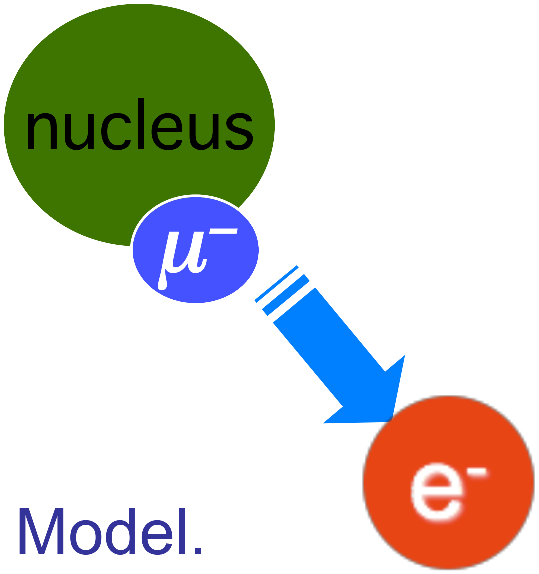


Istituto G. Marconi Roma
Laboratori Nazionale di Frascati
Università di Pisa, Pisa
INFN Lecce and Università del Salento
Gruppo Collegato di Udine

Institute for Nuclear Research,
Moscow, Russia
JINR, Dubna, Russia

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

- Initial state: muonic atom
- Final state:
  - – Single mono-energetic electron.
    - Energy depends on Z of target.
  - – Recoiling nucleus (not observed).
    - Coherent: nucleus stays intact.
  - – Neutrino-less



- Non-zero but negligible rate in Standard Model.
- Observable rate in many New Physics scenarios.
- Related decays: Charged Lepton Flavor Violation (CLFV):

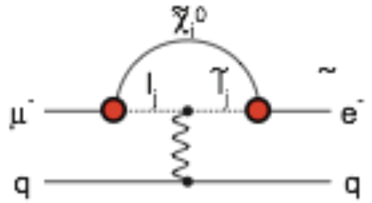
$$\mu \rightarrow e\gamma \quad \mu \rightarrow e^+e^-e^+ \quad K_L^0 \rightarrow \mu e \quad B^0 \rightarrow \mu e$$

$$\tau \rightarrow \mu\gamma \quad \tau \rightarrow \mu^+\mu^-\mu^+ \quad D^+ \rightarrow \mu^+\mu^+\mu^-$$

Survey of New Physics Scenarios

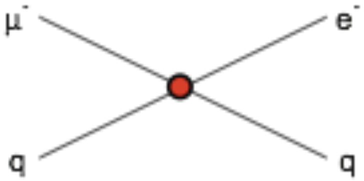
Supersymmetry

rate ~ 10^{-15}



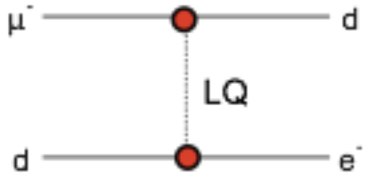
Compositeness

Λ_c ~ 3000 TeV



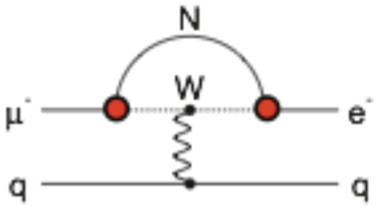
Leptoquark

M_{LQ} =
3000 $(\lambda_{\mu d}\lambda_{ed})^{1/2}$ TeV/c^2



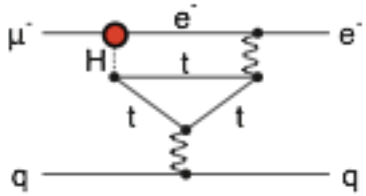
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



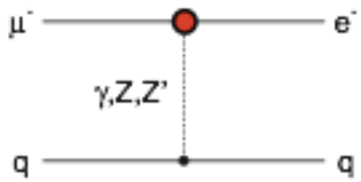
Second Higgs Doublet

$g(H_{\mu e})$ ~ $10^{-4} g(H_{\mu\mu})$



Heavy Z'
Anomal. Z Coupling

$M_{Z'}$ = 3000 TeV/c^2



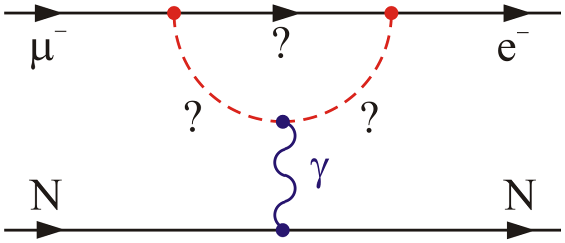
Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J.C57:13-182,2008

Sensitive to mass scales up to O(10,000 TeV)!

Sensitivity to High Mass Scales

$$L_{CLFV} = \frac{m_\mu}{\boxed{(\kappa+1)}\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\boxed{\kappa}}{\boxed{(1+\kappa)}\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

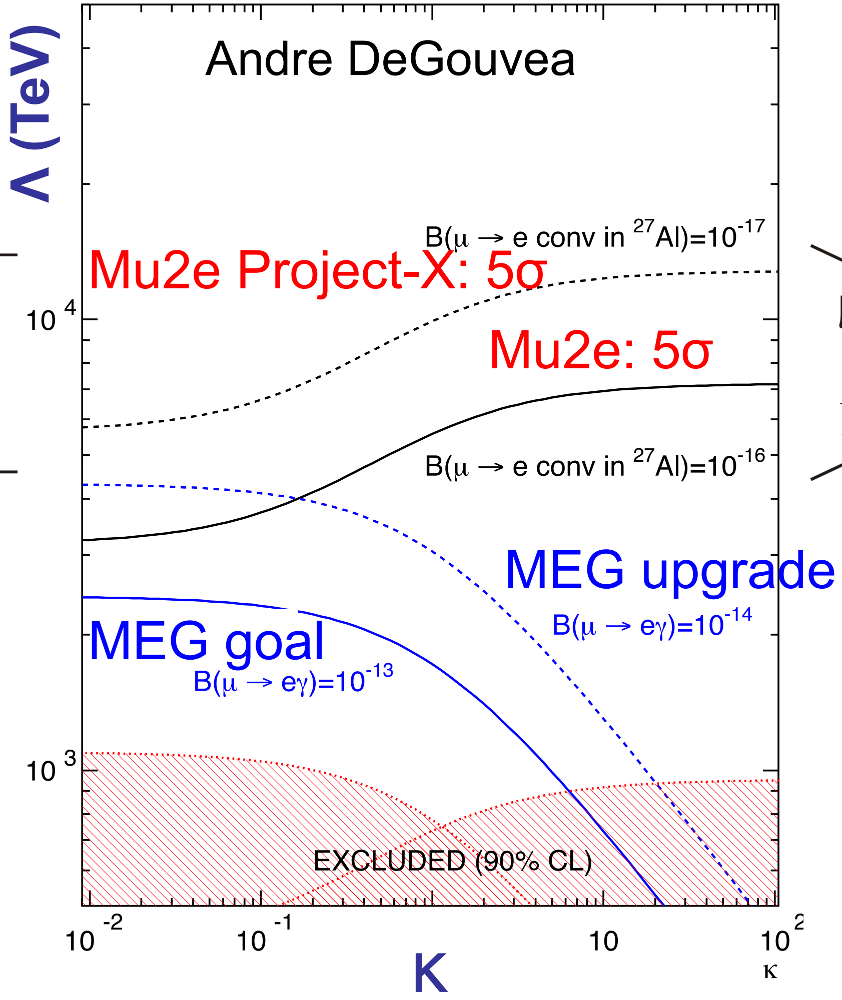
Loops dominate for κ << 1



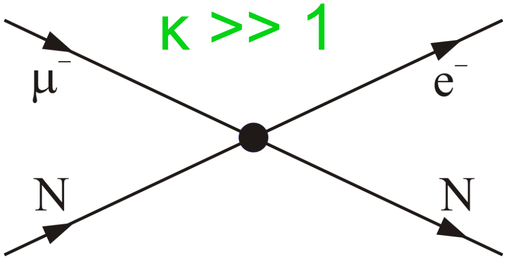
μ→eγ

μN→eN

μ→eee



Contact terms dominate for κ >> 1



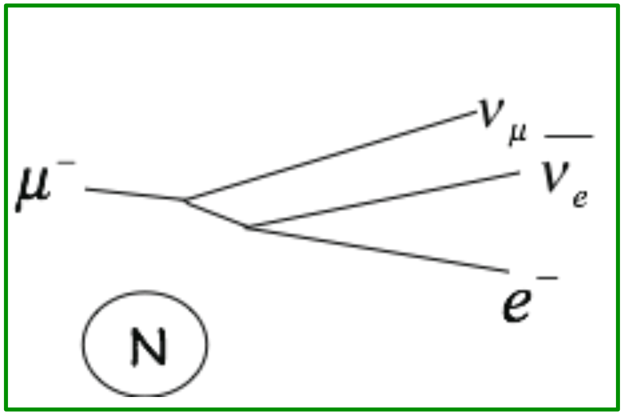
~~μ→eγ~~

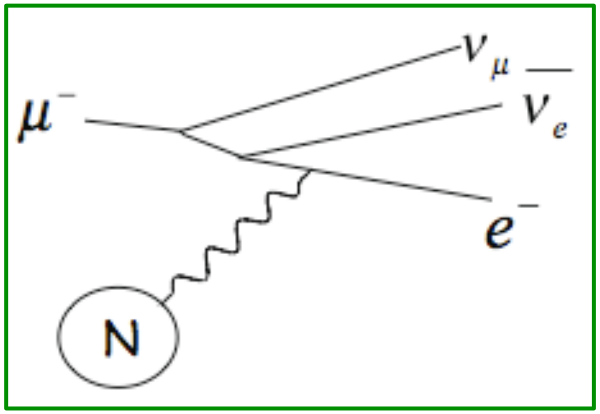
μN→eN

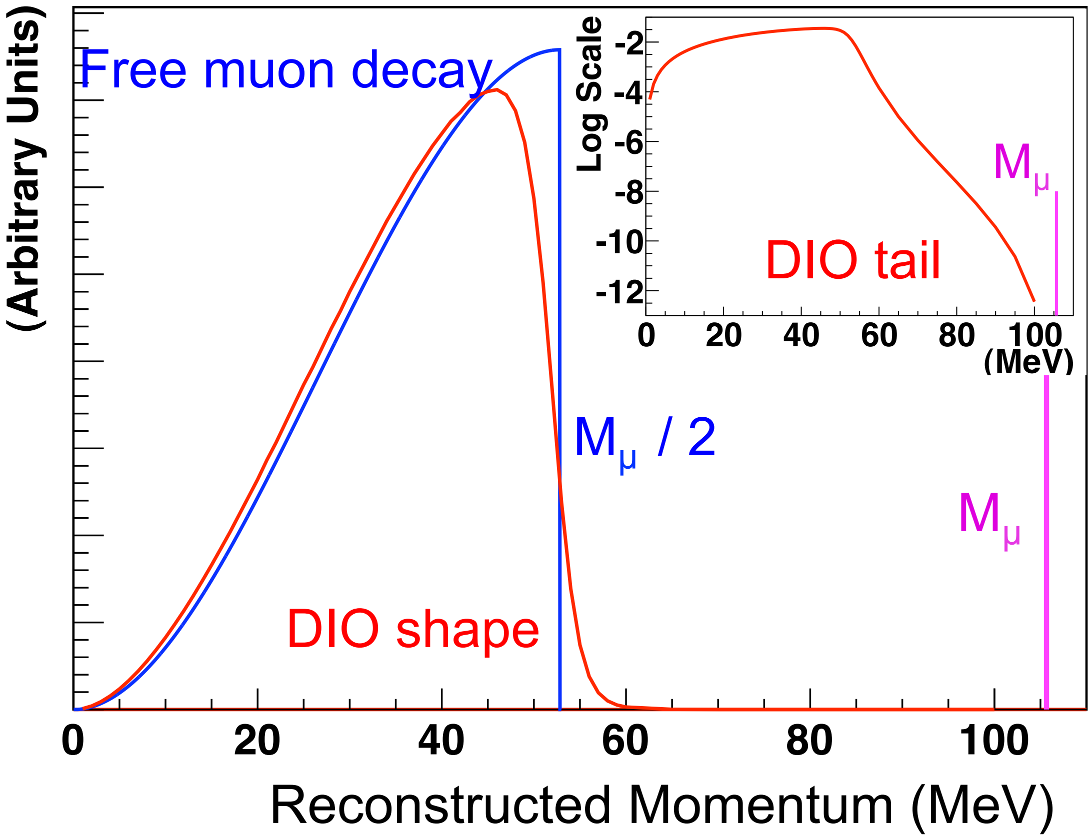
μ→eee

Decay–in-Orbit: Dominant Background

DIO: Decay in orbit

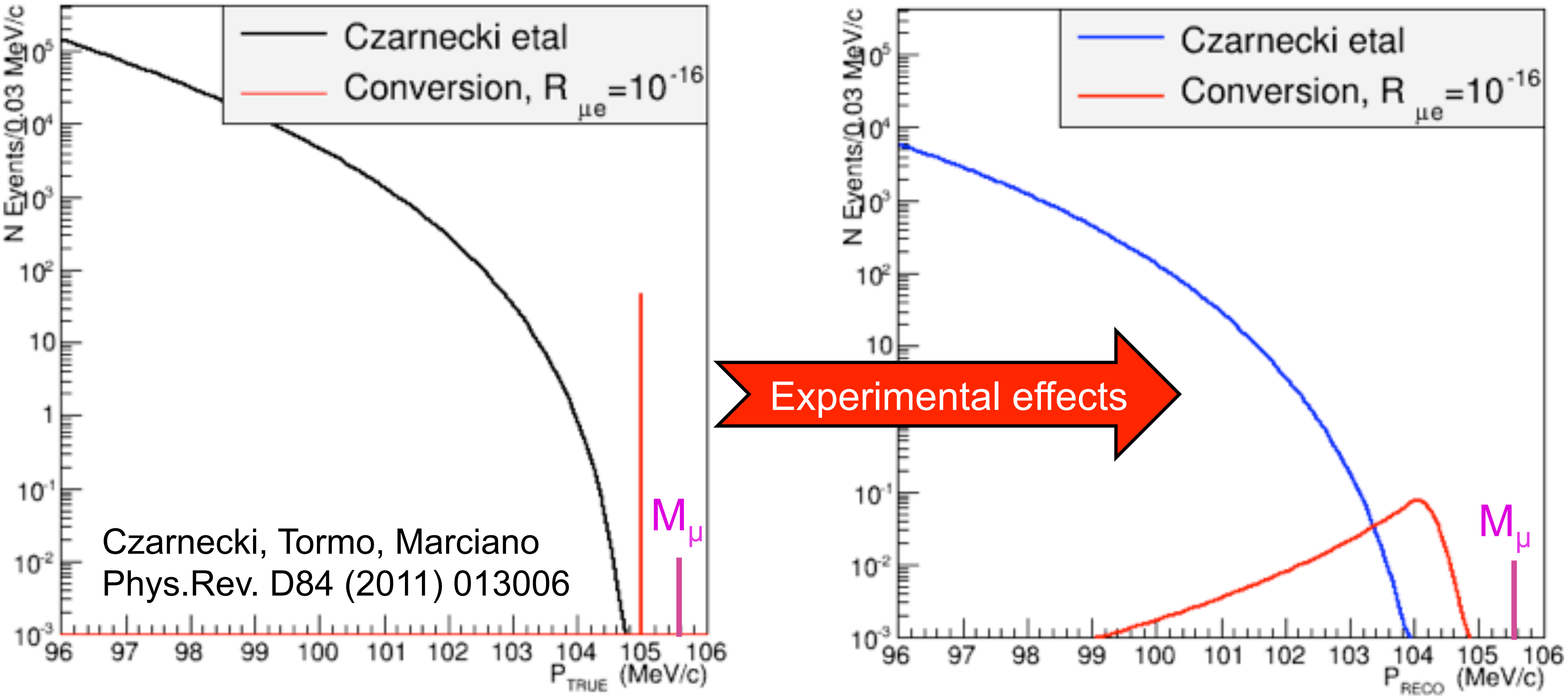






DIO Endpoint

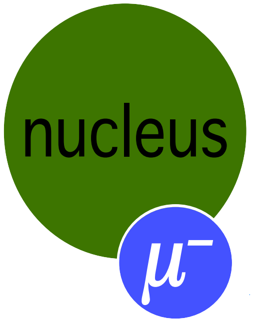
- Tail of DIO falls as $(E_{Endpoint} - E_e)^5$
- Separation of ~few 100 keV for $R_{\mu e} = 10^{-16}$



Czarnecki, Tormo, Marciano
Phys.Rev. D84 (2011) 013006

Mu2e in One Page

- Make muonic Al.
- Watch it decay:
  - Decay-in-orbit (DIO): 40%
    - Continuous E_e spectrum.
  - Muon capture on nucleus: 60%
    - Nuclear breakup: p, n, γ
  - Neutrino-less μ to e conversion
    - Mono-energetic $E_e \approx$ 105 MeV
    - At endpoint of continuous spectrum.
- Measure E_e spectrum.
- Is there an excess at the endpoint?
- Quantitatively understand backgrounds



Bohr radius ≈ 20 fm
Al nuclear radius ≈ 4 fm
Lifetime: 864 ns

What do We Measure?

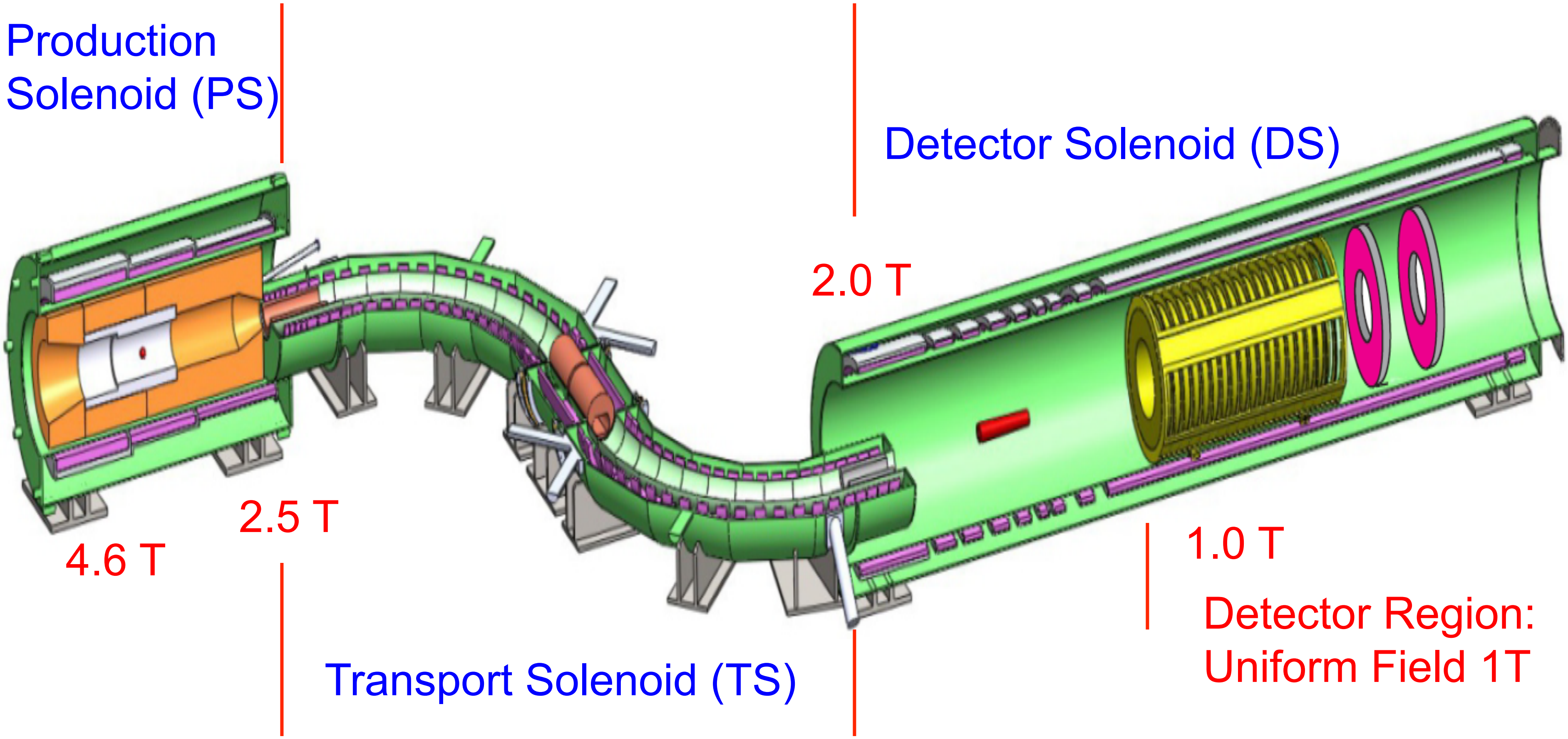
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)}$$

- Numerator:
  - Do we see an excess at the E_e end point?

a

- Denominator:
  - All nuclear captures of muonic Al atoms
- Design sensitivity for a 3 year run
  - $\approx 2.5 \times 10^{-17}$ single event sensitivity.
  - $< 6 \times 10^{-17}$ limit at 90% C.L.
- 10,000 × better than current limit (SINDRUM II).

Superconducting Solenoid System



Production Solenoid (PS)

Detector Solenoid (DS)

2.0 T

2.5 T

4.6 T

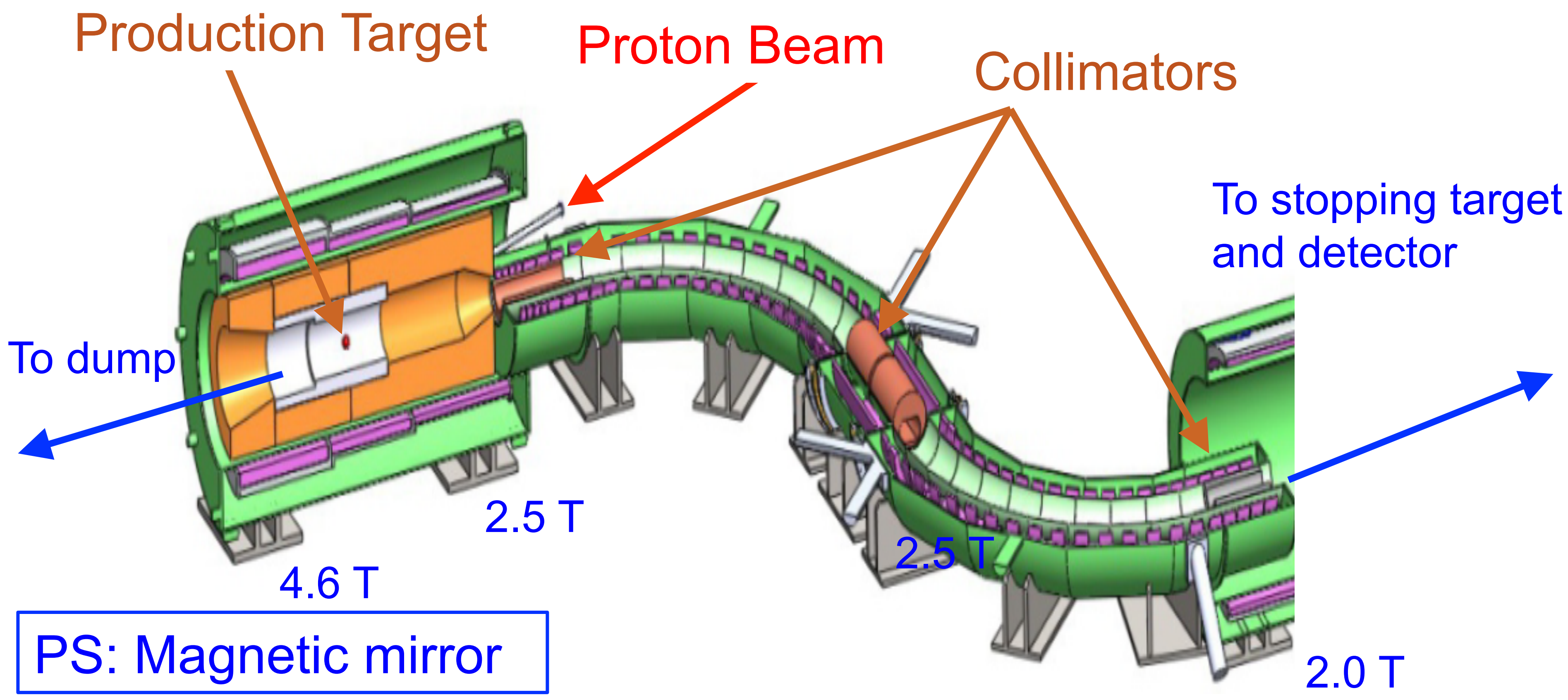
1.0 T

Detector Region: Uniform Field 1T

Transport Solenoid (TS)

Graded B for most of length

Backward Travelling Muon Beam



Production Target

Proton Beam

Collimators

To stopping target and detector

To dump

2.5 T

2.5 T

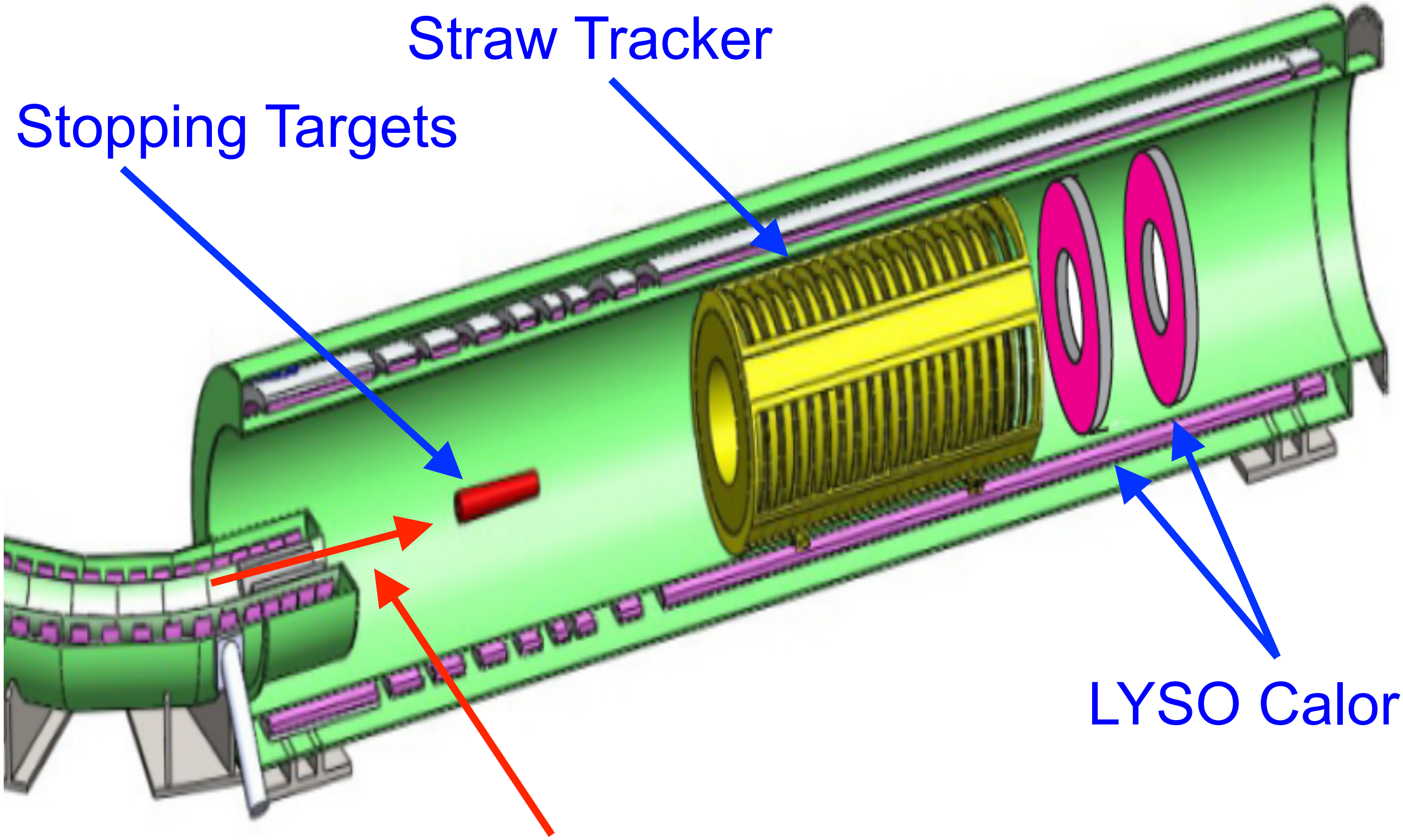
4.6 T

2.0 T

PS: Magnetic mirror

TS: negative gradient and charge selection at central collimator

Stopping Target and Detectors



Straw Tracker

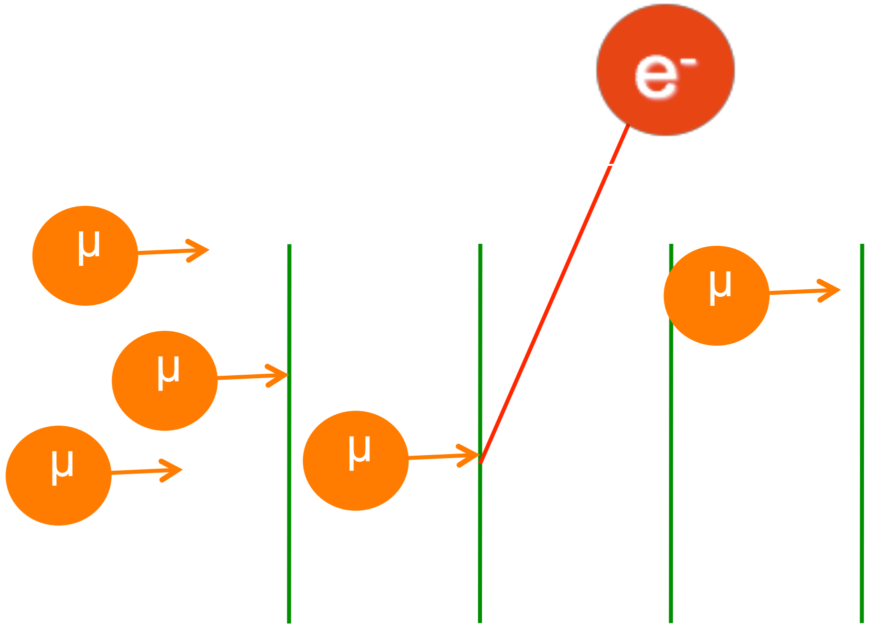
Foil Stopping Targets

LYSO Calorimeter

Incoming muon beam: <Kinetic Energy> = 7.6 MeV

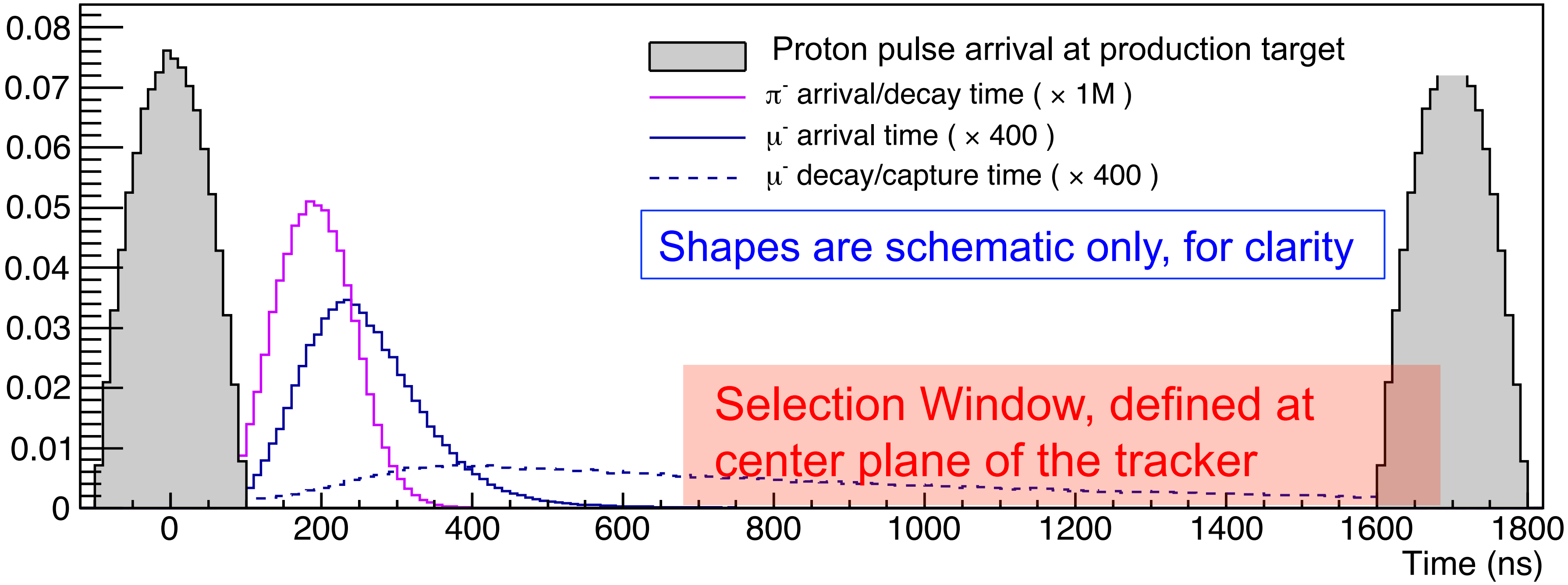
Stopping Target

- Pulse of low energy μ^- on thin Al foils
- ~50% range out and capture to form muonic Al
- ~0.0016 stopped μ^- per proton on production target.
- DIO and conversion electrons pop out of target foils.



- 17 target foils
- 200 microns thick
- 5 cm spacing
- Radius:
  - ≈10. cm at upstream
  - ≈6.5 cm at downstream

One Cycle of the Muon Beamline



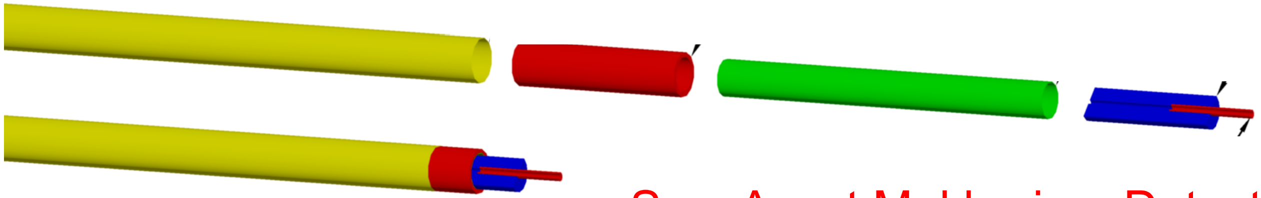
- μ are accompanied by e, π, anti-protons …
    - These create prompt backgrounds
    - Wait for them to decay.
- Extinction = (# protons between bunches)/(protons per bunch)
    - Require: Extinction < 10^{-10}

Tracker: Straw Tubes in Vacuum

1

Straws: 5 mm OD; 15 micron metalized mylar wall.

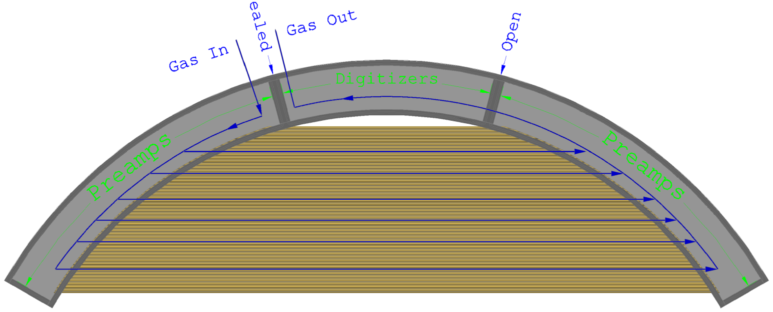
Custom ASIC for time division: σ ≈ 5 mm at straw center



See: Asset Mukherjee, Detector Session, Fri 10:30

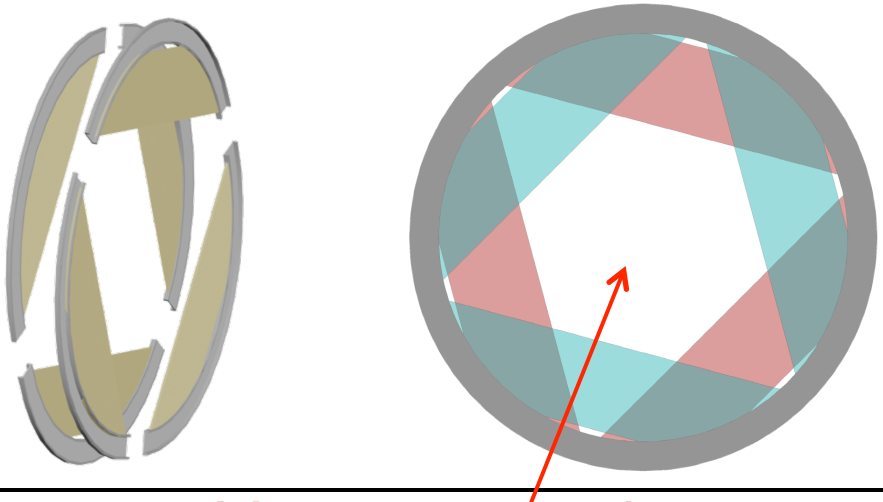
2

Panel: 2 Layers, 48 straws each



3

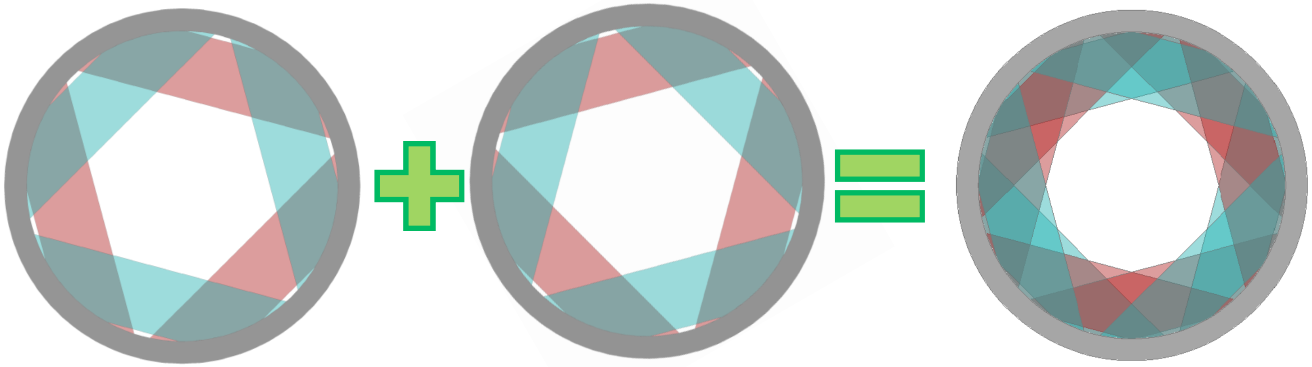
Plane: 6 panels; self supporting



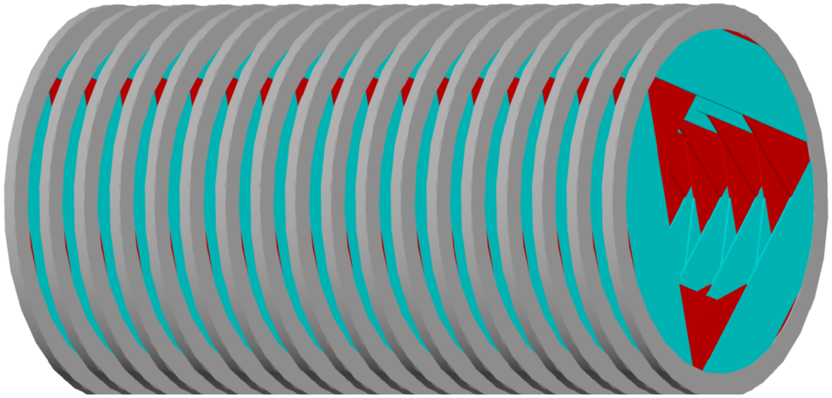
Vacuum on axis

Tracker: Straw Tubes in Vacuum

4 Station: 2 planes; relative rotation under study

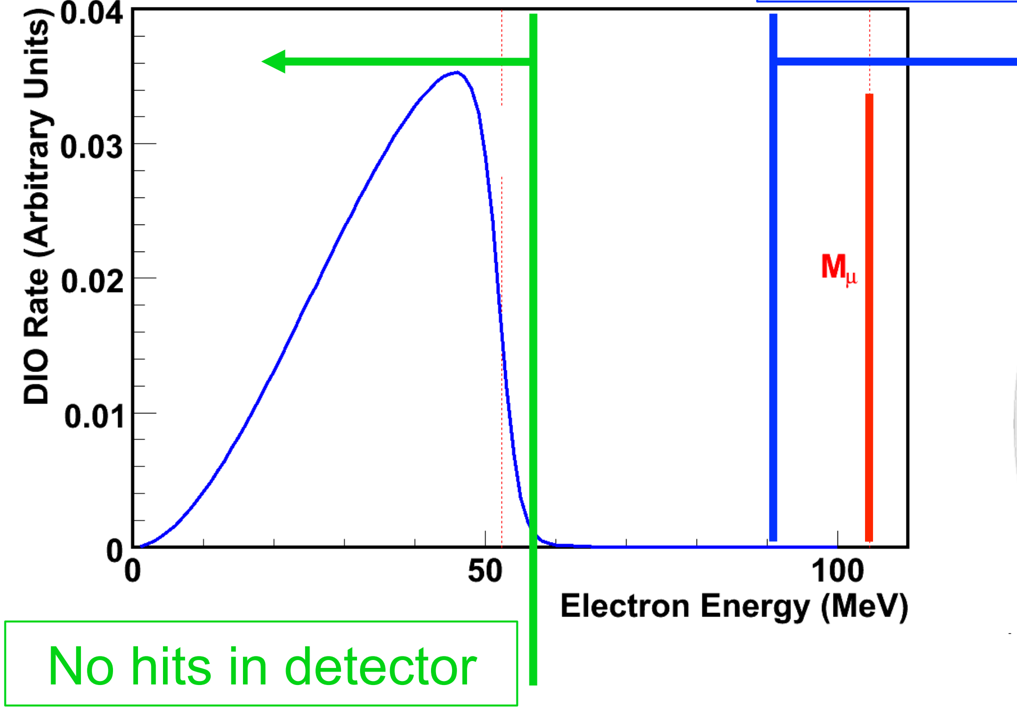


5 Tracker: 18 stations (# and rotations still being optimized)



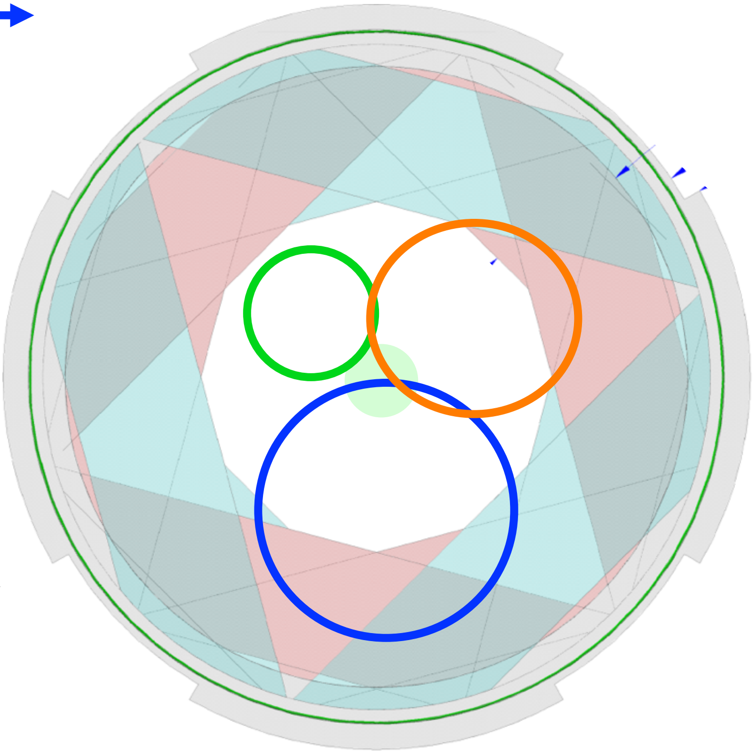
How do you measure 2.5×10^{-17} ?

Reconstructable tracks



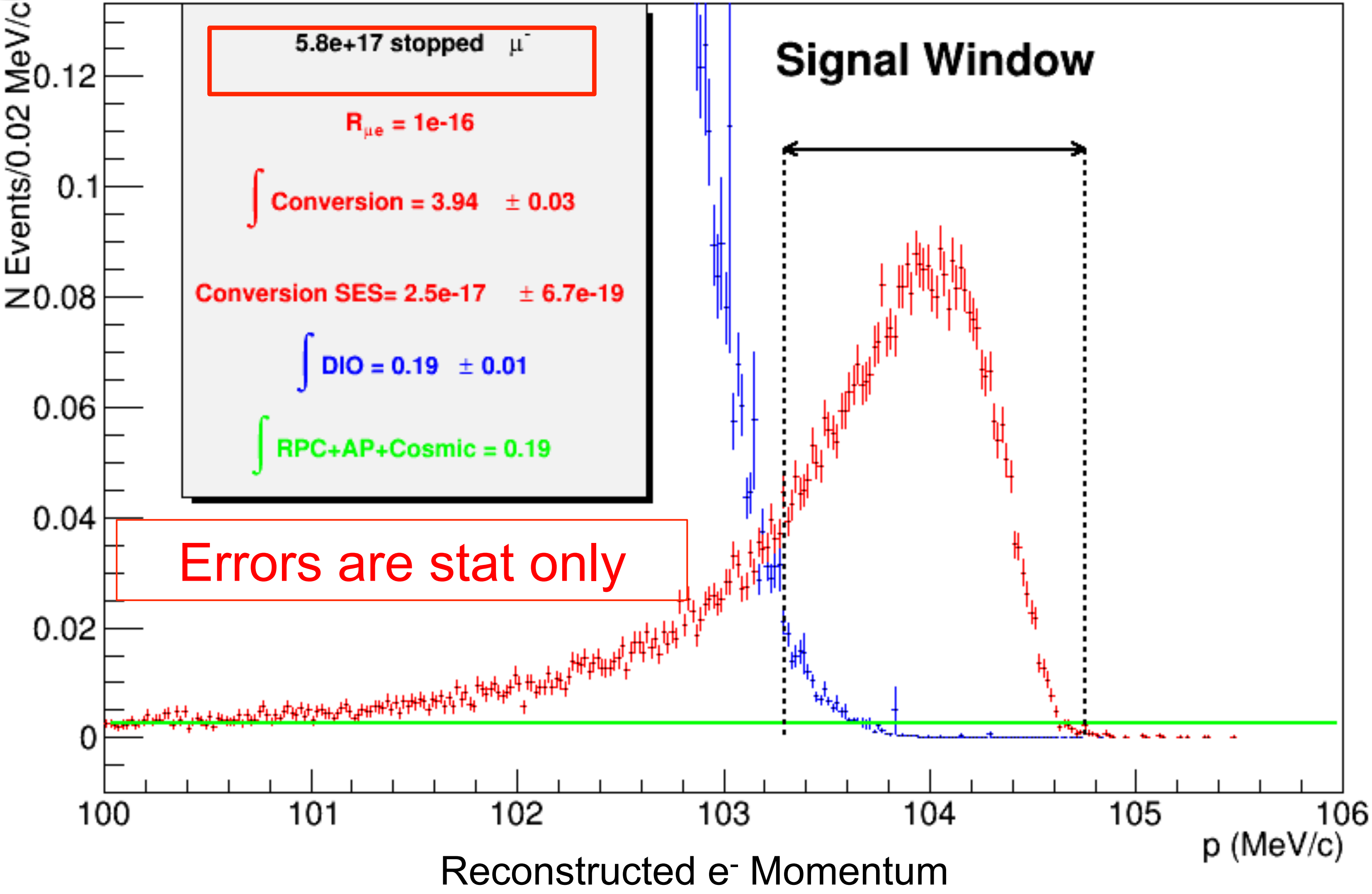
No hits in detector

Some hits in detector.
Tracks not reconstructable.



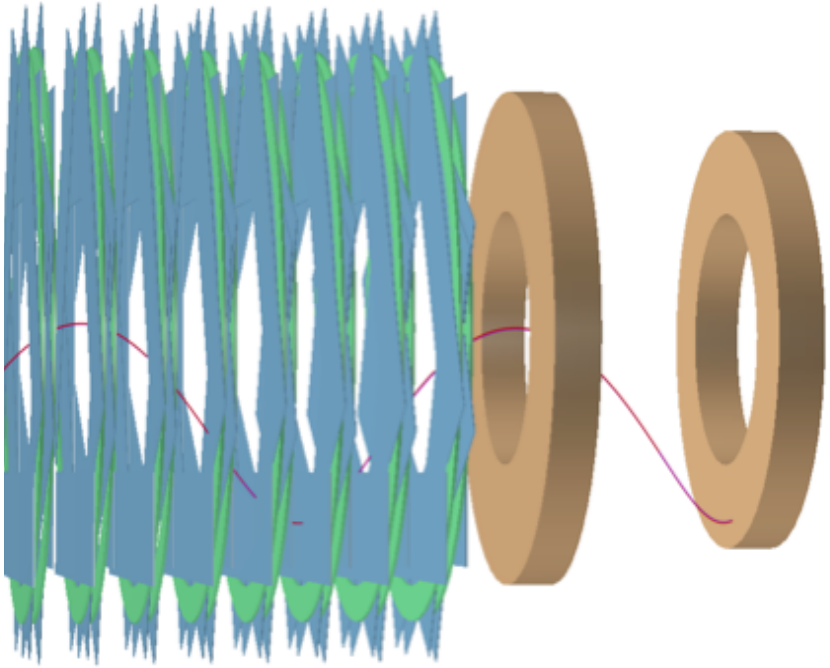
Beam’s-eye view of Tracker

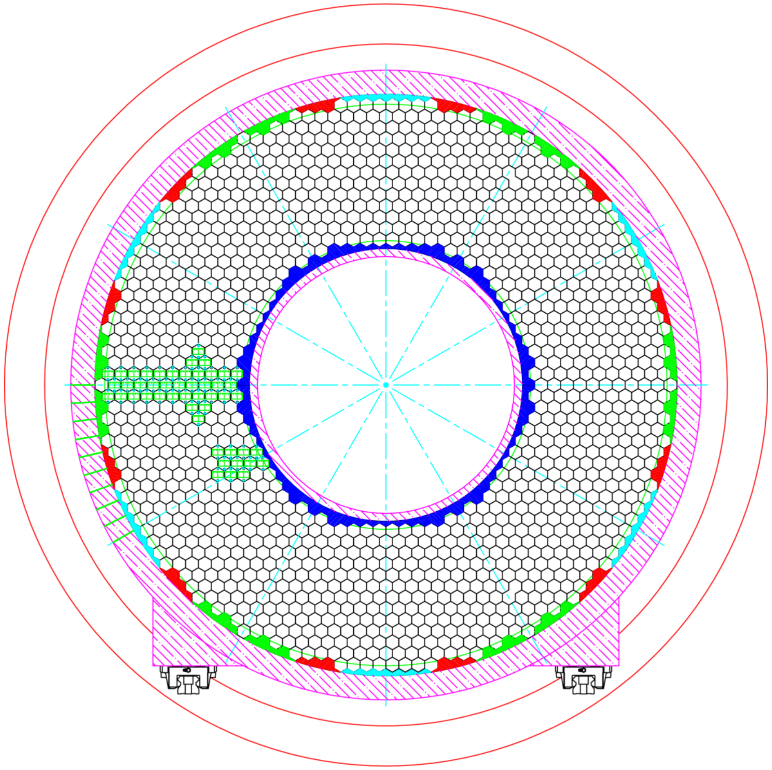
Signal Sensitivity for 3 Year Run



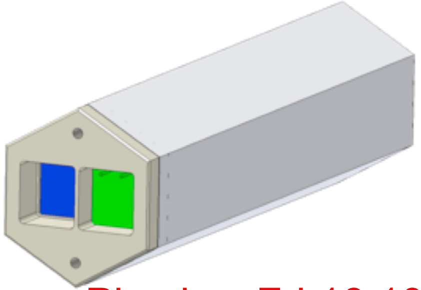
Errors are stat only

Calorimeter





- Two disk geometry
- Hex LYSO crystals; APD or SiPM readout
- Provides precise timing, PID, background rejection, alternate track seed and possible calibration trigger.



See: Chih-Hsiang Cheng, Flavor Physics, Fri 16:10

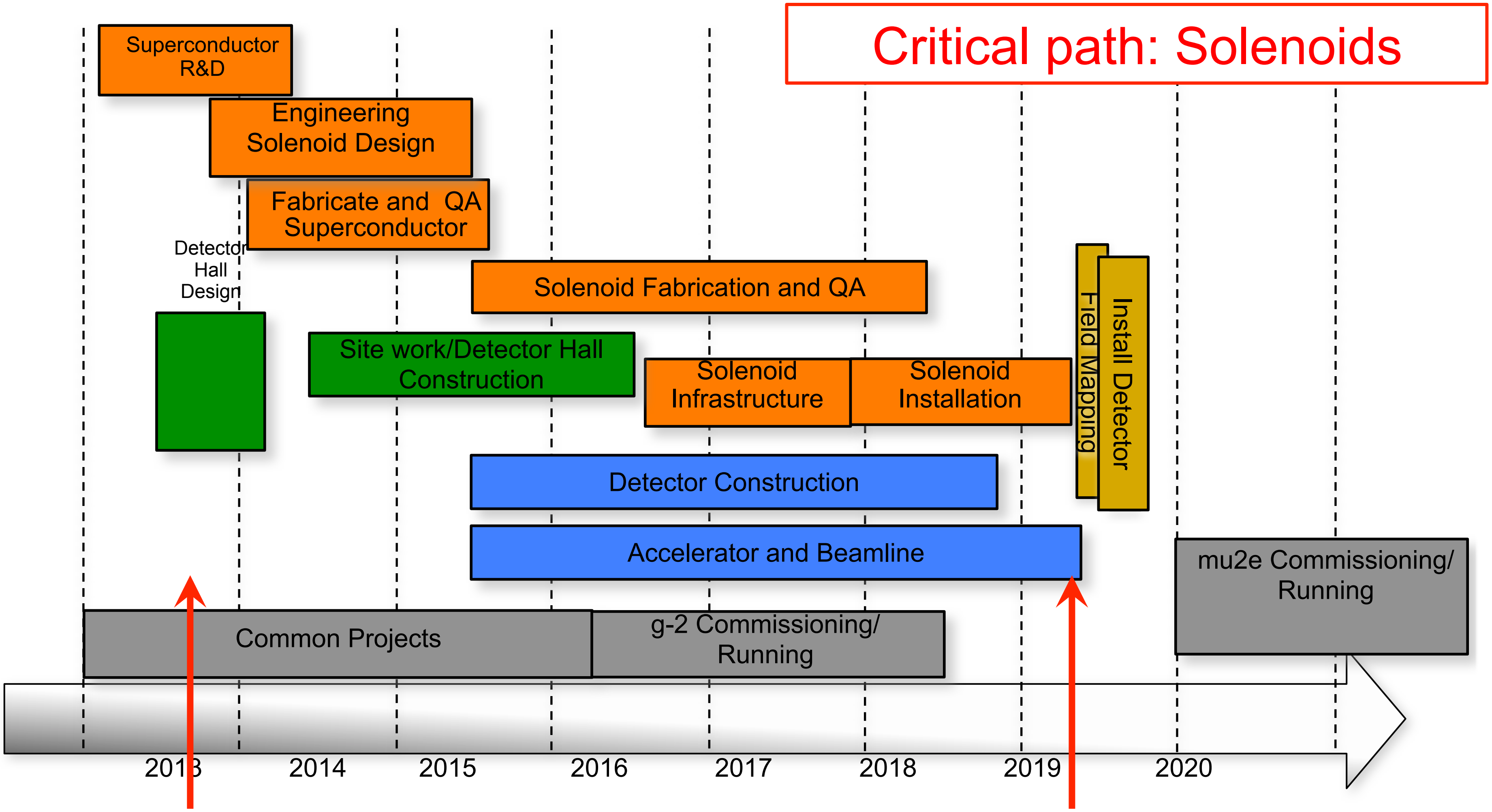
Backgrounds for 3 Year Run

Source	Events	Comment
μ decay in orbit	0.20 ± 0.06	
Anti-proton capture	0.10 ± 0.06	
Radiative π^- capture*	0.04 ± 0.02	From protons during detection time
Beam electrons*	0.001 ± 0.001	
μ decay in flight*	0.010 ± 0.005	With e^- scatter in target
Cosmic ray induced	0.050 ± 0.013	Assumes 10^{-4} veto inefficiency
Total	0.4 ± 0.1	

All values preliminary; some are stat error only.

- Reduce BGs with excellent: momentum resolution, extinction, cosmic ray shielding and veto
- * scales with extinction: values in table assume extinction = 10^{-10}

Mu2e Schedule



Critical path: Solenoids

Superconductor R&D

Engineering Solenoid Design

Fabricate and QA Superconductor

Detector Hall Design

Solenoid Fabrication and QA

Site work/Detector Hall Construction

Solenoid Infrastructure

Solenoid Installation

Field Mapping

Install Detector

Detector Construction

Accelerator and Beamline

mu2e Commissioning/ Running

Common Projects

g-2 Commissioning/ Running

2013
2014
2015
2016
2017
2018
2019
2020

Today

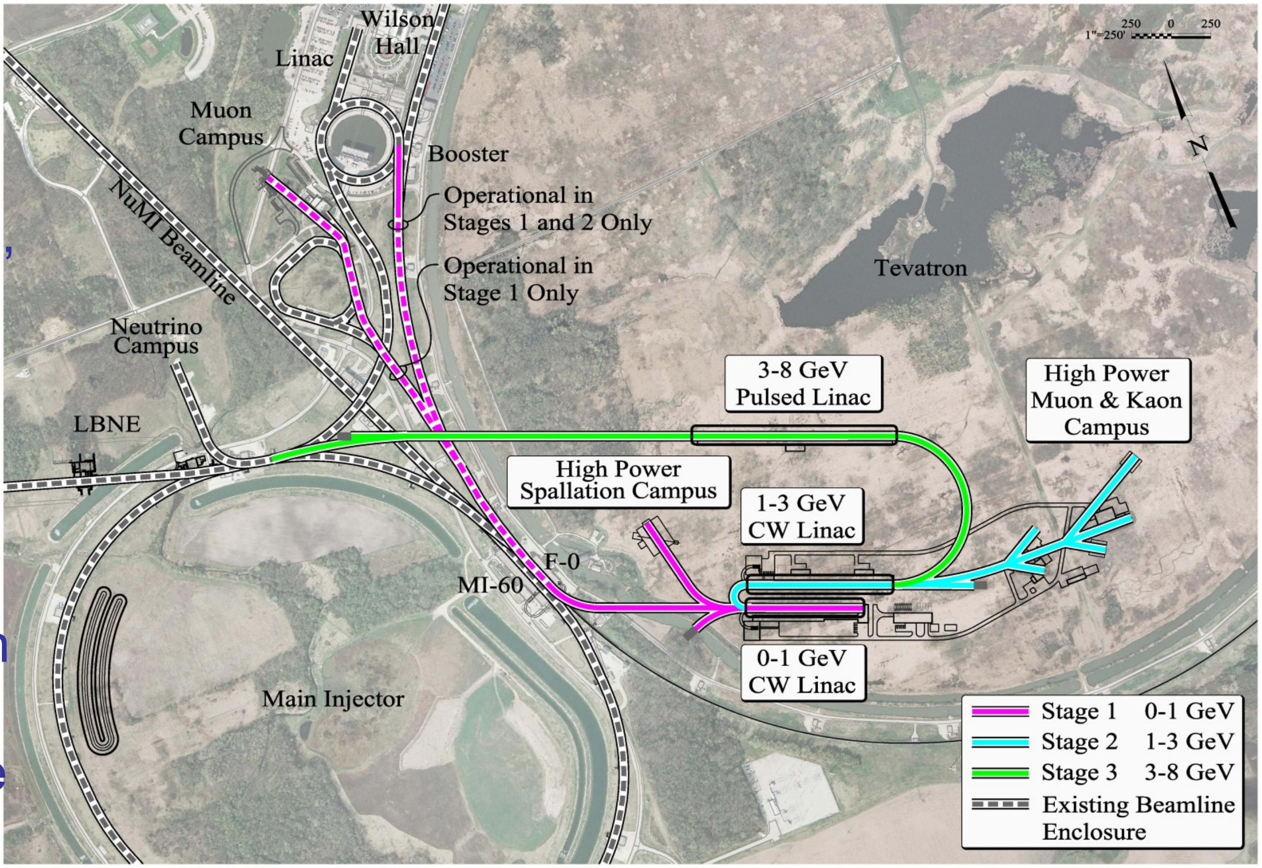
Calendar Year

Assemble and commission the detector: time for students and postdocs

Project X

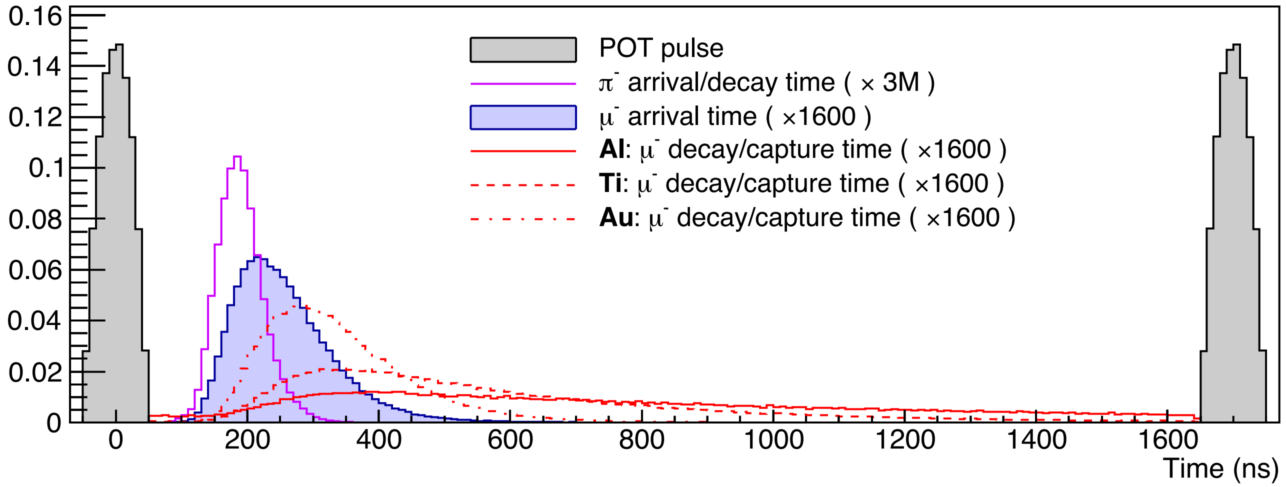
A proposed, new high intensity proton linac for Fermilab

- 3 phases
- Compelling physics opportunities at each stage: neutrinos, kaons, muons, nucleons, and atomic probes: hep-ex:1306.5009
- Programmable pulse structure
- Simultaneous operation of many experiments, each requiring a unique pulse structures.



Mu2e In the Project X Era

- If we have a signal:
  - Study Z dependence: distinguish among theories
  - Enabled by the programmable time structure of the Project X beam: match pulse spacing to lifetime of the muonic atom!



- If we have no signal:
  - Up to to 100 × Mu2e physics reach, Rμe < 10^{-18} .
  - First factor of ≈10 can use the same detector.

Summary and Conclusions

- Discover μ to e conversion or set limit
  - Rμe < 6 × 10^{-17} @ 90% CL.
  - 10,000 × better than previous best limit.
  - Mass scales to O(10,000 TeV) are within reach.
- Schedule:
  - CD-2/3 approval July 2014.
  - Commissioning data in 2019
  - Critical path is the solenoid system:
- Project X era:
  - If a signal: can study N(A,Z) dependence to elucidate the underlying physics.
  - If no signal: improve sensitivity up to 100 ×.

For Further Information

- Home page: http://mu2e.fnal.gov
  - CDR: http://arxiv.org/abs/1211.7019
  - DocDB: http://mu2e-docdb.fnal.gov/cgi-bin/DocumentDatabase
- Mu2e talks at DPF

	Presenter	Abstract	Session	Time
CRV	Craig Group	113	Detector	Thu 10:30
Tracker	Asset Mukherjee	131	Detector	Fri 10:30
Overview	Rob Kutschke	132	Flavor	Fri 15:50
Calorimeter	Chih-Hsiang Cheng	193	Flavor	Fri 16:10

- Project X:
  - Accelerator Reference Design: physics.acc-ph:1306.5022
  - Physics Opportunities: hep-ex:1306.5009
  - Broader Impacts: physics.acc-ph:1306.5024

Backup Slides

Not Covered in This Talk

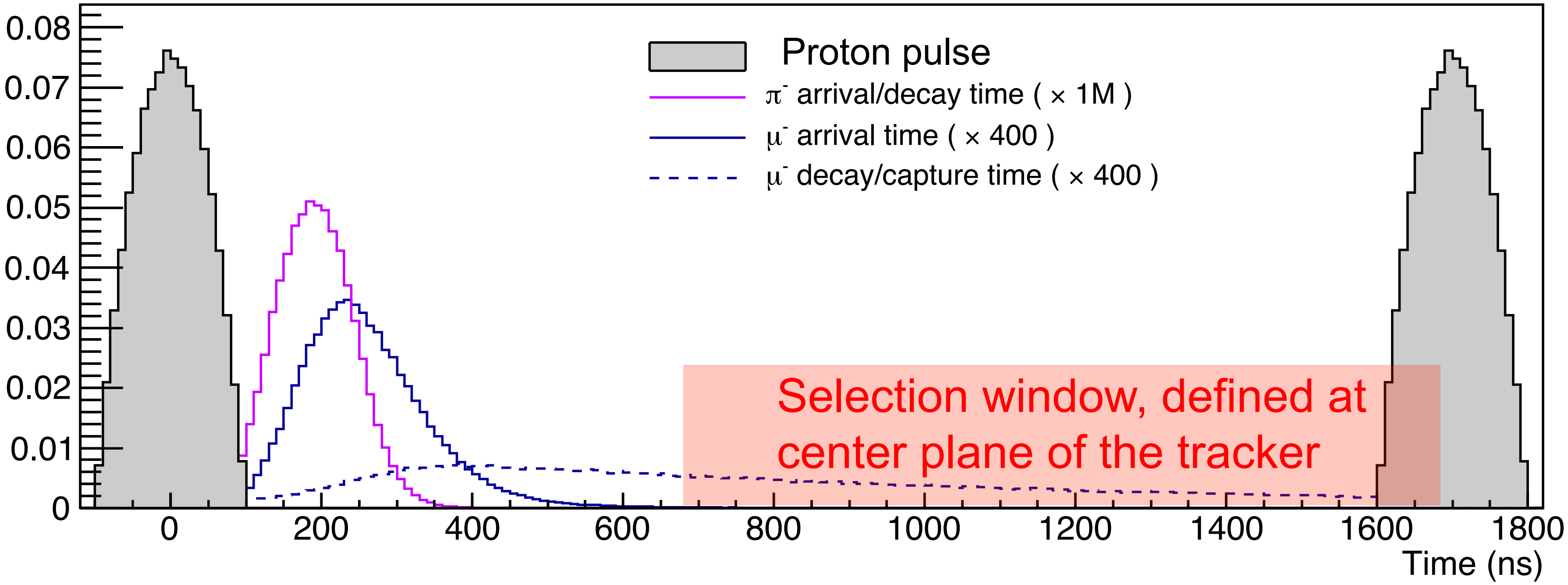
- Pipelined, deadtime-less trigger system
- Cosmic ray veto system
- Stopping target monitor
  - Ge detector, behind muon beam dump
- Details of proton delivery
- AC dipole in transfer line; increase extinction
- In-line extinction measurement devices
- Extinction monitor near proton beam dump
- Muon beam dump
- Singles rates and radiation damage due to neutrons from production target, collimators and stopping target.

Fermilab Muon Program

- Mu2e
- Muon g-2
- Muon Accelerator Program (MAP):
  - MuCool – ionization cooling demonstration
  - Other R&D towards a muon collider
- NuStorm
  - Proposal has Stage I approval from FNAL PAC
- Preliminary studies for Project-X era:
  - $\mu^+ \rightarrow e^+ \gamma$
  - $\mu^+ \rightarrow e^+ e^- e^+$

All envisage x10 or better over previous best experiments

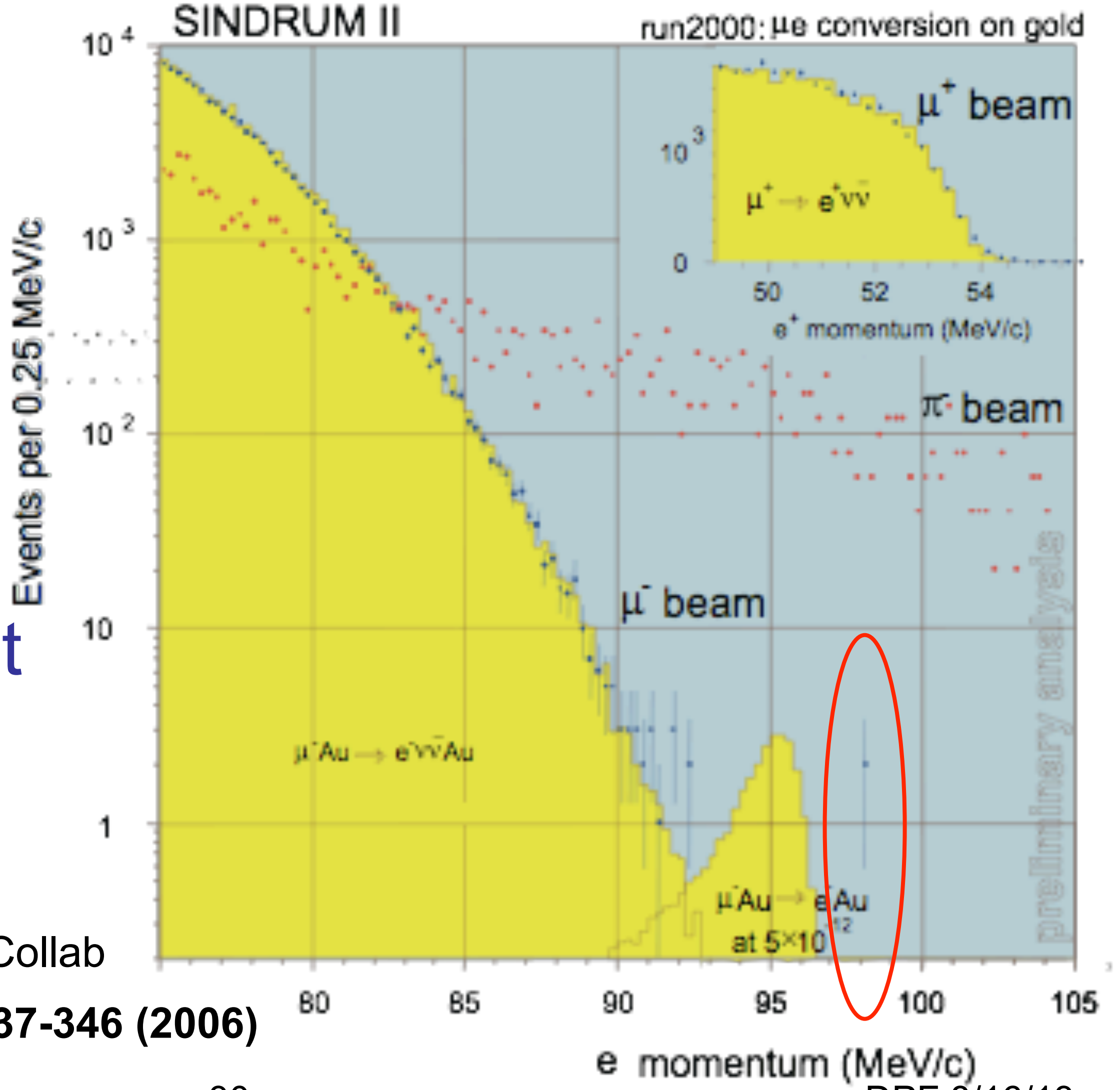
Schematic of One Cycle of the Muon Beamline



- No real overlap between selection window and the second proton pulse!
  - Proton times: when protons arrive at production target
  - Selection window: measured tracks pass the mid-plane of the tracker

Previous Best Experiment

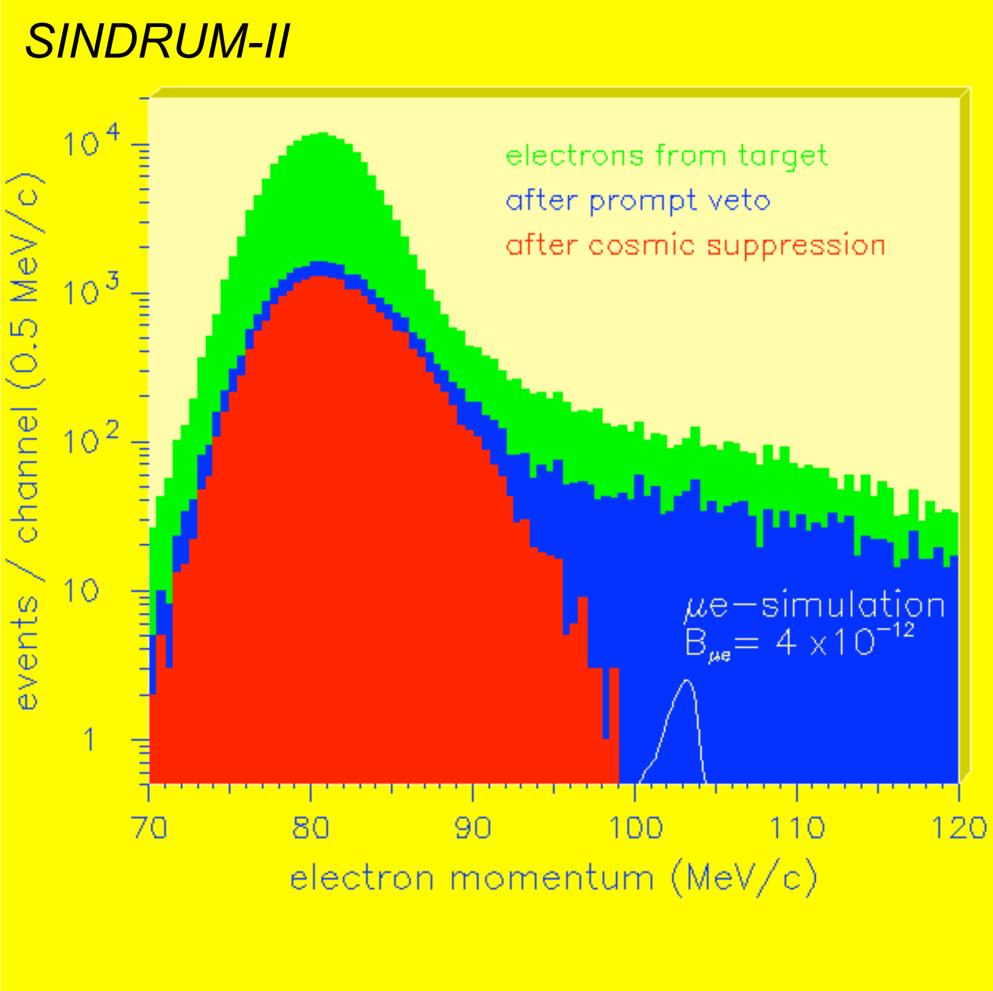
- SINDRUM II
- $R_{\mu e} < 6.1\times10^{-13}$ @90% CL
- 2 events in signal region
- Au target: different E_e endpoint than Al.



HEP 2001 W. Bertl – SINDRUM II Collab

W. Bertl et al, Eur. Phys. J. C **47, 337-346 (2006)**

SINDRUM II Ti Result



- Dominant background: beam π^-
- Radiative Pion Capture (RPC)
- suppressed with prompt veto
- Cosmic ray backgrounds also important

$R_{\mu e}$(Ti) < 6.1X10^{-13}
PANIC 96 (C96-05-22)

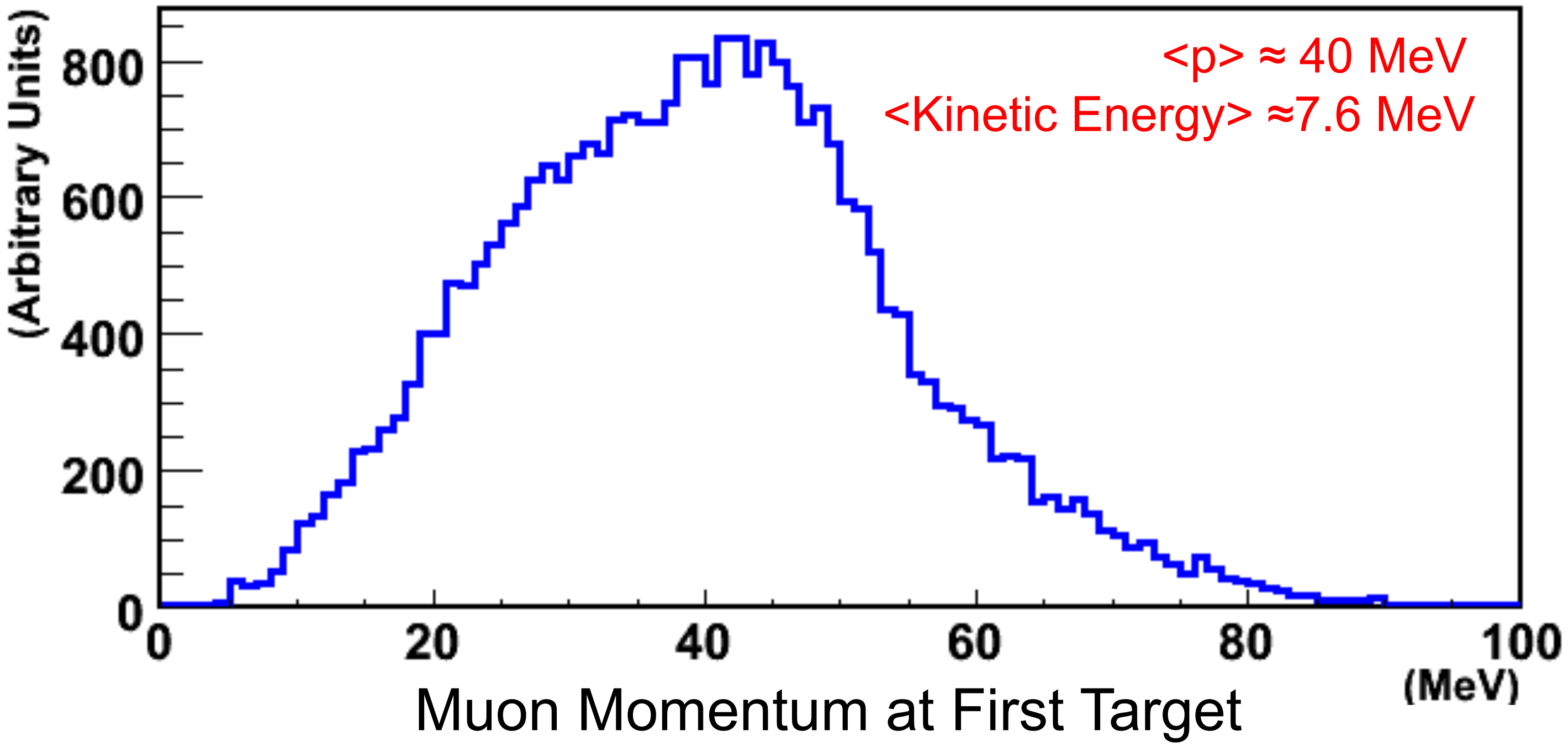
$R_{\mu e}$(Ti) < 4.3X10^{-12}
Phys.Lett. B317 (1993)

$R_{\mu e}$(Au) < 7X10^{-13}
Eur.Phys.J. C47 (2006)

Why Better than SINDRUM II?

- FNAL can deliver ≈1000 × proton intensity.
- Higher μ collection efficiency.
- SINDRUM II was BG limited.
  - Radiative π capture.
  - Bunched beam and excellent extinction reduce this.
  - So Mu2e can use the higher proton rate.

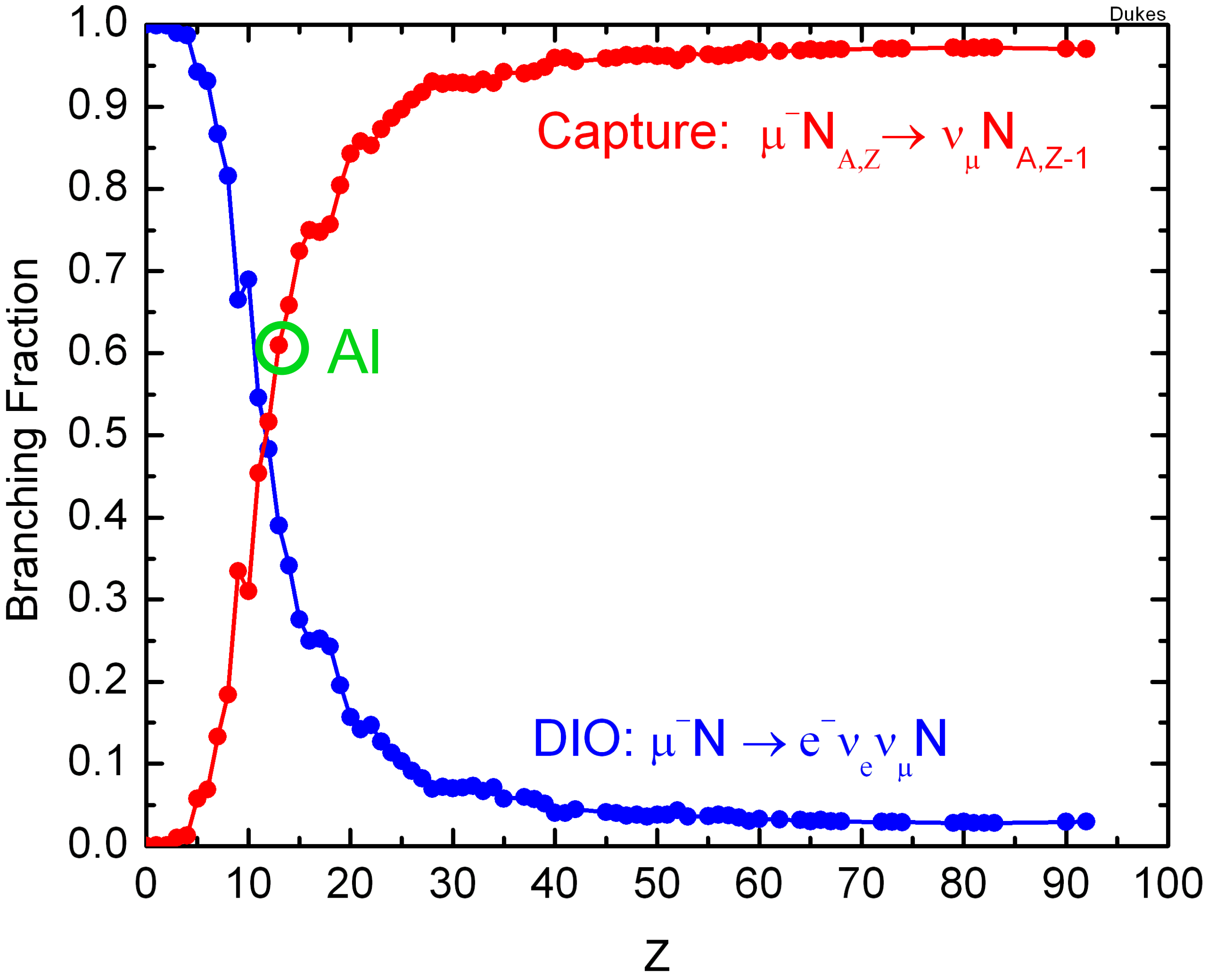
Muon Momentum



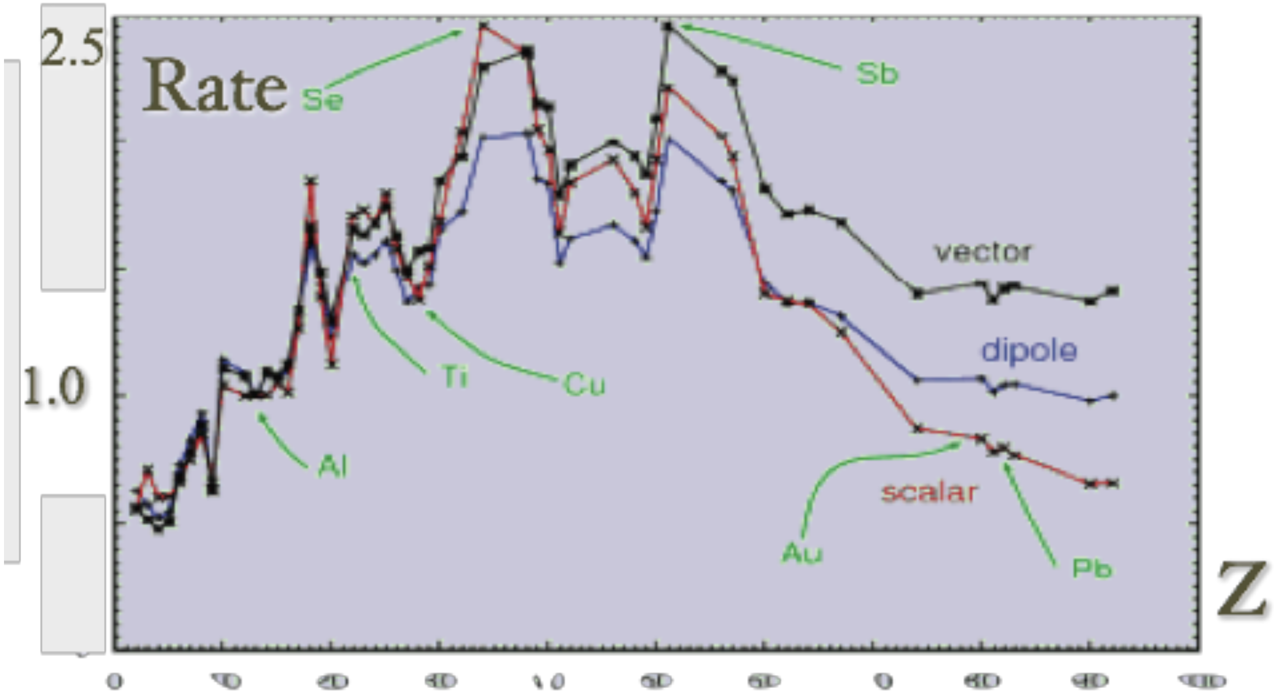
<p> ≈ 40 MeV

<Kinetic Energy> ≈7.6 MeV

Capture and DIO vs Z



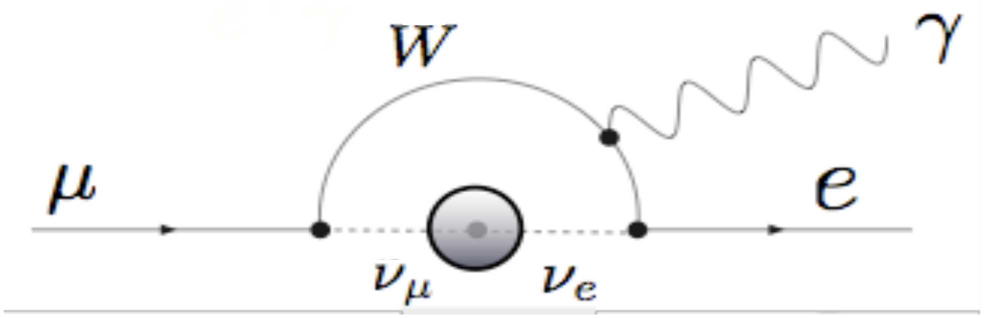
Conversion Rate, Normalized to Al



Kitano, et al., PRD 66, 096002 (2002)

CLFV Rates in the Standard Model

- With massive neutrinos, non-zero rate in SM.
- Too small to observe.



$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

What do We Measure?

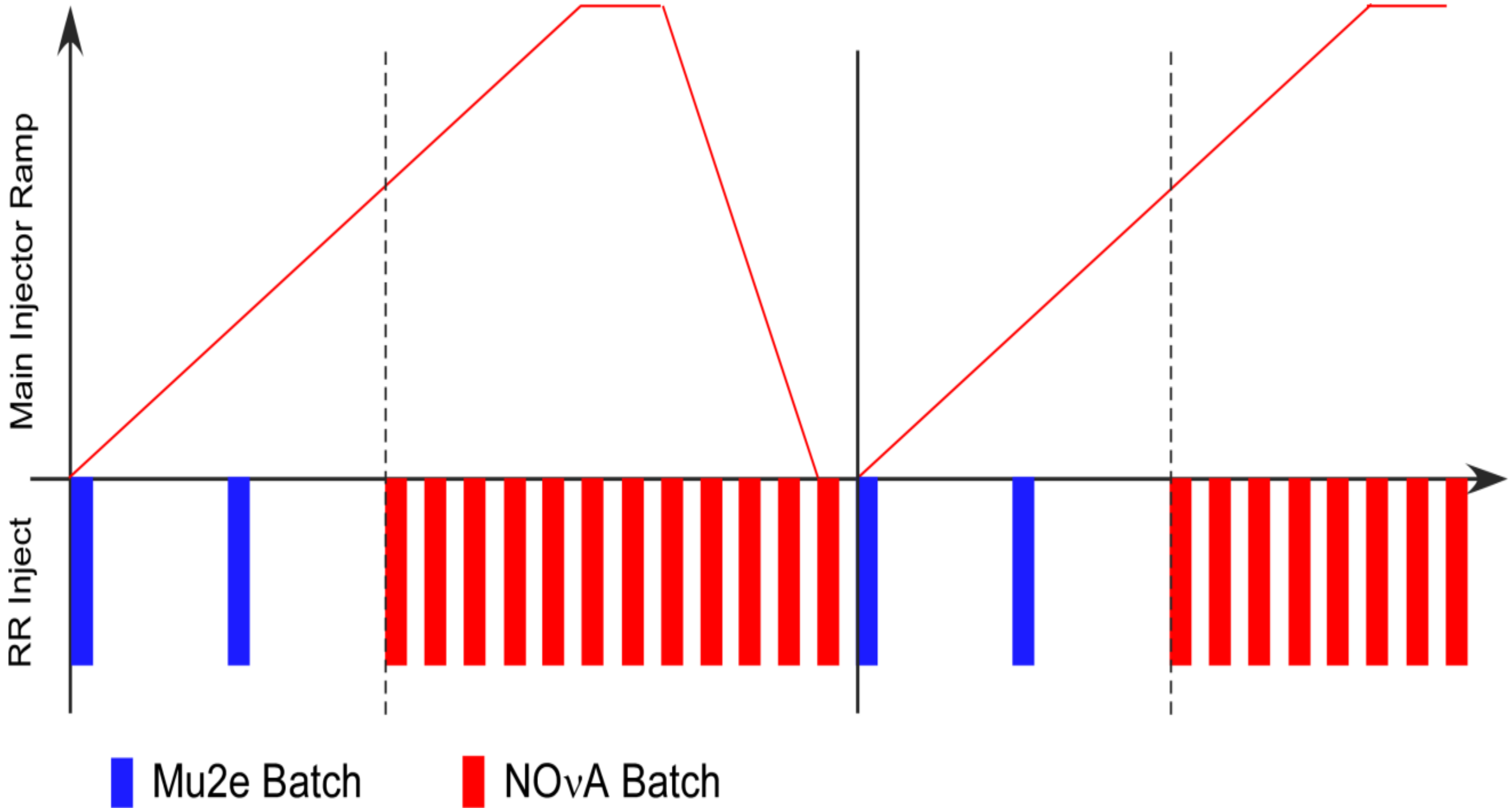
$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \texttt{all captures}}$$

- Numerator:
  - Do we see an excess at the E_e end point?

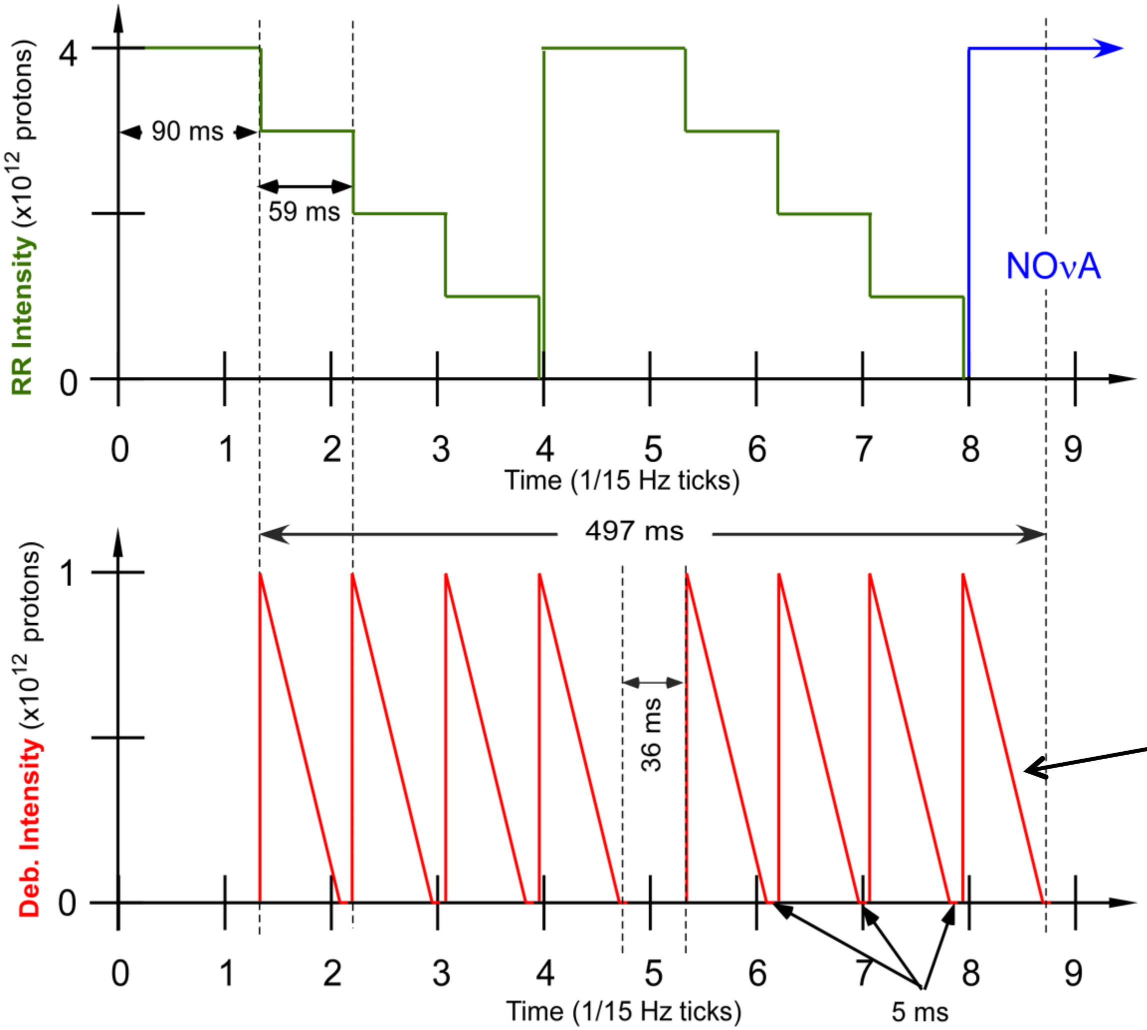
a

- Denominator:
  - All nuclear captures of muonic Al atoms
- Target sensitivity for a 3 year run
  - ≈ 2.5×10^{-17} single event sensitivity.
  - $< 6 \times 10^{-17}$ limit at 90% C.L.
- 10,000 × better than current limit (SINDRUM II).

Proton Beam Macro Structure

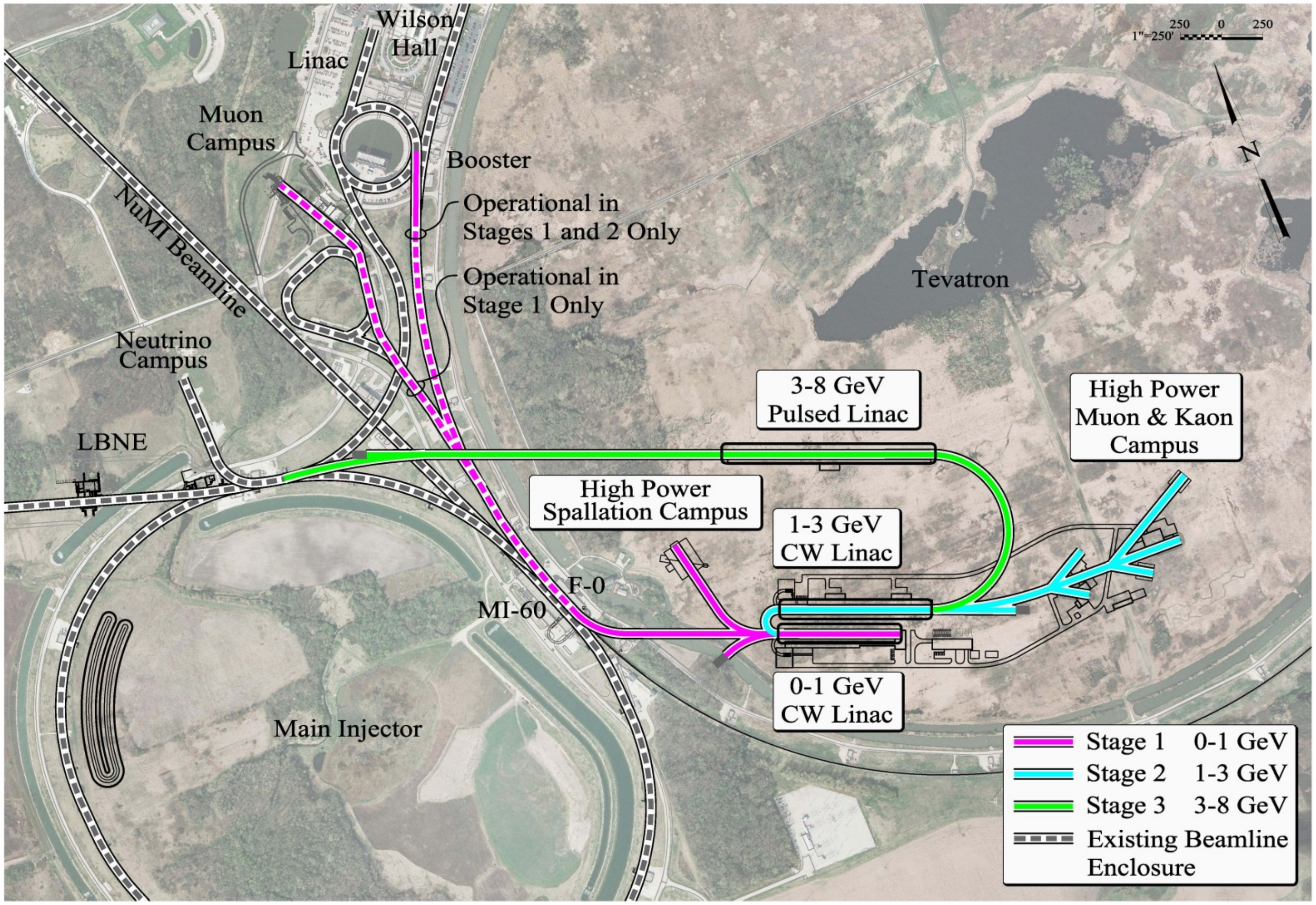


Proton Beam Micro Structure



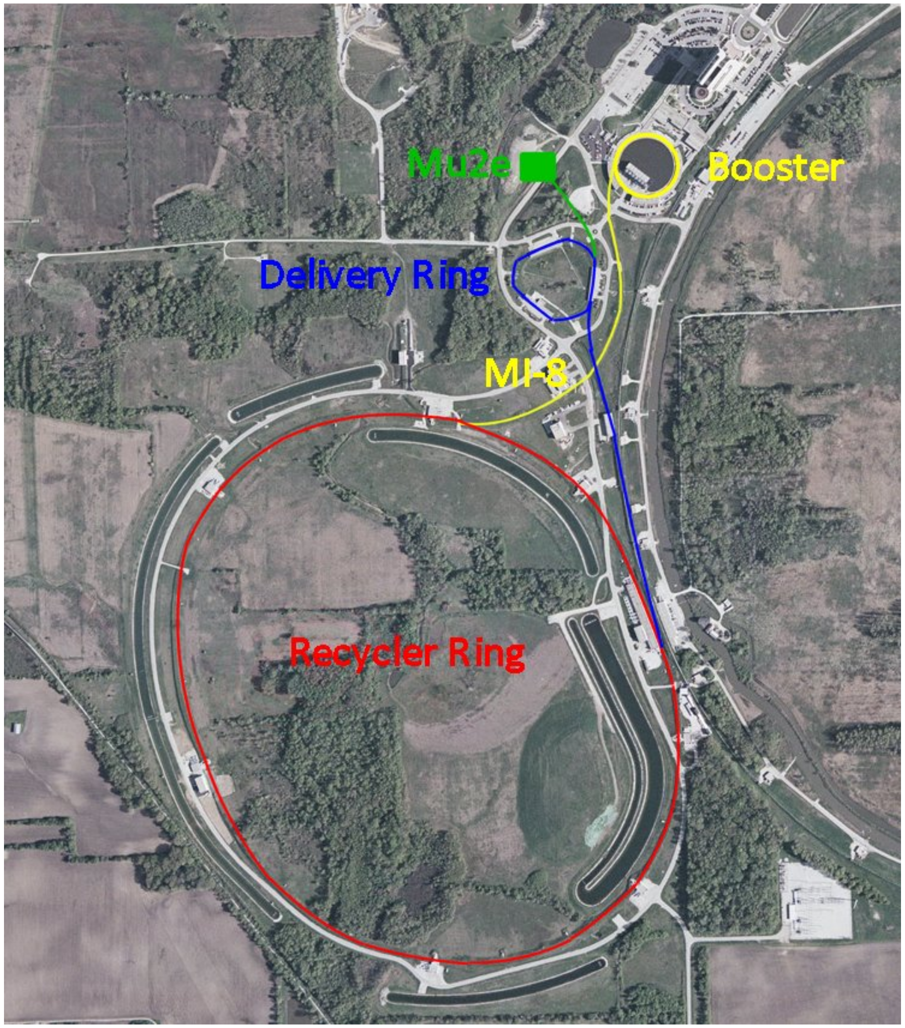
Slow spill:
Bunch of 4 ×10^7
protons every 1694 ns

Project-X Phases



Proton Delivery and Economics

- Reuse existing Fermilab facilities with modest modifications.
- Share cost of most modifications with muon g-2 experiment.
- Protons from Booster to Delivery Ring via Recycler
- Slow spill from Delivery Ring
  - Former pbar Debuncher Ring
- Sharing protons with NOVA:
  - NOVA: 12/20 booster cycles.
  - Mu2e: 8/20 cycles.
- Stable, slow spill with a very intense proton beam is big challenge.



Required Extinction 10^{-10}

- Internal: 10^{-7} already demonstrated at AGS.
  - Without using all of the tricks.
- External: in transfer-line between ring and production target.
  - AC dipole magnets and collimators.
- Simulations predict aggregate 10^{-12} is achievable
- Extinction monitoring systems have been designed.