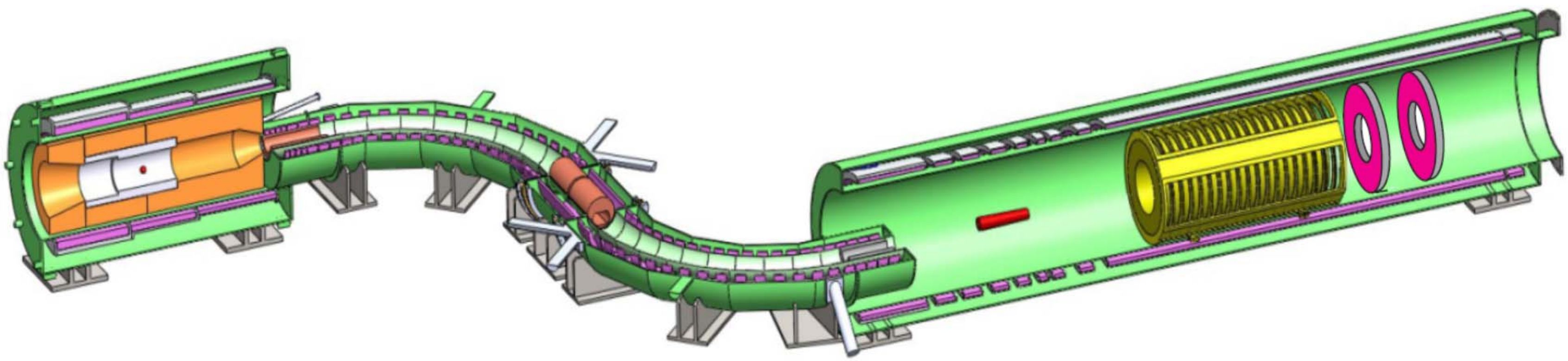
# The Mu2e Experiment at Fermilab

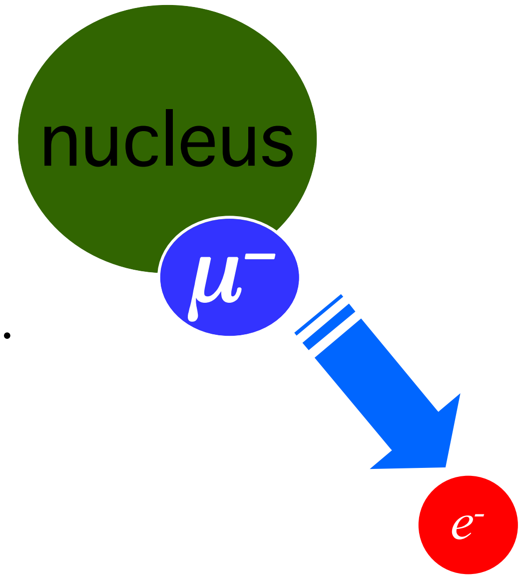


David Hitlin
Caltech
INSTR2014
February 25, 2014

# Muon to electron conversion in the field of a nucleus

$$\mu N \rightarrow eN$$

- Initial state: muonic atom
- Final state:
  - a single mono-energetic electron.
    - the energy depends on *Z* of target.
  - recoiling nucleus is not observed
    - the process is coherent: the nucleus stays intact.
  - neutrino-less
- Standard Model rate is $10^{-54}$
- There is an observable rate in many new physics scenarios.
- Related decays: Charged Lepton Flavor Violation (CLFV):

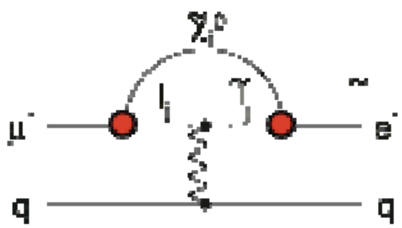



$$\mu \rightarrow e\gamma \quad \mu \rightarrow e^+e^-e^+ \quad K_L^0 \rightarrow \mu e \quad B^0 \rightarrow \mu e$$
$$\tau \rightarrow \mu\gamma \quad \tau \rightarrow \mu^+\mu^-\mu^+ \quad D^+ \rightarrow \mu^+\mu^+\mu^-$$

# New Physics Scenarios

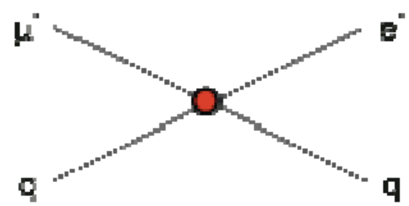
**Supersymmetry**

rate ~ $10^{-15}$



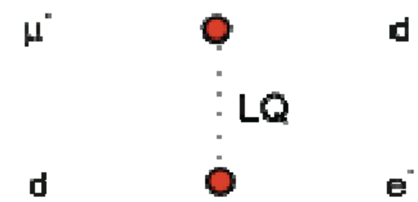

**Compositeness**

$\Lambda_c$ ~ 3000 TeV



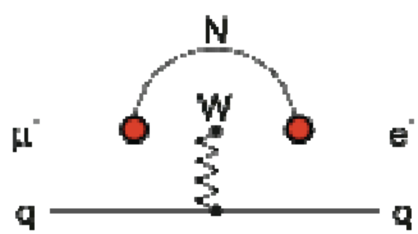

**Leptoquark**

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



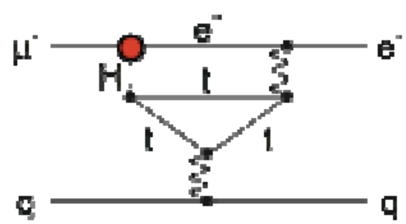

**Heavy Neutrinos**

$|U_{\mu N}U_{eN}|^2$ ~ $8\times10^{-13}$



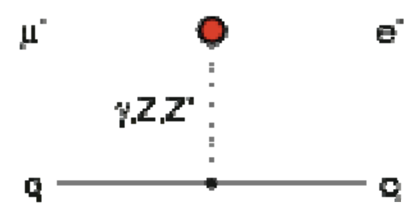

**Second Higgs Doublet**

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




**Heavy Z'**
**Anomal. Z Coupling**

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




M. Raidal, *et al.*, Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J. C57, 13, 2008

Sensitive to mass scales up to $\mathcal{O}(10^4$ TeV)

# CLFV has actually been seen in California

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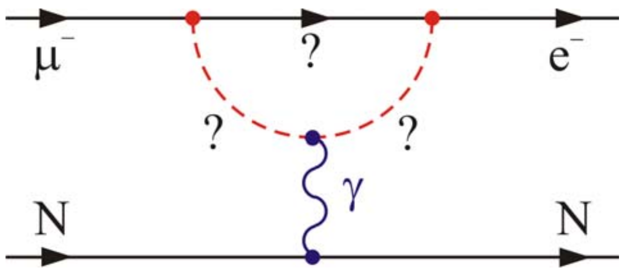
# Two types of amplitudes contribute

## Loops

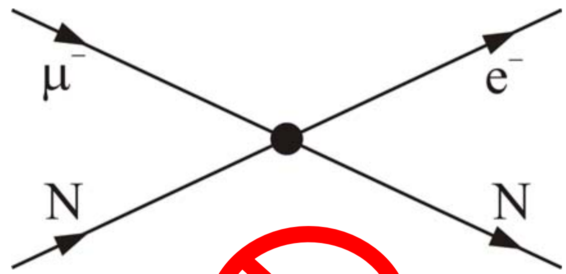



$\mu \rightarrow e\gamma$

$\mu N \rightarrow eN$

$\mu \rightarrow eee$

## Contact terms




$\mu \rightarrow e\gamma$

$\mu N \rightarrow eN$

$\mu \rightarrow eee$

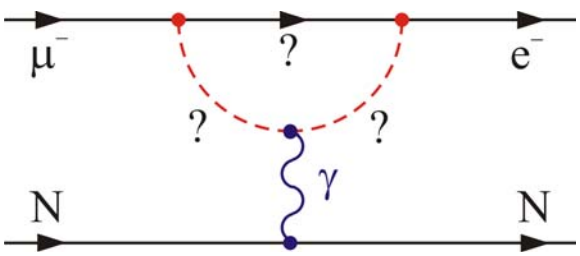
## Effective Lagrangian

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

# Sensitivity to high mass scales

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

Loops dominate for $\kappa << 1$




$\mu \rightarrow e\gamma$

$\mu N \rightarrow eN$

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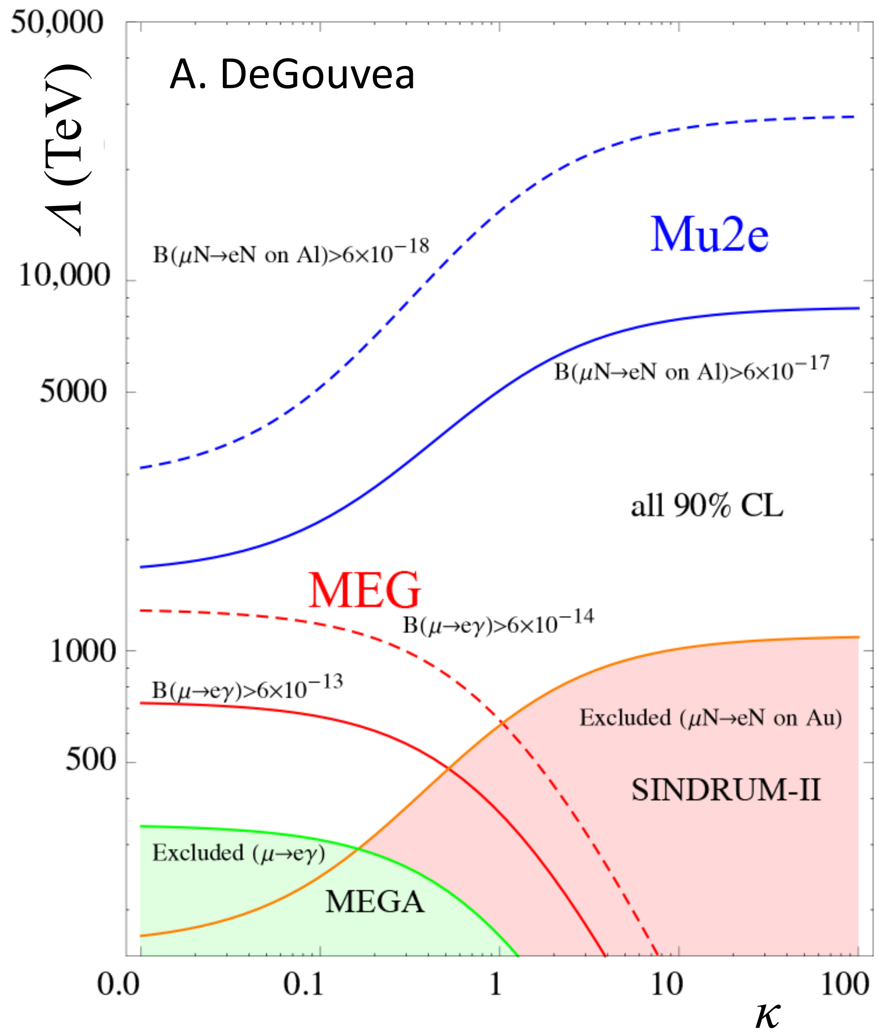
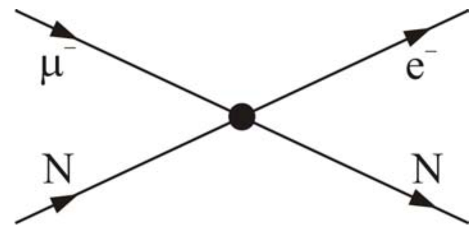



Contact terms dominate for $\kappa >> 1$




$\mu \rightarrow e\gamma$

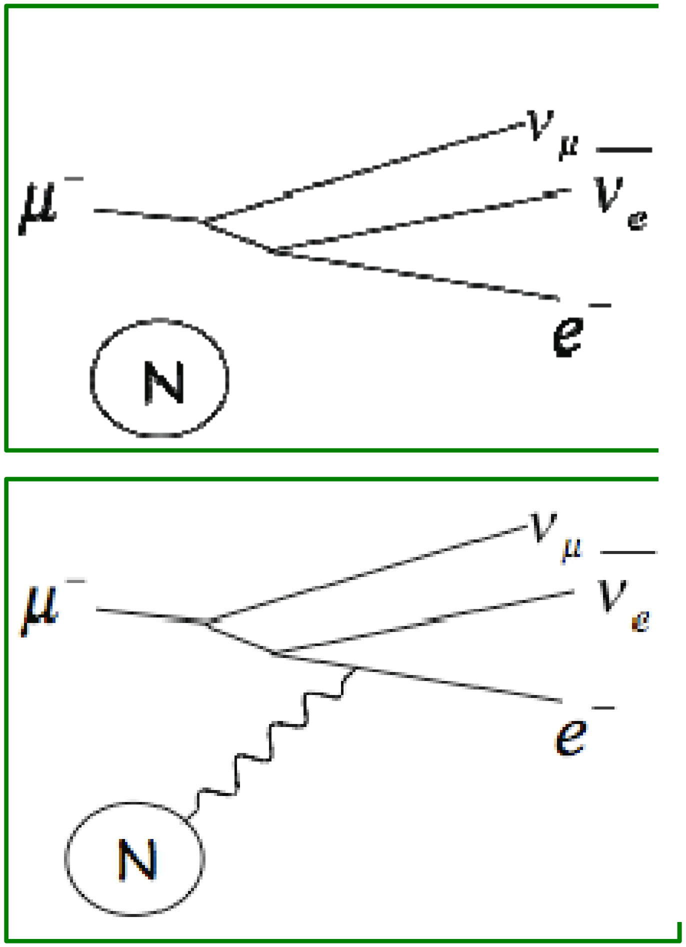
$\mu N \rightarrow eN$

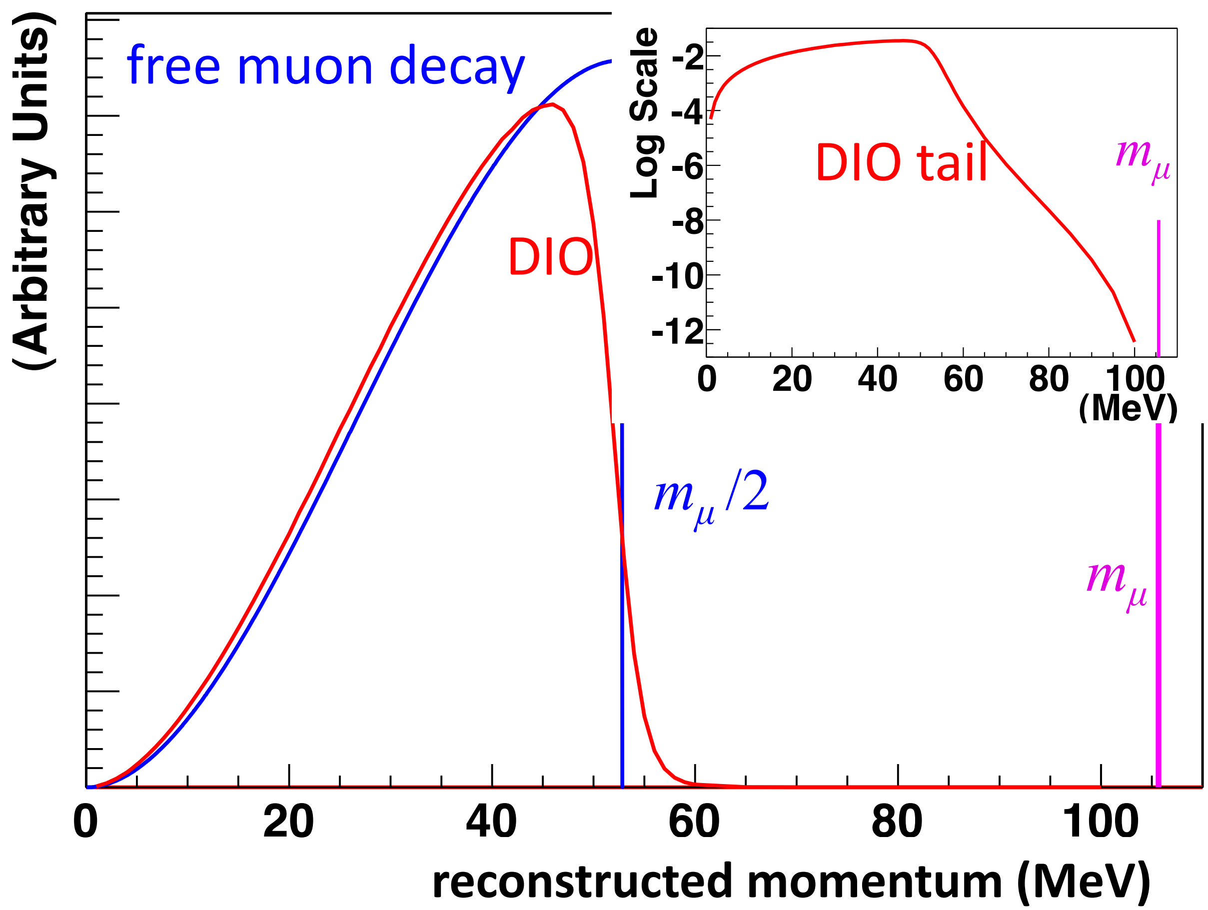
$\mu \rightarrow eee$

# Complementarity with the LHC

- If new physics is seen at the LHC
  - Need CLFV measurements (Mu2e and others) to discriminate among interpretations
- If new physics is not seen at the LHC
  - Mu2e has discovery reach to mass scales that are inaccessible to the the LHC

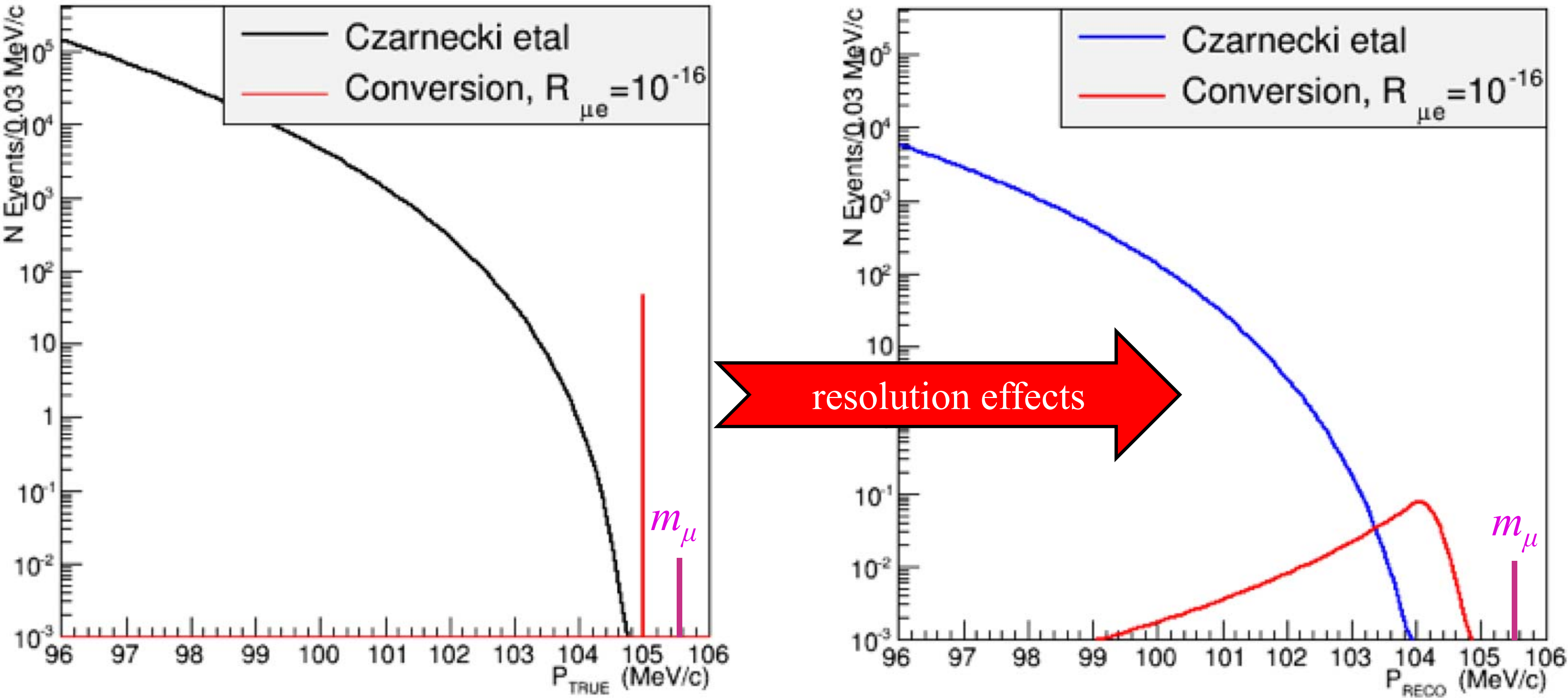
# The dominant background: muon decay in orbit (DIOs)



# Resolution effects extend the DIO endpoint into the signal region

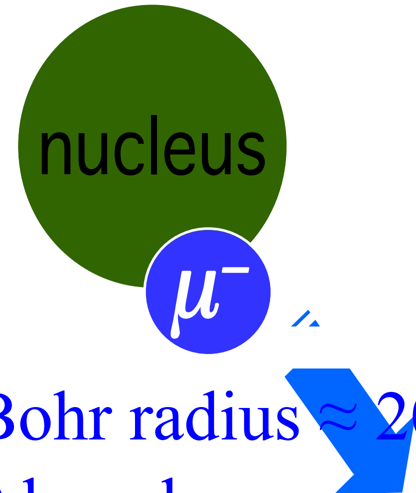
- The tail of the DIOs falls as $(E_{\text{Endpoint}} - E_e)^5$
- Separation of a few hundred keV for $R_{\mu e} = 10^{-16}$




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

# 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: $p$, $n$, $\gamma$
  - Neutrino-less $\mu$ 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

# The Mu2e Collaboration

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

*Laboratori Nazionale di Frascati*
*INFN Genova*
*INFN Lecce and Università del Salento*
*Istituto G. Marconi Roma*
*INFN,, Pisa*
*Universita di Udine and INFN Trieste/Udine*

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


http://mu2e.fnal.gov

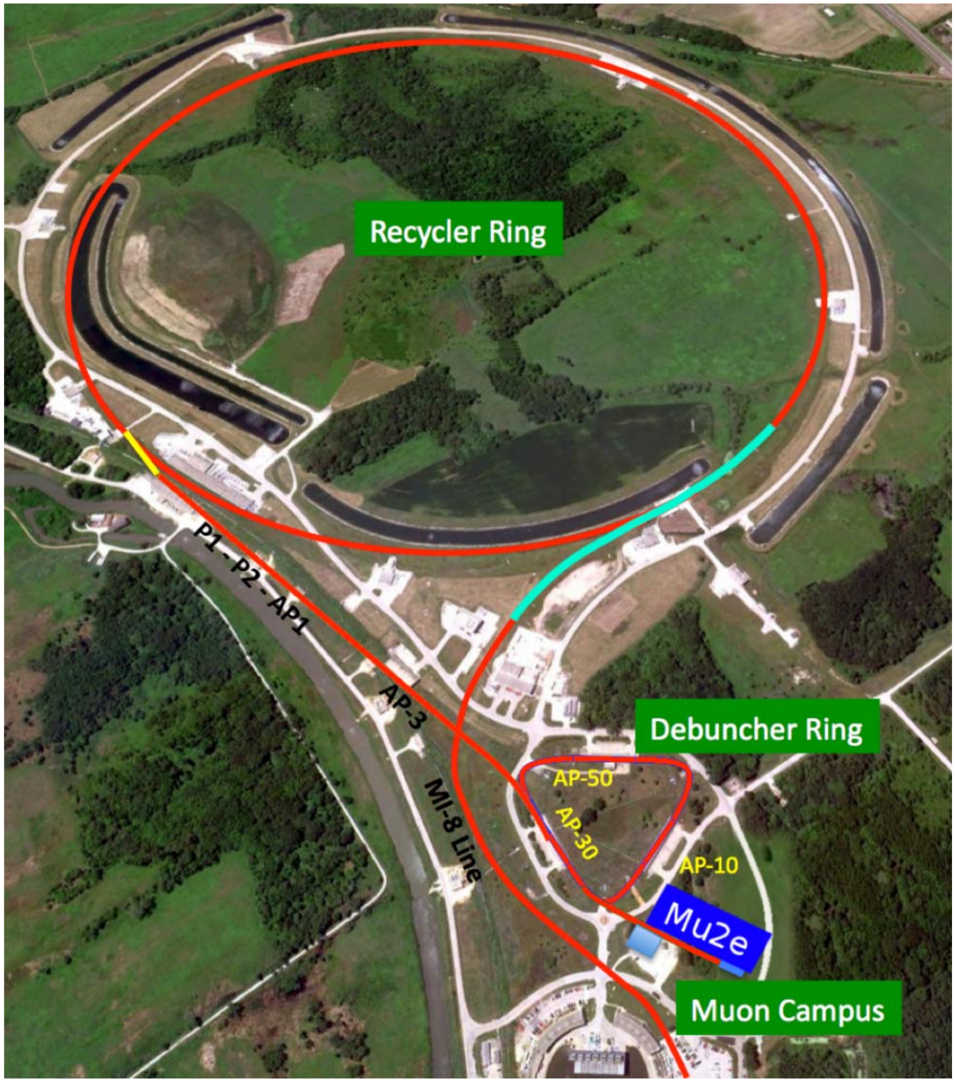
135 members from 28 institutions

# The measurement

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

- Numerator:
  - Do we see an excess at the $E_e$ end point?
- 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.
- Factor of $10^4$ improvement over current limit (SINDRUM II)

# Proton delivery




- The two new muon experiments will reuse Tevatron-era infrastructure
- Mu2e has worked with the new muon *g*-2 project to develop an accelerator and beamline design that works well for both experiments
  - Only one experiment can run at one time
- Either experiment can run simultaneously with NOνA
- With the envisioned longer term Proton Improvement Project (PIP-II), 10x the beam intensity can be obtained

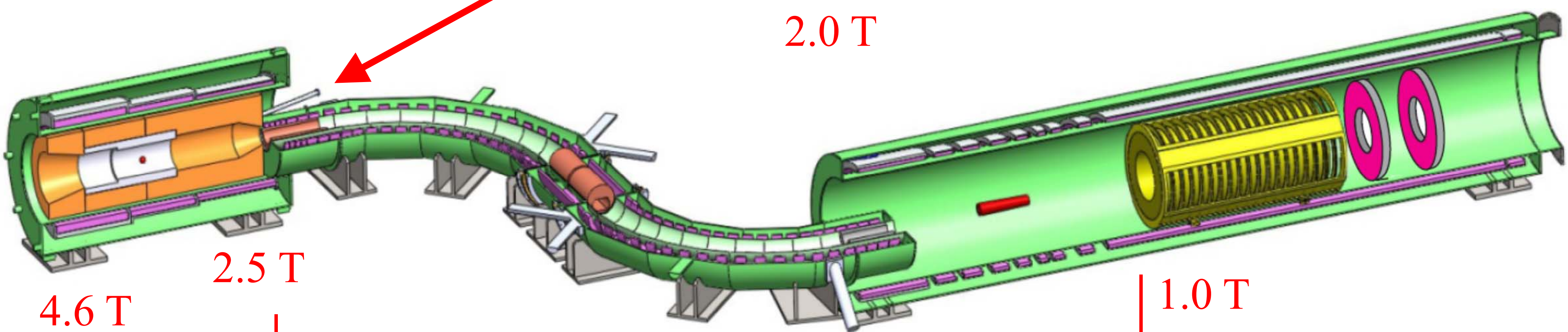
# mu2e has three large superconducting solenoid systems

Production Solenoid (PS)

Proton Beam

Detector Solenoid (DS)

2.0 T



2.5 T

4.6 T

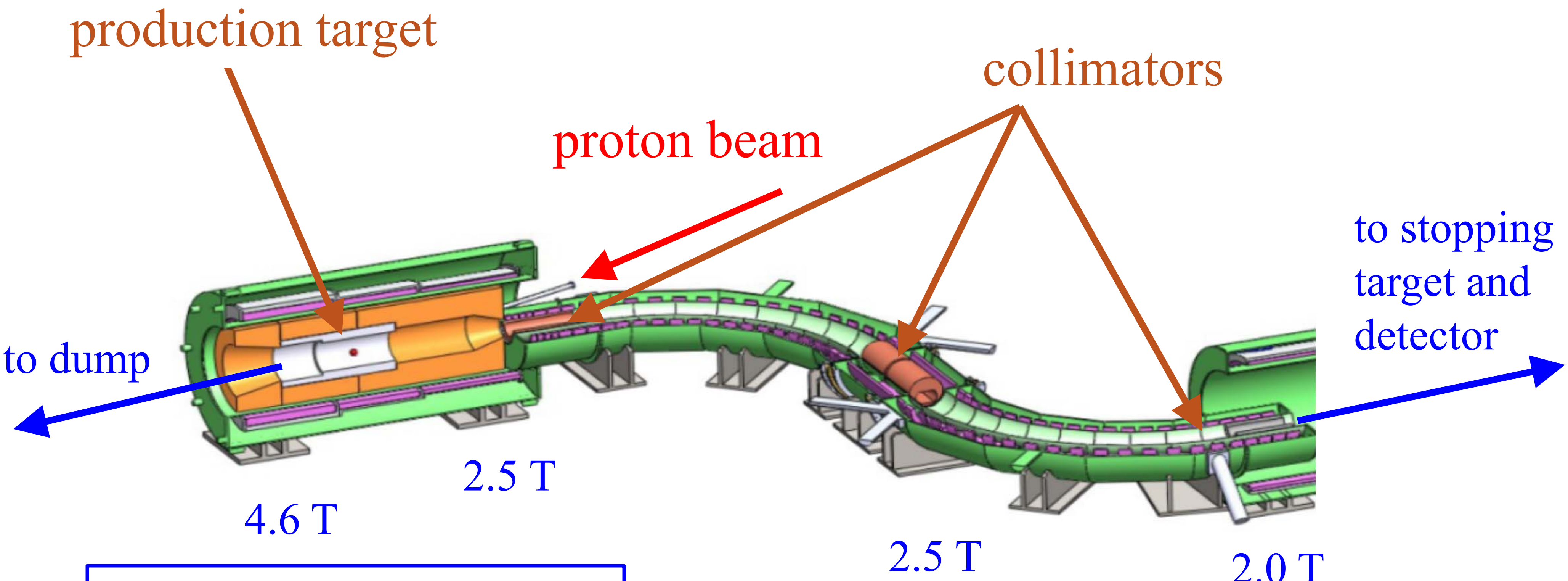
1.0 T

Detector region: uniform field 1T

Transport Solenoid (TS)

Graded *B* field for most of length

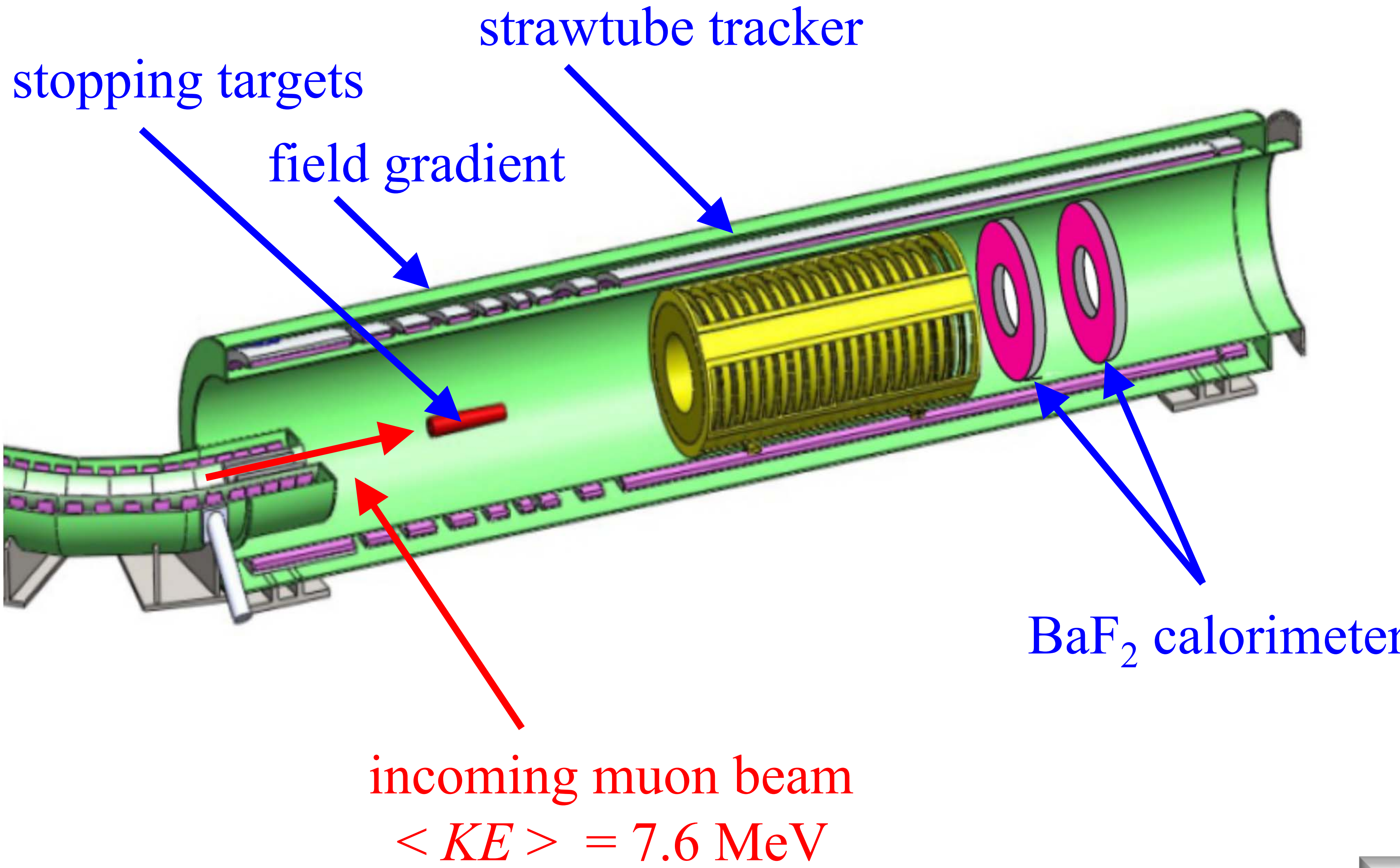
# Backward travelling muon beam




PS: magnetic mirror

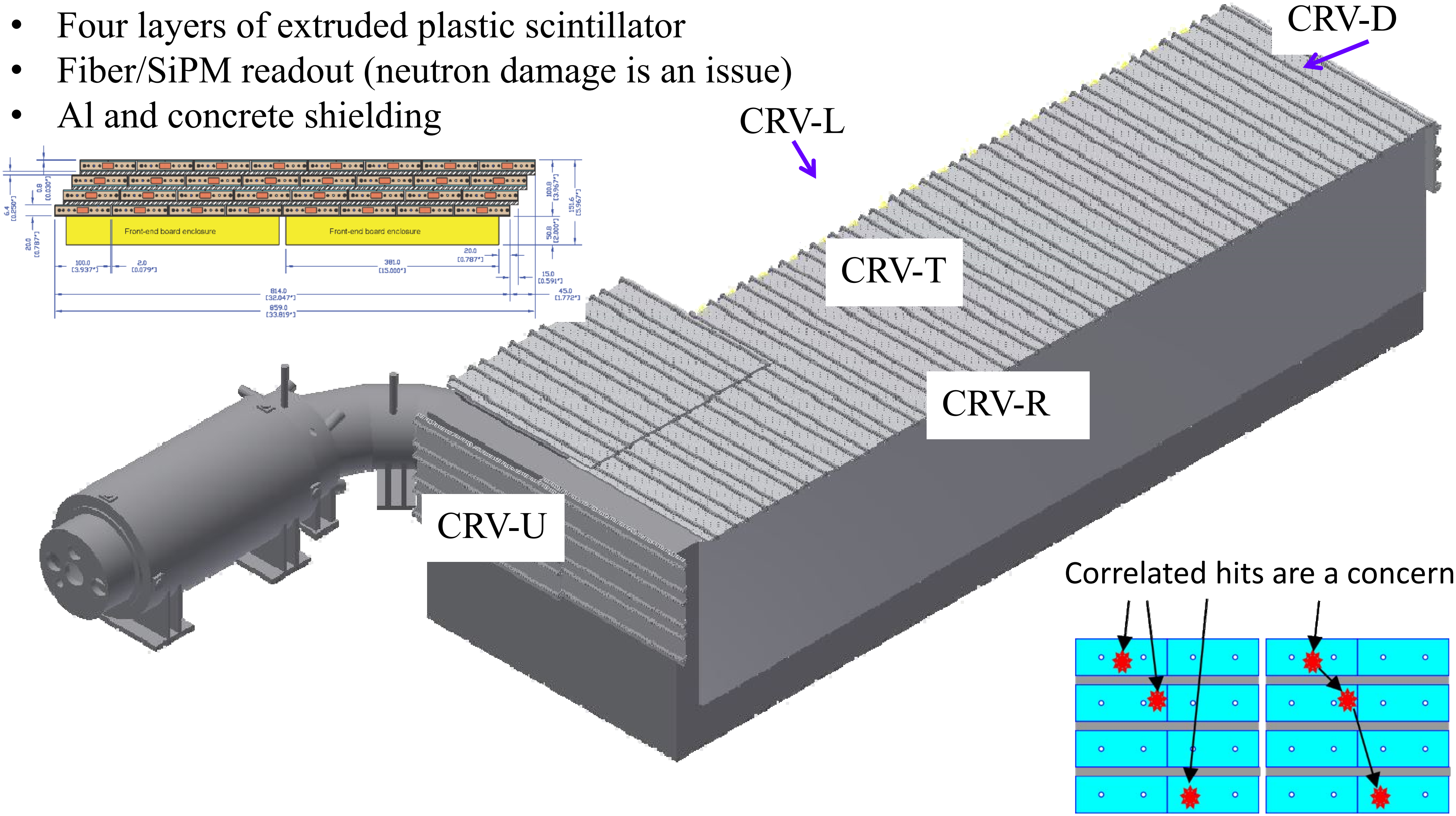
TS: negative gradient and charge selection at the central collimator

# Stopping target and detectors



# Detector solenoid is surrounded by a cosmic ray veto (CRV)

- Four layers of extruded plastic scintillator
- Fiber/SiPM readout (neutron damage is an issue)
- Al and concrete shielding




Correlated hits are a concern

# CRV inefficiency requirement

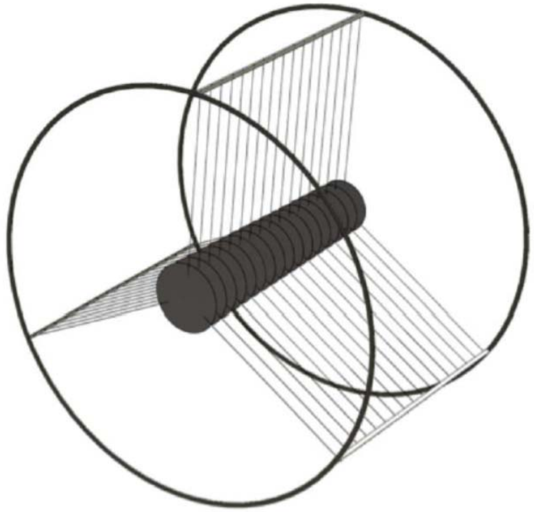
**Required CR Veto Inefficiency**

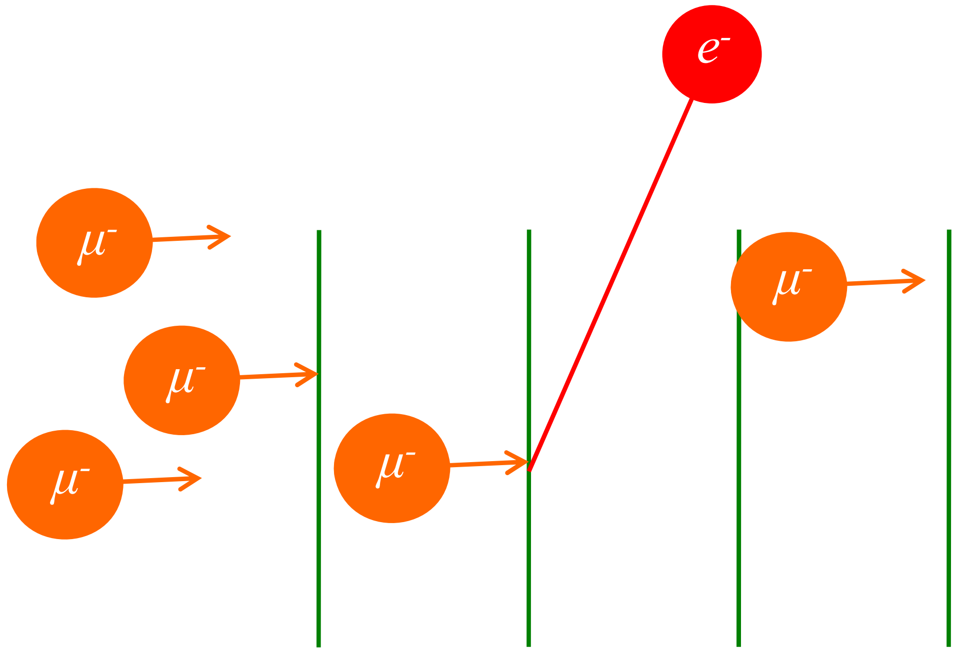
CD-1 Design (3' concrete)

| Quantity | Value | |
|---|---|---|
| Total veto live time [s] | 1.12E+07 | |
| Surface muon flux [$m^{-2}s^{-1}$] | 134.7 | |
| Surface muon energy [GeV] (min,max) | 1 | 300 |
| Area of surface muon generation [$m^2$] | 300 | |
| Incident muon rate [s-1] | 40,424 | |
| MC generated CR muons | 1.52E+10 | |
| Equivalent live exposure [s] : [h] | 3.76E+05 | 104.4 |
| Fractional equivalent exposure | 3.37% | |
| MC energy interval [MeV] | 10 | |
| Signal energy interval [MeV] | 1.20 | |
| Background events in MC energy interval | 342 | +/- 18 |
| Background events in signal energy interval | 41.04 | +/- 2.22 |
| Background event rate [$s^{-1}$] | 1.09E-04 | |
| Time/event [live hr] : [total hr] | 3 | 14 |
| Total background events [live] : [non-live] | 1,218 | 2549 |
| Confidence Limit | 0.90 | |
| Lower limit | 318.52 | |
| Upper limit | 366.94 | |
| Background events per run | 1,218 | +/- 66 |
| Background events per run (90% CL) | 1,307 | |
| **Desired number of background events** | **0.050** | **+/- 0.003** |
| **Required CR veto inefficiency** | **4.11E-05** | |
| **90% CL CR veto inefficiency** | **3.83E-05** | |
| **Desired CR veto inefficiency** | **1.0E-04** | |
| **Number of background events** | **0.122** | **+/- 0.007** |
| **90% CL number of background events** | **0.131** | |

# Stopping target

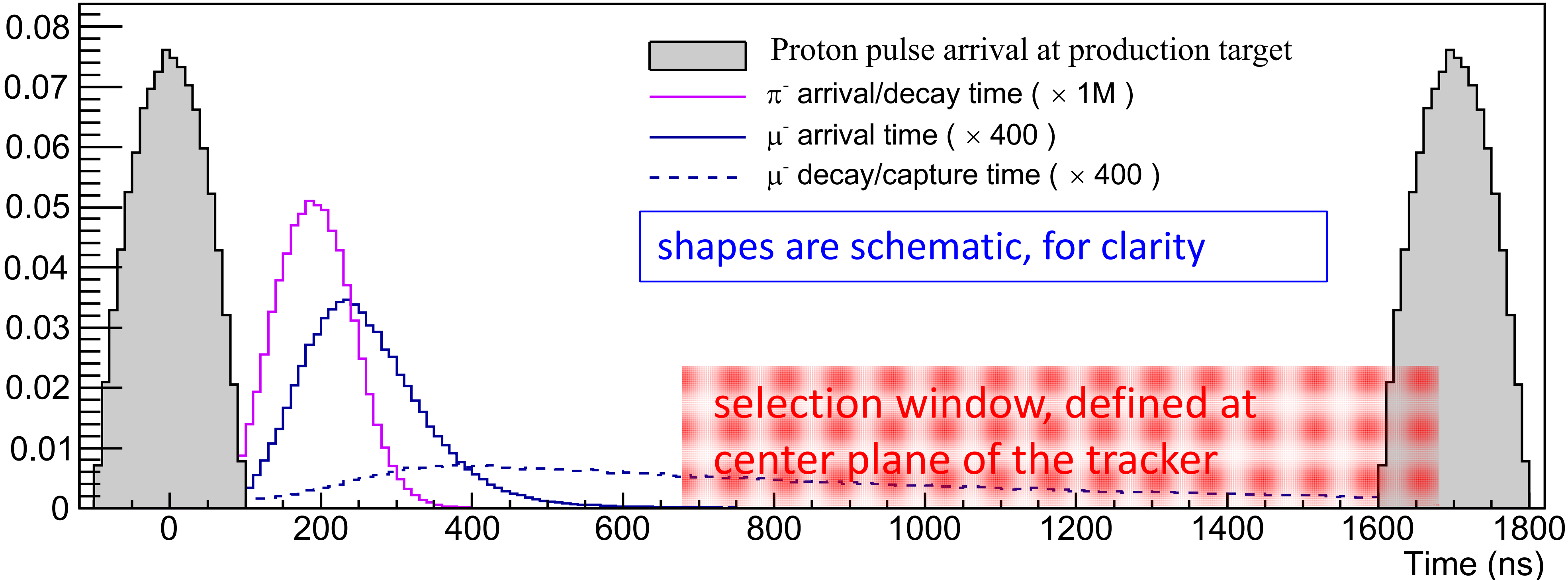
- Pulse of low energy $\mu^-$ on thin Al foils
- ~50% are captured to form muonic Al
- ~0.0016 stopped $\mu^-$ per proton on production target
- DIO and conversion electrons pop out of target foils






Baseline
- 17 target foils
- each 200 microns thick
- 5 cm spacing
- radius:
  - ≈10. cm upstream
  - ≈6.5 cm downstream
- Optimization is ongoing

# One cycle of the muon beamline



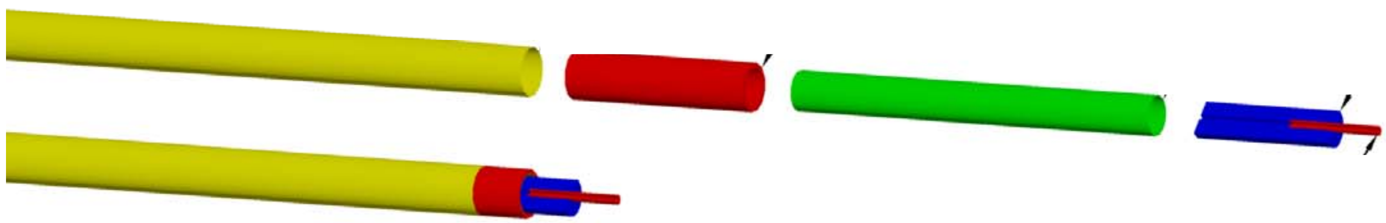

- $\mu$ are accompanied by $e^-$, $e^+$, $\pi$, anti-protons …
  - these create prompt backgrounds
  - strategy: wait for them to decay.
- extinction = (# protons between bunches)/(protons per bunch)
  - requirement: extinction < $10^{-10}$

# Tracker: strawtubes operating in vacuum

1

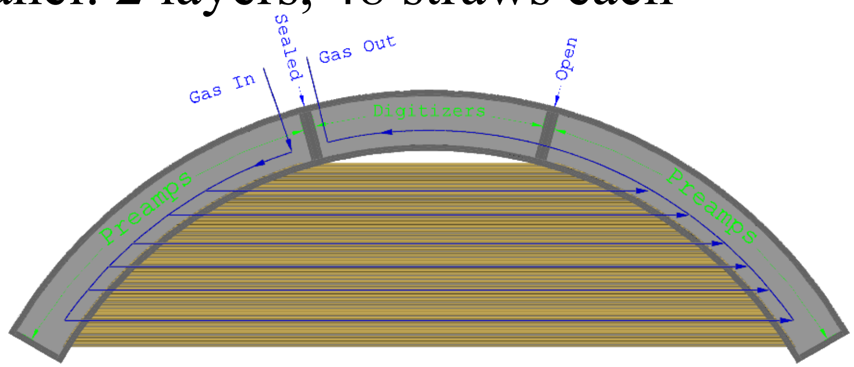
Straws: 5 mm OD; 15 $\mu$m metalized mylar wall.

Custom ASIC for time division: $\sigma \approx$ 5 mm at straw center



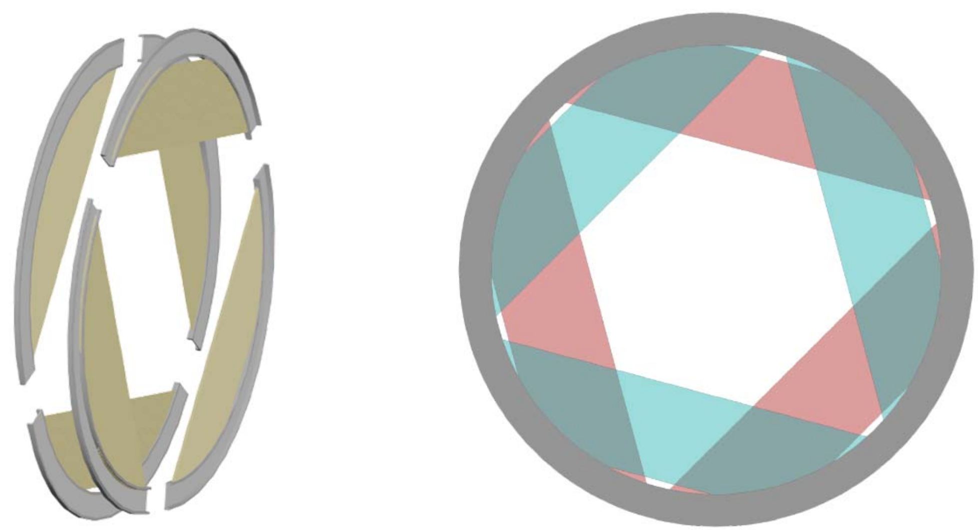
2

Panel: 2 layers, 48 straws each



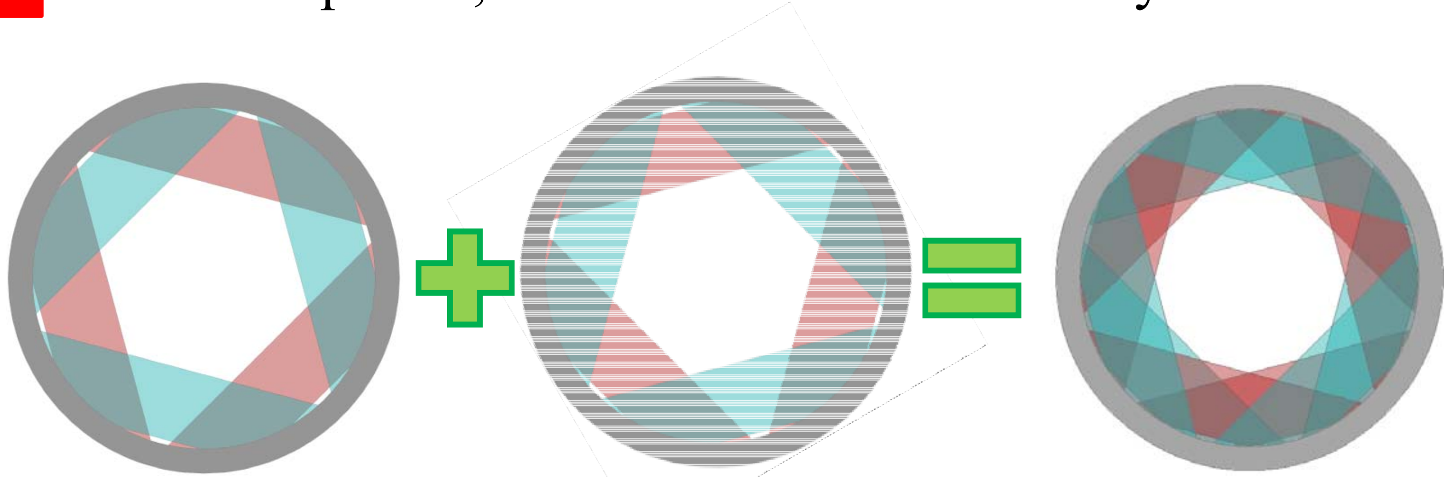

3

Plane: 6 self supporting panels

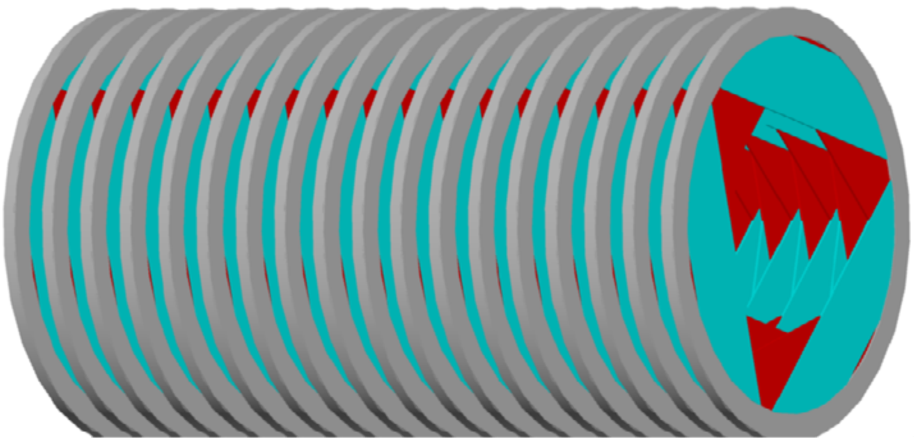


# Tracker: strawtubes in vacuum

4 Station: 2 planes; relative rotation under study

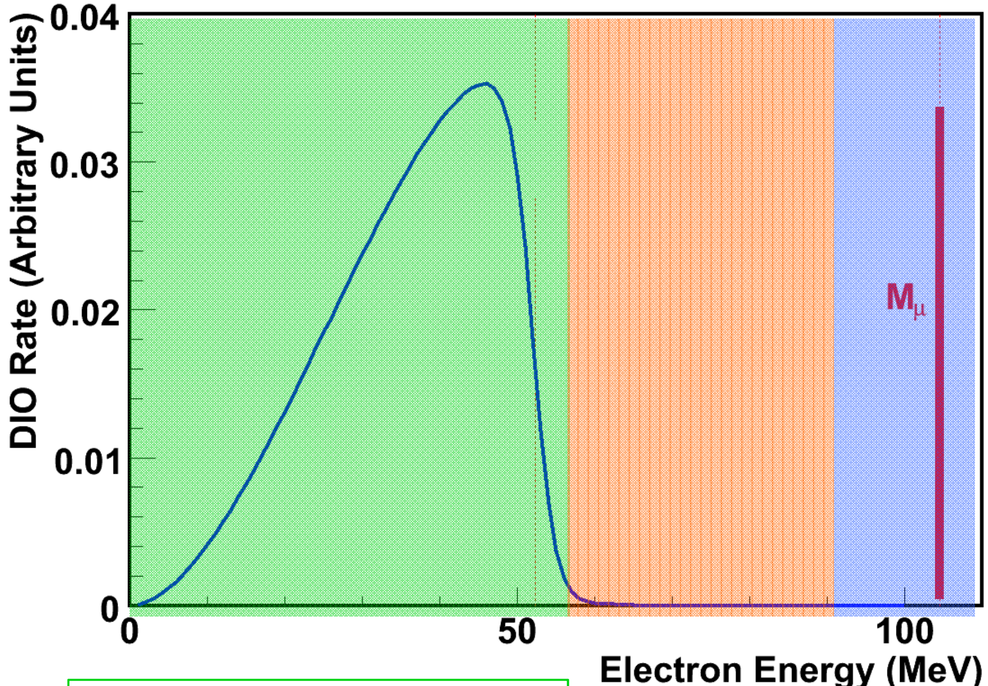


5 Tracker: 22 stations (# and rotations still being optimized)



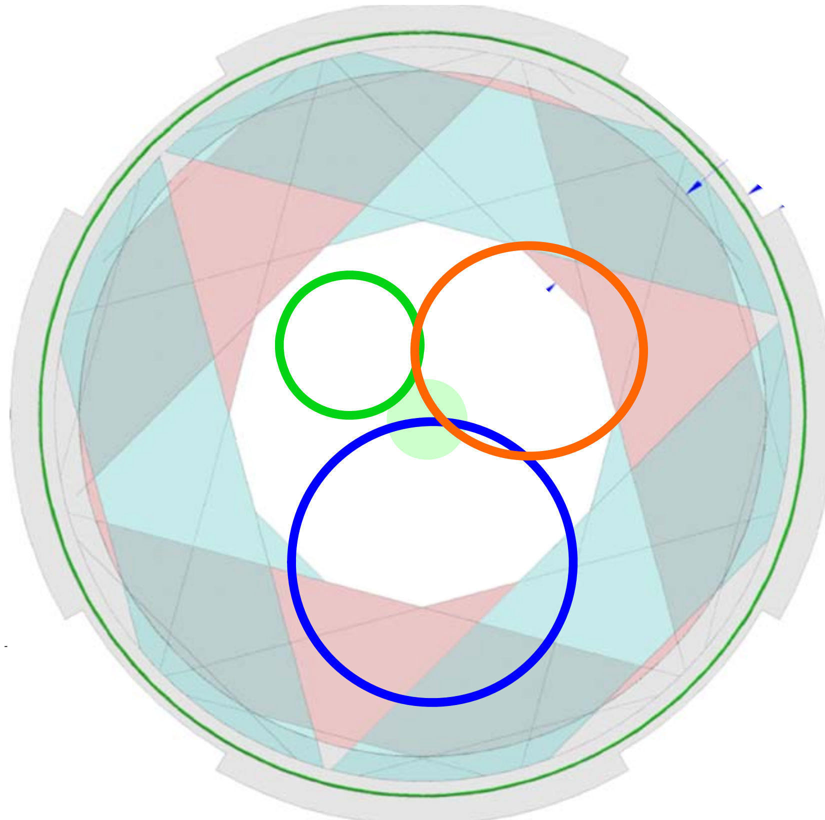
# How do you measure $2.5\times10^{-17}$ ?

reconstructable tracks



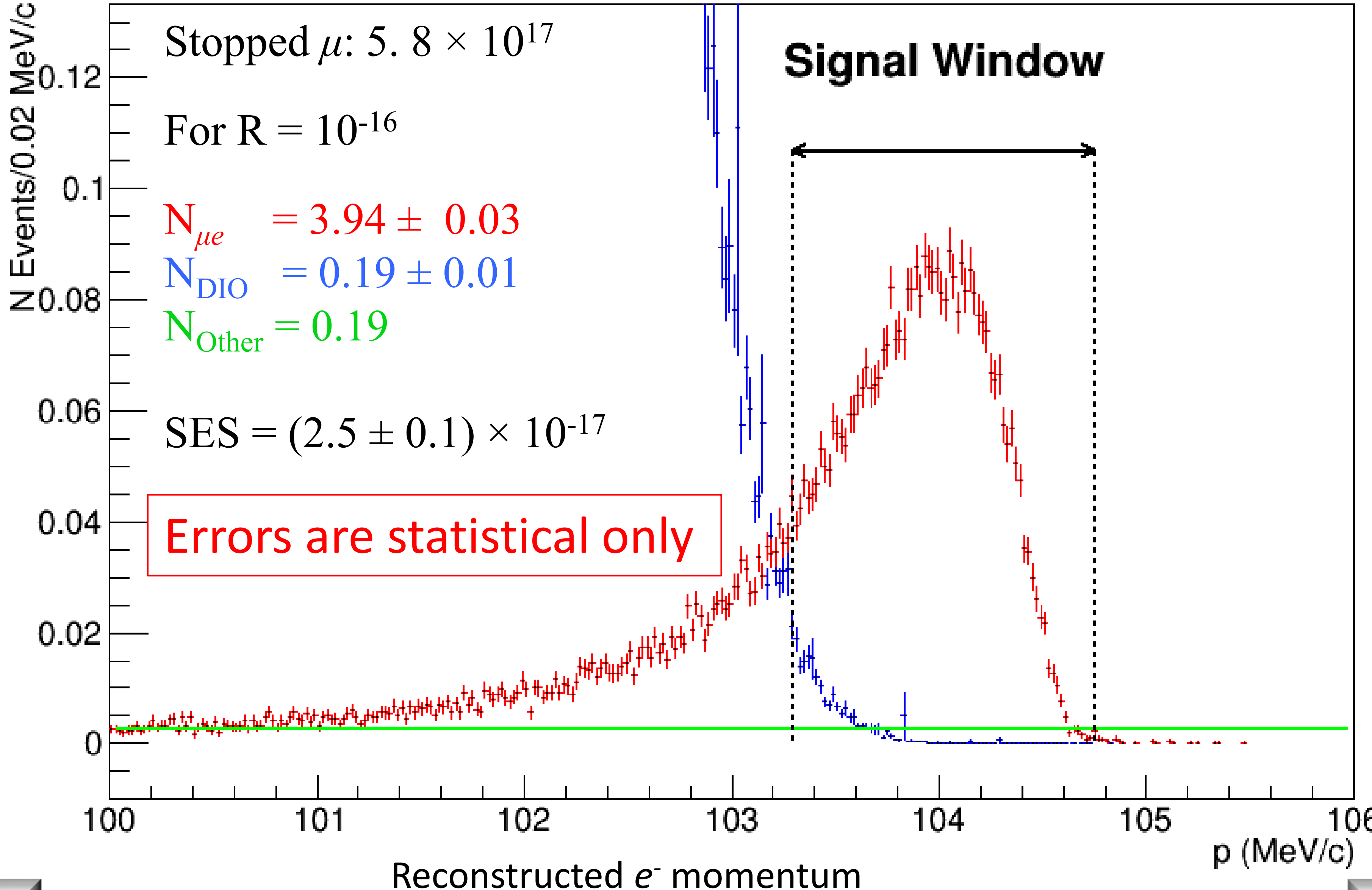

no hits in tracker

some hits tracker, tracks not reconstructable.

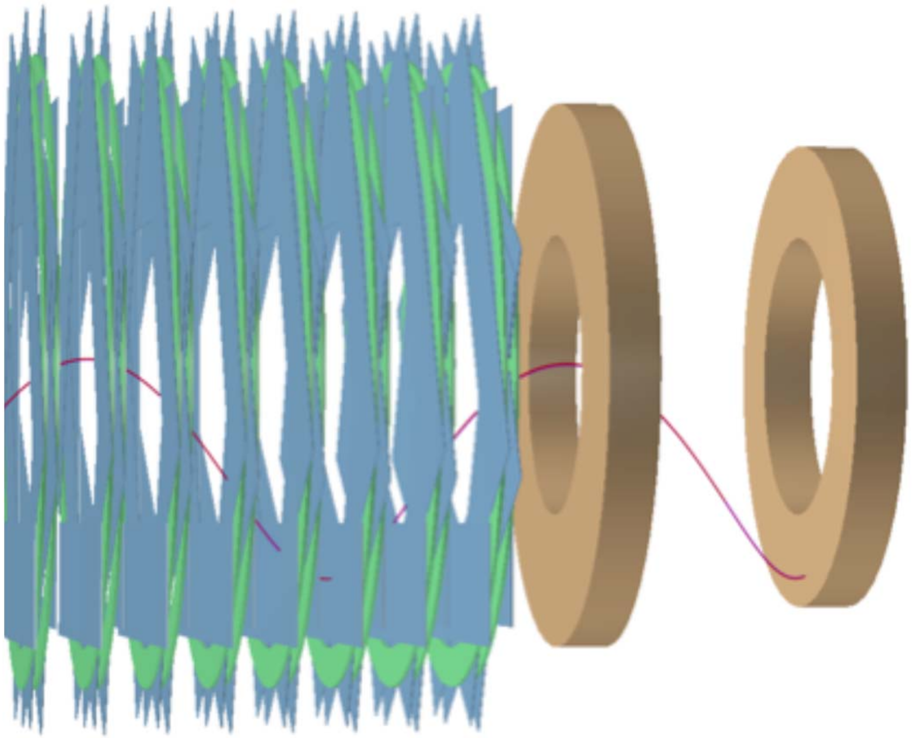


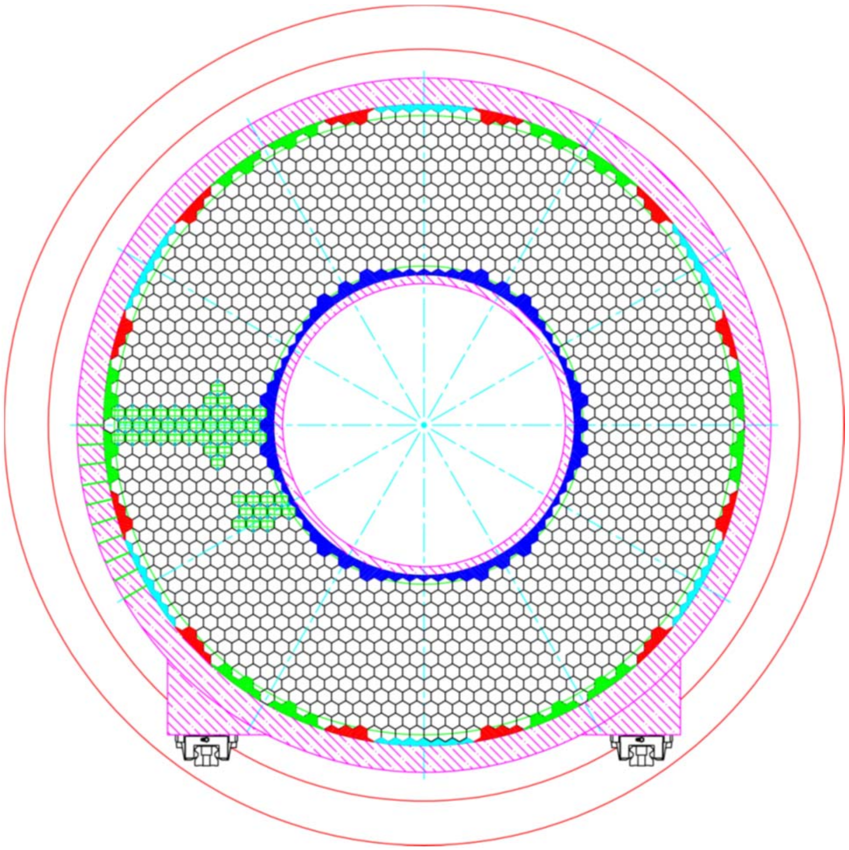
beam's-eye view of the tracker

# Signal sensitivity for a 3 Year Run

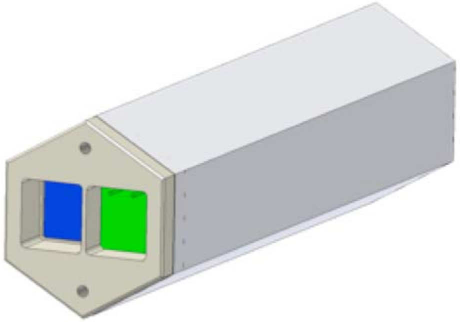


# Scintillating crystal calorimeter





- Two disk geometry
- Hexagonal $BaF_2$ crystals; APD or SiPM readout
- Provides precise timing, PID, background rejection, alternate track seed and possible calibration trigger.



# Calorimeter crystal history

- Initial choice PbWO4: small $X_0$, low light yield, low temperature operation, temperature and rate dependence of light output
- CDR choice LYSO: small $X_0$, high light yield, expensive (→very expensive)
- TDR choice: $BaF_2$: larger $X_0$, lower light yield (in the UV), very fast component at 220 nm, readout R&D required, cheaper,

See Friday presentation

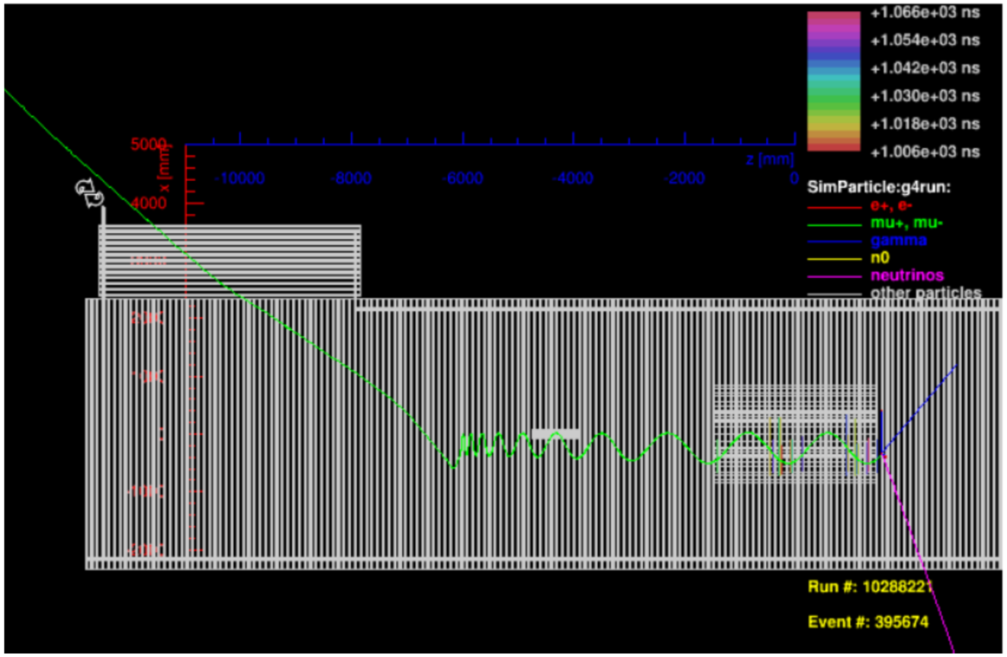
| Crystal | $BaF_2$ | LYSO | $PbWO_4$ |
|---|---|---|---|
| Density (g/cm$^3$) | 4.89 | 7.28 | 8.28 |
| Radiation length (cm) $X_0$ | 2.03 | 1.14 | 0.9 |
| Molière radius (cm) Rm | 3.10 | 2.07 | 2.0 |
| Interaction length (cm) | 30.7 | 20.9 | 20.7 |
| $dE/dx$ (MeV/cm) | 6.5 | 10.0 | 13.0 |
| Refractive Index at $\lambda_{max}$ | 1.50 | 1.82 | 2.20 |
| Peak luminescence (nm) | 220, 300 | 402 | 420 |
| Decay time $\tau$ (ns) | 0.9, 650 | 40 | 30, 10 |
| Light yield (compared to NaI(Tl)) (%) | 4.1, 36 | 85 | 0.3, 0.1 |
| Light yield variation with temperature(% / °C) | 0.1, -1.9 | -0.2 | -2.5 |
| Hygroscopicity | None | None | None |

# Backgrounds

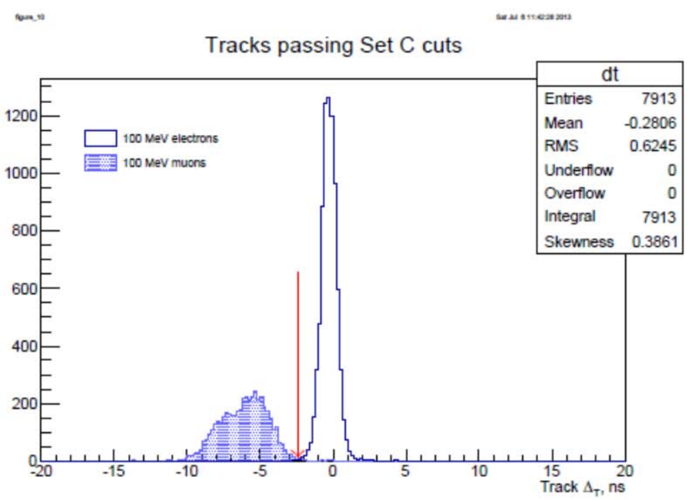
- Stopped muon-induced
  - muon decay in orbit (DIO)
- Out of time protons or long transit-time secondaries
  - radiative pion capture; muon decay in flight
  - pion decay in flight; beam electrons
  - anti-protons
- Secondaries from cosmic rays

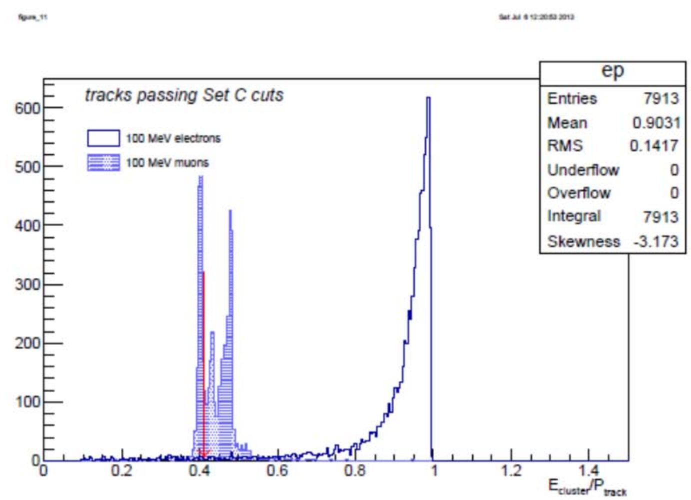
- Mitigation:
  - excellent momentum resolution
  - excellent extinction plus delayed measurement window
  - thin window at center of TS to absorb anti-protons
  - extreme care in shielding and veto

# The "Ralf event"




- In massive MC runs to optimize the CRV, an event was found that evaded the CRV, passed through the target and the tracker, and stopped in the calorimeter
- The calorimeter, however, provides substantial additional background rejection, through *μ/e* PID, with a combination of timing information and *E/p*



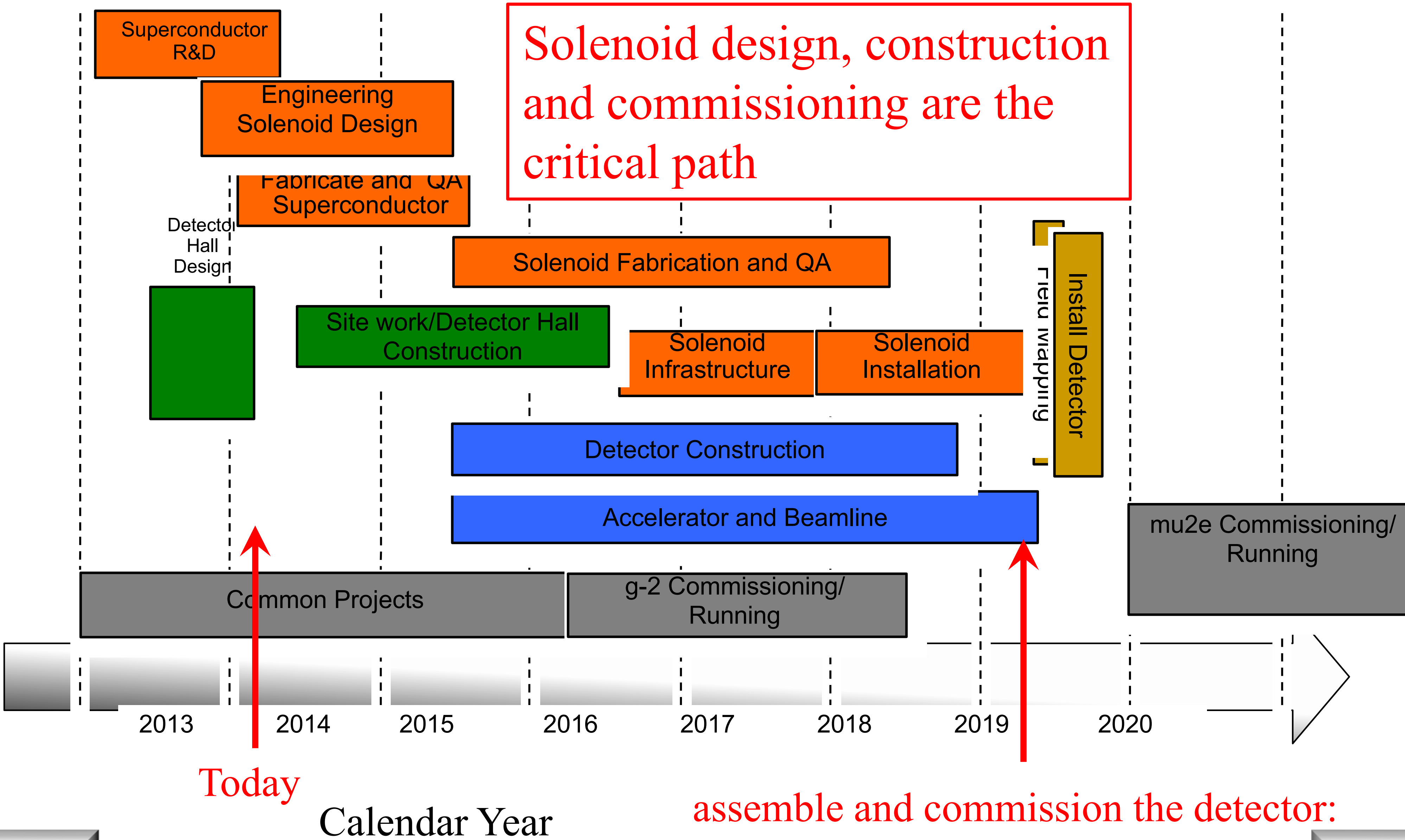
# Backgrounds for a 3 Year Run

| **Source** | **Events** | **Comment** |
|---|---|---|
| | 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 statistical error only.

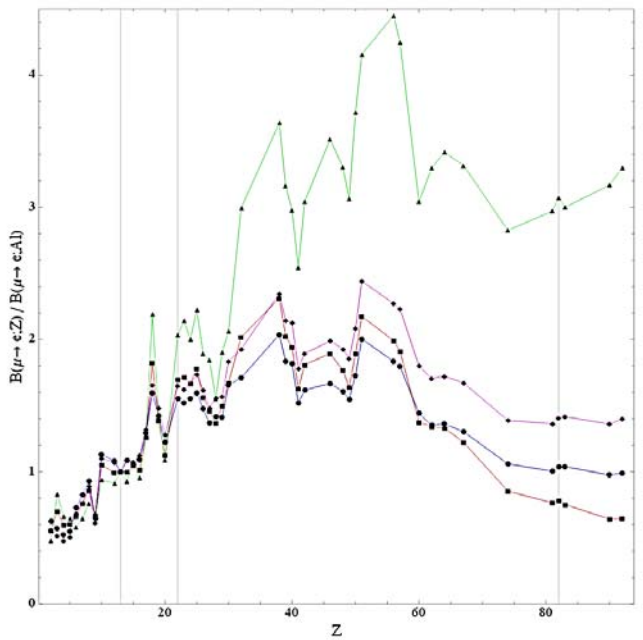
* scales with extinction: values in table assume extinction = $10^{-10}$

# Mu2e schedule



# The mu2e experimental program has a branch point

- If there is a signal:
  - Study *Z* dependence: distinguish among BSM theories
  - Options limited now that the programmable time structure of the proposed Project X beam is no longer anticipated




- If there is no signal:
  - Up to to 10 × Mu2e physics reach, R$\mu e$ < a few × $10^{-18}$
  - Can use the same detector, some modifications

- Both programs can be done with the existing accelerator complex.
  - Both could be done faster with more protons from PIP II

# FNAL accelerator complex

- Proton Improvement Plan (PIP)
  - Improve beam power to meet NOνA requirements
  - Essentially complete.
- PIP-II design underway
  - Project-X reimagined to match funding constraints
  - 1+ MW to LBNE at startup (2025)
  - Flexible design to allow future realization of the full potential of the FNAL accelerator complex
    - ~2 MW to LBNE
    - 10× the protons to Mu2e
    - MW-class, high duty factor beams for rare process experiments

# Summary and conclusions

- mu2e will either discover $\mu$ to $e$ conversion or set a greatly improved limit
  - $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL.
  - $10^4$ improvement over previous best limit
  - Mass scales to $\mathcal{O}(10^4$ TeV$)$ are within reach
- Schedule:
  - Final review ~May 2014; expect approval ~July 2014
  - Construction start fall 2014
  - Installation and commissioning in 2019
  - Solenoid system is the critical path
- mu2e is a program:
  - If there is a signal we will study the $A,Z$ dependence of $R_{\mu e}$ to elucidate the underlying BSM physics
  - If there is no signal we will be able to improve the experimental sensitivity up to a factor of 10

# For Further Information

- Mu2e:
  - Home page: http://mu2e.fnal.gov
  - CDR: http://arxiv.org/abs/1211.7019
  - DocDB: http://mu2e-docdb.fnal.gov/cgi-bin/DocumentDatabase
- PIP-II
  - Steve Holmes' talk to P5 at BNL, Dec 16, 2013 https://indico.bnl.gov/getFile.py/access?contribId=11&sessionId=5&resId=0&materialId=slides&confId=680
  - Conceptual Plan:http://projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232

# Not Covered in This Talk

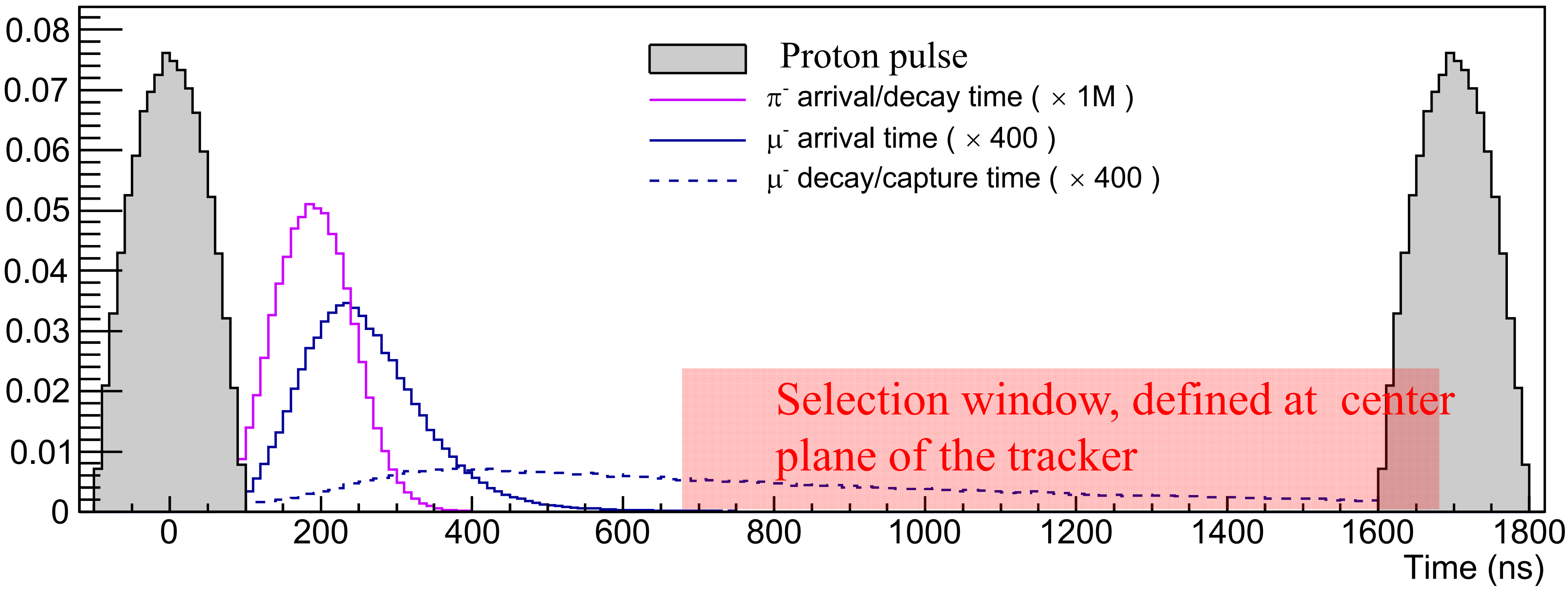
- Pipelined, deadtime-less trigger system
- Cosmic ray veto system
- Stopping target monitor
  - Ge detector, behind muon beam dump
- Details of proton delivery
- AC dipole in transfer line; increase extinction
- In-line extinction measurement devices
- Extinction monitor near proton beam dump
- Muon 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

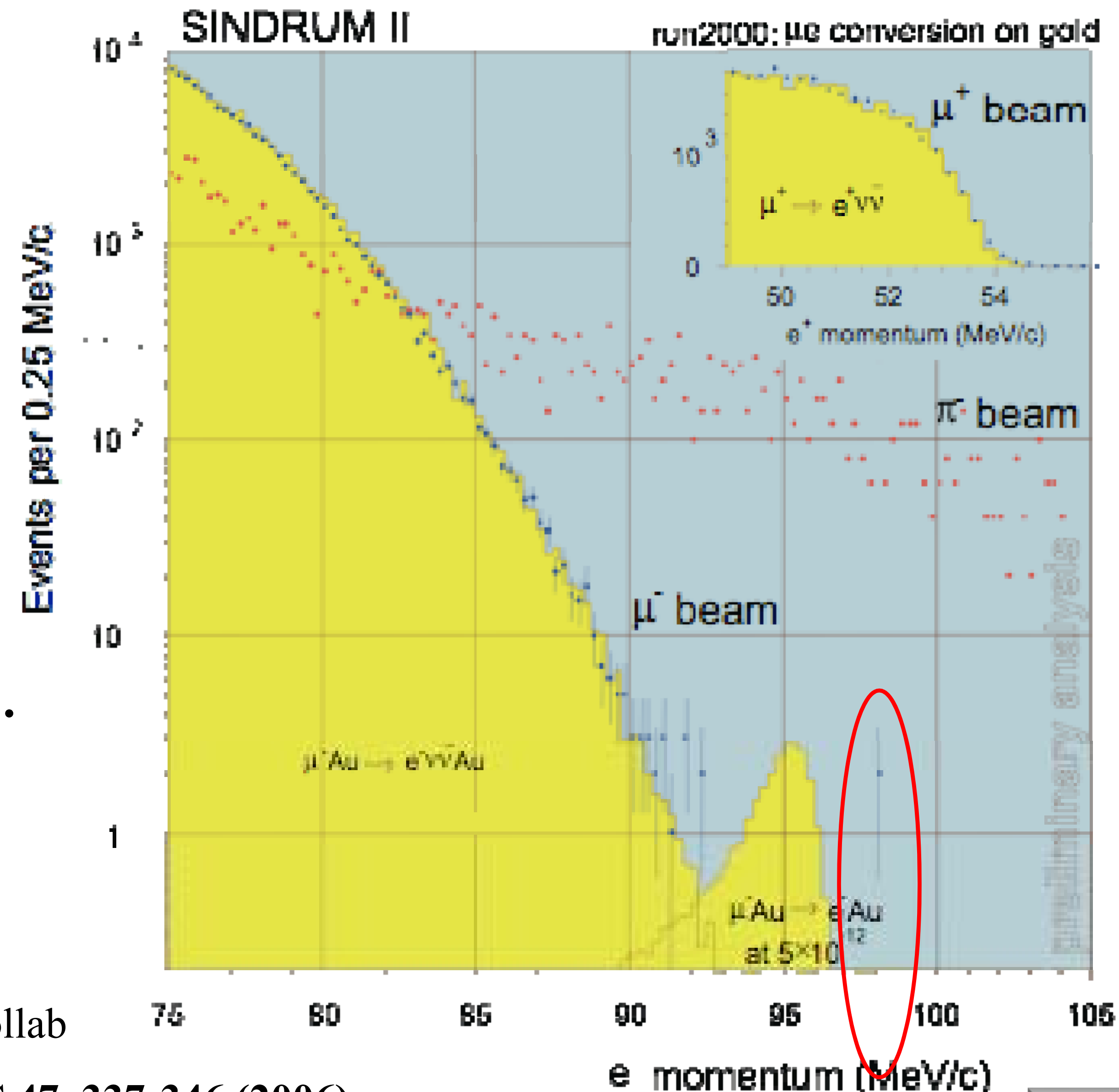
# Schematic of one cycle of the muon beamline




- 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

# The previous best experiment

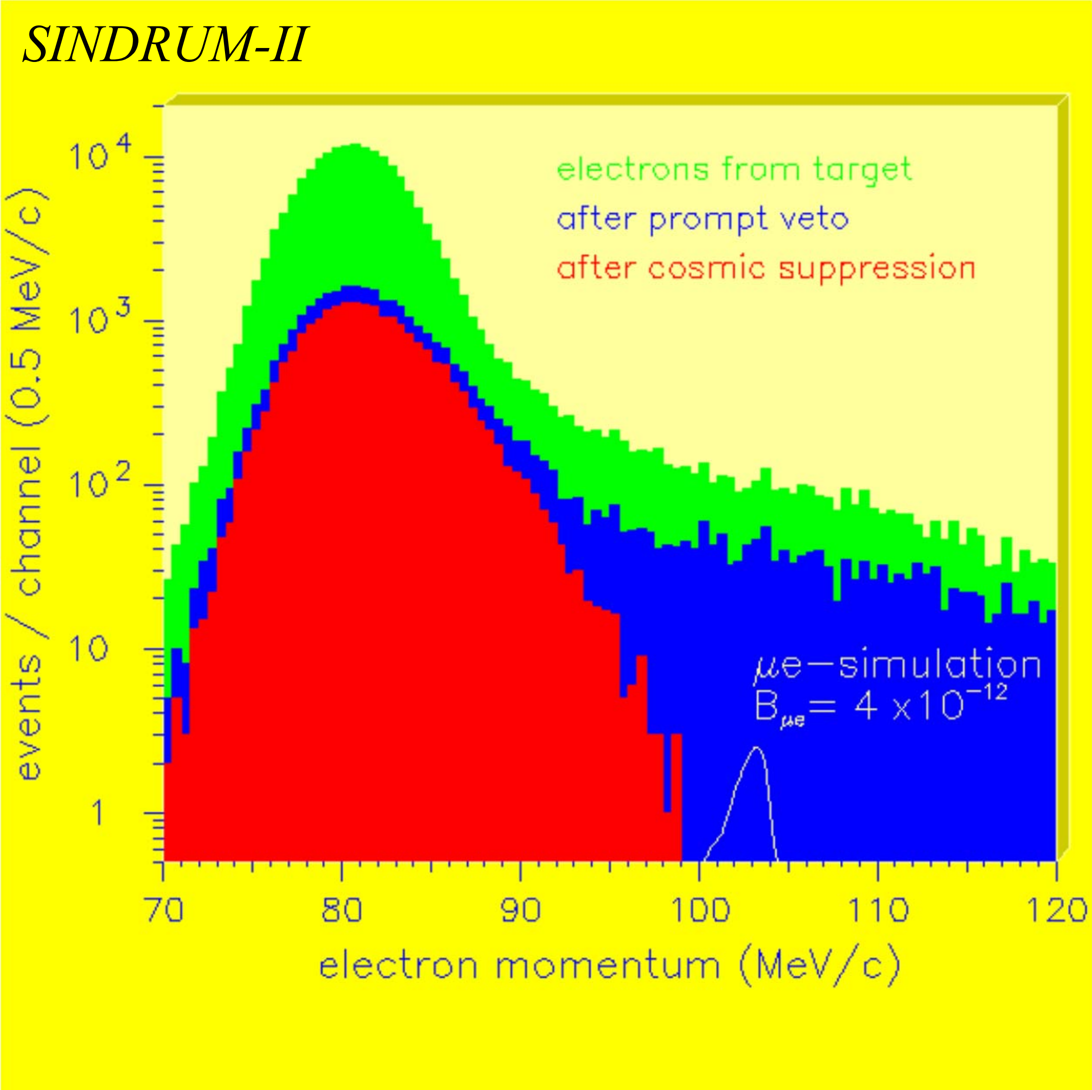
- SINDRUM II
- $R_{\mu e} < 6.1\times10^{-13}$ @90% CL
- 2 events in signal region
- Au target: different $E_e$ endpoint than Al.




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 $\pi^-$
- Radiative pion Capture (RPC), suppressed with prompt veto
- Cosmic ray backgrounds were also important

$R_{\mu e}$(Ti) < $6.1 \times 10^{-13}$
PANIC 96 (C96-05-22)

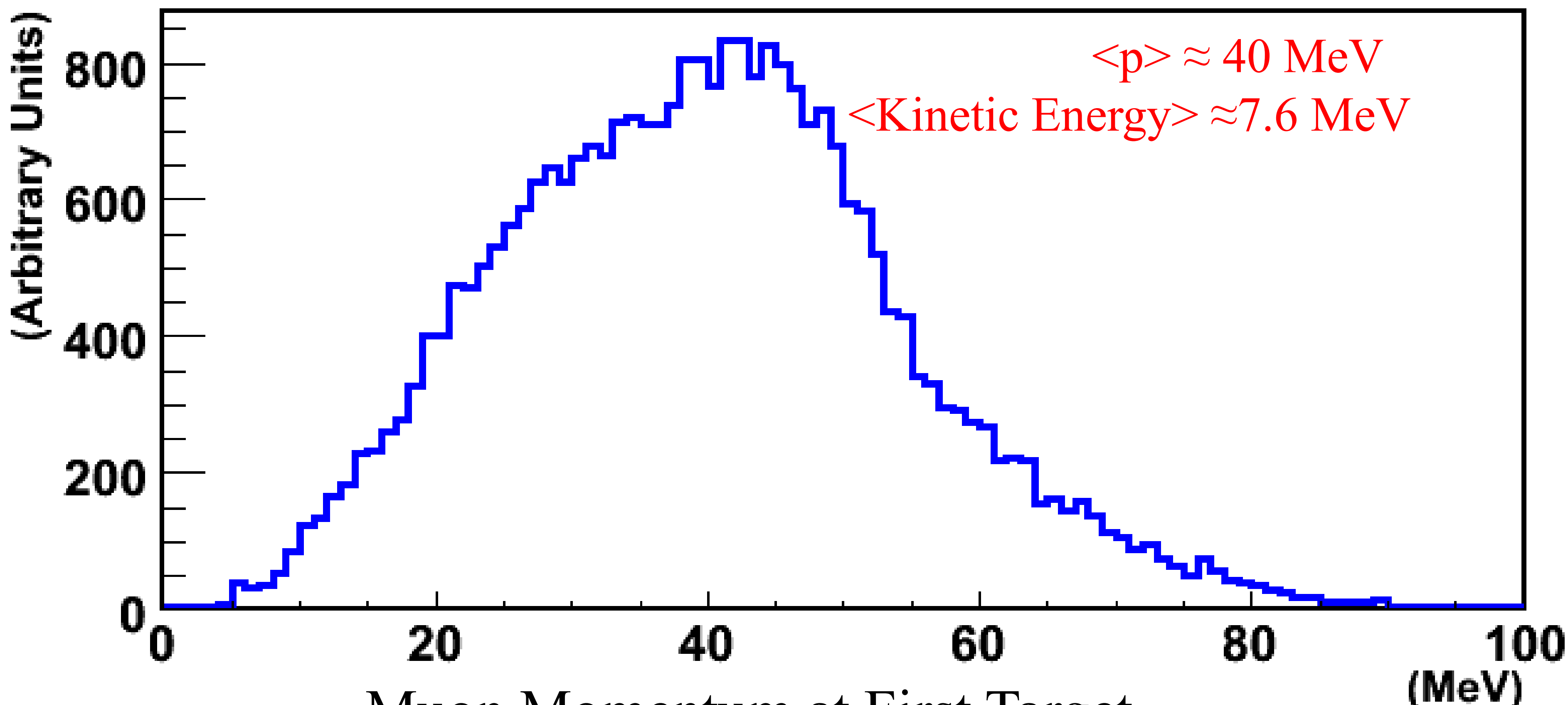
$R_{\mu e}$(Ti) < $4.3 \times 10^{-12}$
Phys.Lett. B317 (1993)

$R_{\mu e}$(Au) < $7 \times 10^{-13}$
Eur. Phys. J. , C47 (2006)

# Why is mu2e more sensitive than SINDRUM II?

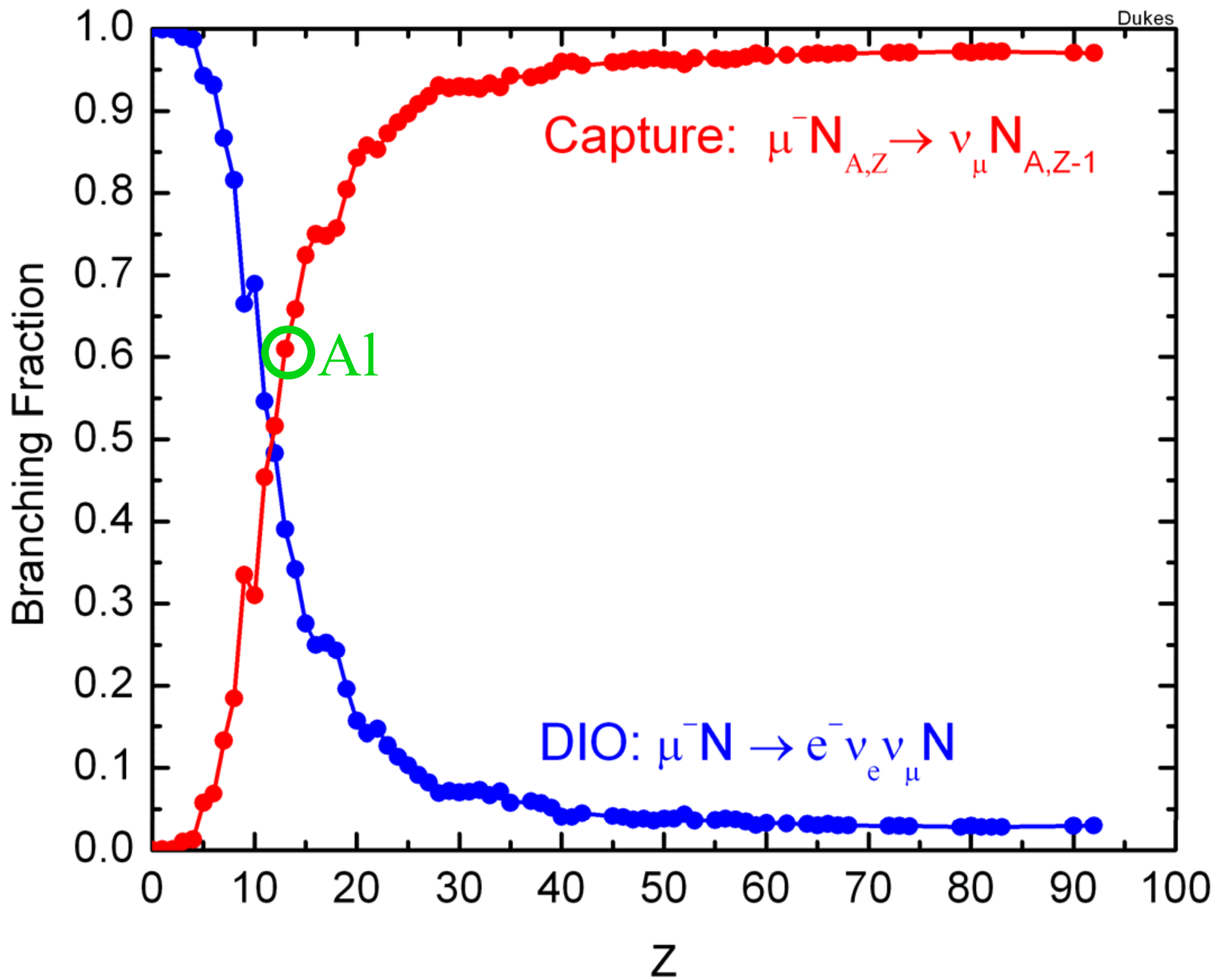
- FNAL can deliver $\approx 10^3 \times$ proton intensity.
- Higher $\mu$ collection efficiency.
- SINDRUM II was background-limited.
  - Radiative $\pi$ capture.
  - Bunched beam and excellent extinction reduce this.
  - Thus mu2e can make use of the higher proton rate.

# Muon Momentum

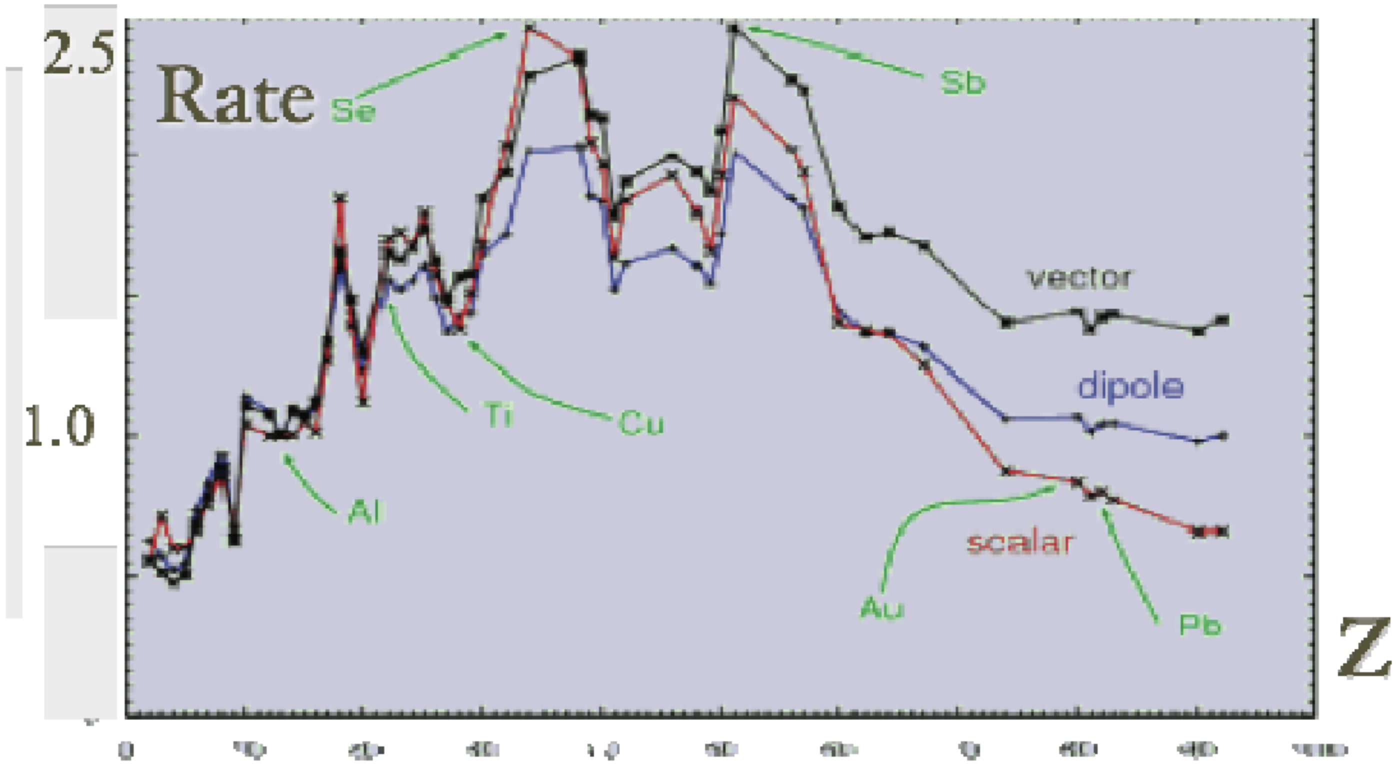


Muon Momentum at First Target

# Capture and DIO *vs Z*



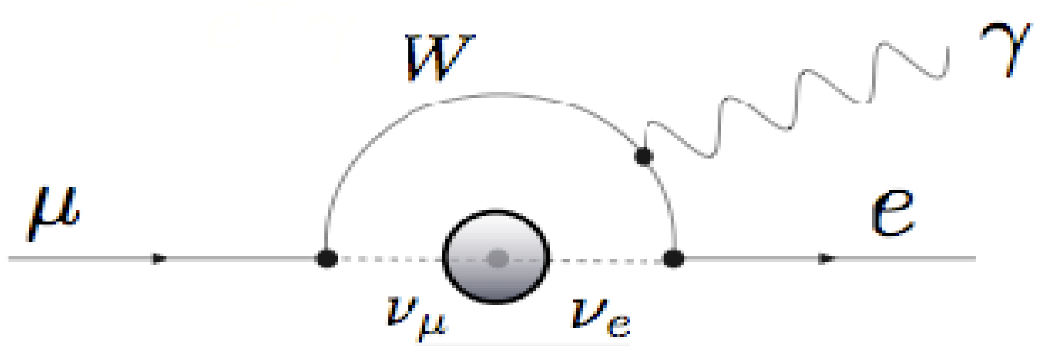
# Conversion Rate, Normalized to Al




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

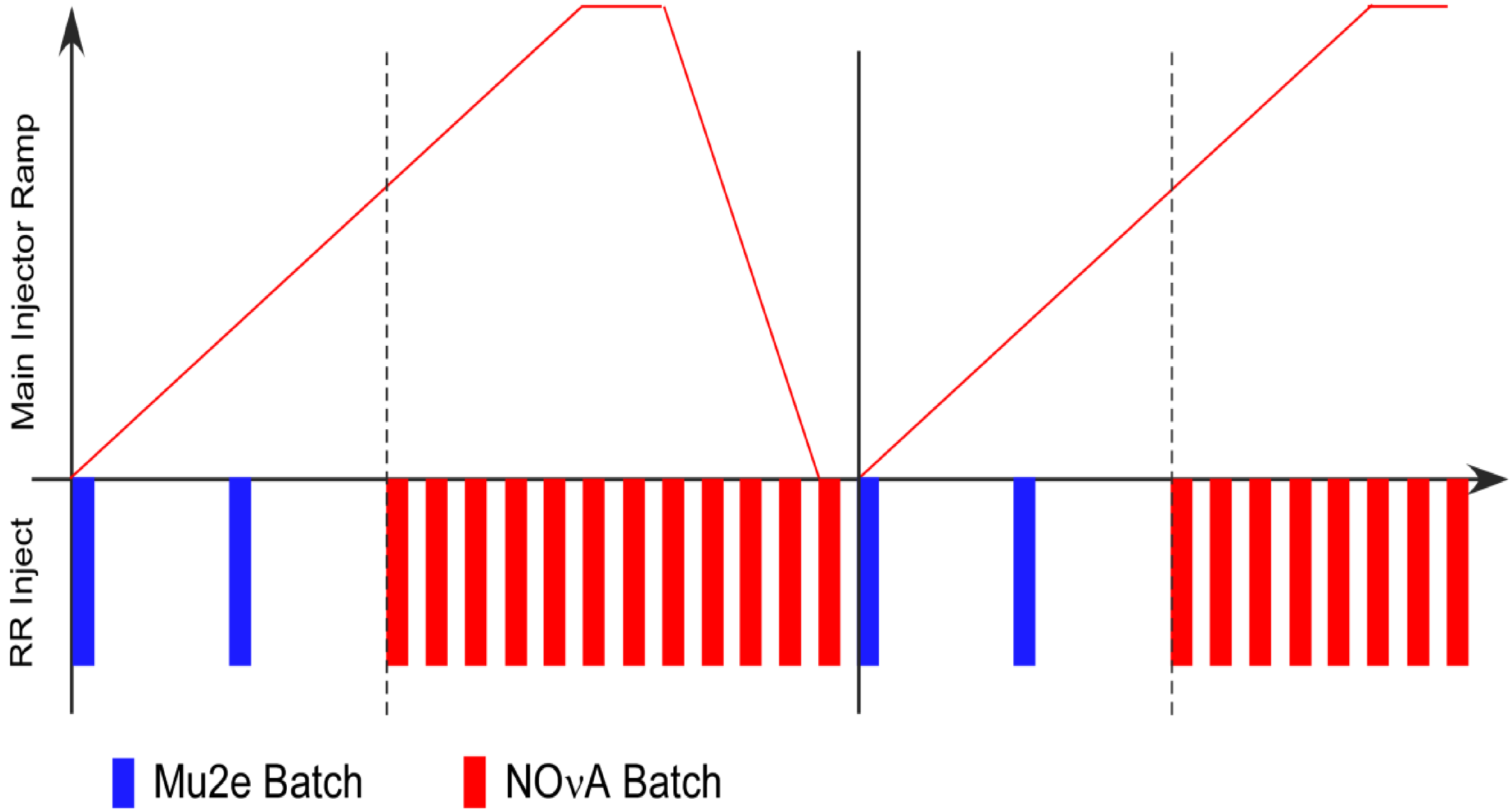
# CLFV Rates in the Standard Model

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

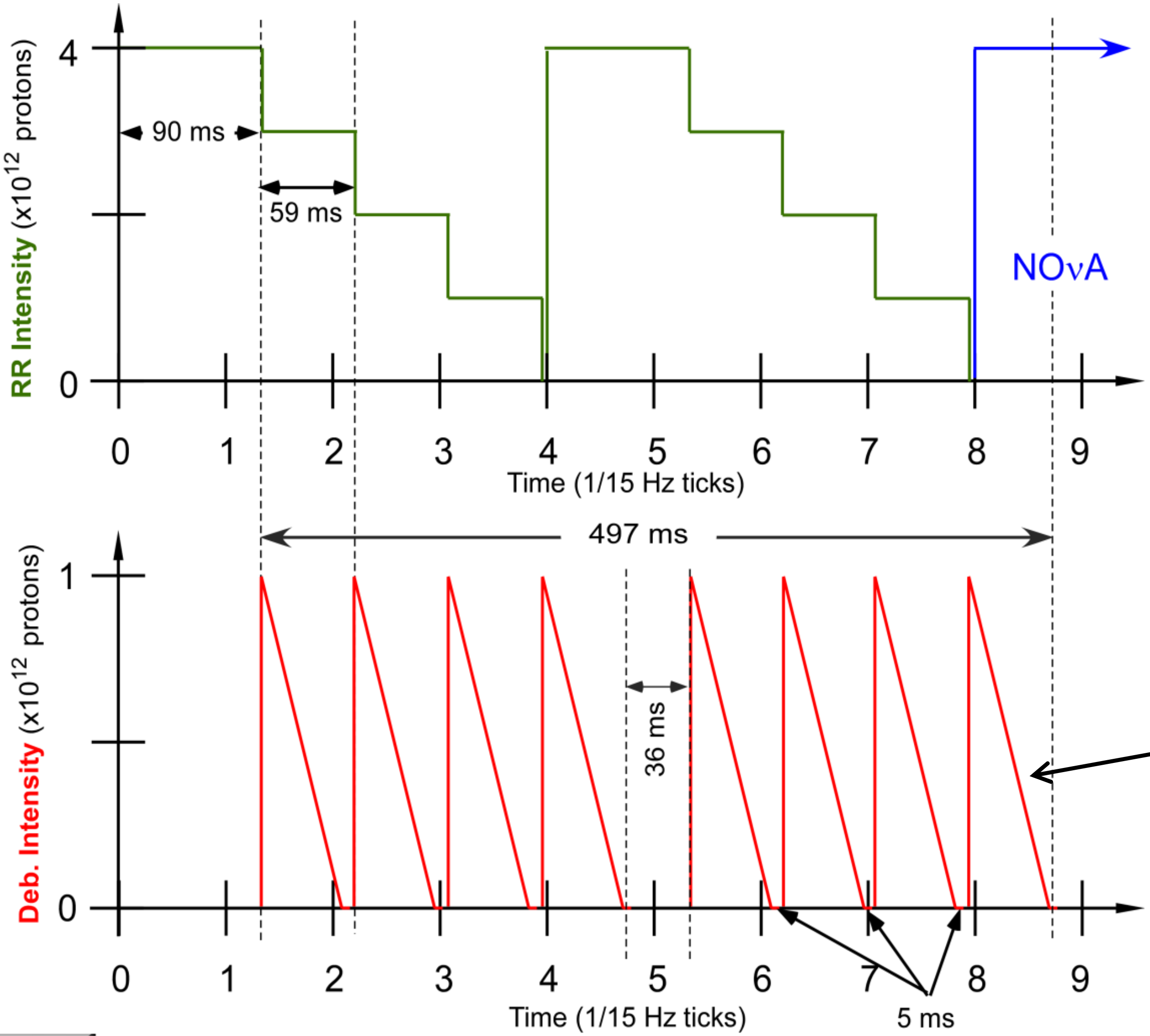



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

# Proton Beam Macro Structure



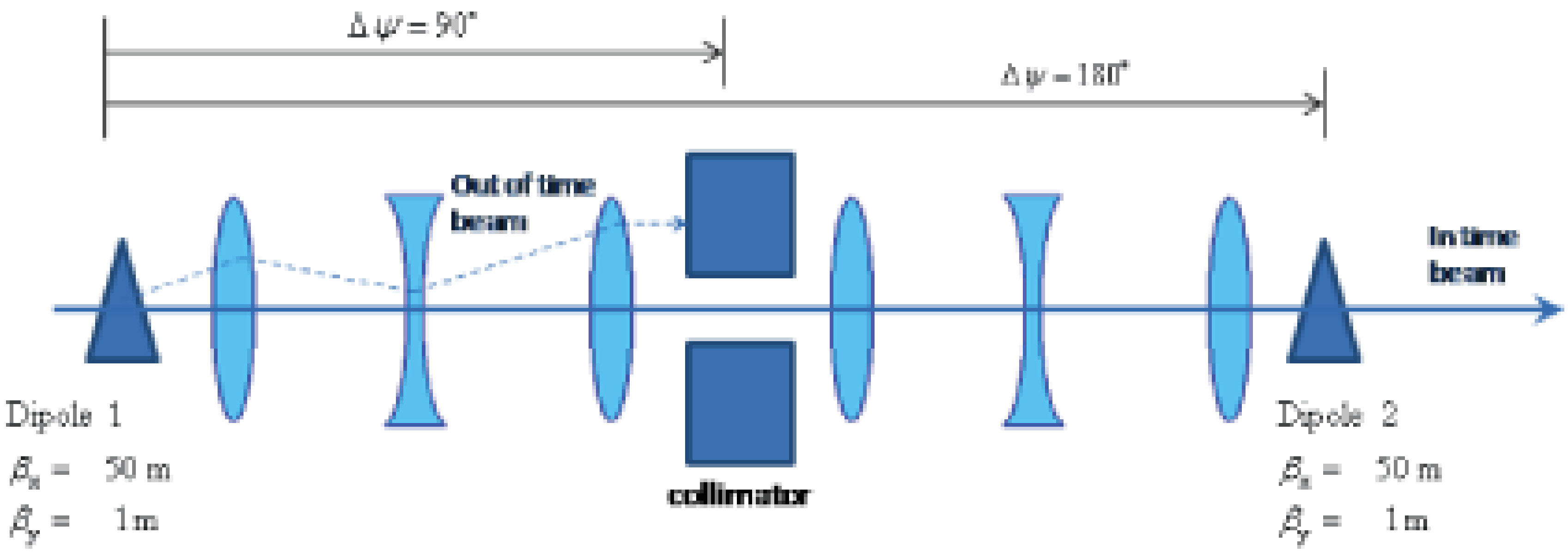
# Proton Beam Micro Structure




Slow spill:
Bunch of $4 \times 10^7$ protons every 1694 ns

# 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

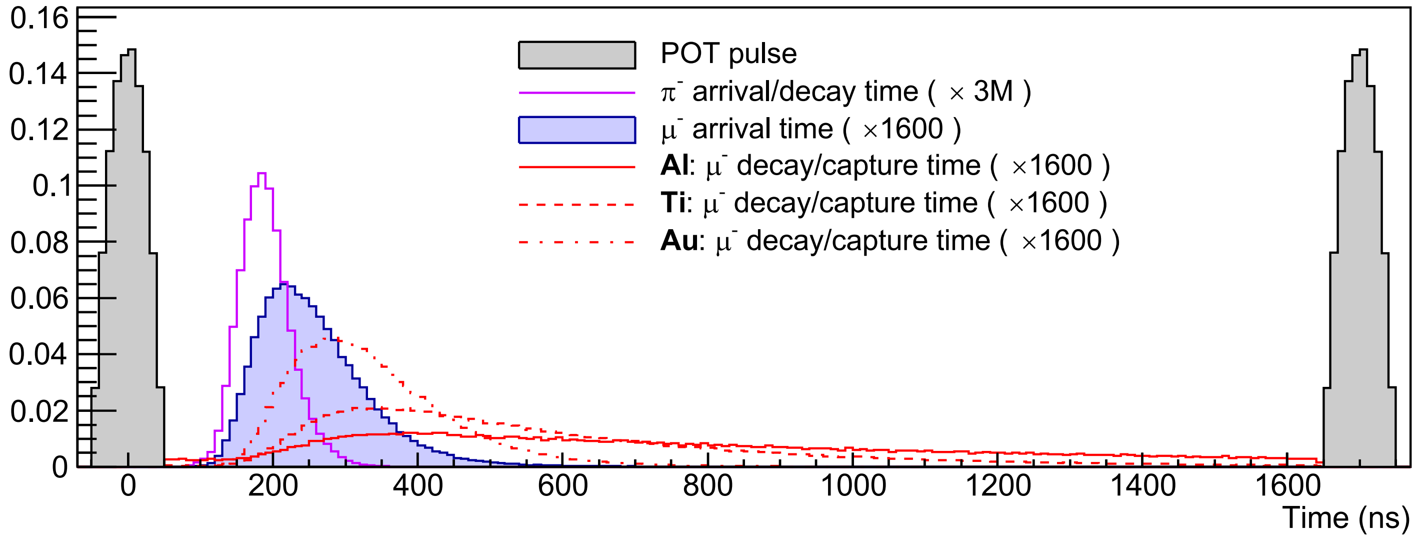


# Project X

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

# 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, $R_{\mu e} < 10^{-18}$ .
  - First factor of ≈10 can use the same detector.