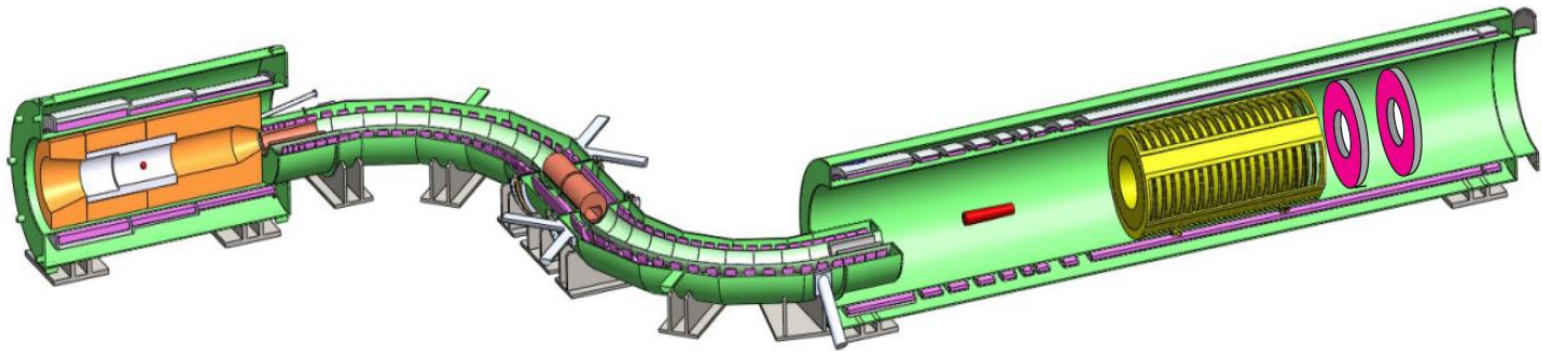


The Mu2e experiment at Fermilab

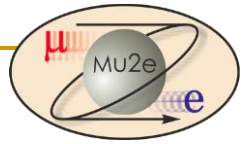
<http://mu2e.fnal.gov/>



Giovanni F. Tassielli

FNAL, INFN Lecce

Xth Rencontres du Vietnam - Flavour Physics Conference



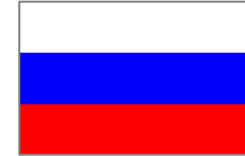
The Mu2e collaboration



- *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*
- *Lewis University*
- *Northern Illinois University*
- *Northwestern University*
- *Pacific Northwest National Laboratory*
- *Purdue University*
- *Rice University*
- *University of Virginia*
- *University of Washington, Seattle*



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



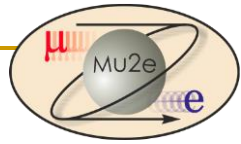
- *Institute for Nuclear Research, Moscow*
- *JINR, Dubna*



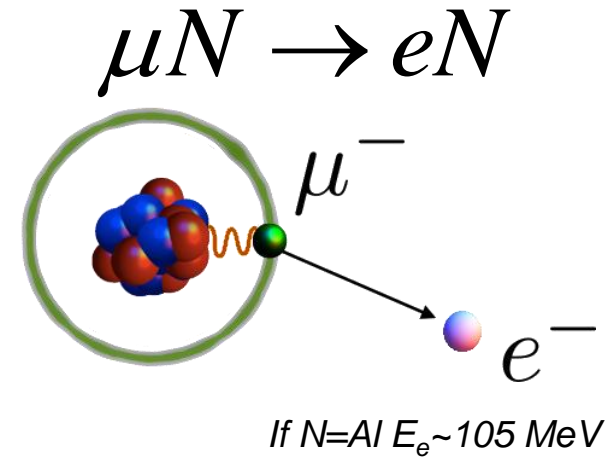
About half of us: Nov 2013

~140 members from 28 institutions

Muon to electron conversion in the field of a nucleus

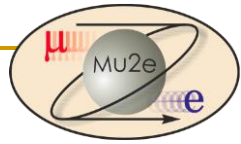


- Initial state: muonic atom
- Final state:
 - a single mono-energetic electron.
 - the energy depends on Z of target.
 - recoiling nucleus is not observed
 - the process is coherent: the nucleus stays intact.
 - neutrino-less

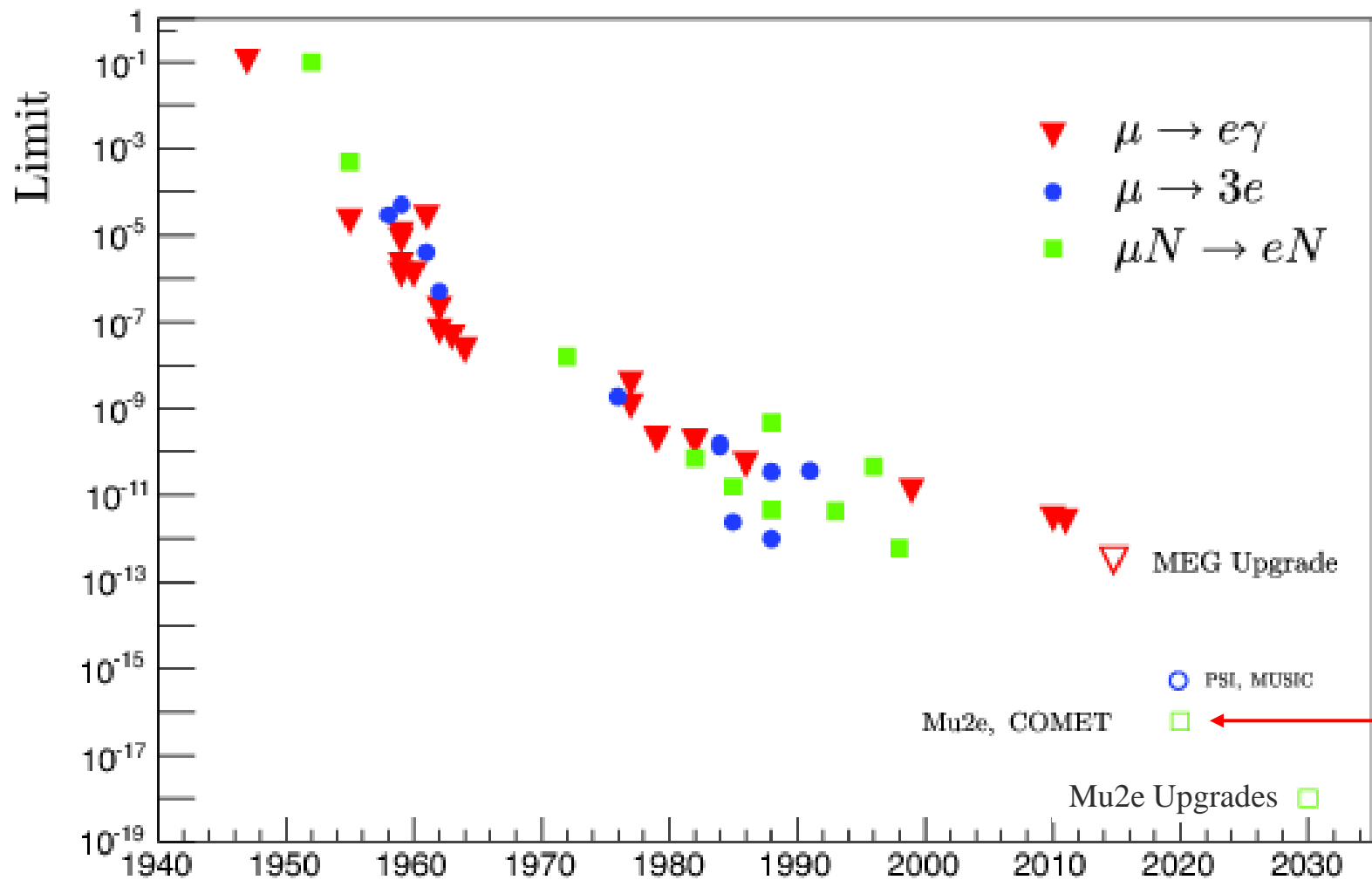


- Conventional Signal Normalization: $R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$
- Standard Model ($m_\nu \neq 0$) rate is $\sim 10^{-52}$
- There is an observable rate in many new physics scenarios.
- Related decays: Charged Lepton Flavor Violation (CLFV):

$$\begin{aligned} \mu &\rightarrow e\gamma & \mu &\rightarrow e^+e^-e^+ & K_L^0 &\rightarrow \mu e & B^0 &\rightarrow \mu e \\ \tau &\rightarrow \mu\gamma & \tau &\rightarrow \mu^+\mu^-\mu^+ & D^+ &\rightarrow \mu^+\mu^+\mu^- \end{aligned}$$

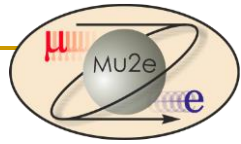


History of $\mu \rightarrow e$, $\mu N \rightarrow eN$ and $\mu \rightarrow 3e$



R.H. Bernstein and P.S. Cooper Phys. Rept. C (1307.5787)

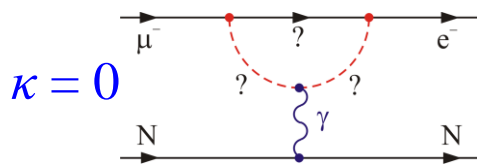
Year



Sensitivity to high mass scales

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

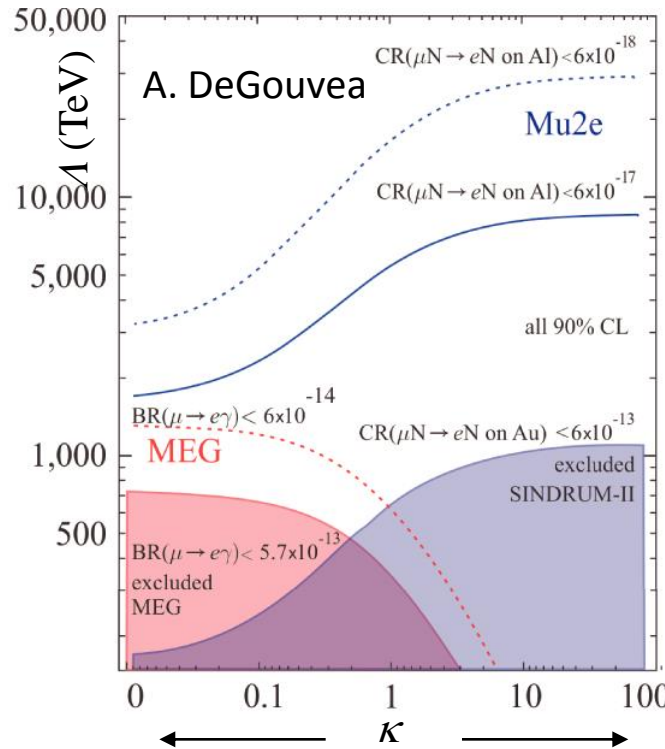
Loops dominate
for $\kappa \ll 1$



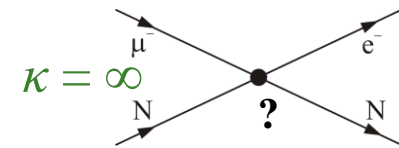
$$\mu \rightarrow e\gamma$$

$$\mu N \rightarrow eN$$

$$\mu \rightarrow eee$$



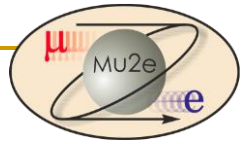
Contact terms
dominate for $\kappa \gg 1$



$\kappa = \infty$

~~$\mu \rightarrow e\gamma$~~
 ~~$\mu N \rightarrow eN$~~
 ~~$\mu \rightarrow eee$~~

- 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

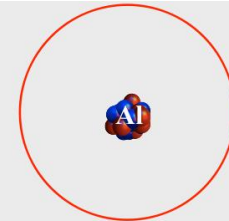


The concept of Mu2e measurement

- Generate pulse beam of low momentum μ^-
- Stop muons in thin foils and form muonic atoms
- Wait for it to 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
 - Monoenergetic, $E_e \approx 105$ MeV
 - At endpoint of continuous spectrum.
- Then measure electron spectrum
 - The signal: monoenergetic electrons at 105 MeV

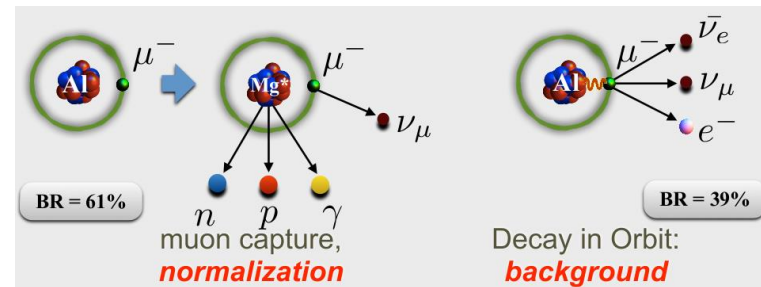
Lifetime 864 ns

the Bohr radius is
 ~ 20 fm, so the μ^-
wavefunction
overlaps the
nucleus

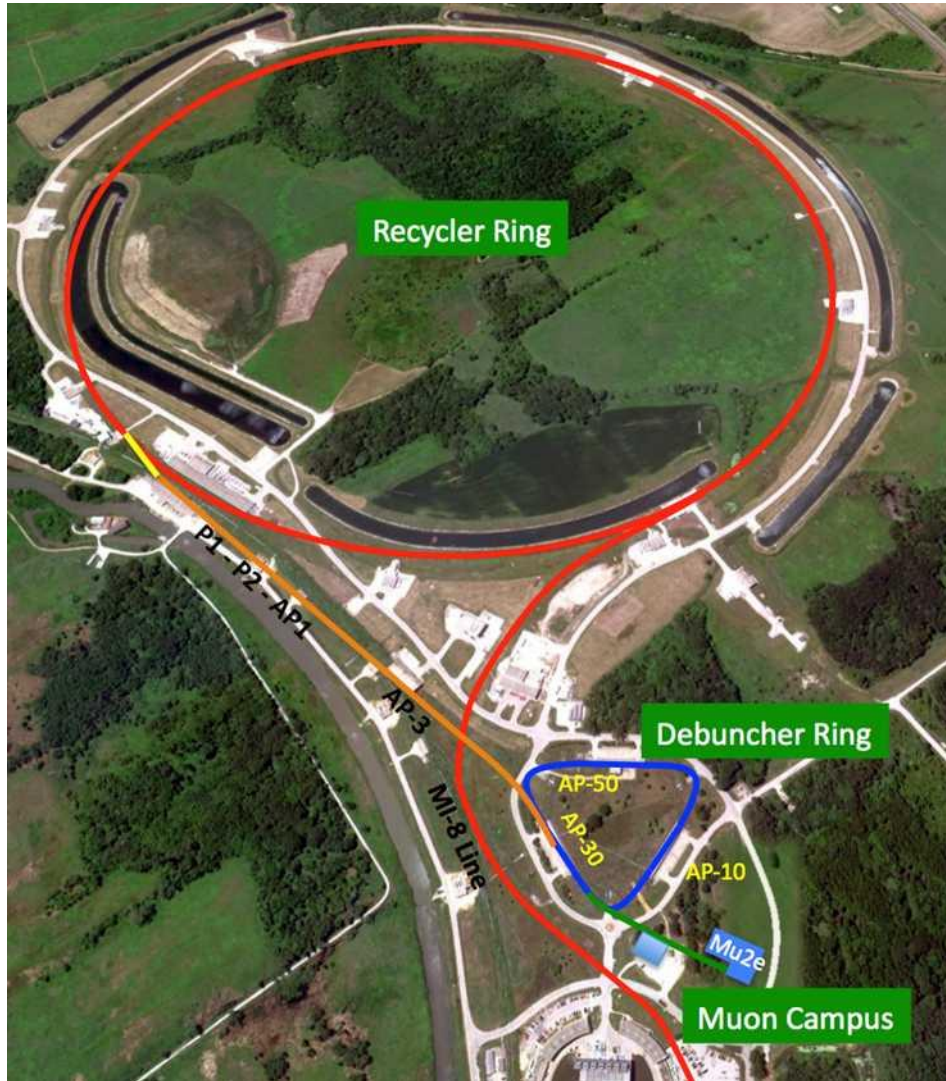
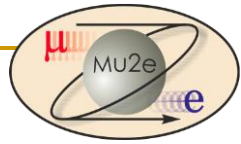


μ^- in 1s state
Al Nucleus
 ~ 4 fm

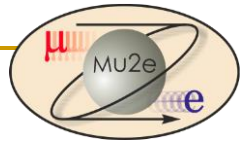
backgrounds



Proton delivery



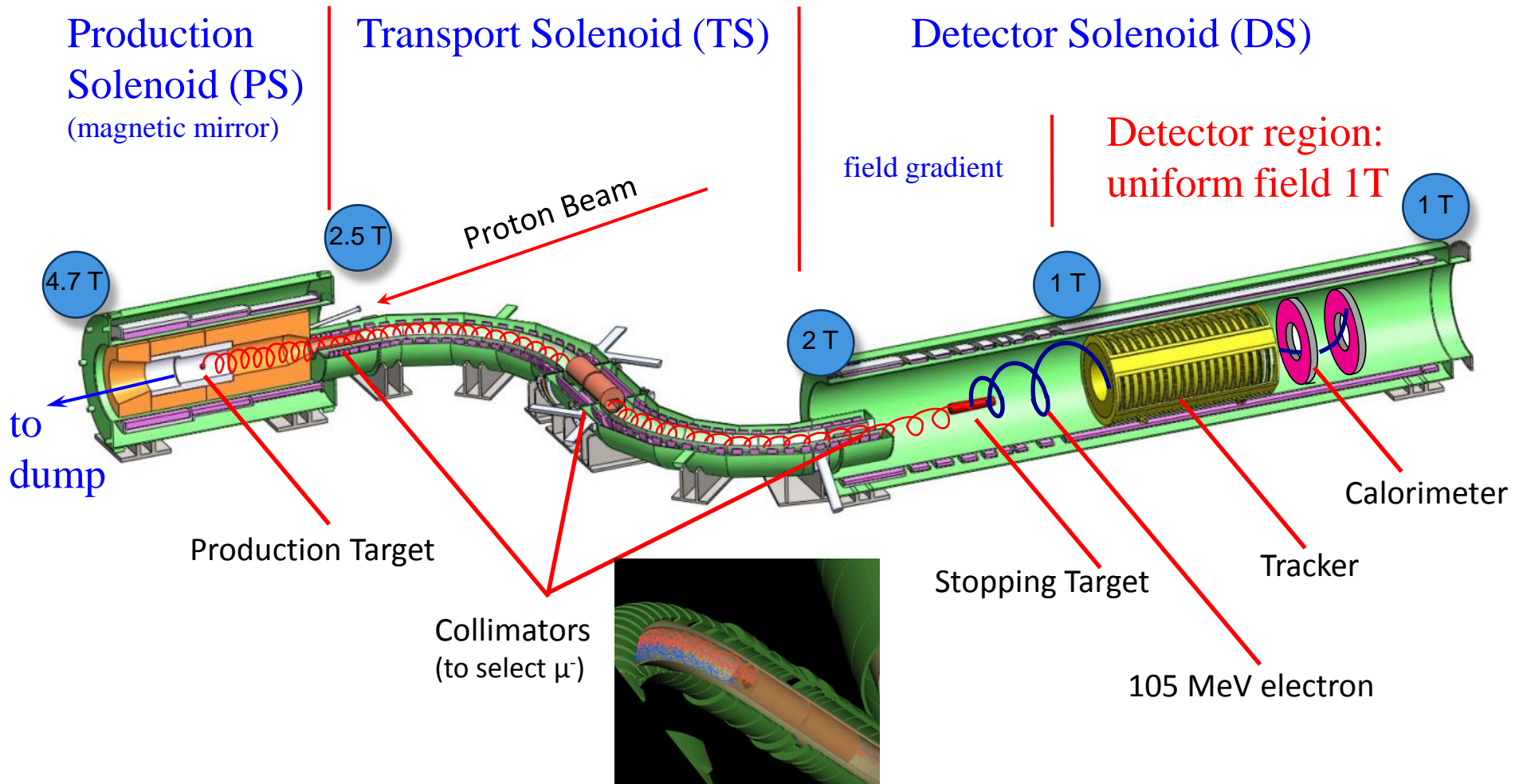
- We make muons by directing 8 GeV protons on to a target.
- Batches of protons from the Booster are transported through existing beamlines to the Recycler Ring where they are re-bunched and transported to the Delivery Ring through existing transport lines.
- Beam is slow extracted from Delivery Ring in microbunches of $\sim 10^7$ protons every 1695 ns through a new external beamline to the Mu2e production target.
- Run simultaneously with NOvA and Booster Neutrino Program.

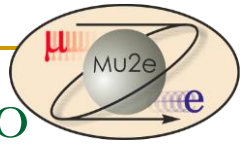


Mu2e Apparatus

The entire system must be evacuated to 10^{-4} to 10^{-5} Torr

Cosmic Ray Veto and Stopping Target Monitor not shown

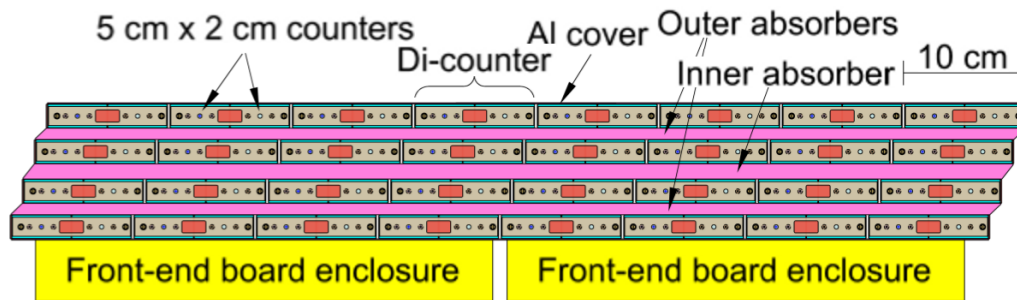




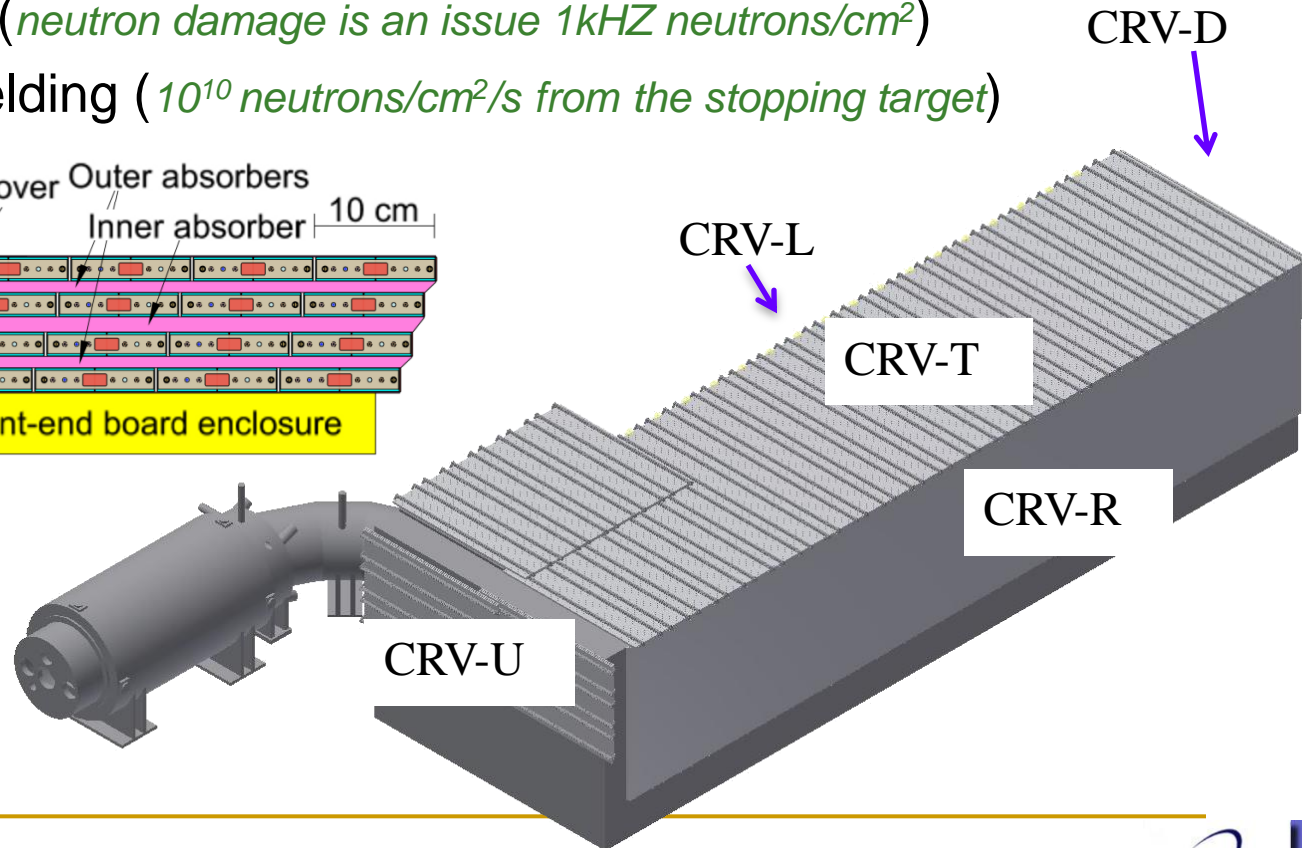
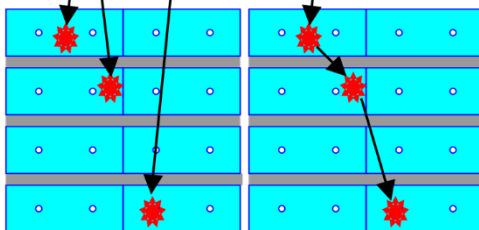
Detector solenoid is surrounded by a Cosmic Ray Veto

Exist a not negligible probability that due to the interaction of a cosmic ray in the DS there will be a particle that can mimic a signal event, a 99.99% efficient CRV is needed!

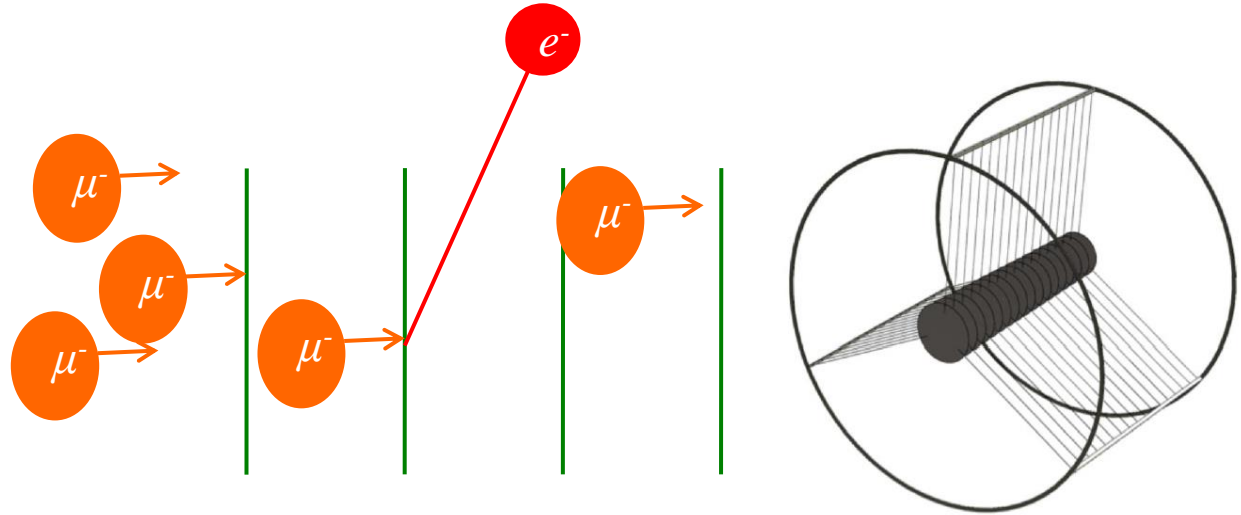
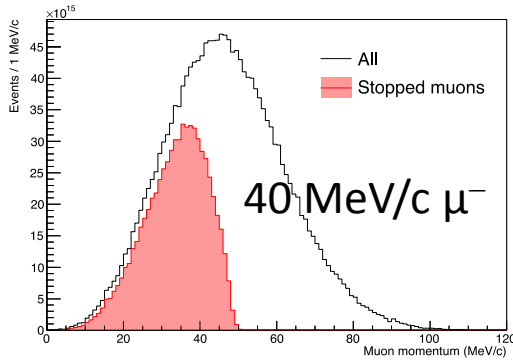
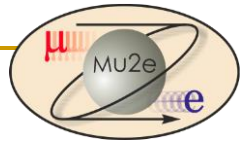
- Four layers of extruded plastic scintillator (~5000 counters)
- Fiber/SiPM readout (*neutron damage is an issue 1kHz neutrons/cm²*)
- Al and concrete shielding (*10¹⁰ neutrons/cm²/s from the stopping target*)



Correlated hits are a concern



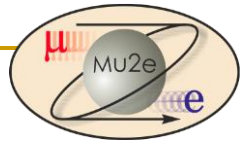
Stopping target



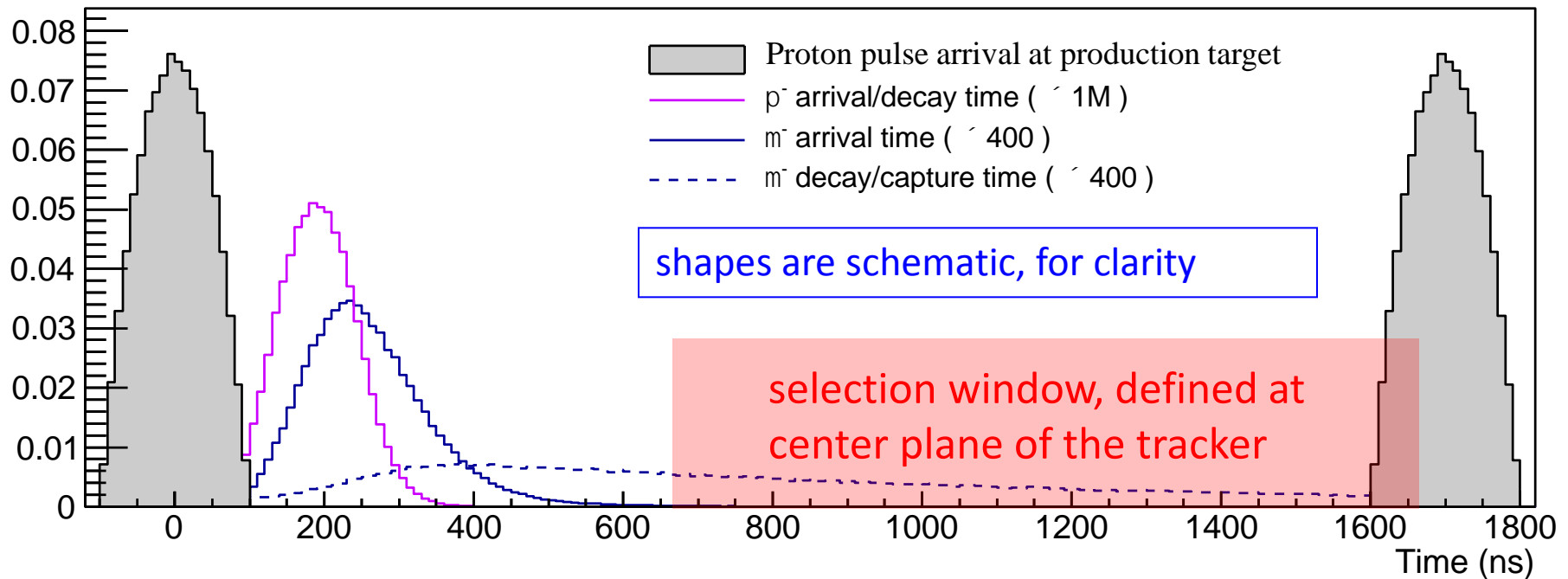
- Pulse of low energy μ^- on thin Al foils
- ~50% are captured to form muonic Al
- ~0.0019 stopped μ^- per proton on production target
- DIO and conversion electrons pop out of target foils

Baseline

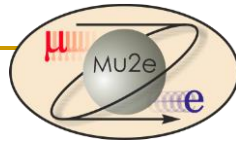
- 17 target foils
- each 200 microns thick
- 5 cm spacing
- radius:
 - ≈ 10 . cm upstream
 - ≈ 6.5 cm downstream
- Optimization is ongoing



One cycle of the muon beamline

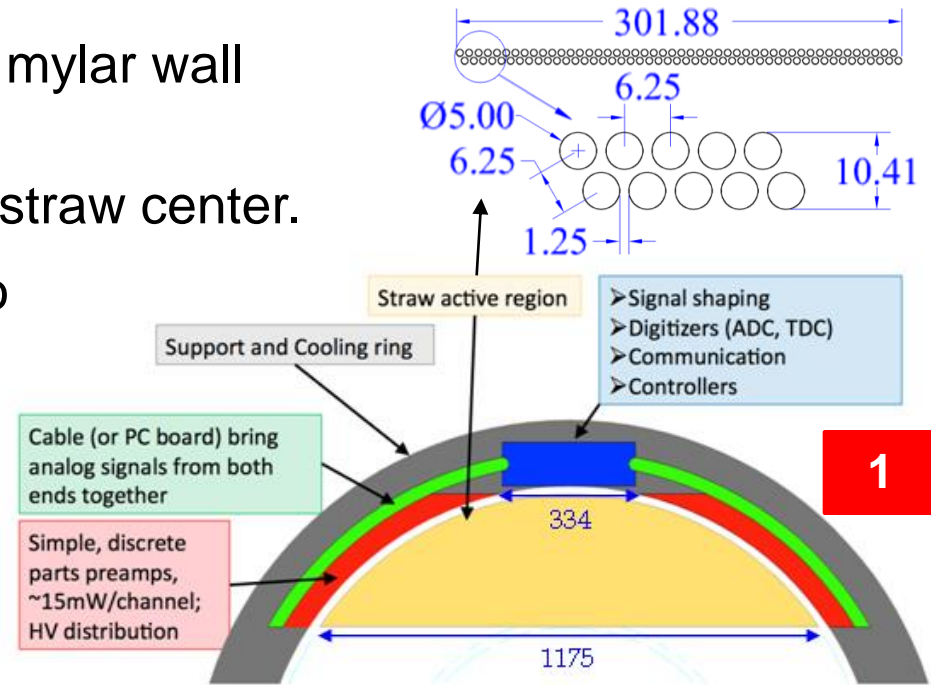


- μ are accompanied by e^- , e^+ , π , anti-protons ...
 - these create prompt backgrounds
 - strategy: wait for them to decay.
- extinction = (# protons between bunches)/(protons per bunch)
 - requirement: **extinction** $< 10^{-10}$

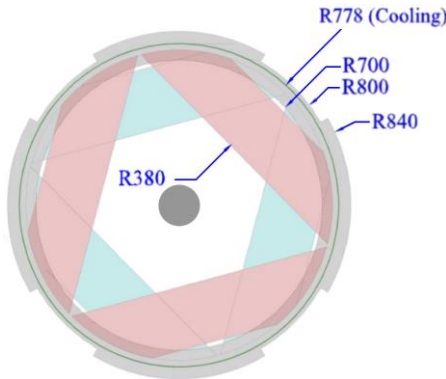


Tracker: strawtubes operating in vacuum

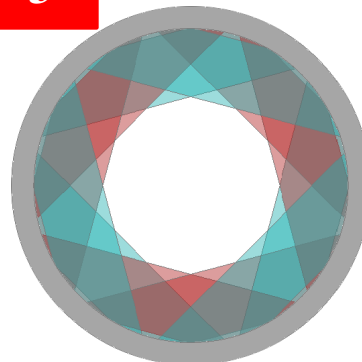
- Straws: 5 mm OD; 15 μm metalized mylar wall (~ 23000).
 - Will employ time division: ~5 mm at straw center.
1. 2 layer of 48 straws are arranged to make a panel;
 2. 6 rotated panels and placed in two different surfaces make a plane;
 3. 2 rotated planes make a station;
 4. 20 station form the tracker.



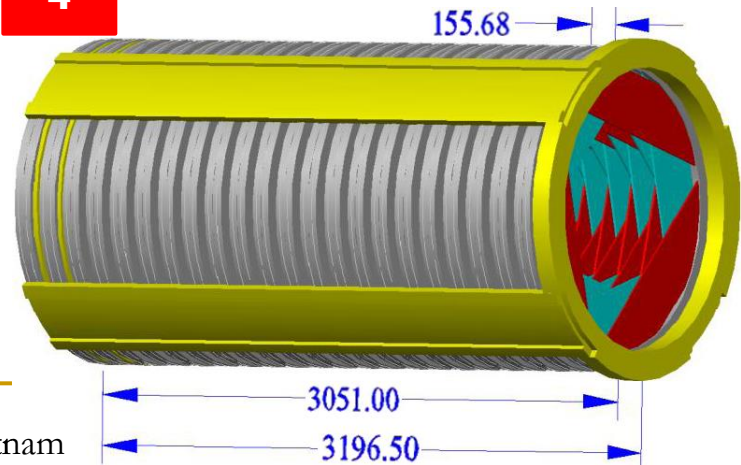
2



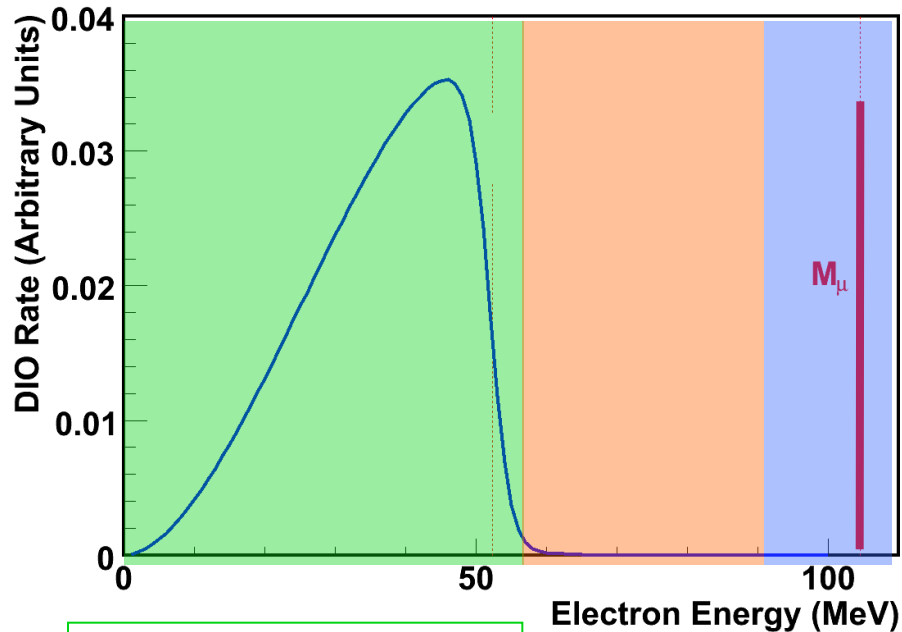
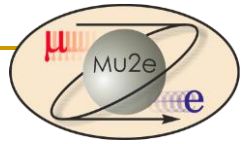
3



4



How do you measure 2.5×10^{-17} ?

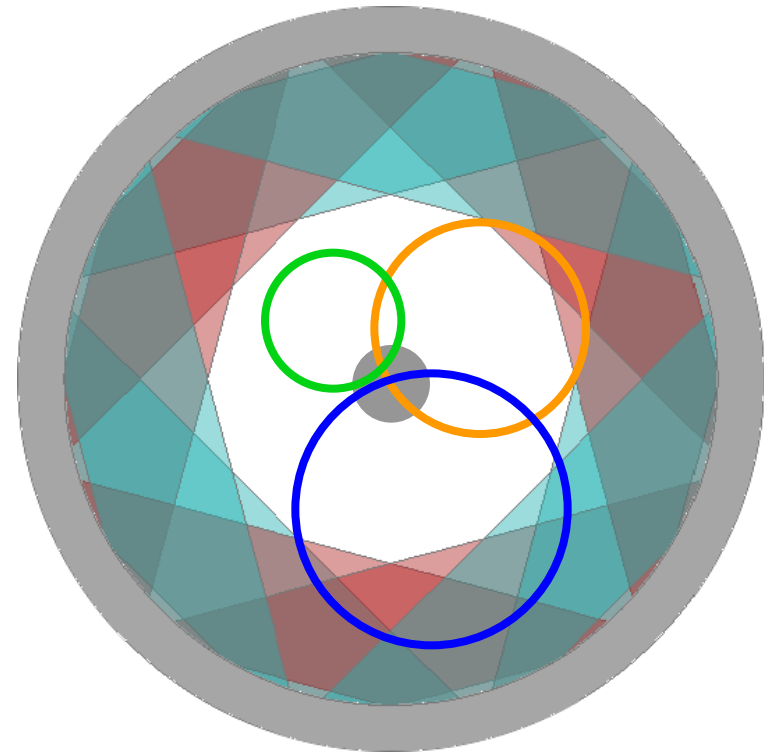


no hits in tracker

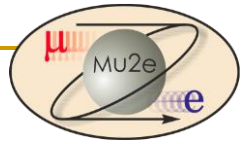
some hits tracker, tracks not reconstructable.

reconstructable tracks

(Only about 10-10 of all the DIO are seen, in order to keep the background rates at a reasonable level.)

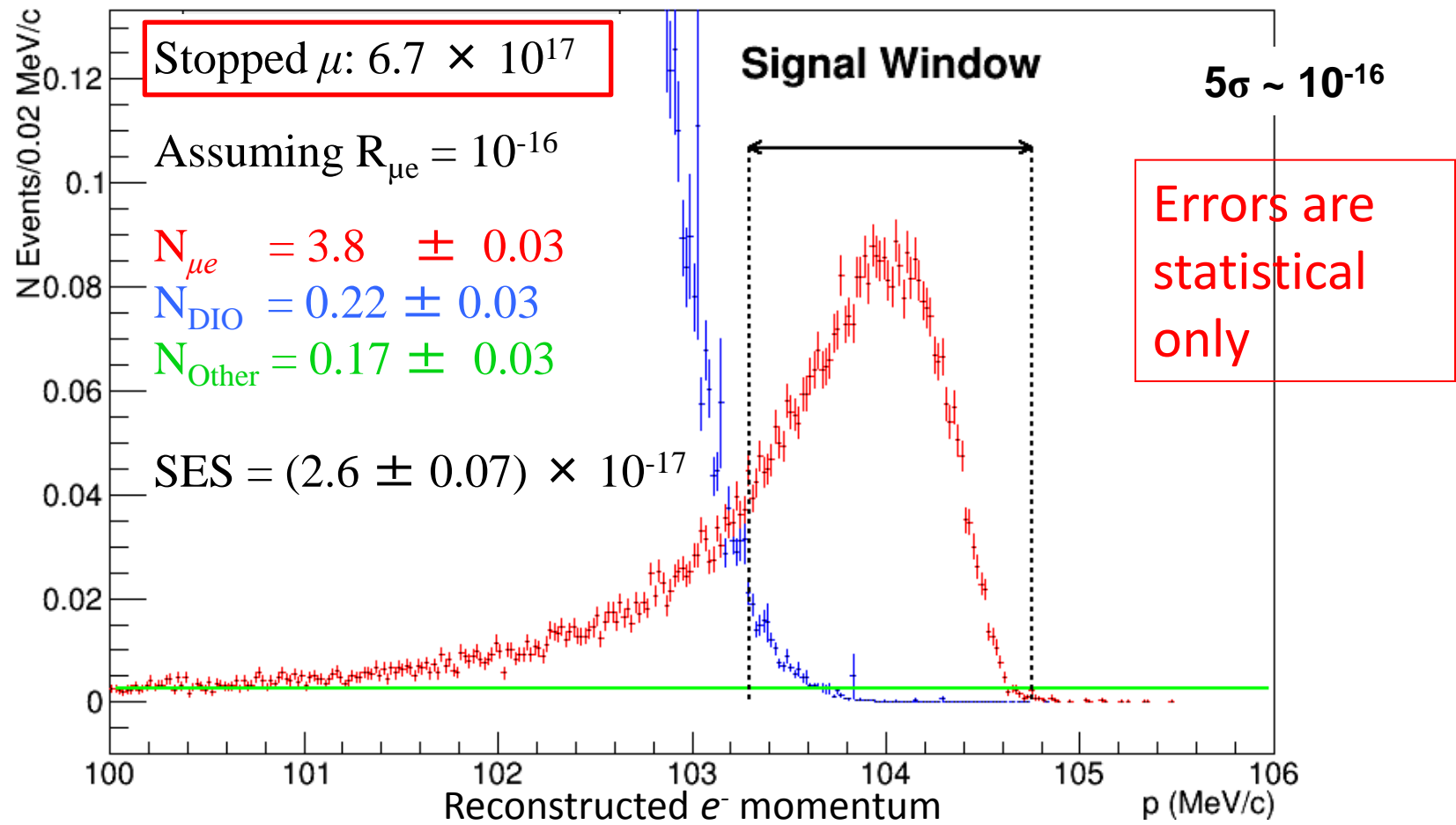


beam's-eye view of the tracker



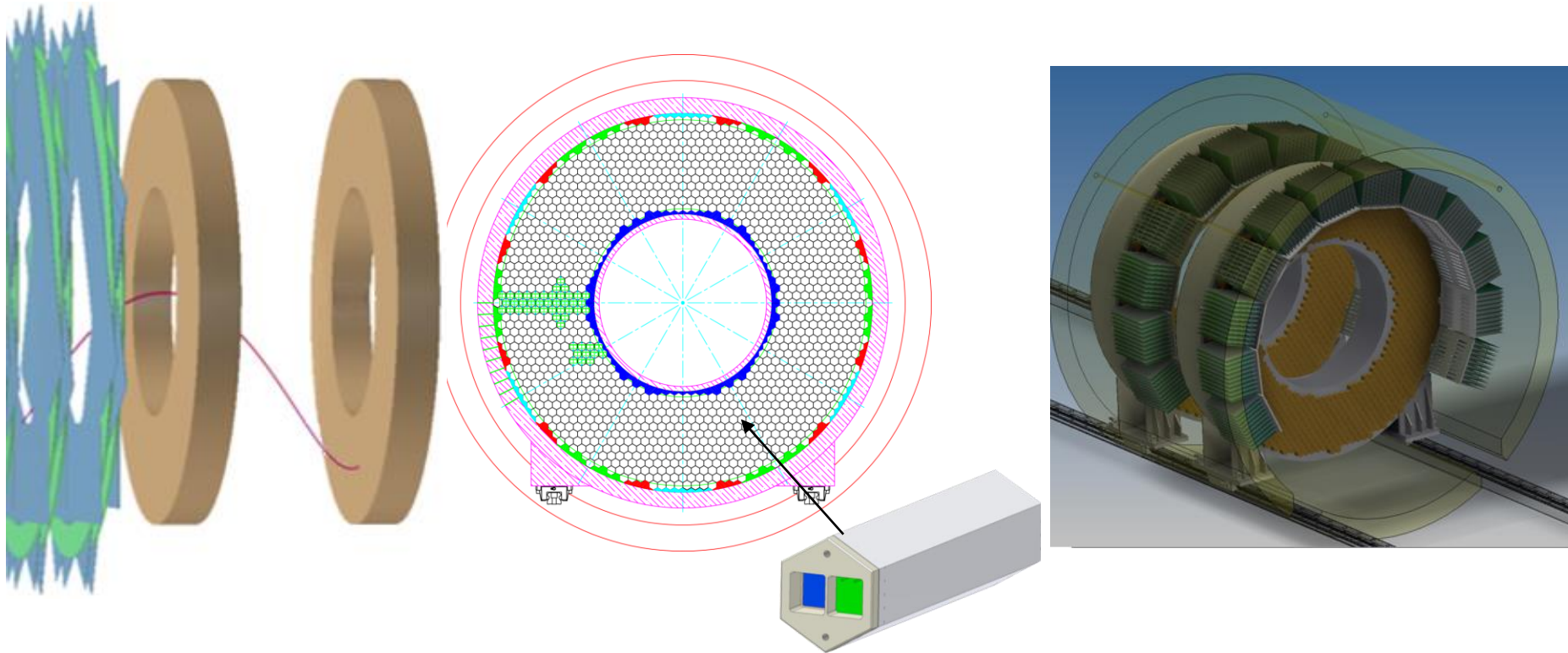
Signal sensitivity for a 3 Year Run

Full Geant4 modeling and reconstruction without any truth input (tracker only)

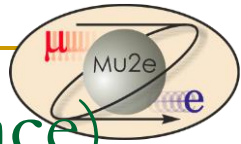


typical SUSY at 10^{-15} : 40 events vs 0.4 backgrounds

Scintillating crystal calorimeter

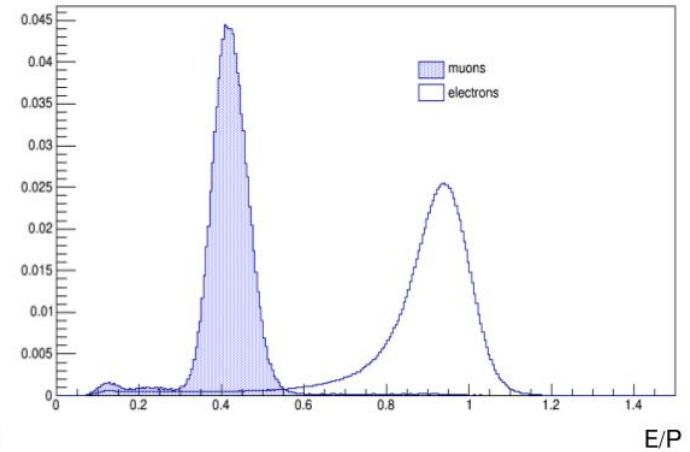
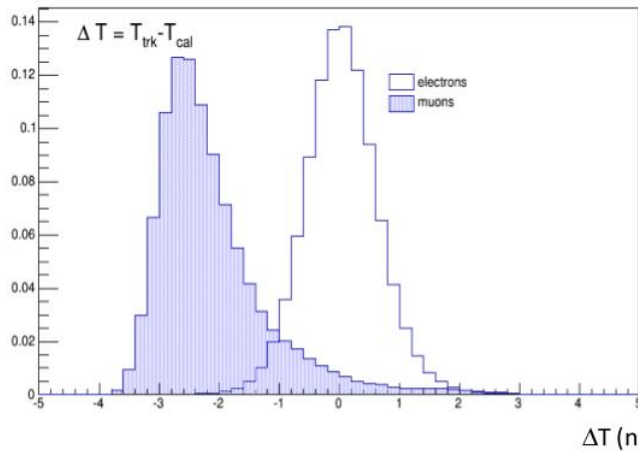


- Two disk geometry (inner radius 351 mm, outer radius 660 mm);
- Hexagonal BaF_2/CsI crystals (33 mm x 180 mm, ~ 1900); two (10 x 10 mm^2) APD or SiPM readout;
- Provides precise timing (< 1 ns), PID (μ/e), background rejection, alternate track seed and possible calibration trigger.

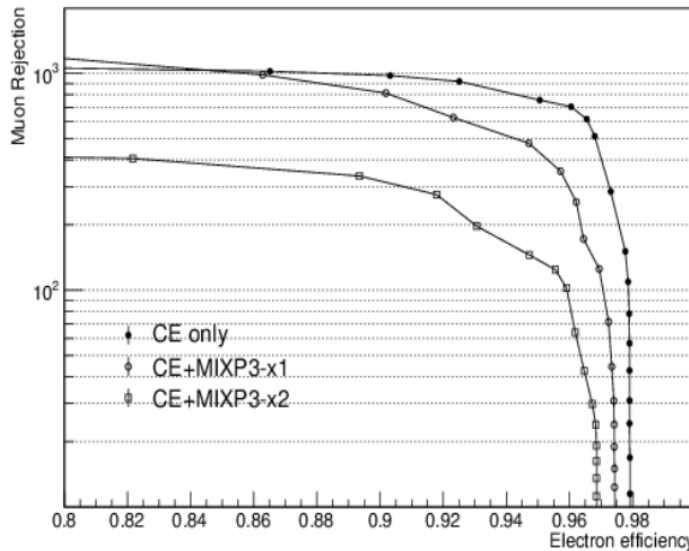


Scintillating crystal calorimeter (PID performance)

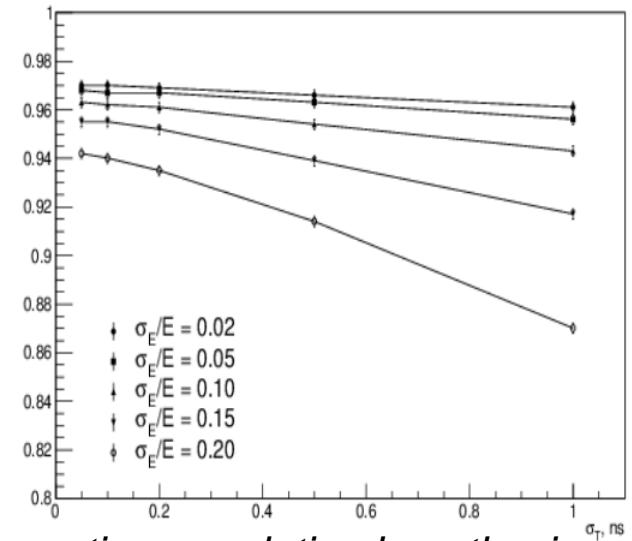
Likelihood PID based on these two variables (combining tracker and calorimeter information):



Muon Rejection Vs Electron Efficiency



Electron efficiency for muon rejection of 200

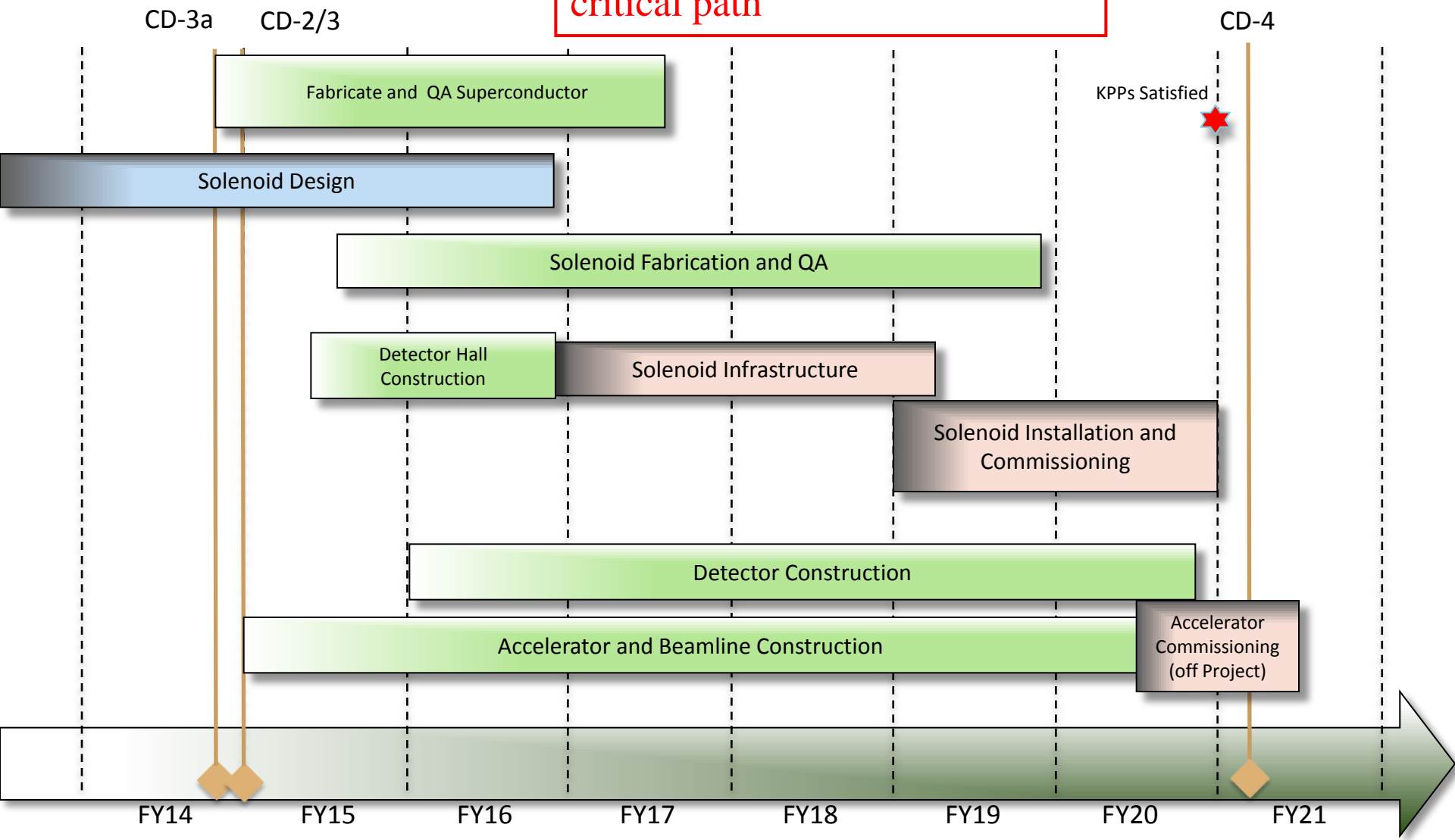
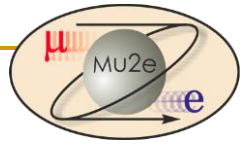


A rejection factor > 100 with a high CE efficiency

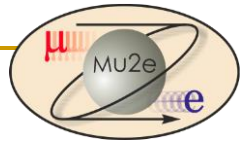
time resolution hypothesis

Mu2e schedule

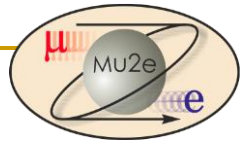
Solenoid design, construction and commissioning are the critical path



Summary and conclusions

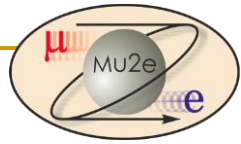


- mu2e will either discover μ to e conversion or set a greatly improved limit
 - $R_{\mu e} < 6 \times 10^{-17}$ @ 90% CL.
 - 10^4 improvement over previous best limit
 - Mass scales to $\mathcal{O}(10^4 \text{ TeV})$ are within reach
- Schedule:
 - Final review ~September 2014; expect approval ~October 2014
 - Construction start fall 2014
 - Installation and commissioning in 2019-2020
 - Solenoid system is the critical path
- mu2e is a long term 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 by a factor of 10 or more



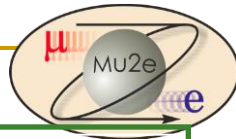
Thank you

Not Covered in This Talk



- Pipelined, deadtime-less trigger 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.

New Physics Scenarios

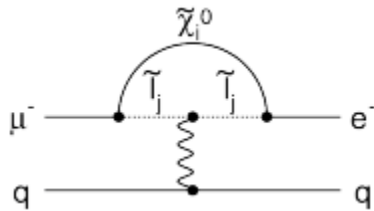


$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

Magnetic moment operator

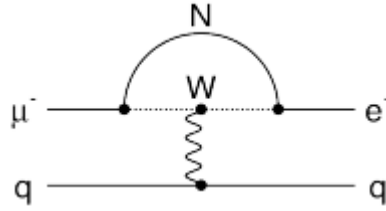
Supersymmetry

rate $\sim 10^{-15}$



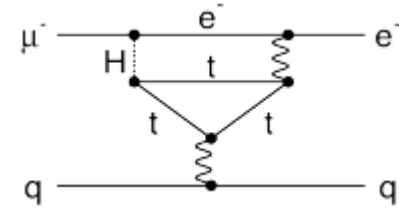
Heavy Neutrinos

$|U_{\mu N} U_{eN}|^2 \sim 10^{-13}$



Two Higgs Doublets

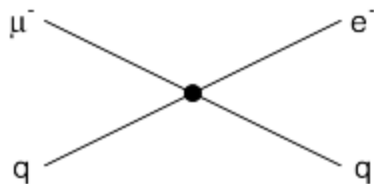
$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Contact term operator

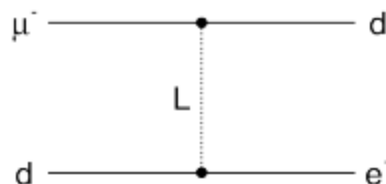
Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$



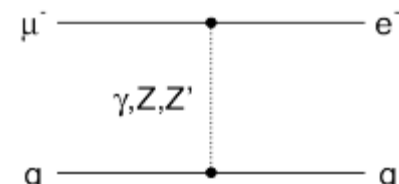
Leptoquarks

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

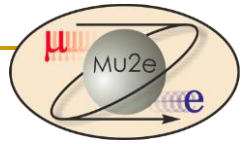


Heavy Z'

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

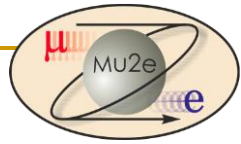


M. Raidal, *et al.*, Flavour Physics of Leptons and Dipole Moments, Eur.Phys.J. C57, 13, 2008



- 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

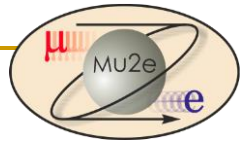
Backgrounds for a 3 Year Run



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}

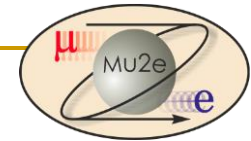


Calorimeter crystal history

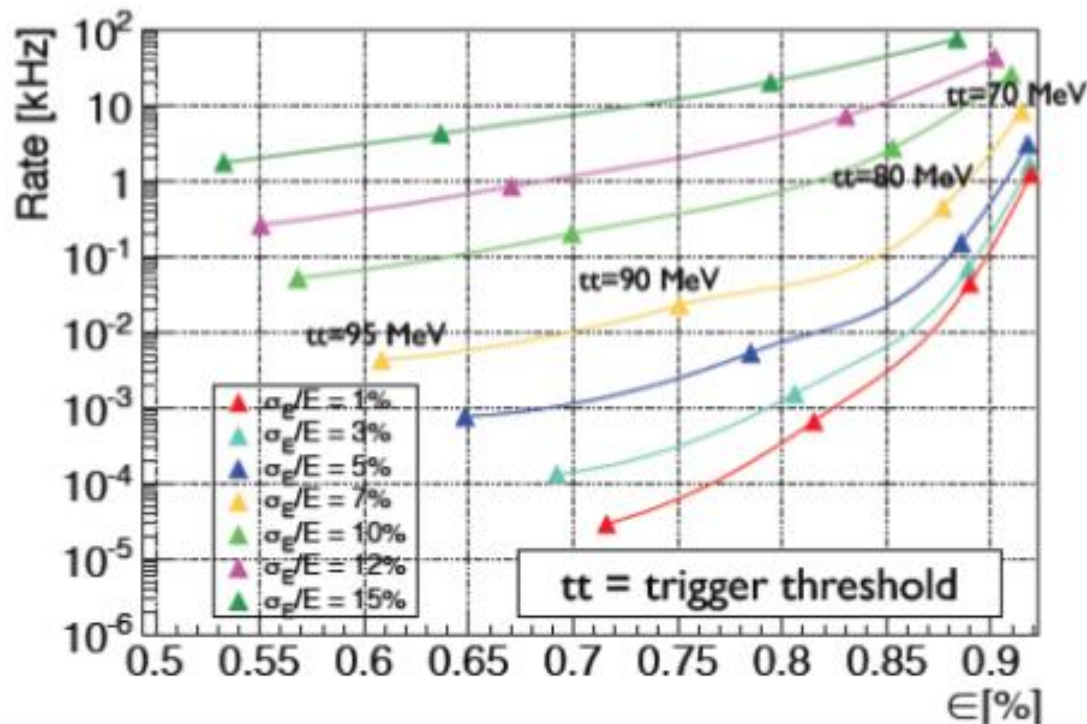
- Initial choice PbWO₄: small X₀, low light yield, low temperature operation, temperature and rate dependence of light output
- CDR choice LYSO: small X₀, high light yield, expensive (→very expensive)
- TDR choice: BaF₂: larger X₀, lower light yield (in the UV), very fast component at 220 nm, readout R&D required, cheaper,

Crystal	BaF ₂	LYSO	CsI	PbWO ₄
Density (g/cm ³)	4.89	7.28	4.51	8.28
Radiation length (cm) X ₀	2.03	1.14	1.86	0.9
Molière radius (cm) R _m	3.10	2.07	3.57	2.0
Interaction length (cm)	30.7	20.9	39.3	20.7
dE/dx (MeV/cm)	6.5	10.0	5.56	13.0
Refractive Index at λ _{max}	1.50	1.82	1.95	2.20
Peak luminescence (nm)	220, 300	402	310	420
Decay time τ (ns)	0.9, 650	40	26	30, 10
Light yield (compared to NaI(Tl)) (%)	4.1, 36	85	3.6	0.3, 0.1
Light yield variation with temperature (% / °C)	0.1, -1.9	-0.2	-1.4	-2.5
Hygroscopicity	None	None	Slight	None

Calorimeter based trigger filter



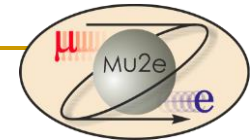
- The trigger algorithm applies a threshold on the reconstructed energy
- Signal efficiency and DIO rate were studied convoluting results from G4 with Gaussian functions (sigma's are showed on figures)



If not further surprises, filter will be applied at HLT level.

Calorimeter thr = 70 MeV, effi ~ 90 %, DIO rate ~ 2 kHz @ 5 % resol.

Crystal and photosensor alternatives

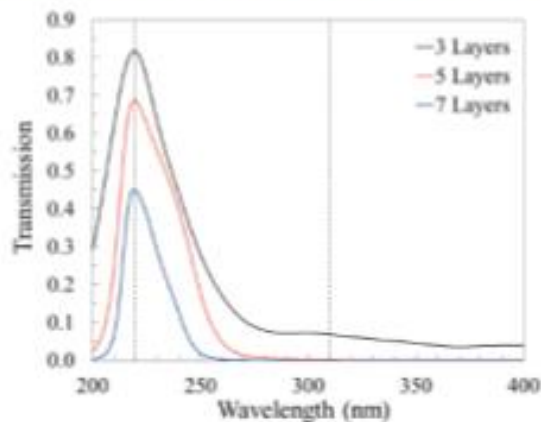


BaF₂ presents several advantages:

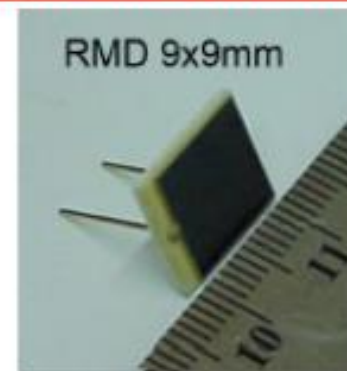
- ✓ **Small decay time**
- ✓ **Non-hygroscopic**
- ✓ **Rad hard**

Crystal	BaF ₂	LYSO	CsI	PbWO ₄
Density (g/cm ³)	4.89	7.28	4.51	8.28
Radiation length (cm) X_0	2.03	1.14	1.86	0.9
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Hygroscopicity	None	None	Slight	None

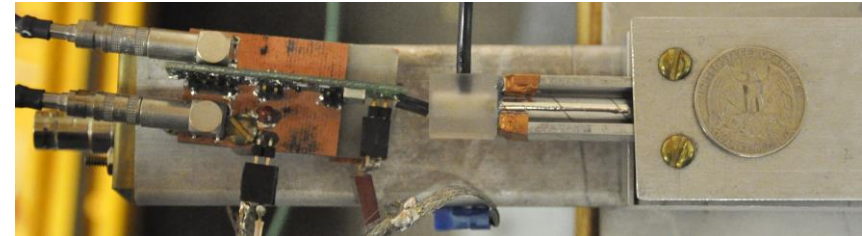
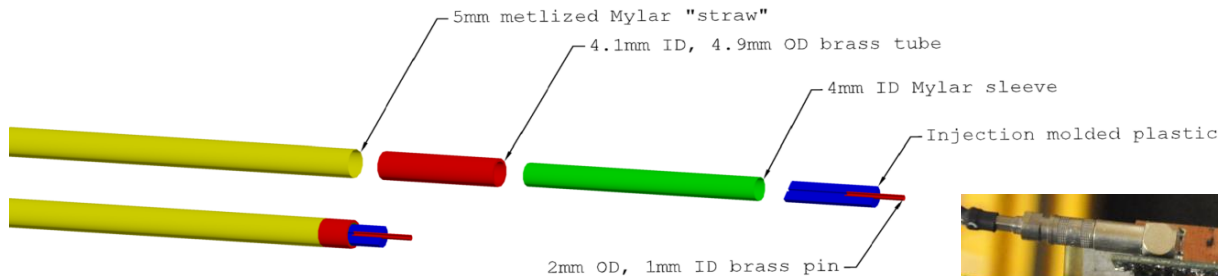
- ✓ 60% QE @ 200 nm (wa
- ✓ ~0.1% QE @ 300 nm
- ✓ capacitance ~ 60 pF
- ✓ operation gain ~ 500



deltadoped APD from RMD

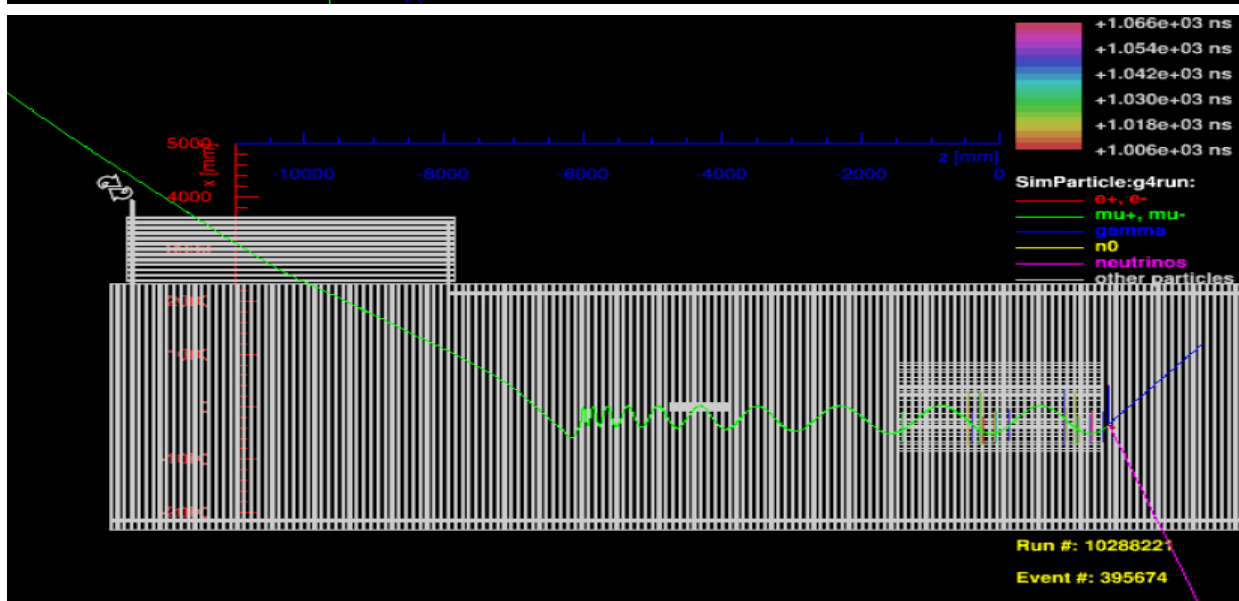
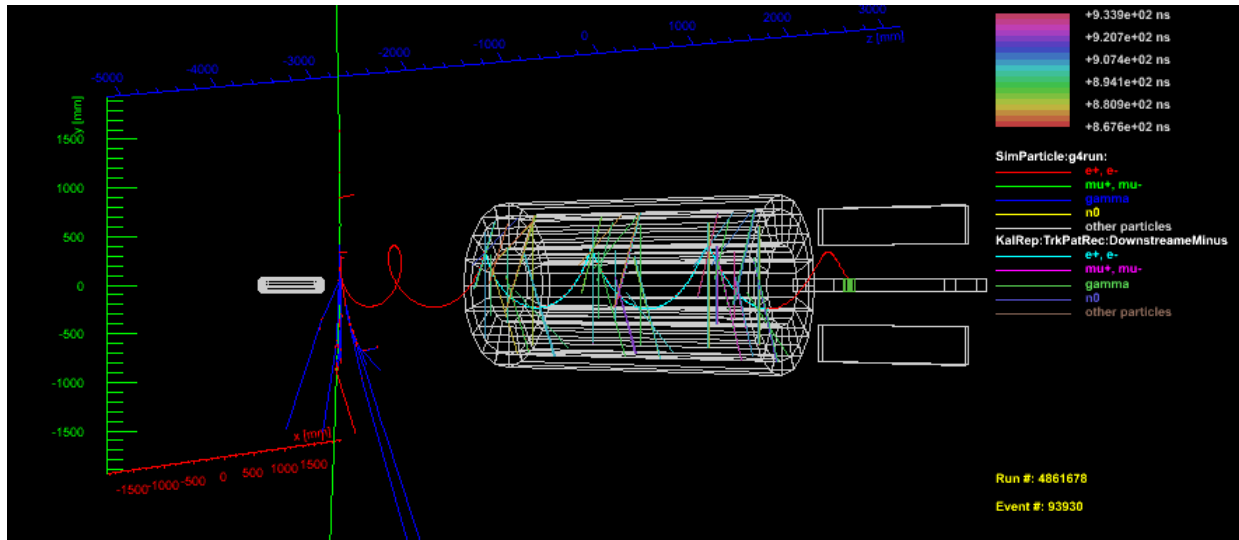


Straw tubes

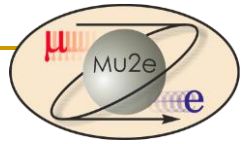


- 5 mm diameter;
- wall thickness of 15 μm :
 - two layers of $\sim 6 \mu\text{m}$ (25 gauge) Mylar®, spiral wound, with a $\sim 3 \mu\text{m}$ layer of adhesive between layers. The inner surface has 500 Å aluminum overlaid with 200 Å gold as the cathode layer. The outer surface has 500 Å of aluminum to act as additional electrostatic shielding and improve the leak rate.
- The straws will be tensioned to 500 g;
- sense wire is 25 μm gold plated tungsten, centered in the straw.
 - The wire will be tensioned to 80 g.
- The drift gas is tentatively taken as 80:20 Argon:CO₂ with an operating voltage of $\sim 1500 \text{ V}$, with maximum drift time of $\sim 50 \text{ ns}$ and gain of $\sim 3 \cdot 10^4$.

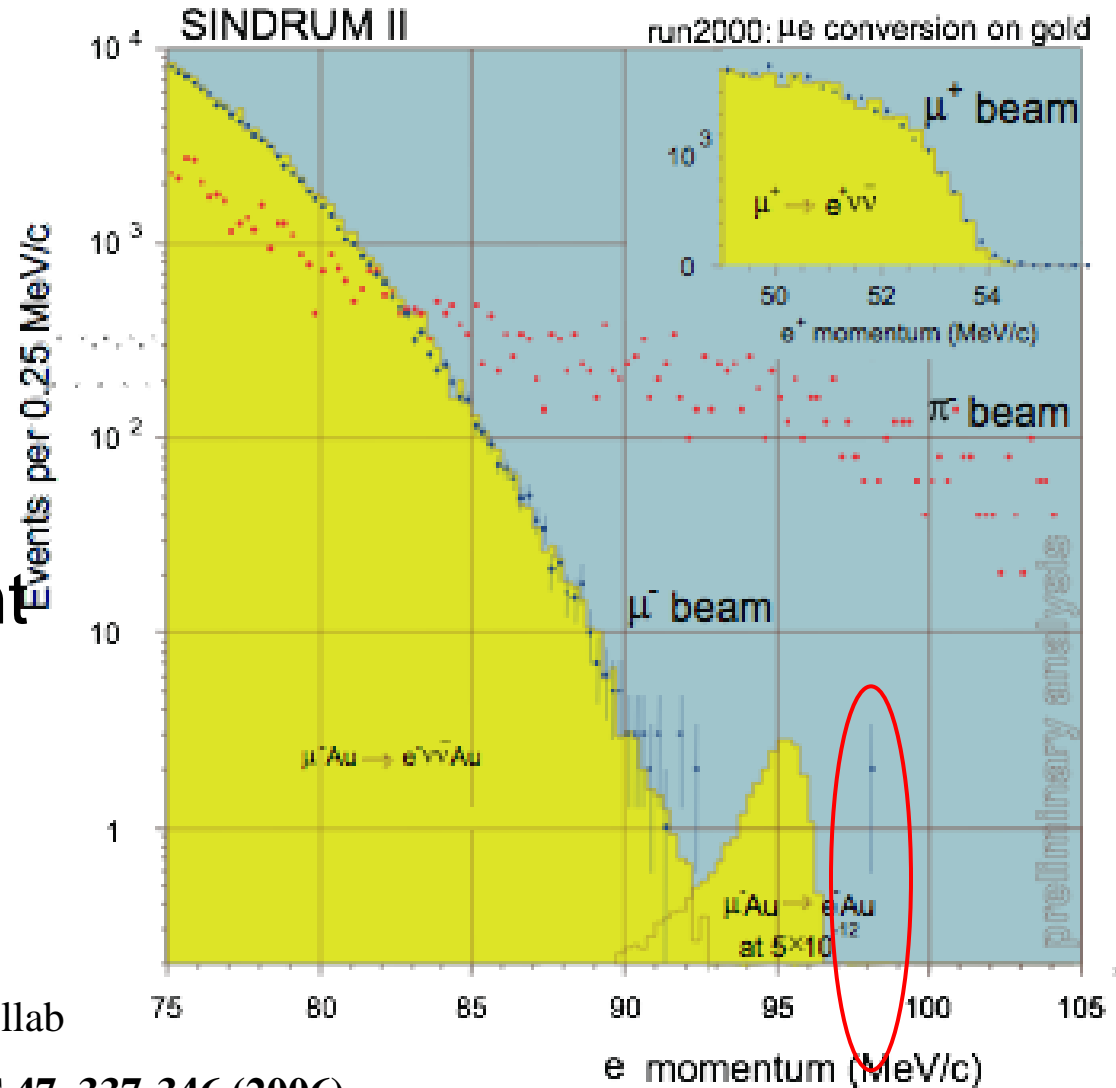
Two example of background from cosmic ray



The previous best experiment

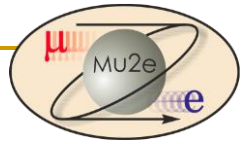


- SINDRUM II
- $R_{\mu e} < 6.1 \times 10^{-13}$
@90% CL
- 2 events in signal region
- Au target: different E_e endpoint than Al.

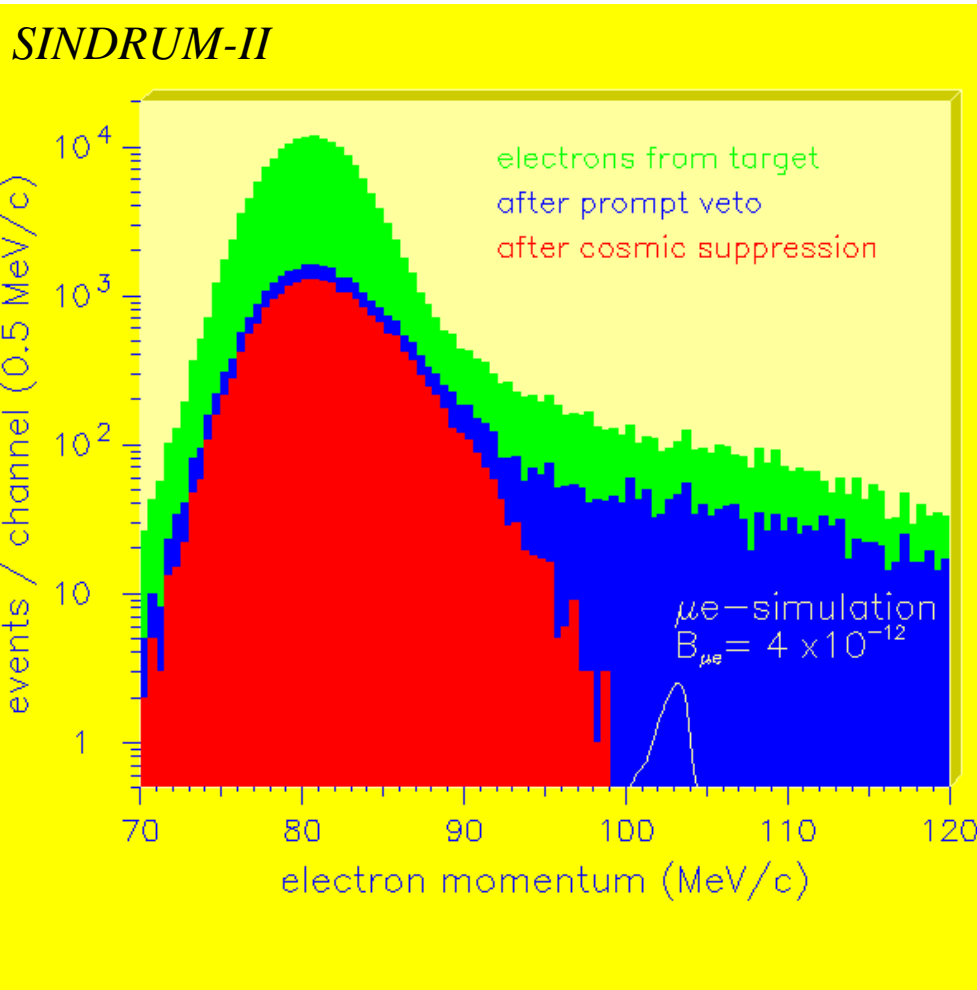


HEP 2001 W. Bertl – SINDRUM II Collab

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 were also important

$$R_{\mu e}(\text{Ti}) < 6.1 \times 10^{-13}$$

PANIC 96 (C96-05-22)

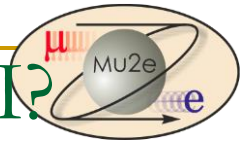
$$R_{\mu e}(\text{Ti}) < 4.3 \times 10^{-12}$$

Phys.Lett. B317 (1993)

$$R_{\mu e}(\text{Au}) < 7 \times 10^{-13}$$

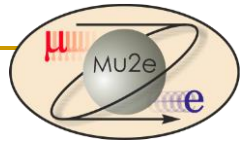
Eur. Phys. J. , C47 (2006)

Why is mu2e more sensitive than SINDRUM II?

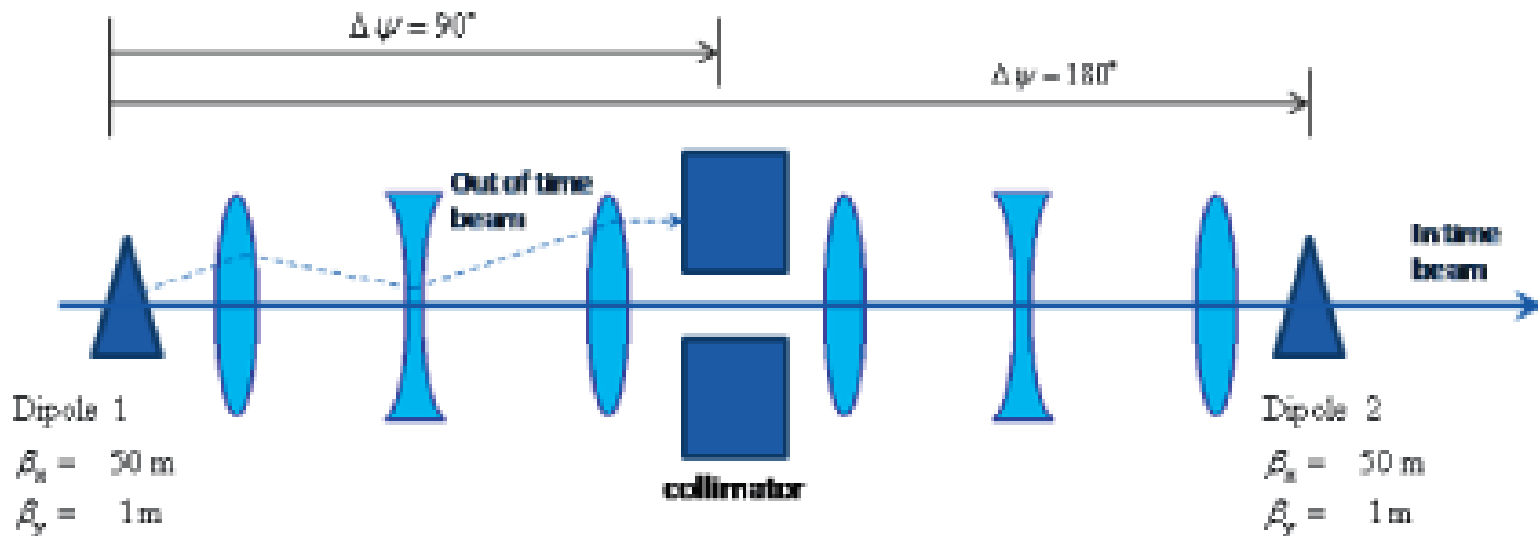


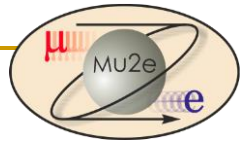
- FNAL can deliver $\sim 10^3 \times$ proton intensity.
- Higher μ collection efficiency.
- SINDRUM II was background-limited.
 - Radiative π capture.
 - Bunched beam and excellent extinction reduce this.
 - Thus mu2e can make use of the higher proton rate.

Required Extinction 10^{-10}

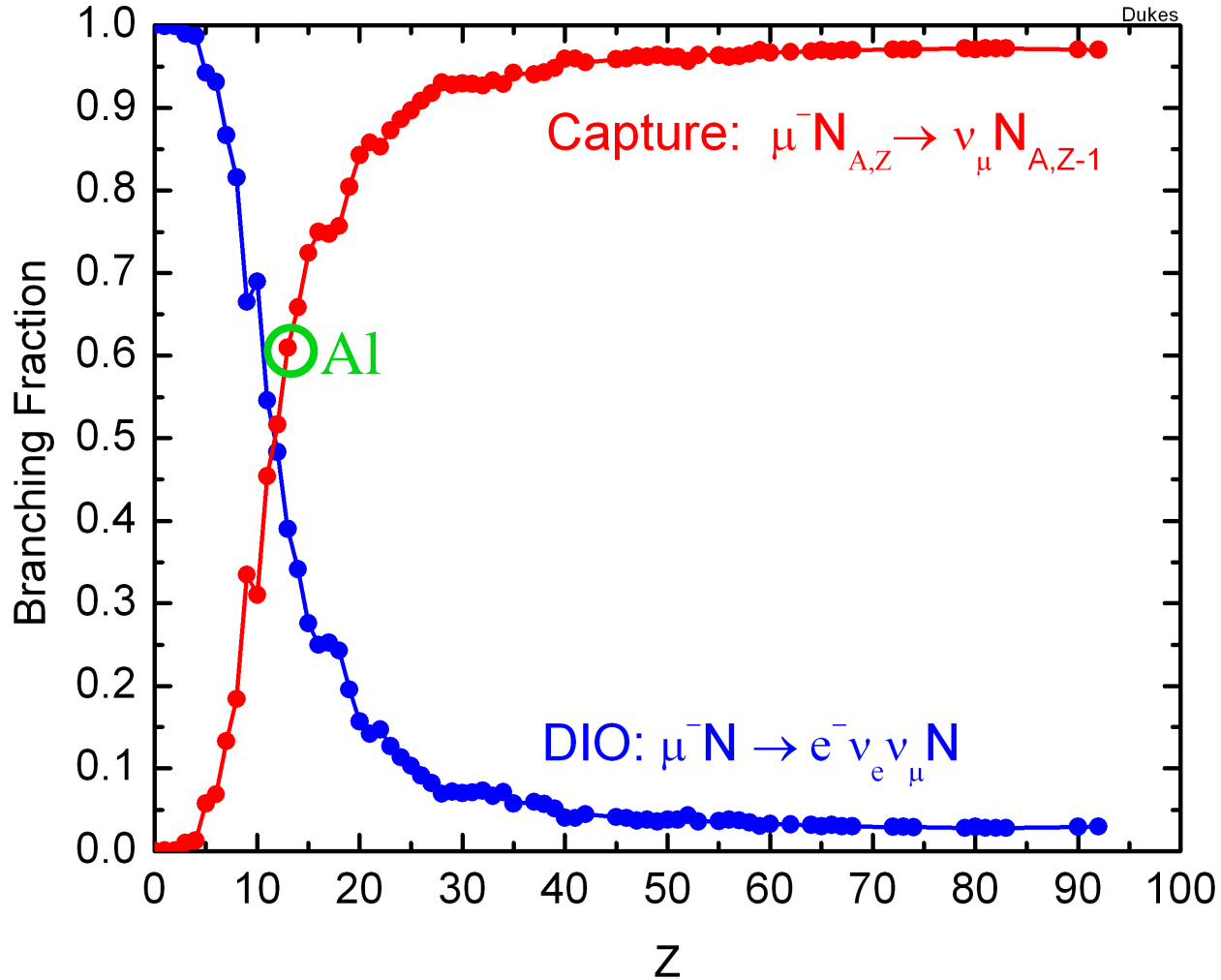


- Internal: 10^{-7} already demonstrated at AGS.
 - Without using all of the tricks.
- External: in transfer-line between ring and production target.
 - AC dipole magnets and collimators.
- Simulations predict aggregate 10^{-12} is achievable
- Extinction monitoring systems have been designed.

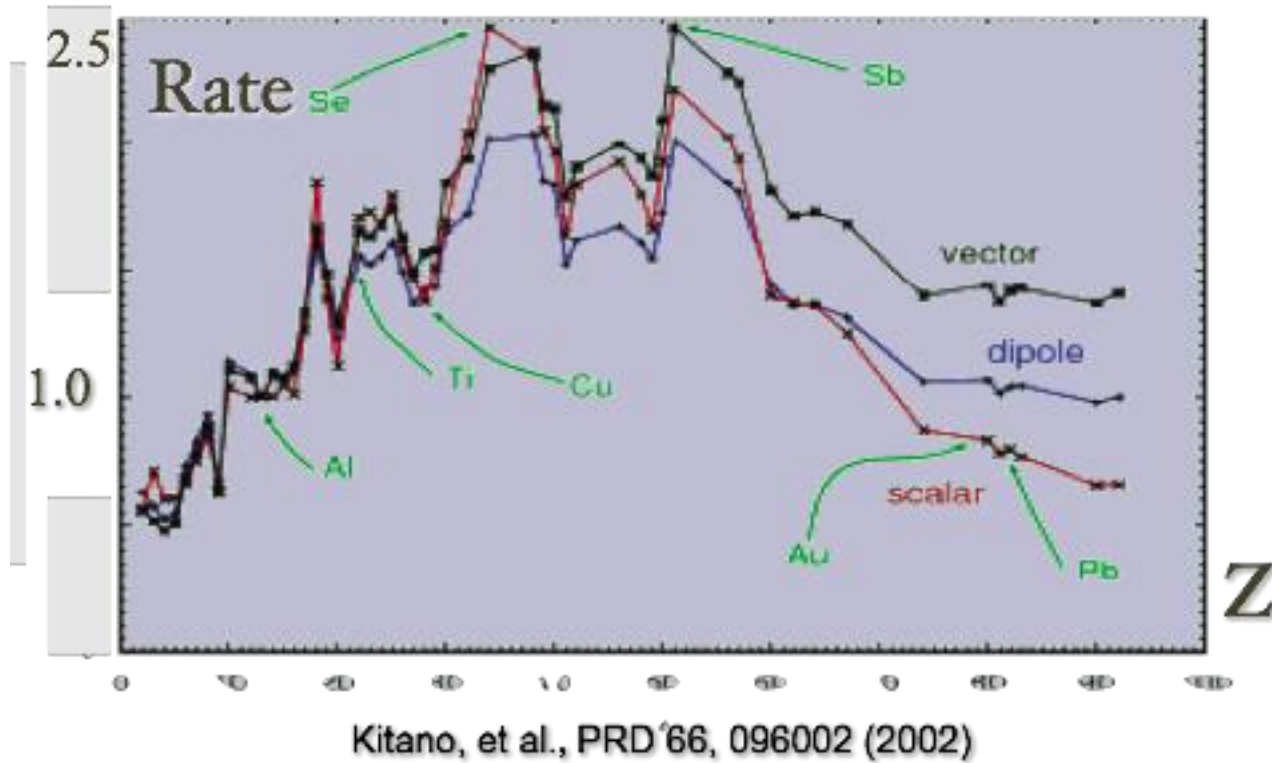




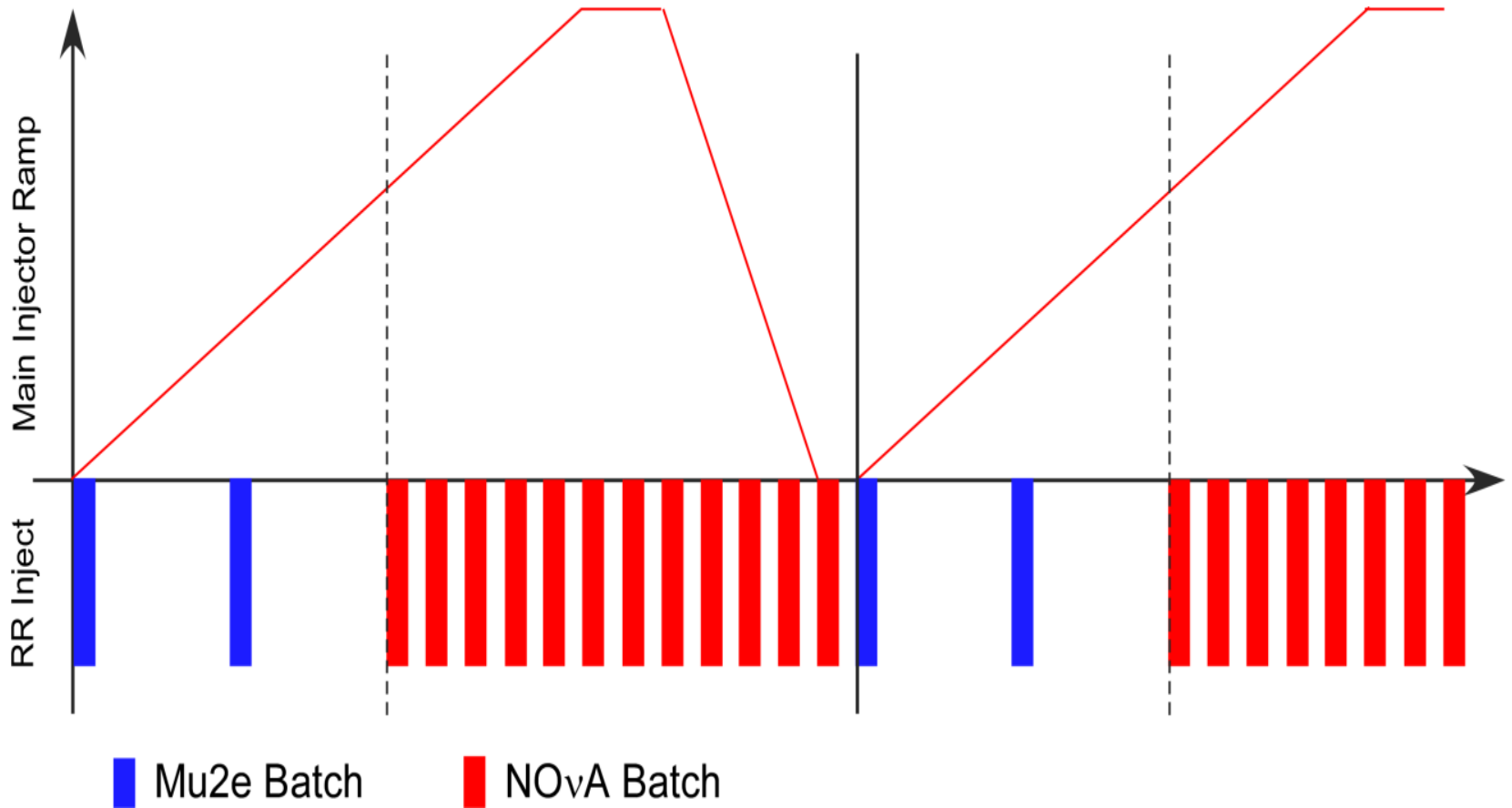
Capture and DIO *vs* Z



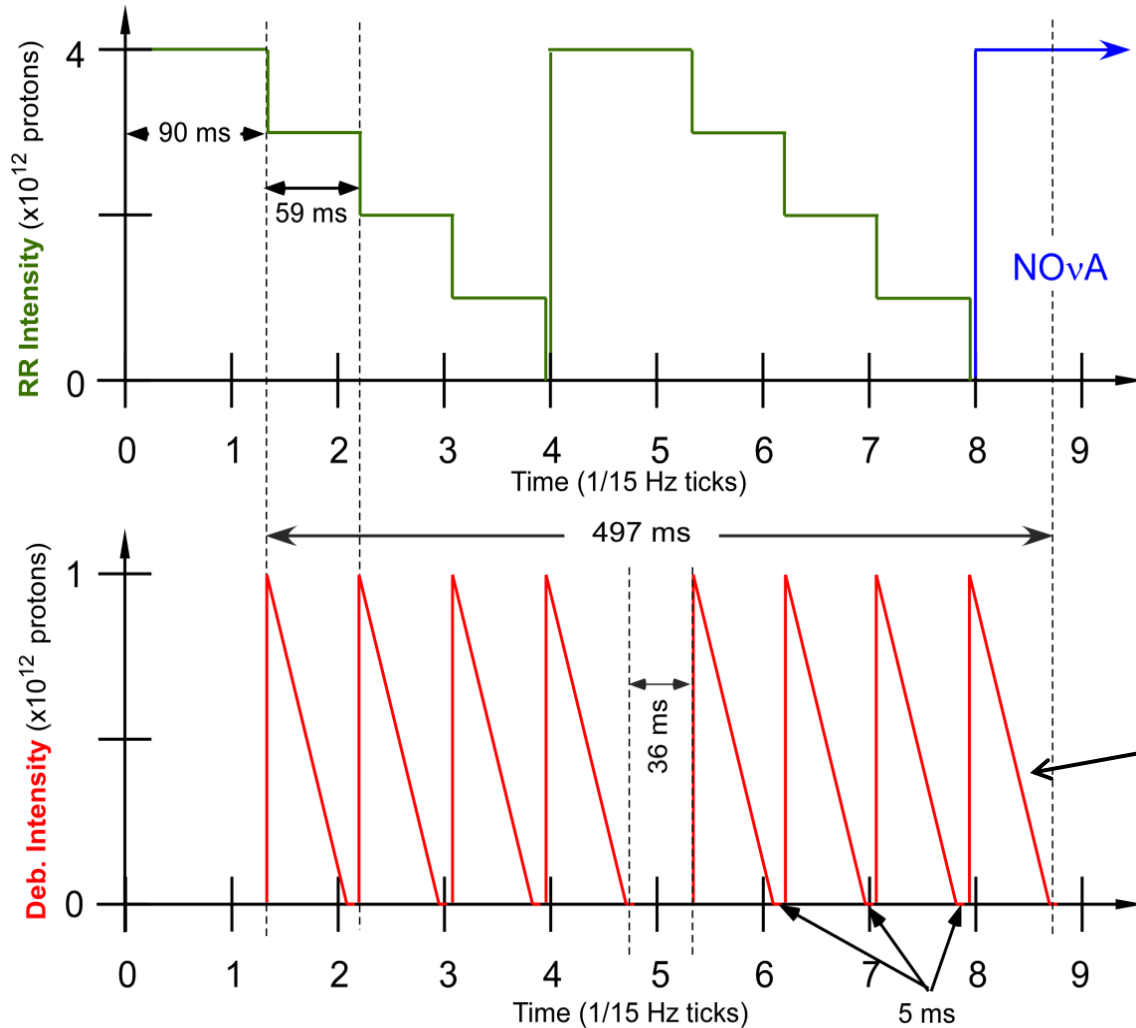
Conversion Rate, Normalized to Al



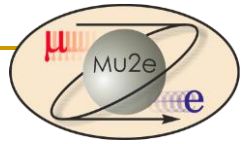
Proton Beam Macro Structure



Proton Beam Micro Structure



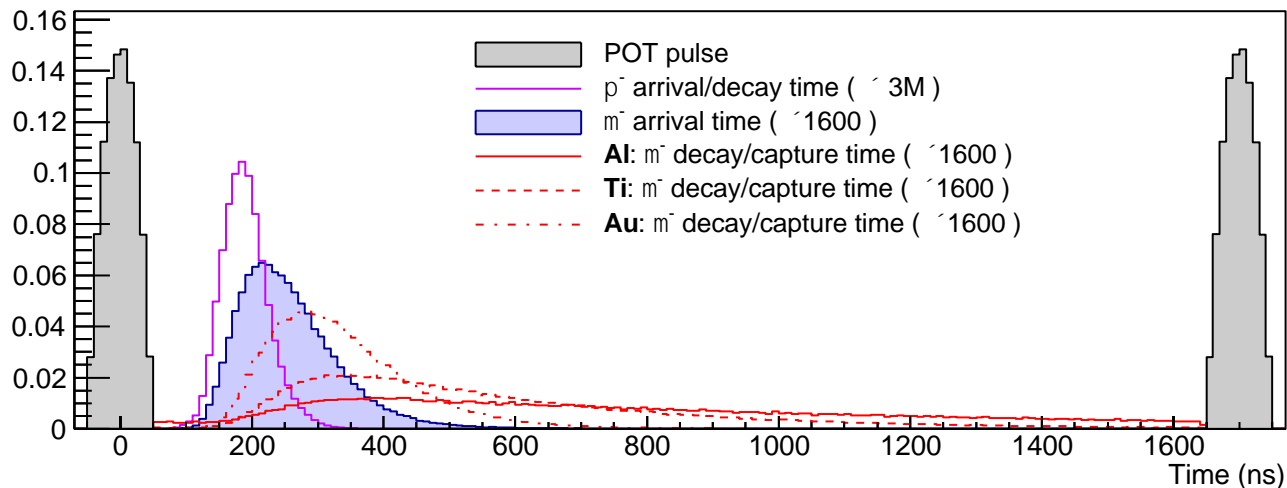
Slow spill:
Bunch of 4×10^7
protons every 1694 ns



- Proton Improvement Plan (PIP)
 - Improve beam power to meet NO ν A requirements
 - Essentially complete.
- PIP-II design underway
 - Project-X reimaged 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 \times the protons to Mu2e
 - MW-class, high duty factor beams for rare process experiments
- 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>

Mu2e in the PIP-II Era

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



- If we have no signal:
 - Up to to $100 \times$ Mu2e physics reach, $R_{\mu e} < 10^{-18}$.
 - First factor of ~ 10 can use the same detector.