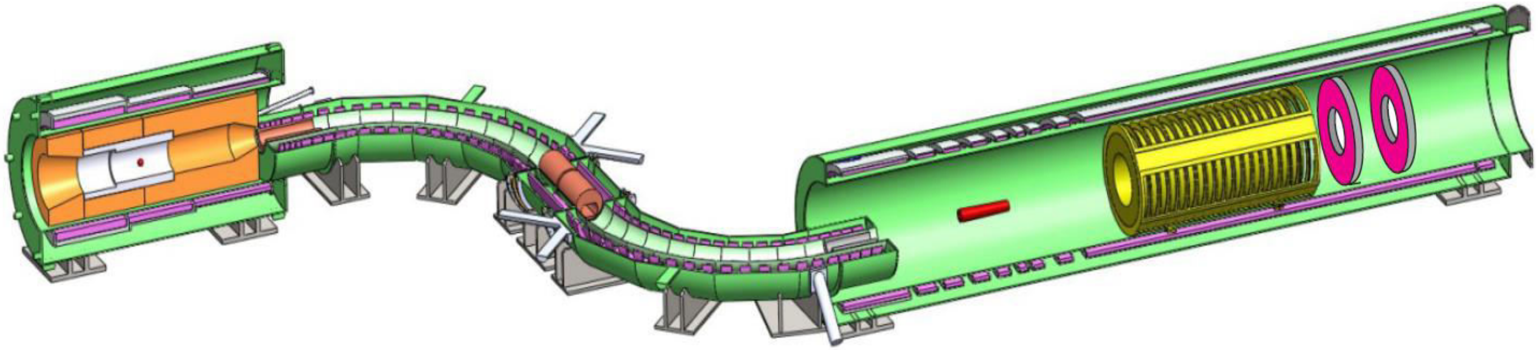
The Mu2e experiment at Fermilab

http://mu2e.fnal.gov/



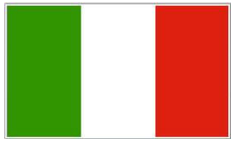
Giovanni F. Tassielli

FNAL, INFN Lecce

20th Particles & Nuclei International Conference – PANIC 2014

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 Nazionale di Frascati
- INFN Genova
- INFN Lecce and Università del Salento
- INFN Pisa and Università di Pisa
- INFN Trieste/Udine and Universita di Udine

- Institute for Nuclear Research, Moscow
- JINR, Dubna

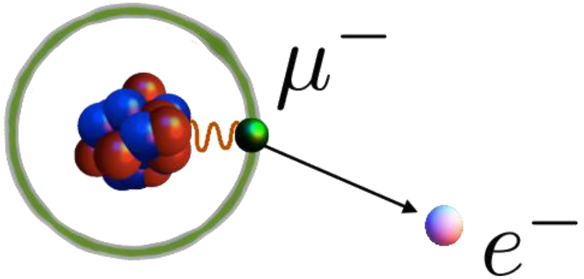
Muon to electron conversion in the field of a nucleus

- 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: $R_{\mu e} = \dfrac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \text{all muon captures})}$
- 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):

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

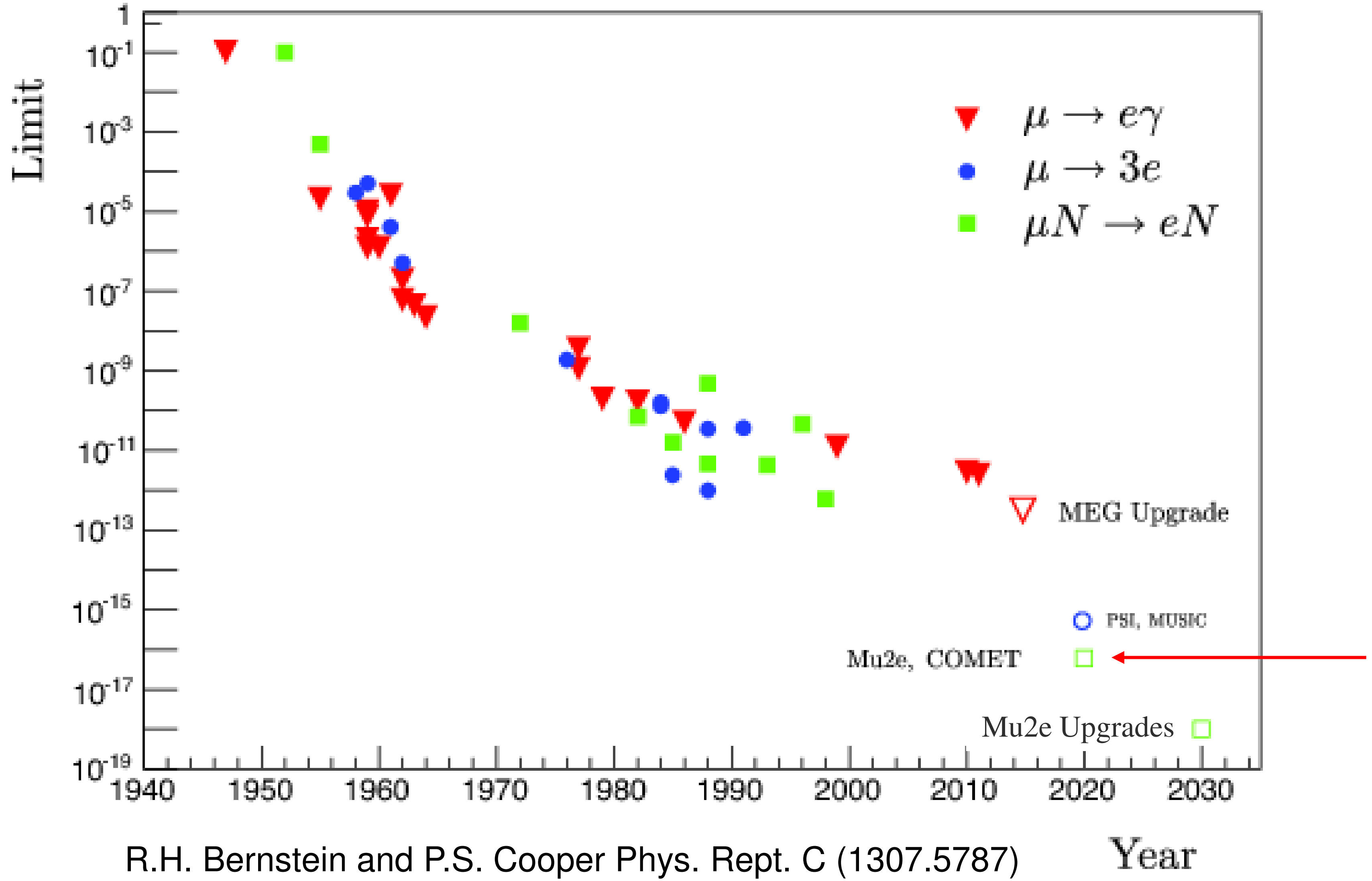
$$\tau \to \mu\gamma \quad \tau \to \mu^+\mu^-\mu^+ \quad D^+ \to \mu^+\mu^+\mu^-$$

$$\mu N \to e N$$



$E_e \sim 105$ MeV

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



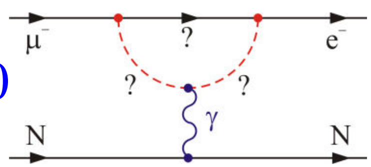
R.H. Bernstein and P.S. Cooper Phys. Rept. C (1307.5787)

Sensitivity to high mass scales

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

Loops dominate for $\kappa \ll 1$

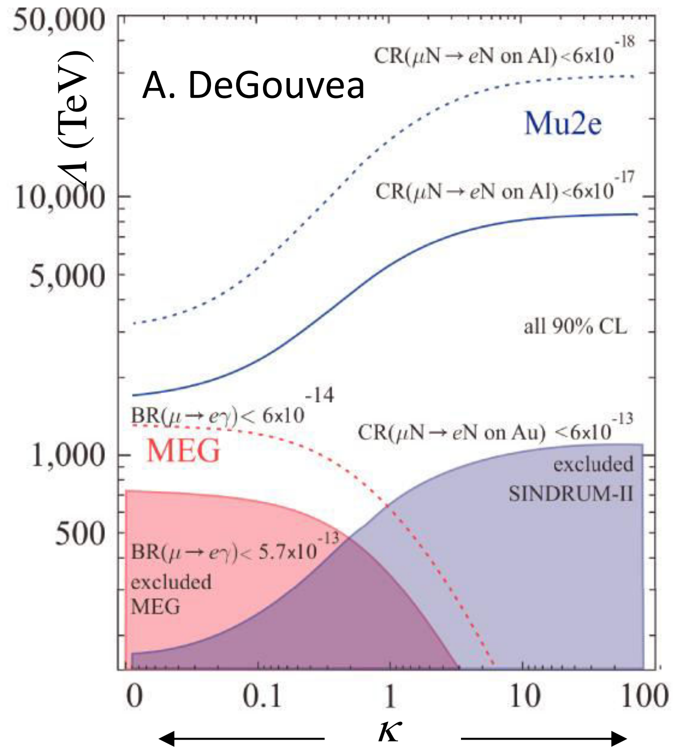
$\kappa = 0$



$\mu \to e\gamma$

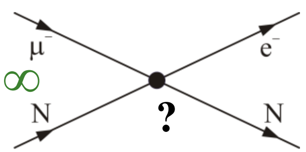
$\mu N \to eN$

$\mu \to eee$



Contact terms dominate for $\kappa \gg 1$

$\kappa = \infty$



$\cancel{\mu \to e\gamma}$

$\mu N \to eN$

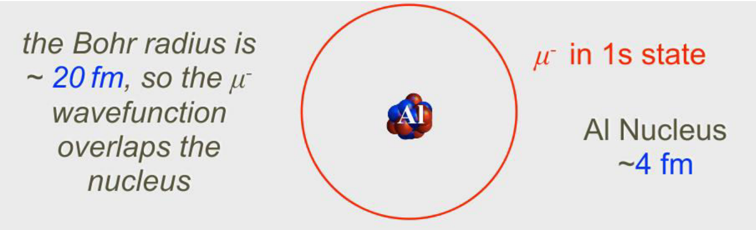
$\mu \to eee$

- 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

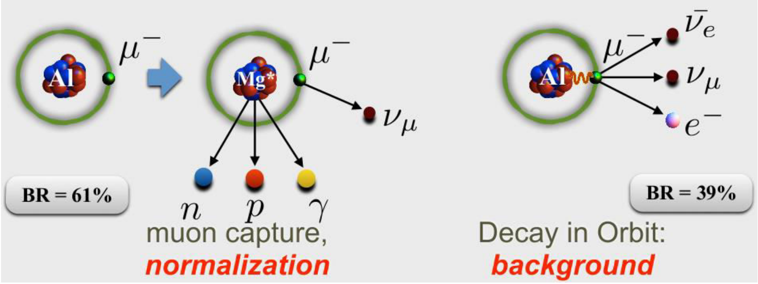
The concept of Mu2e measurement

- 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, $E_e \sim 105$ MeV
    - At endpoint of continuous spectrum.
- Then measure electron spectrum
  - The signal: monoenergetic electrons at 105 MeV

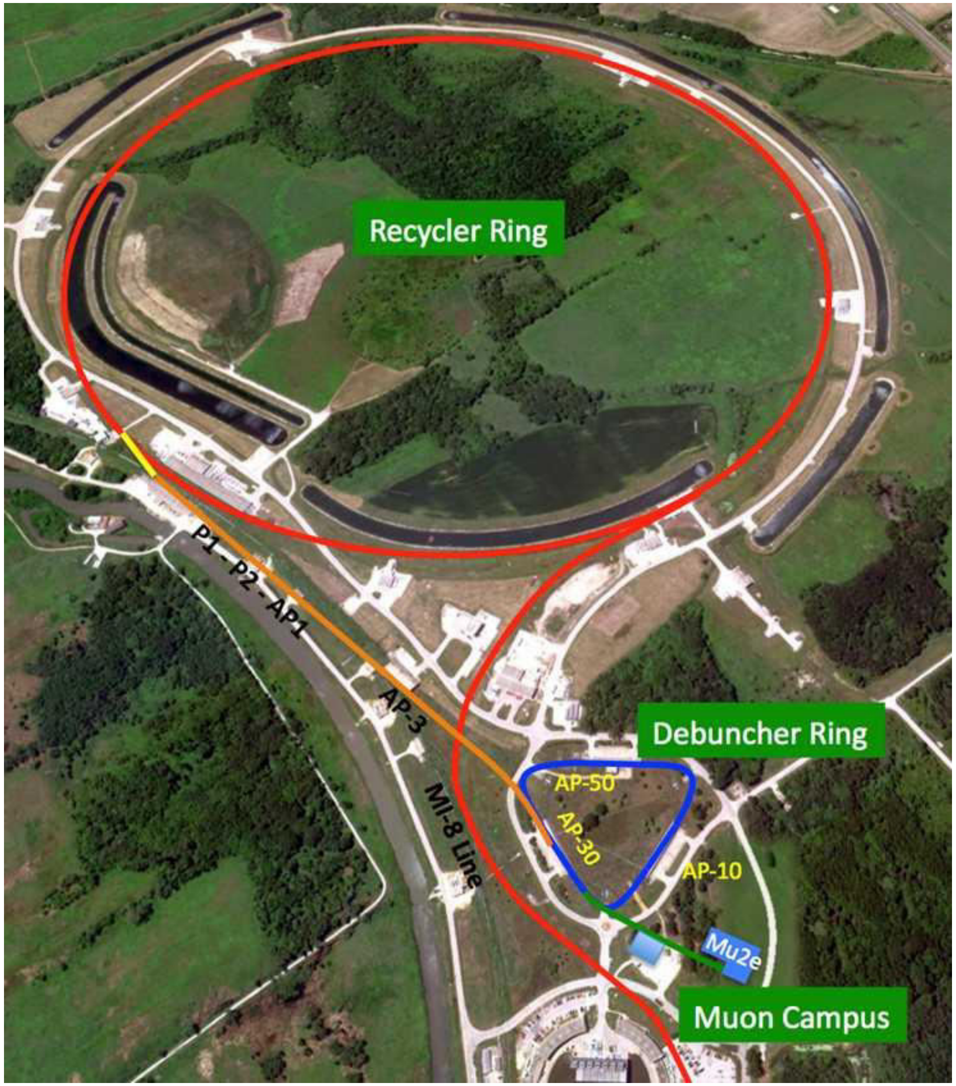
Lifetime 864 ns E_e=104.97 MeV



backgrounds



Proton delivery

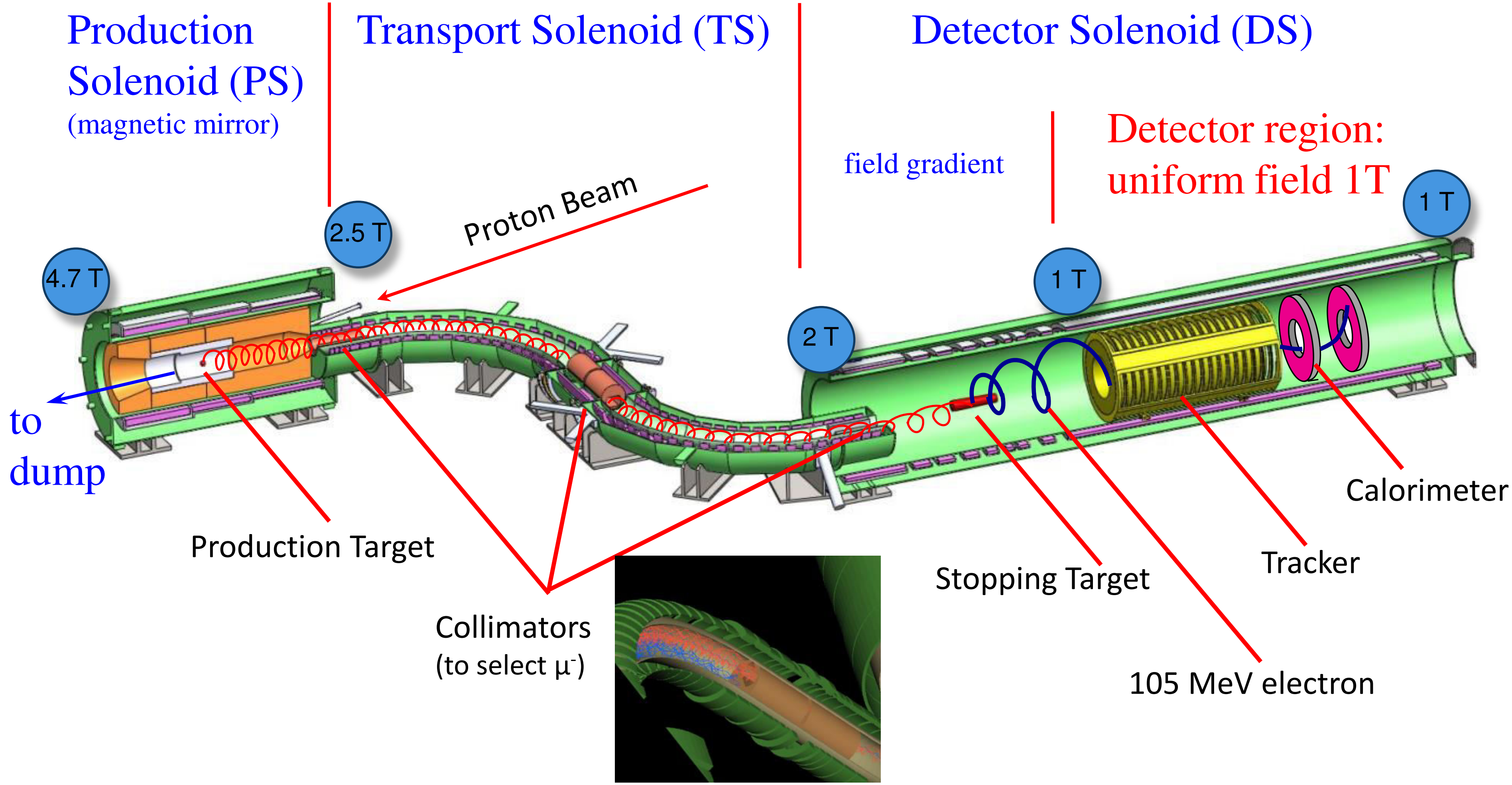


- We make muons by directing 8 GeV protons on to a target.
- Batches of protons from the Booster are transported through existing beamlines to the Recycler Ring where they are re-bunched and transported to the Delivery Ring through existing transport lines.
- Beam is slow extracted from Delivery Ring in microbunches of ~ 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

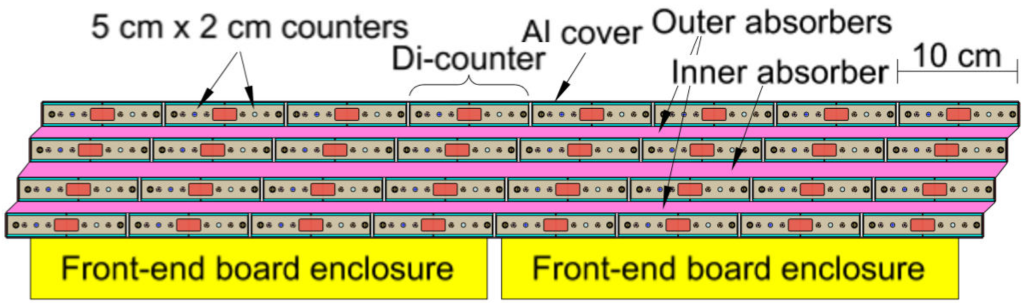
Cosmic Ray Veto and Stopping Target Monitor not shown



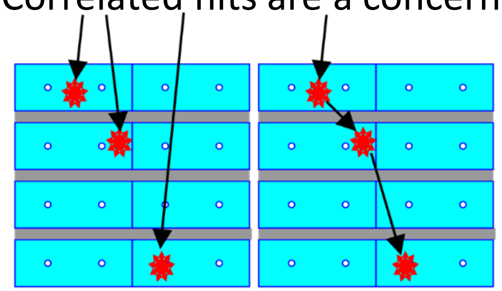
Detector solenoid is surrounded by a Cosmic Ray Veto

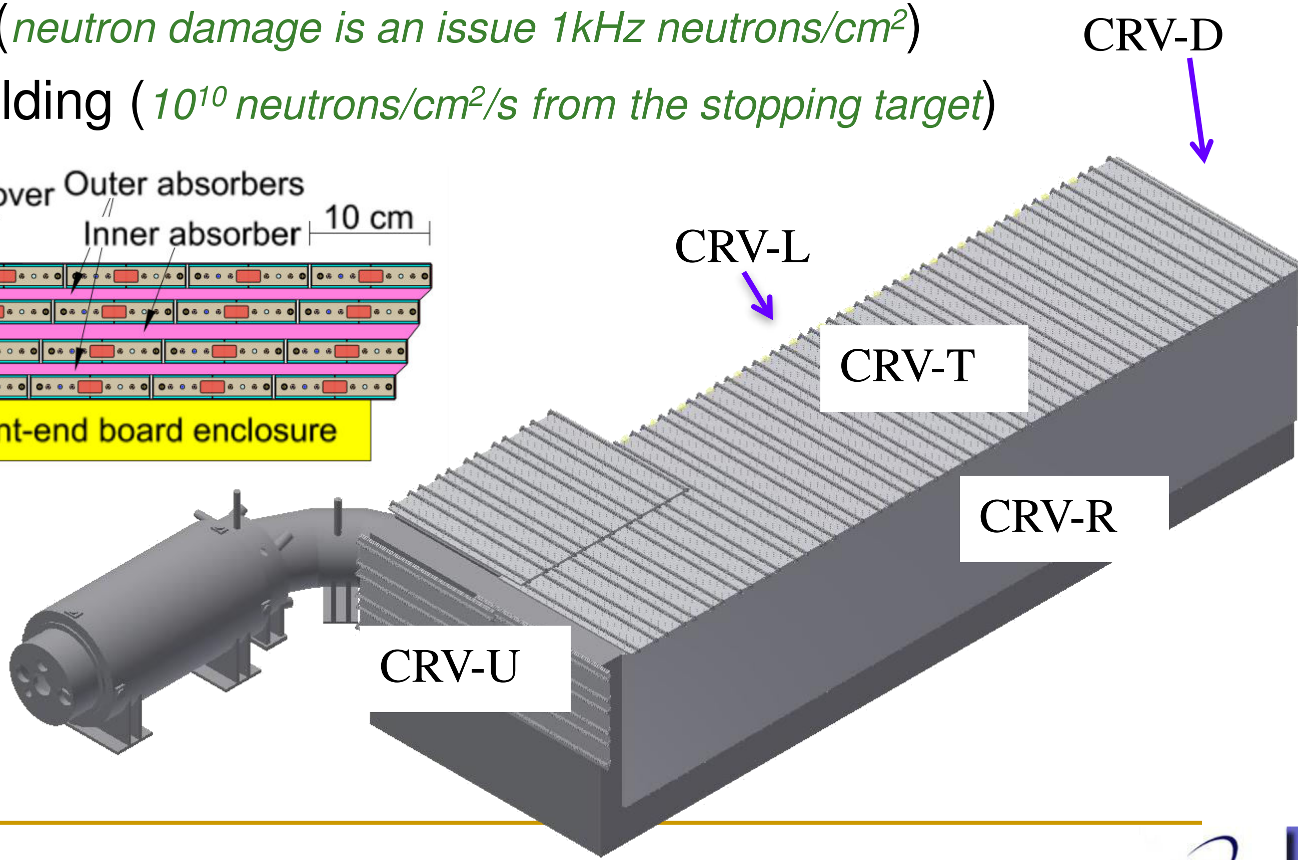
Exist a not negligible probability that due to the interaction of a cosmic ray in the DS there will be a particle that can mimic a signal event, a 99.99% efficient CRV is needed!

- Four layers of extruded plastic scintillators (~5000 counters)
- Fiber/SiPM readout (*neutron damage is an issue 1kHz neutrons/cm^2*)
- Al and concrete shielding (*10^{10} neutrons/cm^2/s from the stopping target*)

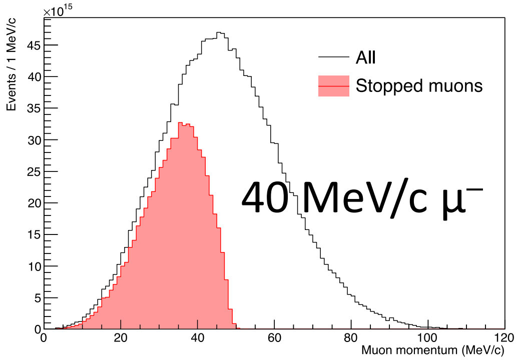


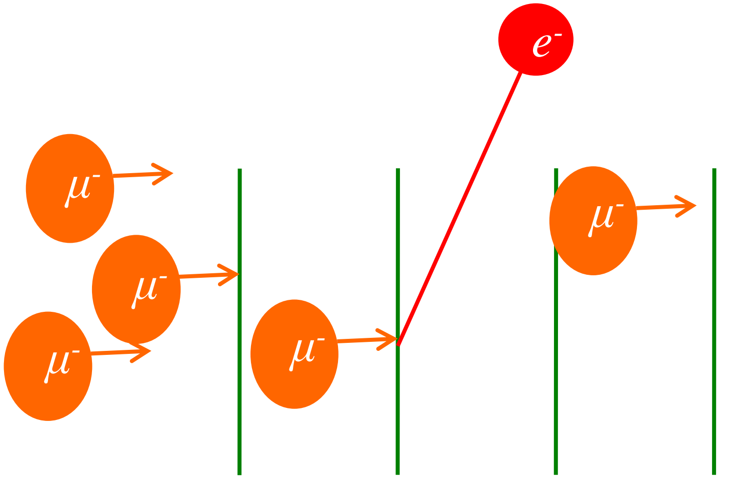
Correlated hits are a concern

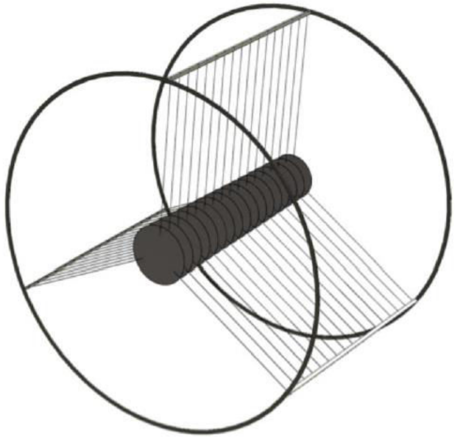




Stopping target



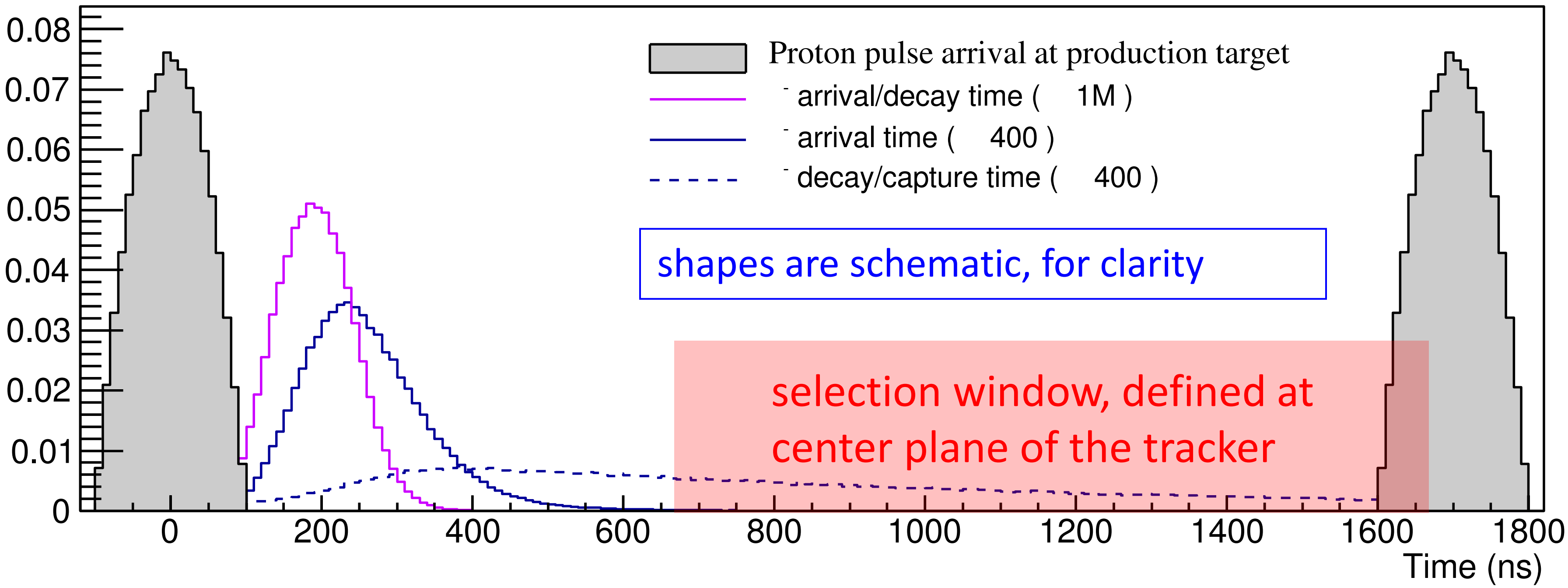




- Pulse of low energy μ^- on thin Al foils
- ~50% are captured to form muonic Al
- ~0.0019 stopped μ^- per proton on production target
- DIO and conversion electrons pop out of target foils

Baseline
- 17 target foils
- each 200 microns thick
- 5 cm spacing
- radius:
  - ~8.3 cm upstream
  - ~6.5 cm downstream
- Optimization is ongoing

One cycle of the muon beamline

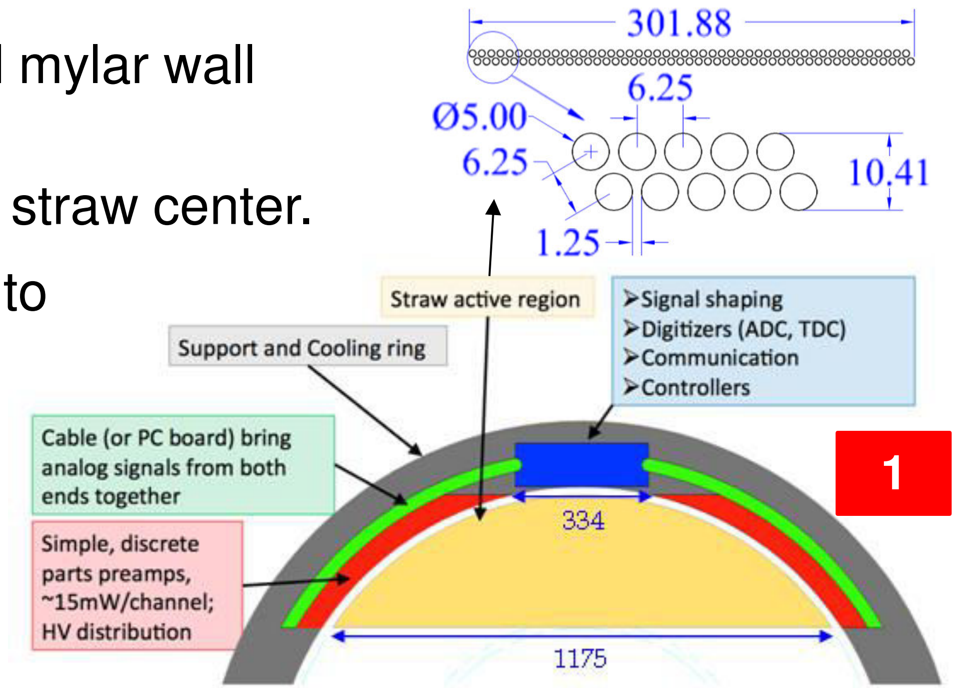


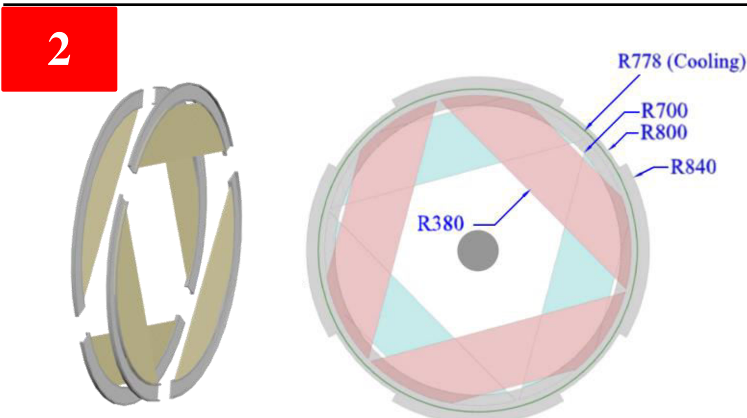
- μ are accompanied by e^-, e^+, π, anti-protons …
  - these create prompt backgrounds
  - strategy: wait for them to decay.
- extinction = (# protons between bunches)/(protons per bunch)
  - requirement: extinction $< 10^{-10}$

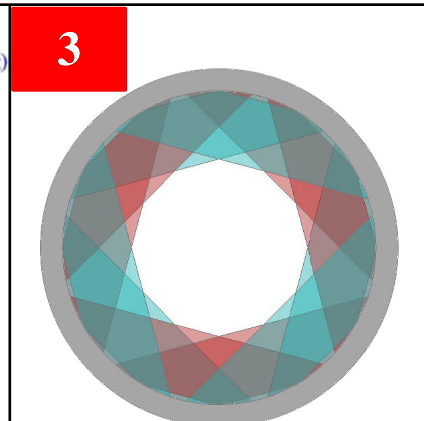
Tracker: strawtubes operating in vacuum

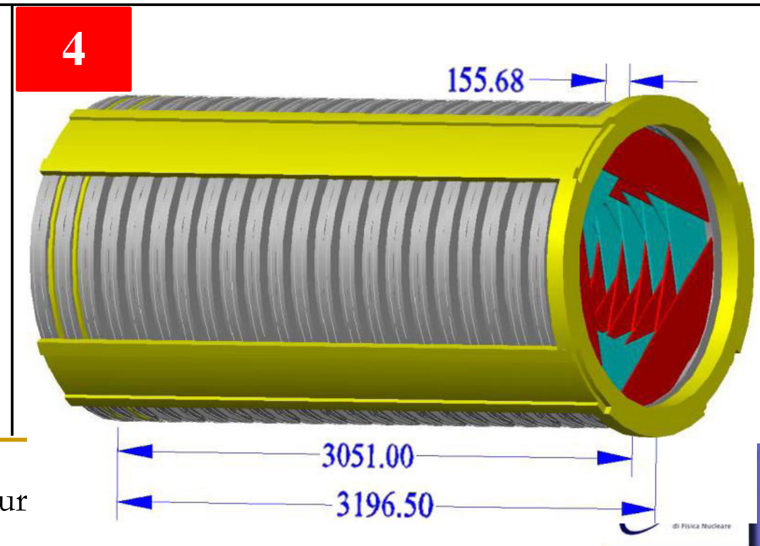
- Straws: 5 mm OD; 15 µm metalized mylar wall (~ 23000).
- Will employ time division: ~5 mm at straw center.

1. 2 layers 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 stations form the tracker.

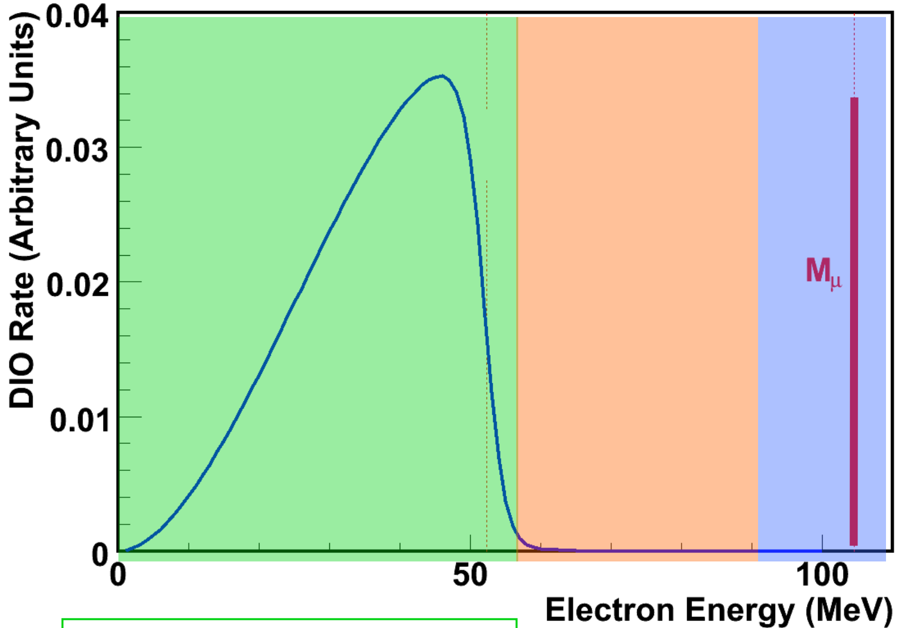








How do you measure 2.5×10^{-17} ?

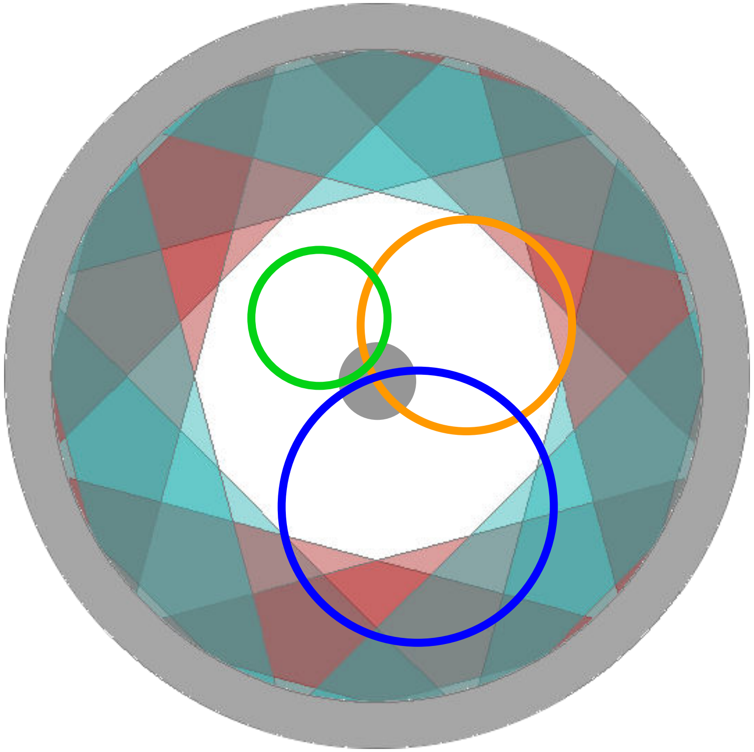


reconstructable tracks

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

no hits in tracker

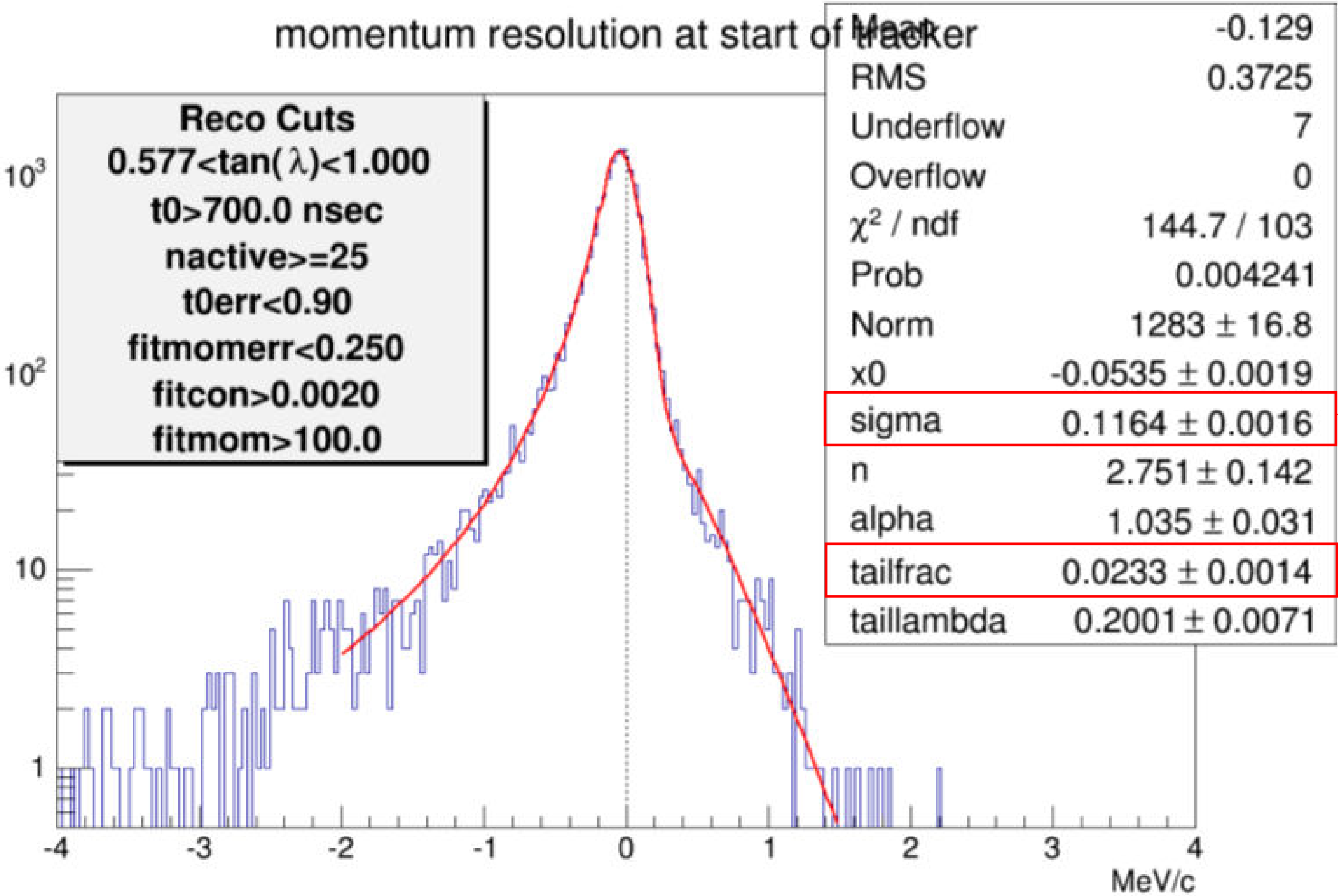
some hits tracker, tracks not reconstructable.



beam's-eye view of the tracker

Tracker performance

Full Geant4 modeling and reconstruction



Reconstructed e^- momentum resolution

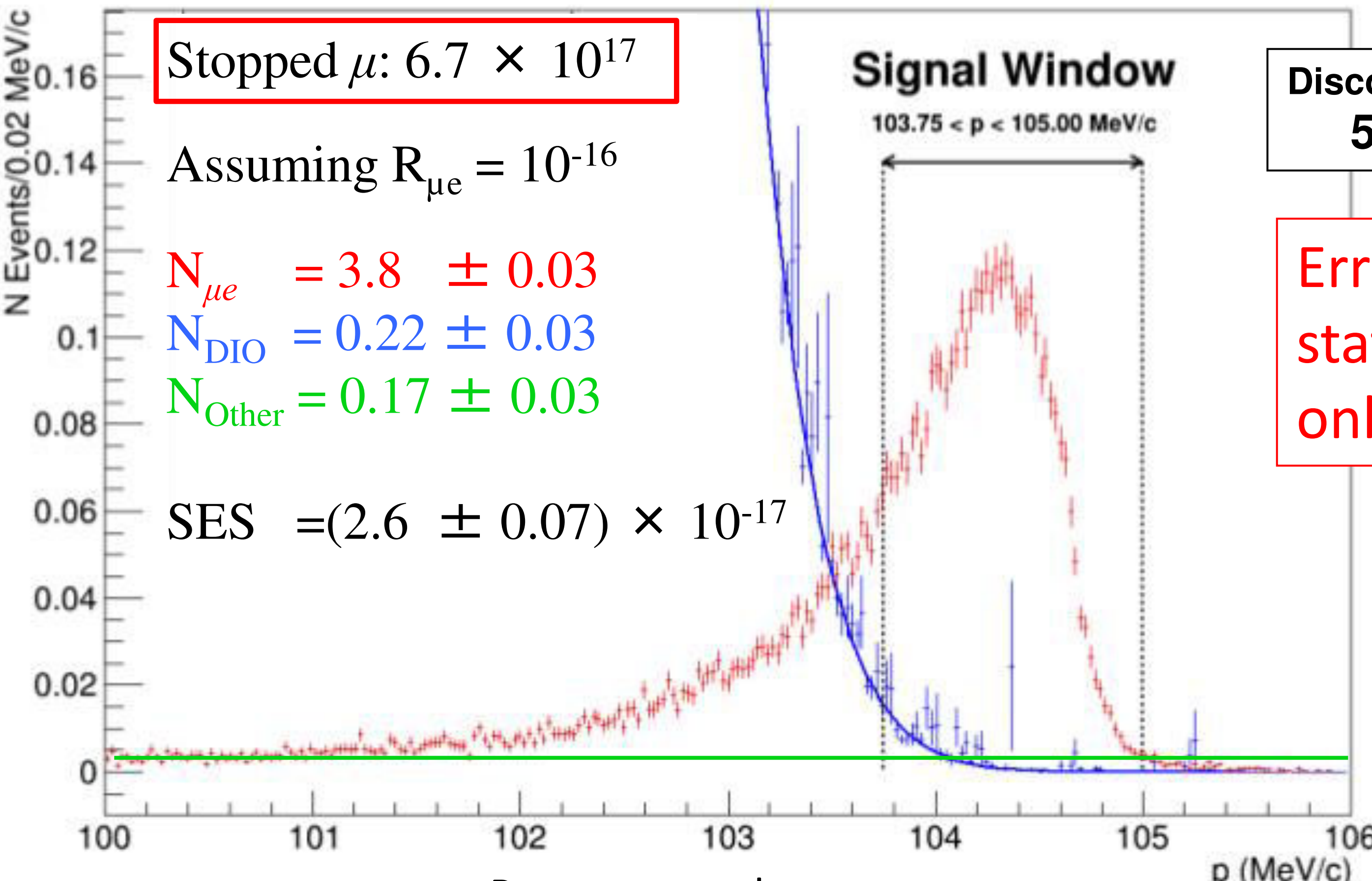
Reconstruction efficiency ~ 95% (in the selection window)

Core resolution ~ 115 keV/c

High side tail ~ 2%

Signal sensitivity for a 3 Year Run

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



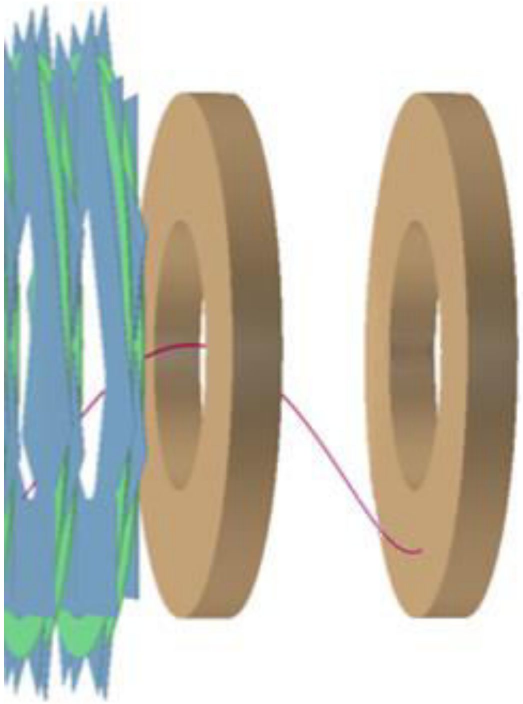
Discovering power
$5\sigma \sim 10^{-16}$

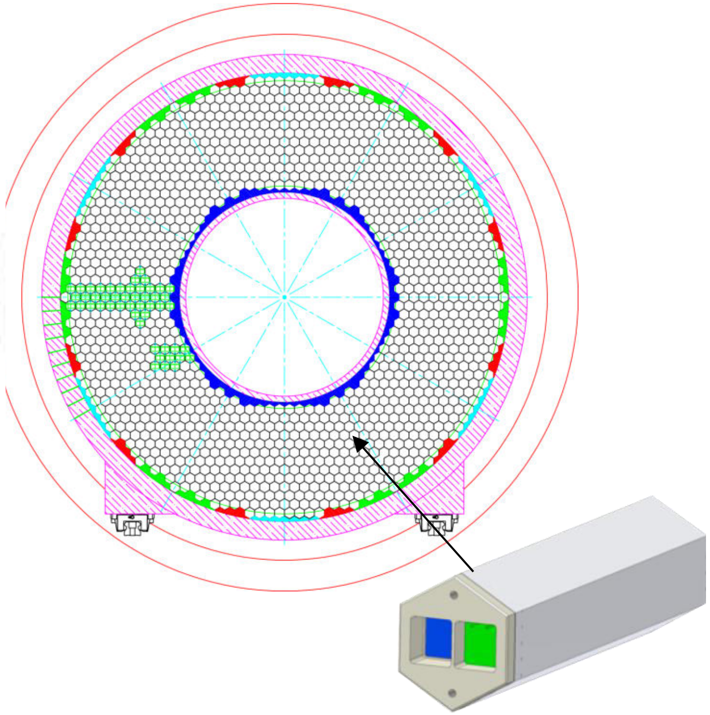
Errors are statistical only

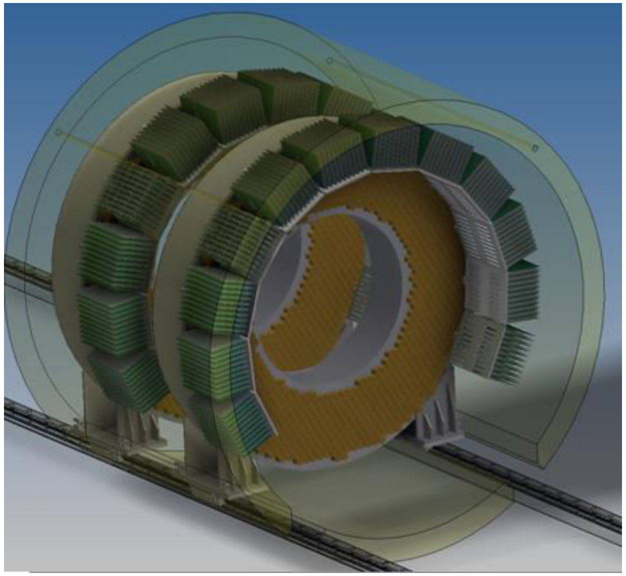
Reconstructed e^- momentum

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

Scintillating crystal calorimeter



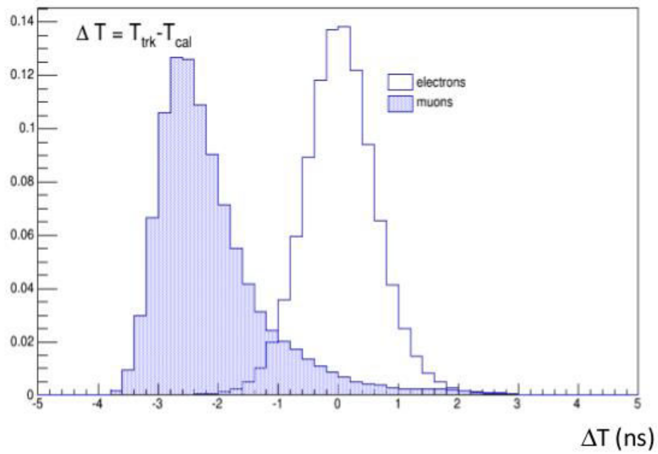


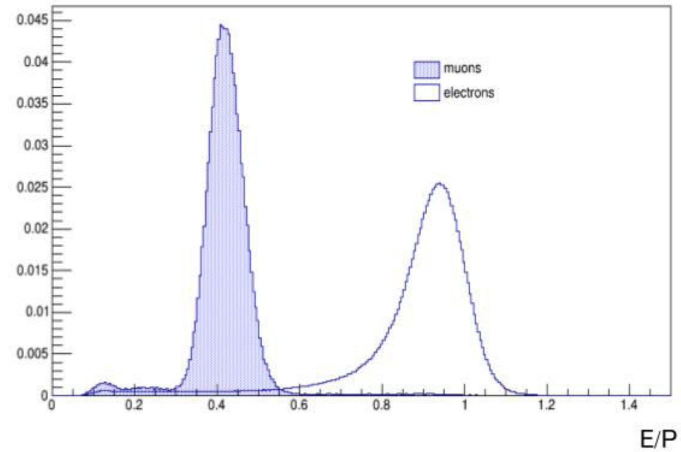


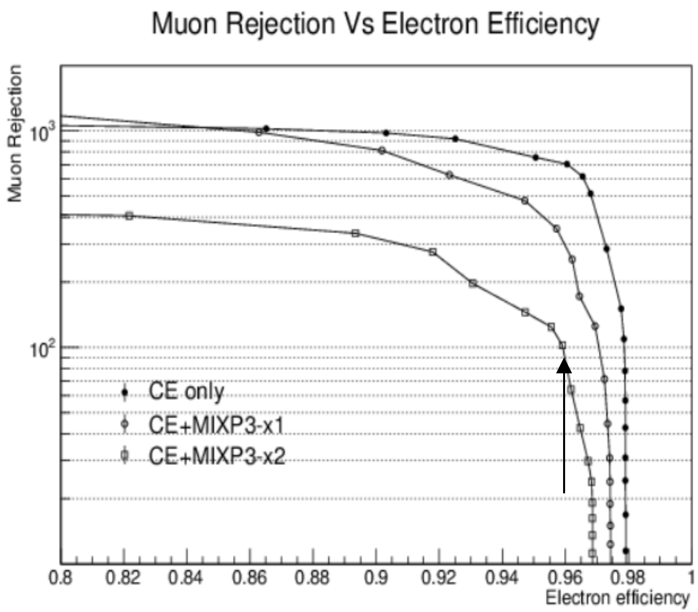
- Two disk geometry (inner radius 351 mm, outer radius 660 mm);
- Hexagonal BaF_2/CsI crystals (33 mm x 180 mm, ~1900); two (10 x 10 mm^2) APD or SiPM readout;
- Provides precise timing (< 1 ns), PID (μ/e), background rejection, alternate track seed and possible calibration trigger.

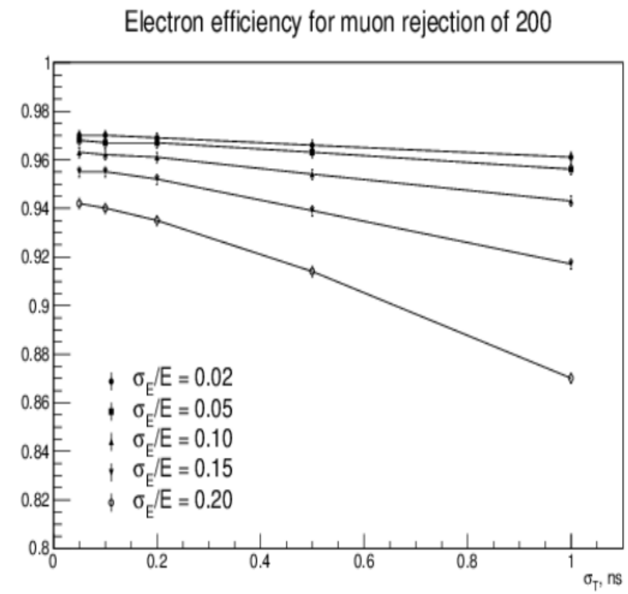
Scintillating crystal calorimeter (PID performance)

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







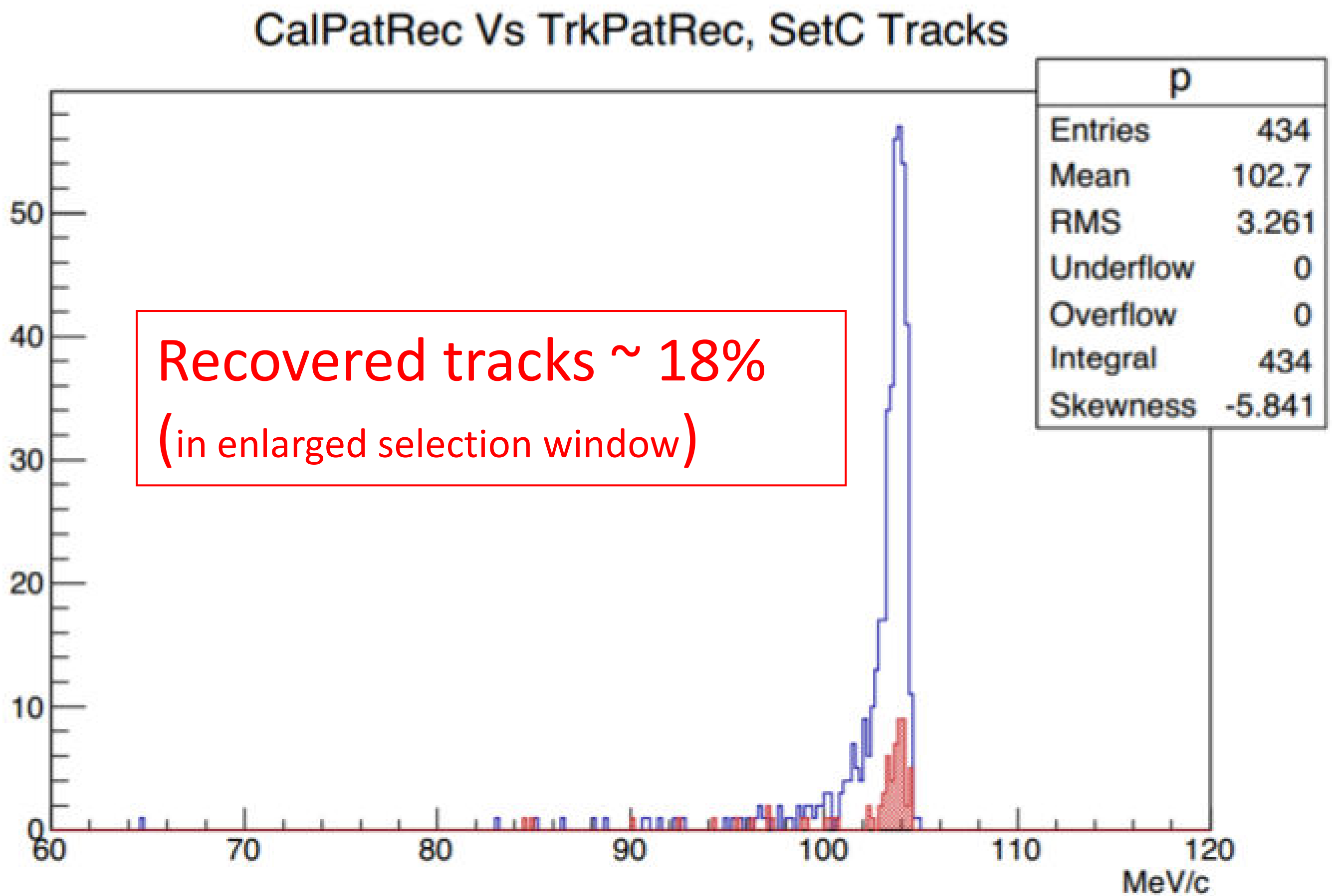


time resolution hypothesis

A rejection factor > 100 with a high CE efficiency >96%

Calorimeter contribution on to track seeding

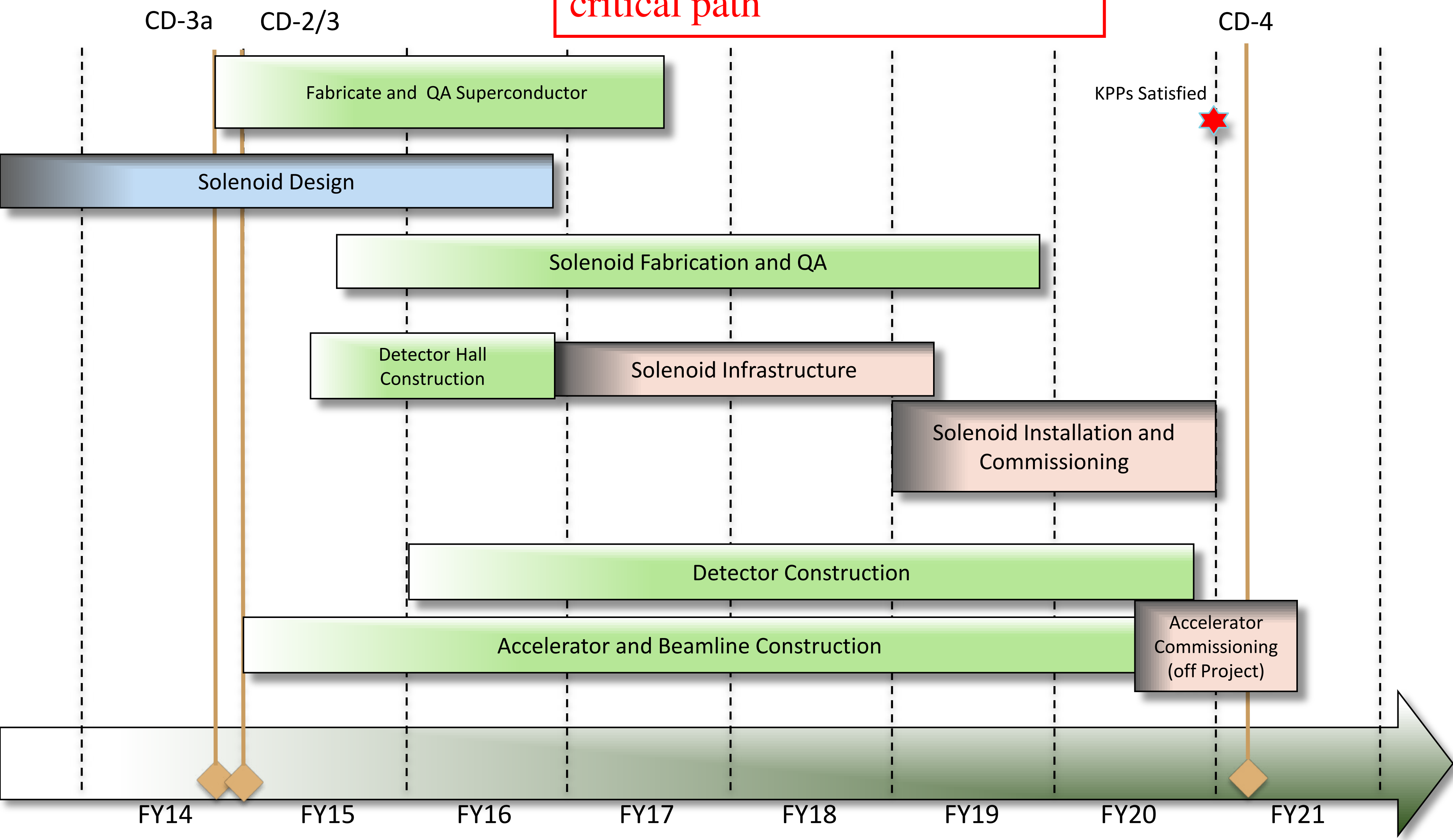
Full Geant4 modeling and reconstruction



Reconstructed *CE* momentum

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 $\mathcal{O}(10^4$ 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.

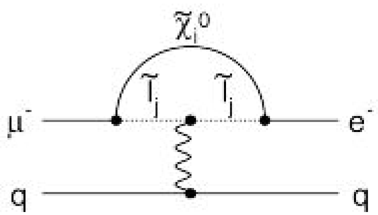
New Physics Scenarios

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

Magnetic moment operator

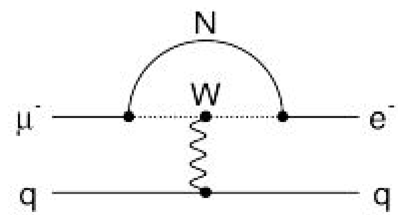
Supersymmetry

rate ~ 10^{-15}



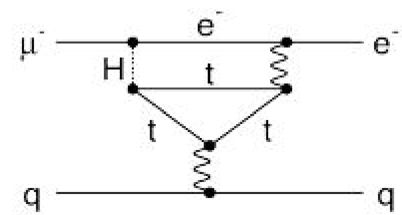
Heavy Neutrinos

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



Two Higgs Doublets

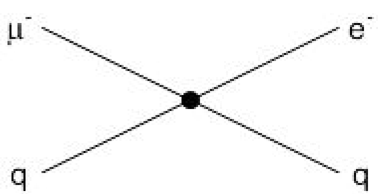
$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Contact term operator

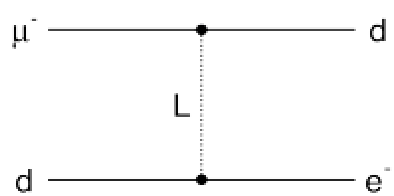
Compositeness

$\Lambda_c \sim 3000$ TeV



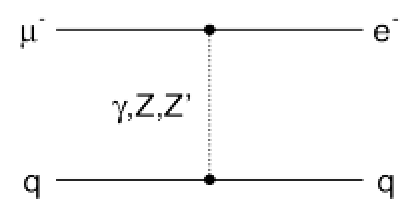
Leptoquarks

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



Heavy Z'

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



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

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

Backgrounds for a 3 Year Run

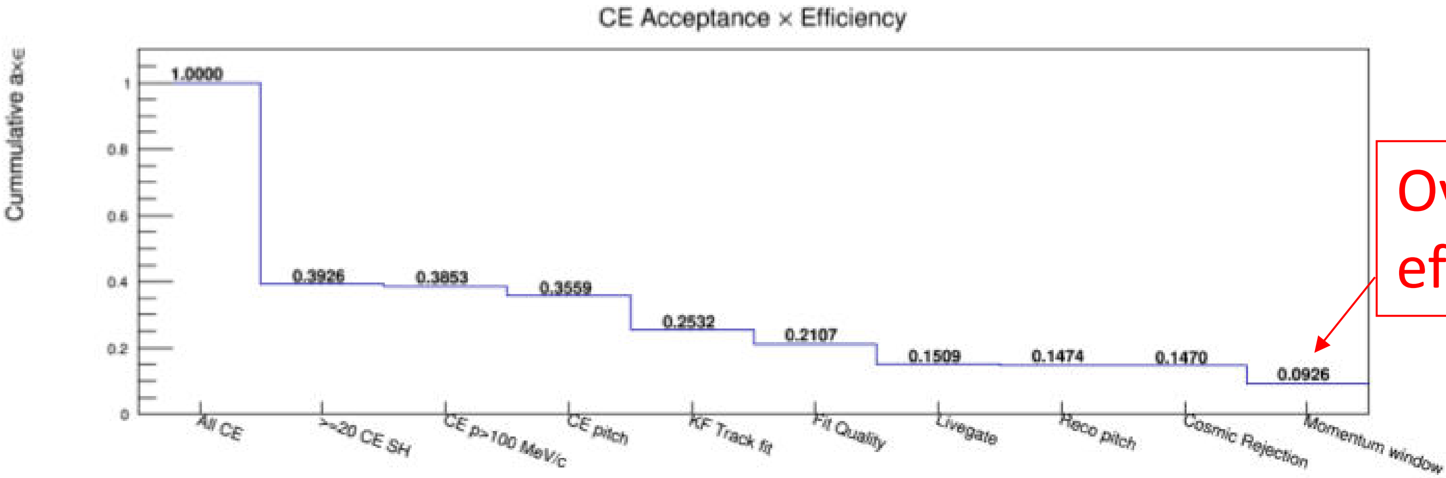
Source	Events	Comment
	0.20 ± 0.06	
Anti-proton capture	0.10 ± 0.06	
Radiative π- capture*	0.04 ± 0.02	from protons during detection time
Beam electrons*	0.001 ± 0.001	
μ decay in flight*	0.010 ± 0.005	with e- scatter in target
Cosmic ray induced	0.050 ± 0.013	assumes 10-4 veto inefficiency
Total	0.4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

All values preliminary; some are statistical error only.

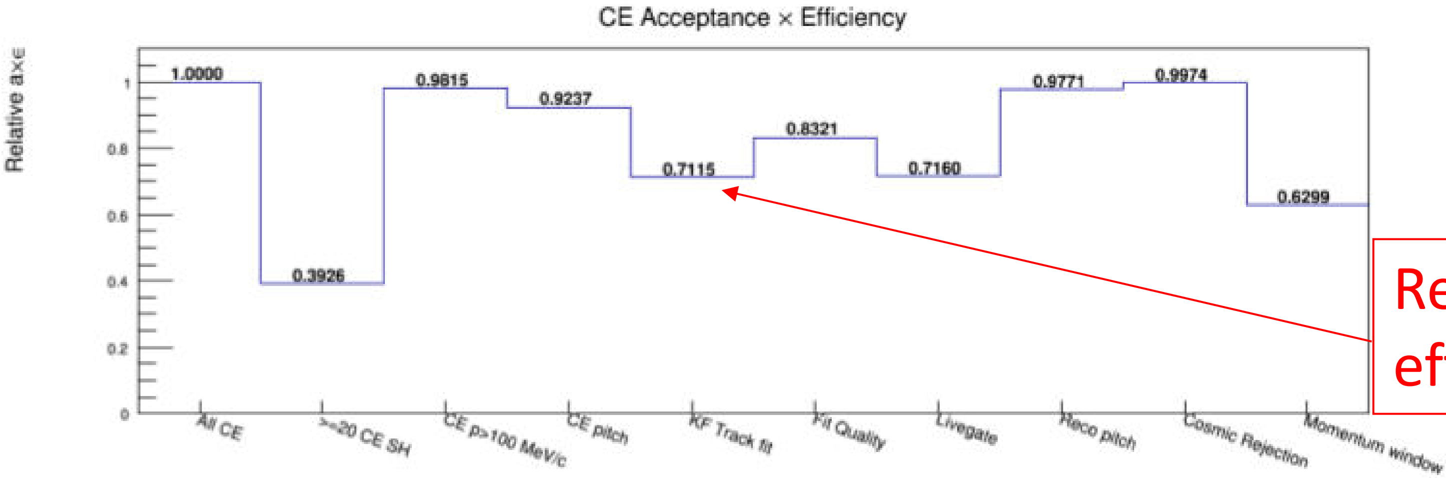
* scales with extinction: values in table assume extinction = 10^{-10}

Tracker performance

Full Geant4 modeling and reconstruction



Overall CE efficiency ~ 10%



Reconstruction efficiency ~ 70%

Calorimeter crystal history

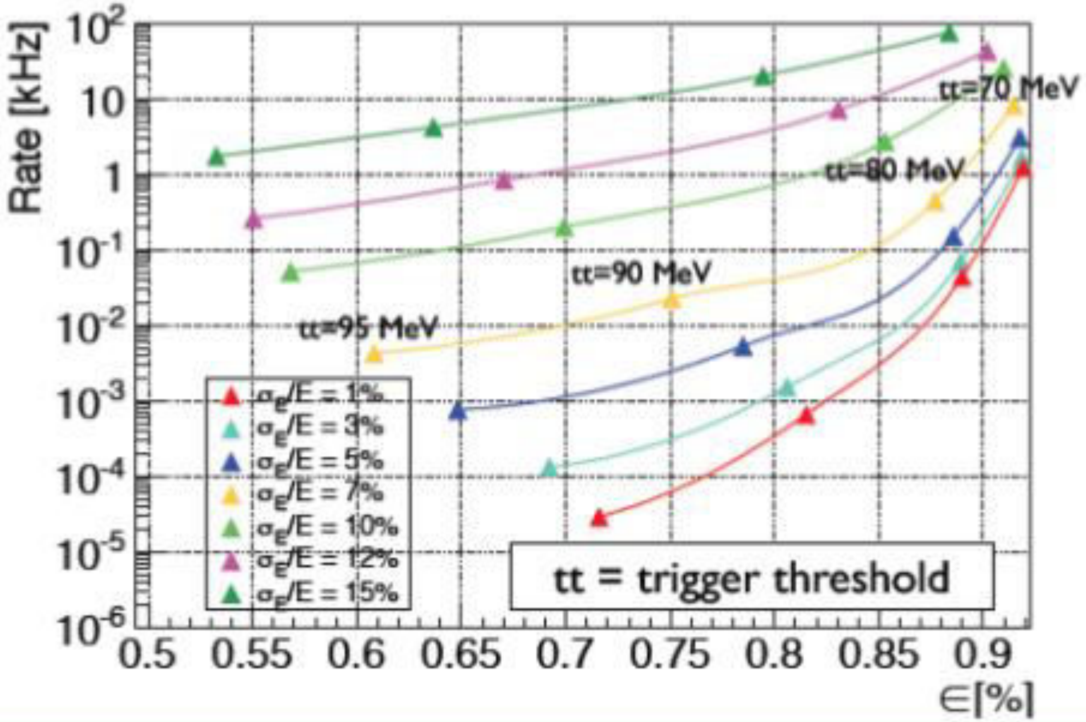
- Initial choice PbWO4: small X0, low light yield, low temperature operation, temperature and rate dependence of light output
- CDR choice LYSO: small X0, high light yield, expensive (→very expensive)
- TDR choice: BaF2: larger X0, lower light yield (in the UV), very fast component at 220 nm, readout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

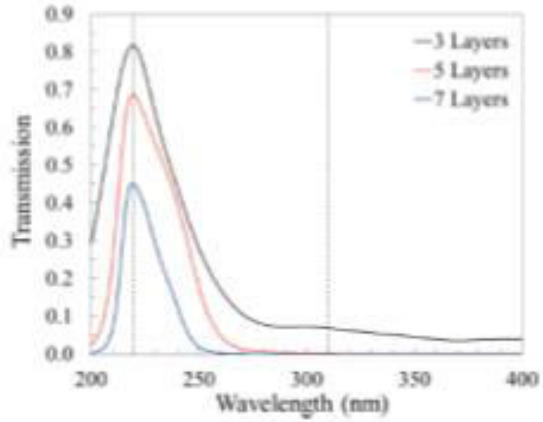
Crystal and photosensor alternatives

BaF2 presents several advantages:

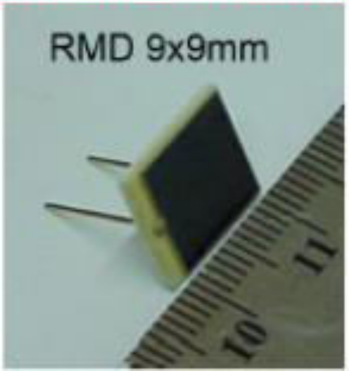
- ✓ **Small decay time**
- ✓ **Non-hygroscopic**
- ✓ **Rad hard**

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
Molière radius (cm) Rm	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

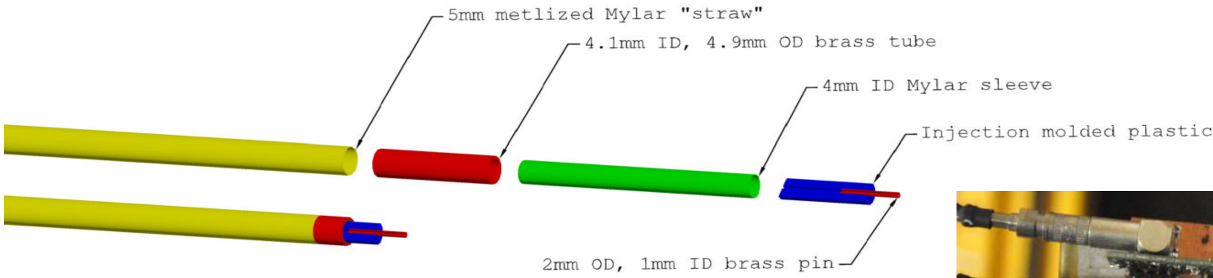
- ✓ 60% QE @ 200 nm (wa
- ✓ ~0.1% QE @ 300 nm
- ✓ capacitance ~ 60 pF
- ✓ operation gain ~ 500

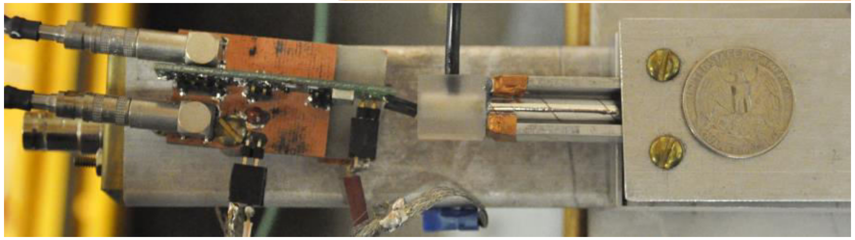


deltadoped APD from RMD



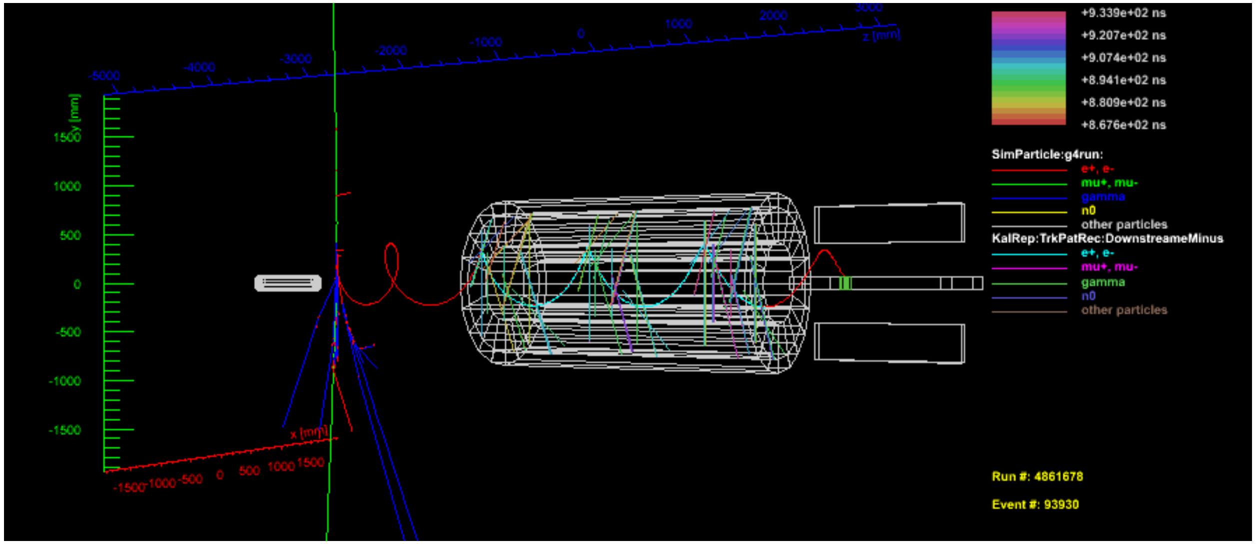
Straw tubes

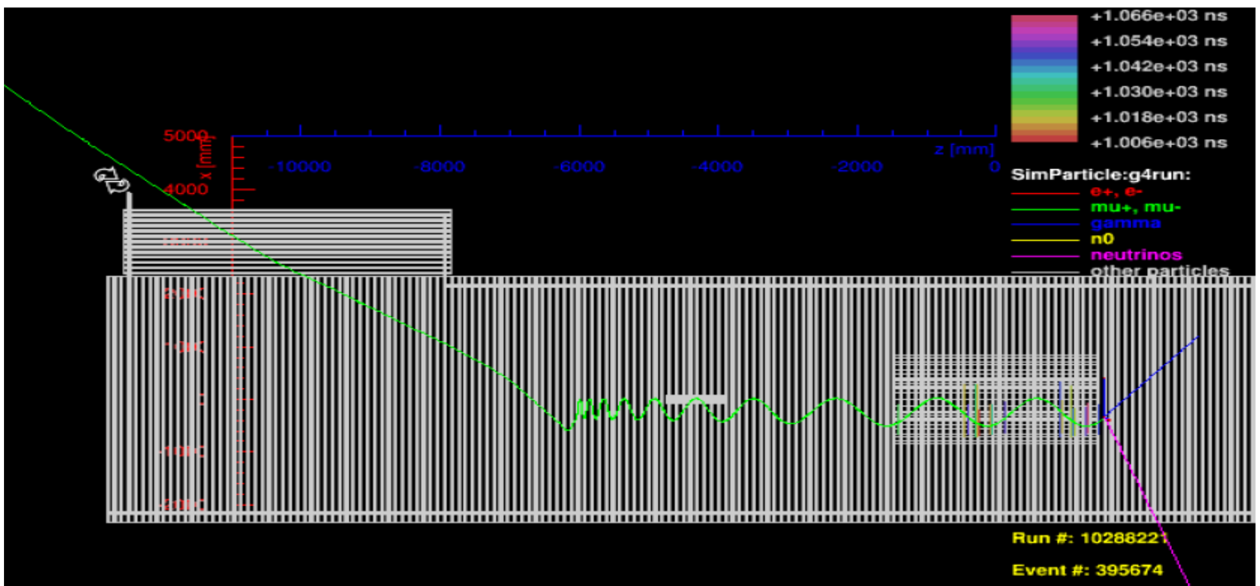




- 5 mm diameter;
- wall thickness of 15 µm:
  - two layers of ~6 µm (25 gauge) Mylar®, spiral wound, with a ~3 µm layer of adhesive between layers. The inner surface has 500 Å aluminum overlaid with 200 Å gold as the cathode layer. The outer surface has 500 Å of aluminum to act as additional electrostatic 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:CO_2 with an operating voltage of ~1500 V, with maximum drift time of ~50 ns and gain of ~$3*10^4$.

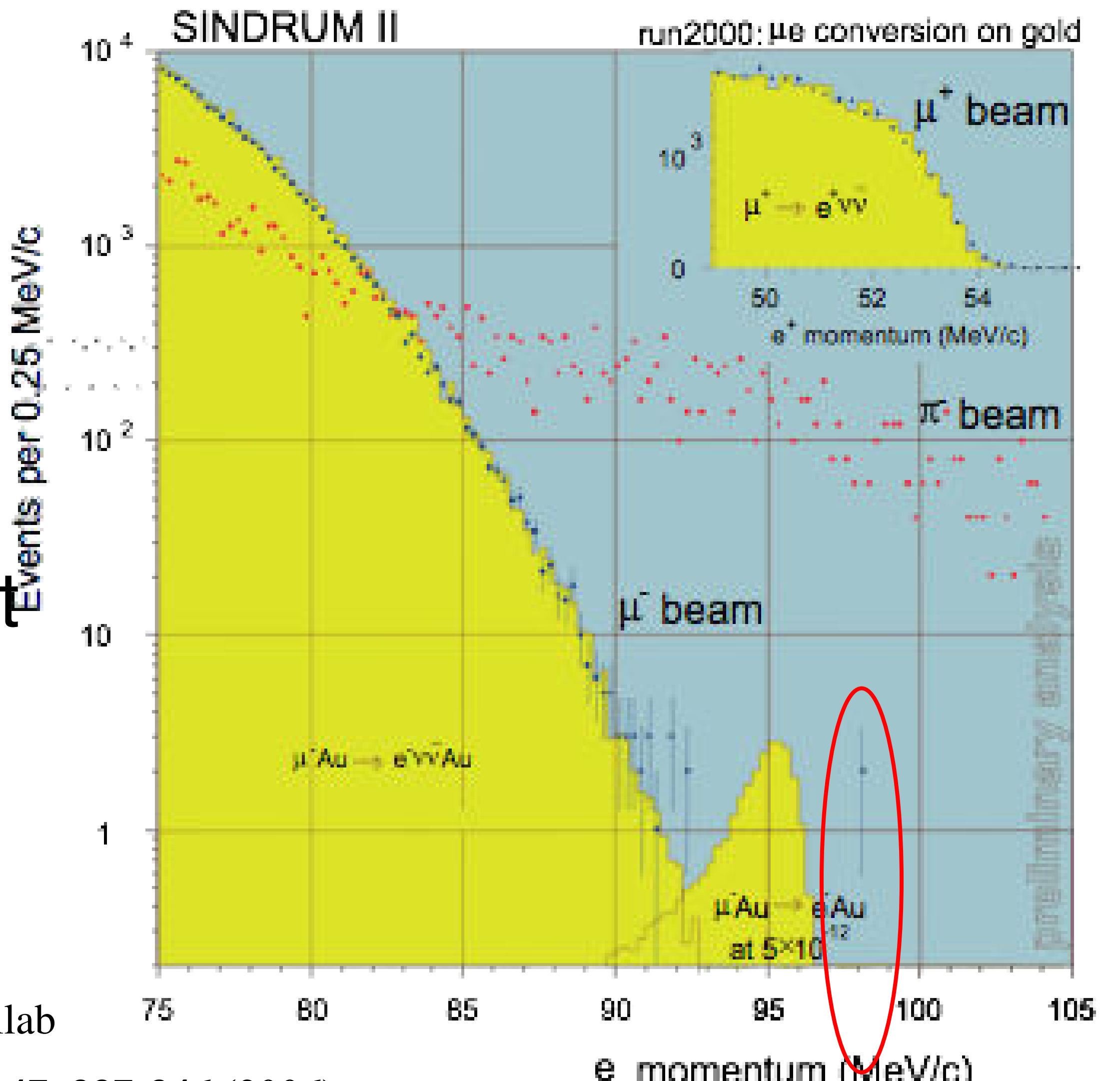
Two example of background from cosmic ray





The previous best experiment

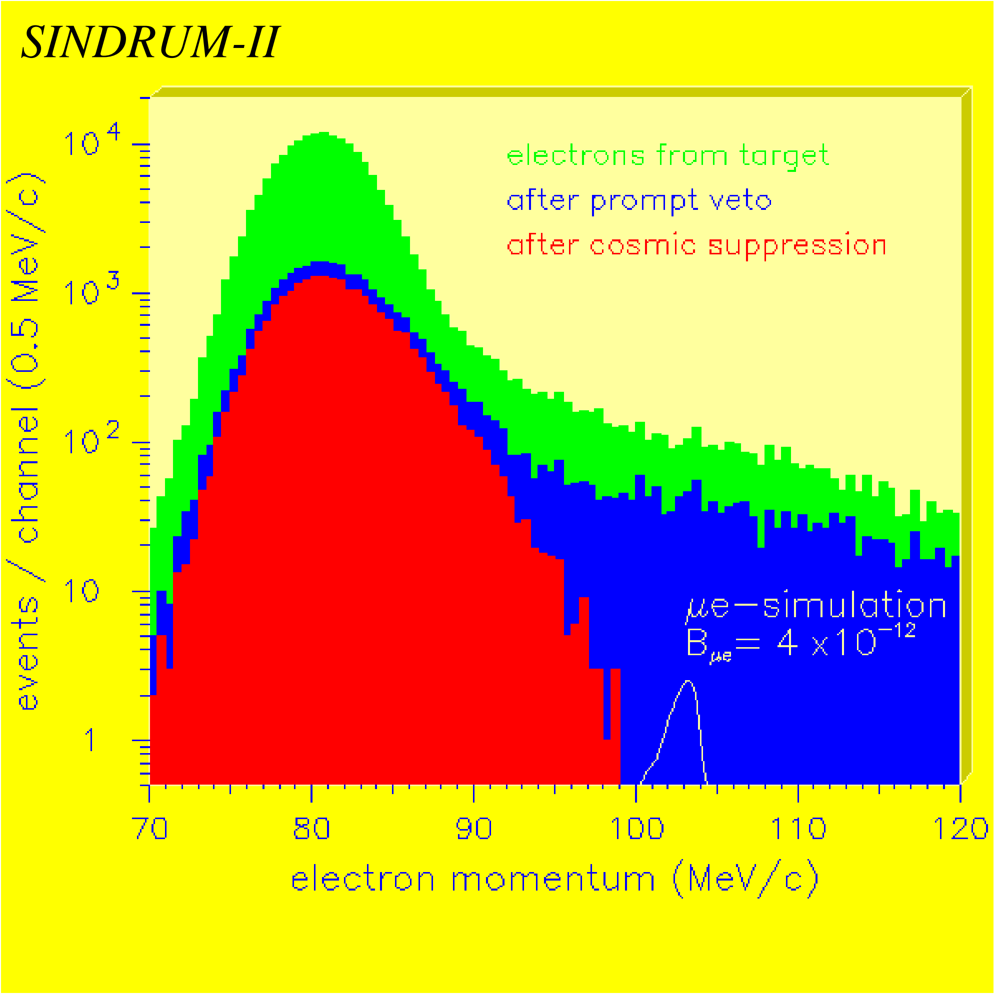
- SINDRUM II
- $R_{\mu e} < 6.1 \times 10^{-13}$ @90% CL
- 2 events in signal region
- Au target: different E_e endpoint than Al.



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

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

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

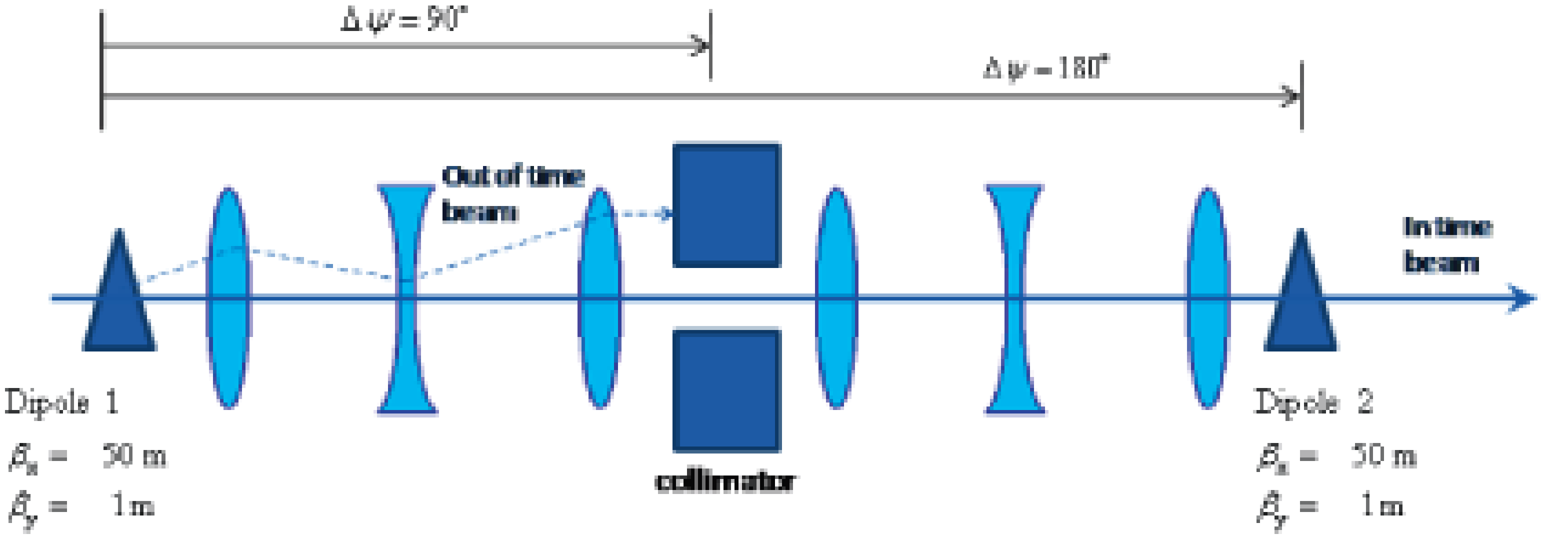
$R_{\mu e}$(Au) < 7X10^{-13}
Eur. Phys. J. , C47 (2006)

Why is mu2e more sensitive than SINDRUM II?

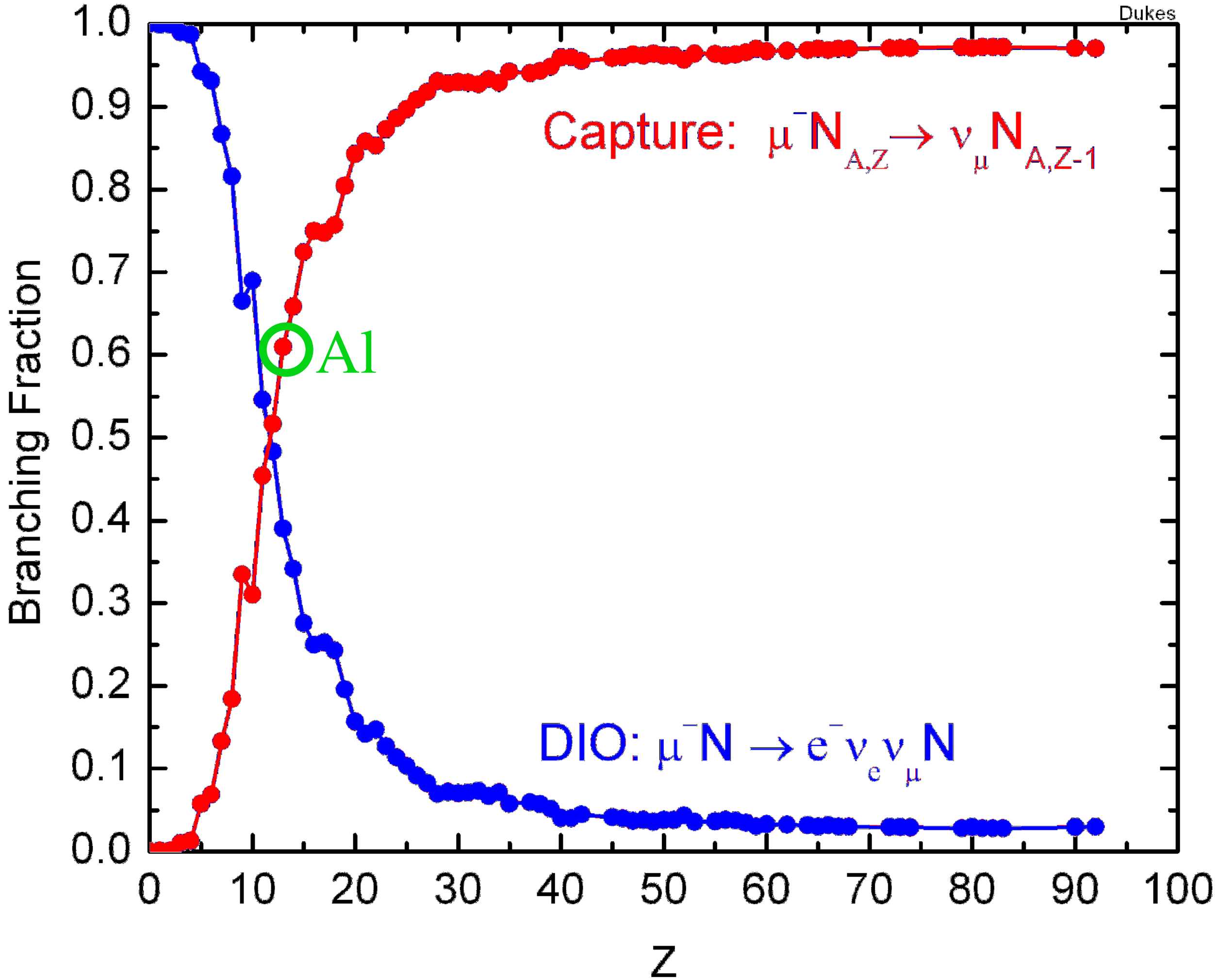
- FNAL can deliver ~10^3 × proton intensity.
- Higher μ collection efficiency.
- SINDRUM II was background-limited.
  - Radiative π capture.
  - Bunched beam and excellent extinction reduce this.
  - Thus mu2e can make use of the higher proton rate.

Required Extinction 10^{-10}

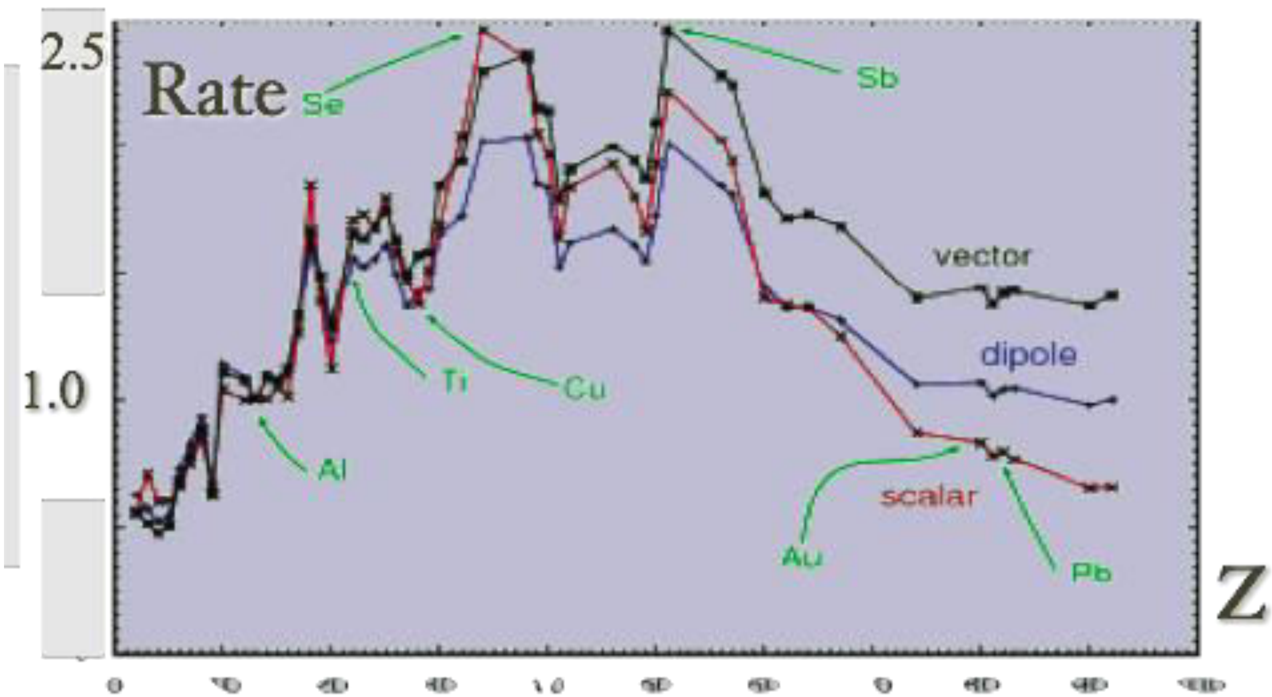
- Internal: 10^{-7} already demonstrated at AGS.
  - Without using all of the tricks.
- External: in transfer-line between ring and production target.
  - AC dipole magnets and collimators.
- Simulations predict aggregate 10-12 is achievable
- Extinction monitoring systems have been designed.



Capture and DIO *vs* Z

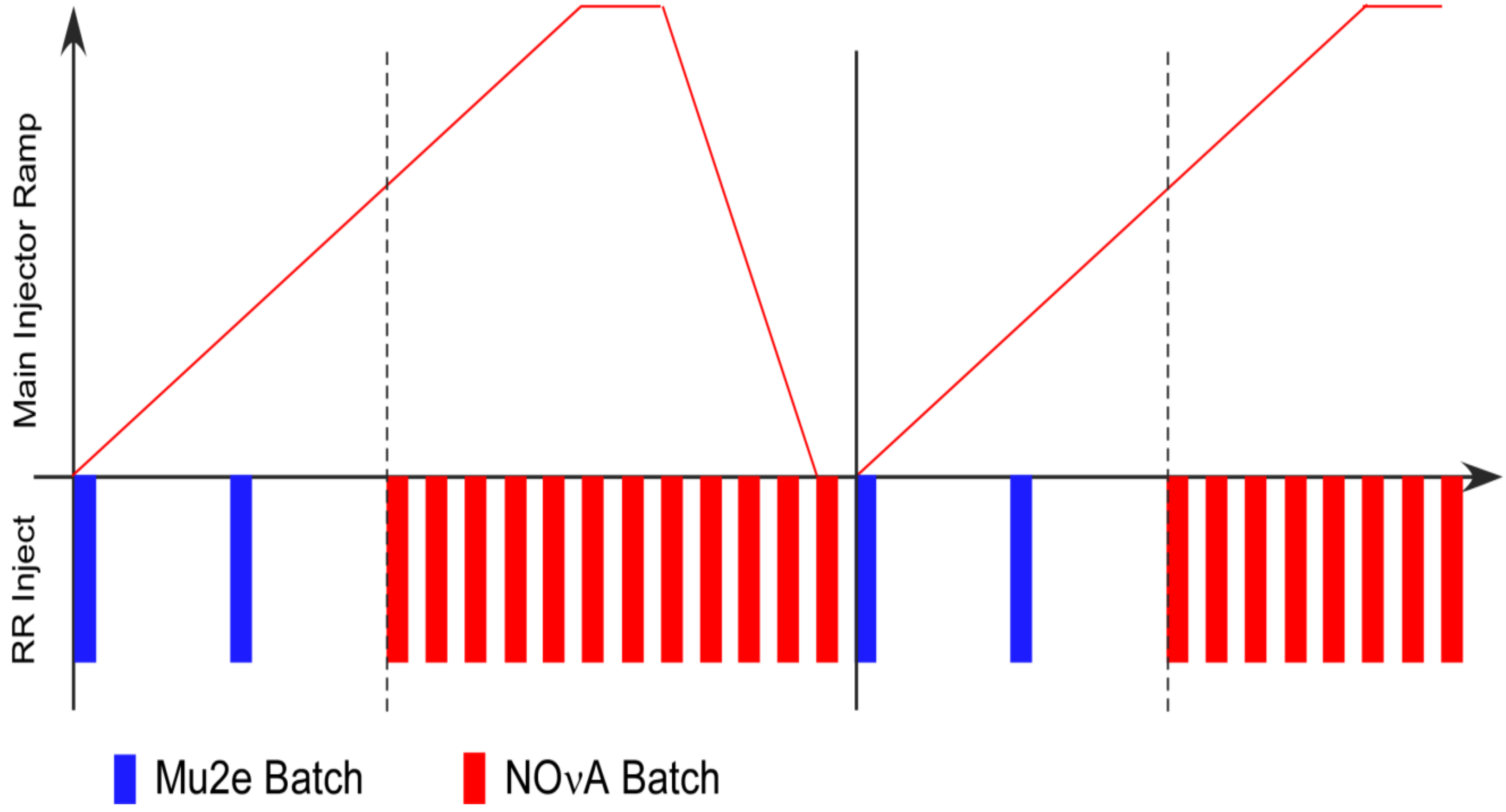


Conversion Rate, Normalized to Al

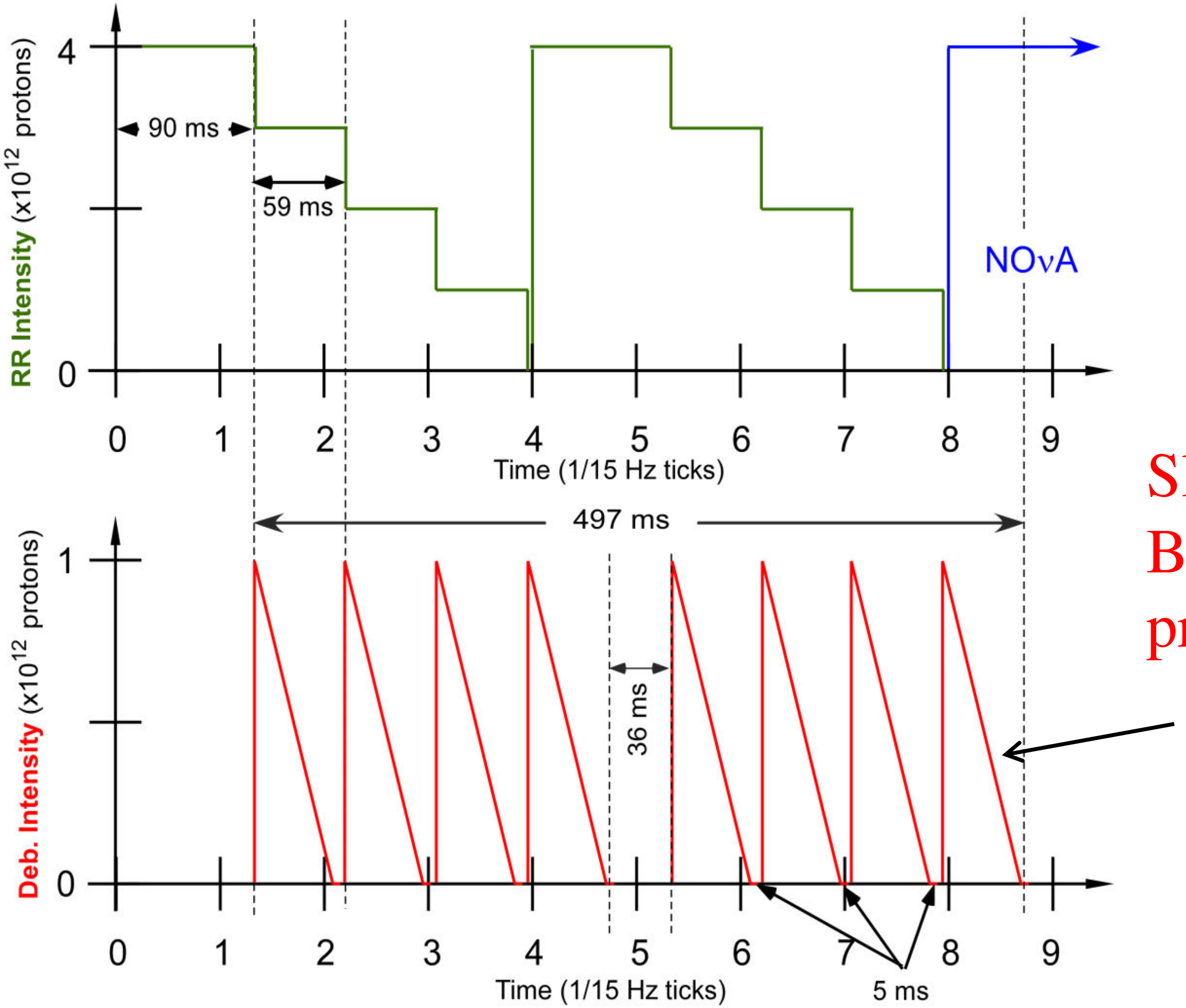


Kitano, et al., PRD 66, 096002 (2002)

Proton Beam Macro Structure



Proton Beam Micro Structure



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

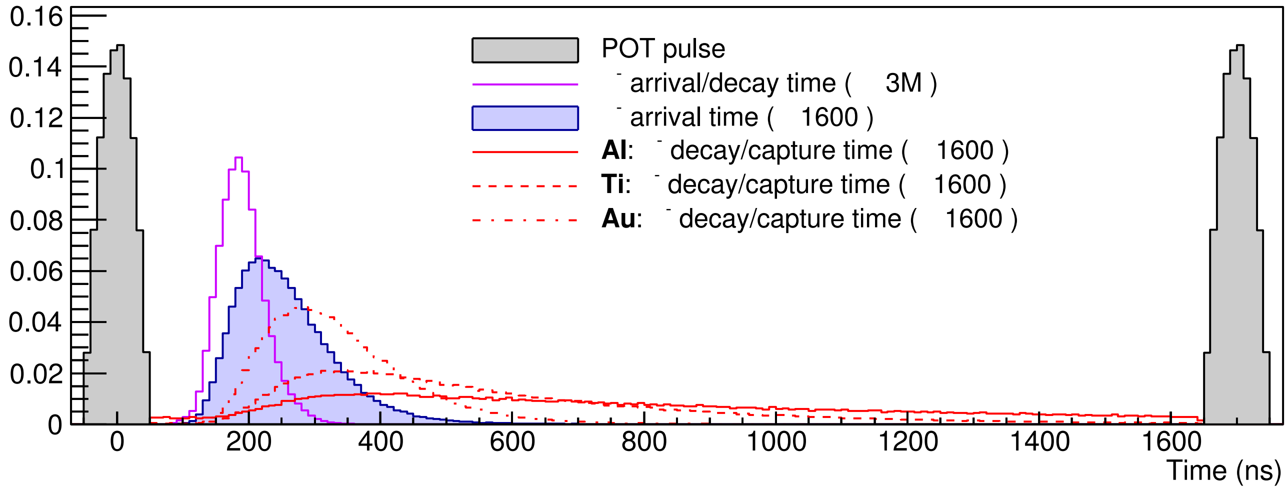
FNAL accelerator complex

- 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 $\times$ 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 × Mu2e physics reach, $R_{\mu e} < 10^{-18}$.
  - First factor of ~10 can use the same detector.