Mu2e Experimental Issues affected by Slow Extraction Variations

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Slow Extraction Workshop

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Basic Problem

More Data!

Less Useful Data

- Finding a balance

Overall Issues for practically any fixed-target experiment

- Relative Importance varies across time scales and any given experiment, but for example:
  - tracker momentum reconstruction degrades from confusion: pile-up leads to tossing tracks
  - extra energy in calorimeter making cluster finding difficult and increases noise terms in resolution function; gain can fluctuate with intensity variations, which is very hard to undo in analysis
  - matching tracker to calorimeter (or any subsystem to any other subsystem)
  - particle ID
  - veto systems lead to unacceptable losses
  - combinatorial background
  - DAQ, front-end electronics, and trigger: bandwidths (or single-event upsets)

Implying More Measurements

- Spill uniformity has to be monitored carefully
  - and there can be multiple time scales even within one detector system
    - for example, calorimeter has ps timing of start of shower; ns for matching to tracker; μs for trigger/DAQ

What is μe Conversion?

muon converts to electron in the field of a nucleus

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

does not change

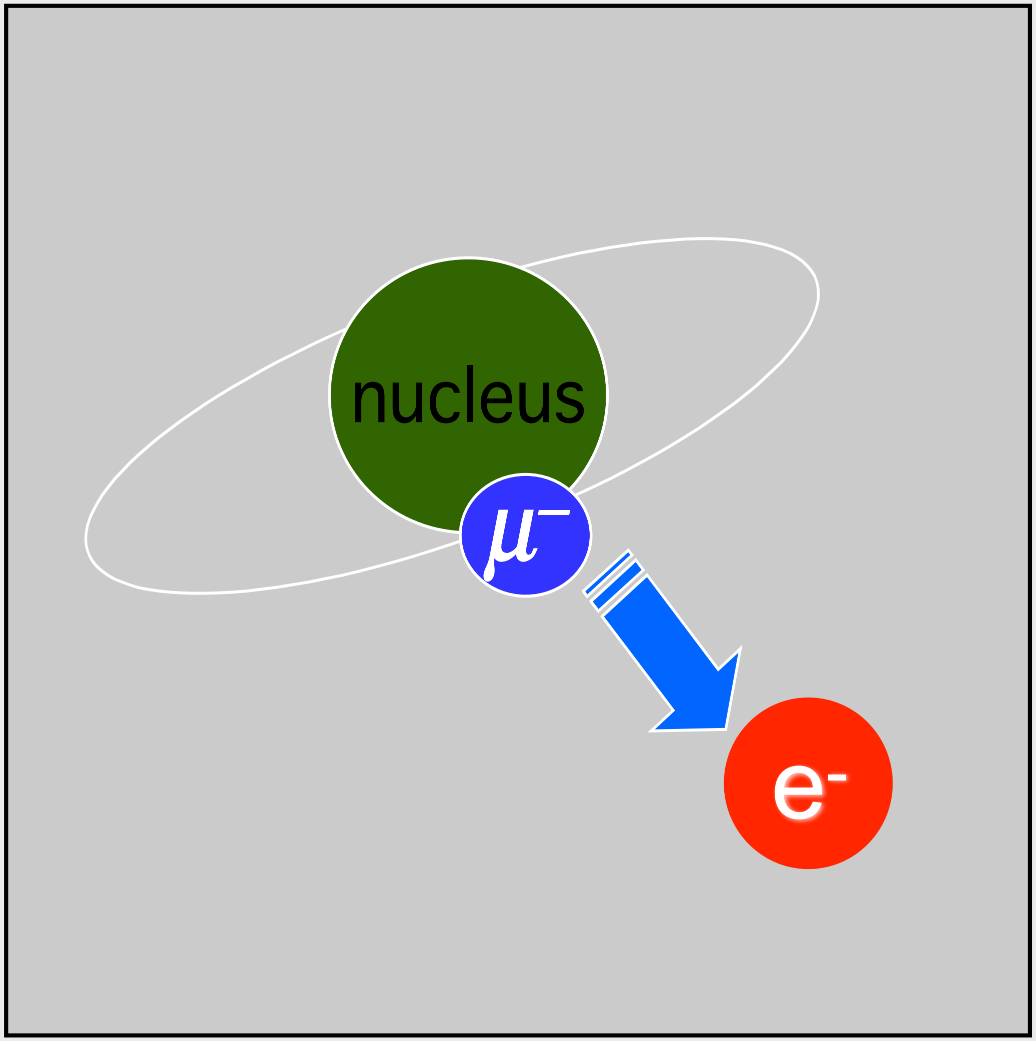
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

- Standard Model Background of 10^{-54}
- Charged Lepton Flavor Violation (CLFV)
  - can measure a signal with SES of ~ 3×10^{-17}
- Related Processes: μ or $\tau \rightarrow e\gamma$, $\tau \rightarrow 3l$, $K_L \rightarrow \mu e$, and more

Experimental Signal

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

- A Single Monoenergetic Electron
- If N = Al, E_e = 105. MeV
    - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup

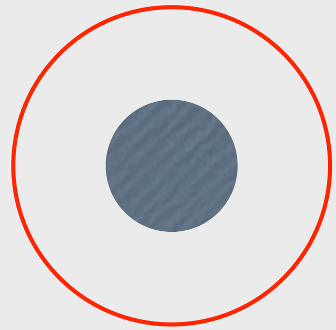


Overview Of Processes

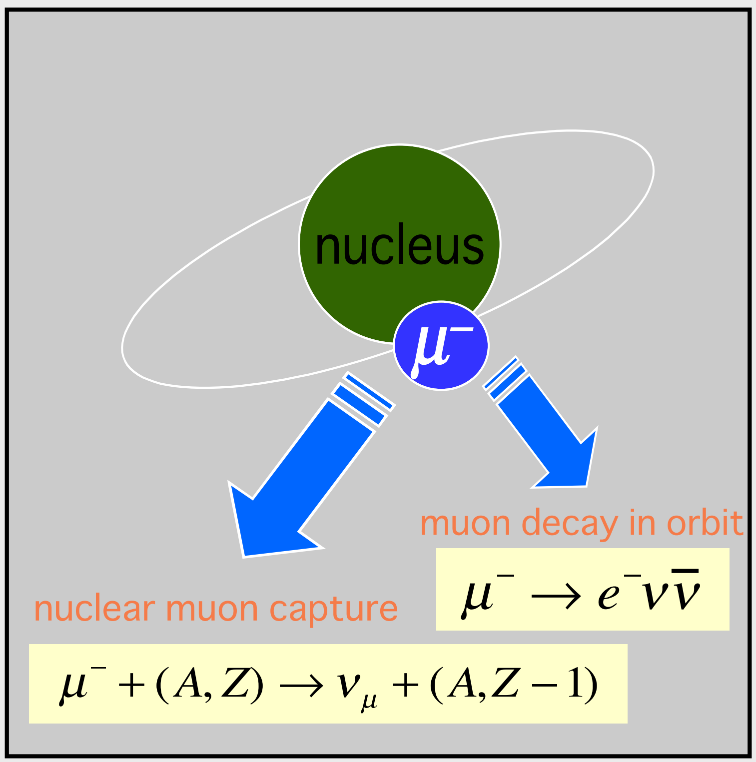
μ^- stops in thin Al foil

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

μ^- in 1s state



Al Nucleus
~4 fm



60% capture
40% decay

muon capture,
muon "falls into"
nucleus:
normalization

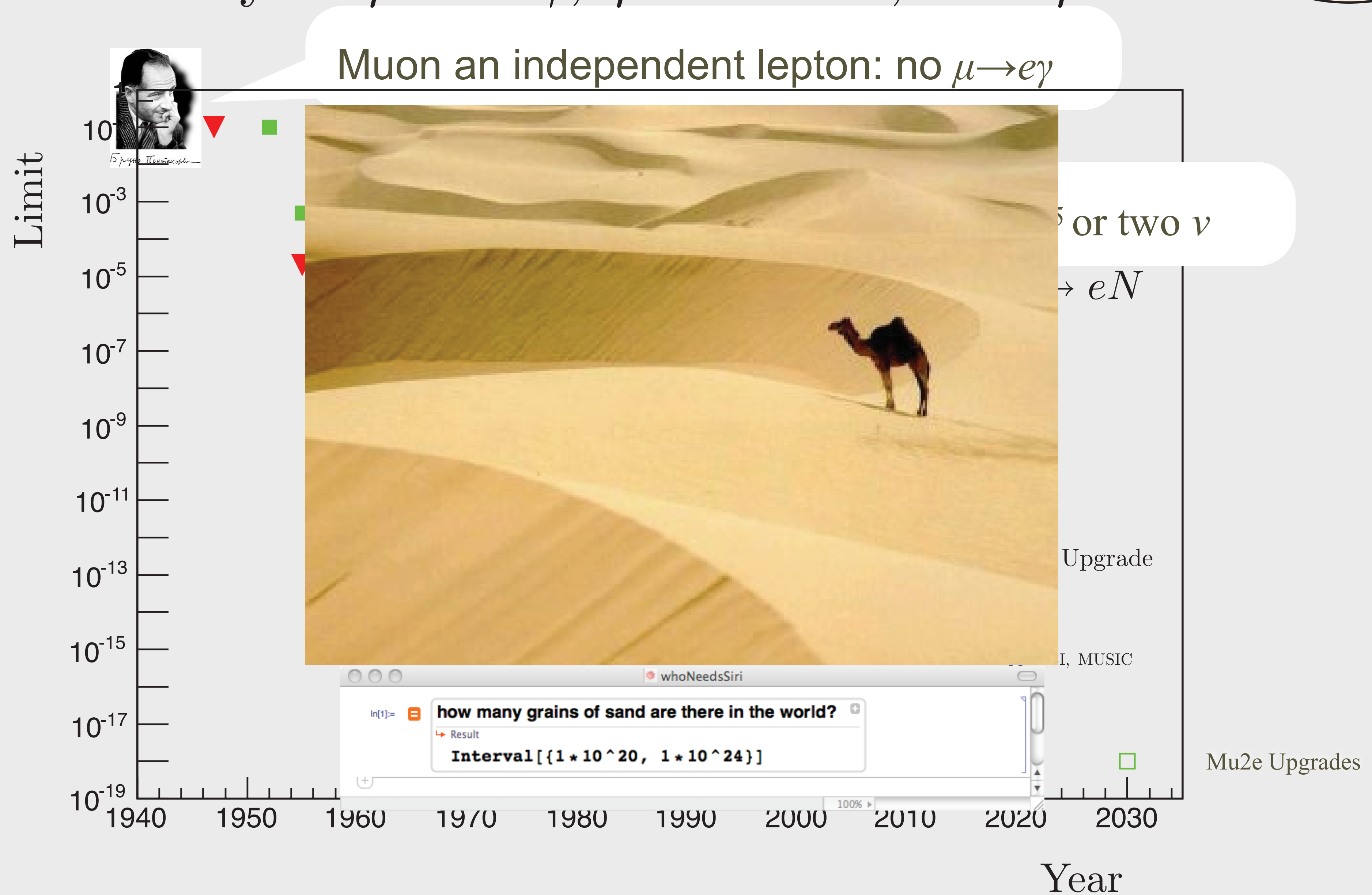
Decay in Orbit:
background

Mu2e In a Sound Bite

—Roni Harnik

- Why are there flavors?
- Why is there more than one generation, and always three!

History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



RHB and P.S. Cooper, Phys Rept C (1307.5787)

How Rare is That?

- Pretty Rare: let us know if this happens to you!

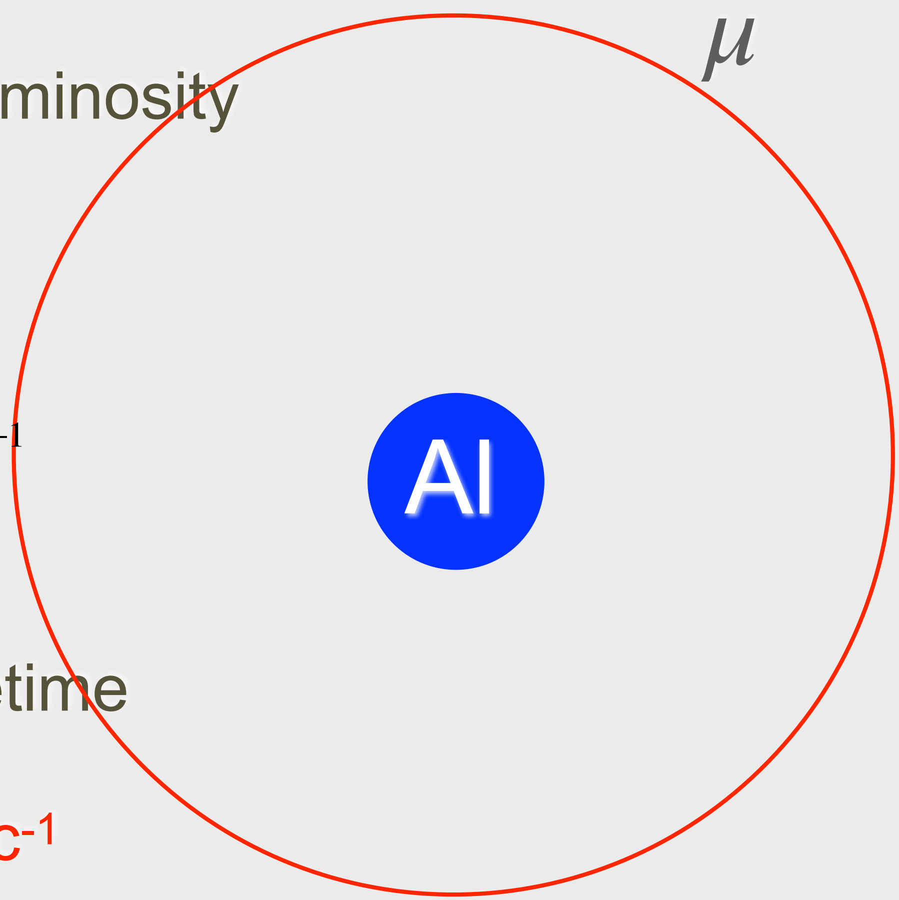
Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

thanks to Eric Prebys

Measuring 10^{-17}

- The captured muon is in a 1s state and the wave function overlaps the nucleus (*picture ~ to scale*)
- We can turn this into an effective luminosity
- Luminosity = density x velocity

$$|\psi(0)|^2 \times \alpha Z = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} = 8\times 10^{43}\,\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$$



- Times 10^{10} muons/sec X 2 μsec lifetime
- Effective Luminosity of 10^{48} cm^{-2}sec^{-1}

Mu2e Specific: How Does this work in one experiment

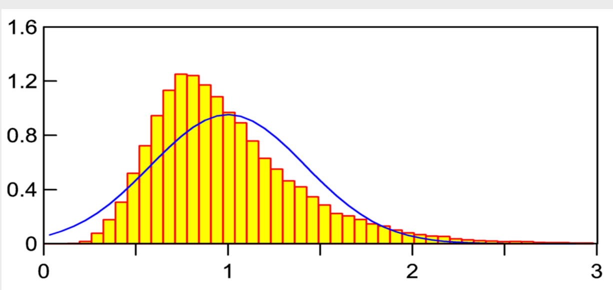
- We see all of these effects but I will focus on just a couple
- Mu2e is "primarily" concerned with backgrounds for this discussion:
  - we need to have our vetoes as close to 100% live as possible
  - we don't want "fake hits" or accidental activity causing track misreconstuction and large tails on resolution
  - and of course we want as high an efficiency as possible. Too-intense spills lead to loss of data.

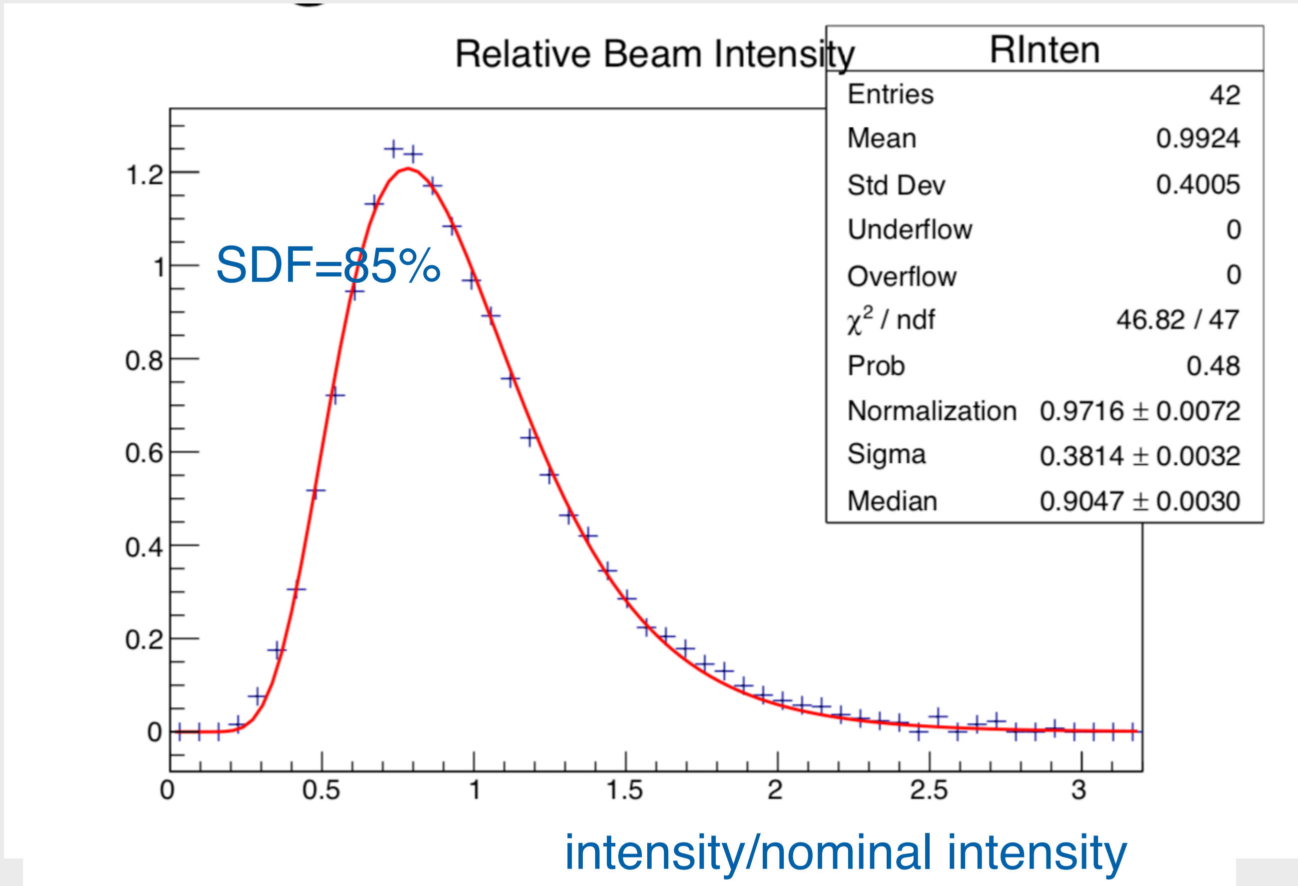
Modeling Intensity Variations

- We have the fitted distribution in our simulations. We did most of the simulations with a +- 50% variation. We recently went to the model below but can change it and test the result (in progress)

$$\mathrm{SDF} = \frac{1}{1 + \left(\frac{\sigma_I}{I}\right)^2}$$

this is from Protvino
https://indico.gsi.de/event/4496/



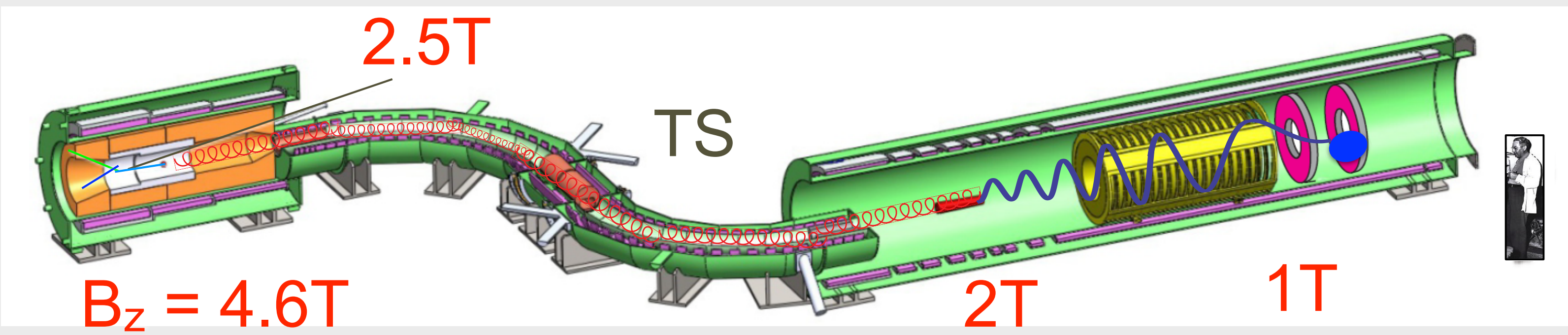


we have no special reason to think we will do this well

Mu2e Muon Beam: Three Solenoids and Gradient

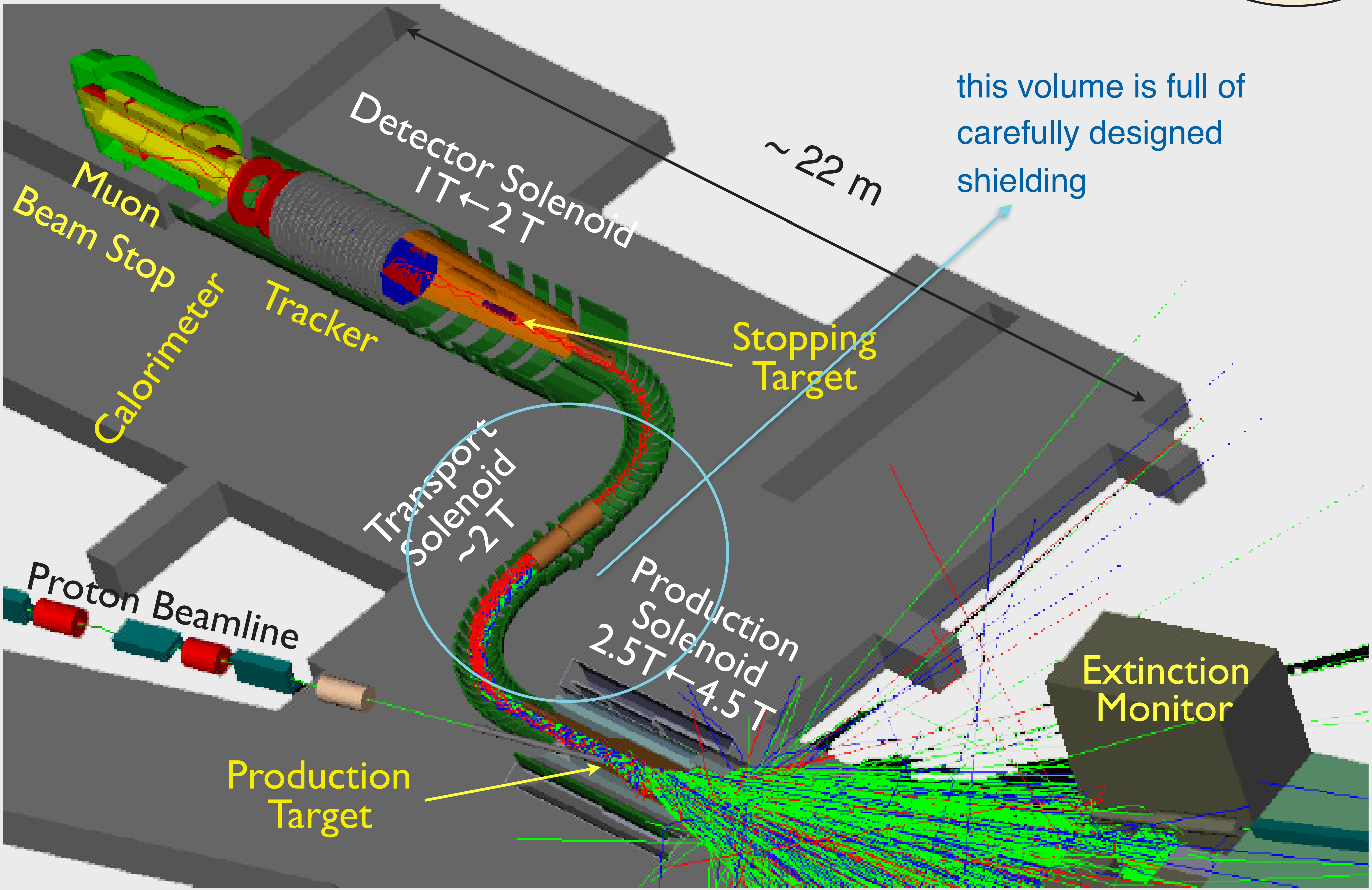
4.6T → B-field gradient → 1T

PS DS



- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

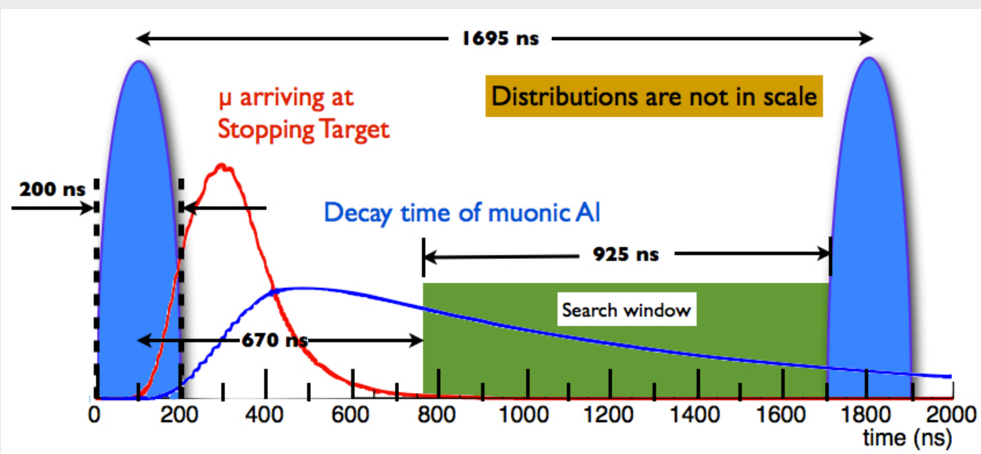
Beam's Eye View



Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_{μ}^{Al}, pulse separation ≈ τ_{μ}^{Al}
  - FNAL Debuncher has circumference 1.7µsec , ~x2 τ_{μ}^{Al}
- Extinction between pulses < 10^{-10} needed

  = # protons out of pulse/# protons in pulse

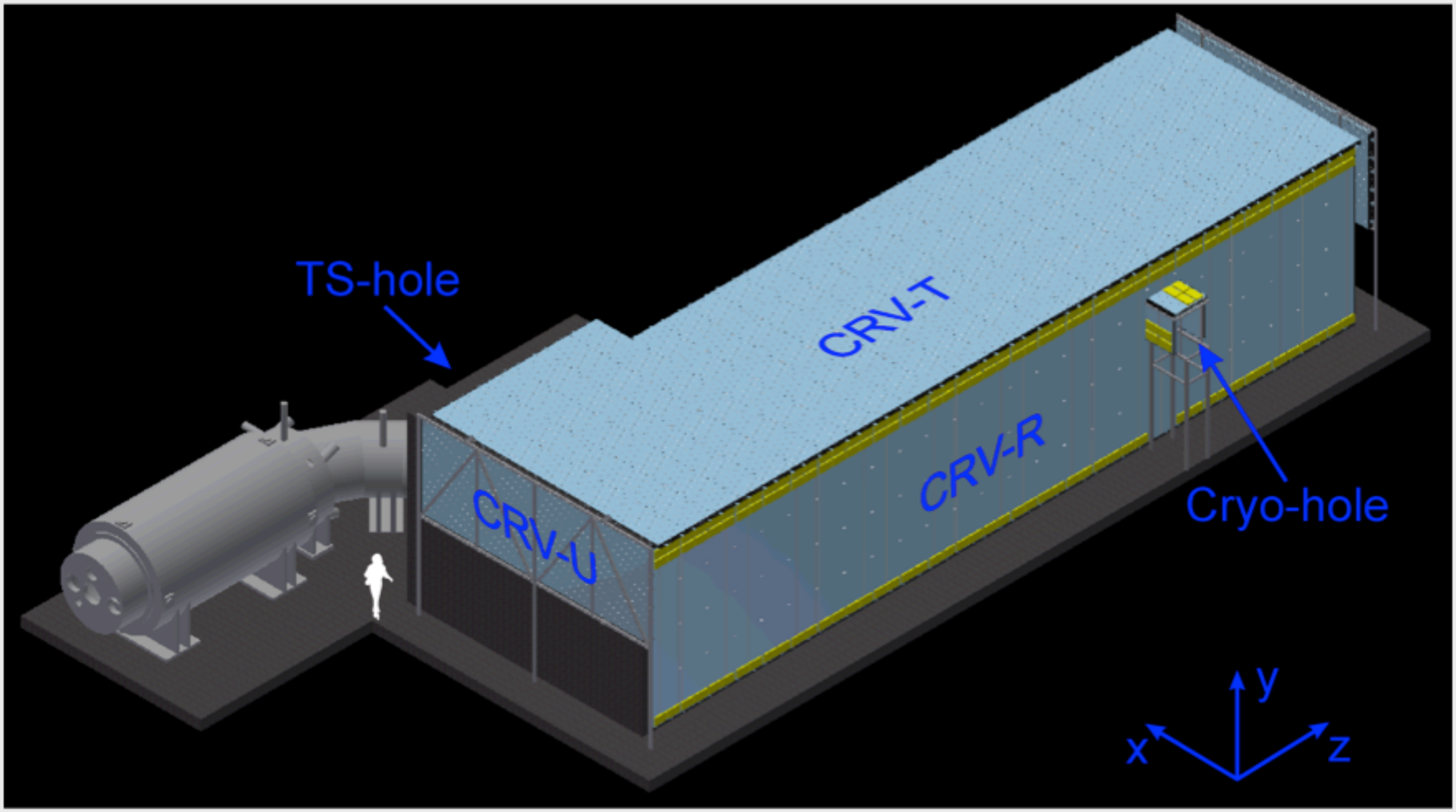


Extinction ~ 10^{-10}

- 10^{-10} based on simulation of prompt backgrounds and beamline

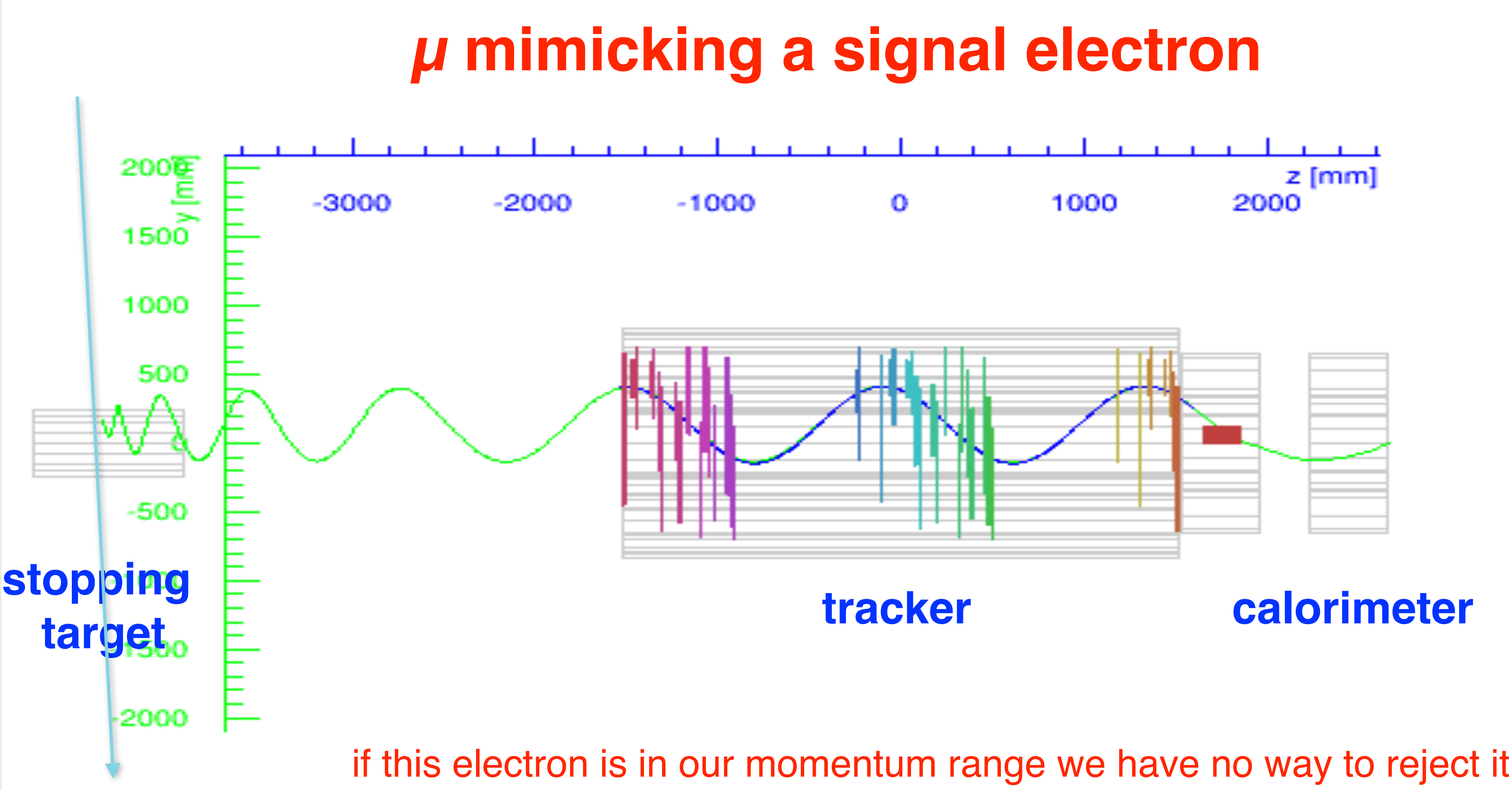
Cosmic Ray Veto

CRV



Sources of CR Background

- Other sources of CR backgrounds come from CR entering upstream in Transport Solenoid, creating electron that is then transported to stopping target



Beam-induced sources of Dead Time

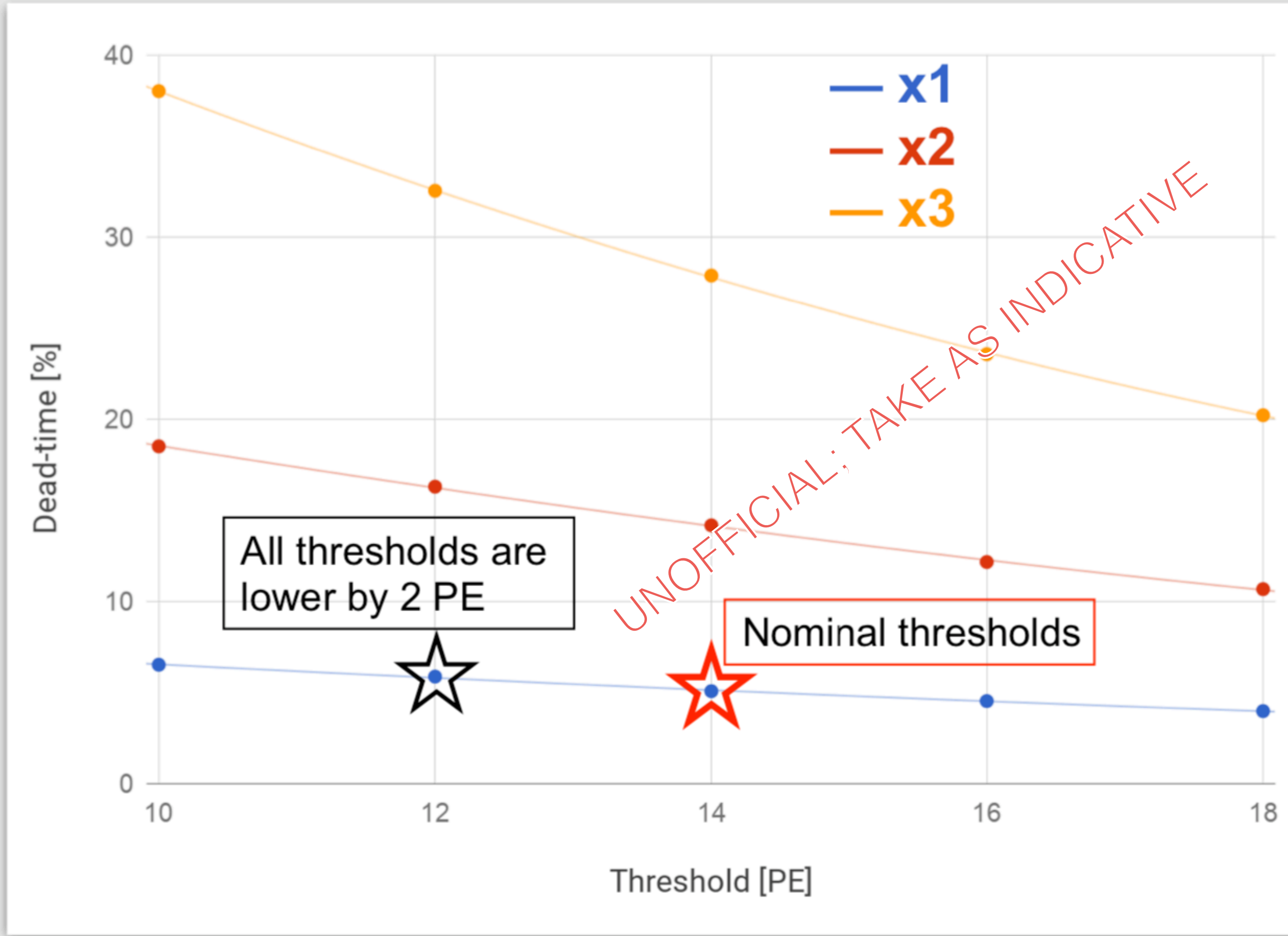
- Neutrons from Production Solenoid: neutrons get thermalized, captured, and produce delayed photons

- Fast neutrons from muon captures in beam line and the stopping target
  - fast neutron recoil off a proton deposits energy

CRV Thresholds

Y. Oksuzian

unofficial and approximate!!

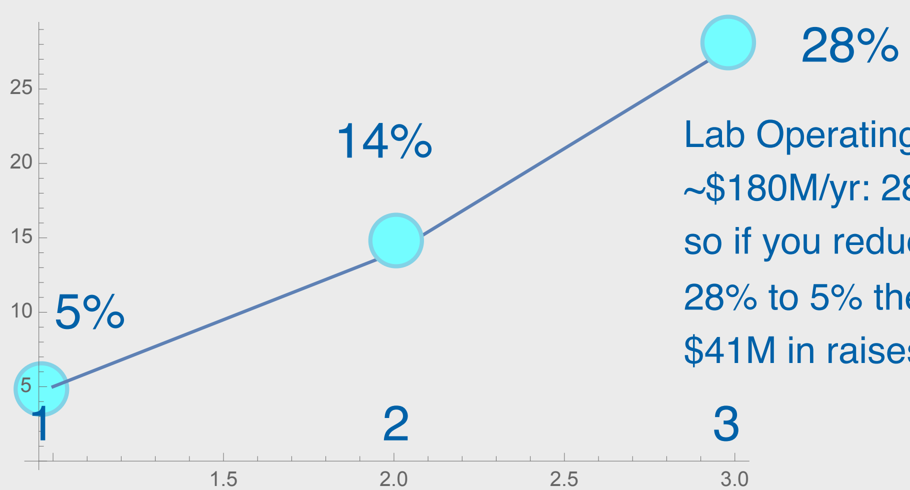


Cosmic Ray Veto

- 3/4 layer veto needs to be 99.99% efficient
- All of this not far from 8 kW, 8 GeV beam, leading to dead time from neutrons. Have to cut if CR veto is dead or we will be open to background
- Dead time:

Y. Oksuzian

Dead time



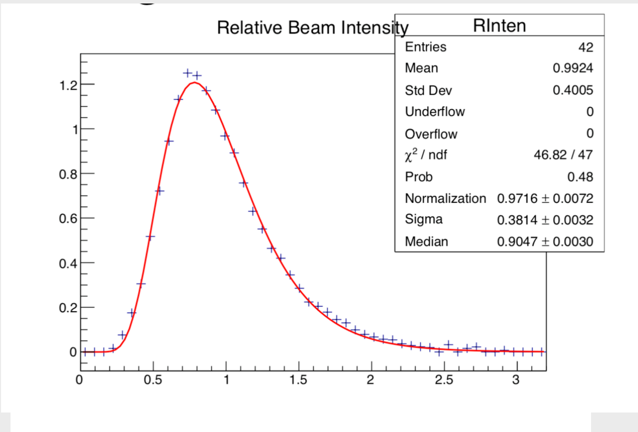
Lab Operating Costs ~$180M/yr: 28% is $50M, so if you reduce our dead time from 28% to 5% they should give you $41M in raises…

unofficial and approximate

Intensity/Nominal

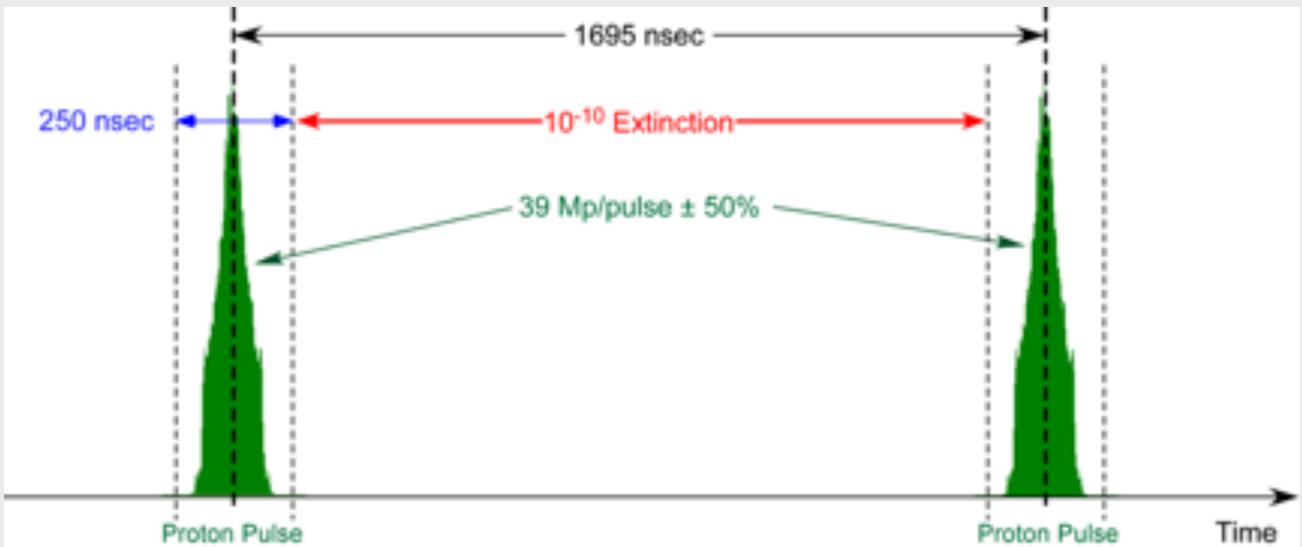
Work Out Some Numbers

- This plot represents the 1695 ns period of 3.9e19 protons/micropulse
- Fit to a lognormal distribution
- Integrate against
  - this intensity function: dead time = 3.8%
  - flat intensity function from 0 to 3: dead time = 11%
- The difference is 3 months of shifts and beam to reach our goals



Pulse Duration

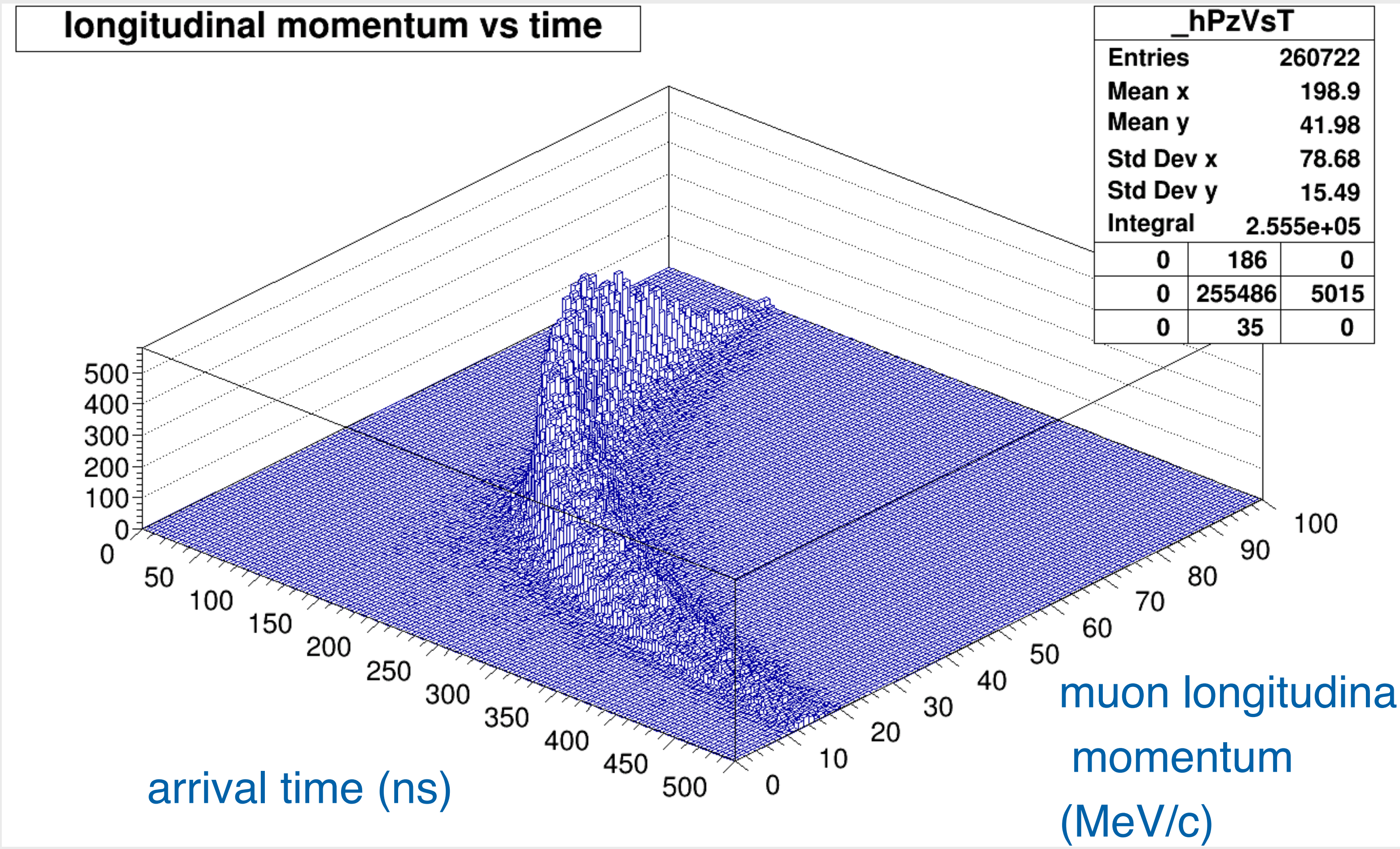
- Mu2e is not as concerned here, as long as the distribution doesn't lose beam outside the indicated limits



- This is because our magnet system uses solenoids. The particles travel in helices and the pitch angle (or p_T) distribution of the muons smears out the arrival time, so there is no close correlation between arrival time and momentum

Pulse Duration

- Here is the correlation for a delta-fcn beam; smear this with 125 ns in time and you see there won't be much correlation



Other Detector Systems

- Calorimeter, Tracker, extinction monitor, FEE, DAQ, not terribly sensitive
- Just don’t give us superbuckets (old phrase meaning x10 or more nominal)
  - these can be real problems in rare decay experiments; we’re fortunate that’s not a source of background in Mu2e
  - we would have to cut these

Summary

- Spill non-uniformity affects every experiment differently but in general:
  - background, dead time go up
  - resolution and stability get worse
- Mu2e's problem is primarily dead time