Design considerations for the cosmic-ray-veto system of the Mu2e experiment at Fermilab

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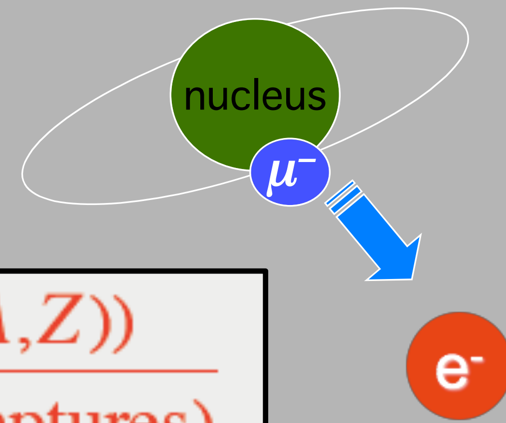
…on behalf of the Mu2e collaboration.
http://mu2e.fnal.gov

Mu2e

Experiment with preliminary approval that is proposed to begin data taking in 2019 at Fermilab.

- Goal: Search for $\mu^- N \rightarrow e^- N$
  - Measure ratio:

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



  - With sensitivity to R at 90% C.L. of $6*10^{-17}$
    - → 4 orders of magnitude better than current limits
    - → Need more than 10^{17} stopped muons!
      - -- $3.6*10^{20}$ protons on target (3 year run ~ $1x10^7$ s)
    - → Need to keep background small and well understood

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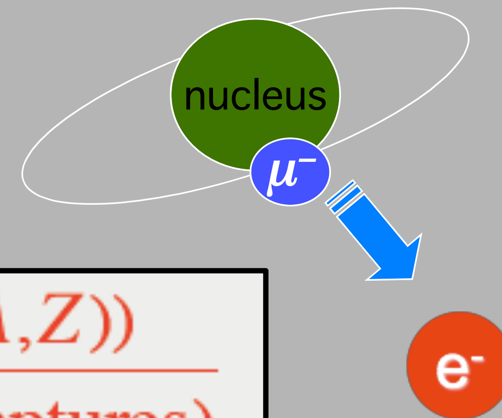

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    - → Need to keep background small and well understood

High radiation Environment!

Background Processes

- Signal is a single mono-energetic 105 MeV e-.
- Many possible sources of background events:
  - Muon decay in Coulomb orbit (DIO)
  - Radiative muon/pion capture
    - →Photon produced that can convert asymmetrically
  - Beam electrons can scatter in target
  - Muon/pion decay in flight
  - Antiprotons and other late arriving particles
  - Cosmic-ray induced electrons

These can all be controlled
and none produce a sharp peak at 105 MeV!

Cosmic Ray Background

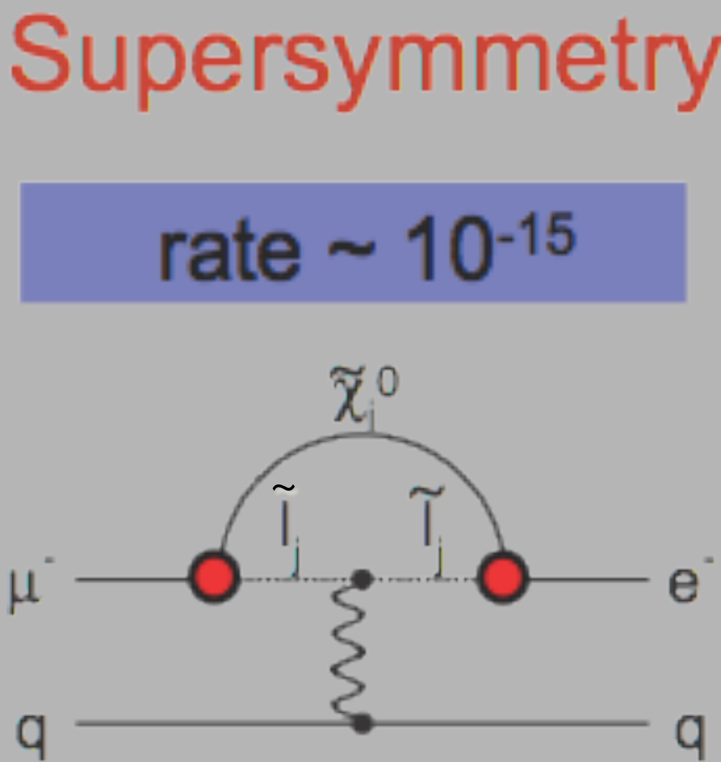
GOAL: single event sensitivity → $N_{background}$ < 1 event:

- Current expected background is 0.4 events
- Expected background from cosmic muons ~0.05 event
  → Assumes 99.99% cosmic ray veto efficiency

Without the CRV there would be hundreds of background events!

Sensitivity to “new physics”

Example: CLFV from SUSY

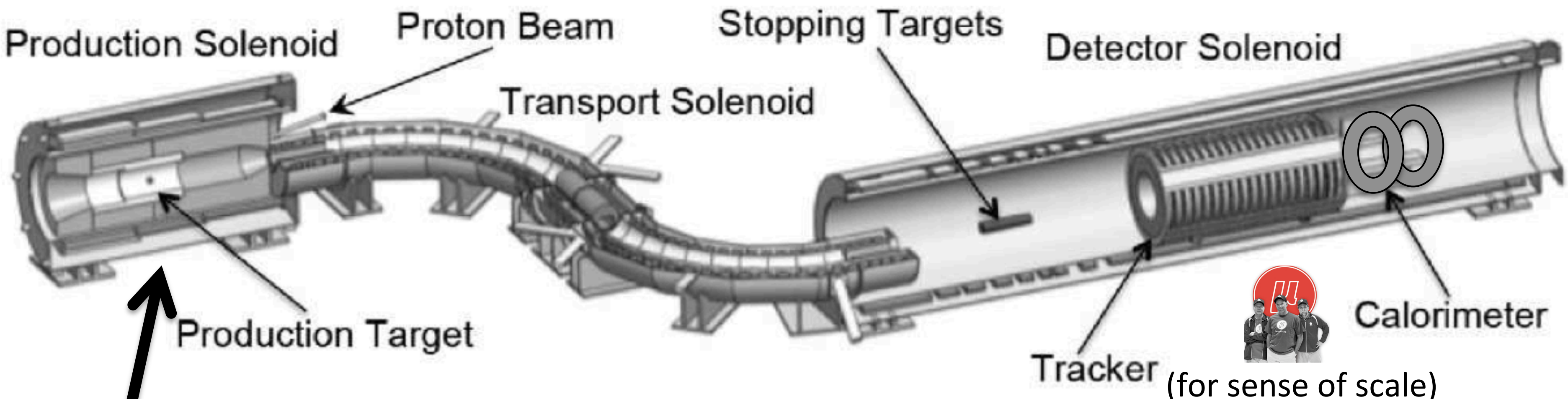


In Mu2e, a signal of Terascale physics at LHC implies:

$$\sim \frac{\textbf{40 signal events}}{\textbf{0.4 background events}}$$

Sensitive also to many other models of “new physics”.
(Contact interactions as well as loops)

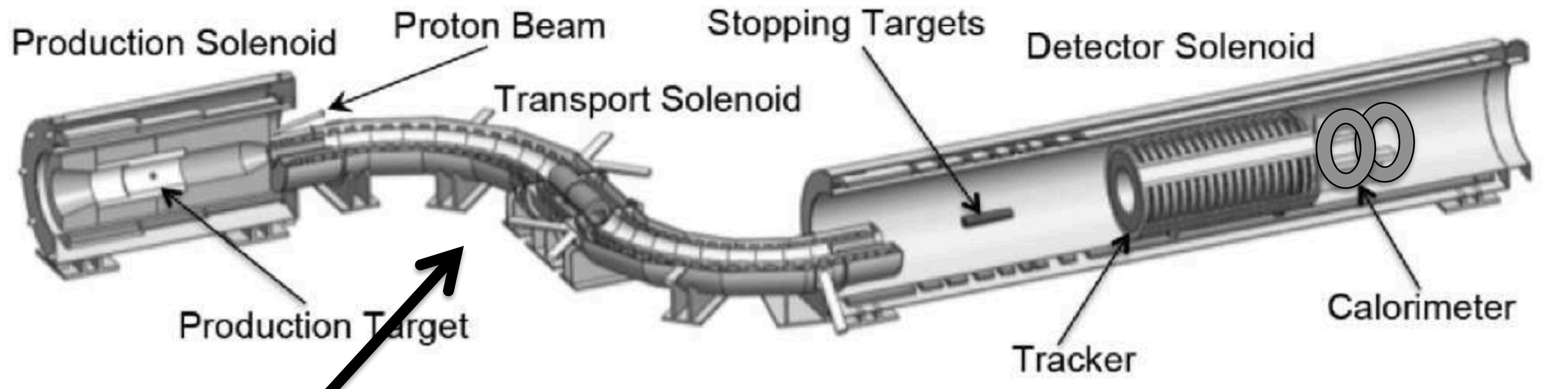
Mu2e Experimental Setup



1)

- Proton beam hits production target in Production Solenoid.
- Pions captured and accelerated towards Transport Solenoid (TS) by graded field.
- Pions decay to muons.

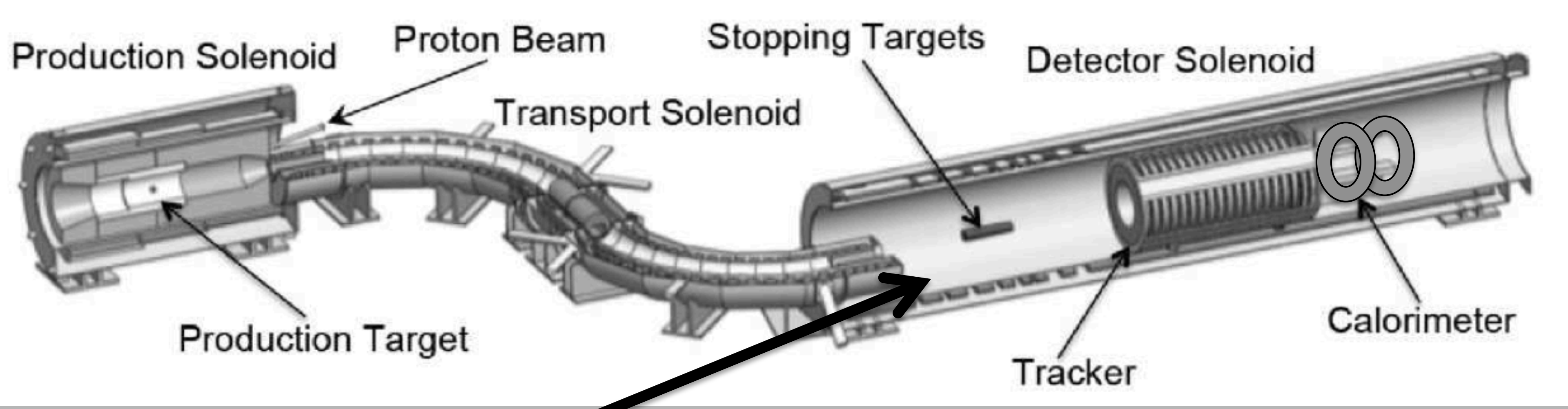
Mu2e Experimental Setup



2)

- Transport Solenoid performs sign and momentum selection.
- Eliminates high energy negative particles, positive particles and line-of-sight neutrals.

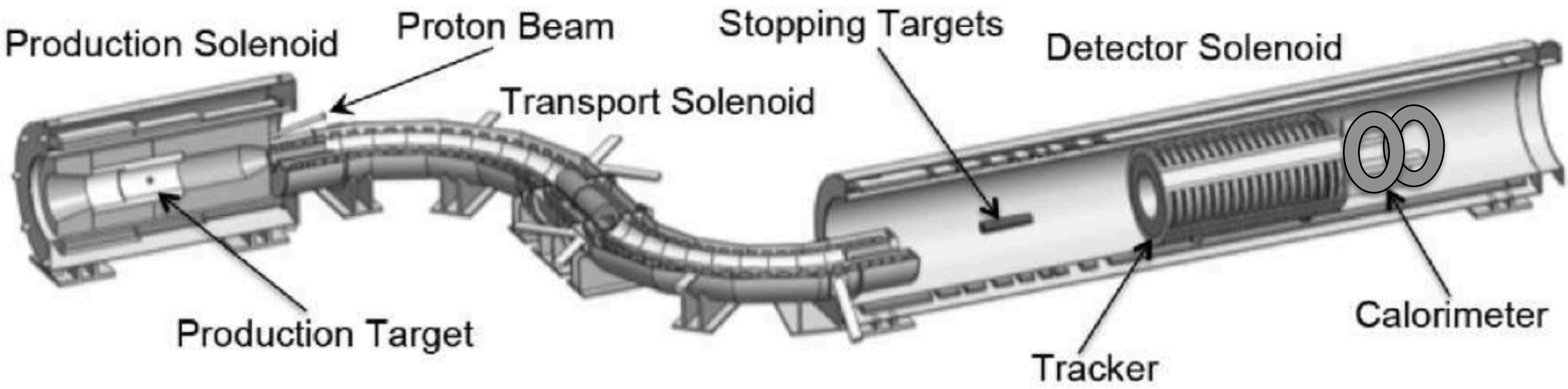
Mu2e Experimental Setup



3)

- Muons stop in target and decay.
- Conversion electron trajectory measured in tracker, validated in calorimeter.
- Cosmic Ray Veto (CRV) surrounds Detector Solenoid.

Mu2e Experimental Setup

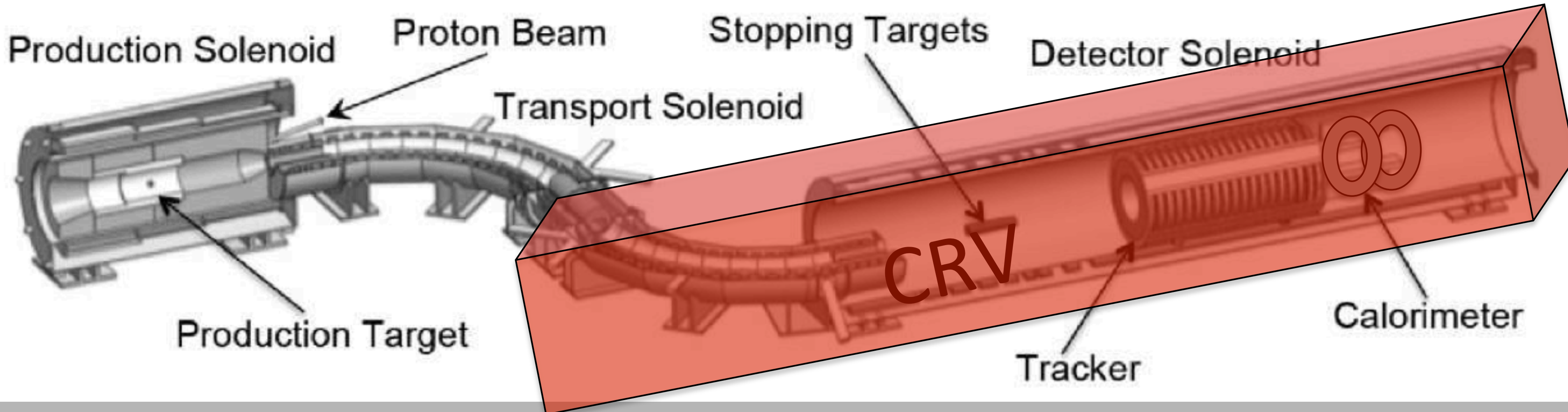


Major sources of neutrons and gamma rays:

- 8 GeV protons striking the Production target.
- Pions, muons, *etc.* strike the collimators in the TS.
- Muons interacting with the Stopping Target or the Muon Beam Stop.

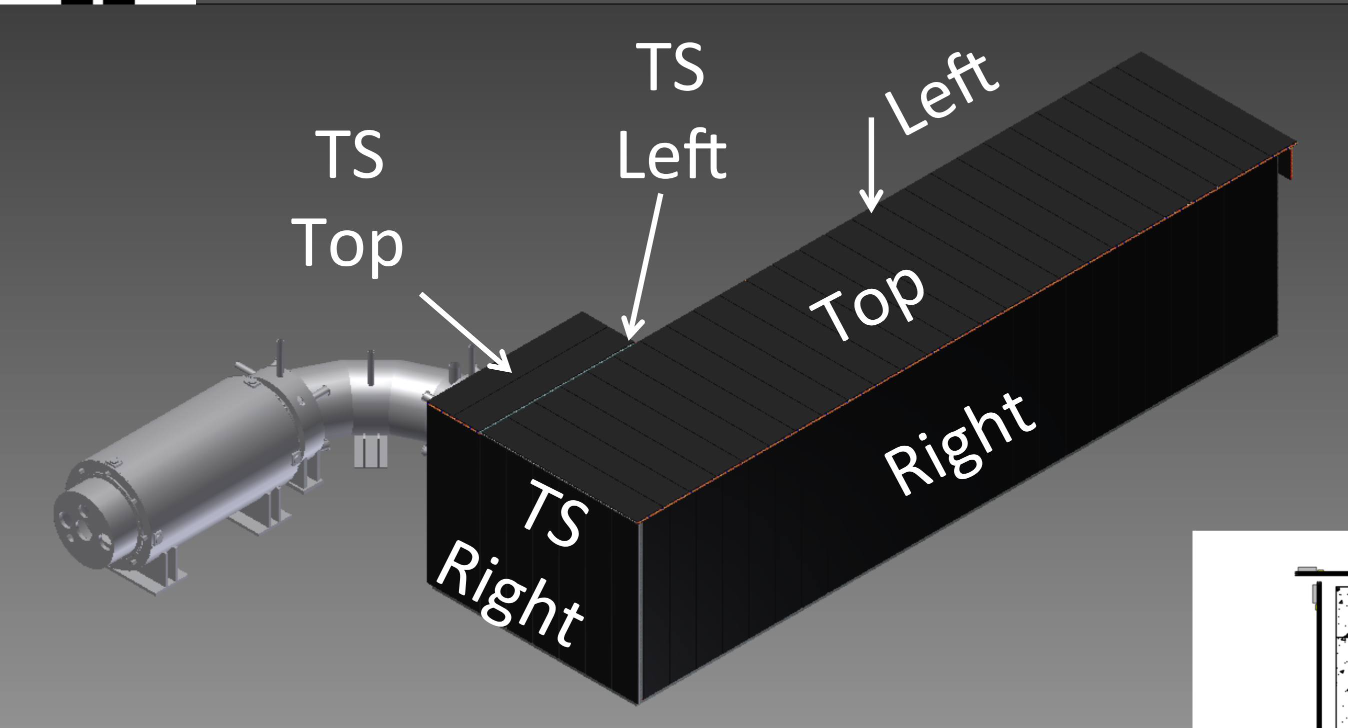
In addition to beam sources, low energy neutrons may produce gammas with energy up to 10 MeV through the process of neutron capture anywhere in the detector hall.

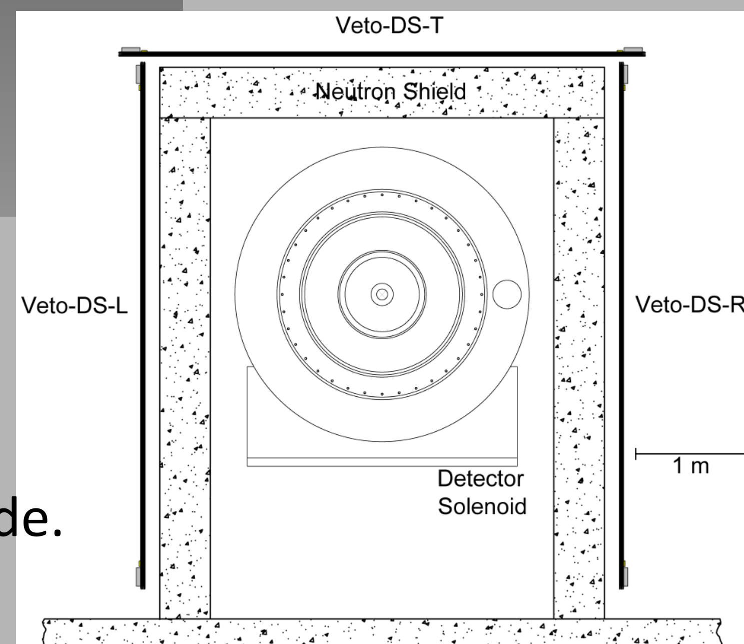
Mu2e CRV Experimental Setup



- The CRV surrounds the Detector Solenoid and part of the TS
- The CRV must:
  - Reject cosmic ray muons with high efficiency (> 99.99 %)
  - Produce little dead time (< 1 % is the stated requirement)
  - Operate in a high-radiation environment
    - 10^{18} muons will be stopped, and it takes more than 10^{20} protons on target to produce these muons
    - Note that the Detector Solenoid and some regions of CRV are in somewhat close proximity to the Production Solenoid

CRV

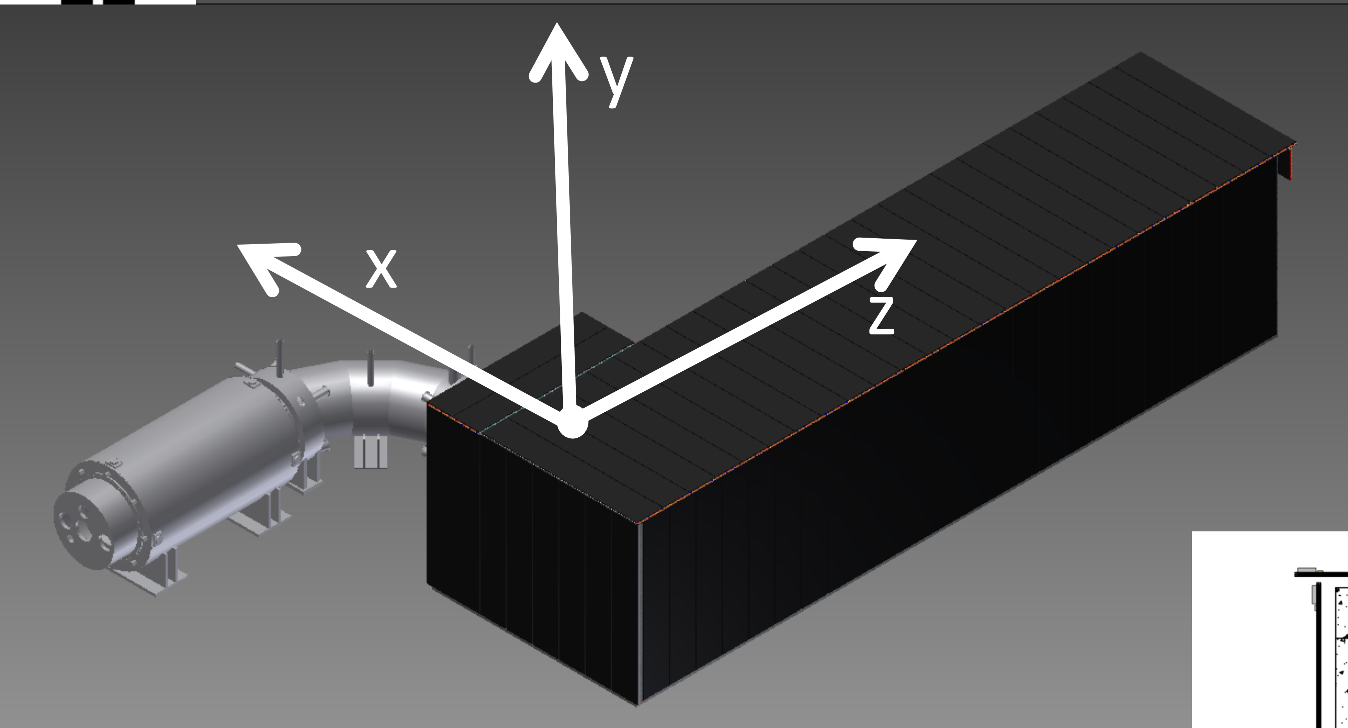


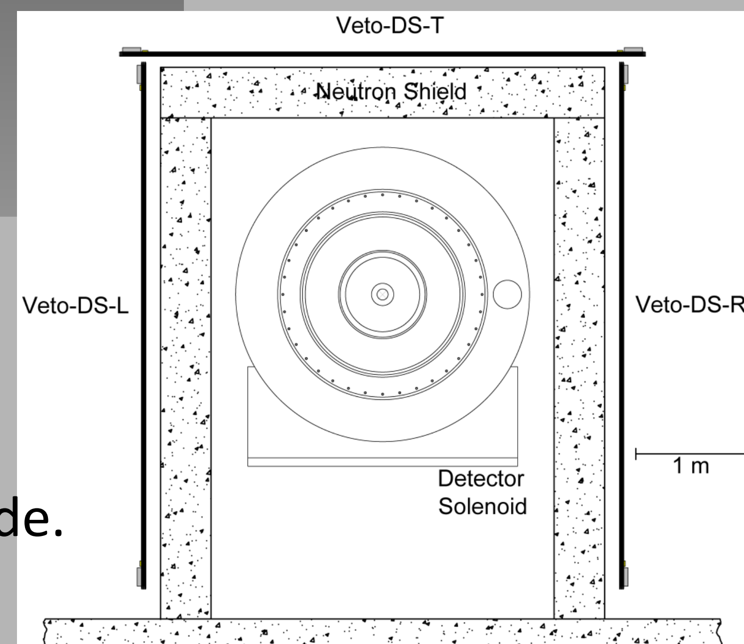


Detector Solenoid surrounded on 5 sides by the CRV modules. (no bottom)

Modules are approximately 5m long and 1m wide.

CRV coordinates



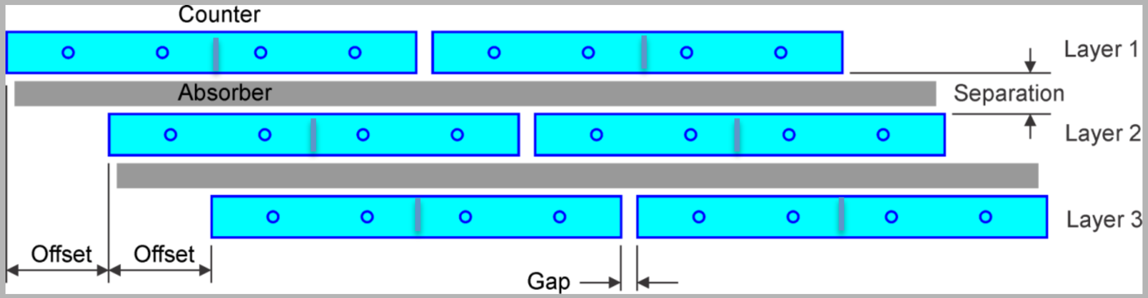


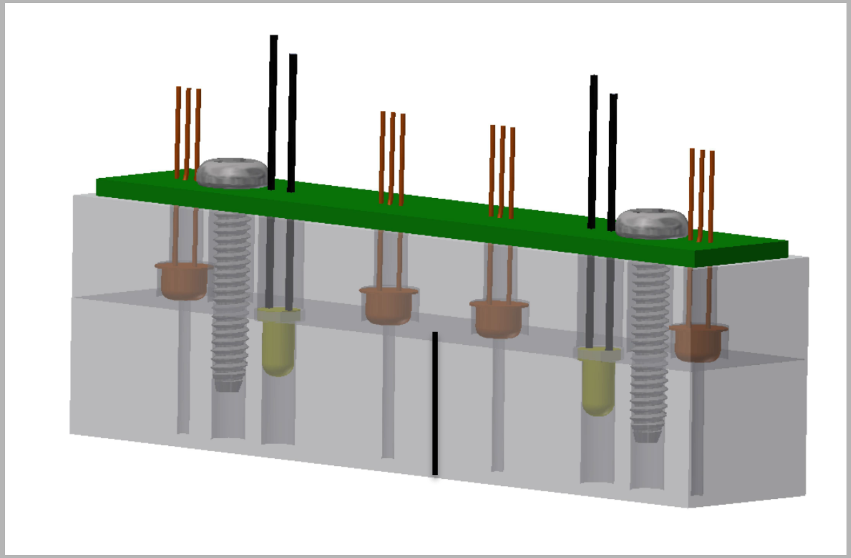
Detector Solenoid surrounded on 5 sides by the CRV modules. (no bottom)

Modules are approximately 5m long and 1m wide.

CRV Modules

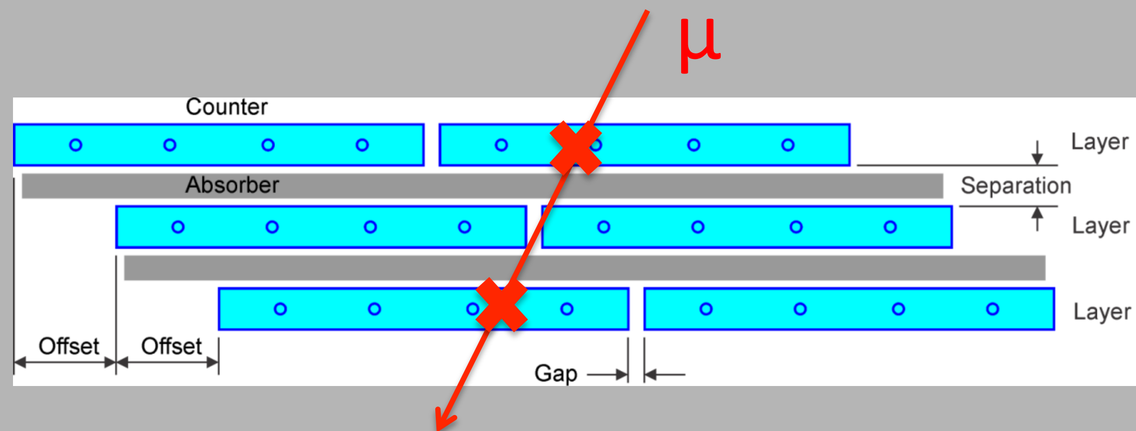
Modules composed of 3 layers of plastic scintillator counters. (10 counters wide)





Each counter read out by WLS fibers and SiPMs using a plastic fiber guide bar and SiPM manifold

Requirements on Muon Veto

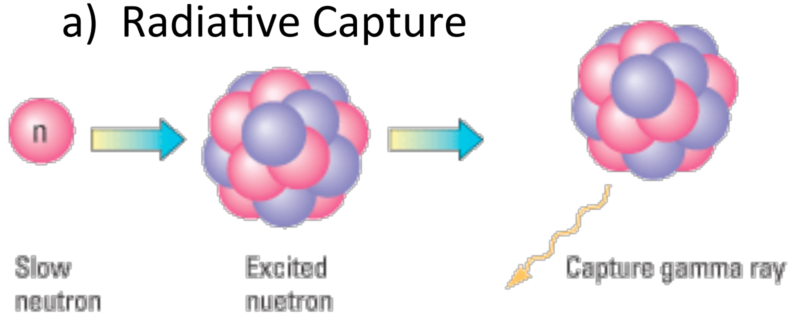


Modules composed of 3 layers of plastic scintillator counters. (10 counters wide)

- Mu2e CDR plan is to require 2-out-of-3 coincidence.
- Simulations suggest 99.99% veto efficiency required.
- 2-out-of-3 requires 99.4% single-counter efficiency. (ignoring the effect of cracks between counters)
- We achieved 15 photo-electrons (PE) with a 1 cm thick counter (test beam studies at Fermilab in 2010)
- We plan to use a 2 cm thick counter, so 30 PE is expected
- Cutting at ~6 PE should achieve desired efficiency (~ 1 MeV) (assuming Poisson statistics)

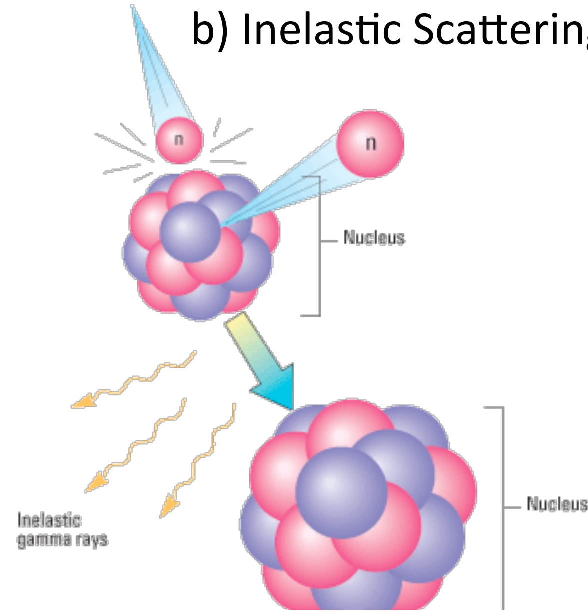
The CRV is not blind to neutrons!

a) Radiative Capture



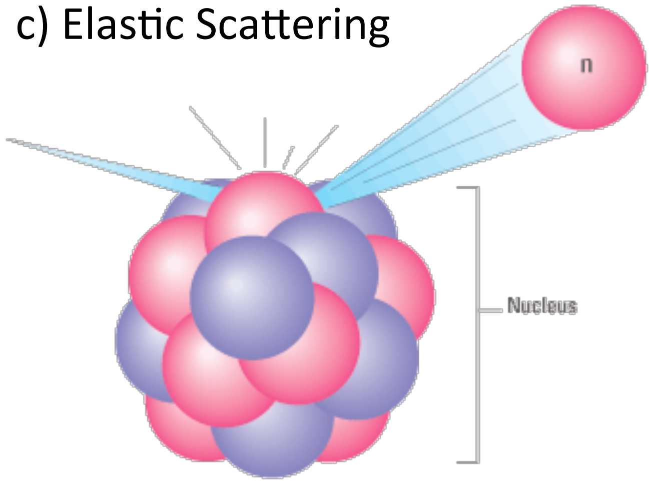
Capture gamma ray may be detected.

b) Inelastic Scattering



Gamma ray or recoil nucleus may be detected.

c) Elastic Scattering

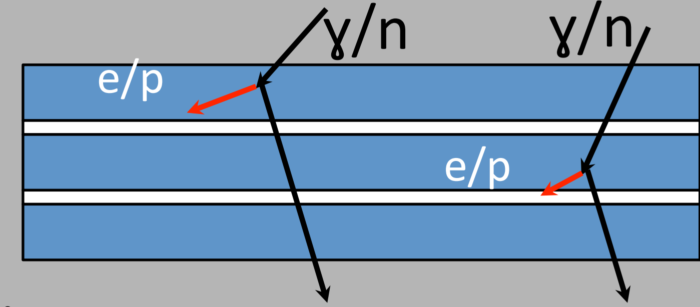


Recoil nucleus may be detected.

Note: - Each neutron can produce one (or more) gamma ray.
- Recoil nucleus may just be proton.

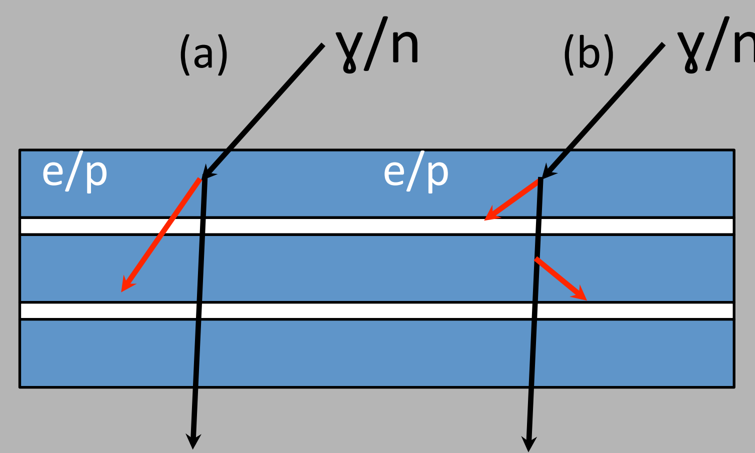
Tolerable CRV rates

Coincidental hits from gammas or neutrons:



→ Based on a 1% deadtime from the CRV we estimate a tolerable hit rate of: $2 \cdot 10^8$ [hits/cm^2]

Correlated hits from a single particle:
(For example delta rays (a), or double Compton scatter (b))



→We estimate a tolerable hit rate of:
$6 \cdot 10^5$ [hits/cm^2]

Note: hit limits assume uniform distribution of hits.

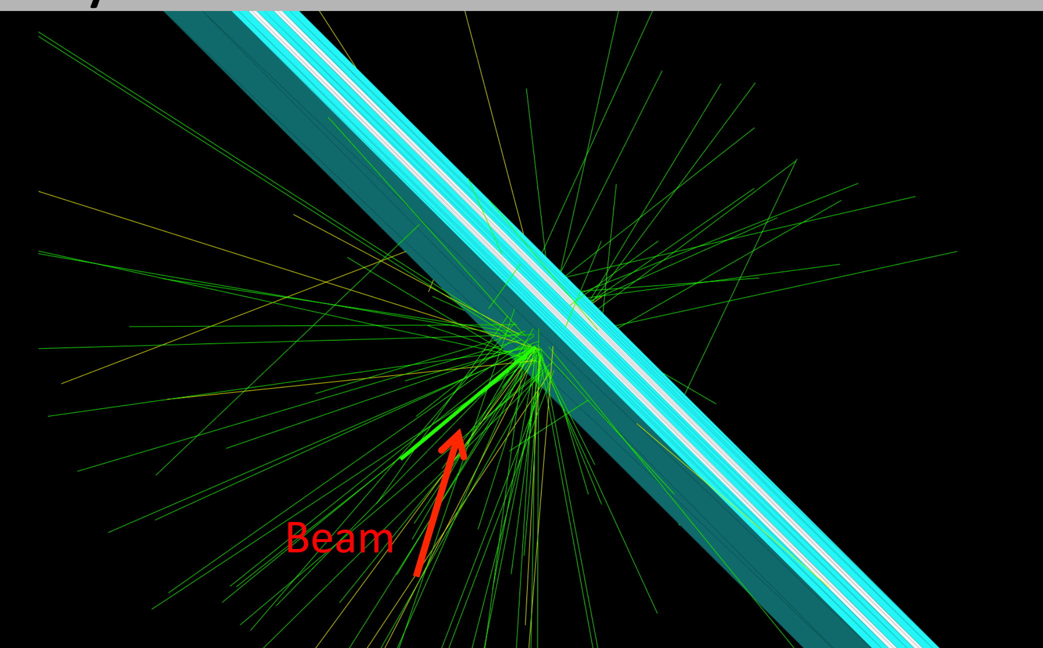
G4BEAMLINE: Simple Counter

- http://www.muonsinternal.com/muons3/G4beamline

A "Swiss Army Knife" for Geant4, optimized for simulating beamlines

- We first use G4BEAMLINE to study counter efficiencies to neutrons and gamma rays.
- Simple 3-counter geometry:

- Example: 10 eV neutrons “beam” (directed at counter center)
- Blue bar – Counter polystyrene
- Silver bar –Aluminum absorber

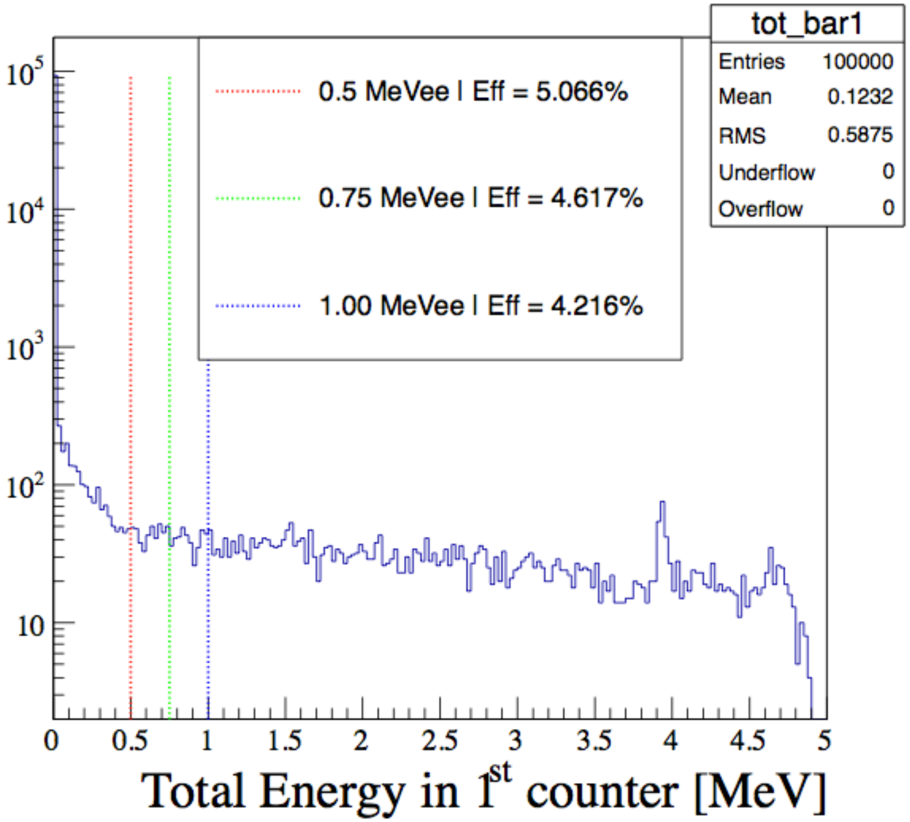


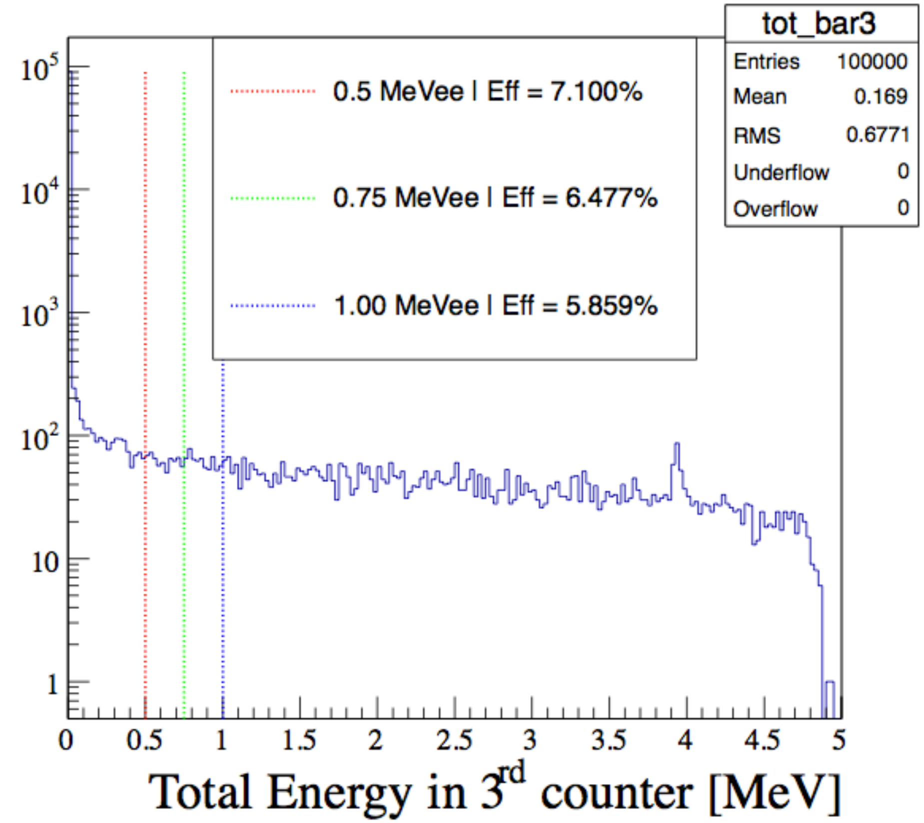
Gamma and Neutron efficiencies

- For varying energies we shoot a beam of neutrons (gammas) at the counter configuration from the previous slide and study the energy deposition.
- For a 2 cm thick counter we estimate our energy threshold will be ~1 MeV which will correspond to several photo electrons (~ 6 PE) for minimum ionizing particle (MIP).
- Birk's law is important for interpreting the energy deposit in terms of light yield for protons and other non-MIP particles.

Example: Energy Deposition

Energy deposition from 5 MeV gamma ray.





Note:

- Not very sensitive to the threshold value
- That the peak at 4 MeV corresponds to the "double escape peak" from pair production.

Neutron and Gamma Efficiencies

We study the single counter efficiencies as a function of incident energy and approximate them as follows for rate calculations:

Neutron energy	$E_N < 1e\text{-}6$	$1e\text{-}6 < E_N < 2$ MeV	2 MeV $< E_N$
Detection efficiency	0.5%	.1%	10%

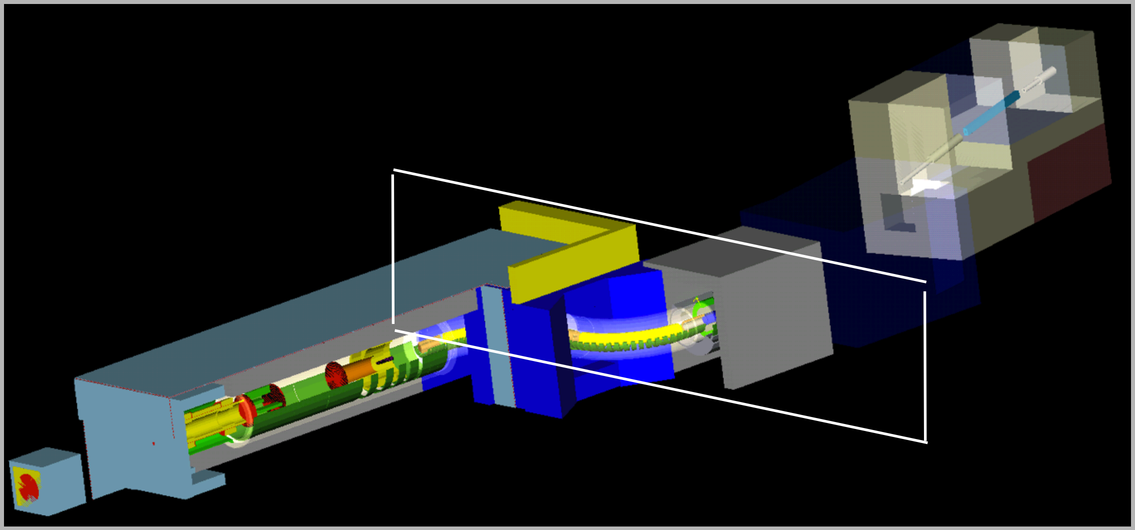
γ energy	$E < 1.0$ MeV	1.0 MeV $< E$
Detection efficiency	0.0%	10%

We also study the efficiency for a 2-out-of-3 coincidence cause by an incident gamma:

γ energy	$E < 5.0$ MeV	5.0 MeV $< E$
Detection efficiency	0.0%	1%

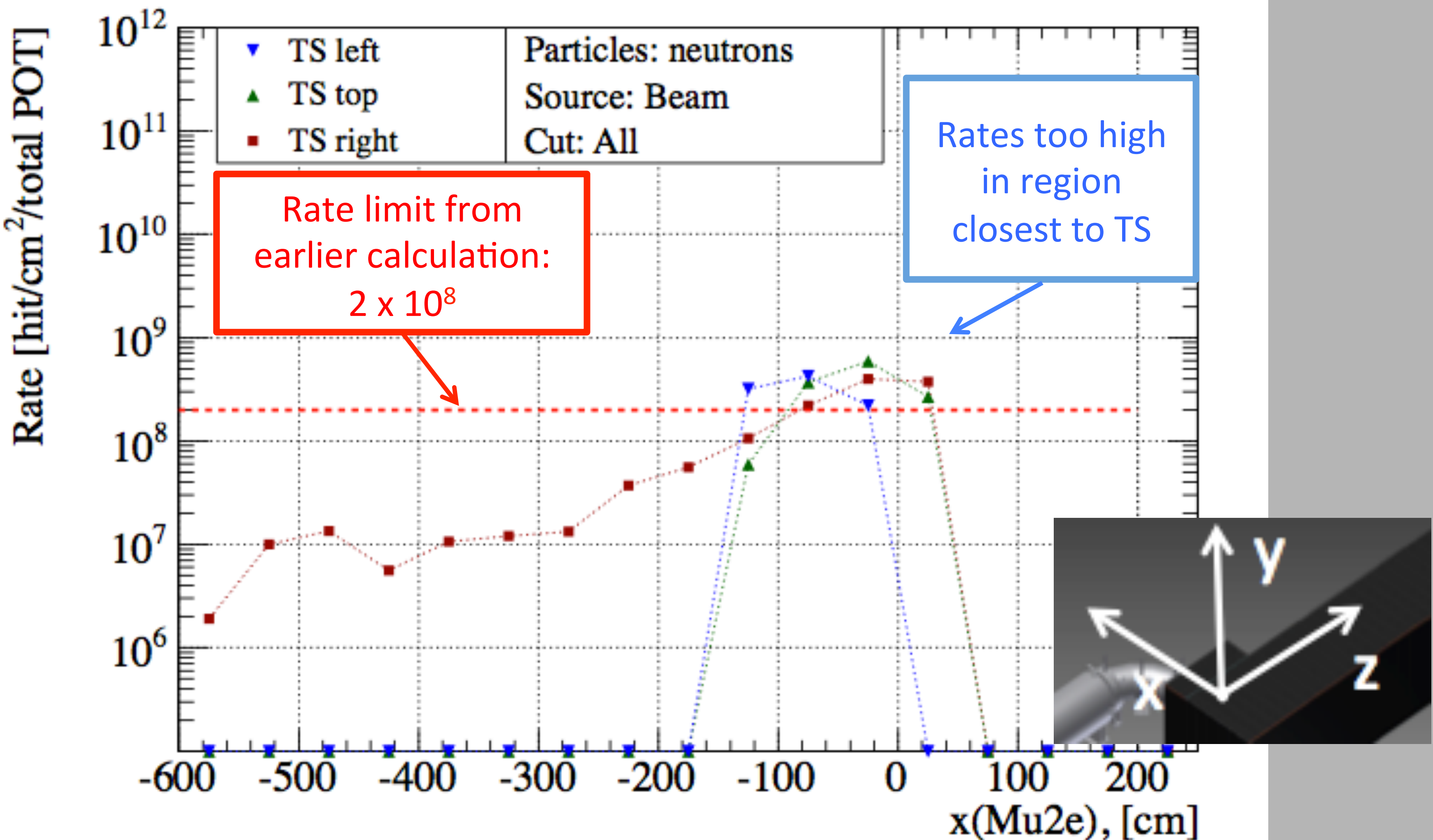
G4BEAMLINE: Full Geometry

The full Mu2e geometry has been included:



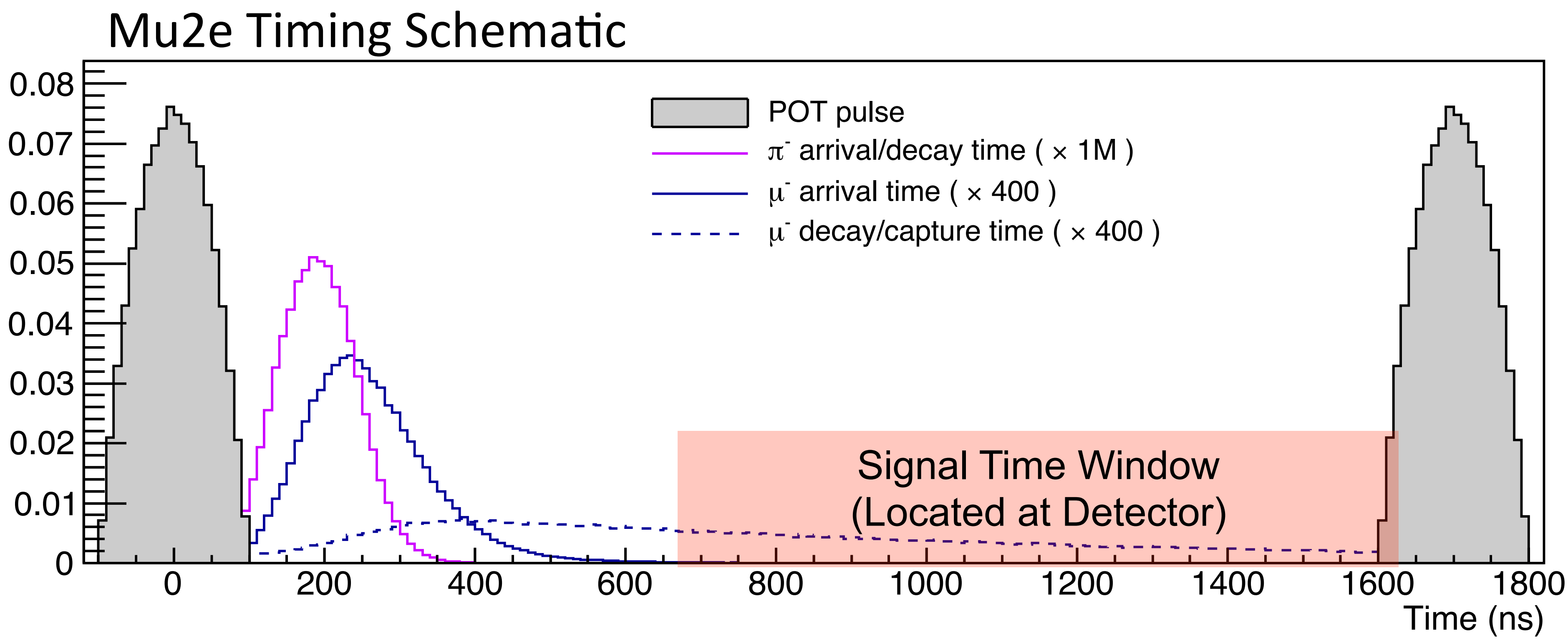
- **First step - produce "beam file":**
  - Hit 8 GeV protons on production target
  - Record all particles on virtual plane at first collimator(white square)
  - Particles split into two categories:
    - Charged particles - **Beam** source
    - Neutrons - **PS only** source
- **Second step - run simulation from "beam file":**
  - Simulate and propagate particles from the virtual plane

First look at rates from all neutrons



(TS counter position)

Timing

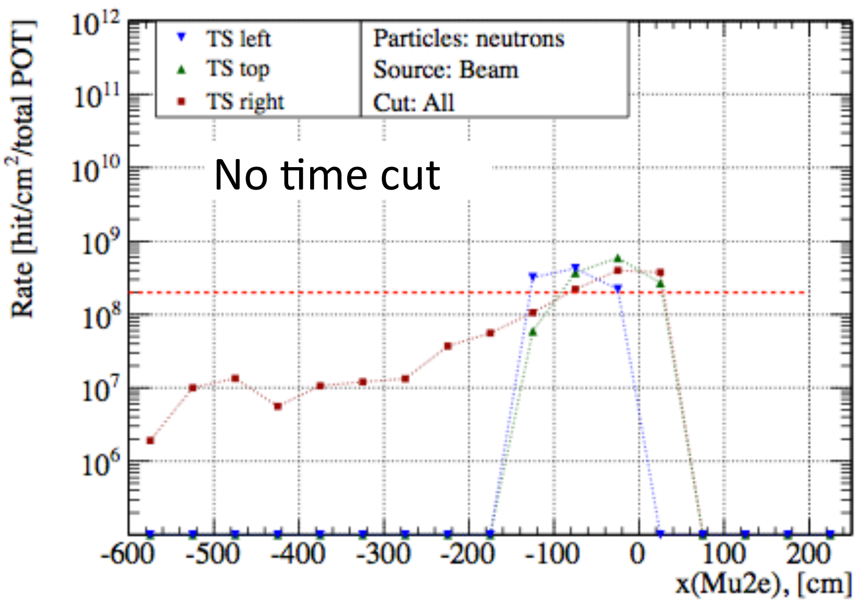


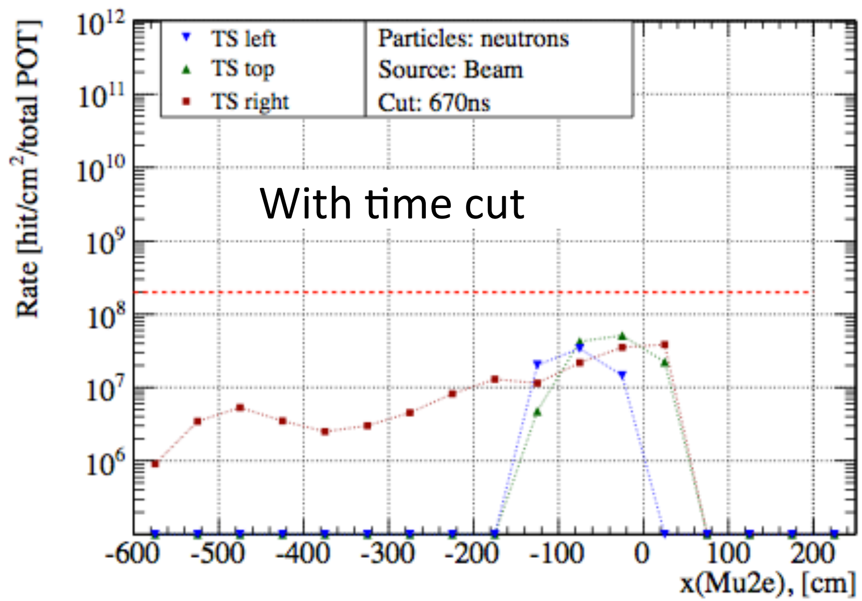
(μ lifetime in 1s orbit of AL ~864 ns)

We should require hits to satisfy: 670 ns < t < 1595 ns
(in each beam pulse and also tracking particles through future pulses)

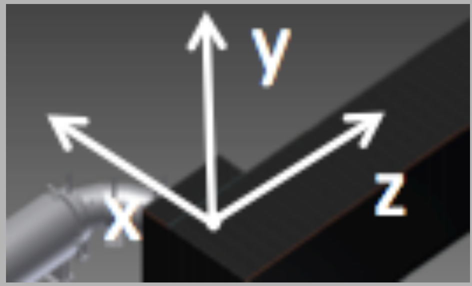
Timing cut: neutron hit rates

Neutron rates: random coincidence

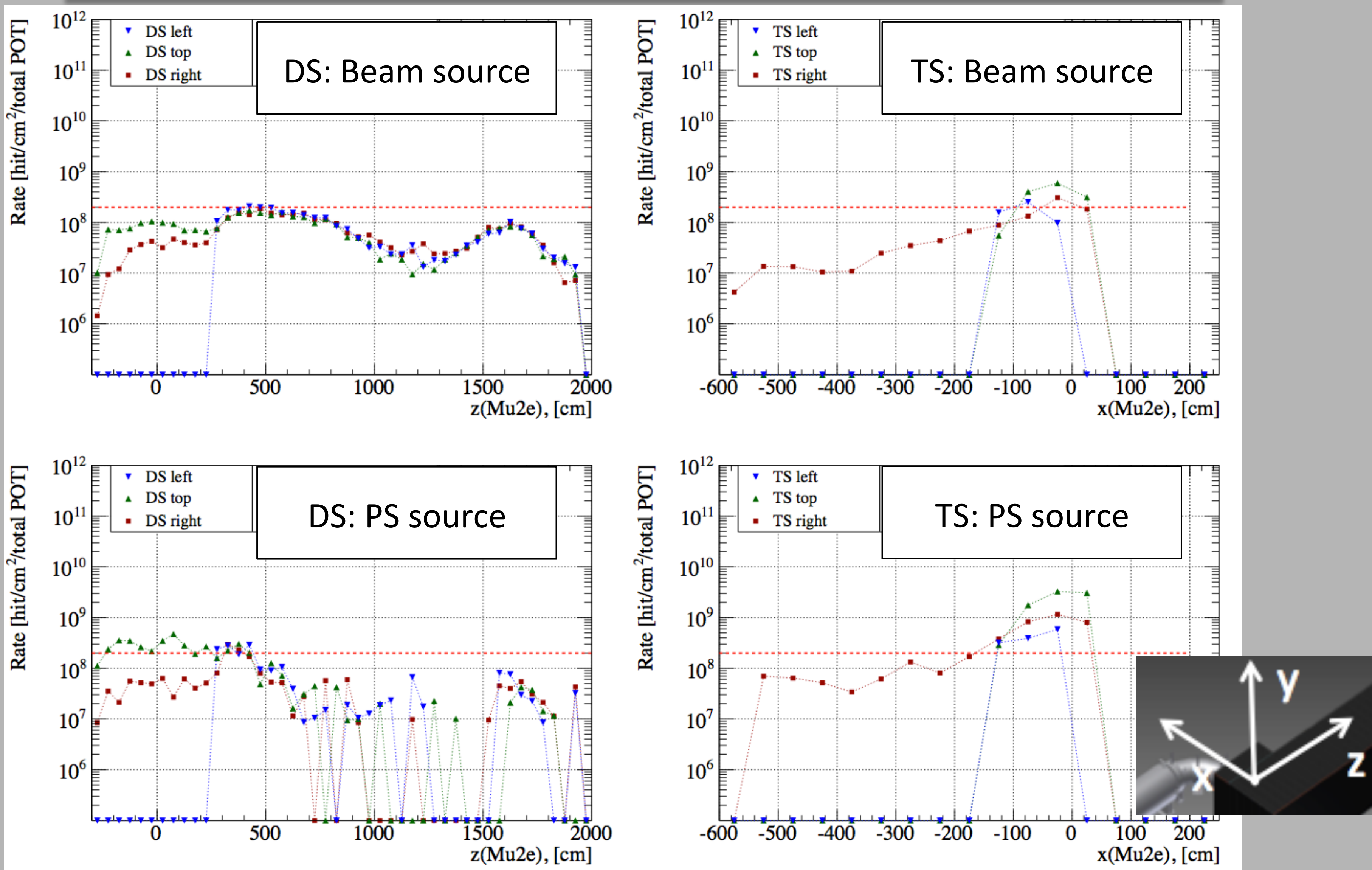




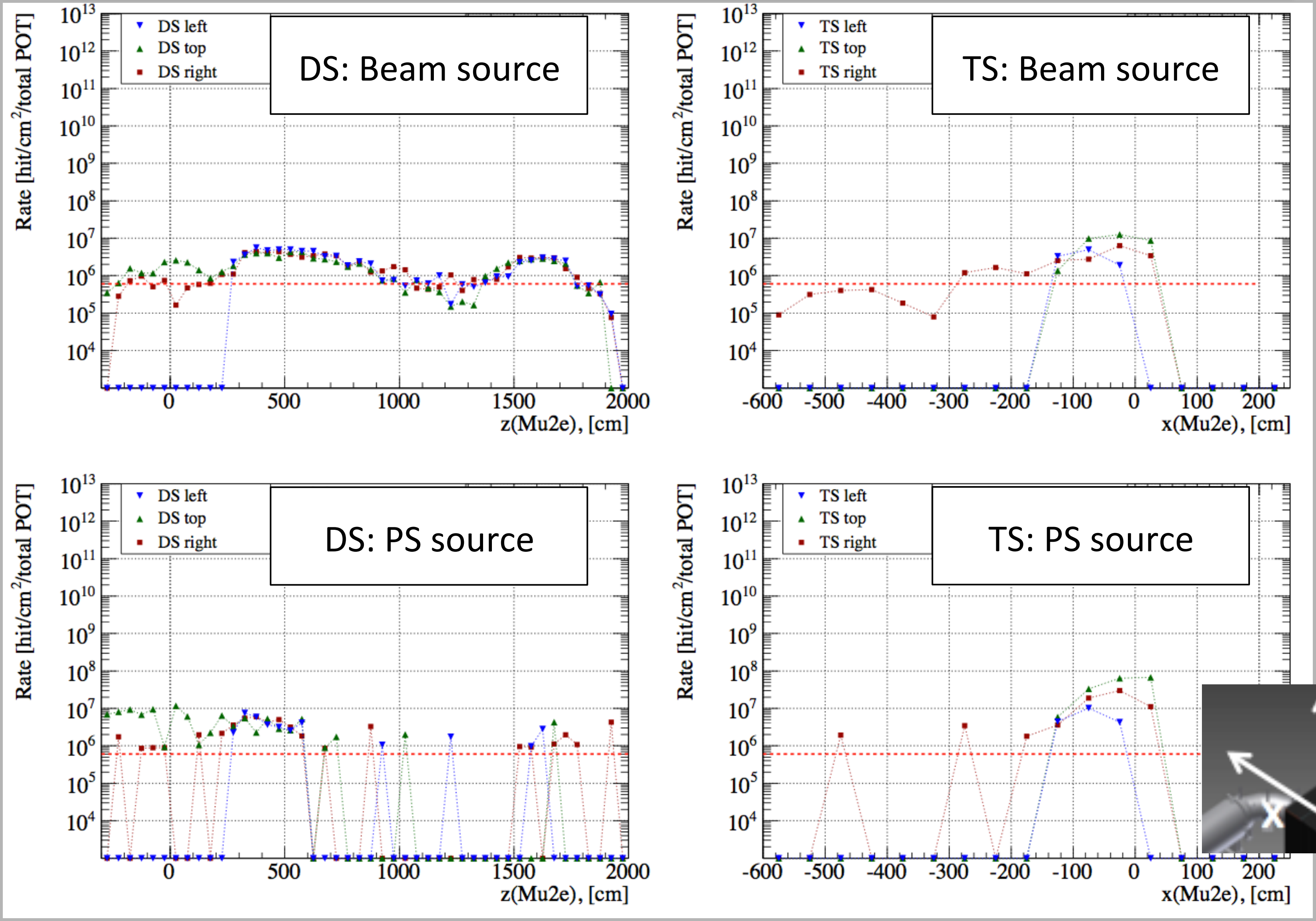
Fast neutrons can be reduced by an order of magnitude from the timing requirement!

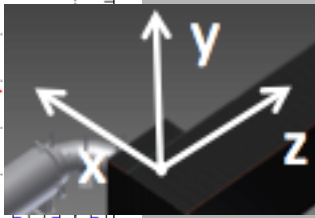


Gamma rates: random coincidence



Gamma rates: correlated hits





Summary from rate studies

- Neutrons are under reasonable control with current Mu2e shielding.
- Gammas from random coincidence are near the limit imposed by a 1% deadtime from the CRV.
- Gammas causing correlated hits in 2-out-of-3 CRV layers occur at a rate about 10 times too high.

Note: comparison between MARS and G4BEAMLINE yield compatible conclusions.

Possible solutions

- Thicker absorber layers will reduce efficiencies for correlated hits from gammas.
- Changing the concrete around the DS to a heavy concrete loaded with Barite reduces the rate by about a factor of 10.
- Adding 5 cm of lead around the DS concrete also would reduce the rate by about a factor of 10.
- Adding a 4th layer to the CRV improves the rate due to correlated hits from gammas by about two orders of magnitude.

Summary

- The cosmic ray veto must operate with high efficiency while producing low deadtime in a high-radiation environment.
- Expected hit rates in the CRV due to gamma rays and neutrons were studied using G4BEAMLINE.
- Current proposed version of shielding effectively suppresses neutrons. Exploring options to address remaining challenges generated by gammas.

References

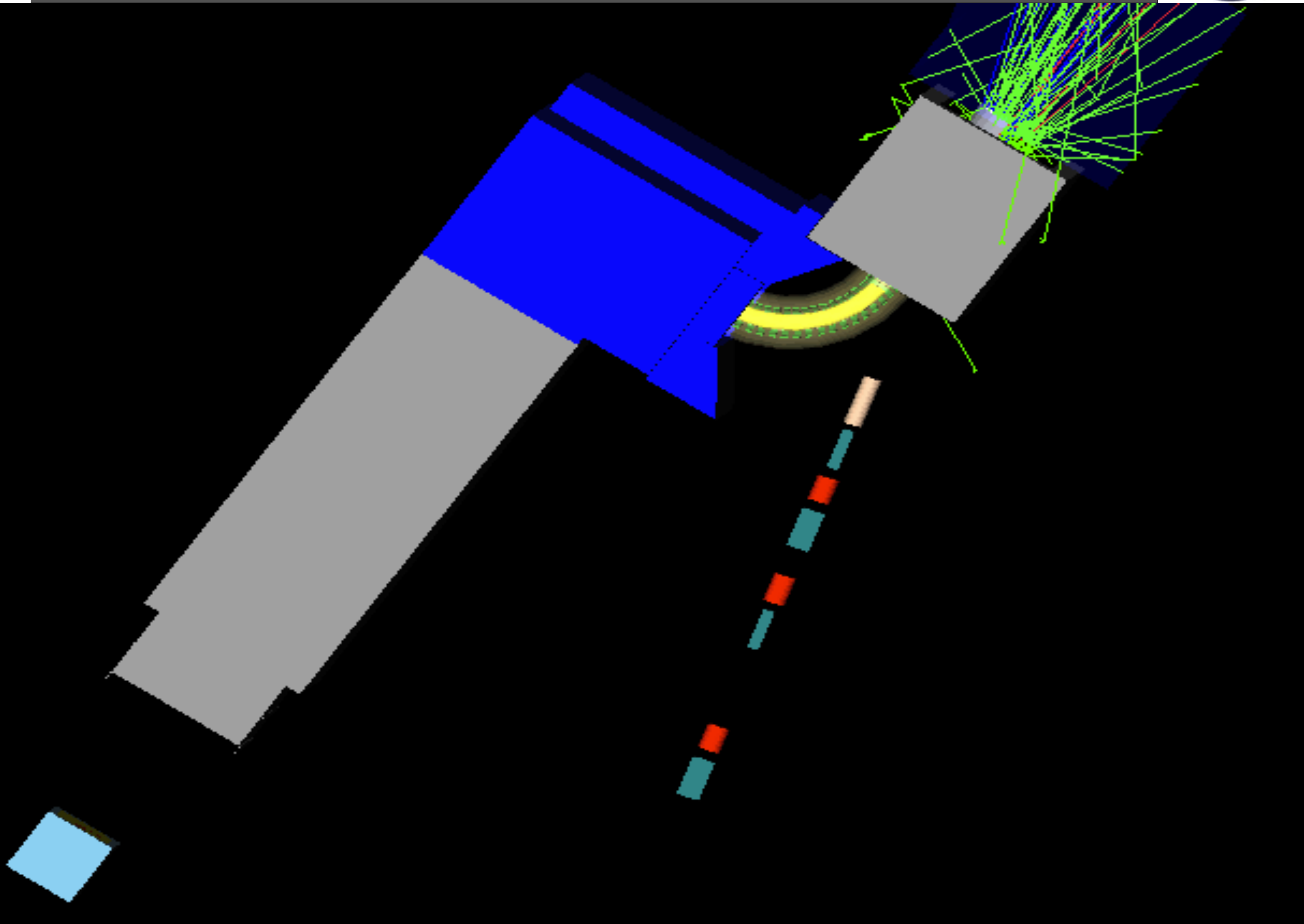
- For overview of Mu2e see Rob Kutschke's talk

  (Tomorrow, in the session on "Quark and Lepton Flavor Physics")

- Mu2e Conceptual Design Report:
  - http://arxiv.org/abs/arXiv:1211.7019

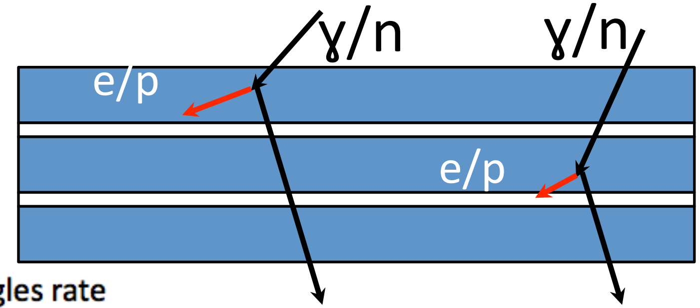
- http://mu2e.fnal.gov/

Backup



Tolerable CRV rates

Coincidental hits from gammas or neutrons:



Single counter time resolution : 5 ns

Single counter singles rate

Pairwise coincidence rate: $n_{pc} = 2\Delta t_c \bullet n_s^2$

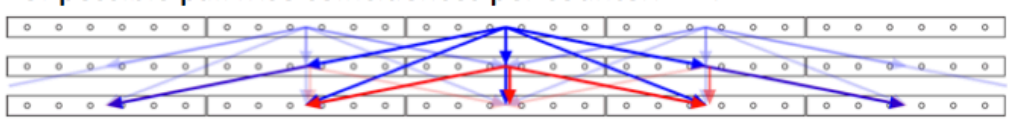
Number of counters per layer: 696

Total pairwise coincidence rate: $n_{tpc} = N_{cl} \bullet N_{pp} \bullet n_{pc}$

1% Deadtime fraction: $f_v = \Delta t_v \bullet n_{tpc} = \Delta t_v \bullet N_{cl} \bullet N_{pp} \bullet 2\Delta t_c \bullet n_s^2$

A valid cosmic-ray muon event is 2/3 adjacent counter hits. Number of possible pairwise coincidences per counter: 11.

Veto time: 50 ns



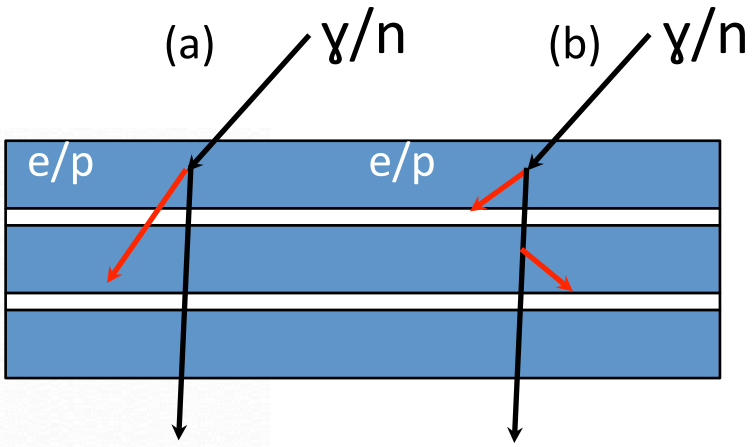
$$n_s = \sqrt{\frac{f_v}{\Delta t_v \cdot N_{cl} \cdot N_{pp} \cdot 2 \cdot \Delta t_c}}$$ = 50 kHz per counter

Experimental lifetime of $1.06*10^7$ s and counter area of 470x5 cm2
→tolerable hit rate ~ $2 \cdot 10^8$ [hits/cm^2]

Tolerable CRV rates

Correlated hits from a single particle:

(For example delta rays from gammas, or double Compton scatter)



- Upper limit hit rate estimation from **2-out-3 hits**
- Assuming:
  - $f_\nu = 0.01$ - the deadtime fraction CRV produces is less than 1%
  - $\Delta t_\nu = 50ns$ - Veto time window
  - $N_c = 696$ - number of counters per layer
  - ϵ_2 - 2-out-3 detection efficiency.
  - n_p - particles rate per counter

$$f_\nu = [n_p \cdot N_c \cdot \epsilon_2] \cdot \Delta t_\nu = 0.01$$

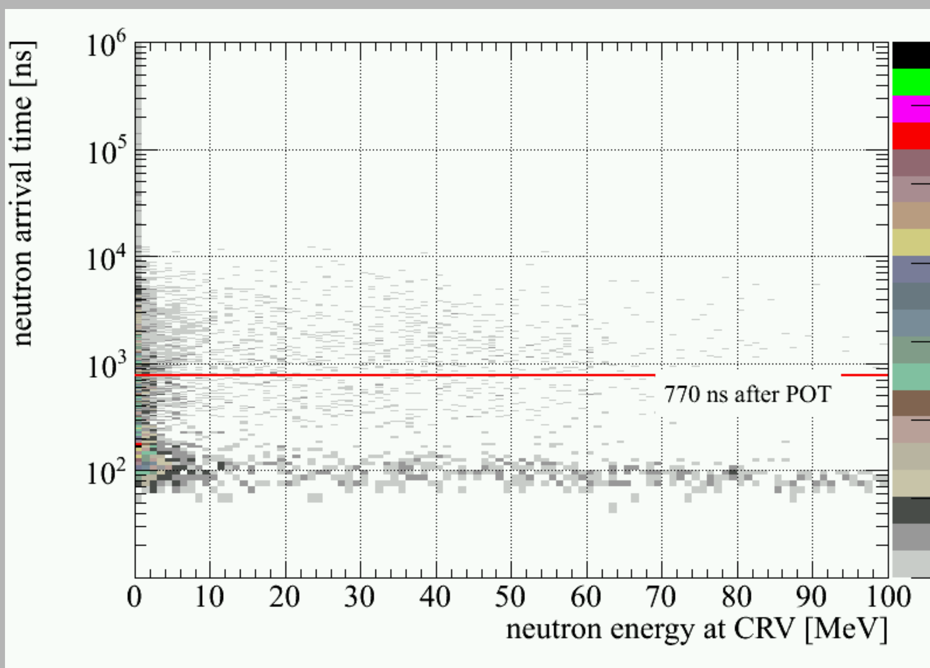
$$n_p = \frac{1}{\epsilon_2} \frac{f_\nu}{\Delta t_\nu \cdot N_c} = \frac{1}{\epsilon_2} \, 300 \; Hz$$

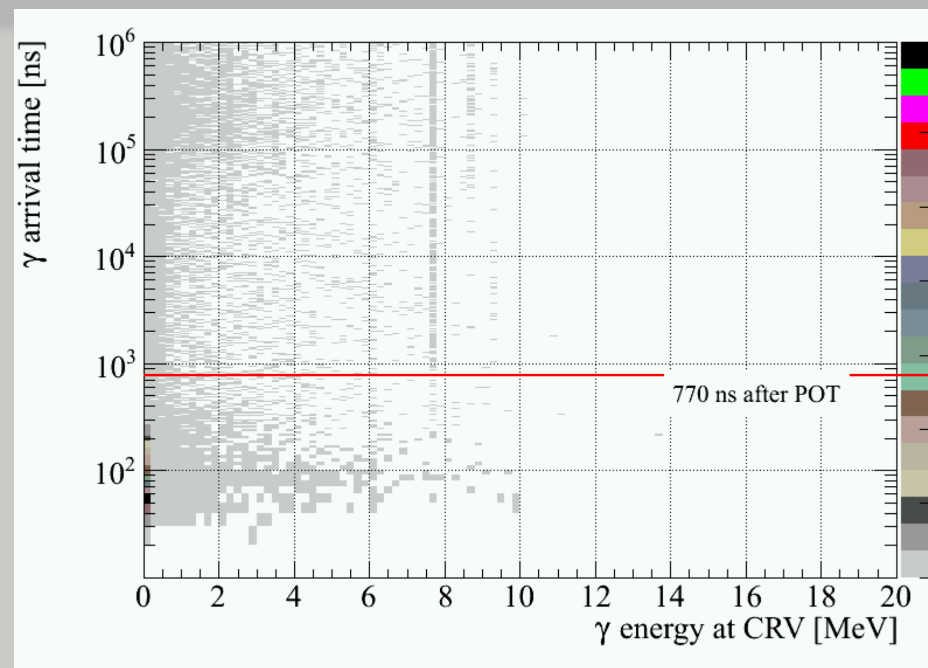
- The total lifetime of the experiment is 1.06E+7 s
- Counter area 4700 cm^2

$$Total \; hits = \frac{1.06 \cdot 10^7 \cdot n_p \cdot \epsilon_2}{4700} = 6 \cdot 10^5 \; [\text{hits/cm}^2]$$

Time v/s Energy

- Neutrons and gammas arrival time at DS left
- Neutrons in TS region(not shown) are even more prompt
- Large fraction of higher-energy neutrons arrive well before the signal time window
- Large fraction of gammas arrive delayed





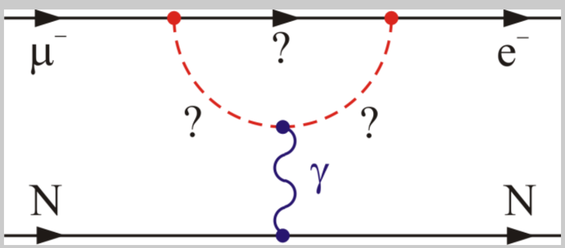
CLFV in $\mu^+ \to e^+\gamma$ and $\mu^- N \to e^- N$

Model independent effective CLFV Lagrangian

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{u}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{u}_L \gamma_\mu e_L \left(\sum \ldots\right)$$

Mass scales probed ~10,000 times that probed directly by LHC

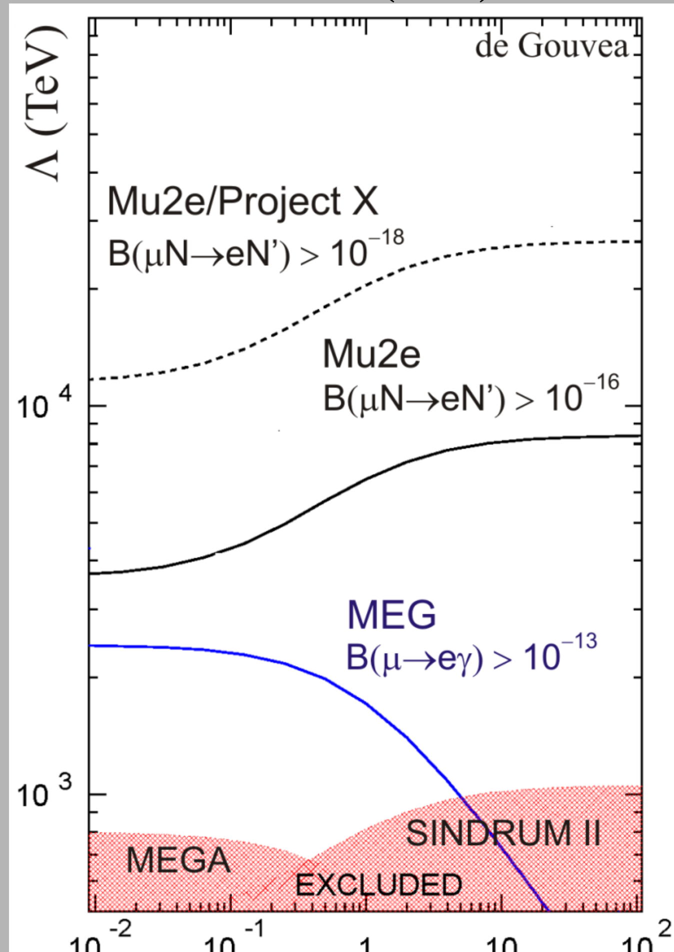
Loops



κ << 1

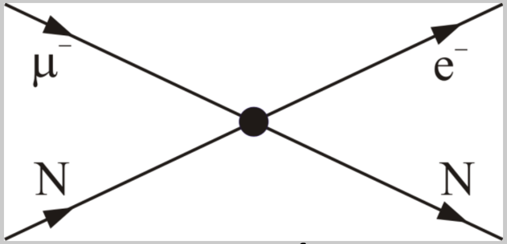
magnetic moment type operator

$\mu \to e\gamma$ rate ~300X $\mu N \to eN$ rate



Loops Contact

Contact Interactions



κ >> 1

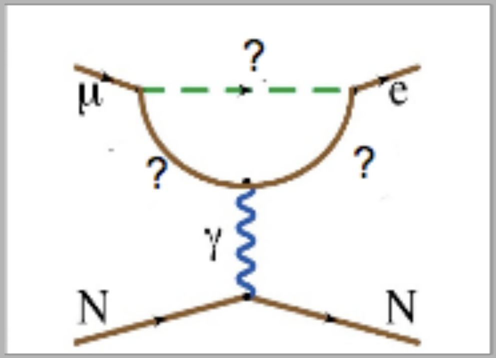
four-fermion interaction

$\mu N \to eN >> \mu \to e\gamma$ rate

Model Independent Parameterization

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

Loops

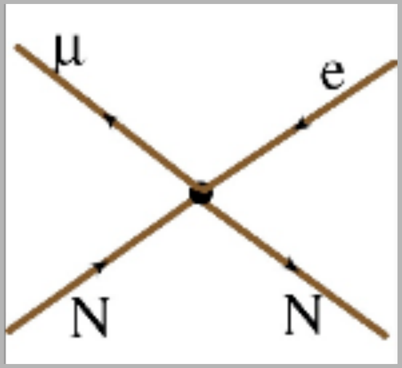


Contributes to μ→eγ

SUSY and massive neutrinos

Dominates if κ<<1

Contact terms



Does not produce μ→eγ

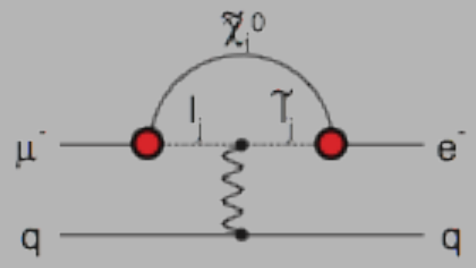
Exchange of a heavy particle

Dominates if κ>>1

Other "new physics" also provide Mu2e signal

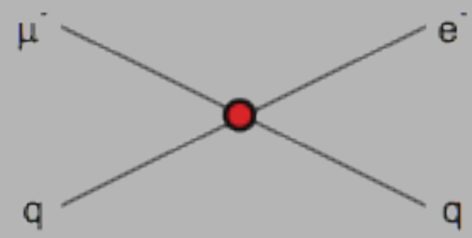
Supersymmetry

rate ~ 10^{-15}



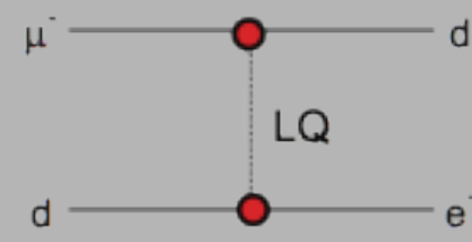
Compositeness

$\Lambda_c \sim 3000$ TeV



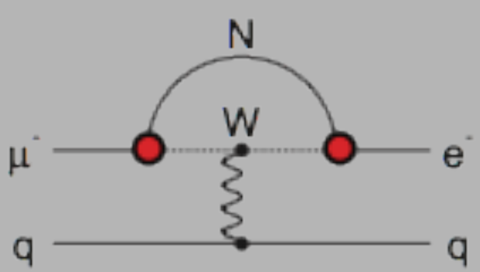
Leptoquark

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



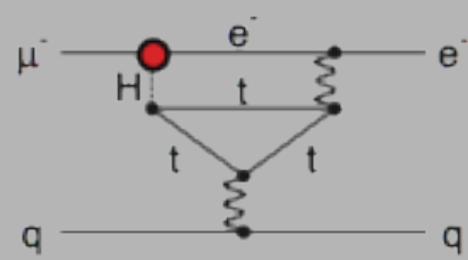
Heavy Neutrinos

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



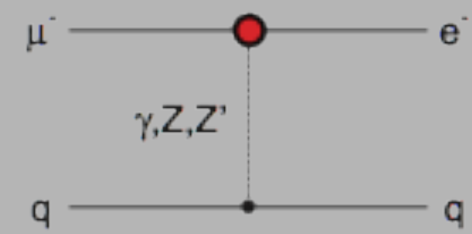
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



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