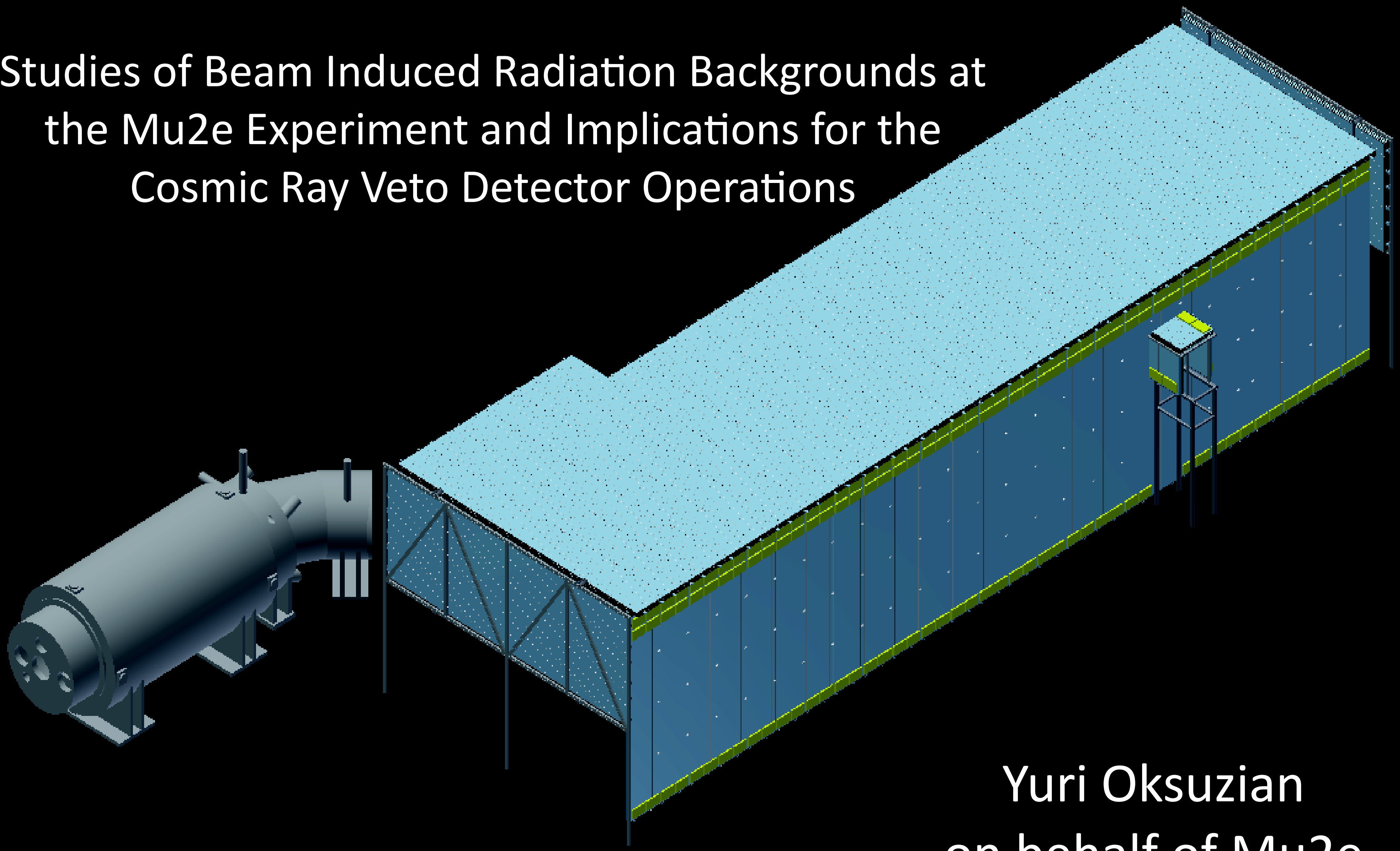
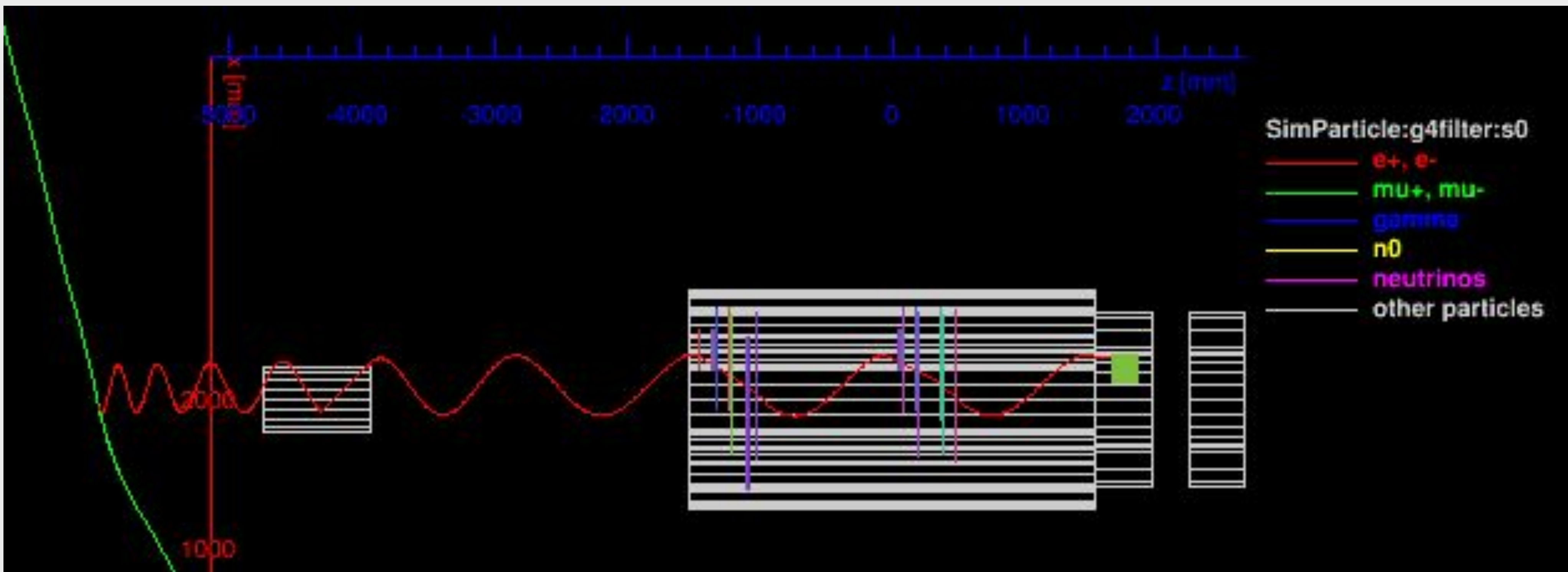
Studies of Beam Induced Radiation Backgrounds at the Mu2e Experiment and Implications for the Cosmic Ray Veto Detector Operations



Yuri Oksuzian
on behalf of Mu2e

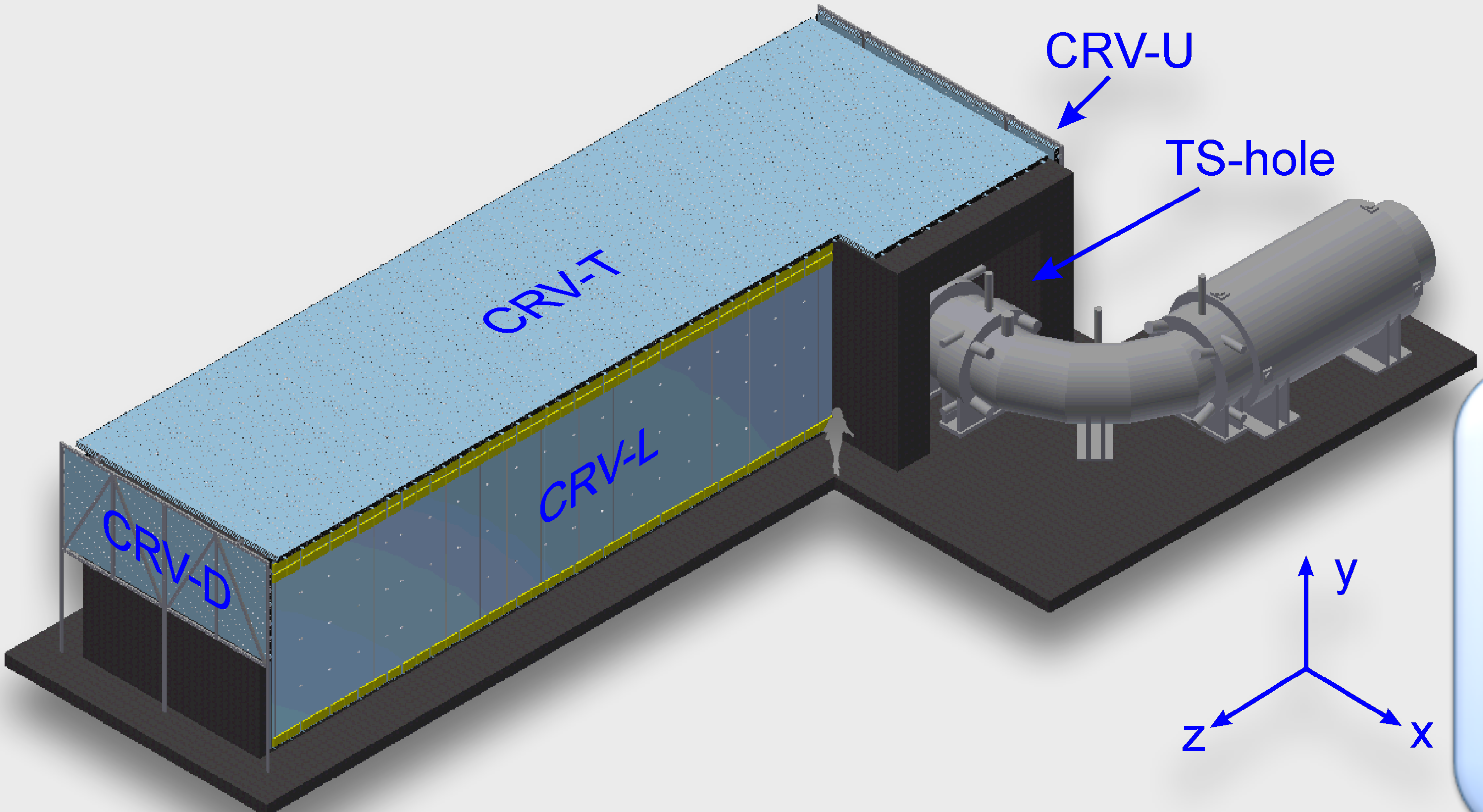
Cosmic Ray Background

- Mu2e will search for a neutrino-less muon to an electron conversion
  - Total expected background is 0.4 events over 3 years
- Mu2e expects 1 signal-like event per day induced by cosmic rays
- Cosmic rays can interact with detector components producing 105 MeV electron
- To achieve experiment's designed sensitivity, cosmic ray veto detection efficiency is required to be > 99.99%



Cosmic Ray Veto

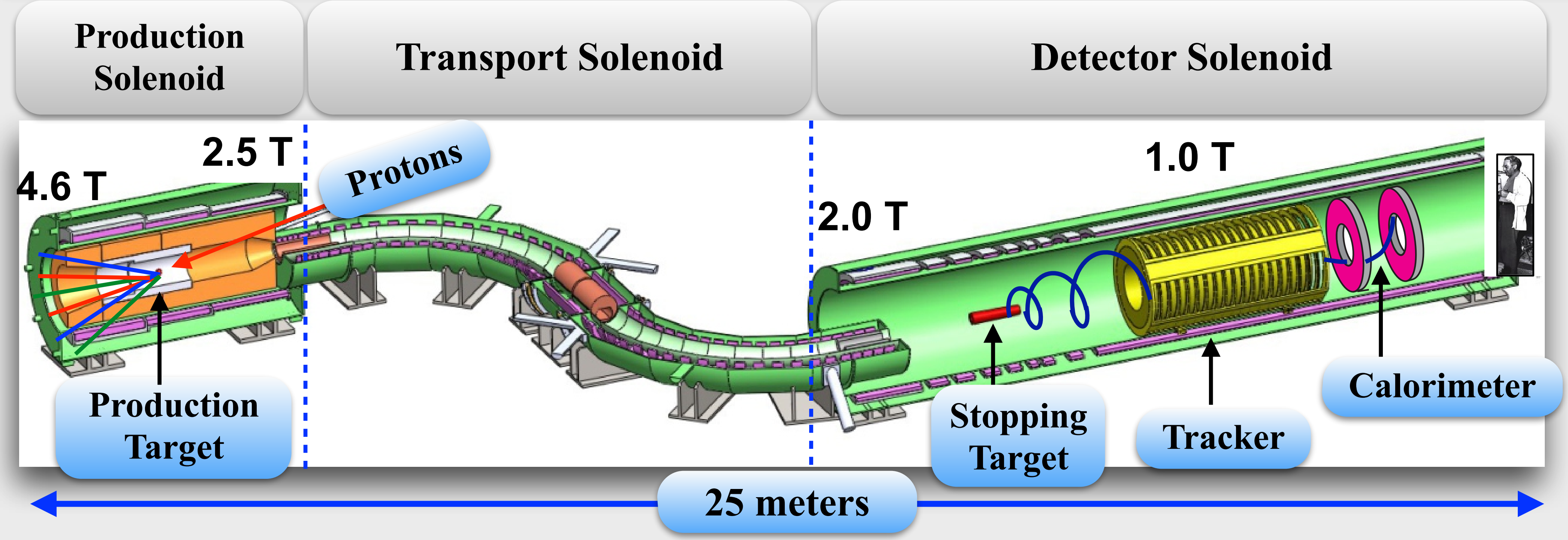
- Cosmic Ray Veto(CRV) consists of 4-layer scintillating 5x2 cm^2 counters, readout though wavelength-shifting fibers by 2x2 mm^2 SiPMs
- We require hit coincidence in at least 3 out of 4 layers localized in time and space for a cosmic ray muon track
- We veto 125 ns from the signal window after each coincidence in the CRV



CRV details:

- Area: 323 m^2
- 82 modules
- 55 tons of counters
- 50 km of fibers
- 18,944 SiPMs

Mu2e apparatus

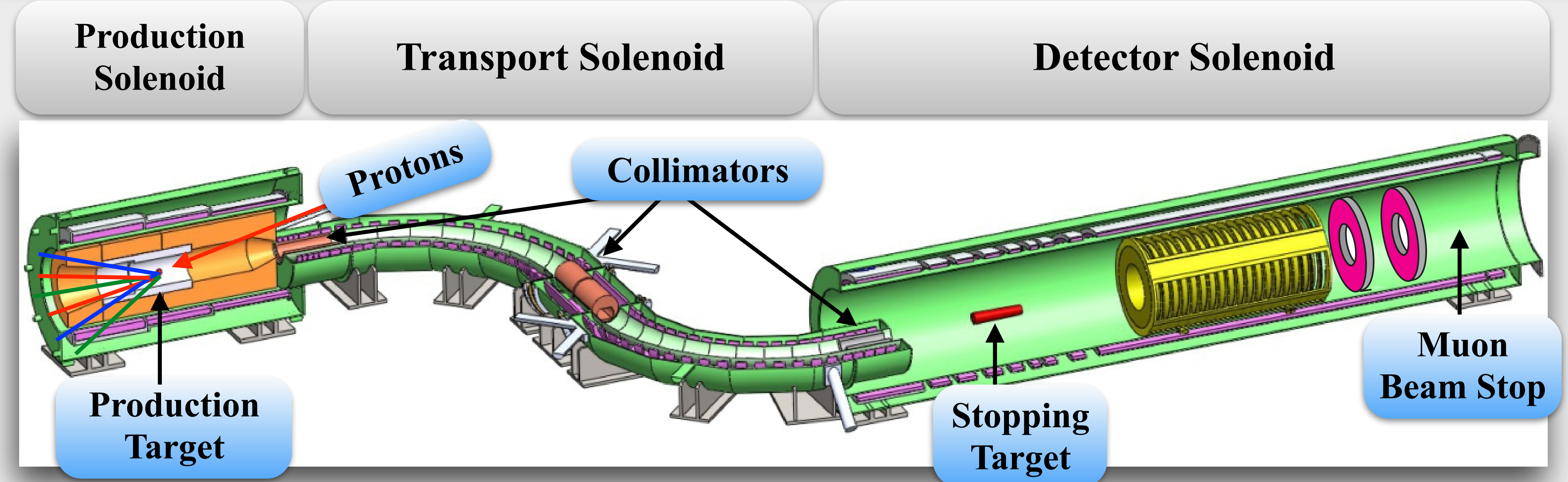


(1) Pulsed (1695 ns) 8 GeV proton beam strikes production target to produce π^-
- Graded B-field reflects π^- toward the transport solenoid

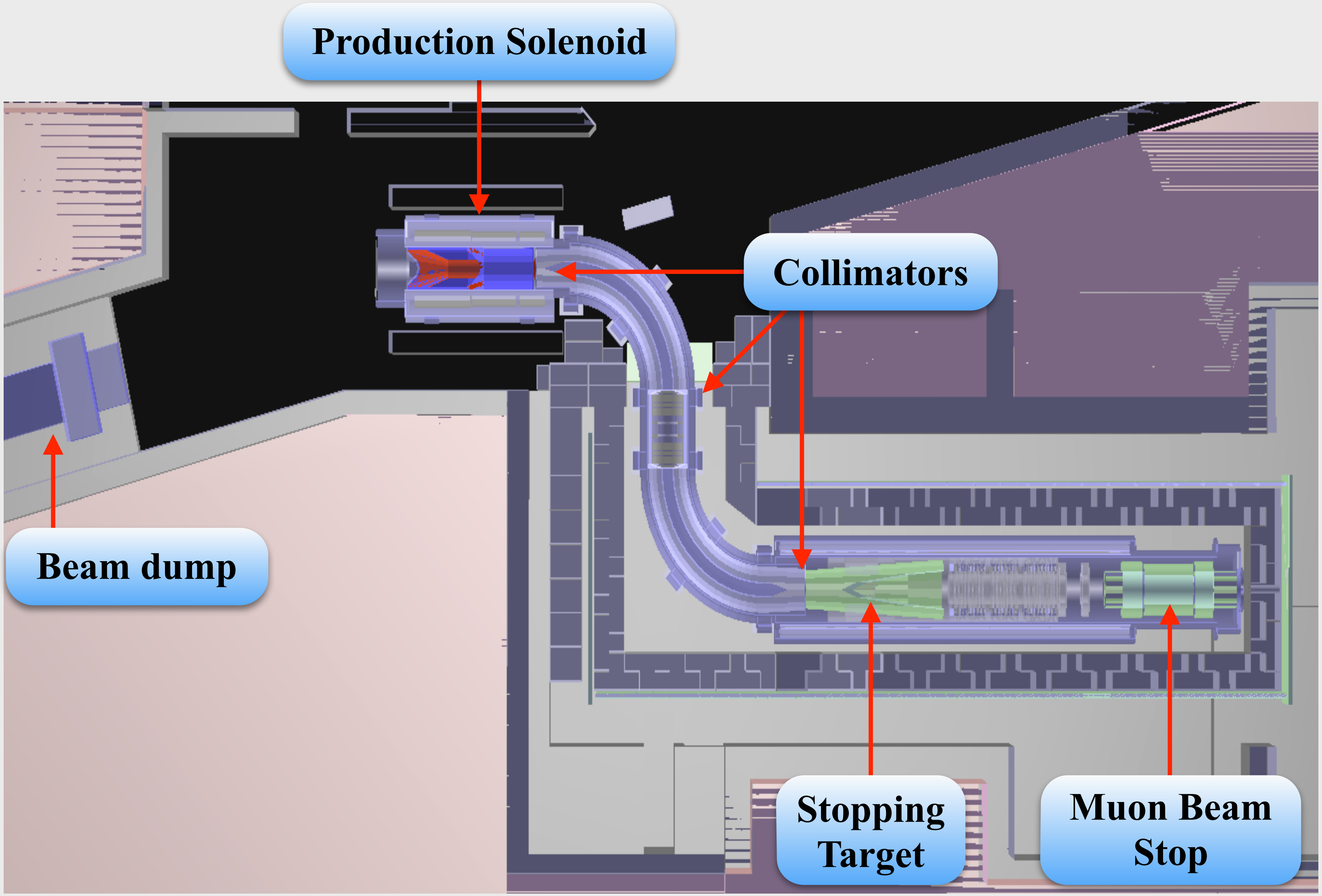
(2) Trasport solenoid:
- Transports π^-/μ^- , selects particle's momentum and charge, avoids direct line of sight

(3) Muons stop on Al target. Wait for 700 ns to avoid prompt backgrounds
- Conversion electron momentum and energy are measured in the tracker and calorimeter

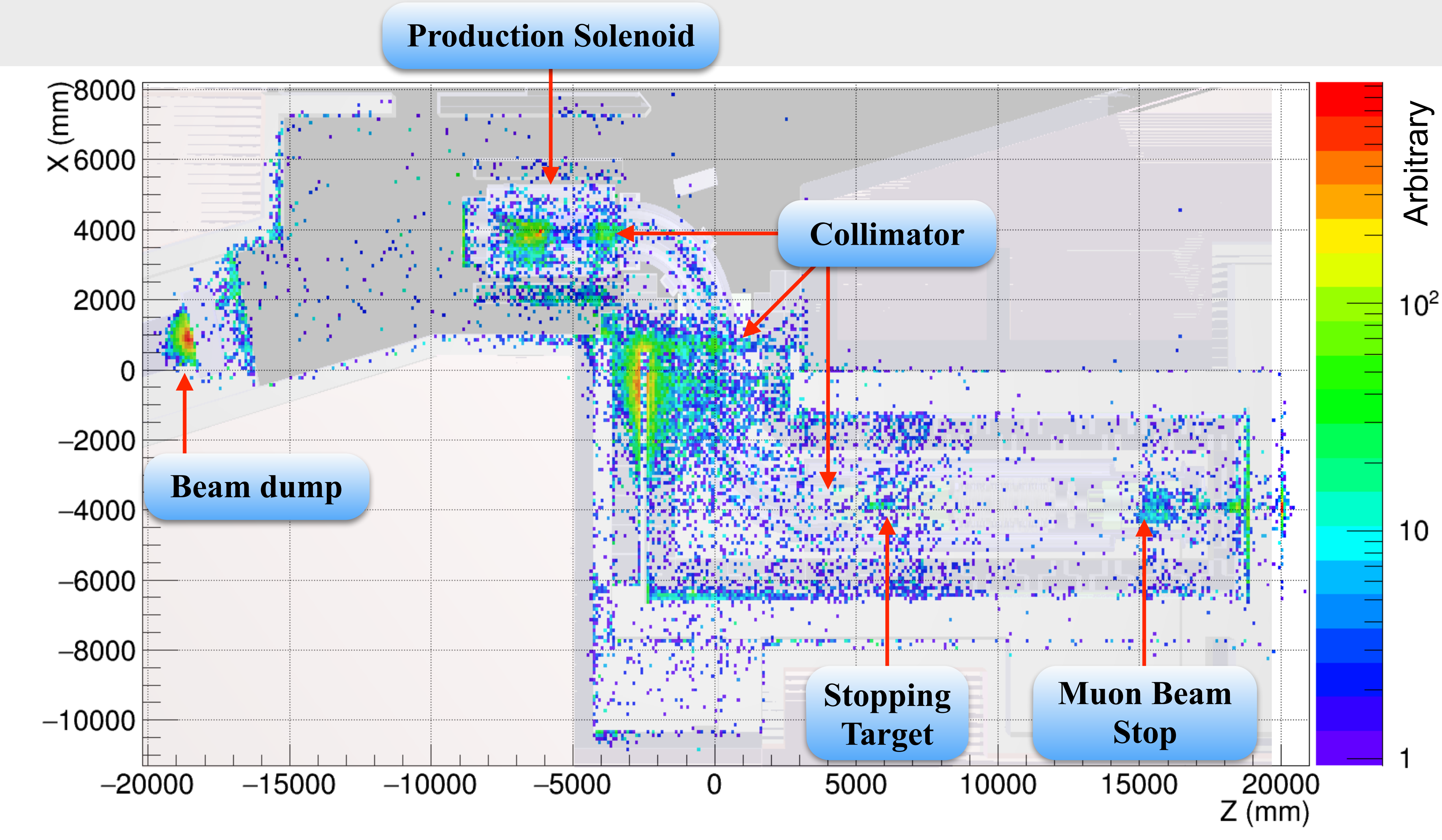
Neutrons and gammas at CRV



- Neutron and gamma fluxes from beam interactions cause challenges to CRV
  - Make hits in the CRV, faking cosmic ray muons and increasing the dead-time
- Largest source of neutrons originate from Production Solenoid after beam flash
  - This source is prompt. It is reduced after 700 ns
- Neutrons get thermalized, captured and produce delayed gammas
  - Other sources of gammas: electrons brems from μ-decays
- Source of delayed neutrons originate from μ-captures on collimators, beam-line and stopping target

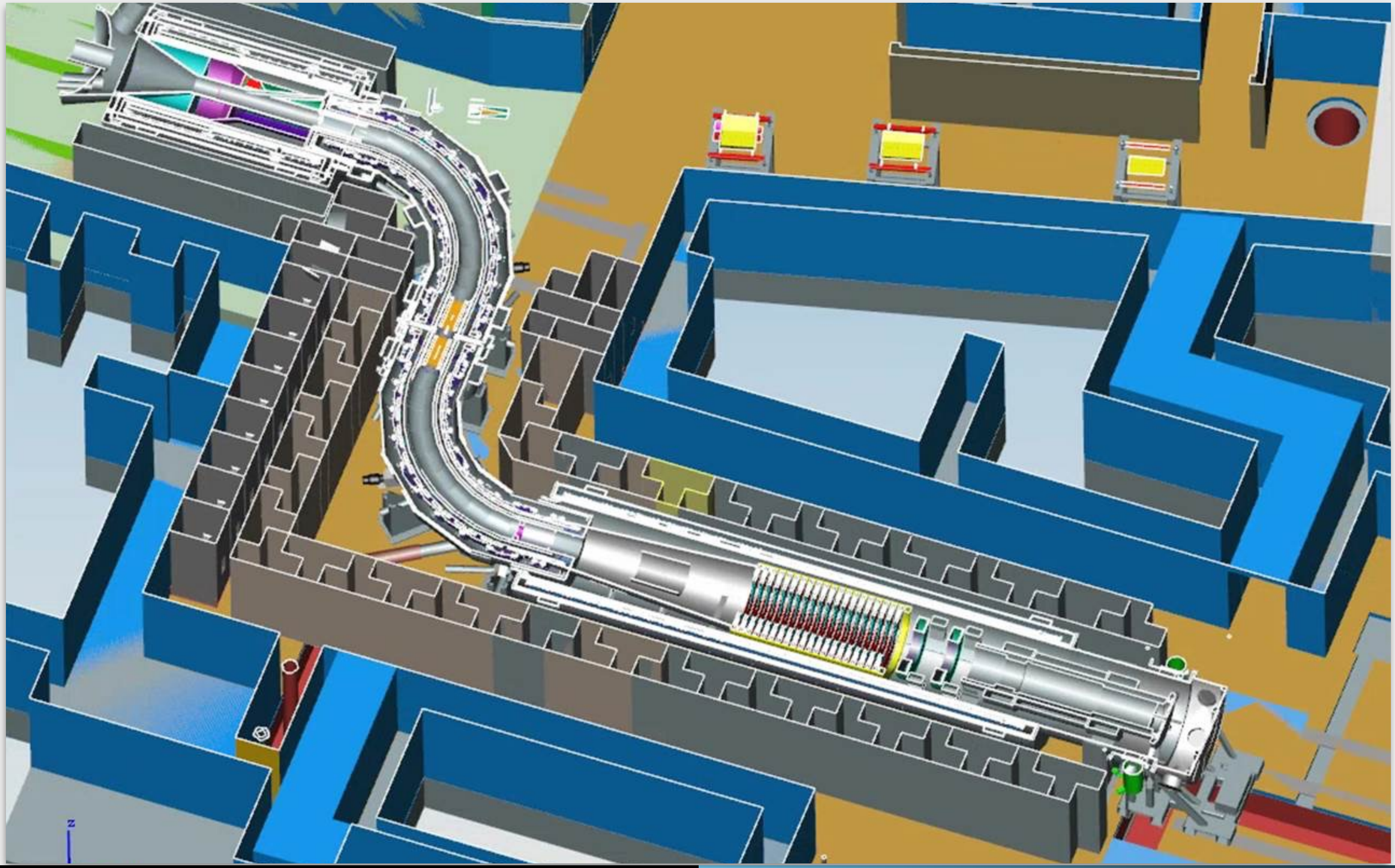

Production Solenoid
Collimators
Beam dump
Stopping Target
Muon Beam Stop

Sources of neutrons and gammas at CRV



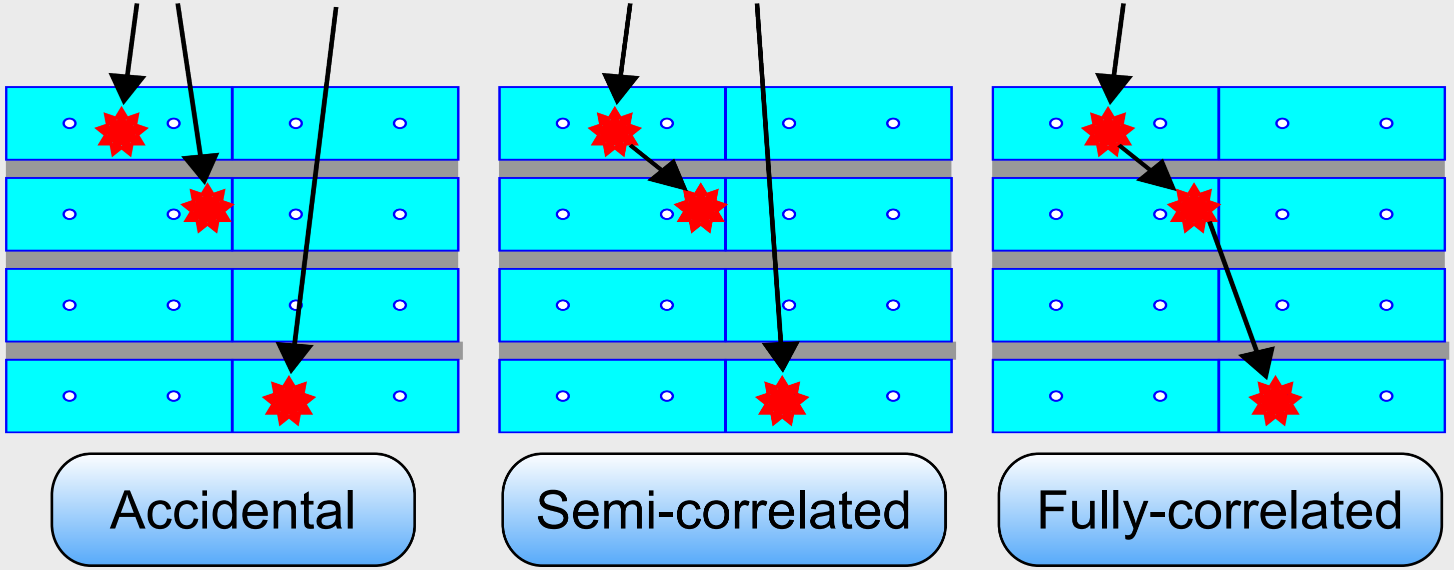
CRV shielding

- CRV needs to be shielded from the beam induced radiation backgrounds
- CRV is mounted on 1 yd of concrete walls
- T-shaped concrete blocks are designed to avoid direct cracks
- Region close to PS/TS is enhanced with heavy barite enriched concrete



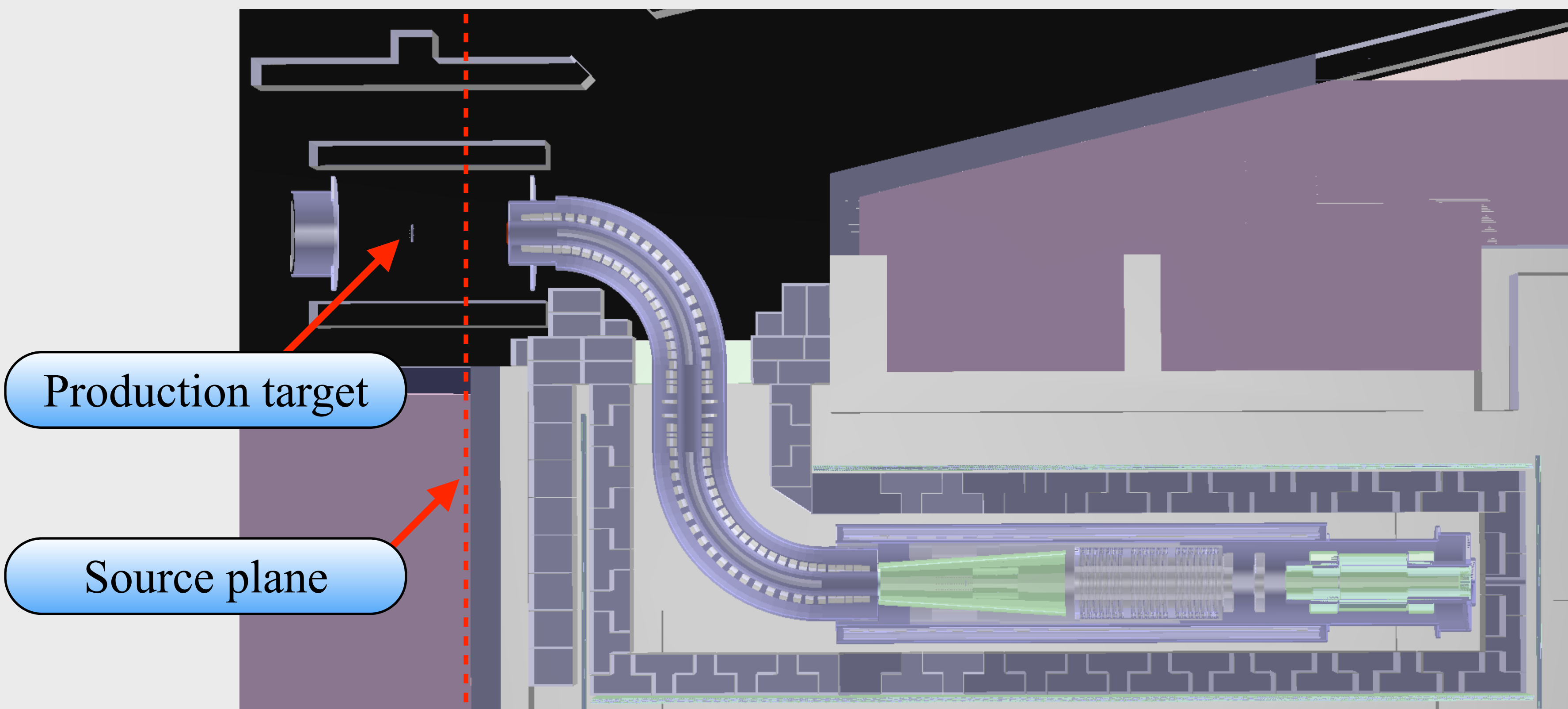
Dead-time estimate

- Neutron and gamma can produce 3/4 veto coincidence:
  - Accidental, semi-correlated, full-correlated coincidences are produced by 3, 2 and 1 incoming particles respectively
- First dead-time estimate was performed using G4beamline
  - It allowed us to quickly adjust the CRV and shielding design
  - Original CRV design: 3-layers of 10x1 cm^2 counters



G4beamline: Simulations

- G4beamline simulation is performed in the following steps
- Stage 1: Simulate POT and record all particles on the source plane
- Stage 2: Resample from the source plane
- The result of stage 2: neutron and gamma fluxes at the CRV
- For each geometry design iteration, we simulate 1E6 (1E9) POT on the 1st (2nd) stage



G4beamline: Dead-time estimate

Estimate the neutron/gamma fluxes at the CRV

Estimate the neutron/gamma efficiency to produce n-fold coincidence above 0.5 MeV

→ Produce n-fold hit rates at the CRV → Calculate the dead-time

Accidental

$$f_v = \sum_{i=1}^{N_{cl}} 3 n_{1i}^3 \Delta t_v N_1 \Delta t_c^2 \quad = 3 \Delta t_v N_1 \Delta t_c^2 \sum_{i=1}^{N_{cl}} n_{1i}^3$$

Semi-correlated

$$f_v = \sum_{i=1}^{N_{cl}} 2 n_{12i} n_{2i} \Delta t_v N_2 \Delta t_c \quad = 2 \Delta t_v N_2 \Delta t_c \sum_{i=1}^{N_{cl}} n_{12i} n_{2i}$$

Fully-correlated

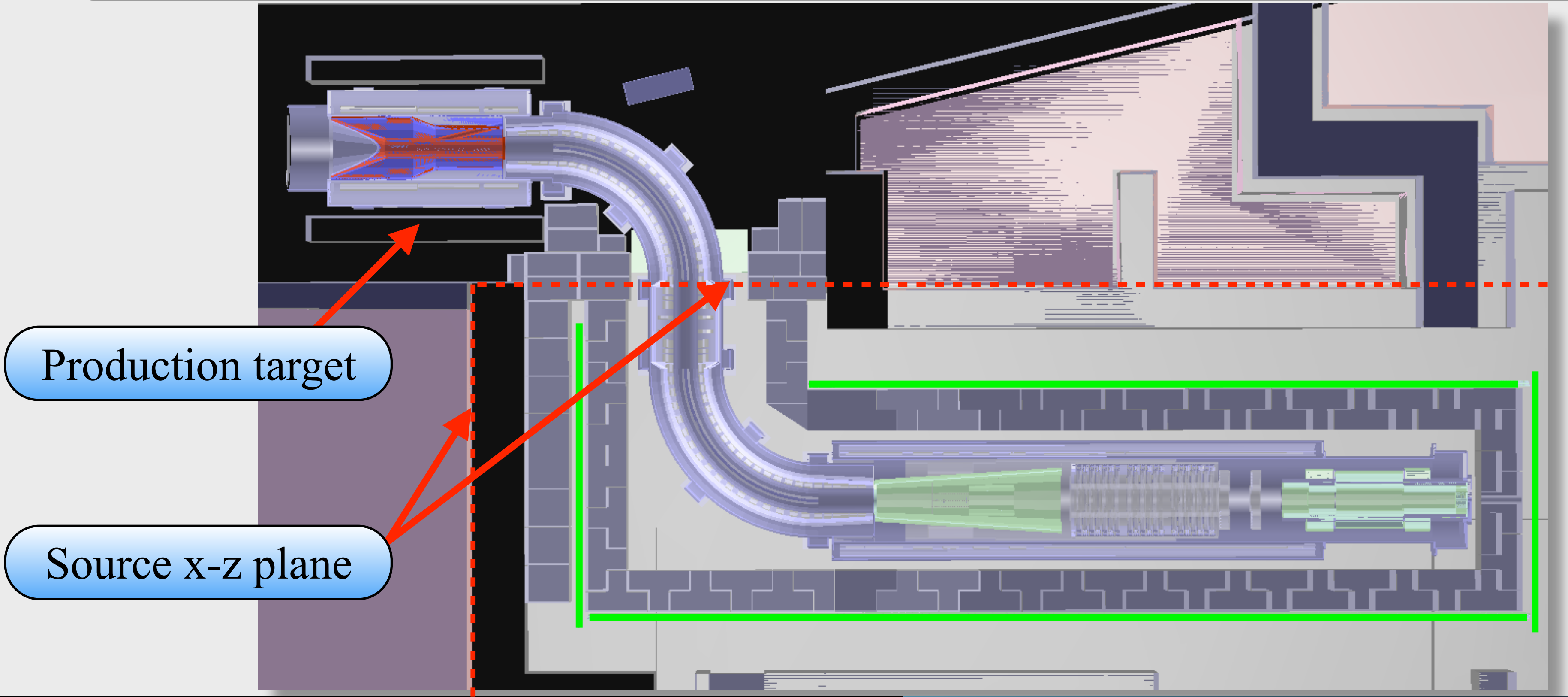
$$f_v = \sum_{i=1}^{N_{cl}} n_{3i} \Delta t_v \quad = \Delta t_v \sum_{i=1}^{N_{cl}} n_{3i}$$

- Total dead-time was estimated to be 4%
- The number is sensitive to hit time resolution, effective energy threshold…

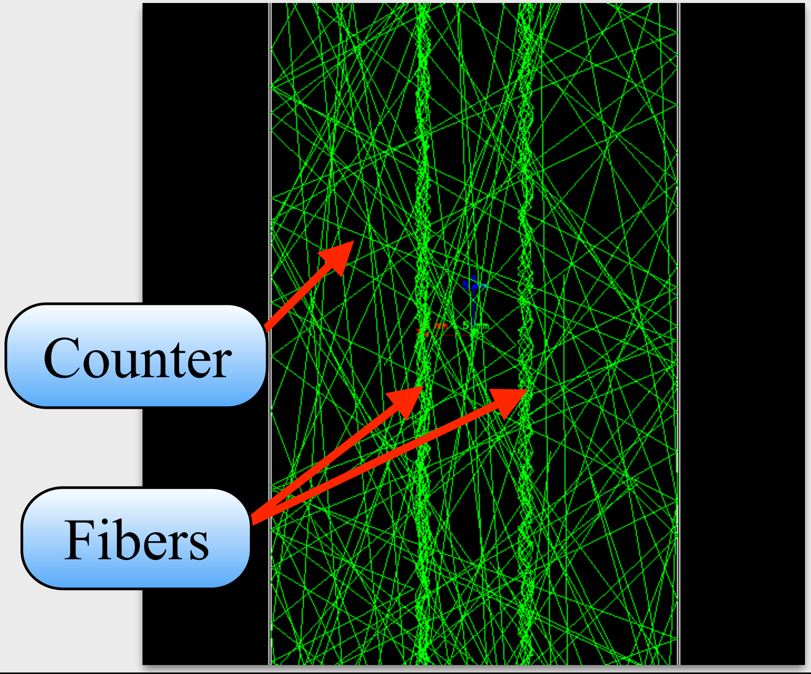
Mu2e simulation framework

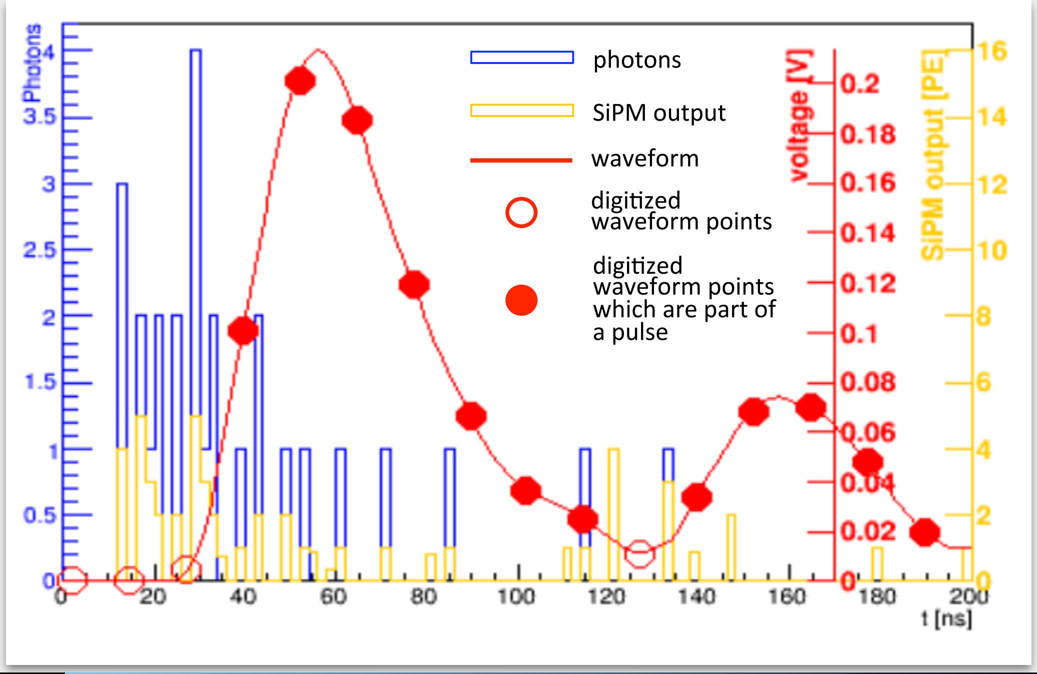
1: Use multi-stage simulation approach in Mu2e simulation framework

- 1: Simulate POT and record all the products at the x-z plane
- 2: Resample all particles except muons from the x-z plane
- 3: Propagate muons from x-z plane until they stop
- 4: Resample daughters from the muon stops
- 5: Mix (2) and (4) to form micro-bunches



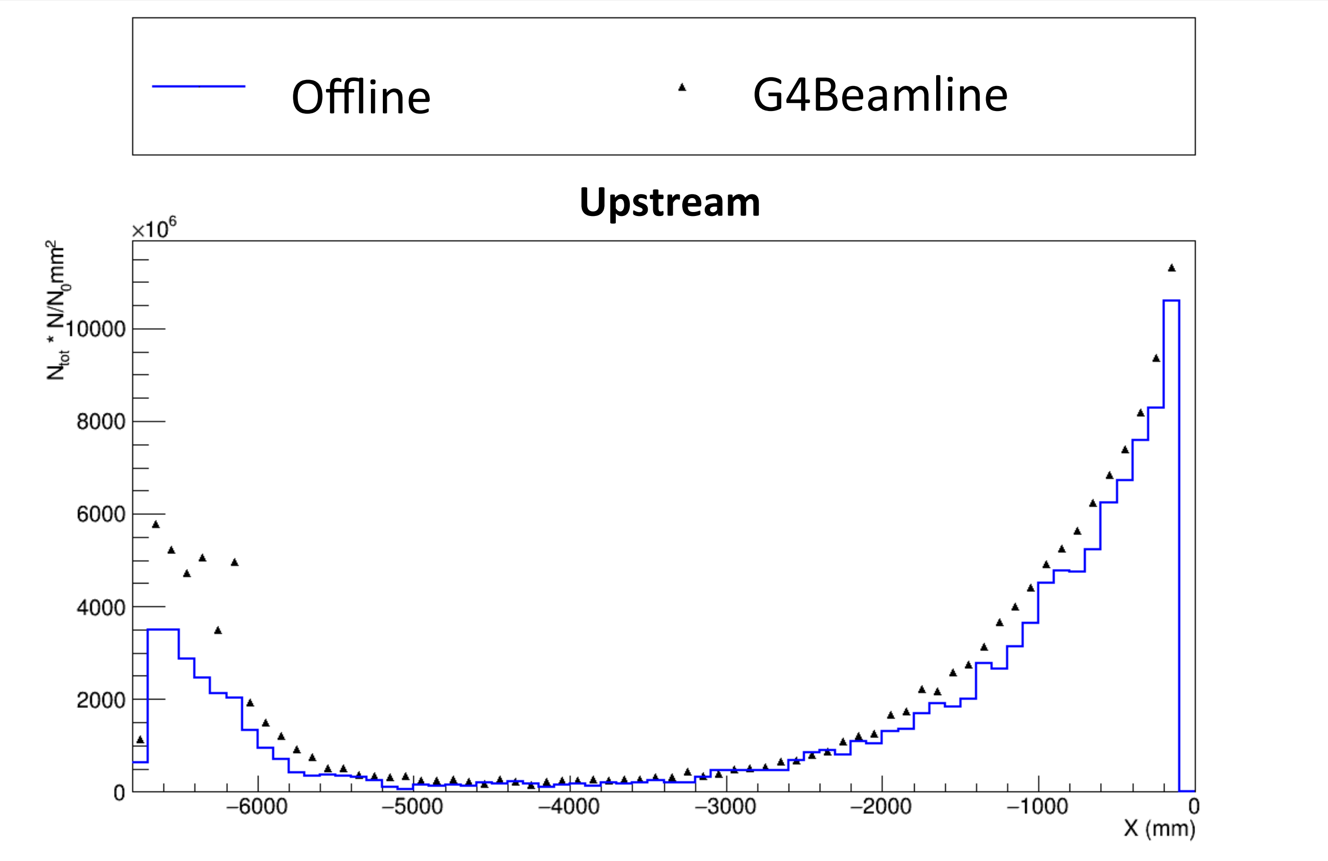
- CRV dead-time in the Mu2e simulation framework is estimated
  - Simulation of light production, propagation, SiPM response, digitization and reconstruction have been recently implemented
  - Shielding geometry has been recently refined to the best of our knowledge
- Simplified version of a coincidence finder algorithm has been implemented
  - Consider reconstructed pulses above 10 PE threshold
  - Localized in time (15 ns) and space (30 cm)
- The total dead-time is estimated to be 12%





Fluxes comparison

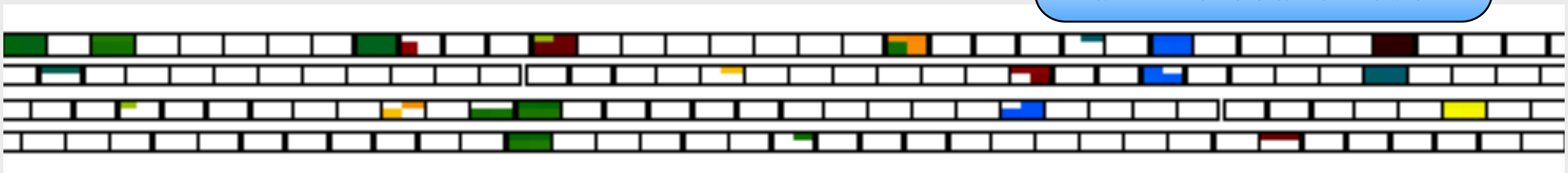
- We cross-check the neutron and gamma fluxes between G4beamline and Mu2e framework
- The agreement is good
- Both framework use G4 under the hood
- We're currently working to compare the fluxes with MARS



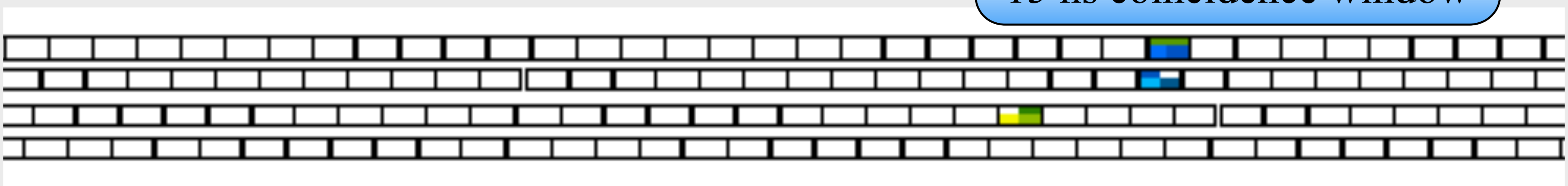
Event display

- Event display has been developed to visualize coincidences
  - Each box corresponds to a counter divided into for quadrants (SiPMs)
  - Each SiPM hit is color coded in time
- Large number of CRV hits from neutrons and gammas in a single event
- Small fraction of hits are localized in space and time to form coincidence
- Future improvements to coincidence finder algorithm will further reduce the number of coincidences

Full microbunch event



15 ns coincidence window



Summary

- Cosmic ray veto is an essential component for the Mu2e experiment
  - Suppress the background by 4 orders of magnitude
- CRV design is challenging
  - Maintain 99.99% cosmic ray veto efficiency over 3 years
  - Operate in high radiation environment, and produce small dead-time for the experiment
- CRV and shielding design has been modified to reduce the impact
  - Further optimization is in progress
- First Mu2e framework simulation results show the dead-time of 12%
  - Expect to reduce the number with further optimizations
- Details in Mu2e TDR