A Beam-Based Production Target Monitor for the Mu2e Experiment at Fermilab

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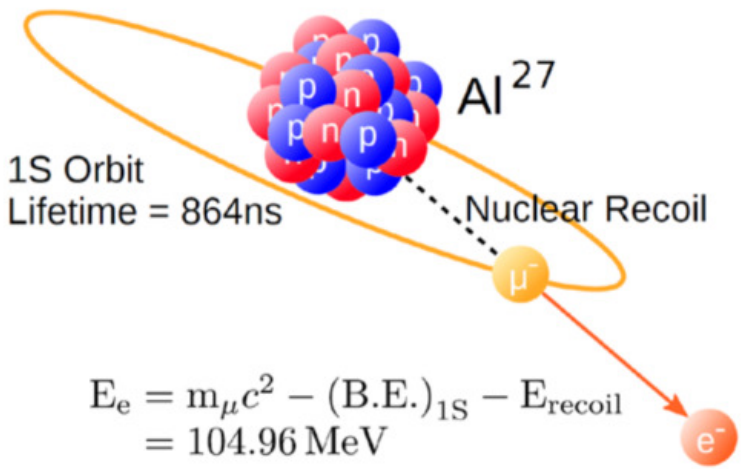
What is Mu2e

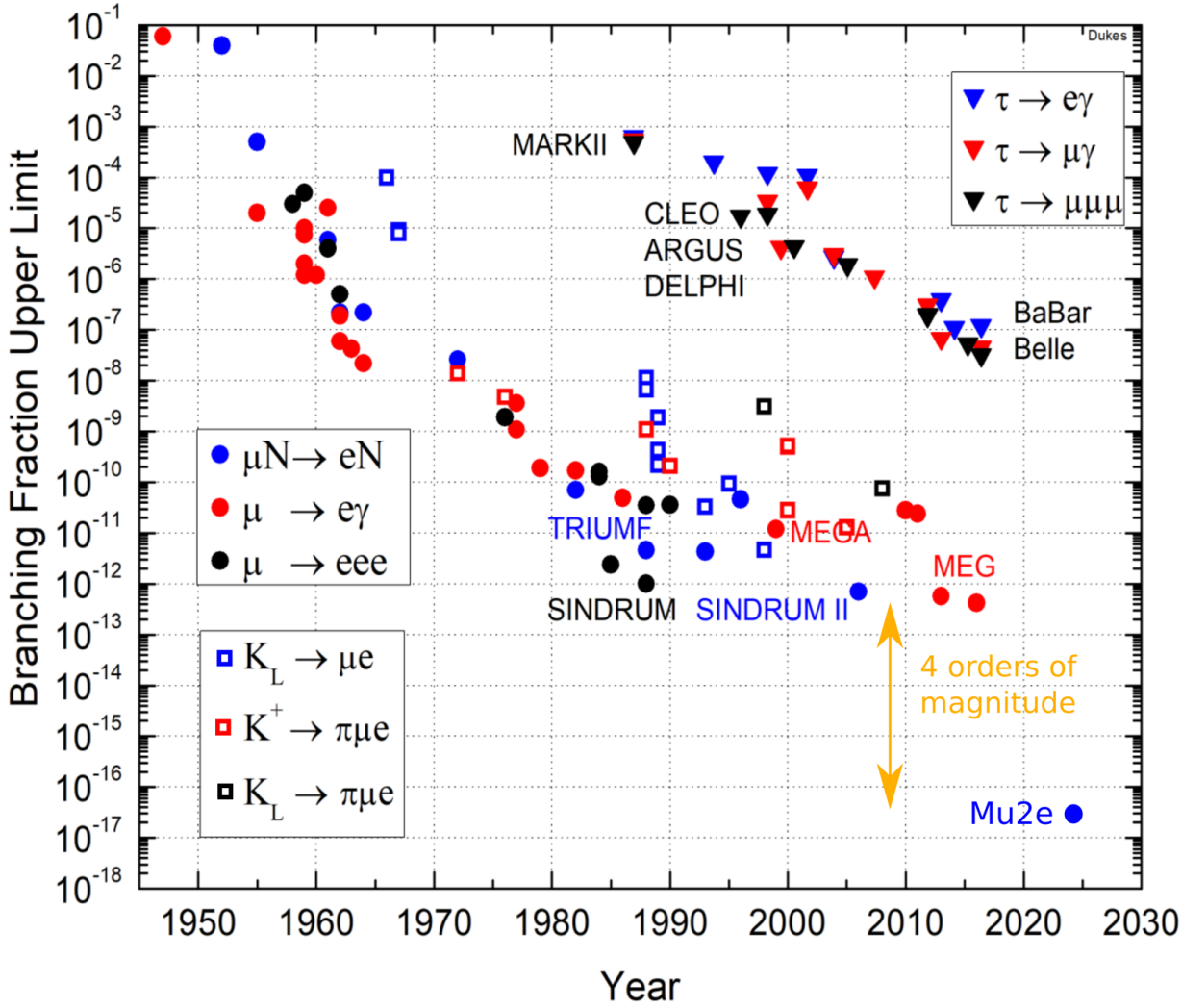
New experiment under construction at Fermilab.
We are looking for new physics – **charged lepton flavor violation**.
Rare interaction: muon converting to electron, without neutrinos, in the presence of an atomic nucleus.



Standard Model rate: $< 10^{-50}$
New physics rates: $10^{-17} - 10^{-15}$

What is Mu2e

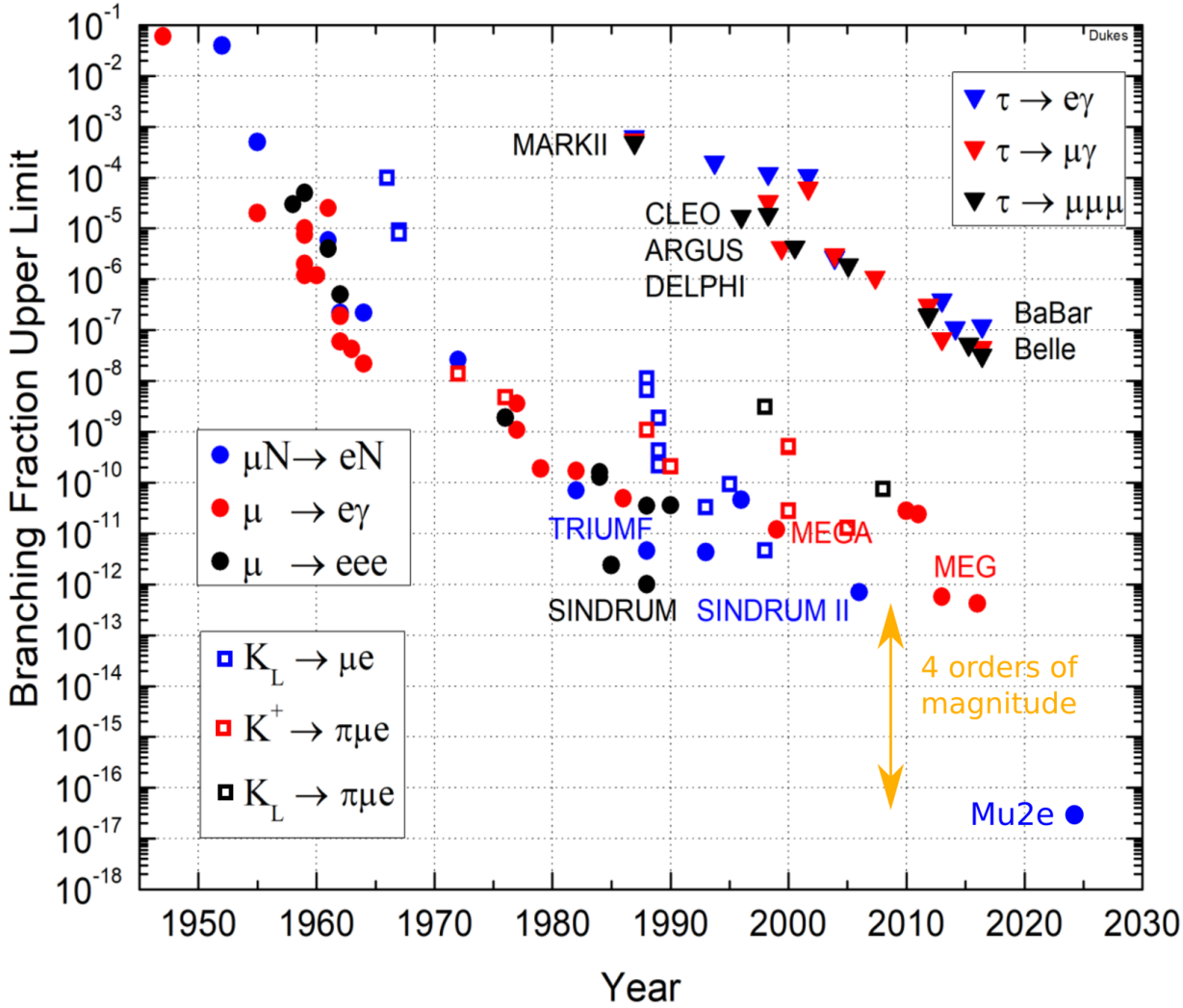
Mu2e will detect branching ratios as low as 8×10^{-17} at 90% CL



which is four orders of magnitude more sensitive than previous experiments.

What is Mu2e

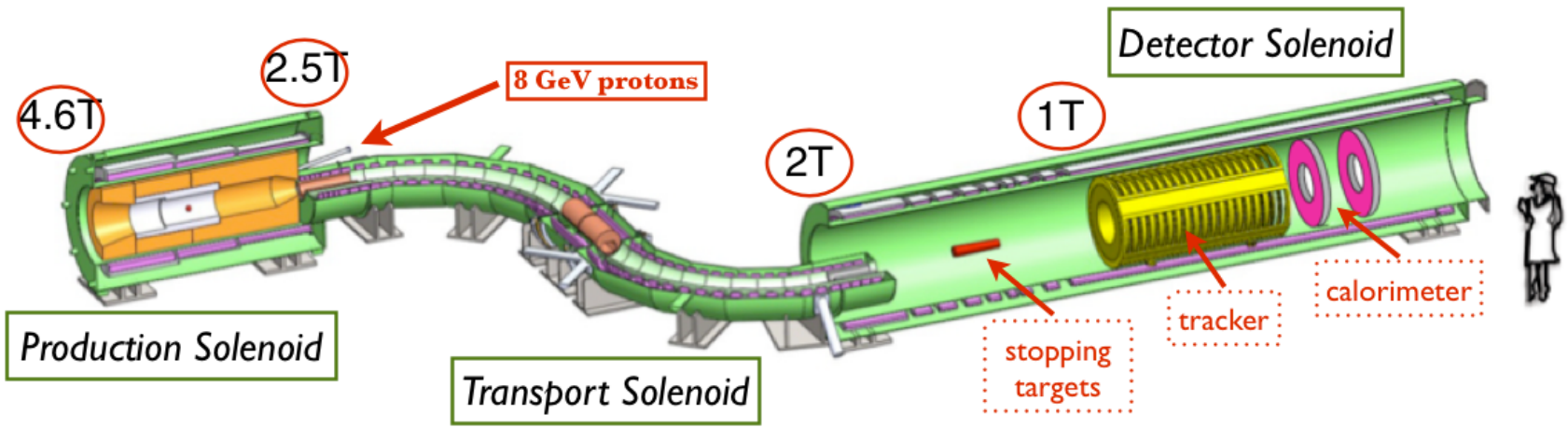
Single event sensitivity 3×10^{-17}



Requires most intense muon beam ever developed – 10^{10} μ/s!

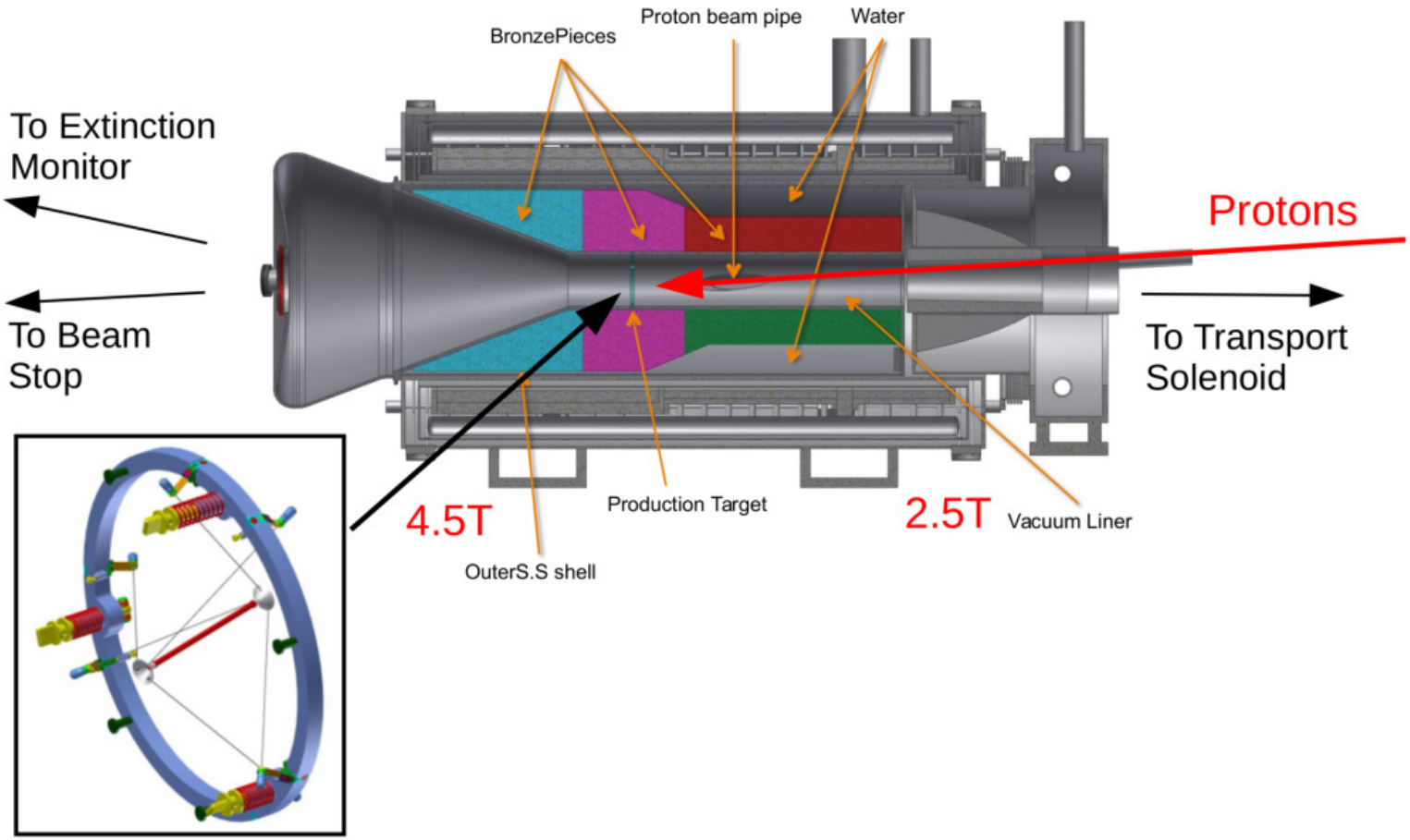
What is Mu2e

Experimental overview:



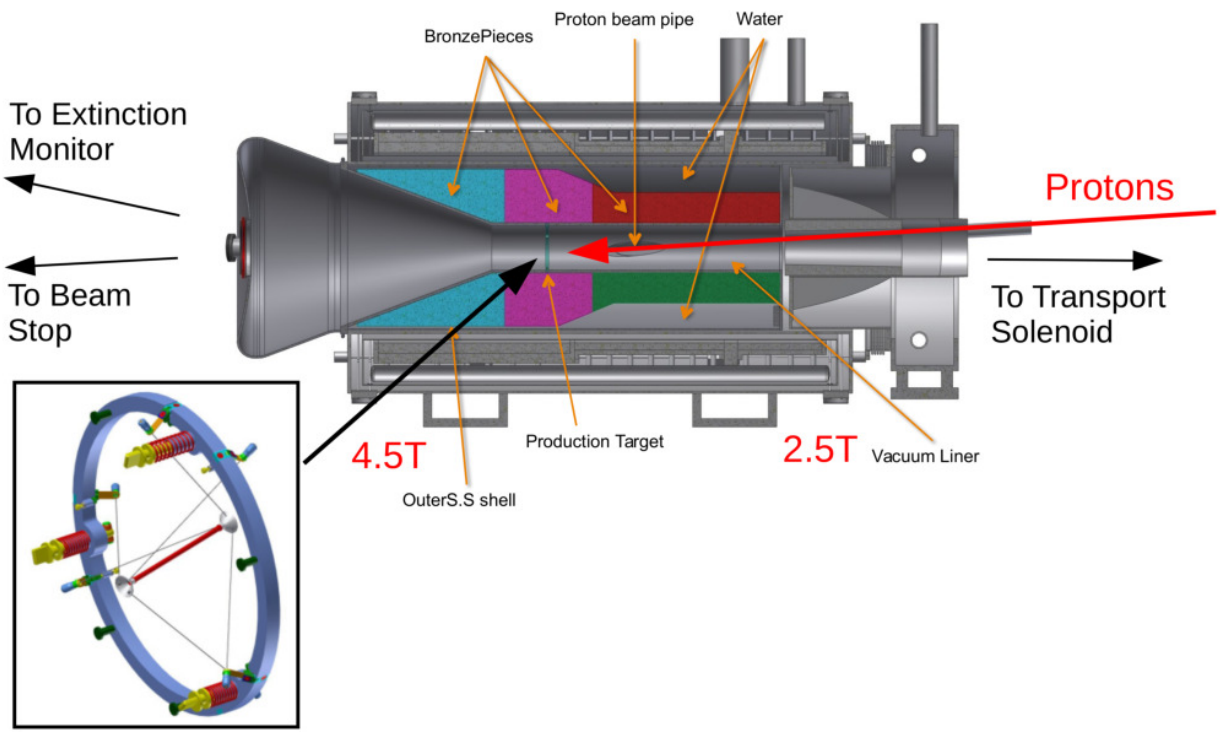
Production Target

Muons are produced for Mu2e in the Production Solenoid (PS), which contains the production target.



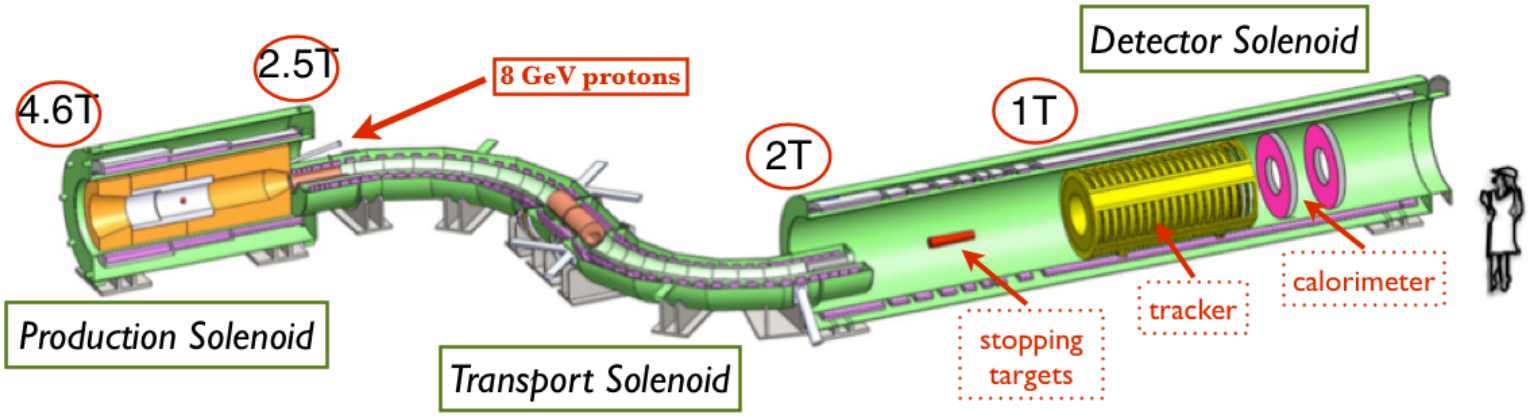
Production target: tungsten, 6.3 mm diameter, 160 mm long, held in place by thin spokes

Production Target



- 8 GeV pulsed proton beam
- Target absorbs $\sim$ 700 W from beam, or 140 W/cm^3
- Beam-target interactions produce pions which decay to muons

Production Target

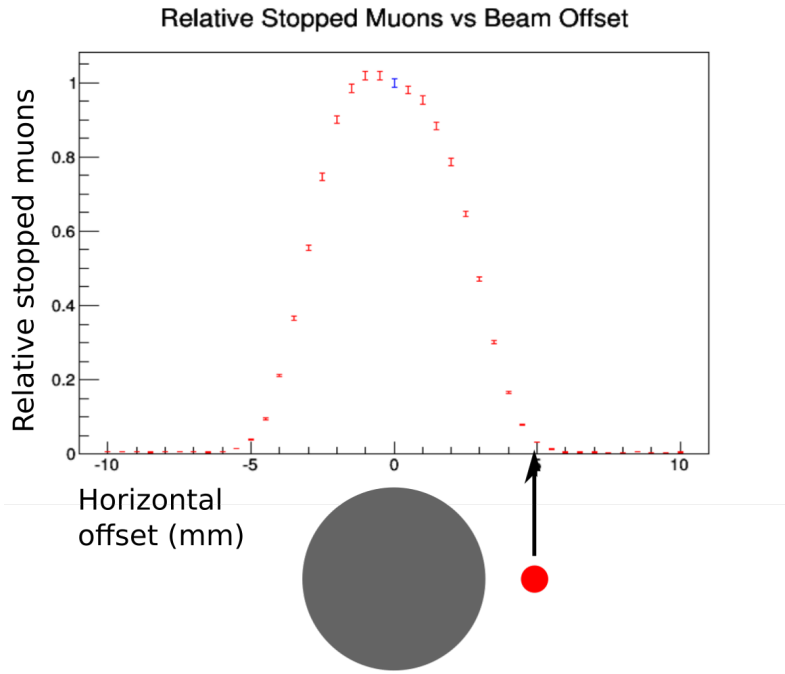


- Magnetic field gradient guides backwards μ^- toward the Transport Solenoid (TS)
- Spent beam and beam backgrounds directed away from muon stopping target and detectors

A Production Target Requirement

Primary goal = **maximize muon production**.

Muon stops in the stopping target drop significantly if proton beam is even slightly mis-aimed.



Requirement: proton beam hits the target along its central axis, to within ± 0.5 mm.

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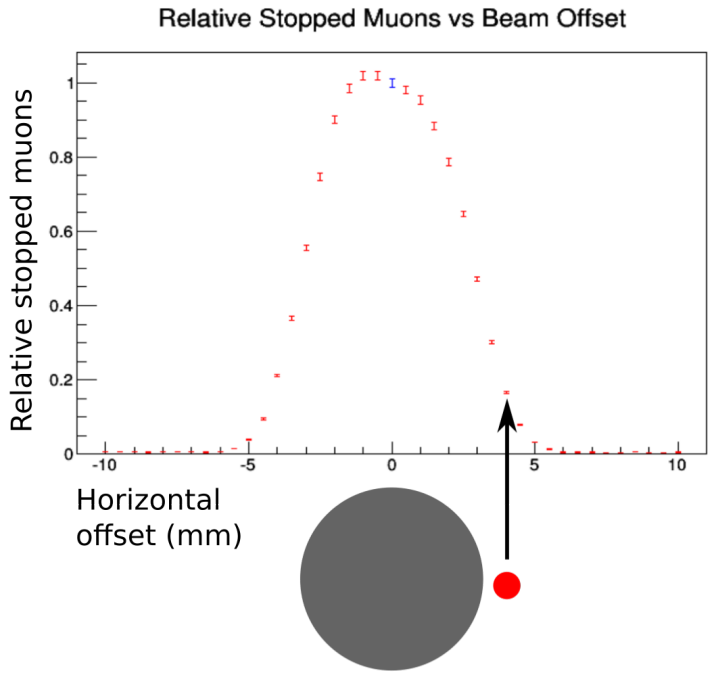

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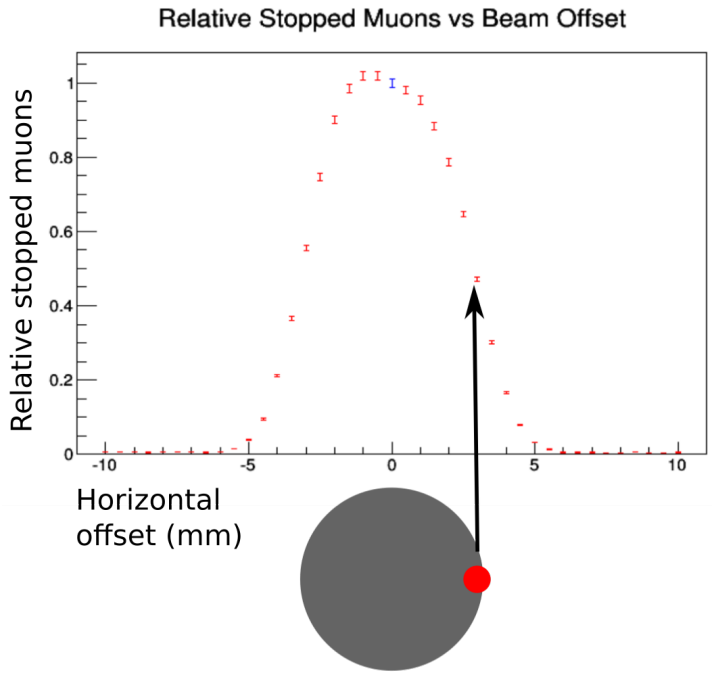

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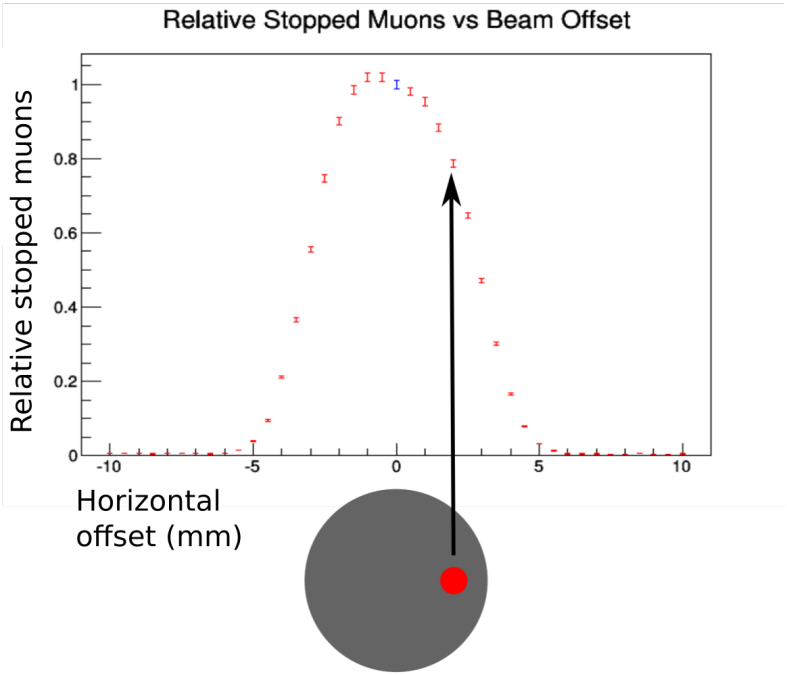

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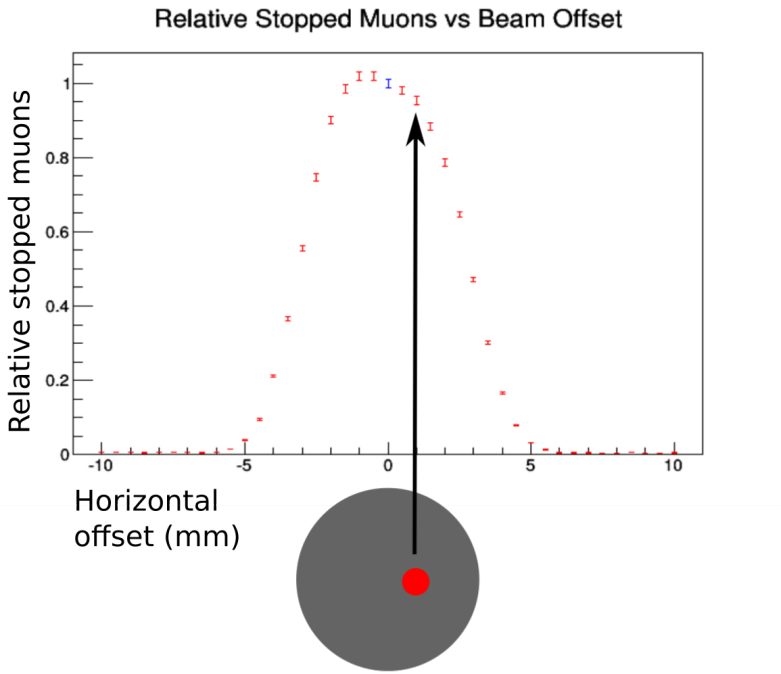

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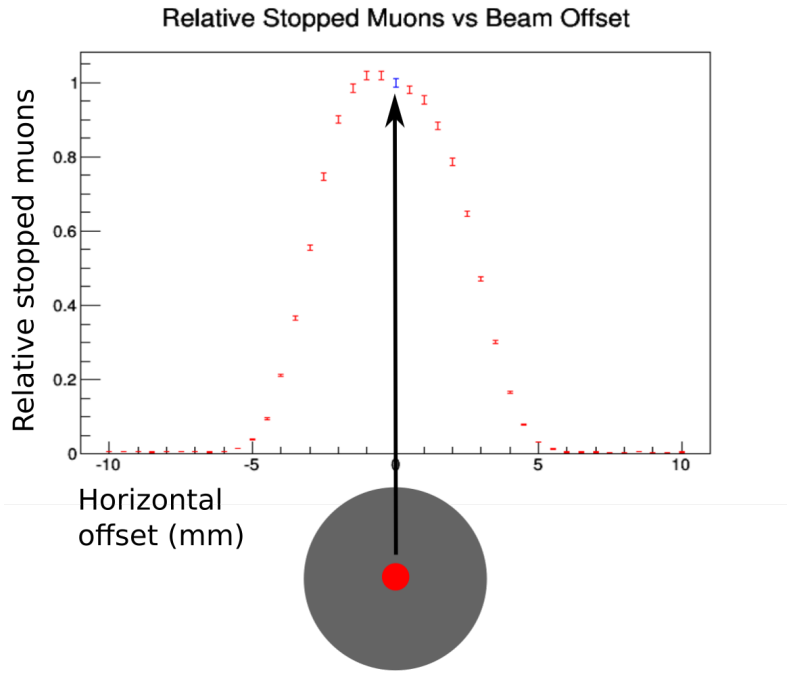

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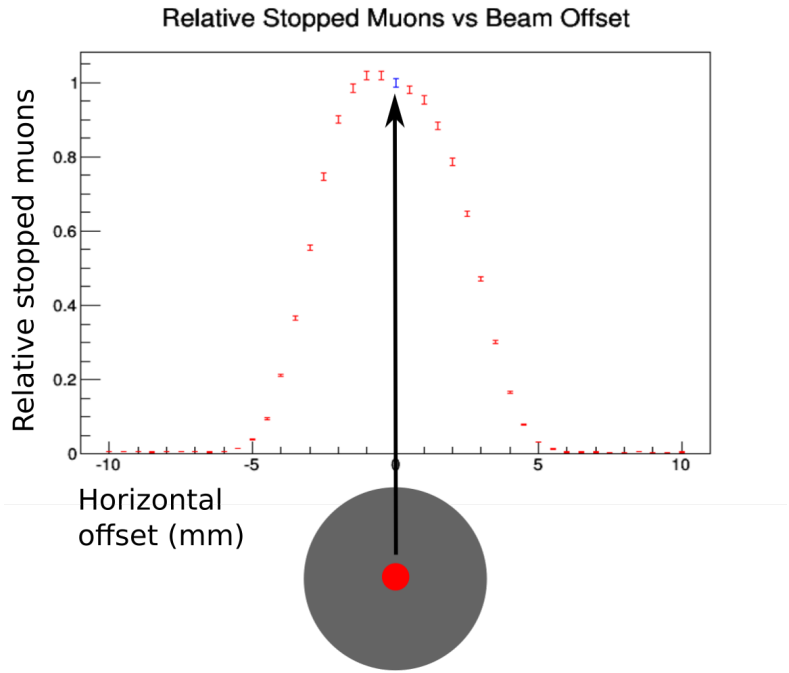
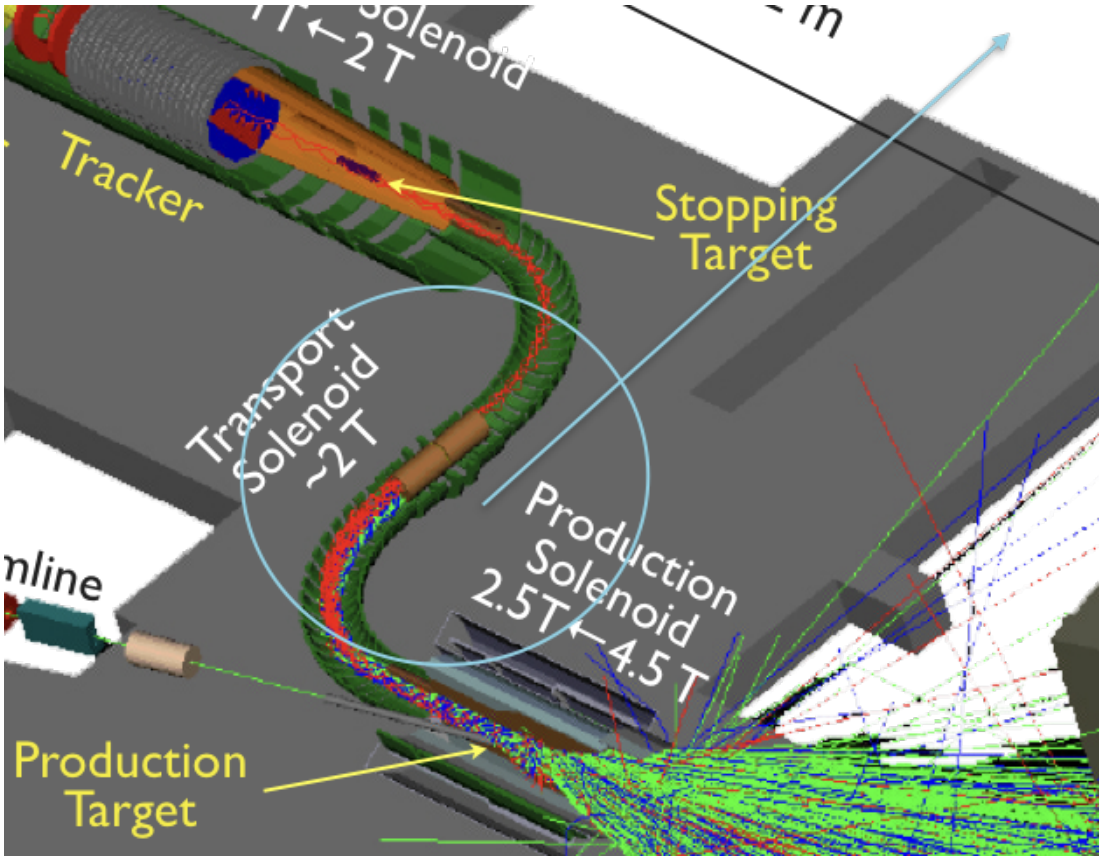


Requirement: proton beam hits the target along its central axis, to within ± 0.5 mm.

Some type of instrumentation will be necessary to ensure this.

The Challenge

No instrumentation can go inside the PS.

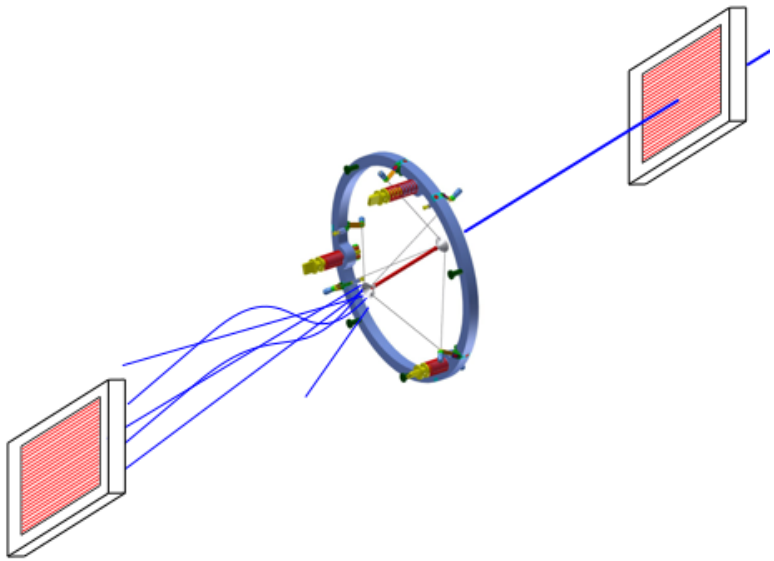


- Any additional material will absorb pions and reduce muon production
- Hypothetical unobtrusive instrumentation has to contend with heat and radiation from the target, magnetic field gradient

Any instrumentation has to be outside the PS, far from the target.

Goal

Instrumentation outside the PS – wire chambers upstream and downstream

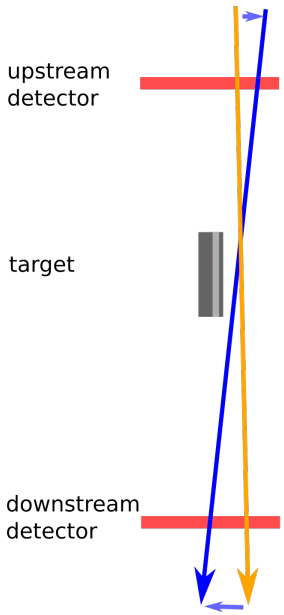


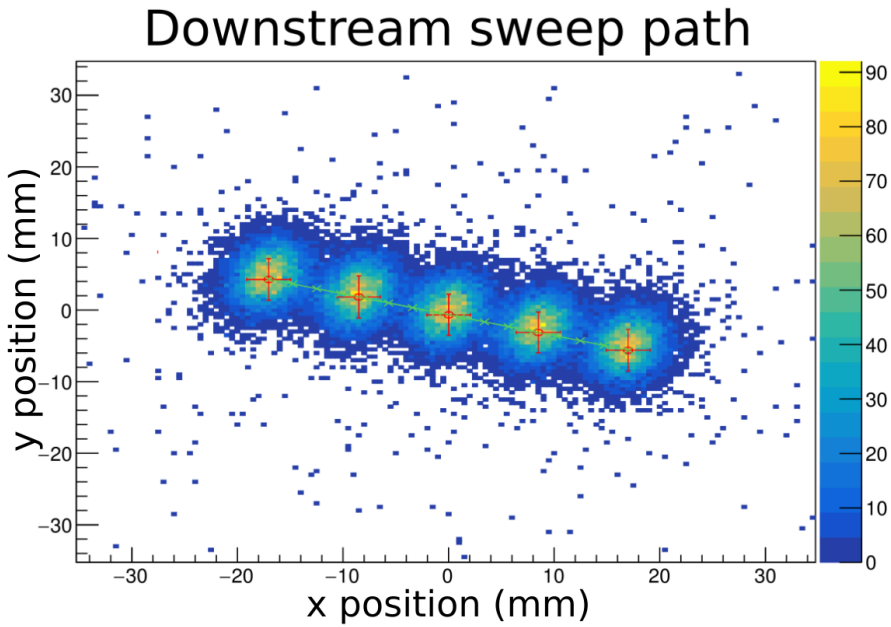
Goal: take beam position and intensity before AND after interacting with target, and reconstruct what happened at the target.

Multiple measurements, scanning beam across target $\rightarrow$ find optimal positioning

Beam Position

Steering the beam around the target traces paths on the upstream and downstream detectors.



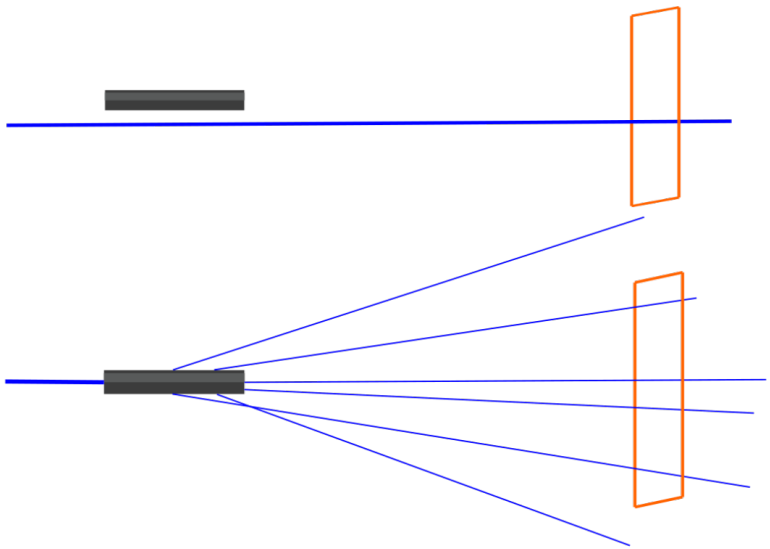


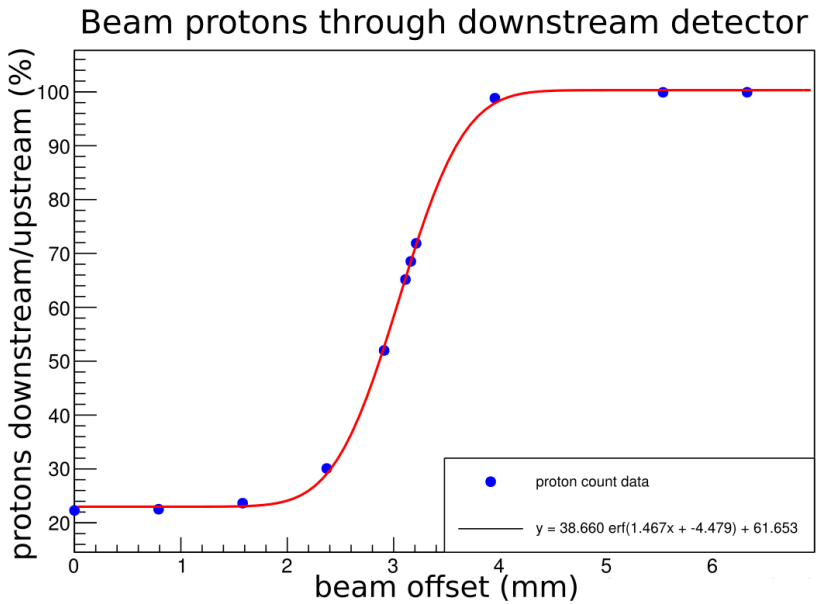
Simulation: steering beam angle or position on target traces out straight line on upstream and downstream detectors.
Relationship between beam at target and beam on detectors appears simple

- Confirmation of beam steering
- Calculate position of target

Total Integrated Signal

Proportional chambers respond to particle energy passing through.
Beam misses target $\rightarrow$ entire beam passes through upstream and downstream detectors.
Beam hits target $\rightarrow$ target scatters beam, downstream detector picks up fewer total beam protons than upstream



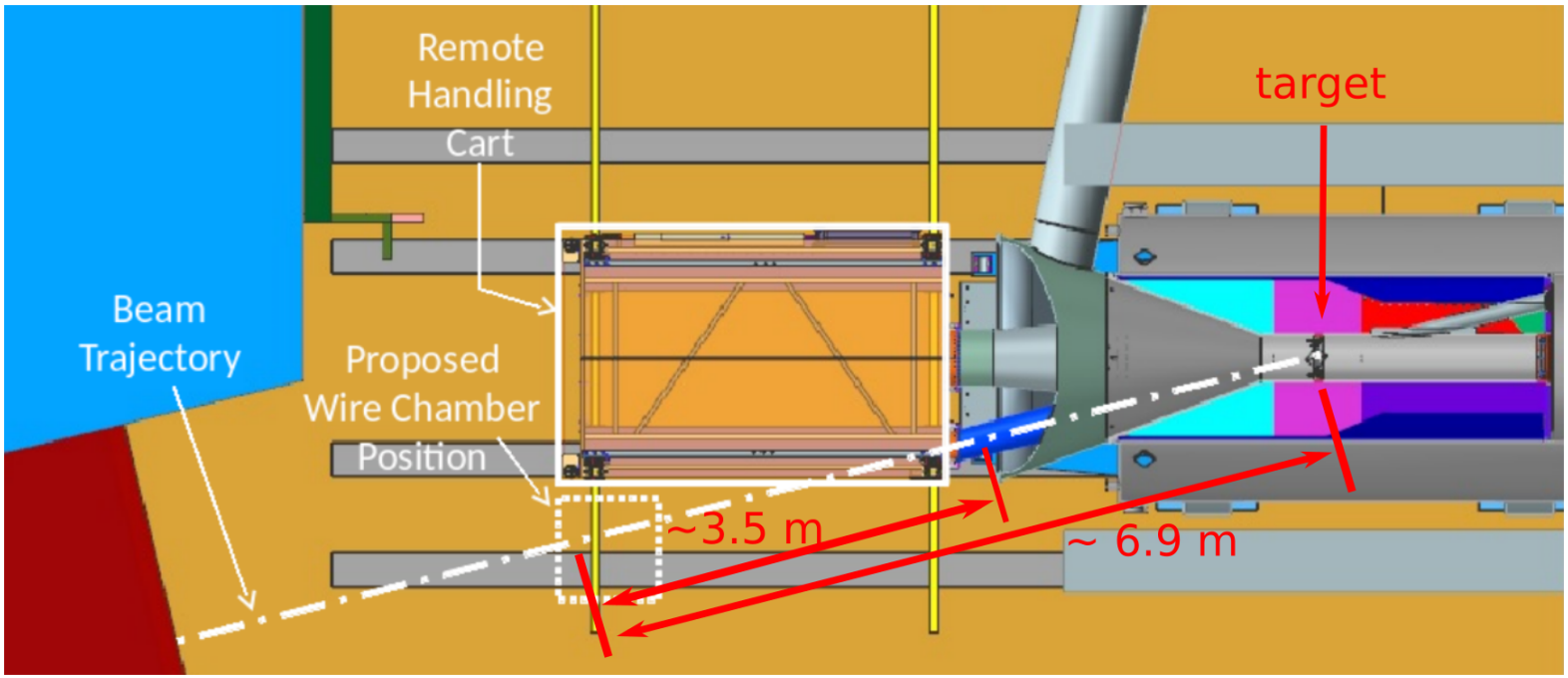


Downstream proton count varies with beam aim on target in a predictable way

Detector Requirements

Location

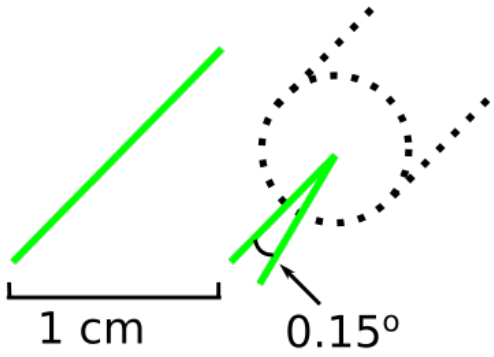
- Close to target: beam path is short, less opportunity to curve in the magnetic field, BUT detector cannot go inside PS
- Far from target: beam angle changes result in large position changes $\rightarrow$ easier to reconstruct beam angle
- Upstream detector as close to PS as possible
- Downstream detector 3.5 m downstream from PS

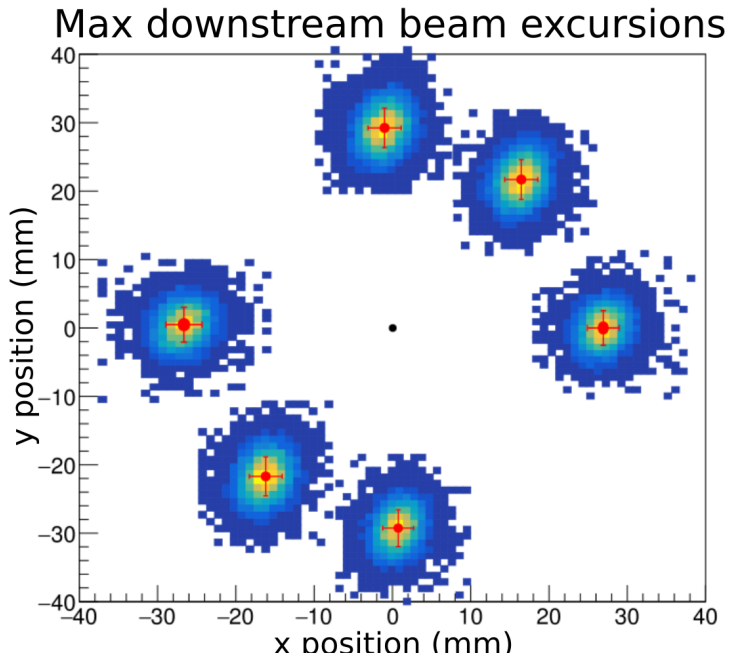


Detector Requirements

Size

- Active cross section must cover entire area beam can be steered – range of motion is $\pm$ 1 cm, $\pm$ 0.15° in x and y at the target
- Upstream: inside beam pipe
- Downstream: simulation indicates beam covers 8 cm $\times$ 8 cm area in proposed location
- This size requirement allows us to use standard detectors produced at Fermilab

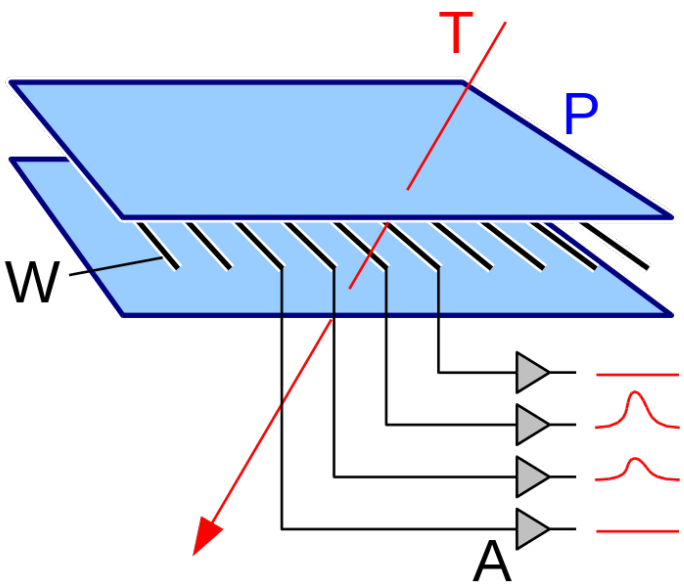


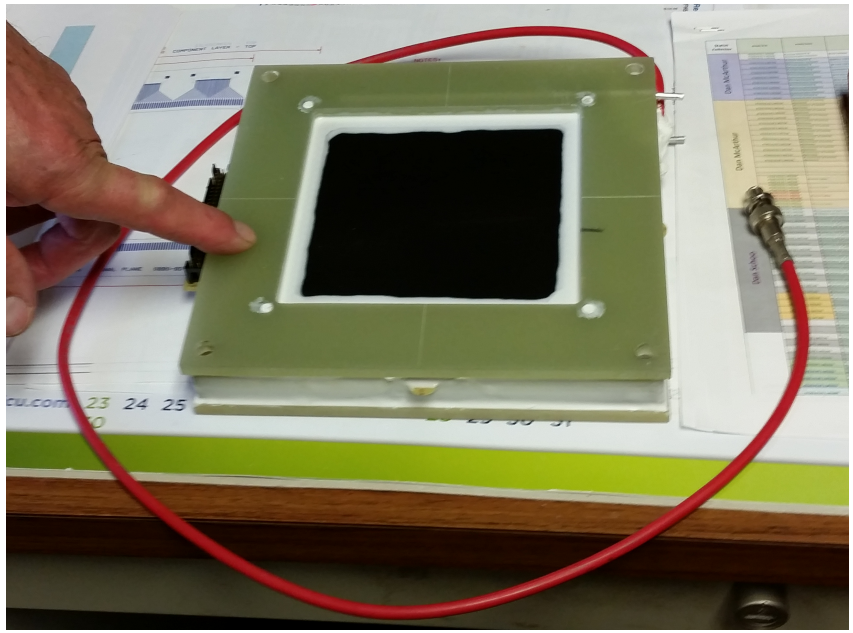


Detector Requirements

Type

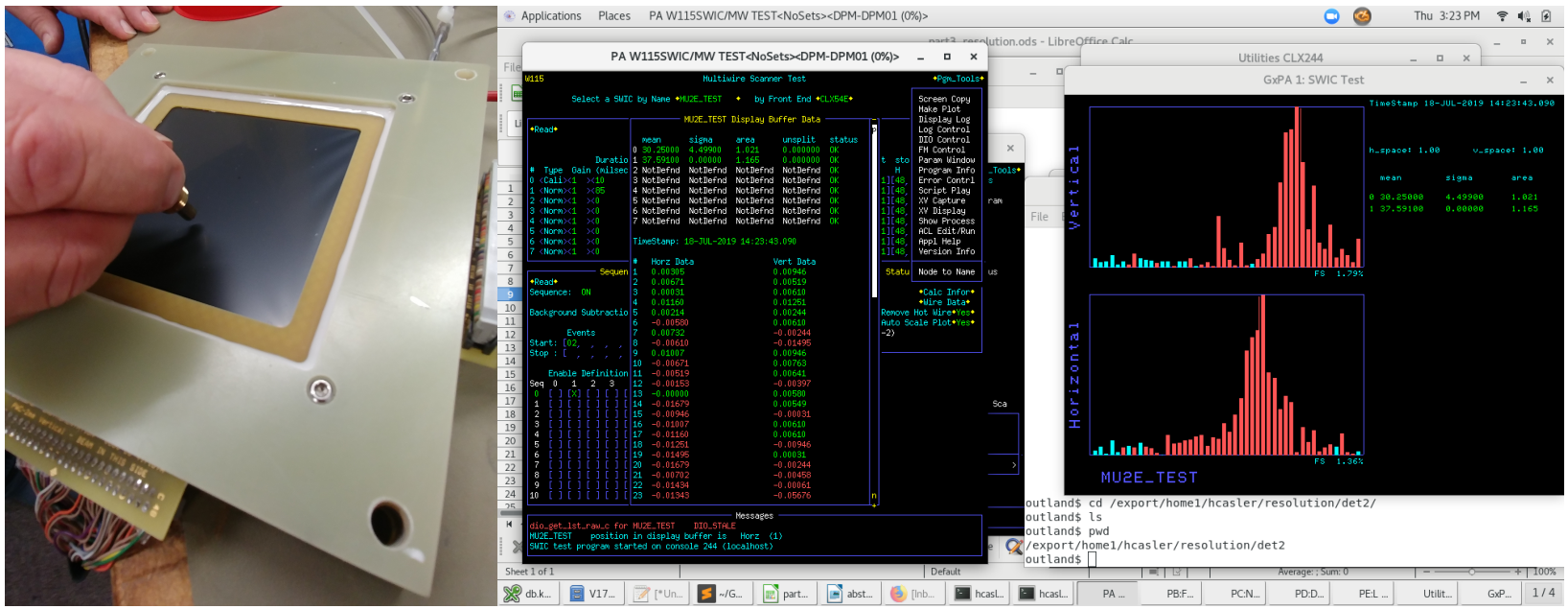
- Need beam position and intensity – proportional wire chambers
- Commonly-used type at Fermilab:
  - 9.6 cm $\times$ 9.6 cm active cross section
  - 2 mm wire pitch
  - tungsten wire
  - $ArCO_2$ gas, near atmospheric pressure





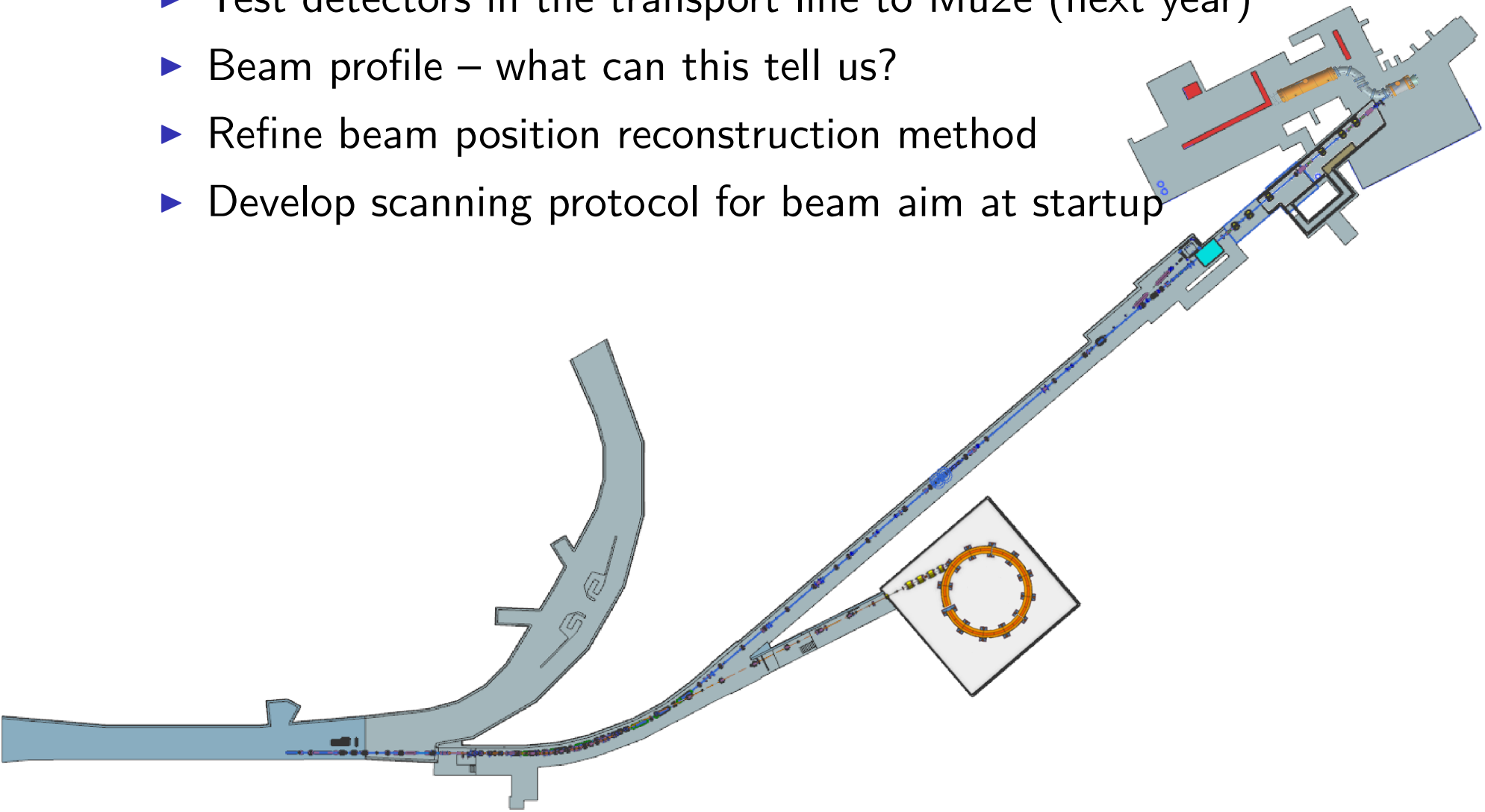
Detector construction

Selected a design for downstream detector.
Built two wire chambers to be placed downstream.
Have built one set of readout electronics.
Source tests with Sr-90 indicate detectors and electronics are working.



Remaining work

- Test detectors in the transport line to Mu2e (next year)
- Beam profile – what can this tell us?
- Refine beam position reconstruction method
- Develop scanning protocol for beam aim at startup



Summary

- Mu2e is looking for new physics in neutrinoless muon-to-electron conversion
- We will create the most intense muon beam in history, using a radiation-cooled production target under harsh conditions and which cannot be instrumented directly
- In order to understand how our proton beam is interacting with our production target, we are developing a remote monitoring system composed of wire chambers upstream and downstream of the target
- These wire chambers can give us position and intensity measurements, which, when combined, will allow us to align the beam with the target
- Data in 2023!

Acknowledgements

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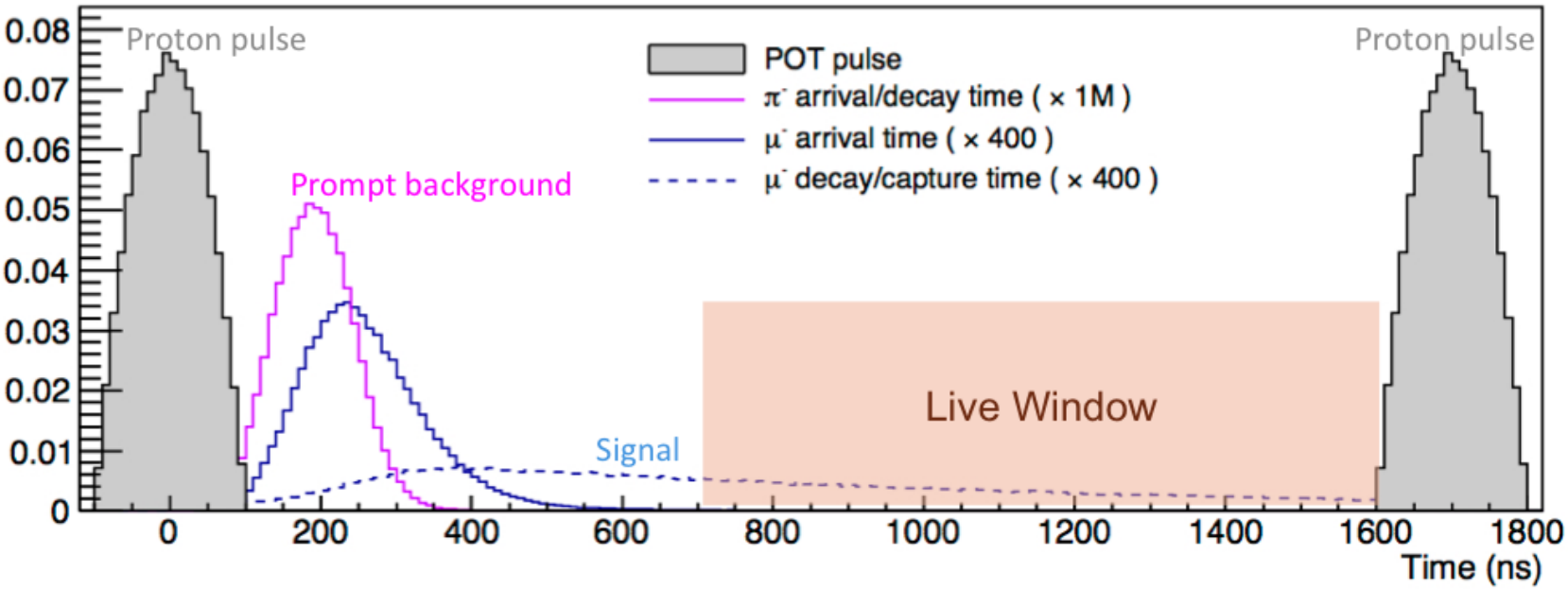
- Daniel Schoo (FNAL)
- Daniel McArthur (FNAL)
- Wanda Newby (FNAL)
- Rick Pierce (FNAL)
- Jeremy Arnold (FNAL)
- Dave Pushka (FNAL)

Backup Slides

Mu2e Pulsed Proton Beam



Target Shadow at Positions Downstream