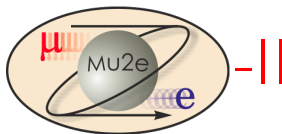# Mu2e-II Production Target Impact on Sensitivity

## Future Muon Program Workshop – Mu2e-II Sensitivity

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# Mu2e-II goals

- Effectively utilize the 100 kW PIP-II 800 MeV proton beam
- Probe $R_{\mu e}$ values down to the level of $\sim$ a few $\times 10^{-18} \rightarrow$ collect $\mathcal{O}(10^{19})$ muons over the lifetime of the experiment
- Reuse as much of the Mu2e infrastructure as possible
- Consider alternate stopping target materials to probe the new physics underlying mechanism in the case of a discovery
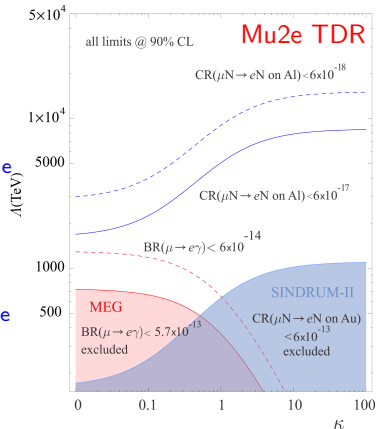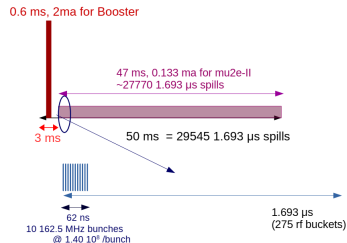


Whether or not a signal is seen in Mu2e, Mu2e-II will offer significant physics value

# Accelerator and beamline

| Parameter | Mu2e | Mu2e-II |
|---|---|---|
| Proton source | Slow extraction from DR | PIP-II Linac |
| Proton kinetic energy | 8 GeV | 0.8 GeV |
| Beam Power for expt. | 8 kW | 100 kW |
| Proton rms emittance | 2.7 | 0.25 |
| Proton geometric emittance | 0.29 | 0.16 |
| Proton Energy Spread ($\sigma_E$) | 20 MeV | 0.275 MeV |
| $\delta p/p$ | $2.25 \times 10^{-3}$ | $2.2 \times 10^{-4}$ |
| Pulse time width | 250 ns | $\sim$100 ns |

- The Mu2e and Mu2e-II beam parameters are compared above

- Mu2e-II would require post-construction upgrades of PIP-II of a beamline to Mu2e-II, beam-switching magnets, and possibly an RF separator for other experiments

- The Mu2e-II beam will be much more narrow at $\sim$100 ns, which will lead to reduced in-time beam backgrounds (e.g. RPC) surviving into the livegate

- The $\mu$-bunch time structure is flexible here, where the right example shows a 1.693 $\mu$s example



0.6 ms, 2ma for Booster

47 ms, 0.133 ma for mu2e-II
~27770 1.693 µs spills

3 ms

50 ms = 29545 1.693 µs spills

62 ns
10 162.5 MHz bunches
@ 1.40 10⁸ /bunch

1.693 µs
(275 rf buckets)

The Mu2e-II production target will need to survive at 100 kW as well as accommodate the trajectory of the 800 MeV proton beam in the PS field
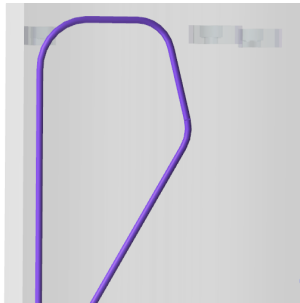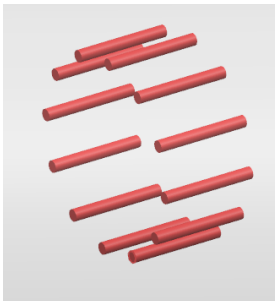


- An LDRD project to study future target options are shown above, a rotating target (left) and a conveyor target that uses circulating target balls (right)
- The conveyor target has been considered the best candidate and is used for all Mu2e-II sensitivity estimates

# Production target materials
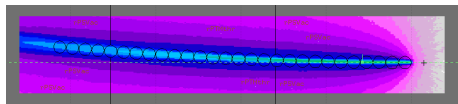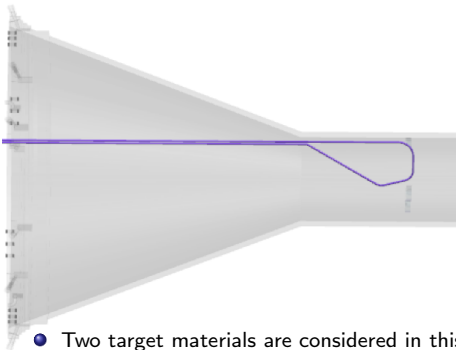




- Two target materials are considered in this study: tungsten and carbon
- The left figure shows the full tungsten conveyor target ball layout, where the right figure shows the carbon conveyor ball target region layout with the proton beam fluence
- The carbon target region is 28 balls due to the lower density compared to tungsten, which has 11 balls in the target region
- The target region must bend to accommodate the curved beam trajectory in the solenoidal field, where the beam fluence nicely follows the longer carbon target region
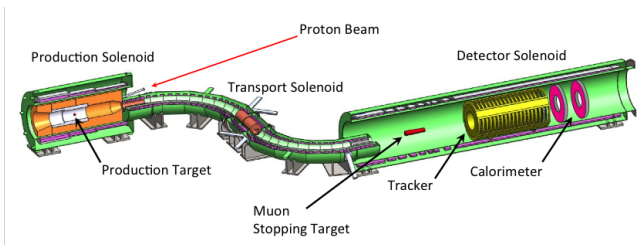
$$\frac{1}{\text{SES}} = \epsilon_{\text{selection}} \cdot \epsilon_{\text{reco}} \cdot \text{N(POT)} \cdot \text{R(muon stops)} \cdot \text{BR(capture)}$$

- The sensitivity at Mu2e/Mu2e-II depends on many factors, but the element most relevant to the production target is the rate of muons stopped in the stopping target per primary proton

- At Mu2e, this rate is about $\sim 1.6 \times 10^{-3}$ with an expected $3.6 \times 10^{20}$ primary protons over the course of the experiment $\rightarrow \sim 6 \times 10^{17}$ stopped muons expected at Mu2e

- At Mu2e, $\epsilon_{\text{reco}} \approx 33\%$ and $\epsilon_{\text{selection}} \approx 25\text{-}35\% \rightarrow \mathcal{O}(10\%)$ overall efficiency per signal event depending on the signal window size
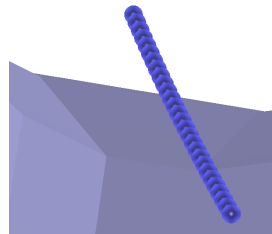
## Production target comparisons

- Utilizing multiple MCs to perform production target studies: Mu2e-II Offline/Geant4, G4Beamline, MARS15, FLUKA, and MCNP6
- Targets to compare: Tungsten conveyor, carbon conveyor, and Mu2e era Hayman tungsten target
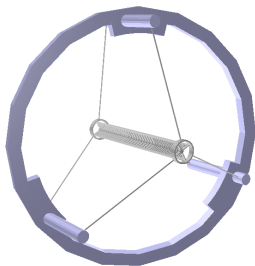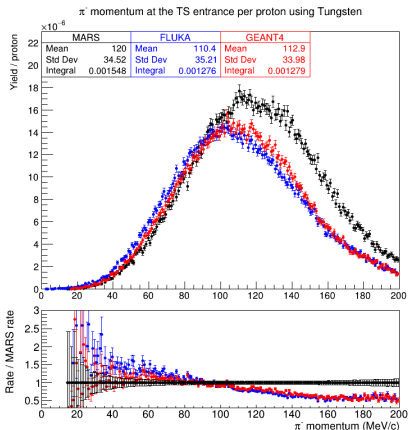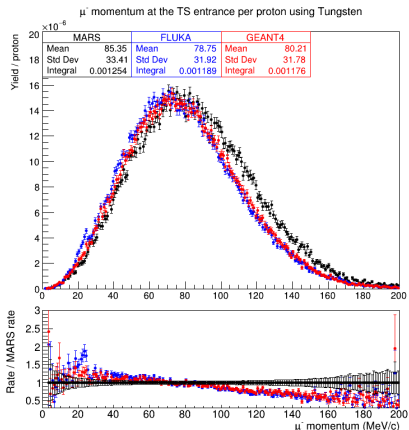


(a) Mu2e era Hayman target
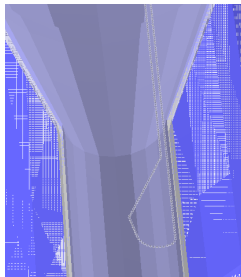
(b) Tungsten conveyor target
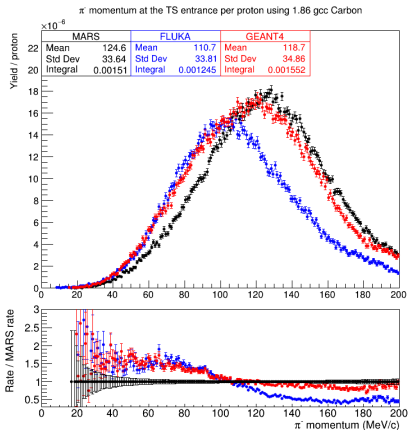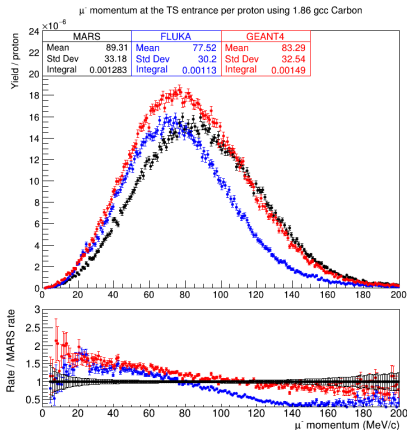
(c) Carbon conveyor target

- Compare these targets at 800 MeV and 8 GeV (Mu2e era proton beam)

# Particle production MC comparison (tungsten conveyor)



- FLUKA, MARS, and Geant4 all agree fairly well for negative muon and pion production at the TS entrance using the tungsten conveyor target
- The TS acceptance is very low for particles above 100 MeV/c, so below this is the most important

# Particle production MC comparison (carbon conveyor)



- FLUKA, MARS, and Geant4 all agree less well for negative muon and pion production at the TS entrance using the carbon conveyor target
- Geant4 appears to agree with the low momentum FLUKA predictions and the high momentum MARS predictions
- This is still being investigated

# Muon stopping rate

| Target | Proton KE (MeV) | R(muon stops / POT) |
|--------|-----------------|---------------------|
| Carbon | 800 | $(9.044 \pm 0.095) \times 10^{-5}$ |
| conveyor | 8000 | $(3.824 \pm 0.062) \times 10^{-4}$ |
| Tungsten | 800 | $(7.190 \pm 0.085) \times 10^{-5}$ |
| conveyor | 8000 | $(1.132 \pm 0.016) \times 10^{-3}$ |
| Hayman | 800 | $(1.034 \pm 0.032) \times 10^{-4}$ |
| | 8000 | $(1.866 \pm 0.014) \times 10^{-3}$ |

- The tungsten conveyor target performs worse than the Mu2e era tungsten Hayman target, though the Hayman target would not survive the higher beam power used at Mu2e-II

- The stopping rate is higher for the carbon conveyor target, but this could be a feature of the Geant4 modeling used in Offline as MARS/FLUKA predicted lower particle production rates for carbon

- We should be able to achieve a stopping rate of $\mathcal{O}(10^{-4})$

- Depending on the target's and the detector's ability to survive the high beam power, it's possible to increase the 800 MeV beam power to compensate for low muon production rates but this needs to be investigated

## Sensitivity results

| Results | Mu2e (CD3) | Mu2e-II (carbon) |
|---|---|---|
| Backgrounds | | |
| DIO | 0.144 | 0.263 |
| Cosmics | 0.209 | 0.171 |
| RPC (in-time) | 0.009 | 0.033 |
| RPC (out-of-time) | 0.016 | $< 0.0057$ |
| RMC | $< 0.004$ | $< 0.02$ |
| Antiprotons | 0.040 | 0.000 |
| Decays in flight | $< 0.004$ | $< 0.011$ |
| Beam electrons | 0.0002 | $< 0.006$ |
| Total | 0.41 | 0.47 |
| N(muon stops) | $6.7 \times 10^{17}$ | $5.5 \times 10^{18}$ |
| SES | $3.01 \times 10^{-17}$ | $3.25 \times 10^{-18}$ |
| $R_{\mu e}$(discovery) | $1.89 \times 10^{-16}$ | $2.34 \times 10^{-17}$ |
| $R_{\mu e}$(90% CL) | $6.01 \times 10^{-17}$ | $6.39 \times 10^{-18}$ |

- The total background is $\sim$0.5 events, with an improvement in the 90% CL upper limit by a factor of 10 over Mu2e in the absence of a signal

# Mu2e-II distributions
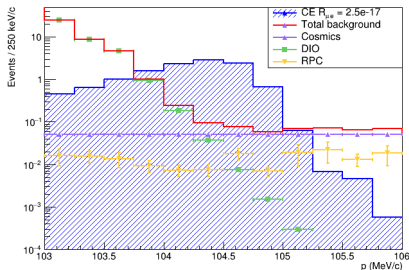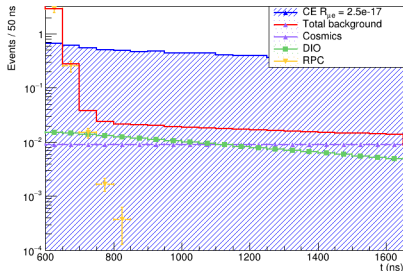


- The expected background distributions for a 5-year run with an example signal
- The DIO background drives the low momentum edge of the search window and RPC drives the low time edge of the search window
- The momentum distribution includes the time cut $t \in [690, 1650]$ ns and the time distribution includes the momentum cut $p \in [104.05, 104.90]$ MeV/c

# Mu2e-II sensitivity vs stopping rate



Median 90% CL vs stopping rate
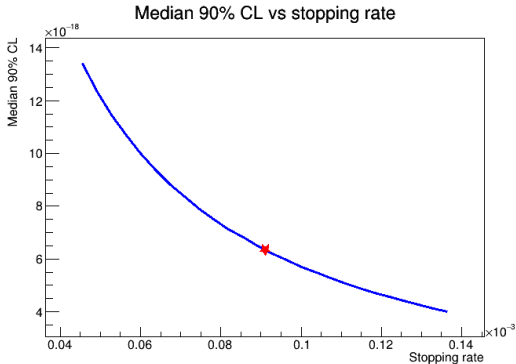
- The above plot shows the median expected 90% CL using Feldman Cousins while varying the muon stopping rate at Mu2e-II
- Clearly the stopping rate has a significant impact on the experiment sensitivity
- This does not include re-optimizing the search window, which would improve the expected sensitivity, or the change in the detector pileup with different production target particle yields

# Summary

- The most promising production target design for Mu2e-II currently is the conveyor target
- We have studied a tungsten and a carbon version of this target
- Using Geant4, the carbon target appears to have a higher muon stopping rate, but it's unclear if this is just a feature of the Geant4 modeling or not
- Using the carbon target stopping rate, we can expect to improve upon the Mu2e CD3 era sensitivity values by about a factor of 10 at Mu2e-II
- More work is needed in optimizing the production target both in terms of survival as a target in the 100 kW beam as well as maximizing the muon stopping rate
- The sensitivity can be further improved by further cosmic ray and decay in orbit electron background rejection, while maintaining the signal efficiency
- Future studies should include the full carbon target apparatus as well as include some idea of infrastructure to support the conveyor targets

Backup slides

## Accelerator and beamline
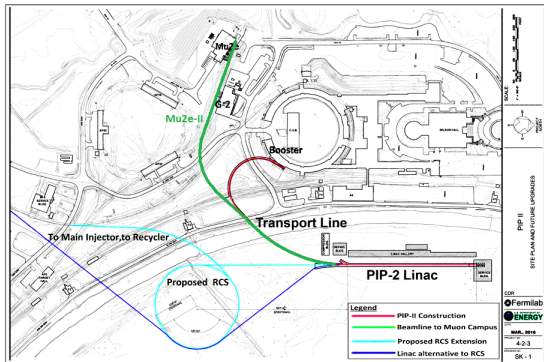


- Construction of the PIP-II accelerator is underway, and is expected to be completed in 2028
- 250 m linac that produces a 2 mA 800 MeV $H^-$ beam, delivering 1.6 MW of power
- Foil stripping in the transport line can be used to produce a proton beam from the $H^-$ before arriving at Mu2e-II
- A chopper in the Low Energy Beam Transport allows **arbitrary bunch patterns** to be produced
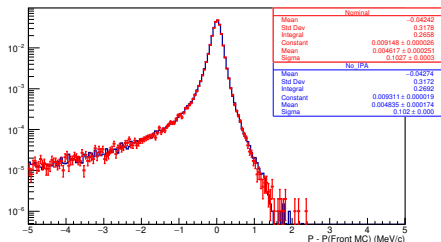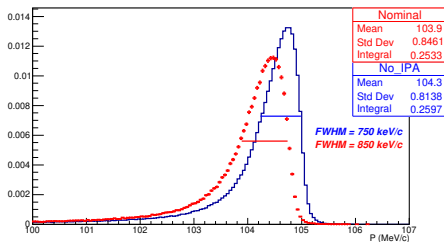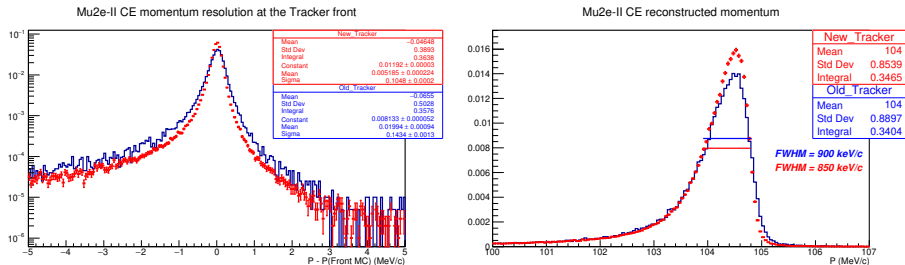
- Comparing tracker resolution at the tracker front and the reconstructed CE spectrum with and without the IPA, after applying selection cuts
- The tracker resolution is unaffected (without mixing considered, where the charge load on the tracker would increase without the IPA), but the energy losses are significantly reduced
- The figures are normalized to the rate per generated CE event

- Comparing the tracker resolution at the tracker front and the reconstructed CE spectrum before and after changing the tracker straws to the 8 $\mu$m design, without applying selection cuts