Mu2e-II Snowmass 2021 Sensitivity Group Update

Mu2e-II Workshop

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White Paper

- The "Backgrounds and Physics Sensitivity" section draft is nearing completion, with only a few decisions left to be made
- Section outline:
  - Stopped muon rate discussion: discuss the dependence on the production target
  - Background overview and theoretical models used: brief overview of each background and how we simulate it
  - Stopping target studies: alternative geometries, different elements/isotopes
  - Selection cuts: detail each cut and justify
  - Tracker resolution studies: plots showing δp and p_{reco} of CE with the Mu2e/Mu2e-II era target, with/without pile-up, and with/without cuts
  - Sensitivity study and summary table: optimized sensitivity, backgrounds. We assumed a 5 year run period, compare to the full Mu2e experiment (CD3)
  - Discussion and room for improvement
- This talk walks through each component briefly, focusing most of the discussion on outstanding issues

N(muon) stops

- The carbon conveyor production target has a muon stopping rate of 9.1×10^{-5} per POT, estimated using Offline
- CD3 assumed 3.6×10^{20} POT and a stopping rate of 1.87×10^{-3}, which corresponds to 6.7×10^{17} stopped muons
- If we use the same N(POT) as CD3 but the SU2020 stopping rate of 1.59×10^{-3}, this corresponds to 5.7×10^{17} stopped muons
- With the Mu2e-II stopping rate, to have a factor of 10 more muon stops than Mu2e we would need 7.4×10^{22} POT given the CD3 estimate (6.7×10^{18} stopped muons) and 6.3×10^{22} POT given the SU2020 estimate (5.7×10^{18} stopped muons)
- If we assume 1.25×10^{22} POT / year, this corresponds to 5.9 and 5.0 years of running
- A 4-year run at this POT rate would have 4.6×10^{18} stopped muons

Muon stopping rate study

Target	Proton KE (MeV)	N(POT)	N(muon stops)	R(muon stops / POT)
Carbon conveyor	800	10^8	9044	$(9.044 \pm 0.095) \times 10^{-5}$
	8000	10^7	3824	$(3.824 \pm 0.062) \times 10^{-4}$
Tungsten conveyor	800	10^8	7190	$(7.190 \pm 0.085) \times 10^{-5}$
	8000	10^7	11323	$(1.132 \pm 0.016) \times 10^{-3}$
Hayman	800	10^7	1034	$(1.034 \pm 0.032) \times 10^{-4}$
	8000	10^7	18657	$(1.866 \pm 0.014) \times 10^{-3}$

- The muon stopping rate is lower than initially expected for Mu2e-II
- To study this, we compared using carbon conveyor to a tungsten design, and also to the standard Hayman target
- We performed this measurement at 800 MeV and 8 GeV, where the Hayman at 8 GeV performs better than SU2020 due to removed $\bar{p}$ absorber elements along the beamline
- Even with the Hayman target, we still see $\mathcal{O}(10^{-4})$ for the stopping rate, though the lower rate for the tungsten conveyor is unexpected
- This is not seen with MARS, where the negative muon yields at the TS entrance and the muon stopping rate agree using tungsten but disagree using carbon
- The ratio between 8 GeV and 800 MeV is different for carbon, but this target is much longer and so the curve may be more impactful at 8 GeV

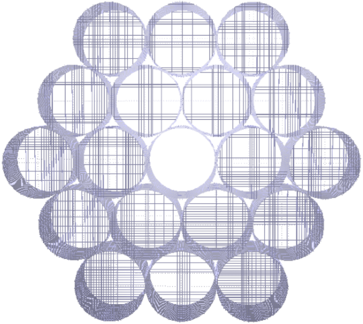
Background modeling and estimates

- The Mu2e-II sensitivity estimate working group has performed a simulation campaign using the carbon conveyor production target, creating Mu2e-II era primary particle samples and mixed background frames
- The tracker and calorimeter were both updated to potential designs for Mu2e-II
- Unmixed CE and DIO datasets and a mixed CE dataset are now on tape and TrkAna ntuples were generated for each dataset
- These ntuples were analyzed and written into histogram files with similar layout and histogram definitions as used in SU2020 (code is currently available on github here)
- Ntuples and histograms are available in */mu2e/data/projects/mu2eii_snowmass/*

Sensitivity estimate strategy

- It's very computationally expensive and takes a lot of time and effort to generate every needed dataset to make the background estimates and perform the full experimental sensitivity estimate
- The strategy is to reuse as much of the SU2020 work as possible, generating only a few select datasets with and without mixing
  - Currently DIO and CE are both going to be generated with and without mixing
  - $\bar{p}$ is not a relevant background for the 800 MeV POT
  - RPC will be further suppressed at Mu2e-II as the POT timing structure is now more narrow, requiring a longer time needed to survive into the livegate $\rightarrow$ Likely will not regenerate this, leading to a more conservative estimate
  - Cosmics are estimated using the Run I prediction in docdb-40469 scaled to the Mu2e-II livetime and assumed to be flat in momentum and time with a factor of 2 improvement in the rejection efficiency
  - RMC is considered negligible for this, but we can re-evaluate the upper limit using the SU2020 sample if needed
- Likely there will be many inaccuracies in the SU2020 $\rightarrow$ Mu2e-II estimates, but hopefully these will not be too much larger than the uncertainty on the many other assumptions being made for these estimates

Stopping target design



- The stopping target is a fundamental element of the experimental design, where we investigate different stopping target designs and masses for the Mu2e-II era
- Sophie investigate many different geometries and masses, and found the 37 foil aluminum Mu2e-era target is near optimal, with at most a few percent gain in the SES/expected 90% CL upper limit by using more complex geometries
- The sensitivity estimate therefore assumes a Mu2e-era stopping target design for Mu2e-II

Mu2e-II track selection

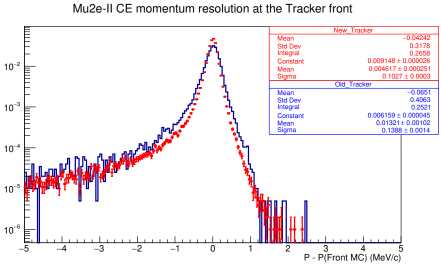
- Starting from a similar selection as in the SU2020 analysis:
  - N(hits) ≥ 20
  - $|D_0| < 100$ mm
  - $R_{max} < 680$ mm
  - $0.5 < \tan(\text{dip}) < 1$
  - $\sigma_{T_0} < 0.9$ ns
  - $E_{\text{cluster}} > 10$ MeV and $E_{\text{cluster}}/P_{\text{track}} < 1.05$
  - TrkQual > 0.8 (Offline MVA training)
  - $T_0 < 1650$ ns
- It's worth noting that the Mu2e-II datasets use PAR tracks and different quality/PID MVAs, so the selection won't be identical
- The Mu2e-II CE datasets are LO, and the unmixed sample has a reconstruction efficiency of 36.7% and a track selection efficiency of 72.7% for a total efficiency of 26.7%

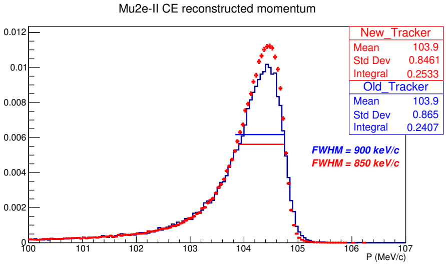
Mu2e-II era CE sample efficiencies with and without mixing

Sample	Selection	$\epsilon_{\mathrm{Total}}$	$\epsilon_{\mathrm{Triggered}}$	$\epsilon_{\mathrm{Trigger}}$	R_{Total}	$R_{\mathrm{Triggered}}$
CE	Reco	0.376	0.367	0.977		
	TrkID	0.255	0.253	0.992		
CE-Mix	Reco	0.304	0.266	0.876	0.808	0.724
	TrkID	0.178	0.163	0.914	0.698	0.643

- Comparing efficiencies with and without mixing, where R is the ratio of the efficiencies with and without mixing
- The track selection efficiency before trigger selection ($\epsilon_{\mathrm{Total}}$) is significantly worse when pileup is added, with a 20% reduction in efficiency for reconstructed tracks and a 30% reduction for tracks passing the Track ID selection with $p > 100$ MeV/c
- The trigger efficiency is $>$ 90% for tracks above 100 MeV/c passing the track ID selection
- This is likely a bug, where Giani showed the calo-tracker timing offset seemed to be incorrect on our branch, leading to the loss of the CPR algorithm tracks
- Is it reasonable to assume 95% trigger efficiency (SU2020 is $>$ 98%) and 95% selection efficiency after mixing (SU2020 2-batch mode is 97.5%) instead of 90% and 70%?

Mu2e-II era CE sample before and after tracker straw wall change





- Comparing the tracker resolution at the tracker front and the reconstructed CE spectrum before and after changing the tracker straws to the 8 μm design, after applying selection cuts
- The core resolution (fit between -200 and 200 keV/c) decreases from 140 keV/c to 100 keV/c, and the
- The figures are normalized to the rate per generated CE event

Sensitivity optimization

Results	Mu2e Run I	Mu2e (CD3)	Mu2e-II (5-year)	Mu2e-II (5-year*)
Window $(p, T)_{\mathrm{min}}$	(103.6,640)	(103.85,700)	(104.05,690)	(104.05,690)
Backgrounds				
DIO	0.038	0.144	0.207	0.187
Cosmics	0.047	0.209	0.264	0.264
RPC (in-time)	0.011	0.009	0.033	0.033
RPC (out-of-time)	< 0.0015	0.016	< 0.0057	< 0.0057
RMC	< 0.0024	< 0.004	< 0.02	< 0.02
Antiprotons	0.010	0.040	0.000	0.000
Decays in flight	< 0.002	< 0.004	< 0.011	< 0.011
Beam electrons	< 0.001	0.0002	< 0.006	< 0.006
Total	0.106	0.41	0.504	0.483
N(muon stops)	6.0×10^{17}	6.7×10^{18}	5.7×10^{19}	5.7×10^{19}
SES	2.34×10^{-16}	3.01×10^{-17}	4.65×10^{-18}	3.25×10^{-18}
$R_{\mu e}$(discovery)	1.07×10^{-15}	1.89×10^{-16}	3.33×10^{-17}	2.33×10^{-17}
$R_{\mu e}$(90% CL)	5.45×10^{-16}	6.01×10^{-17}	8.98×10^{-18}	6.34×10^{-18}

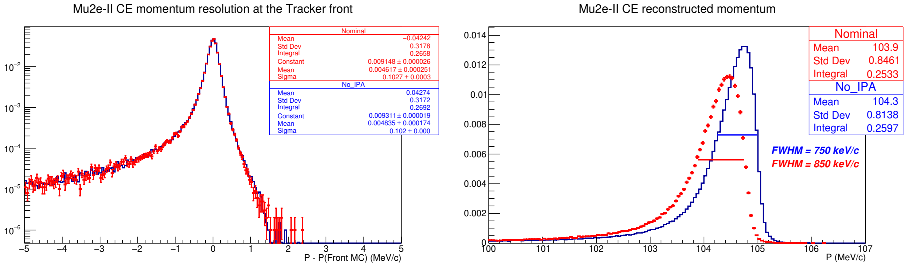
- As with SU2020, we optimize the *mean* $R_{\mu e}$ discovery value by varying the time vs momentum window (all optimizations find $p_{\mathrm{max}} = 104.9$ MeV/c and $T_{\mathrm{max}} = 1650$ ns)
- Given the optimized window, we estimate the *median* expected $R_{\mu e}$ discovery value and 90% CL upper limit on $R_{\mu e}$ in the absence of a signal (without systematic uncertainties)
- The "Mu2e-II (5-year*)" column gives the sensitivity values setting the trigger and after pileup efficiencies to 95% each

Summary

- CE and DIO samples have been generated for the Mu2e-II configuration using the carbon conveyor production target, with an expectation of and 5.5×10^{18} stopped muons for a 5-year run
- The CE efficiency significantly drops after the introduction of pileup, which is likely due to Offline code being designed for the nominal beam intensity and detector designs
- The optimized signal window for the 5-year run is $104.05 < p < 104.90$ MeV/c and $690 < T_0 < 1650$ ns
- The SES of the 5-year run is 4.65×10^{-18} with a total expected background of 0.50 events
- The median expected discovery $R_{\mu e}$ is 3.33×10^{-17} and the median expected 90% CL upper limit on $R_{\mu e}$ is 8.98×10^{-18} without systematic uncertainties included
- If the trigger and after pileup efficiencies are set to 95%, the SES is 3.25×10^{-18}, the median discovery potential is 2.33×10^{-17}, and the median 90% CL is 6.34×10^{-18}
- The CD3 values for Mu2e are: SES of 3.01×10^{-17}, total background of 0.41 events, median discovery potential of 1.89×10^{-16}, and median 90% CL limit of 6.01×10^{-17}
- The Mu2e-II 5-year* run plan values are just about a factor of 10 improved on the CD3 Mu2e expectations
- The sensitivity whitepaper section draft is almost complete, where the main element left is to select a N(POT)/N(muon stops) assumption and decide how to handle the pileup efficiency effects

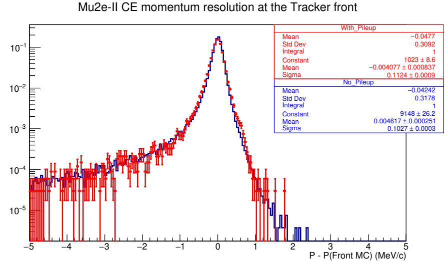
Backup slides

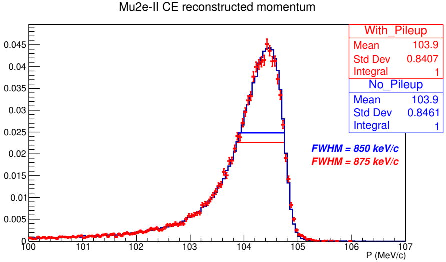
Mu2e-II era CE sample with and without the IPA



- 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

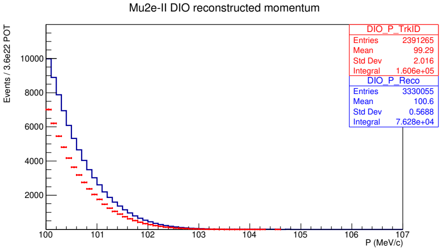
Mu2e-II era CE sample with and without mixing

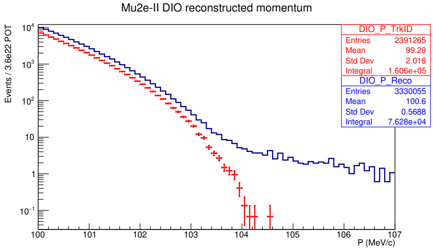




- Comparing tracker resolution at the tracker front and the reconstructed CE spectrum with and without pileup, after applying selection cuts
- The figures are normalized to the rate per generated CE event for the 3-year run
- The CE efficiency decreases by 35% when mixing is introduced, which was unexpected

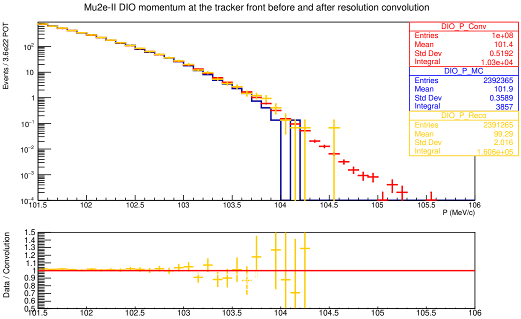
Mu2e-II era DIO





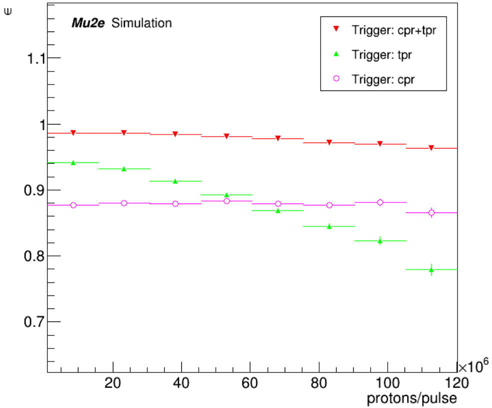
- Mu2e-II DIO sample before and after track selection cuts, normalized to the expected number of muon stops in Mu2e-II
- The DIO sample was generated with a natural spectrum, and so it doesn't include any event weights
- This leads to most of the 10^7 generated events generated close to 100 MeV, with few events above 104 MeV/c $\rightarrow$ significant uncertainty in the background estimate and large steps/potential bias in the optimization of the signal window

Mu2e-II era DIO estimate after mixing



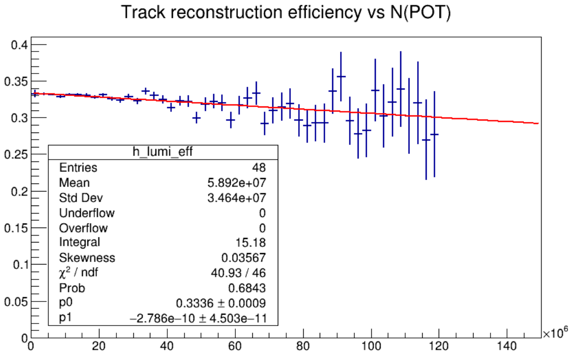
- The Mu2e-II DIO sample does not include pileup, which can be an important factor in the estimate as it changes the resolution function's tails
- To estimate the impact of mixing, the DIO MC momentum at the tracker front is convolved with the mixed CE tracker front resolution function
- The convolution is then fit to create a 2D time vs momentum PDF of the DIO background
- This estimates 0.263 events in the signal window, a 40% increase from the unmixed, low statistics estimate
- Using this, the total background expectation is 0.560, the median discovery potential is 2.31×10^{-17}, and the median 90% CL limit is 6.09×10^{-18}

SU2020 era trigger efficiency



- The figure above is from the SU2020 note, where the total efficiency is still ∼96% for ∼3x nominal intensity
- Mu2e-II has around 4x the Mu2e era occupancy in the tracker
- The Mu2e-II trigger efficiency is 88% before track selection cuts and 91% after track selection and requiring $p > 100$ MeV/c
- The trigger efficiency would likely be better as the trigger selection would be re-optimized for the new environment

SU2020 CE efficiency with pileup



- The figure above shows the one-batch mode CE reconstruction efficiency from SU2020 as a function of N(POT)
- Mu2e-II has around 4x the Mu2e era occupancy in the tracker, where the mean for two-batch mode is 3.9×10^7
- Using the linear fit, this predicts a drop in efficiency by $\sim$15% at 4x the mean intensity of 3.9×10^7
- This isn't too far off from the 20% we're seeing in Mu2e-II