Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Mu2e-II Experiment at Fermilab

Mete Yucel

Snowmass Rare Processes and Precision Measurements Frontier

Spring Meeting May-2022

Community Summer Study SNOWMASS 2022 July 17 - 26 Seattle

Mu2e II

Mu2e-II Collaboration

Mu2e-II: Muon to electron conversion with PIP-II
Contributed paper for Snowmass

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hep-ex > arXiv: 2203.07569

What is Mu2e-II

- Current experiments searching muon sector of CLFV;

Experiment	Institute	Process	Sensitivity
MEG II	PSI	$\mu^{\pm} \to e^{\pm} + \gamma$	4.2×10^{-14}
Mu2e	FNAL	$\mu^{-} + N \to e^{-} + N$	6.0×10^{-17}
COMET	JPARC	$\mu^{-} + N \to e^{-} + N$	$10^{-15} - 10^{-17}$
Mu3e	PSI	$\mu^{\pm} \to e^{\pm} + e^{+} + e^{-}$	$10^{-14} - 10^{-16}$

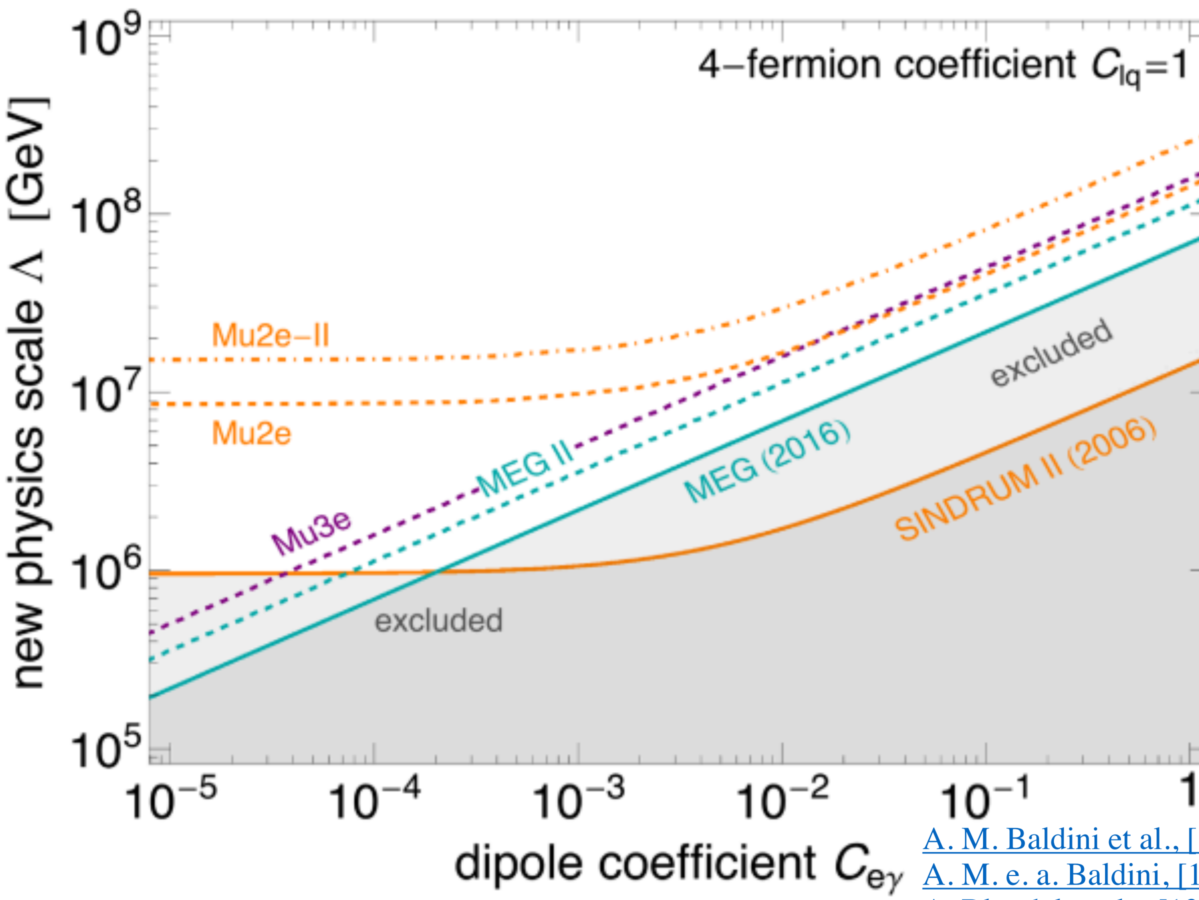
Mu2e focuses on the **neutrino-less conversion of the muon** in the presence of **Al nuclei**.

Increasing Mu2e capability

- Improve sensitivity.
- Probe higher mass scale.

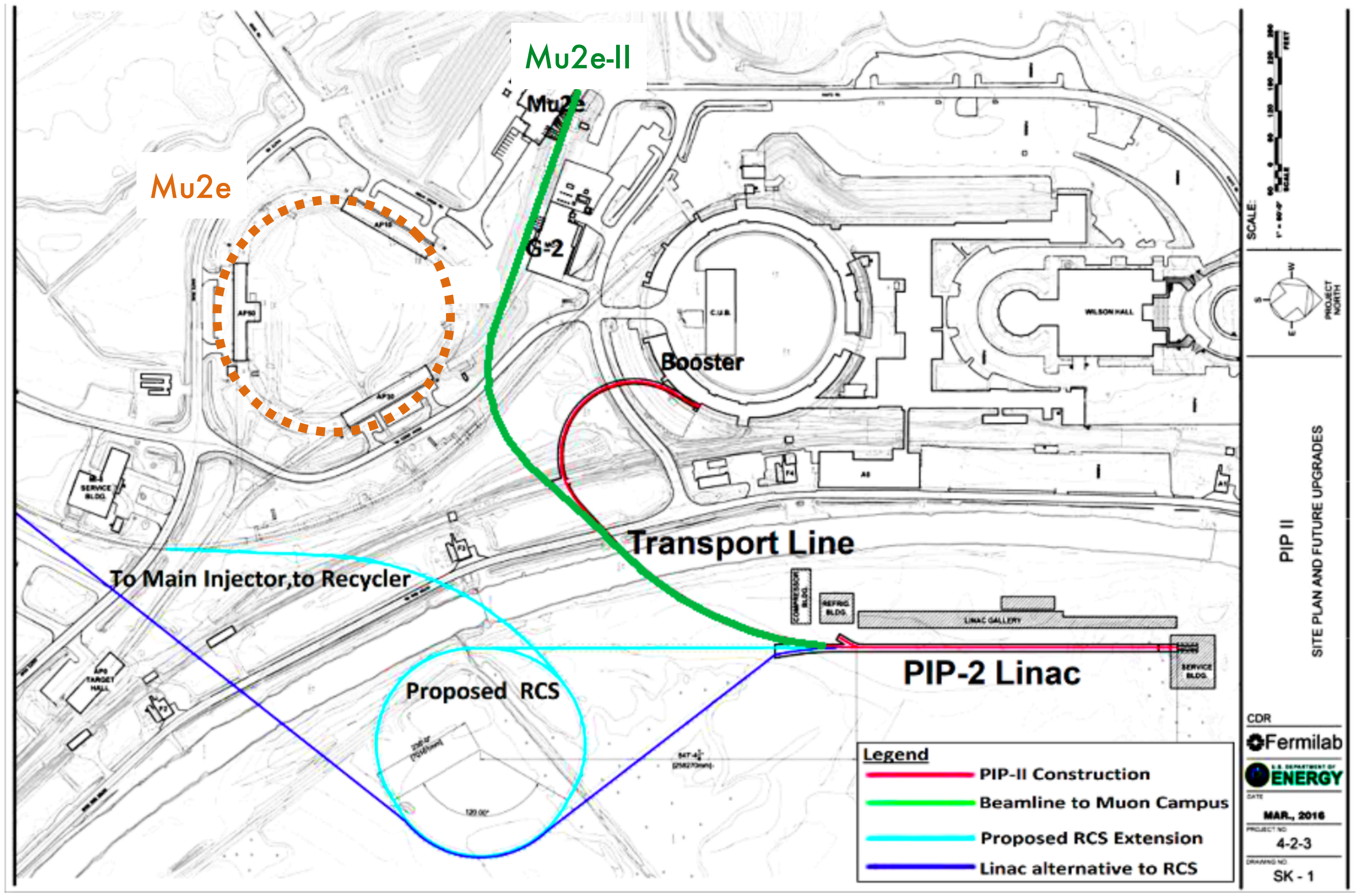
Expanding upon Mu2e goals

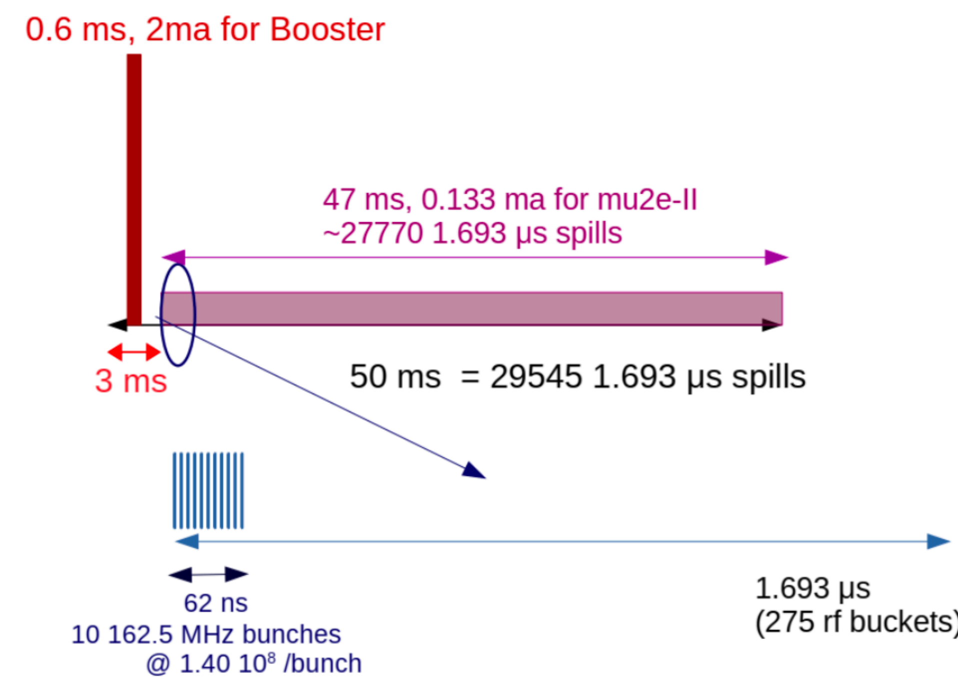
- Change targets.
- Focus on excluding/including models.
- $\mu^{-} + N \to e^{+} + N'$
- $\mu \to eX$



A. M. Baldini et al., [1605.05081]
A. M. e. a. Baldini, [1801.04688]
A. Blondel et al. , [1301.6113]

PIP-II



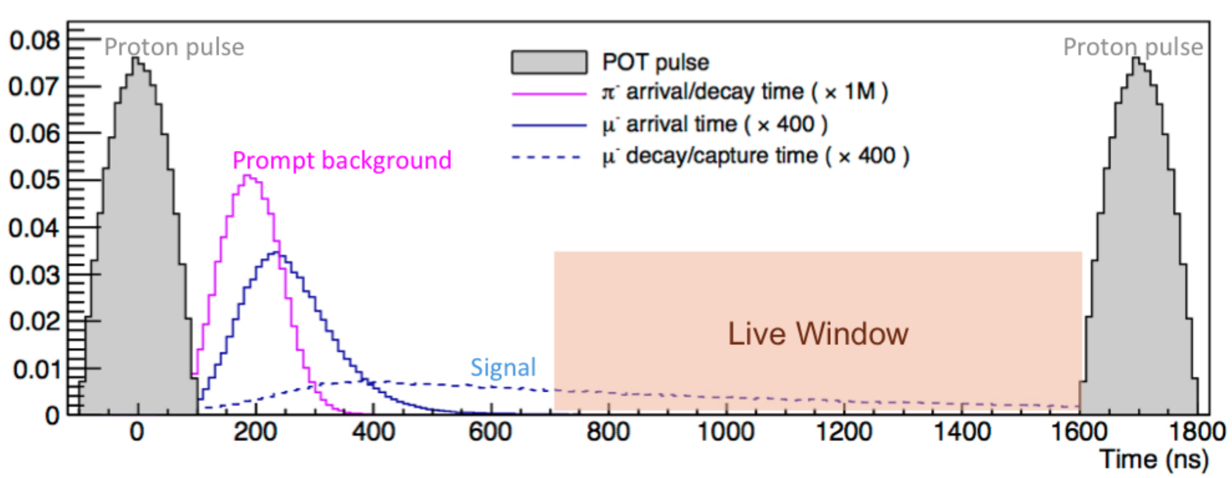


- Mu2e-II beam is delivered using CW of magnetically stripped H^- directly from LINAC instead of slow extracted protons from delivery ring(DR).
- 1.4×10^9 H^- per spill, 62 ns bunch width compared to 250 ns for Mu2e.
- 10^{-11} extinction is required for the beam compared to 10^{-10} for Mu2e.

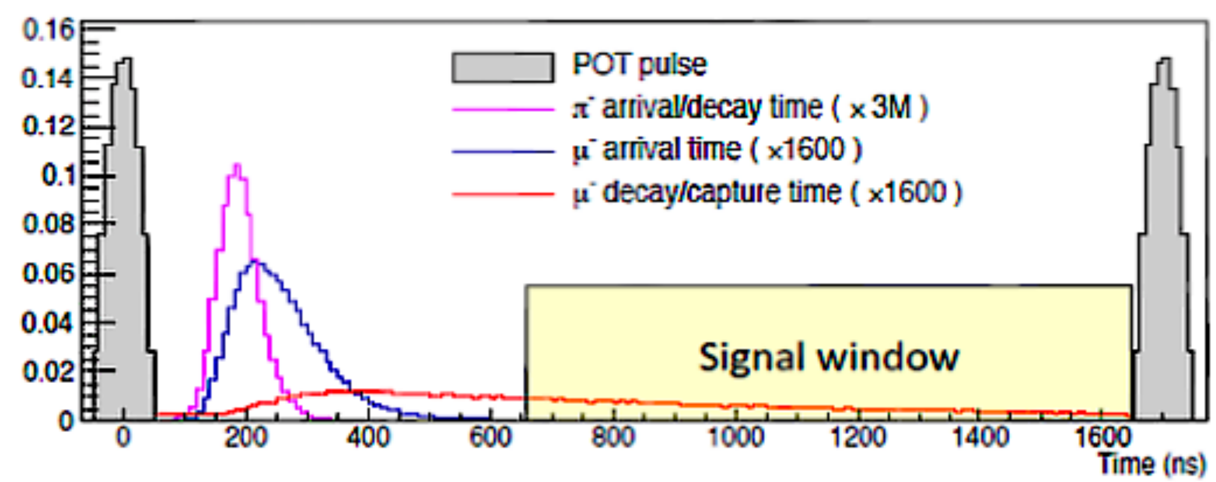
Mu2e vs Mu2e-II Beam Comparison

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
Protons/s	6.25×10^{12}	7.8×10^{14}
Pulse Cycle Length	1.693 μs	1.693 μs
Proton rms emittance	2.7	0.25
Proton geometric emittance	0.29	0.16
Proton Energy Spread (σ_E)	20 MeV	0.275 MeV
$\delta p/p$	2.25×10^{-3}	2.2×10^{-4}
Stopped μ per proton	1.59×10^{-3}	9.1×10^{-5}
Stopped μ per cycle		1.2×10^{5}

Mu2e

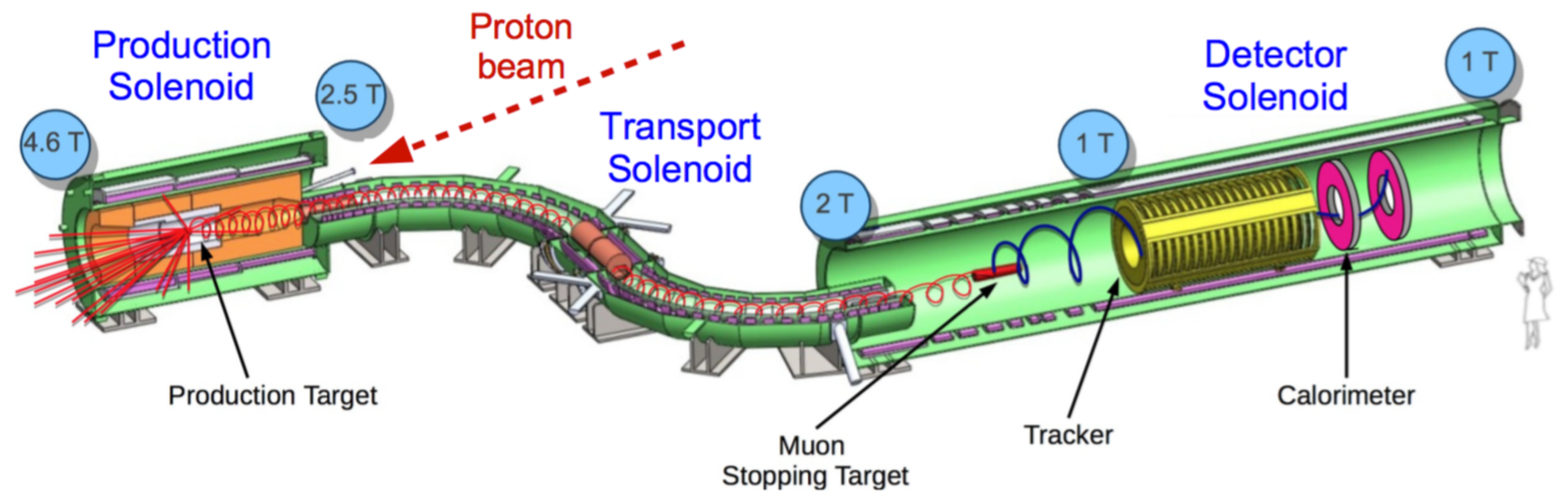


Mu2e-II

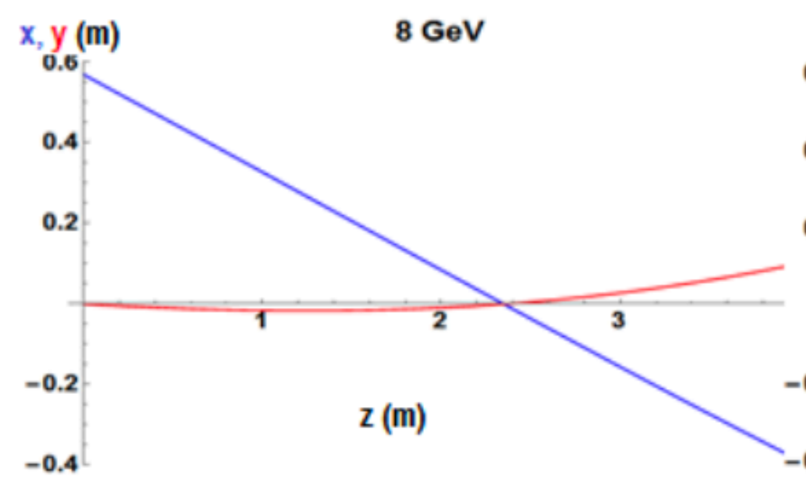


Solenoids

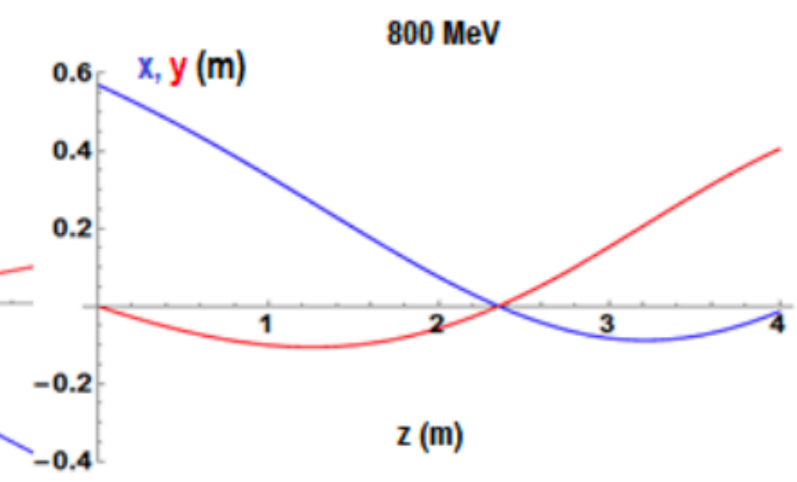
- Production solenoid(PS) needs to change(cold mass) to handle the increased power delivered by PIP-II beam line.
- Lower energy beam is deflected more in vertical direction entering PS.
- Replacing PS cold mass;
  - Superconducting;
    - Cable-in-conduit conductor(CICC).
    - Internally cooled Al cable.
    - High-temperature superconducting(HTS) coils.
  - Resistive;
    - Water cooled resistive Cu coil.
    - LN_2 cooled resistive Cu or Al coil.
- TS may require some modifications.
- DS will be used as is.



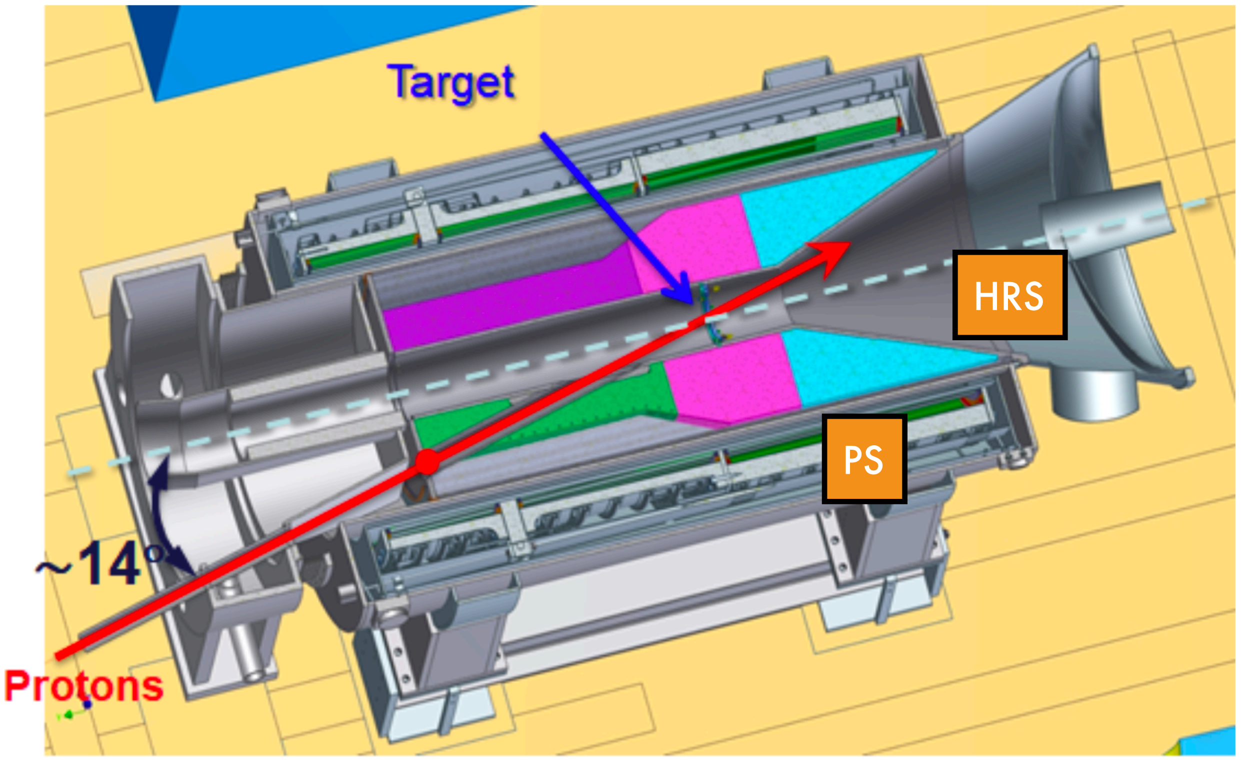
Mu2e

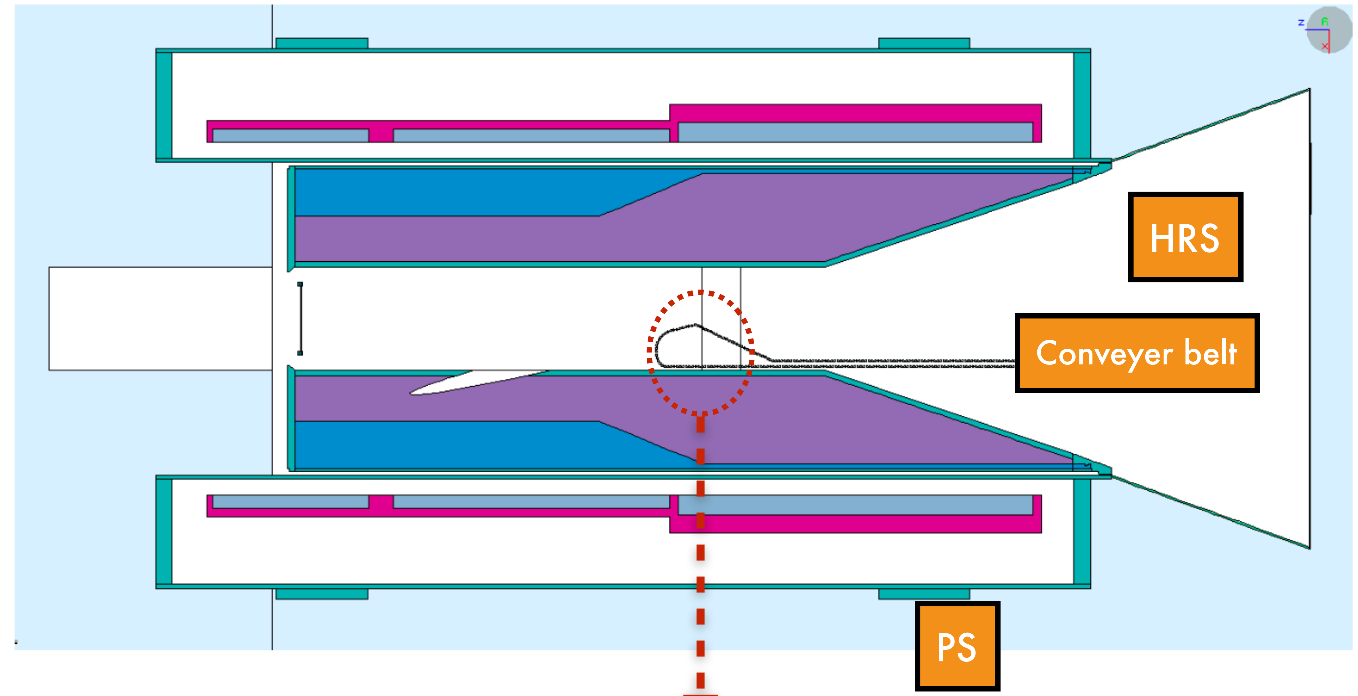


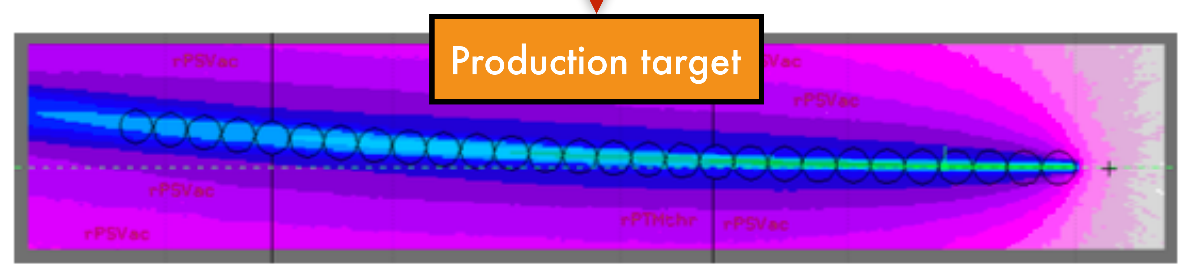
Mu2e-II

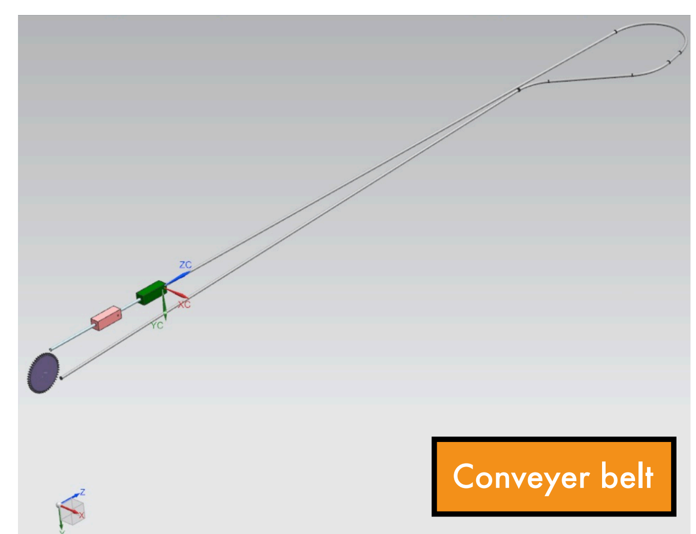


Production target





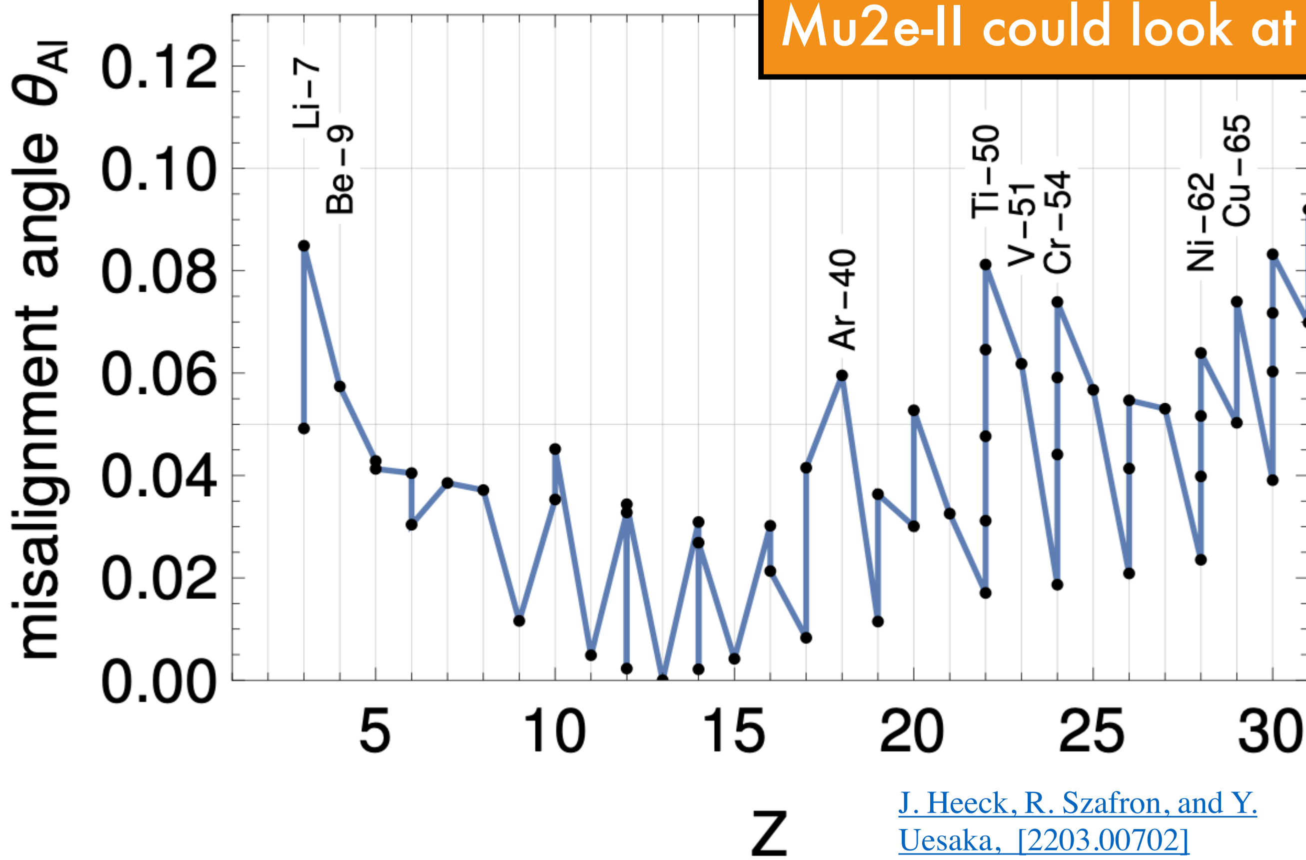




- 8 kW on Mu2e target went through significant design challenges
- 100 kW on Mu2e-II target needs active cooling.
  - Carbon or Tungsten spheres on a conveyer belt.
  - PS and Heat and Radiation Shield(HRS) design needs to change.
  - Switch from copper to tungsten for HRS.
  - Need in situ monitoring of the target.

Potential stopping targets

Mu2e-II could look at different targets!



J. Heeck, R. Szafron, and Y. Uesaka, [2203.00702]

- Misalignment angle probes different Wilson coefficients.
- Preferably, for a complementary study one requires large angle -> heavy Z.
- Need muon lifetime > 250 ns, therefore Z < 25.

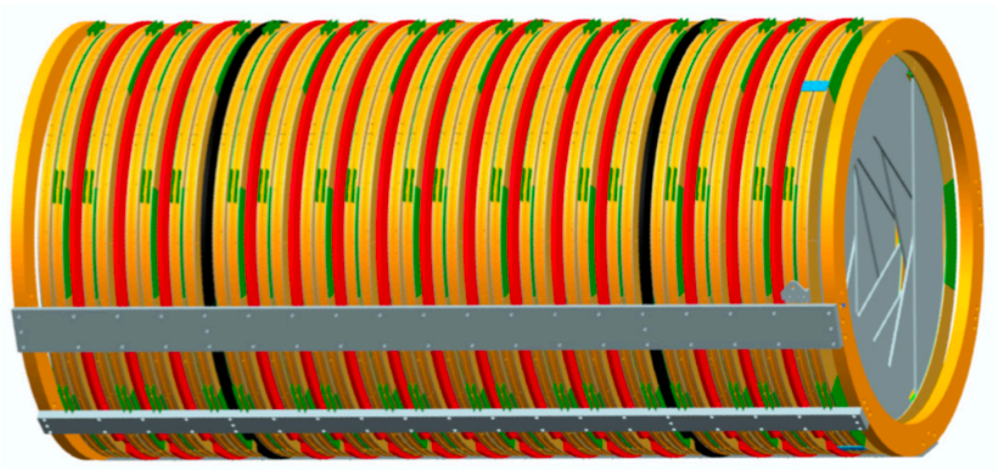
Decay In Orbit comparison

	spin	NA/%	$E_{\text{end}}/\text{MeV}$	B/MeV^{-6}	τ_μ/ns	$\Gamma_{\text{cap}}/s^{-1}$
$^{6}_{3}\text{Li}$	1	7	104.64	1.3×10^{-19}	2175.3	4680
$^{7}_{3}\text{Li}$	$\frac{3}{2}$	93	104.78	1.3×10^{-19}	2186.8	2260
$^{27}_{13}\text{Al}$	$\frac{5}{2}$	100	104.97	8.9×10^{-17}	864	662×10^3
$^{46}_{22}\text{Ti}$	0	8	104.25	5.2×10^{-16}		
$^{47}_{22}\text{Ti}$	$\frac{5}{2}$	7	104.26	5.3×10^{-16}		
$^{48}_{22}\text{Ti}$	0	74	104.26	5.3×10^{-16}	329.3	2.59×10^6
$^{49}_{22}\text{Ti}$	$\frac{7}{2}$	5	104.26	5.4×10^{-16}		
$^{50}_{22}\text{Ti}$	0	5	104.26	5.4×10^{-16}		
$^{51}_{23}\text{V}$	$\frac{7}{2}$	100	104.15	6.3×10^{-16}	284.5	3.07×10^6
$^{50}_{24}\text{Cr}$	0	4	104.04	7.1×10^{-16}	233.7	3.82×10^6
$^{52}_{24}\text{Cr}$	0	84	104.04	7.2×10^{-16}	256.0	3.45×10^6
$^{53}_{24}\text{Cr}$	$\frac{3}{2}$	10	104.05	7.1×10^{-16}	266.6	3.30×10^6
$^{54}_{24}\text{Cr}$	0	2	104.05	6.9×10^{-16}	284.8	3.06×10^6

T. Suzuki, D. F. Measday, and J. P. Roalsvig, "Total Nuclear Capture Rates for Negative Muons," Phys. Rev. C 35 (1987) 2212.
J. Heeck, R. Szafron, and Y. Uesaka, [2110.14667]

Tracker

Biggest difference is the reduced straw thickness from 15 μm to 8 μm

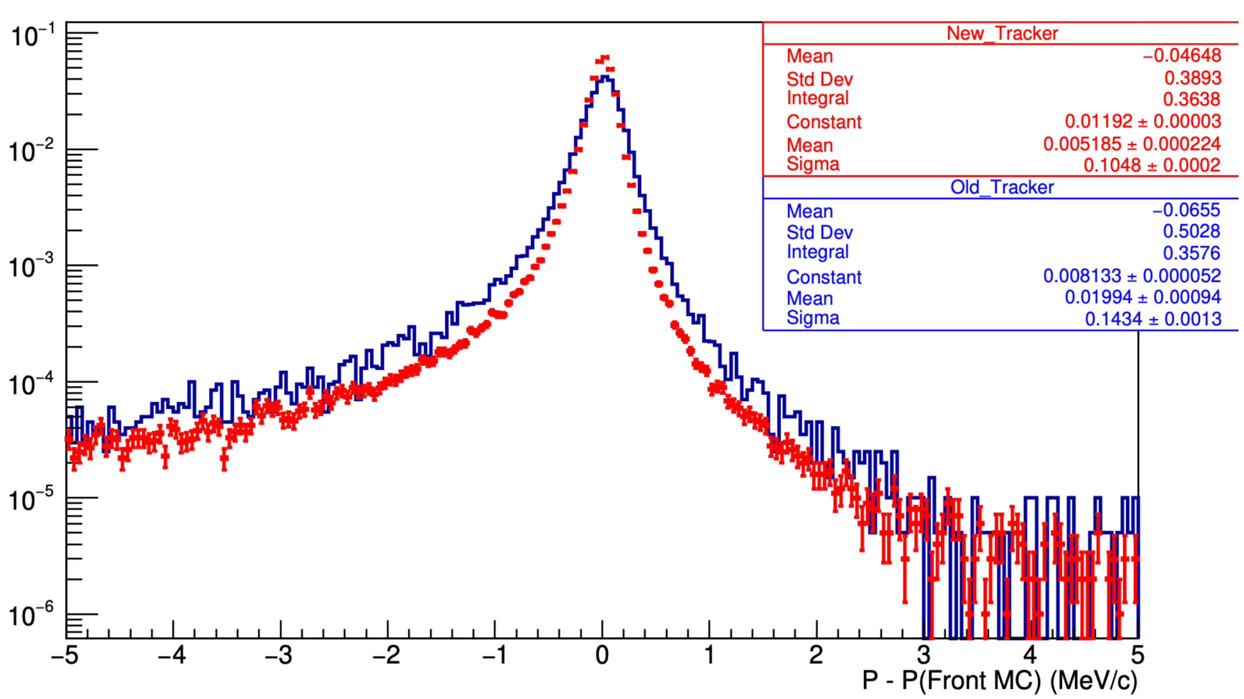


Mu2e

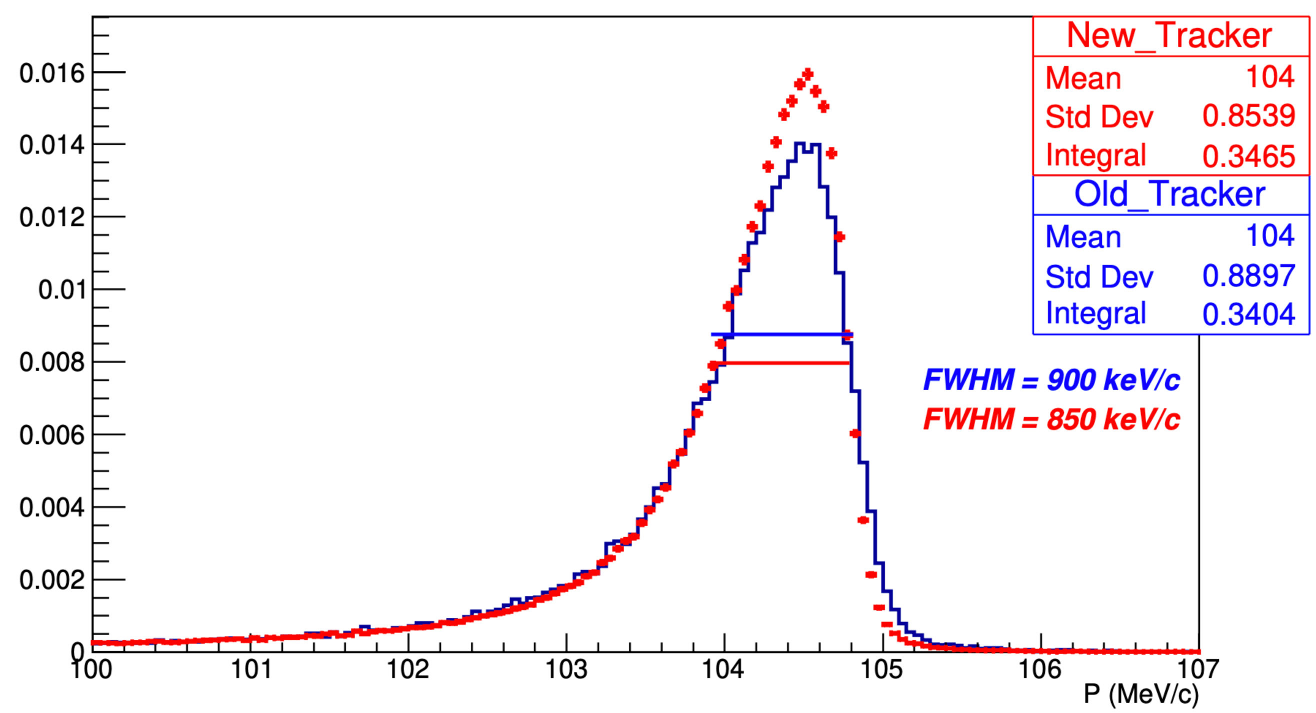
- 25 μm sense wire.
- 5 mm OD straws.
- 15 μm metalized mylar.
- $ArCO_2$ drift gas.

	Mu2e	Mu2e-II
Wall thickness (μm)	18.1	8.2
Al thickness (μm)	0.1	0.2
Au thickness (μm)	0.02	0.0
Linear Density (g/m)	0.35	0.15
Pressure limits (atm)	0–5	0–3
Elastic Limit (gf)	1600	500

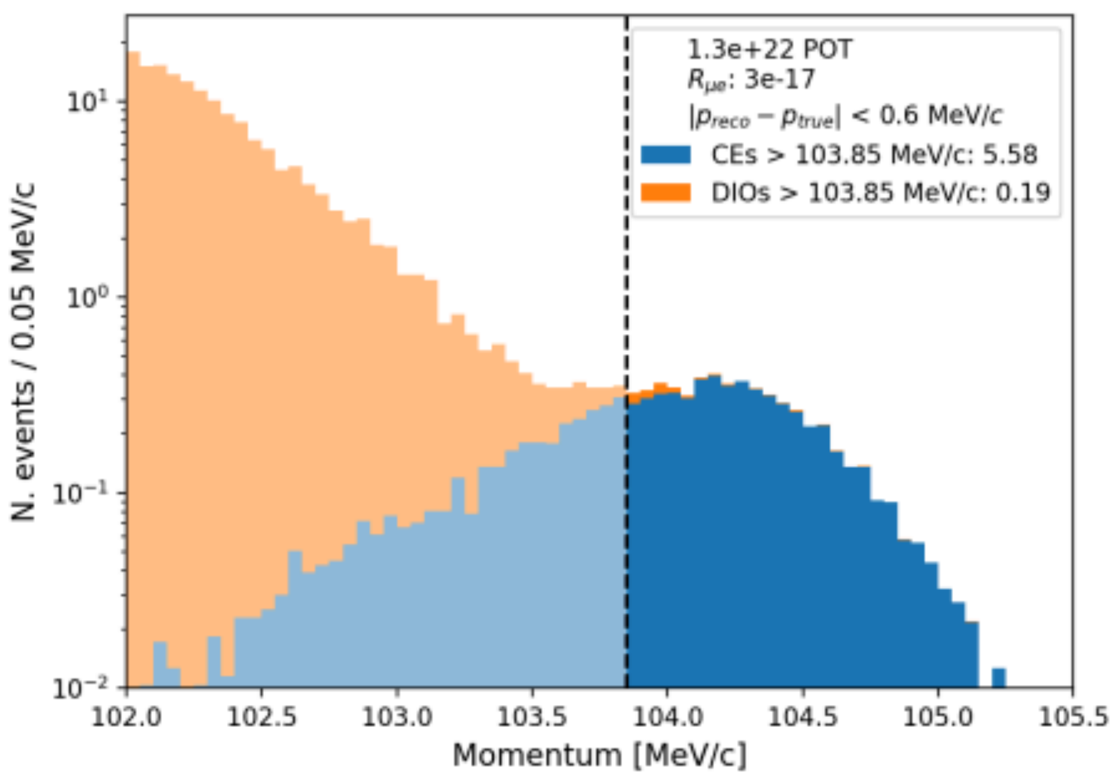
Mu2e-II CE momentum resolution at the Tracker front



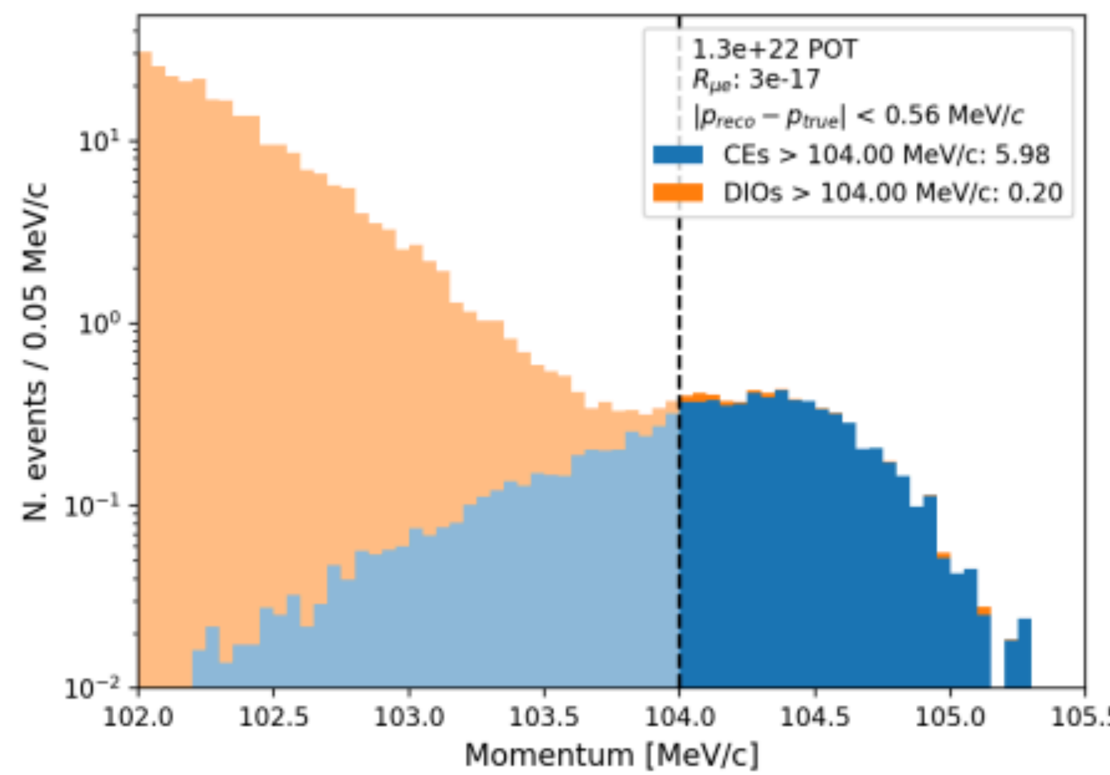
Mu2e-II CE reconstructed momentum



Conversion electron



15 μm straws (Mu2e)

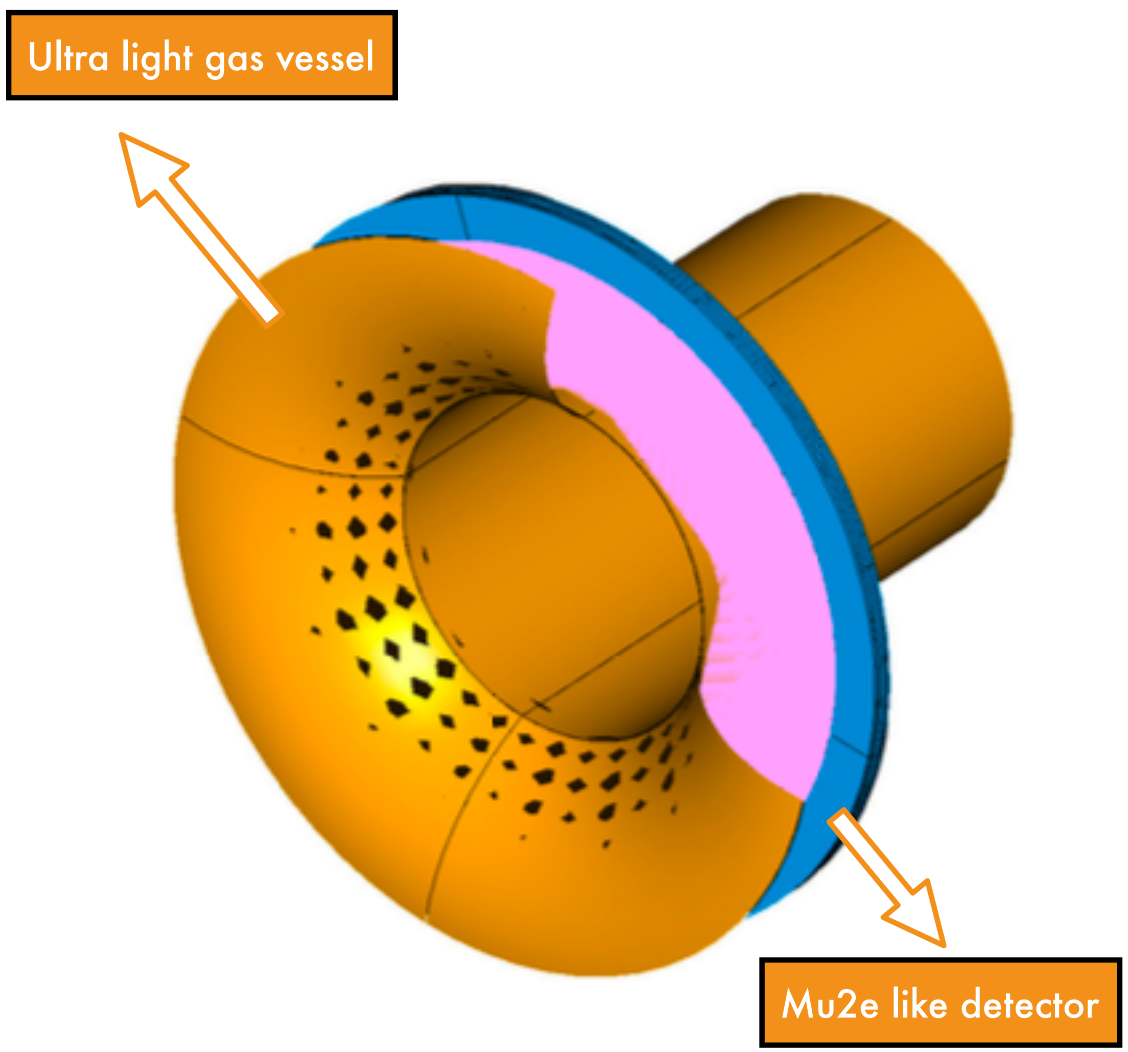


8 μm straws (Mu2e-II)

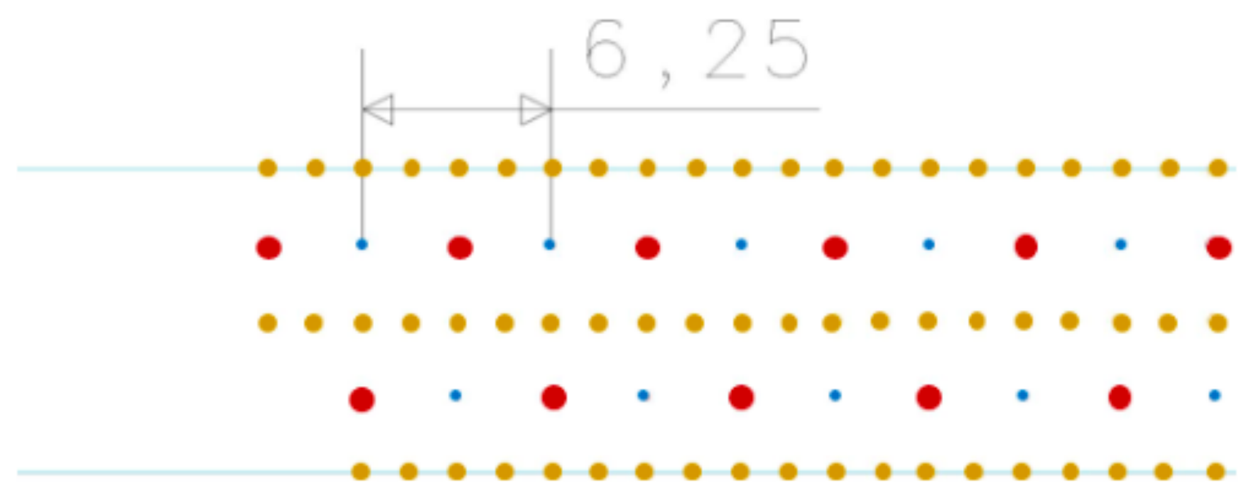
10% improvement on CE efficiency

R&D is needed to improve pattern recognition and track finding

Alternative tracker geometry



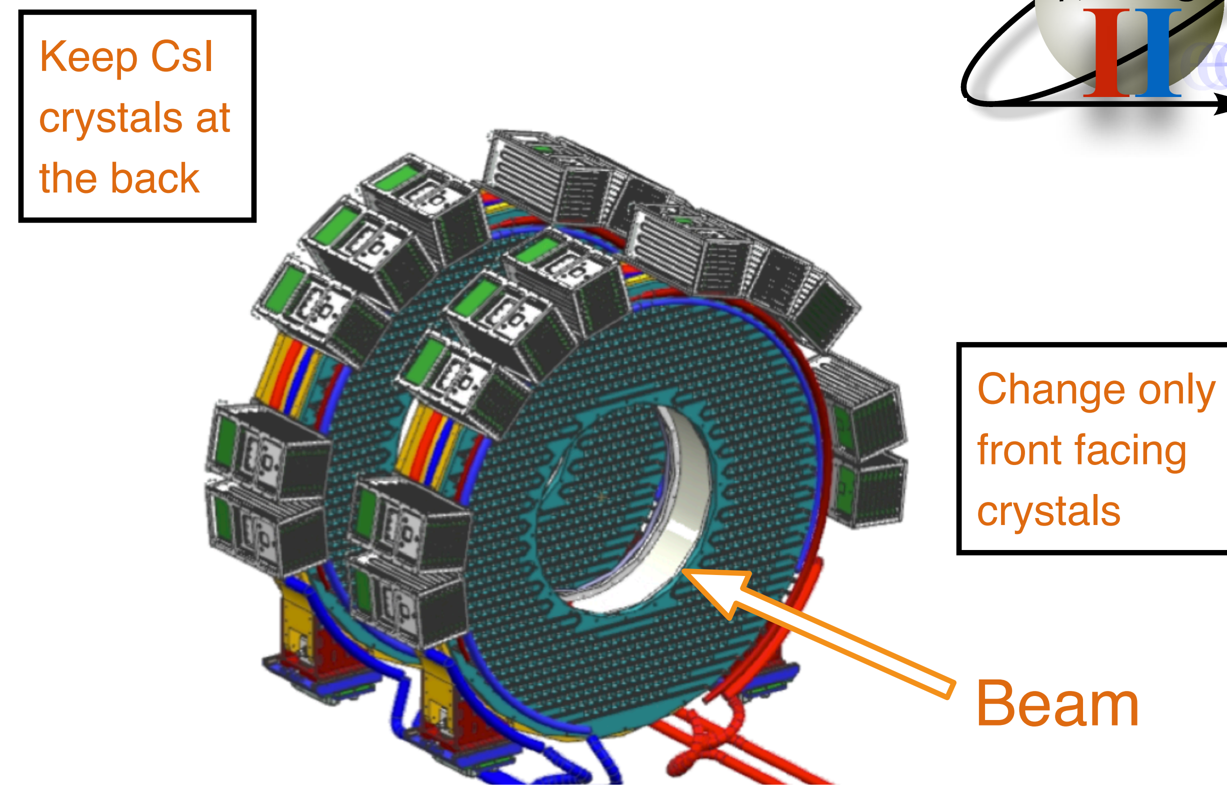
Blue is 25 μm W sense wire, **red** is 50 μm Al and **orange** is 40 μm Al field wires. Alternatively 5 μm metaled mylar foils can replace the field layer.

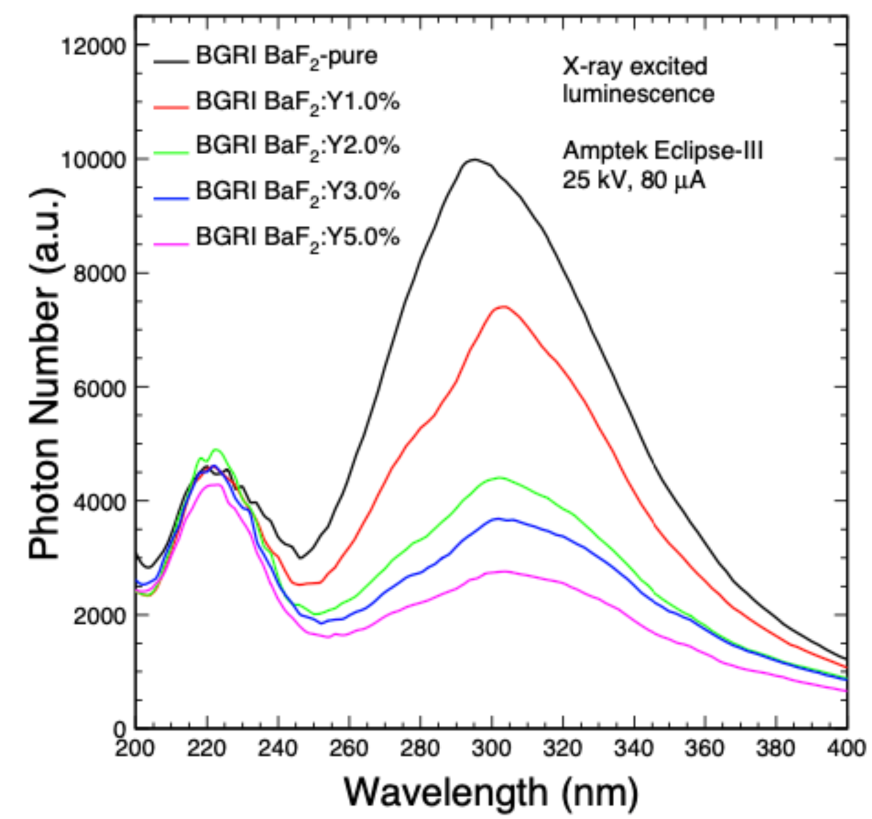


- No glueing is needed as there is no need to eliminate leaks.
- He is needed for the drift gas to minimize multiple scattering.
- However He is $\times 2$ slower than $ArCO_2$ and will reduces rates.

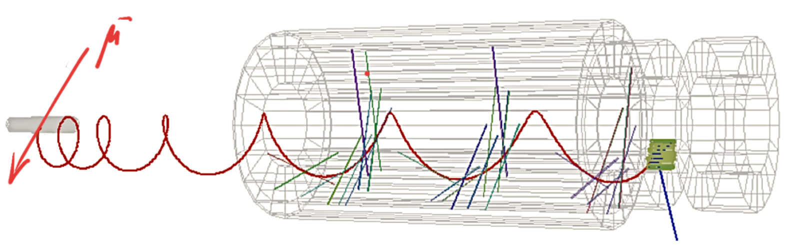
Calorimeter

- Calo requirements are same as Mu2e;
  - Energy reso < 10%
  - Timing reso < 500 ps
- Crystal needs to withstand 0.1-1 Mrad;
  - BaF_2 met requirements but long wavelengths must be suppressed.
  - LYSO:Ce also met requirements but is slower(40 ns decay time).
- Photosensors has the same rad requirements;
  - For BaF_2 they must be sensitive to 220 nm fast component and insensitive to 300 nm slow component.
  - AlGaN photocathode works well with BaF_2.
  - R&D is underway to improve radiation hardness of these SiPMs.

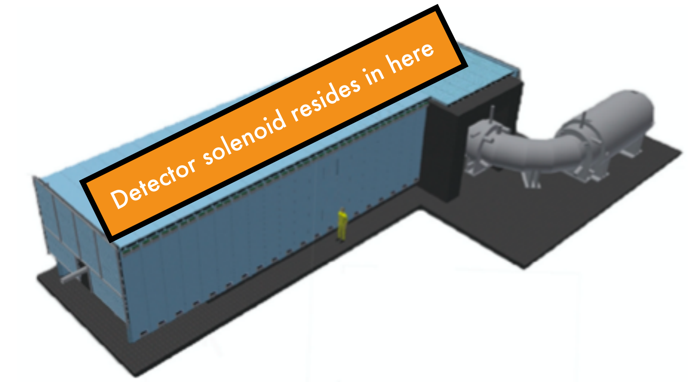




Cosmic ray veto

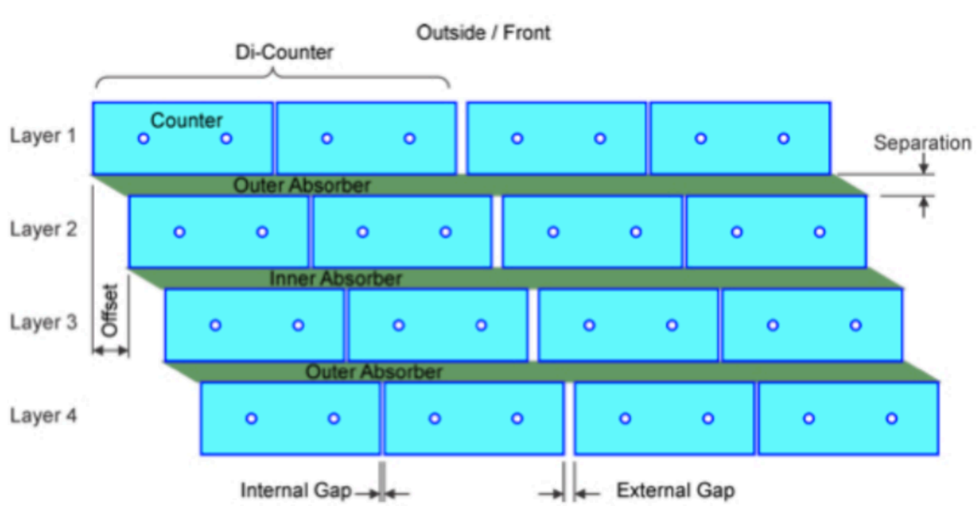


Cosmic background ~= 1 bg event per day.
Covers all DS and part of TS.

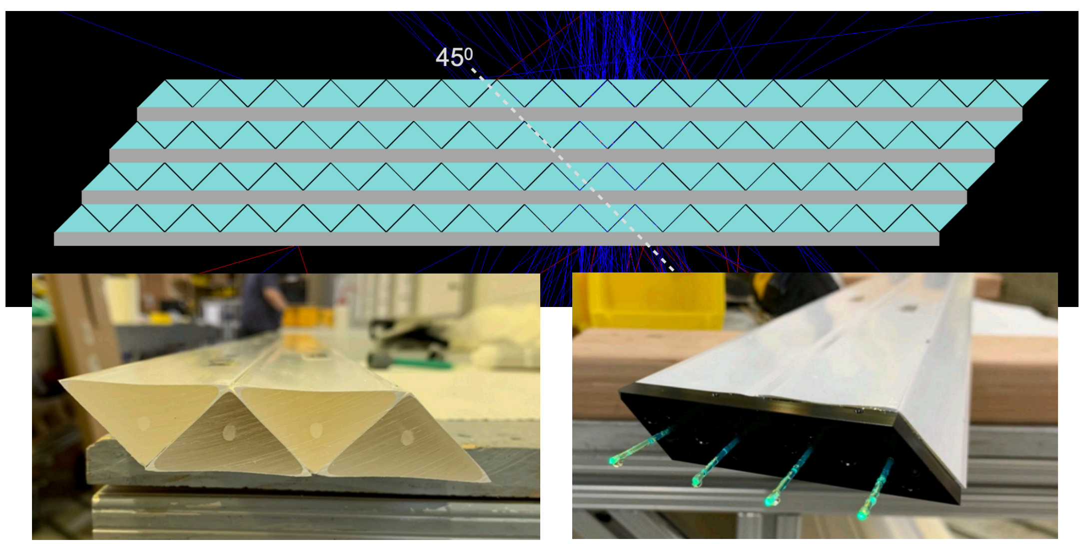


Mu2e → Mu2e-II

- Polystrene scintillators coated with TiO2 sandwiched between Al absorbers.
- 4 overlapping layers of scintillators.
  - 3 layer coincidence veto
- Readout through WLS fibers & 2x2 mm^2 SiPMs on both ends.

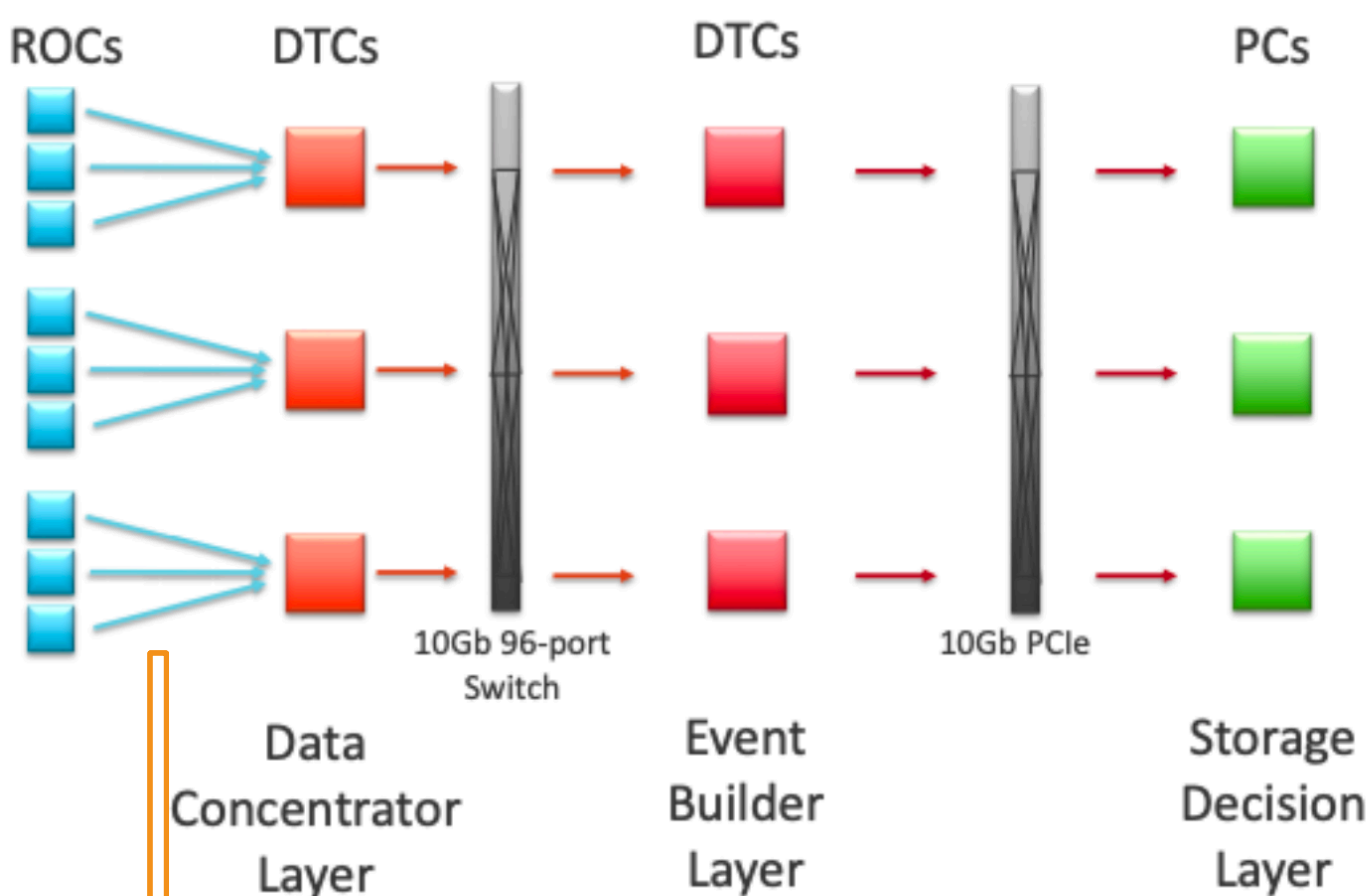


- Improve concrete shielding with Barite and Boron loaded concrete.
- Change geometry to further minimize gaps between scintillators and increase granularity.
- SiPMs with better PDE and potted fibers to increase light yield.



Trigger and Data Acquisition(TDAQ)

- × 6 event size @ 1MB/s.
- Reduced period with no beam.
- × 5 better Mu2e trigger rejection.
- × 10 Rad dose.
- 14 PB/y data.



Track reconstruction;

1. Hit preparation.
2. Pattern recognition.
3. Track fit.

Use FPGA for L1 hardware trigger

Use GPUs for software trigger

Development can start now!

Backgrounds and sensitivity

- Preliminary results are for a C production target.
- More R&D and software optimization is needed.
- This estimate is considered to be conservative.

Results	Mu2e	Mu2e-II (5-year)
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)	6.7×10^{18}	5.5×10^{19}
SES	3.01×10^{-17}	3.25×10^{-18}
$R_{\mu e}$(discovery)	1.89×10^{-16}	2.34×10^{-17}
$R_{\mu e}$(90% CL)	6.01×10^{-17}	6.39×10^{-18}

PRELIMINARY

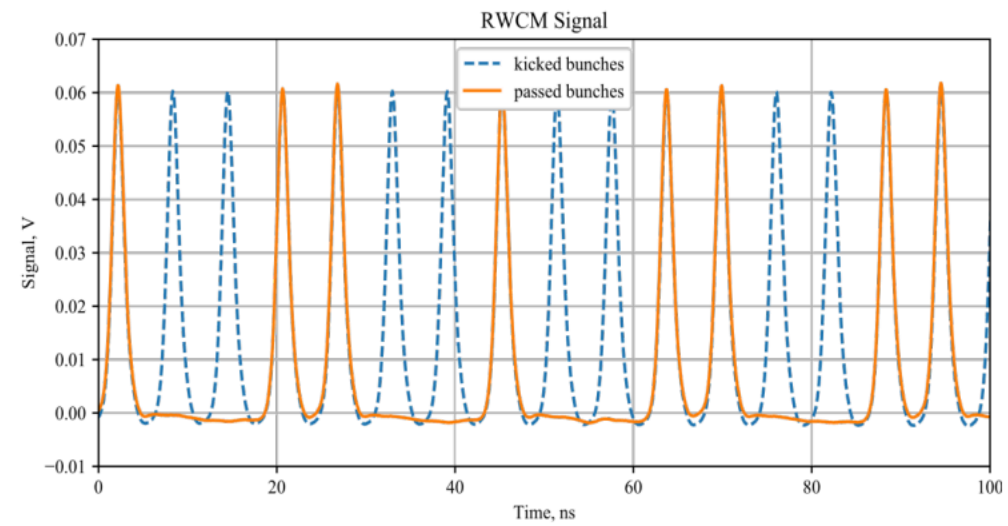
Summary

- Mu2e-II is a worthwhile follow up to Mu2e in all cases with respect to Mu2e result.
- PIP-II will provide a much finer beam allowing Mu2e-II and other muon experiments to flourish.
- However more intense beam brings a harsher environment in terms of radiation. All subsystems will require significant R&D to meet this criteria.
- Mu2e-II offers many challenges and opportunities to work on regardless of the subsystem.

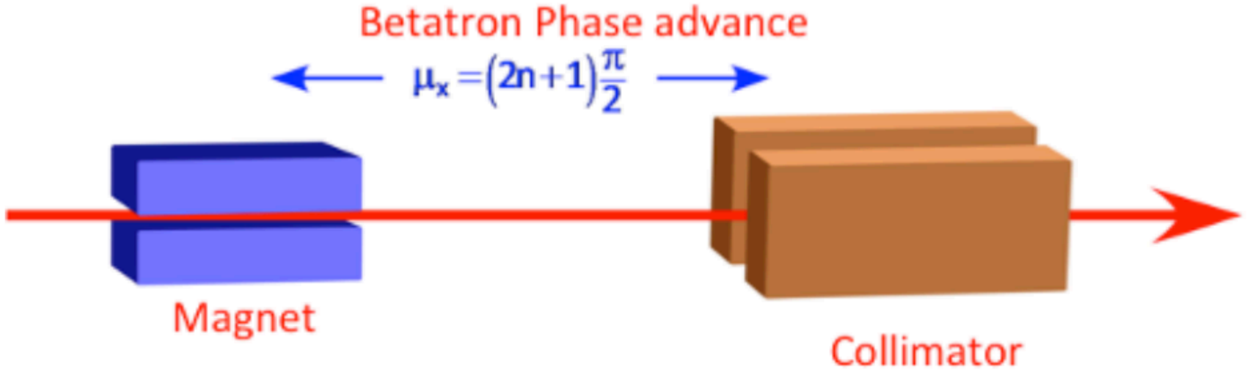
BACKUP

Extinction

- Extinction is measure of out-of-time beam
- Mu2e-II requires extinction < 10^{-11}
    - cf Mu2e requirement < 10^{-10}
- PIP-II specification is 10^{-4}
    - Likely will be better
- Second stage (10^{-9} with safety margin) with resonant dipoles and collimators, modified from Mu2e
    - Lower momentum means larger deflection
    - No beam halo from Mu2e's slow extraction septum
    - Lower momentum means lower punch through at collimator



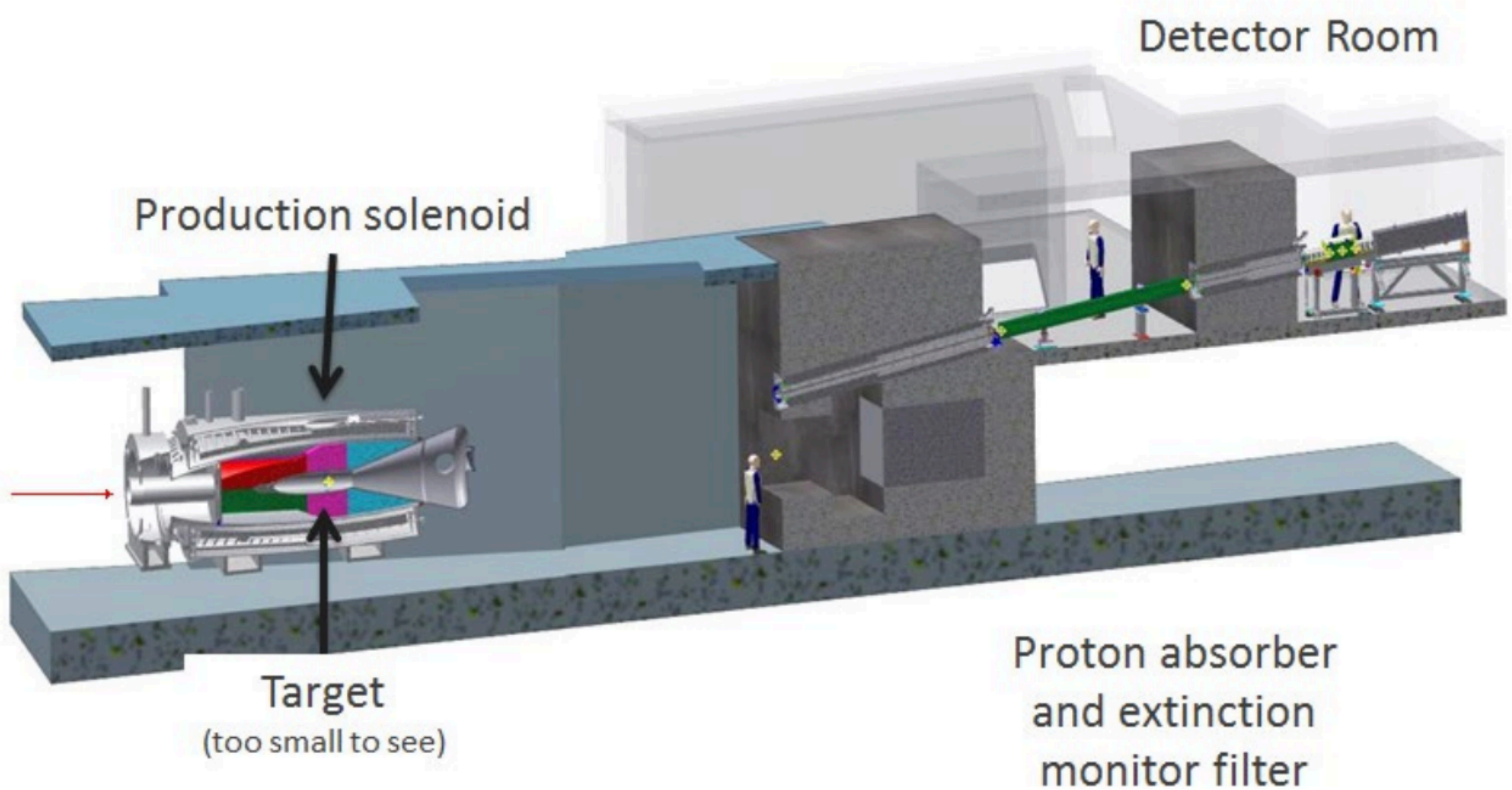
Measured bunch-by-bunch extinction from PIP-II linac



Extinction monitor

Mu2e's extinction monitor is integrated into beam dump shielding

- Sees about one ~4 GeV/c particle per 10^6 protons on target
- Statistical measurement of extinction over several hours
- Monitor adaptable to Mu2e-II (800 MeV beam)
- Acceptance of channel is a challenge since trajectory much different
- Reworking requires R&D



Mu2e Extinction monitor

Radiation

Radiation around production target

- Displacements/atom (DPA) damage to PS coil
  - FOM is ratio of muon stops in stopping target to hottest DPA rate in PS coil
  - For Mu2e-II beam this FOM is close to or better than for Mu2e 8 GeV beam
  - DPA level around 4×10^{-5} DPA/yr
  - Allows to run without annealing for ~1 yr

Beam power may imply different HRS

- W HRS with 25 cm inner bore radius would tolerate 100 kW beam

Radiation at the detector

- Doses ~20 times Mu2e at electronics and equipment alcoves
- Scaling by beam power yields estimated hadron fluxes (E > 30 MeV):
  - 3.7×10^{5} h/cm2/yr at rack electronics
  - 750 h/cm^2/yr tracker and calorimeter electronics
- Estimates will be improved, but will require radiation-tolerant electronics

Environmental radiation

- MARS simulations suggest approximately 20 times Mu2e
- Mitigation to be evaluated, may require, e.g.,
  - Increasing berm
  - Fencing a controlled area

Stopping Target Monitor

Stopping Target Monitor (STM) measures denominator of Rme

- Monitors X-ray and g-ray emission from stopping target during muon capture
- 10% accuracy
- For Al target:
  - 347 keV from 2p to 1s transition, prompt with muon stop
  - 1809 keV from nuclear capture, with 864 ns muon lifetime in Al
  - 844 keV from $^{26}Mg^*$ capture product, lifetime 9.5 minute
- Mu2e uses HPGe detector (excellent resolution) and $LaBr_3$ crystal (high rate, radiation hard) at 34 m from target
- To continue to use in higher rate and higher dose Mu2e-II may:
  - Increase absorber in STM beamline to reduce “beam flash”
  - Use HPGe at low intensity to calibrate $LaBr_3$
  - Move detectors off-axis
  - Replace some calorimeter crystals with $LaBr_3$ or LYSO
  - Create tertiary photon beam and measure that
- Subject of further R&D