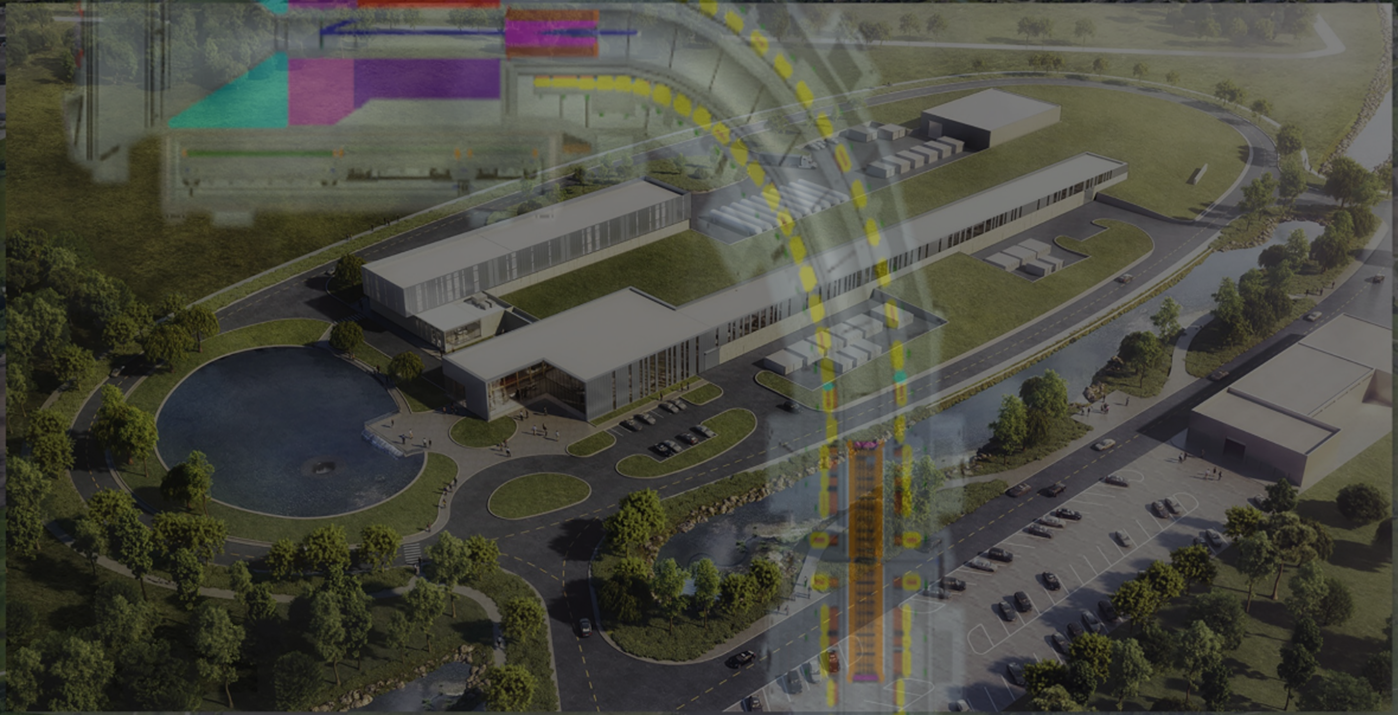

Mu2e-II: Sensitivity Intro.

Sophie Middleton

March 2023

Future Muon Workshop

Today’s Agenda

11:00 AM → 12:30 PM **Parallel Mu2e-II: Physics and Sensitivity** — 269 (Lauritsen)

Convener: Sophie Middleton (Caltech)

11:00 AM	**Introduction** **Speaker**: Sophie Middleton (Caltech)	10m
11:10 AM	**Stopping target** **Speaker**: Leo Borrel (California Institute of Technology)	25m
11:35 AM	**Normalization** **Speaker**: David Hitlin (Caltech)	25m
12:00 PM	**Exotic physics signatures** **Speaker**: Ryan Plestid (Caltech)	25m

1:30 PM → 3:30 PM **Parallel Mu2e-II: Physics and Sensitivity** — 269 (Lauritsen)

Convener: Sophie Middleton (Caltech)

1:30 PM	**Implication of production target design on sensitivity** **Speaker**: Michael Mackenzie	25m
1:55 PM	**Implication of tracker design on sensitivity** **Speaker**: David Brown (LBNL)	25m
2:20 PM	**Challenges and on-going efforts** **Speaker**: All	30m

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Physics and phenomenological considerations and motivations

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Physics and phenomenological considerations and motivations

Technical aspects

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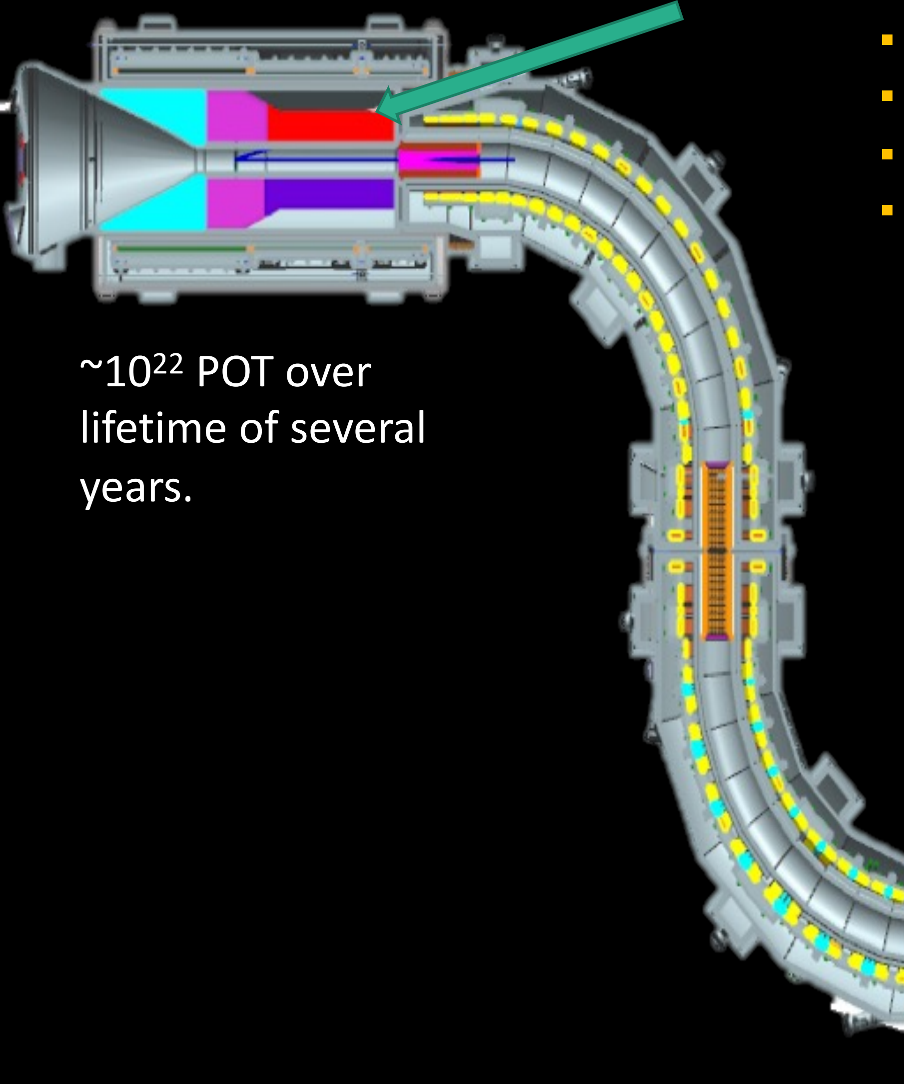
Final discussion:
Google doc of on-going efforts:

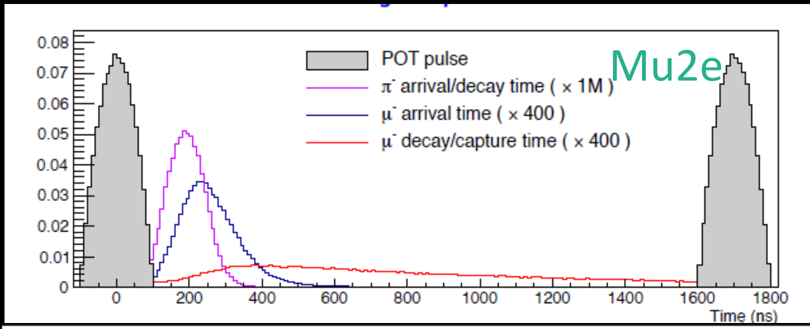
https://docs.google.com/document/d/1A9Svwji3Bg4WVGkR1S0fIciyRWj7YsnN_uQwfCF742Y/edit?usp=sharing

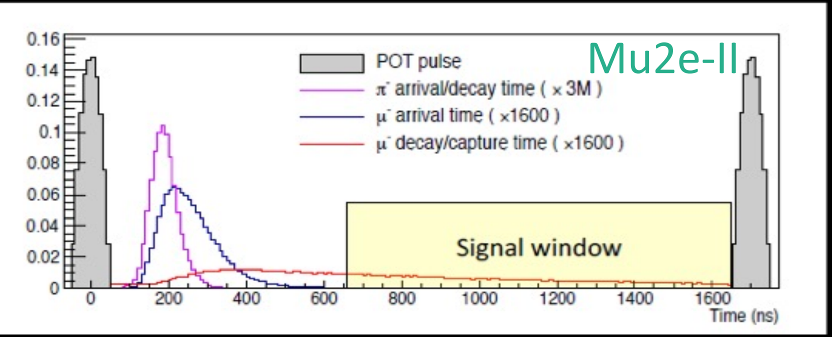
Mu2e-II

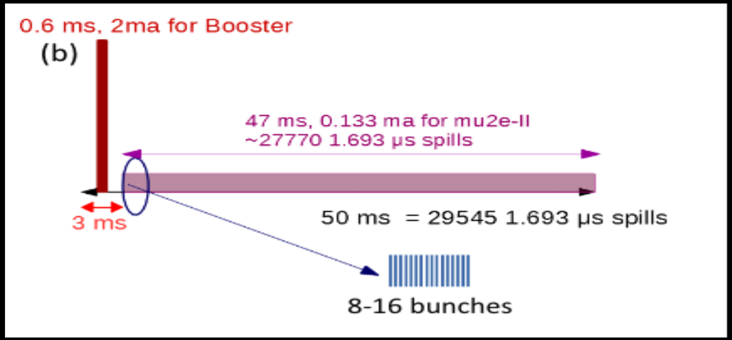
800MeV PIP-II beam means:

- Narrower pulses;
- Less pulse-to-pulse variation;
- Higher intensity;
- Higher duty factor.



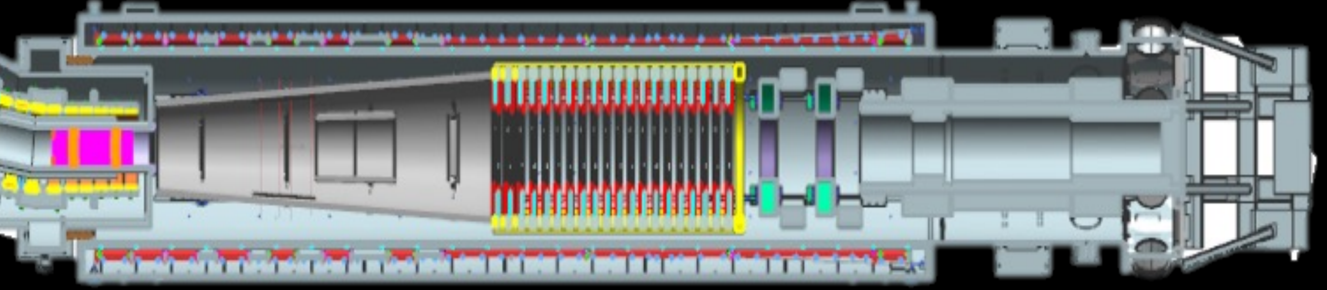






~10^{22} POT over lifetime of several years.

Estimated Stopped Muon rate = 0.00009/POT



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Beam Requirements

Snowmass simulation study assumed:

- 4.5×10^{22}
- 5 years of running

- PIP-II can deliver these requirements to Mu2e-II

	Mu2e	Mu2e-II	comments
Source	Slow extracted from Delivery Ring	H- direct from PIP-II Linac	Mu2e-II will need t strip H- ions upstream of the production target
Beam energy [MeV]	8000	800	Optimal beam energy 1-3 GeV
Total POT	3.6×10^{20}	4.5×10^{22}	Approx.
Lifetime [yr]	3	5	
Run Time [sec/yr]	2×10^7	2×10^7	
Duty factor	25%	>90%	Important for keeping instantaneous rates under control
P pulse width [ns]	250	62	
P pulse spacing [ns]	1695	1700	Assumes Al target
Extinction	1×10^{-10}	1×10^{-11}	Ratio of out:in time protons
Average beam power [kW]	8	100	100kW approx.

Mu2e-II: 2022 Snowmass Contributed Paper

https://arxiv.org/abs/2203.07569

2-year long effort resulted in Snowmass Contributed Paper

~100 co-signed

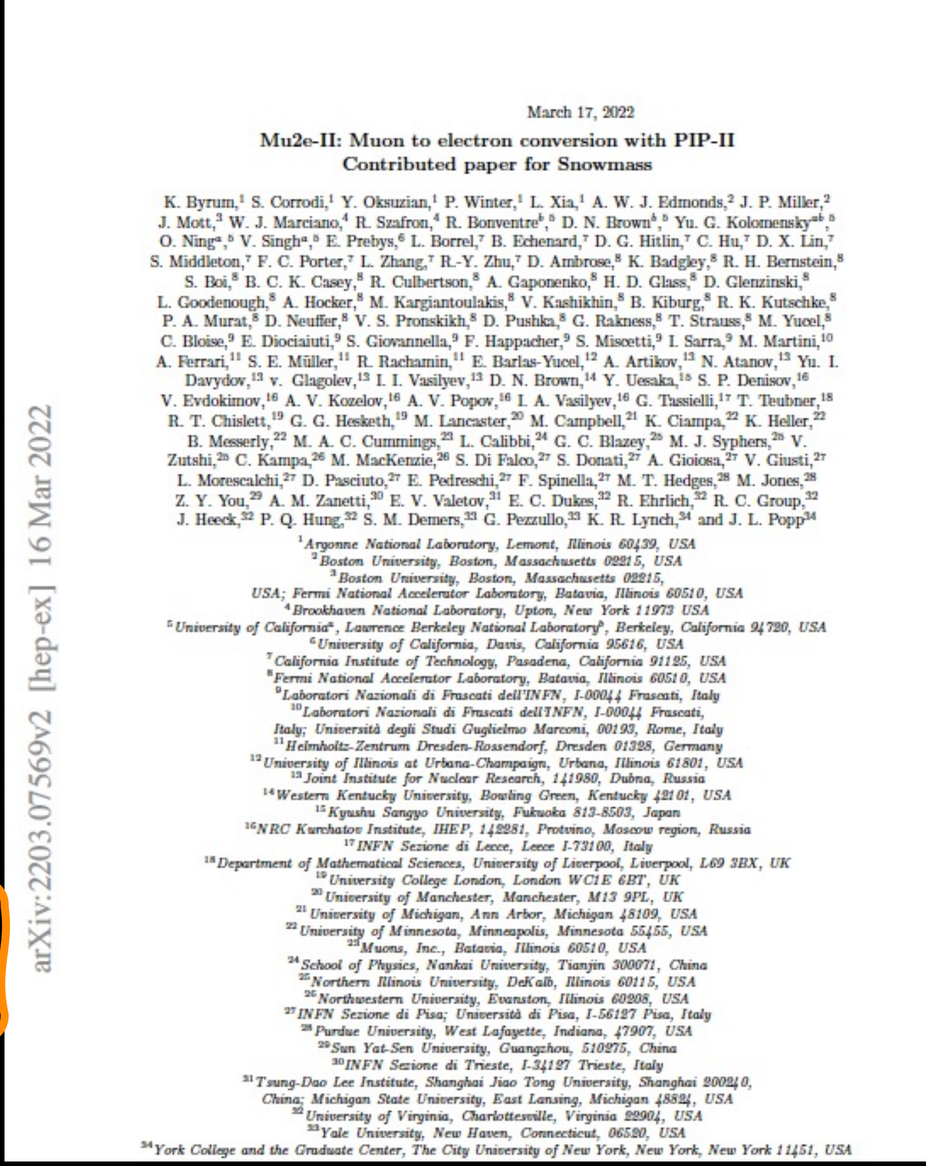
34 institutions

6 countries

Assumed:

- POT = 4.5 x 10^{22}
- 5 years of running
- **BaF_2 calorimeter crystals** - same dimensions as CsI
- **Straw tube tracker** - no gold layer and 8 µm straws
- **Carbon production target, conveyor design**.
- No $\bar{p}$ windows in TS.
- Mu2e Al stopping target with foil design.
- Mu2e reconstruction and trigger algorithms.
- Mu2e IPA dimensions.

Background	Mu2e	Mu2e-II (5 years)
Decay in orbit	0.144	0.263
Cosmics	0.209	0.171
Radiative Pion Capture (in-time)	0.009	0.033
Radiative Pion Capture (out-of-time)	0.016	< 0.0057
Radiative Muon Capture	< 0.004	< 0.02
Anti-protons	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% *C.L.*)	6.01×10^{-17}	6.39×10^{-18}



March 17, 2022

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

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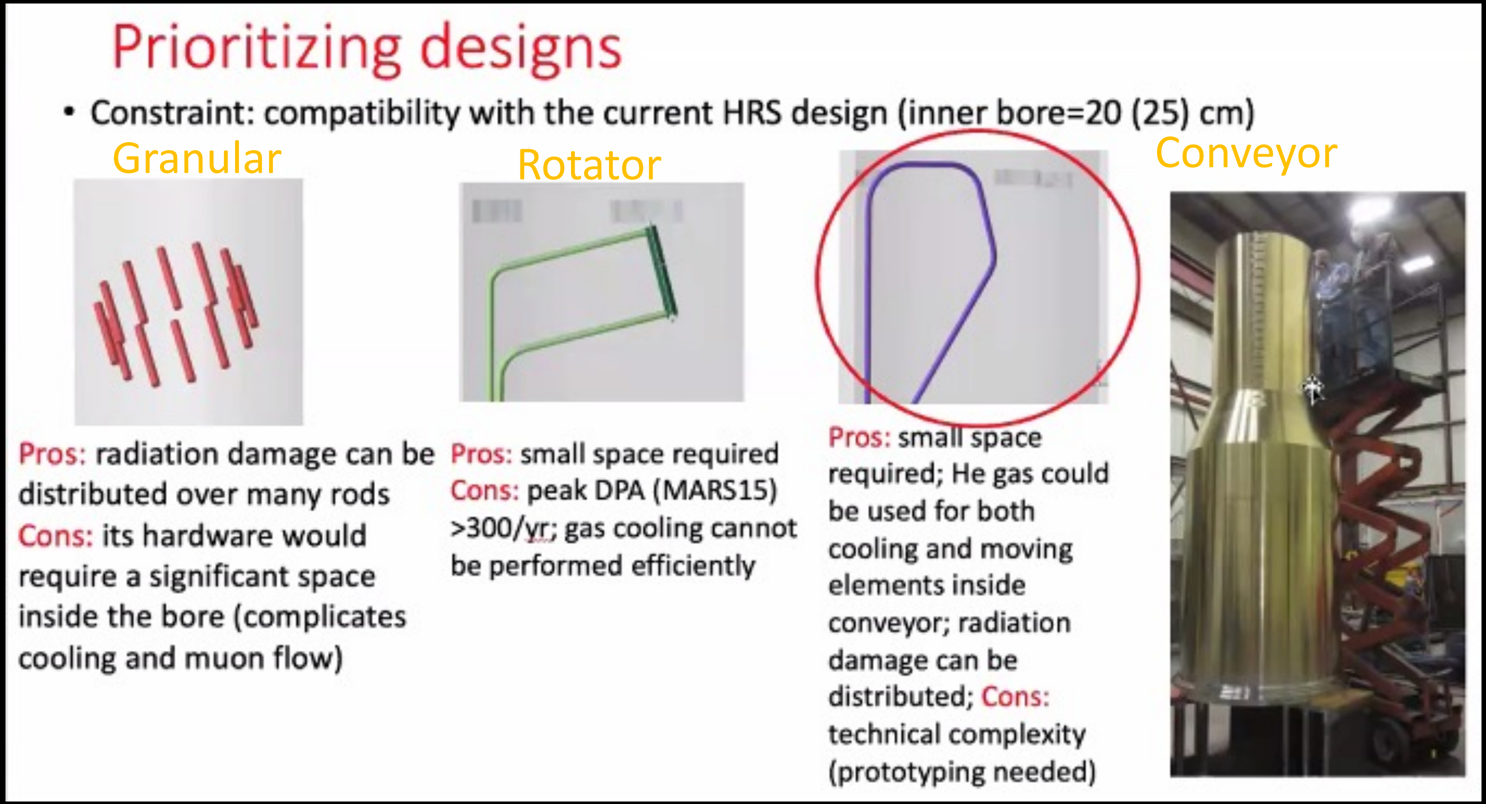
Caltech

Production Target

Front runner is Conveyor design - W or C?

	Tungsten/WC	Lower-density bent (Carbon)
Rotated	Requires a large hardware in HRS	Too large to fit HRS
Fixed granular	DPA is too high	DPA is high; lower pion production
Conveyor	Thermal analysis is ongoing	Lower pion production; thermal analysis is ongoing

Future study: Friction, shape of elements, charge distribution



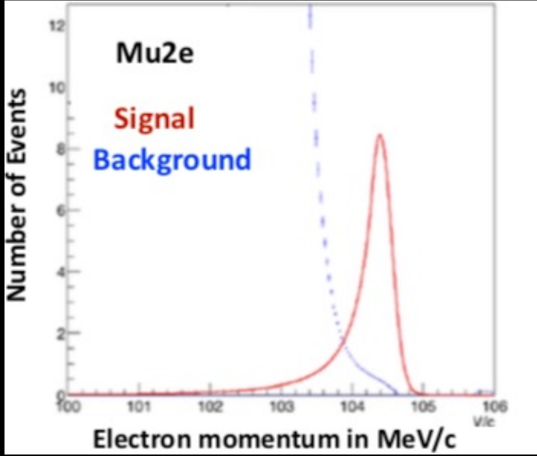
R&D on-going - Vitaly given many talks at conferences.

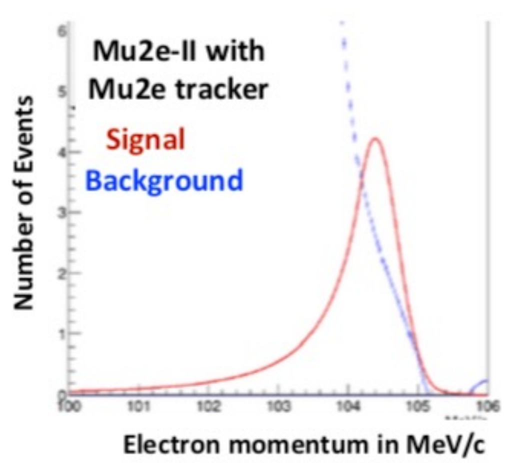
Tracker Requirements

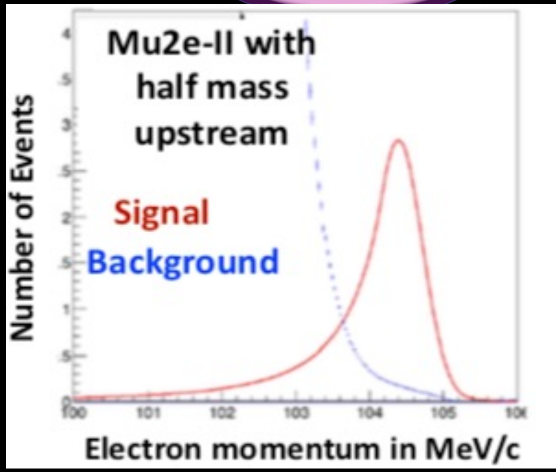
DIO background would increase x10 in Mu2e-II.
Must improve momentum resolution to suppress DIO.

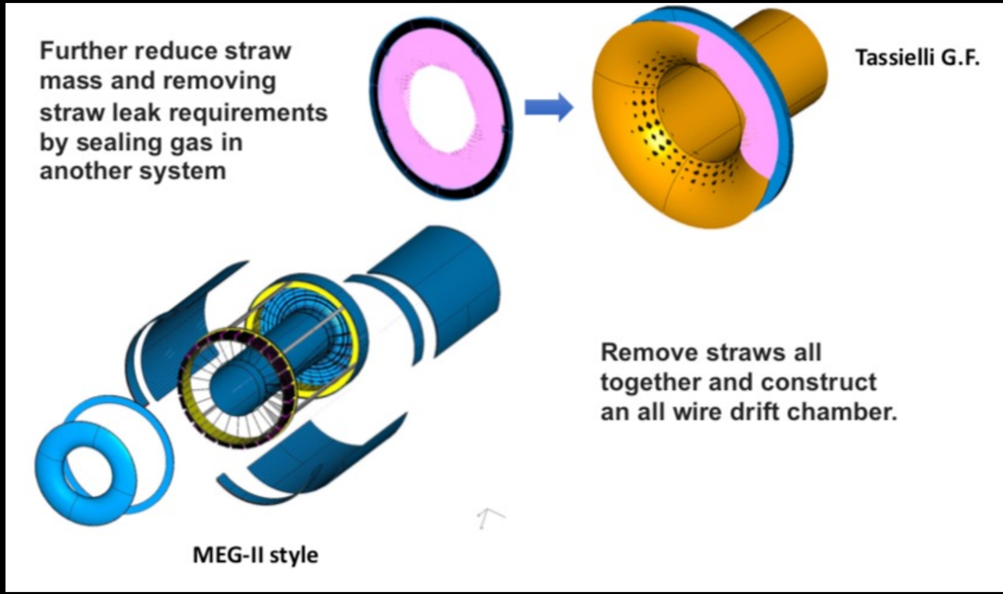
Simulation assumes 8 μm straws and no gold

	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









To meet Mu2e-II momentum resolution/background separation goals:

Reduce total Tracker Mass:

- Thinner straws (8μm)
- Remove the 200 angstrom gold layer from inside straw

Change detector design:

- Use an ultra light gas vessel to ease straw leakage requirements
- Use different gas
- Consider all wires construction and remove the straws
- Or wires separated by mylar walls

Increased hit occupancy and timing window:

- 4x increase in PBI is estimated to reduce reconstruction efficiency by 30%.

Stopping Targets: Materials

Lithium:

- No detailed study, hard to contain, but not impossible.
- Weak signal, low discrimination power.
- (see Davidson et al 2019)

Aluminum:

- Single stable isotope
- Al(27) (spin 5/2)

Sulphur:

- Advantageous for e+ channel (see Beomki et al 2017)

Titanium:

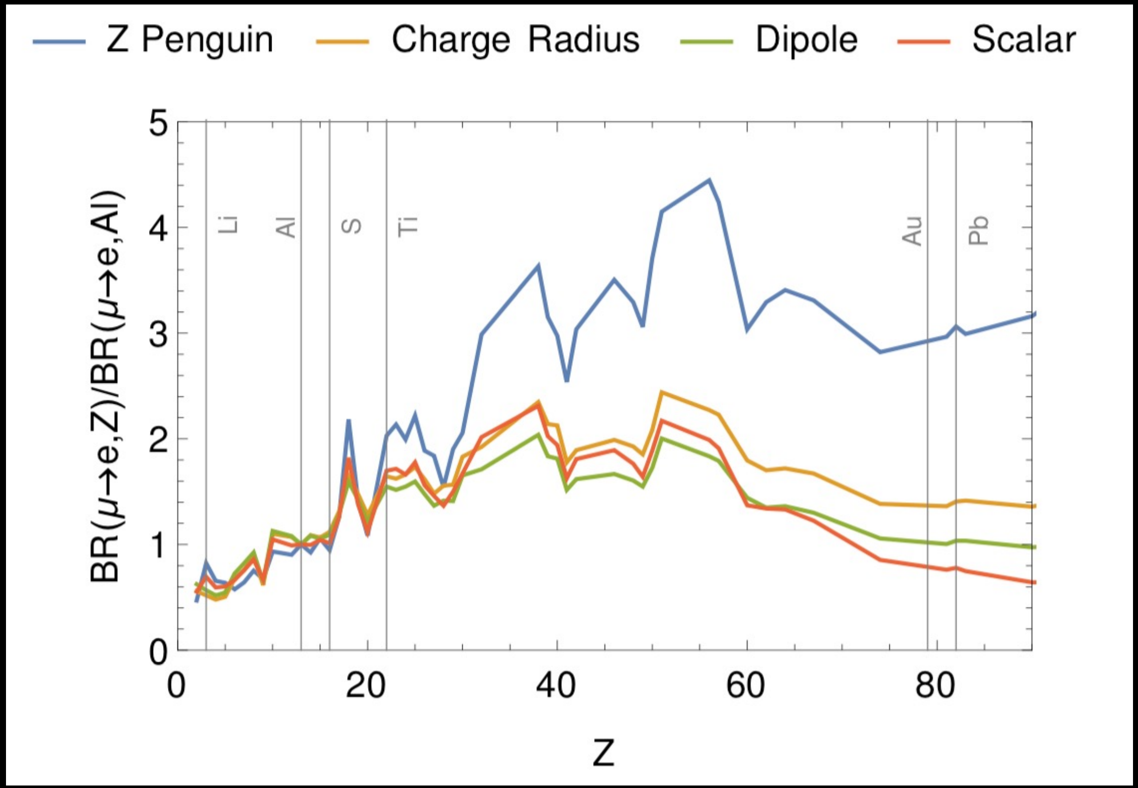
- Multiple isotopes
- Ti(48) Ti(46)Ti(50) (spin-0)→ no SD contribution
- Ti (47) (spin-5/2) or Ti(49)(spin-7/2) can measure SI contribution.

Vanadium:

- Single isotope: V(51) makes up > 99% (spin-7/2)

Heavy Nuclei (Au or Pb):

- Strong discrimination.
- Short muon lifetime (increased pion backgrounds).
- Low sensitivity to spin-dependent contribution.



Timeline

S&T Precision Science

Vision: Fermilab is a world center for accelerator-based Charged-lepton flavor violation (CLFV) and Dark Matter experiments, driven by intense particle beams and PIP-II/Booster Replacement

Major decadal goals

- Muon g-2: Complete data production, analysis, theory to achieve 5σ
- Complete Mu2e project and start science
- Design and build Mu2e-II, other upgrades

Challenges and Next Steps

- The remain several challenges to achieving the design sensitivity:
  1. **Production target design** – pion/muon yield is not the driving factor in the design, but it dictates our sensitivity (see Michael Mackenzie's talk)
  2. **Tracker design** – achievable tracker resolution drives how tight our signal window is and therefore our reconstruction/selection efficiency and therefore our sensitivity (see Dave Brown's talk)
  3. **Calorimeter/CRV design** – crucial to achieving goals, currently unfunded (see CRV/Calo sessions)
  4. **Stopping target design** - several aspects to consider:
     - *Geometry design* – see previous talks by Sophie Middleton
     - *Alternative materials in case of Mu2e signal* – see talk by Leo Borrel

At the end of session 2 we will have a "round table" discussing what the main efforts will be moving forward.

https://docs.google.com/document/d/1A9Svwji3Bg4WVGkR1S0fIciyRWj7YsnN_uQwfCF742Y/edit?usp=sharing – please add ideas and questions here!