Mu2e-II: The Mu2e Experiment in the PIP-II Era

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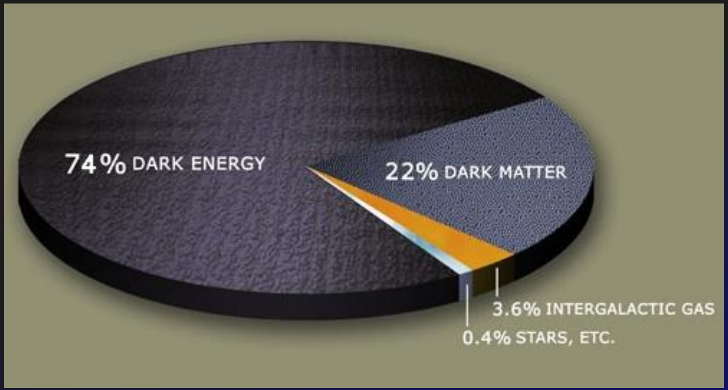
Why We Think the Standard Model is Incomplete

Theory

- Quantum theory of gravity
- Origin of neutrino mass hierarchy
- Solution to hierarchy problem ⇨ supersymmetry, something else?

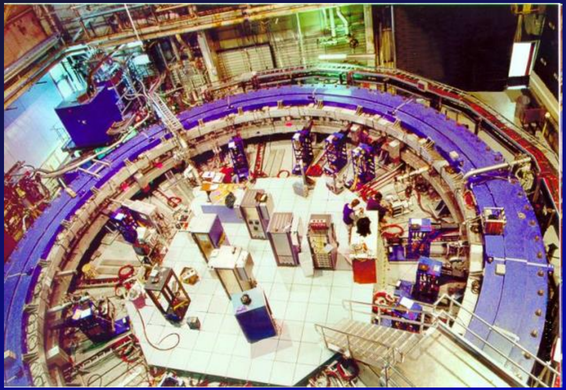
Cosmology

- Matter-antimatter asymmetry in the universe
- Dark matter
- Dark energy

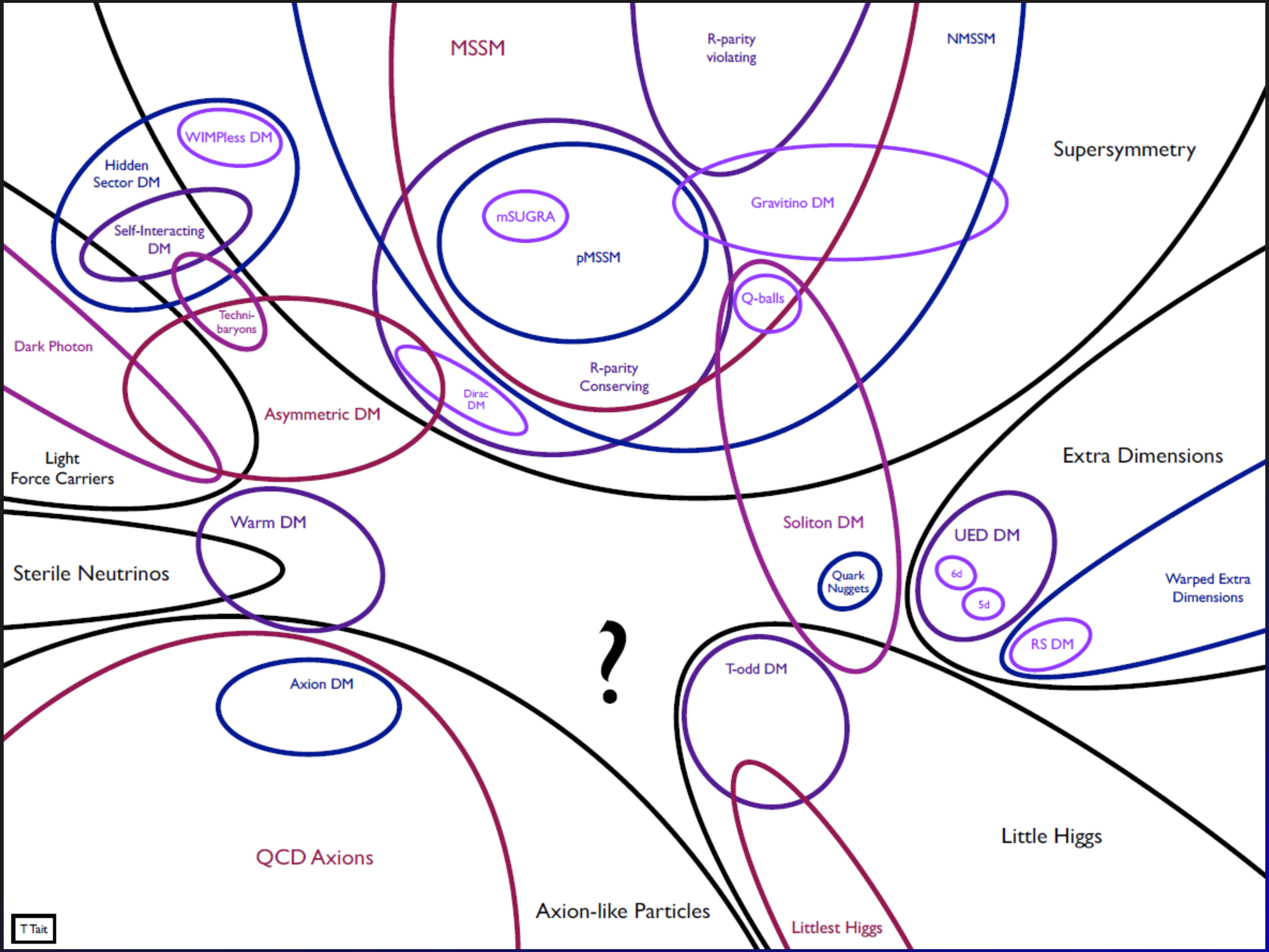


Experiment

- Neutrino mass ⇨ first evidence of physics beyond the standard model
- Occasional hints appear, and often disappear: muon g-2, $B^+ \rightarrow l^+l^-$, NuTeV, CP phases in B_s mixing, D_s decay rates, W+jets, Top AFB



No Lack of Theoretical Ideas, but Little Guidance

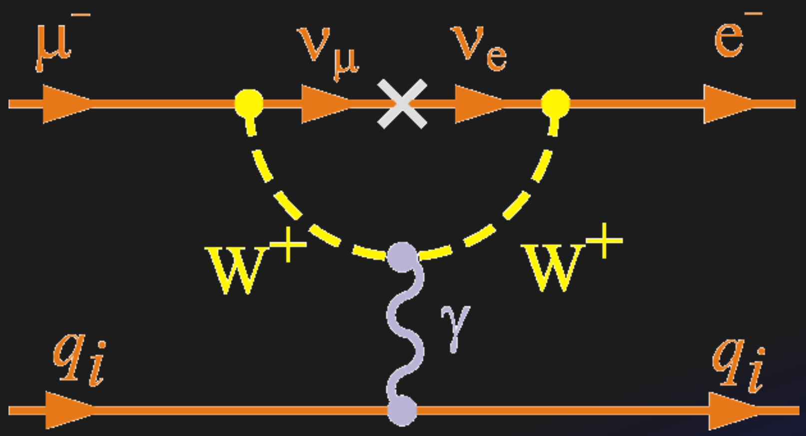


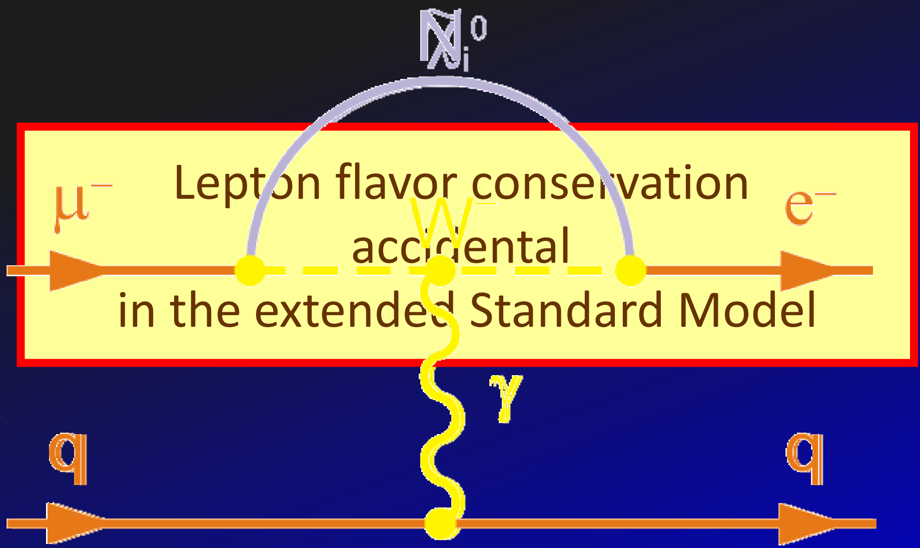
Why Search for Charged Lepton Flavor Violation?

$$\mu^- N \rightarrow e^- N$$

- In Standard Model not there ⇨ neutrino mass discovery implies an unobservable 10^{-52} rate
- Hence, any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally

  ⇨ sensitivities that allow favored beyond-the-standard-model theories to be tested





Lepton flavor conservation accidental in the extended Standard Model

New heavy neutrino

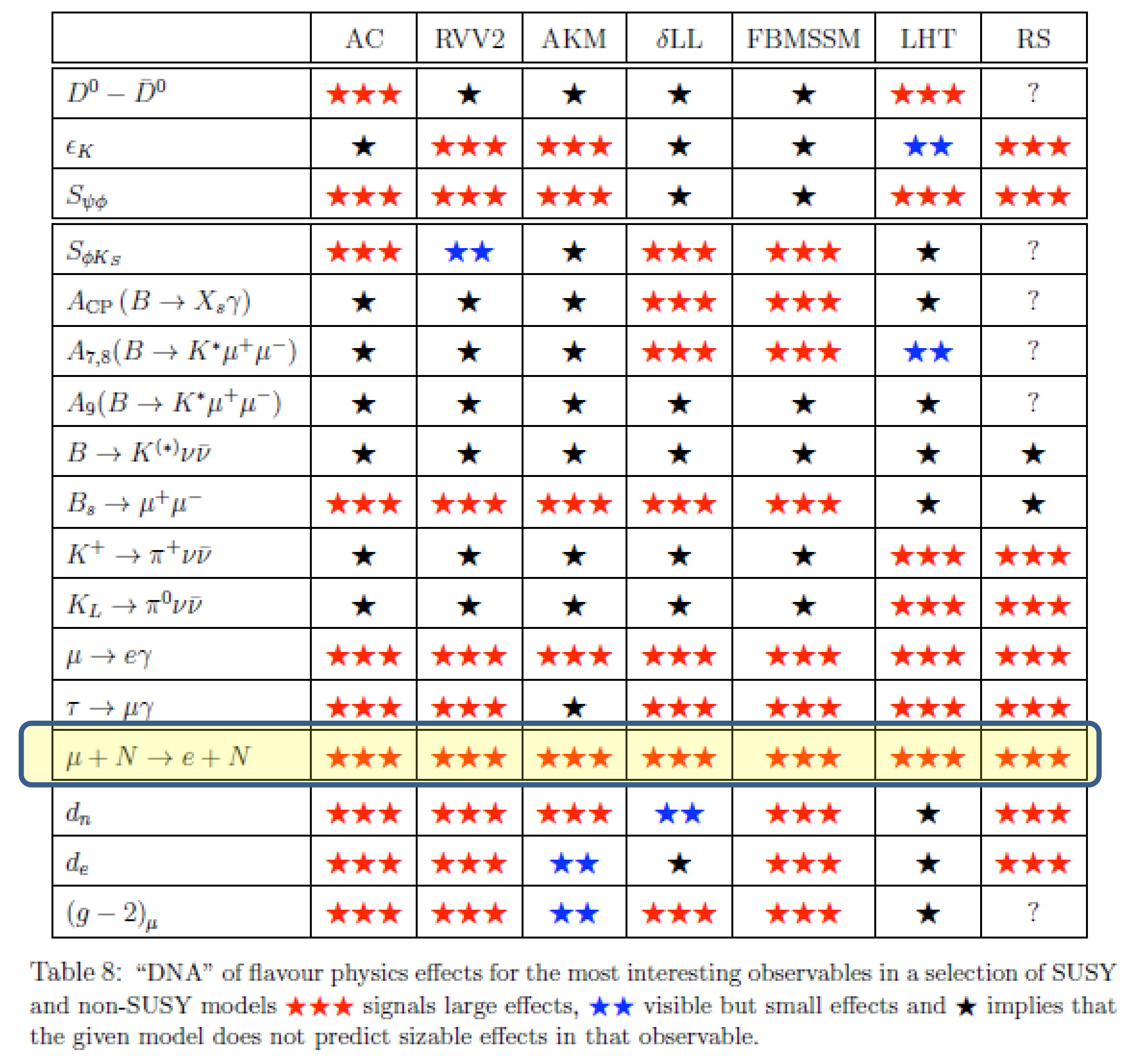
Why Muon-to-Electron Conversion?

Probes of different SUSY and non-SUSY BSM models

★★★ Large effects

★★ Visible, but small

★ No sizable effect

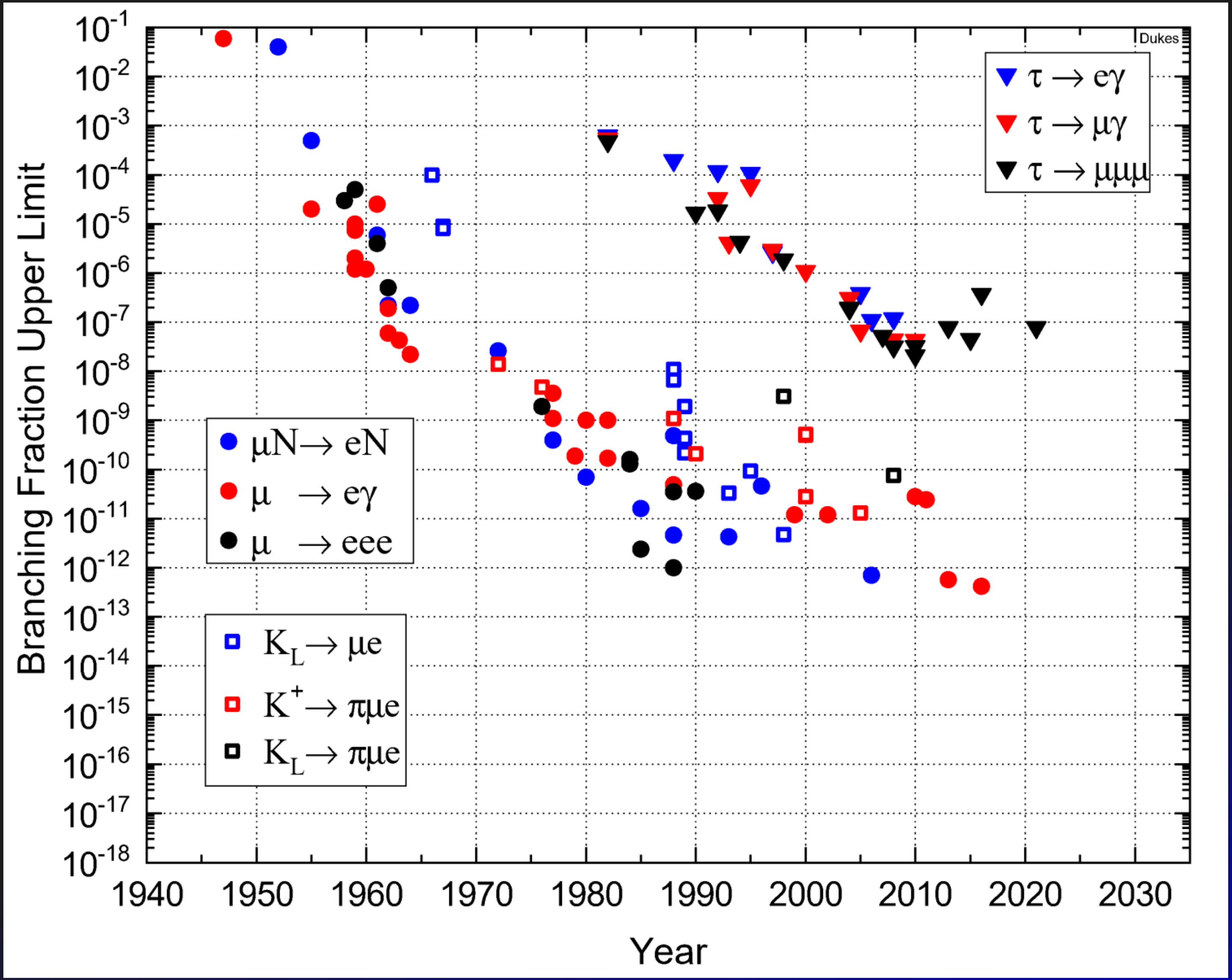


	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

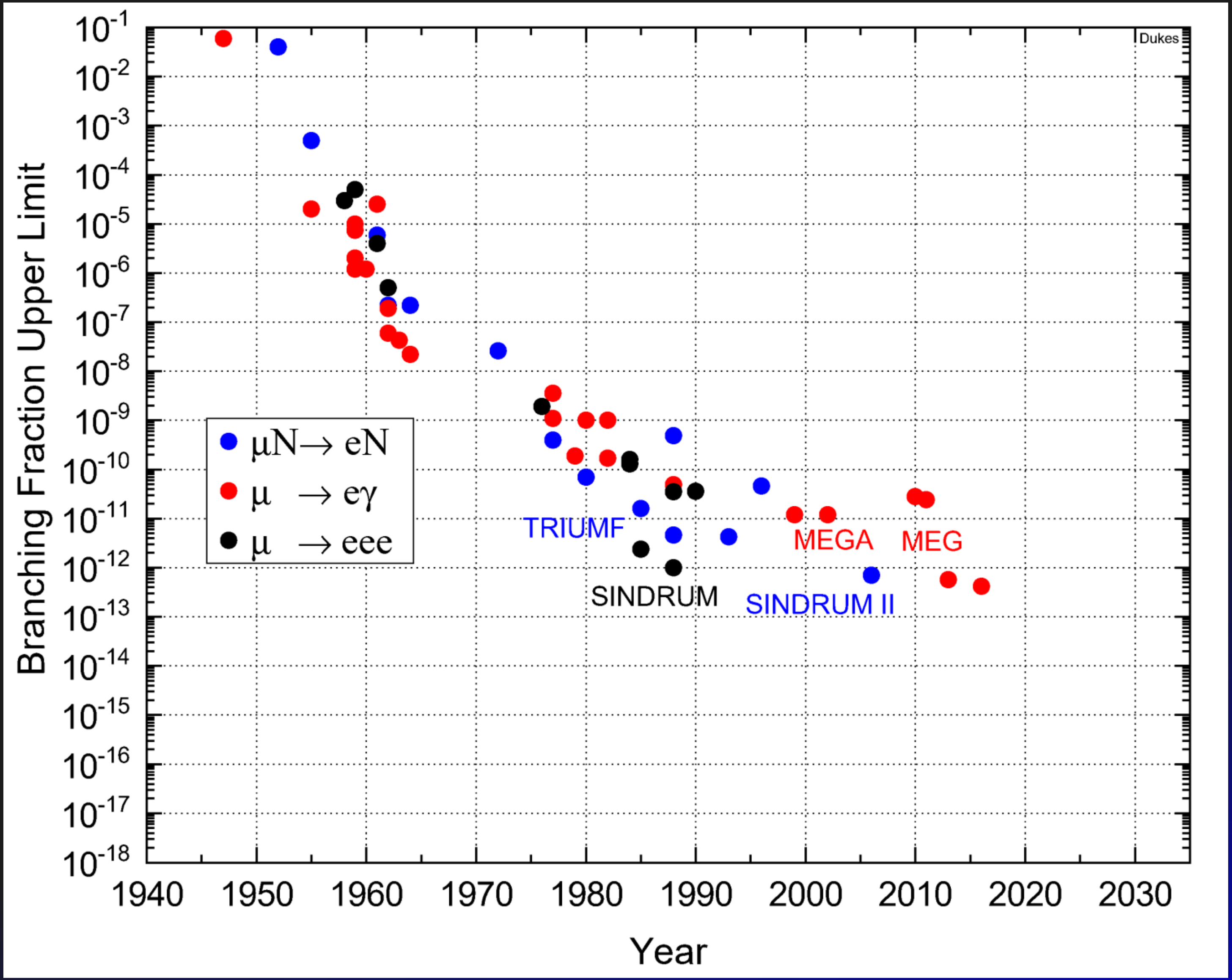
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Altmannshofer, Buras, et al., NPB 830, 17 (2010)

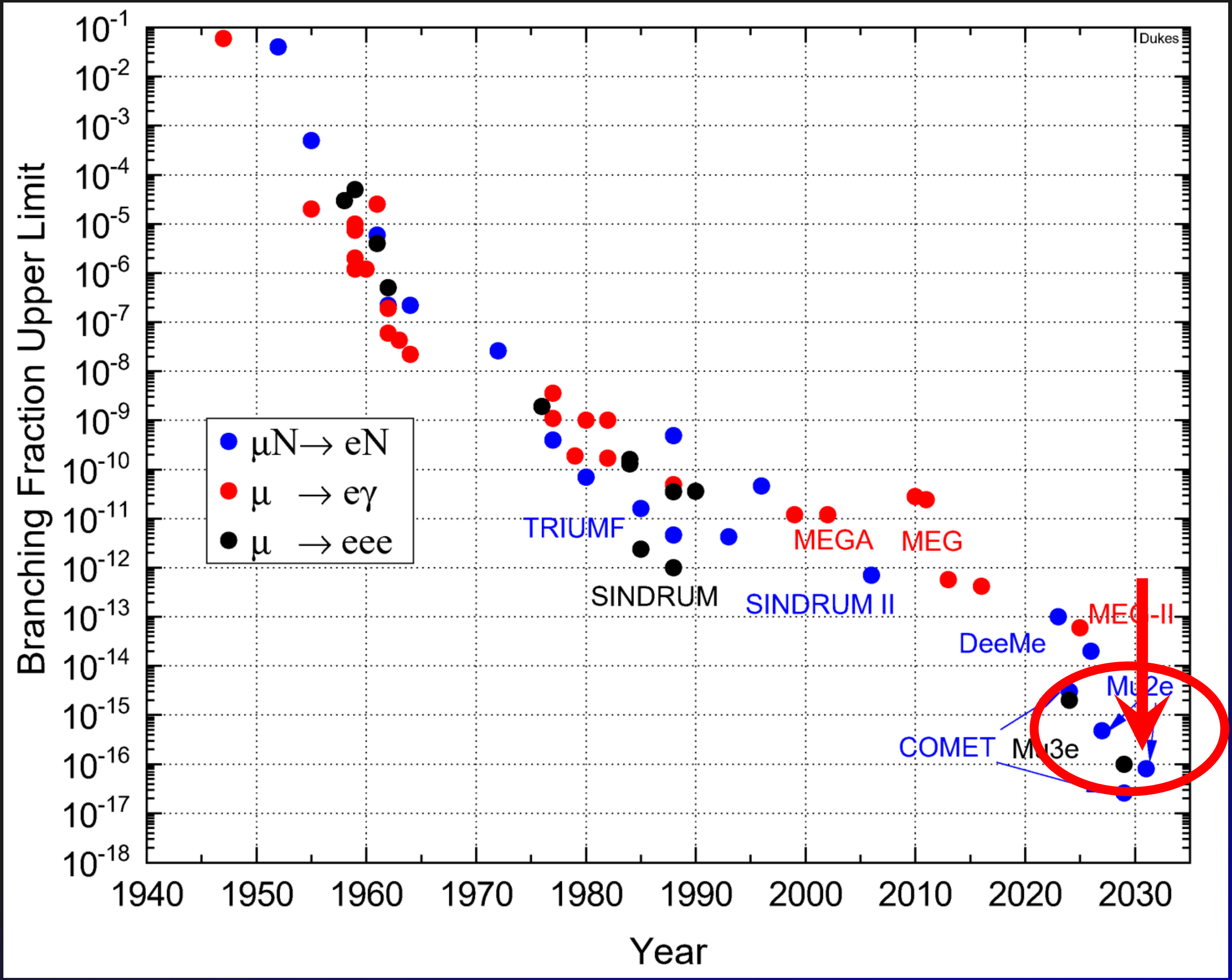
(Incomplete) History of CLFV Searches



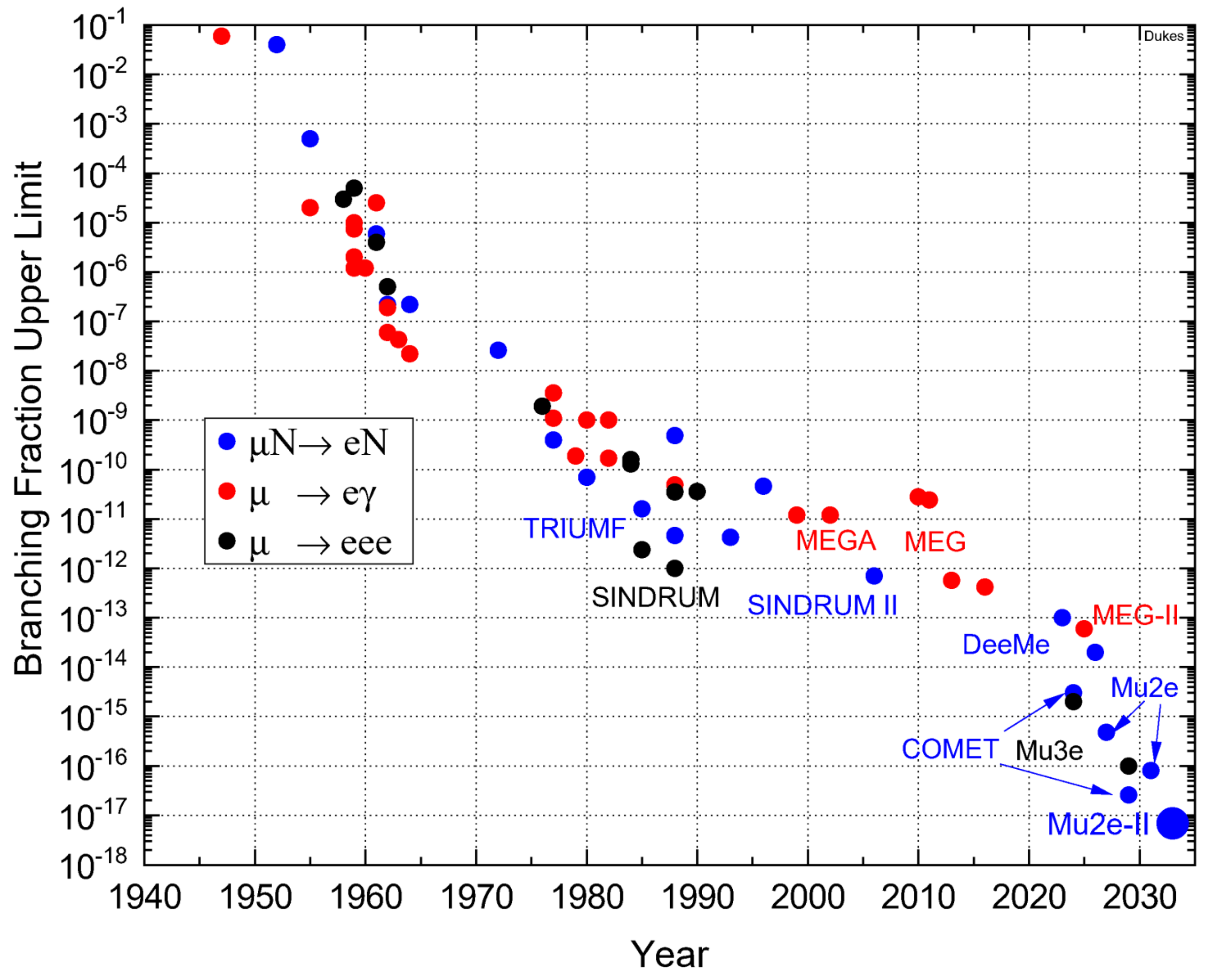
History of Muon CLFV Searches



Future Searches of Muon CLFV



Mu2e-II Goal: O(10^{-18}) Single Event Sensitivity

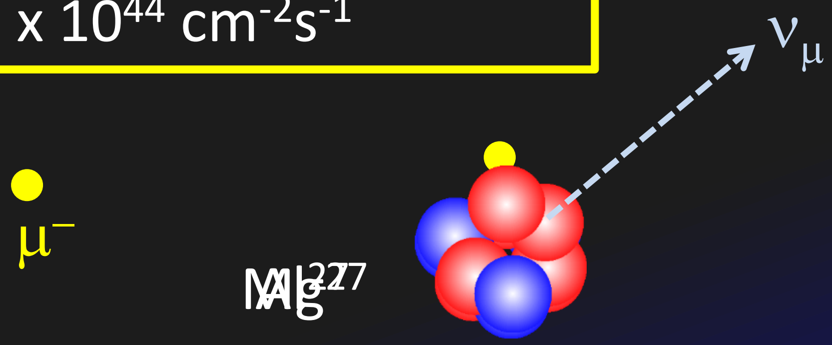


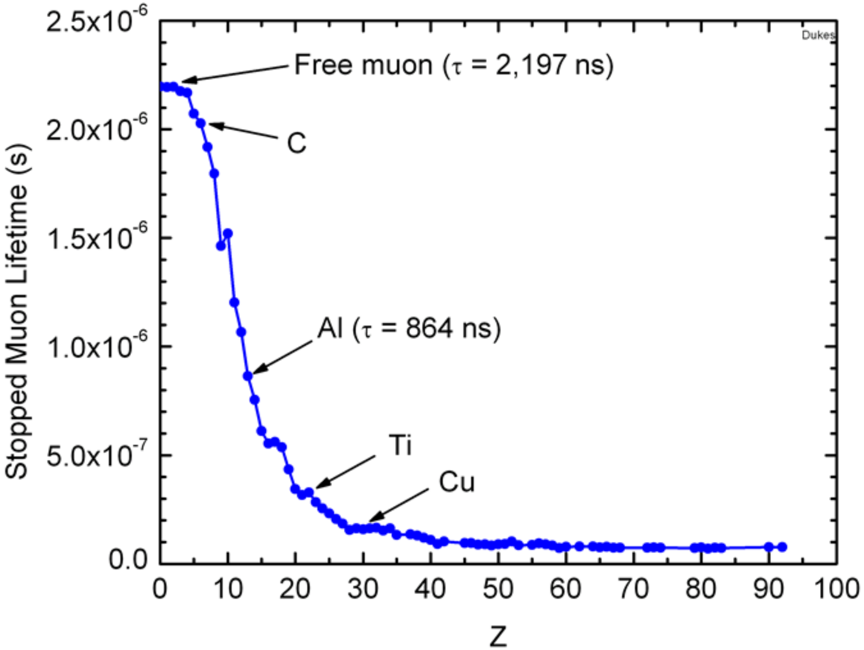
How to Search for $\mu^- N \to e^- N$

- Stop muon in atom
- Muon rapidly (10^{-13}s) cascades to 1S state
- Circles the nucleus for up to ~2 μs (in Al τ = 864 ns)
- Two things most likely happen:

1. muon is captured by the nucleus: $\mu^- N_{A,Z} \to \nu_\mu N_{A,Z-}$

Single atom luminosity:
~ 1 x 10^{44} $cm^{-2}s^{-1}$

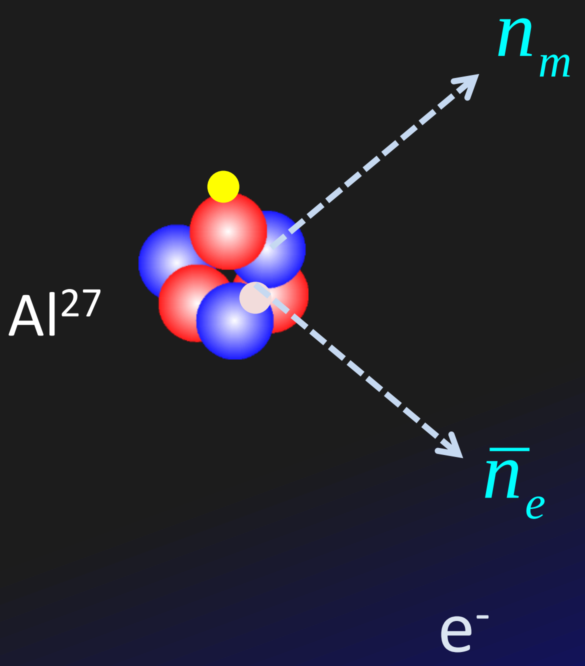


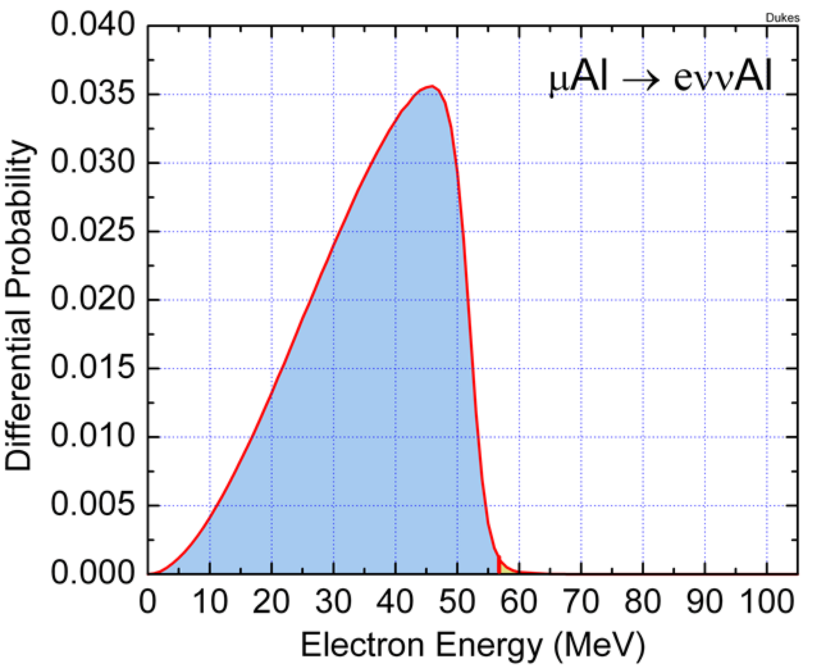


How to Search for $\mu^- N \to e^- N$

- Stop muon in atom
- Muon rapidly (10^{-16}s) cascades to 1S state
- Circles the nucleus for up to ~2 μs
- Two things most likely happen:

1. muon is captured by the nucleus: $\mu^- N_{A,Z} \to \nu_\mu N^*_{A,Z-1}$
2. muon decays in orbit: $\mu^- N_{A,Z} \to e^- \nu_\mu \nu_e N_{A,Z}$



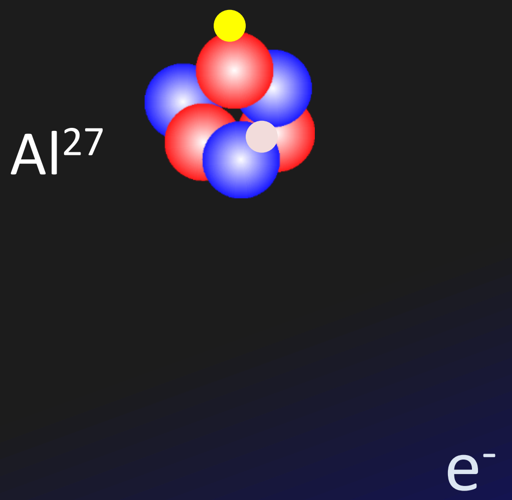


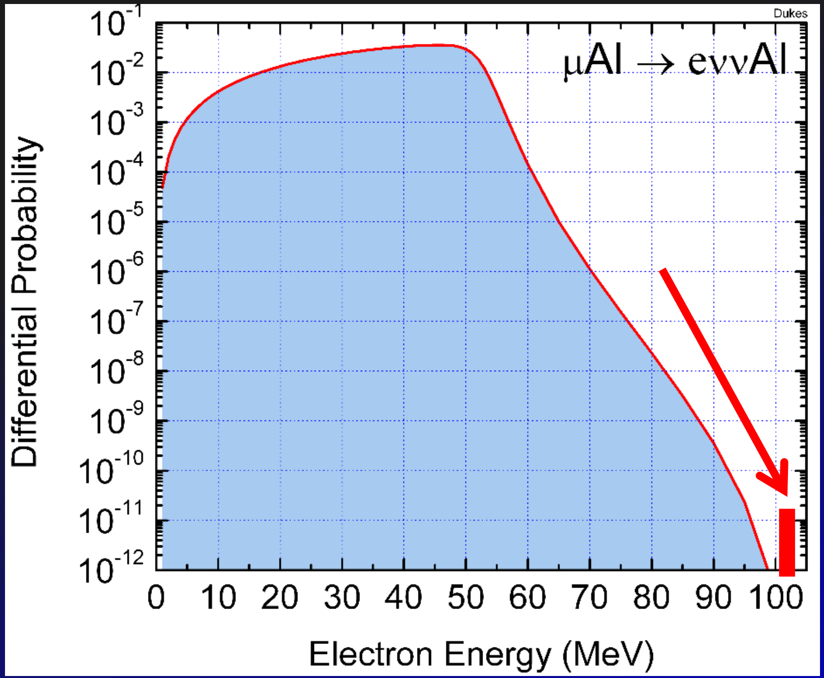
Mu2e Searching for a Third Process: $\mu^- N \to e^- N$

The muon turns into an electron $\mu^- N \to e^- N$ leaving the nucleus in ground state

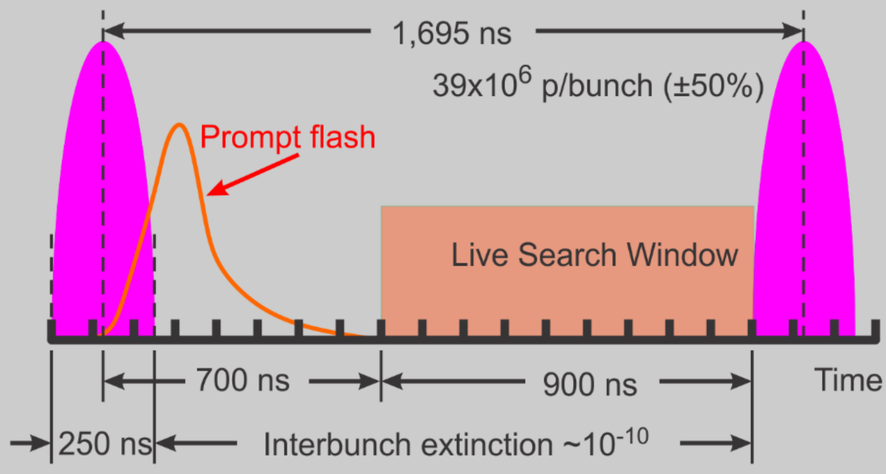
- signature single delayed (τ = 864 ns in Al) isolated electron
- Electron energy given by the rest mass of the muon minus the nucleus recoil energy and the binding energy:

  $E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)





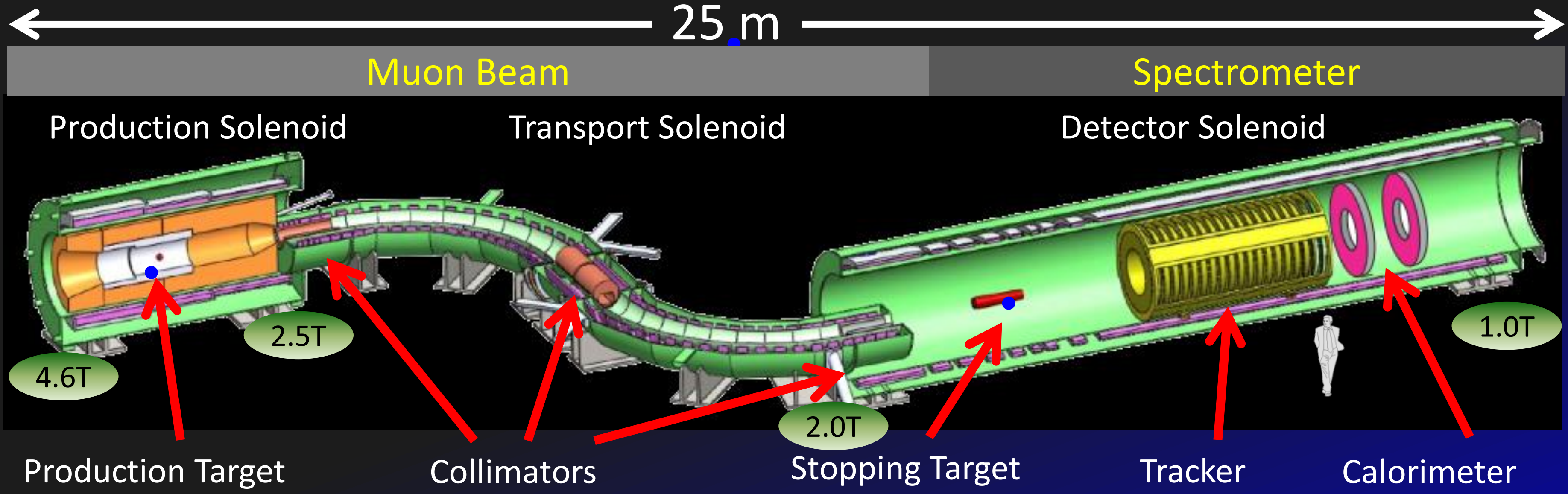
Mu2e Apparatus



39 x 10^6 protons every 1.7 μs

74 x 10^3 μ^- stops every 1.7 μs

43 billion μ^- stops/spill-second



25 m

Muon Beam

Spectrometer

Production Solenoid

Transport Solenoid

Detector Solenoid

4.6T

2.5T

2.0T

1.0T

Production Target

Collimators

Stopping Target

Tracker

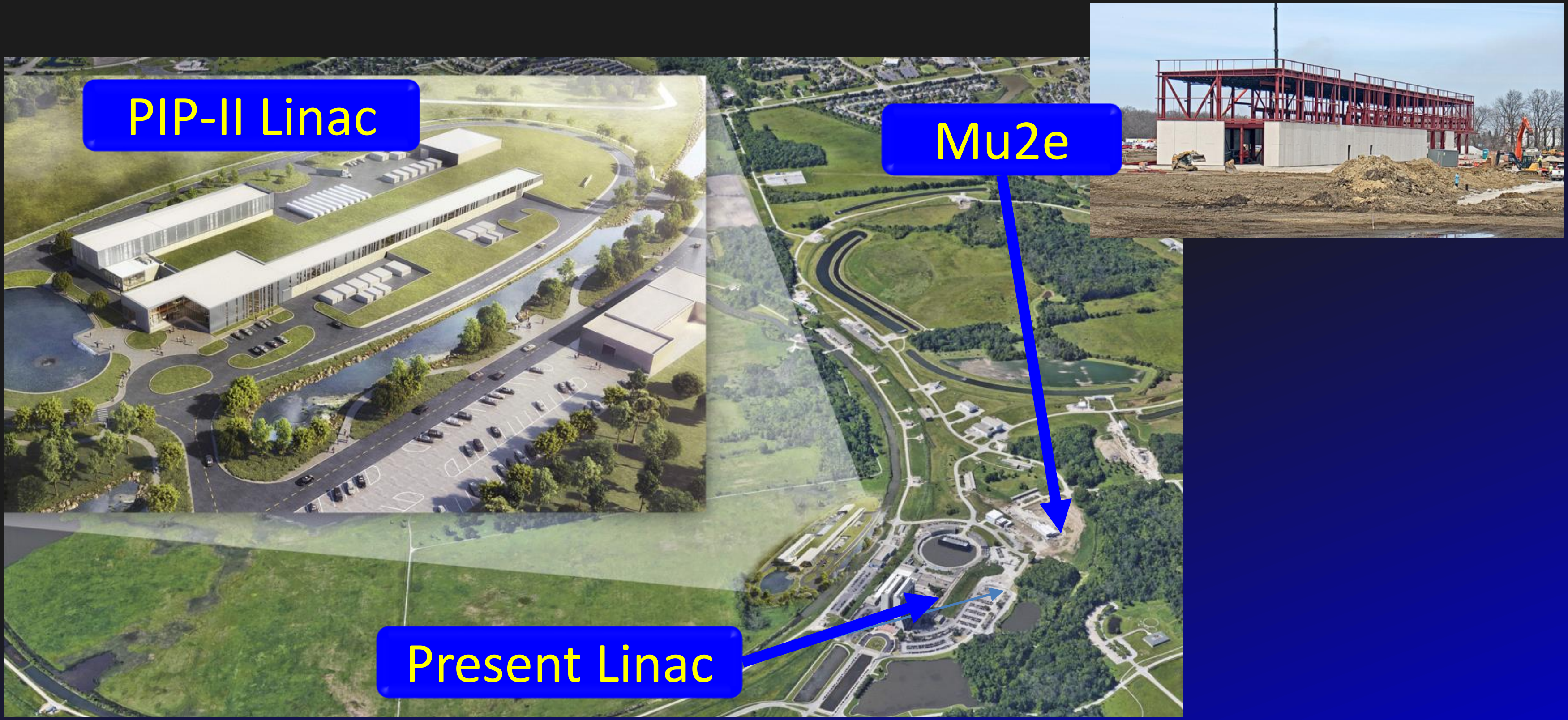
Calorimeter

$$p + tgt \rightarrow \pi's + X$$

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

PIP-II: Fermilab Proton Improvement Plan II

- Present Fermilab Linac replaced with 800 MeV Continuous Wave SRF Linac
- High intensity H^- beam: up to 4x10^8 p/bunch, 162.5 MHz bunch frequency
- Design driven by needs of the Fermilab neutrino program
  - However: LBNF/DUNE only needs ~1% of the available beam a fraction of the time, limited by (the increased) Booster rep rate of 20 Hz
- Construction has begun; scheduled to end in 2027



Mu2e-II: Goal of Mu2e in the PIP-II Era

We wish to seize the opportunity provided by upgrades of the Fermilab accelerator complex being built for DUNE to:

- **Increase sensitivity over Mu2e by 10X while keeping backgrounds < 1 event**
- This is to be done by:
  - ~3X increase in muon beam intensity (through ~30X p beam intensity)
  - ~3X increase in live time (through a better duty factor)

O(10^{-18}) SES

Advantages:

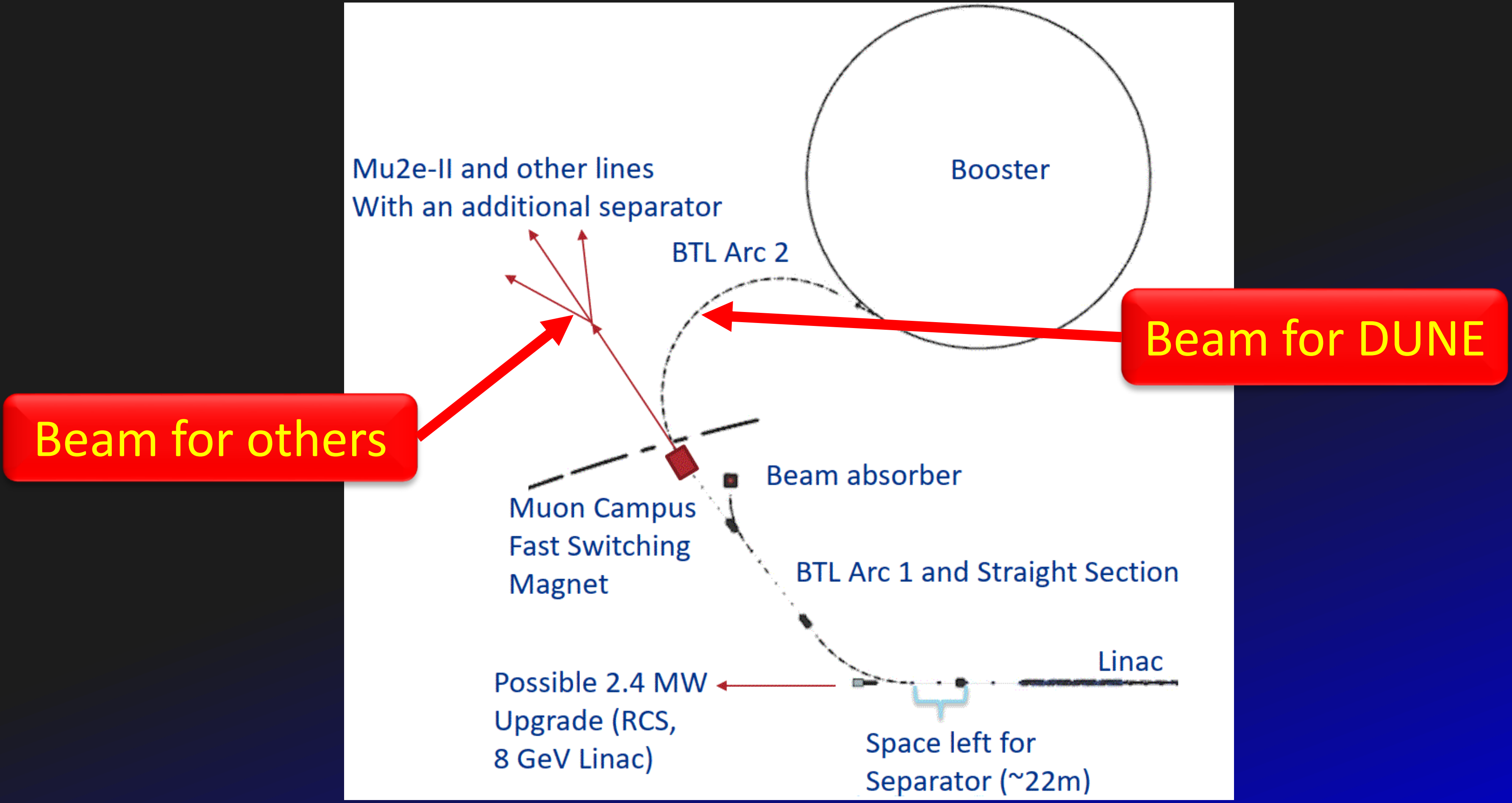
- Higher duty factor (~3X)
- More intense muon beam (~3X)
- Beam structure can be tuned to the needs of the Mu2e target choice
- Narrower beam pulse
- Lower energy eliminates anti-proton background

Challenges:

- Getting the lower-energy beam on the production target
- Dealing with higher rates
- Dealing with higher radiation levels

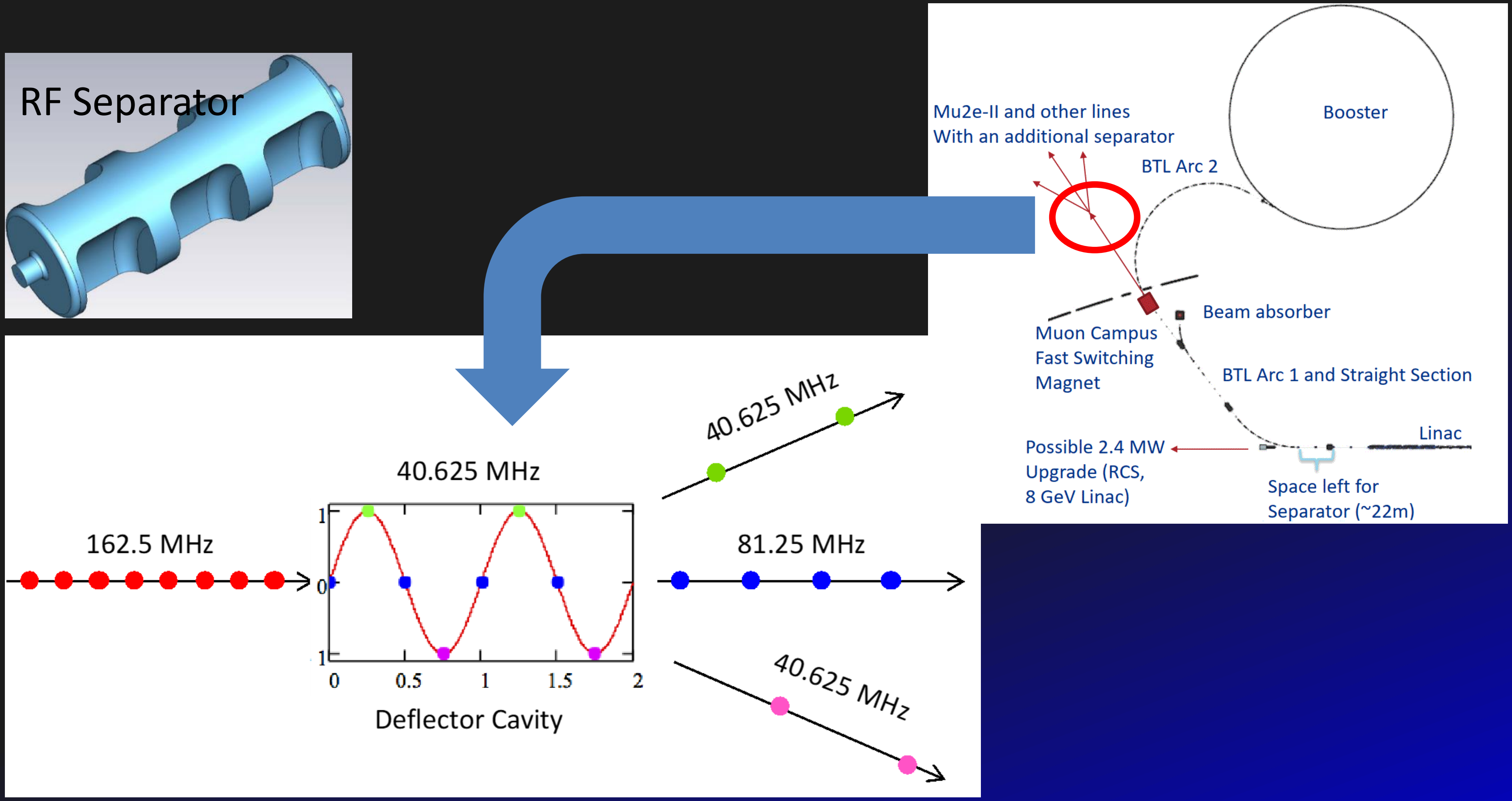
PIP-II: Getting the Proton Beam to Mu2e

- Fast dipole magnet (20 μs) switches beam between Booster and Mu2e-II + other potential experiments/beamlines
- Not in PIP-II baseline: an ongoing dialog with PIP-II designers heading off potential show-stoppers



Mu2e-II: Proton Beam Splitting

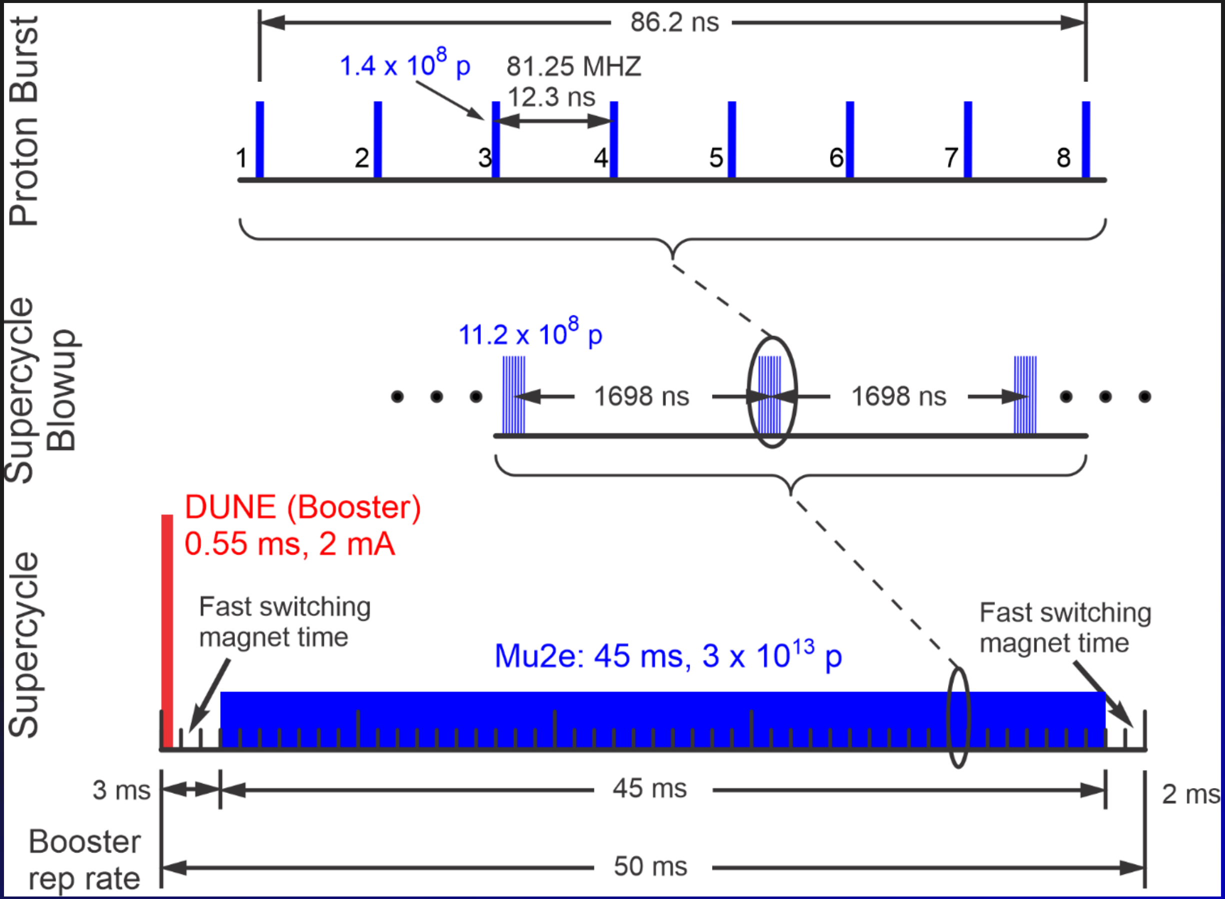
- Mu2e would take ½ of full bunch rate: 162.5 MHz
- Two other beam lines could be selected with an RF beam separator



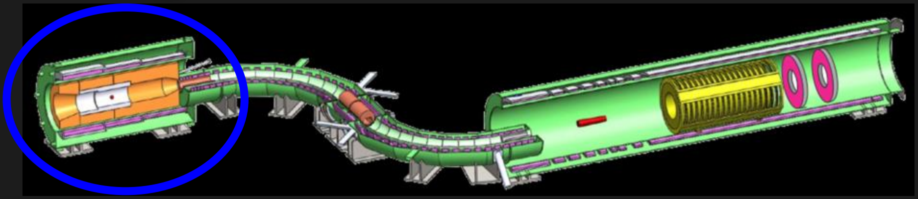
Mu2e-II: Beam Structure

- PIP-II allows programmable proton pulse patterns
- Need a burst separation of ~1700 ns (with Al target)
- Burst: 8 pulses (1.4x10^8 p each), each separated by 12.3 ns (81.25 MHz)
- Burst train: Burst followed by gap of 1698 ns, then another burst of 8 pulses, this repeated for ~45 ms of beam every 50 ms
- 90% duty factor

76 kW average power (compared to 7.3 kW for Mu2e)



Production Solenoid: Challenges



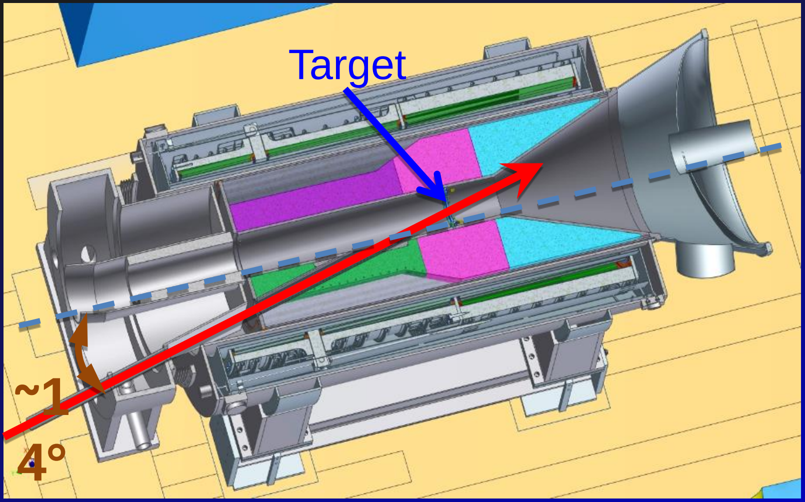
Radiation and heat load:

- Some coils will have been subjected to ~7 MGy and become activated
- Insulation damage (conventional epoxy limit ~10 MGy)
- Degradation of Al stabilizer (RRR)
- Large heat load: power density increases by 10X
  - present magnet already pushed to limit
  - ΔT in coil goes from 0.25 K to 2.5 K: quench temperature is 6.6 K – 2.5 K = 4.1 K. With a thermal margin of 1.5 K the magnet temperature of 2.6 K is close to the lambda point (2.17 K)

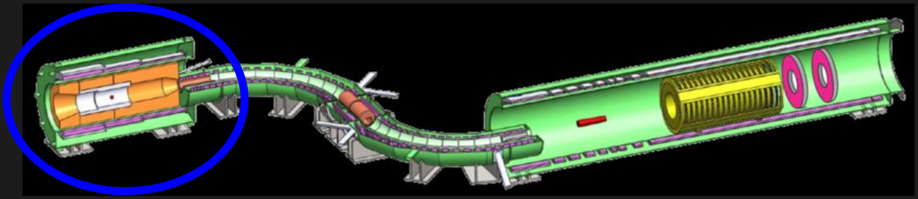
Beam transport with lower momentum beam

- 0.800 GeV rather than 8 GeV
- How do we steer it onto the target, dump, and extinction monitor?

Finding a target to handle 76 kW beam power



Production Solenoid: Solutions

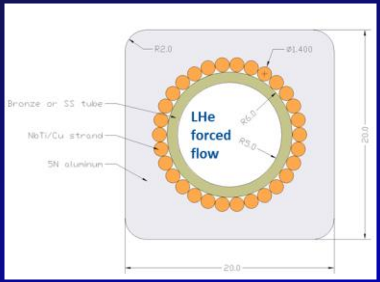


Use the present Production Solenoid

- Upgrade the cryo-system
- Replace bronze Heat/Radiation shield (HRS) with W to reduce power density by 2.5X → note, may not be viable
- Will have to operate it at a lower temperature and/or with lower margin

Replace or rebuild much of the Production Solenoid

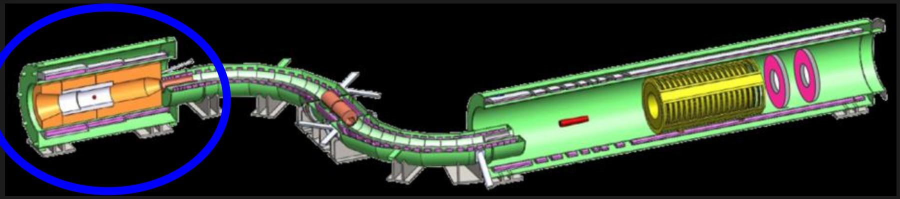
- Some parts – vacuum vessel, thermo-shield, cold-mass supports reused
- New cable and coils would have to be made:
    - Cable-in-Conduit Conductor
        - Direct cooling increases heat load capability
        - Technically challenging, but being used (ITER)
    - Internally-cooled Al-stabilized cable
    - Non superconducting magnet:
        - Room temp resistive coil (replace HRS): ~ 5 MW
        - Cyro-cooled resistive coil (replace HRS): ~ 1 MW

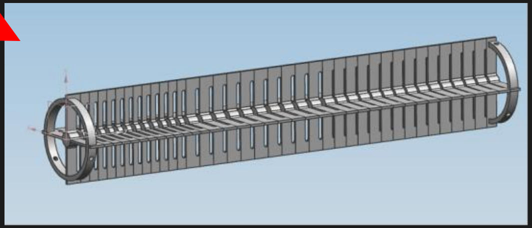


Production Solenoid: Target Solutions

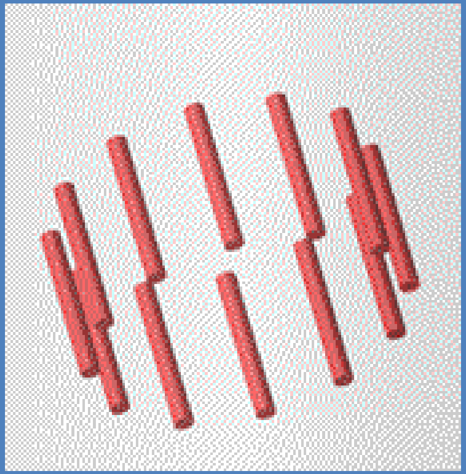
- Mu2e: ~1 kW in passively cooled W target
- Mu2e-II: ~15 kW in target
  - DPA >> 1

New target design needed



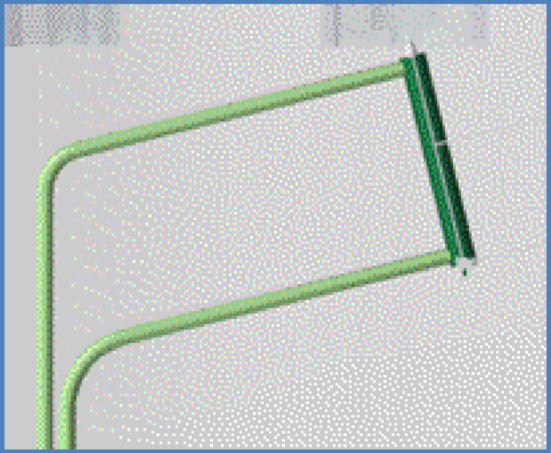


Rotating Elements



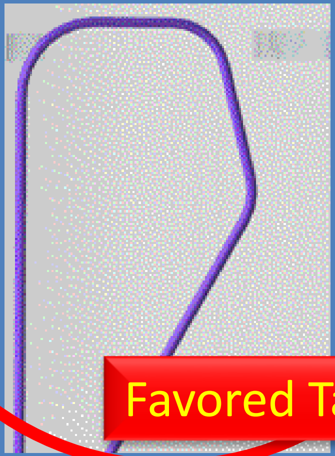
Pro: survives radiation
Con: large profile

Fixed Granular w Gas Cooling



Pro: small profile
Con: peak DPA > 300/yr

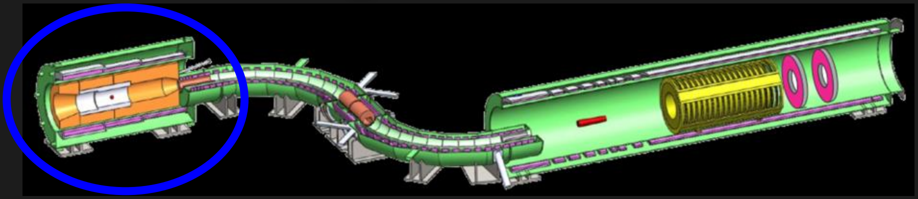
Conveyor Tube w Balls



Favored Target

Pro: modest profile
Con: technically challenging

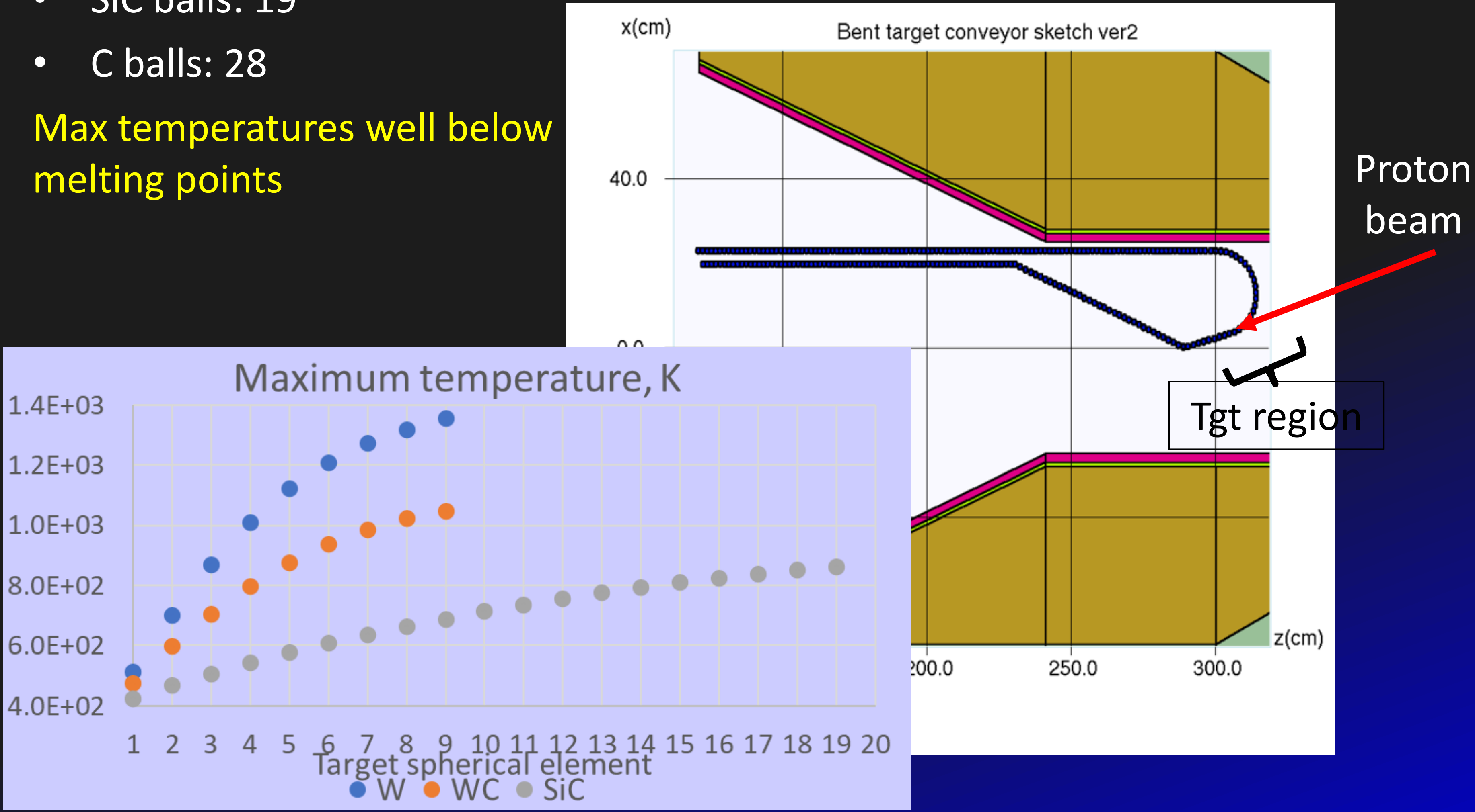
Production Solenoid: Conveyor Target



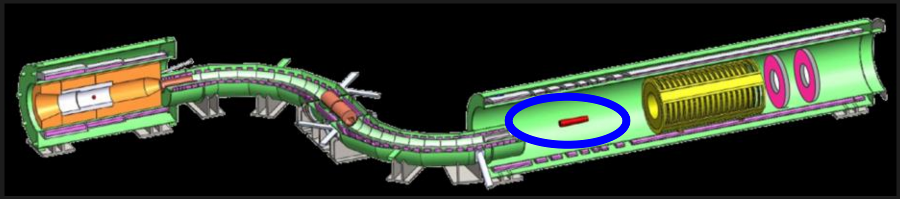
Exploring different target materials

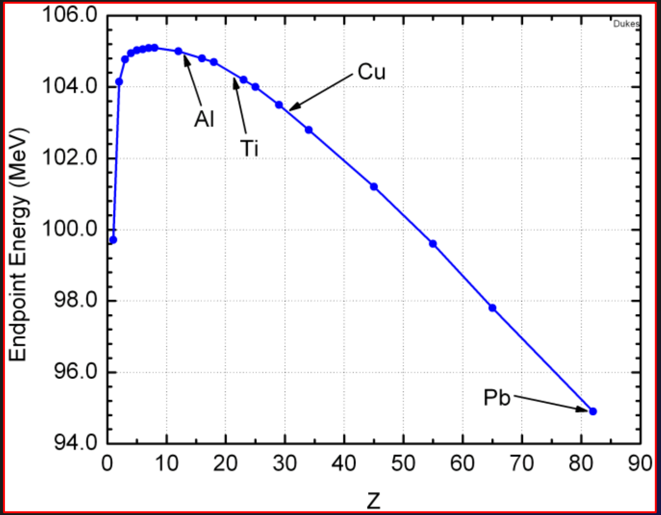
- W/WC balls: 9
- SiC balls: 19
- C balls: 28

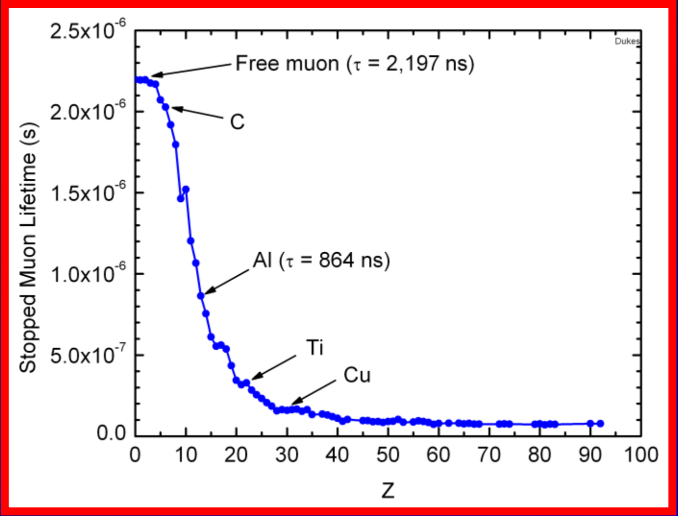
Max temperatures well below melting points



Mu2e-II: Stopping Target







Al is ideal first target

- High endpoint energy
  - muons captured on other (higher Z) detector material not a background
- Capture daughter more massif $m_{Z-1} > m_Z$
  - keeps max. energy of radiative capture muons below signal electrons
- Long lifetime
  - keeps proton blast separated from live window

Would continue with this target if Mu2e sees nothing

Mu2e-II: Other Stopping Target Choices

If Mu2e observes conversion, a different target would be ideal in order to narrow down the physics process

The opportunities and challenges of the following targets are being explored:

Lithium

- Low discrimination

Sulpher

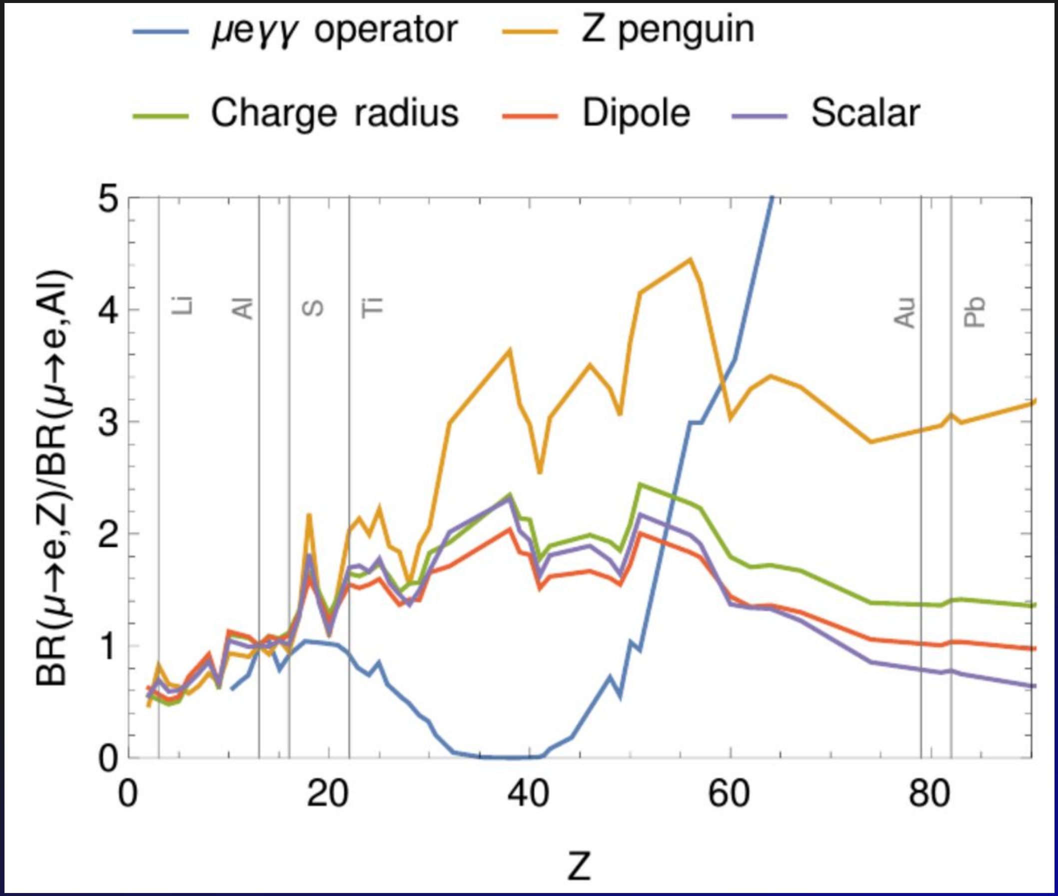
- Advantages for e$^+$ channel

Titanium

- Multiple isotopes

Au/Pb

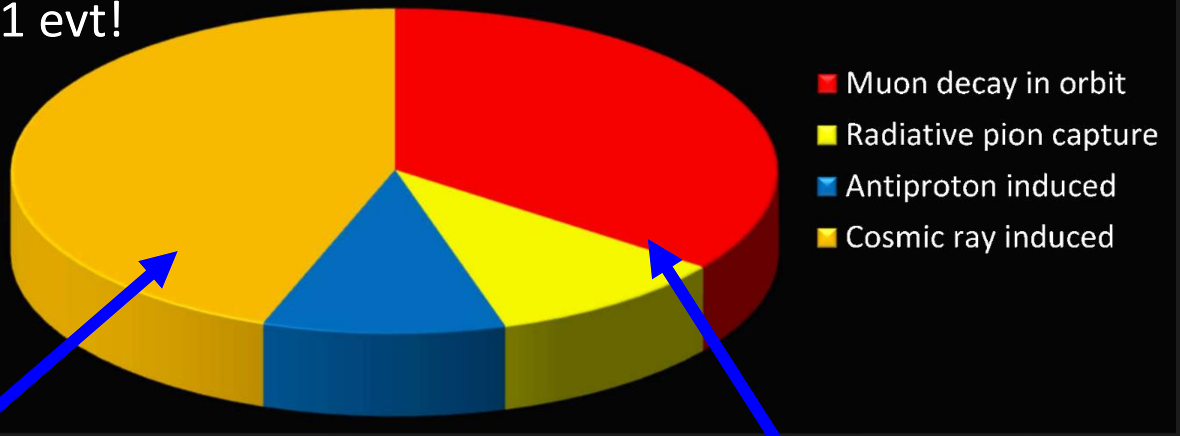
- Good discrimination
- Short lifetime → low rate



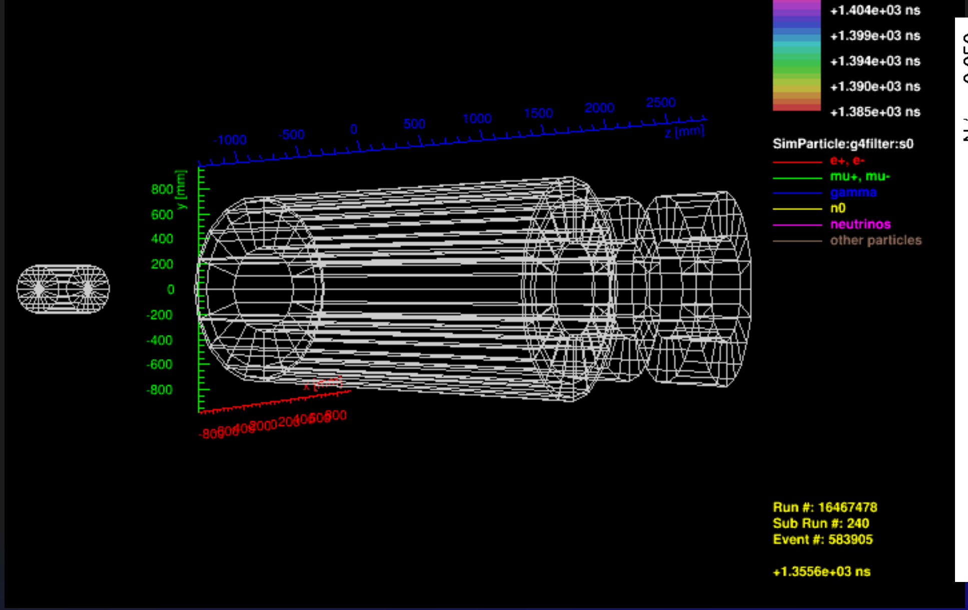
Keeping Backgrounds in Check

Need to keep backgrounds to < 1 evt!

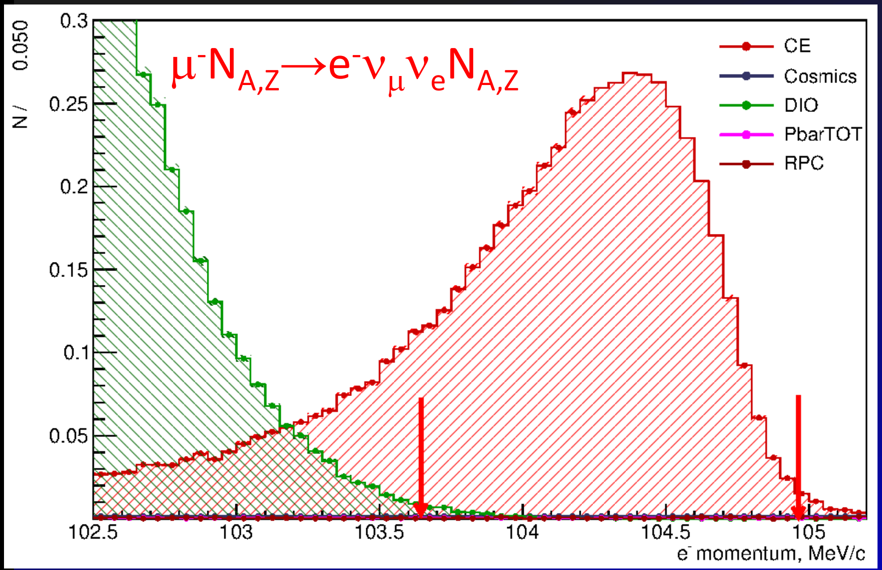
Two biggest backgrounds are Muon decay-in-orbit and cosmic-ray induced electrons



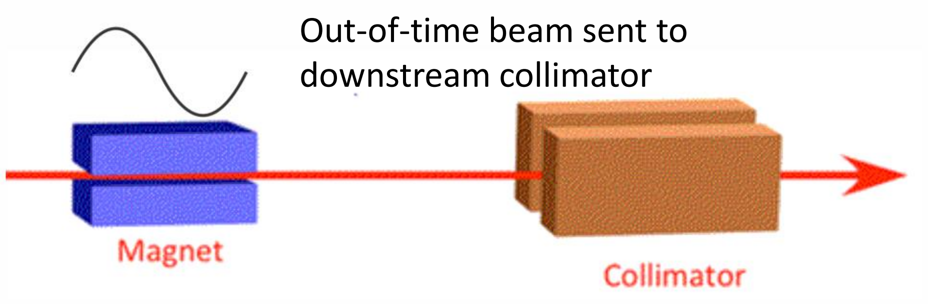
Cosmic-Ray Induced



Muon Decay in Orbit



Extinction

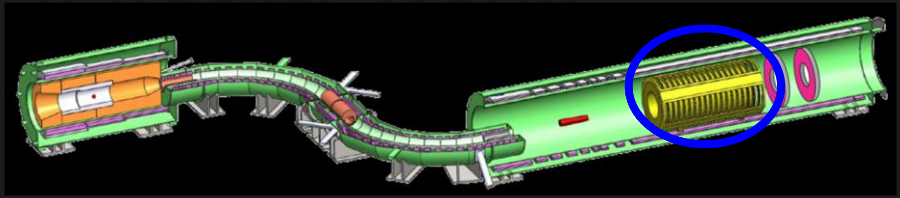

Out-of-time beam sent to downstream collimator

Needed to remove out of time protons that can produce conversion-like electrons from captured pions and from electrons that scatter in the stopping target

- Mu2e:
  - Need 10^{-10} reduction (out of bunch/in bunch)
  - 10^{-5} from bunch formation in Recycler/Delivery RIng
  - 10^{-7} from AC Dipole extinction system
  - 100X safety factor
- Mu2e-II:
  - Need 10^{-11} reduction
  - 10^{-4} (at least) from chopper
  - Need additional 10^{-9} from extinction system to get same safety factor
  - Should be easy: lower energy, smaller emittance beam, etc

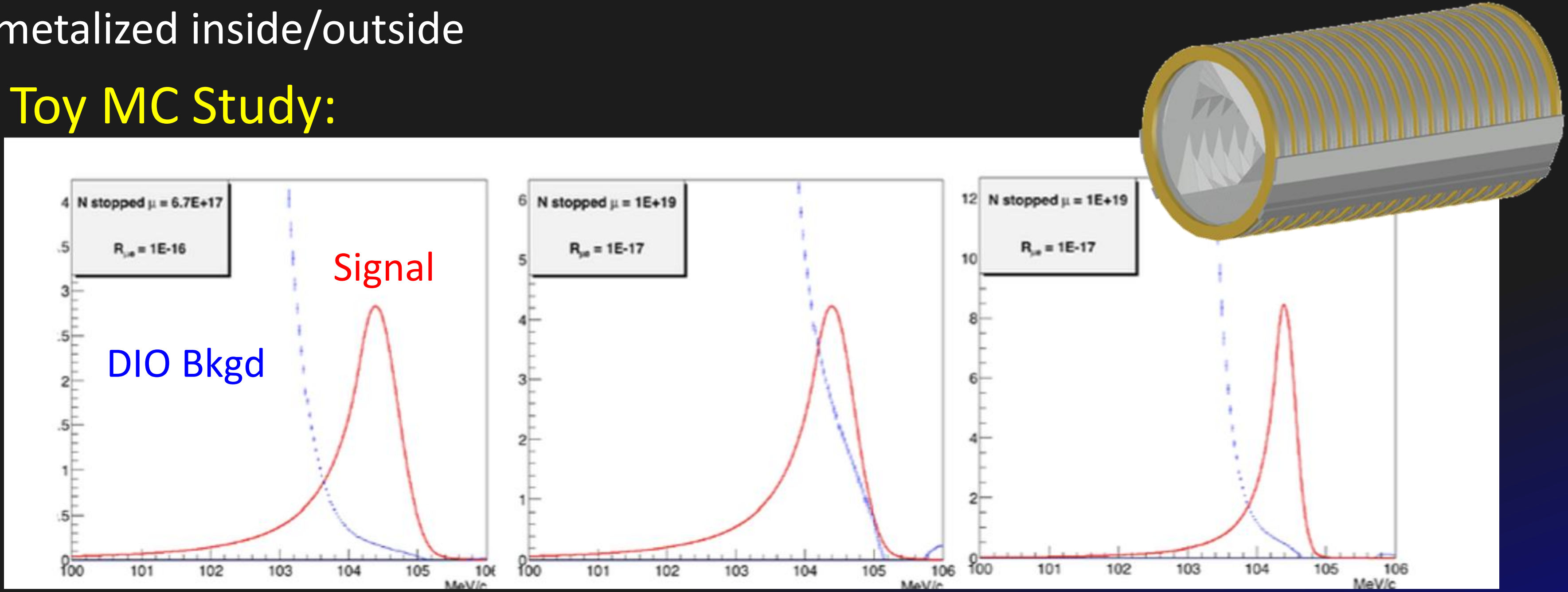
This looks very feasible

Tracker: Would the Mu2e-II Tracker Work?



- 21,000: 5 mm diam straws Ar:CO_2
- 15 μm Mylar thick
- metalized inside/outside

Toy MC Study:



Mu2e Rate and Background

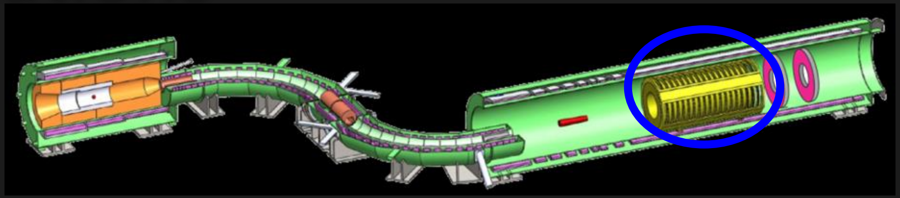
Mu2e-II Rate and Background
Mu2e Tracker: 15 μm straws

Mu2e-II Rate and Background
Tracker w ½ resolution

No! It must be replaced as background would exceed 1 event

- DIO background moves to the right (into signal region)
- Signal region needs to be narrowed, DIO moved to left, by reducing material

Tracker: Challenges & Solutions



Challenge: increased radiation load

- Radiation-hard front-end electronics: ASICs, DC-DC converters, optical readout

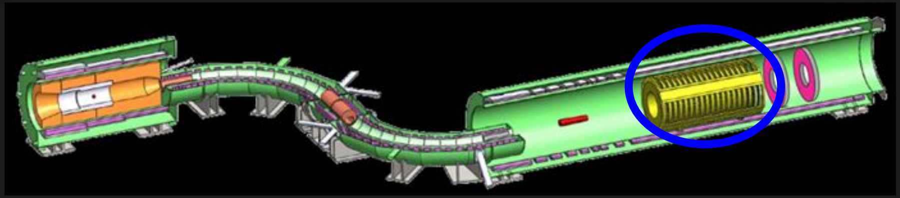
Challenge: ~4X Increase in bunch intensity

- Only produces a 5% reduction in momentum resolution and reconstruction efficiency
- Current design and software is capable of this

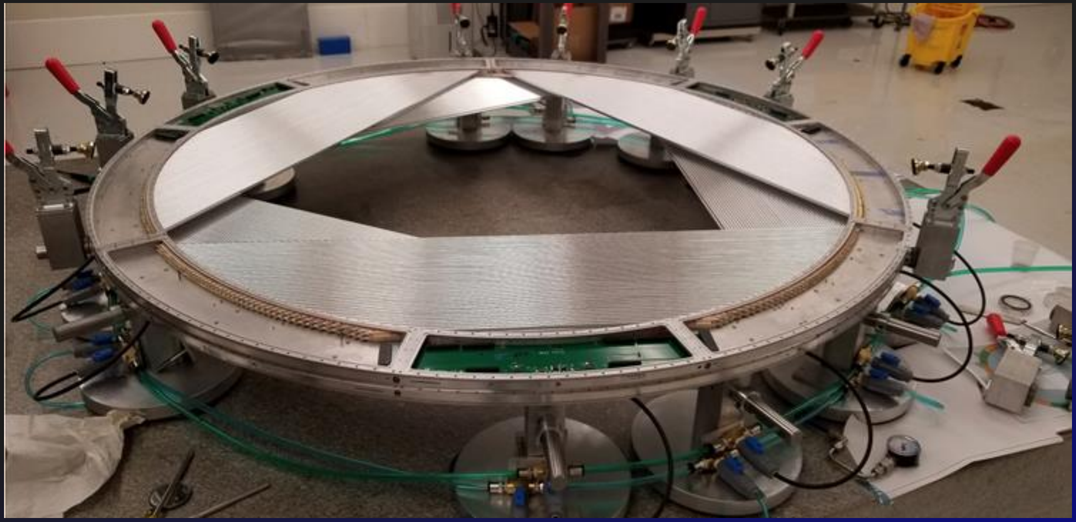
Challenge: Lower mass to meet momentum resolution goal

- Solutions:
    - Thinner straws
    - Lower mass gas/sense wires
    - Completely different technology

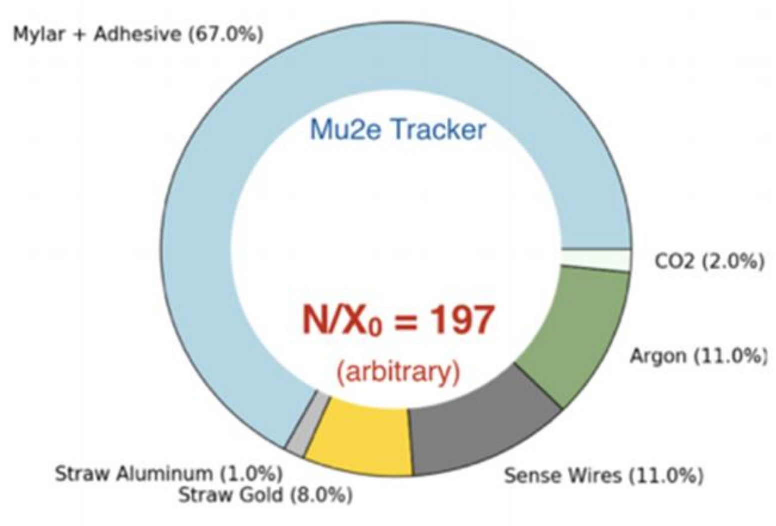
Tracker: Straw Challenges



- Straw thickness: 15 μm must be reduced to at least ~8 μm
- Fabricating issues: butt vs overlap seams, winding schemes, etc
- Sustaining 1 atm pressure difference a challenge (significantly higher Hoop Stress)
- Increased leak rate (Mu2e has a ~15% straw failure rate)
- Mechanical properties: less strength to keep straw straight
- Aging: large additional charge of ~10 C/cm (Mu2e: ~1 C/cm)

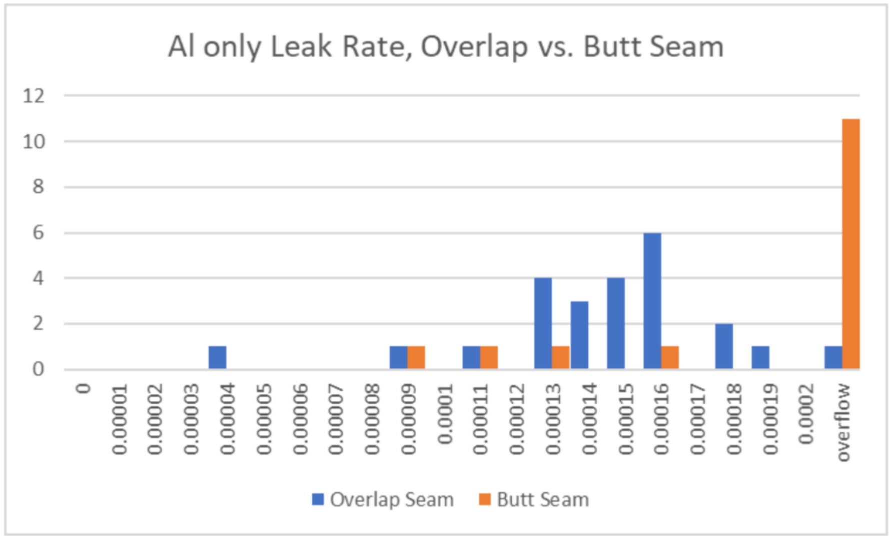


Material Budget for Mu2e Straws



Tracker: Straw Solutions

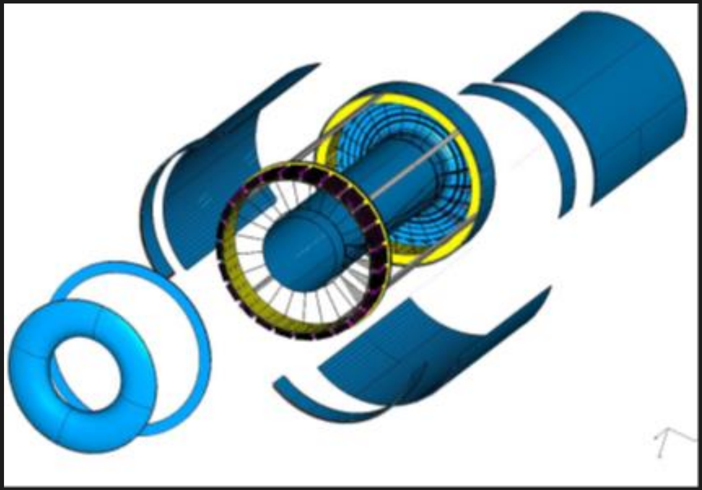
- Fermilab has LDRD team (Brendan Casey et al) researching thinner straws
- Fabricating straws with 3-8 μm wall thickness
- Gases:
  - Can the pressure be less than 1 atm?
    - Reduces leak rate (CO_2) through straws
    - Reduces Hoop Stress
    - Slight reduction in mass
- Note: thinner walls reduce charge load (largely caused by photon conversions in walls)



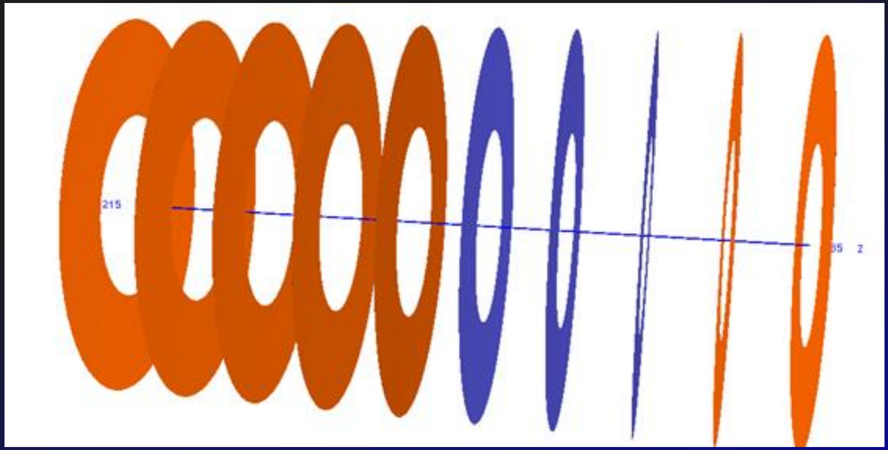

8 μm Mylar Straws

Tracker Solutions: Straw Alternatives

Drift chamber similar to MEG-II

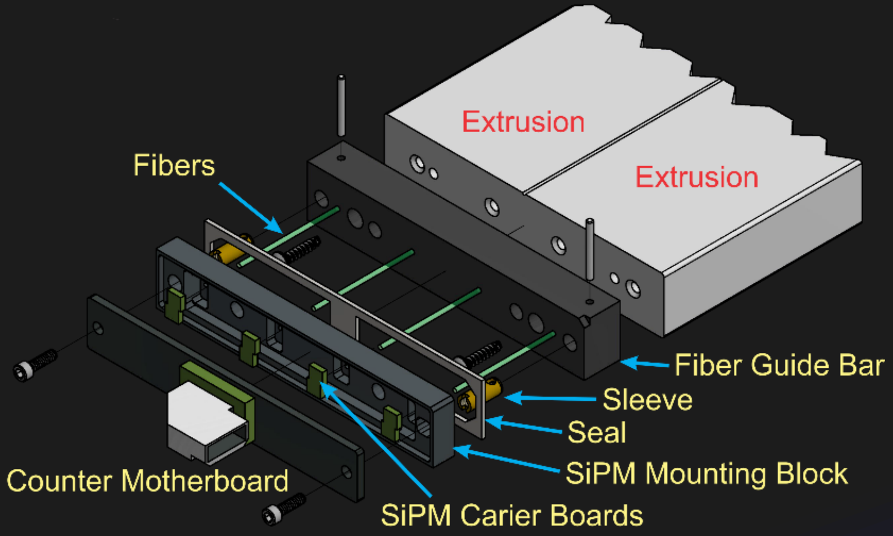


Other alternatives: Light Si, Micro Pattern Gas Detector, radial TPC

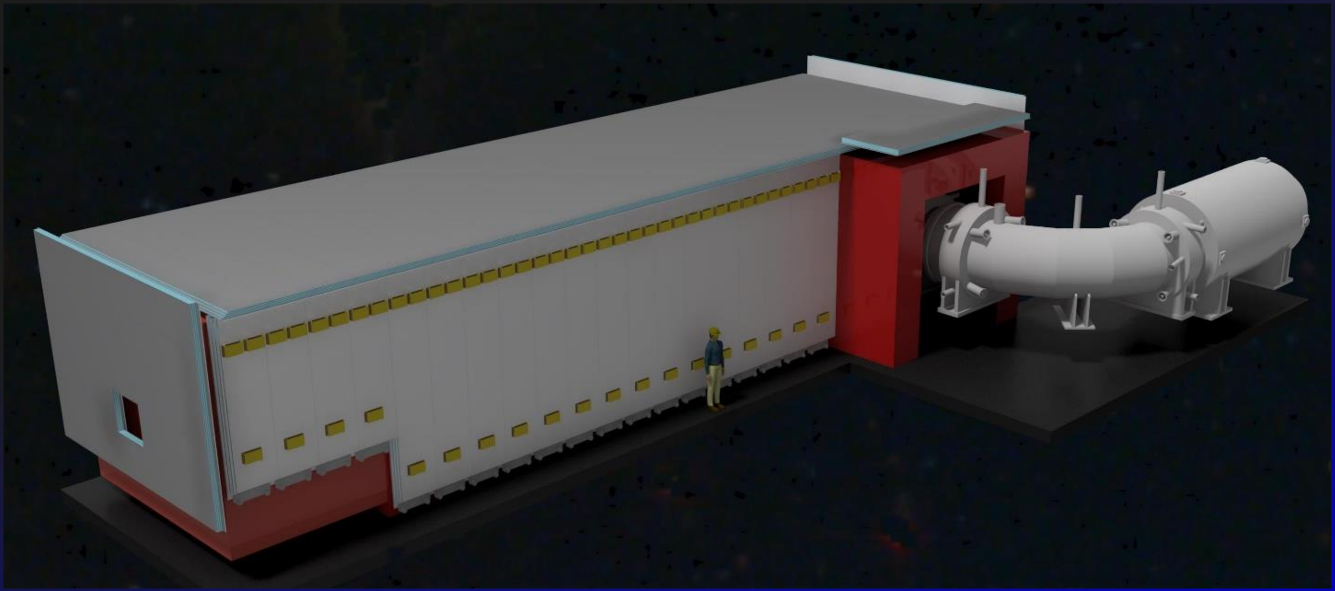


Cosmic Ray Veto (CRV): Mu2e

- About 1 fake event/day from cosmic-ray muons
- Hence need ~99.99% efficiency in an intense radiation environment
- Surround Detector Solenoid by 4 layers of scintillator read out by waveshifting fibers, and silicon photomultipliers



Details:
- 5,344 counters
- Area: 335 m^2
- 10,688 fibers
- 19,392 SiPMs



Cosmic Ray Veto: Challenges

Live time: ~3X higher (due to larger duty factor)

- Directly increases cosmic-ray induced background by same amount → Cosmic-ray induced background scales as live time, not beam intensity!

Light yield degradation: expected scintillator light yield will be significantly less

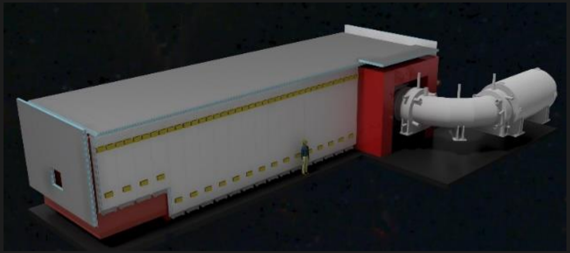
- Scintillator aging directly impacts efficiency in detecting cosmic-ray muons

With present CRV expect ~4 background events in a 3-year run of 4.56E7 s beginning in 2030 due to the live time increase and effects of light yield decline

Noise rates: expect ~3X higher noise rates from neutrons, gammas, etc. coming from the production target, stopping target, collimators, and muon beam stop

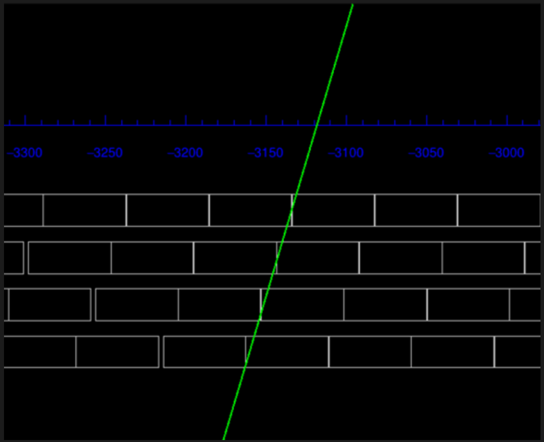
- Rates in some sectors of the CRV are already at the limit of what the electronics can handle
- Radiation damage to photodetectors and front-end electronics close to becoming an issue
    - Mu2e max non-ionizing: 1×10^{10} n/cm^2 for Front-end electronics, 1×10^{11} n/cm^2 for SiPMs

CRV: Improving Muon Veto Efficiency



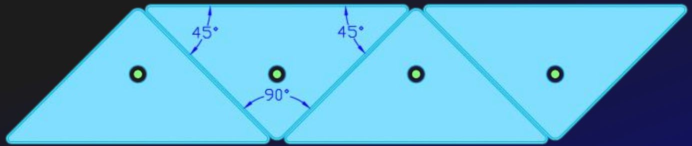
Overall efficiency needs to be improved by ~3X do to longer livetime Note: 20% of CRV vetoes 80% of background-creating muons

Most non-vetoed CR muons come at nearly vertical angles, and traverse gaps between counters



Replace rectangular counter with triangular design to avoid vertical gaps

Mu2e “di-counter”



Mu2e-II “quad-counter”

- Increase light yield: New counters reset light-yield decline; use new, higher efficiency SiPMs; pot fibers in their channels
- Other solutions: employ high-rate gas detectors in critical sectors

Cosmic Ray Veto: Handling 3X Muon Intensity

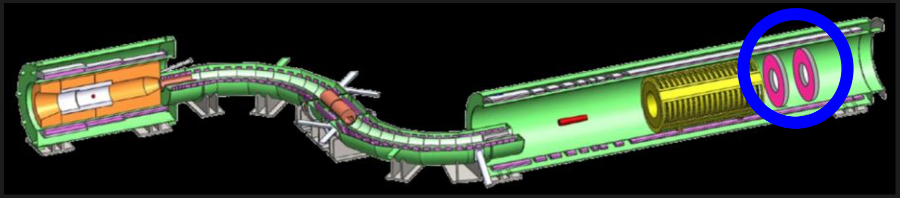
Problems:

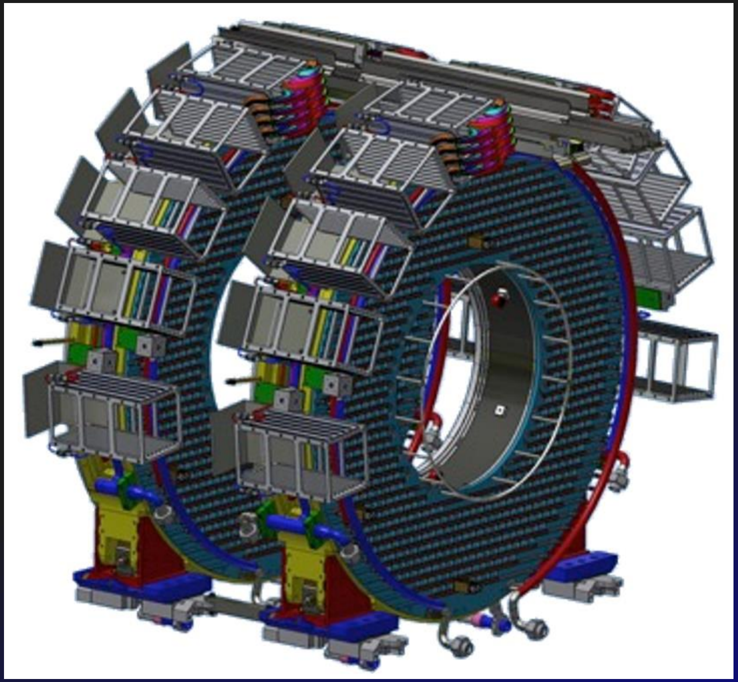
- Front-end Electronics throughput at its maximum limit
- Radiation damage becoming an issue, particularly for SiPMs
- Deadtime, presently about 5-10%, will become uncomfortably large
- Larger duty factor reduces 'off-spill' time used for data transmission, calibration, etc

Solutions:

- Note: only about 10% of the CRV is adversely affected: increased rates not a problem for the remainder of the CRV
- Better shielding: Boron and barite loaded concrete
- Smaller counters: Triangular counters
- Non-scintillator designs: employ high-rate gas detectors in critical sectors

Calorimeter

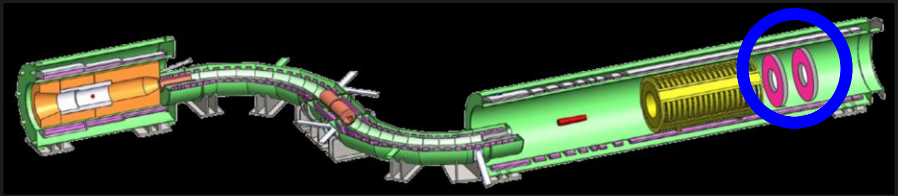




Needed for:

  - Seeding track finder
  - Particle ID: e vs μ
  - Trigger
- Two disks separated by ½ λ of helix
- 2 x 674 un-doped CsI crystals: 34x34x200 mm^3 ($10X_0$)
- Dual UV-extended SiPM readout
- Conversion electron resolution: σ_E/E O(5%)
- Timing: $\sigma_t < 0.50$ ns

Calorimeter: Problems and Solutions

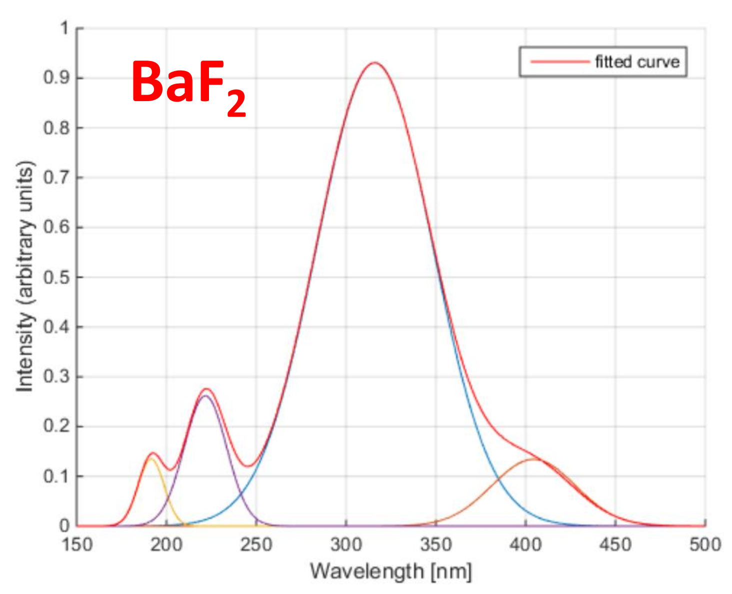


Problems:

- Not sufficiently rad hard for Mu2e-II: ~10 kGy/yr IR; ~10^{13} n/cm^2
- Not fast enough: 30 ns

Solutions:

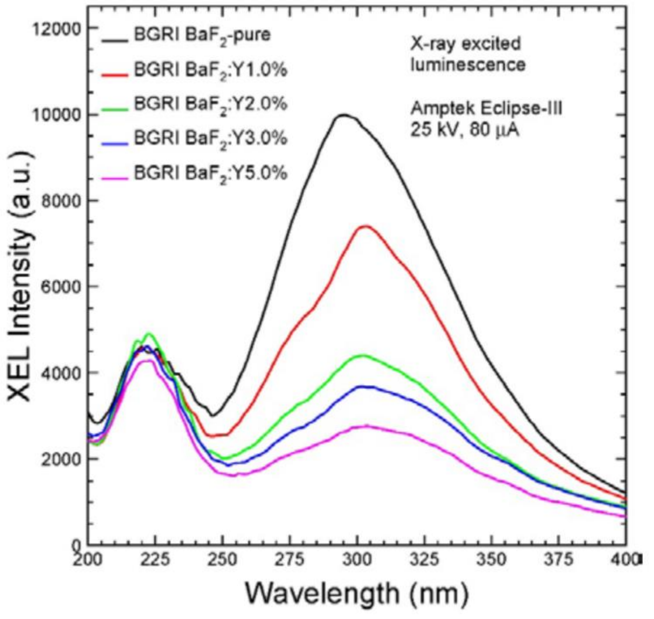
- Fast, rad hard crystals:
  - BaF_2 with suppressed slow component readout
  - BaF_2 doped with Y to suppresss slow component



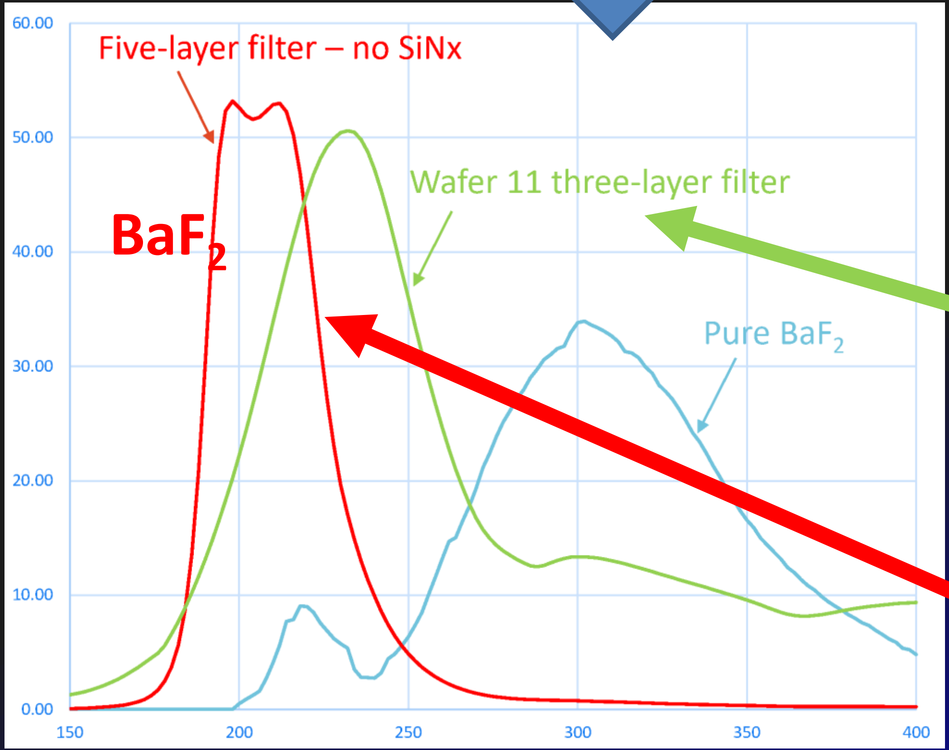
Crystal	CsI	BaF_2	BaF_2(Y)
Density (g/cm3)	4.51	4.89	4.89
Hygroscopicity	Slight	None	None
λ_{peak} (nm)	420 310	300 220	300 220
Light Yield (% NaI(Tl))	3.6 1.1	42 4.8	1.7 4.8
Decay Time (ns)	30 6	600 0.5	600 0.5

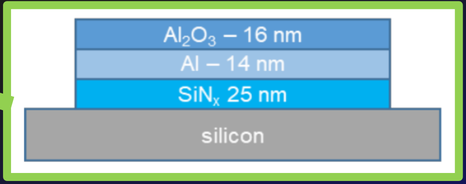
Calorimeter: Fast Readout of BaF_2

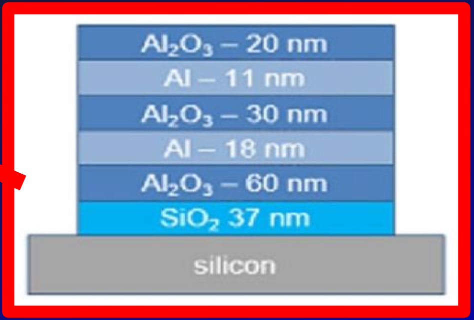
- Caltech working on Y-doped BaF_2



- Caltech, JPL, FBK working on UV-only sensitive SiPM







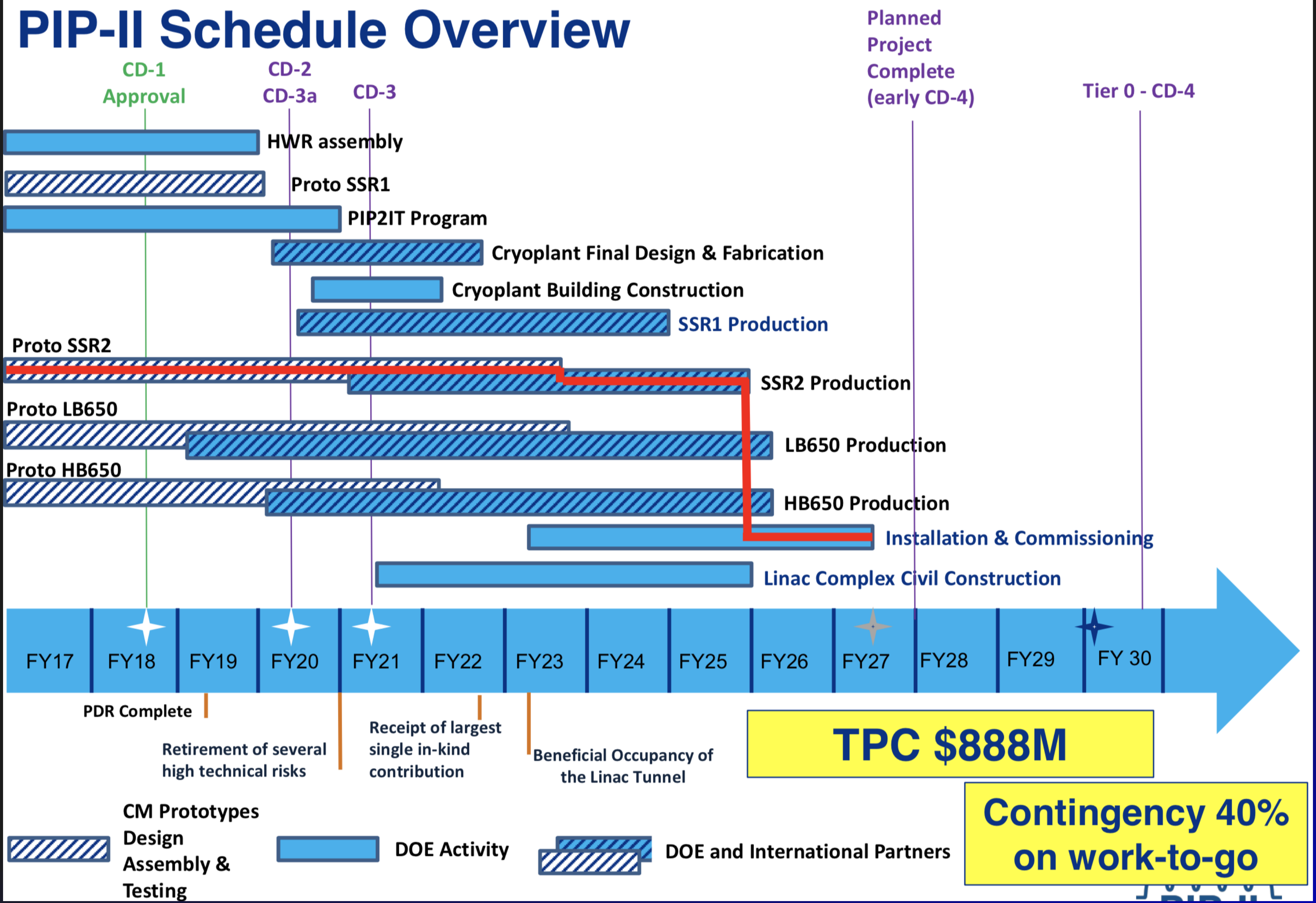
Summary

- Muon-to-electron conversion provides one of the most sensitive probes of new physics
- PIP-II has the potential to allow an improvement of 10X over the expected Mu2e sensitivity through a more intense muon beam and better duty factor
- The PIP-II beam provides several other advantages over the present booster beam
- However, there are significant challenges:
  - Handling the lower energy proton beam, 0.800 GeV vs 8 GeV
  - Handling the higher rates
- Significant parts of the apparatus will have to be replaced
- Opportunities of achieving a SES O(10^{-18}) far outweigh the challenges
- A small, enthusiastic team is working on Mu2e-II, the immediate goal is to produce a strong conceptual design for the US Snowmass-2022 process, which is mapping out a USA plan for the next generation of experiments and facilities
- If you are interested in joining our team, there are many opportunities

Thanks to my many colleagues on Mu2e-II and Mu2e!

Backup Slides

PIP-II Schedule



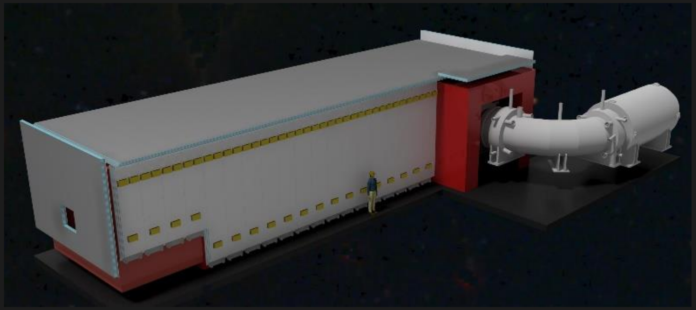
TPC $888M

Contingency 40% on work-to-go

General requirements for Mu2e PS

- Magnetic:
  - Nominal peak field on the axis 4.6 T;
  - Maximum peak field on axis 5.0 T;
  - Axial gradient -1 T/m;
  - Gradient uniformity ±5 %.
- Electrical:
  - Operating margins: ≥ 30 % in I_c, ≥ 1.5 K in T_c;
  - Operating current 9÷10 kA;
  - Peak quench temperature ≤ 130 K;
  - Voltage across terminals ≤ 600 V.
- Structural:
  - Withstand forces at all conditions while part of the system or stand-alone;
  - Cryostated magnet weight ≤ 60 tons;
  - Compliance with applicable structural codes.
- Cryogenic:
  - Cooling agent: LHe at 4.7 K;
  - Total heat flow to LHe ≤ 100 W;
  - Cryostat ID 1.5 m;
  - Conduction cooling.
- Radiation:
  - Absorbed dose ≤ 7 MGy total;
  - Minimum RRR of Al stabilizer in the operating cycle ≥ 100.

CRV: Reducing Neutron Induced Background

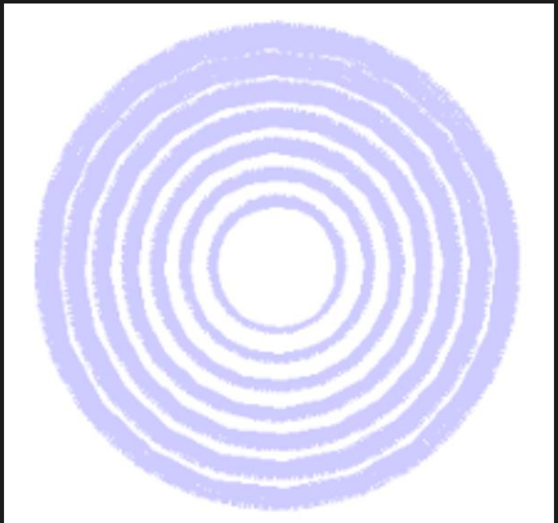


Estimate 0.007 background events per 1E6 seconds: 0.175 events in a run of 2.5E7 live seconds

- Increase shielding above detector pit to reduce number of cosmic-ray neutrons
  - This is feasible and sufficient
- Find a way to place a veto around the stopping target region
  - Extremely challenging – high rates, low mass (including cable plant), operation in vacuum
  - Could replace much of the present Mu2e CRV

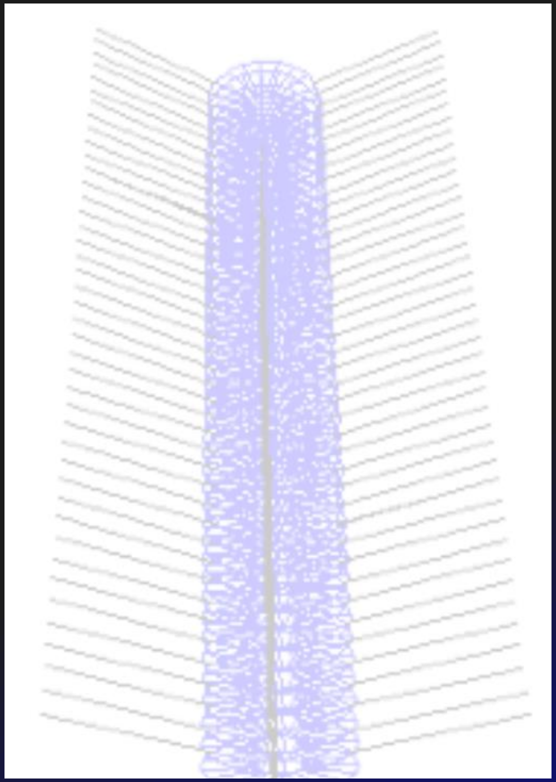
Mu2e-II: Other Stopping Target Designs

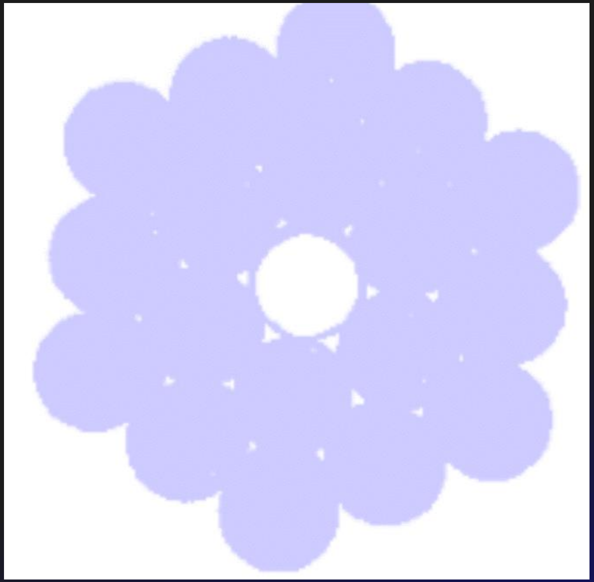
Can we increase the stopping fraction; lower the electron escape mass?



Concentric Cylinders

Foils & Frame





Hexagonal Cylinders

No significant improvement in stopping fraction: Present design close to optimal