Fermilab

Mu2e Motivation, Sensitivity, and Science Requirements

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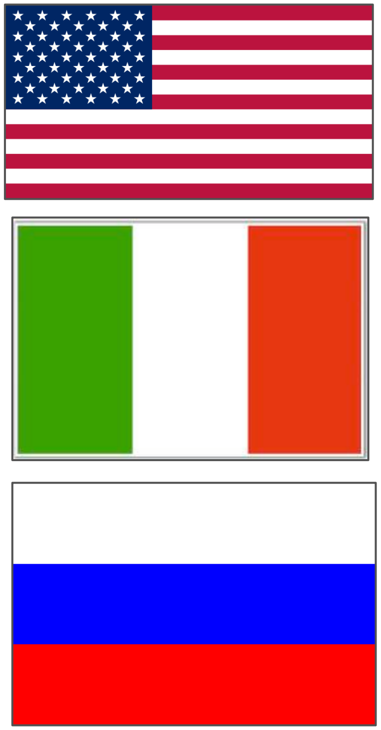
Mu2e Co-spokesperson

10/21/2014

Mu2e Collaboration


Mu2e Collaboration, November 2013



About 140 scientists from 26 institutions from 3 countries

Applying: S. Dehmers (Yale), G. Blazey, S. Uzunyan, V. Zutshi (NIU), M. Schmitt, M. Velasco (NU), D. Brown (Louisville), D. Cronin-Hennessey (UMinn), D. Jenkins (S. Alabama), S. Magill, J. Repond, R. Talaga, P. Winter (ANL)

Mu2e in a Nutshell

- Mu2e is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \rightarrow e^- N$
  - Most new physics models so far postulated provide new sources of flavor phenomena
  - Observation is unambiguous evidence for new physics.
  - CLFV physics being pursued on 3 continents (e.g. COMET)

- Target sensitivity has genuine discovery potential
  - Aiming for x10^4 improvement over current world's best
  - Will provide discovery sensitivity for all rates > few 10^{-16}
  - Many BSM models predict rates in the (10^{-15} - 10^{-16}) range

- Quark flavor is violated. Neutrino flavor is violated.
  - Both implied something profound about the underlying physics
  - Both garnered Nobel Prizes

- Mu2e enables a search for charged lepton flavor violation with unprecedented precision that could prove to be equally profound.

Mu2e – a high priority for US HEP

- In the 2008 P5 report Mu2e was strongly supported:
  - “Mu2e should be pursued in all budget scenarios considered by the panel”
  - 2010 P5 reiterated their support of the 2008 plan

- In 2013 the Facilities Panel gave Mu2e the highest endorsement:
  - “The science of Mu2e is *Critical* to the DOE OHEP mission and is *Ready to Construct*.”

- In the 2014 P5 report Mu2e is strongly supported:
  - Recommendation 22, “Complete the Mu2e and Muon (g-2) and Projects.”

Improving the Previous Experiment

- Current world's best limit on $\mu N \rightarrow eN$ is from SINDRUM-II:
  - Took data at PSI in 2000
  - $R_{\mu e}(\mu N_{Au} \rightarrow eN_{Au}) < 7 \times 10^{-13}$ @ 90% CL (2006)
  - Limited by
    - Prompt backgrounds from pion captures
    - Stopped-μ rate ($\sim 10^{7}$ μ/s using ~1 MW beam)

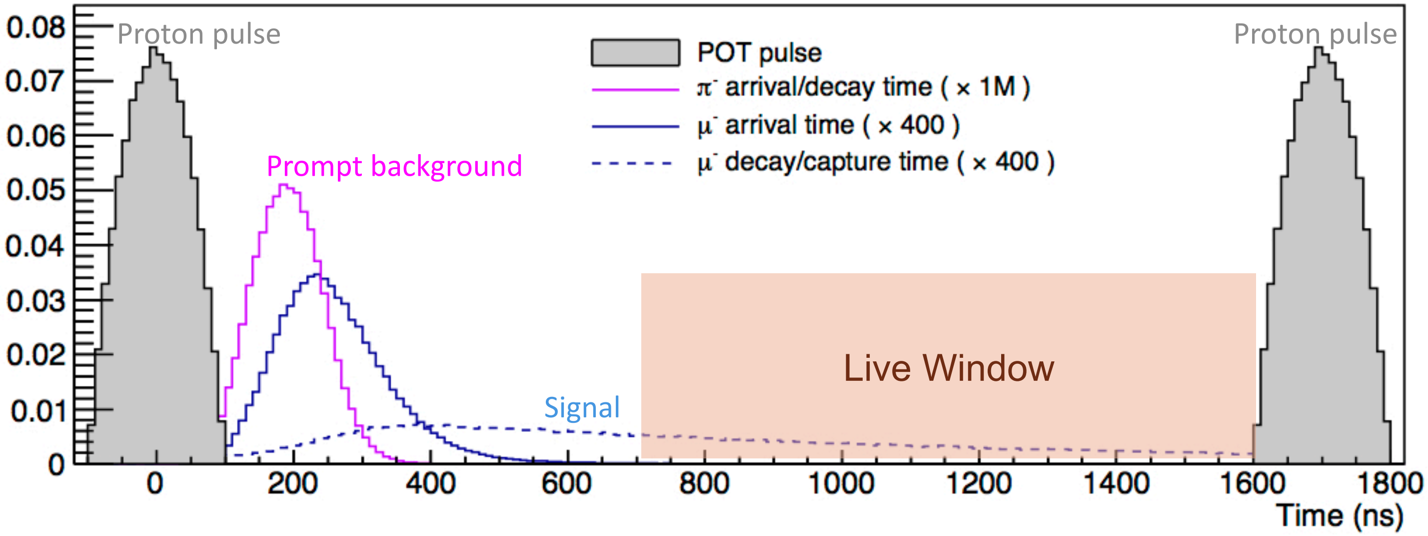
- Any improvement to SINDRUM-II needs to address these two limitations.

Improving the previous experiment

- In 1989 Lobashev and Djilkabaev published a paper proposing an experiment that solved these two problems by
  1. Utilizing a pulsed proton beam
  2. Employing solenoids to collect muons

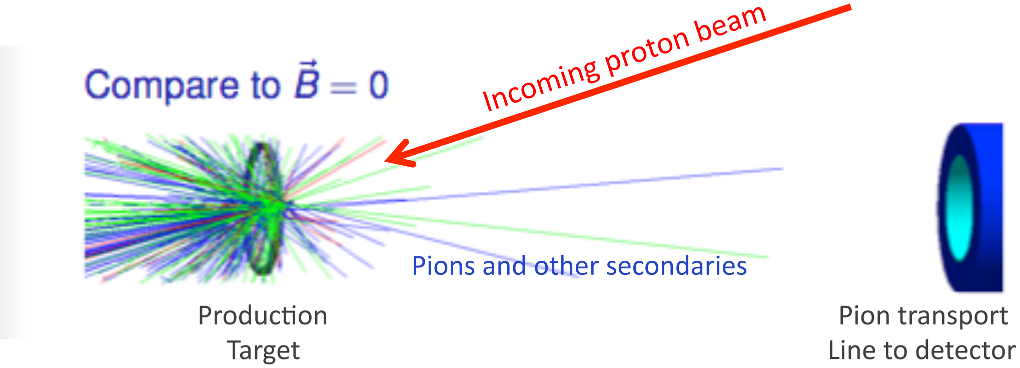
- Mu2e is the realization of their proposed technique
  - Pulsed beam from the existing Fermilab complex
  - Solenoid system capable of delivering a high intensity stopped-muon beam

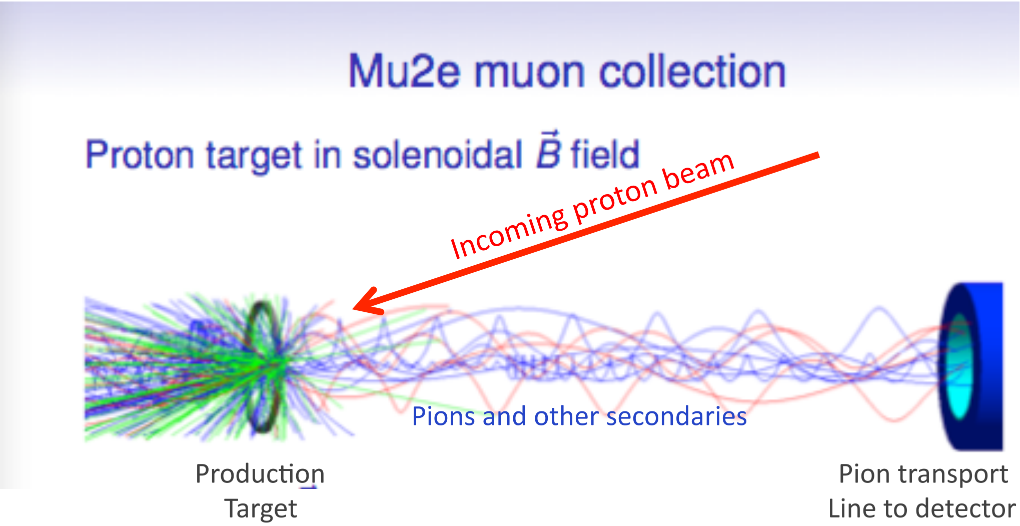
Pulsed Beam



- Suppress prompt backgrounds by many orders of magnitude by employing a delayed live gate.

Using Solenoids to Collect Muons



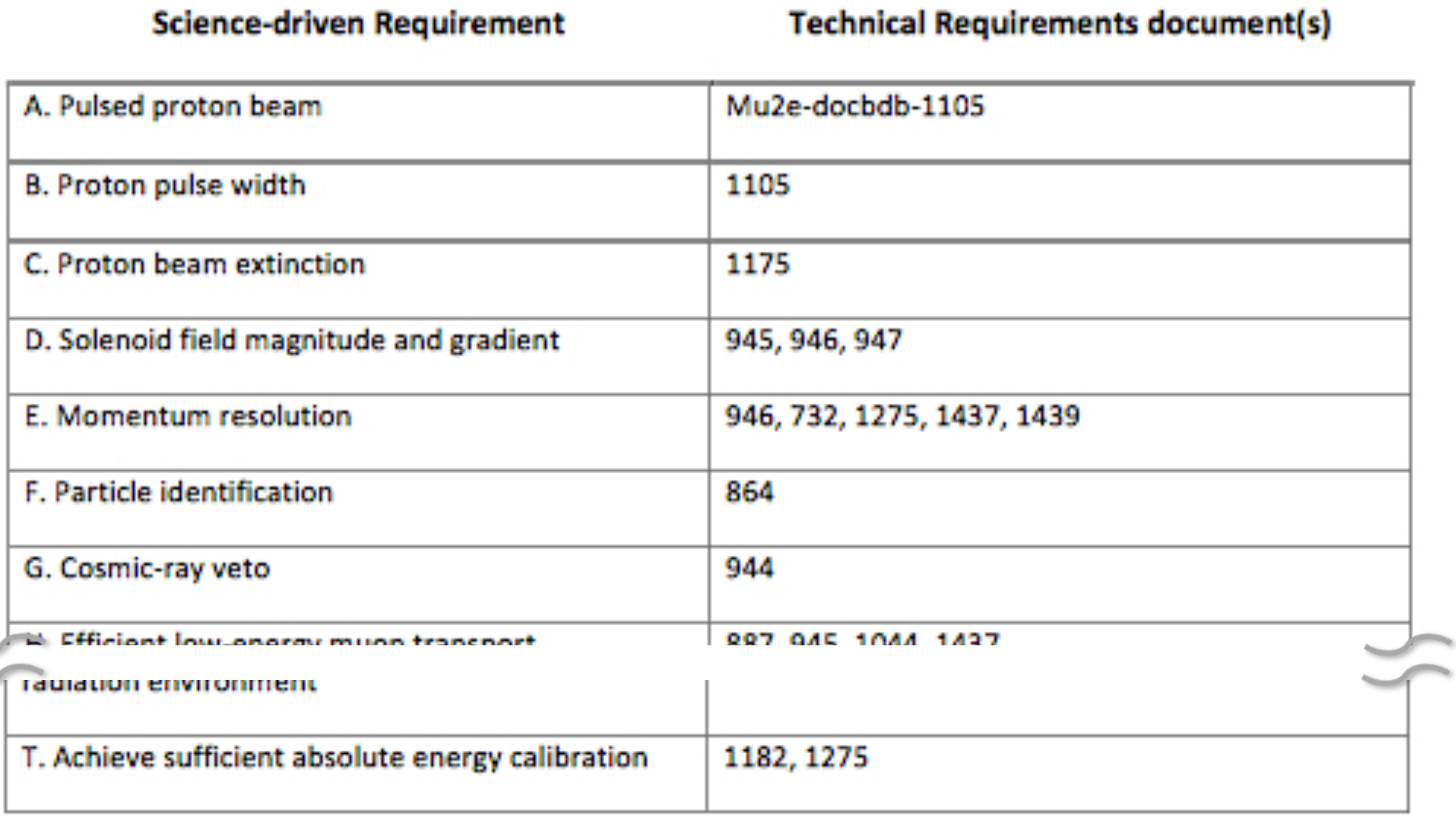


Courtesy of Andrei Gaponenko

- SINDRUM-II used ~1 MW beam to produce ~10^7 stopped μ/s

- Solenoids enable us to collect ~10^{10} μ/s using an 8kW beam.

Science-driven Requirements



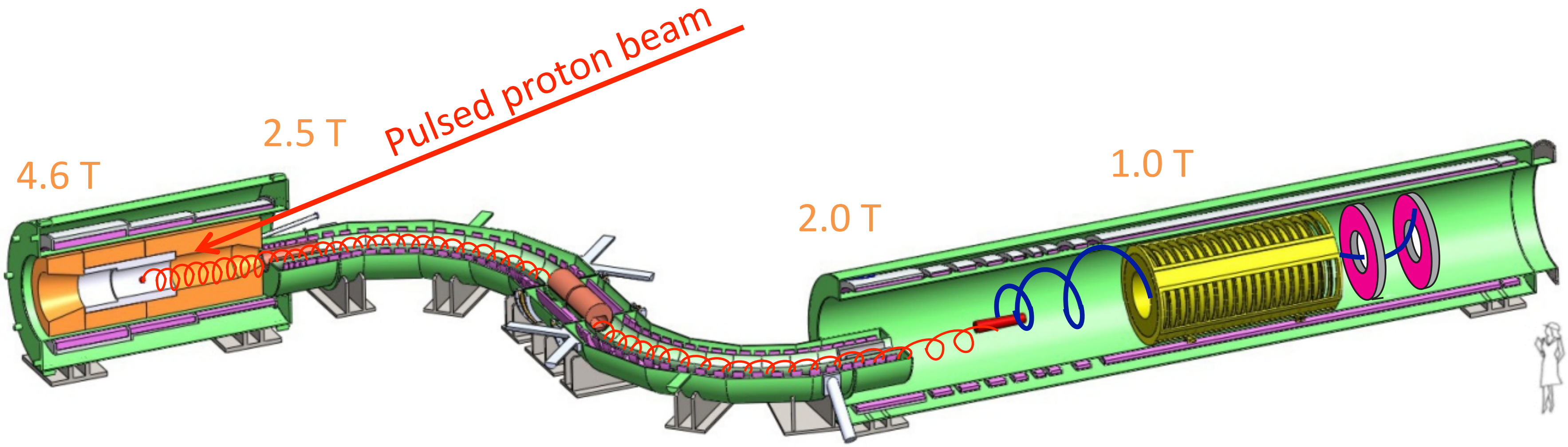
Science-driven Requirement	Technical Requirements document(s)
A. Pulsed proton beam	Mu2e-docbdb-1105
B. Proton pulse width	1105
C. Proton beam extinction	1175
D. Solenoid field magnitude and gradient	945, 946, 947
E. Momentum resolution	946, 732, 1275, 1437, 1439
F. Particle identification	864
G. Cosmic-ray veto	944
H. Efficient low-energy muon transport	887, 945, 1044, 1437
radiation environment	
T. Achieve sufficient absolute energy calibration	1182, 1275

- Enumerated in mu2e-doc-db-4381
    - Controlled document
    - Flow down to technical requirements for each sub-system

Technical Design Report

- Available from review web site
  - ~800 pages long
- Describes in detail the Mu2e apparatus that's been costed for purposes of this baseline review
- This apparatus
  - Meets the requirements
  - Achieves the physics goals of the experiment
  - Is robust

Mu2e Experimental Apparatus



Production Solenoid (PS)

Transport Solenoid (TS)

Detector Solenoid (DS)

- Consists of 3 solenoids, pulsed proton beam, active detector elements
  - nb. mean momentum of muons that stop ~ 40 MeV/c
  - nb. signal is 105 MeV/c electron and nothing else

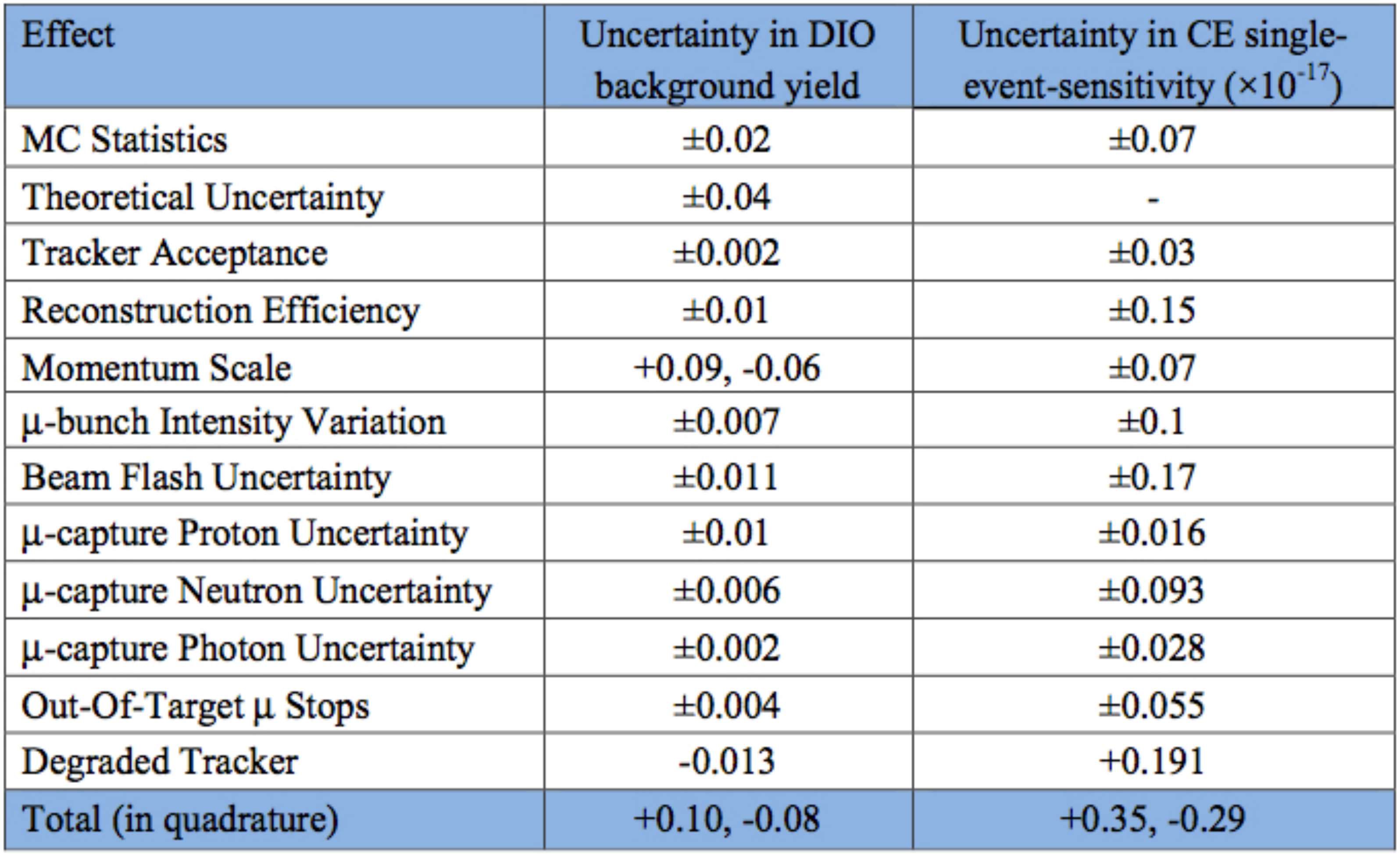
Mu2e Sensitivity

- Single-event-sensitivity
  - Goal : 2.4 x 10^{-17} (relative to normal μ capture)
    corresponds to an expected limit of 7 x 10^{-17} @ 90% CL
  - Achieved : (2.9 +/- 0.3) x 10^{-17} (cf. 5.6 x 10^{-17} at CD-1)
    corresponds to an expected limit of 8 x 10^{-17} @ 90% CL
- Background yield
  - 0.37 +/- 0.10 events
- Above numbers
  - Assume 3.6 x 10^{20} POT delivered in 6 x 10^{7} s collected over 3 years of physics data-taking (plan for +1y for special runs)
  - Based on detailed simulations and including uncertainties

Mu2e Simulation

- GEANT4 with detailed geometry description including building, overburden, detector elements, target supports, solenoid coils and cryostats
- Physics list chosen to best describe HARP pion production data in relevant kinematic region. Utilize high precision list for neutrons < 20 MeV. Customized for muon capture/decay.
- Detailed hit-level tracker simulation includes effects of ionization drift in straws, gas amplification, signal transit, and electronic amplification, shaping, and digitization.
  - Also includes overlay of accidental occupancy from unstopped beam, μ capture and decay, etc.
- Data-like reconstruction begins with simulated digitized output, forms hits, performs full pattern recognition and track fitting.

Systematic uncertainties



Effect	Uncertainty in DIO background yield	Uncertainty in CE single-event-sensitivity ($\times 10^{-17}$)
MC Statistics	±0.02	±0.07
Theoretical Uncertainty	±0.04	-
Tracker Acceptance	±0.002	±0.03
Reconstruction Efficiency	±0.01	±0.15
Momentum Scale	+0.09, -0.06	±0.07
μ-bunch Intensity Variation	±0.007	±0.1
Beam Flash Uncertainty	±0.011	±0.17
μ-capture Proton Uncertainty	±0.01	±0.016
μ-capture Neutron Uncertainty	±0.006	±0.093
μ-capture Photon Uncertainty	±0.002	±0.028
Out-Of-Target μ Stops	±0.004	±0.055
Degraded Tracker	-0.013	+0.191
Total (in quadrature)	+0.10, -0.08	+0.35, -0.29

- A thorough error analysis was performed

Solenoid Field Specifications

- Field specifications subject of intense study over last 5 years
  - Explored many alternatives and simplifications
  - Investigated what the minimum requirements were (e.g. relaxed DS field uniformity from 0.1% to 1%)
- Arrived at a design that
  - Saves a few $M by minimizing the number coils and shortening the solenoids (cf. COMET system is ~ 10m longer than ours)
  - Simplifies fabrication by minimizing variation of conductor geometries
  - Uses coils with dimensions comparable to what's been done before
- Our design meets the physics goals
  - Including fabrication tolerances (studied in detail)
  - With performance margins (>10%)
  - With healthy operating margins (current margins of 30-50%, temp. margins of 1.5-2.0 K)

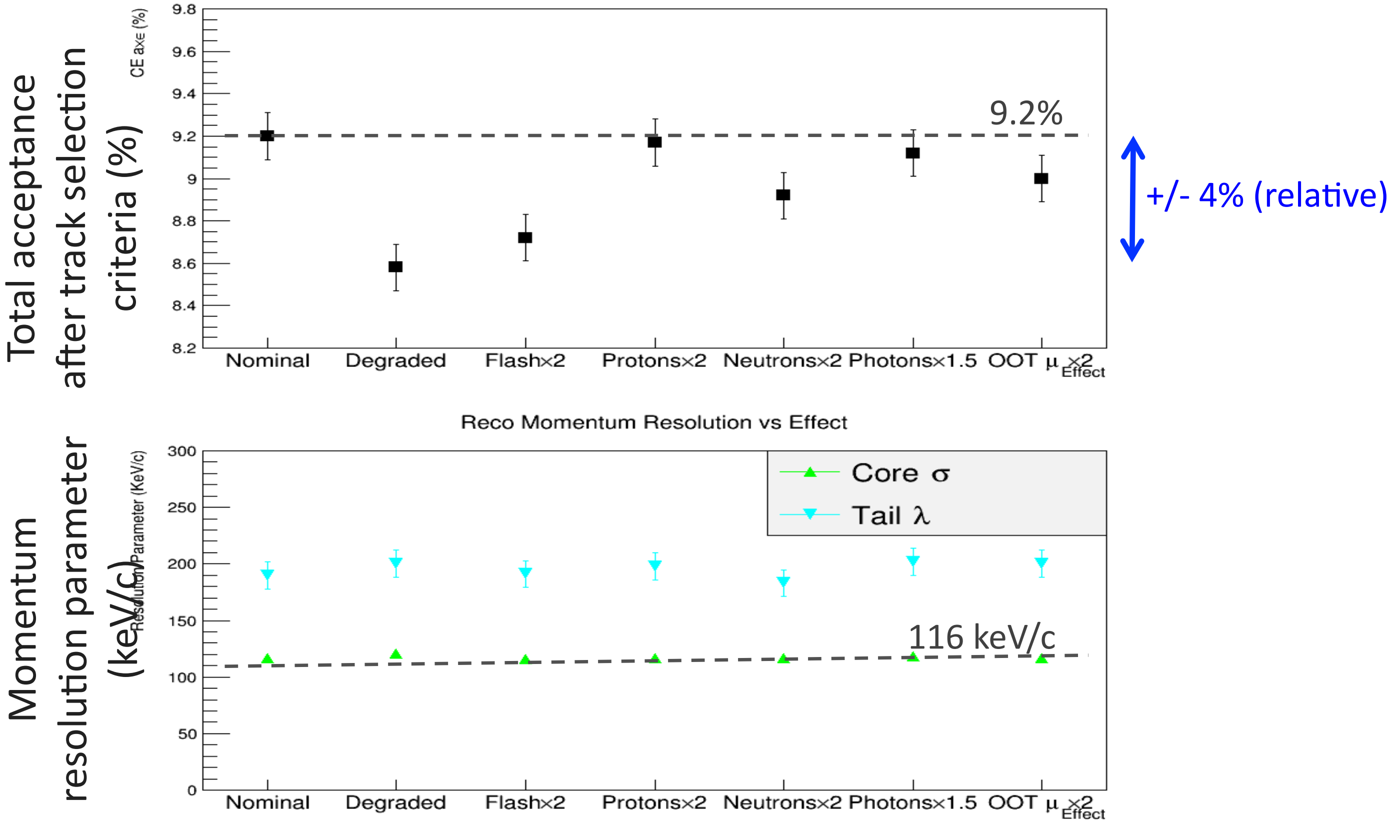
Solenoid Fabrication Tolerances

- Studies described in mu2e-docdb-2870, 2156, 2403, 652
- What we did:
  - Recalculated B-field map 100+ times randomly varying coil positions, pitch, within fabrication tolerances
    - Also explored variations within conductor tolerances
  - Compared resulting maps to nominal and identified outliers
  - Used outliers to investigate effects on signal and background
- What we found: even worst case scenarios achieve Mu2e physics goals
- We are confident that conductor and magnets built to our specifications will allow Mu2e to meet its physics goals.

Solenoid performance margins

- The experiment will work perfectly fine, even if the solenoids don't
  - The stopped-μ yield depends on the peak field in the PS
    - Stopped-μ yield decreases by 10% if peak field only 4.1 T (nb. the specification is 4.6 T)
  - The signal acceptance and detector occupancy depend on the field in the DS spectrometer region
    - The signal acceptance and beam-related occupancy in the tracker are affected by a few % for a DS field 0.9 T in spectrometer region (nb. the specification is 1.0 T)

Systematic study of accidental occupancy



Total acceptance after track selection criteria (%)

9.2%

+/- 4% (relative)

Momentum resolution parameter (keV/c)

116 keV/c

variations affecting occupancy or tracker performance

- Similar studies performed for other detector elements – we are not sitting on a “performance edge”.

Closing Remarks

- Mu2e will search for charged lepton flavor violation at 10^{-17}
  - Provides discovery sensitivity across wide array of BSM models
  - Complementary to rest of world's HEP program
  - We have the opportunity to be first

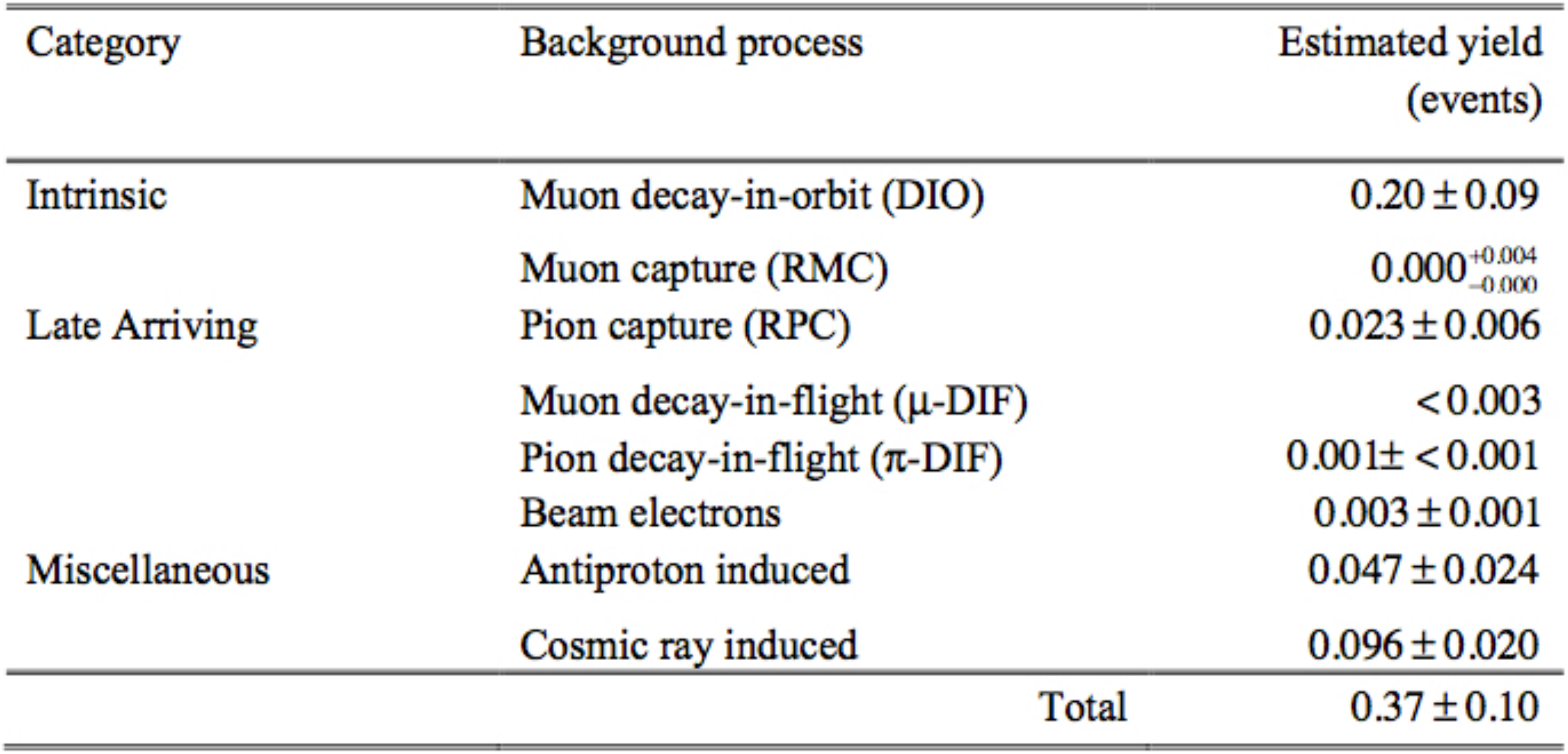
- Science requirements well understood
  - mu2e-doc-db-4381
  - Flow down to technical requirements

- Accelerator, Solenoid and Detector performance are
  - well understood
  - based on detailed simulation and sophisticated reconstruction
  - include a thorough uncertainty analysis – Robust!

- We are confident that TDR apparatus achieves physics goals

Backup Slides

Mu2e Background

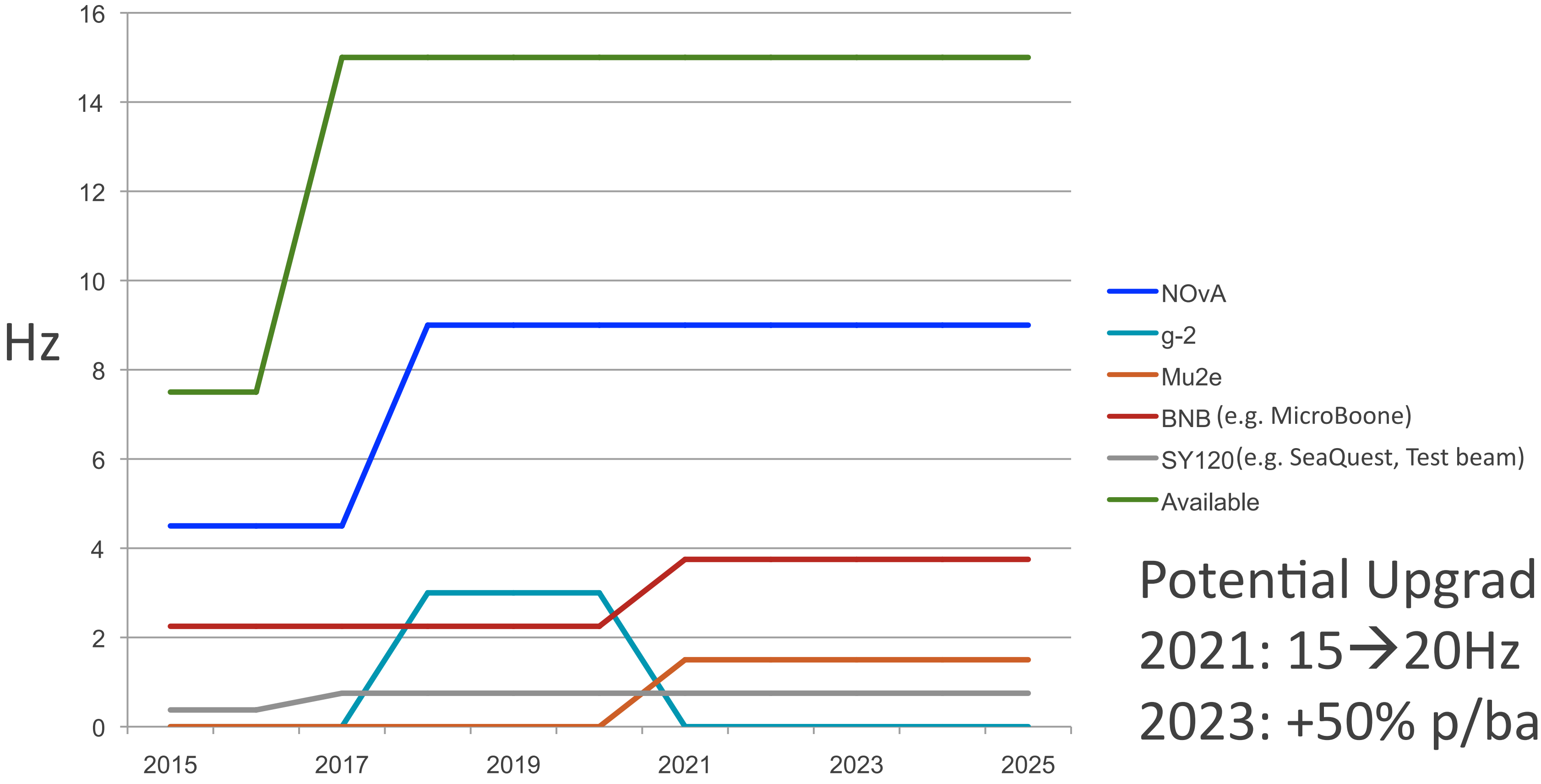


Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.20 ± 0.09
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	< 0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.096 ± 0.020
	Total	0.37 ± 0.10

- Table 3.4 in Technical Design Report

Proton Plan (straw man)

Illustration of plausible proton allocations subject to program planning



Potential Upgrades
2021: 15→20Hz
2023: +50% p/batch

- Assumes PIP-I upgrade is completed prior to g-2 running
- Mu2e needs ~7e17 stopped-muons (estimated to take ~4e20 POT) for physics plus another ~1e20 POT for calibrations, special background runs, etc. (ie. ~4y total run time)

Proton timing

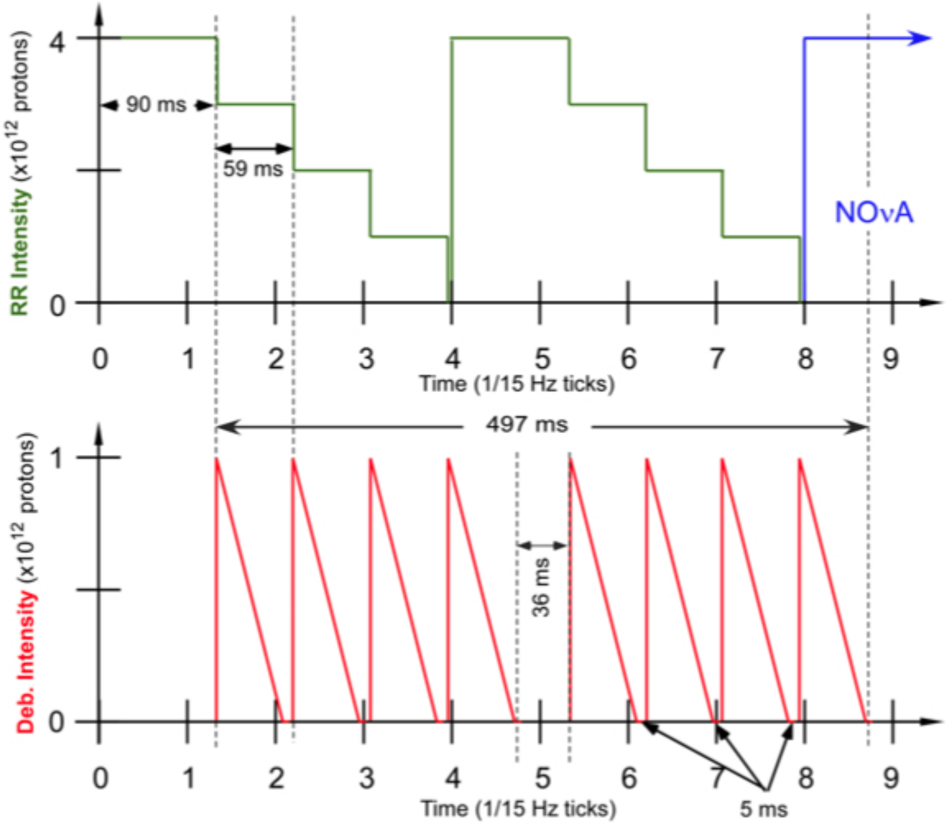
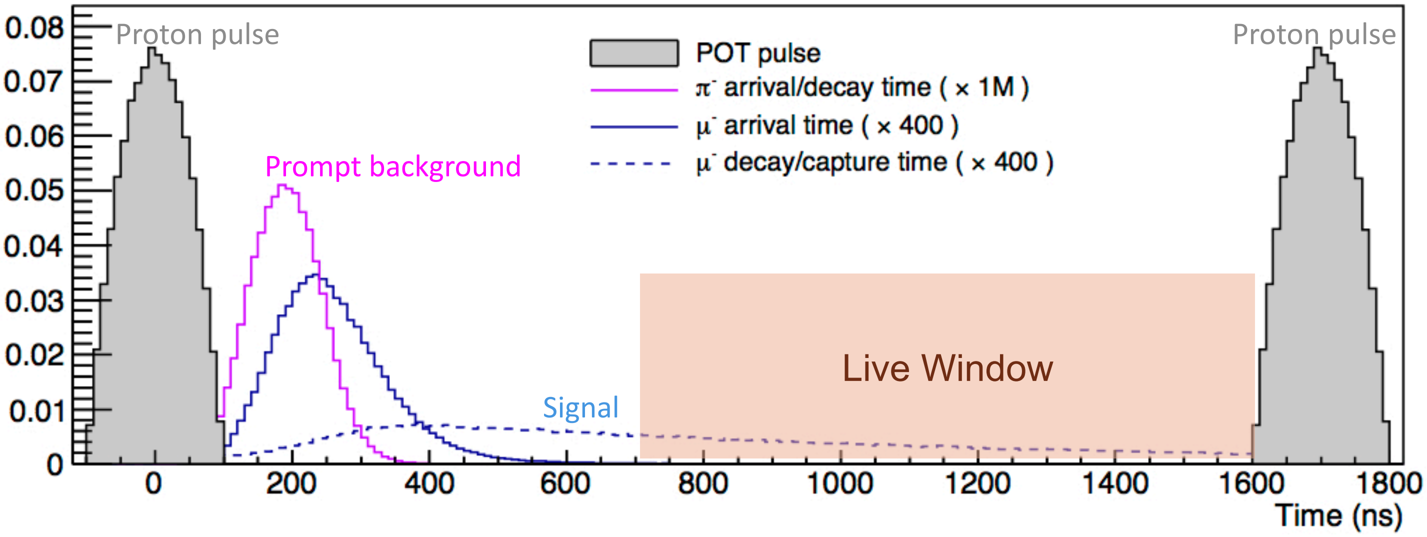


Figure 5.4. This figure shows the first eight Booster ticks of a Main Injector cycle. Proton batches are injected into the Recycler at the beginning of the cycle and again at the fourth tick. After each injection, the beam is bunched with 2.5 MHz RF and extracted one bunch at a time.

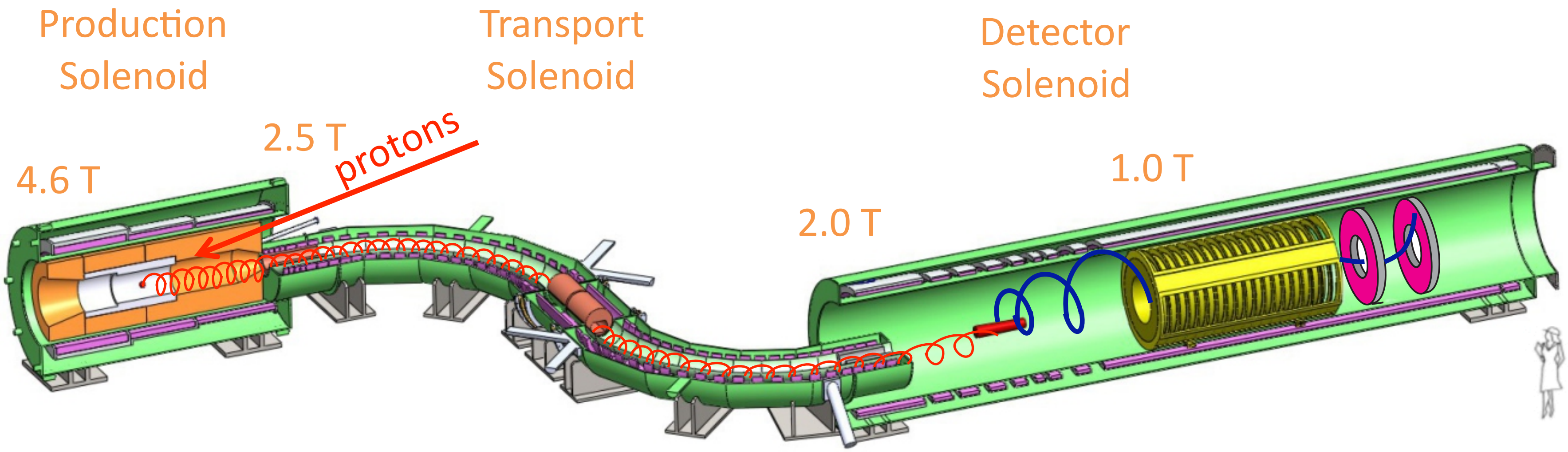
- Mu2e will use 2 of 20 Booster batches / MI cycle
- Mu2e will run simultaneously with NOvA and the Short baseline ν program

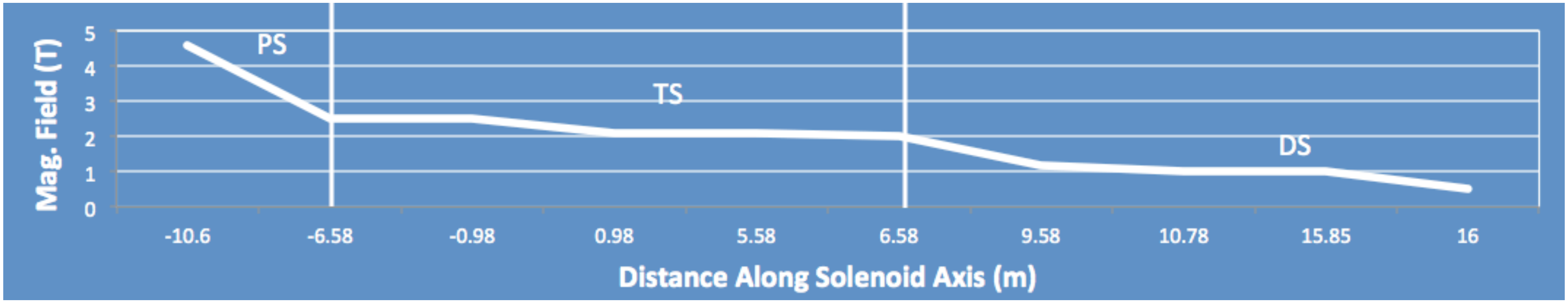
Pulsed Beam Requirements



- Suppress prompt backgrounds by many orders of magnitude by employing a delayed live gate.
  - Proton pulses must be narrow
  - Out-of-time protons must be suppressed

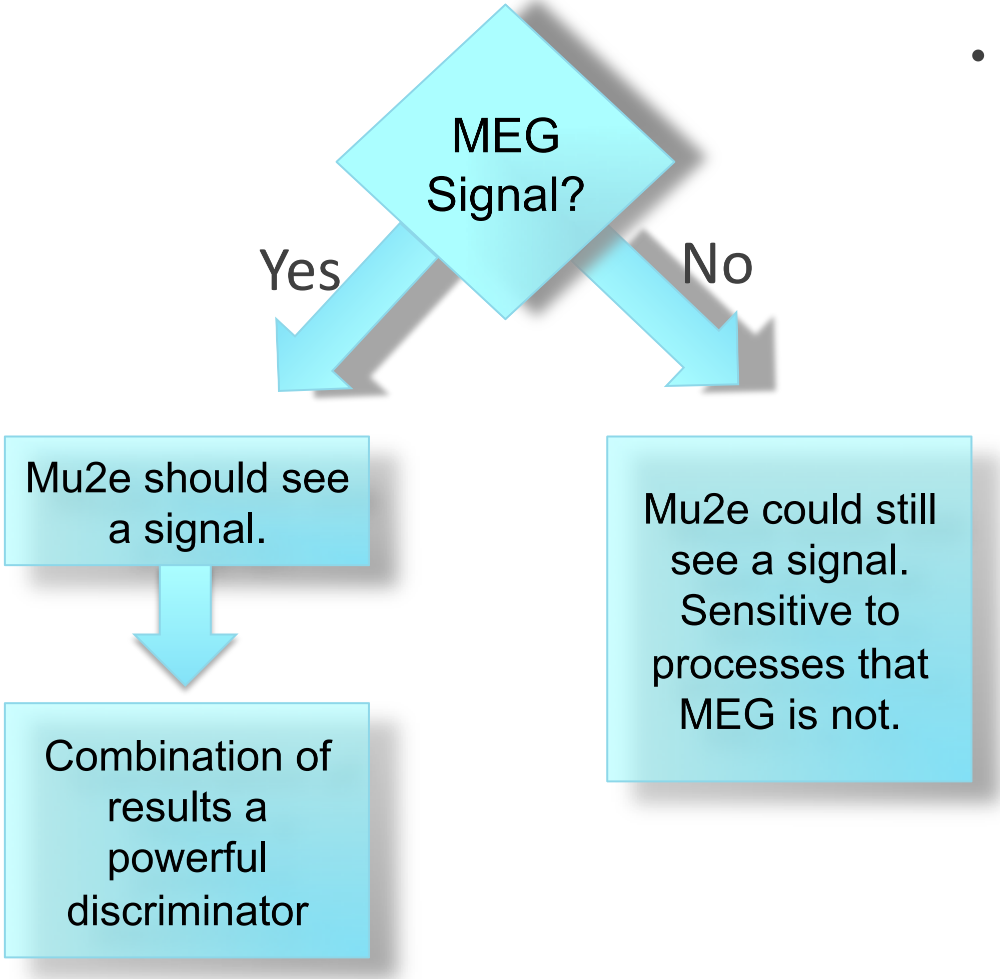
Solenoid Field Requirements





- Graded field essential to suppress backgrounds

Mu2e and MEG



MEG Signal?

Yes

No

Mu2e should see a signal.

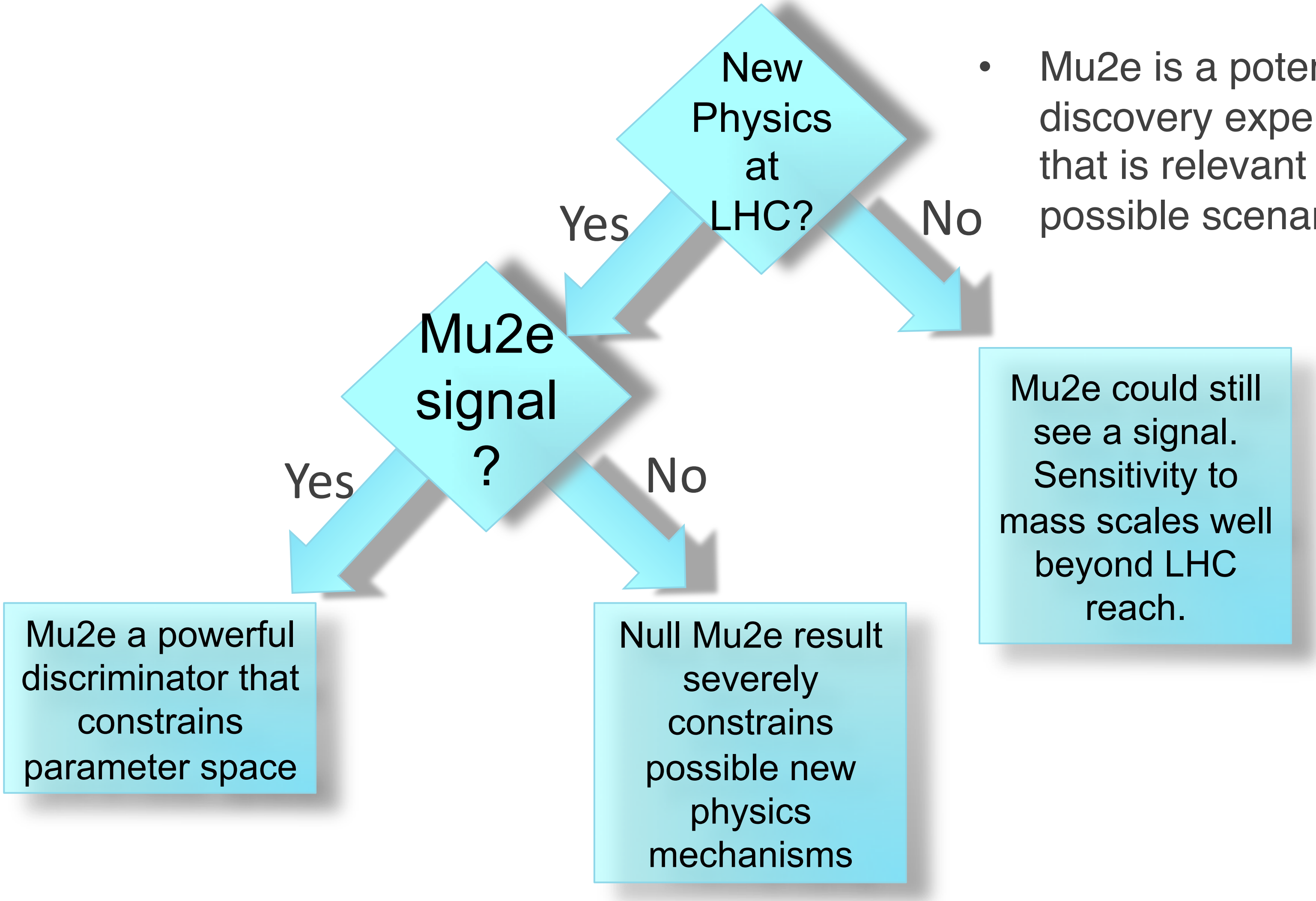
Combination of results a powerful discriminator

Mu2e could still see a signal. Sensitive to processes that MEG is not.

- Mu2e is a potential discovery experiment that is relevant in all possible scenarios

Mu2e and the LHC

- Mu2e is a potential discovery experiment that is relevant in all possible scenarios



New Physics at LHC?

Yes

Mu2e signal ?

Yes

Mu2e a powerful discriminator that constrains parameter space

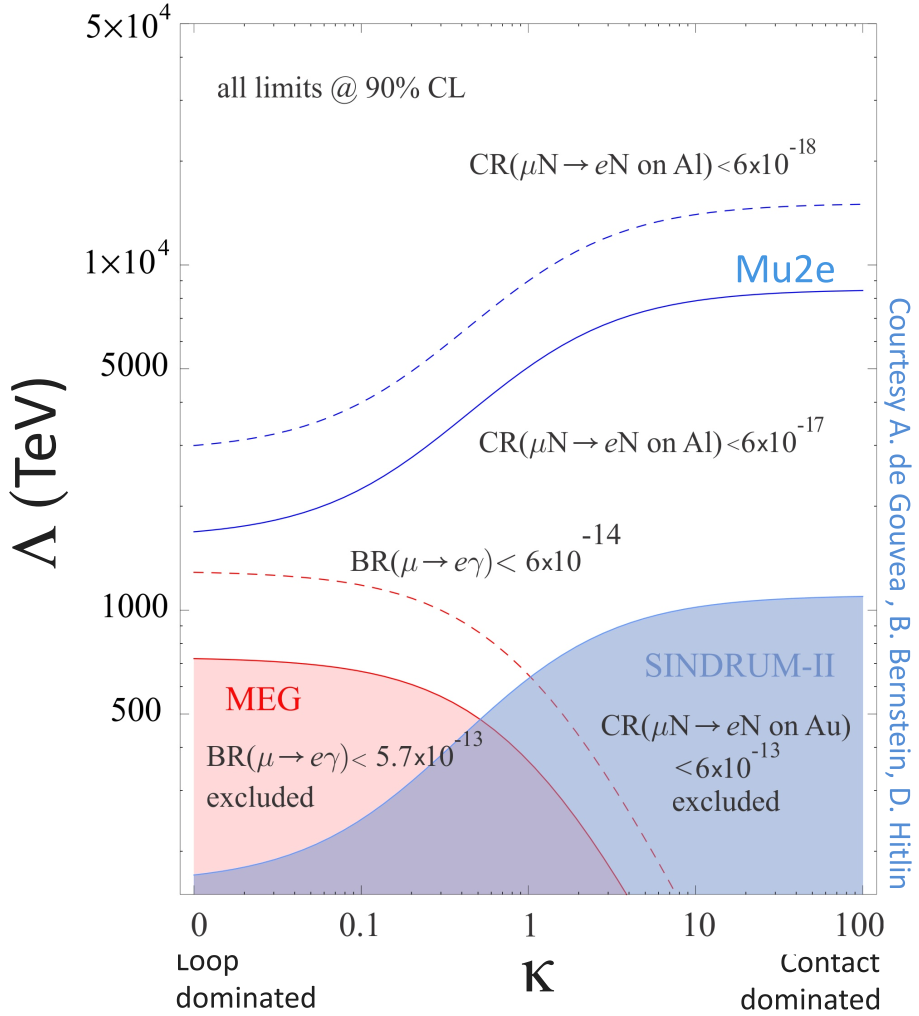
No

Null Mu2e result severely constrains possible new physics mechanisms

No

Mu2e could still see a signal. Sensitivity to mass scales well beyond LHC reach.

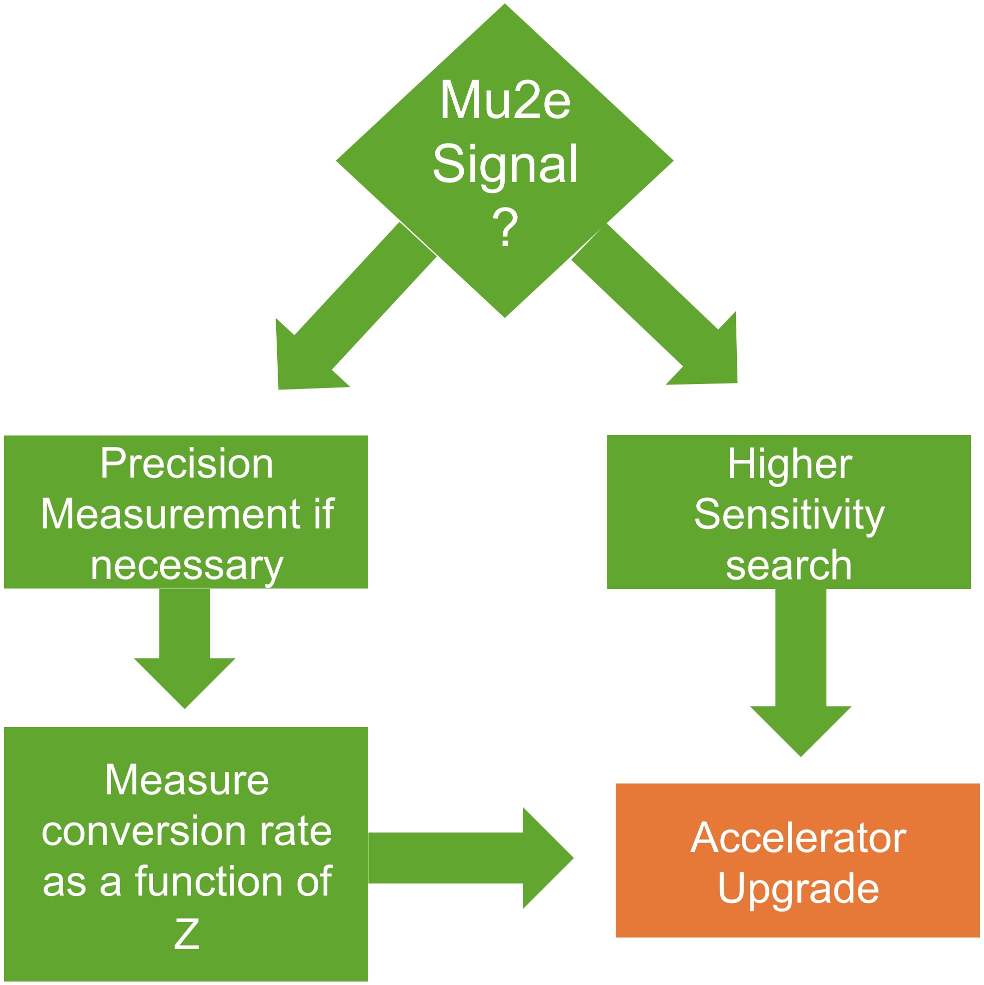
Mu2e and MEG Sensitivities



Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

- Mu2e has world-class sensitivity regardless of NP scenario

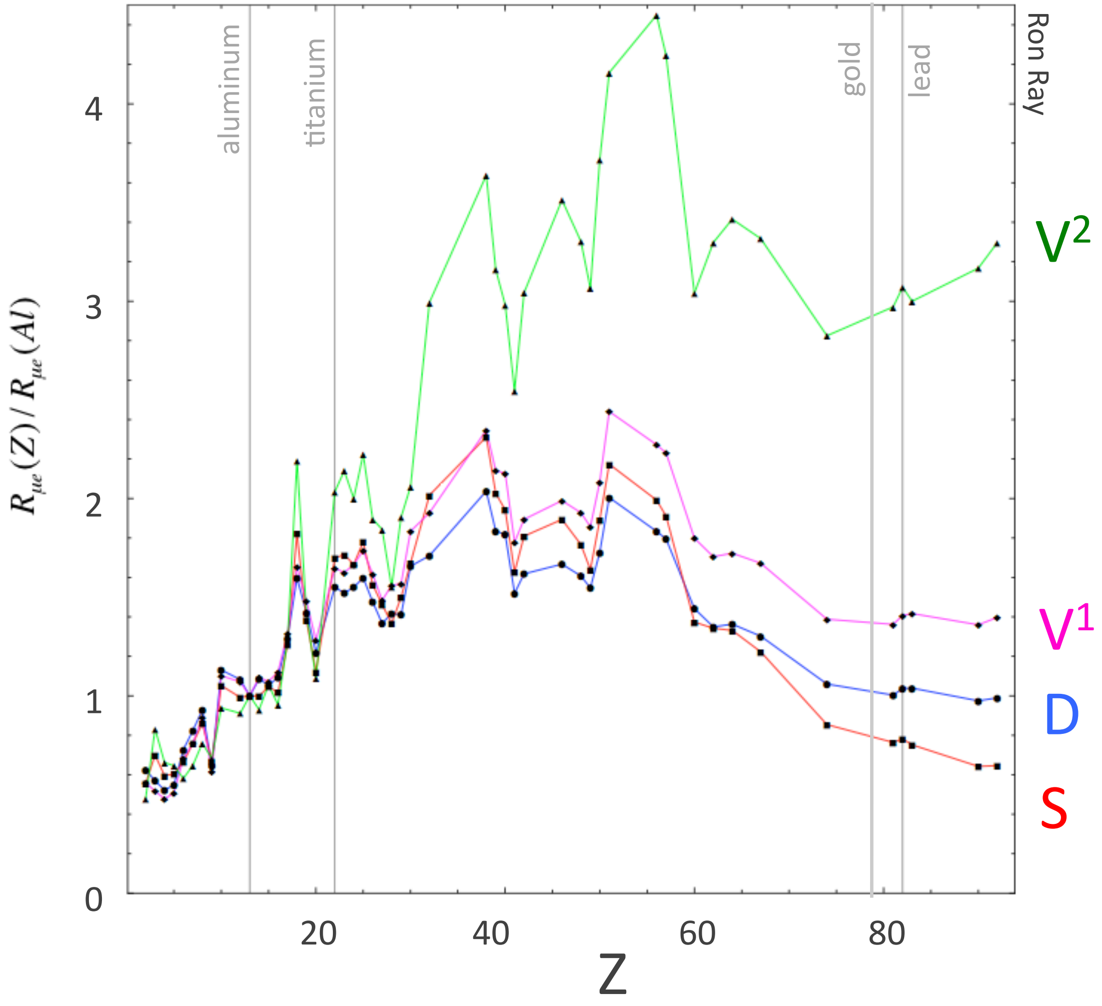
Next Generation Mu2e



- A next-generation Mu2e experiment makes sense in all scenarios
  - Push sensitivity or
  - Study underlying new physics
  - Will need more protons → upgrade accelerator
  - Snowmass white paper, arXiv:1307.1168

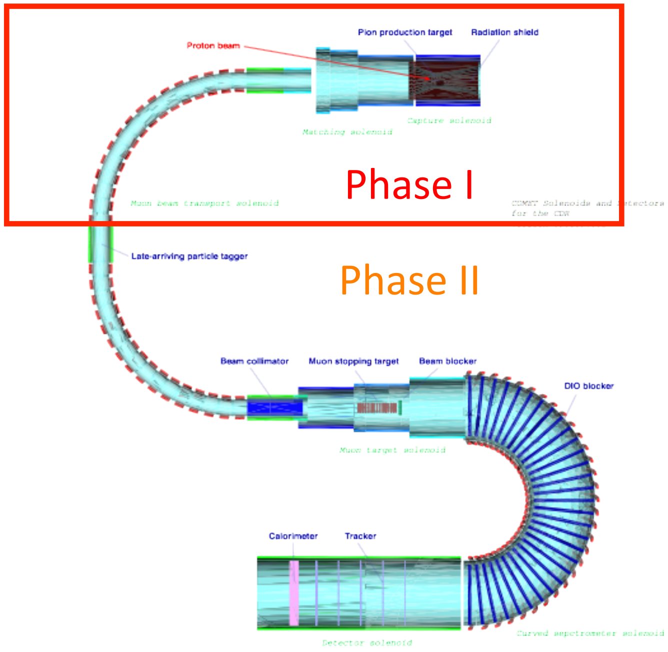
μ-to-e as a function of stop-target Z

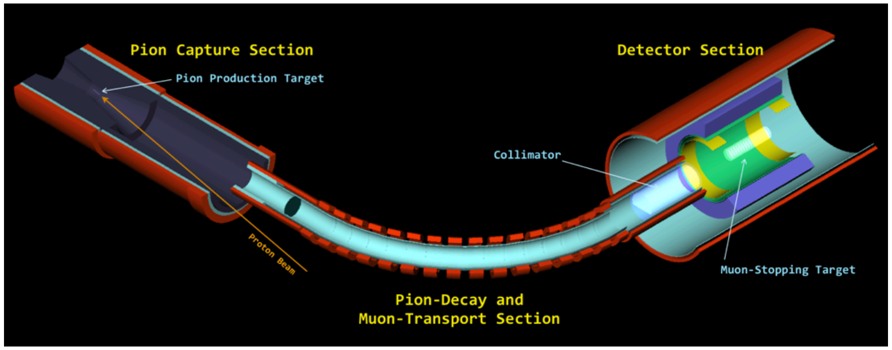
- By measuring ratio of rates using different stopping targets, Mu2e can unveil details of underlying New Physics mechanism



V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)

COMET





- Design beam power: 56 kW (8kW for Mu2e)
- Path length of solenoids: ~38m (28m for Mu2e)

- Phase 1: scheduled to begin 2016, x100 improvement
- Phase 2: aim to begin so that they're competitive with Mu2e, another x100 improvement