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Mu2e Scientific Highlights

Kyle J. Knoepfel
Scientific Computing Division

DOE Institutional Review

12 February 2015

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Mu2e Project discussed by
R. Ray [Breakout 1D]

Mu2e collaboration

Mu2e collaboration

Roughly 170 collaborators from 32 institutions

Argonne National Laboratory*
Boston University
Brookhaven National Laboratory
Lawrence Berkeley National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
University of Houston
University of Illinois
Lewis University
University of Louisville*
University of Massachusetts, Amherst
University of Minnesota*
Muons, Inc.
Northern Illinois University
Northwestern University
Purdue University
Rice University
University of South Alabama*
University of Virginia
University of Washington
Yale University*

Laboratori Nazionali di Frascati
INFN Genova*
INFN Lecce and Universita del Salento
Laboratori Nazionali di Frascati and Universita Marconi Roma
INFN Pisa

Joint Institute for Nuclear Research, Dubna
Novosibirsk State University/Budker Institute of Nuclear Physics*
Institute for Nuclear Research, Moscow

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University of Louisville*
University of Massachusetts, Amherst
University of Minnesota*
Muons, Inc.
Northern Illinois University

7 new institutions
20% more collaborators
since last S&T review

Northwestern University
Purdue University
Rice University
University of South Alabama*
University of Virginia
University of Washington
Yale University*

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Mu2e – the physics

- Mu2e is an experiment searching for charged lepton flavor violation (CLFV) in muons:

$$\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$$

- This reaction is suppressed by the standard model (SM) to a level smaller than **10^{-50}**.

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- The experimental signature?

$$\begin{aligned} E_e &= m_\mu c^2 - E_b - E_{\text{recoil}} \\ &= 104.973 \text{ GeV} \quad (\text{for Al}) \end{aligned}$$

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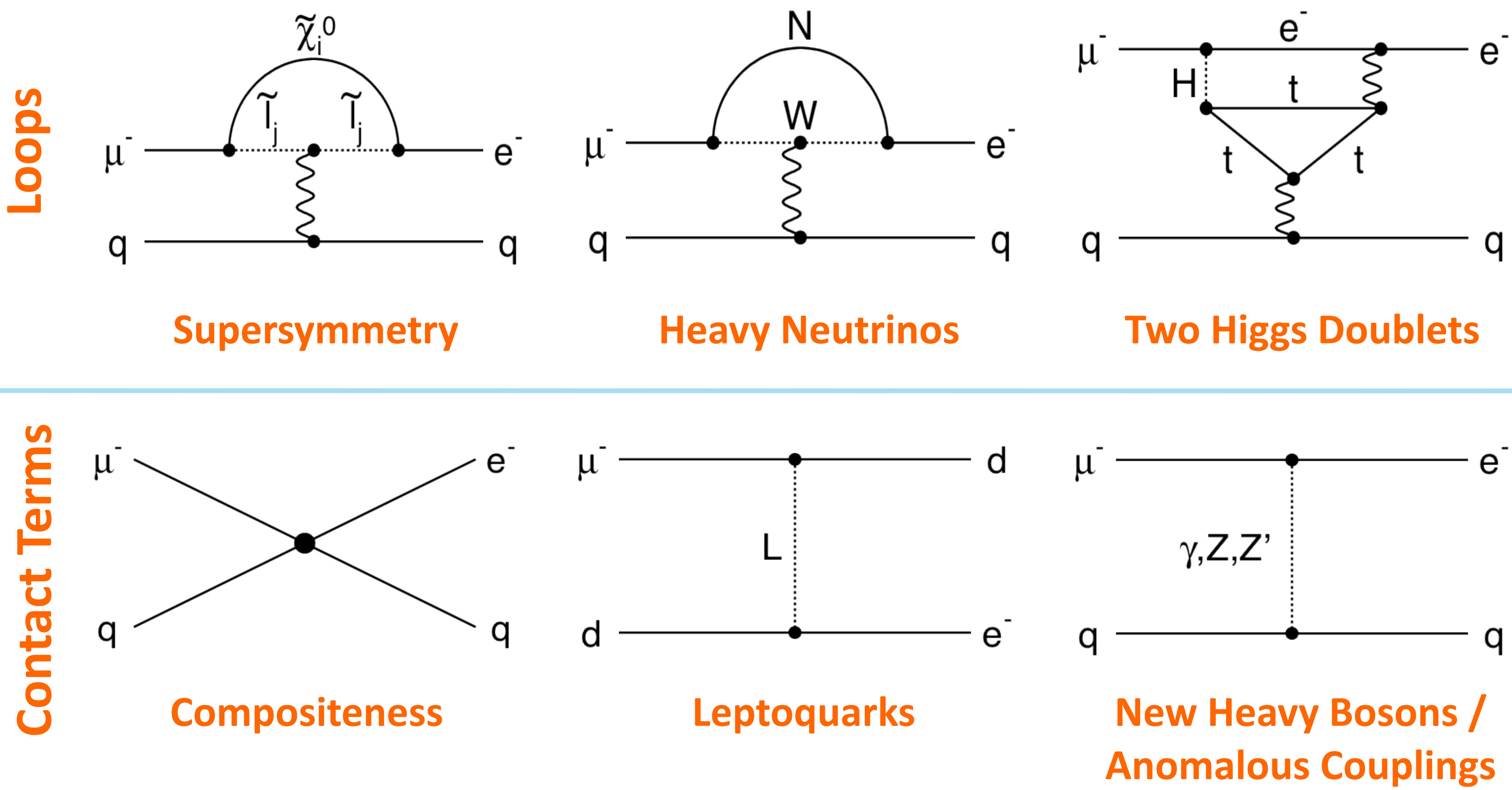
An observed signal means unambiguous new physics.

- Allowed by many beyond-the-SM (BSM) models at levels just beyond current experimental limits.

Engagement with theory



- Muon-to-electron conversion allowed via loop diagrams **or** contact terms.
  - cf: $\mu \rightarrow e\gamma$ happens via loops.
- Muon-to-electron conversion enables discovery sensitivity over broad swath of BSM parameter space.

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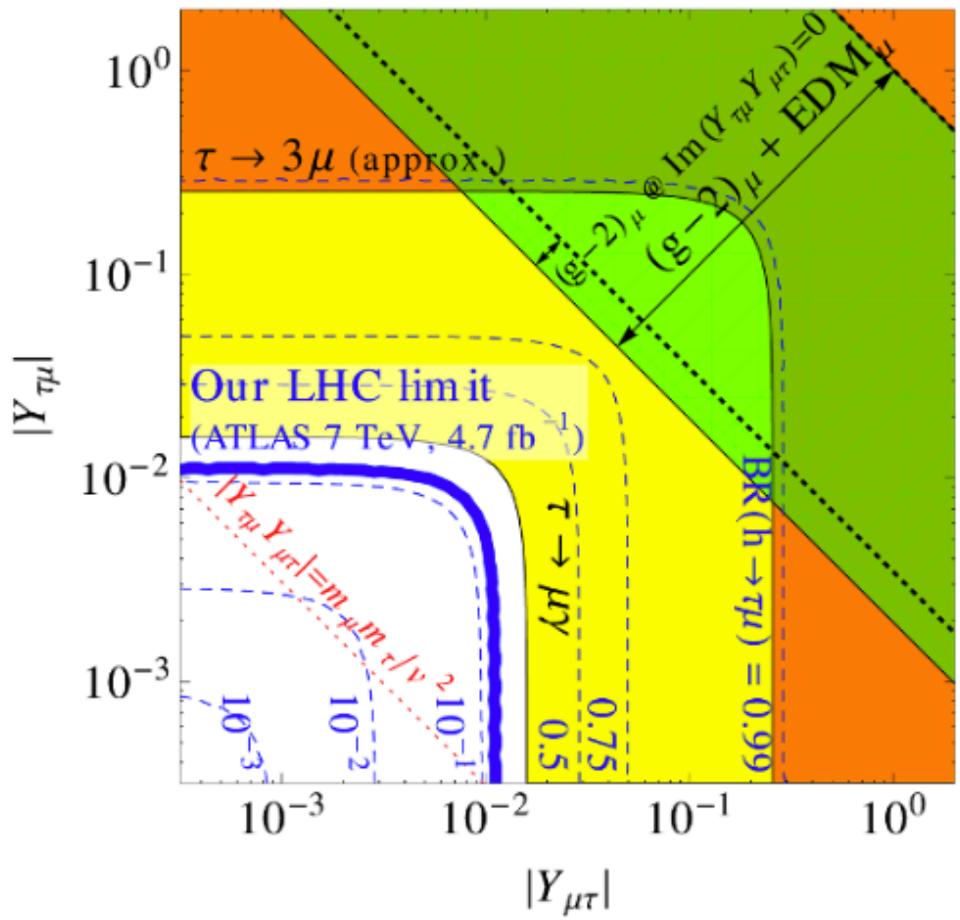
Engagement with theory

- BSM physics
  - FNAL theorists Harnik and postdocs studying new-physics sensitivity of Mu2e
  - If Higgs boson flavor violation exists, Mu2e provides farthest reach.
  - Complements LHC searches.

Harnik*, Kopp*, and Zupan 1209.1397



Flavor-violating Yukawa couplings and their associated limits.

See Campbell [Plenary]
See Parke [Breakout 4C]

*** FNAL Theoretical Physics Dep't**

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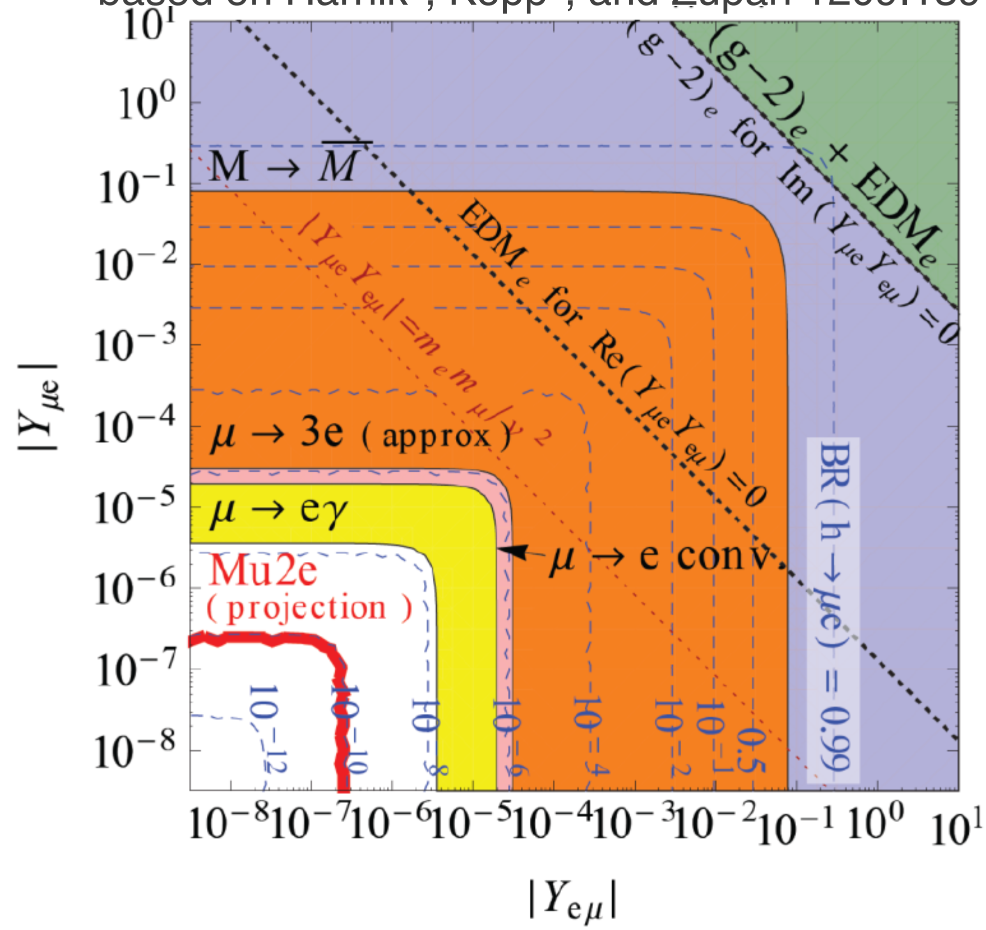

italic

See Campbell [Plenary]
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Flavor-violating Yukawa couplings and their associated limits.

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Engagement with theory

- BSM physics
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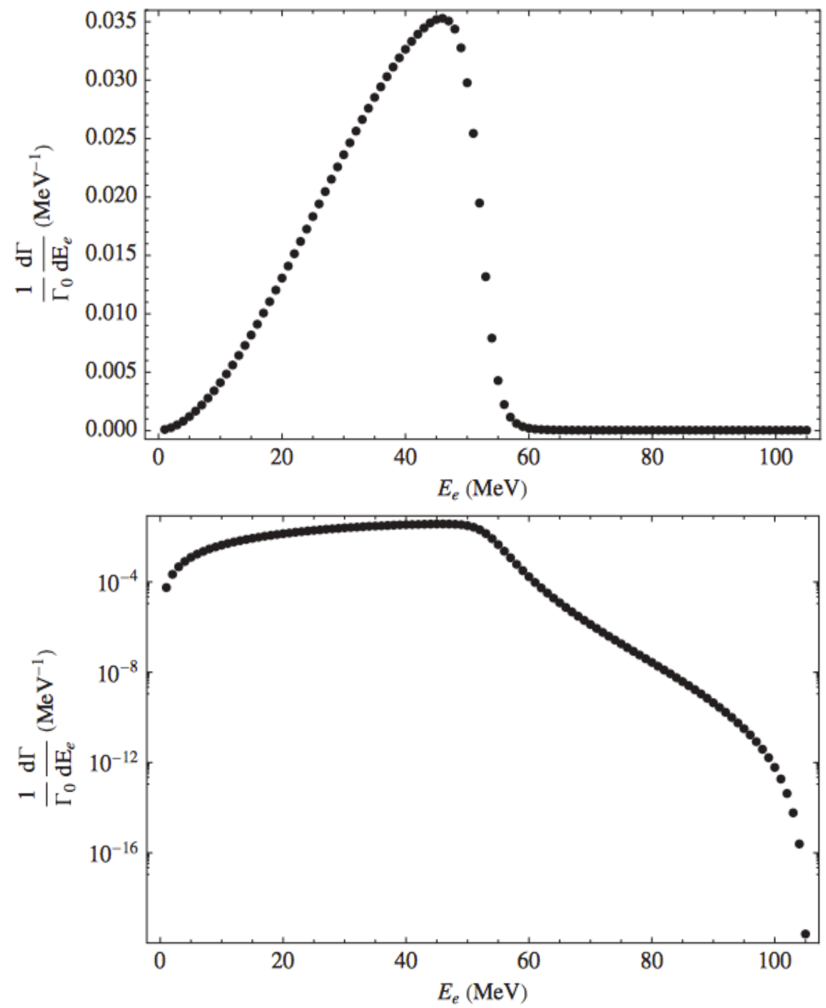
  - If Higgs boson flavor violation exists, Mu2e provides farthest reach.
  - Complements LHC searches.
- SM physics
  - Dominant Mu2e background is from SM decays of muons in orbit.
  - Collaborate with U. Alberta colleagues A. Czarnecki and R. Szafron (2014 IF Fellow) to determine radiative corrections to electron energy spectrum.

A. Czarnecki, *et al*, Phys. Rev. D **84**, 013006 (2011)



What is Mu2e measuring?

- Measure ratio of $\boldsymbol{\mu} \rightarrow \boldsymbol{e}$ conversions (CLFV) to the number of μ captures (SM).

$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N)]}$$

(BSM)

(SM)

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- Mu2e goal for *R*:
  - Single-event-sensitivity: 2.5×10^{-17}
  - Upper limit (90% C.L.): 6×10^{-17}
  - Probe BSM eff. mass scales of: $10^3 - 10^4$ TeV/c^2

- Background goal: less than 1 event.

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Factor **<u>10,000</u>** improvement wrt. SINDRUM-II.

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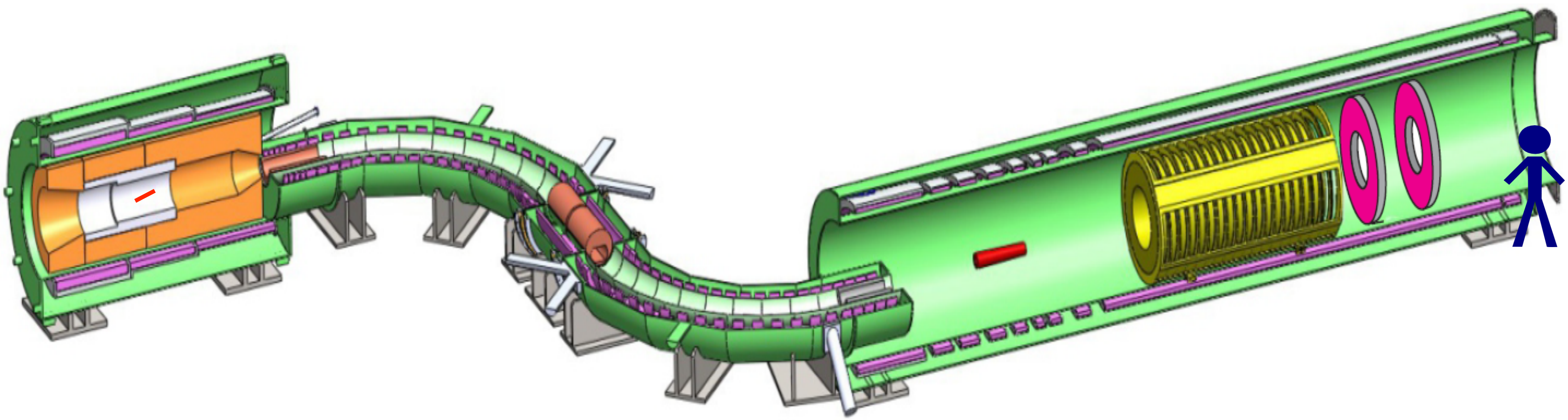
Need at least $\mathbf{10^{18}}$ stopped muons.

- Background goal: less than 1 event.

Mu2e apparatus



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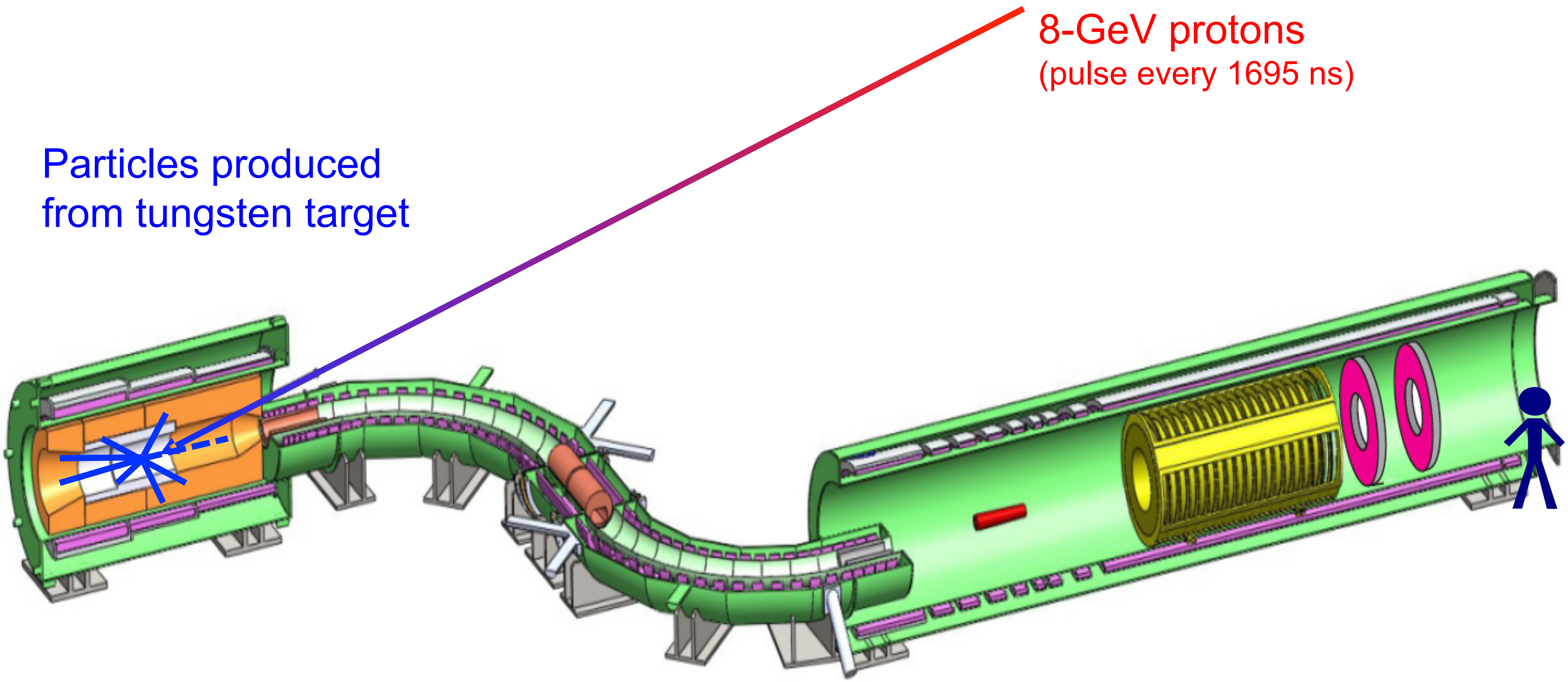

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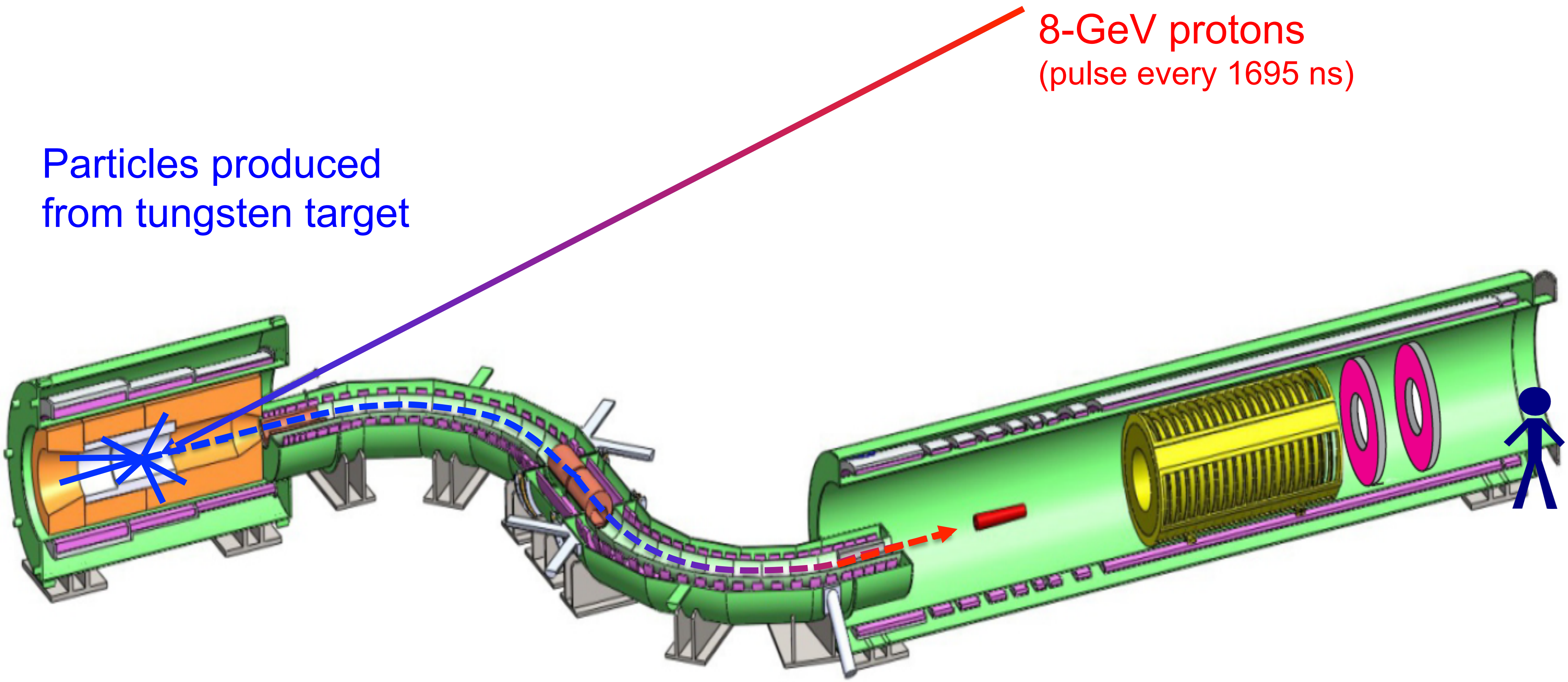
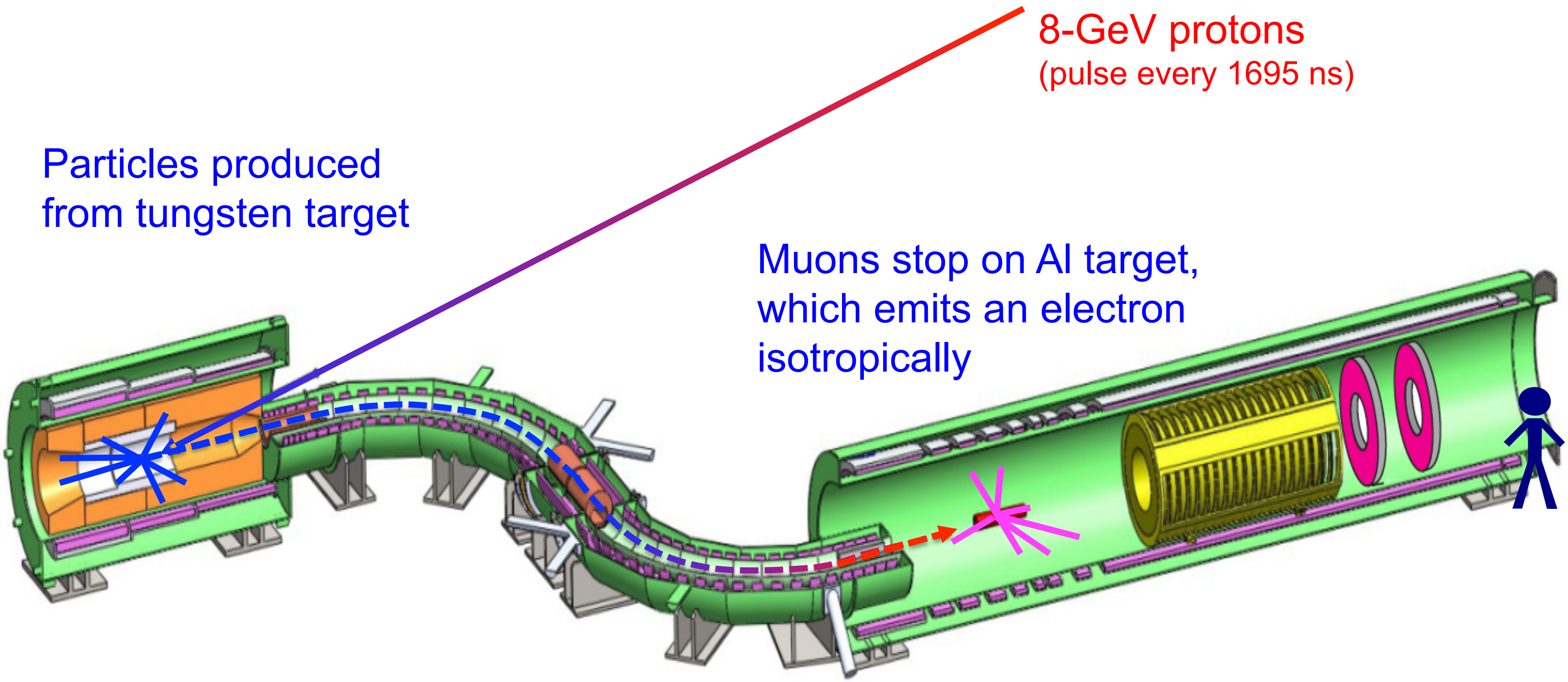


S-shaped solenoid:

- collimator selects negatively-charged particles
- transports particles to detector area, and
- allows remaining pions to decay to muons

Mu2e apparatus



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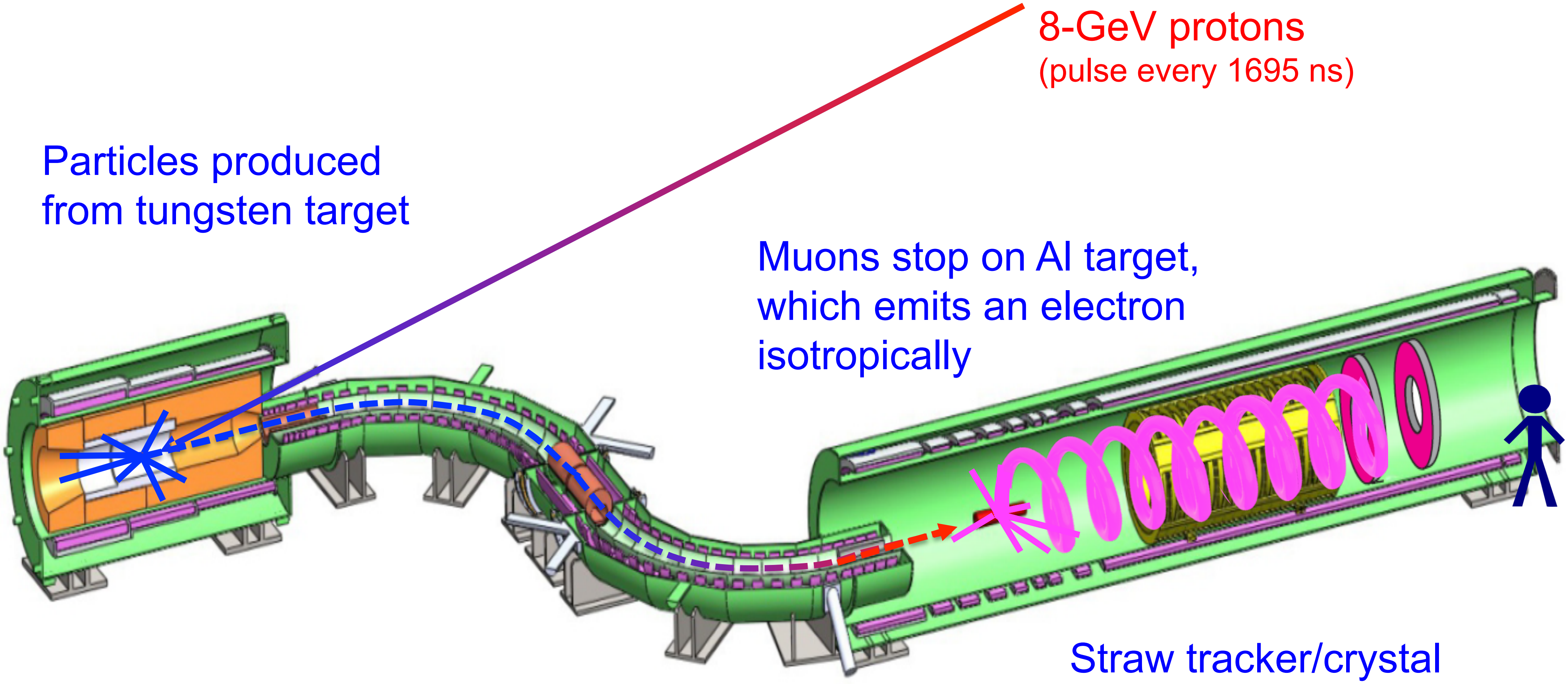

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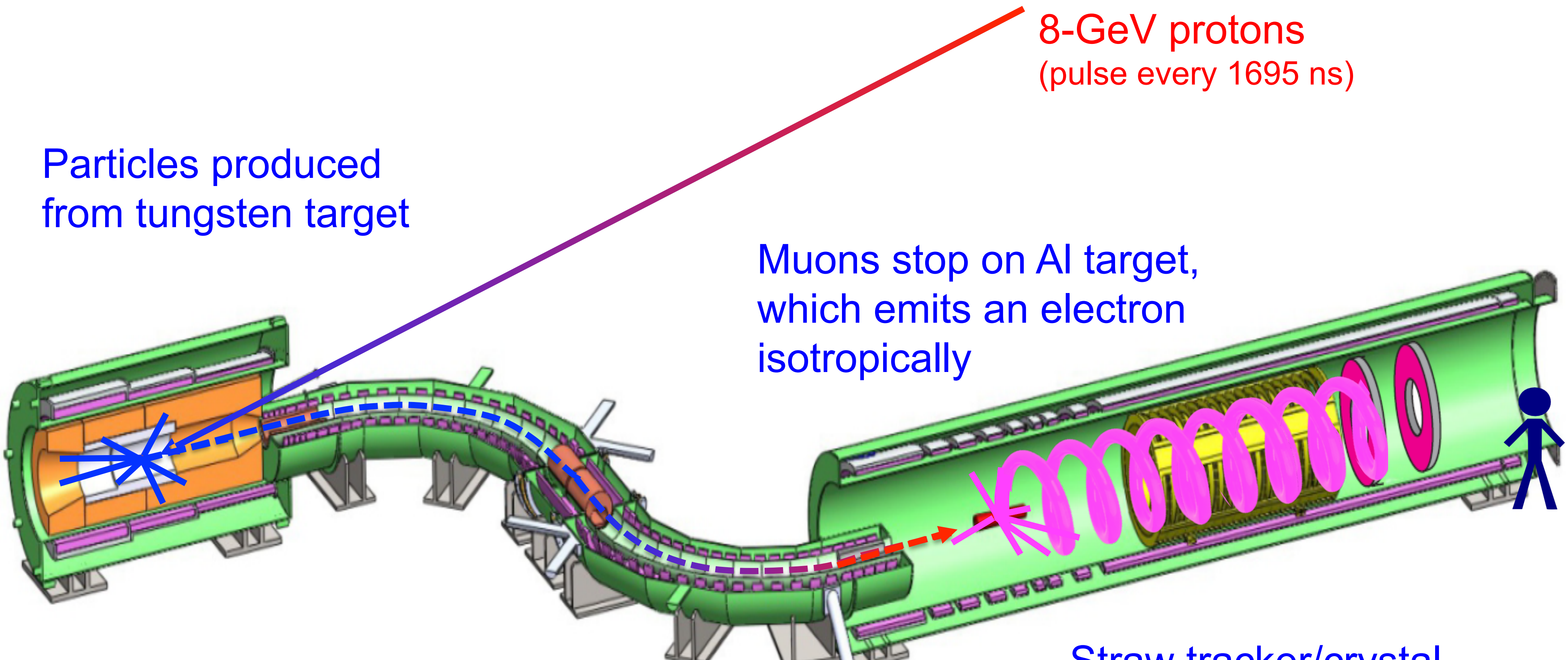

S-s
- co
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Factor of 10,000 improvement due to:

1) *Pulsed beam, with protons delivered every 1695 ns*
2) *Solenoids used to efficiently create secondary muon beam*

Mu2e – Important dates in the last year

- June 2014 – CD-3a granted for solenoid conductors
  - Since then 4 purchase orders for solenoids issued.
- July 2014 – Director's CD-2/3b Review
- August 2014 – Independent Cost Review
- October 2014 – DOE CD-2/3b Review
- January 2015 – Release of TDR preprint on arXiv
- February 2015 – DOE CD-2/3b Follow-up Review

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Will focus on scientific accomplishments over the last year, particularly those necessary to complete the TDR:

Understanding Mu2e sensitivity, the associated backgrounds and uncertainties.

Mu2e collaboration

- Spokespersons

Doug Glenzinski (FNAL) **Jim Miller (Boston U.)**

- Various working groups and task forces:

	Leader(s)
Calibration Working Group	**D. Brown (LBNL)**
Background Task Force	**A. Gaponenko (FNAL)**
Neutron Working Group	**D. Hedin (NIU)** **I. Oksuzian (U. Virginia)**
Software and Simulations Working Group	**R. Kutschke (FNAL)**
- Geometry Czar	**D. Brown (U. Louisville)**

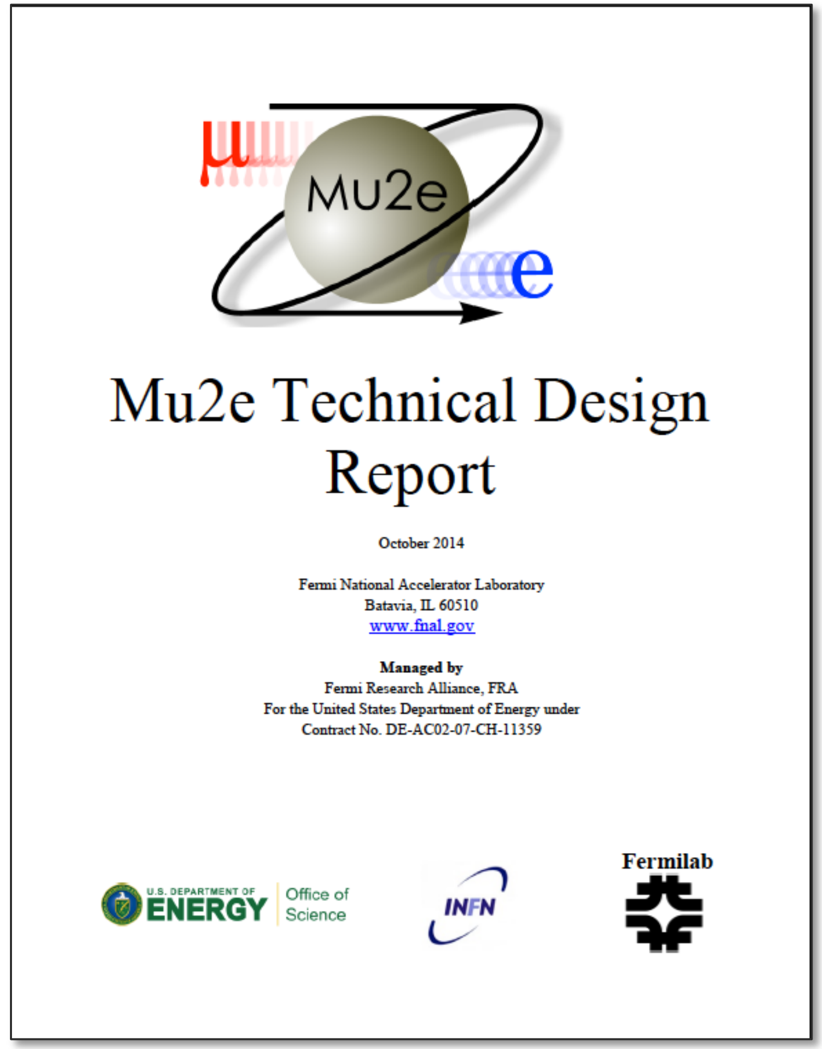
- All members played crucial roles in the last year.

Completion of Mu2e Technical Design Report

arXiv:1501.05241 [physics.ins-det]

- 888 pages
- 621 figures
- 126 tables

- Significant joint effort among members of the Project and the Collaboration.
- Authors from:
  - Fermilab
    - Particle Physics Division
    - Accelerator Division
    - Technical Division
    - Scientific Computing Division
  - Collaborating university and laboratories,
  - And industry



Mu2e Technical Design Report

October 2014

Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

Background task force

- Created group dedicated for determining the yields and corresponding uncertainties of all backgrounds
  - Lead by FNAL Wilson Fellow (A. Gaponenko)
  - Analysis, simulation, and software experts and analysts from

Fermilab	**Novosibirsk**	**U. Virginia**	**INFN Pisa**
LBNL	**UC, Irvine**	**Boston U.**	

  - Backgrounds calculated via the *art* framework:
    - Developed and maintained by FNAL scientific computing division personnel, designed to support any HEP experiments' data-collection and production-level needs
    - Weekly stakeholder meetings to facilitate good communication between scientists and computing professionals
  - Over 10^{11} events simulated for TDR calculations.
    - Requires intense use of grid resources and data storage facilities.

Expected Mu2e backgrounds (4×10^{20} POTs)

Category	Background process	Est. yield	Institution
Intrinsic	Muon decay-in-orbit	0.199 ± 0.092	LBNL
	Muon capture	$0.000^{+0.004}_{-0.000}$	FNAL
Late-arriving	Radiative pion capture	0.023 ± 0.006	FNAL
	Beam electrons	0.003 ± 0.001	Novosibirsk Boston U.
	Muon decay-in-flight	<0.003	FNAL
	Pion decay-in-flight	0.001 ± <0.001	FNAL
Miscellaneous	Antiproton capture	0.047 ± 0.024	UC, Irvine
	Cosmic ray	0.082 ± 0.018	U. Virginia INFN Pisa
Total		**0.36 ± 0.10**	

- Includes all known systematic uncertainties
- Expected upper limit in *R* of $\mathbf{6 \times 10^{-17}}$ (90% C.L.)

Expected Mu2e backgrounds (3 years running)

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	Will present one example …		
			Boston U.
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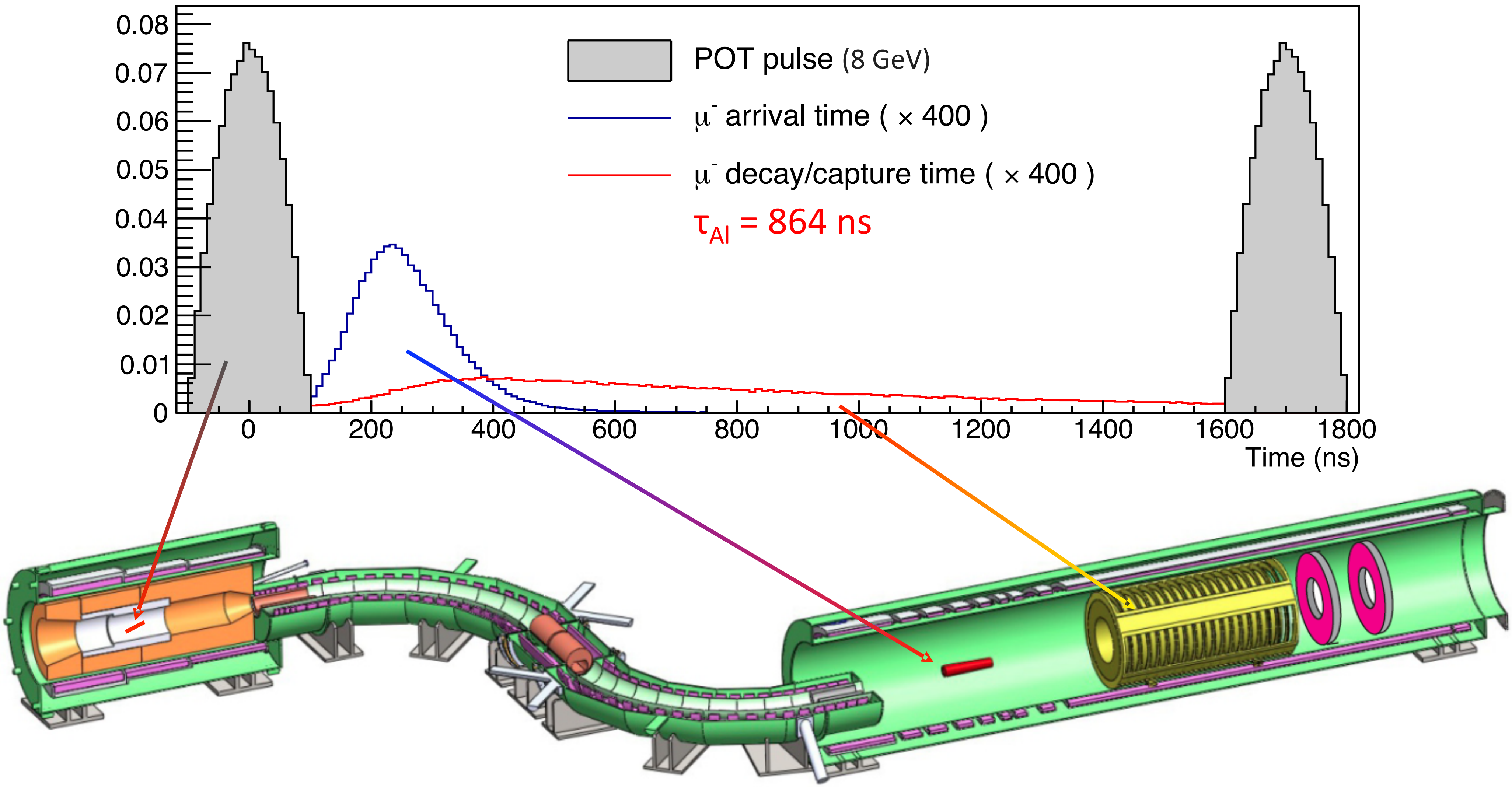
Proton timing is important



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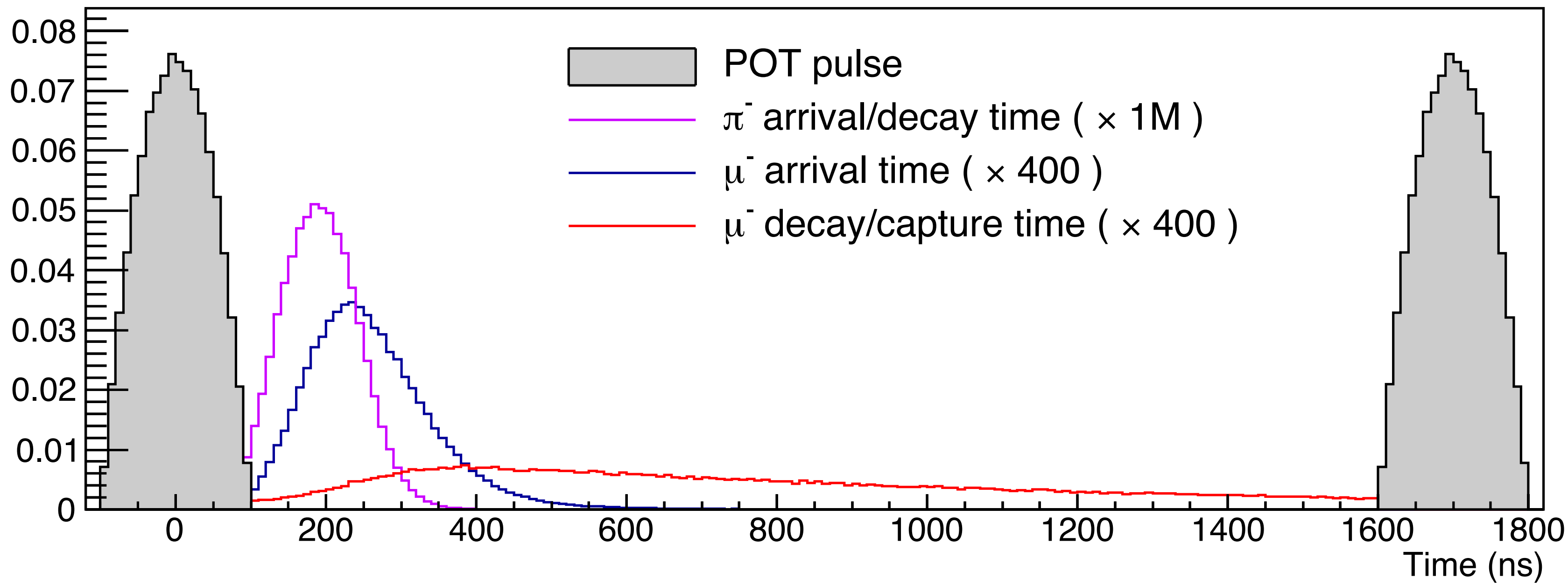

- Significant background is from prompt pion backgrounds

$$\pi^- + \mathbf{Al} \rightarrow \gamma^{(*)}_{e^+e^-} + \mathbf{Mg}^*$$

- Can produce electron at same energy as the signal electron
- Muon decays from Al are slow; pion backgrounds are prompt.

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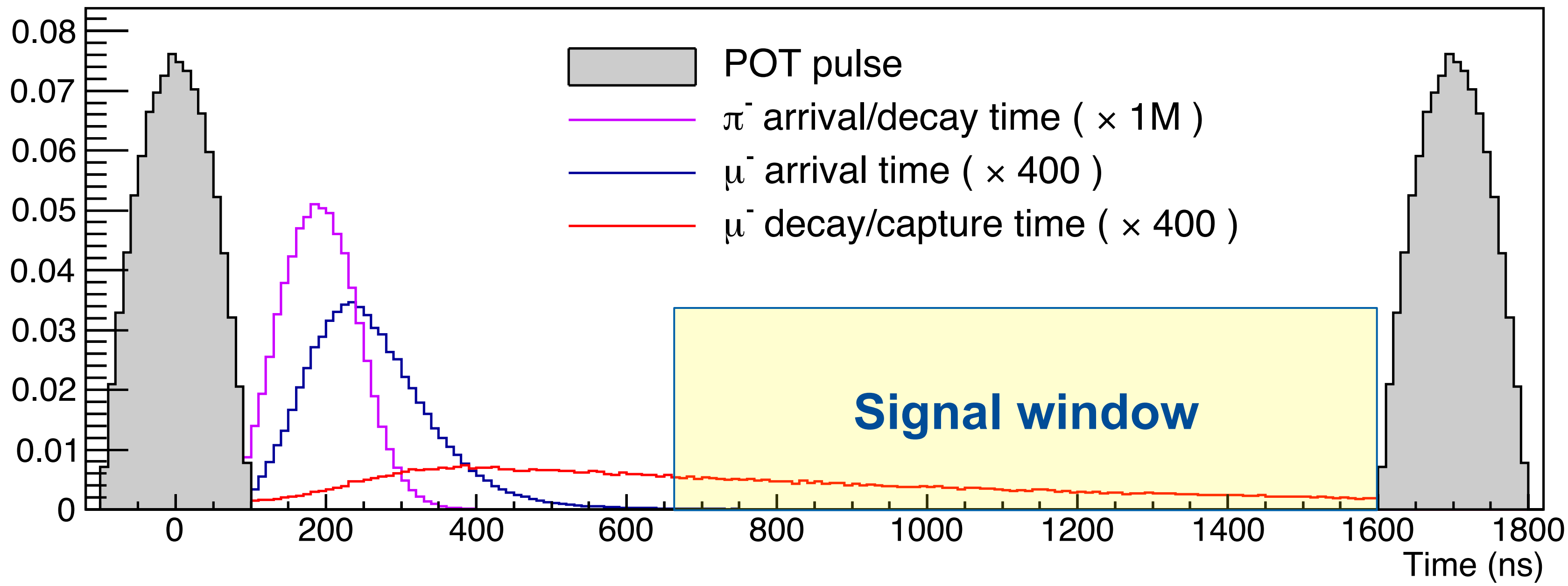

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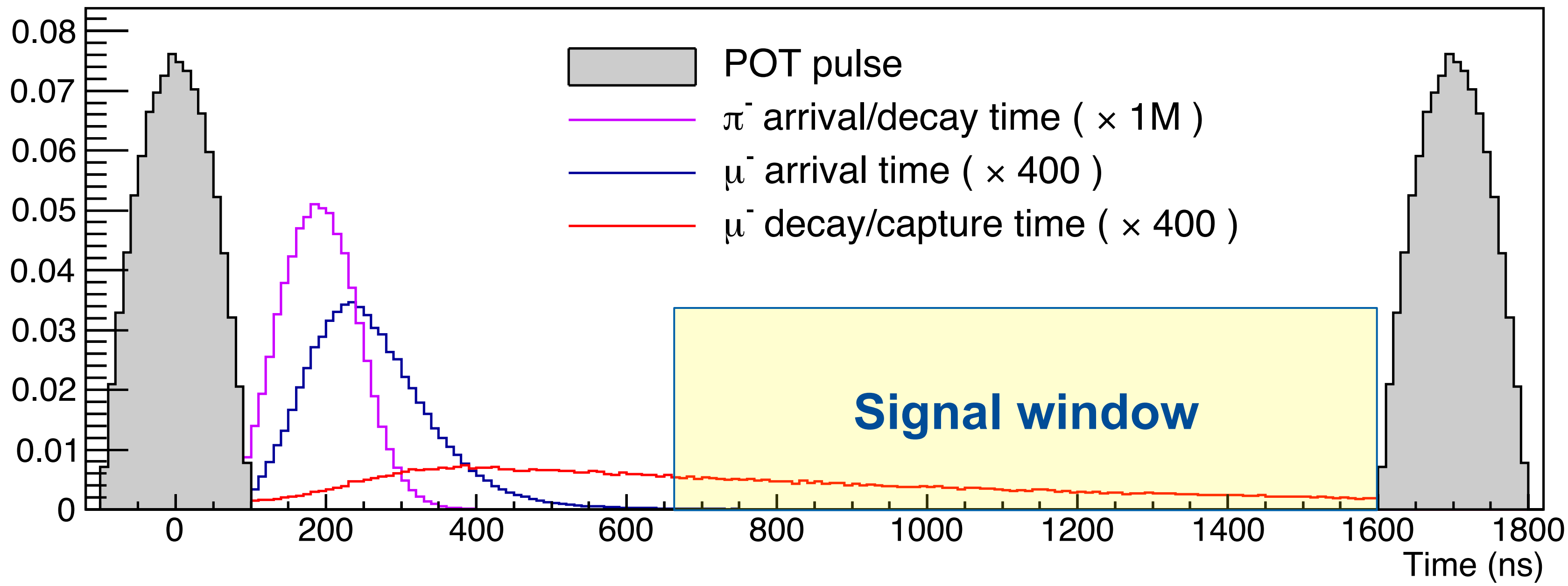
Wait out the pion backgrounds before starting the live gate.

Proton timing is important



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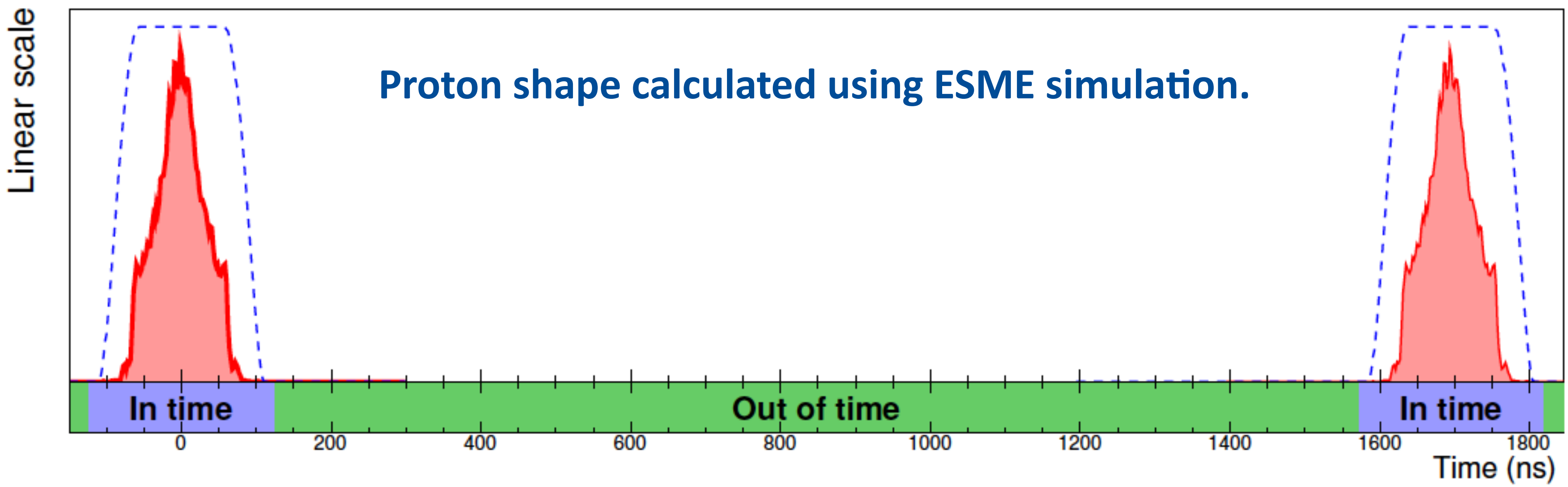
- Can produce electron at same energy as the signal electron
- Muon deca[…]ompt.

Wait […] live gate.

Calculating this background required in-depth understanding of bunch structure.
Excellent interaction between AD and PPD.

Some details

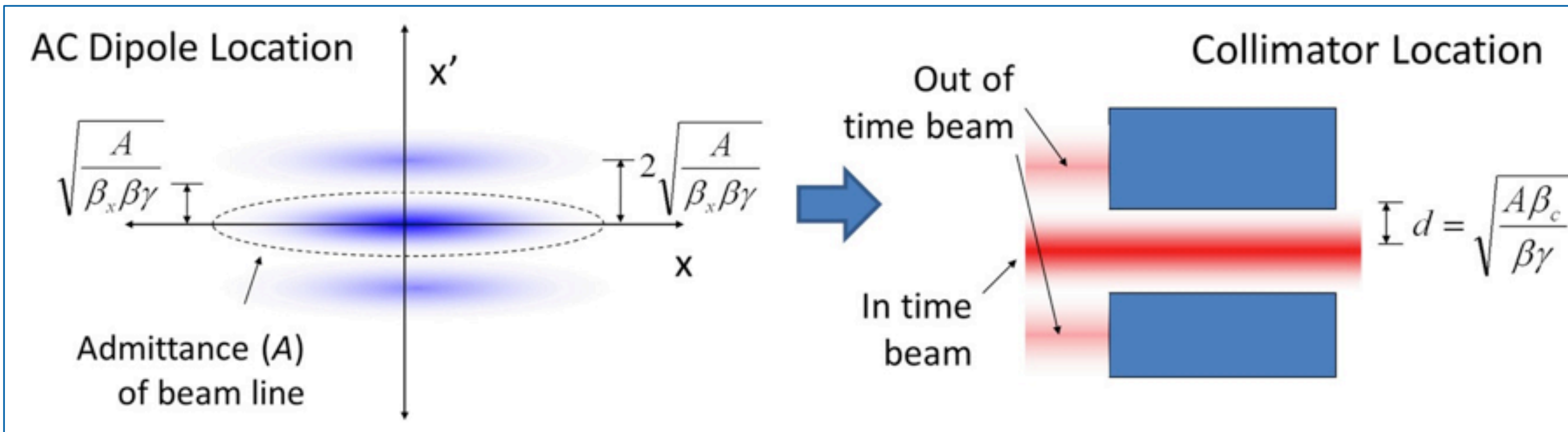


- Need to include POT time structure in simulation.
  - Tails of "in-time" distribution are important.
  - Need to know the fraction of protons that are "out-of-time".

Need extinction level < 10^{-10}.

Achieving a proton extinction level of 10^{-10} …

- RF structure of recycler gives extinction level of $\mathbf{10^{-4}}$ to $\mathbf{10^{-5}}$.
- Additional suppression obtained using sweeping AC-dipole magnet (developed by AD)
  - Out-of-time protons are deflected out of the line-of-sight into a suitably placed collimator.



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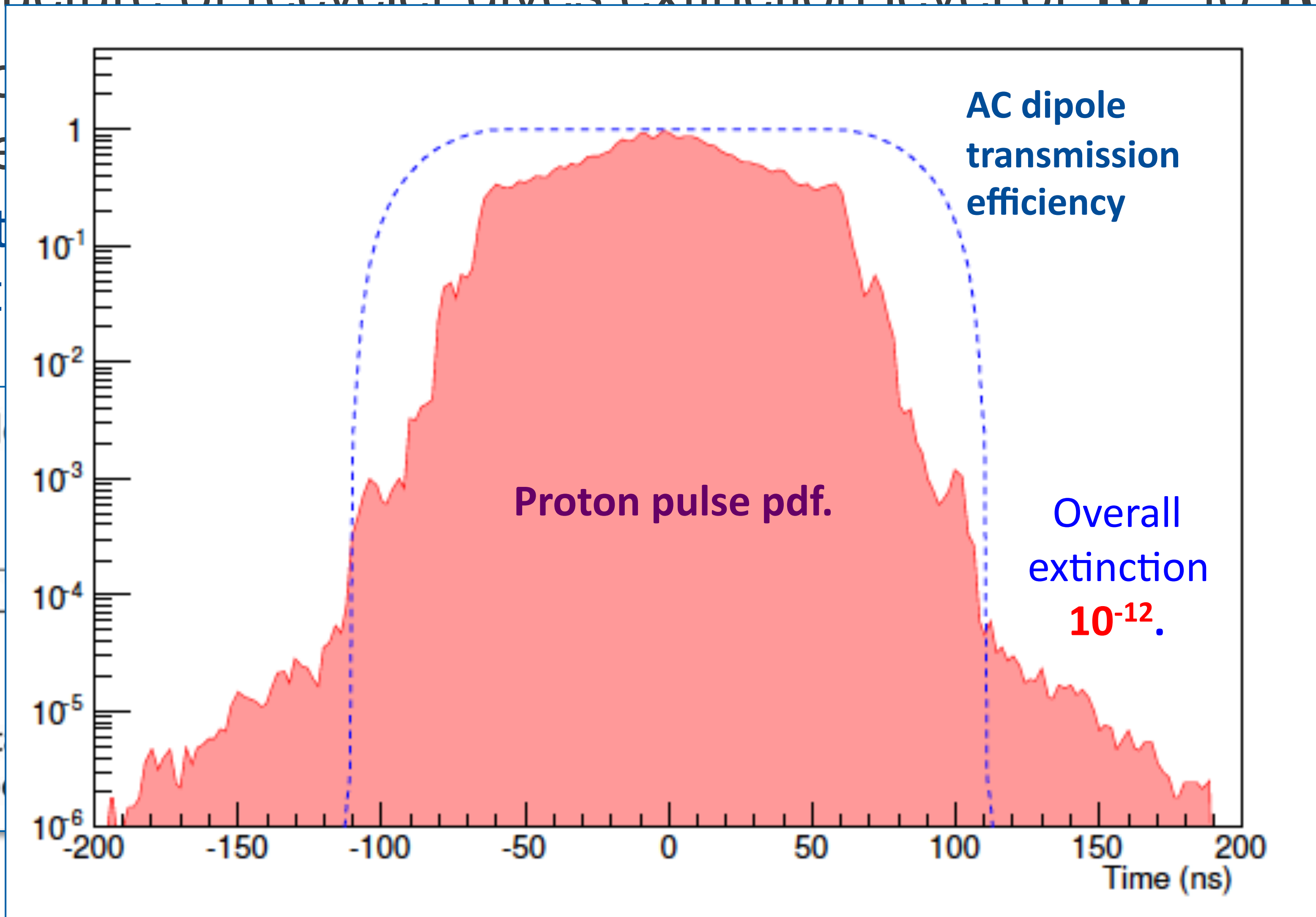
- Additic … e
  magne …
  - Out … o a
    suit …

AC Dipol … ation

$\sqrt{\frac{A}{\beta_x \beta\gamma}}$ … $\sqrt{\frac{A\beta_c}{\beta\gamma}}$

Admitt…
of b…



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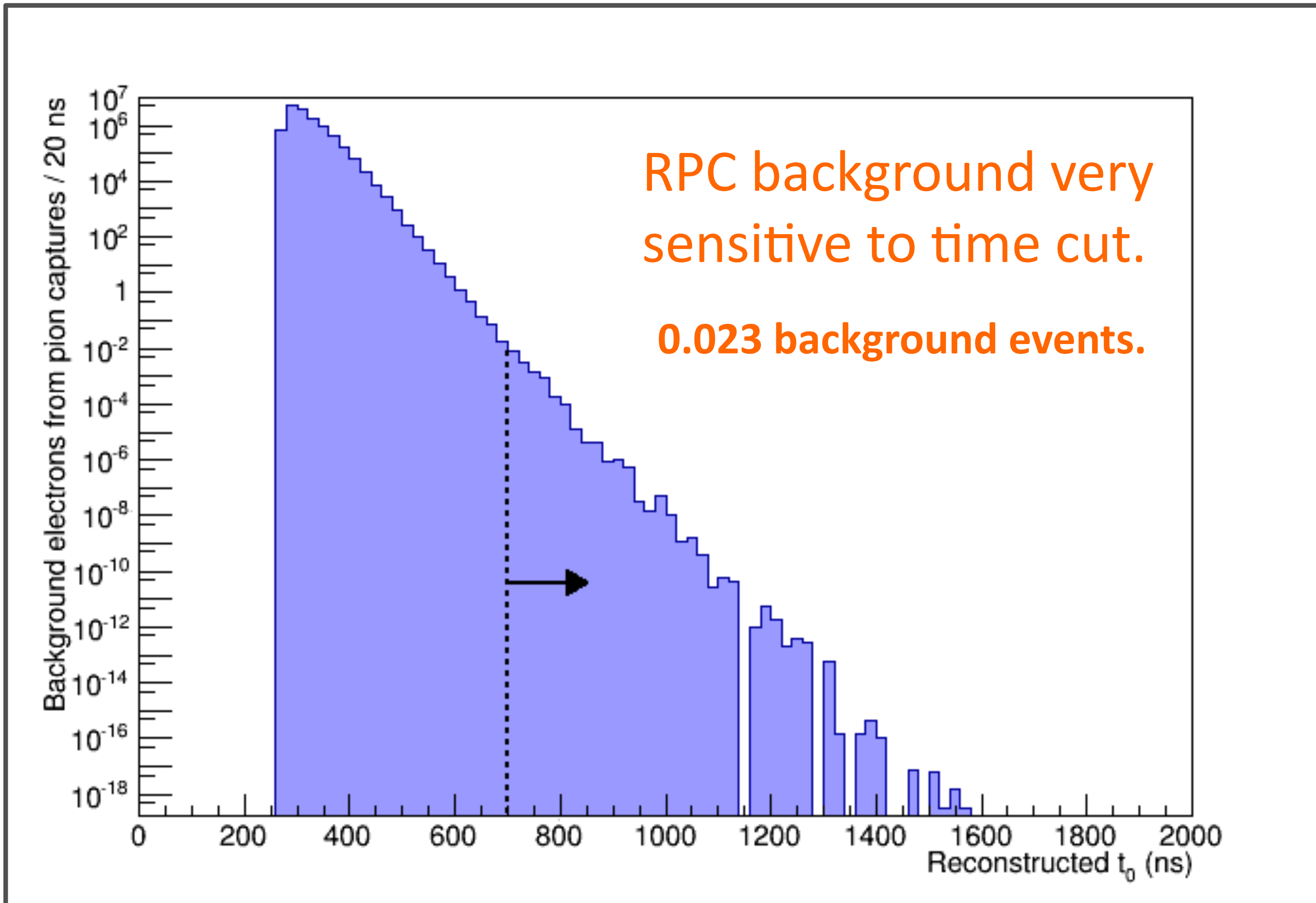
In the end …

Background e^- from RPC normalized to three years running.



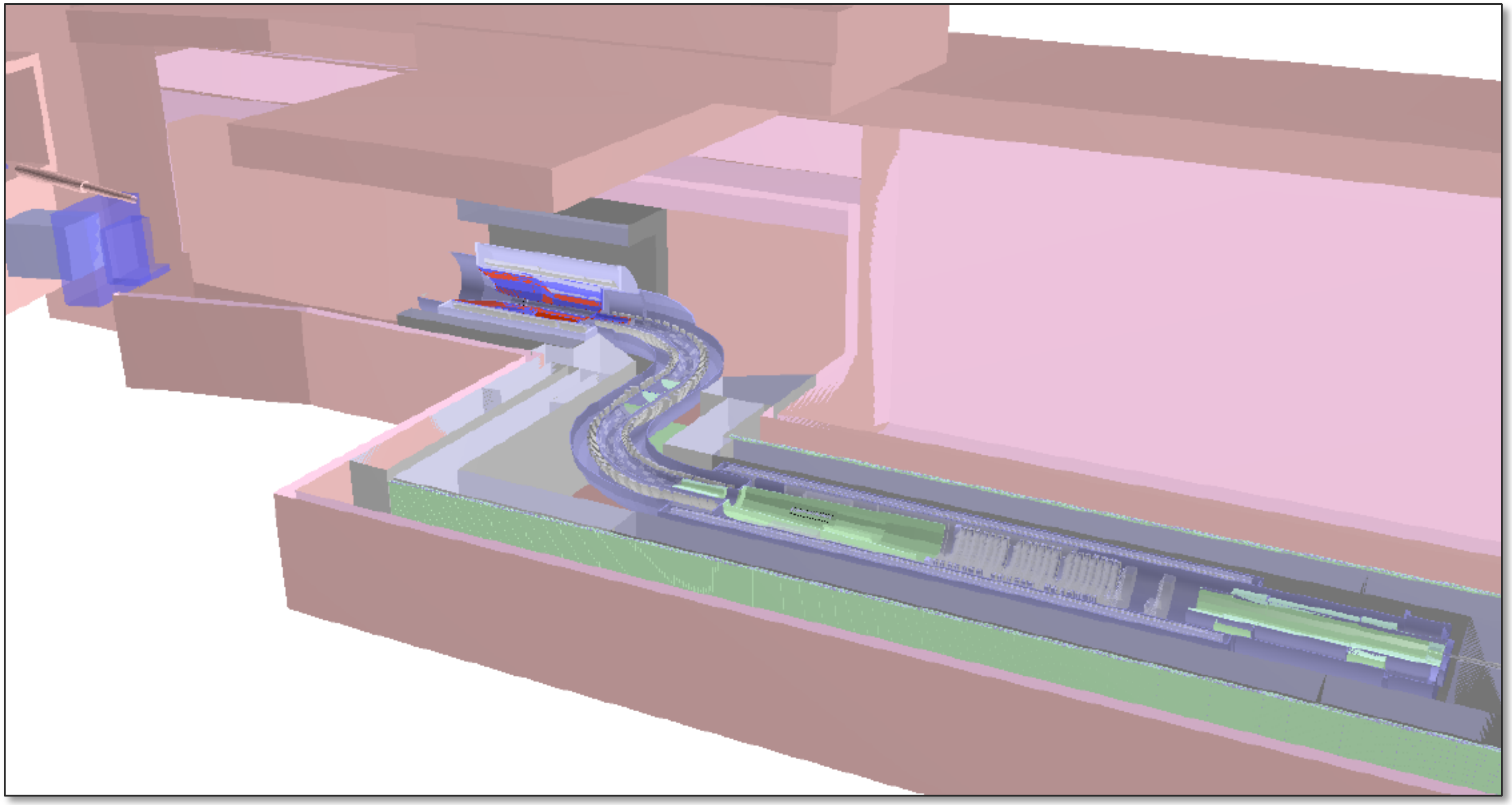
***t_0* = reconstructed time when track reaches center of tracker.**

t = 0 corresponds to when POT pulse center impinges on production target.

Designing the simulation

- Fully developed GEANT4 geometry

FNAL	**California Institute of Technology**	**U. Virginia**	**U. Louisville**
LBNL	**Northern Illinois University**	**UC, Irvine**	**Boston University**



Designing the simulation

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Many interactions between Collaboration and
TD **:** building/detector design
SCD **:** software infrastructure

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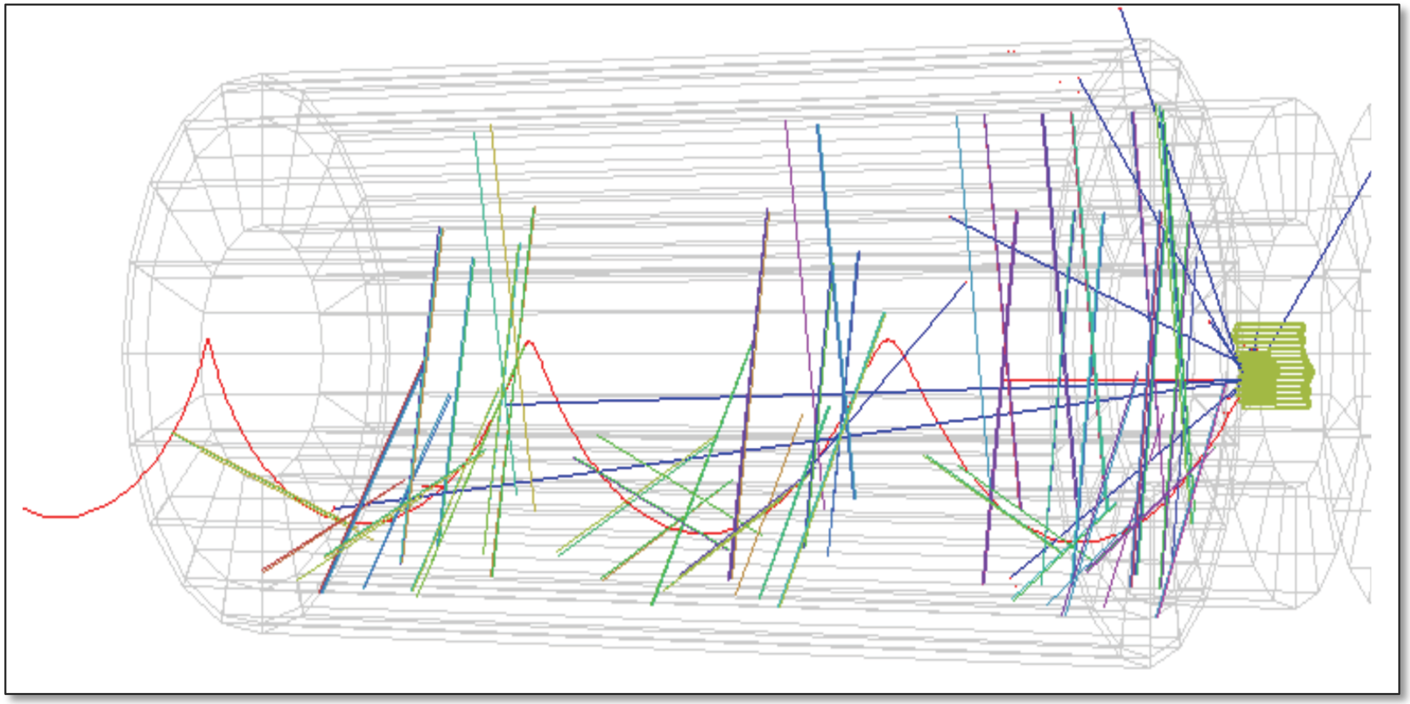
Designing the simulation

- Fully developed GEANT4 geometry
- Complete tracking simulation and reconstruction algorithms including all known effects.
  - Gas ionization model
  - Straw drift simulation
  - Gas amplification
  - Signal transit
  - Electronic amplification and shaping
  - Electronic signals aggregated into waveform
  - Waveform digitized
  - “Digis” converted to hits
  - Hits categorized according to time and position
  - Then the track fitting …

LBNL



Longitudinal view

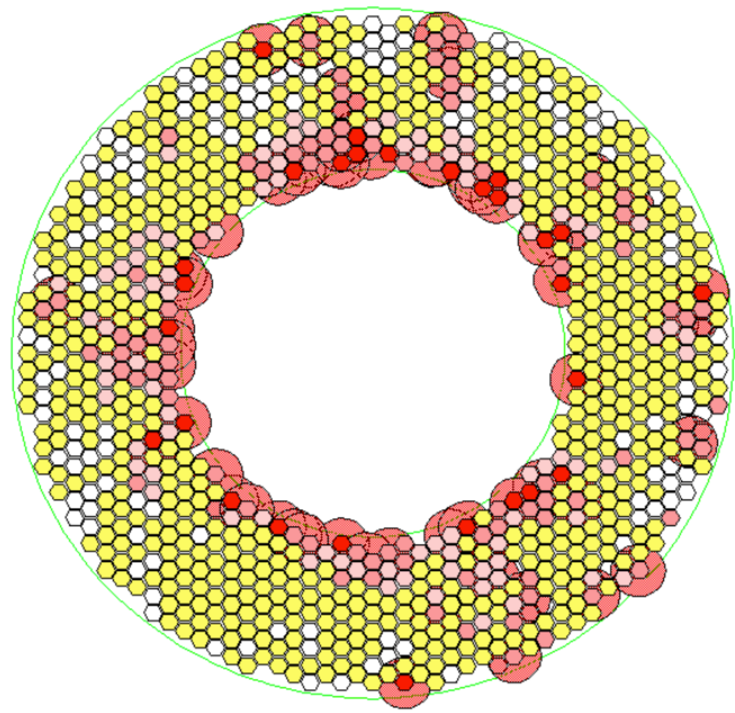
Designing the simulation

- Fully developed GEANT4 geometry
- Complete tracking simulation and reconstruction algorithms including all known effects
- Calorimeter clustering algorithms

FNAL

California Institute of Technology

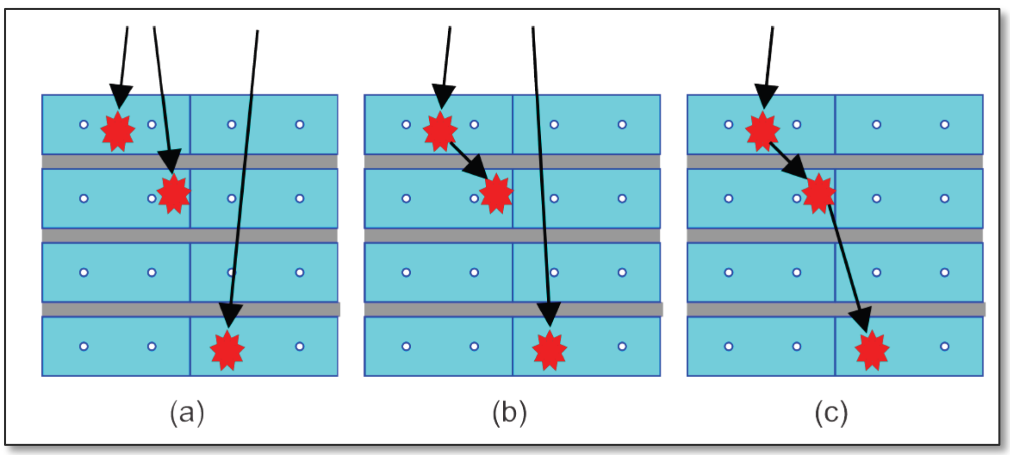
INFN, Lecce

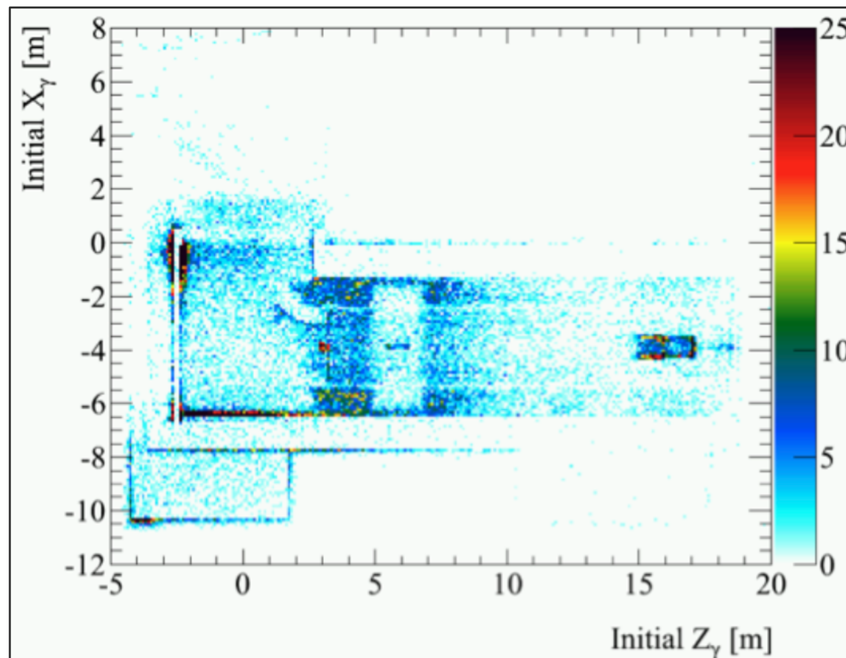


Designing the simulation

- Fully developed GEANT4 geometry
- Complete tracking simulation and reconstruction algorithms including all known effects
- Calorimeter clustering algorithms
- Algorithms for determining cosmic-ray backgrounds

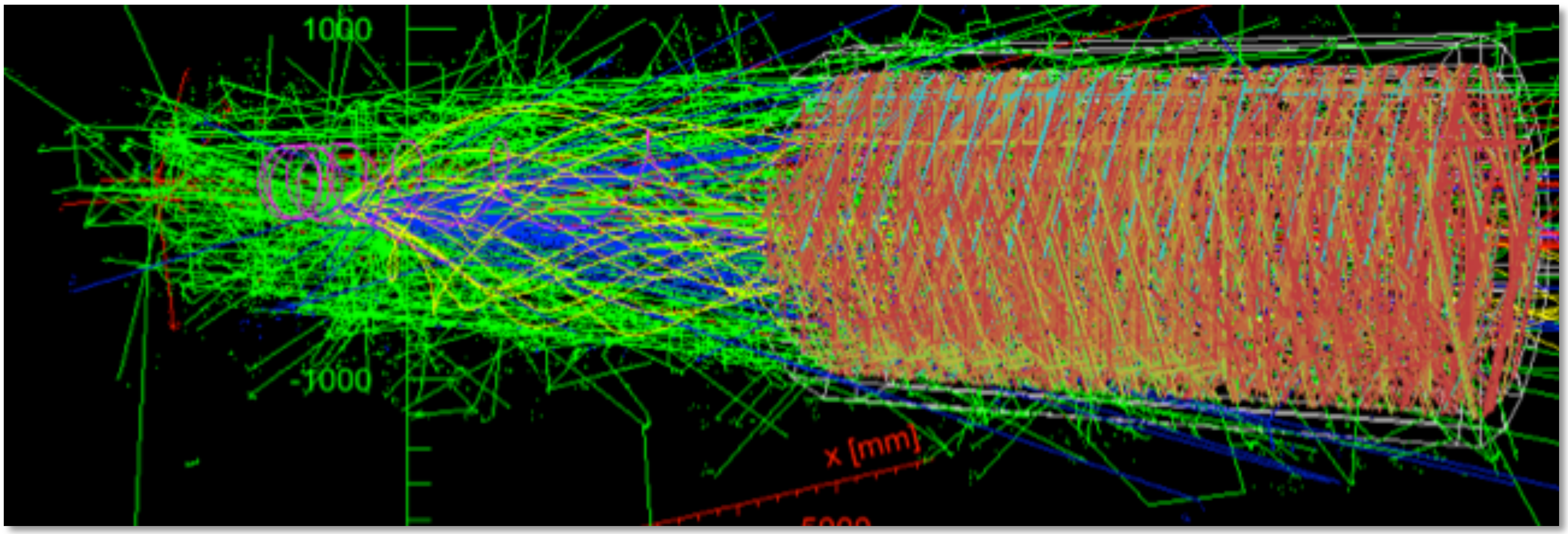
University of Virginia





Event noise

- We do not simulate individual signal and background particles.
- For each proton pulse, the detector elements are bombarded with **~10^5** particles from the
  - Production target, and
  - Stopping target (2-3 neutrons per captured muon)



- Event noise mixed in with signals and backgrounds.
- Mix-in rates determined by experimental measurements.
  - Uncertainties taken into account.

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

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Out-Of-Target μ	[illegible]	[illegible]
Degraded Track	[illegible]	[illegible]
Total (in quadrature)	+0.10, -0.08	+0.35, -0.29

Emission rates normalized to existing measurements.
Need more data, though.

Ejected proton measurement at TWIST

- A. Gaponenko (FNAL Wilson Fellow) involved in measuring the proton emission from muon-Al capture at TWIST.
  - Wine & Cheese seminar on 2/6.

"Never throw away your old data"

- ▸ Use an existing TWIST dataset to measure charged particles from μ^- capture on Al
- ▸ Extend to a lower energy range than previous Al results
- ▸ Determine both spectrum shape and normalization
- ▸ Some PID capability
- ▸ Advance understanding of the muon capture physics
- ▸ First measurement of μ^- capture with a tracker

The competition

- ▸ The AlCap collaboration at PSI
- ▸ Dedicated setup to measure μ^- capture on Al
- ▸ Calorimetric measurement using Si detectors $\Longrightarrow$ very different backgrounds and systematics

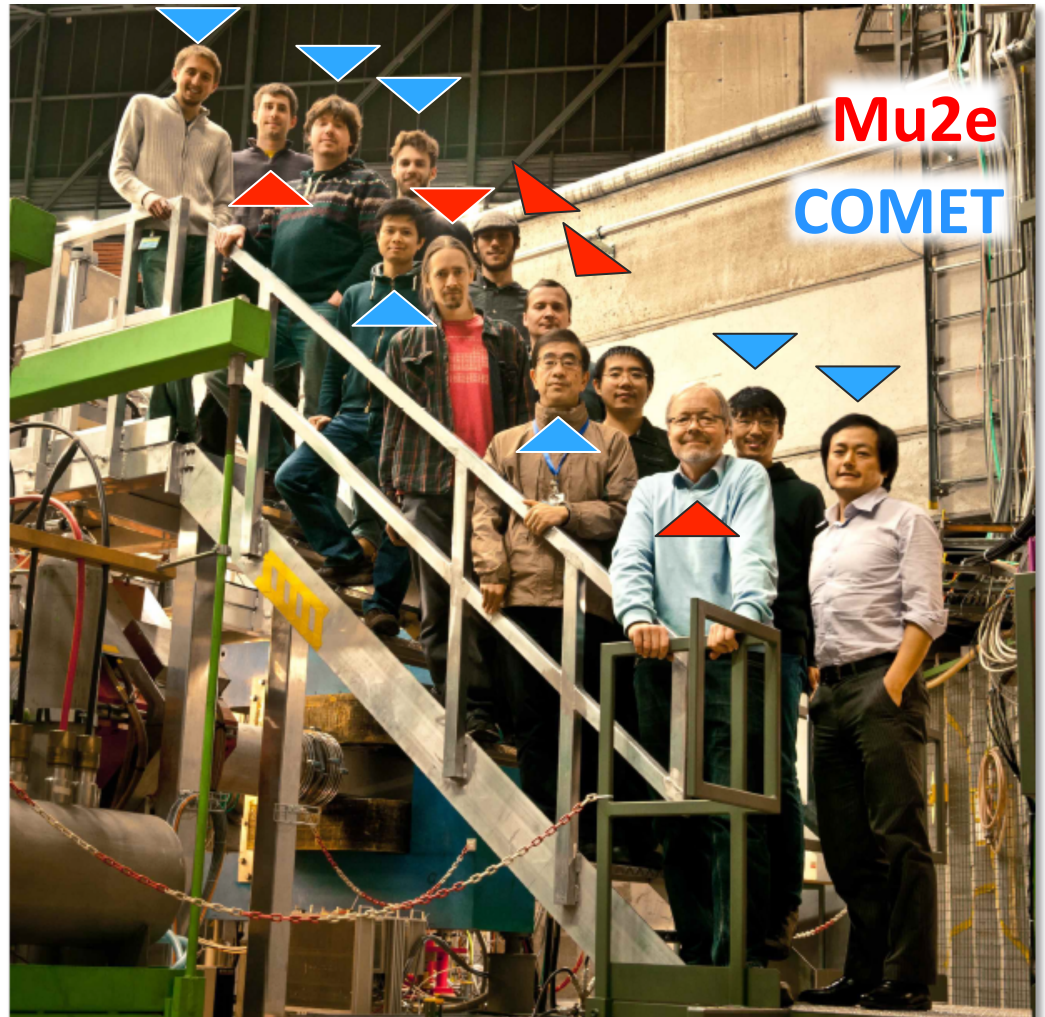
Courtesy: A. Gaponenko

Preliminary results obtained.

AlCap Collaboration: Ejected particle measurements at PSI

- Joint effort of Mu2e and COMET collaborators for measuring energy spectra and rates of particles emitted from muon capture.

Mu2e collaborators from
ANL
Boston U.
FNAL
U. of Houston
U. of Massachusetts, Amherst
U. of Washington



- 1-mon. run in 2013 to measure proton/neutron emission.
  - Preliminary results exist – analysis ongoing.
- 2-week run likely in 2015.

AlCap Collaboration: Ejected particle measurements at PSI

- Joint effort of Mu2e and COMET collaborators for measuring energy spectra and rates of particles emitted from muon capture.

Mu2e collaborators from
ANL
Boston U.
FNAL
U. of Houston
U. of Massachusetts, Amh
U. of Washington

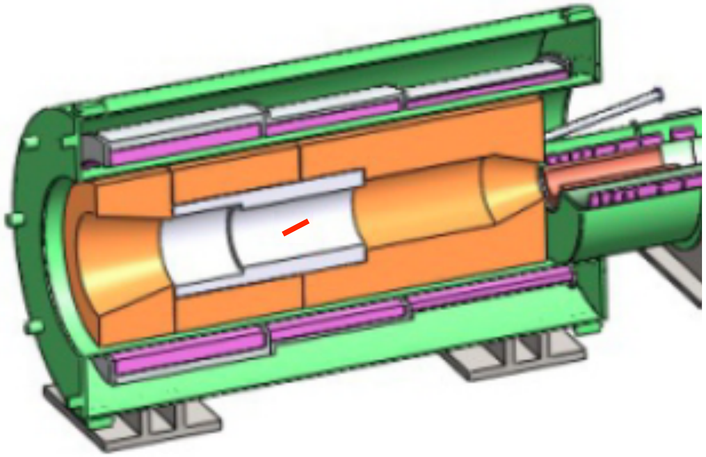
Thesis students:

D. Alexander (U. Houston)
A. Edmonds (UCL)*
B. Krikler (ICL)
J. Quirk (Boston U.)
N. Tranh (Osaka)

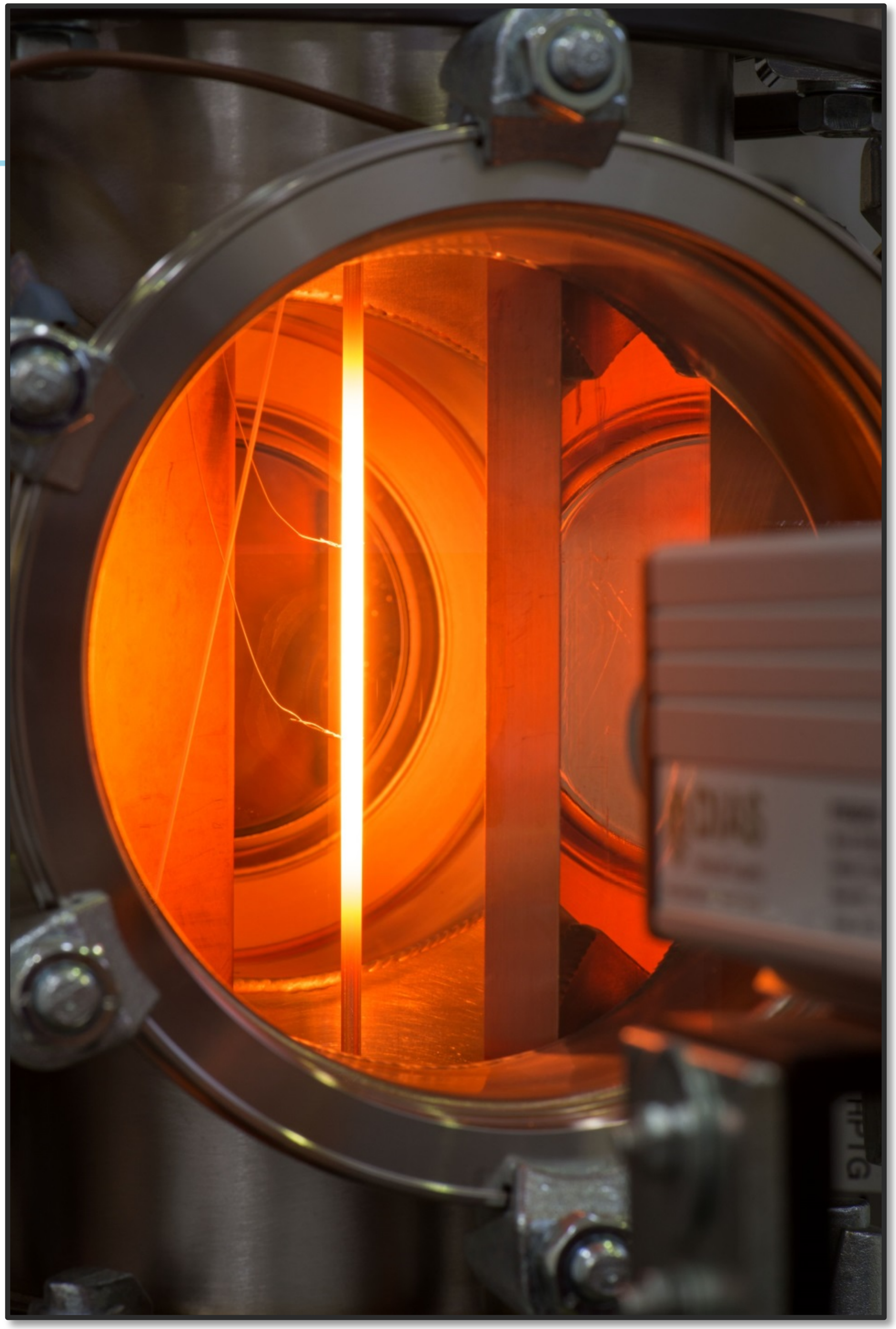
*now LBNL postdoc on Mu2e

- 1-mon. run in 2013 to proton/neutron emissi
  - Preliminary results e analysis ongoing.
- 2-week run likely in 20

Production target testing

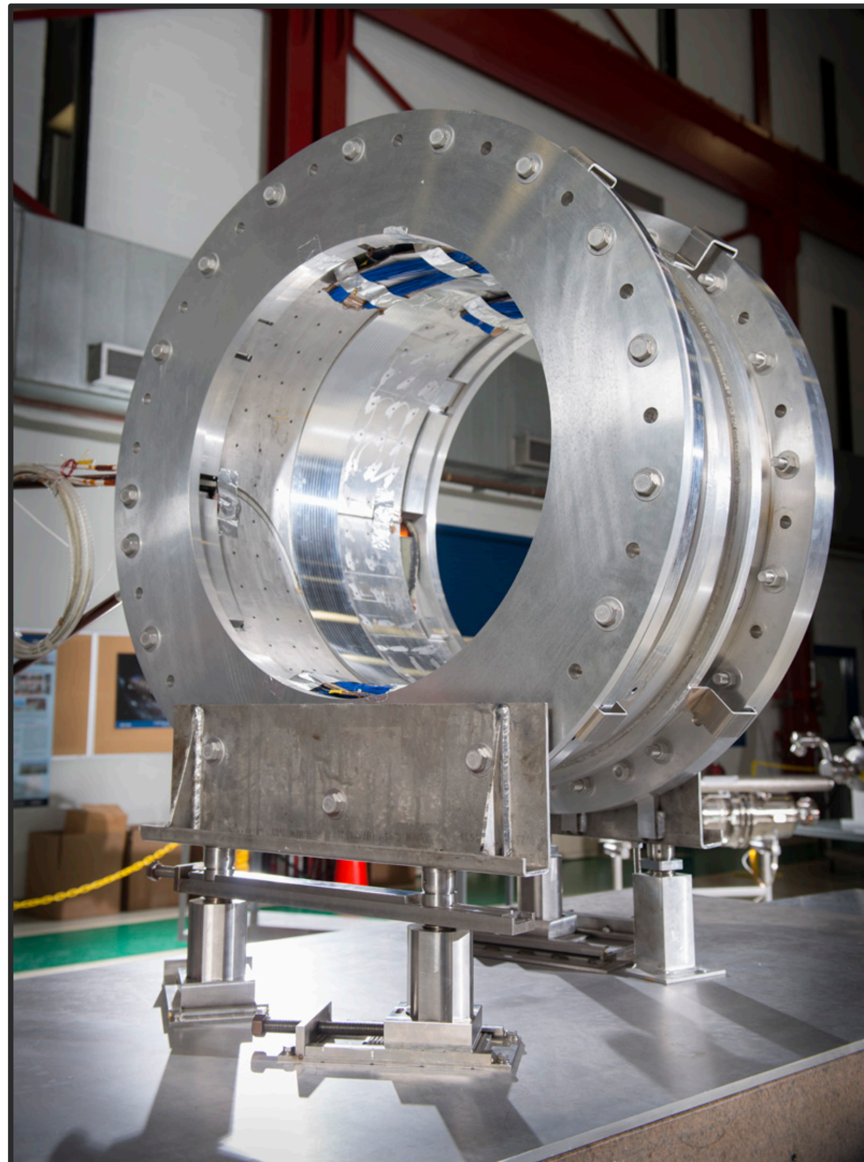


- Made of tungsten.
- Must be able to withstand max. operating temperature of 1700°C.
- Concern at last S&T review that radiation cooling could be problematic.
- Since then, significant progress in testing and understanding radiation cooling (RAL).
  - SiC coating looks promising.



Mu2e Solenoids – prototype of TS coil module

- TS solenoid coil module prototype completed.
- Contributions from **FNAL TD** and **INFN**.
- After successful testing, all 27 TS modules will be produced.
- Featured in *FermilabToday,* Jan. 23, 2015.



Prototype of Mu2e tracker panel

- Prototype assembled to test procedure for constructing straw panels.
- Will then undergo vacuum and readout checks.
- Contributions from

FNAL PPD

City University of New York

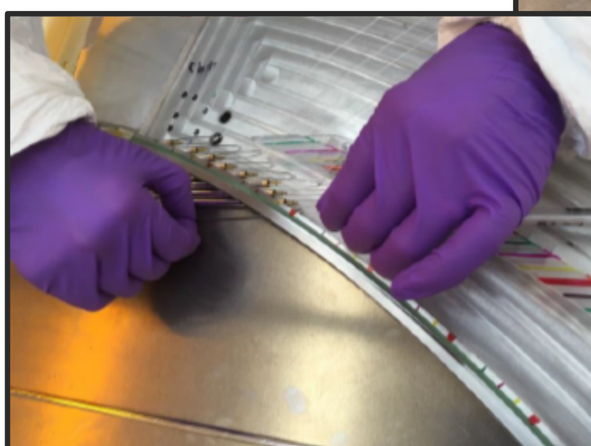
Duke University

LBNL

Rice University

U. of Minnesota

U. of Houston

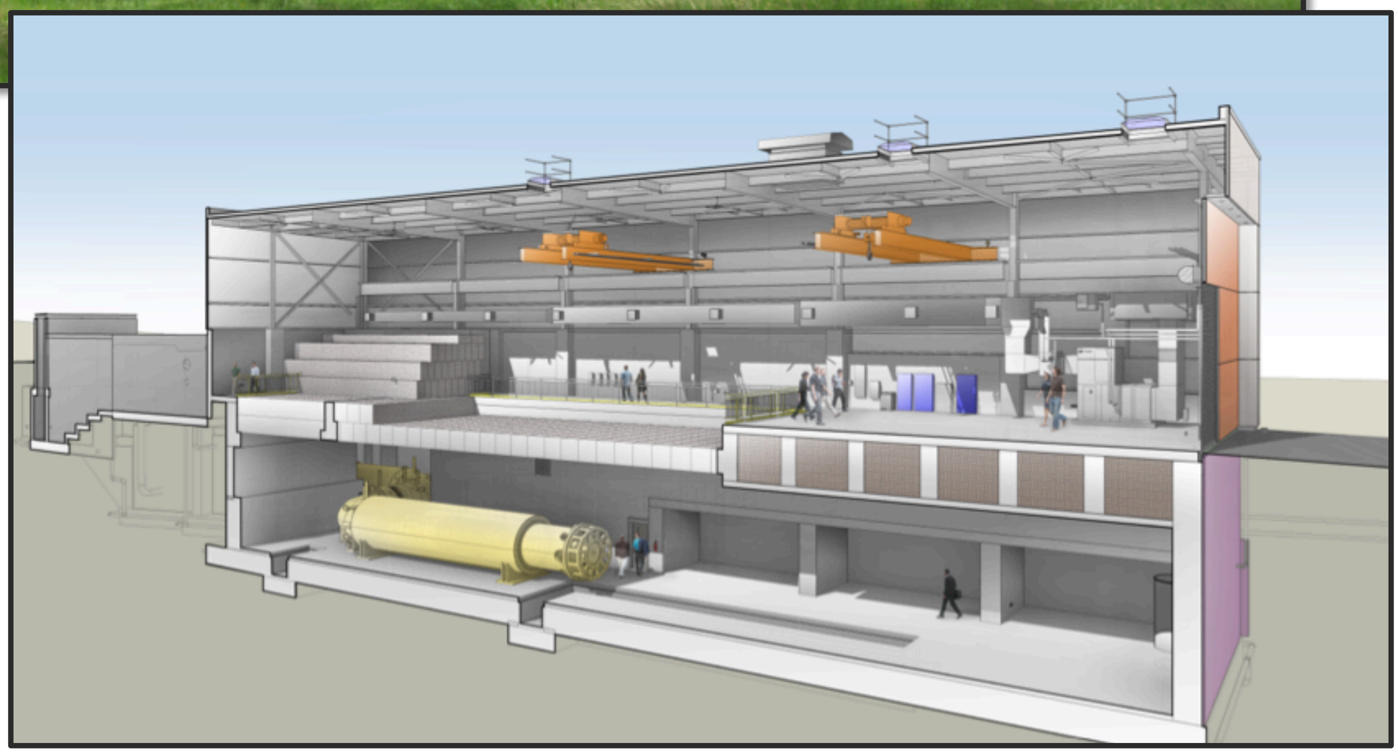


Excavation of muon beamline enclosure

- Part of Muon Campus Program coordinated by Mary Convery (FNAL AD)

See Convery [Breakout 1D]

Mu2e hall groundbreaking in March



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The next-generation Mu2e study (2013)

- A concentrated study was undertaken by Mu2e collaborators to determine the feasibility of a next-generation Mu2e experiment.
  - Dedicated session at Snowmass for next-generation Mu2e
- Our work is summarized here:
  - K. Knoepfel, *et al*, `arXiv:1307.1168`

Feasibility Study for a Next-Generation Mu2e Experiment

K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7], R. Ehrlich[7], M.J. Frank[7], D. Glenzinski[3], R.C. Group[3,7], D. Hedin[6], D. Hitlin[2], M. Lamm[3], J. Miller[1], S. Miscetti[4], N. Mokhov[3], A. Mukherjee[3], V. Nagaslaev[3], Y. Oksuzian[7], T. Page[3], R.E. Ray[3], V.L. Rusu[3], R. Wagner[3], and S. Werkema[3]

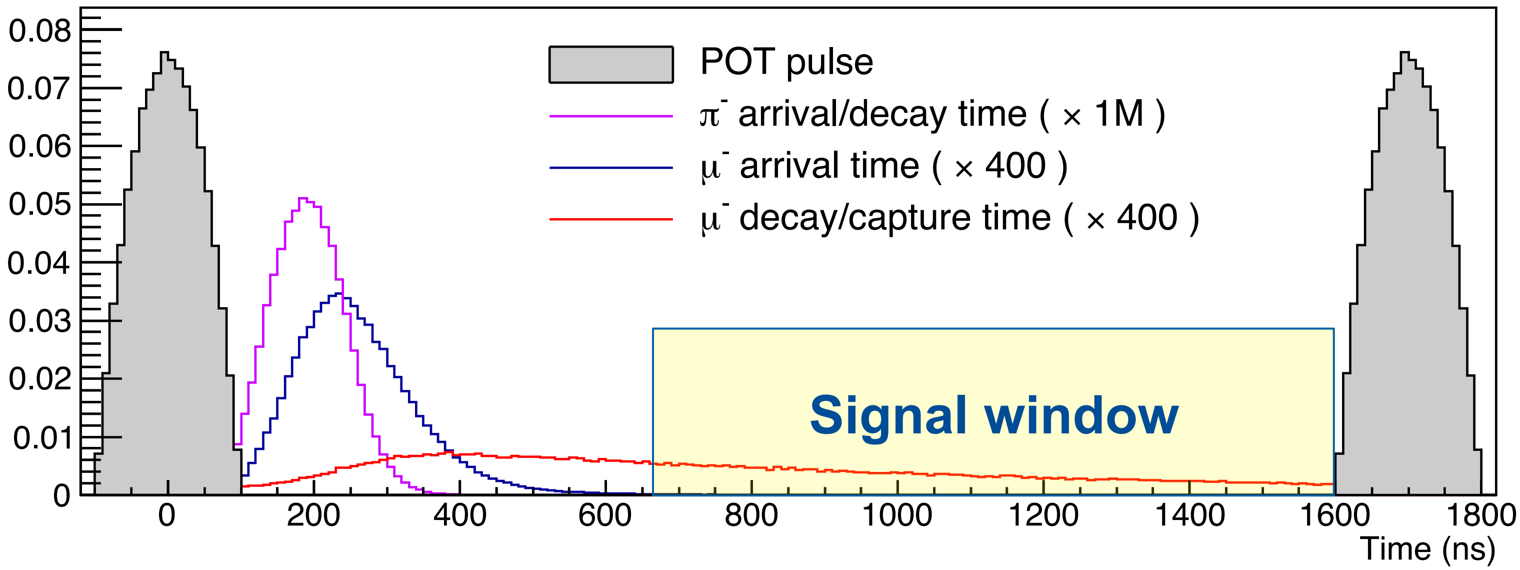
[1] *Boston University, Boston, Massachusetts 02215, USA*
[2] *California Institute of Technology, Pasadena, California 91125, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[4] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[5] *Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[6] *Northern Illinois University, DeKalb, Illinois 60115, USA*
[7] *University of Virginia, Charlottesville, Virginia 22906, USA*

- Considered 100 kW, 1 GeV beam and how it could be used to achieve x10 improvement in sensitivity, implementing only modest upgrades.
  - Used *art* framework and `g4beamline` program.

Anticipating the future

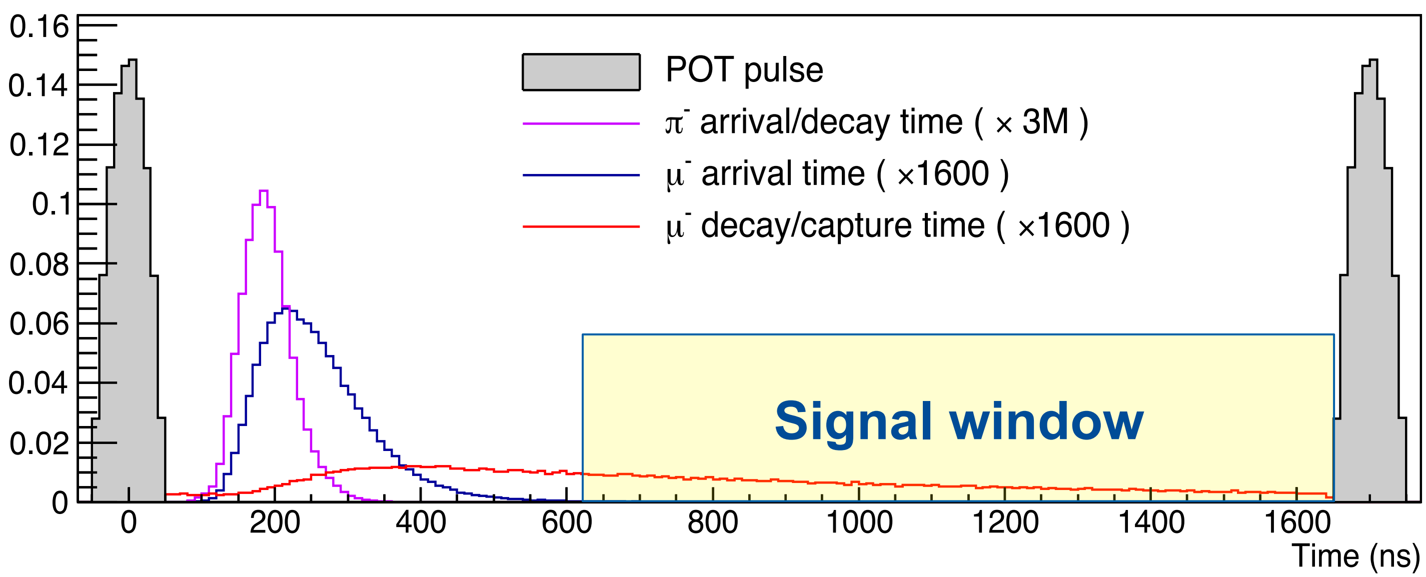
- Regardless of the Mu2e result, Mu2e-II is important:
  - Mu2e observed CLFV at ≥ 5σ
    - Switch targets and measure ratio of rates to further disciminate models of underlying physics
      - Cirigliano, et al PRD **80**, 013002 (2009)
  - Mu2e observes hints of CLFV at 3σ
    - Collect ×10 data to definitively resolve the situation
  - Mu2e sets stringent new limit on CLFV
    - Collect ×10 data and explore new parameter space

Moving to PIP-II



Baseline

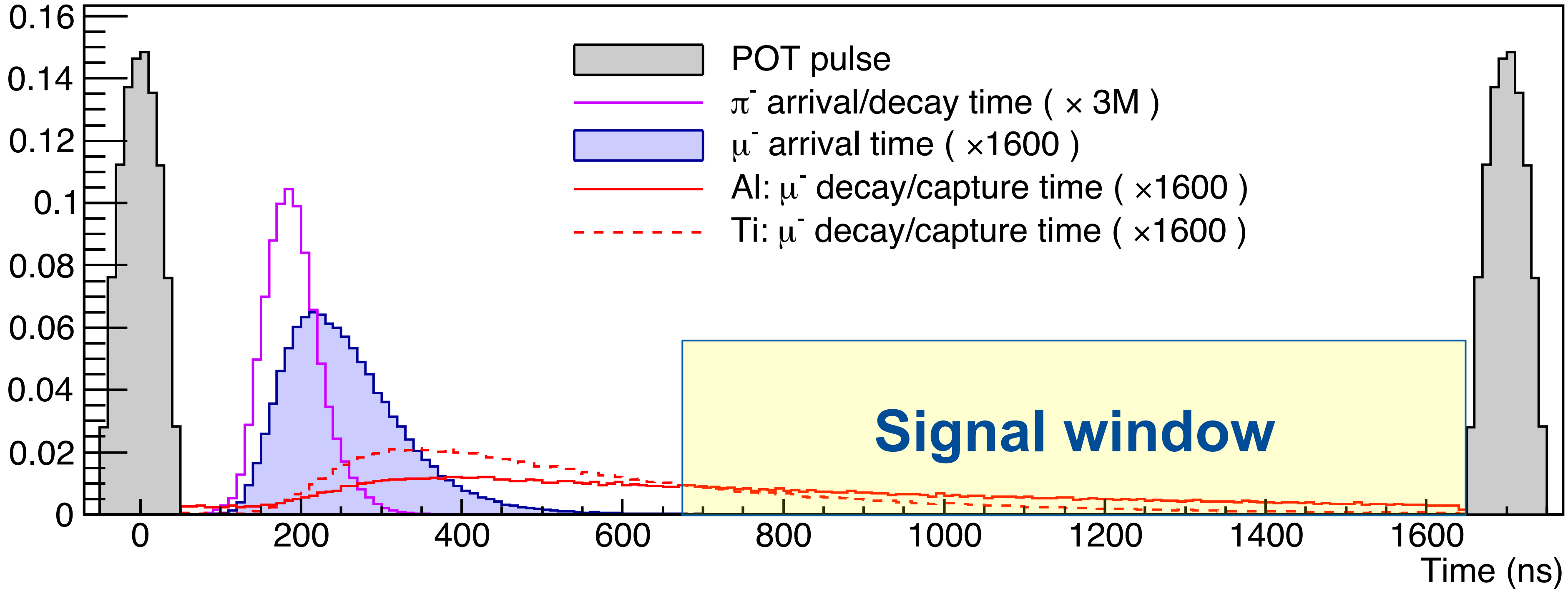
- Proton bunch full width of 200 ns
- Ext. level < 10^{-10}
- 30% duty cycle



PIP-II

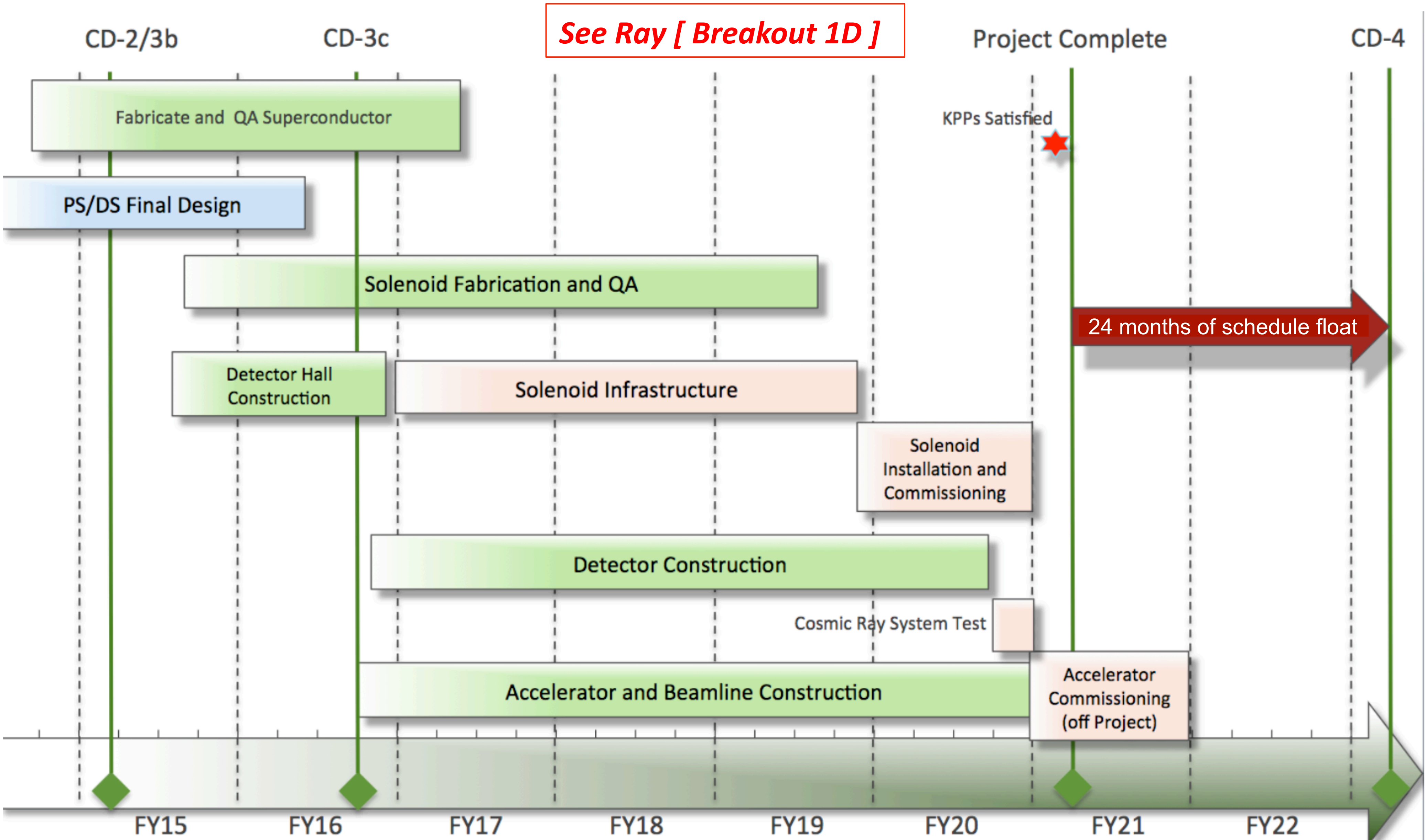
- Proton bunch full width of 100 ns
- Ext. level < 10^{-12}
- 90% duty cycle
- No antiproton backgrounds.

Moving to a different target



PIP-II configuration (×10 POTs)	Aluminum	Titanium
Stopped muons/POT (norm. to Al.)	1	1.3
% muons that decay	39%	15%
% of decays in signal window	50%	30%
Time constant for muon decay	864 ns	297 ns
Background events	**0.26**	**1.40**

Mu2e Schedule



Summary

- Mu2e will improve current muon-to-electron conversion rate measurement by a factor of 10,000
  - Offers discovery sensitivity over a broad array of BSM models
- Mu2e identified as a high priority and is engaging the HEP community
  - Significant interest in theory community
  - Collaboration engaged and making important contributions
  - Collaboration continues strong growth
- Mu2e enjoyed significant progress over the last year
  - Completed TDR – `arXiv:1501.05241 [physics.ins-det]`
  - Production of superconductor well along
  - Solenoid designs and prototyping well along
  - Detector prototyping has begun

Summary

- Mu2e enjoys strong support from Fermilab
  - AD, TD, PPD, SCD engaged in Project and operations planning
  - Theory engaged in the science

- Mu2e has a bright future
  - Expect beam commissioning to begin in 2020
  - Modest upgrades allow x10 improvement in sensitivity or exploration of underlying new physics with PIP-II beam

Summary

- Mu2e enjoys strong support from Fermilab
  - AD, TD, PPD, SCD engaged in Project and operations planning
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- Mu2e has a bright future
  - Expect beam commissioning to begin in 2020
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Thank you.

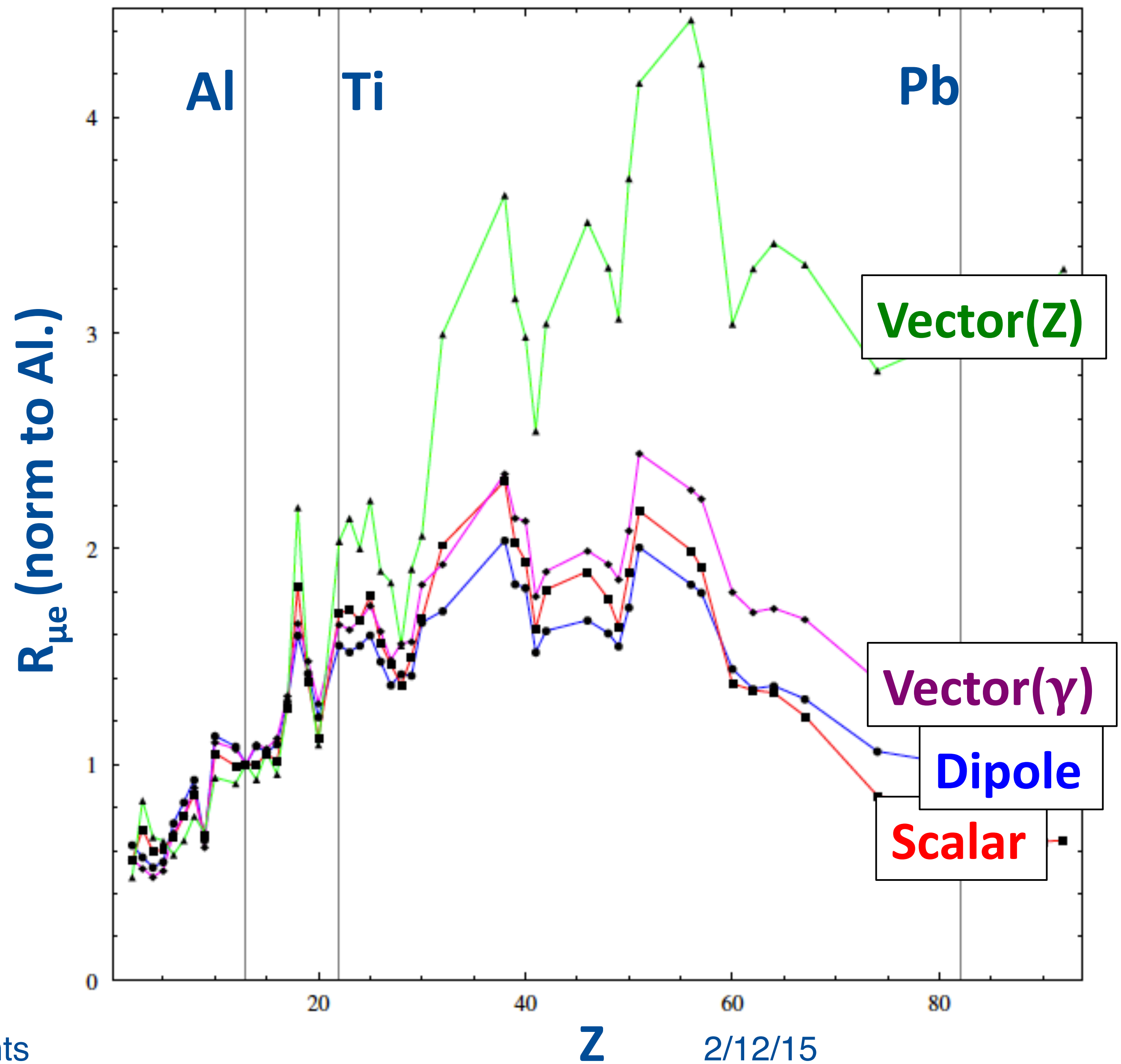
Extra slides

Why use different targets?

- *R* is *Z*-dependent, and depends on the dominant operator in the Lagrangian

- Measuring *R* for different-*Z* targets gives some discrimination in pinning down the model

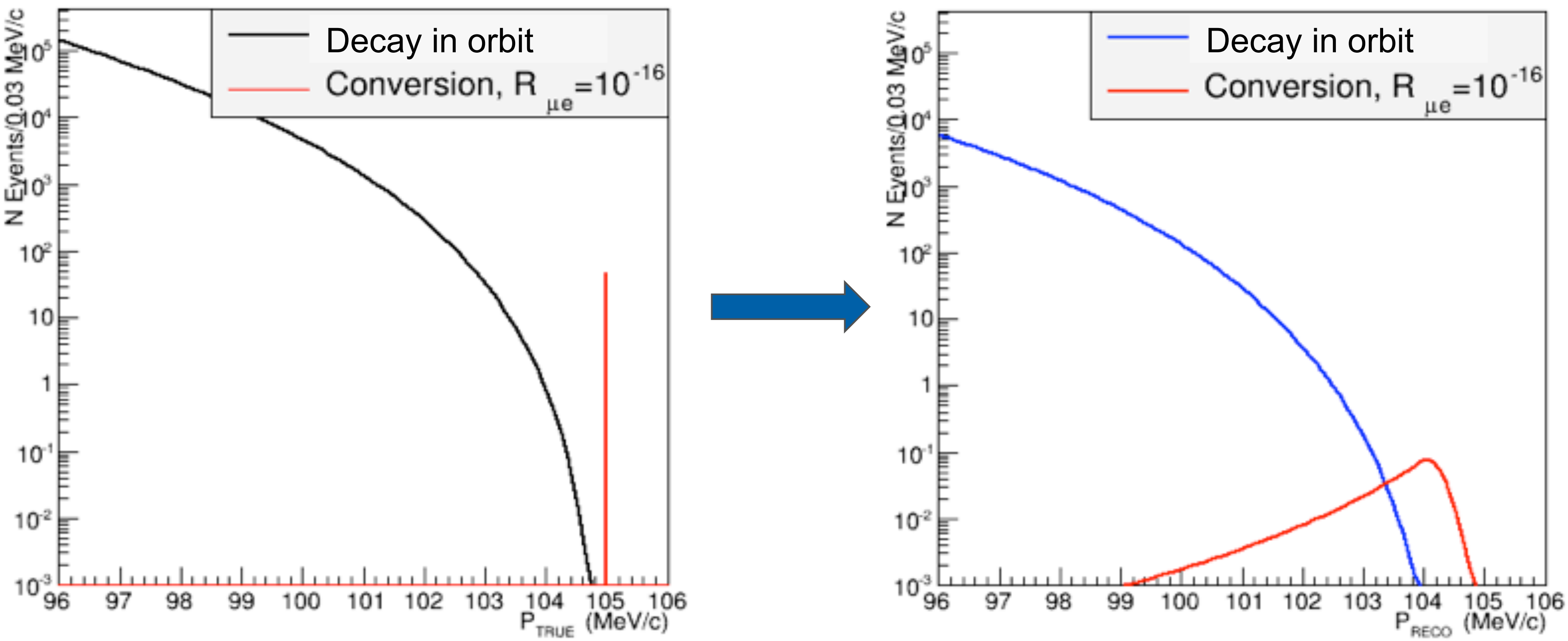
Cirigliano, et al PRD **80**, 013002 (2009)



Complications to measuring the signal

- Other effects decrease and smear out the mono-energetic peak
- Signal peak runs into another background from muon decays-in-orbit

$$\mu^- + N \rightarrow e^- \overline{\nu}_e \nu_\mu + N$$



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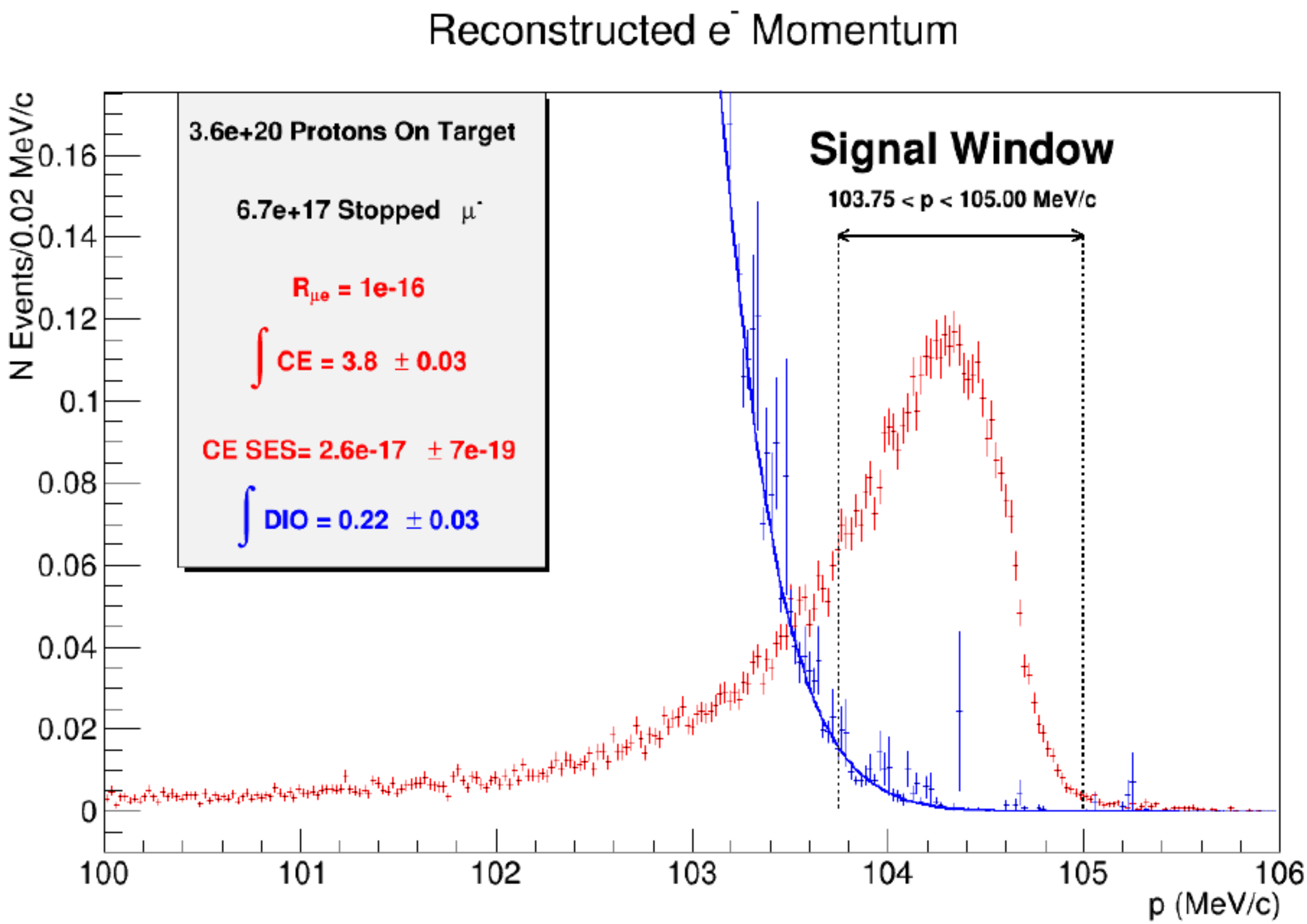
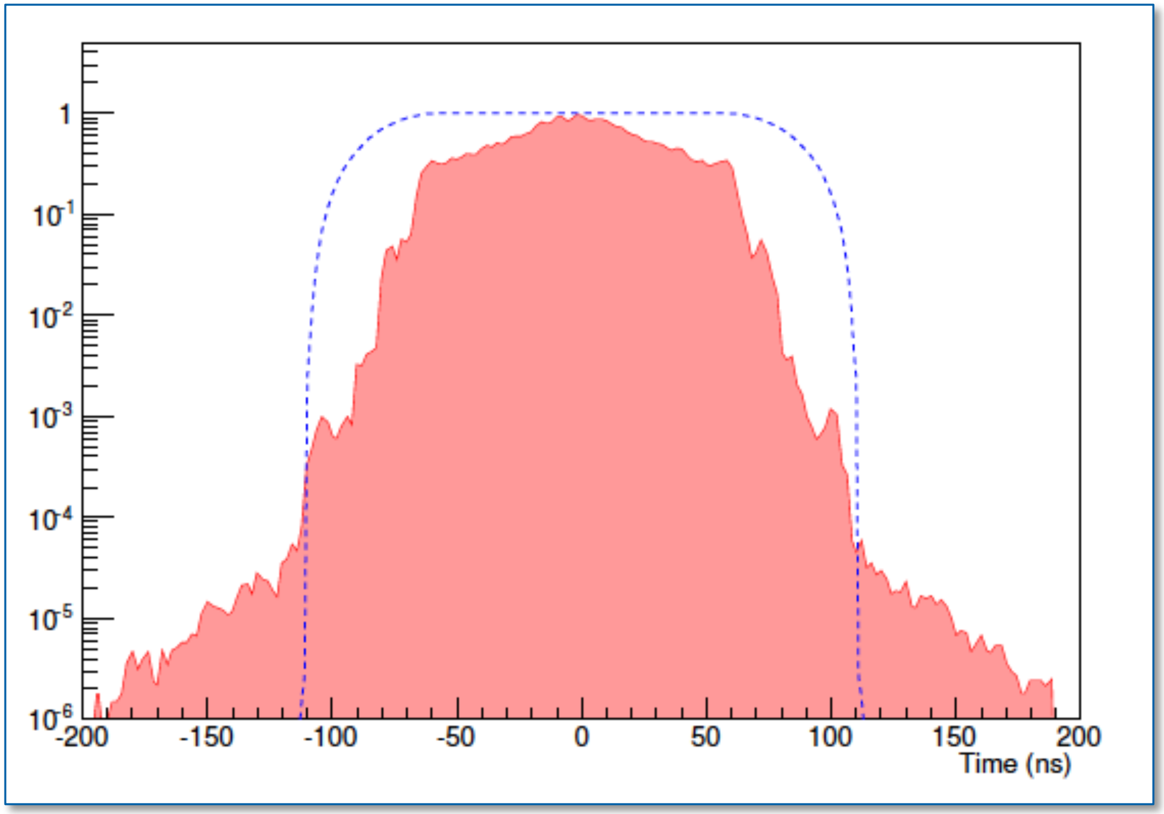
DIO and signal simulation



Assumed POT time distribution

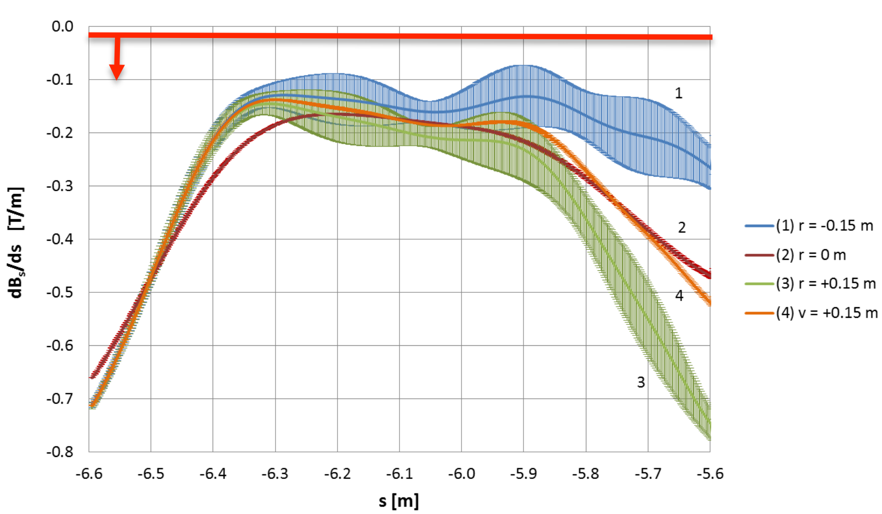


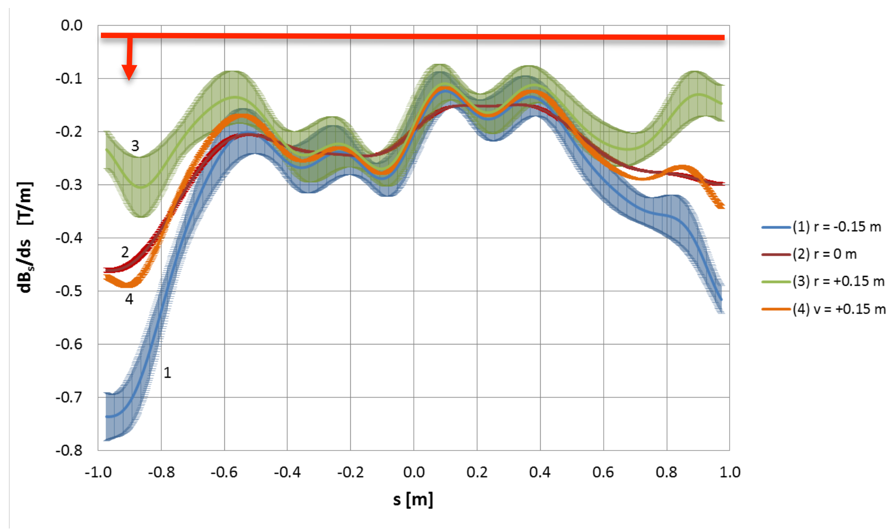
- Timing structure due to artifacts of matching the 53 MHz beam from booster to the 2.5 MHz bucket in the recycler.
- For more details, see:

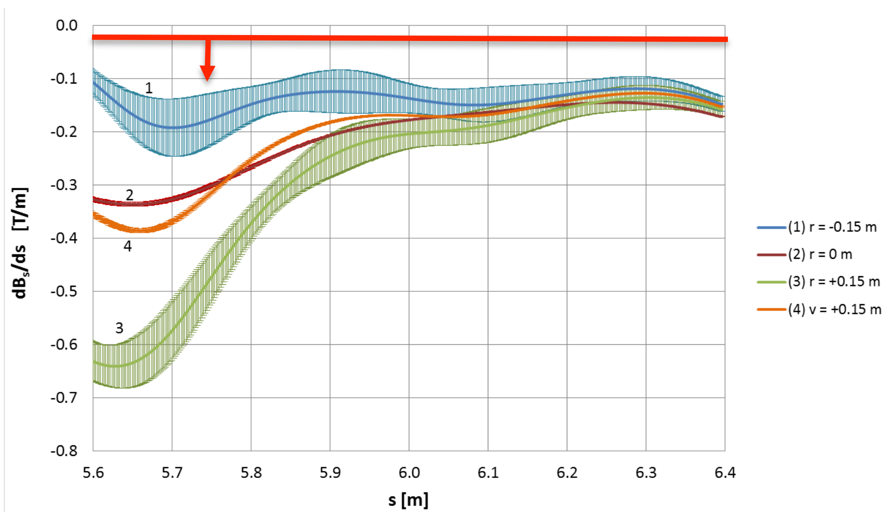
Mu2e Technical Design Report, Ch. 5.

arXiv:1501.05241 [physics.ins-det]

Solenoid tolerance studies







- Vary positions and angles of conductor and coils and recalculate B-fields (OPERA-3D)
- Random and systematic variations
- Magnitudes much larger than fabrication tolerances (by x3-10)
- Repeat x100 and look for outliers
- Even worst case scenarios still satisfy Mu2e field specifications

We are confident that solenoids built to our specifications will accomplish the Mu2e physics goals.

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