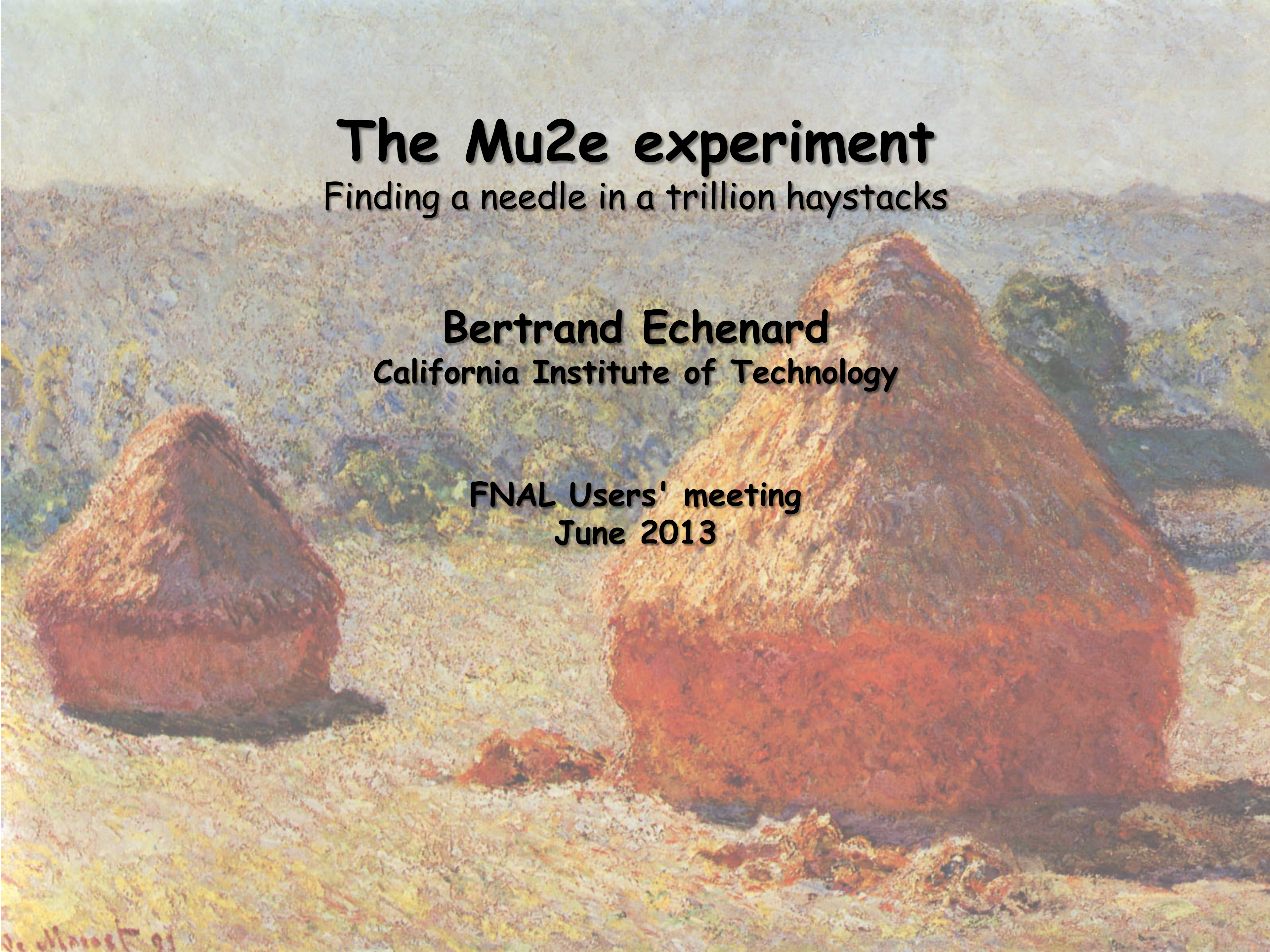


The Mu2e experiment

Finding a needle in a trillion haystacks

Bertrand Echenard

California Institute of Technology

FNAL Users' meeting

June 2013

Overview

arXiv:1211.7019

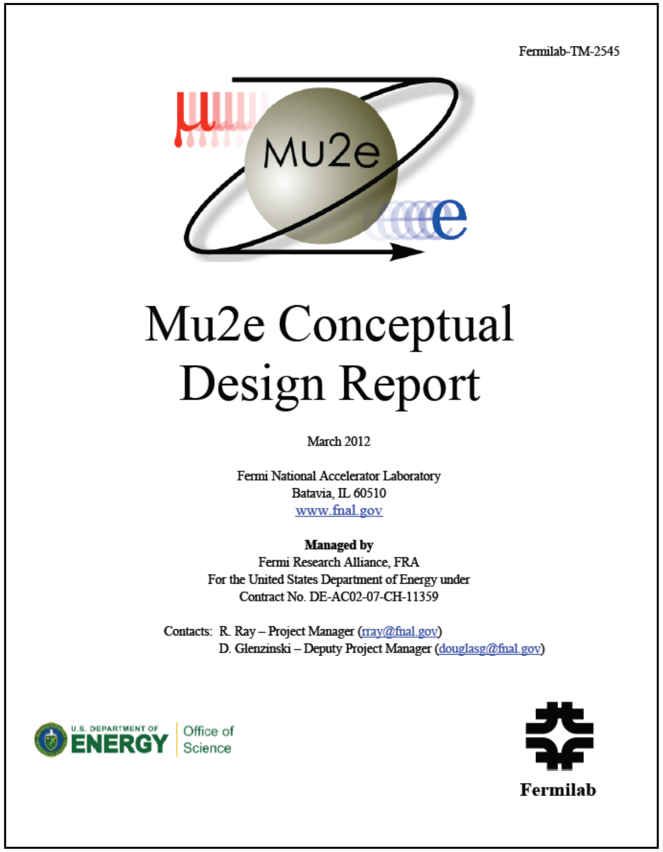
The physics
Charged lepton flavor violation and muon-to-electron conversion

The signal
Experimental signature

The experiment
The Mu2e experiment

Current status

Conclusion


Fermilab-TM-2545

Mu2e

Mu2e Conceptual Design Report

March 2012

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

Contacts: R. Ray – Project Manager (rray@fnal.gov)
D. Glenzinski – Deputy Project Manager (douglasg@fnal.gov)

U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

http://mu2e.fnal.gov/

The Mu2e collaboration

Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
California Institute of Technology
City University of New York
Duke University
Fermilab
University of Houston
University of Illinois, Urbana-Champaign
University of Massachusetts, Amherst
Lawrence Berkeley National Laboratory
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of Virginia
University of Washington, Seattle

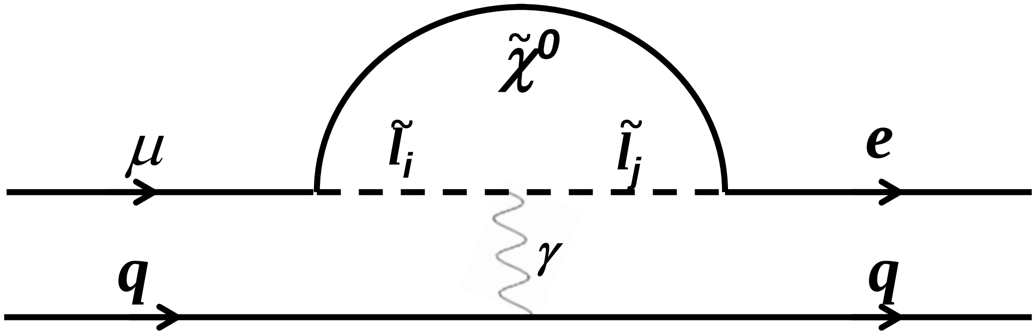
Istituto G. Marconi Roma
Laboratori Nazionale di Frascati
Università di Pisa, Pisa
INFN Lecce and Università del Salento
Gruppo Collegato di Udine

Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia

~140 collaborators and growing…

- The Mu2e experiment will study muon-to-electron conversion in the coulomb field of a nucleus: $\mu N \rightarrow eN$
- Muon-to-electron conversion is a charged lepton flavor violating process (CLFV).
- These reactions are strongly suppressed in the Standard Model. For example, BR($\mu \rightarrow e\gamma$) ~ 10^{-54} in the SM, effectively zero!!!
- New Physics could enhance CLFV rates to observable values

Observation of CLFV is New Physics

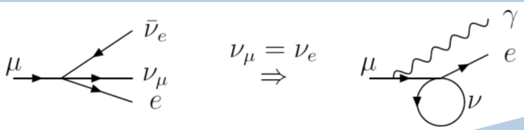


Already a long history…

Many people have searched for CLFV in muon decays

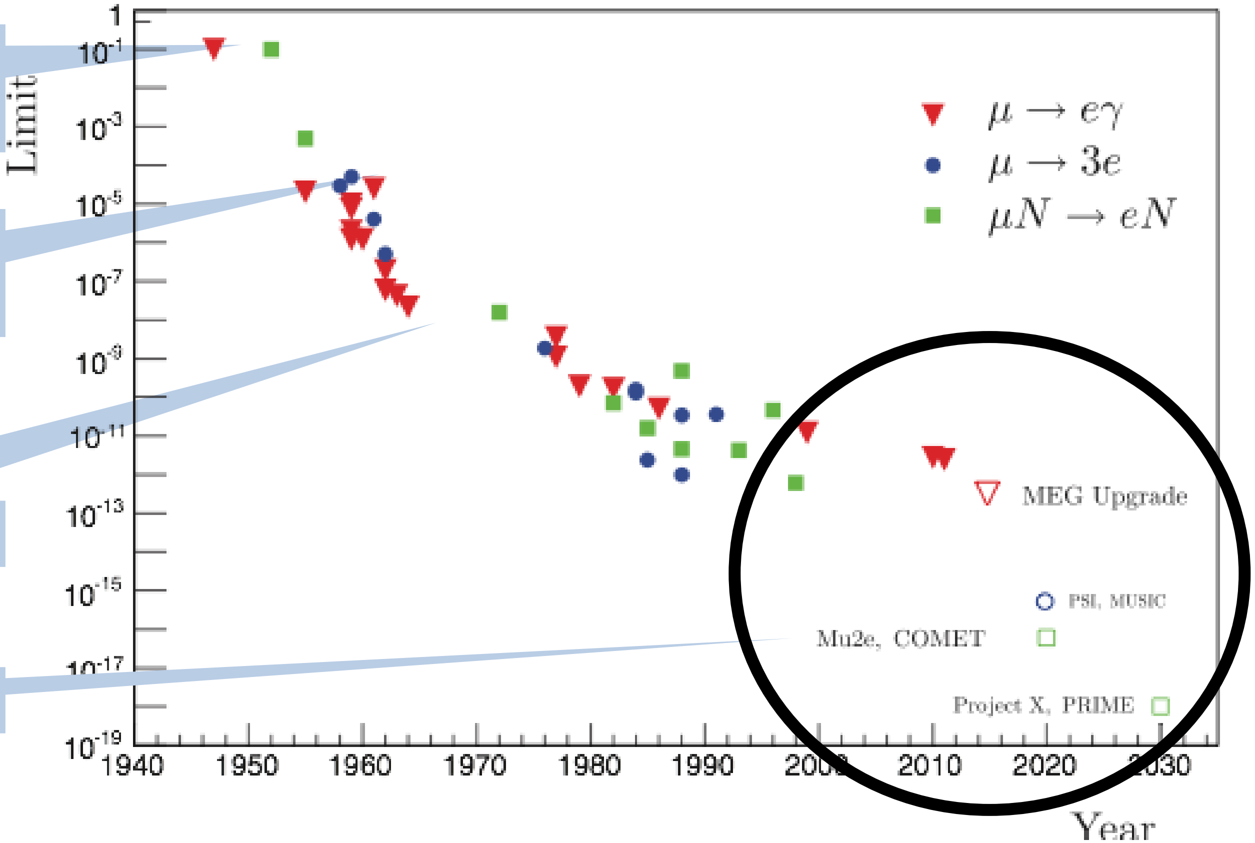
Muon an independent lepton, no $\mu \rightarrow e\,\gamma$

$\mu \rightarrow e\,\gamma \sim 10^{-4}/10^{-5}$ or two ν
Feinberg (1958)

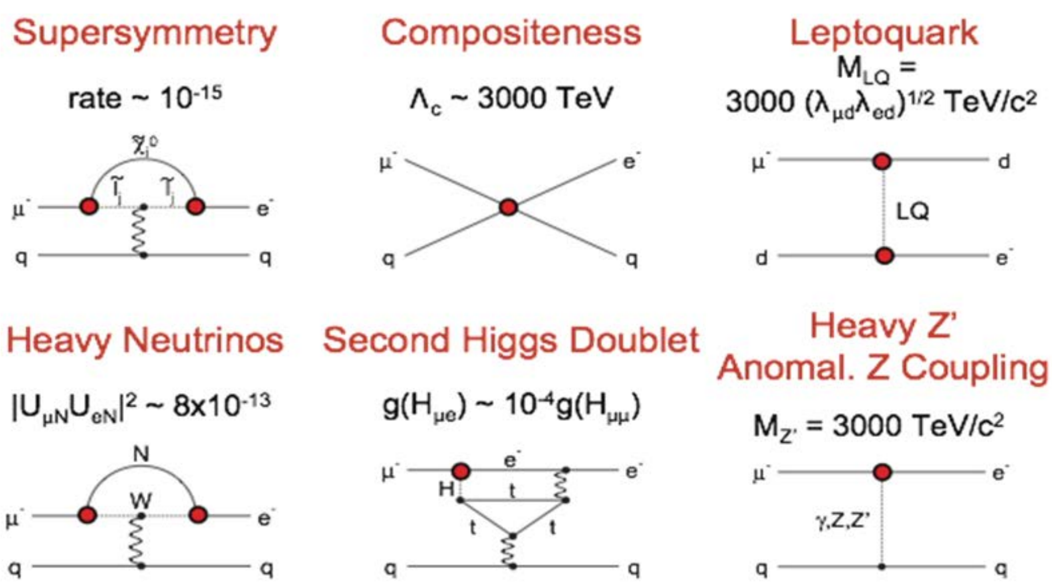


No $\mu \rightarrow e\,\gamma$ ⇨ Two neutrinos!

Mu2e goal

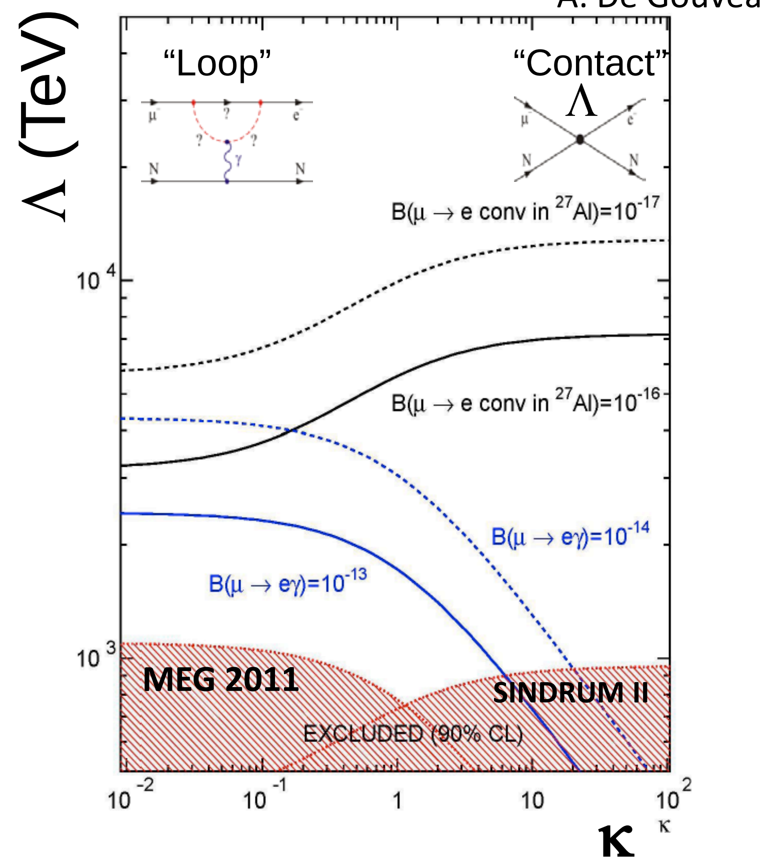


New Physics can enhance rate to observable values, either through loops or exchange of heavy intermediates particles



$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

A. De Gouvea

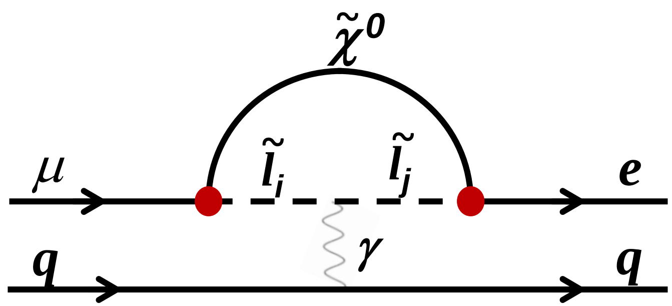


Complementary to other CLFV searches (e.g. $\mu \to e\gamma$) and direct searches at the LHC

Can probe many scenarios of New Physics and mass scales way beyond direct reach of LHC

L. Calibbi et al., hep-ph/0605139

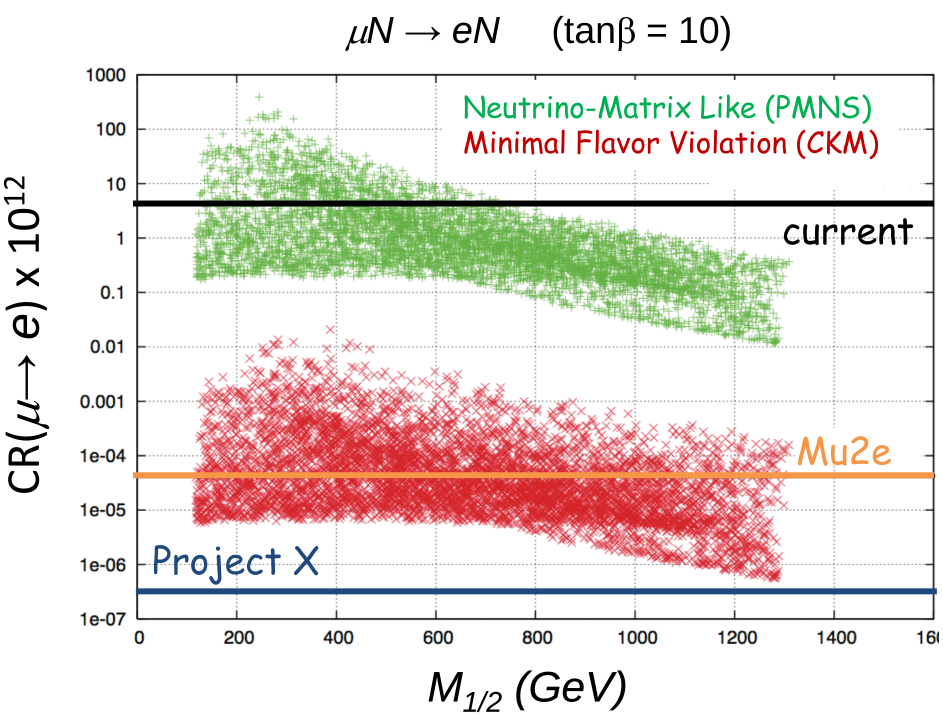
Probe SUSY through loops



If SUSY seen at LHC → rate ~10^{-15}

Implies dozens of signal events with negligible background in Mu2e for many SUSY models.

SUSY GUT in an SO(10) framework



Complementary with the LHC experiments and provide model discrimination

Muon-to-electron conversion

Neutrinoless conversion of a muon to an electron in the field of a nucleus

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

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

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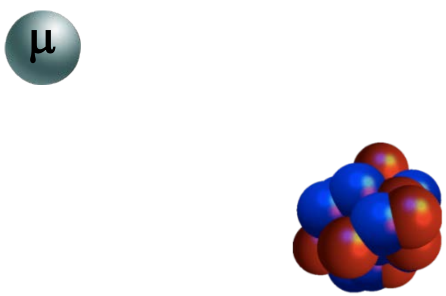

Experimental signature:

One single mono-energetic electron

For N=Al, electron energy = 105 MeV

Coherent process, the nucleus remains intact

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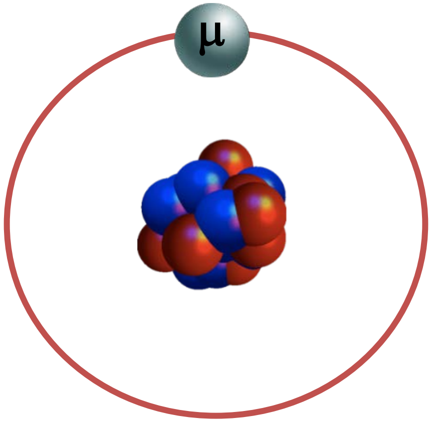

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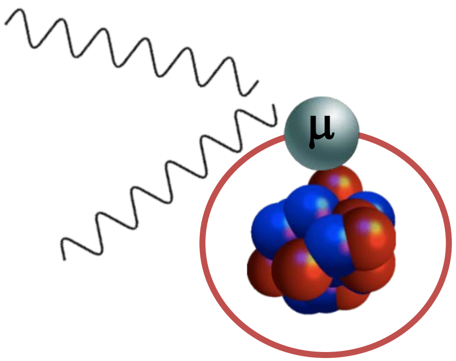

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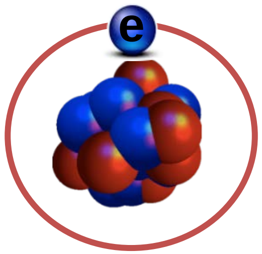

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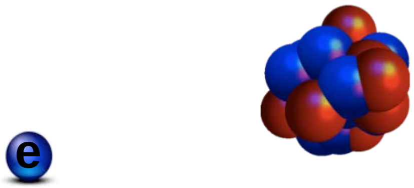


Experimental signature:

One single mono-energetic electron

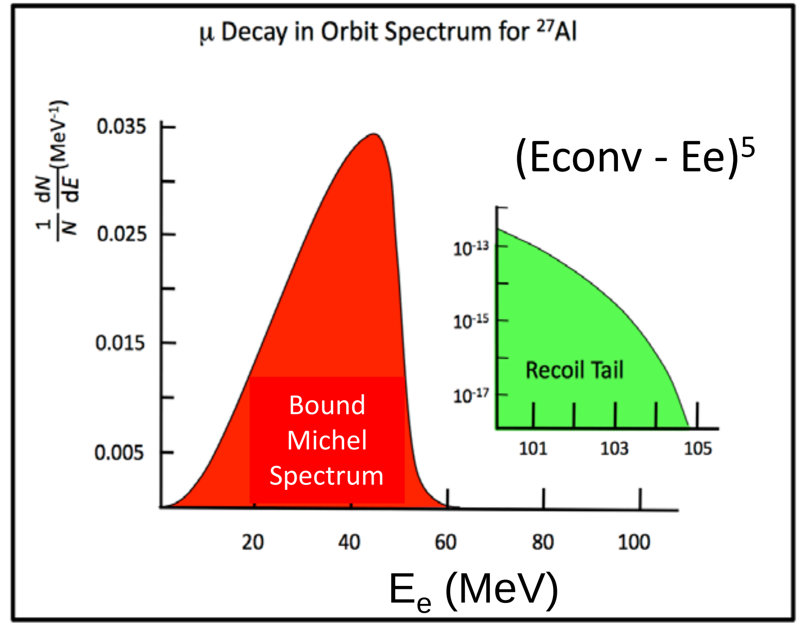
For N=Al, electron energy = 105 MeV

Coherent process, the nucleus remains intact

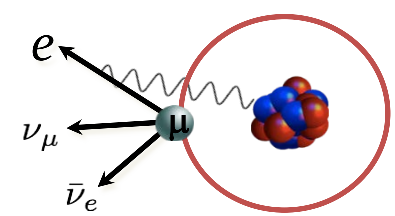
- Muon decay in orbit (DIO)
- Radiative pion capture (RPC)

  $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+e^-$ and $\pi^- N \rightarrow e^+e^- N'$
- Antiprotons: produce pions when they annihilate in the target
- Pion/muon decay in flight
- Electrons from beam
- Cosmic rays
- …

Muon decay in orbit

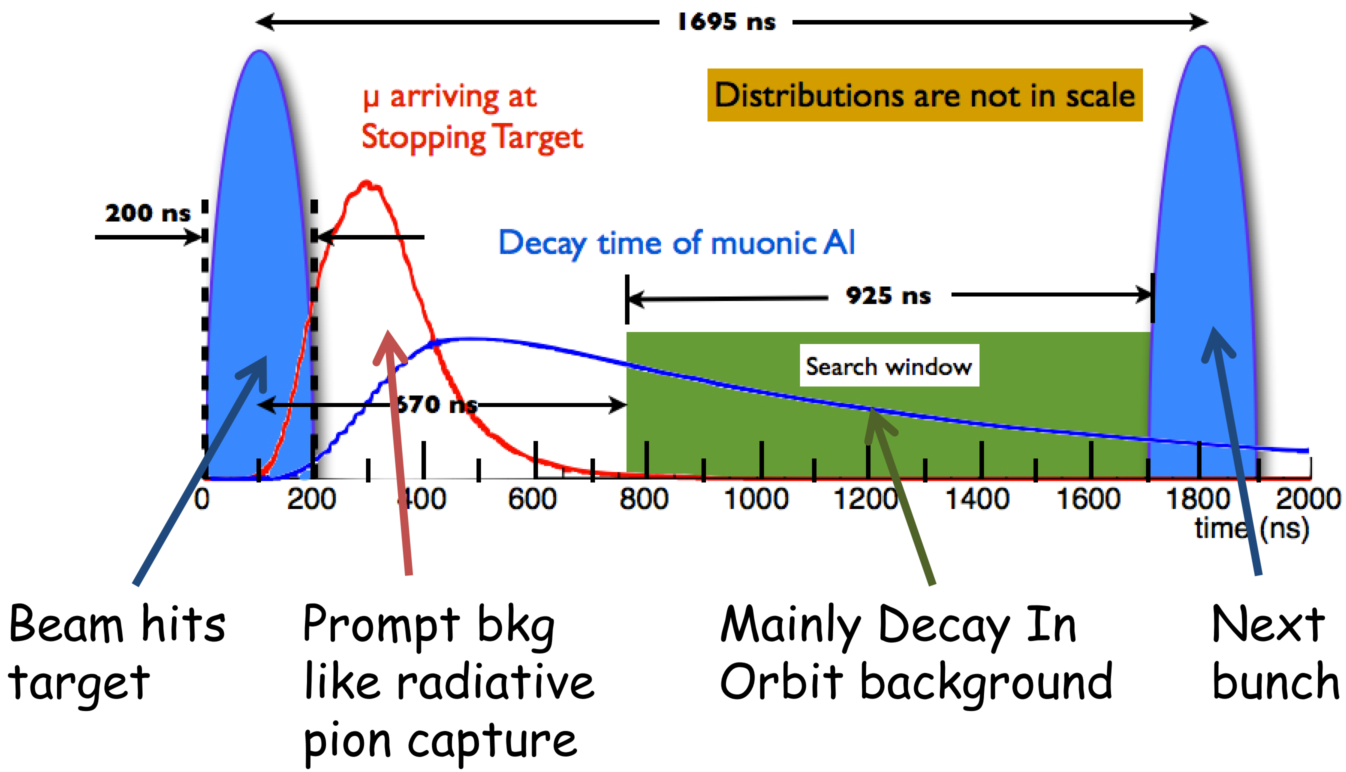


Czarnecki et al., Phys. Rev. D 84, 013006 (2011)
arXiv:1106.4756v2



Need to suppress both DIO and prompt backgrounds

Pulsed beam and prompt background



Need a pulsed beam to wait for prompt background to reach acceptable levels!

Fermilab can provide the beam we need !

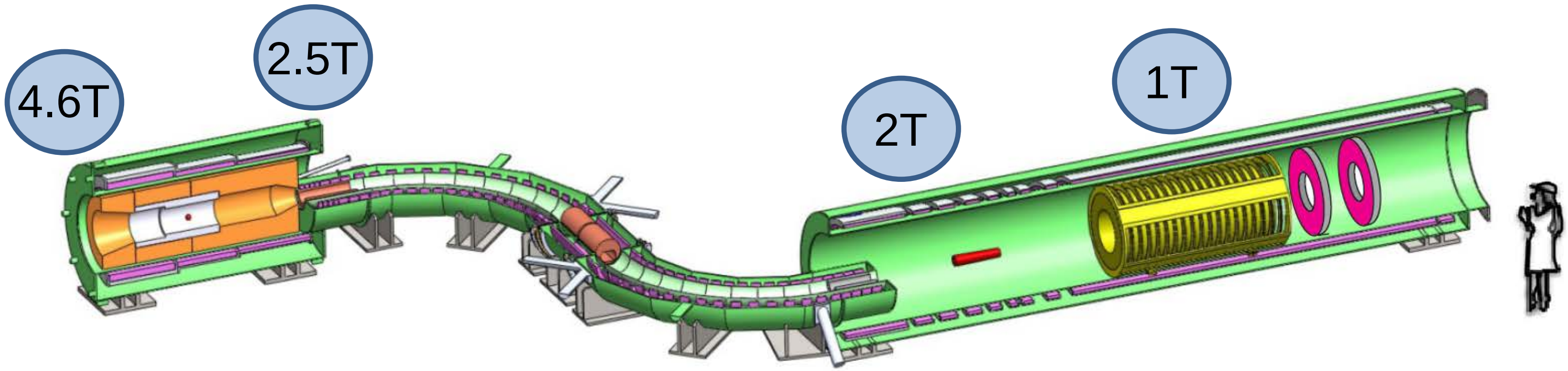
Mu2e building

- Small changes to existing accelerator complex, reuse as much as possible
- Mu2e and g-2 can run this decade
- Run in parallel with Nova, no interference with neutrino program
- And you're close to the cafeteria, can't hurt in winter…

Mu2e overview

Production Target / Solenoid (PS)

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons



Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field “reflects” downstream conversion electrons emitted upstream (isotropic process)

Transport Solenoid (TS)

Selects low momentum, negative muons
Antiproton absorber in the mid-section

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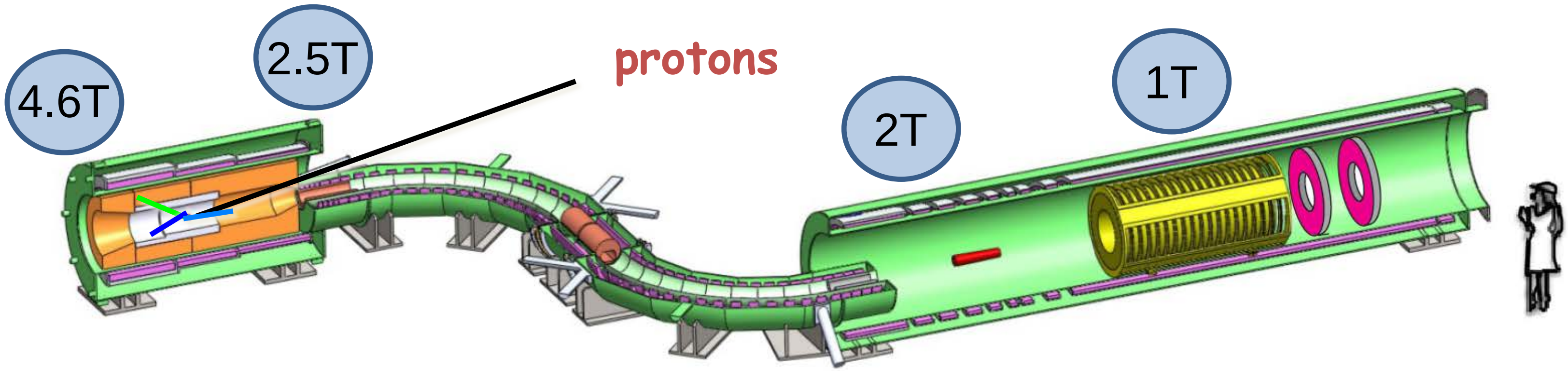

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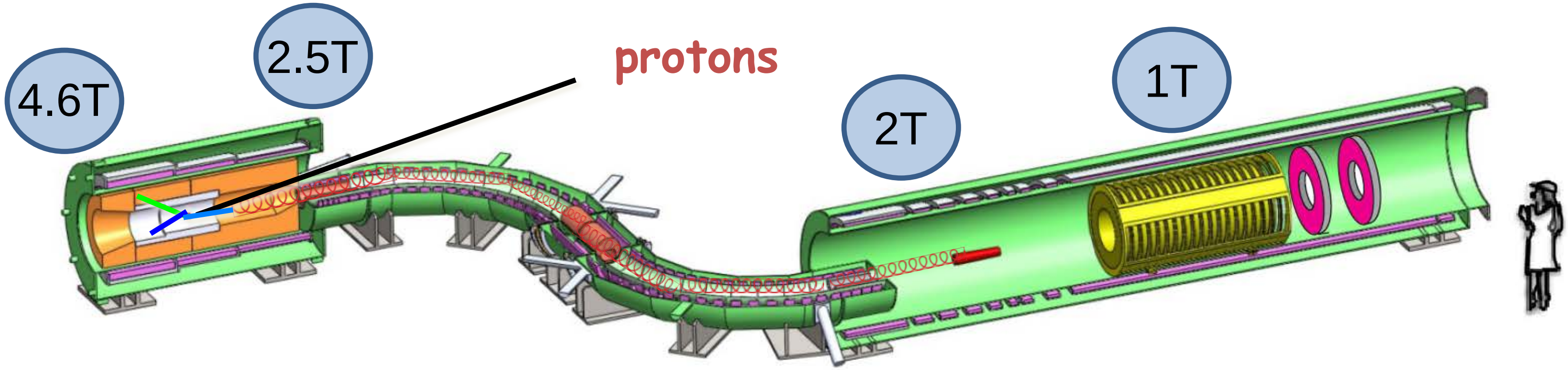

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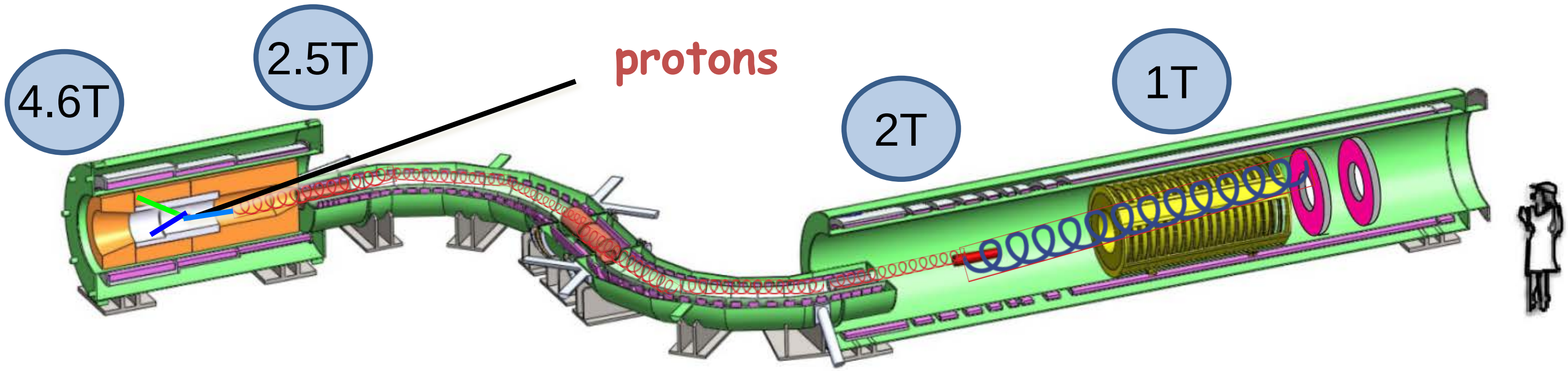

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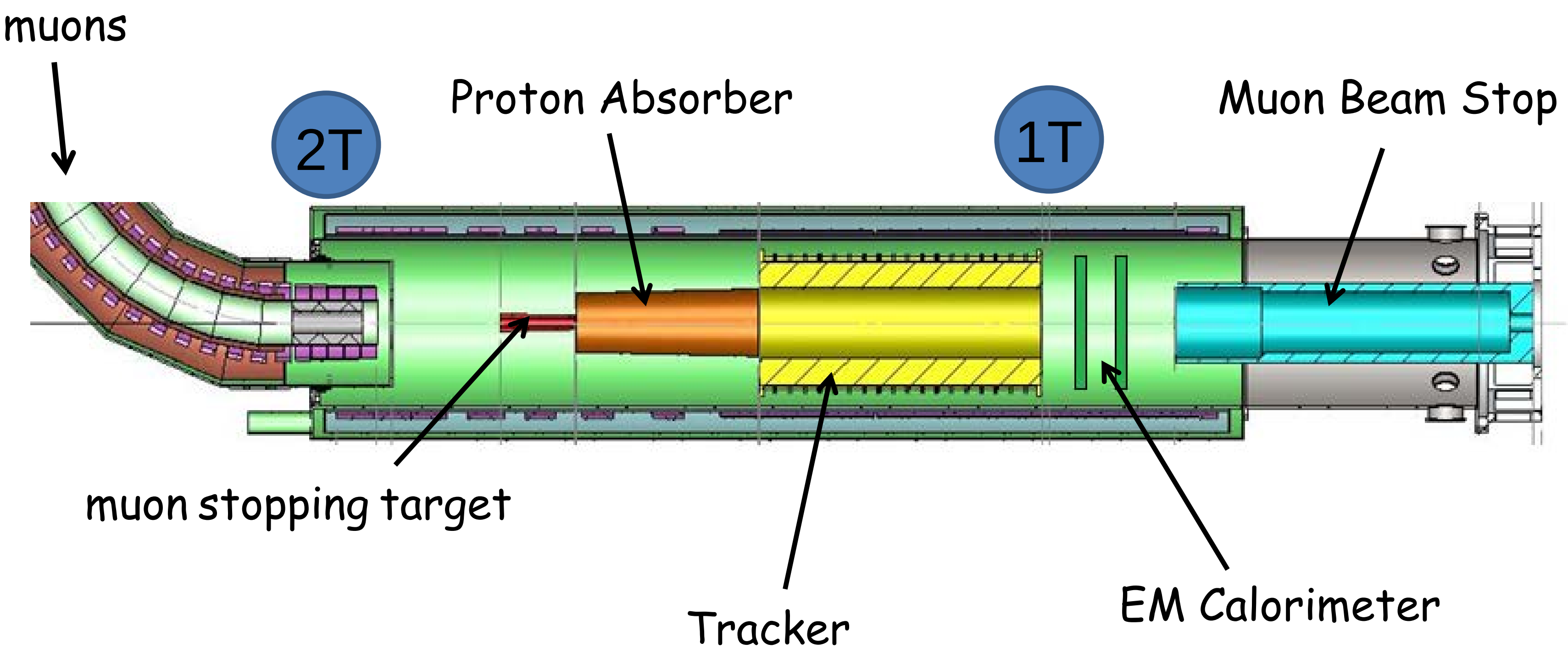
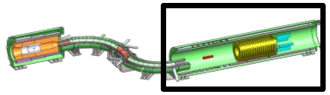
Detector



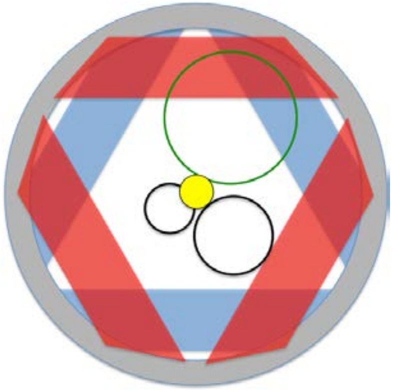
Graded field "reflects" downstream a fraction of conversion electrons emitted upstream (isotropic process)



Tracker

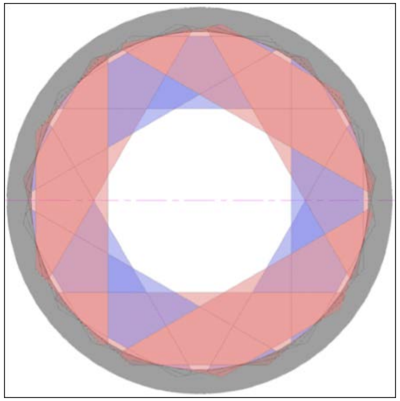
- Tracker is made of arrays of straw drift tubes (red/blue stripes in tracker stations)
- 21600 tubes (and many more screws) arranged in planes on stations, the tracker has 18 stations
- Tracking at high radius only ensures operability (beam flash produces a lot of low momentum particles, large DIO background later)

Tracker station



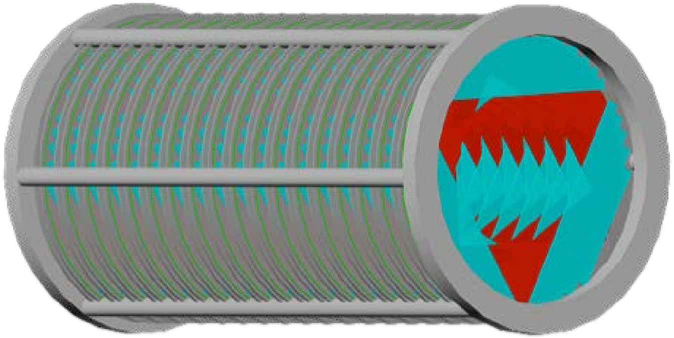
→

Stations are rotated



→

Tracker

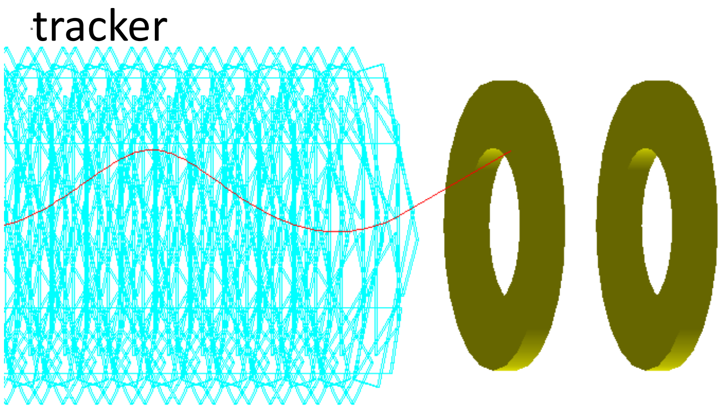


Calorimeter

Two disks composed of hexagonal LYSO crystals

- Provide independent measurement of energy / time / position
- Alternative tracking, seed for track finding algorithm
- Particle identification
- Independent trigger

Two disks separated by ½ wavelength



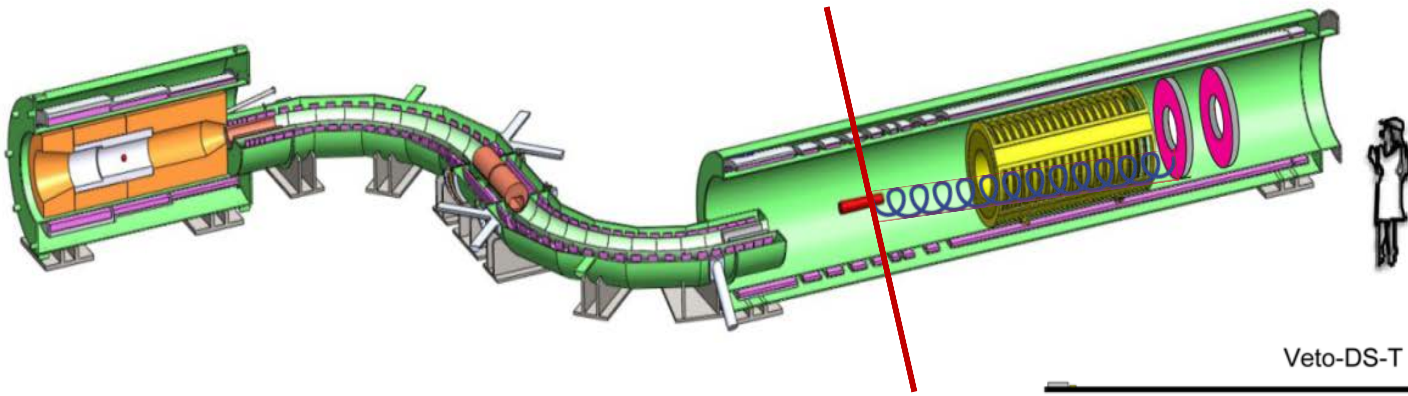
Disk geometry

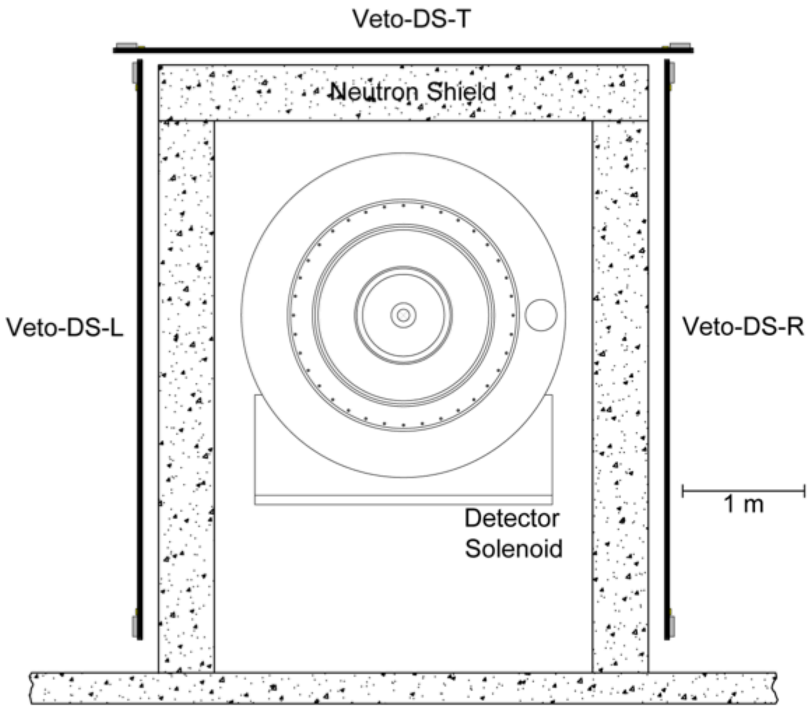
- Charge symmetric, can measure $\mu^- N \rightarrow e^+ N$
- Allow pion $\pi^+ \rightarrow e^+ \nu_e$ calibration *in situ*
- Use e^+ from RPC to estimate background from e^- in signal region without opening "the box"

Hexagonal crystals

The $\mu^- N \rightarrow e^+ N'$ channel can probe heavy neutrinos and leptoquarks models.
Mu2e will greatly improve the existing limits!

Cosmic muons can easily fake a conversion electron!



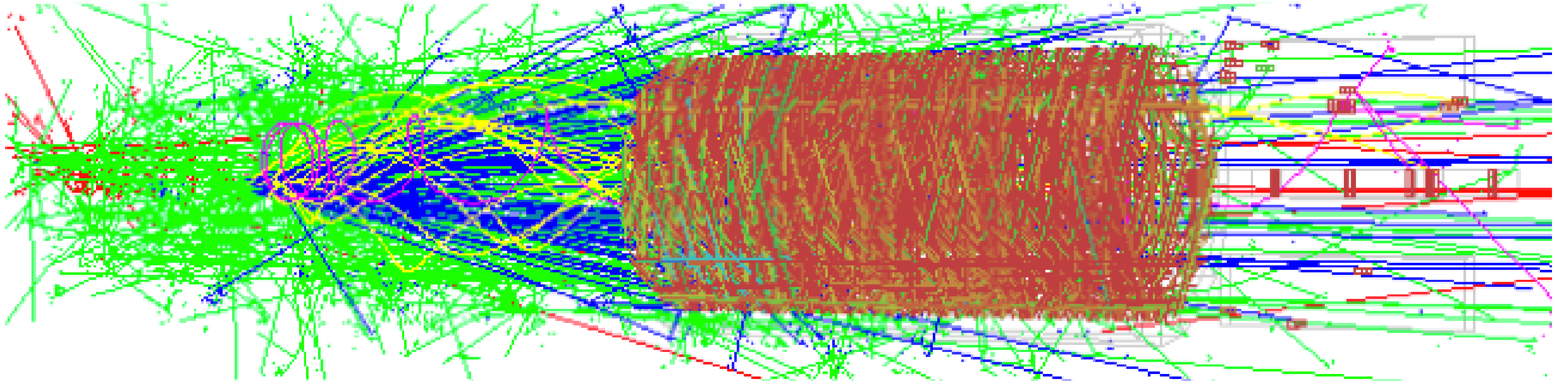


Solution: cosmic ray veto

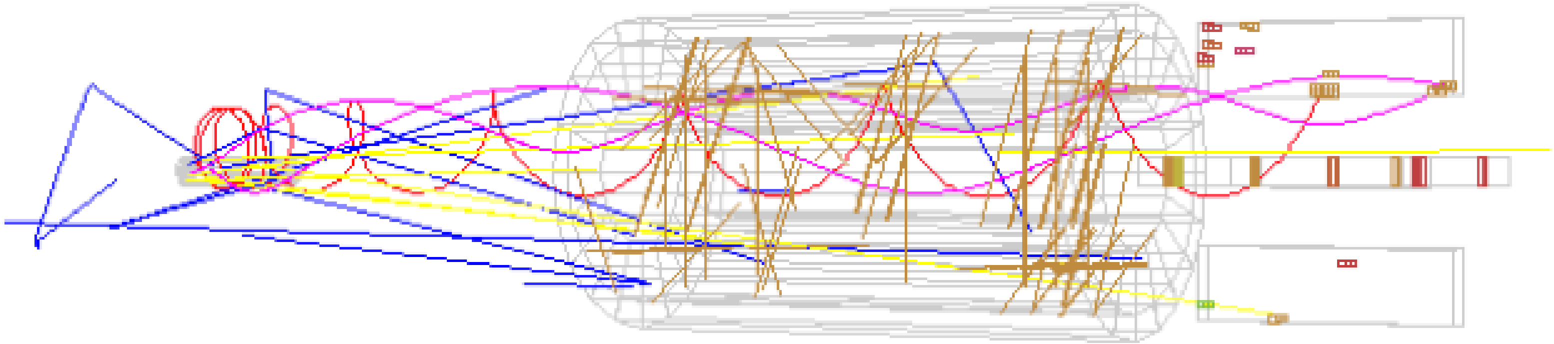
- Three sides around the detector
- Scintillating counters read by silicon photomultipliers
- 99.99% efficiency
- Excellent time resolution (< 5 ns)
- Resistant to neutrons

Activity in one measurement period

500 – 1695 ns window



± 50 ns around conversion electron



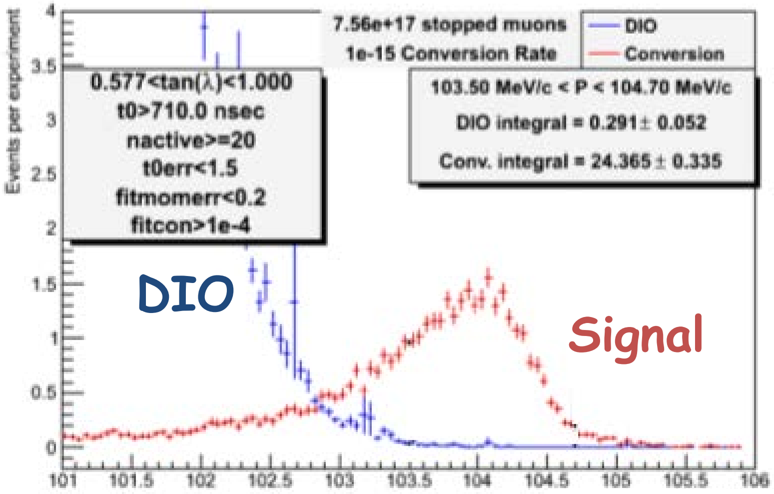
Quite challenging to find the conversion electron, good tracker performance and pattern recognition algorithm critical !!!

Expected sensitivity

3 years running period with $1.2x10^{20}$ protons on target per year

Background	Size	Uncertainty
Muon Decay-In-Orbit	0.22	±0.06
Antiproton RPC	0.10	±0.05
Cosmic Rays	0.05	±0.05
Radiative Pion Capture	0.03	±0.007
Muon Decay-in-Flight	0.01	±0.003
Pion Decay-in-Flight	0.003	±0.0015
Beam Electrons	0.0006	±0.0003
Radiative Muon Capture	$< 2 \times 10^{-6}$	—
Sum	0.41	±0.08

Reconstructed momentum
assuming conversion rate 10^{-15}



p MeV/c

Bottom line:

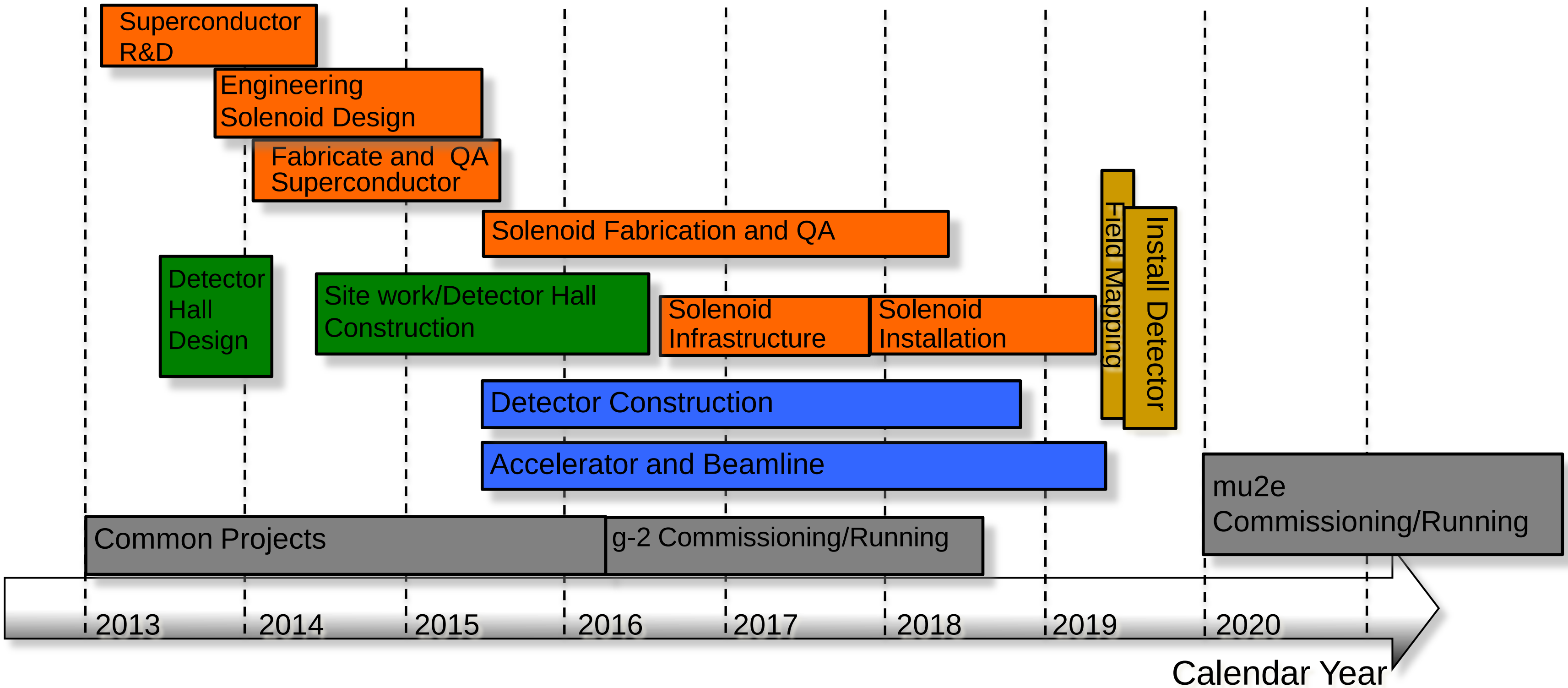
Single event sensitivity: $R_{\mu e}=2x10^{-17}$

90% C.L. (if no signal) : $R_{\mu e}<6x10^{-17}$

Typical SUSY Signal: ~50 events or more for rate 10^{-15}

Mu2e schedule

The schedule is technically limited , driven by the solenoid construction
Start construction in 2014 and start taking data (cosmic rays) by ~2019.



Current status:

- CD1 granted in June 2012
- Preparing CD2/CD3 review mid-2014 (TDR + final or near-final design)
- Break ground on building fall 2014

Mu2e possible upgrade at Project X

Signal ?

Yes →

Have a well deserved drink!

Change the target to study the underlying New Physics

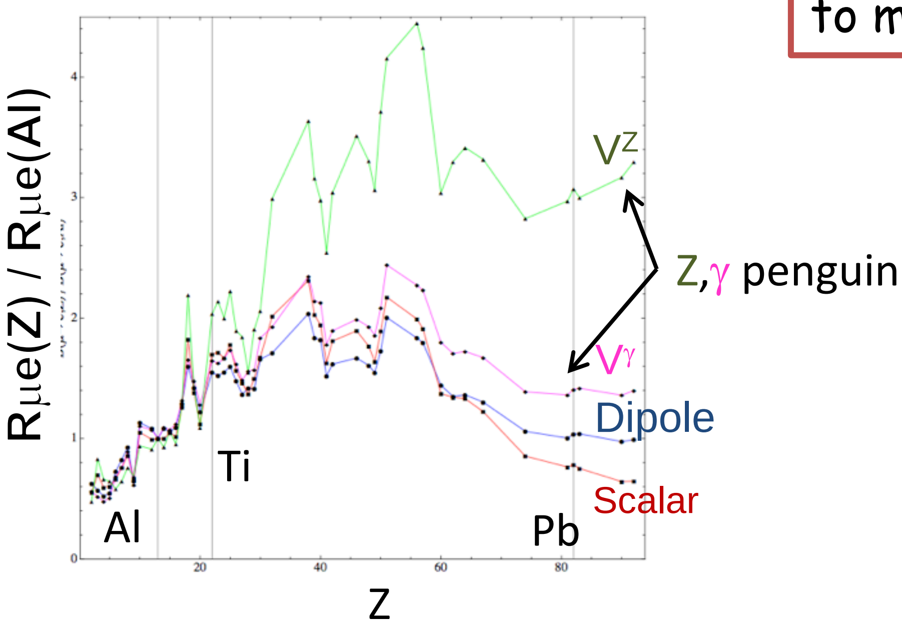
No →

Have a drink anyway…

Background must decrease to measure $R_{\mu e}$ at 10^{-18}

→ Redesign muon transport and detector to run at Project X

V. Cirigliano et al., PRD 80 (2009) 013002



Conclusion

We will measure muon-to-electron conversion with a single event sensitivity $R_{\mu e} \sim 2 \times 10^{-17}$.

Mu2e is complementary to the LHC , and will either

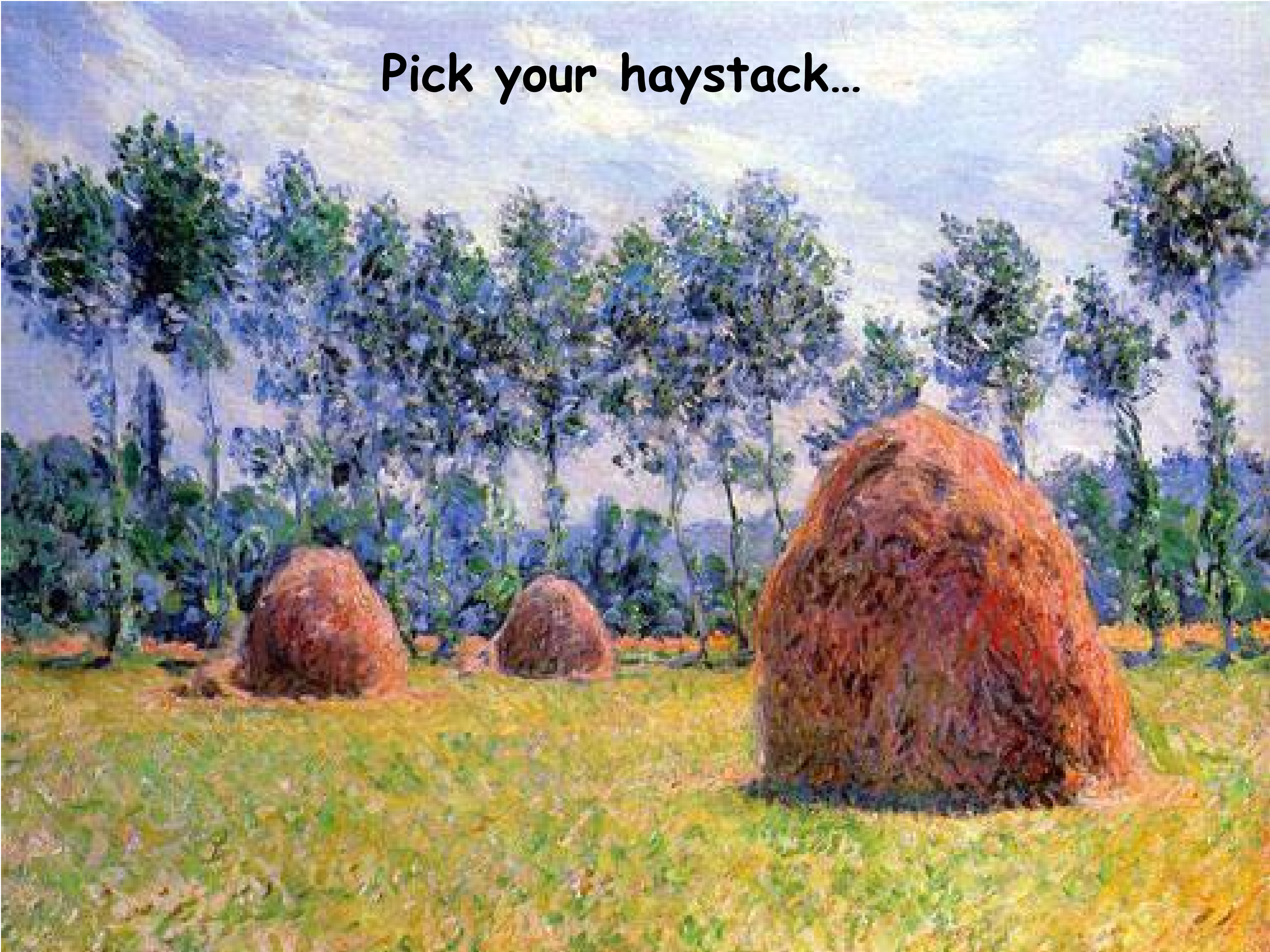
provide unambiguous evidence of Physics beyond the Standard Model, and help elucidate the nature of New Physics

OR

improve the current limit on $R_{\mu e}$ by four orders of magnitude, probing New Physics up to 10^4 TeV.

Mu2e at Project X could further improve the limits by two orders of magnitude or study the signal in detail.

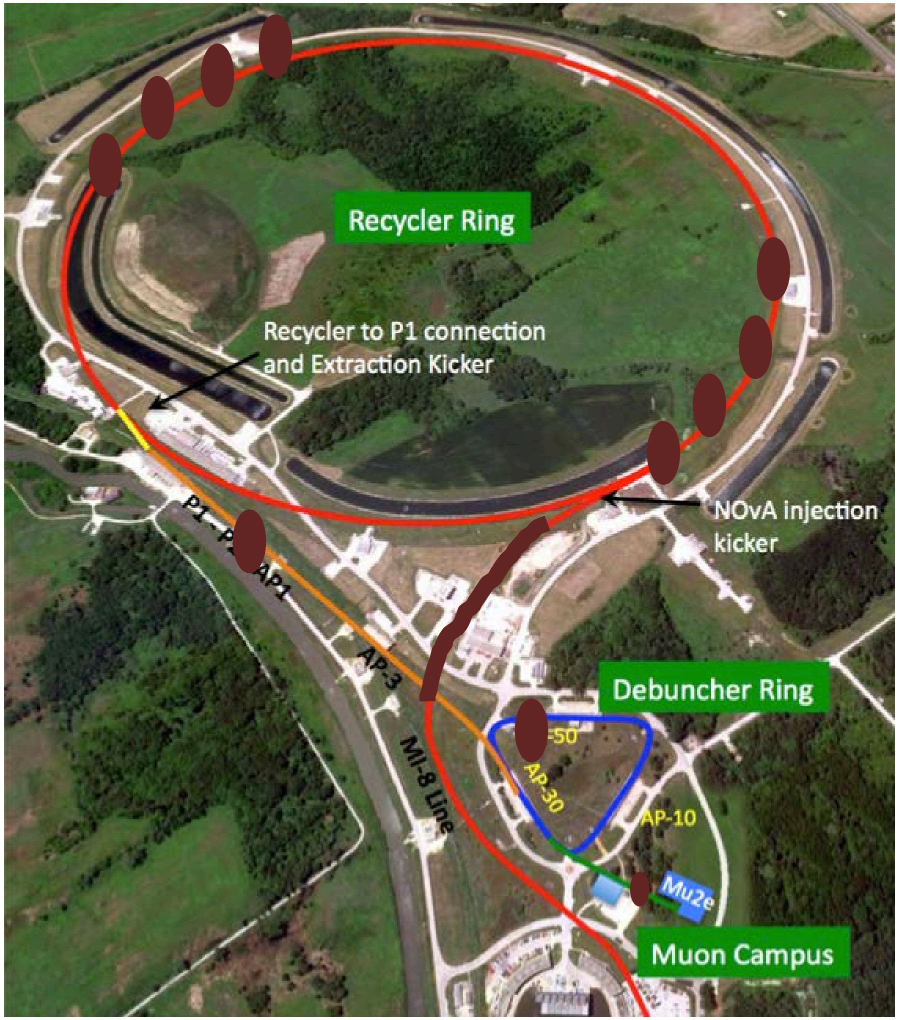
Pick your haystack…



EXTRA MATERIAL

Fermilab ideally suited for Mu2e

- Booster: batch of 4×10^{12} protons every 1/15th second
- Booster "batch" is injected into the Recycler ring
- Batch is rebunched into 4 bunches
- These are extracted one at a time to the Debuncher ring
- As a bunch circulates, protons are extracted to produce the desired beam structure
- Produces bunches of $\sim3\times10^{7}$ protons each, separated by $1.7\mu s$ (debuncher ring period)



Pulse structure: width « τ_μ(Al) with separation ~ 2 x τ_μ(Al)

W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

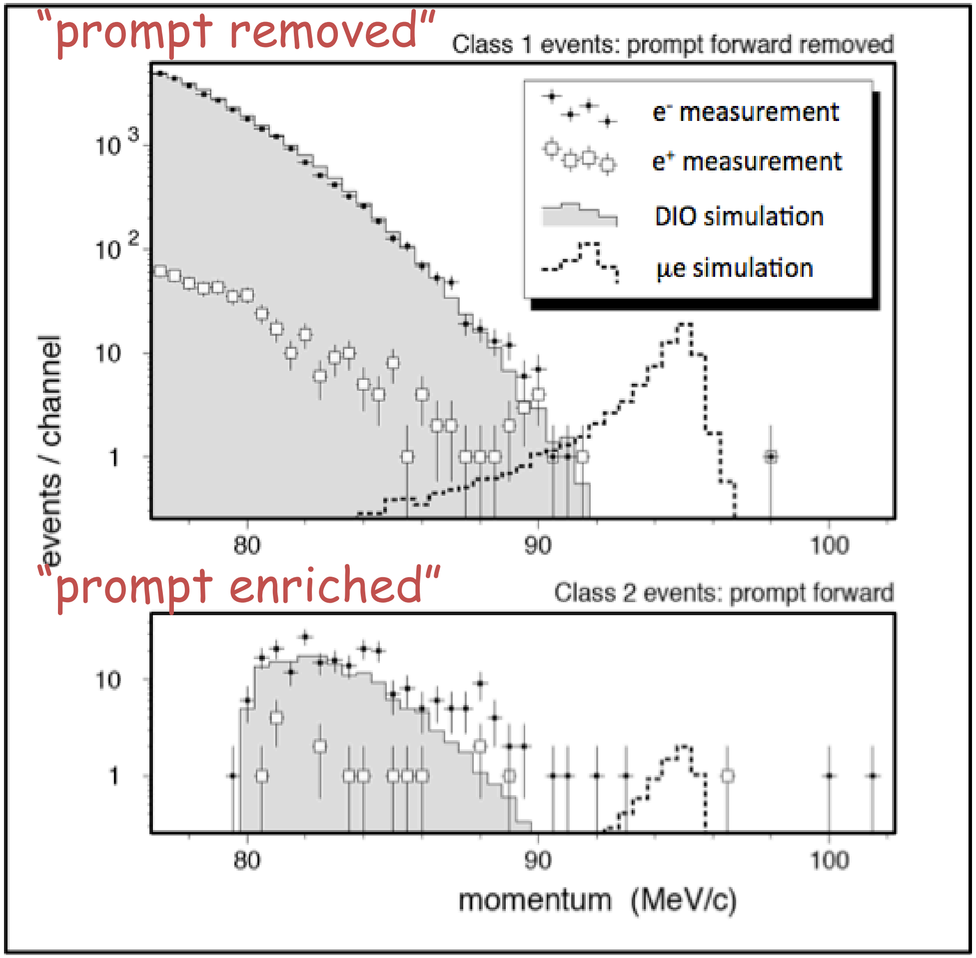
SINDRUM II at PSI

Final results on Au:

$R_{\mu e} < 7\times10^{-13}$ @ 90% CL

One candidate event past the end of the spectrum. Pion capture, cosmic ray?

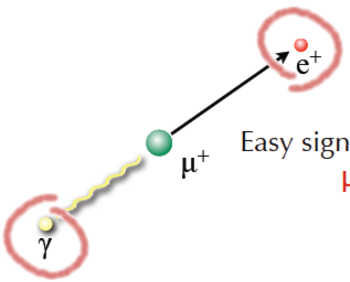
Timing cut shows the contribution of prompt background (0.3 ns muon pulse separated by 20 ns)



G. Signorelli

arXiv:1303.0754

MEG experimental method



Easy signal selection with μ+ at rest

PAUL SCHERRER INSTITUT

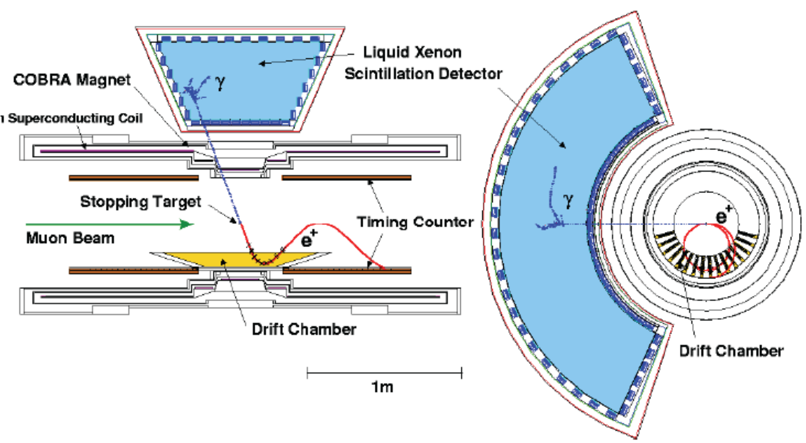
PSI

- μ: stopped beam of 3 x 10^7 μ /sec in a 205 μm polyethylene target
  - PSI πE5 beam line: 29 MeV μ+
- e+ detection

  magnetic spectrometer composed by solenoidal magnet and drift chambers for momentum

  plastic counters for timing
- γ detection

  Liquid Xenon detector based on the scintillation light
  - fast: 4 / 22 / 45 ns
  - high LY: ~ 0.8 * NaI
  - short X_0: 2.77 cm



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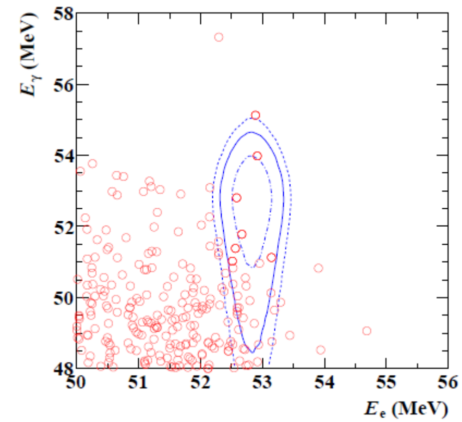

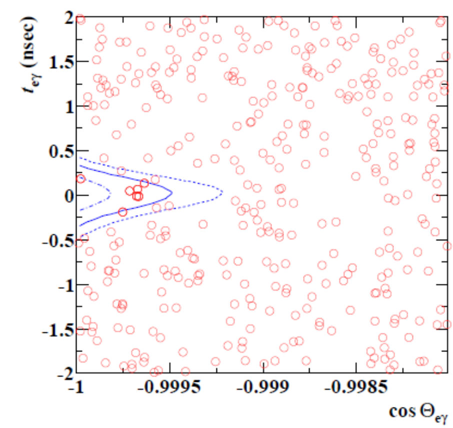

$$\frac{\Gamma(\mu^+ \to e^+\gamma)}{\Gamma(\mu^+ \to e^+\nu\bar{\nu})} \leq 5.7 \times 10^{-13}$$