The Mu2e experiment

Finding a needle in a trillion haystack

Bertrand Echenard

On behalf of the Mu2e Collaboration*

California Institute of Technology

ICHEP 2016 – Chicago

* The full Mu2e Collaboration is listed at http://mu2e.fnal.gov/collaboration.shtml

The Mu2e collaboration

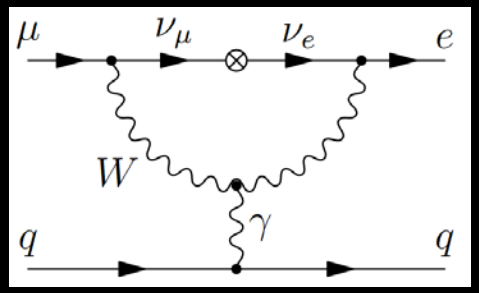
About 200 scientists from 35 institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Kansas State University, Lewis University, University of Louisville, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Sun Yat-Sen University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

Mu2e in a nutshell

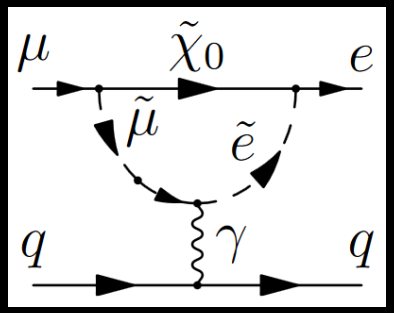
The Mu2e experiment at Fermilab will search for the neutrinoless conversion of a muon to an electron in the Coulomb field of a nucleus $\mu N \rightarrow eN$

$\mu N \rightarrow eN$



This reaction violates charged lepton flavor conservation (CLFV) and is extremely suppressed in the Standard Model because it occurs through neutrino mixing).

The conversion ratio $R_{\mu e} \sim 10^{-52}$ in the νSM, effectively zero! This is virtually a background free environment.



Many New Physics scenarios can enhance CLFV rates to observable values.

Mu2e aims to improve the current sensitivity by four orders of magnitude.

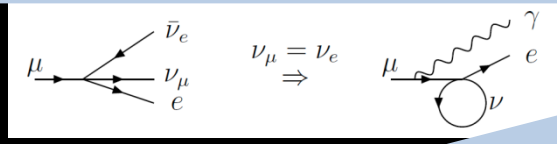
Observation of CLFV is an unambiguous sign of New Physics

Already a long history…

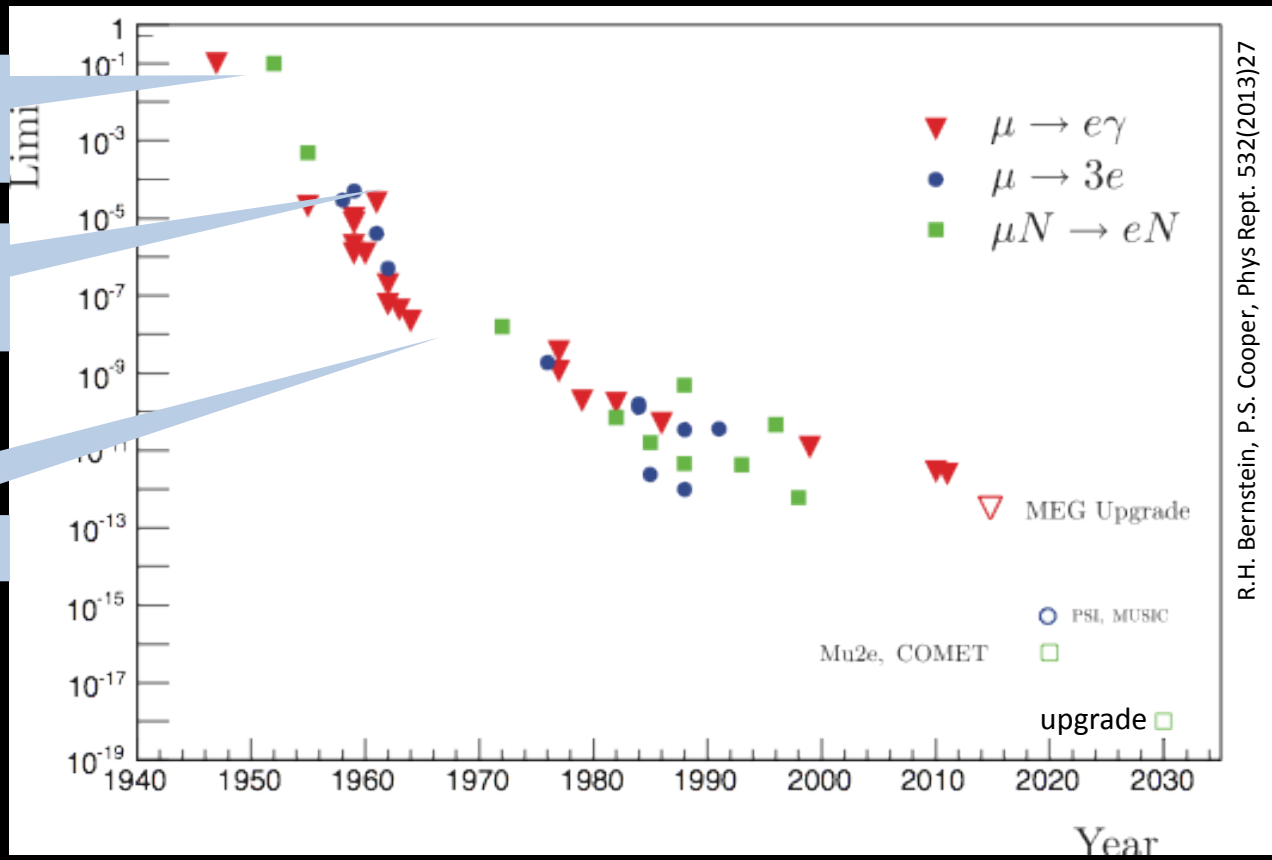
Many people have searched for CLFV in muon decays

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!



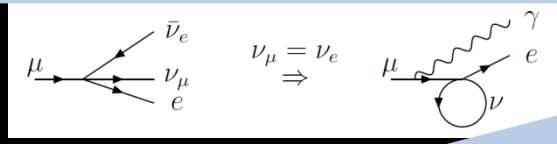
R.H. Bernstein, P.S. Cooper, Phys Rept. 532(2013)27

Already a long history…

Many people have searched for CLFV in muon decays

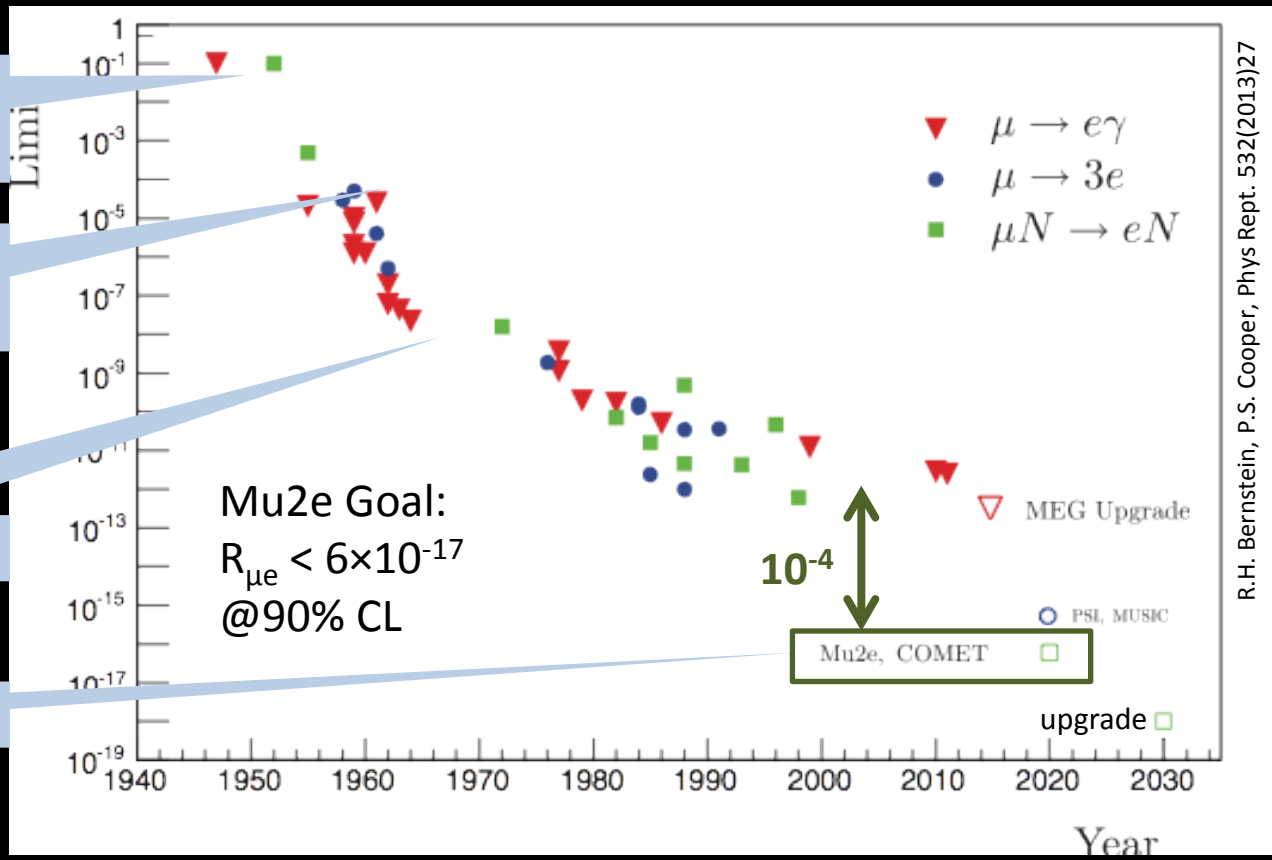
Muon an independent lepton, no $\mu \rightarrow e\,\gamma$

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



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

Mu2e goal



R.H. Bernstein, P.S. Cooper, Phys Rept. 532(2013)27

The Mu2e experiment will search for muon-to-electron conversion in the coulomb field of a nucleus $\mu N \rightarrow eN$ with a sensitivity 10000 better than the current world's best limit

How rare is that?

Probability of...	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

Courtesy of R. Hooper

~ Mu2e single event sensitivity

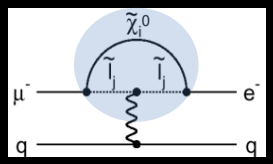
Pretty rare!!! Please let us know if this happens to you…

Probing New Physics

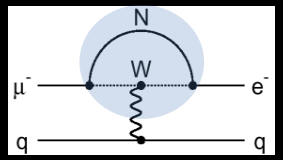
New Physics can enhance rate to observable values, either through loops or exchange of heavy intermediates particles

Loops

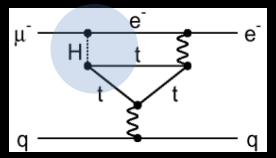
Supersymmetry



Heavy neutrino

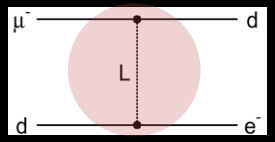


Two Higgs doublet

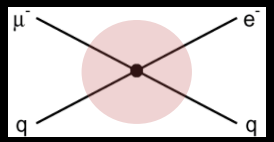


Contact interaction

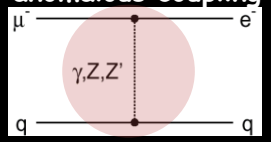
Leptoquarks



Compositness



New heavy bosons / anomalous coupling

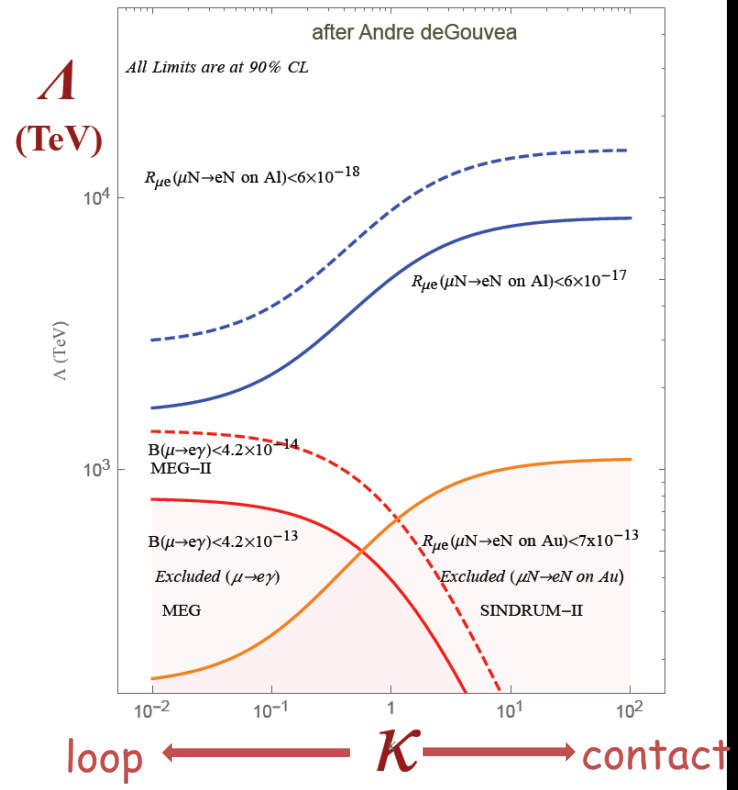


Can probe mass scales way beyond direct reach of colliders

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

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

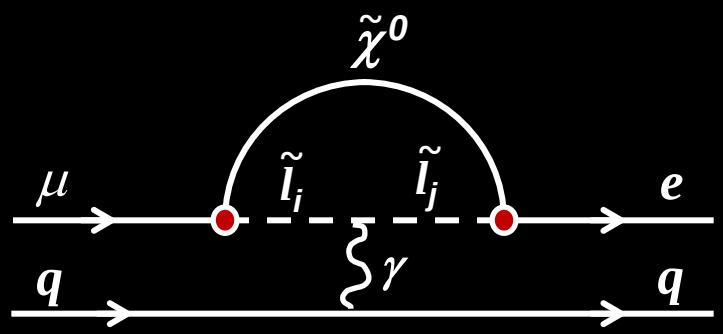
After A. de Gouvêa, P. Vogel, arXiv:1303.4097



See for example
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58
M. Raidal *et al*, Eur.Phys.J.C57:13-182,2008
A. de Gouvêa, P. Vogel, arXiv:1303.4097

CLFV and SUSY

Probe Supersymmetry (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.

Complementarity between measurements

SUSY models

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

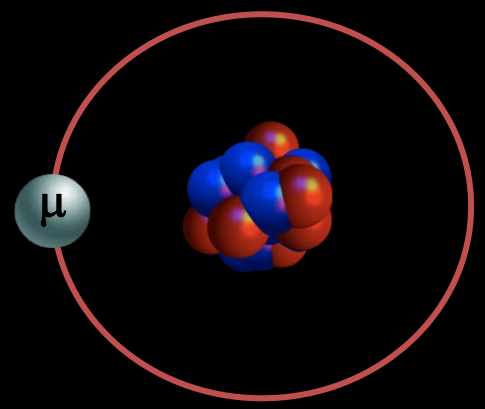
Altmannshofer, Buras, *et al*, **Nucl.Phys.B830:17-94, 2010**

Muon-to-electron conversion : experimental concept

Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

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

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



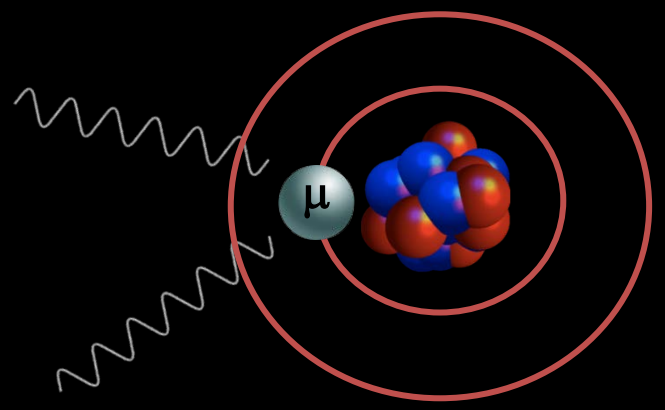
Muon is captured by Al nucleus

Muon-to-electron conversion : experimental concept

Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

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

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



Muon quickly cascades to 1s orbit (~ps), emitting x-ray in the process.

Measure x-ray spectrum to estimate number of muon captures

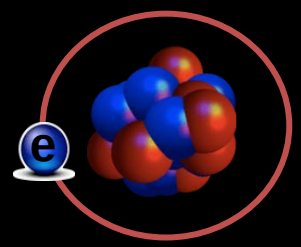
Muon-to-electron conversion : experimental concept

Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

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

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

Muon converts into an electron

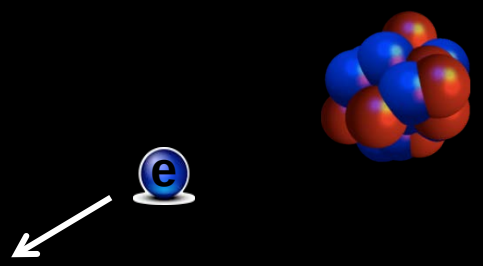


Muon-to-electron conversion : experimental concept

Neutrinoless muon-to-electron conversion in the Coulomb field of a nucleus

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

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



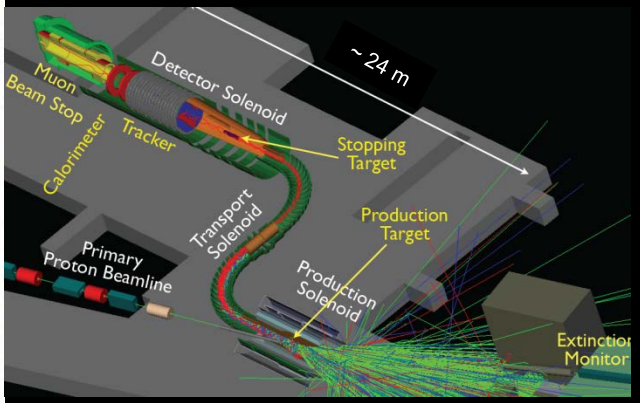
Experimental signature:

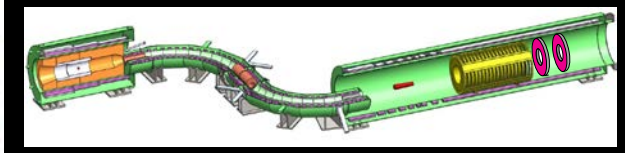
One single mono-energetic electron of 105 MeV for Al nucleus

Coherent process, the nucleus remains intact

Mu2e at Fermilab

Mu2e experiment



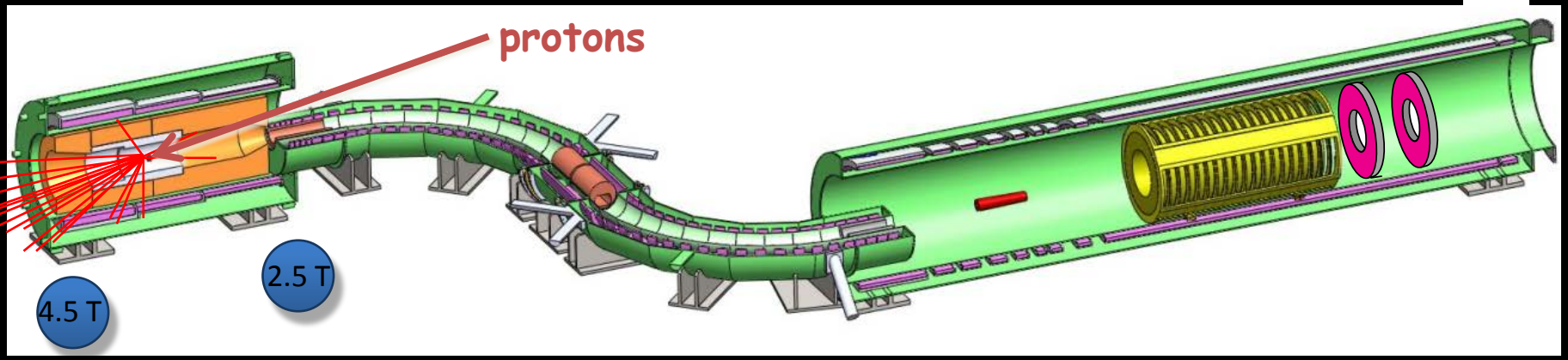


We need both an accelerator complex that can produce a pulsed muon beam
and
an experiment that can detect the conversion signal with the required sensitivity

Muon campus at Fermilab. Bonus: you're not too far from the cafeteria…

Production Target / Solenoid (PS)

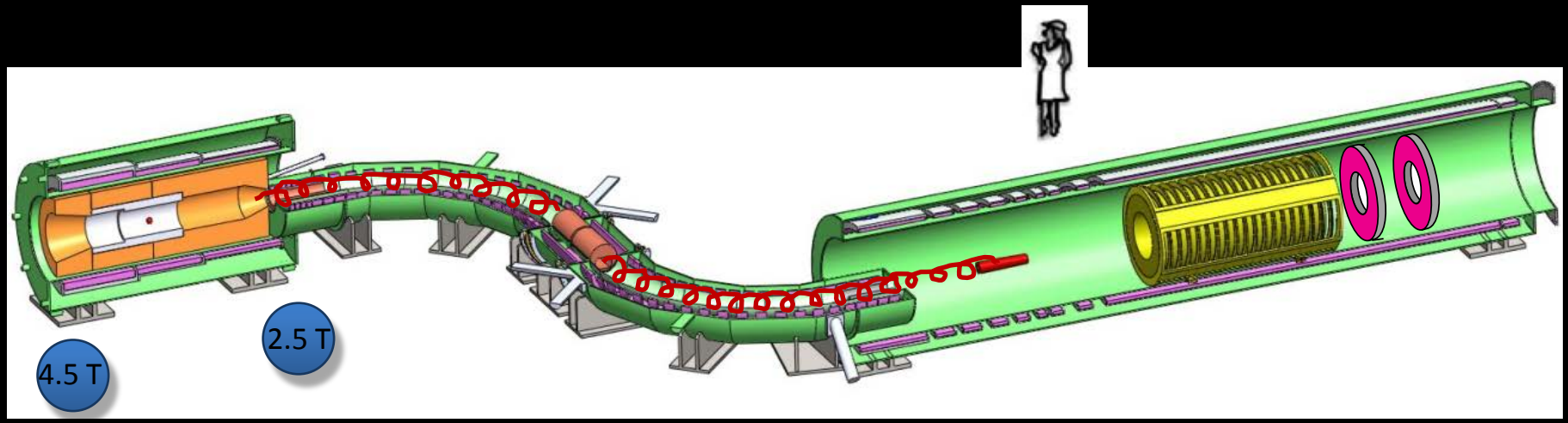
- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid → high muon intensity



Mu2e overview

Production Target / Solenoid (PS)

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid → high muon intensity



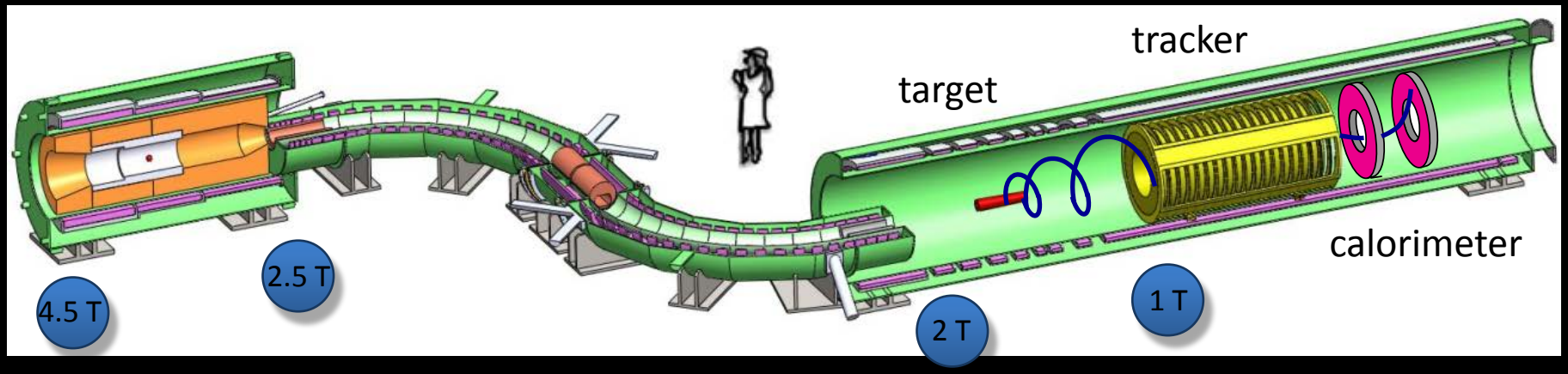
Transport Solenoid (TS)

- Collimator selects low momentum, negative muons
- Antiproton absorber
- The S shape eliminates photons and neutrons

Mu2e overview

Production Target / Solenoid (PS)

- Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid → high muon intensity



Transport Solenoid (TS)

- Collimator selects low momentum, negative muons
- Antiproton absorber
- The S shape eliminates photons and neutrons

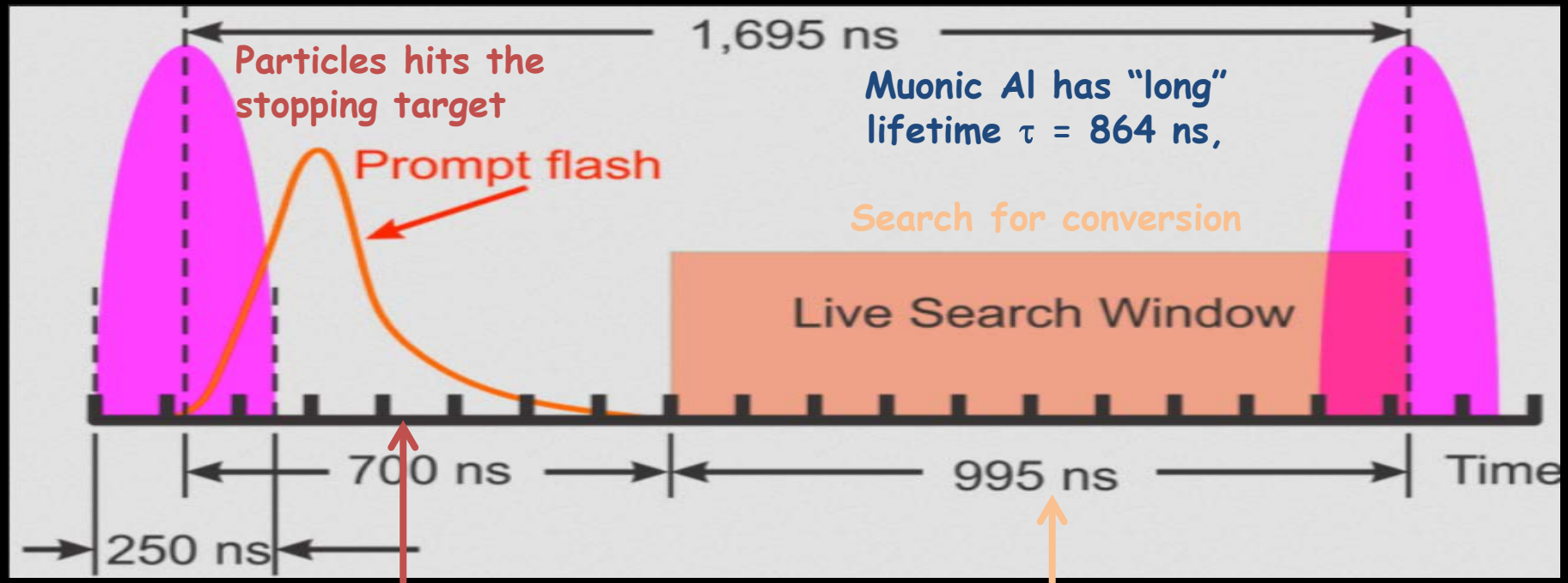
Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field "reflects" downstream conversion electrons emitted upstream, improving efficiency

Pulsed beam and delayed search window

Proton beam hits target

Next bunch after 1700 ns



Prompt background like radiative pion capture decreases rapidly (~10^{11} reduction after 700 ns)

Mostly muon decay in orbit background

Pulsed beam with beam extinction between bunches and delayed search window reduces prompt backgrounds like $\pi^- N \rightarrow \gamma N^*$, $\gamma \rightarrow e^+e^-$ and $\pi^- N \rightarrow e^+e^- N^*$.

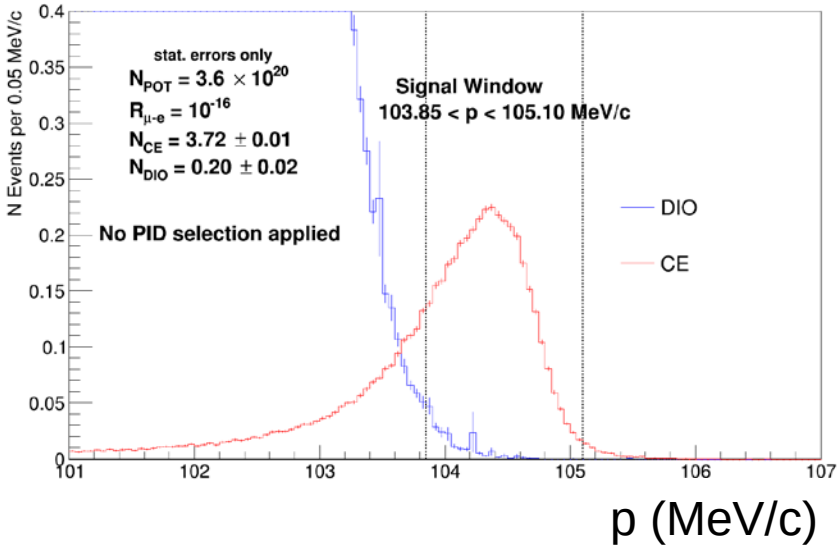
Expected sensitivity

3 years running period with 1.2×10^{20} protons on target per year

Estimated background

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	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	0.092 ± 0.020
	Total	0.37 ± 0.10

Reconstructed e^- momentum



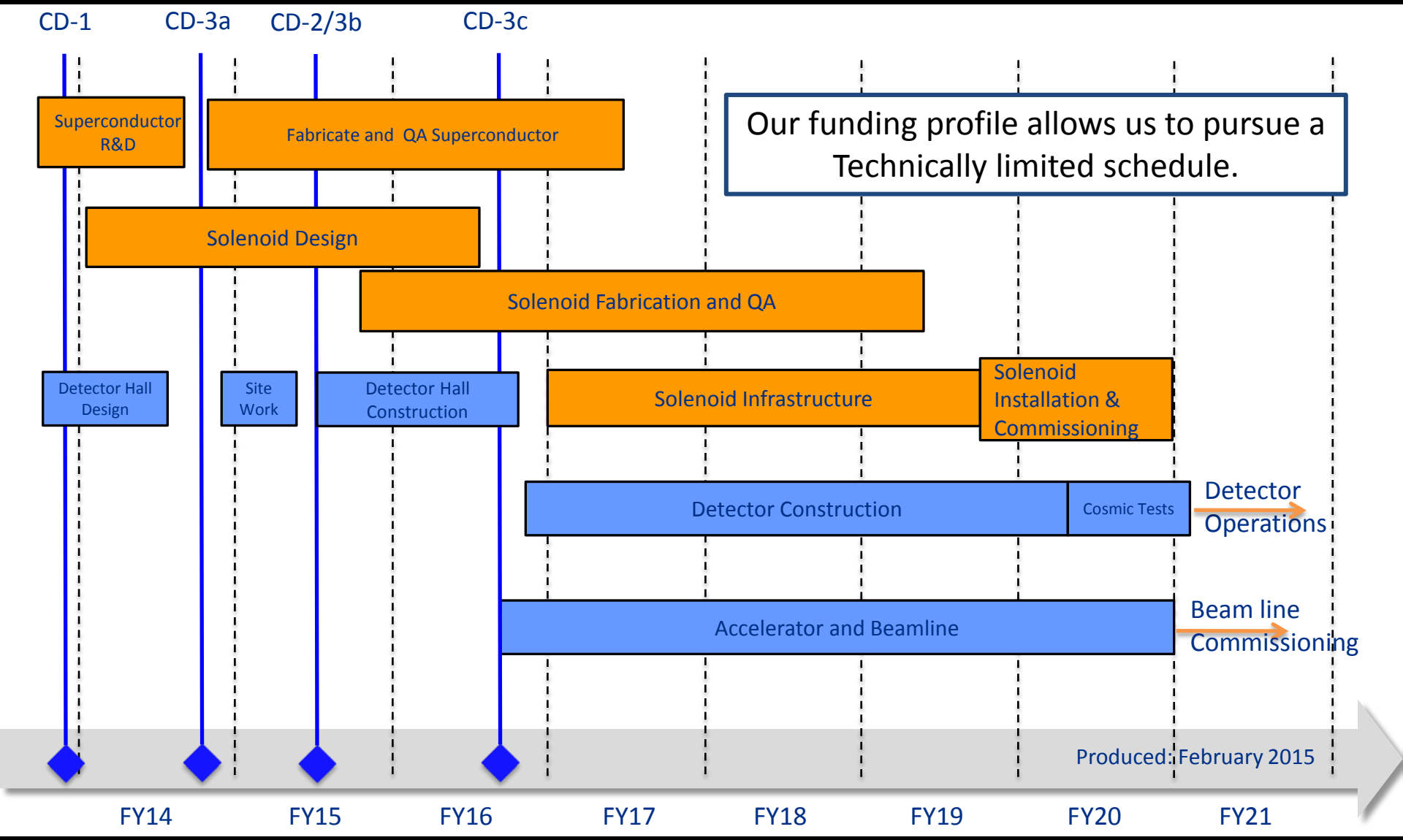
Bottom line:

Almost background free: background < 0.5 event

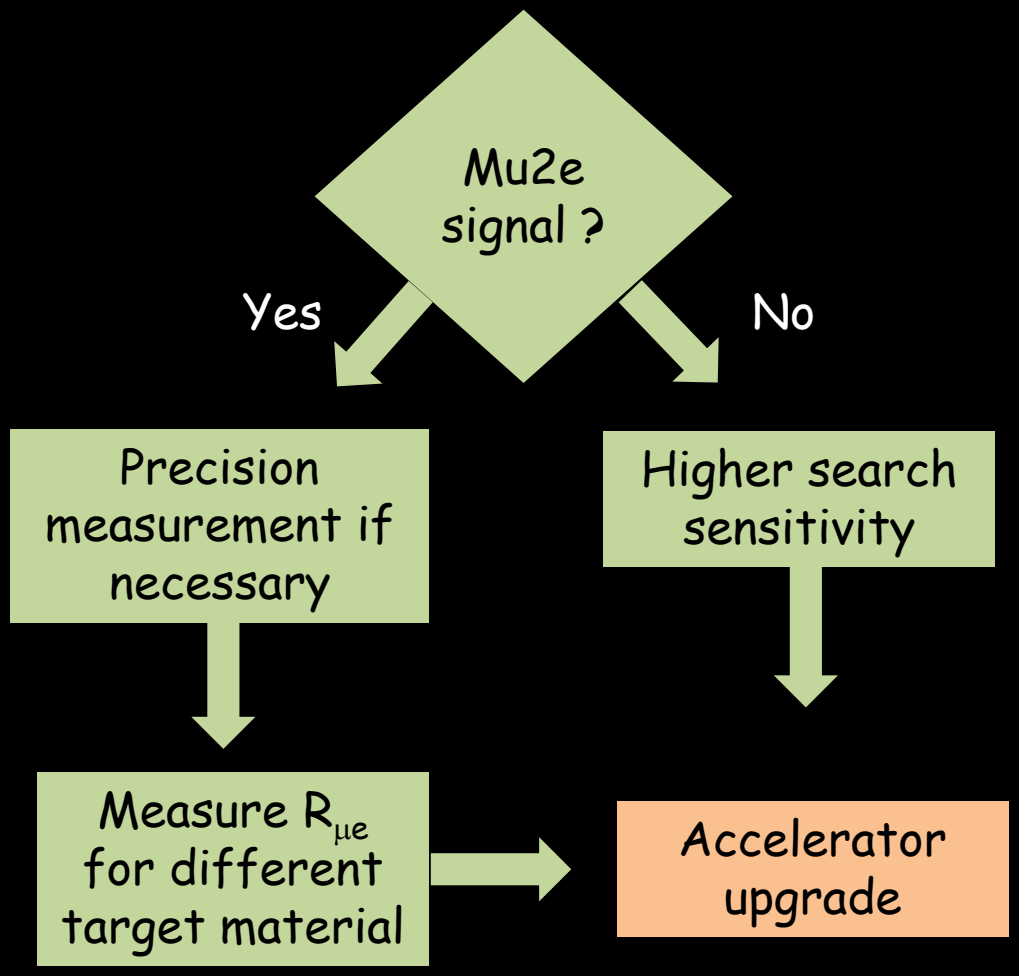
Single event sensitivity: $R_{\mu e} = 2.9 \times 10^{-17}$ (goal is 2.5×10^{-17})

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

Mu2e schedule



What is next?



A next generation Mu2e experiment makes sense in all scenarios

Study underlying New Physics if signal is seen **or** improve sensitivity

We will need more protons ! Upgrade accelerator (PIP II project at Fermilab)

Upgrade Mu2e experiment, see arXiv:1307.1168

Conclusion

Mu2e will search for muon-to-electron conversion

Discovery capabilities over a wide range of models

Improves sensitivity by factor 10^4

Complementary to the LHC, flavor and neutrino physics

Operations should begin by the beginning of the next decade (that's not that far), join us if you are interested …

Bonus material

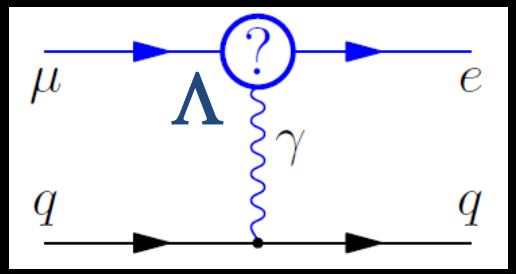
Model independent parametrization

Generic parametrization of CLFV process into two terms

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

"Electromagnetic" (Loop)

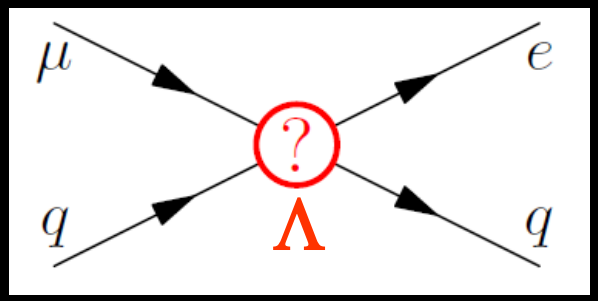
κ=0



Contributes to $\mu \to e\,\gamma$

κ

"Contact"



κ=∞

No contribution to $\mu \to e\,\gamma$

Two parameters

- κ: relative contribution of the contact term
- Λ: effective mass scale of New Physics

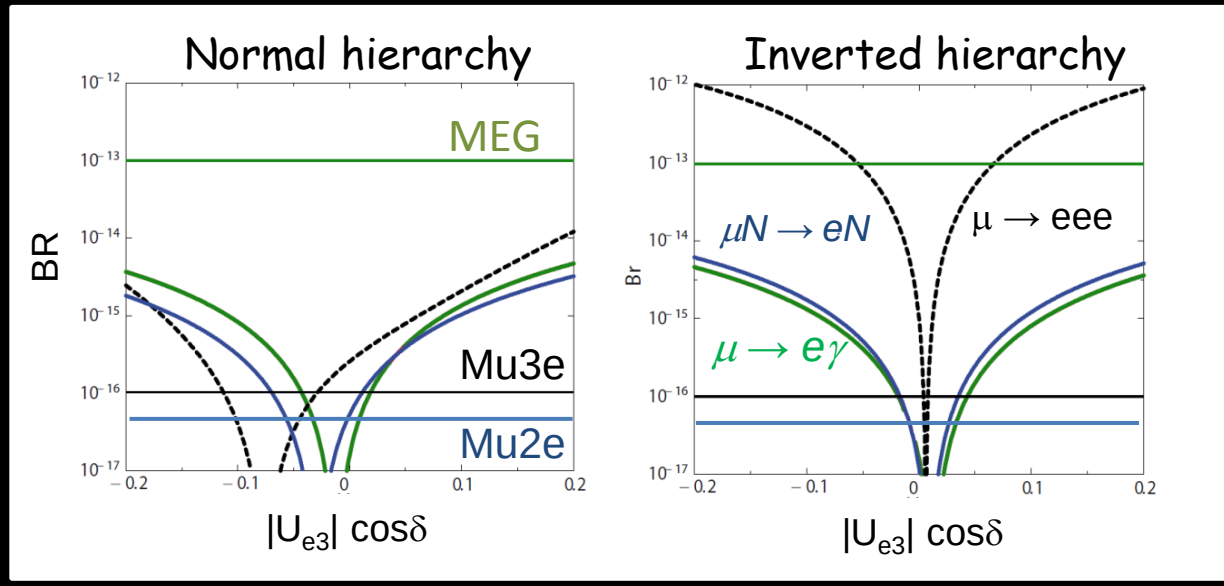
Each New Physics model predicts a different value of κ → model diagnosis

A few more models…

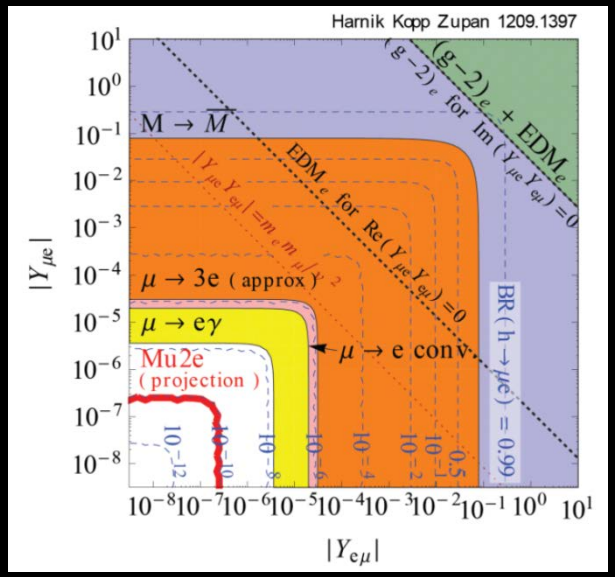
M. Kakizaki et al., PLB566 (2003) 210

Higgs triplet model

Dependence on neutrino mass hierarchy and CP-violating phase δ

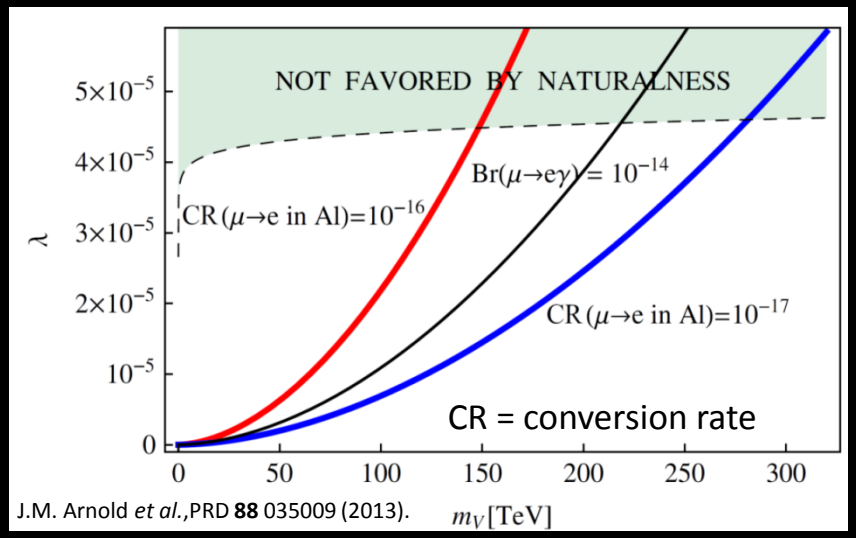


Flavor violating Yukawa couplings



R. Harnik *et al.*, JHEP **3**, 26 (2013).

Leptoquarks

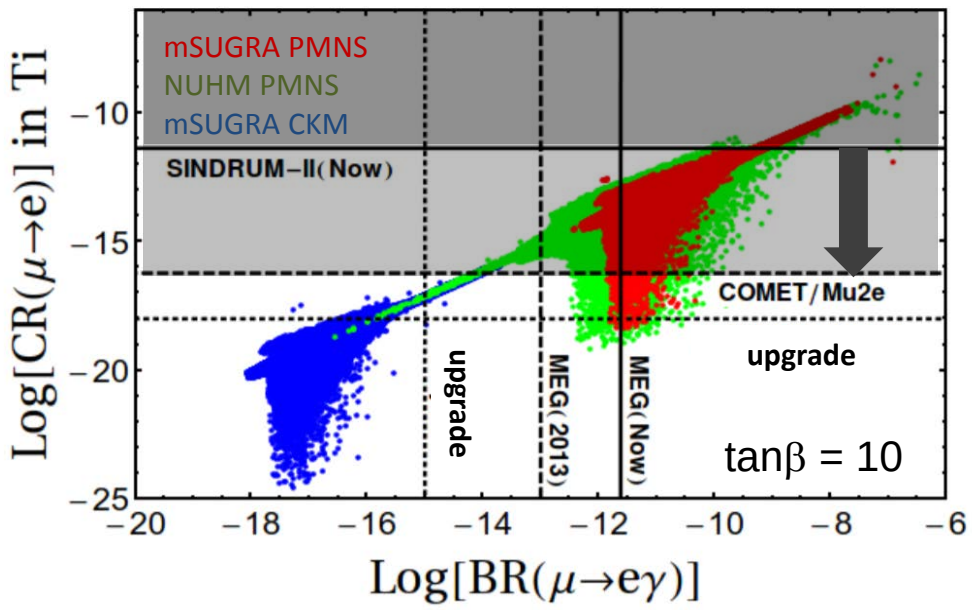


J.M. Arnold *et al.*,PRD **88** 035009 (2013).

SUSY model diagnosis

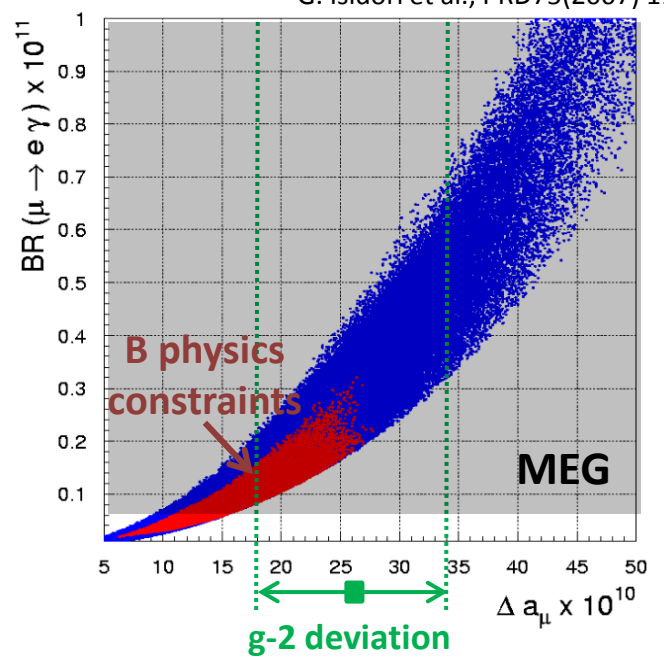
Measurement of CLFV in different channels has powerful discrimination power over the model parameters and is complementary to searches at the LHC

SUSY GUT Models



L. Calibbi et al., JHEP 1211 (2012) 040

G. Isidori et al., PRD75(2007) 115019



a_μ (EXP): PRD73(2006) 072
a_μ(SM): Hagiwara *et al.*, JPG38(2011)085003

Current best limits – SINDRUM II at PSI

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

SINDRUM II at PSI

Final results on Au:

$R_{\mu e} < 7 \times 10^{-13}$ @ 90% CL

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

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