A High-Sensitivity Search for Charged Lepton Flavor Violation at Fermilab

Mu2e Experiment

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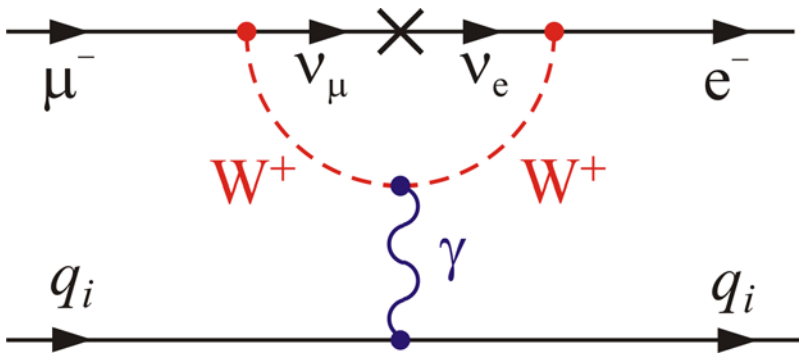
Currently:

50 scientists

11 institutions

Why Search for Charged Lepton Flavor Violation?

- In Standard Model not there
- Neutrino mass discovery ⇨ CLFV exists, but unobservable at: ~10^{-52}

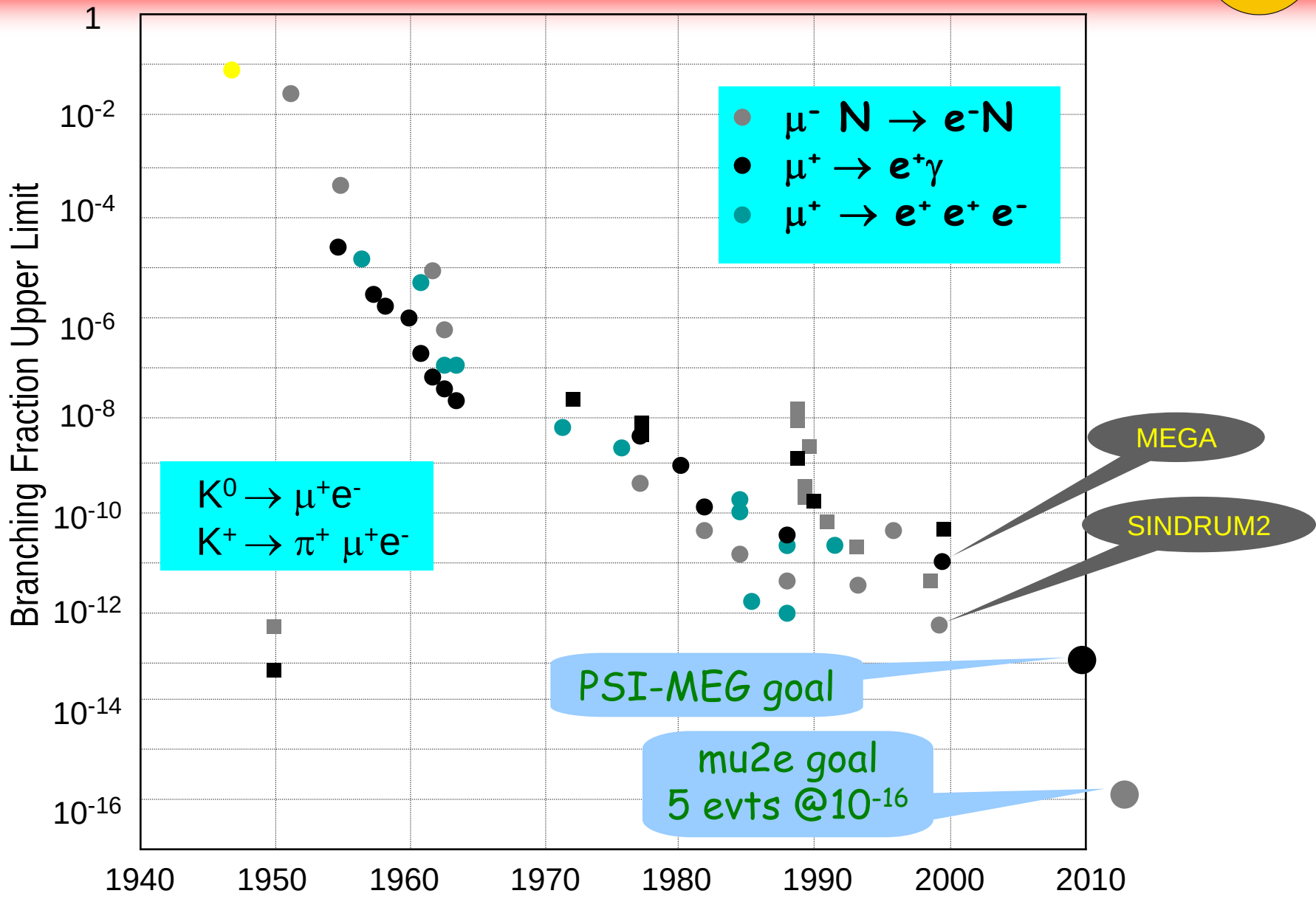


$$\mu^- N \rightarrow e^- N$$

- Any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally
  - ⇨ such sensitivities that probe mass scales unavailable by direct searches
  - ⇨ sensitivities that should allow favored beyond-the-standard-model theories to be tested
  - ⇨ mu2e proposes to reach a single-event sensitivity of $R_{\mu e} = 2\times10^{-17}$

$$R_{\mu e} = \frac{\Gamma(\mu^- Al \rightarrow e^- Al)}{\Gamma(\mu^- Al \rightarrow \nu_\mu Mg)}$$

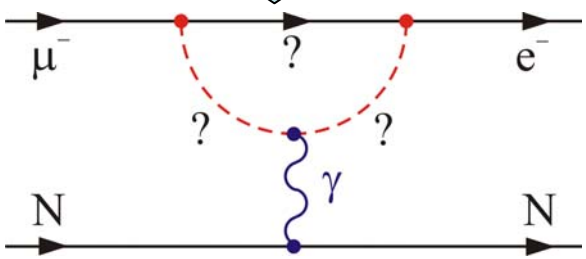
Goal is to improve $\mu^- N \rightarrow e^- N$ sensitivity by ~10,000

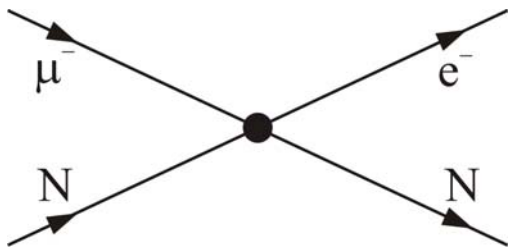


CLFV Probes Large Mass Scales

Model independent CLFV Lagrangian:

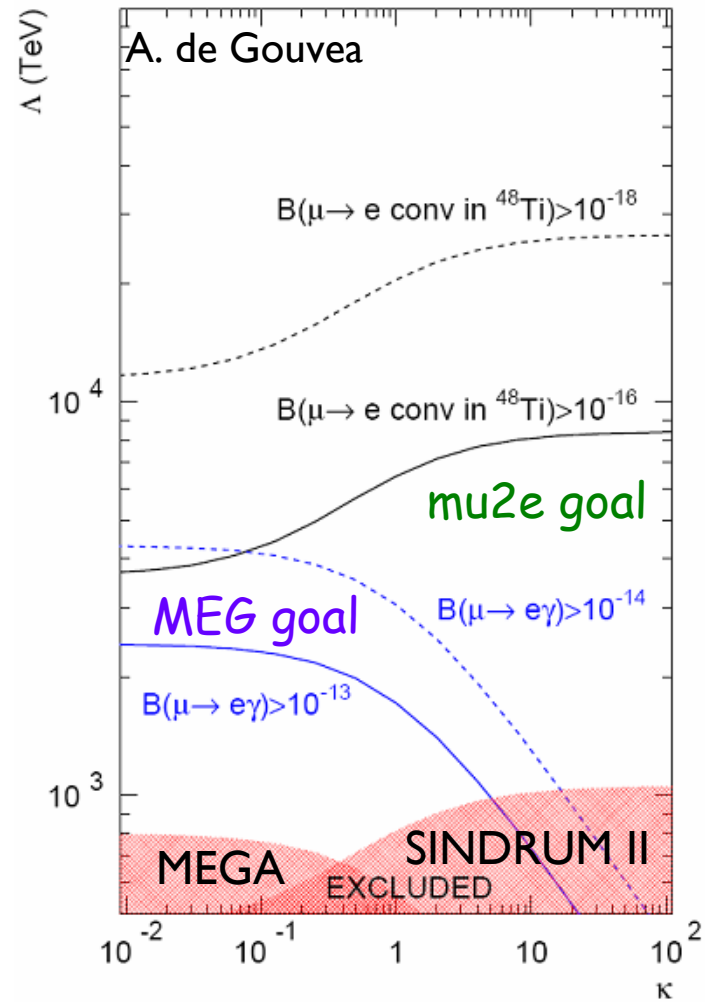
$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\overline{\mu}R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\overline{q}_L\gamma^\mu q_L$$





κ<<1
magnetic moment type operator

κ>>1
four-fermion interaction



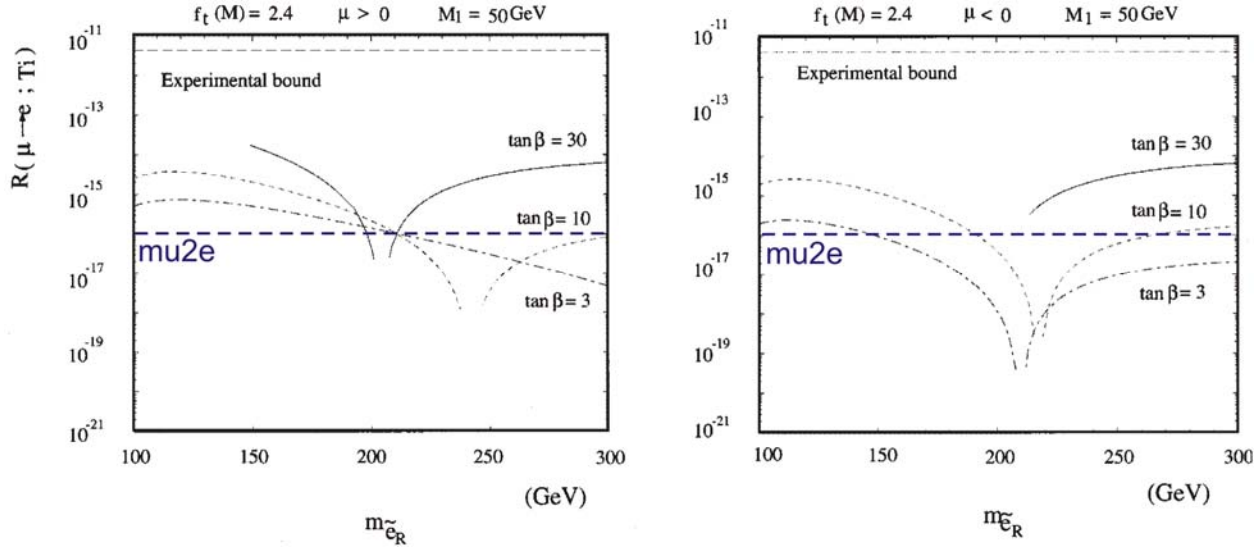
κ<<1 : μ → eγ rate ~300X μN → eN rate

κ>>1 : μN → eN rate many orders of magnitude greater than μ → eγ rate

Both types of searches need be done!

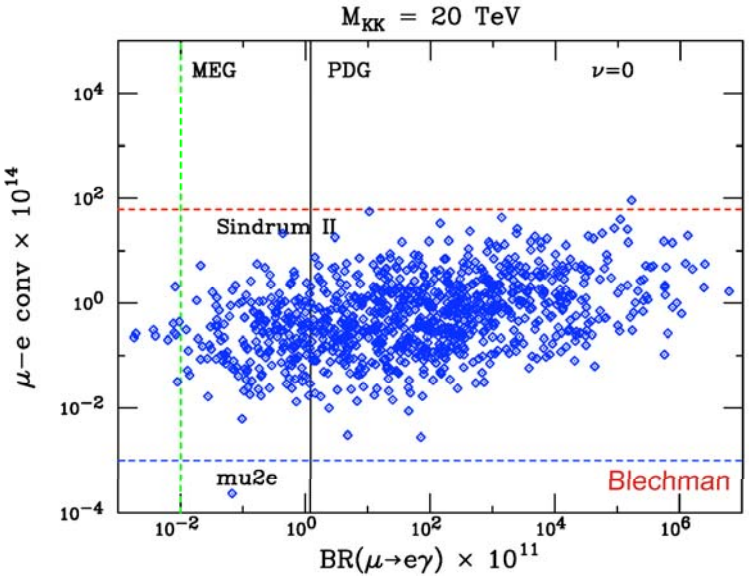
Specific Model Examples

SU(5) GUT SUSY ($\kappa << 1$)

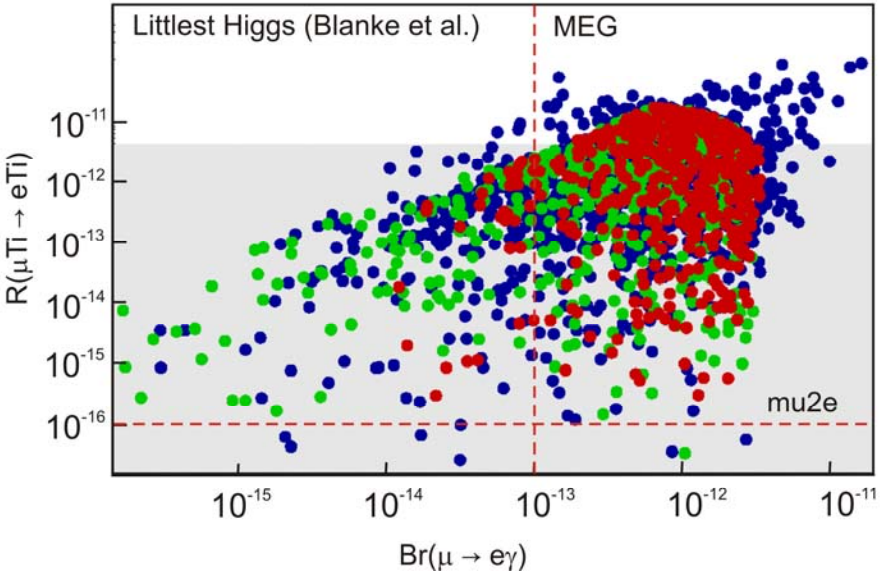


- Examples with $\kappa << 1$ (no $\mu \to e\gamma$ signal):
  - Leptoquarks
  - Z-prime
  - Compositeness
  - Heavy neutrino

Randall-Sundrum ($\kappa \approx 1$)

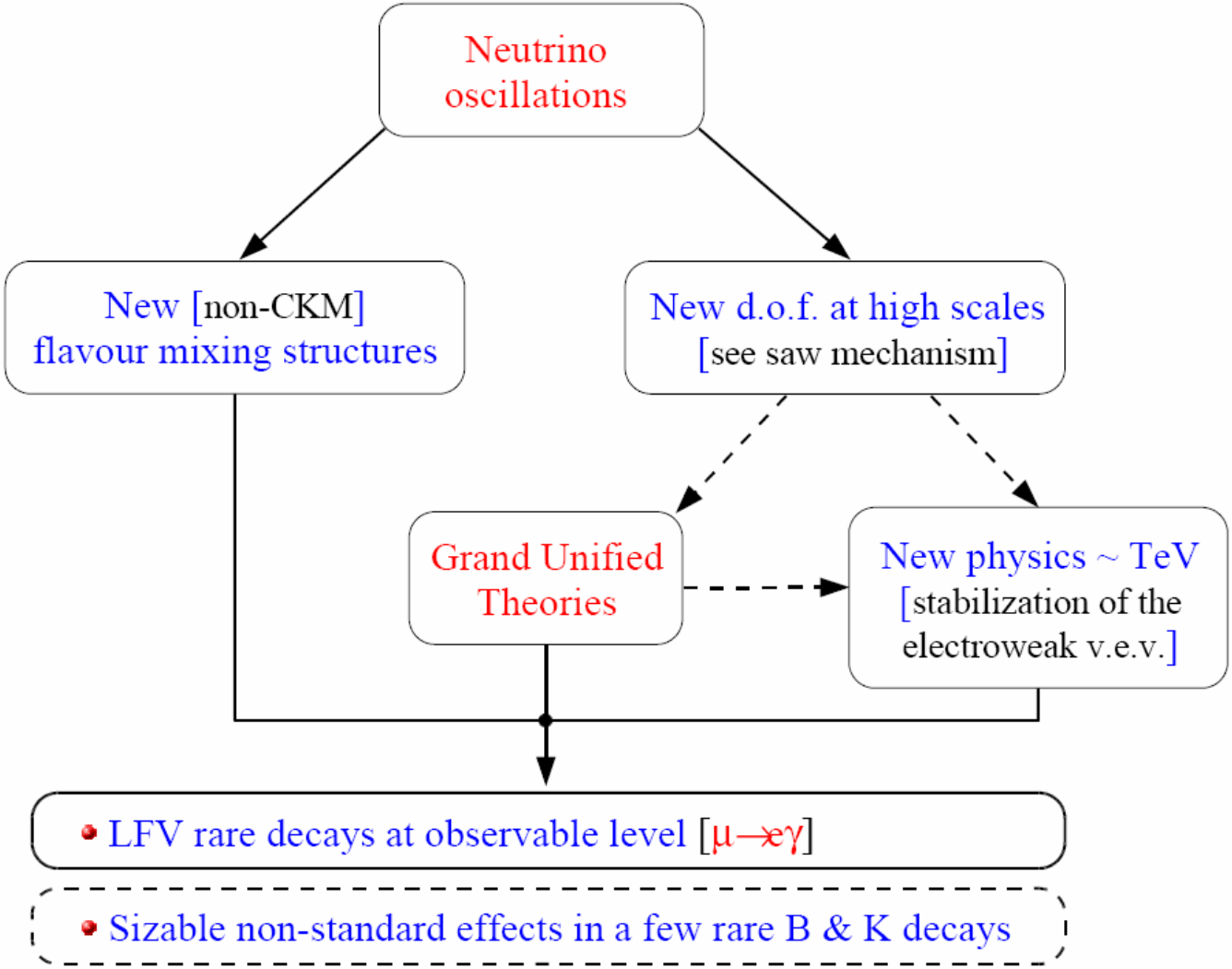


Littlest Higgs ($\kappa \approx 1$)



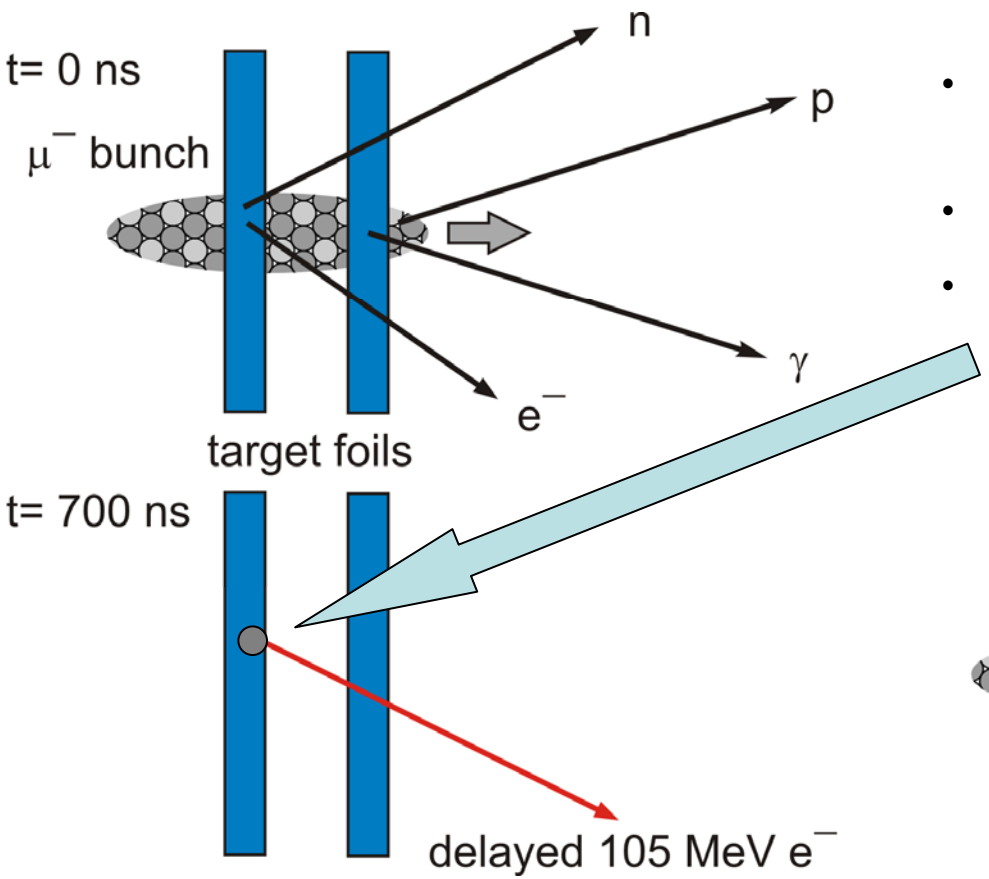
Isidori's Summary Talk from HQL-2006

G. Isidori – Future prospects in flavour physics — *Heavy Quarks & Leptons 2006*

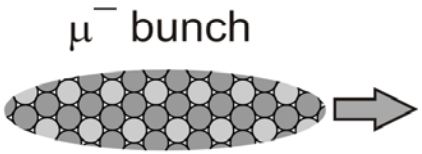


Signal

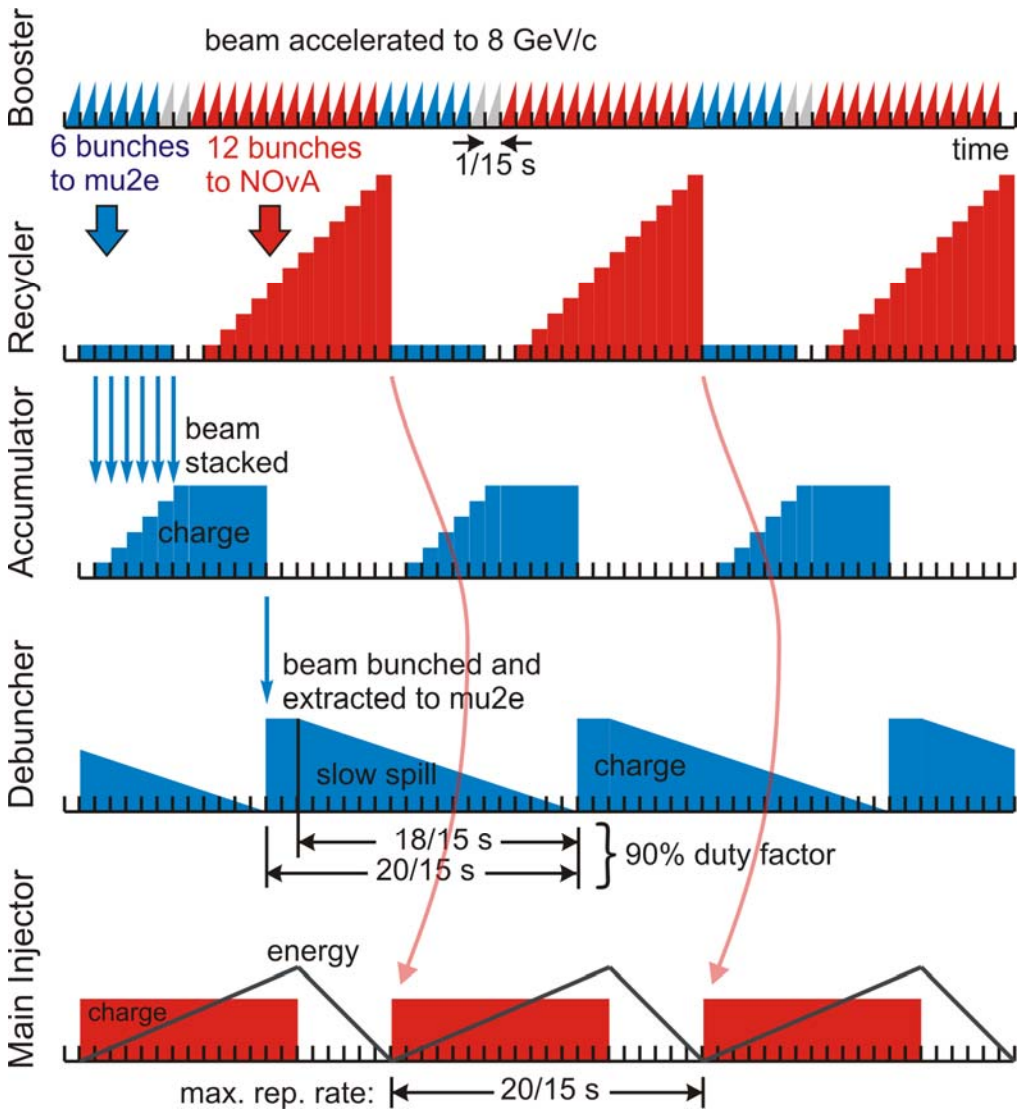
Single, monoenergetic electron with E=105 MeV, coming from the target, produced ~1 μs ($\tau_{\mu Al}$ ~ 880ns) after the "μ" bunch hits the target foils



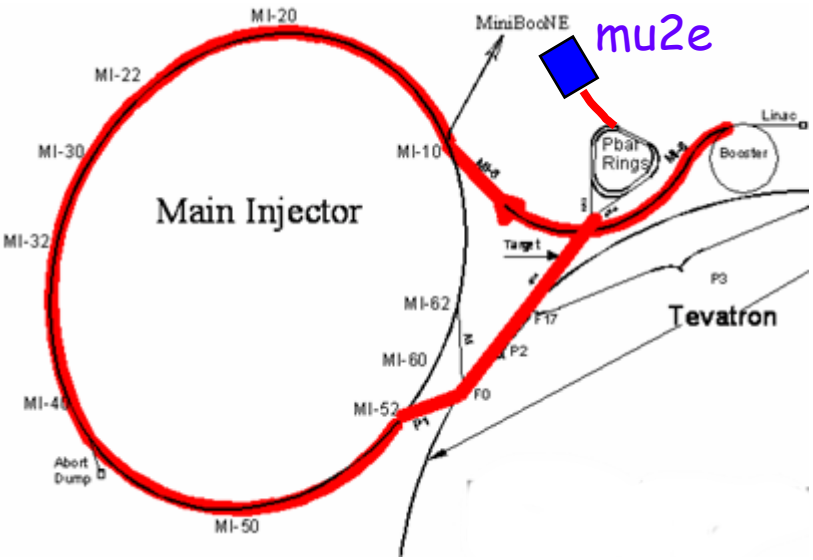
- Need good energy resolution: ≲ 0.200 MeV
- Need particle ID
- Need a bunched beam with less than 10^{-9} contamination between bunches



Producing ~10^{18} μ^-



Note: 8 GeV booster energy is the optimal energy for mu2e muon beam

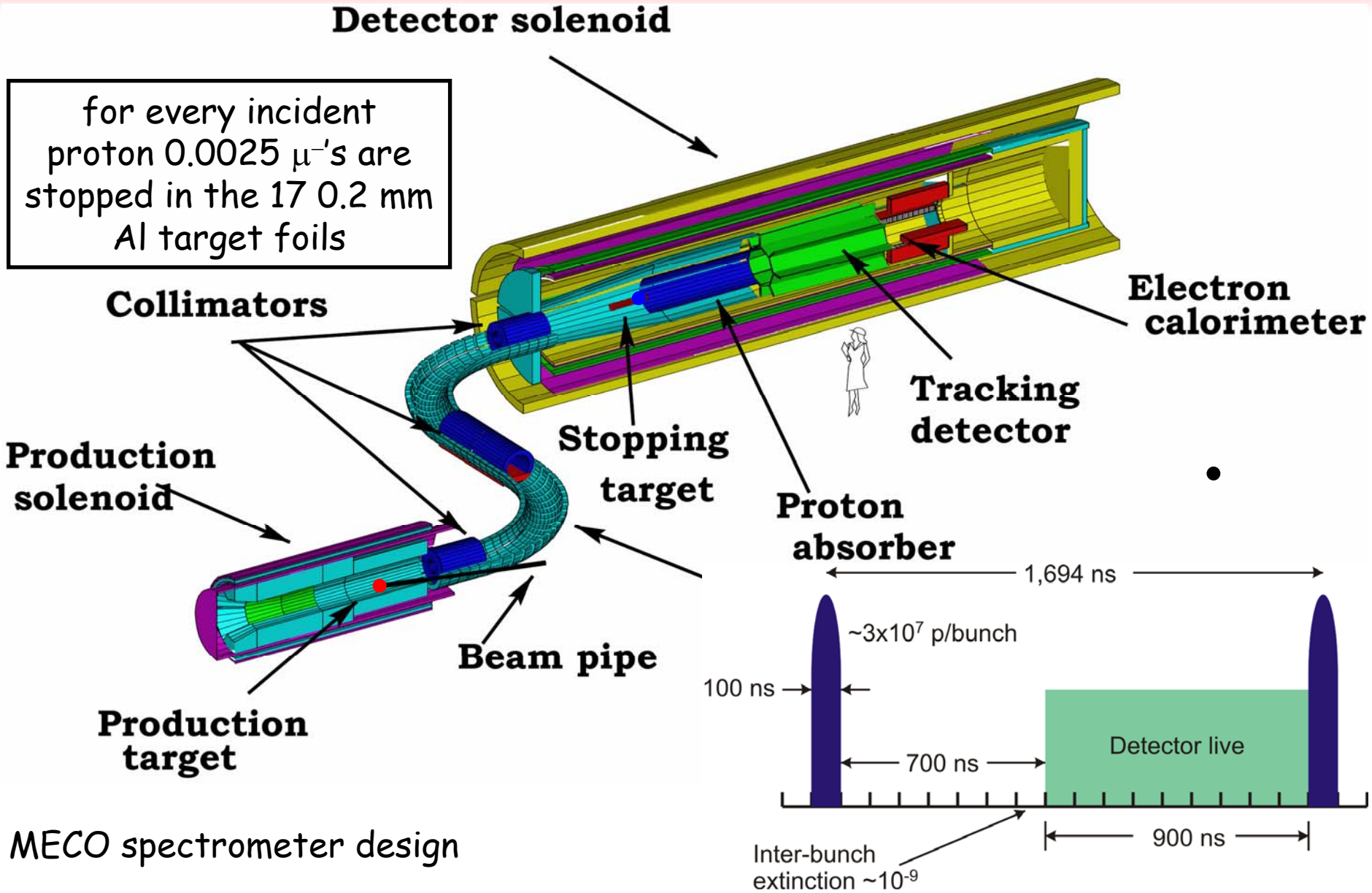


6 batches x 4×10^{12} /1.33 s x 2×10^{7} s/yr

= 3.6×10^{20} protons/yr

mu2e Muon Beam and Detector

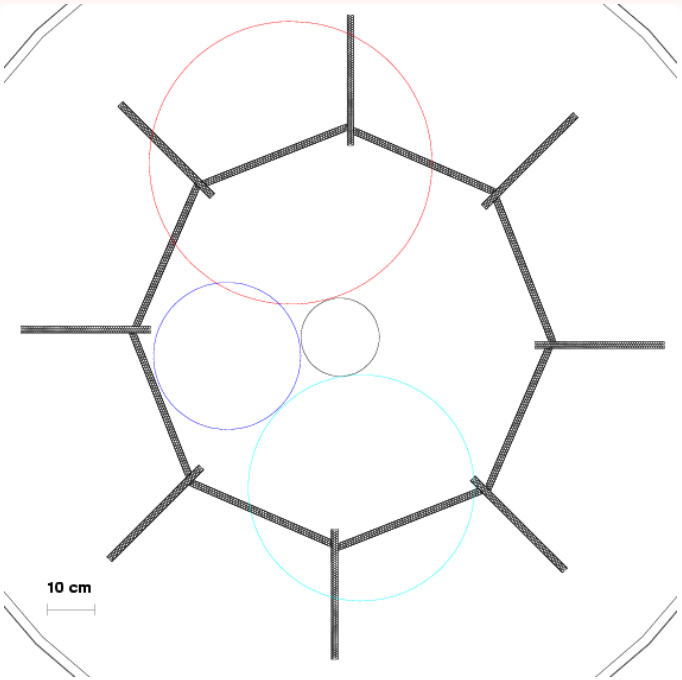
for every incident proton 0.0025 μ^-'s are stopped in the 17 0.2 mm Al target foils

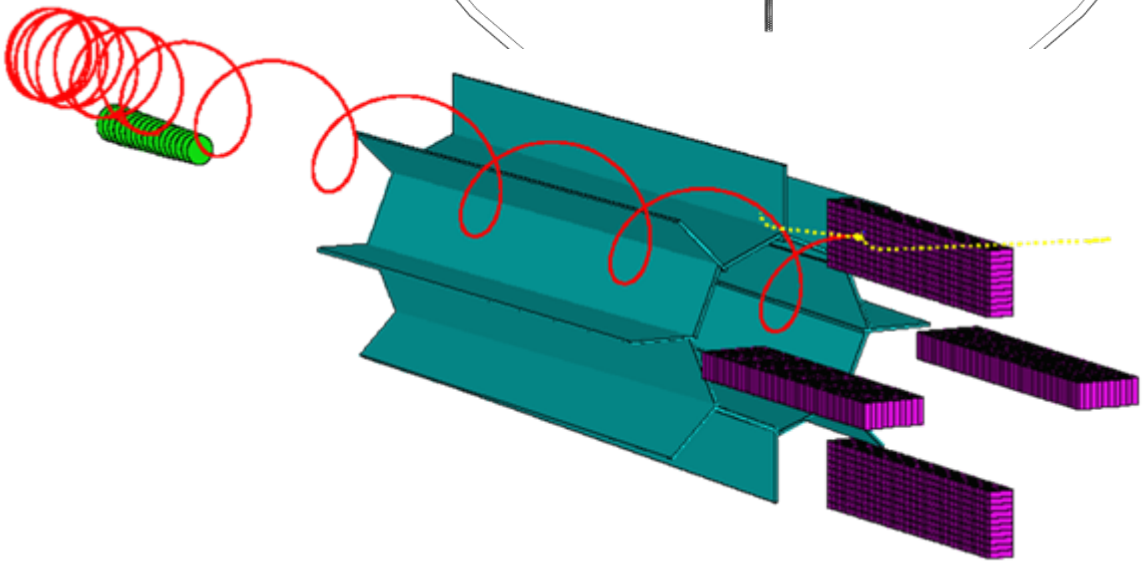


MECO spectrometer design

mu2e Detector

- Target is in graded solenoidal field which reflects decay electrons downstream
- Detector must withstand high instantaneous rates from bunches hitting target foils
- Rates are suppressed by designing detector to be insensitive to major backgrounds
- Magnetic spectrometer
  - 3,000 5 mm straw tubes with cathode strip readout
  - 17,000 cathode strips
  - 0.2 MeV/c resolution
- Electromagnetic calorimeter
  - 1,200 $PbOW_4$ crystals
  - provides particle ID
  - provides trigger
  - $\sigma(e)/E \sim 3.5\%$





What we Get

Proton flux	1.8×10^{13} p/s
Running time	2×10^{7} s
Total protons	3.6×10^{20} p/yr
μ^- stops/incident proton	0.0025
μ^- capture probability	0.60
Time window fraction	0.49
Electron trigger efficiency	0.90
Reconstruction and selection efficiency	0.19
Detected events for $R_{\mu e} = 10^{-16}$	4.5

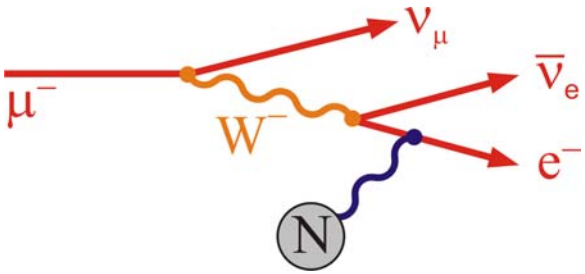
Three Types of Backgrounds

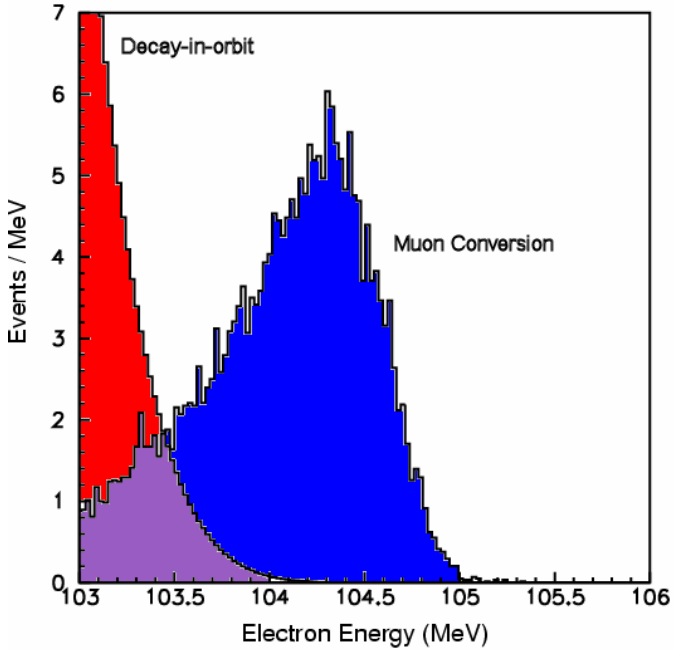
1. Stopped Muon Induced Backgrounds

- Muon decay in orbit:

  $\mu^- \rightarrow e^- \nu\nu$

  - $E_e < m_\mu c^2 - E_{NR} - E_B$
  - $N \sim (E_0 - E_e)^5$
  - Fraction within 3 MeV of endpoint ~ 5×10^{-15}
  - Defeated by good energy resolution

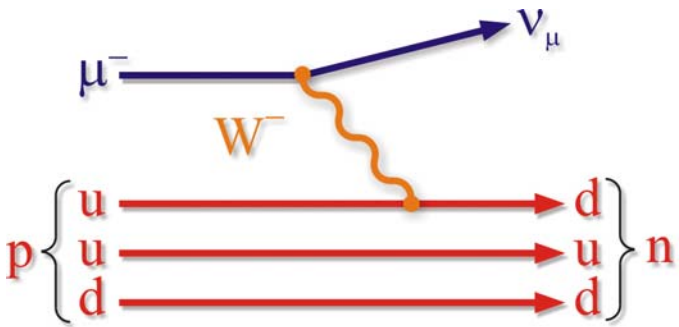




- Radiative muon capture:

  $\mu^- Al \rightarrow \gamma\nu Mg$

  - γ endpoint 102.5 MeV
  - 10^{-13} produce e^- above 100 MeV



Backgrounds (continued)

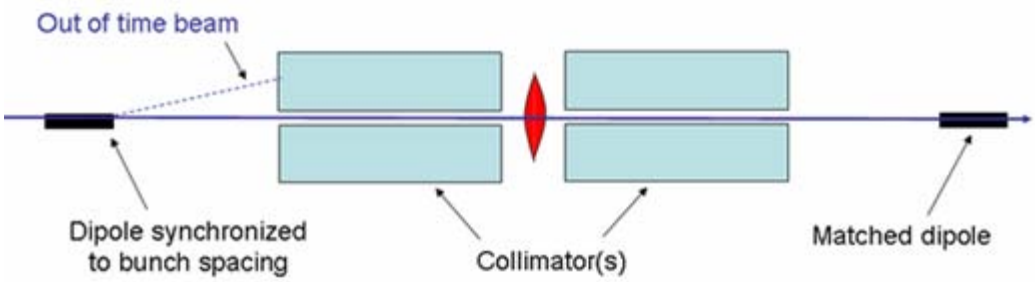
2. Beam Related Backgrounds

- Suppressed by minimizing beam between bunches
  - Need ≤ 10^{-9} extinction
  - Get 10^{-3} for free
- Muon decay in flight:

  $\mu^- \rightarrow e^- \nu\nu$
  - Since $E_e < m_\mu c^2/2$, $p_\mu > 77$ GeV/c
- Radiative π^- capture:

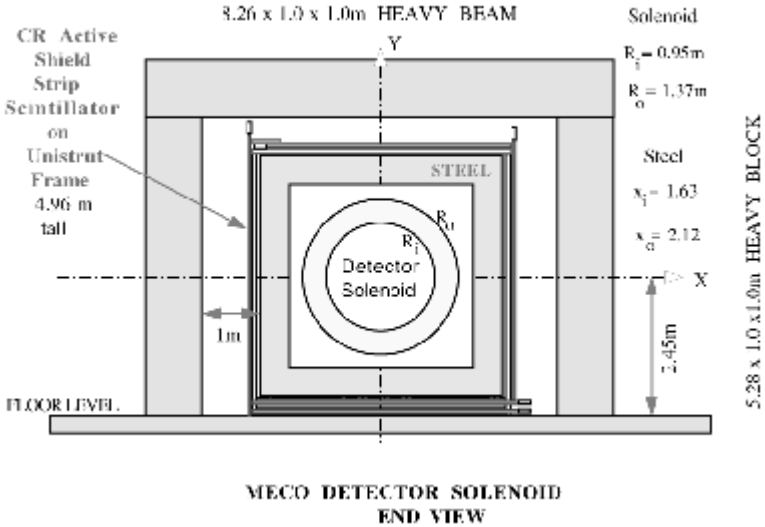
  $\pi^- N \rightarrow N^* \gamma$, $\gamma Z \rightarrow e^+ e^-$
- Beam electrons
- Pion decay in flight:

  $\pi^- \rightarrow e^- \nu_e$

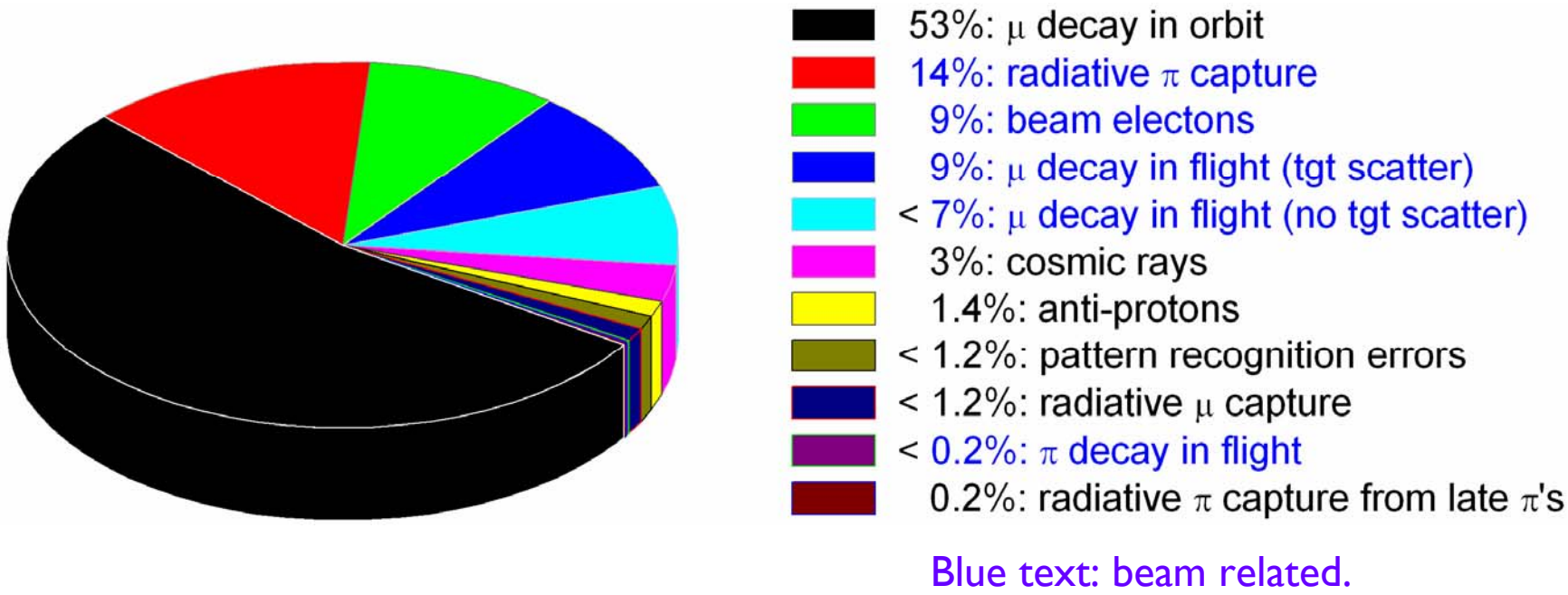


3. Time Dependent Backgrounds

- Cosmic rays
  - suppressed by active and passive shielding



Background Fractions



Roughly half of background is beam related, and half interbunch contamination related

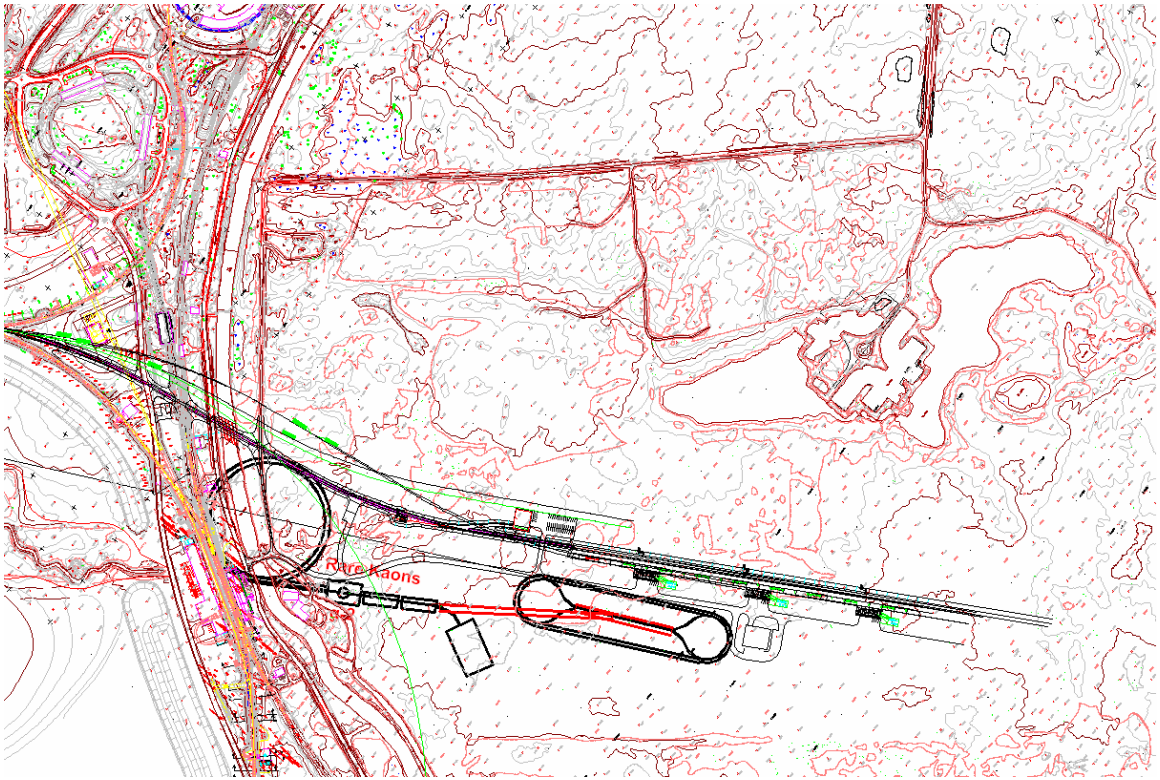
Total background per 3.4×10^{20} protons, 2×10^{7} s: 0.43 events

Signal for $R_{\mu e} = 10^{-16}$: 5 events

Going beyond 2×10^{-17} single event sensitivity

- We've designed mu2e to run at rates 3X possible using the Fermilab booster/accumulator/debuncher
- 35-year old booster cannot provide any higher rates
- Fermilab is proposing to replace booster with high-intensity proton LINAC ⇨ "Project X"

- 4 year run at 3X intensity would provide 2×10^{-18} single event sensitivity.
- To exploit the full Project X intensities to go beyond 2×10^{-18} a new muon production target and detector are needed to handle the rates and to reduce backgrounds (so sensitivity scales as $N\mu c$).



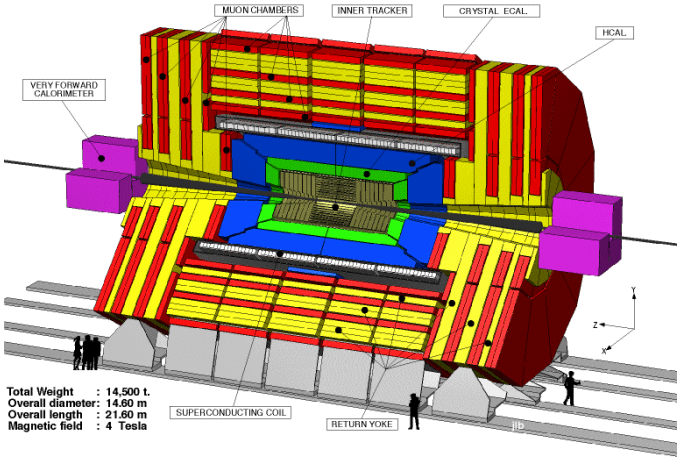
mu2e Status

1992	MELC proposed at Moscow Meson Factory
1997	MECO proposed for the AGS at Brookhaven as part of RSVP
1998-2005	intensive work on MECO technical design: magnet system costed at $58M, detector at $27M
July 2005	RSVP cancelled for financial reasons
2006	MECO subgroup + Fermilab physicists work out means to mount experiment at Fermilab
June 2007	mu2e EOI submitted to Fermilab
October 2007	LOI submitted to Fermilab
November 2007 January 2008	mu2e participates in Fermilab Project X workshop
Fall 2008	mu2e submits proposal to Fermilab
2010	technical design approval: start of construction
2014	first beam

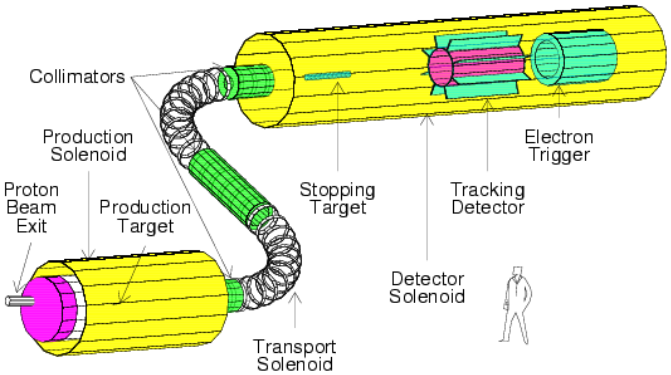
Summary

- We live in an exciting time in particle physics ⇨ we know something great, "New Physics", is just around the corner
- Two ways to look for New Physics:

Direct Searches



High-Sensitivity Searches



- All possible avenues need be explored!
- mu2e will greatly expand our window into Lepton Flavor Violation, and will perhaps have something exciting to report at some future Lake Louise meeting