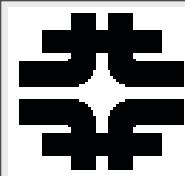
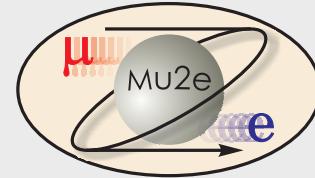


A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

R. Bernstein
FNAL



R.M. Carey, K.R. Lynch, J.P. Miller*, B.L. Roberts
Boston University



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M.A. Martens, D.V. Neuffer, M. Popovic, E.J. Prebys, M. Syphers, R.E. Ray, H.B. White, K. Yonehara, C.Y. Yoshikawa
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Muons, Inc.

J.L. Popp
City University of New York, York

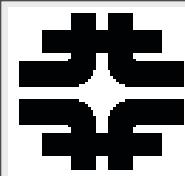
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M. Corcoran
Rice University

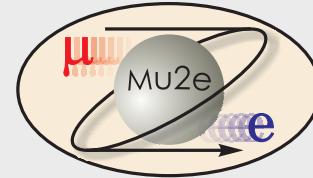
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Syracuse University

M.A. Bychkov, E.C. Dukes, E. Frlez, R.J. Hirosky, A.J. Norman, K.D. Paschke, D. Pocanic
University of Virginia

64 collaborators
16 institutions



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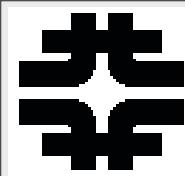
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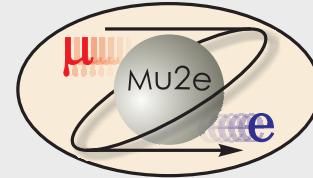
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many MECO
collaborators with
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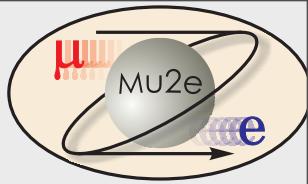
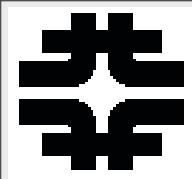
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added since June 2008
now international

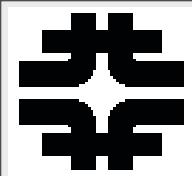
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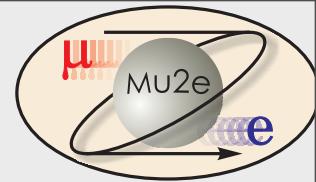


Outline

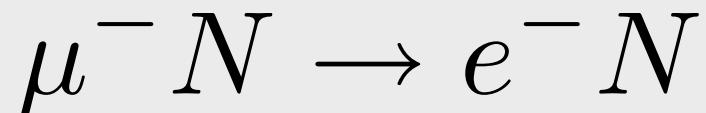
- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e



What is μe Conversion?



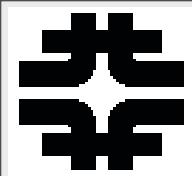
muon converts to electron in the presence of a nucleus



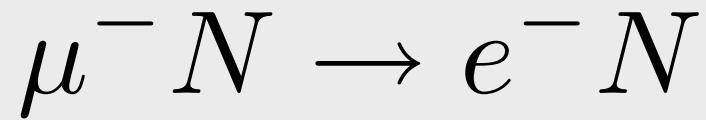
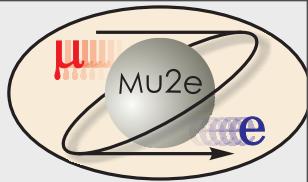
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

- Charged Lepton Flavor Violation (CLFV)
- Related Processes:

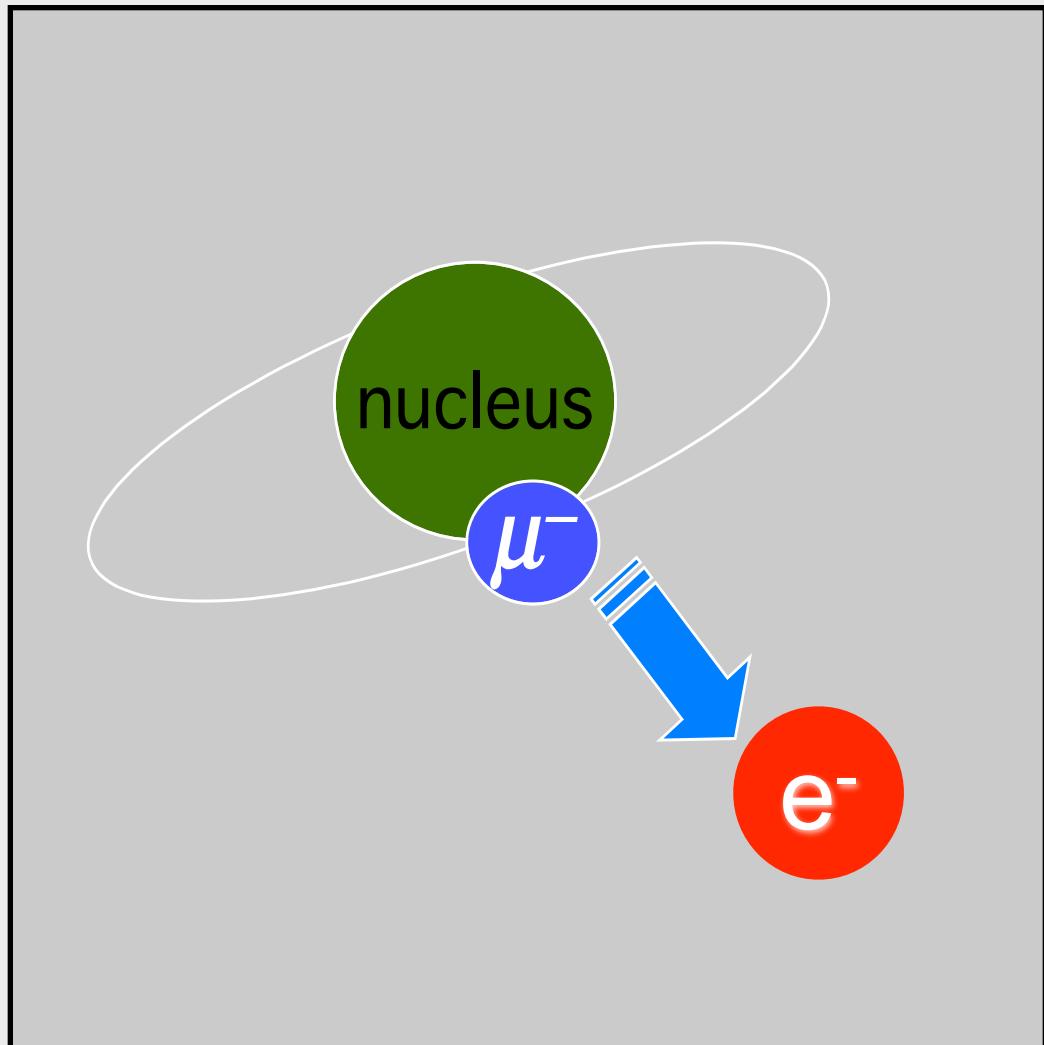
μ or $\tau \rightarrow e\gamma$, e^+e^-e , $K_L \rightarrow \mu e$, and more

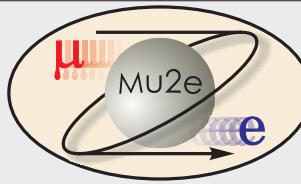
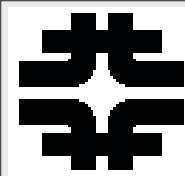


Experimental Signal



- A Single Monoenergetic Electron
- If $N = Al$, $E_e = 105.$ MeV
 - electron energy depends on Z





“Who ordered that?”

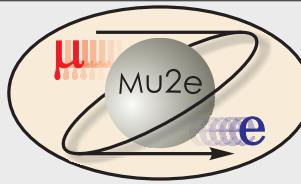
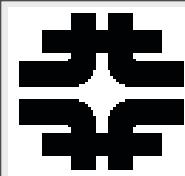


– I.I. Rabi, 1936

After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another ν , in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)

→ same as GIM mechanism!



“Who ordered that?”



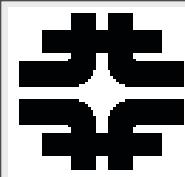
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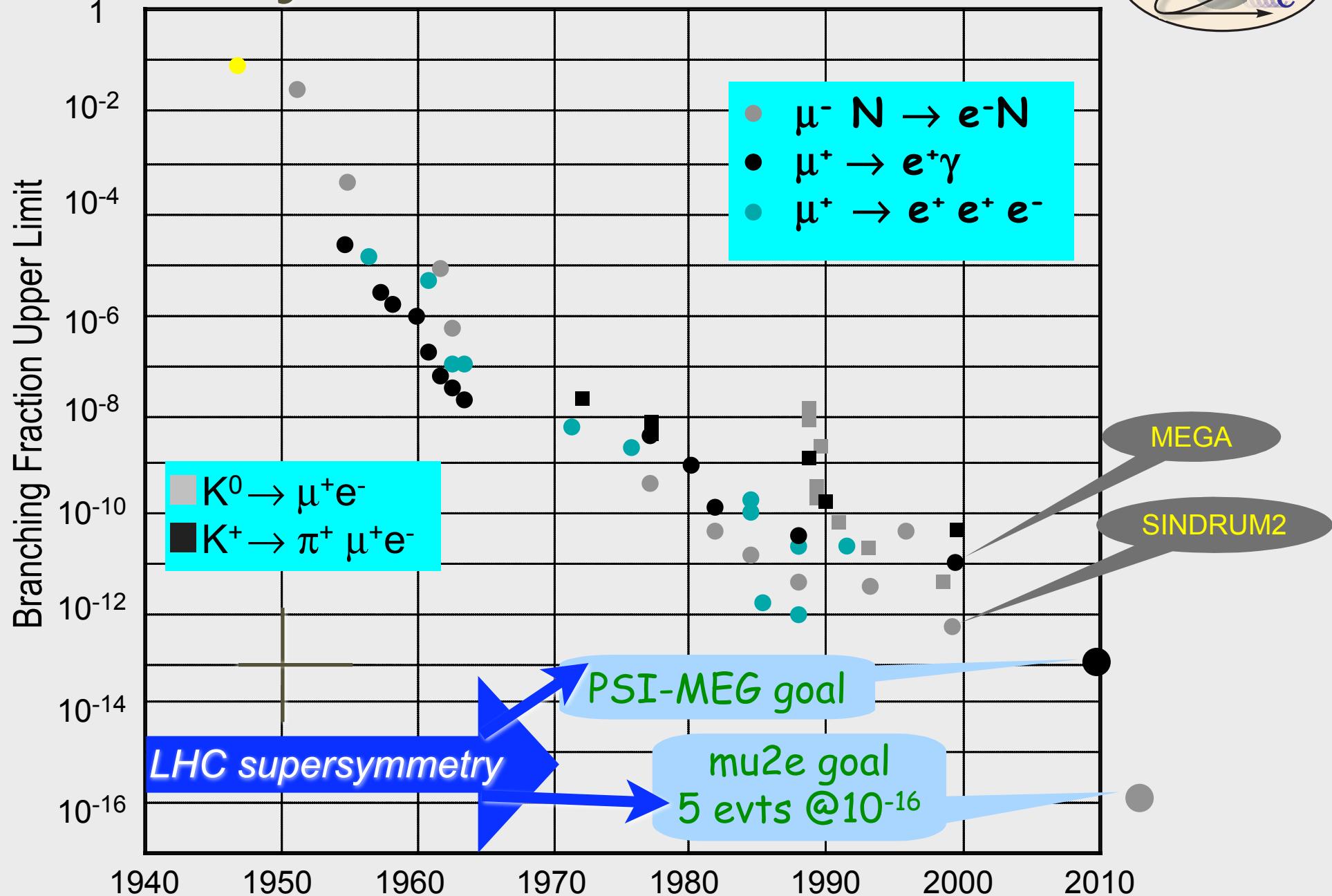
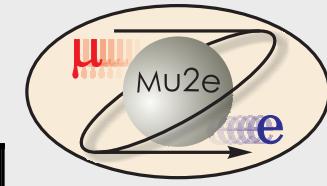
- expect $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another ν , in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)

→ same as GIM mechanism!

¹Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.



History of CLFV Searches





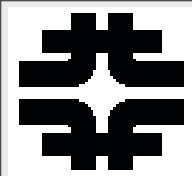
Endorsed in US Roadmap

FNAL has proposed muon-electron conversion as a flagship program for the next decade

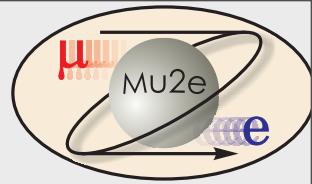
Strongly endorsed by P5:

“The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. **The panel recommends pursuing the muon-to-electron conversion experiment... under all budget scenarios considered by the panel**”

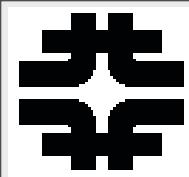
Mu2e is a central part of the future US program



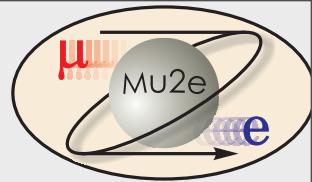
Current and Planned Lepton Flavor Violation Searches



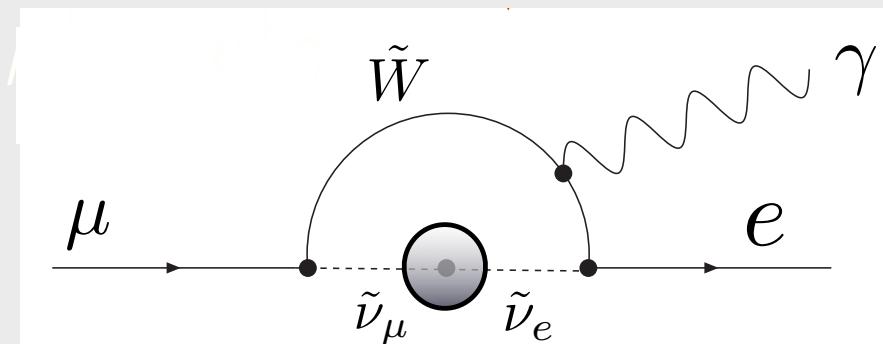
- Neutrino Oscillations!
- CLFV in SUSY
- LFV current limits at $\tau \rightarrow \mu\gamma$ and $B^0 \rightarrow \mu e$
- MEG and $\mu \rightarrow e\gamma$
- Mu2e:
 - Strengths of muon-electron conversion
 - Complementarity to other processes



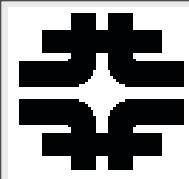
Neutrino Oscillations and Muon-Electron Conversion



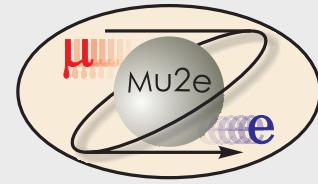
- ν's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



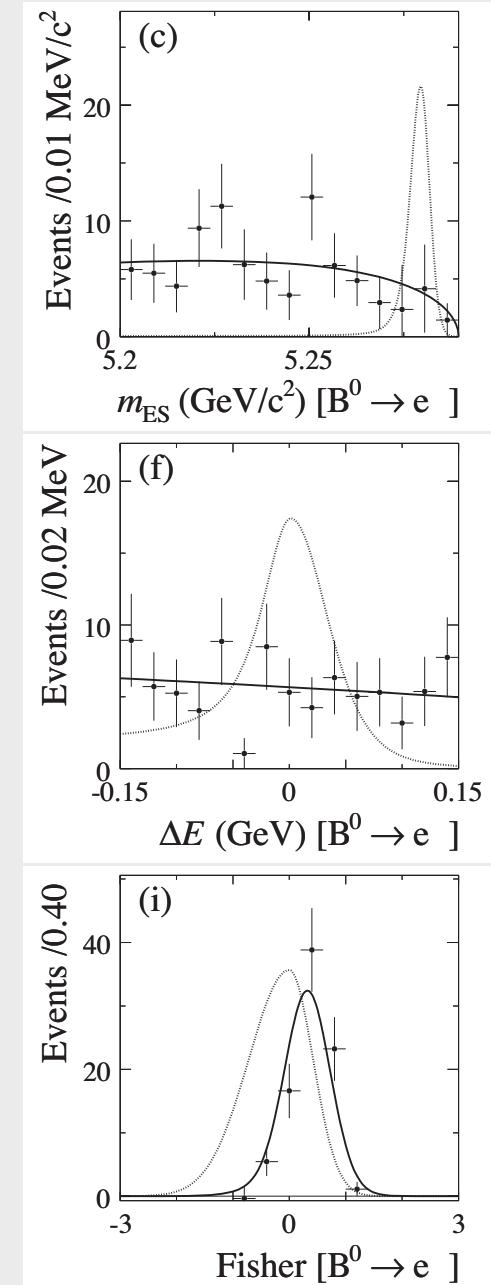
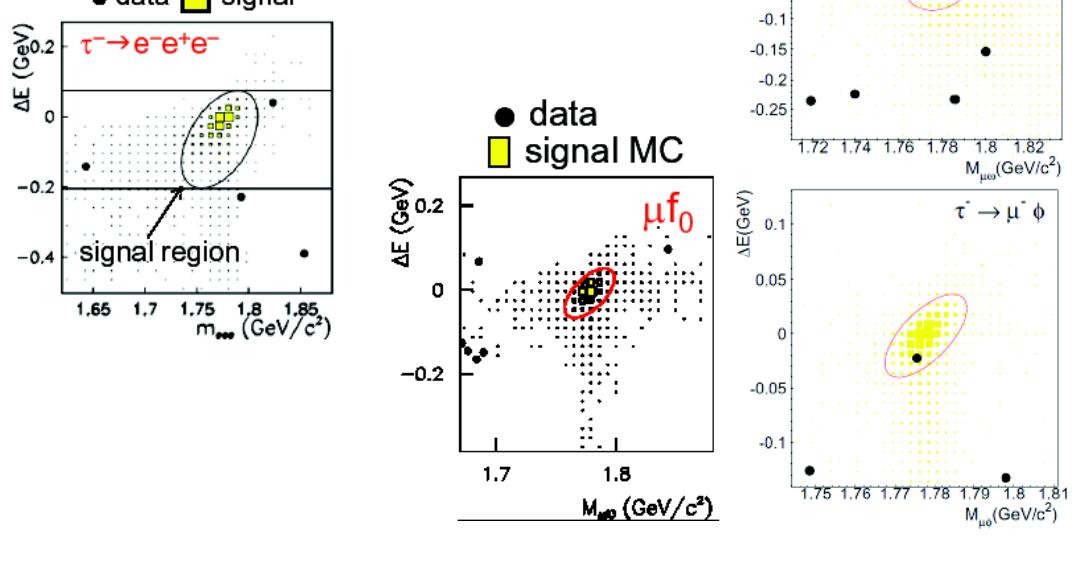
$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54} \quad \frown \smile$$



Lepton Flavor Violation

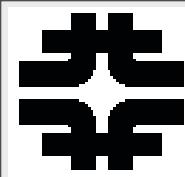


τ LFV at Belle



BABAR
Pub-07057
 $< 9 \times 10^{-8}$

Belle and BABAR

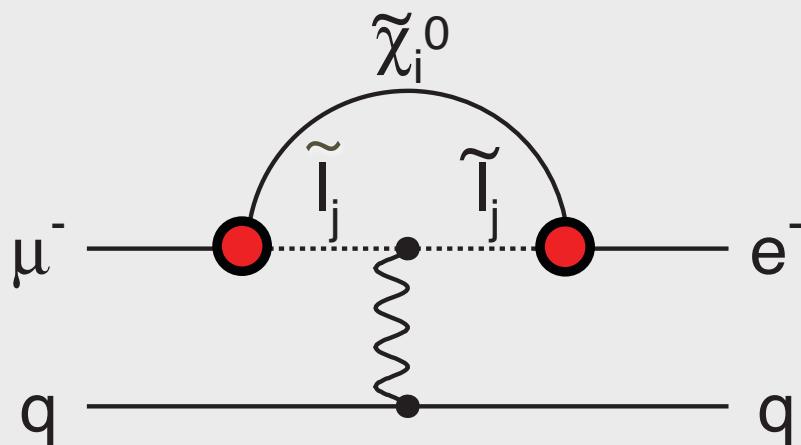


LFV, SUSY and the LHC



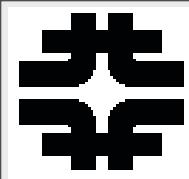
Supersymmetry

rate $\sim 10^{-15}$

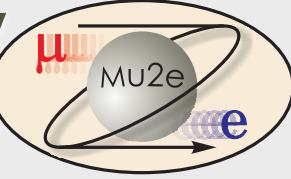


**Access SUSY
through loops:**

***signal of
Terascale at
LHC implies
~50 event signal
in this
experiment***

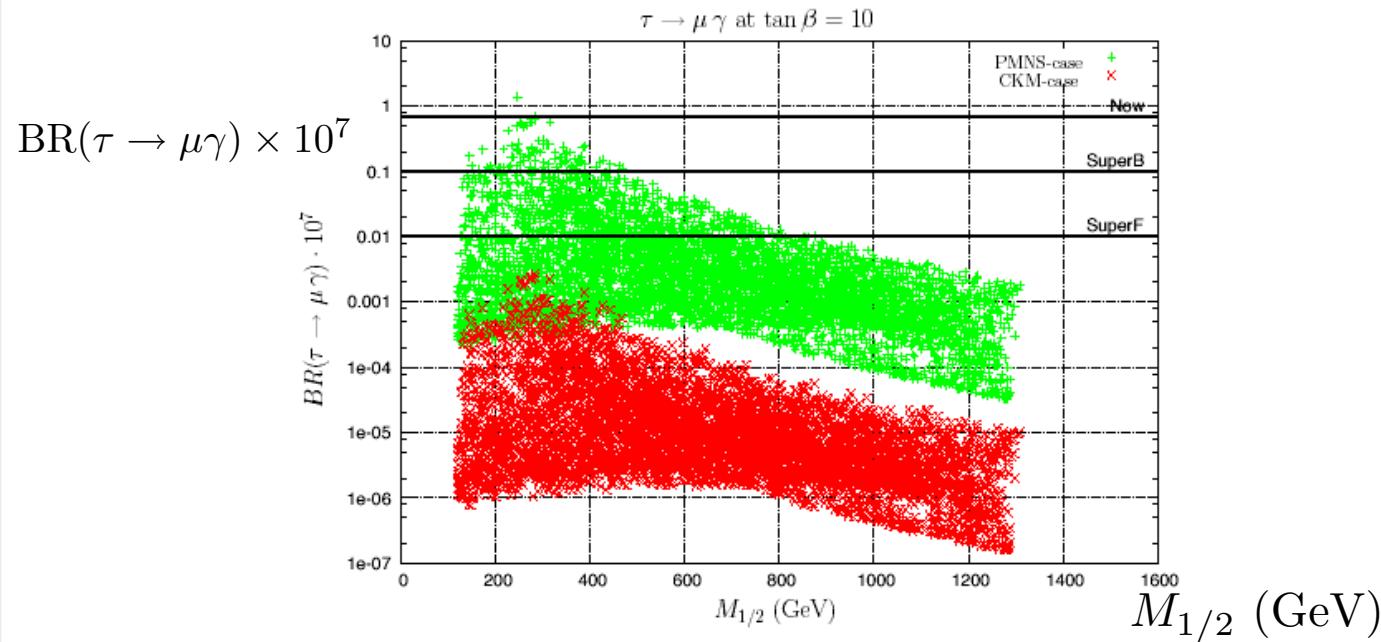


Supersymmetry in Tau LFV



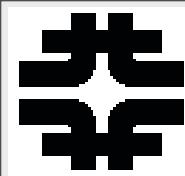
L. Calibbi, A. Faccia, A. Masiero, S. Vempati hep-ph/0605139

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

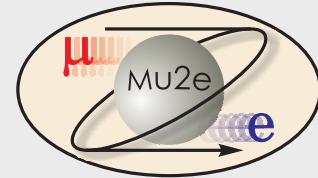


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

neutrino mass via the see-saw mechanism, analysis is performed in an SO(10) framework

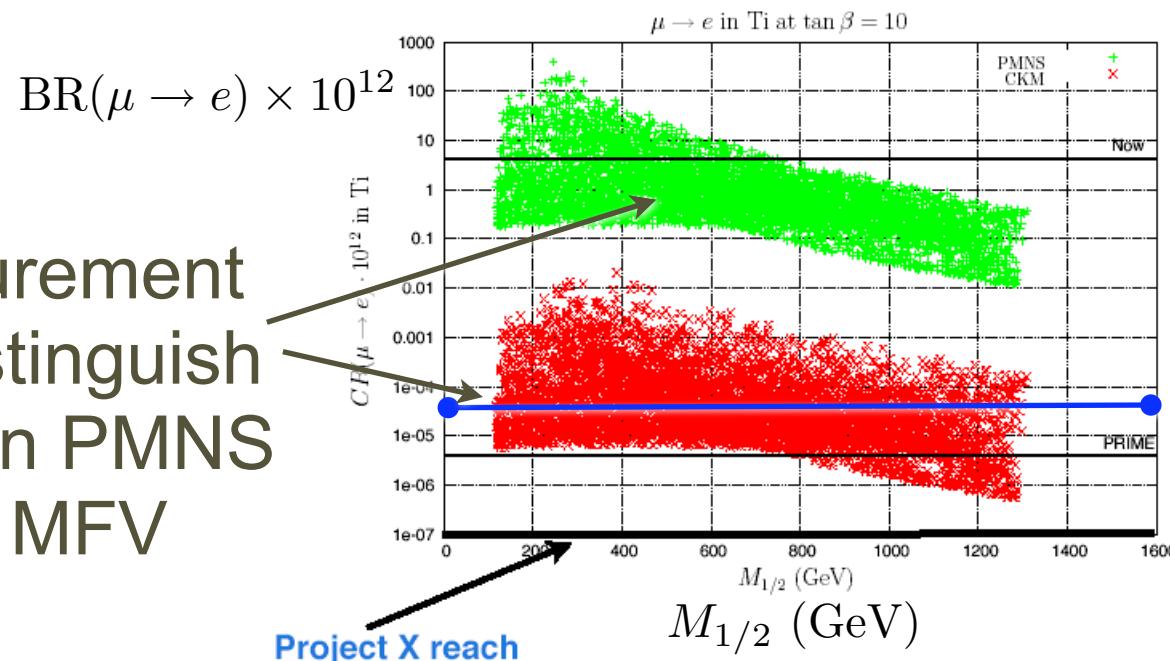


And Muon-Electron Conversion



Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

measurement
can distinguish
between PMNS
and MFV

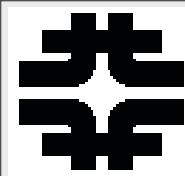


Current

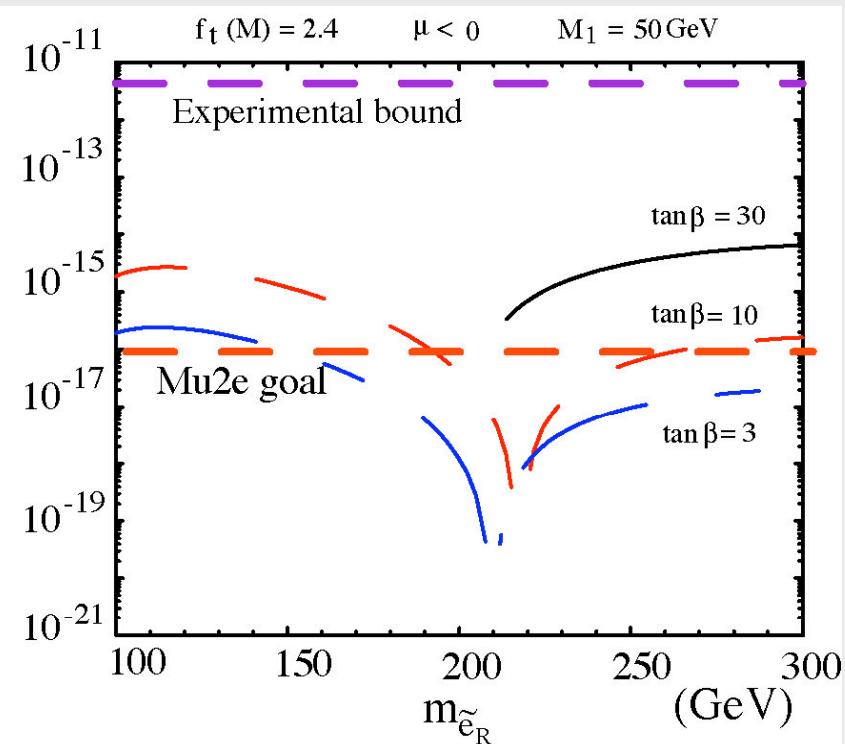
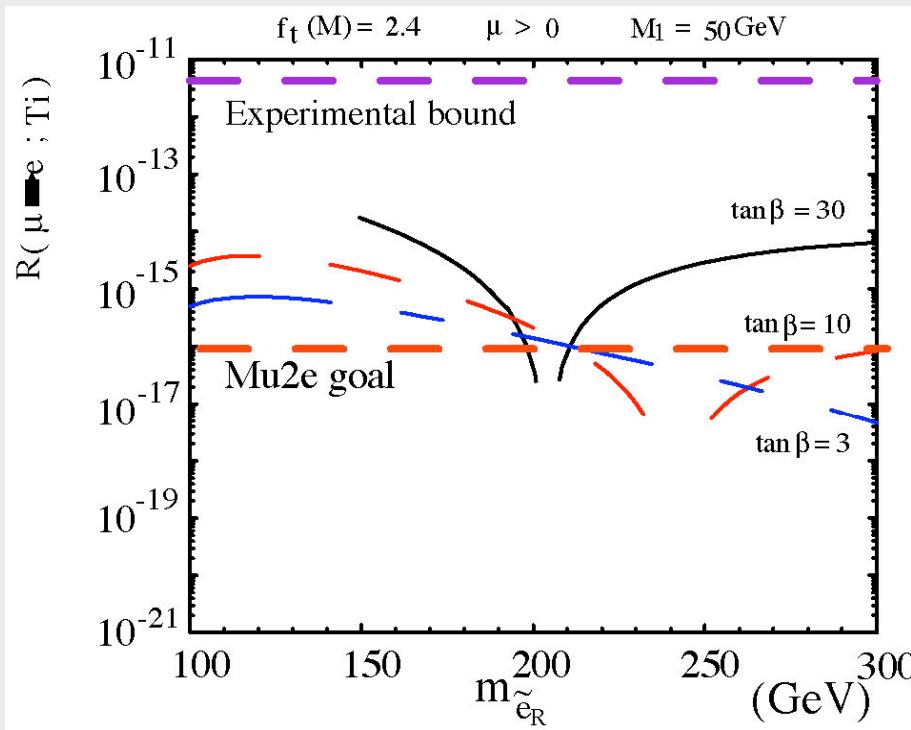
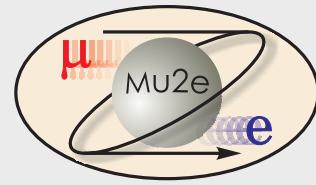
Mu2e

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

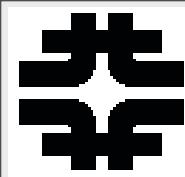
complementarity between Lepton Flavor Violation (LFV) and LHC experiments!



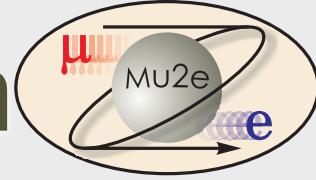
Supersymmetry and Mu2e in Minimal SU(5)



J. Hisano, T. Moroi, K. Tobe and M. Yamaguchi, Phys. Lett. B 391, 341 (1997).
[Erratum-ibid. B397, 357 (1997).]

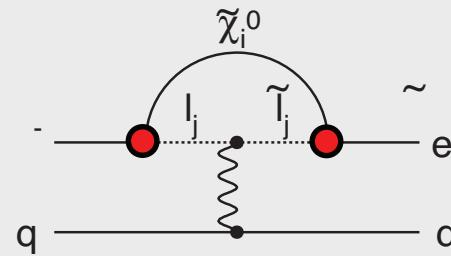


Contributions to μe Conversion



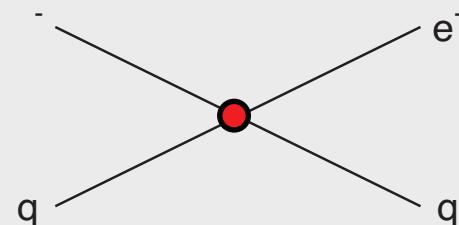
Supersymmetry

rate $\sim 10^{-15}$



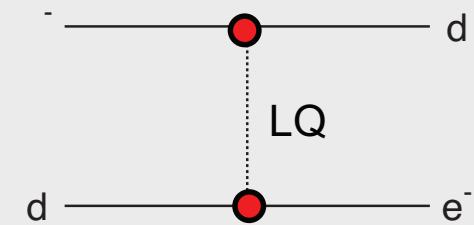
Compositeness

$\Lambda_c \sim 3000$ TeV



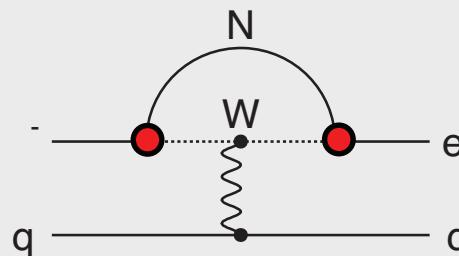
Leptoquark

$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$$



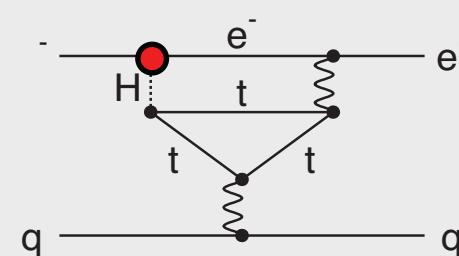
Heavy Neutrinos

$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$



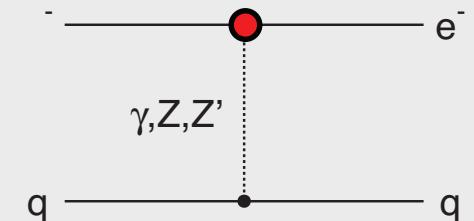
Second Higgs Doublet

$$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu \mu})$$

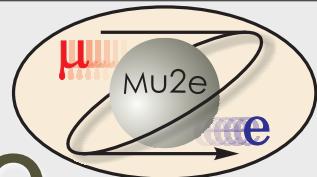
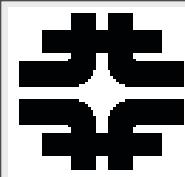


Heavy Z' Anomal. Z Coupling

$$M_{Z'} = 3000 \text{ TeV}/c^2$$



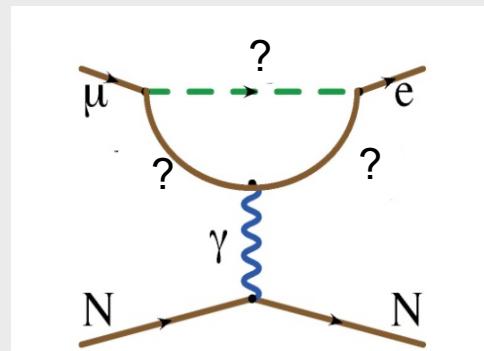
also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)



“Model-Independent” Picture

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

“Loops”

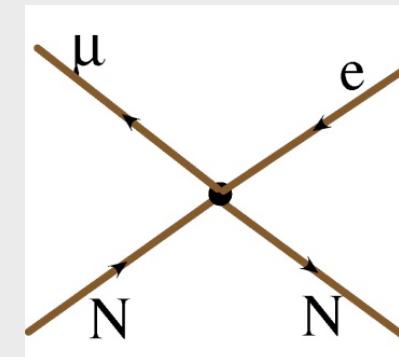


κ

Supersymmetry and Heavy Neutrinos

Contributes to $\mu \rightarrow e\gamma$

“Contact Terms”

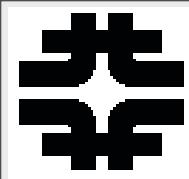


Λ

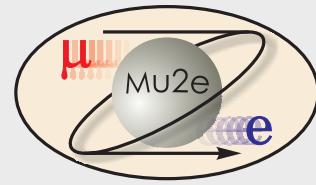
Exchange of a new, massive particle

Does not produce $\mu \rightarrow e\gamma$

Quantitative Comparison?



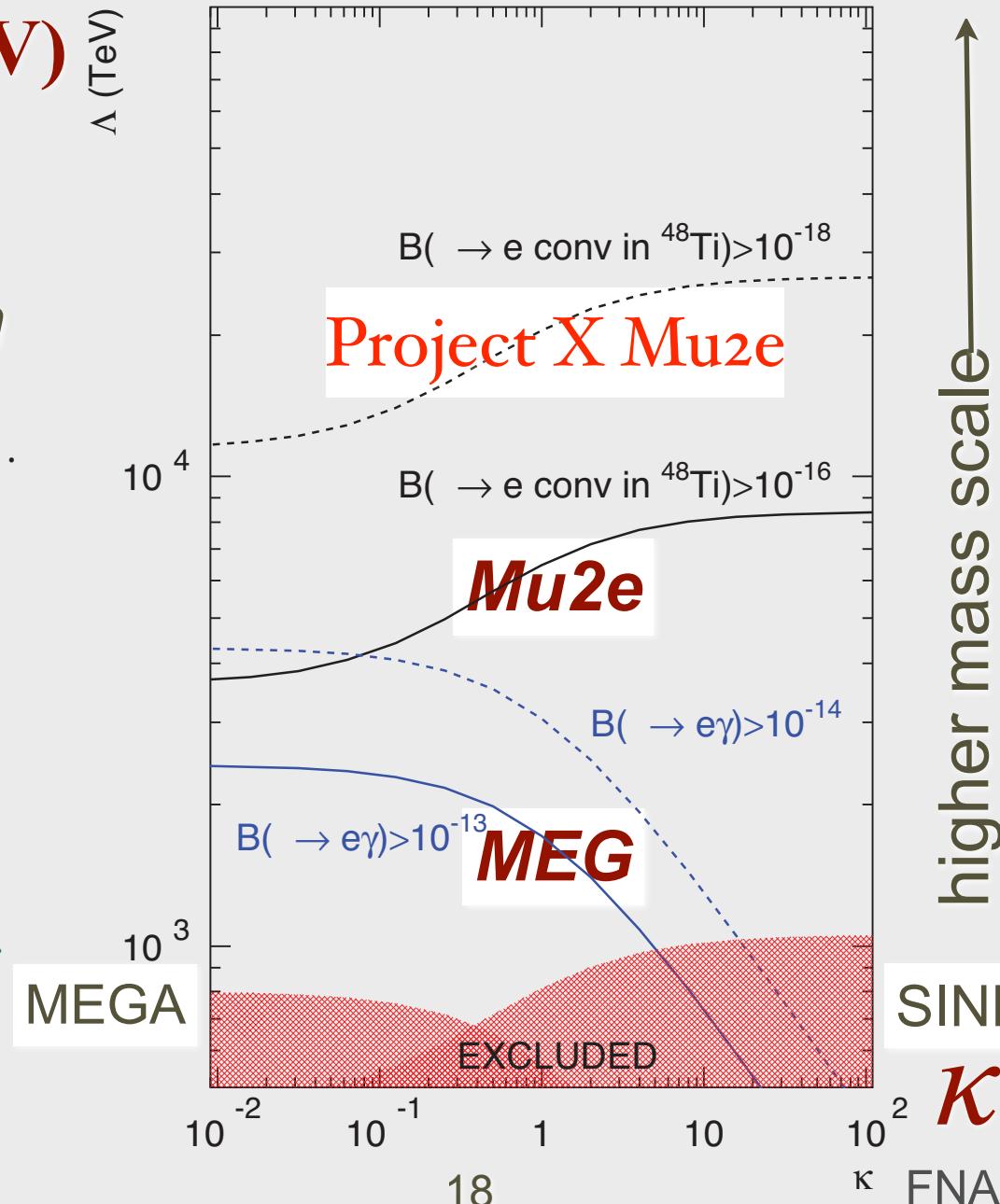
μe Conversion and $\mu \rightarrow e\gamma$

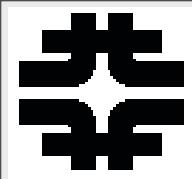


Λ (TeV)

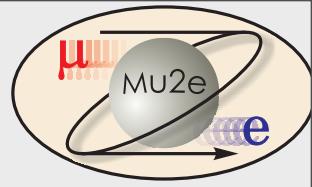
1) Mass Reach
to 10^4 TeV

2) $\times 10$ beyond
MEG in loop-
dominated
physics

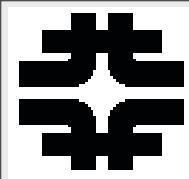




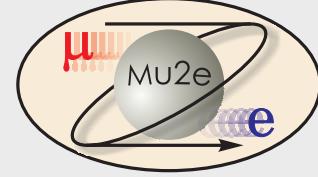
Outline



- The search for muon-electron conversion
- *Experimental Technique*
- Fermilab Accelerator
- Project X Upgrades and Mu2e



Overview Of Processes

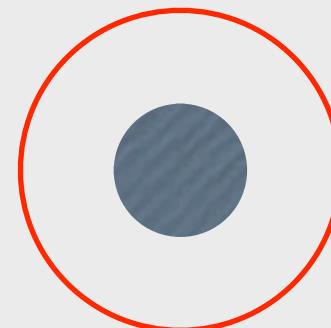


μ^- stops in thin Al foil



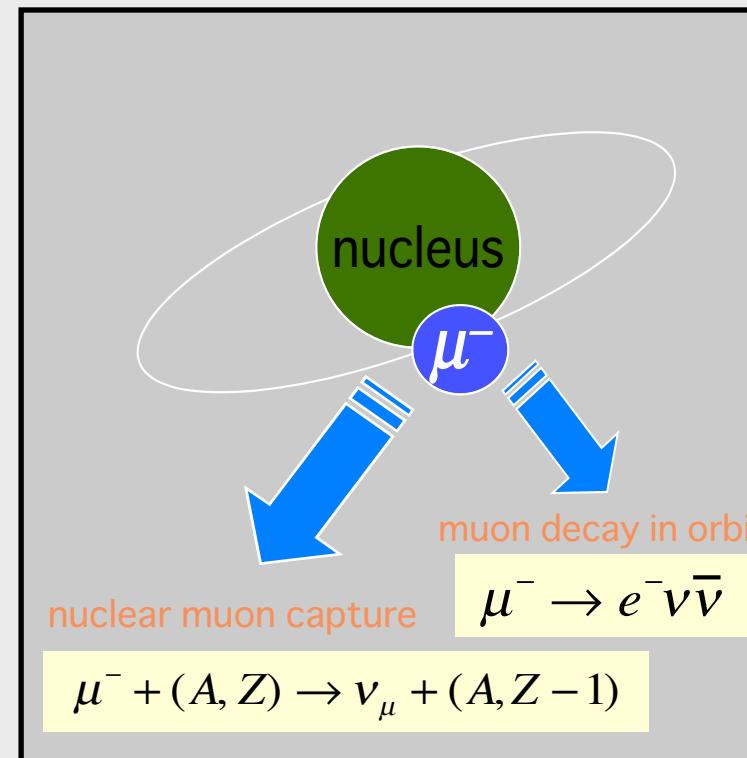
*the Bohr radius is $\sim 20 \text{ fm}$,
so the μ^- sees the nucleus*

μ^- in 1s state



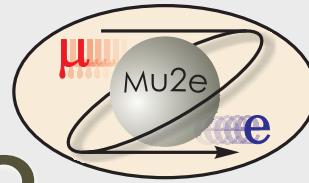
Al Nucleus
 $\sim 4 \text{ fm}$

muon capture,
muon “falls into”
nucleus:
normalization



60% capture
40% decay

Decay in Orbit:
background



Why Normalize to Capture?

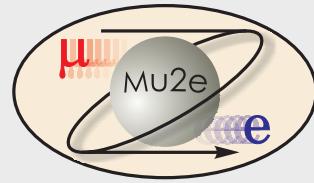
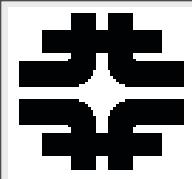
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

Al turns into Mg

- As muon cascades to 1s, X-rays give stop rate
- and $Mg \rightarrow Al$ yields a 2.6 MeV β followed by γ that can be used to measure capture rate

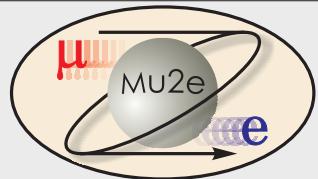
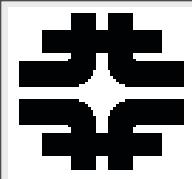
1. μ^- emits ν
2. Al turns into Mg

NORMALIZATION



Two Classes of Backgrounds

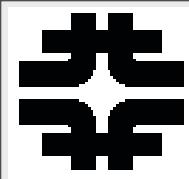
	Prompt	Decay-In-Orbit
Source	Mostly π 's produced in target	Physics Background nearly indistinguishable from signal
Solution	Design of Muon Beam, formation, transport, and time structure	Spectrometer Design: resolution and pattern recognition



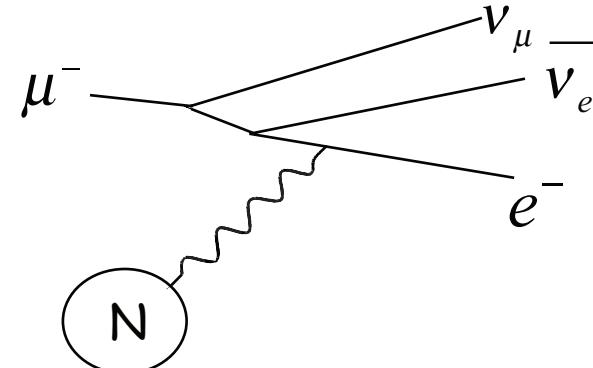
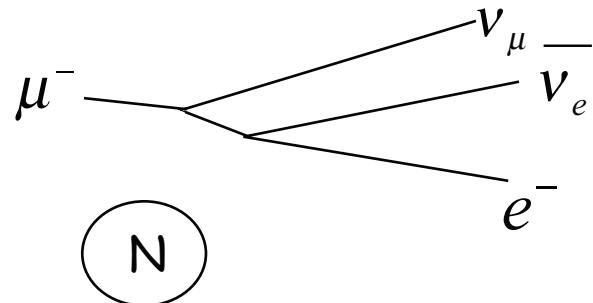
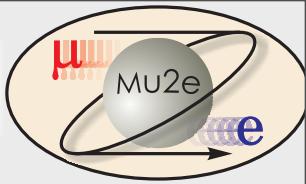
Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π , neutrons, pbars

- Radiative pion capture, $\pi^- + A(N, Z) \rightarrow \gamma + X$.
 - γ up to m_π , peak at 110 MeV; $\gamma \rightarrow e^+ e^-$; if one electron ~ 100 MeV in the target, looks like signal: ***limitation in best existing experiment, SINDRUM II?***
- Beam electrons: incident on the stopping target and scatter into the detector region. Need to suppress e^- with $E > 100$ MeV near 105 MeV signal
- In-flight muon decays yielding electrons: if they decay with momentum > 76 MeV/c, can yield electron in signal region

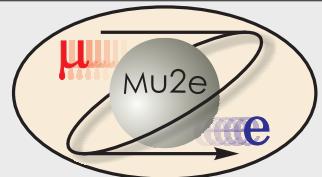
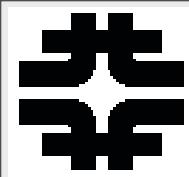


Decay-in-Orbit Background



- High Rate
- Peak 52.8 MeV
- Detector insensitive to electrons at this energy

- *Zero energy neutrinos and coherent scatter off nucleus put DIO's at conversion energy*
- Rate falls as $(E_{\text{max}} - E)^5$
- Fraction within 2 MeV of signal is 1.2×10^{-15}



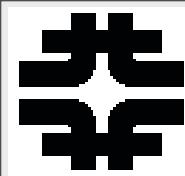
Design of Mu2e

Examine previous best experiment

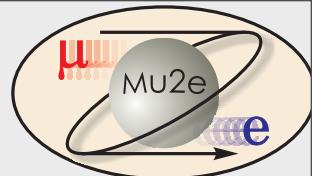
- What were the limitations?
 - limitations from prompts
 - limitations from Decay-in-Orbit

How can we do better?



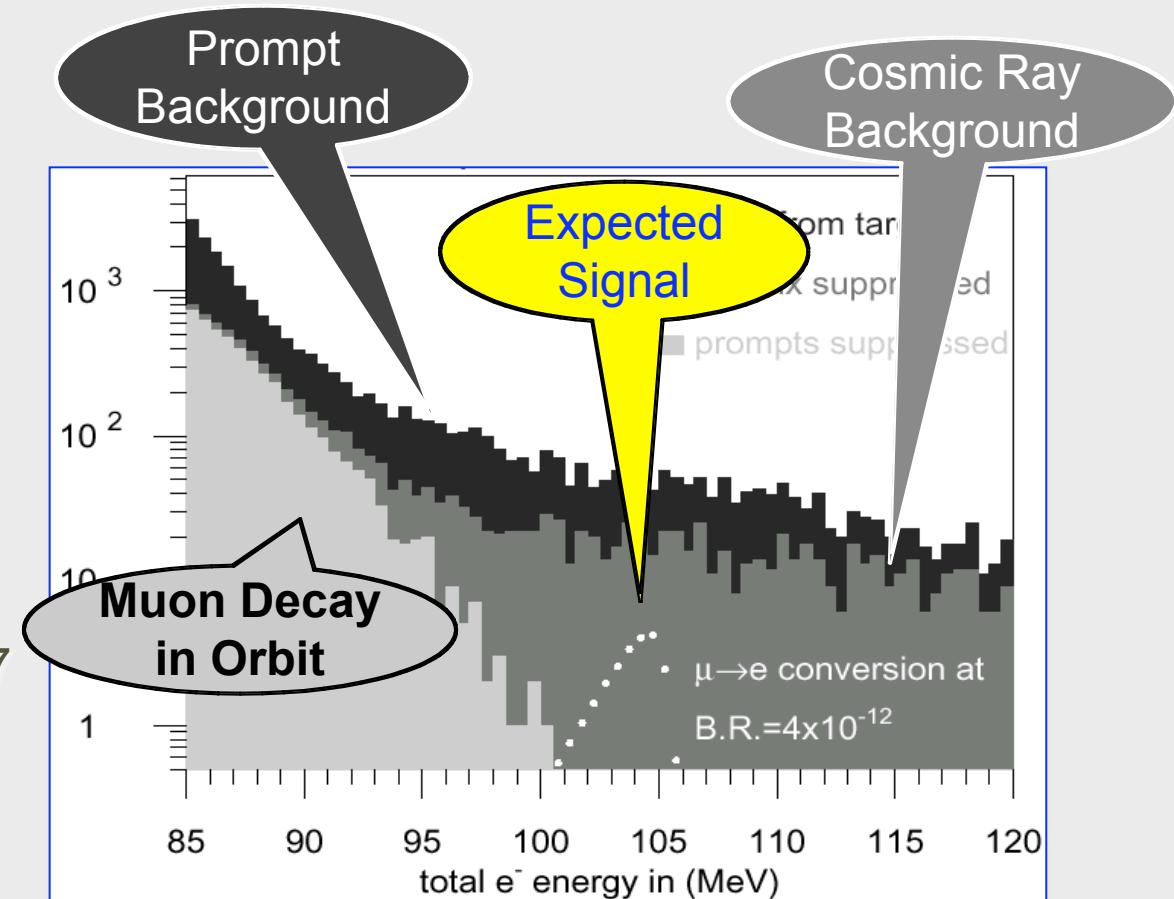


Previous Best Experiment

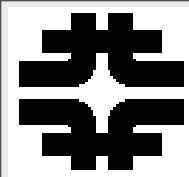


SINDRUM-II

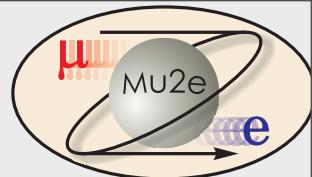
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au
- Want to probe to 6×10^{-17}
- $\approx 10^4$ improvement



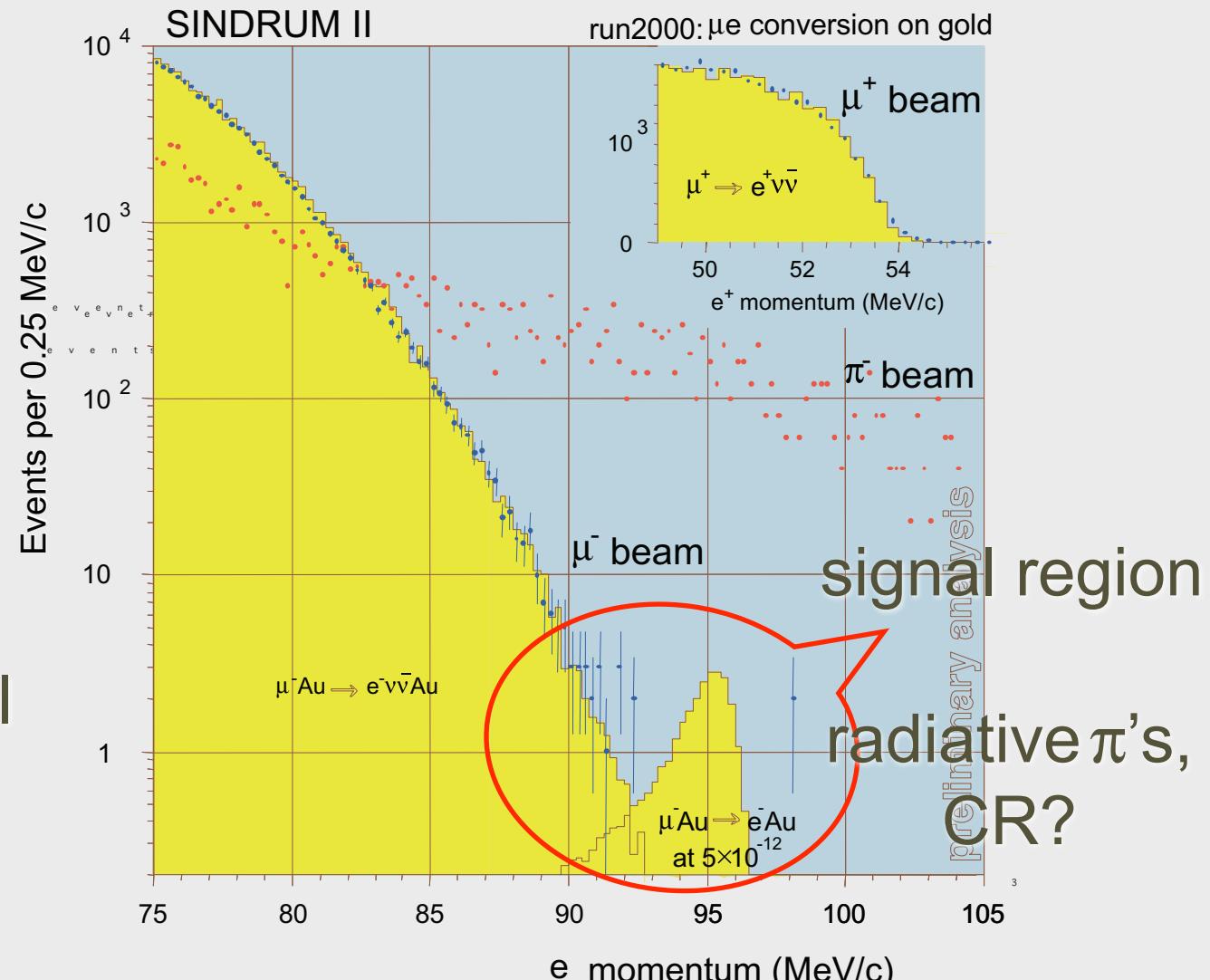
Experimental signature is 105 MeV e^- originating in a thin Ti stopping target



SINDRUM II Results

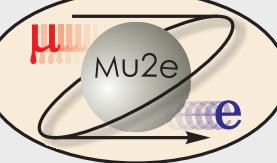


- Final SINDRUM-II on Au
- Note Two Background Events past Signal Region



July 14, 2001

HEP 2001 (W.Bertl - SINDRUM II collaboration)



What Limited SINDRUM-II?

DC Beam

no time separation
between
signal and prompt
background

radiative π capture

PSI PAUL SCHERRER INSTITUT

Background : b) pion induced

Radiative Pion Capture (RPC) : $\pi^- Au \rightarrow \gamma + Pt^*$ followed by $\gamma \rightarrow e^+ e^-$

Kinematic endpoint of photon spectrum around 130 MeV ! Branching ratio of order 2%.

No way to distinguish an asymmetric $e^+ e^-$ -pair (with little e^+ energy and e^- energy at 95 MeV) from μe !

⇒ Needs strong pion suppression : only ~ 1 pion every 5 minutes is allowed to reach gold target!

⇒ tune beamline to suppress high momentum tail

⇒ use degrader 8m in front of gold target to separate μ 's and π 's by their different stopping power. Penetrating slow pions decay in PMC.

positron distributions

$E / 75 \text{ MeV}$

dZ/cm

$r.f. \text{ phase (ns)}$

dz/cm

$E (\text{MeV})$

$in \text{ phase}$

July 14, 2001

BUT: Degrader is now pion stop target → $e^+ e^-$ pairs from RPC are collected by B_{PMC} and transported towards the gold target where they may scatter into spectrometer acceptance (typ. forward scattering)

⇒ use solid angle and cyclotron phase correlation to cut.

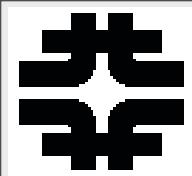
$\pi E5$

PMC

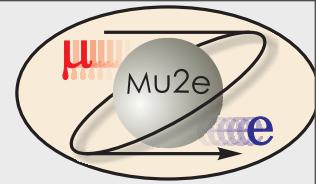
SINDRUM

HEP 2001 (W.Bertl - SINDRUM II collaboration)

cosmic rays also near-limiting for DC beam



How Can We Do Better?

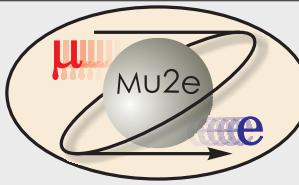
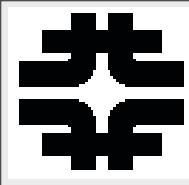


>10³ increase in muon intensity from SINDRUM

Requiring

Pulsed Beam to Eliminate prompt backgrounds like
radiative π capture and CR

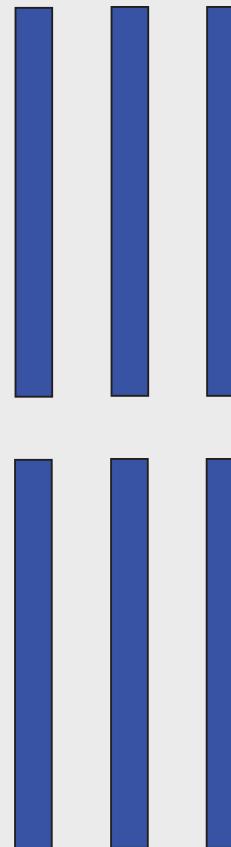
protons out of beam pulse/ protons in beam-pulse < 10⁻⁹
and we must measure it



Advantage of Pulsed Beam

target foils: muon converts here

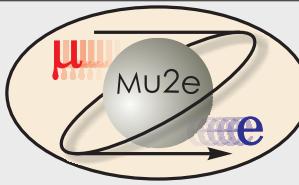
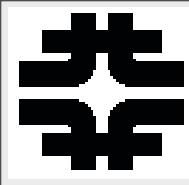
 = muons, electrons, pions



Recall:
Muon-electron
conversion signal is a

single, monoenergetic
electron

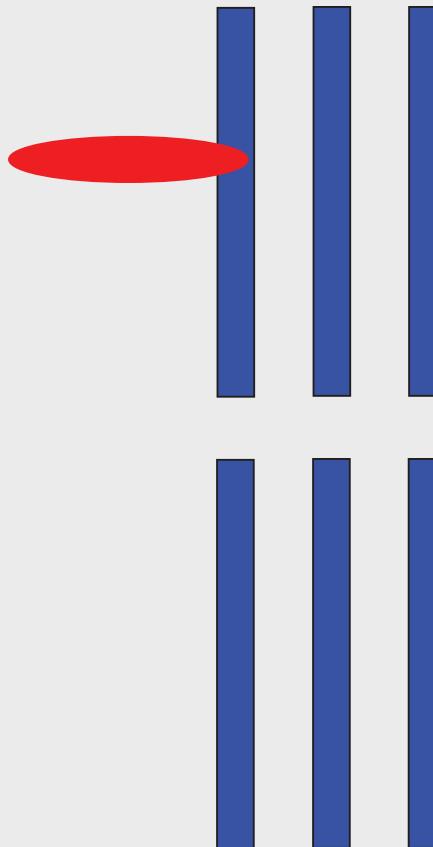
pulsed beam lets us
wait until after prompt
backgrounds
disappear



Advantage of Pulsed Beam

target foils: muon converts here

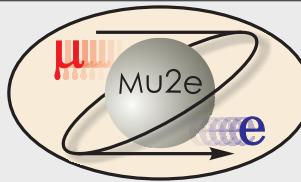
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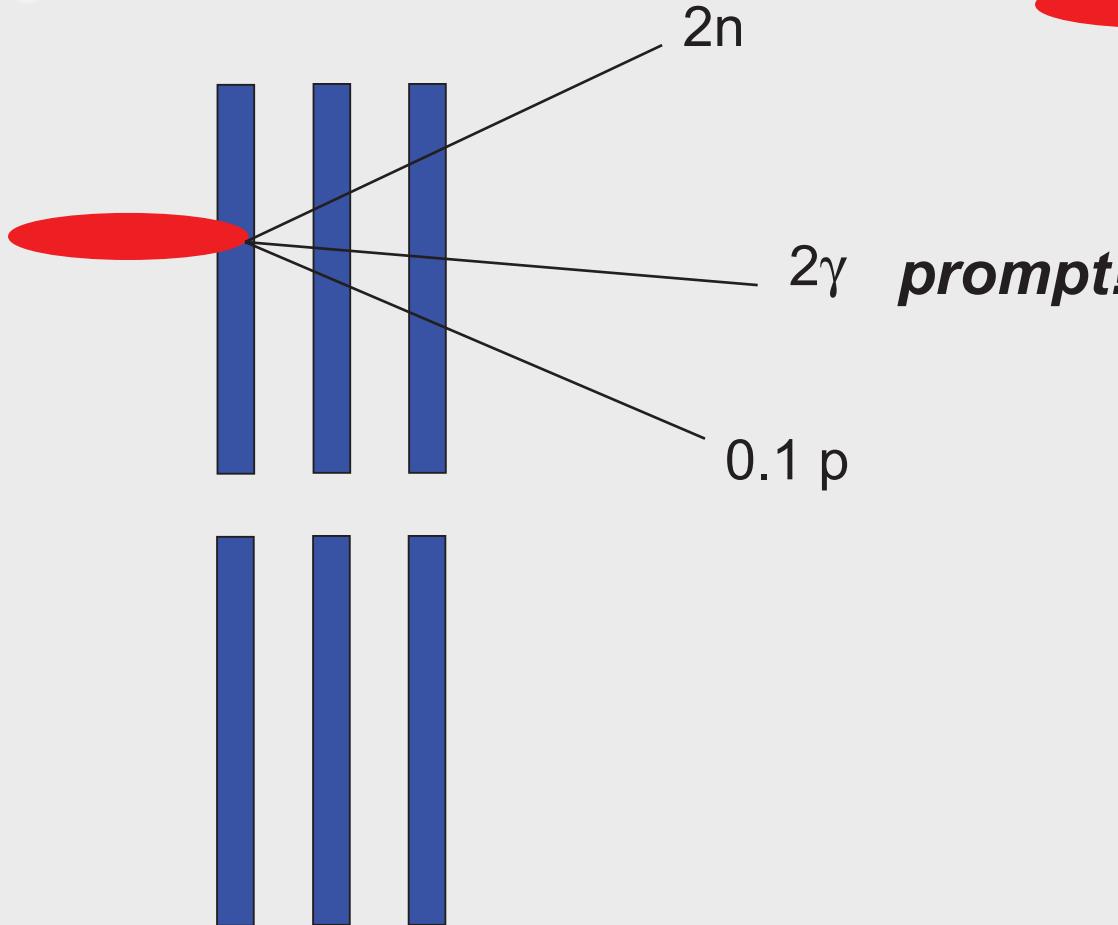
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Advantage of Pulsed Beam

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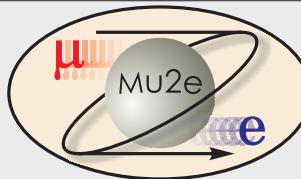


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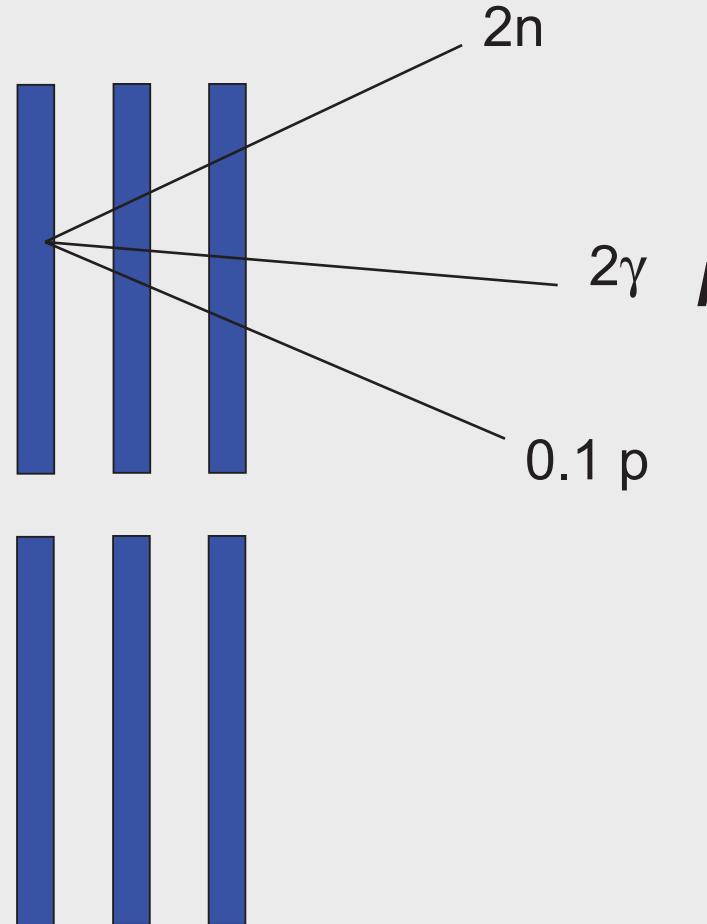
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Advantage of Pulsed Beam

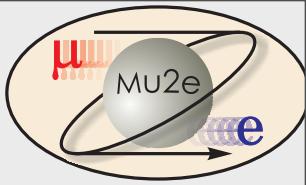
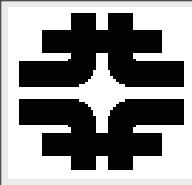
target foils: muon converts here



= muons, electrons, pions
Recall:
Muon-electron
conversion signal is a

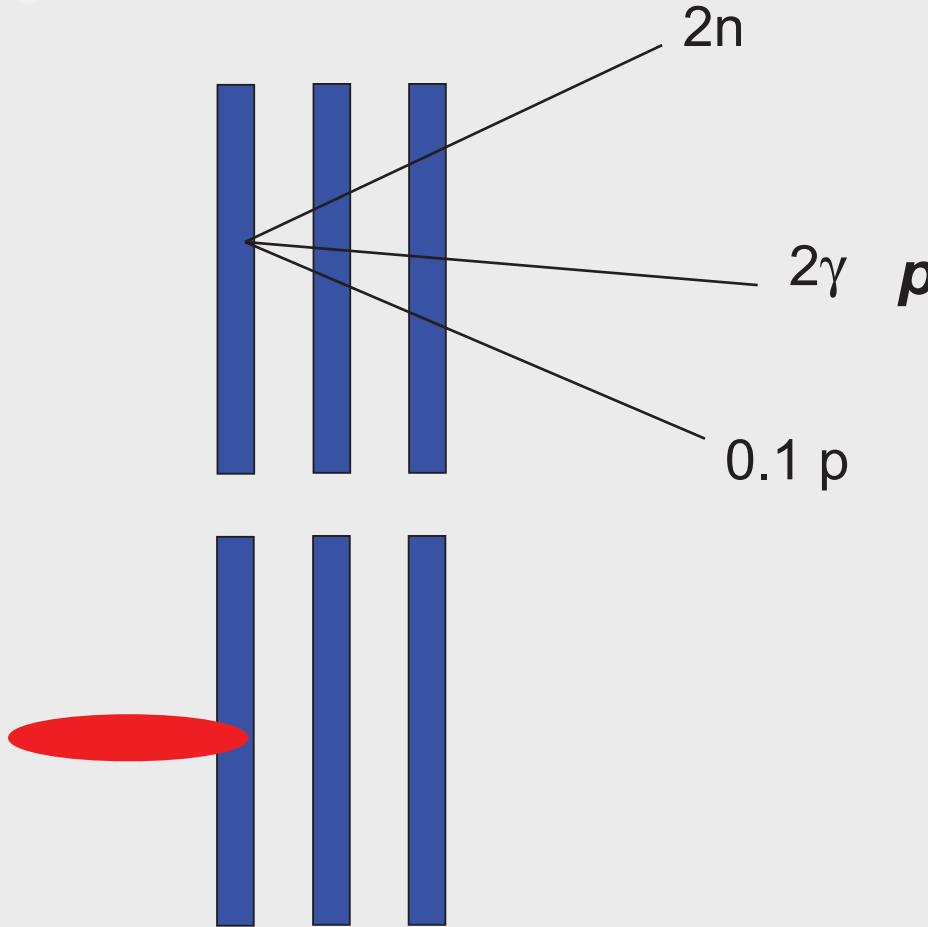
**single, monoenergetic
electron**

pulsed beam lets us
wait until after prompt
backgrounds
disappear



Advantage of Pulsed Beam

target foils: muon converts here

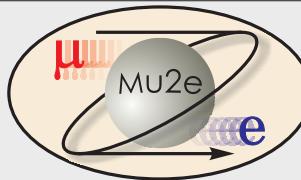


= muons, electrons, pions

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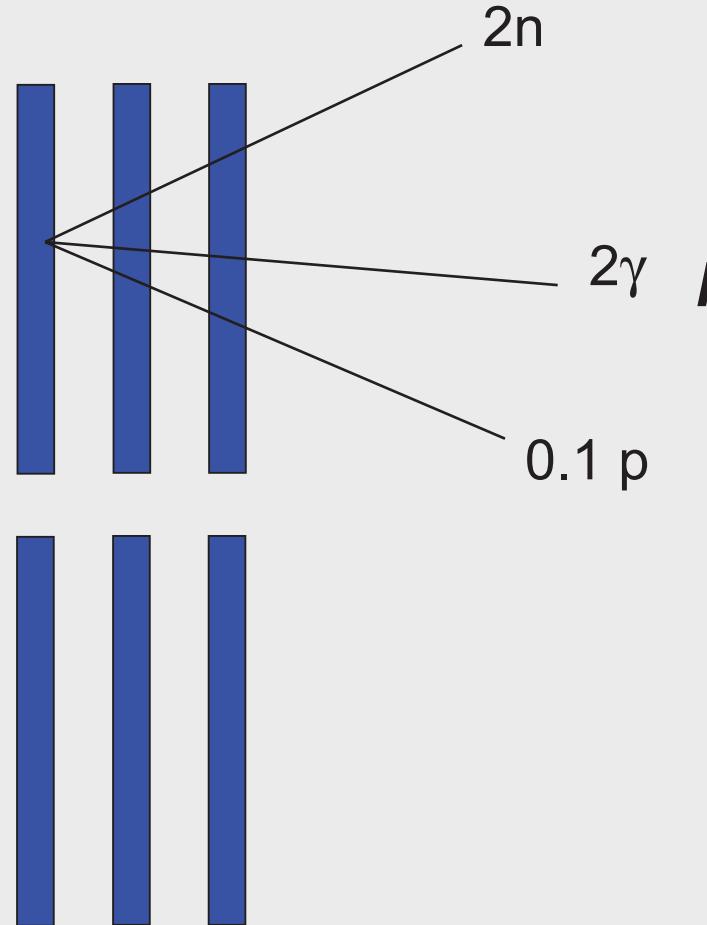
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Advantage of Pulsed Beam

target foils: muon converts here

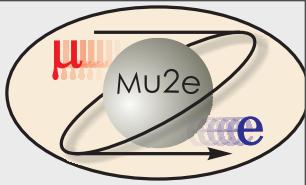
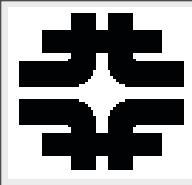


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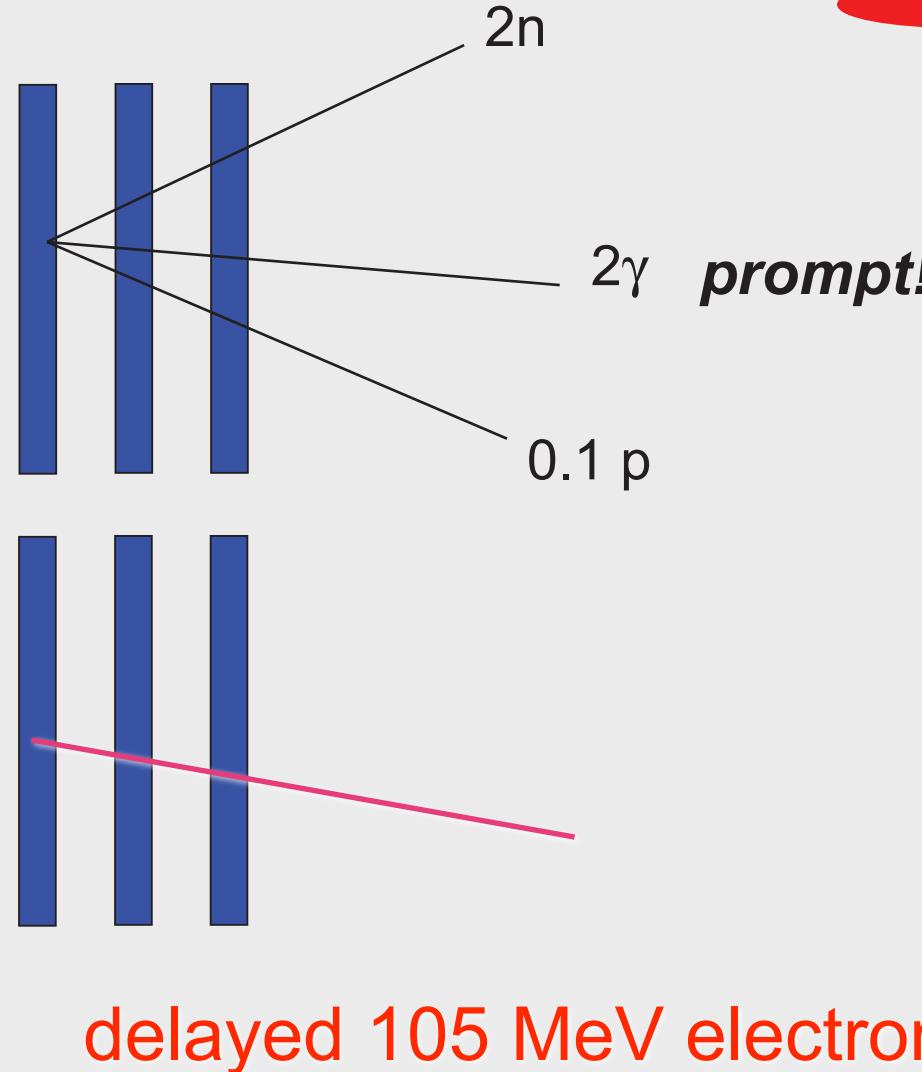
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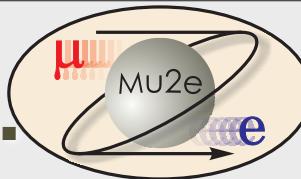
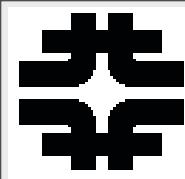


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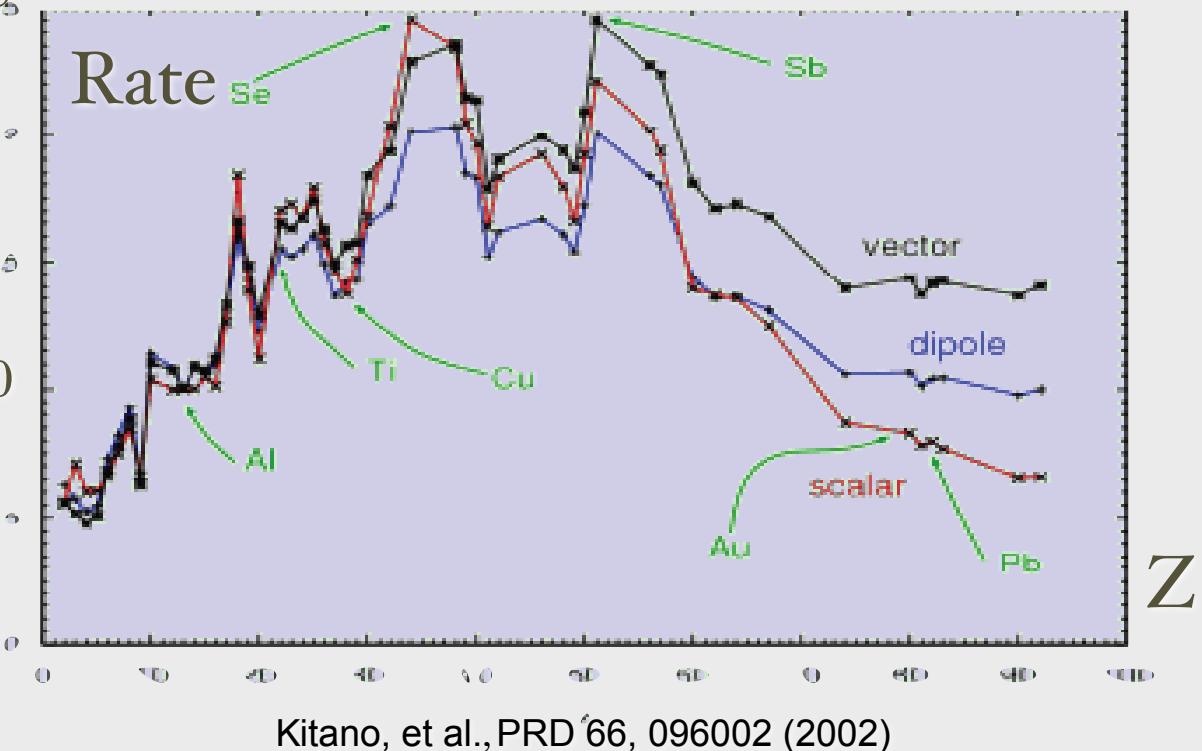
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Choice of Stopping Material: rate vs wait

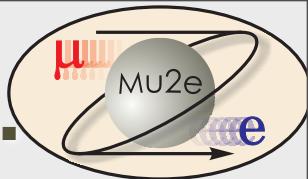
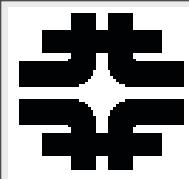
rate normalized to Al

- Stop muons in target (Z, A)
- Physics sensitive to Z : with signal, can switch target to probe source of new physics
- Why start with Al?



Kitano, et al., PRD 66, 096002 (2002)

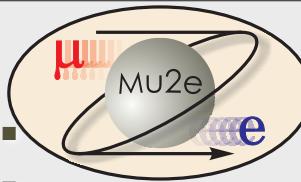
shape governed by relative conversion/capture rate, form factors, ...



Choice of Stopping Material: rate vs wait

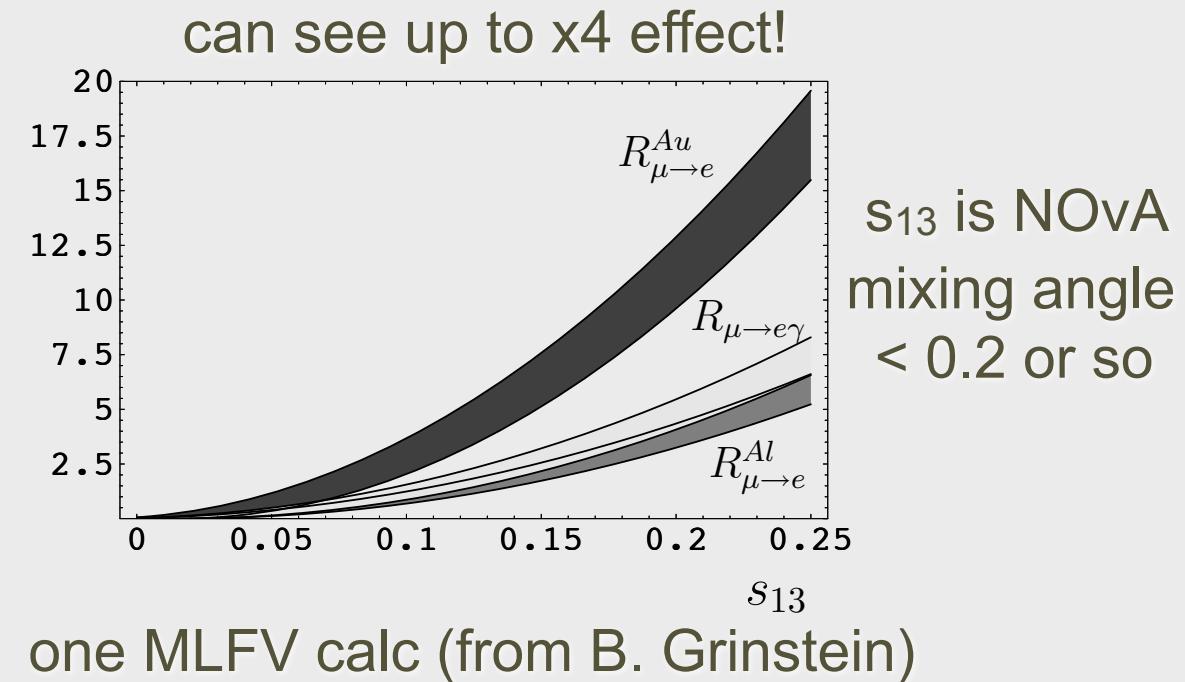
- Stop muons in target 2.5
(Z,A)
- Physics sensitive to
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physics
- Why start with Al?

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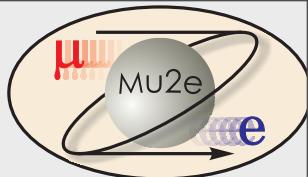
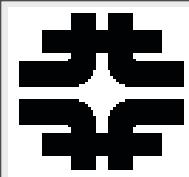


Choice of Stopping Material: rate vs wait

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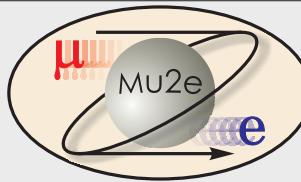
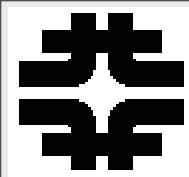
shape governed by relative conversion/capture rate, form factors, ...



Prompt Background and Choice of Z

choose Z based on tradeoff between rate and lifetime:
longer lived reduces prompt backgrounds

Nucleus	$R_{\mu e}(Z) / R_{\mu e}(\text{Al})$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

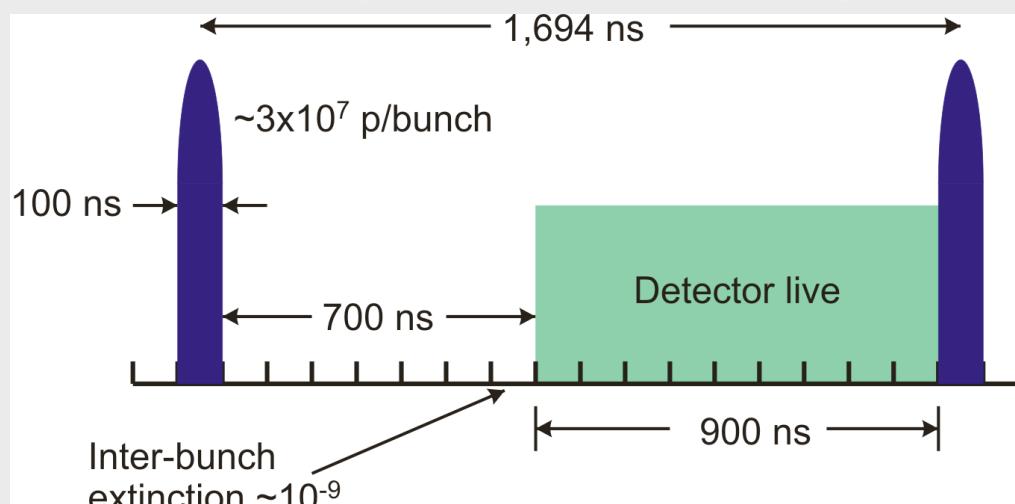


Pulsed Beam Structure

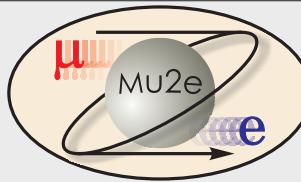
- Tied to prompt rate and machine: FNAL “perfect”
- Want **pulse duration $\ll \tau_\mu^{\text{Al}}$, pulse separation $\approx \tau_\mu^{\text{Al}}$**
- FNAL Debuncher has circumference **$1.7\mu\text{sec}$!**

- Extinction between pulses $< 10^{-9}$ needed

= # protons out of pulse/# protons in pulse



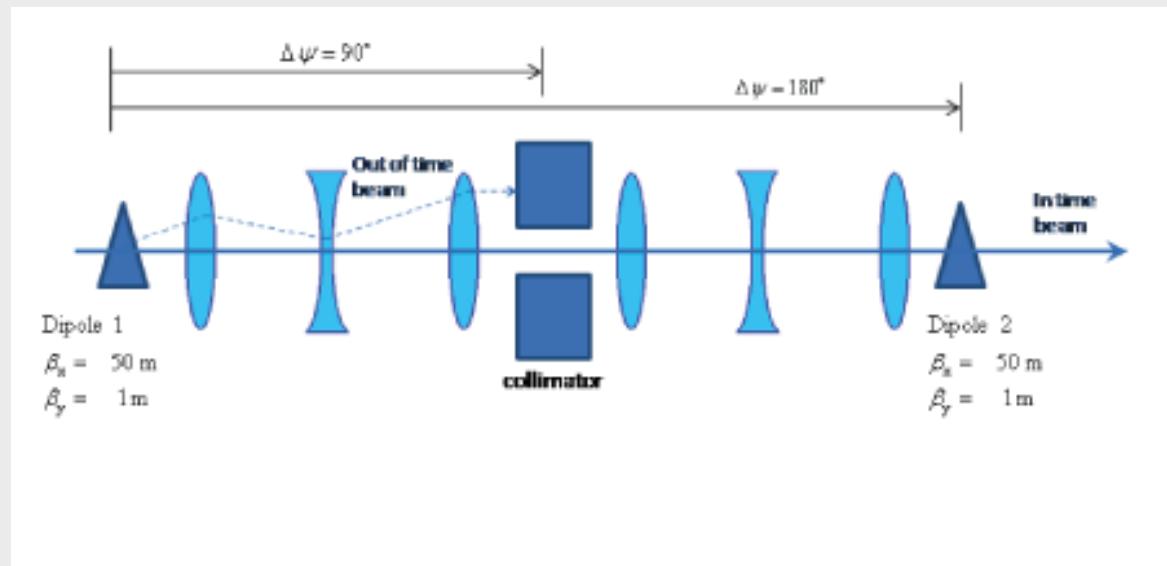
- 10^{-9} based on simulation of prompt backgrounds



Extinction Scheme

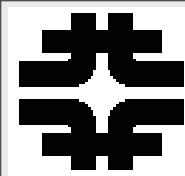
achieving 10^{-9} is hard; normally get $10^{-2} - 10^{-3}$

- Eliminate protons in beam in-between pulses:

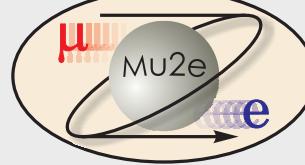


CDR under development

- “Switch” dipole timing to switch signal and background: accept only out-of-time protons for direct *measurement* of extinction
- Other schemes under investigation: *simulation and design help!*



AC-Dipole R&D



Conceptual Design of AC Dipole Magnet for μ to e- Experiment

V.S. Kashikhin, D. Harding, V. V. Kashikhin, A. Makarov, D. Wolff Fermilab

Table I. AC Dipole specification.

Parameter	Unit	Value
Integrated strength	T-m	0.12
Magnet gap	mm	10
Effective length	m	2.0
Good field area width	mm	50
Center field	T	0.06
Current form		Sine wave
Current frequency	kHz	300
Operational regime		Continuous
Radiation level		low

\$\phi_{1,750}\$
[19.05 mm]
\$\phi_{2,000}\$
[50.80 mm]

\$\phi_{0,500}\$ (COPPER TUBE I.D.)
[12.71 mm]
\$\phi_{0,750}\$ (COPPER TUBE O.D.)
[19.05 mm]
\$\phi_{1,250}\$ (CERAMIC O.D.)
[31.75 mm]
\$1.250\$ [31.75 mm]
\$\phi_{1,000}\$ (CERAMIC I.D.)
[25.40 mm]

PACK LEG WIDTH

[98.45 mm]

E WIDTH

[mm]

\$\phi_{0,740}\$
[95.00 mm]

0.394

[10.00 mm]

1.000

[25.40 mm]

9.500

[241.30 mm]

10.500

[266.70 mm]

14.000

[355.60 mm]

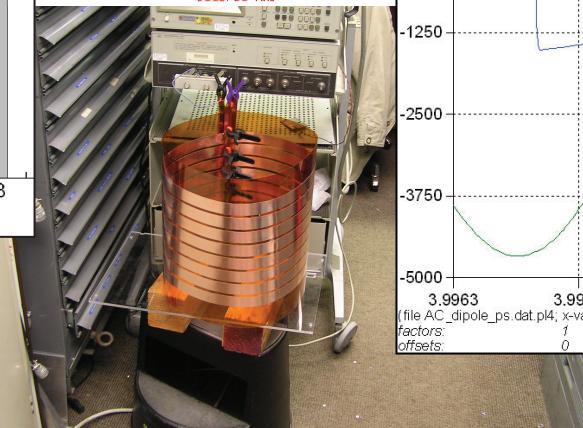
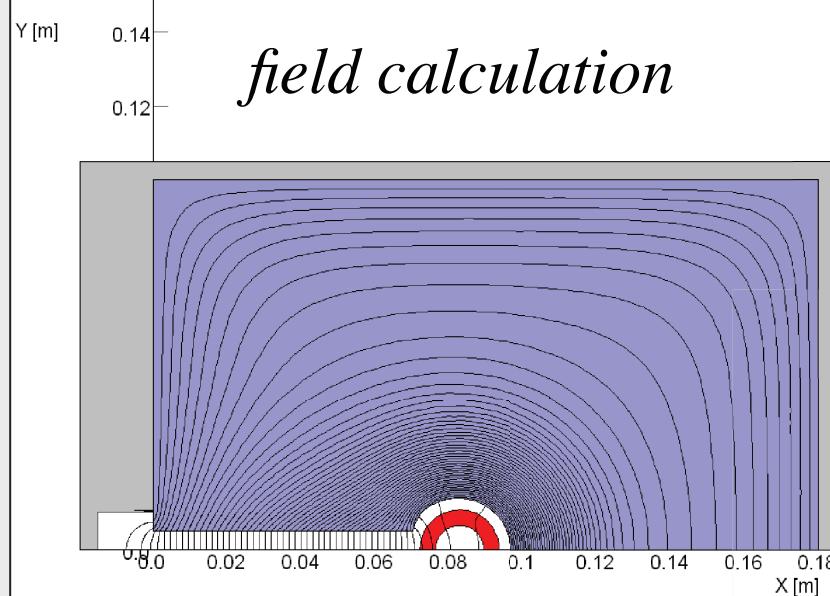
VACUUM BOX

0.650

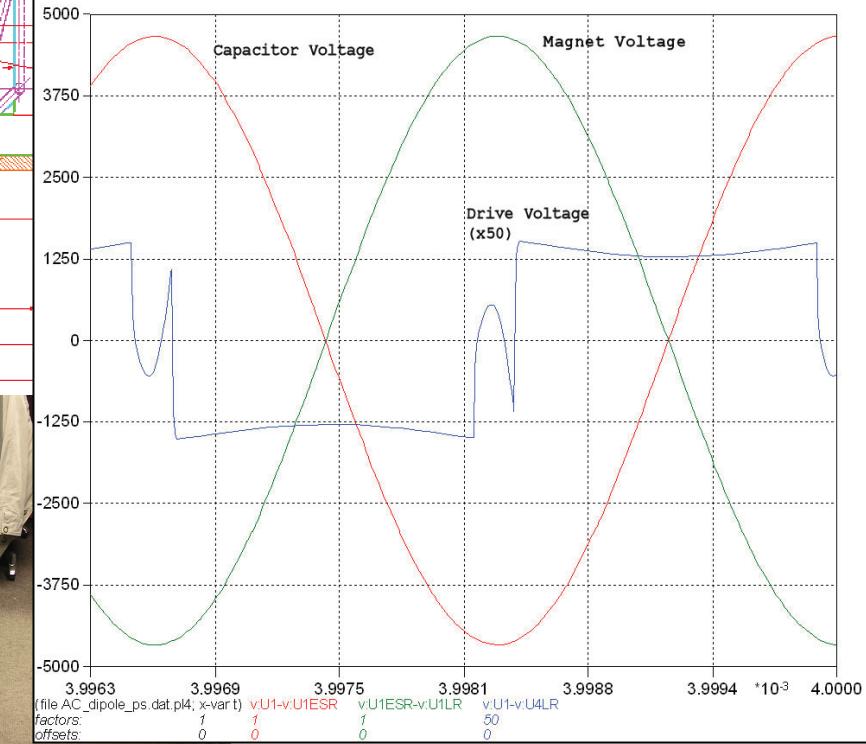
[16.51 mm]

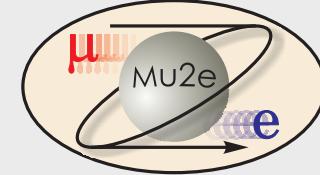
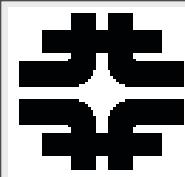
Magnet Design

Power Supply Calc



prototype transformer

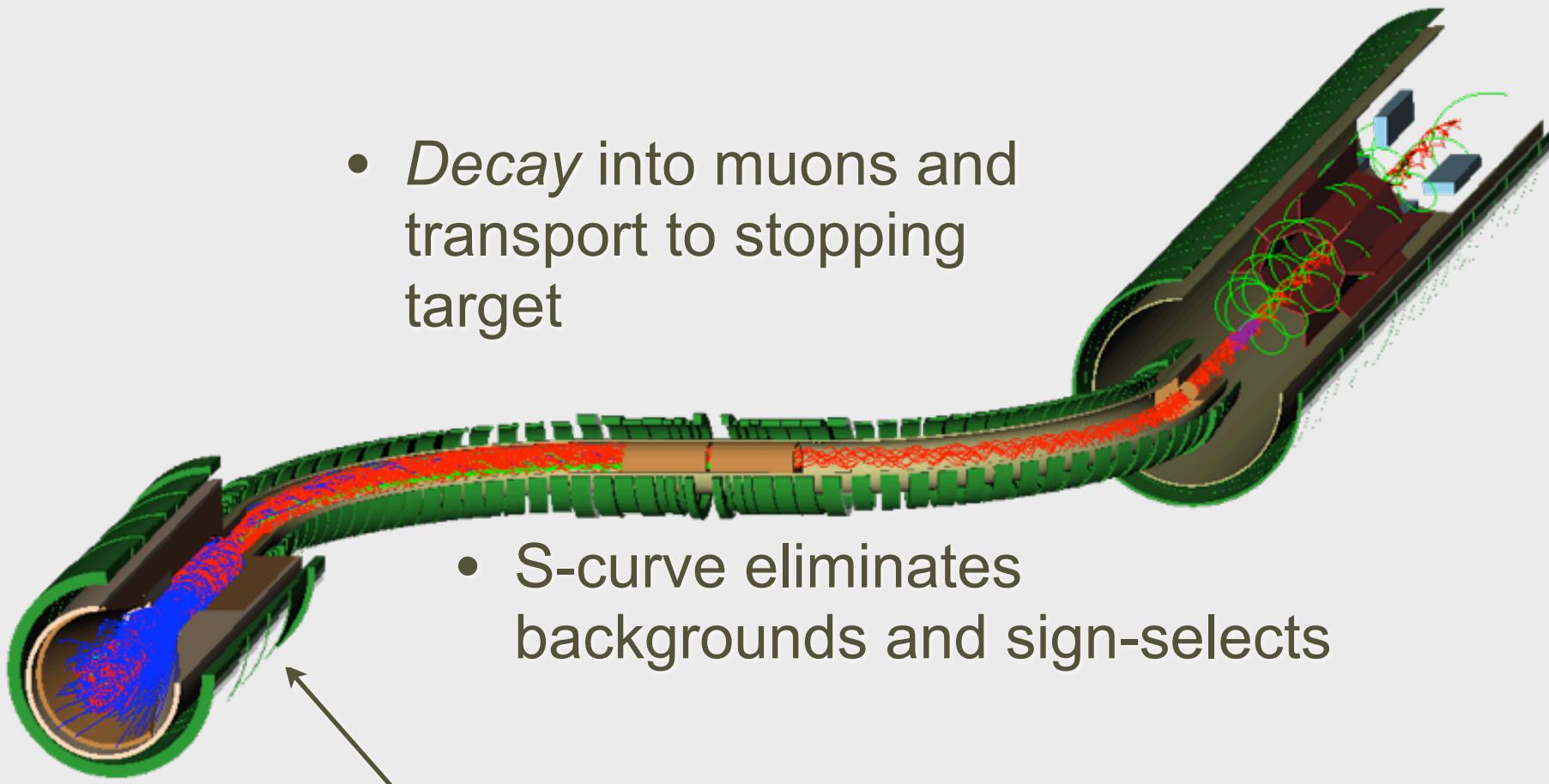




Detector and Solenoid

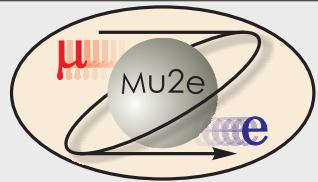
- *Tracking and Calorimeter*

- *Decay into muons and transport to stopping target*



- S-curve eliminates backgrounds and sign-selects

- *Production:* Magnetic bottle traps backward-going π^- that can decay into accepted μ^+ 's



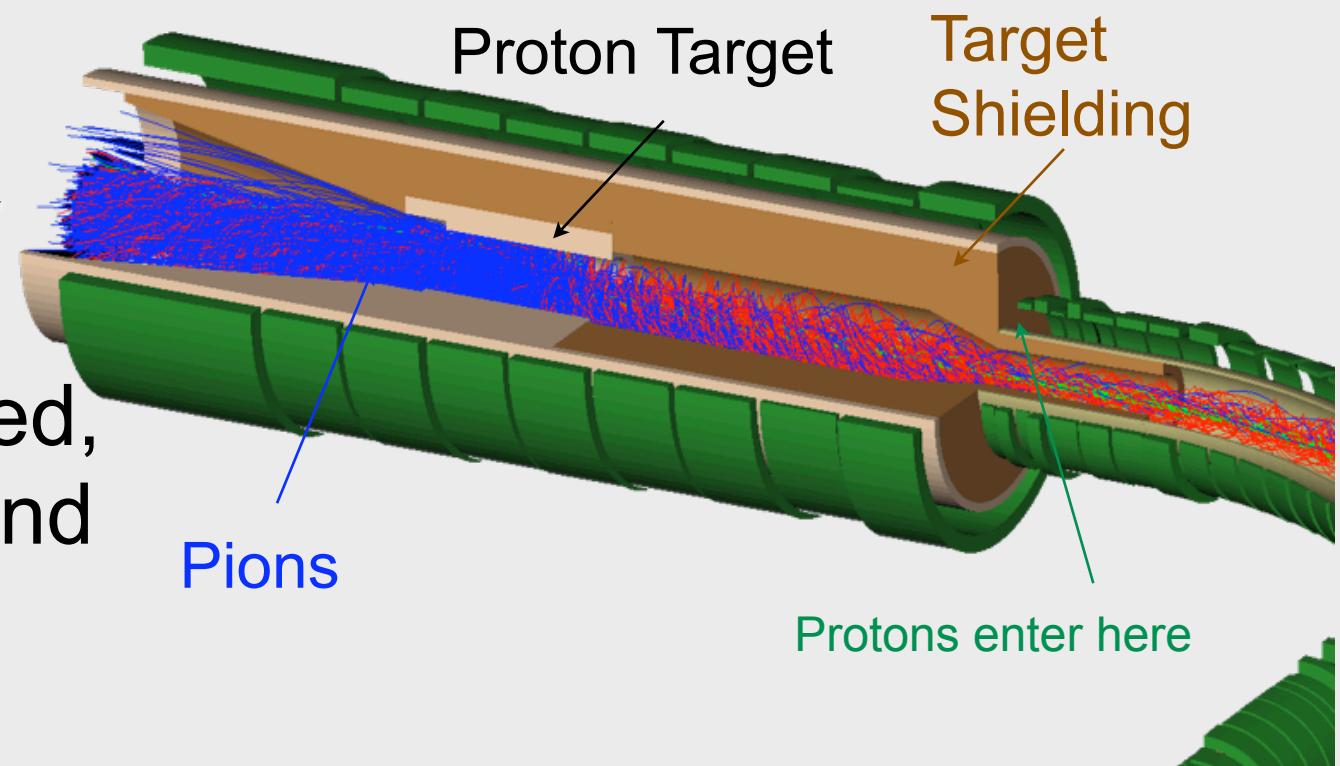
Production Solenoid:

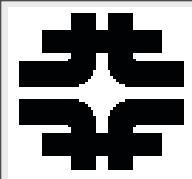
Protons enter opposite to outgoing muons – this is a central idea to remove prompt background

Protons leave through thin window

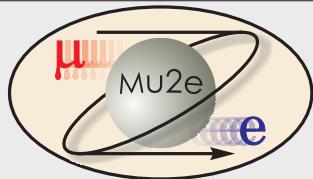
π 's are captured, spiral around and decay

muons exit to right

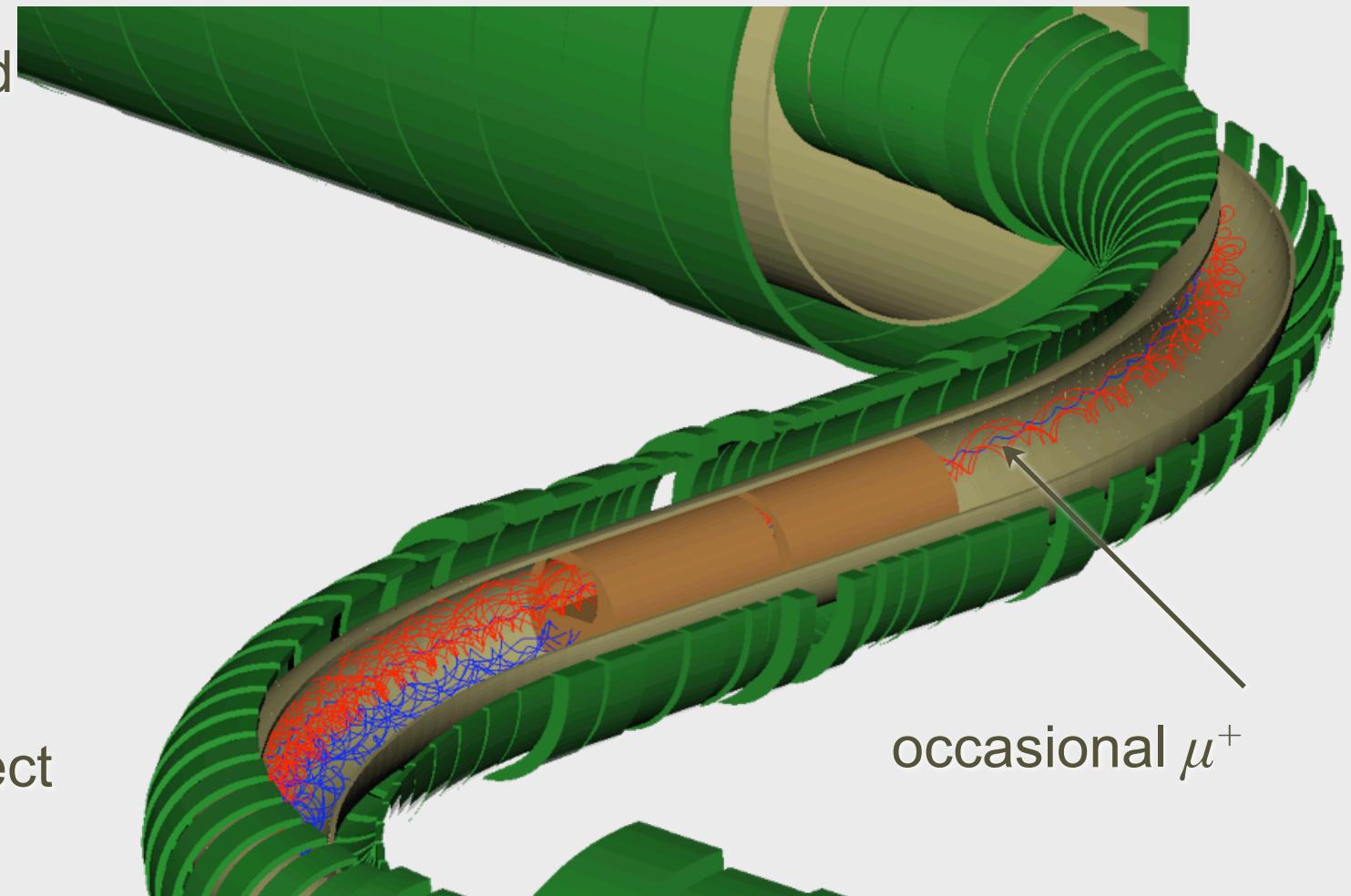


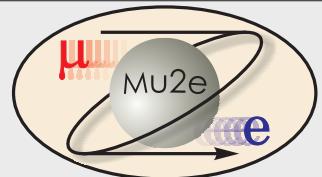
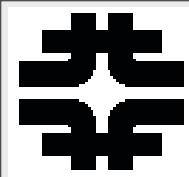


Transport Solenoid



- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam

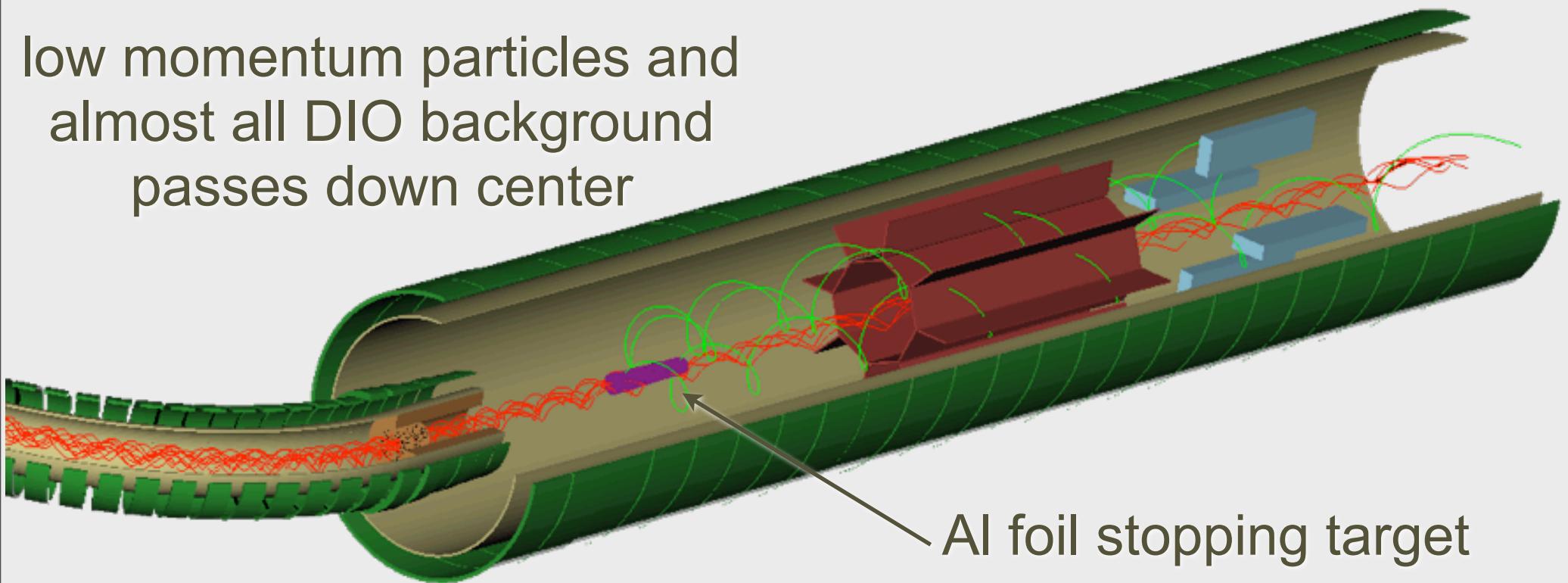




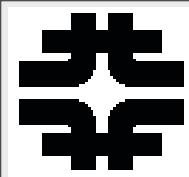
Detector Solenoid

*octagonal tracker surrounding central region:
radius of helix proportional to momentum*

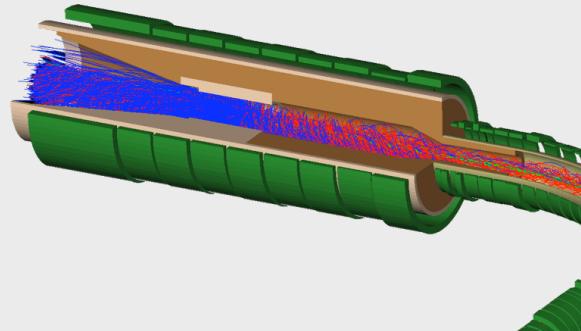
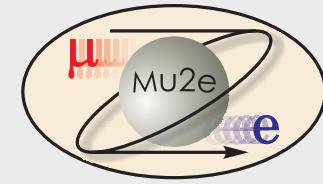
low momentum particles and
almost all DIO background
passes down center



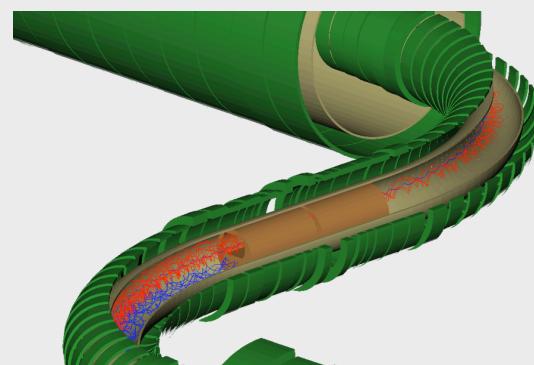
signal events pass *through* octagon of tracker
and produce hits



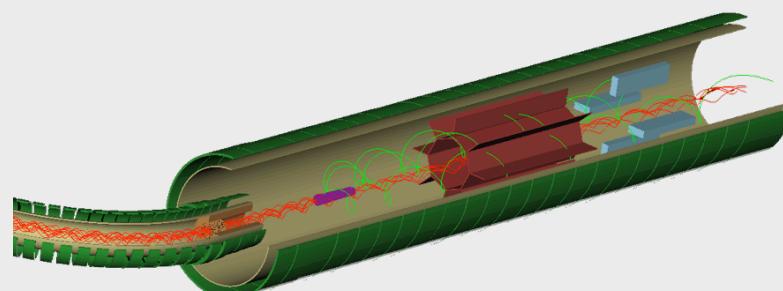
Graded Fields



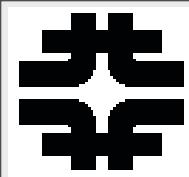
Production Solenoid:
graded from ~5.0 to 2.5T
to (a) capture backwards-going pions
and allow them to decay and (b) “reflect”
backward-going muons



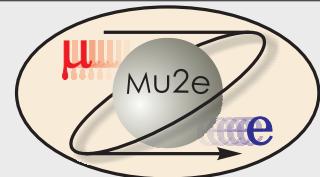
Transport Solenoid:
graded from ~2.5 to 2.0T
to accelerate muons along beamline



Detector Solenoid:
graded from ~2.0 to 1T
to “reflect” backwards-going electrons
and send them into detector

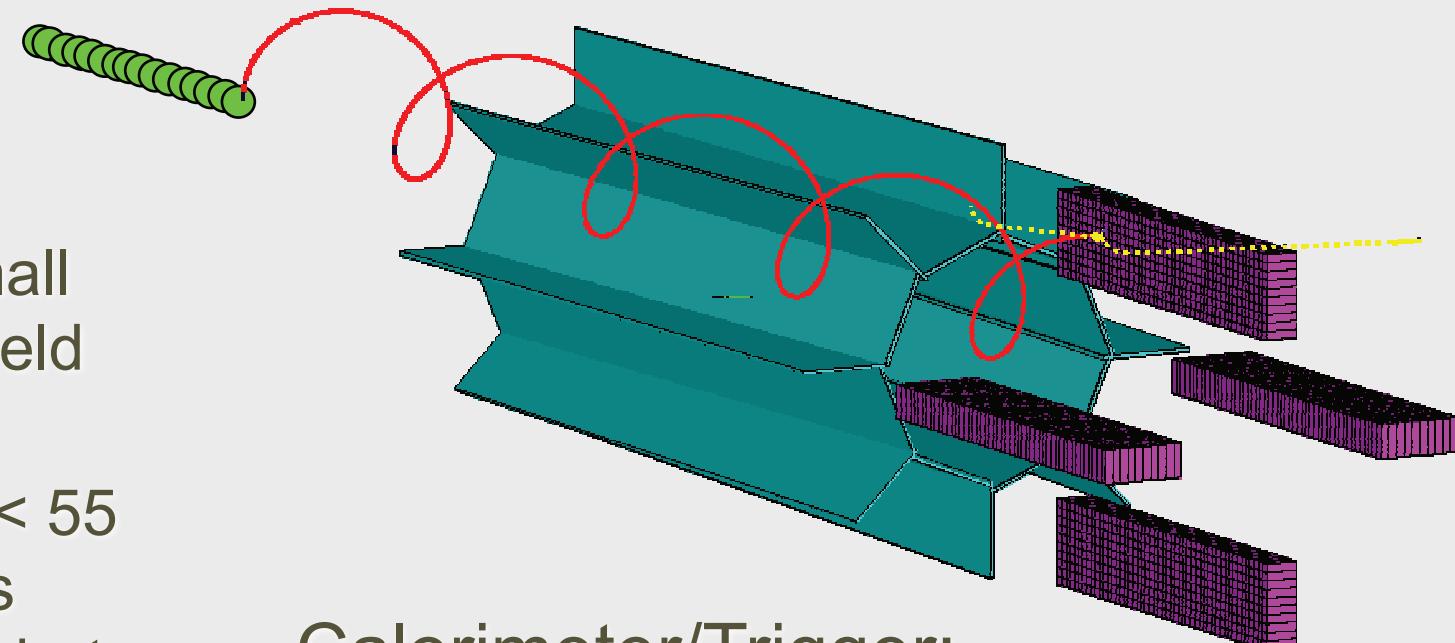


Detector



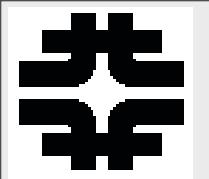
- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
 - up to dE/dx , scattering, small variations in field
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center

$\sigma = 200 \mu$ transverse, 1.5 mm axially
2800 axial straw tubes, 2.6 m by 5 mm, 25μ thick
use return yoke as CR shield

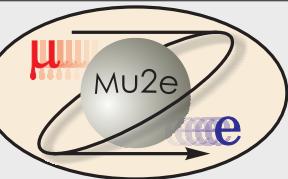


Calorimeter/Trigger:

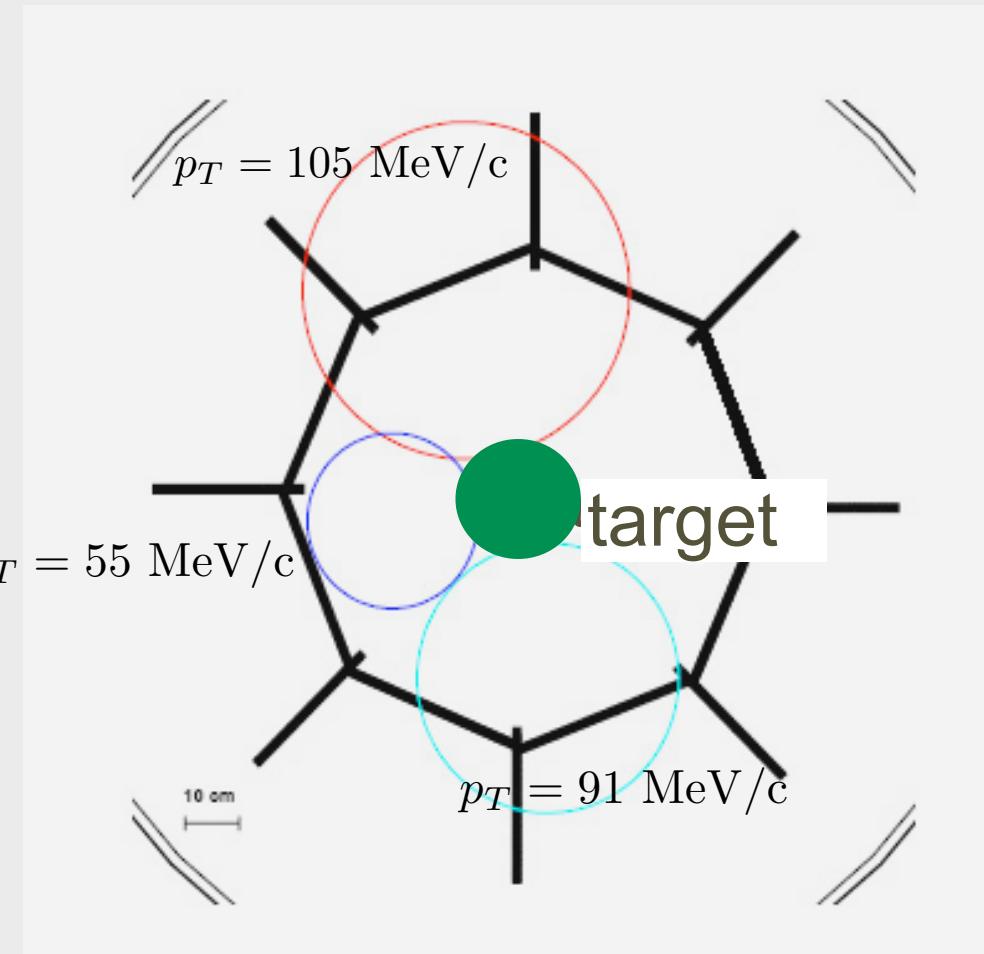
$\sigma /E = 5\%$, 1024 $3.5 \times 3.5 \times 12$ cm PbWO_4



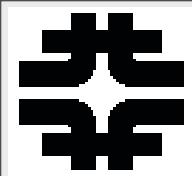
Beam's Eye View of Tracker



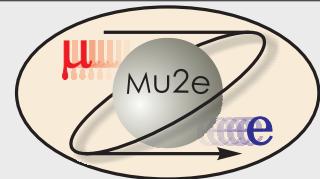
- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field
- Below $p_T = 55$ MeV, electron stays inside tracker and is not seen; about 60° at 103.5 MeV
- Looking for helix as particle propagates downstream



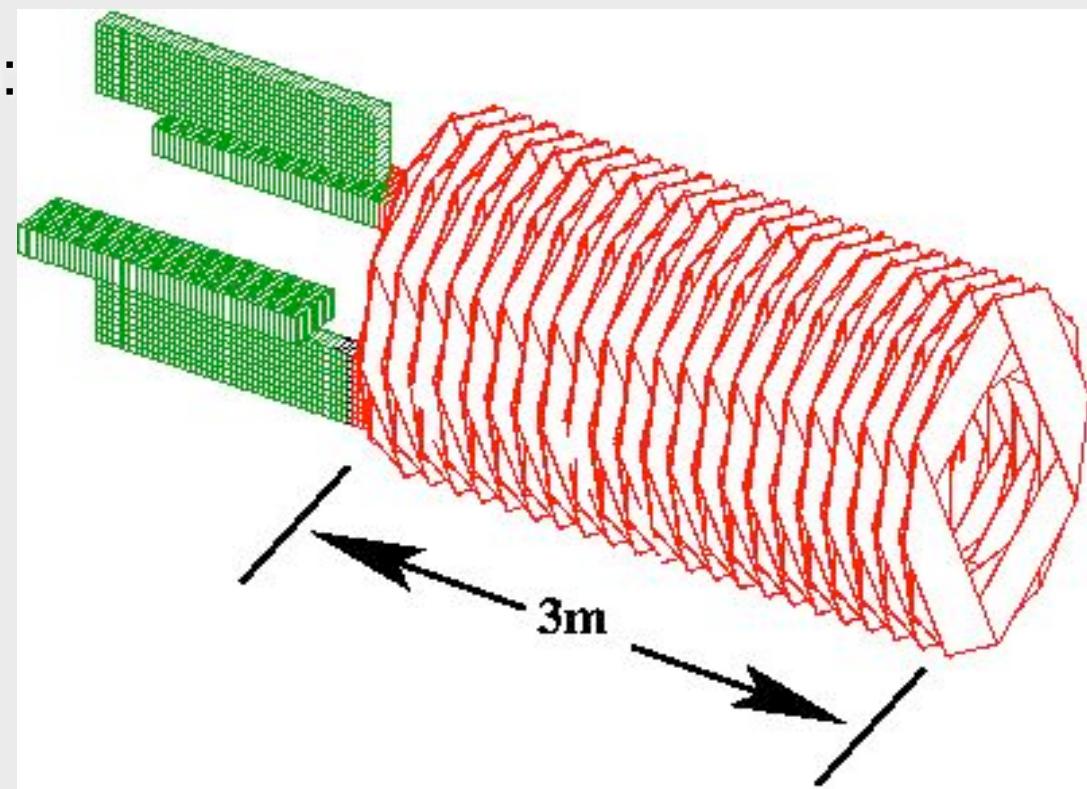
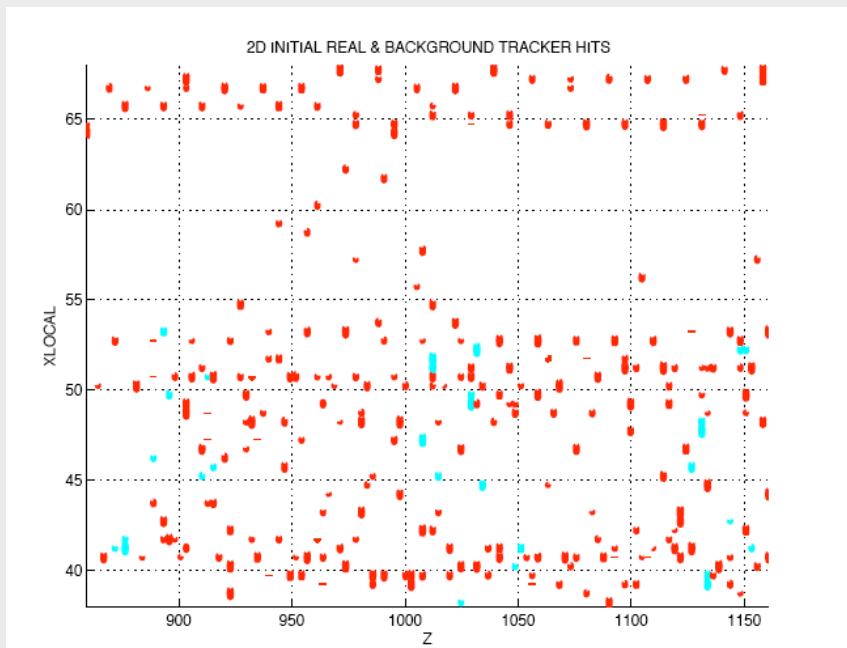
Only $\sim 0.3\%$ of DIO's are even accepted



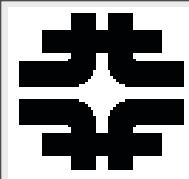
Alternative Tracker



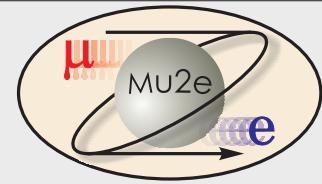
- T-tracker (T for transverse):
- 260 sub-planes
 - sixty 5 mm diameter conducting straws
 - length from 70-130 cm
 - total of 13,000 channels



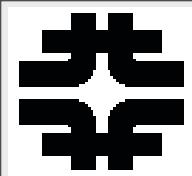
T-Tracker Pattern Recognition
Difficult but
Kalman Filter is promising



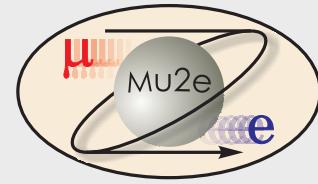
L-Tracker vs. T-Tracker



- L-Tracker: straws along beam
 - Conceptually simpler tracking
 - Basis of MECO
 - Where does support/infrastructure go?
Material in electron path
 - Can anyone build straws $0.5\text{ cm} \times 2.6\text{m}$ in vacuum?
- T-Tracker: straws perp to beam
 - More prone to pattern recognition errors?
 - **Active Investigation:**
 - **kalman filter, applied to both on same events**
 - **work just beginning**
 - **help welcome!**

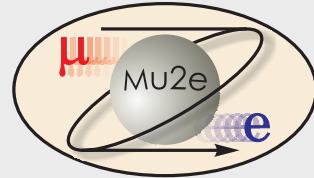
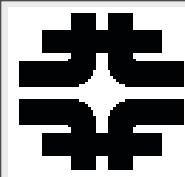


Backgrounds...

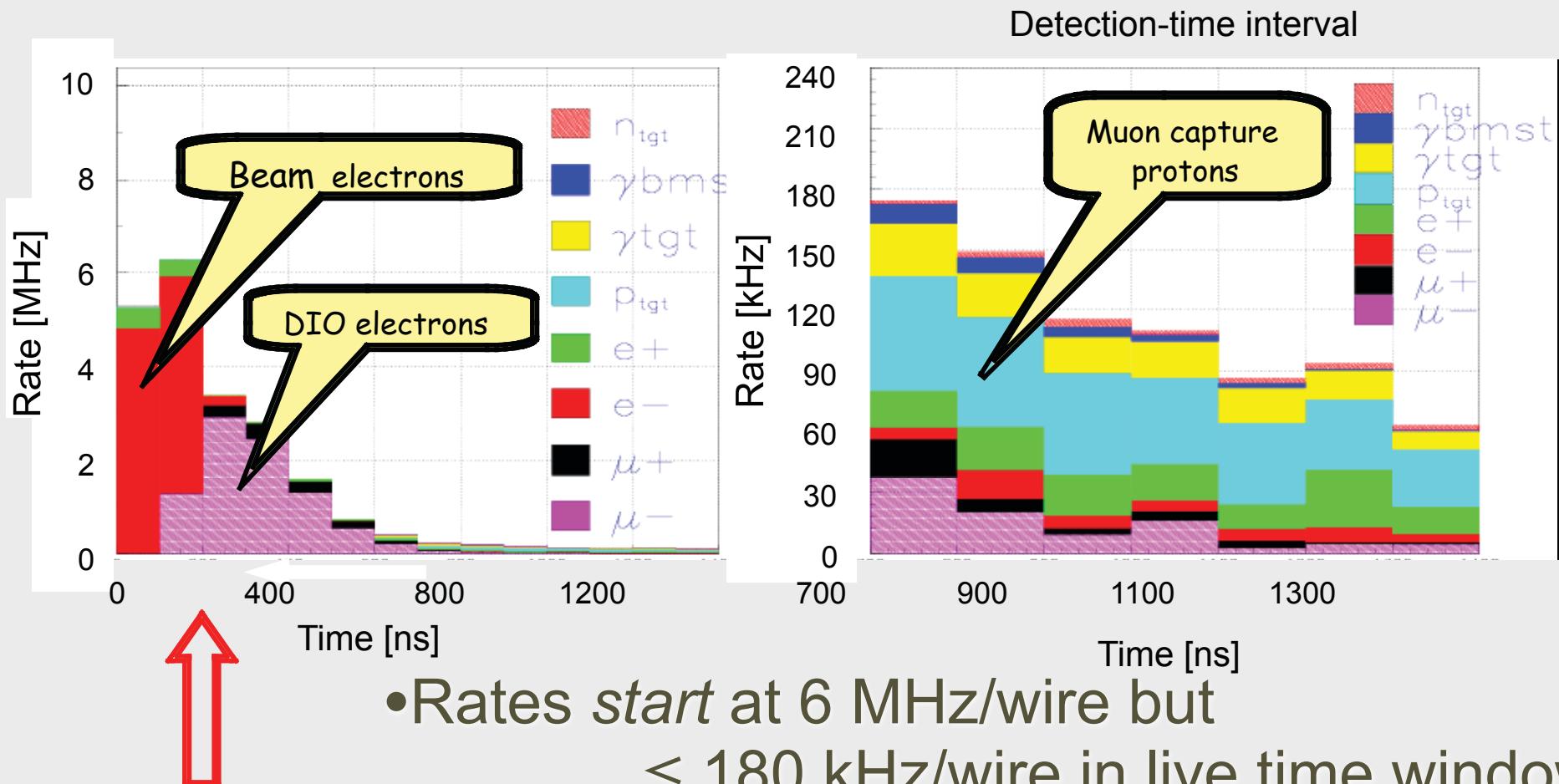


Type	Description
e_t	beam electrons
n_t	neutrons from muon capture in muon stopping target
γ_t	photons from muon capture in muon stopping target
p_t	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, < 55 MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, > 55 MeV
n_{bd}	neutrons from muon capture in beam stop
γ_{bd}	photons from muon capture in beam stop
$e(DIO)_{bd} < 55$	DIO from muon capture in beam stop, < 55 MeV
$e(DIO)_{bd} > 55$	DIO from muon capture in beam stop, > 55 MeV
$e(DIF)$	DIO between stopping target and beam stop

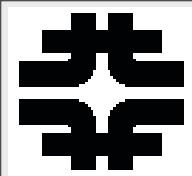
bd = albedo from beam stop (after calorimeter): flashback, extra hits
confusing pattern recognition



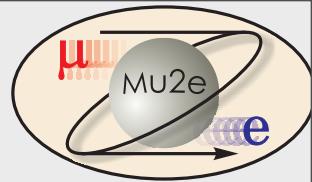
Magnetic Spectrometer: Rates vs. Time



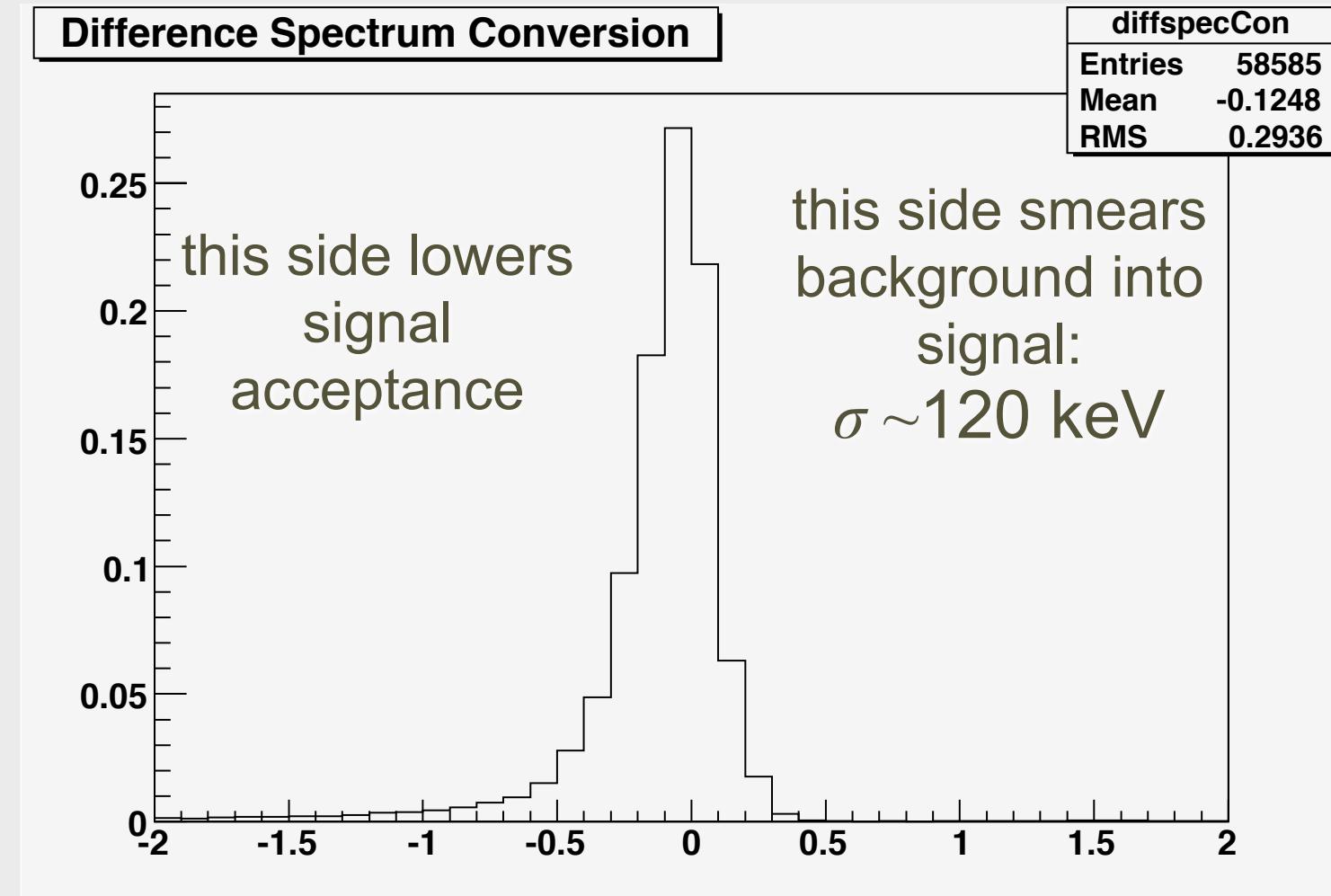
- Rates start at 6 MHz/wire but $\lesssim 180$ kHz/wire in live time window
- Each muon capture produces 2γ , $2n$, $0.1p$

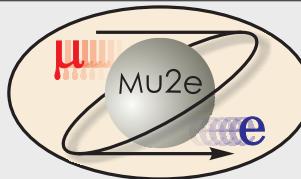


Expected Resolution

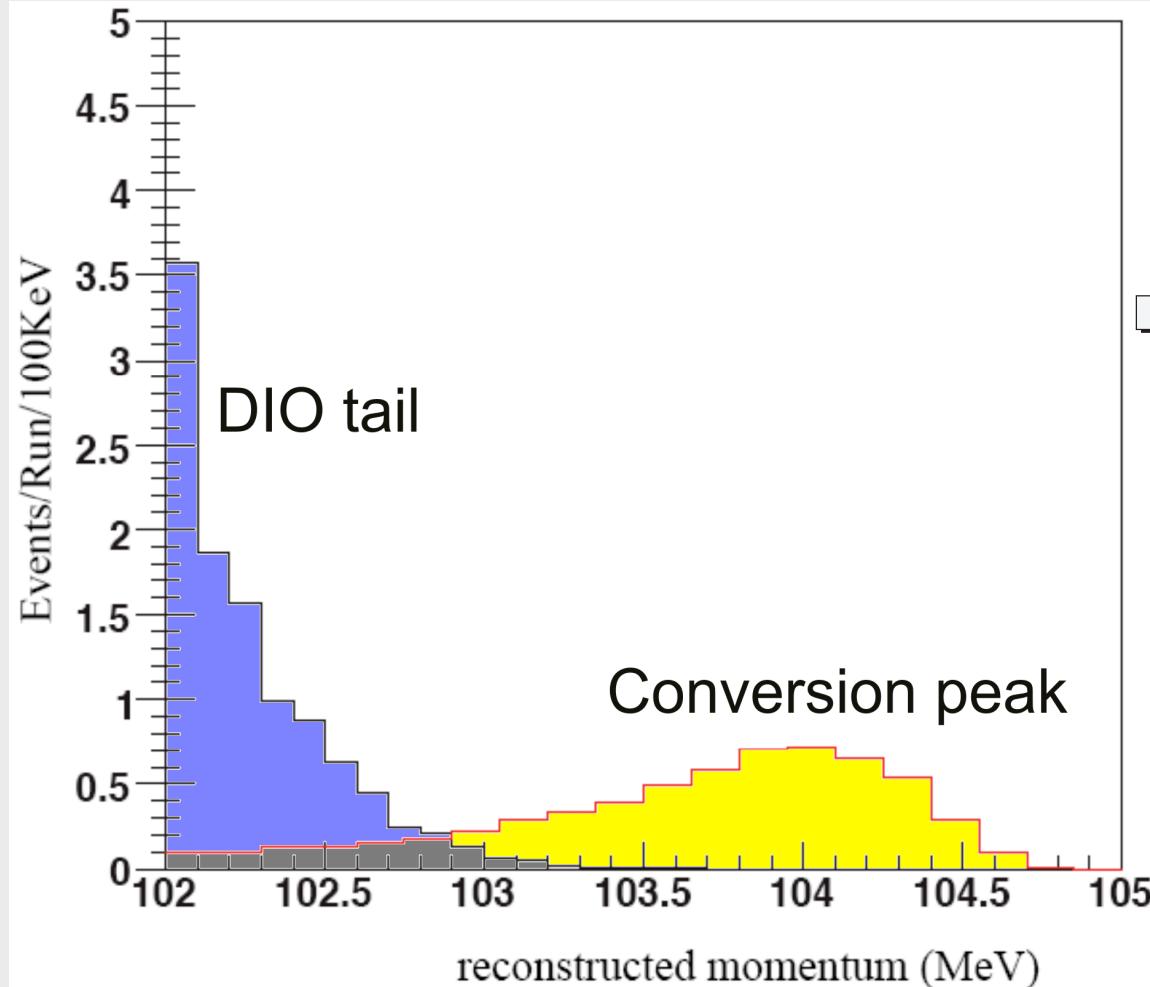


- We must understand resolution
- Measure resolution with special runs varying target foils, field, location of stopping target

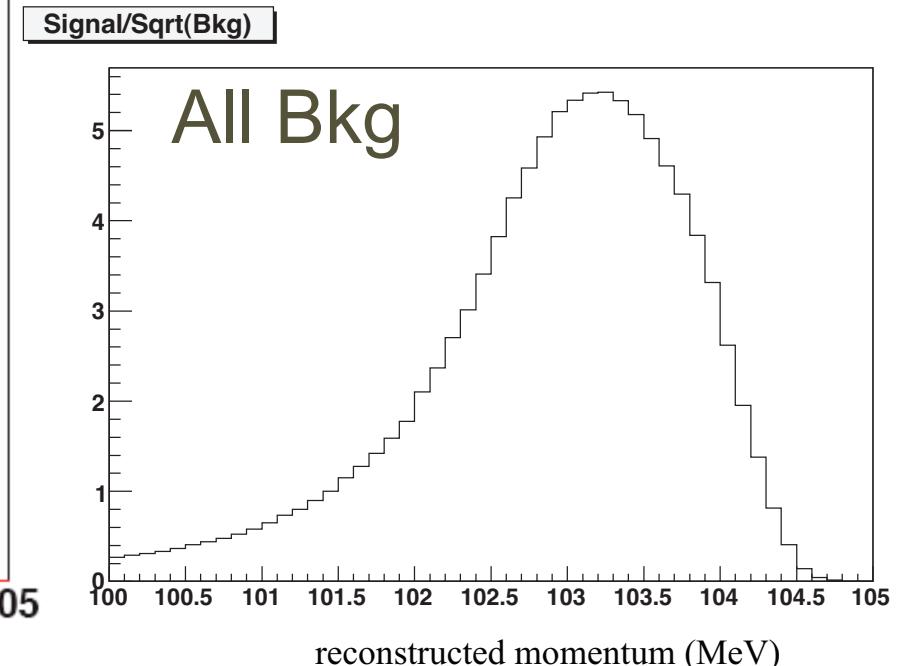


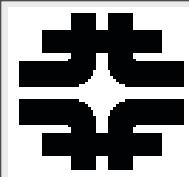


Signal and Background



- $R_{\mu e} = 10^{-16}$
- $\frac{S}{\sqrt{B}} \sim 5.5$



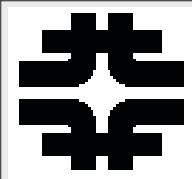


Final Backgrounds

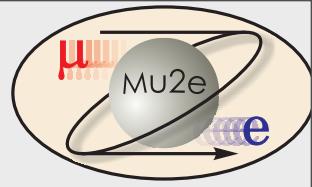


- For $R_{\mu e} = 10^{-15}$
~50 events / 0.5 bkg
(LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
~5 events / 0.5 bkg
- Extinction factor of
 10^{-9}

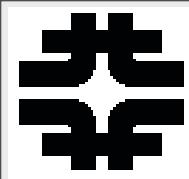
Source	Number/ 4×10^{20}
DIO	0.25
Radiative π capture	0.08
μ decay-in-flight	0.08
Scattered e-	0.04
π decay in flight	<0.004



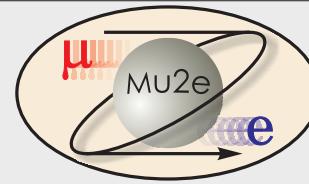
Outline



- The search for muon-electron conversion
- Experimental Technique
- *Fermilab Accelerator*
- Project X Upgrades and Mu2e



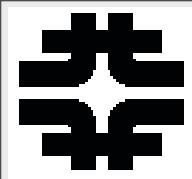
FNAL Beam Delivery



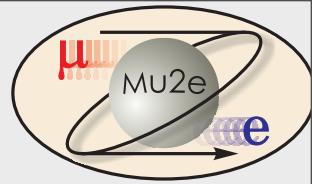
- FNAL has unique, major strength:

Multiple Rings

- *no interference* with NOvA neutrino oscillation experiment
- reuse existing rings with only minor modifications



NovA Era and Mu2e

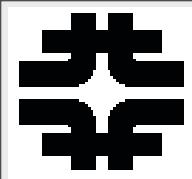


- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

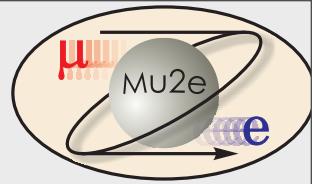


booster batches

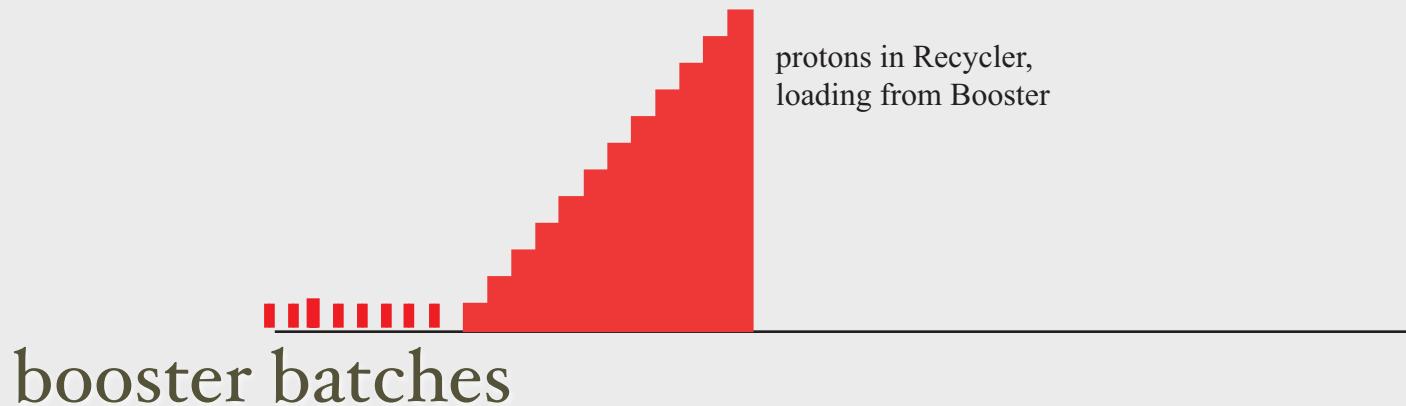
- Single-Turn Transfer to MI



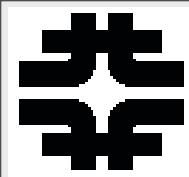
NovA Era and Mu2e



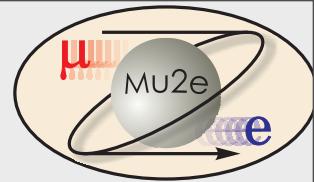
- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz



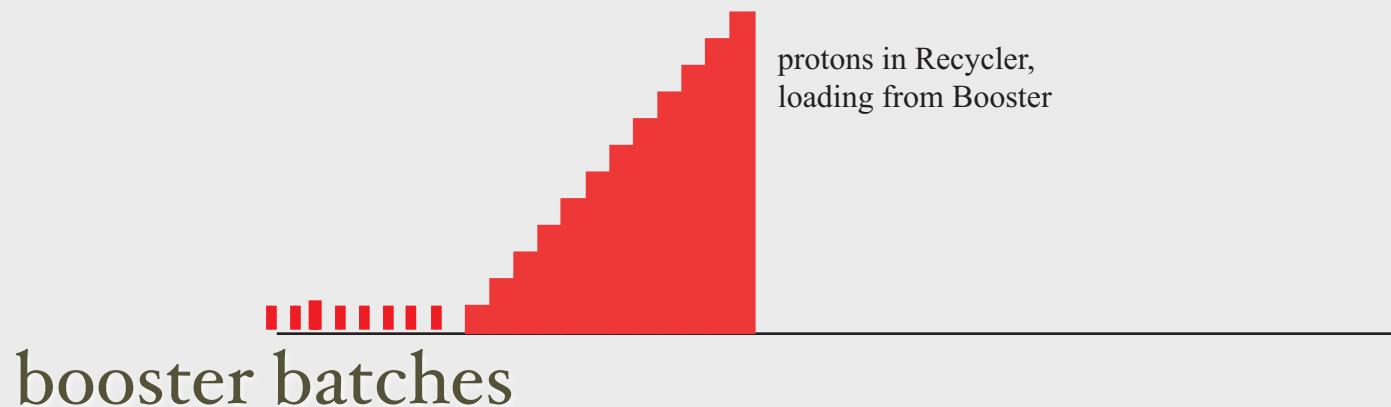
- Single-Turn Transfer to MI



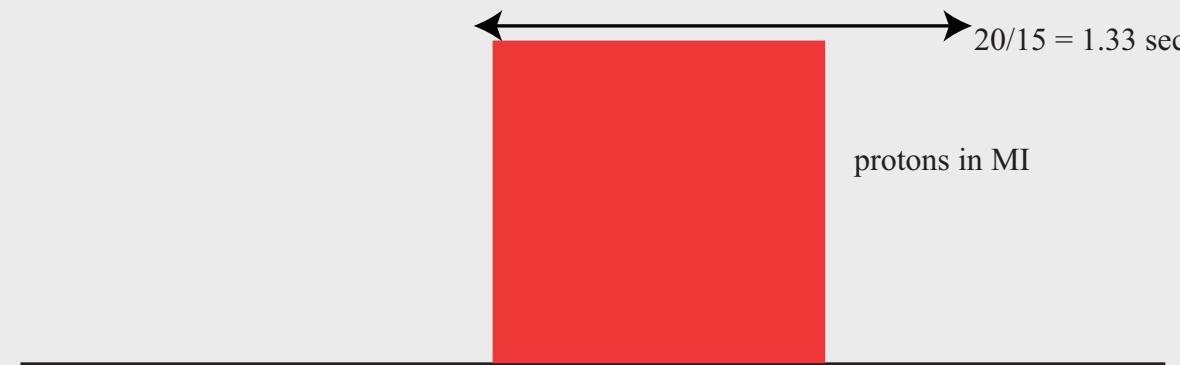
NovA Era and Mu2e

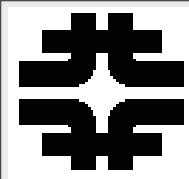


- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz

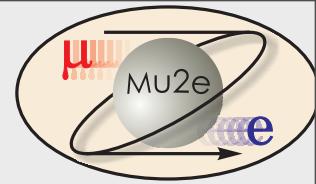


- Single-Turn Transfer to MI

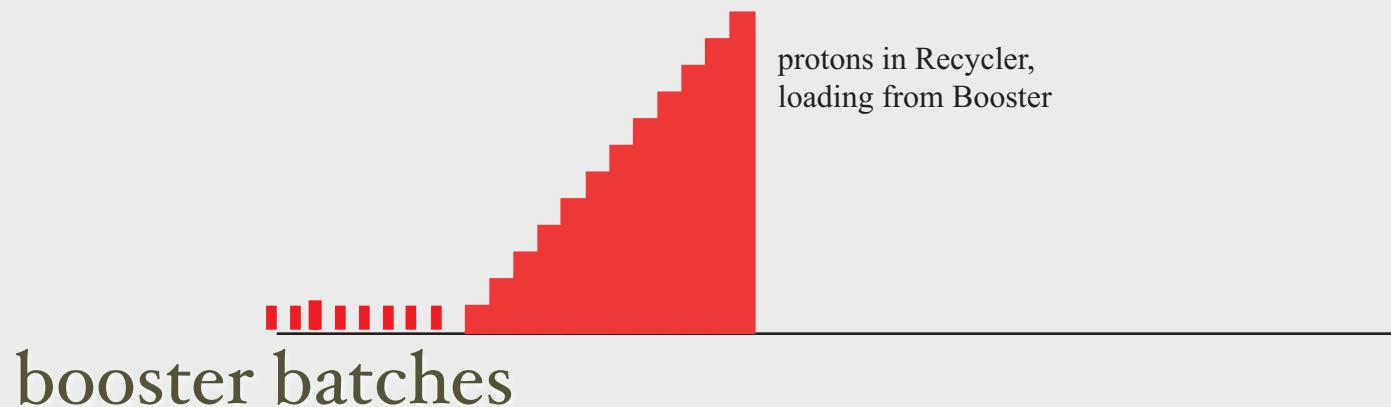




NovA Era and Mu2e

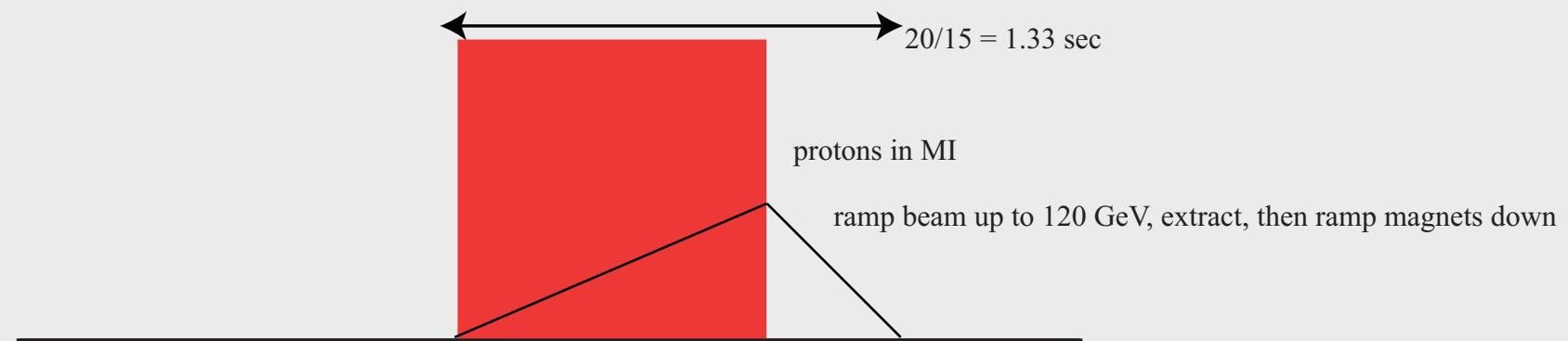


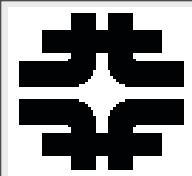
- Load from Booster to Recycler; Booster ‘ticks’ at 4E12, 15 Hz



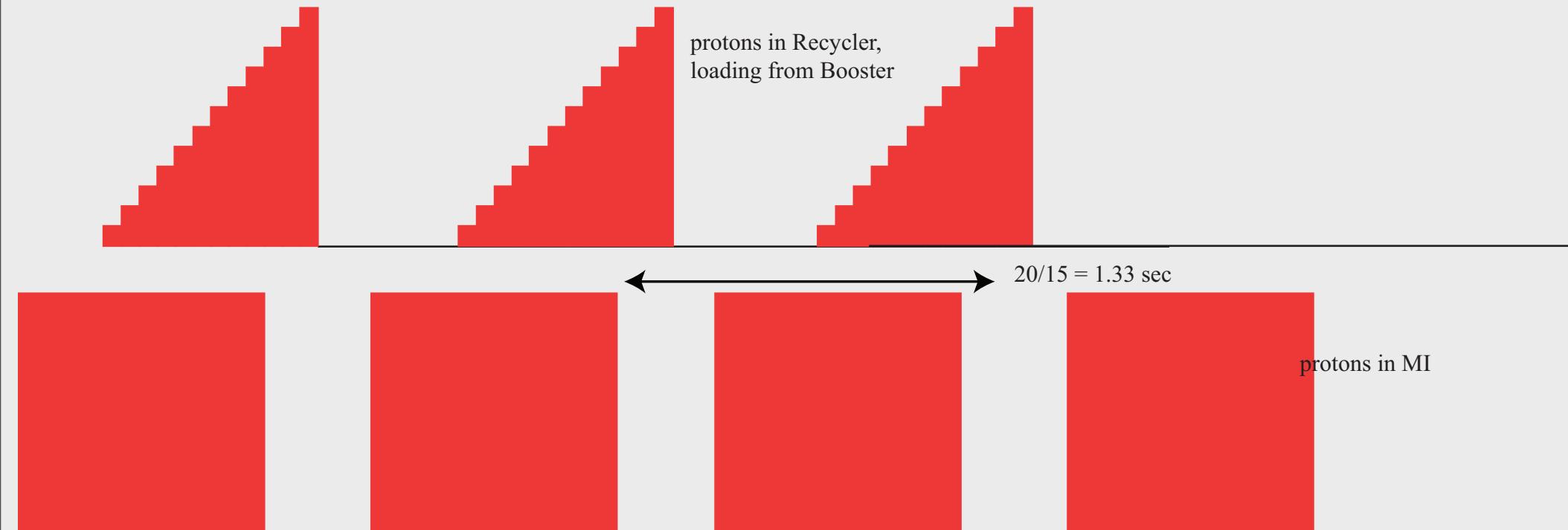
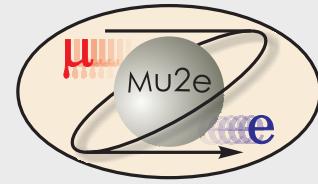
booster batches

- Single-Turn Transfer to MI



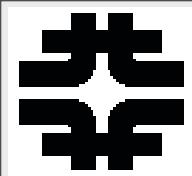


All Together...

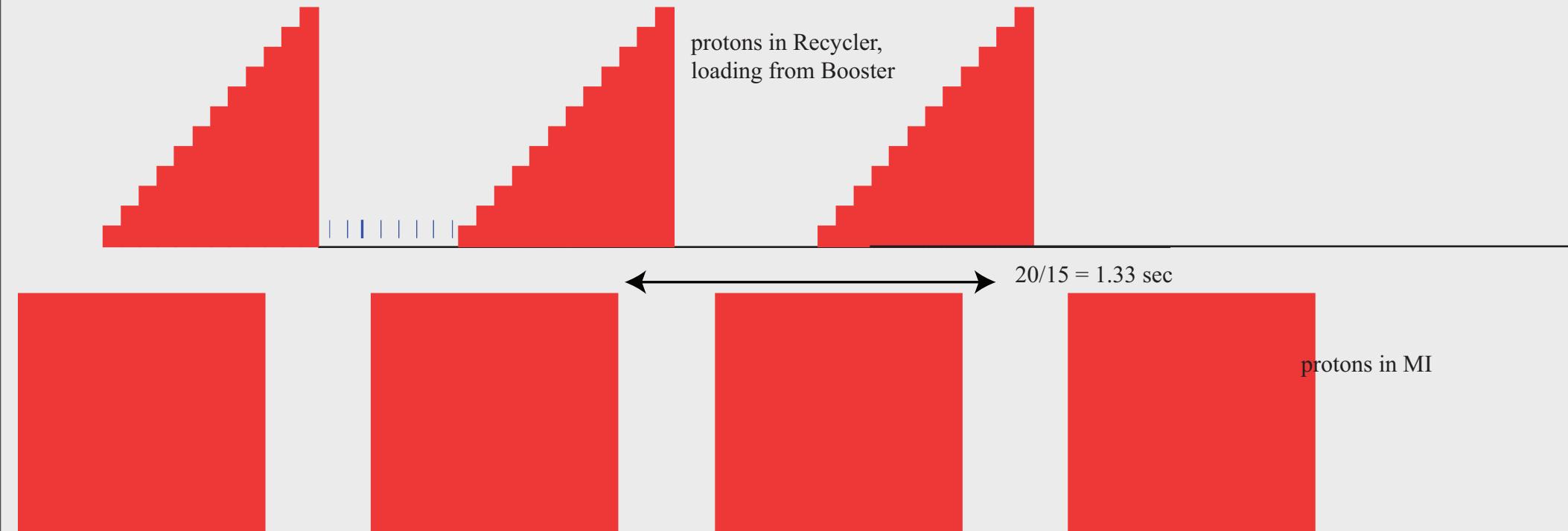
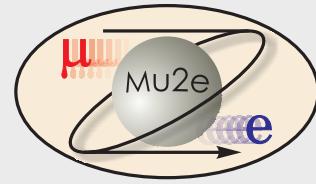


time to ramp allows us to fit eight extra Booster batches for Mu2e
(can use 6)

ramp beam up to 120 GeV, extract, then ramp magnets down

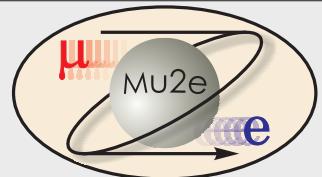
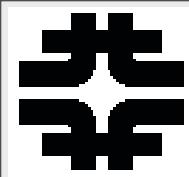


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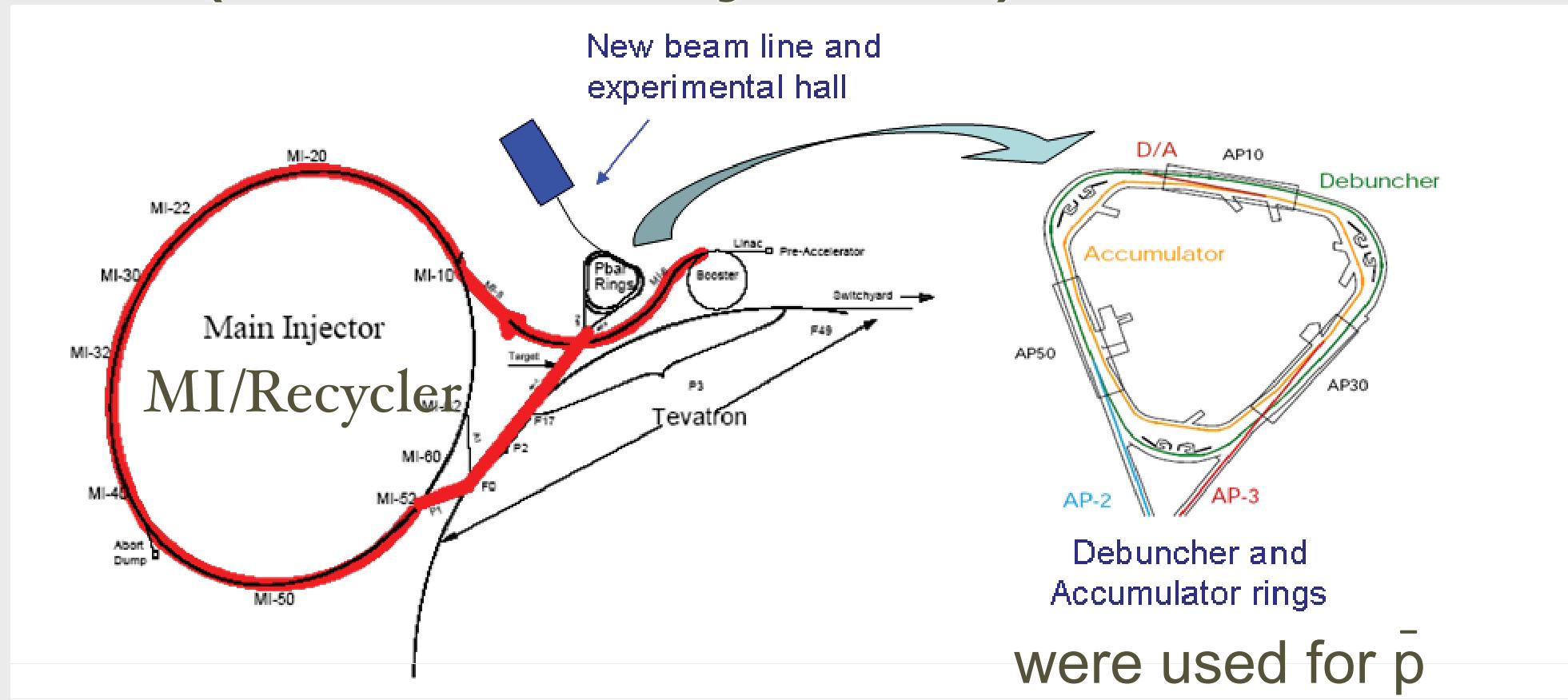


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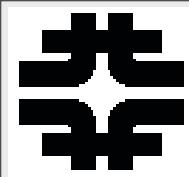
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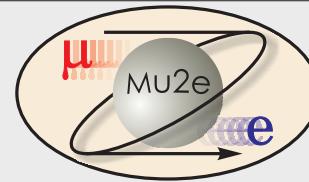
Booster-Era (before Project X) Beam



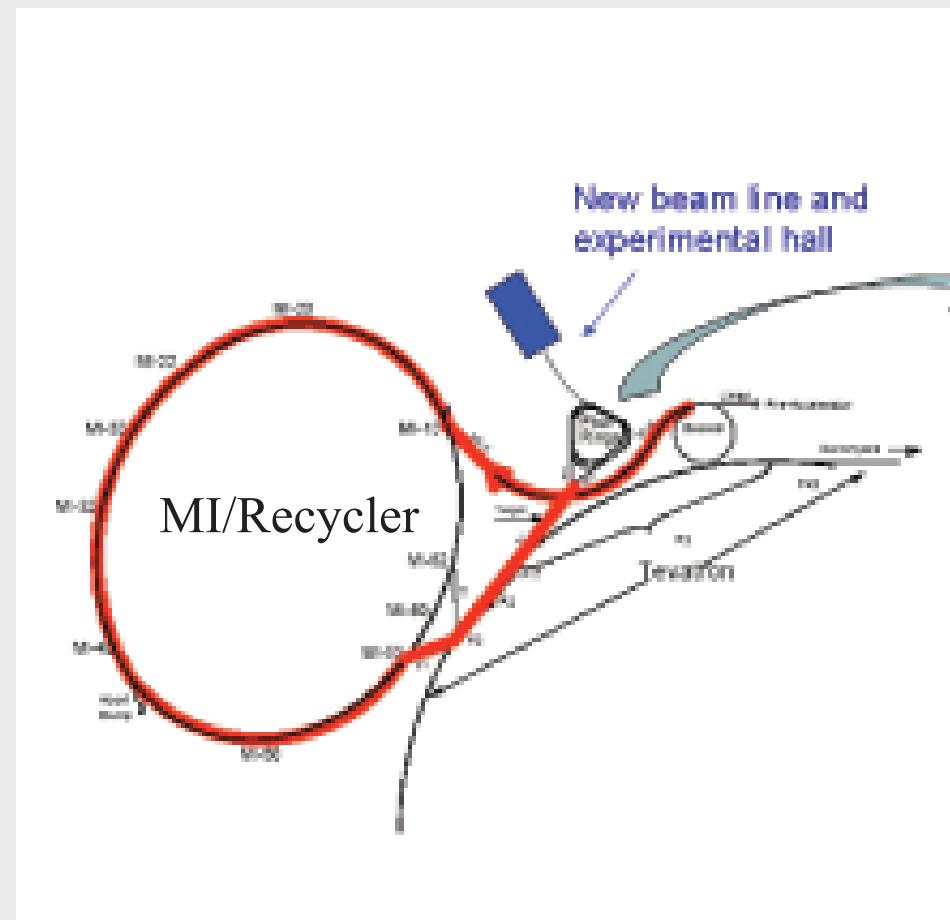
- After TeVatron shut-down, Accumulator, Debuncher, and Recycler no longer needed for antiprotons

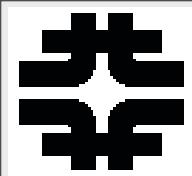


“Boomerang Scheme”

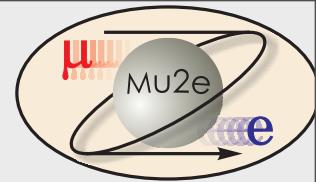


- Booster Batches transported partway through Recycler and injected directly into Accumulator
- “Momentum-Stack” batches in Accumulator
- Transfer to Debuncher
- Rebunch into Single Bunch:
 - 38 nsec RMS, ± 200 MeV
- Slow Extraction: transverse, yields bunch “train”
- Resonant Extraction of Bunch

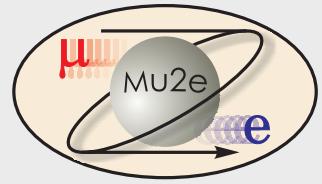
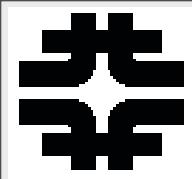




“Boomerang Scheme”

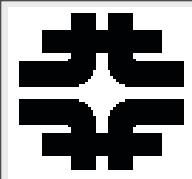


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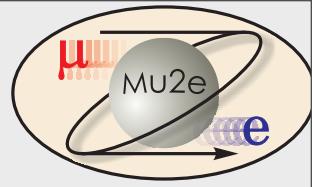


Proposed Site

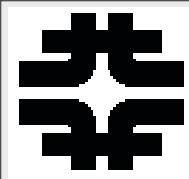




Outline



- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e

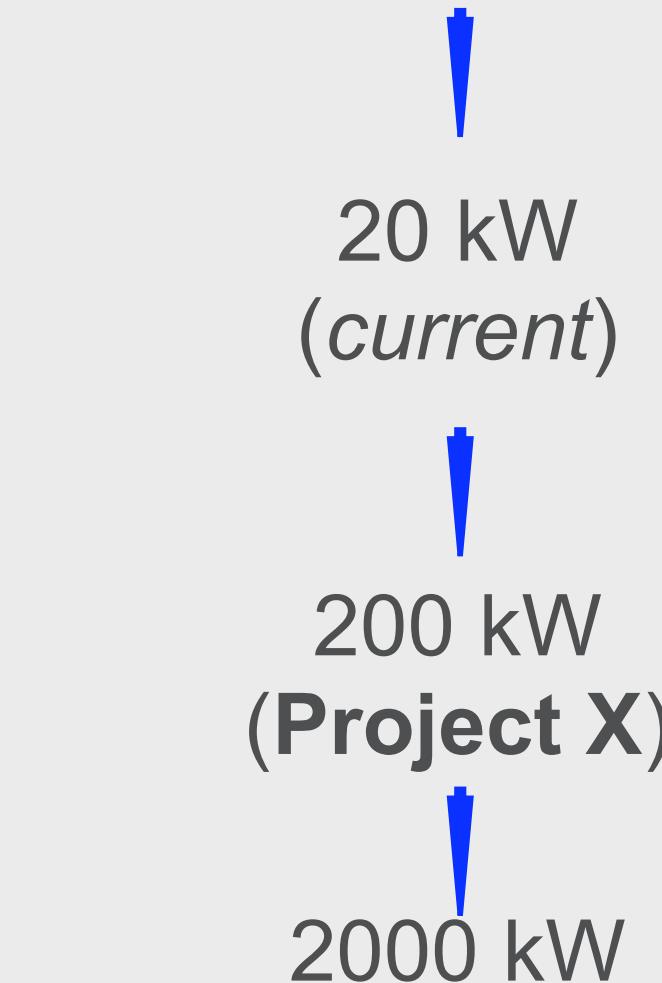


Mu2e and Project X

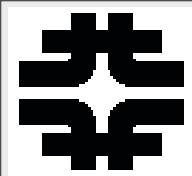


*available 8 GeV Power
for intensity frontier*

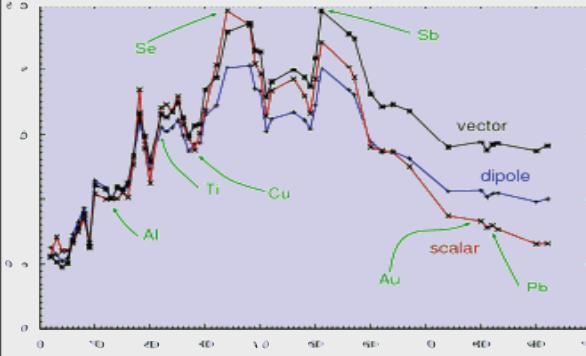
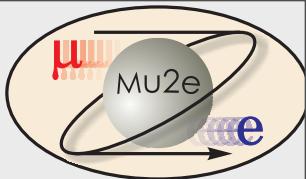
- Project X is **required** for the next step
- Needed whether first phase sees a signal or sets a limit
- Well timed for Mu2e first phase, late this decade or early next



(Project X Upgrades)



Mu2e Phase II



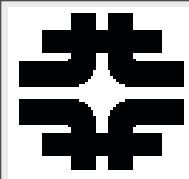
Yes

Signal?

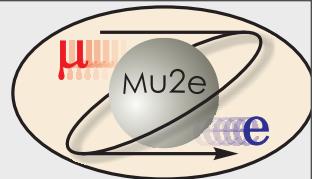
No

1. Change Z of Target to determine source of new physics
2. Need Project X to provide statistics

1. Probe additional two orders of magnitude made possible by Project X
2. Need upgrades to muon transport and detector



Experimental Challenges



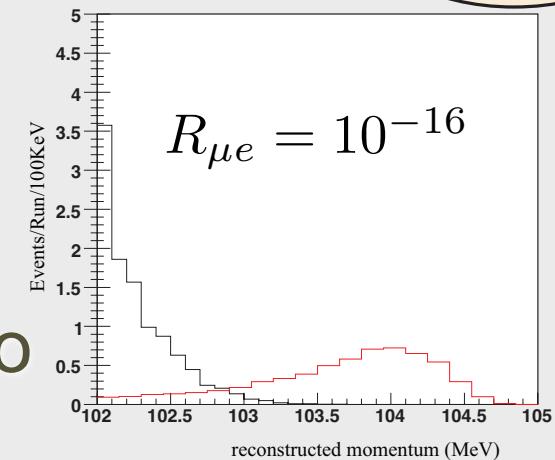
Nucleus	$R_{\mu e}(Z) / R_{\mu e}(\text{Al})$	Bound Lifetime	Conversion Energy	Fraction >700 ns
Al(13,27)	1.0	864 nsec	104.96 MeV	0.45
Ti(22,~48)	1.7	328 nsec	104.18 MeV	0.16
Au (79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV	negligible

Yes

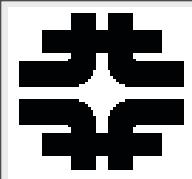
Signal?

No

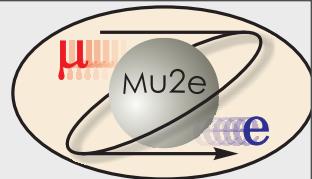
1. Change Z of Target to determine source of new physics
2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport



1. Both Prompt and DIO backgrounds must drop to measure $R_{\mu e} \sim 10^{-18}$
2. Detector, Muon Transport, Cosmic Ray Veto, Calorimeter

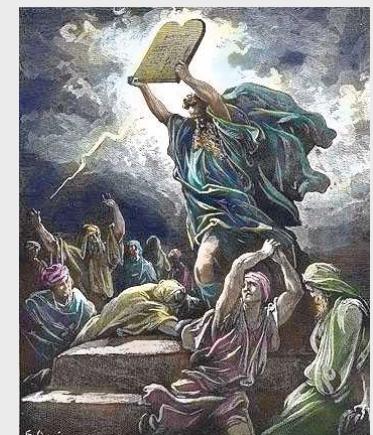


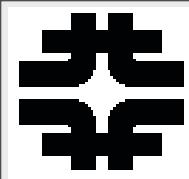
Cost and Schedule



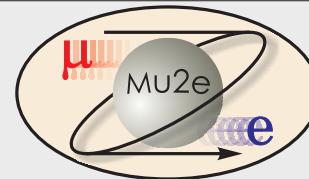
- Use MECO for Solenoids and Detector
 - Inflated at 3.5%/yr from FY2005 to FY2009
 - 50% contingency on MECO
- FESS Project Definition Report for Conventional Construction, their methodology
- Accelerator Division Estimate for Modifications
100% contingency

\$200.0M
fully-loaded TPC with R&D
in FY2009\$





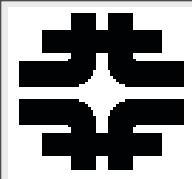
Cost and Schedule



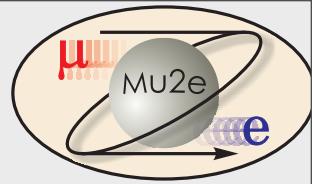
- *This is a technically limited schedule*
- Critical Path is Superconducting Solenoids
- Use MECO and FNAL TD estimates:
 - 1 yr to finish conceptual design
 - 6 yrs for final design through construction
 - t=0 is 1st Quarter Calendar 2009

Solenoids	2009				2010				2011				2012				2013				2014				2015				
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
Conceptual Design																													
Final Design/place contracts																													
Construction/installation/commissioning																													

commissioning 1st quarter Calendar 2016



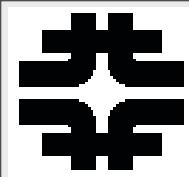
Project X Timing



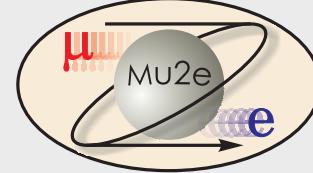
- Must run and analyze Mu2e Phase I
- We will continue to refine our existing design and look for new ideas
 - solenoid? tracking? time structure?
- Finish analysis Phase I around 2020

then

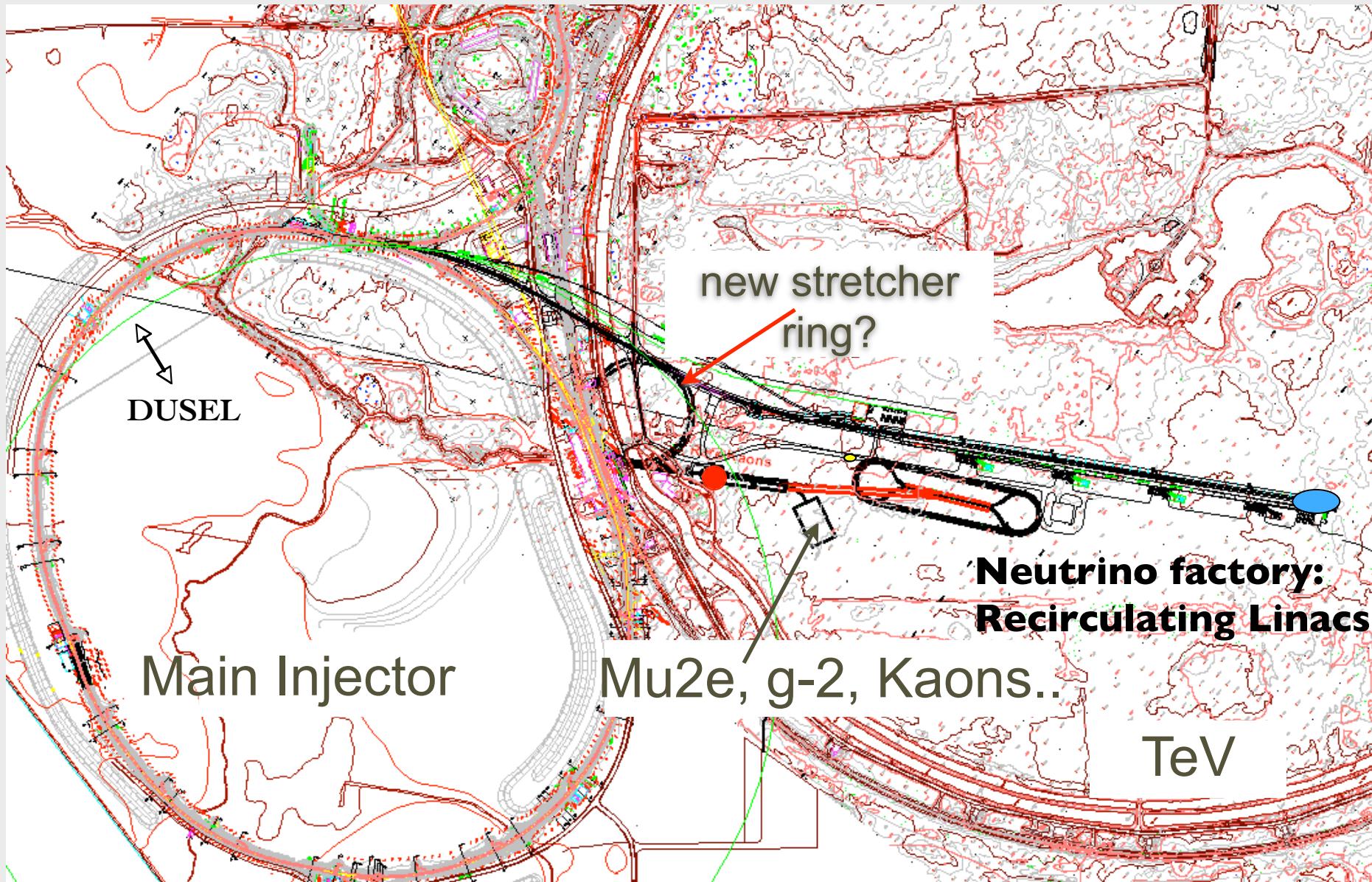
- ***Project X makes a **program** possible, improving as we learn***

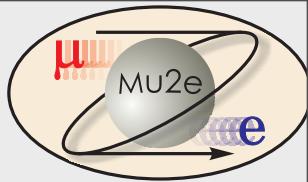
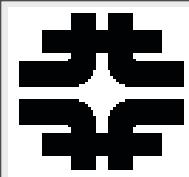


Project X Era?



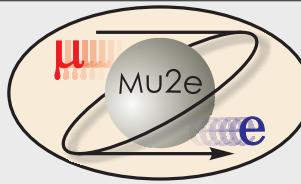
not approved or part of any official plan...



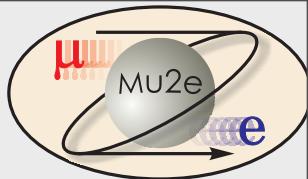
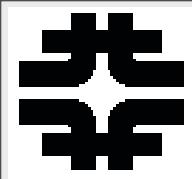


Conclusions

- In the initial phase (without Project X) we would either:
 - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)*
 - *Discover unambiguous proof of Beyond Standard Model physics*
- With a combination of Project X and/or improved muon transport, we could either
 - *Extend the limit by up to two orders of magnitude*
 - *Study the details of new physics*



And Perhaps Answer Rabi's Question about the physics of flavor and generations



And Perhaps Answer Rabi's Question about the physics of flavor and generations



Who ordered that?