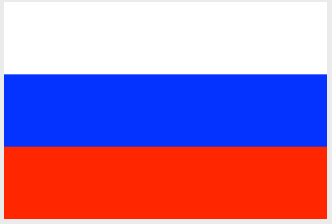
A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at Sensitivity < 10^{-16}

R. Bernstein
Fermilab
for the Mu2e Collaboration

Collaboration

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

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



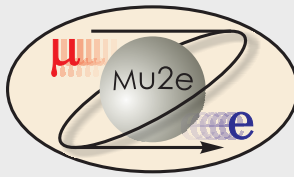
Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia

~130 collaborators

Outline

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

What is μe Conversion?



muon converts to electron in the presence of a nucleus

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

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

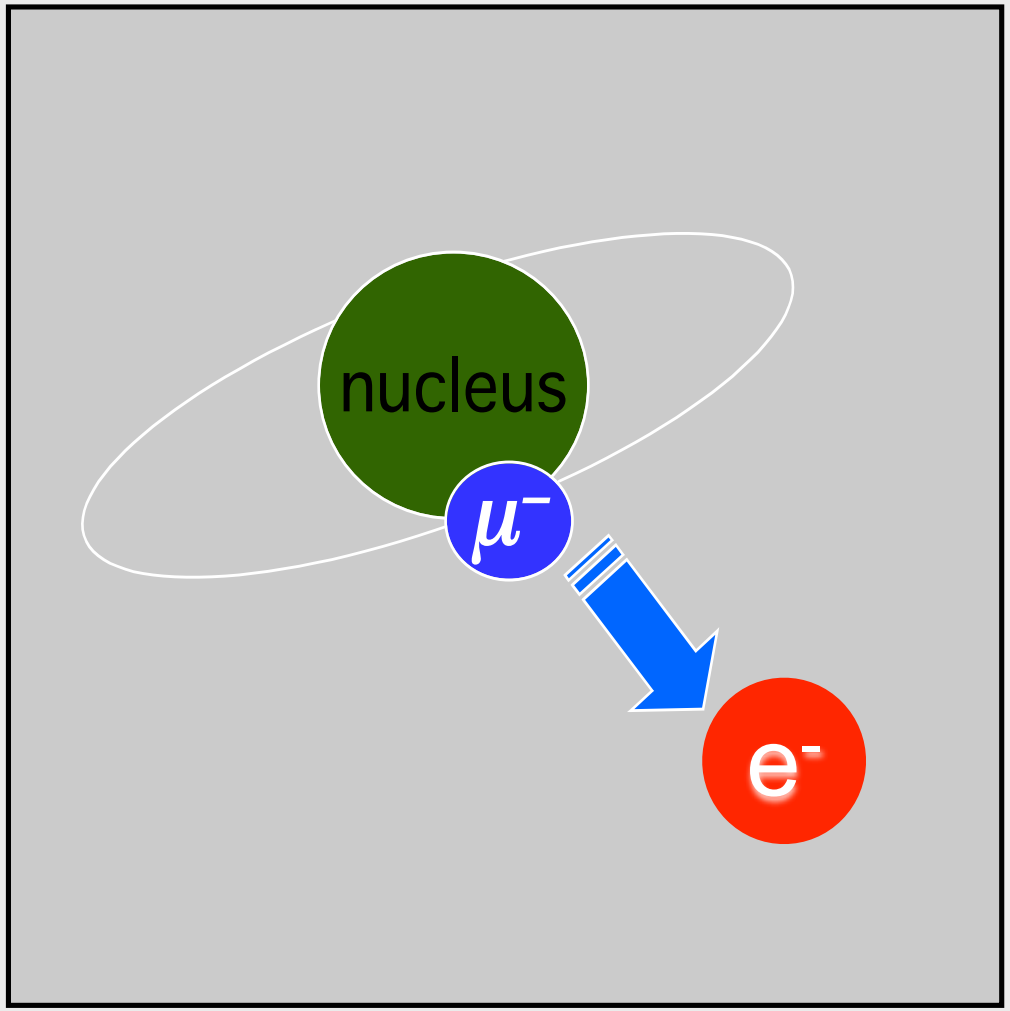
- Charged Lepton Flavor Violation (CLFV)
  - will measure $R_{\mu e} < 6 \times 10^{-17}$ @ 90%CL
- Related Processes:

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

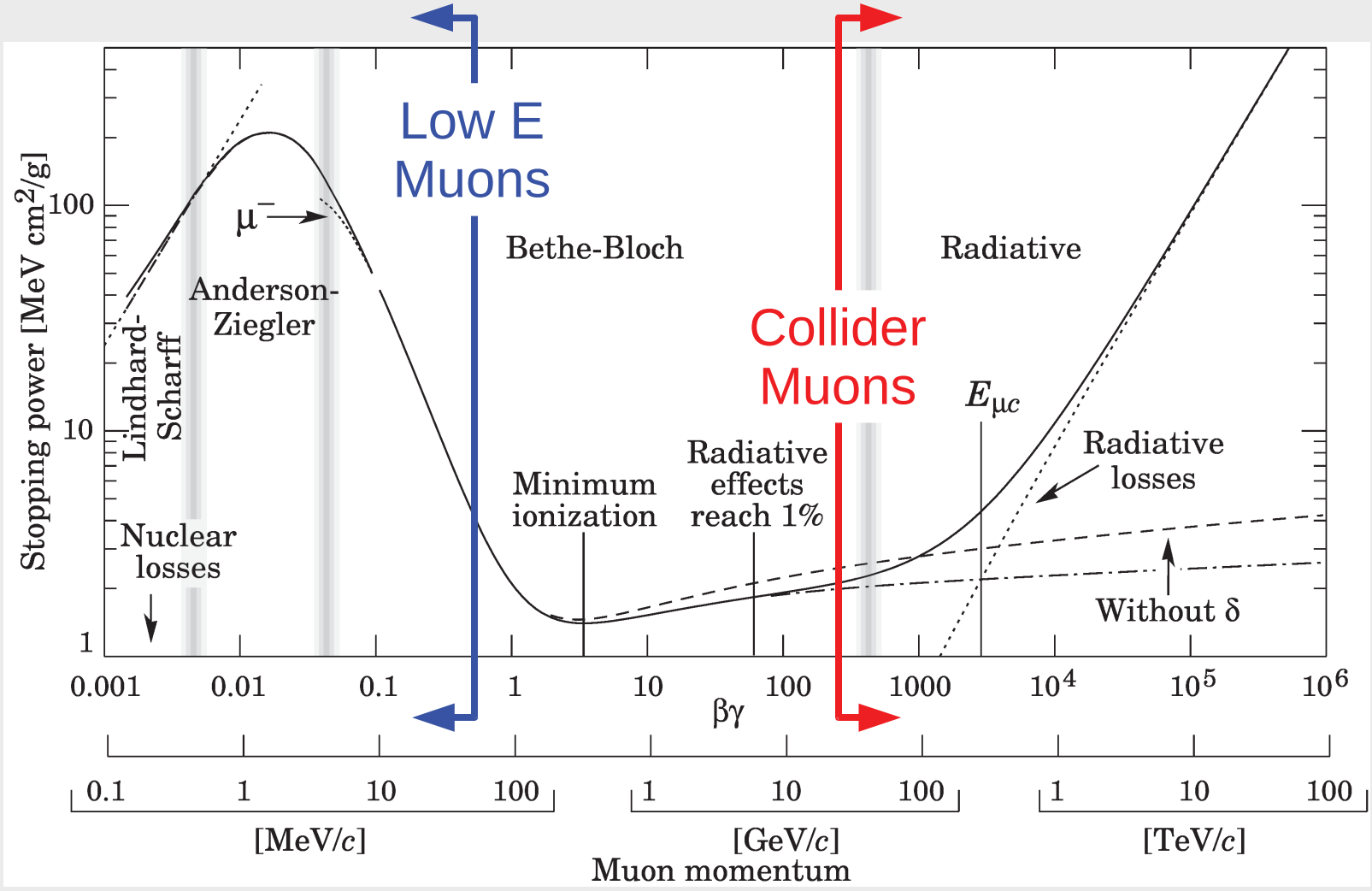
Experimental Signal

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

- A Single Monoenergetic Electron
- If *N* = Al, E_e = 105. MeV
  - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup



Physics is Different at these energies!



"Who ordered that?"

– I.I. Rabi

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

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

➡ same as GIM mechanism!

"Who ordered that?"

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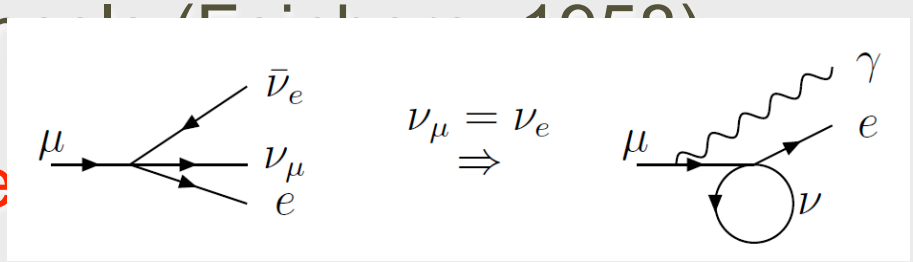
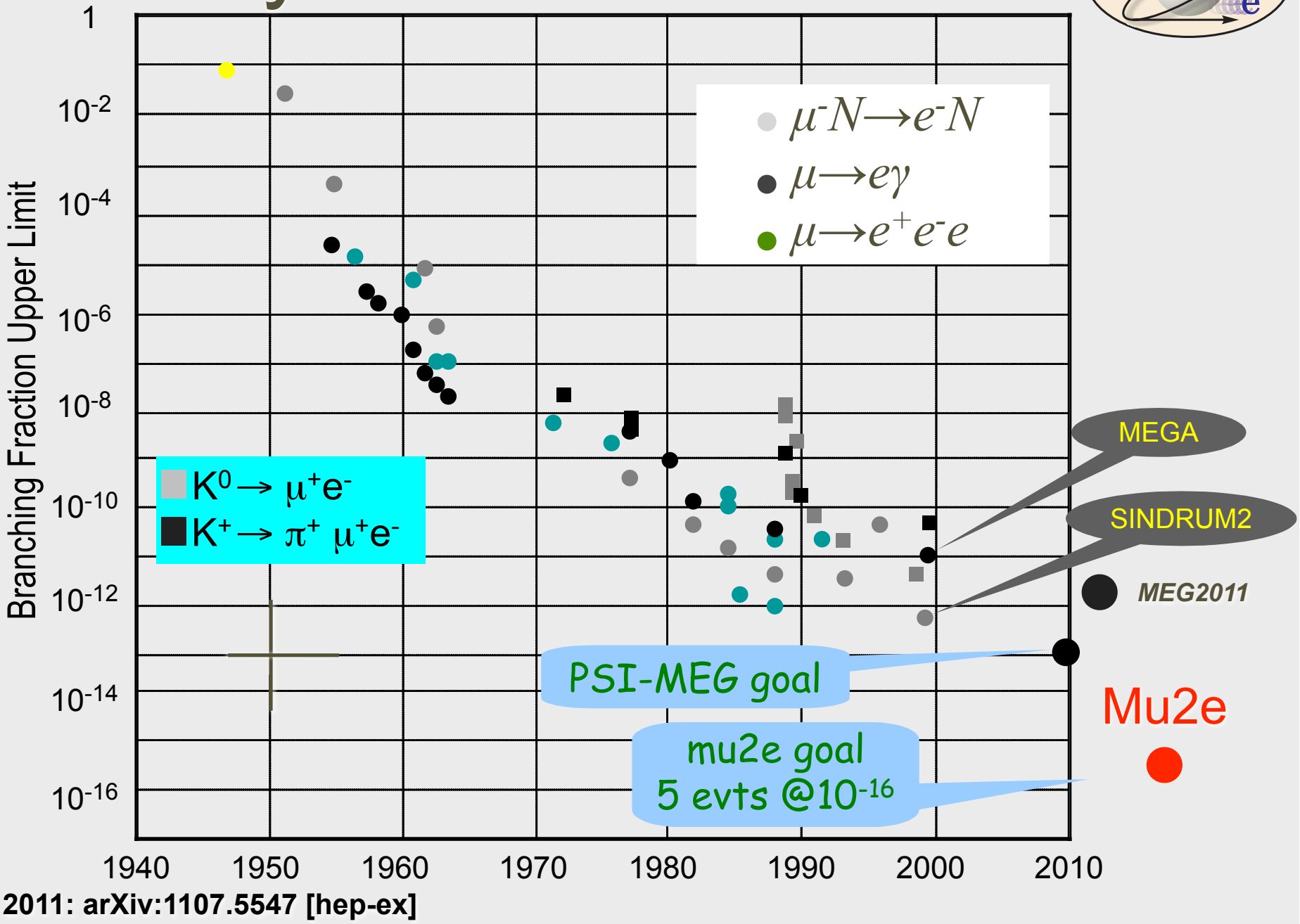


[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \to e + \nu + \bar{\nu}$.

History of CLFV Searches



MEG 2011: arXiv:1107.5547 [hep-ex]

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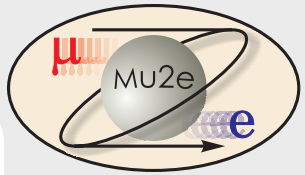

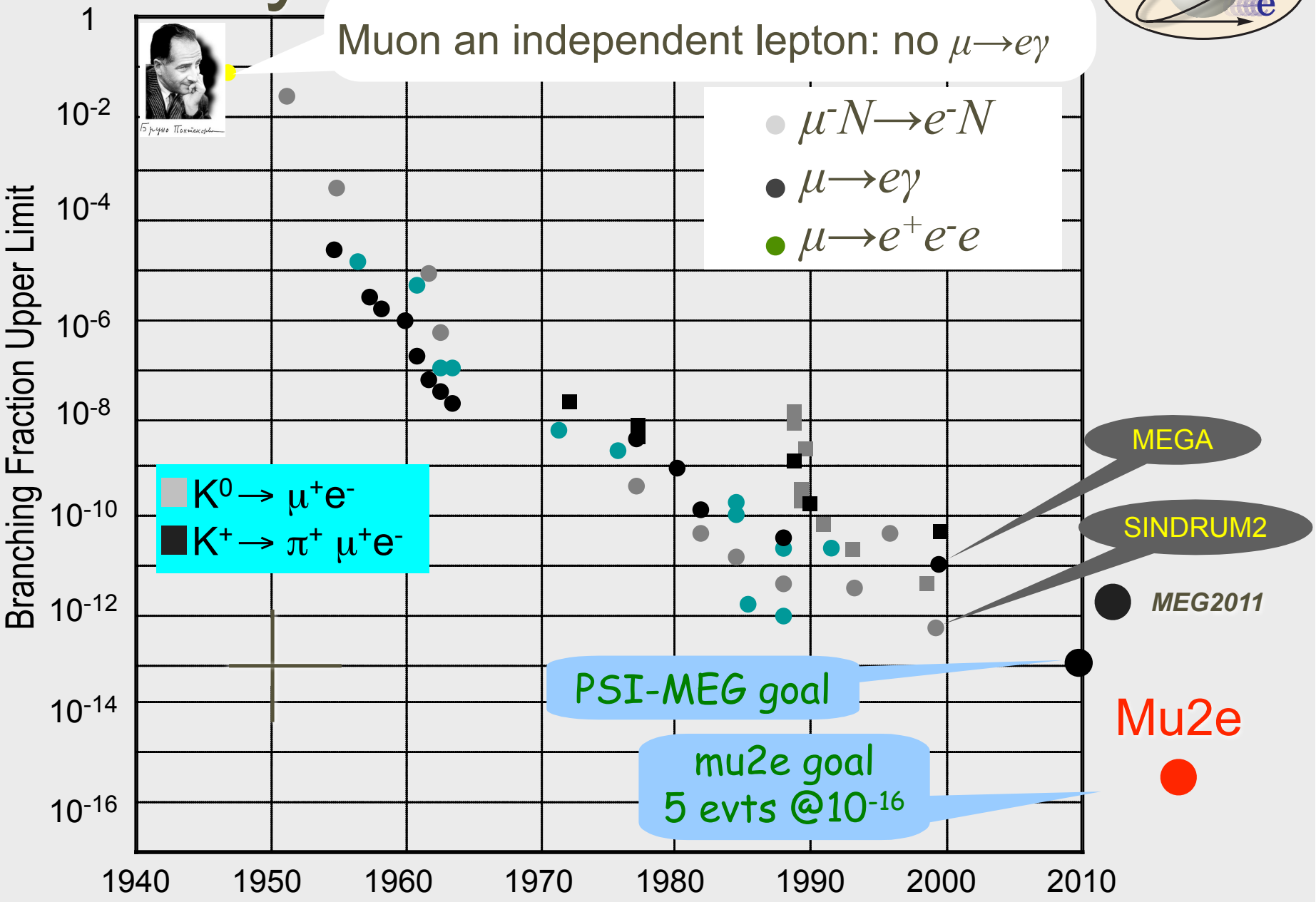

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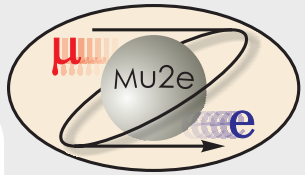

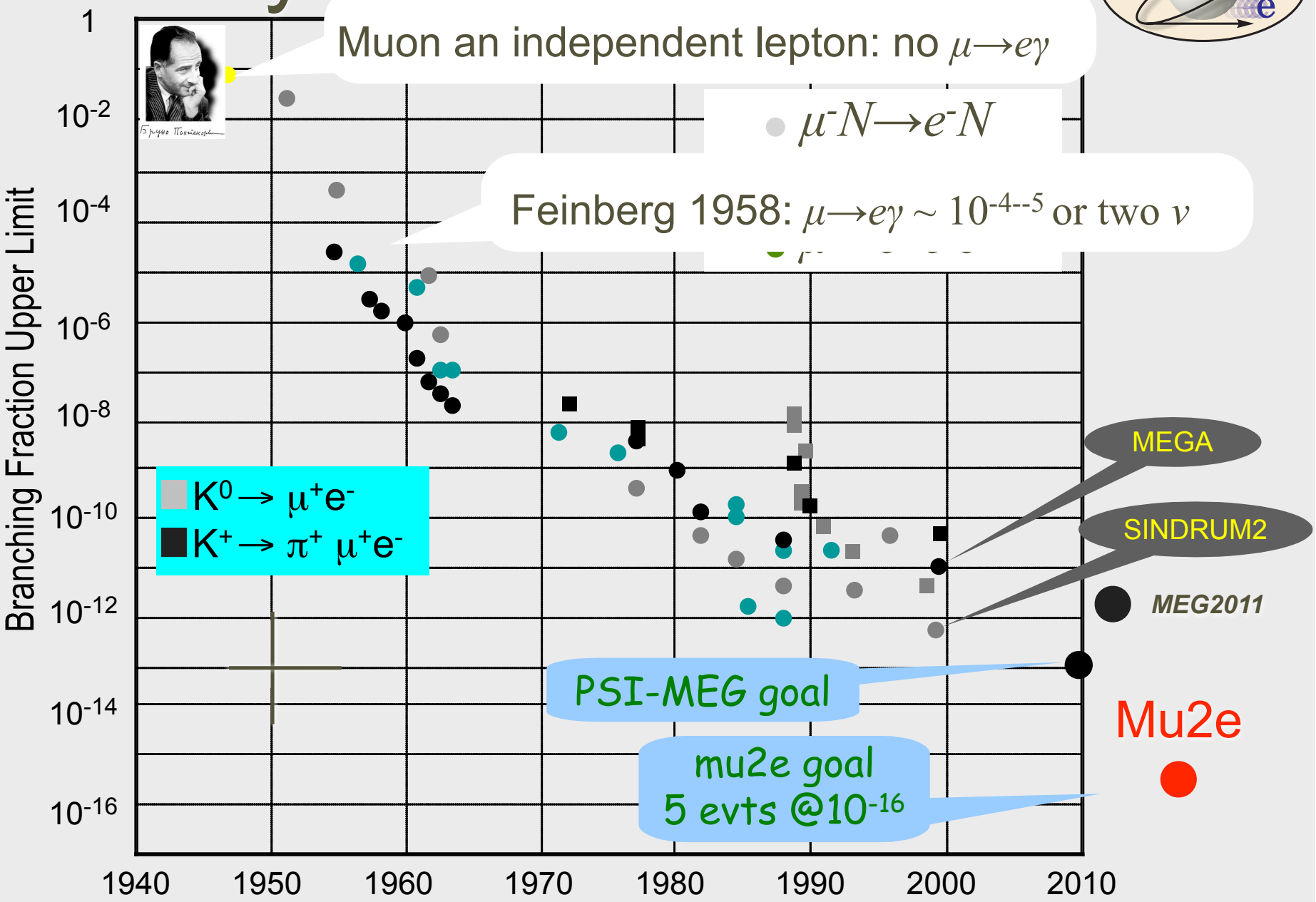

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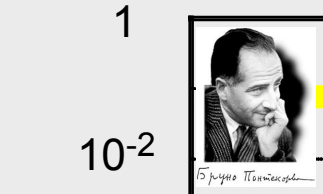

Muon an independent lepton: no $\mu \rightarrow e\gamma$

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

Feinberg 1958: $\mu \rightarrow e\gamma \sim 10^{-4\text{--}5}$ or two ν

Two neutrinos!

Branching Fraction Upper Limit

1, 10^{-2}, 10^{-4}, 10^{-6}, 10^{-8}, 10^{-10}, 10^{-12}, 10^{-14}, 10^{-16}

1940 1950 1960 1970 1980 1990 2000 2010

$K^0 \rightarrow \mu^+ e^-$

$K^+ \rightarrow \pi^+ \mu^+ e^-$

MEGA

SINDRUM2

MEG2011

PSI-MEG goal

Mu2e

mu2e goal
5 evts @10^{-16}

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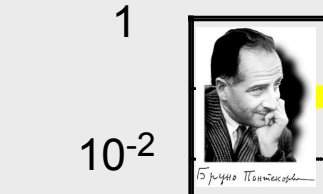

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LHC supersymmetry

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5 evts @10^{-16}

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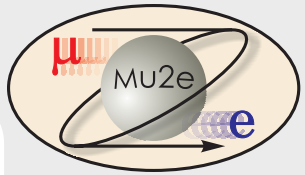

Muon an independent lepton: no $\mu \rightarrow e\gamma$

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

10^{-4}--^{5} or two ν

Number of muons needed: ~5×10^{19}
Number of grains of sand on Earth: ~10^{19}

o neutrinos!

Branching Fraction Upper Limit

1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
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1940 1950 1960 1970 1980 1990 2000 2010

K^0
K^+

MEGA
SINDRUM2
MEG2011

-MEG goal

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mu2e goal
5 evts @10^{-16}

MEG 2011: arXiv:1107.5547 [hep-ex]

Where did that last estimate come from?

http://www.hawaii.edu/suremath/jsand.html

Moral: jobs at Hawaii are more fun than at Fermilab

Estimate the number of grains of sand on all the beaches of the earth.

The number of grains of sand will be the volume of sand divided by the the volume per grain.

$$N = \frac{Volume\_of\_sand}{Volume\_of\_grain}$$

The volume of sand is available from the product of the length of all beaches in the world, their average width and average depth.

$$Volume\_of\_sand = (length\_of\_beaches)(width)(depth)$$

We will need to estimate the parameters on the right. To get going we use the idea that the length of beaches is some percentage of the length of shores.

$$length\_of\_beaches = \frac{\%shores}{100}\, length\_of\_shores$$

The length of shores is related to the size of the earth. We choose to include the size in terms of the circumference.

$$length\_of\_shores = (multiple\_of\_circumference)(earth\_circumference)$$

$$N = \frac{\left(\frac{\%shores}{100}\left((multiple\_of\_circumference)\, earth\_circumference\right)\right)(width)(depth)}{Volume\_of\_grain}$$

We use rough but reasonable values for the parameters.

$\%shores = 25$

$multiple\_of\_circumference = 5$

$earth\_circumference = 40000\ km$ $\quad km = 1000\ m$ $\quad m = 1000\ mm$

$width = 30\ m$

$depth = 5\ m$

$Volume\_of\_grain = 1\ mm^3$

$$N = \frac{\left(\frac{25}{100}\left((5)\left(40000\left(1000\left(1000\ mm\right)\right)\right)\right)\right)\left(30\left(1000\ mm\right)\right)\left(5\left(1000\ mm\right)\right)}{1\ mm^3}$$

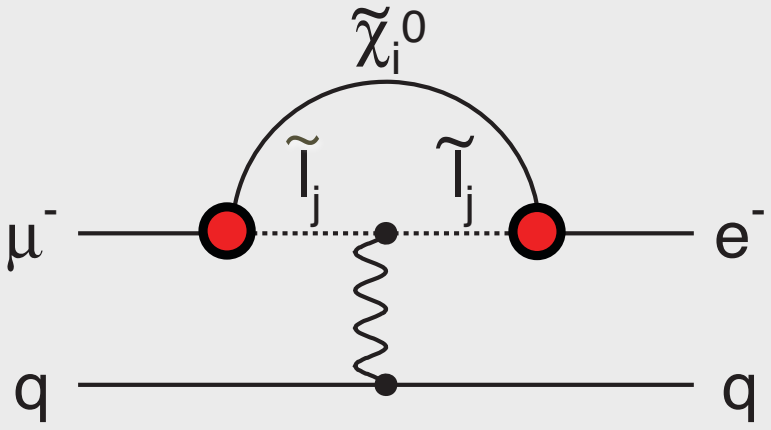
$N = 7.5 \times 10^{18}$

The numbers used can readily be varied to introduce more refined estimates of the parameters.

LFV, SUSY and the LHC

Supersymmetry

rate ~ 10^{-15}

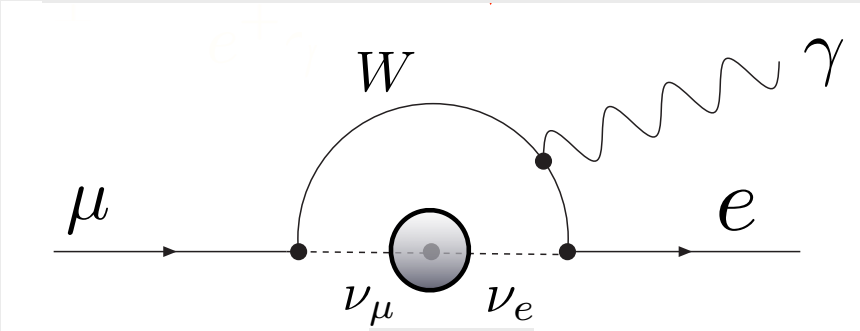


Access SUSY through loops:

signal of Terascale at LHC implies ~40 event signal / <0.2 bkg in this experiment

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



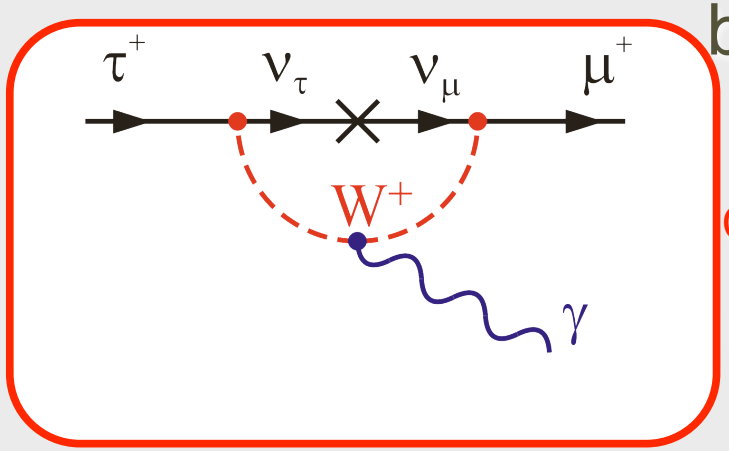
NO STANDARD MODEL BACKGROUND!

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

CLFV and Tau Decays

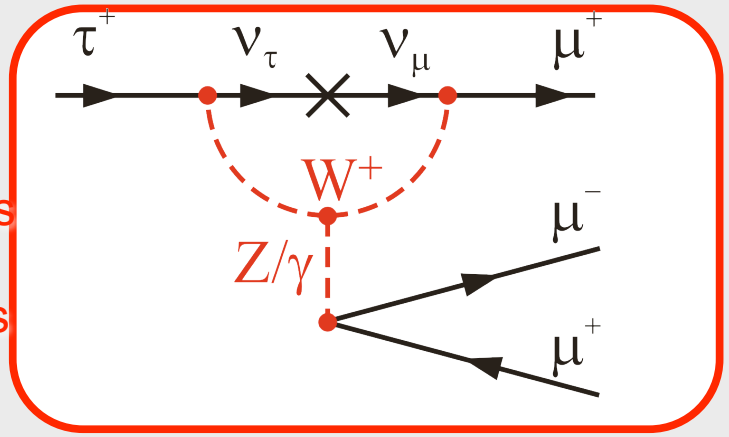
τ processes also suppressed in Standard Model but less:

Lee, Shrock
Phys.Rev.D16:1444,1977



SM ~ 10^{-40}

Smaler GIM Cancellations because of large τ mass



SM ~ 10^{-14}

Pham, hep-ph/9810484

Good News:

Beyond SM rates are several orders of magnitude larger than in associated muon decays

Bad News:

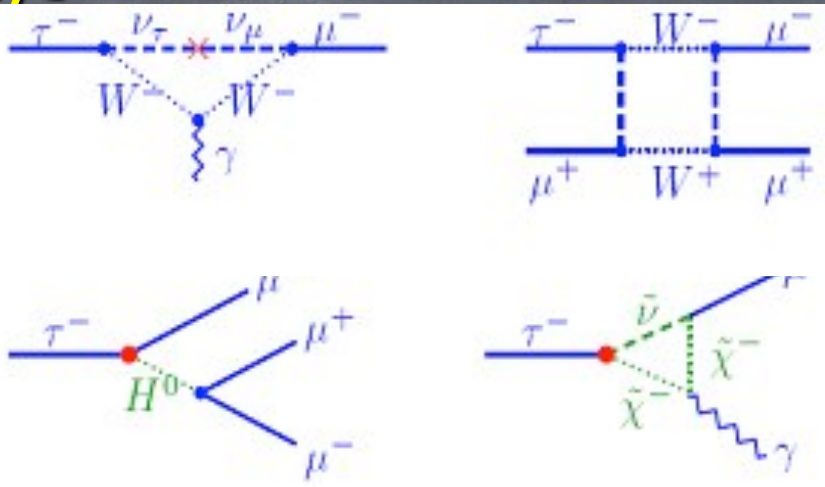
τ's hard to produce:
~10^{10} τ/yr vs ~10^{11} μ/sec in fixed-target experiments (Mu2e/COMET)

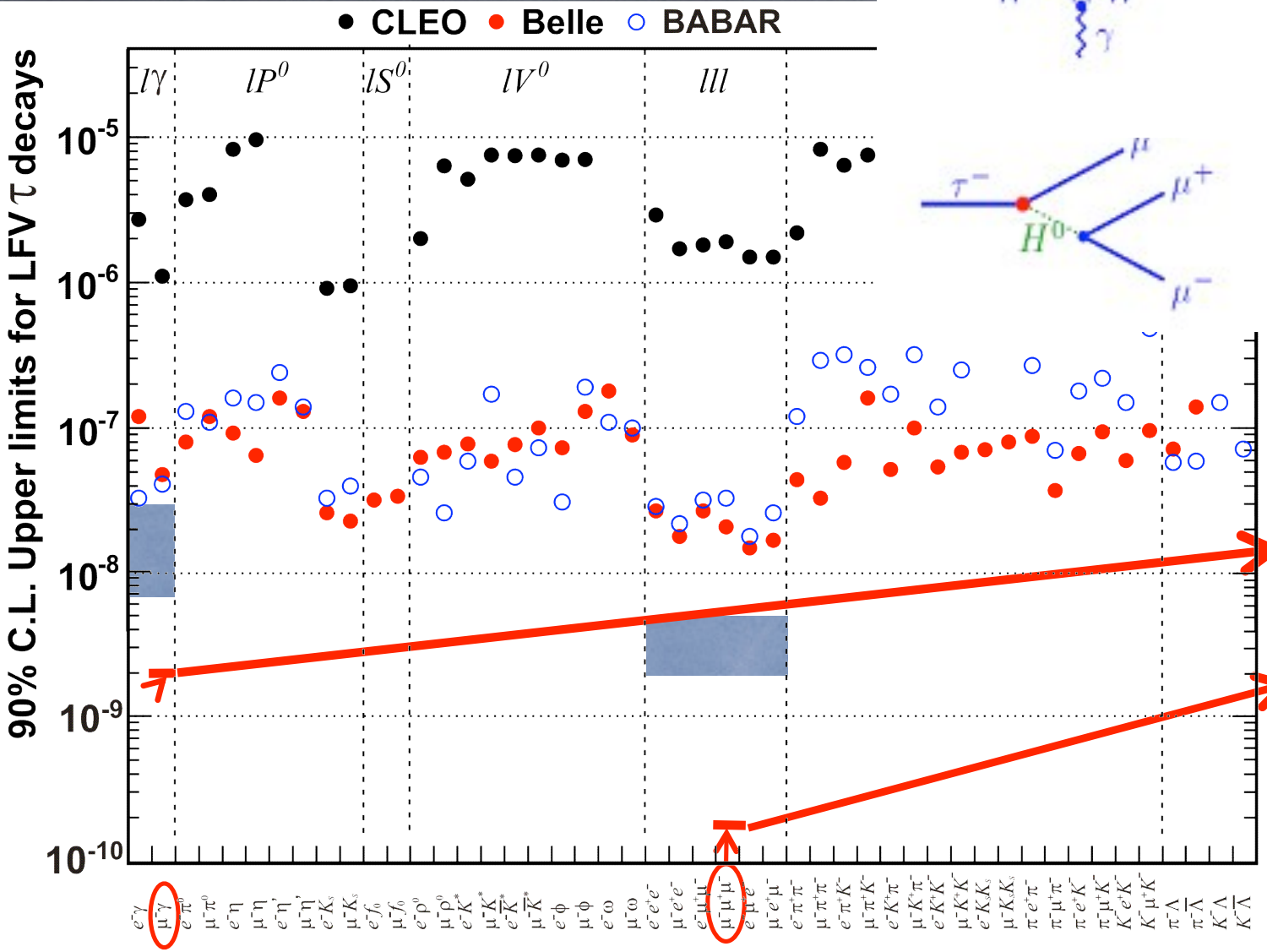
also e$\rightarrow\tau$ at electron-ion collider?

M. Gonderinger, M. Ramsey-Musolf, arXiv:1006.5063v1

Lepton Flavor Violation in τ decays

Super B Factory sensitivity directly confr





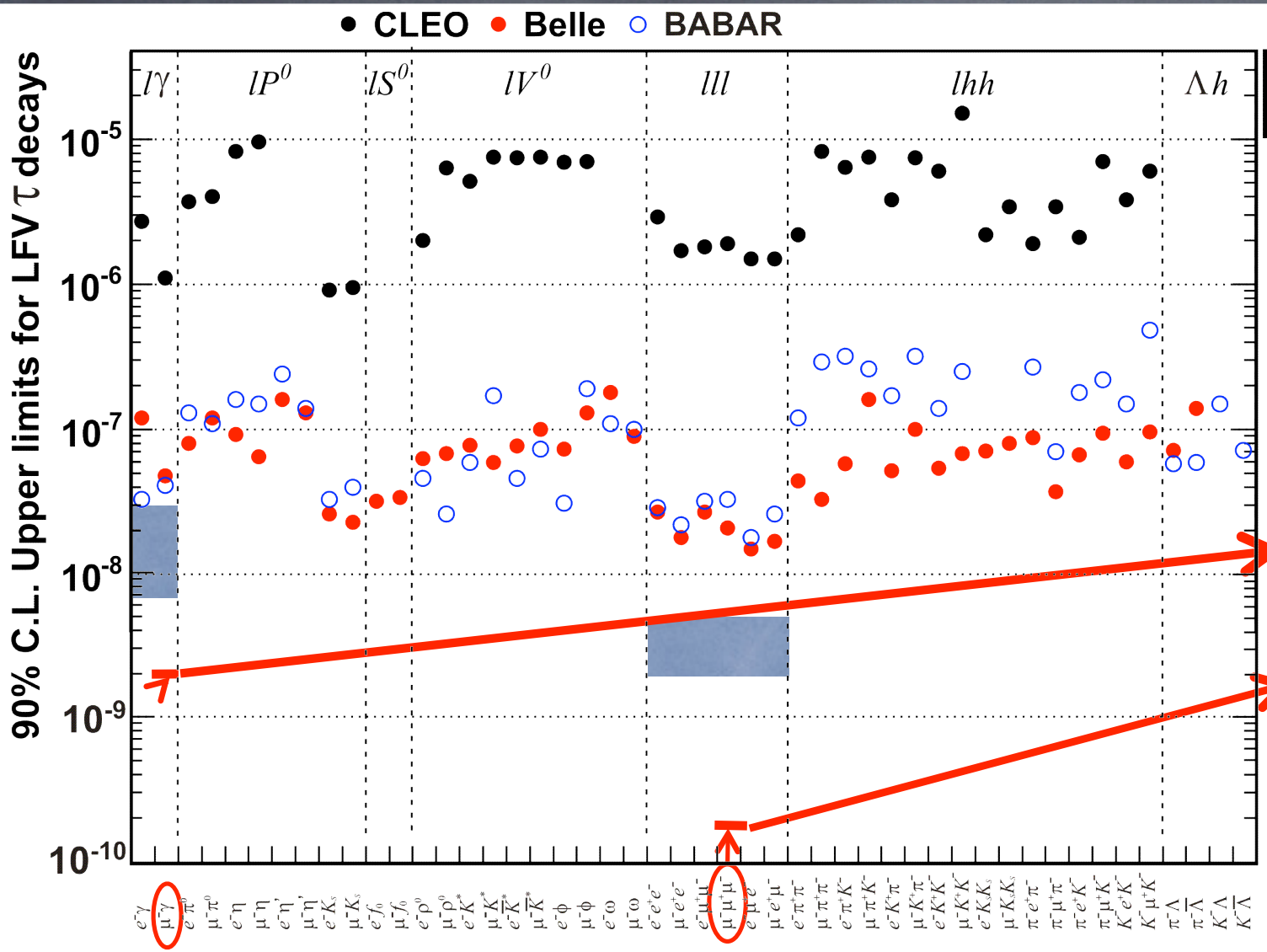
sensitivity
For 75 ab^{-1}

Process	Sensitivity
$\mathcal{B}(\tau \to \mu\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to e\gamma)$	2×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$	2×10^{-10}
$\mathcal{B}(\tau \to eee)$	2×10^{-10}
$\mathcal{B}(\tau \to \mu\eta)$	4×10^{-10}
$\mathcal{B}(\tau \to e\eta)$	6×10^{-10}
$\mathcal{B}(\tau \to \ell K^0_S)$	2×10^{-10}

We expect to see LFV events, not just improve limits

Lepton Flavor Violation in τ decays

Super B Factory sensitivity directly confronts New Physics models



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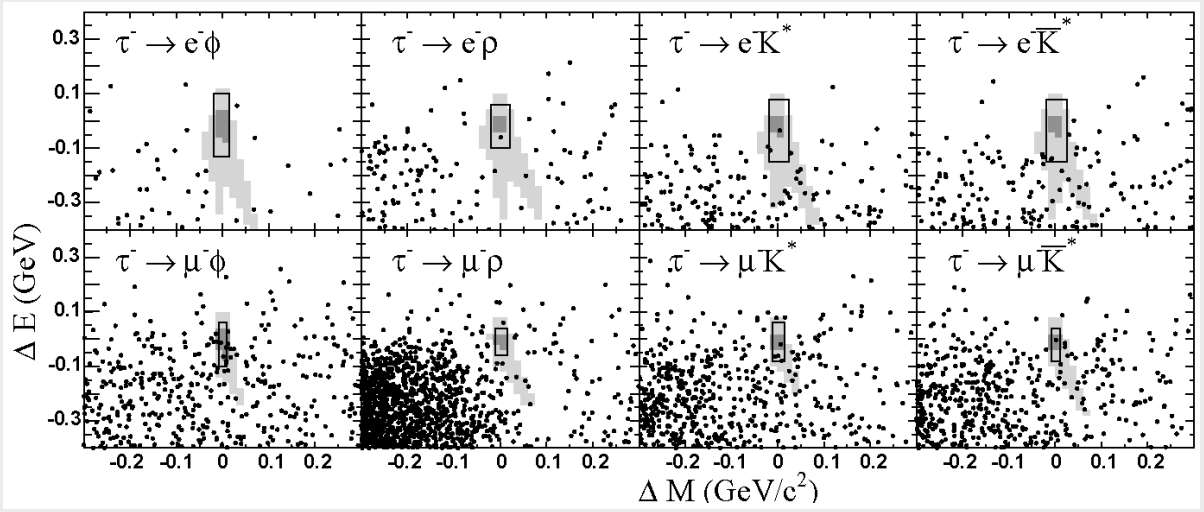
We expect to see LFV events, not just improve limits

LFV branching fraction ratios are discriminators

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.02 \ldots 1$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.4$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.4$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.04 \ldots 0.3$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.04 \ldots 0.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$0.8 \ldots 2.0$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$0.7 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-3} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

Blanke, Buras, Duling, Recksiegel & Tarantino, arXiv:0906.545v1

Semi-leptonic Modes



Non-zero Background

Mode	ε[%]	$N_{\rm bgd}$	$N_{\rm obs}$	$N_{\rm UL}^{90}$	$\mathcal{B}_{\rm exp}^{90}$	$\mathcal{B}_{\rm UL}^{90}$
$e\phi$	6.43 ± 0.16	0.68 ± 0.12	0	1.8	5.0	3.1
$\mu\phi$	5.18 ± 0.27	2.76 ± 0.16	6	8.7	8.2	19
$e\rho$	7.31 ± 0.18	1.32 ± 0.17	1	3.1	4.9	4.6
$\mu\rho$	4.52 ± 0.41	2.04 ± 0.19	0	1.1	8.9	2.6
eK^*	8.00 ± 0.19	1.65 ± 0.23	2	4.3	4.8	5.9
μK^*	4.57 ± 0.36	1.79 ± 0.21	4	7.1	8.5	17
$e\overline{K}^*$	7.76 ± 0.18	2.76 ± 0.28	2	3.2	5.4	4.6
$\mu\overline{K}^*$	4.11 ± 0.32	1.72 ± 0.17	1	2.7	9.3	7.3

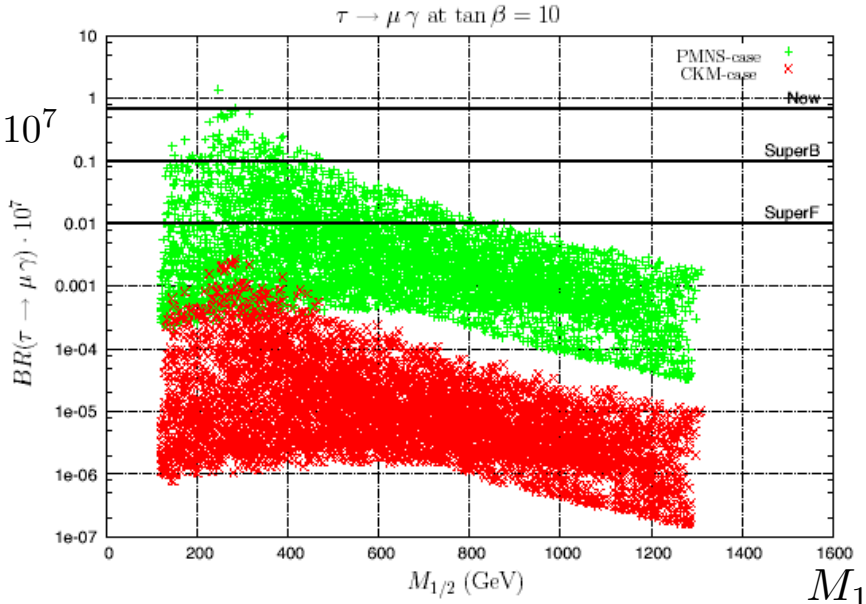
} x 10^{-8}

Supersymmetry in Tau LFV

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

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

$\mathrm{BR}(\tau \to \mu\gamma) \times 10^7$



$\tan\beta = 10$

$M_{1/2}$ (GeV)

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

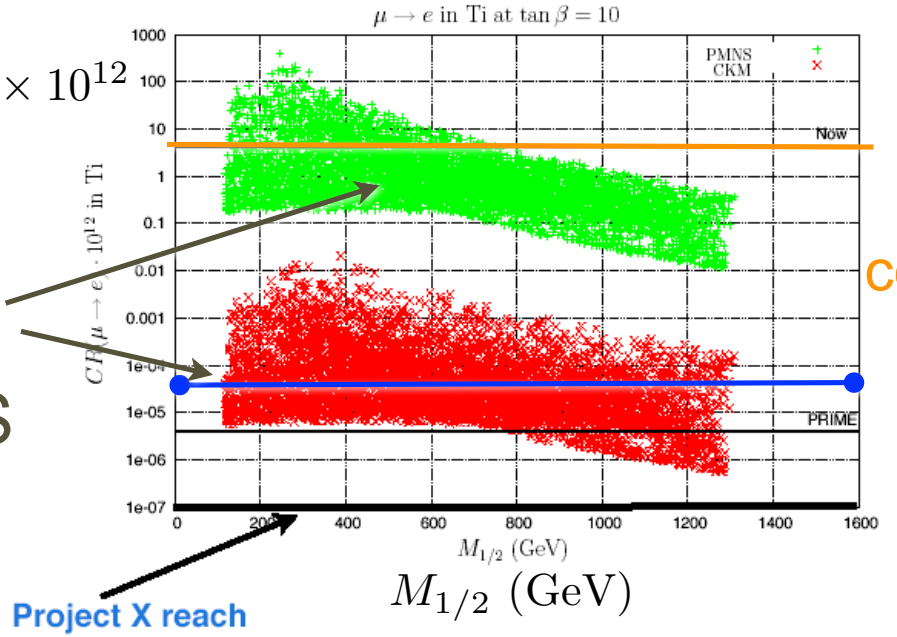
neutrino mass via the see--saw mechanism, analysis is performed in an SO(10) framework

And Muon-Electron Conversion

$\tan\beta = 10$

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

$\mathrm{BR}(\mu \to e) \times 10^{12}$



Current μe conversion

Mu2e

measurement can distinguish between PMNS and MFV

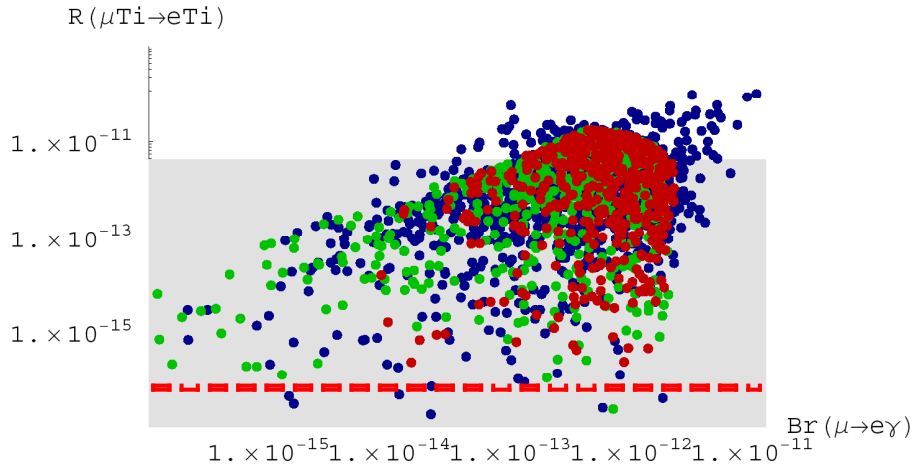
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

complementarity between Lepton Flavor Violation (LFV) and LHC experiments

Combining $\mu \rightarrow e\gamma$ with $\mu \rightarrow e$ Conversion

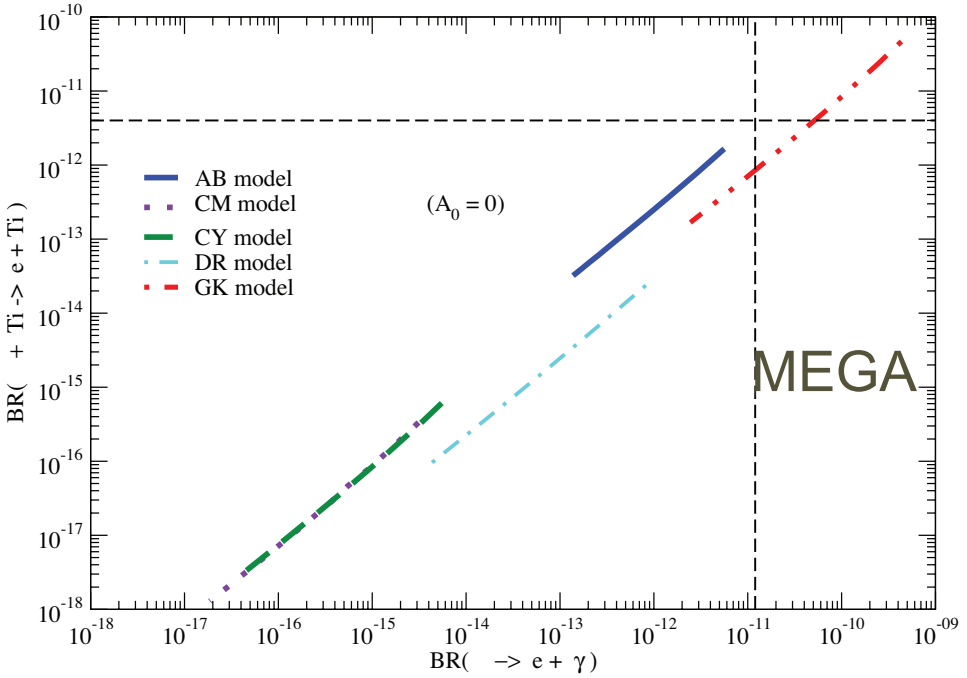
Randall-Sundrum

M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).



SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.



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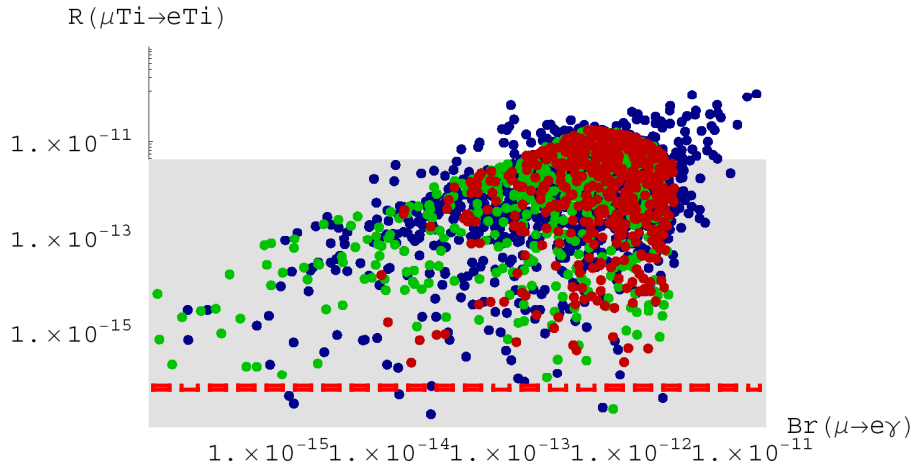
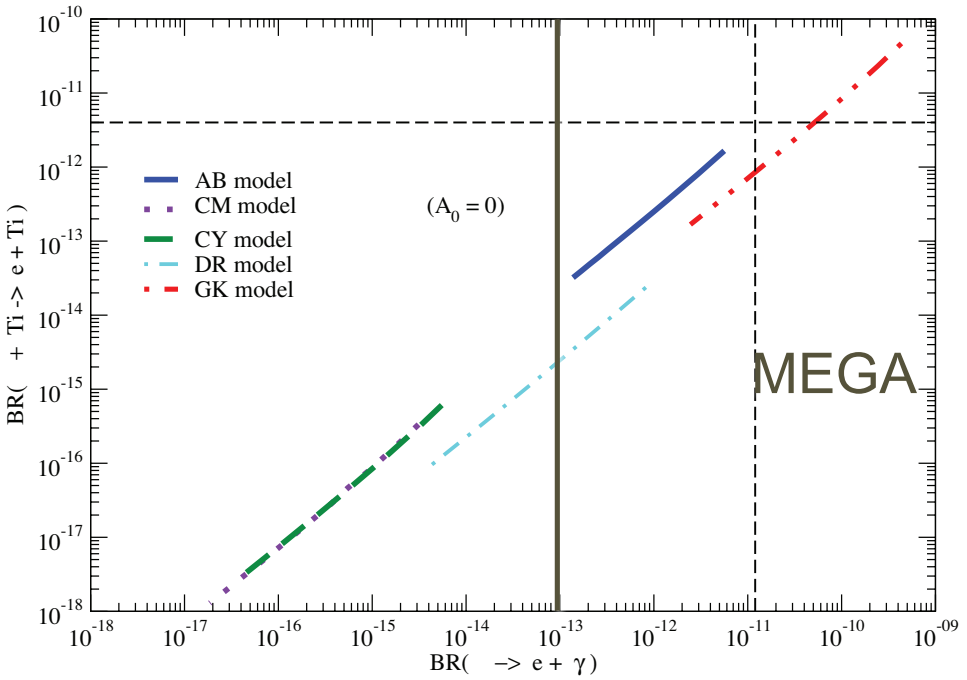


MEG



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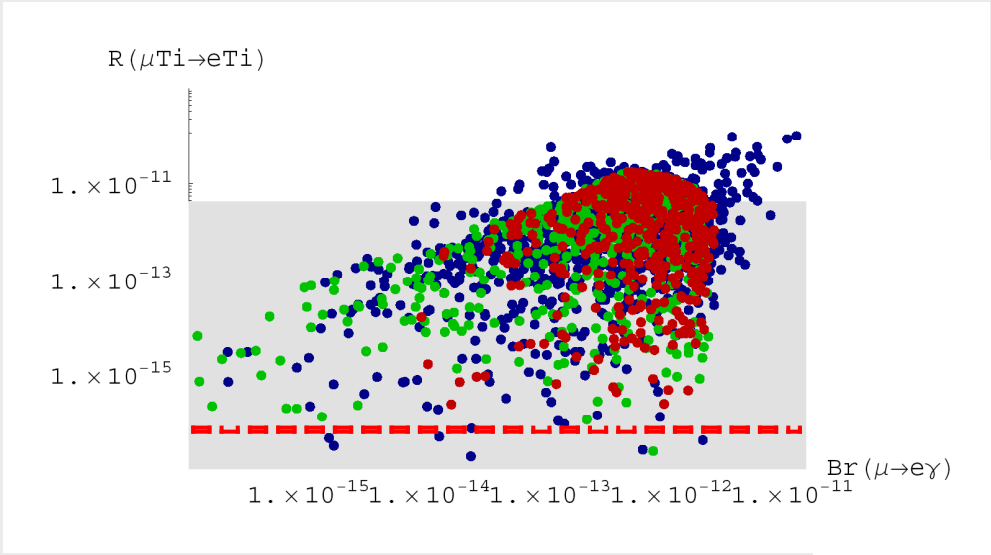

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Mu2e

MEG

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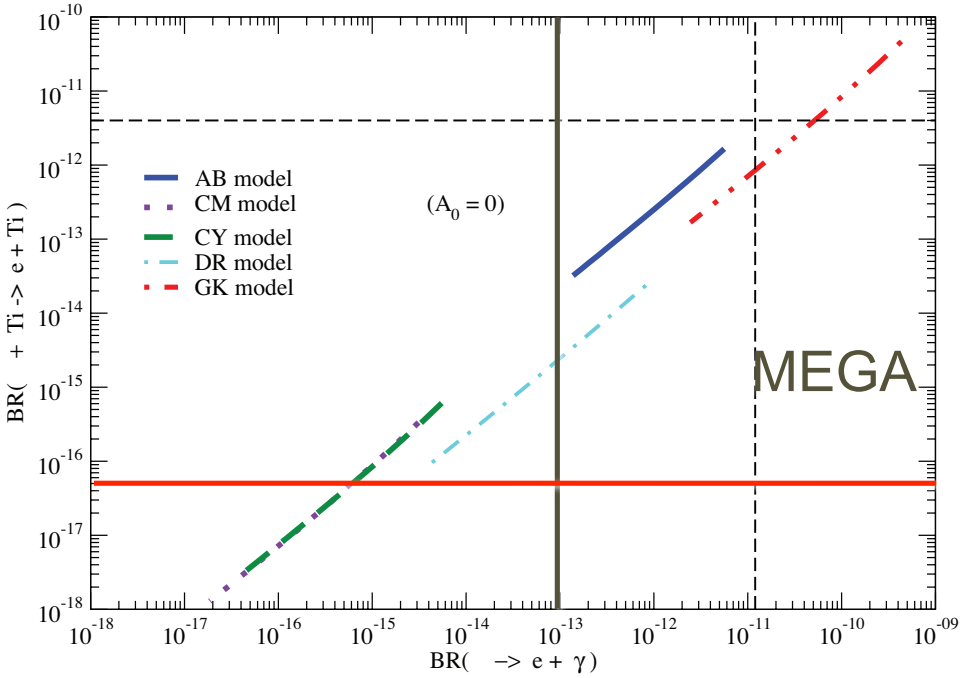
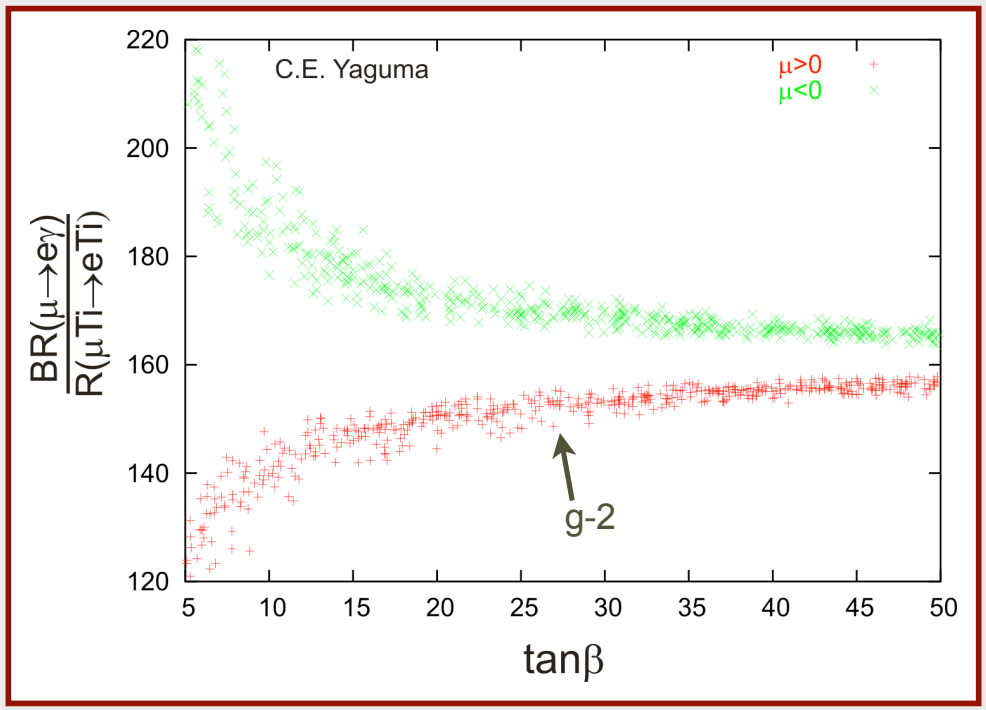


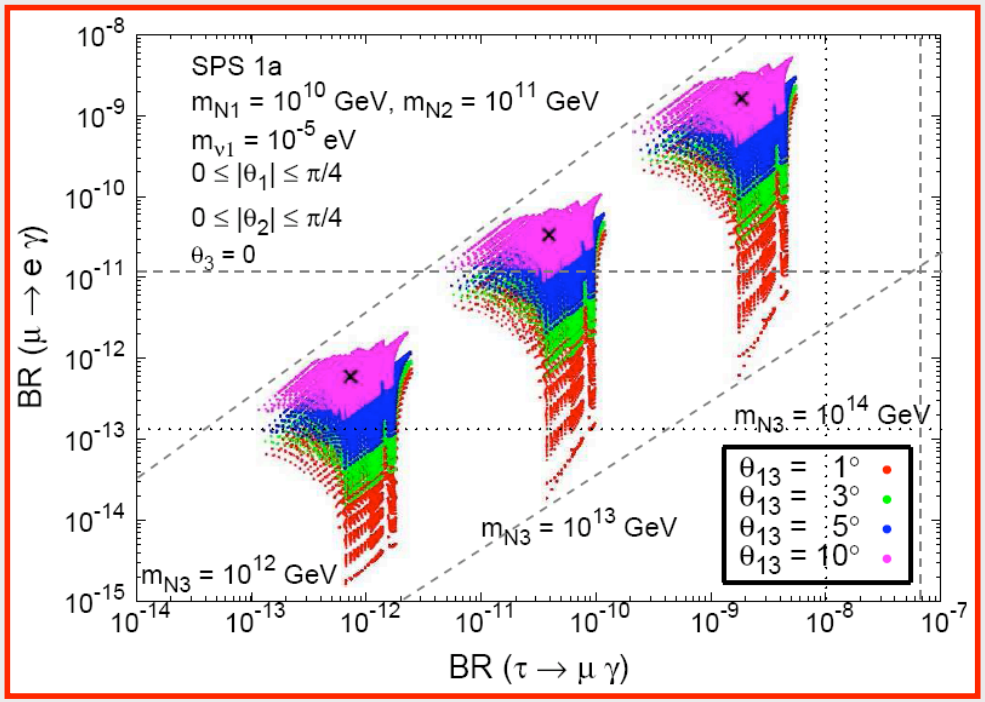
Pinning Down SuperSymmetry

MSSM w mSUGRA



Yaguna, hep-ph/0502014v2

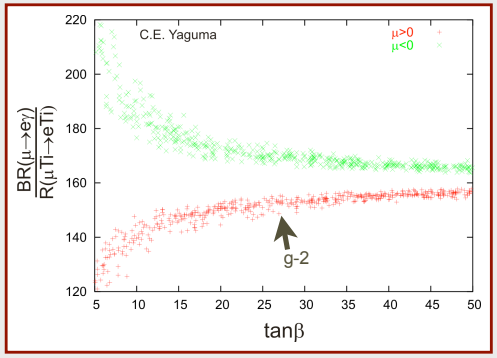
CMSSM - seesaw



Antusch et al.,hep-ph/0610439

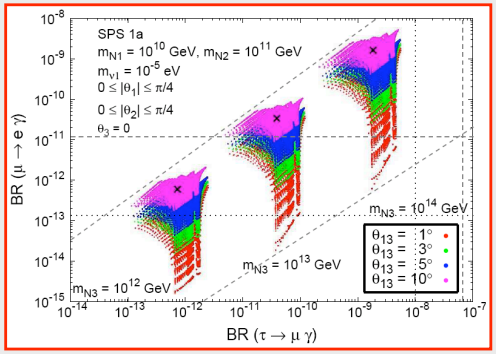
Pinning Down SuperSymmetry

MSSM w mSUGRA



Yaguna, hep-ph/0502014v2

CMSSM - seesaw



Antusch et al.,hep-ph/0610439

- Need:
  - observation of CLFV in more than one channel, and/or
  - evidence from LHC, g-2, or elsewhere

to allow discrimination among different models

In SUSY

- Large effects in many models
  - only $\mu \to e\gamma$ and μe conversion

	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

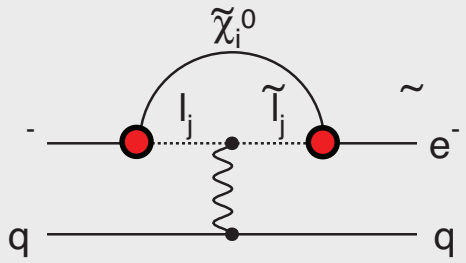
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

W. Altmanshofer et al., arXiv:0909.1333v2 [hep-ph] 26 Jan 2010

Contributions to μe Conversion

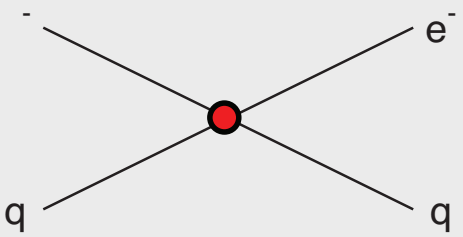
Supersymmetry

rate ~ 10^{-15}



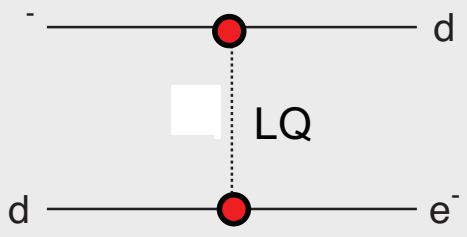
Compositeness

Λ_c ~ 3000 TeV



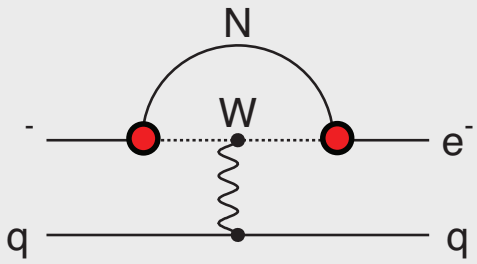
Leptoquark

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



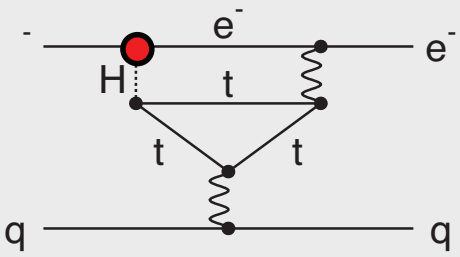
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



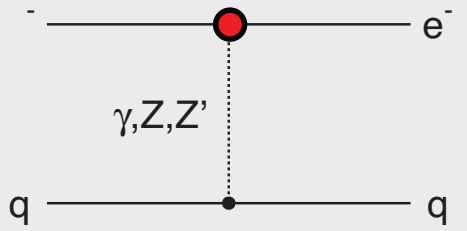
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;

"Model-Independent" Form

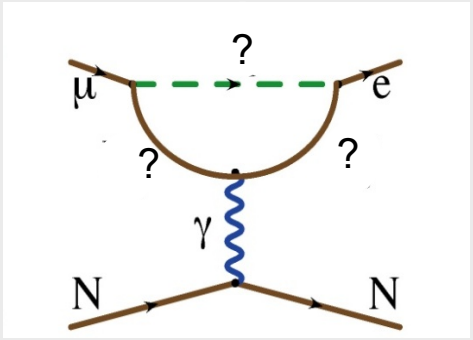
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

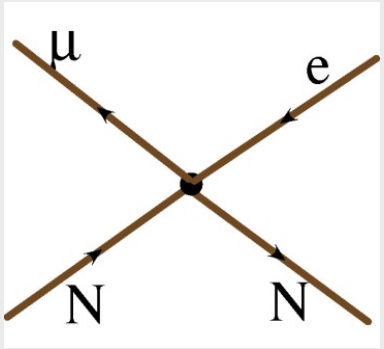
"Loops" **"Contact Terms"**

mass scale Λ

κ

$\kappa=0$





$\kappa=1$

Supersymmetry and Heavy Neutrinos

Contributes to $\mu\rightarrow e\gamma$

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

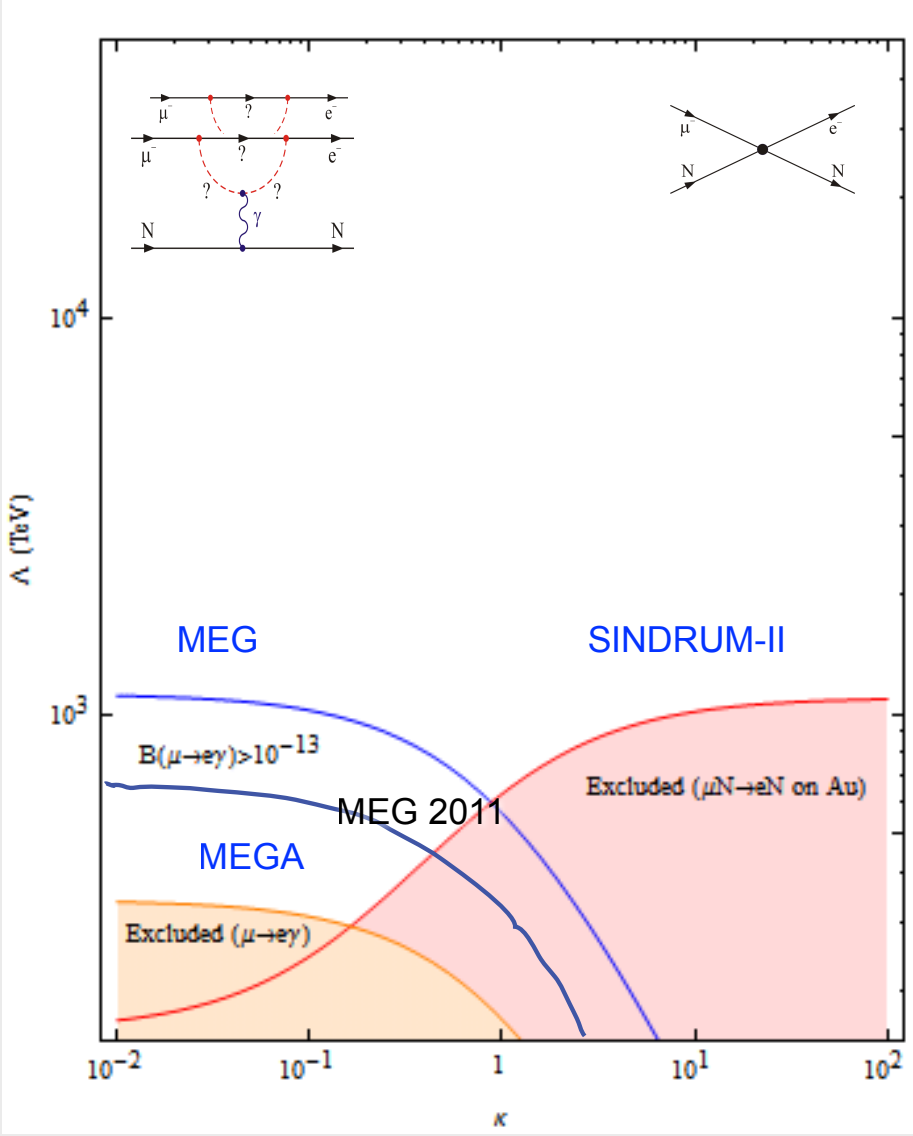
Quantitative Comparison?

μe Conversion and μ→eγ

Λ (TeV)

1) *Mass Reach to ~10^4 TeV*

2) *about x2 beyond MEG in loop-dominated physics*



higher mass scale

κ

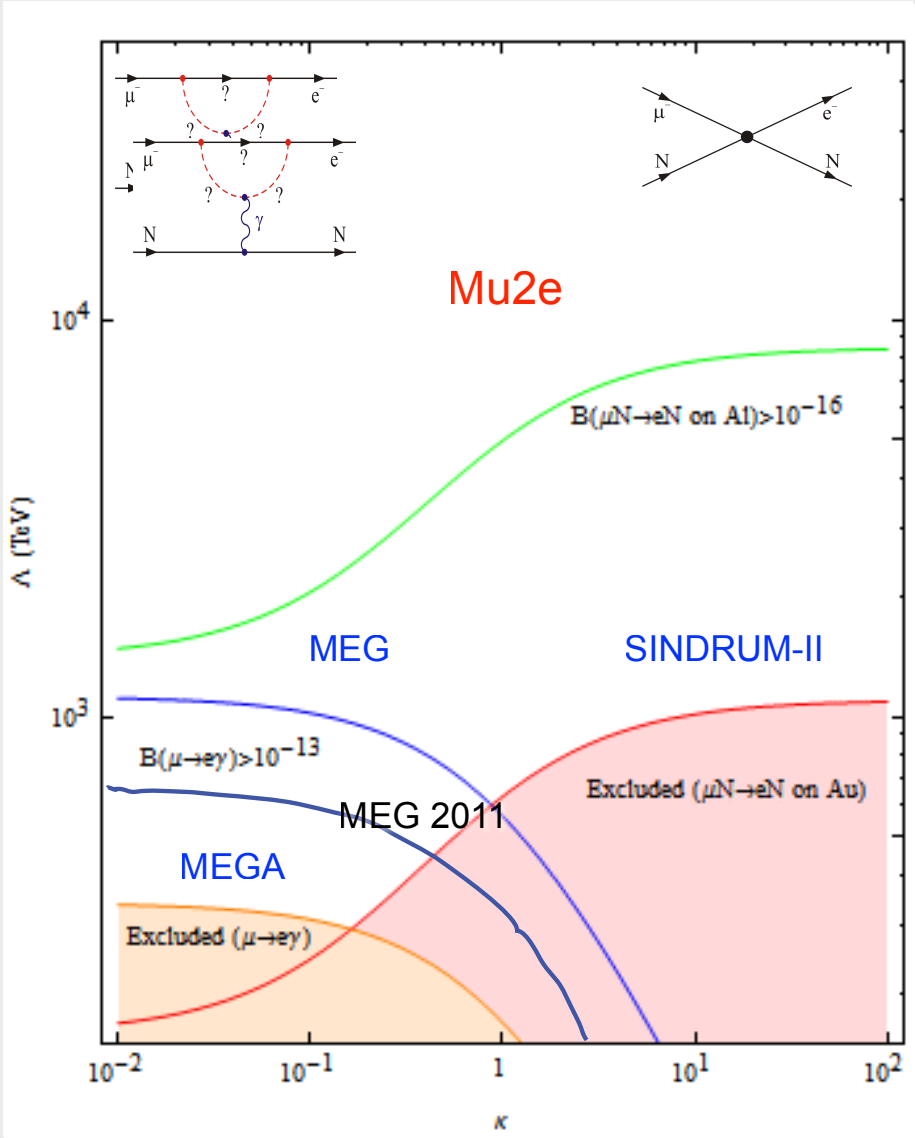
André de Gouvêa, Project X Workshop Golden Book

μe Conversion and μ→eγ

Λ (TeV)

1) *Mass Reach to ~10^4 TeV*

2) *about x2 beyond MEG in loop-dominated physics*



higher mass scale

κ

André de Gouvêa, Project X Workshop Golden Book

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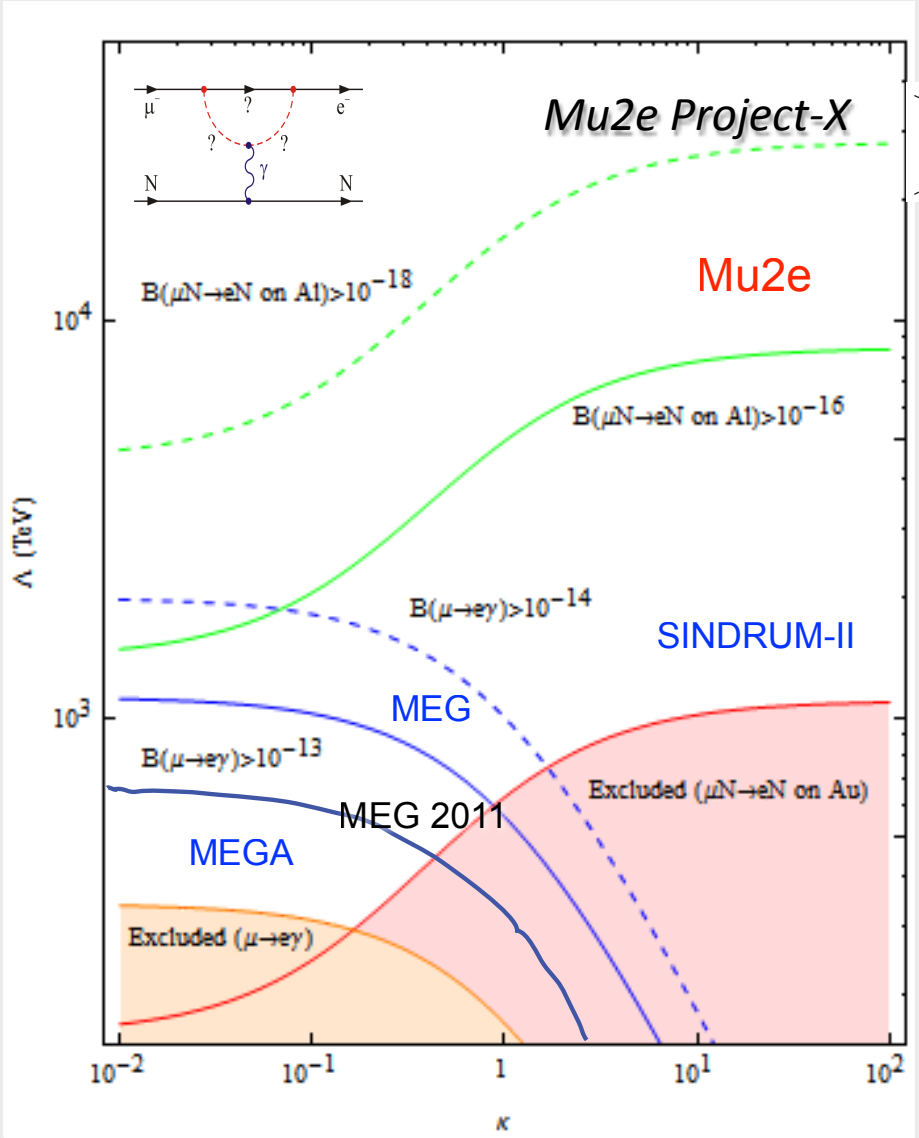


higher mass scale

André de Gouvêa, Project X Workshop Golden Book

Outline

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

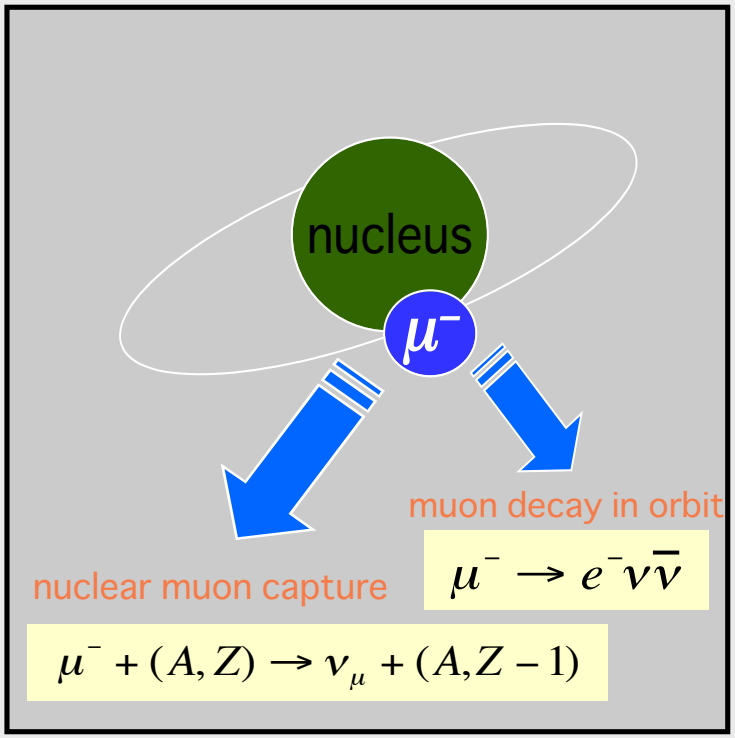
Overview Of Processes

μ^- stops in thin Al foil

the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

μ^- in 1s state

Al Nucleus
~4 fm

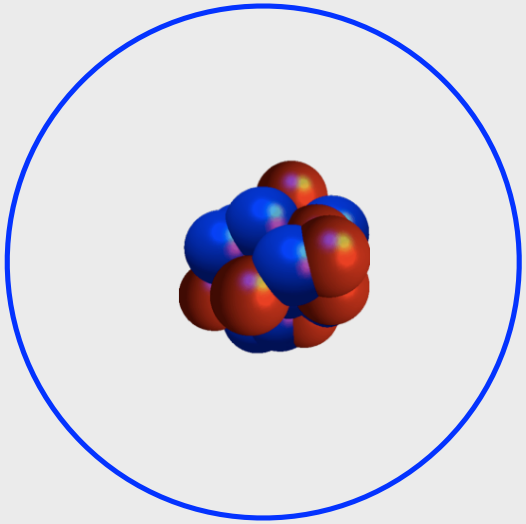


60% capture
40% decay

muon capture, muon "falls into" nucleus: ***normalization***

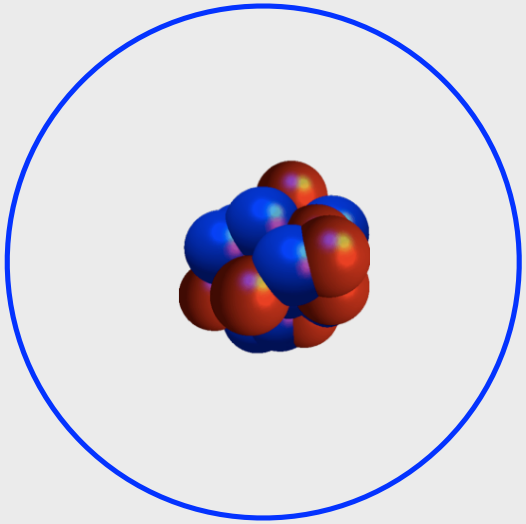
Decay in Orbit: ***background***

Three Possibilities: Normalization



Three Possibilities: Normalization

muon stops



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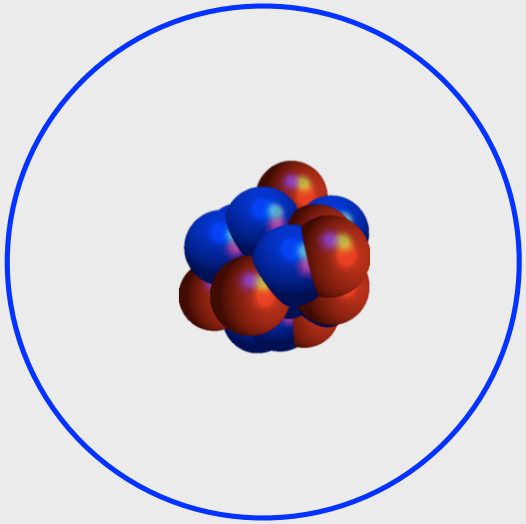

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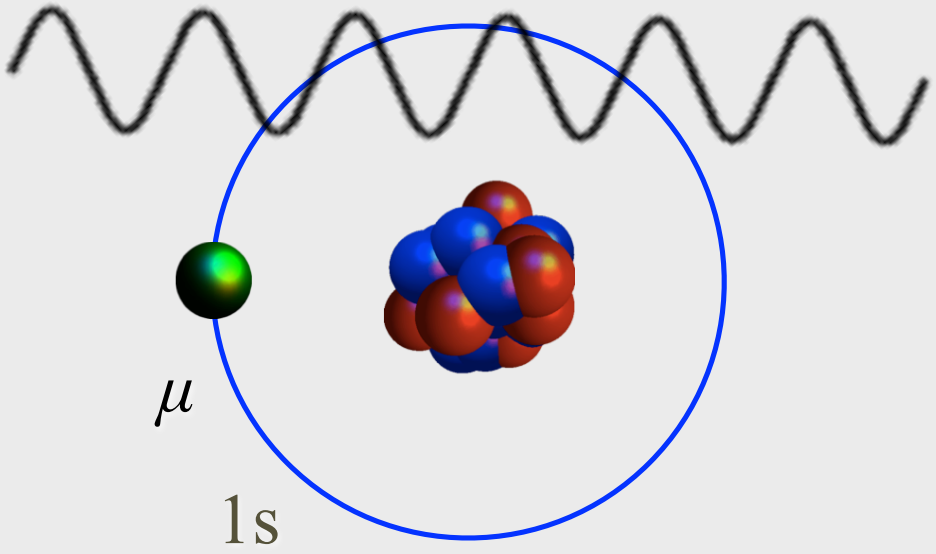
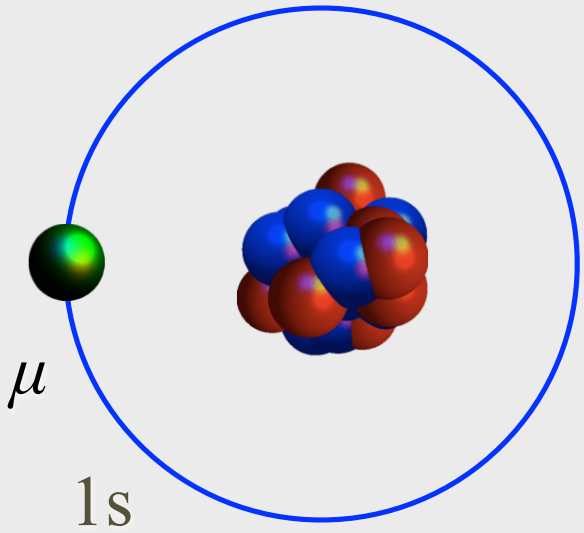


Three Possibilities: Normalization

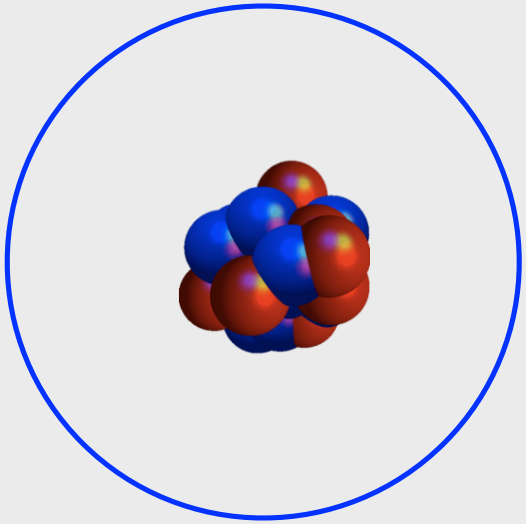
X-Rays from cascade (occurs in <psec)



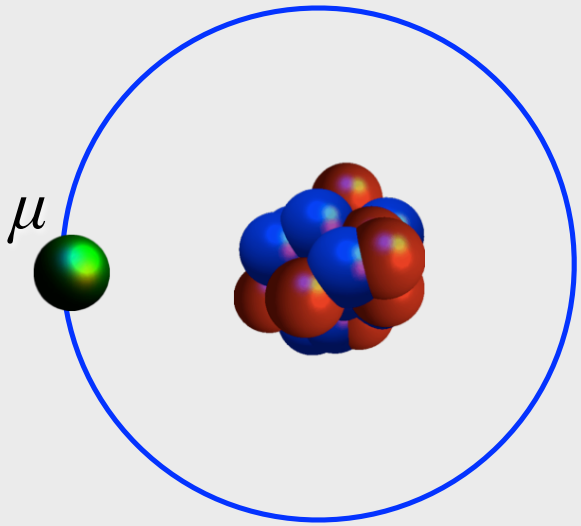
detect these for normalization

Transition	Energy
3d→ 2p	66 keV
2p→ 1s	356 keV
3d→ 1s	423 keV
4p→ 1s	446 keV

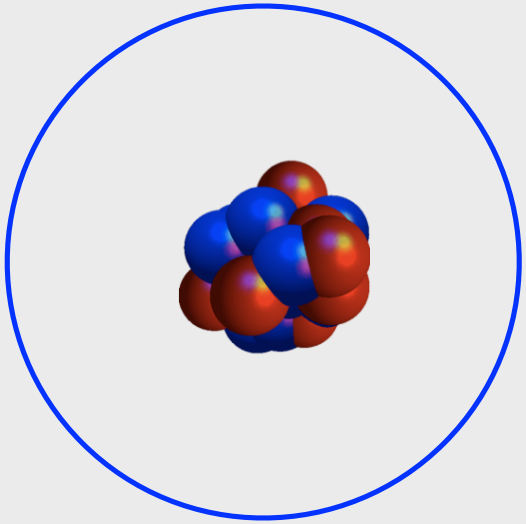
Normalization to Nuclear Capture



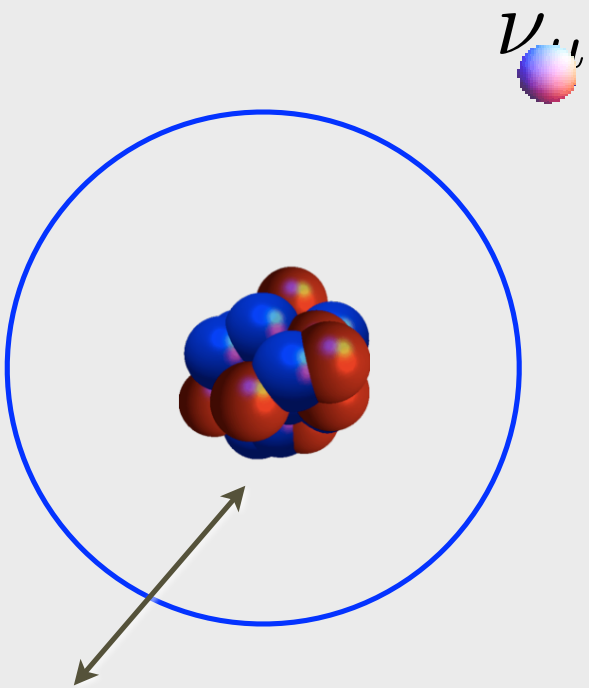
Normalization to Nuclear Capture



Normalization to Nuclear Capture



Normalization to Nuclear Capture

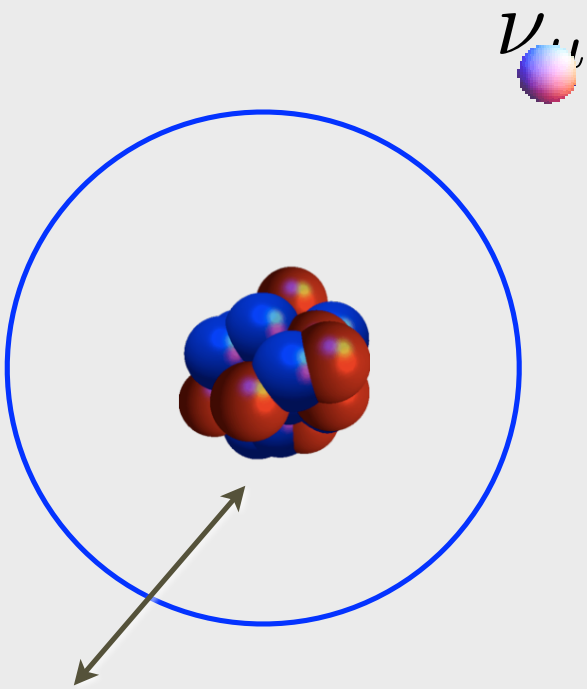


$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

Normalization to Nuclear Capture

1) measure stop rate 2) calculate capture rate/stop

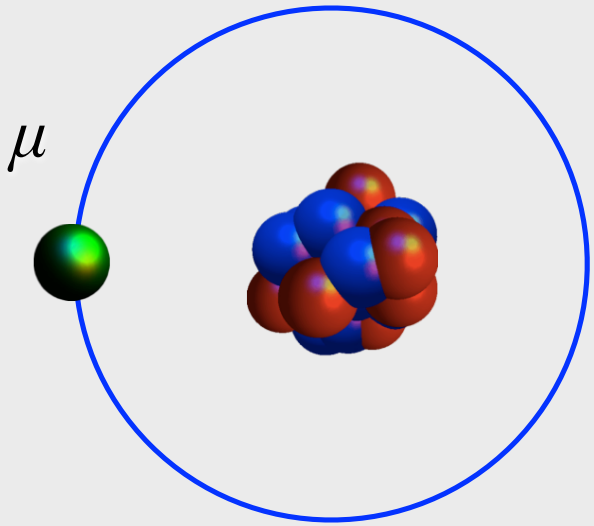
Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110



$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

$$\text{then compute } R_{\mu e} = \frac{\mu N \rightarrow e N}{\mu\ \mathrm{Al}(27,13) \rightarrow \nu_\mu\ \mathrm{Mg}(27,12)}$$

Three Possibilities: Signal



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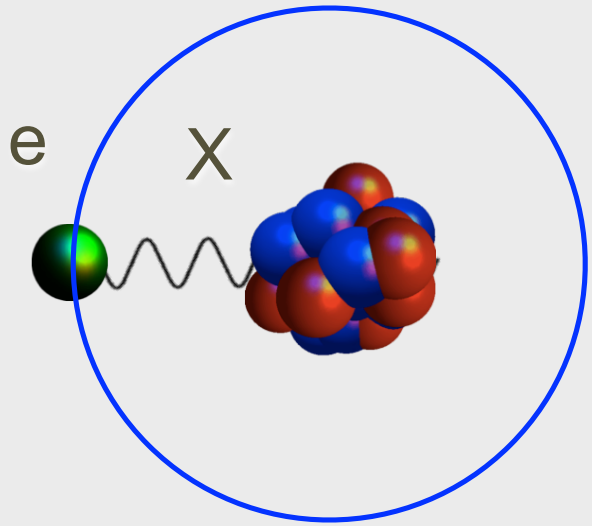
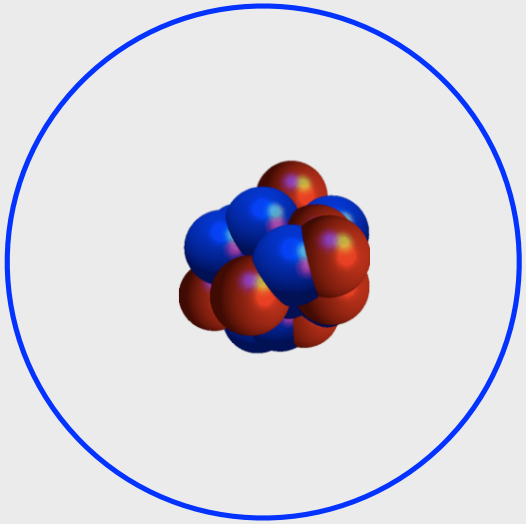


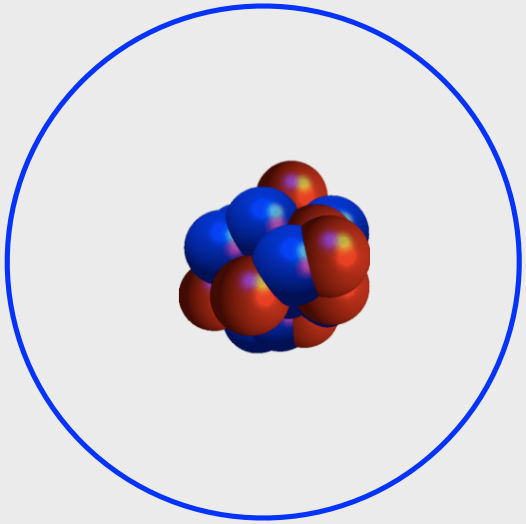
Three Possibilities: Signal

e



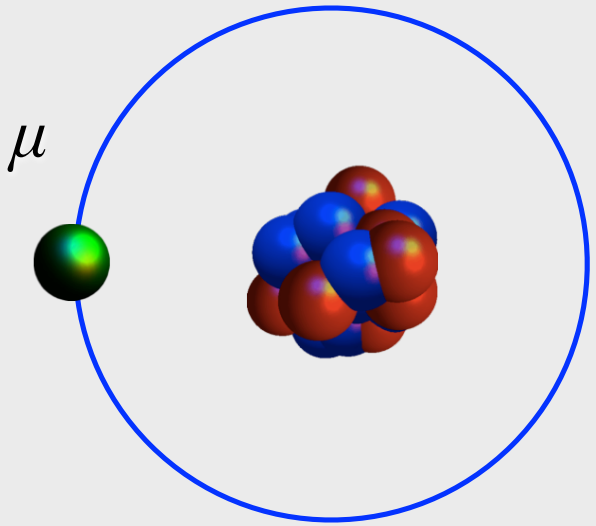
Three Possibilities: Signal

e *off to detector!*

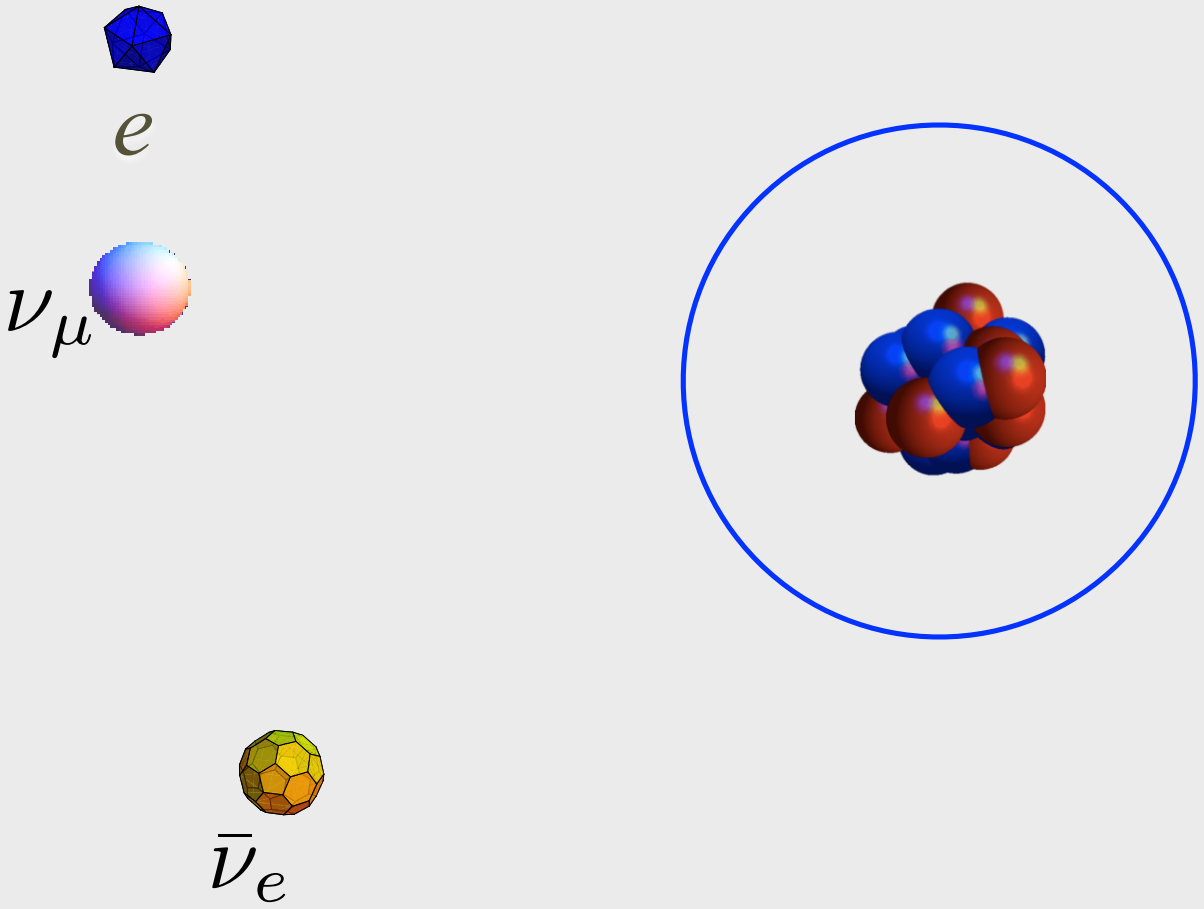


coherent recoil of nucleus

Three Possibilities: Background



Three Possibilities: Background



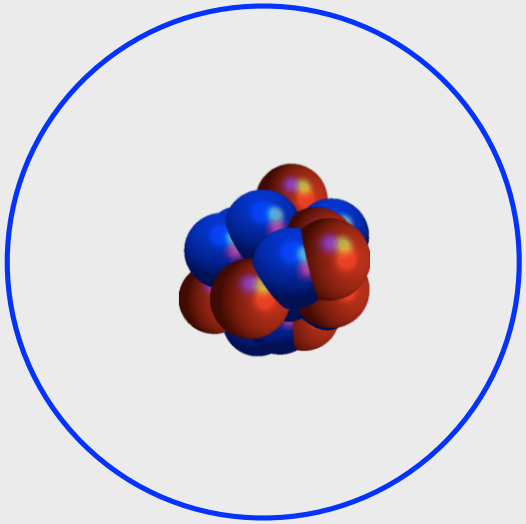
Three Possibilities: Background

this electron can be background;
let's see how

e

ν_μ

$\bar{\nu}_e$

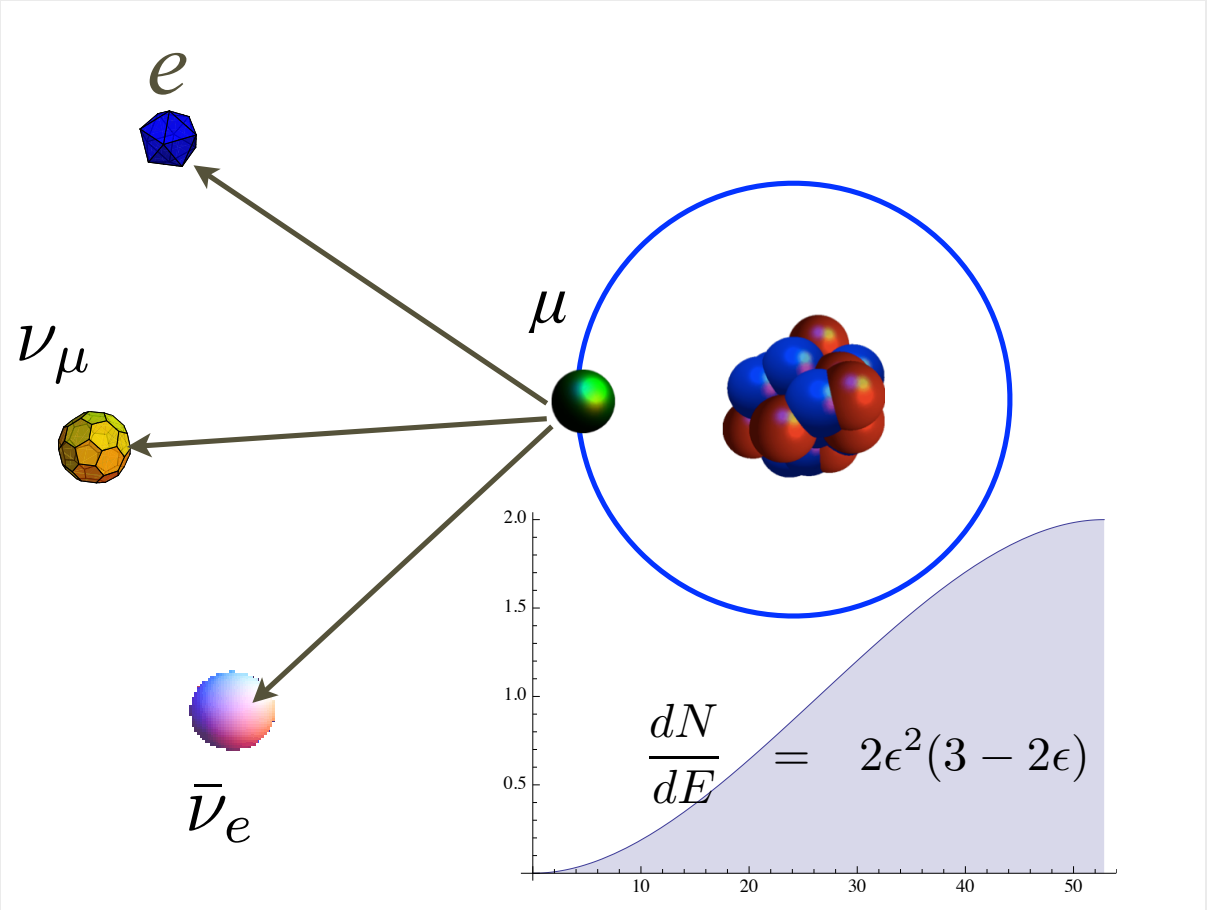


Decay-In-Orbit: Not always Background

- Peak and Endpoint of Michel Spectrum is at

$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

- Detector will be insensitive to electrons at this energy
- Recall *signal* at 105 MeV>>52.8 MeV



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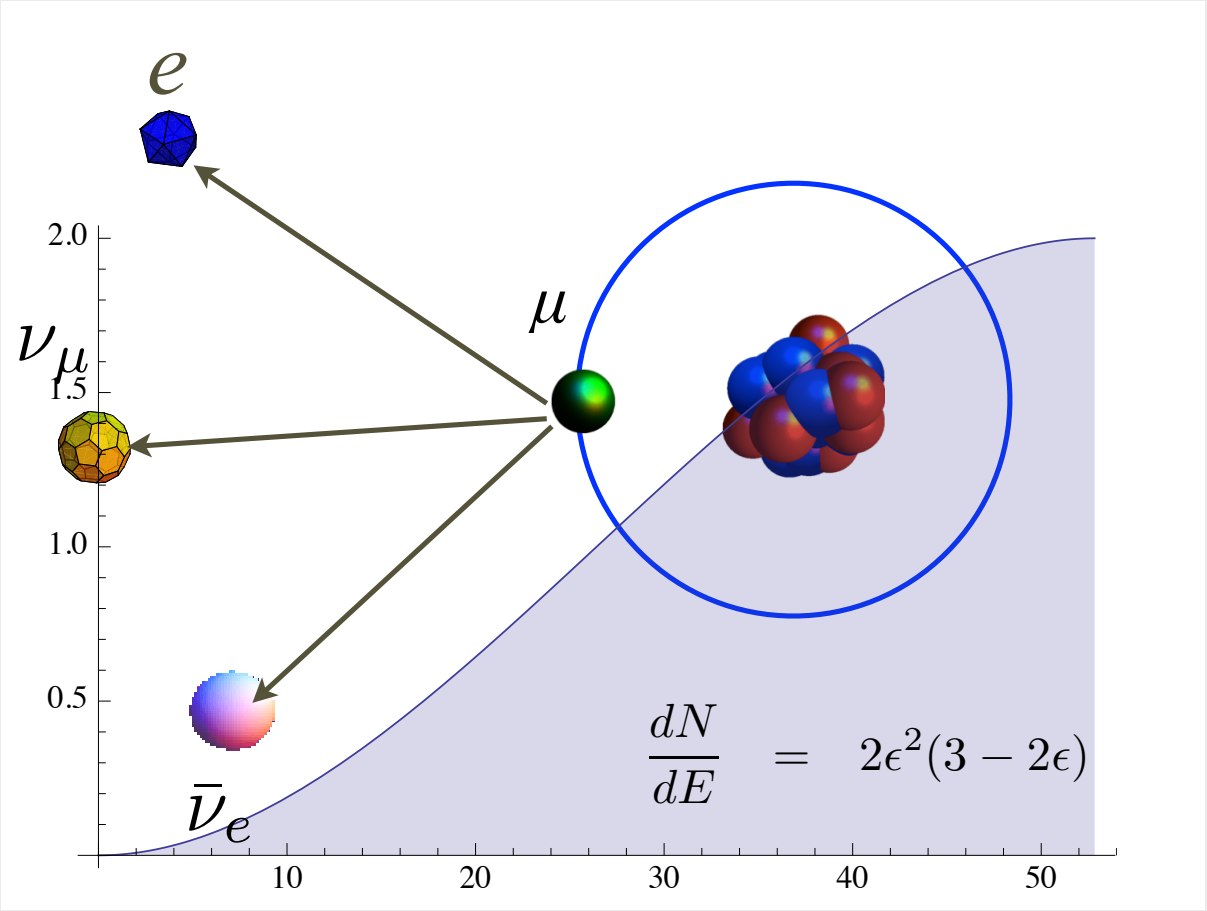
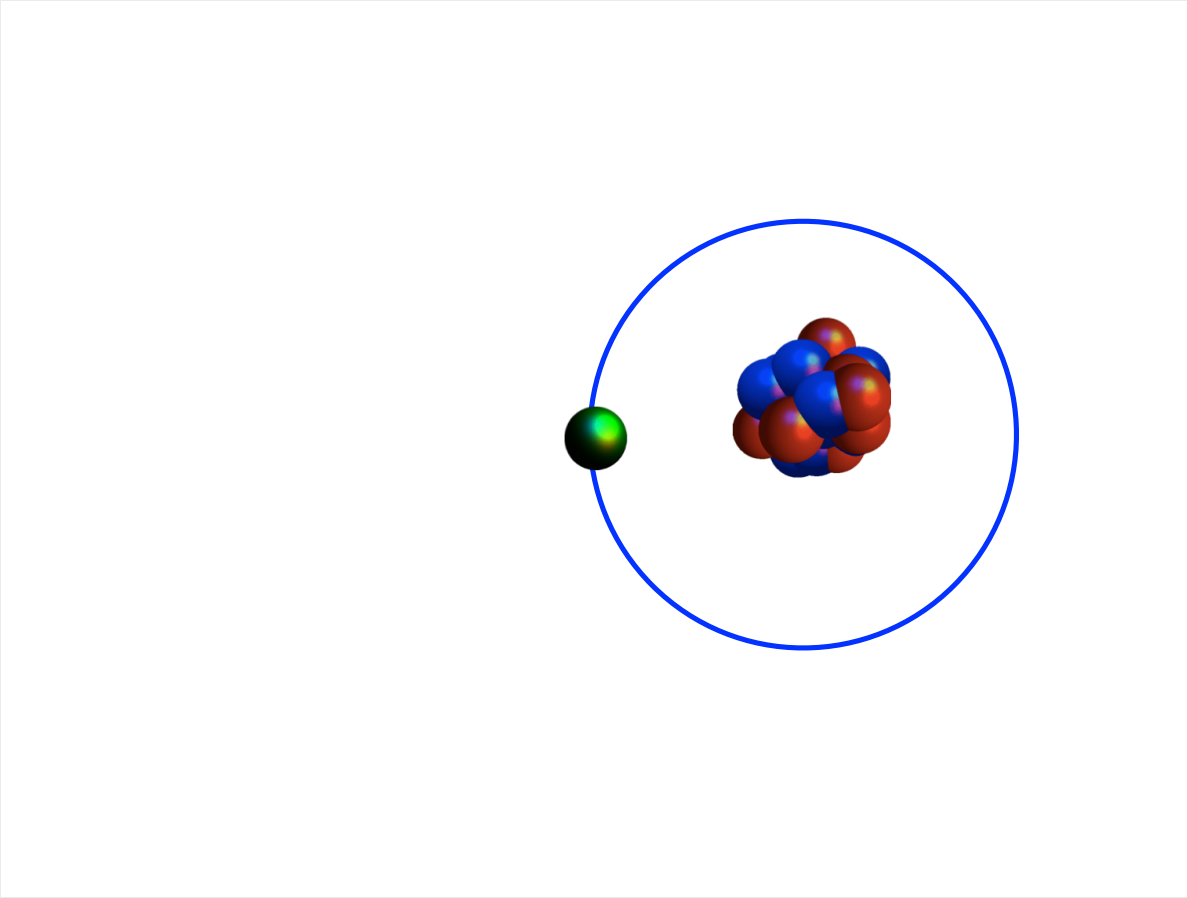


Decay-In-Orbit Background

- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, the DIO electron can be exactly at conversion energy (up to neutrino mass)



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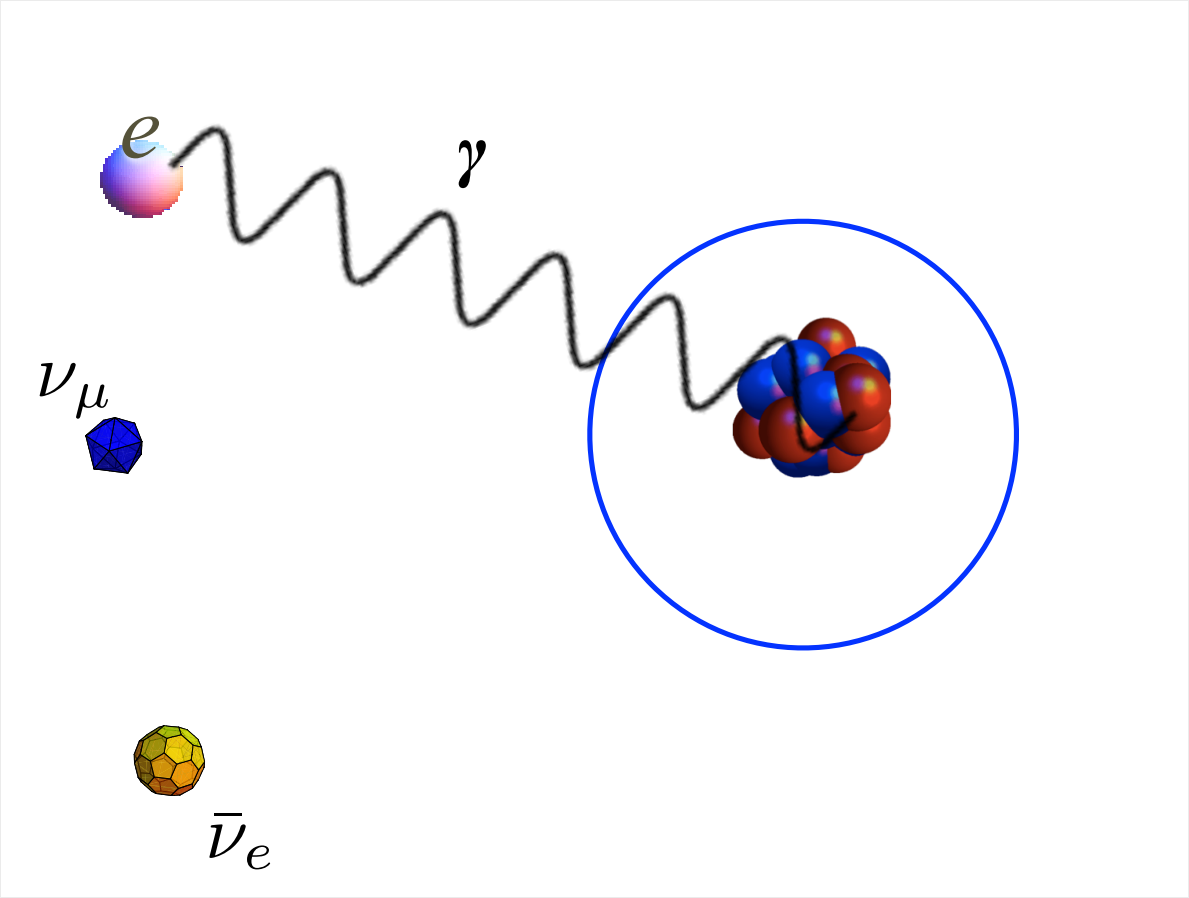

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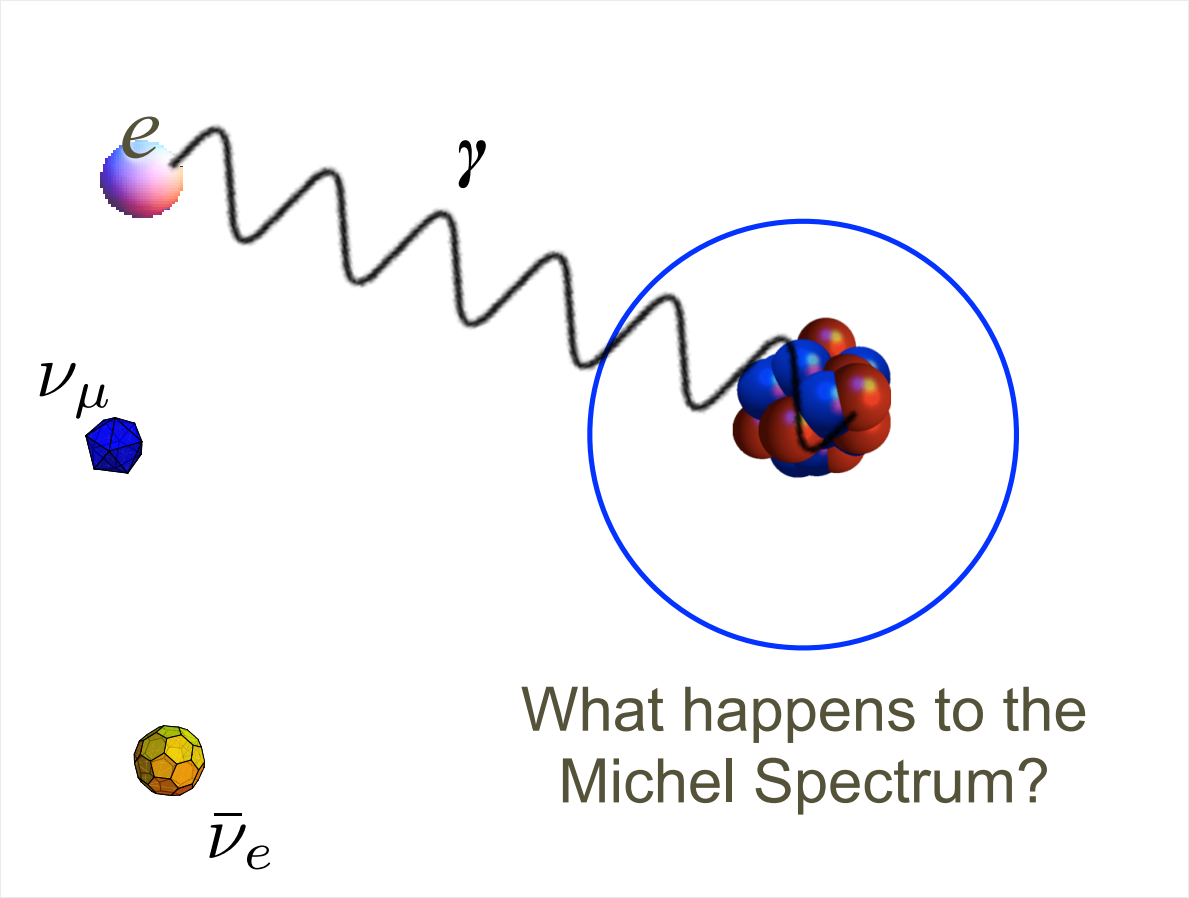
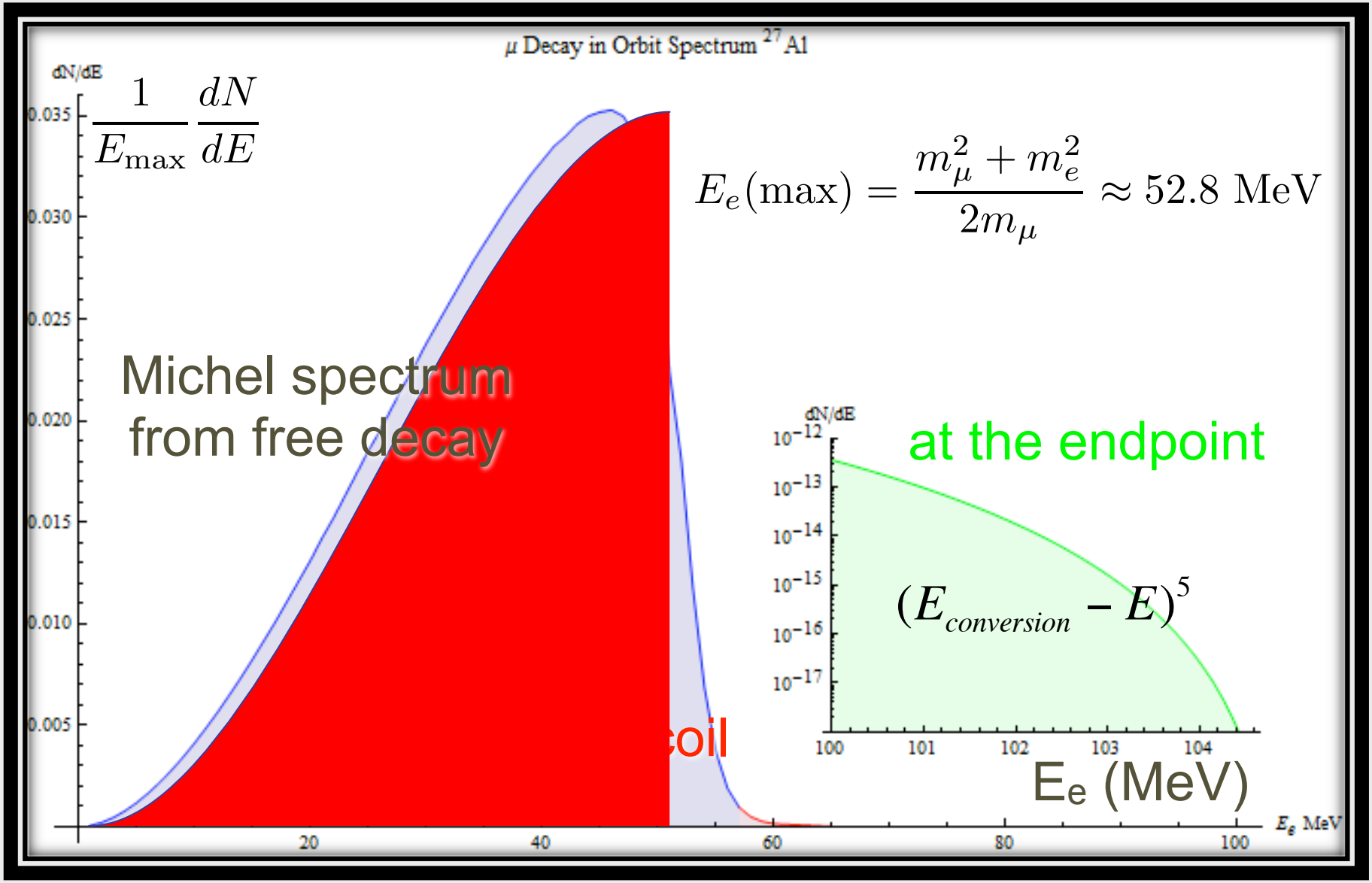


Decay-in-Orbit Shape

Czarnecki et al., arXiv:1106.4756v2 [hep-ph] Phys. Rev. D 84, 013006 (2011)



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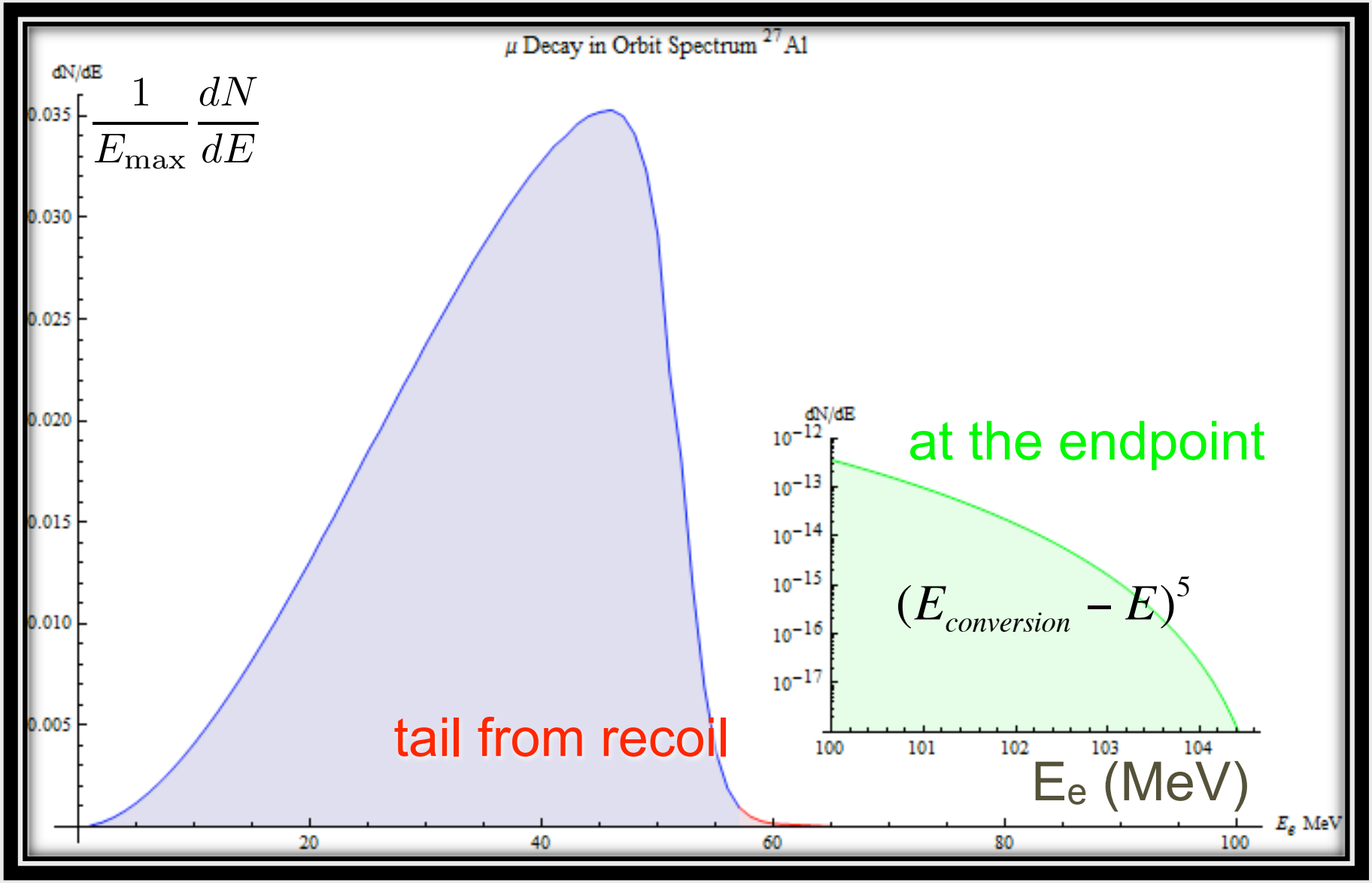
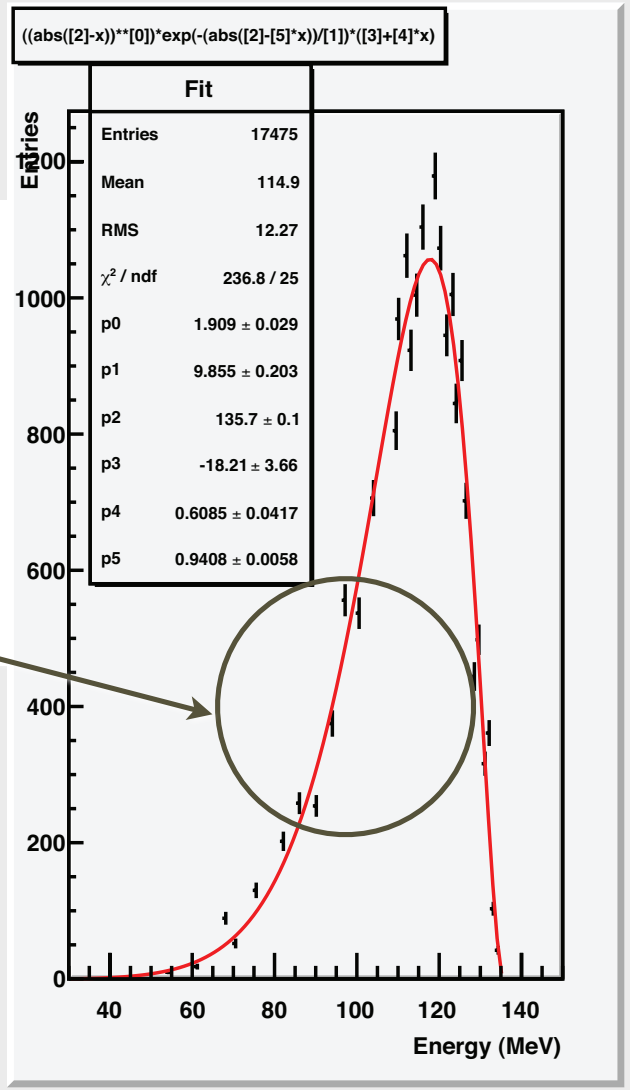
Czarnecki et al., arXiv:1106.4756v2 [hep-ph] Phys. Rev. D 84, 013006 (2011)



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 mπ, 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?***



energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

also included internal conversion, $\pi^- N \rightarrow e^+ e^- X$

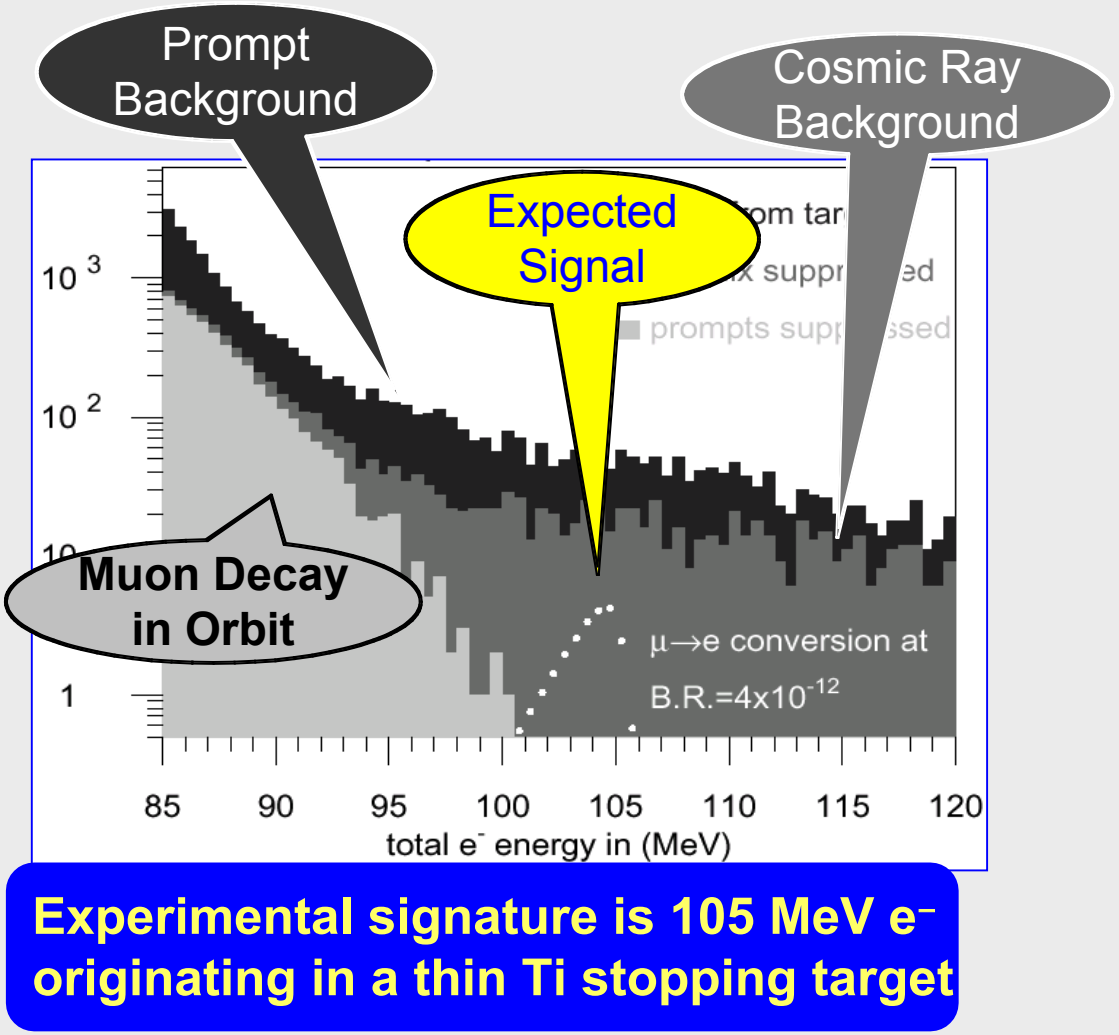
Review:
Two Classes of Backgrounds

	Decay-In-Orbit	Prompt
Source	Intrinsic Physics Background	Radiative π Capture: Mostly π's produced in production target
Solution	Spectrometer Design: resolution and pattern recognition	Design of Muon Beam, formation, transport, and time structure

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

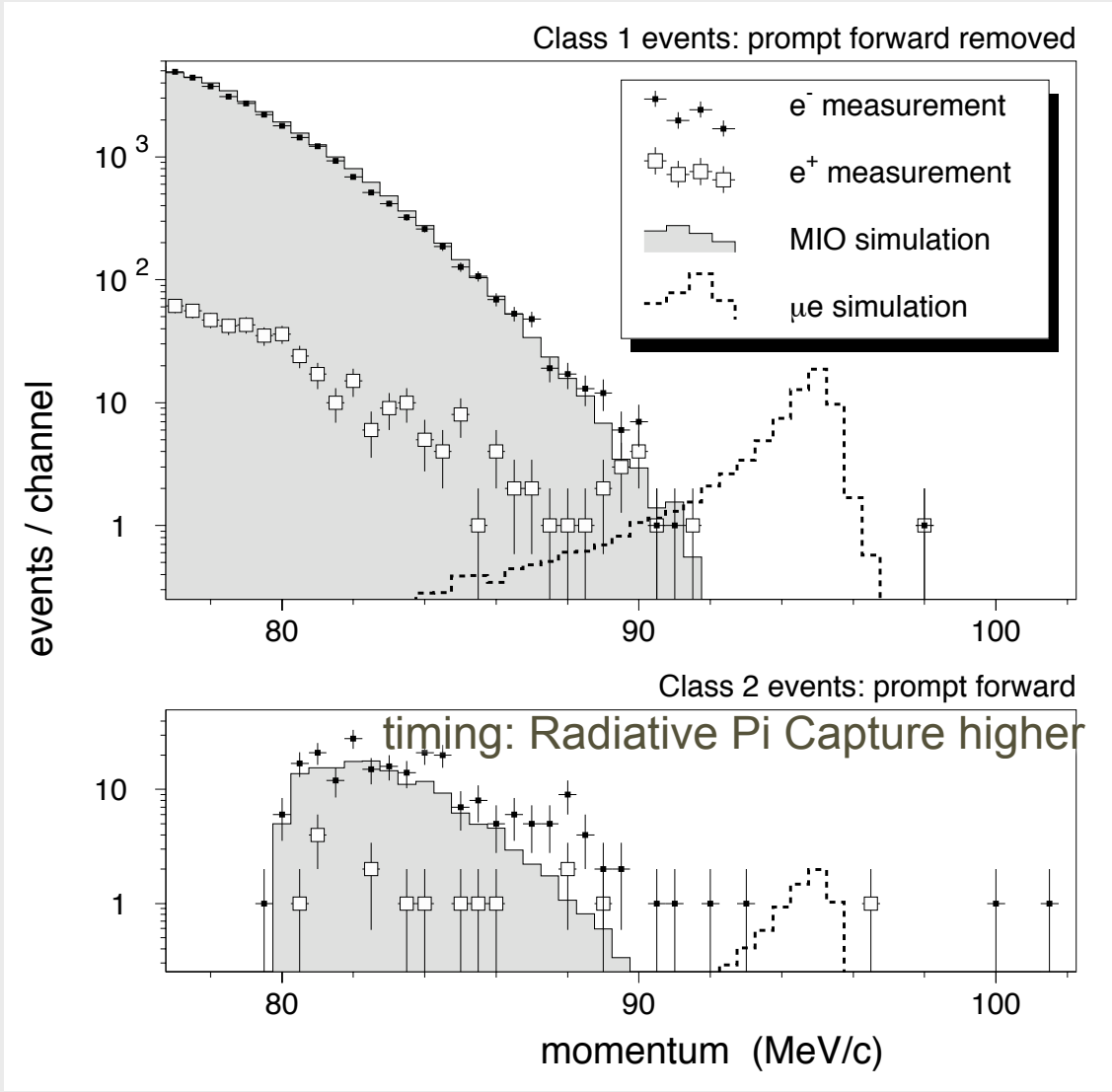
- Final Results on Au:

$$B_{\mu e}^{\mathrm{Au}} \quad < \quad 7 \times 10^{-13} \ @ \ 90\% \ \mathrm{CL}$$

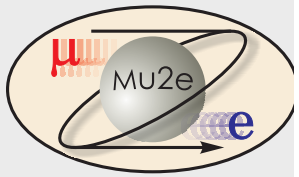
51 MHz (20 nsec) repetition rate, width of pulse ~0.3 nsec

little time separation between signal and prompt background

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



How Can We Do Better?



>10^3 increase in muon intensity from SINDRUM

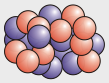
Requiring

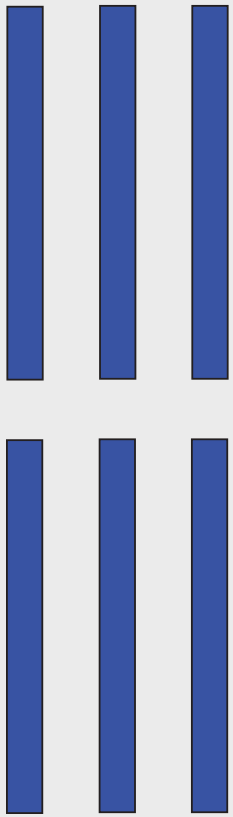
Pulsed Beam to Eliminate prompt backgrounds like radiative π capture and CR

protons out of beam pulse/ protons in beam-pulse < 10^{-10}
and we must measure it

Advantage of Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions



pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

RPC:

$\pi N \rightarrow \gamma N$

$\gamma \rightarrow e^+ e^-$ *in foils*

Advantage of Pulsed Beam

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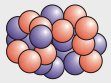
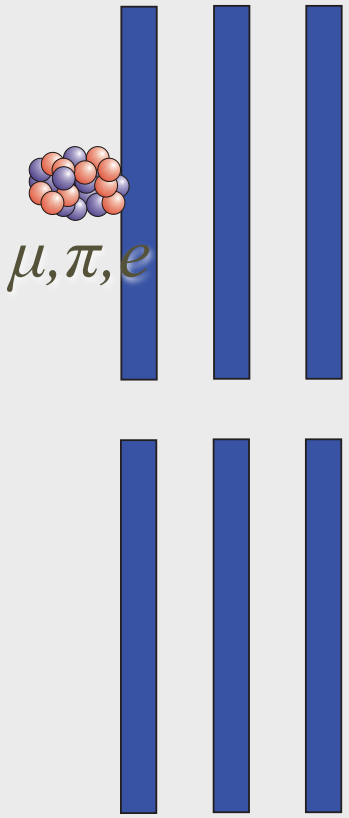
 = muons, electrons, pions



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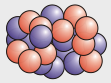
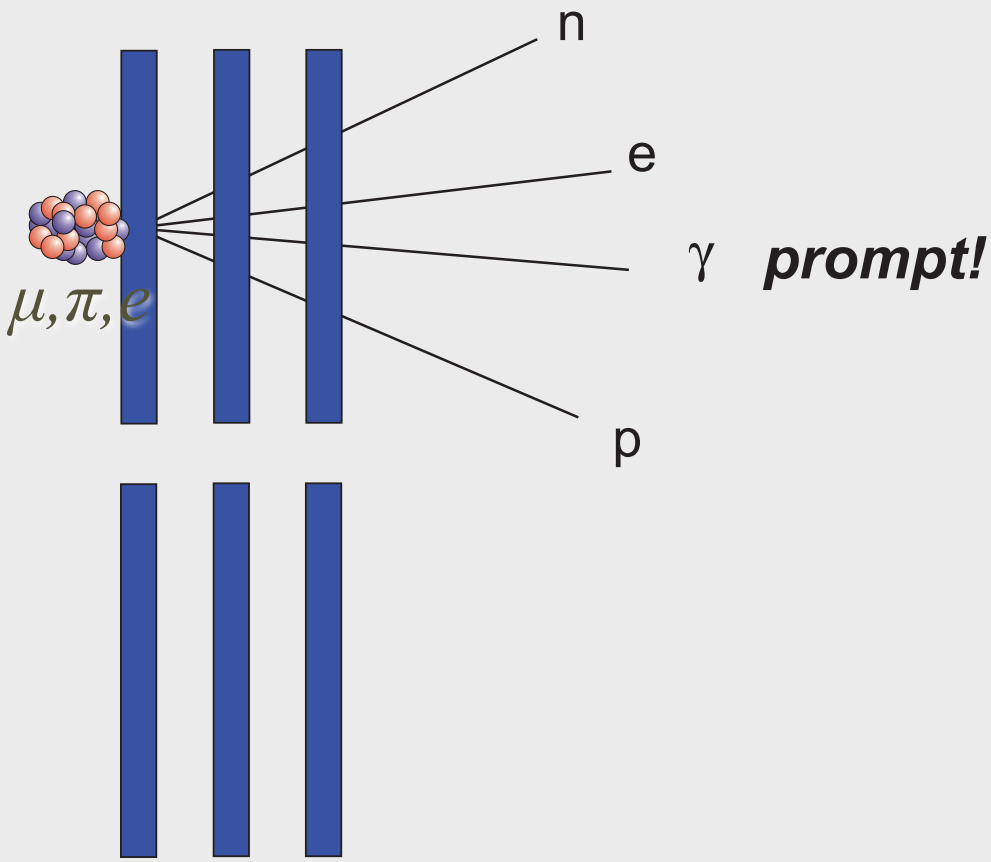
 = muons, electrons, pions



prompt!

pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

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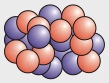
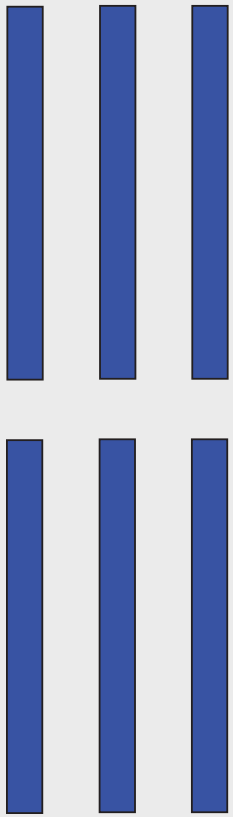
$\gamma \rightarrow e^+e^-$ *in foils*

Advantage of Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions



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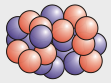
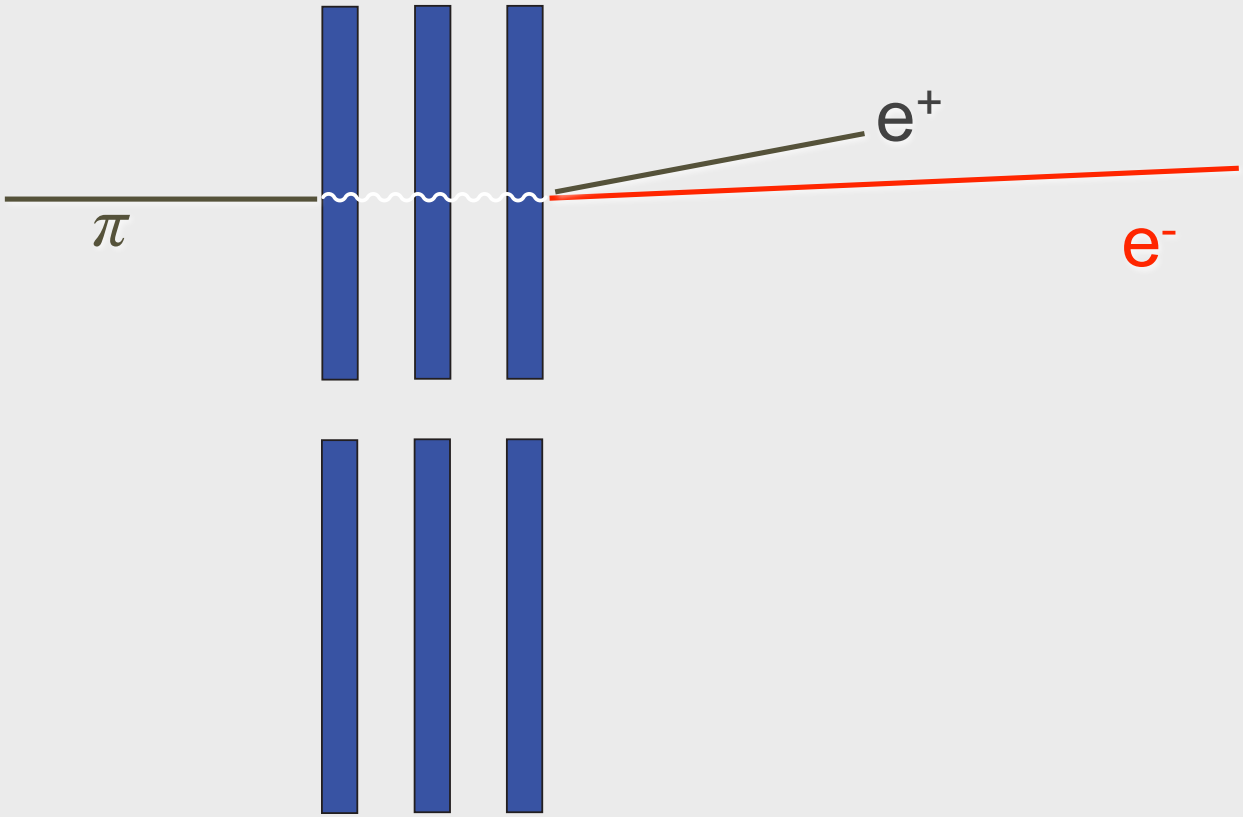
 = muons, electrons, pions



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Advantage of Pulsed Beam

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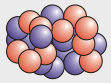
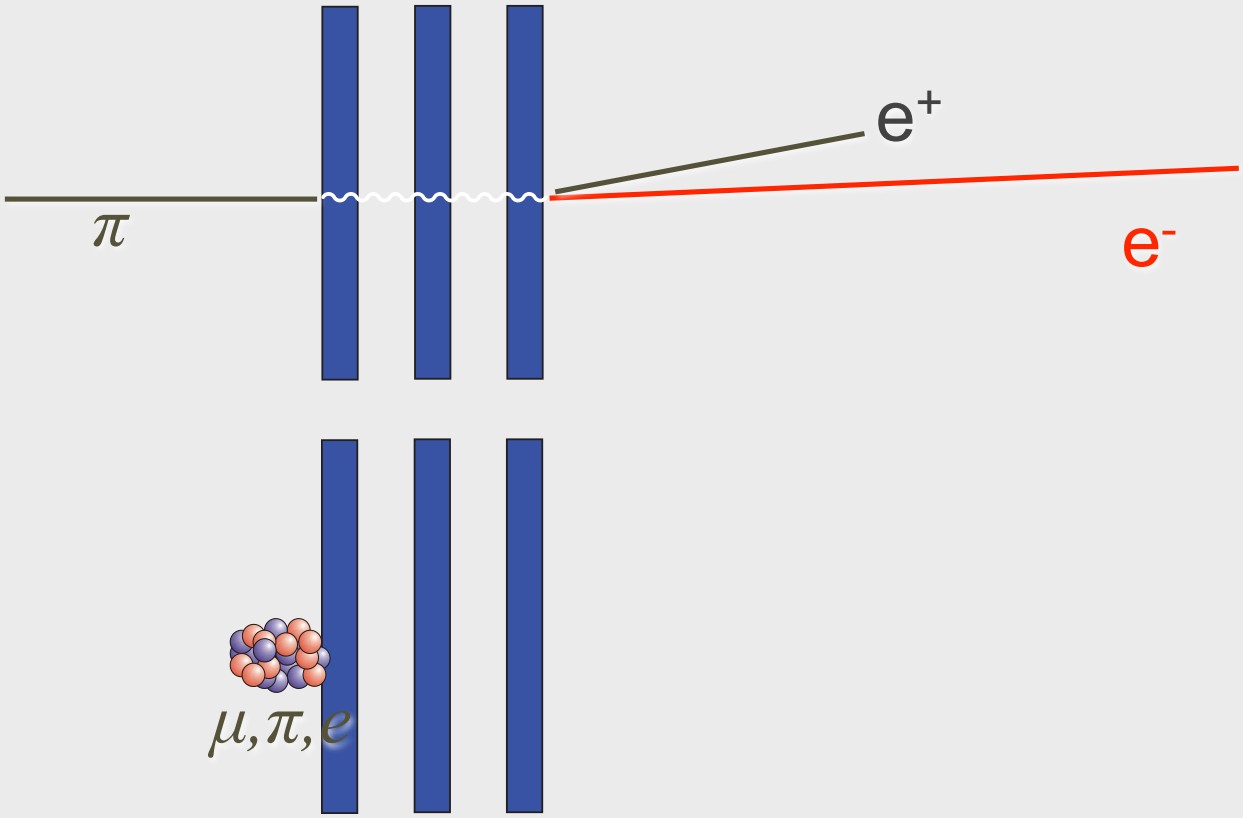
 = muons, electrons, pions



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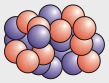
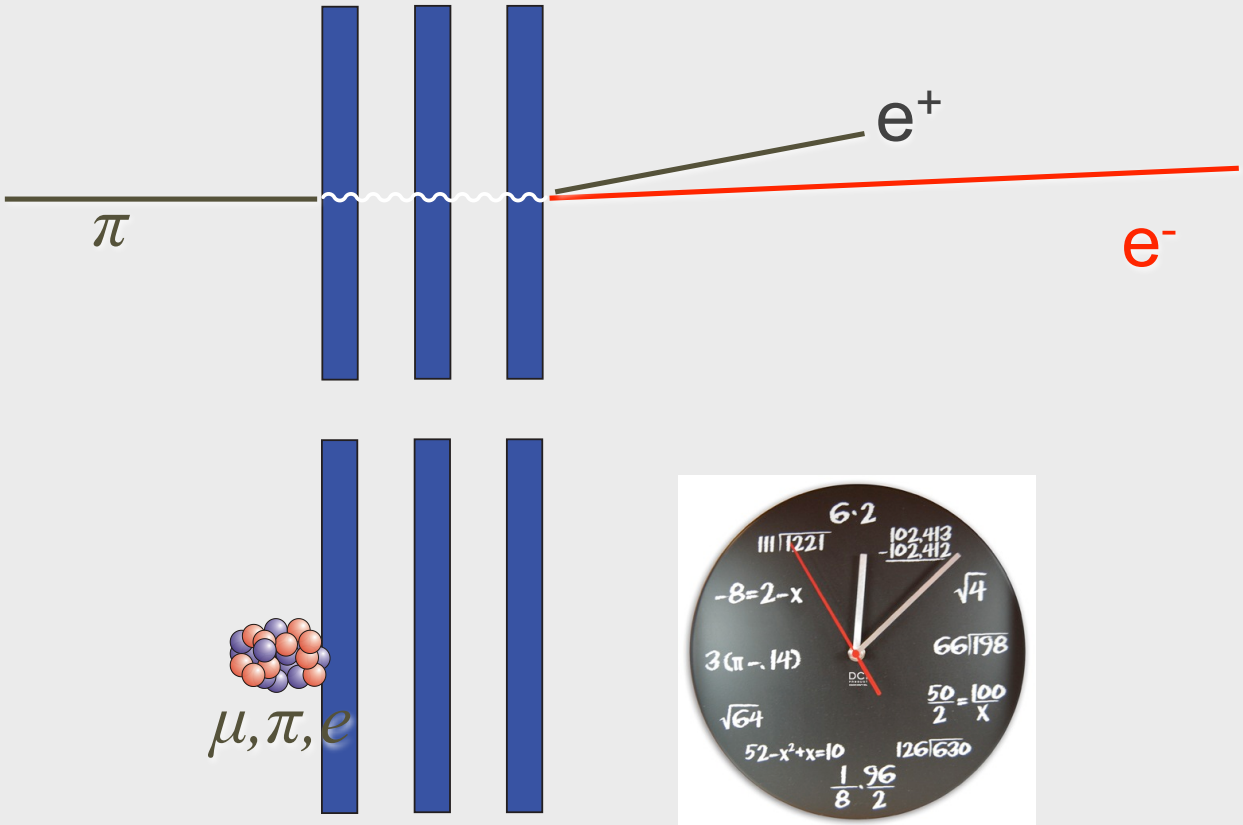
target foils: muon converts here

 = muons, electrons, pions



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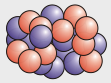
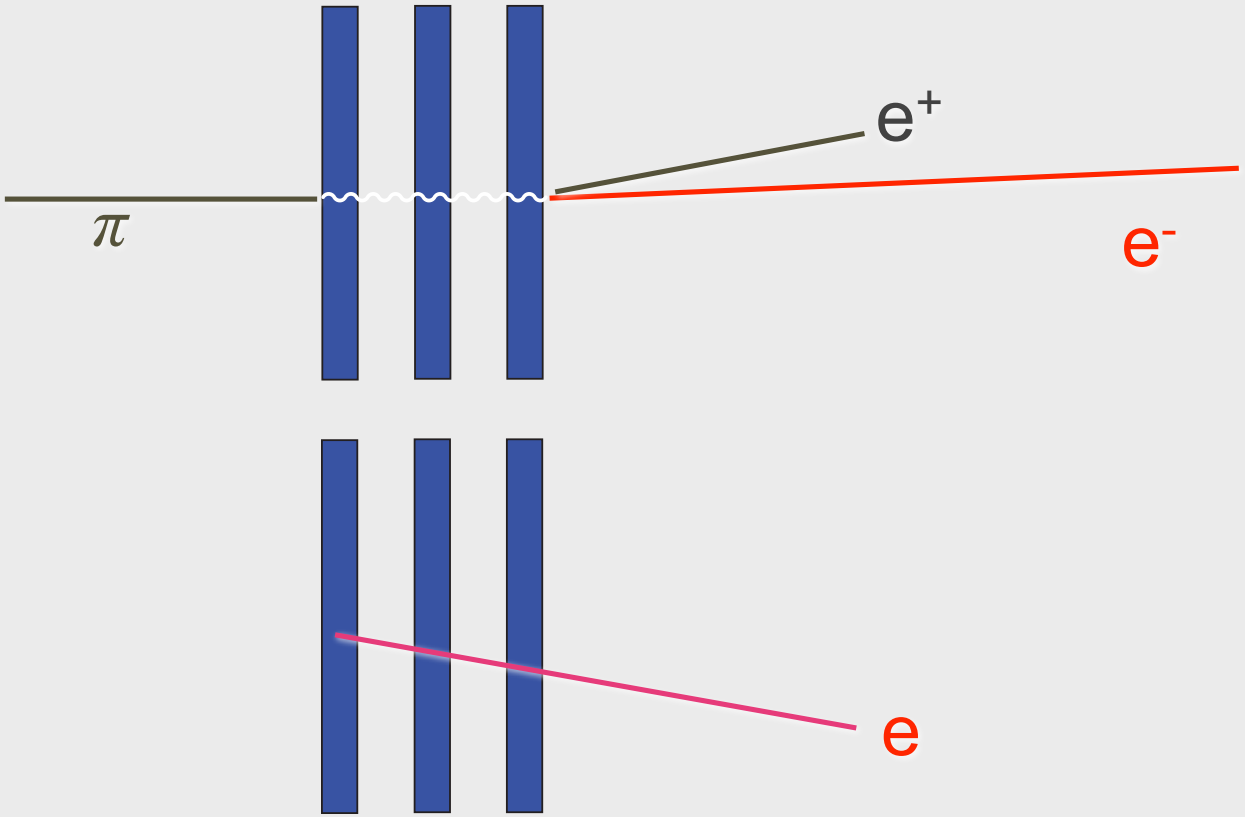
 = muons, electrons, pions



pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

RPC:

$\pi N \rightarrow \gamma N$

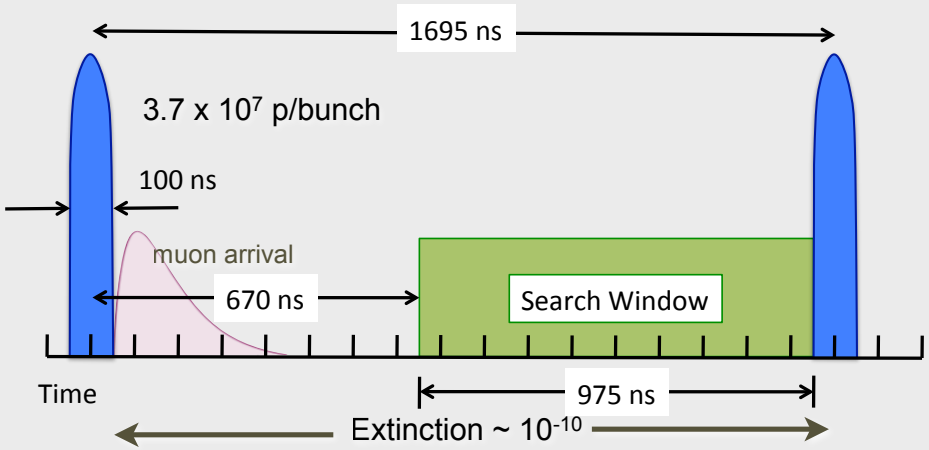
$\gamma \rightarrow e^+e^-$ *in foils*

delayed 105 MeV electron

Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_μ^{Al} , pulse separation ≈ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7μsec , ~x2 τ_μ^{Al}
- Extinction between pulses < 10^{-10} needed

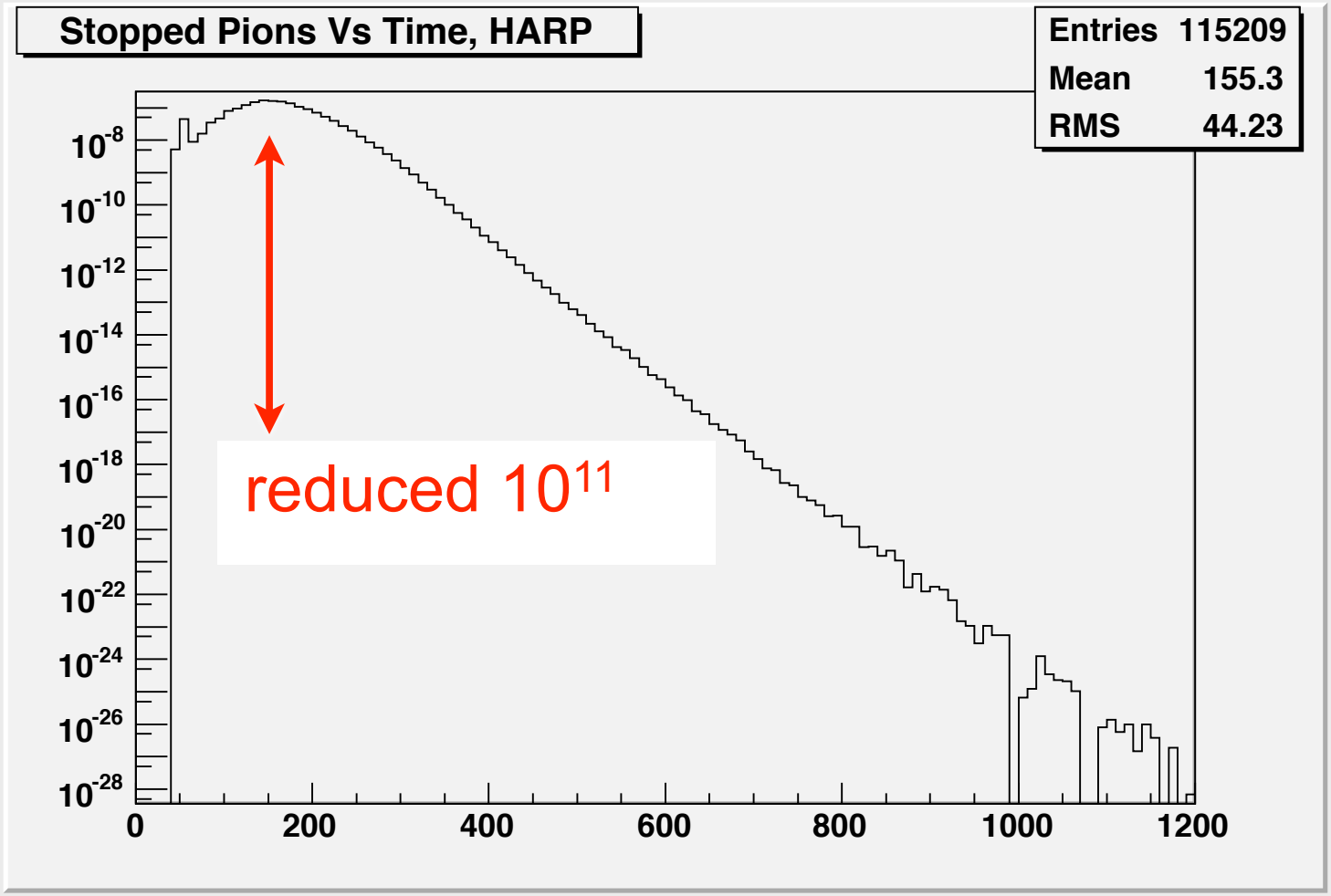
  = # protons out of pulse/# protons in pulse



- 10^{-10} based on simulation of prompt backgrounds and beamline

Pulsed Beam Structure and Radiative π Capture

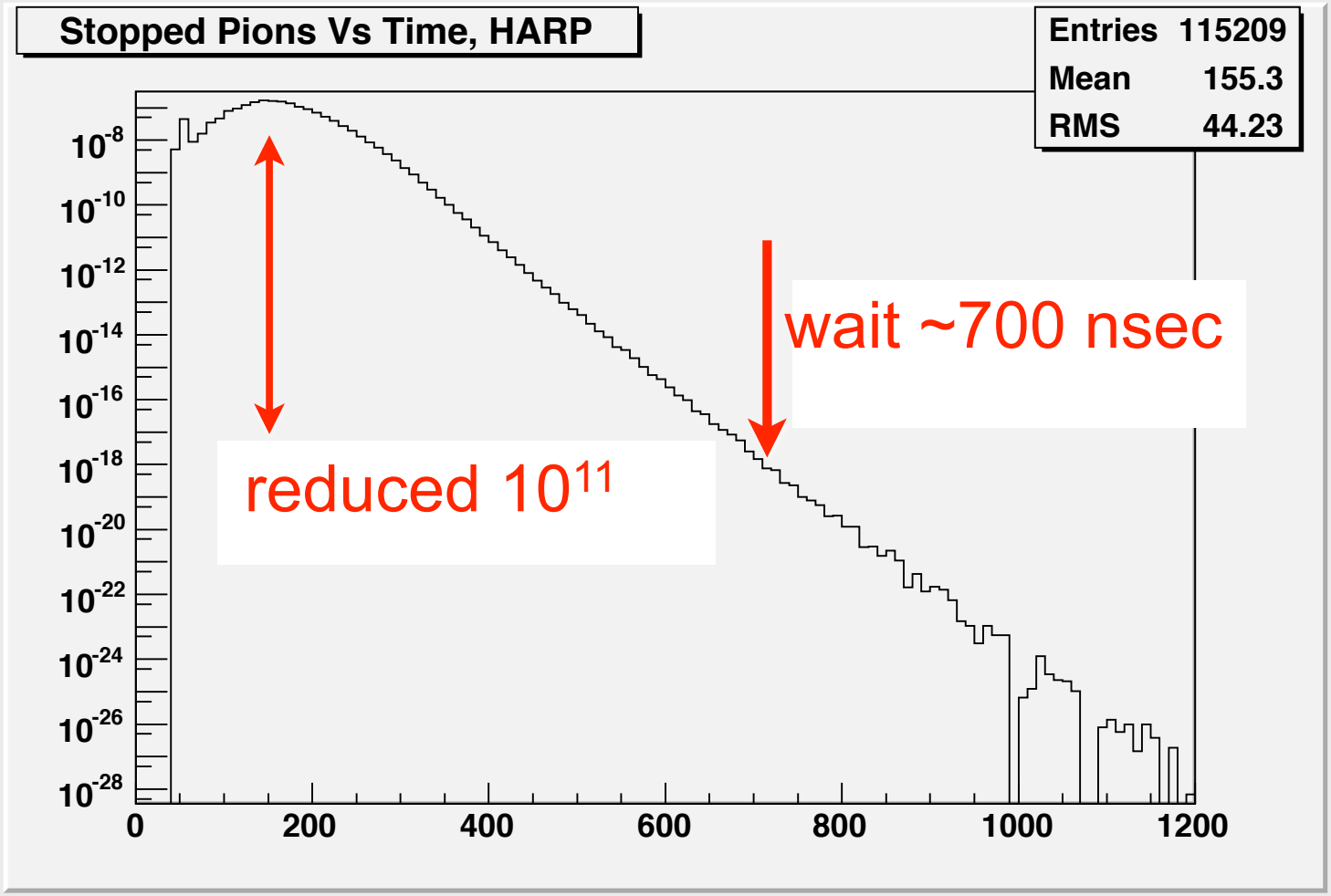
$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+ e^-$$



need a beam that lets us wait this long: FNAL

Pulsed Beam Structure and Radiative π Capture

$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+ e^-$$



need a beam that lets us wait this long: FNAL

Choice of Stopping Material: rate vs wait

- 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?

V. Cirigliano et al., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

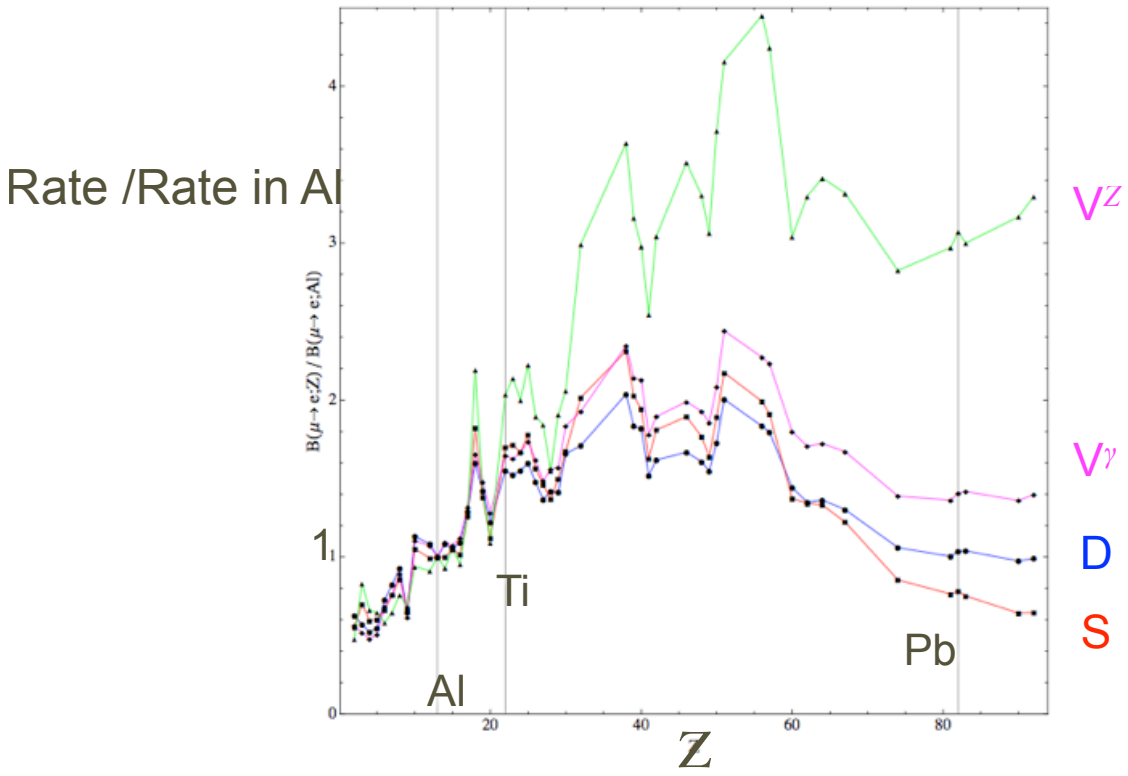


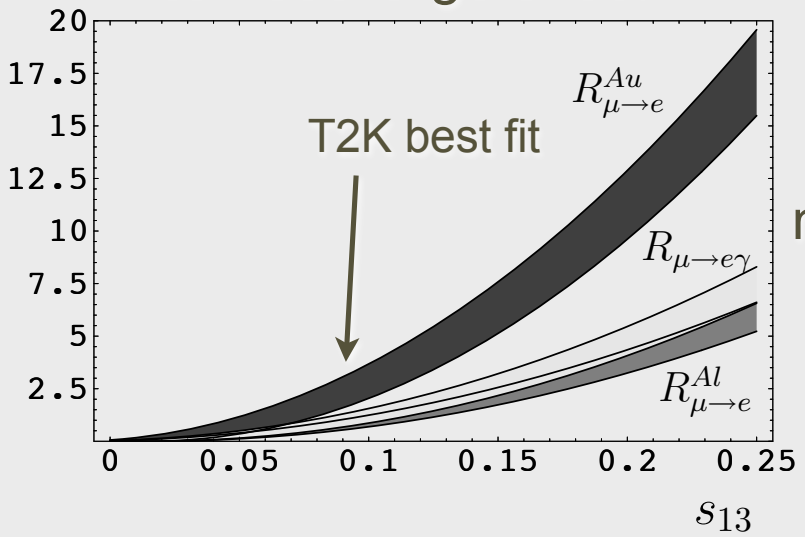
Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

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

Choice of Stopping Material: rate vs wait

- 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?

can see large effect



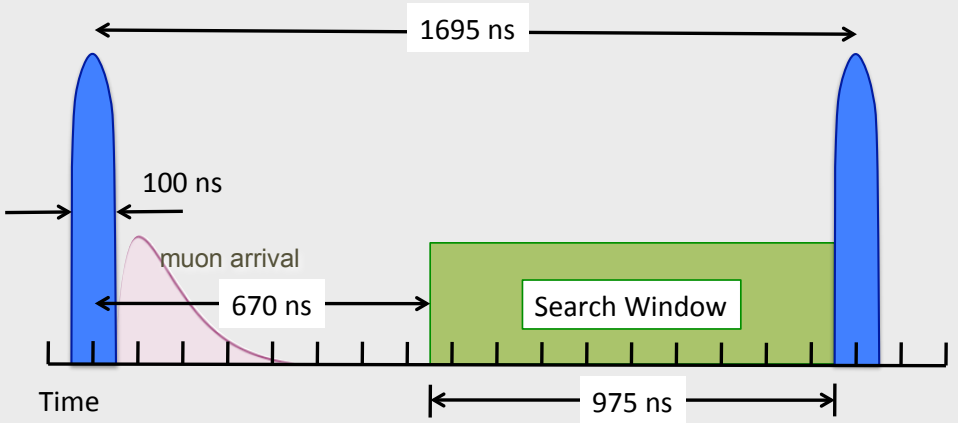
s_{13} is NOvA mixing angle < 0.2 or so

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005**.
e-Print: **hep-ph/0507001**

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

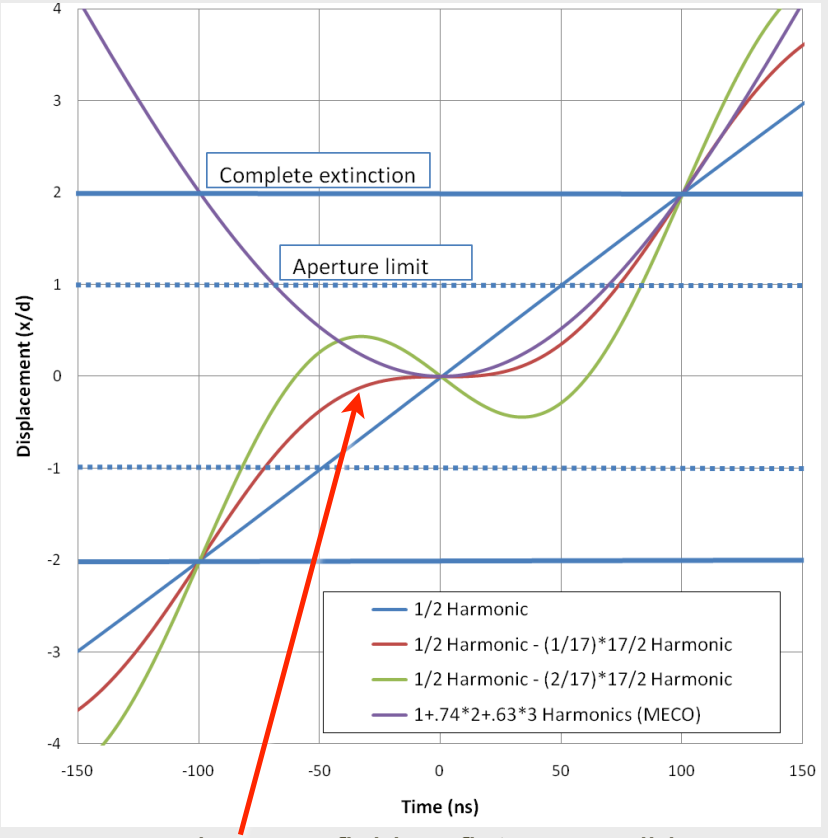


Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1.0	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV

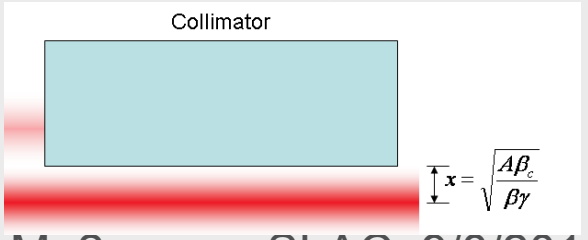
Extinction Scheme

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

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators
- Calculations (MARS) show this combination gets ~10^{-12}

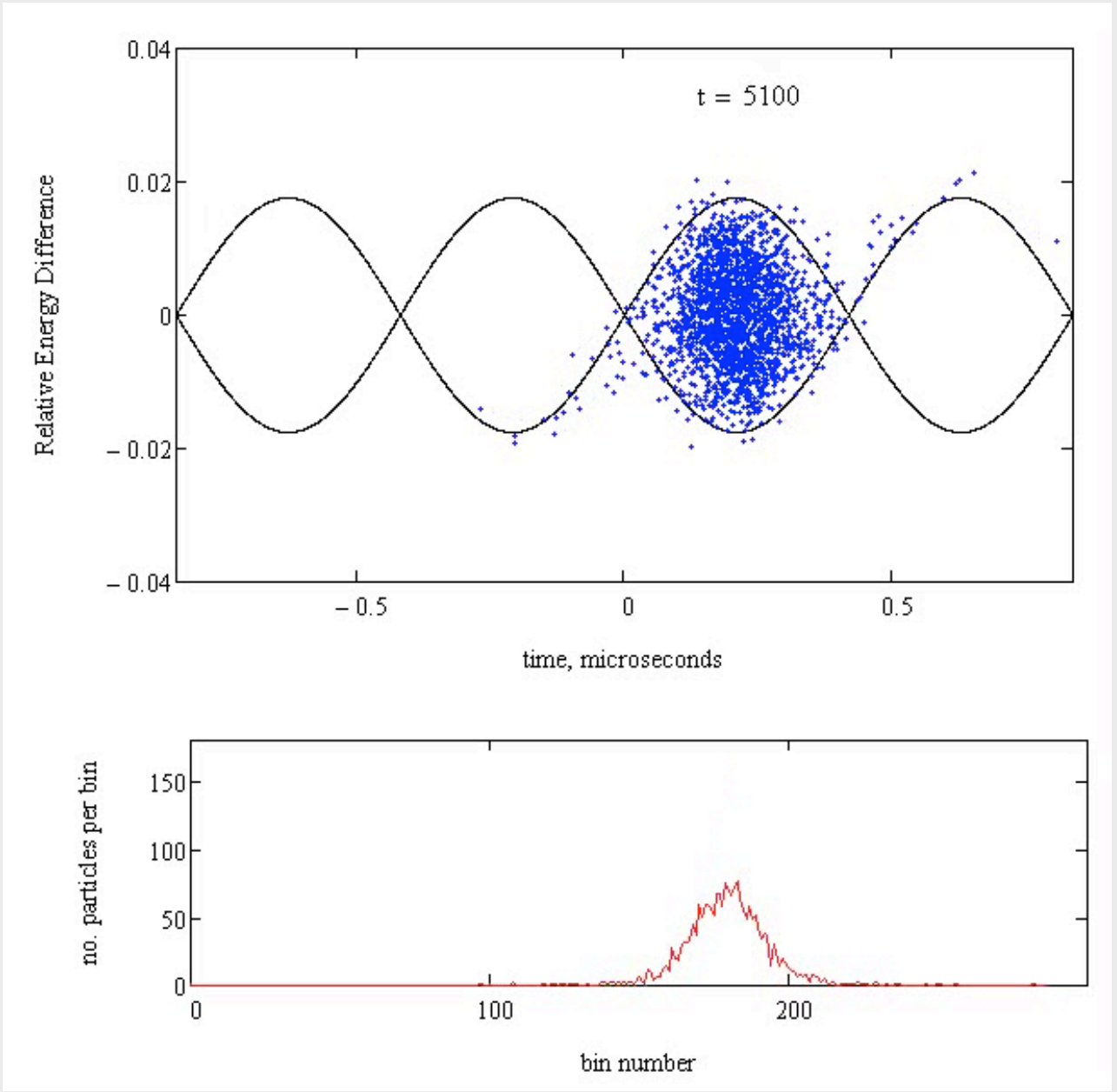


choose a field as flat as possible during the pulse that kicks beam out as quickly as possible



Extinction (Internal)

- RF jitter, scattering, etc can cause protons to wander out of their bucket



Extinction (internal)

- *Internal*:"momentum scraping": wait for beam to be wide, then use collimators
- Perform in Debuncher
- Have also modified beam transfer scheme from Accumulator to Debuncher to improve cleanliness

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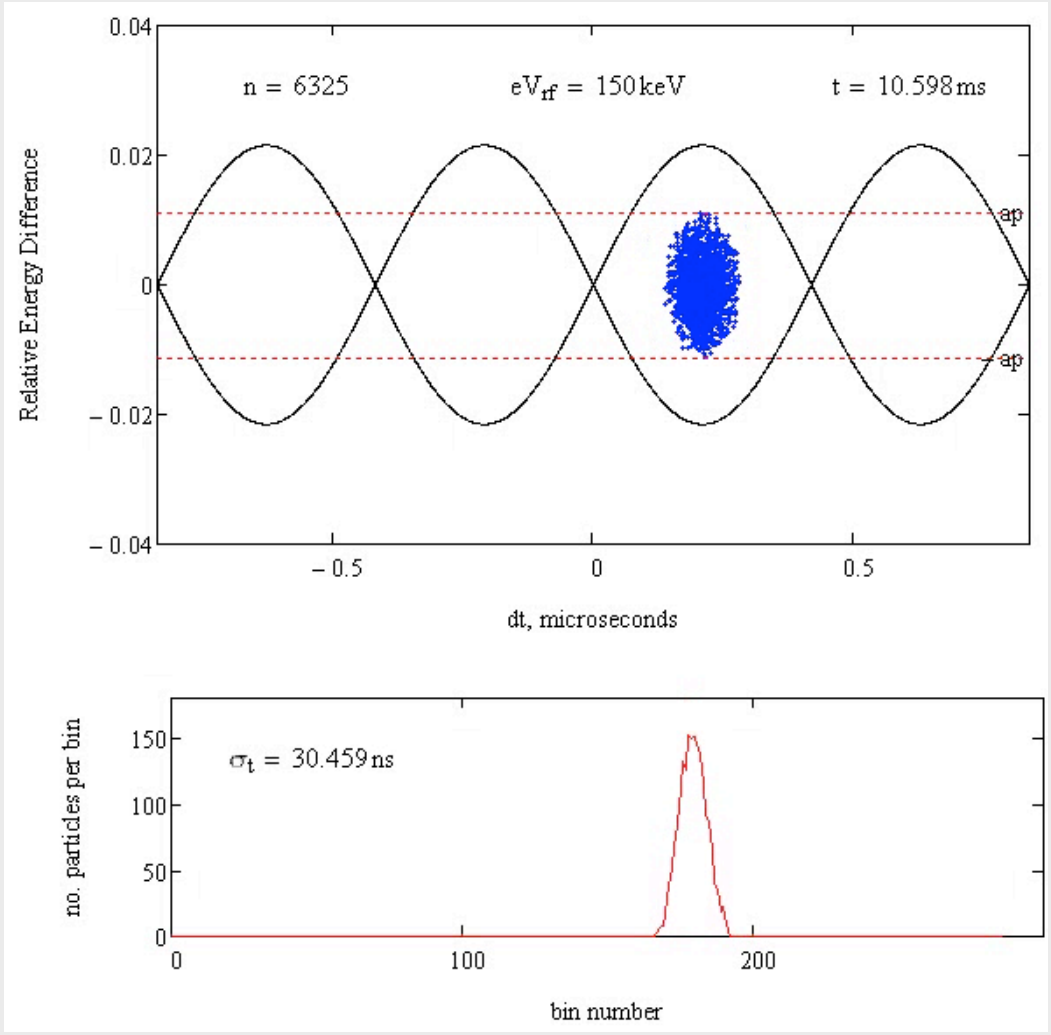

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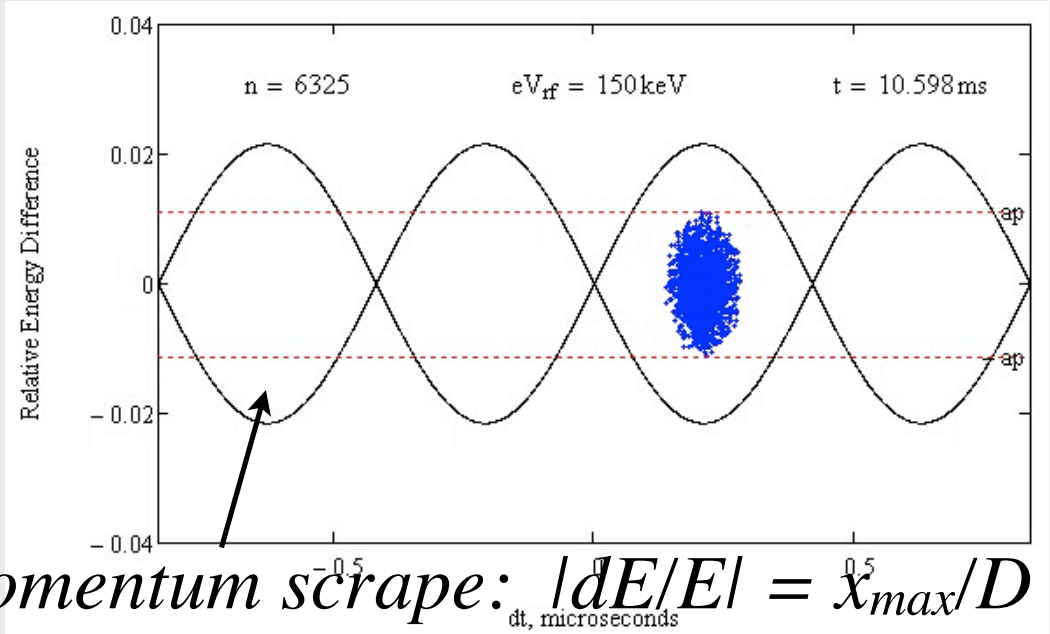
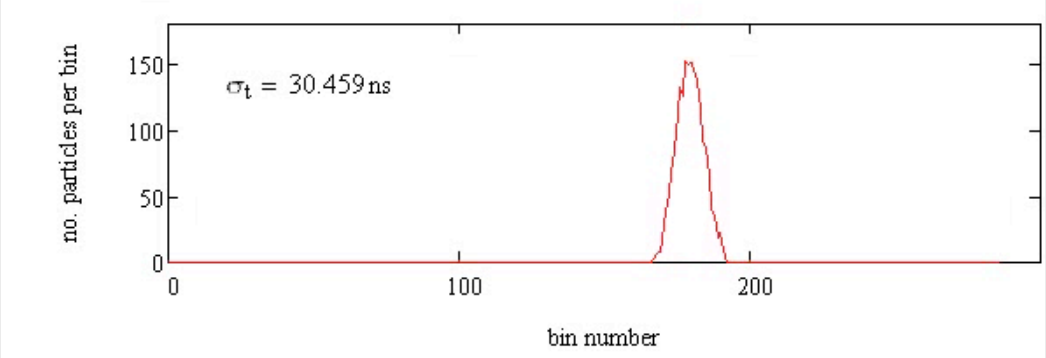
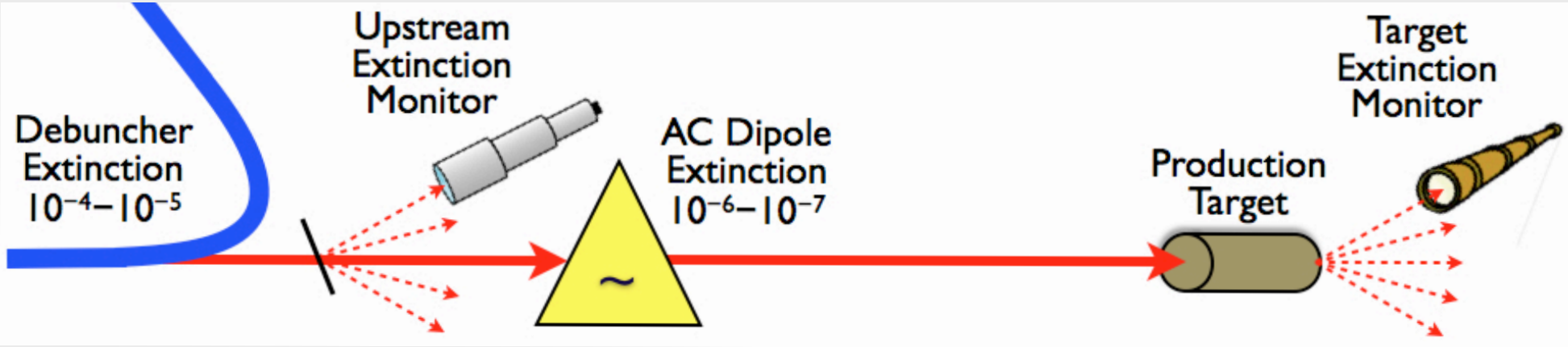


$$momentum\ scrape:\ |dE/E| = x_{max}/D$$



Extinction Measurement



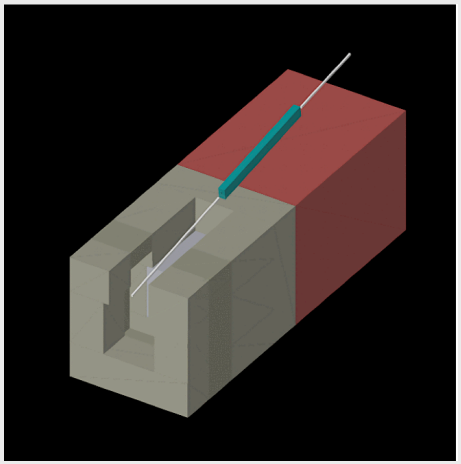
- Beam Formation(Debuncher, Momentum Scraping) and AC-Dipole provide extinction
- Measure with:
  - Thin foils in 8 GeV transport line (fast feedback on machine performance)
  - Off-axis telescope looking at production target (time scale of hour)
  - Also considering detecting individual out-of-time protons but very difficult

Current Extinction Plan

- Look at secondaries from target
  - Use a magnet to pick out signal
  - Count hits in-and-out of pulse, compare
  - Current plan -- *not proton-by-proton*

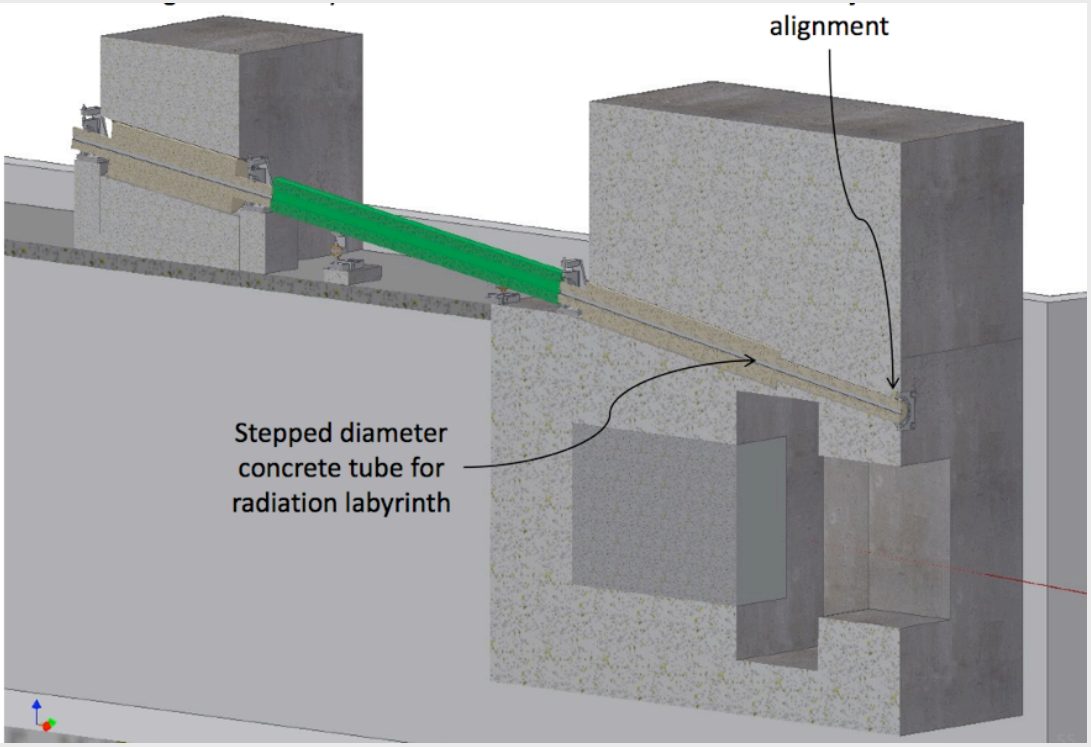
Nominal Momentum (GeV/c)	Transmitted tracks / bunch			Integration Time (min)		Proton Percentage	MeV Deposited / Proton-on-Target		
				No Bkgnd.	5 / hr		Entry Channel	Magnet	Exit Channel
2.0	40.5	±	4.4	6.9	10.8	77.6	0.293	0.167	0.007
3.0	151.4	±	8.5	1.8	2.1	82.7	0.258	0.168	0.037
4.0	240.0	±	10.7	1.2	1.3	89.9	0.246	0.164	0.037
5.0	191.0	±	9.5	1.5	1.6	93.0	0.201	0.128	0.037
6.0	119.1	±	5.8	2.3	2.8	96.4	0.172	0.112	0.026
7.0	69.4	±	4.5	4.0	5.3	97.1	0.149	0.100	0.021
8.0	39.8	±	2.9	7.0	11.0	99.0	0.133	0.095	0.015
9.0	26.1	±	2.3	10.6	20.1	100.0	0.116	0.089	0.011

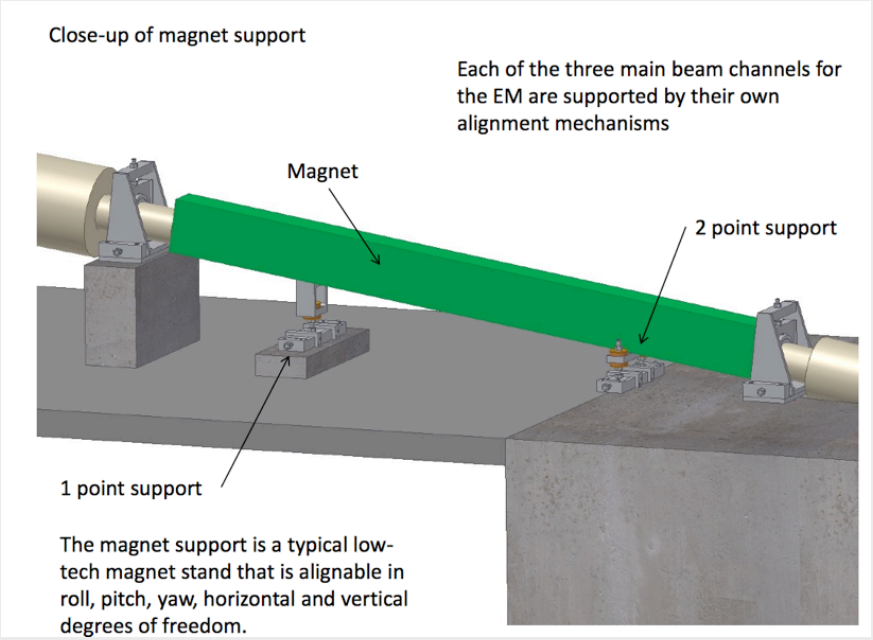
G4Beamline Model



working on using diffractive protons:
little-to-no background, easier to model

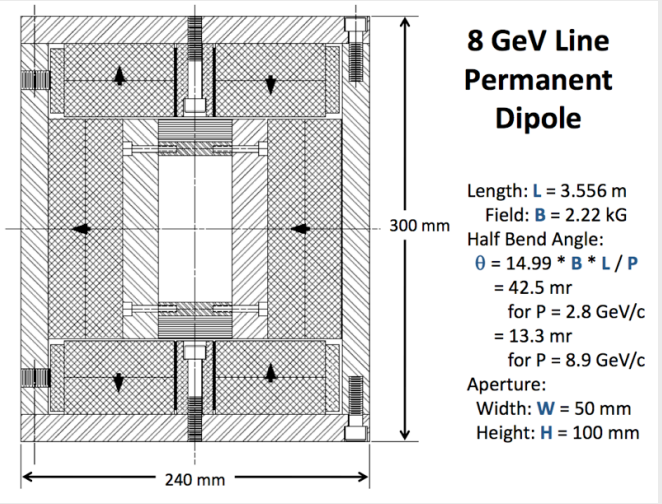
Wide Variety of choices





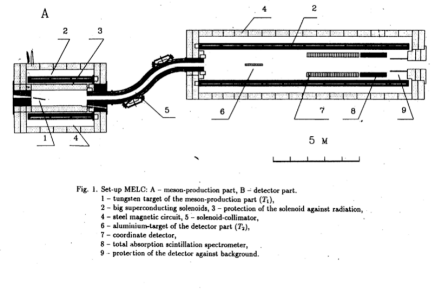
- Working on detector modeling
  - ATLAS pixels?
  - TOF?
  - Calorimeter?

interesting problem for post-docs!!

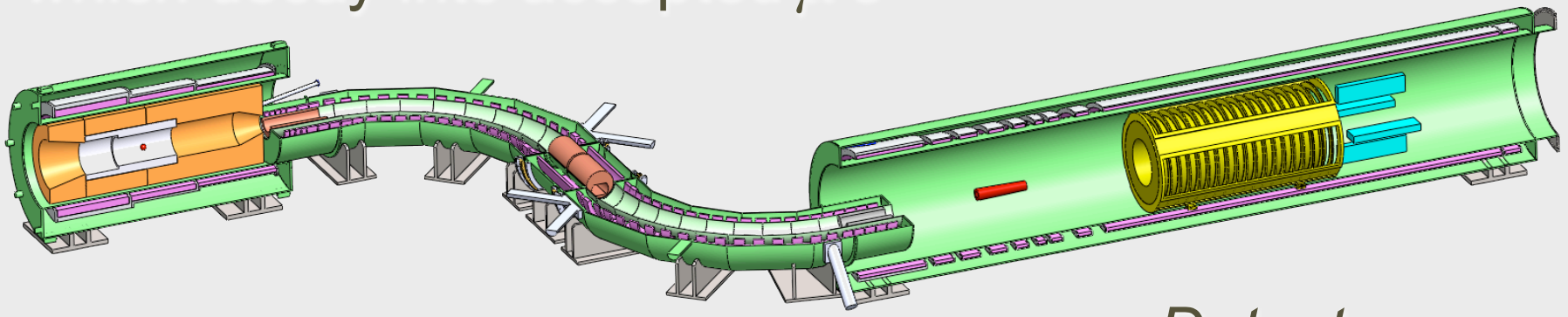


Mu2e Overview

V. Lobashev, MELC 1992:



- *Production*: Magnetic bottle traps π's, which decay into accepted μ's

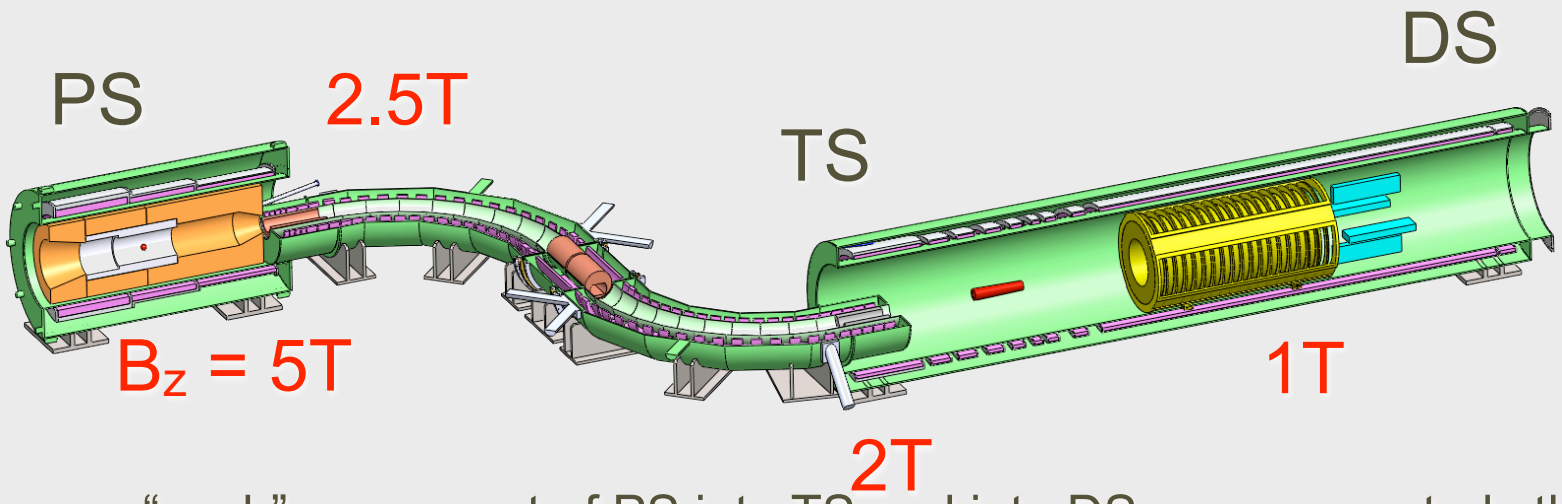


- *Transport:* S-curve eliminates backgrounds and sign-selects
- *Detector:* Stopping Target, Tracking and Calorimeter

entire system in vacuum < 10^{-4} torr

Gradient Fields in Mu2e

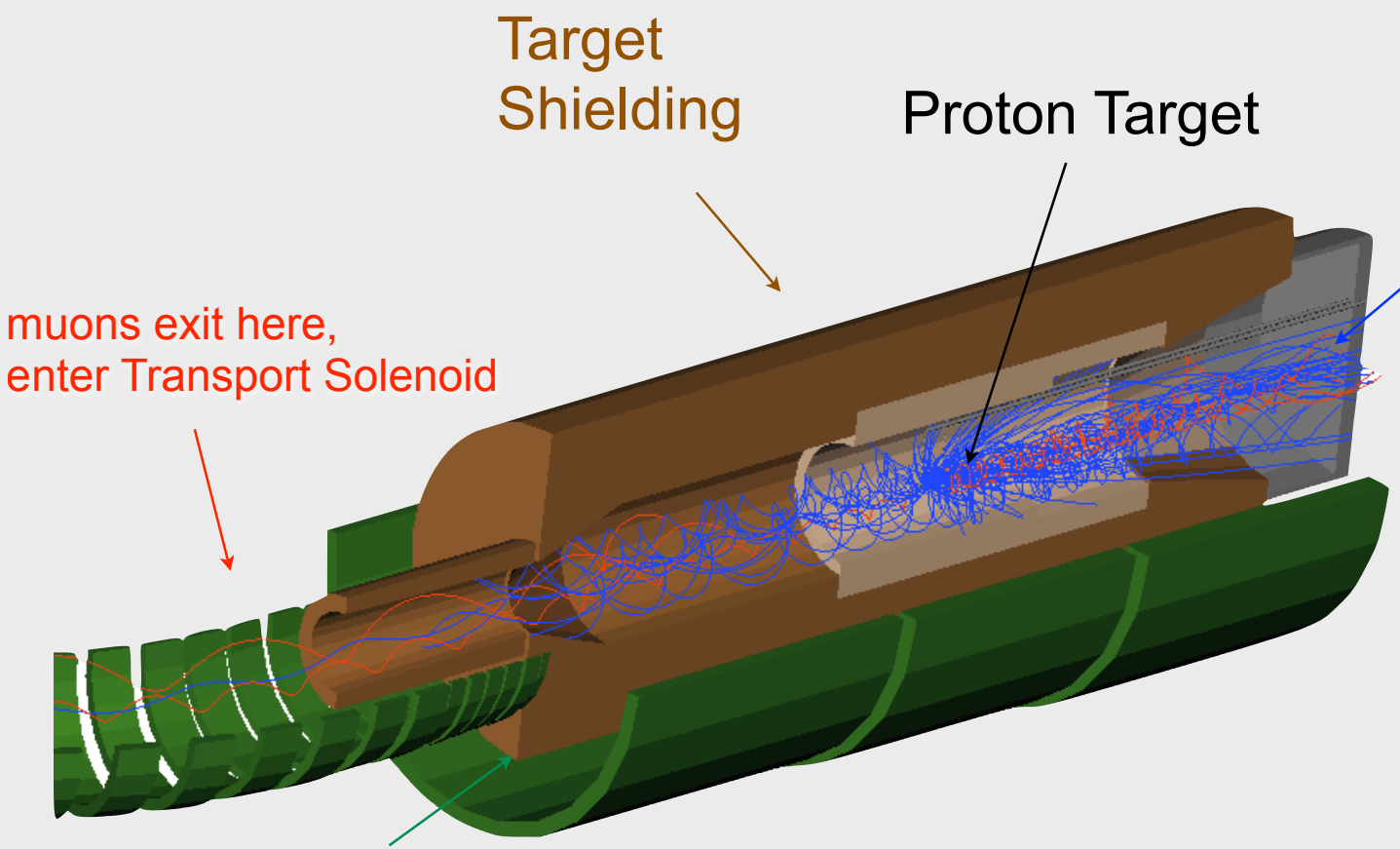
- Play a vital role throughout the design
- A lot of our intellectual effort!!



- "push" muons out of PS into TS and into DS so we can study them
- keep particles from spiraling around, arriving late
- conversions are isotropic in stopping target; the gradient over stopping target "reflects" backward going muons and nearly doubles the acceptance

Production Solenoid:

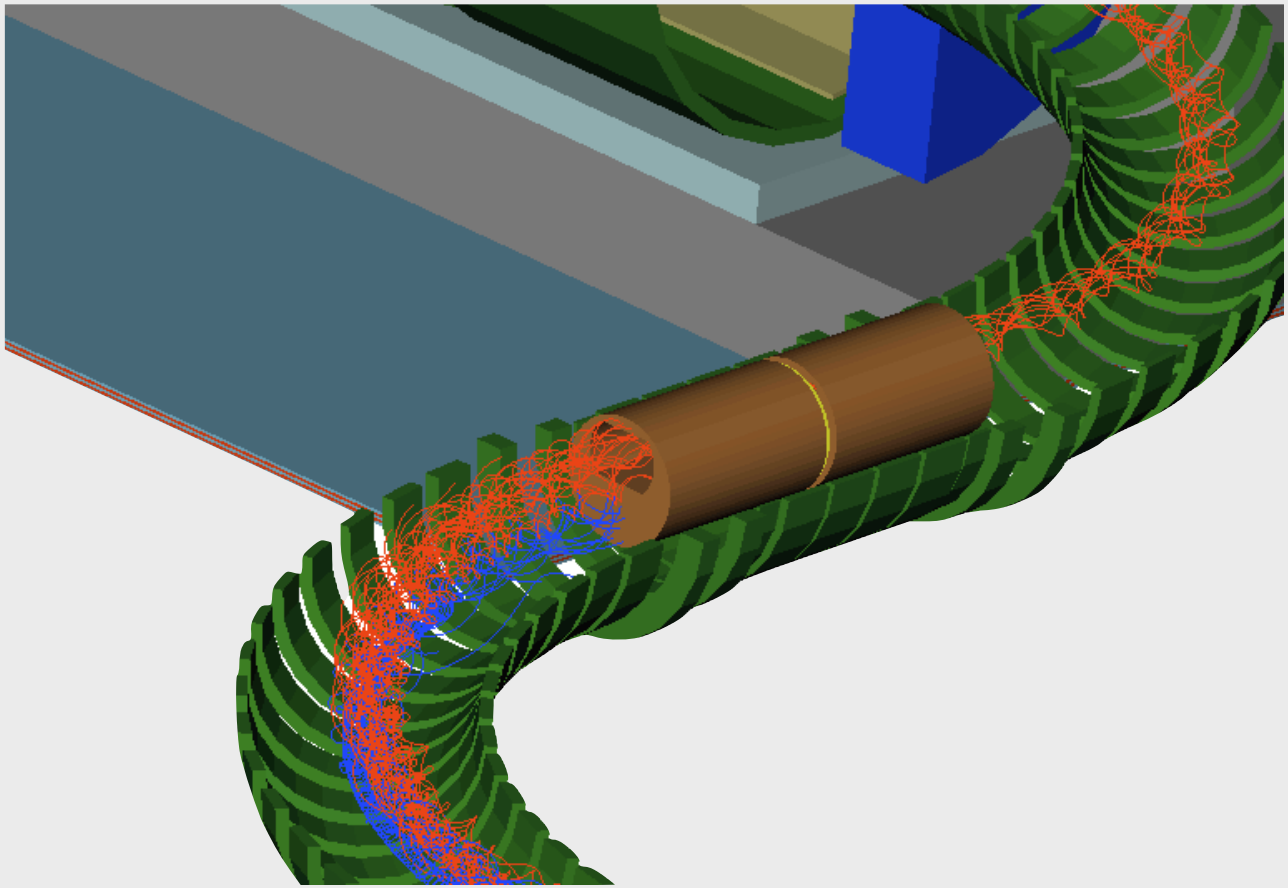
Protons enter opposite to outgoing muons



π's are captured, spiral around and decay

Transport Solenoid

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



13.1 m along axis × ~0.25 m

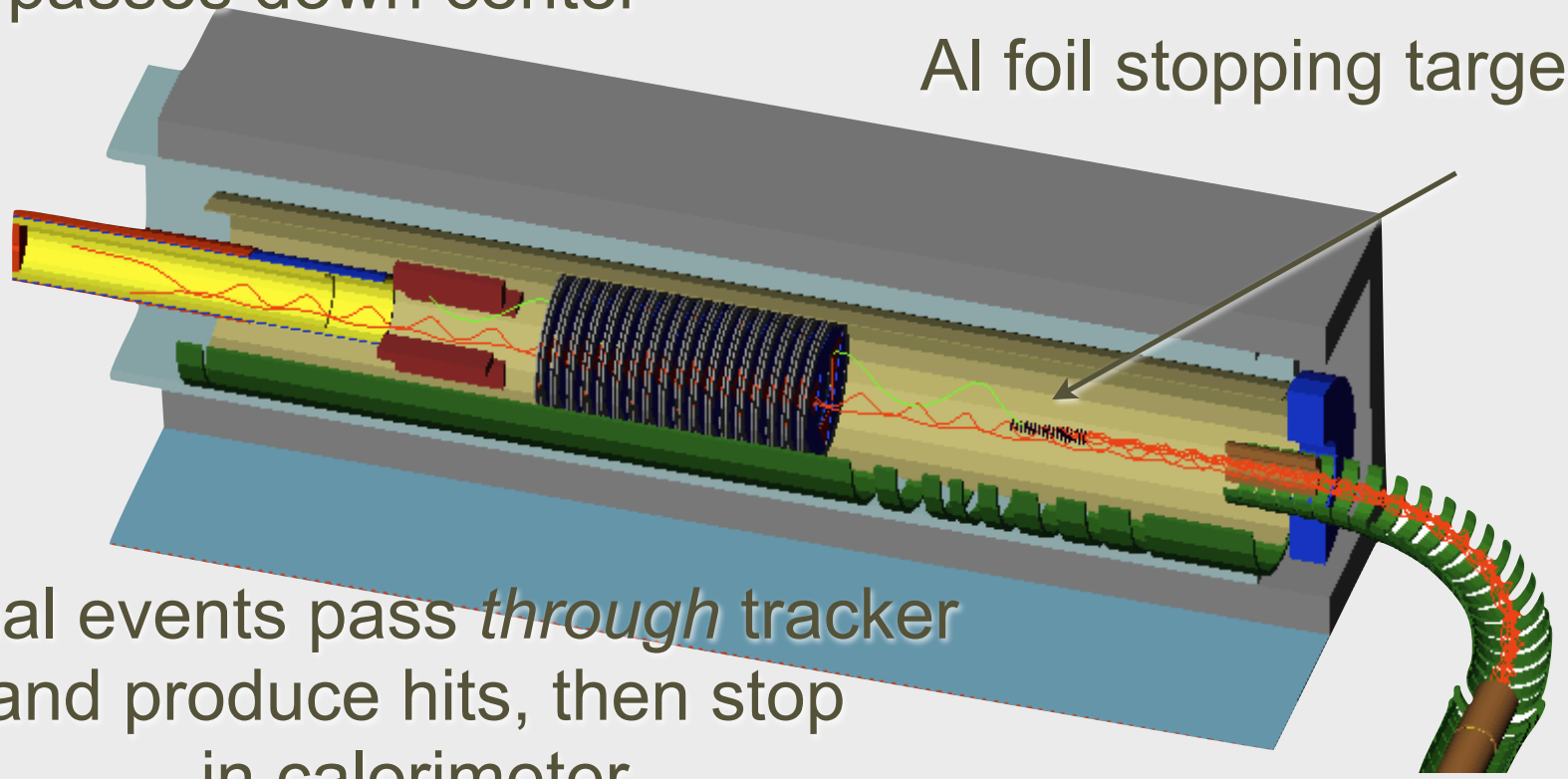
Detector Solenoid

octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down center

10 m × 0.95 m

Al foil stopping target



signal events pass *through* tracker and produce hits, then stop in calorimeter

Detector Solenoid

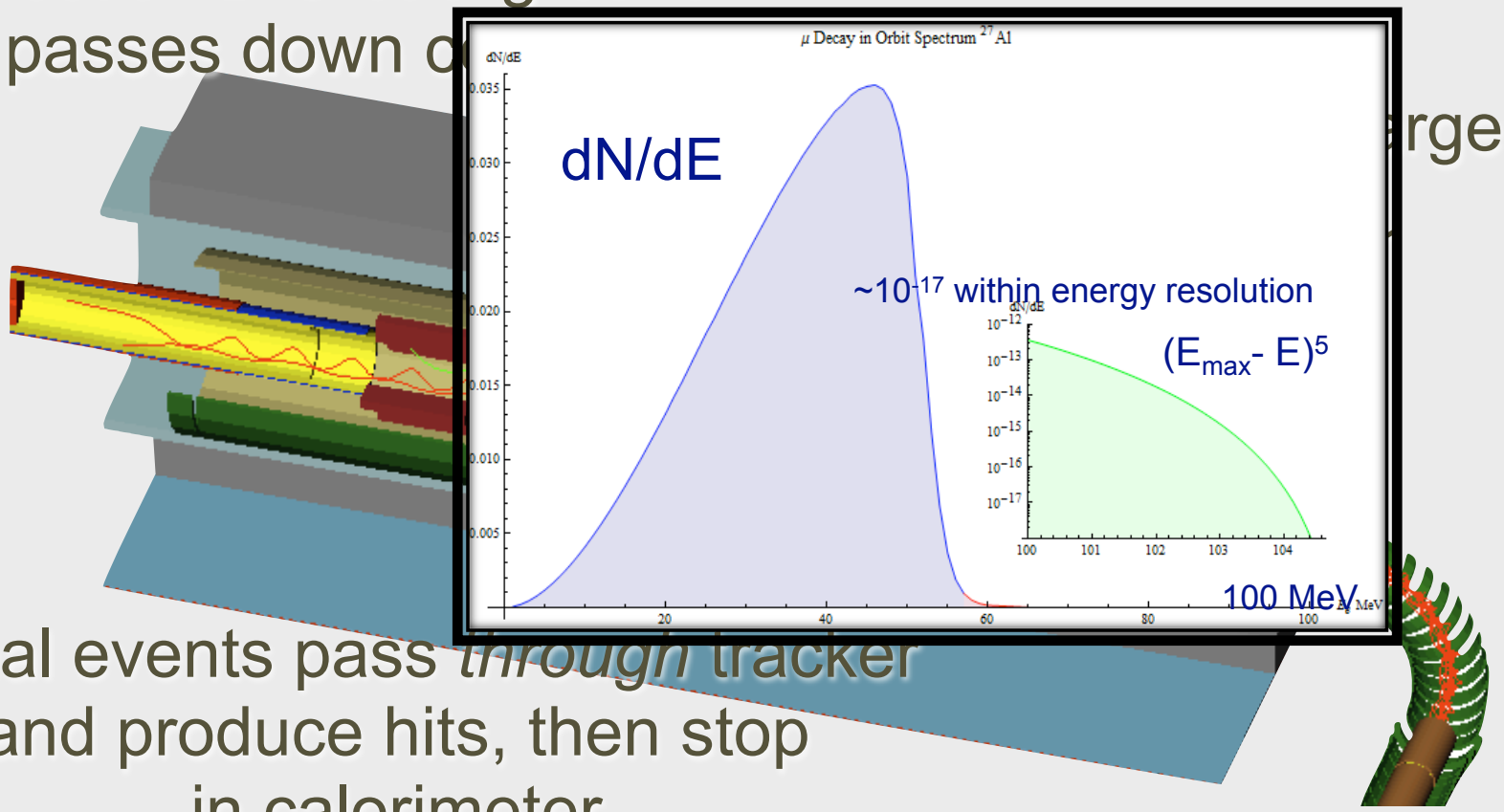
octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR

low momentum particles and almost all DIO background passes down c

10 m × 0.95 m

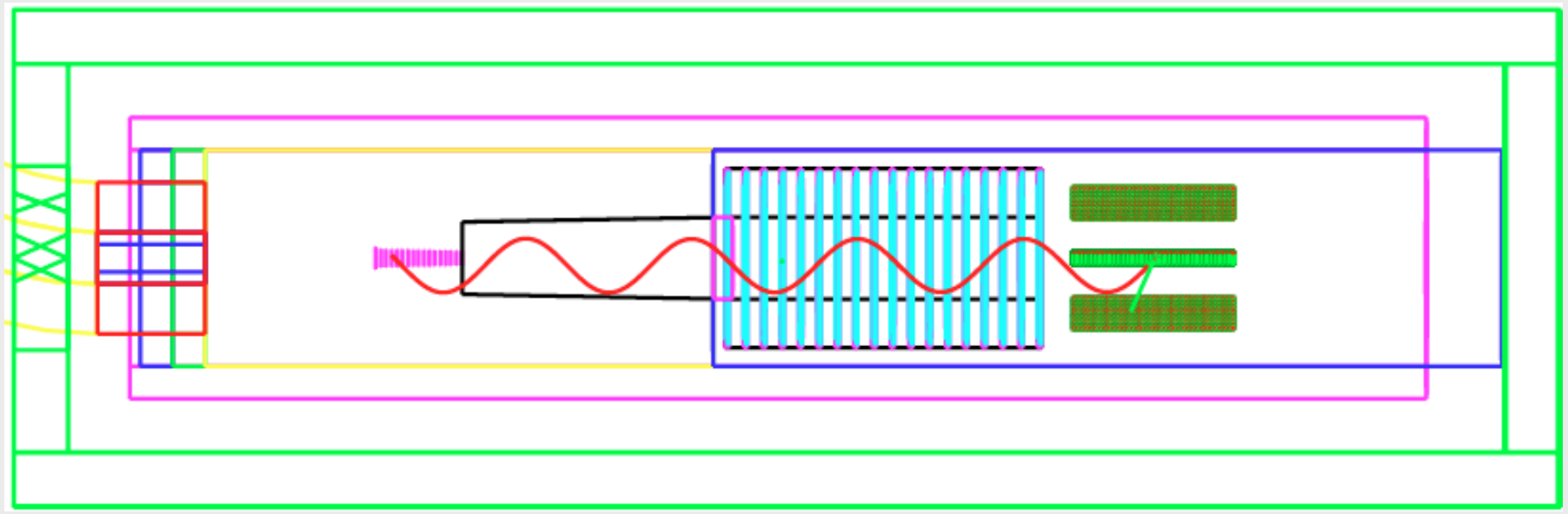
rget

muon beam stop



signal events pass *through* tracker and produce hits, then stop in calorimeter

Detector

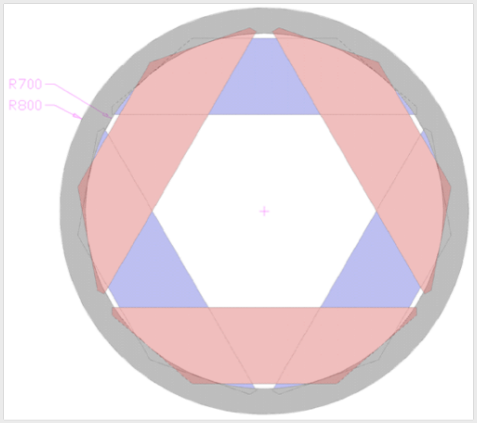


- Immersed in solenoidal field, so electrons follow near-helical path
- Conversion Electron born in Stopping Target
- Tracker followed by Calorimeter

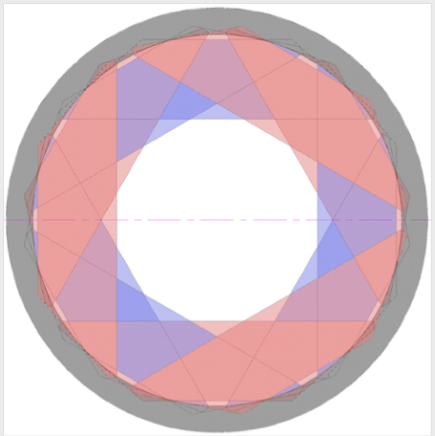
- Tracker: (straw tubes with axes transverse to beam)
  - 21,600 straws
    - 18 stations of 5 mm diameter conducting straws
    - length from 33-118 cm
- Calorimeter:
  - 1024 3.5 × 3.5 × 12 cm $PbWO_4$ or LYSO
  - 4--5% resolution

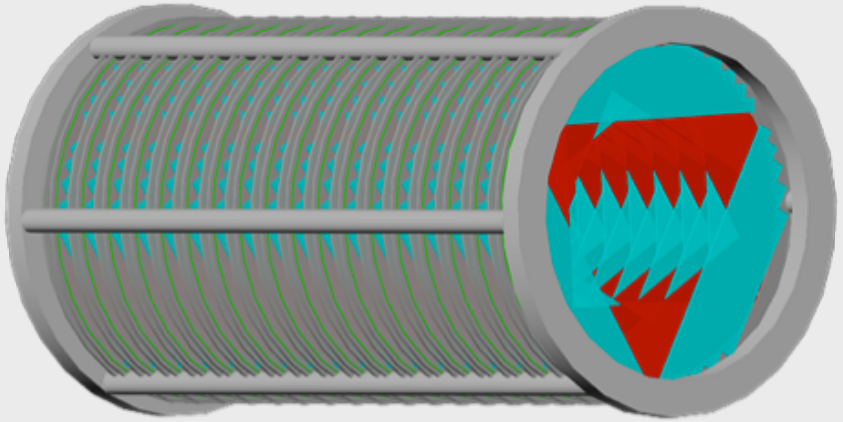
T-Tracker Details

- This “windowframe” is repeated, rotated each time
- Just know which straw is hit
  - Makes PR complicated!
- Using time division~ 8 cm σ to give (r,ϕ) and seed KF
  - very successful!



typical track sees ~0.25 X_0





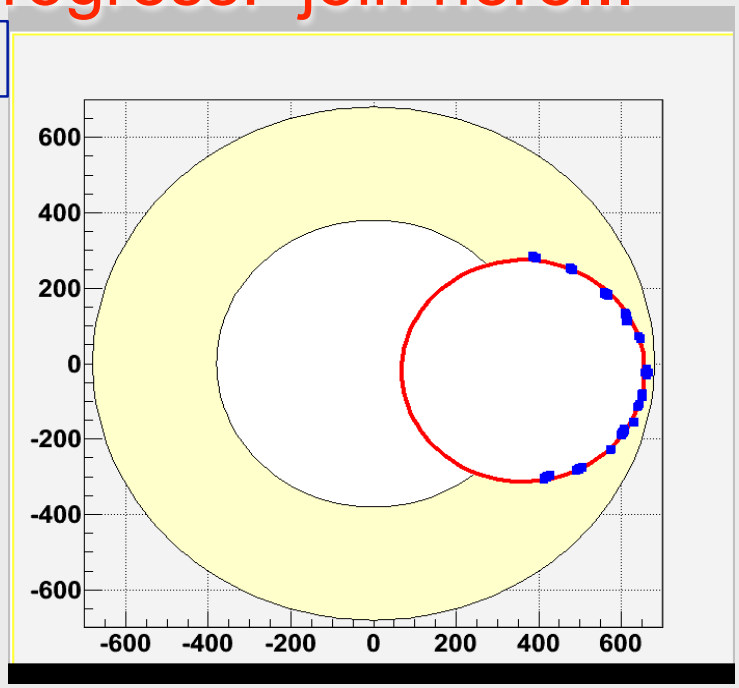
entire system in vacuum < 10^{-4} torr

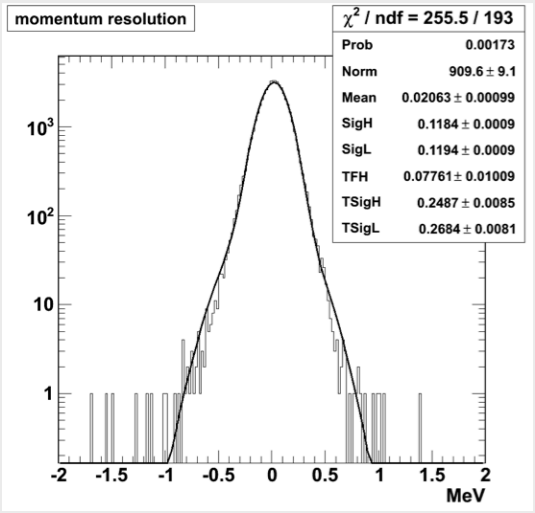
Pattern Recognition and Tracking

- Unified simulation from protons on target to end of detector in GEANT4
- Pattern Recognition Program joined to BaBar Kalman Filter
  - No sign of significant mis-reconstruction background with realistic rates from all known sources

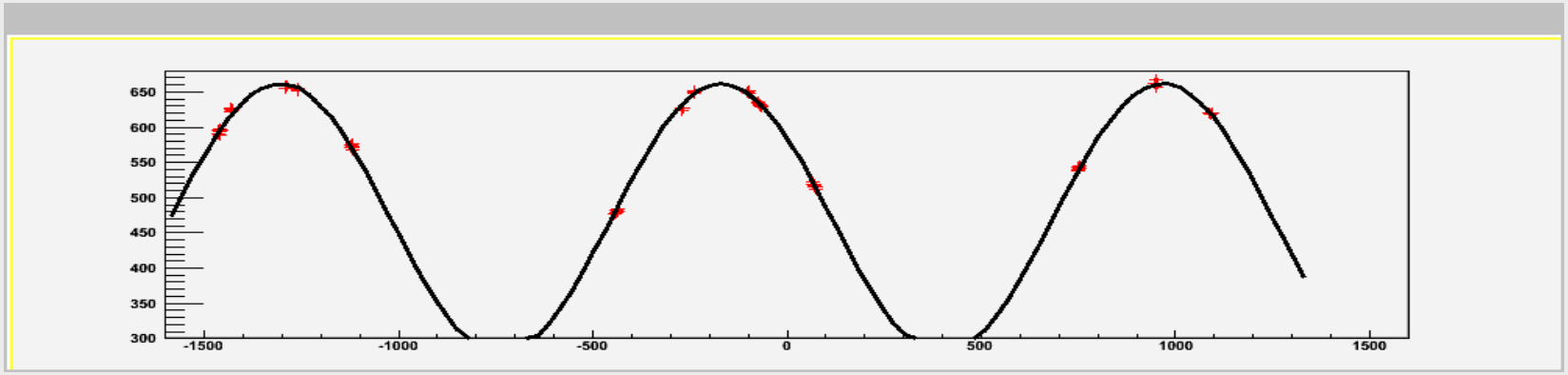
work in progress! join here...

X-Y View



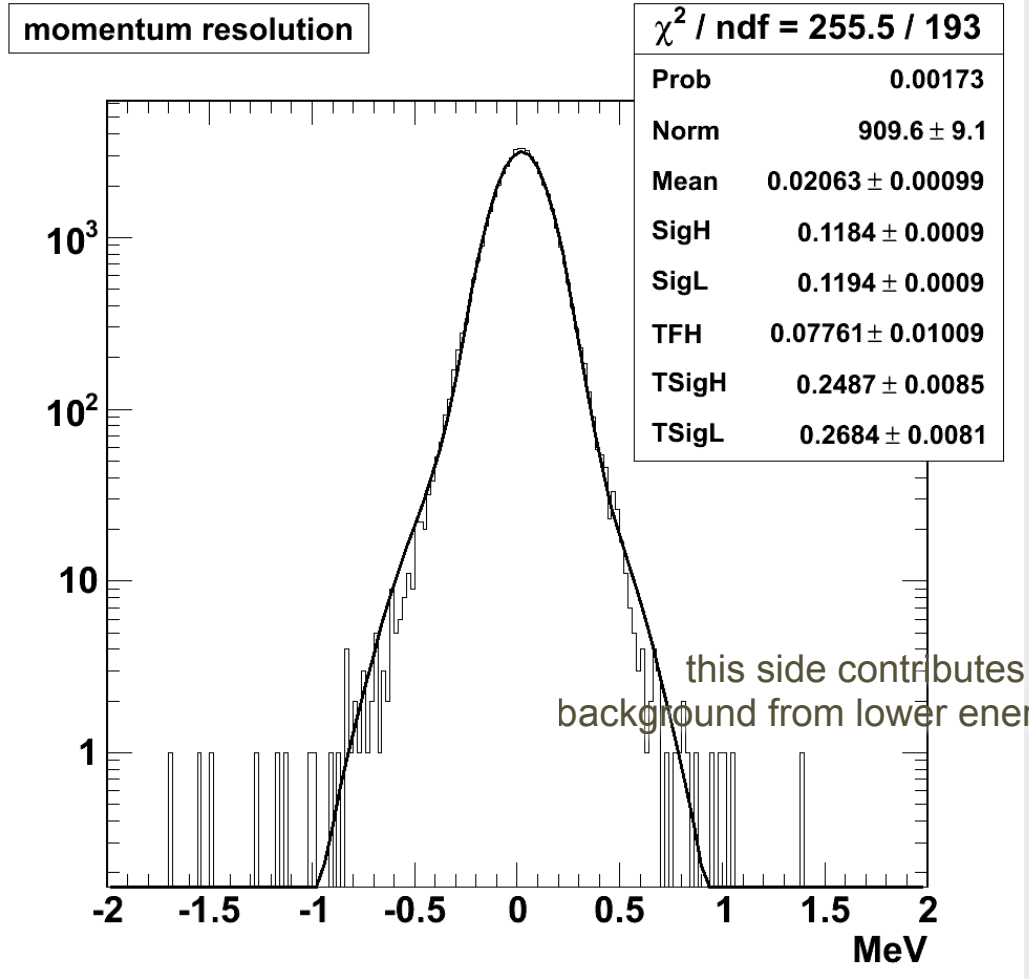


R-Z view



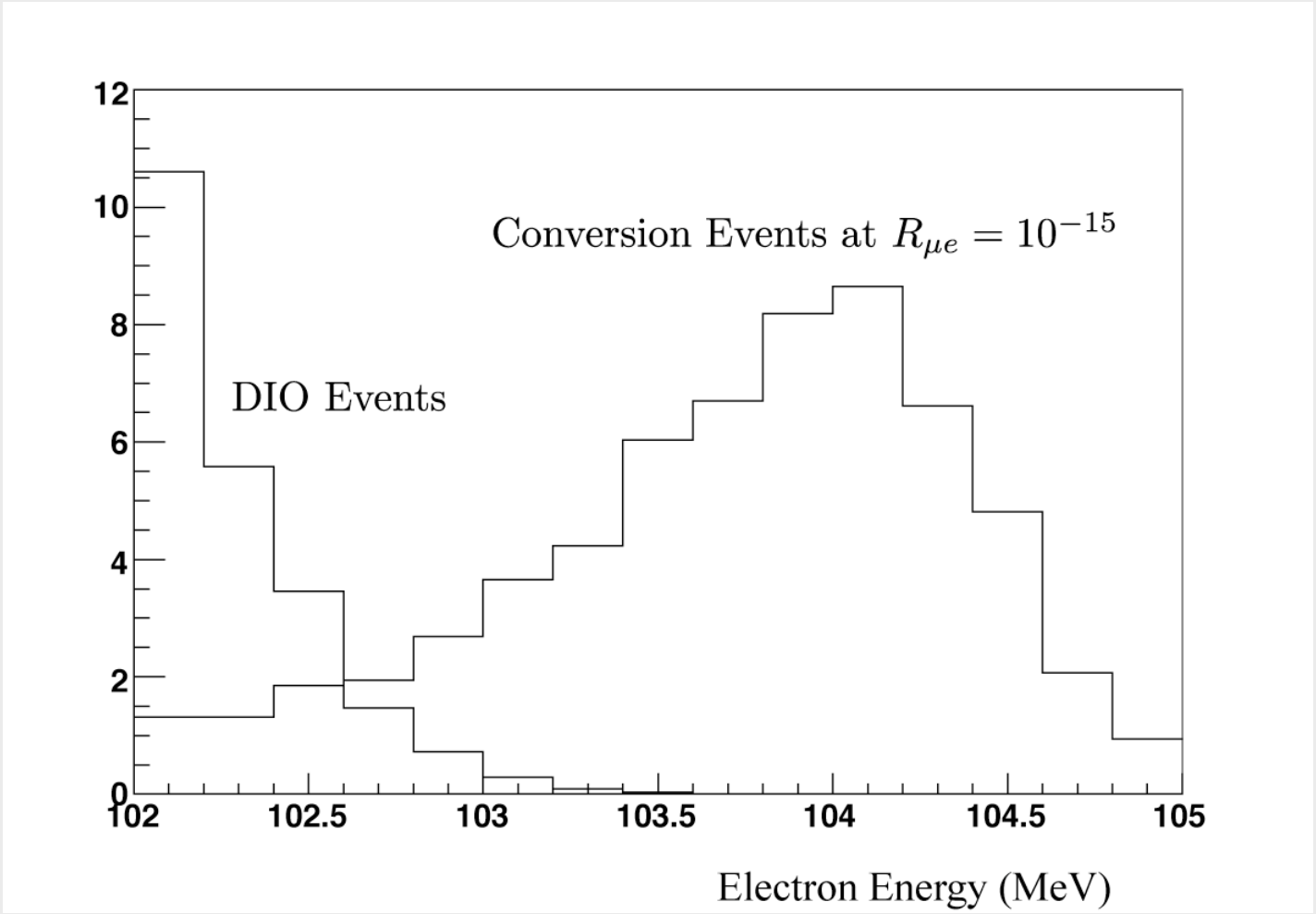
Understanding Resolution

- Measure resolution/ check acceptance:
  - special runs varying target foils, field, location of stopping target
  - Use $\pi^+ \rightarrow e\nu$ decay: monochromatic line at ~70 MeV
  - Gaussian part yield ~ .035 DIO smeared upwards



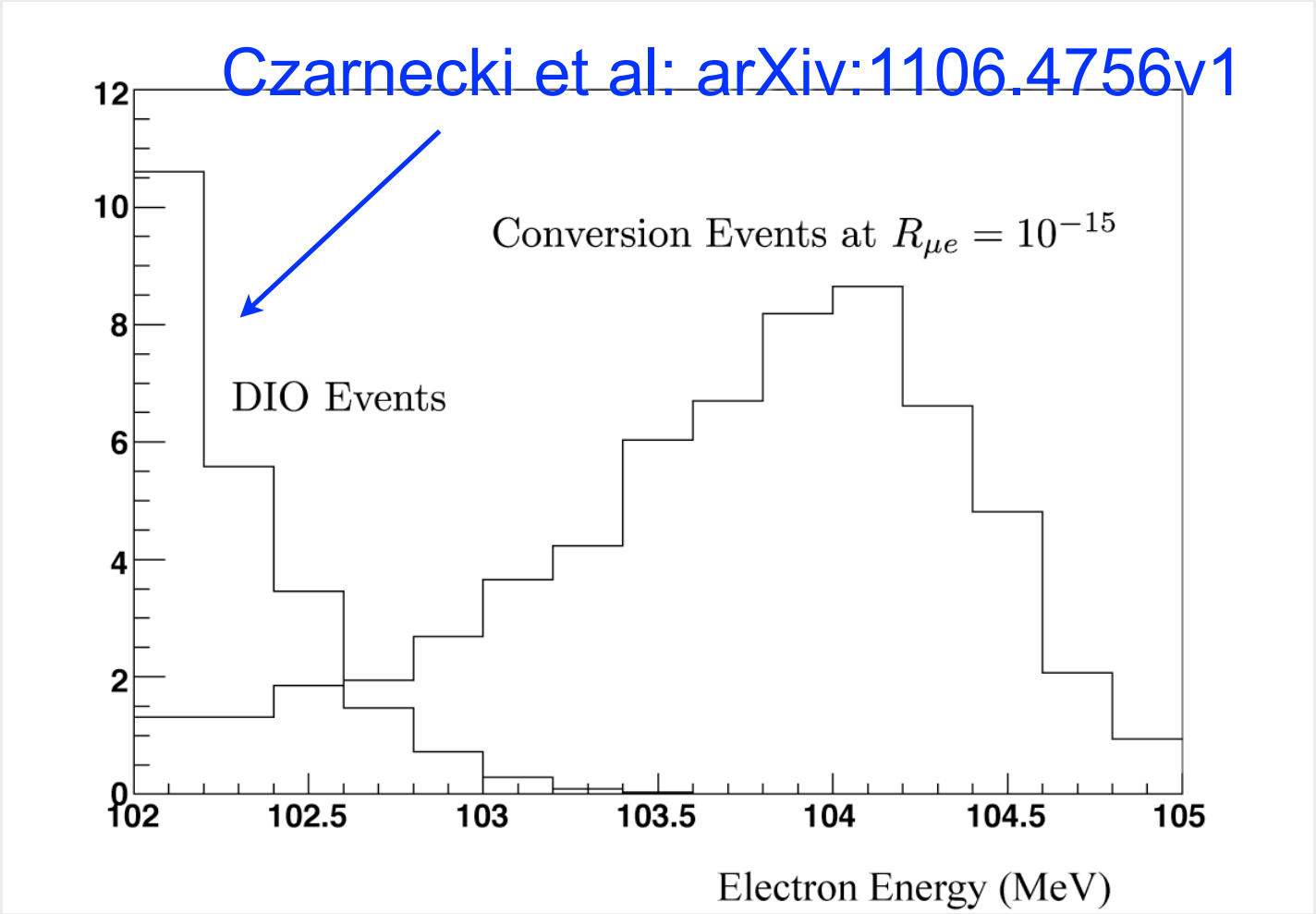
core: 92% 120 keV/c
tail: 8% 250 keV/c

Signal and Background



energy loss in stopping target and other material shifts electron down to ~104 MeV

Signal and Background



energy loss in stopping target and other material shifts electron down to ~104 MeV

Final Backgrounds

- For $R_{\mu e} = 10^{-15}$
  ~40 events / 0.18 bkg
  (LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
  ~4 events / 0.18 bkg

Source	Size	Error (not symmetric)
RPC ($\bar{p}$-induced)	0.06	± 0.060
RPC (π-induced)	0.04	± 0.020
CR	0.025	± 0.025
DIO	0.035	± 0.018
μ induced in-flight	0.01	± 0.0005
π induced in-flight	0.003	± 0.0015
Scattered e^-	0.0006	± 0.0003
Radiative μ Capture	$< 2 \times 10^{-6}$	—
TOTAL	**0.18**	$\pm$ **0.08**

Outline

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

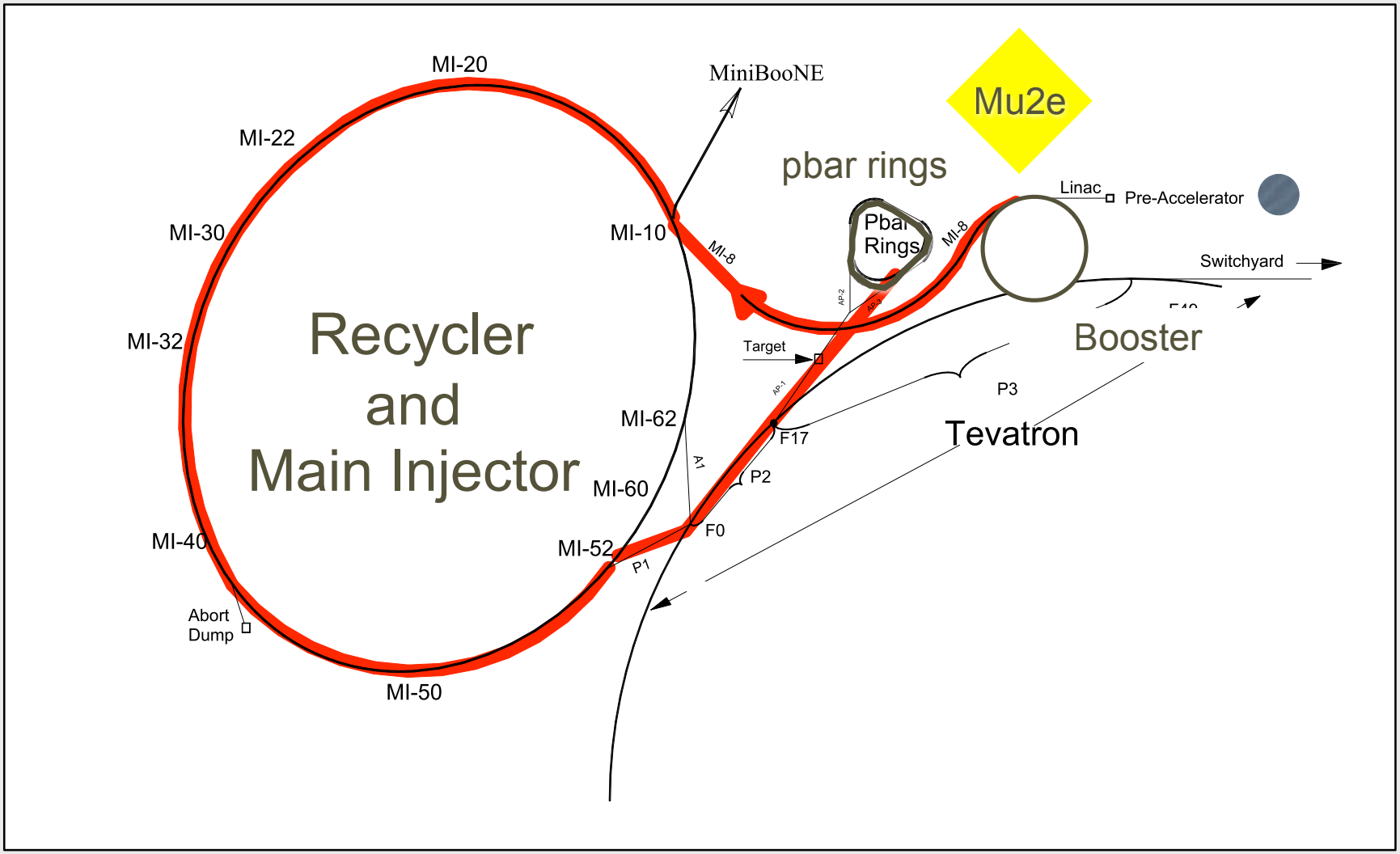
FNAL Beam Delivery

- FNAL has unique, major strength:

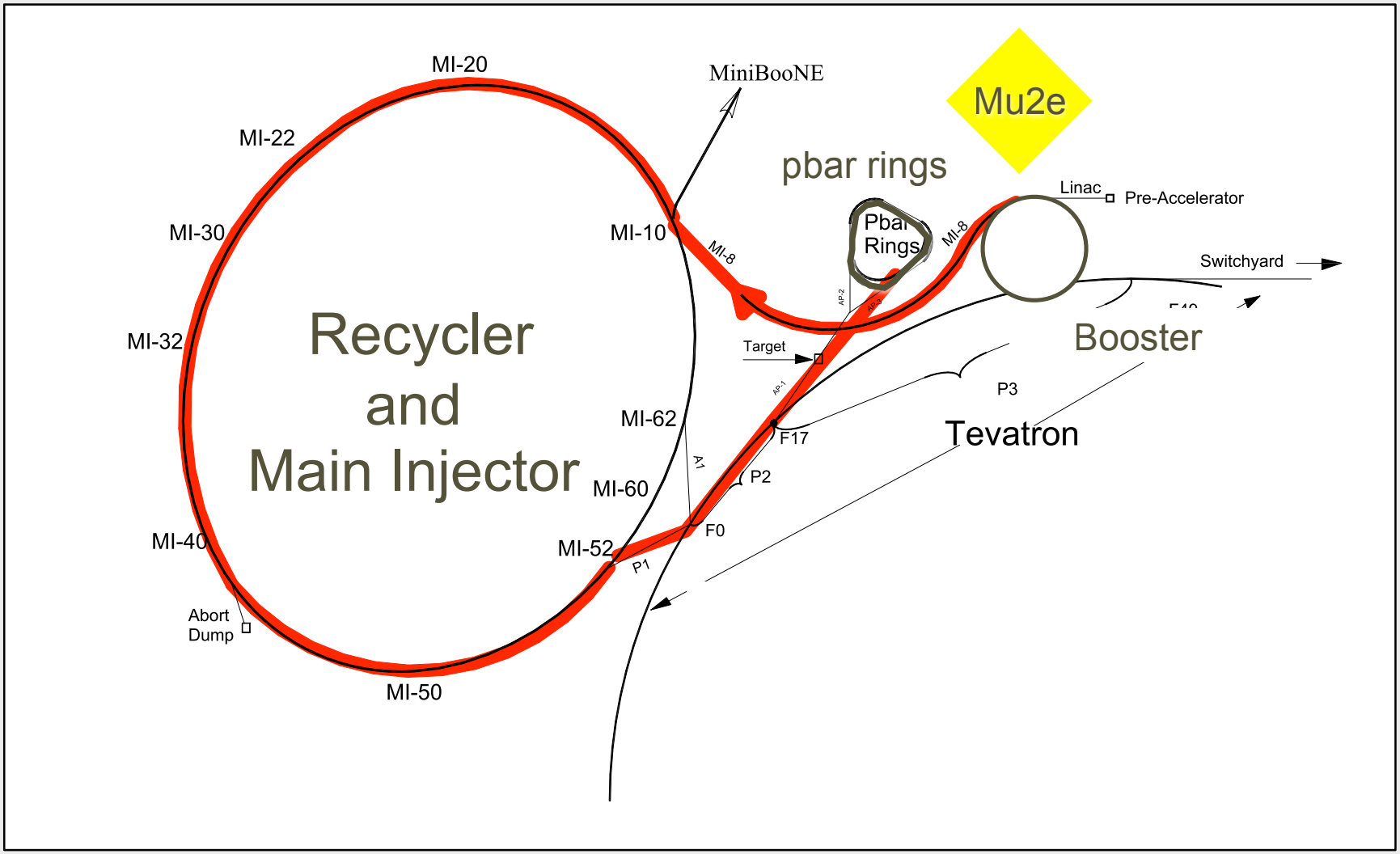
  Multiple Rings

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

“Boomerang” Scheme



“Boomerang” Scheme



And on the Civil Construction

Figure 2 –Site Photo Indicating Location of Proposed mu2e Conventional

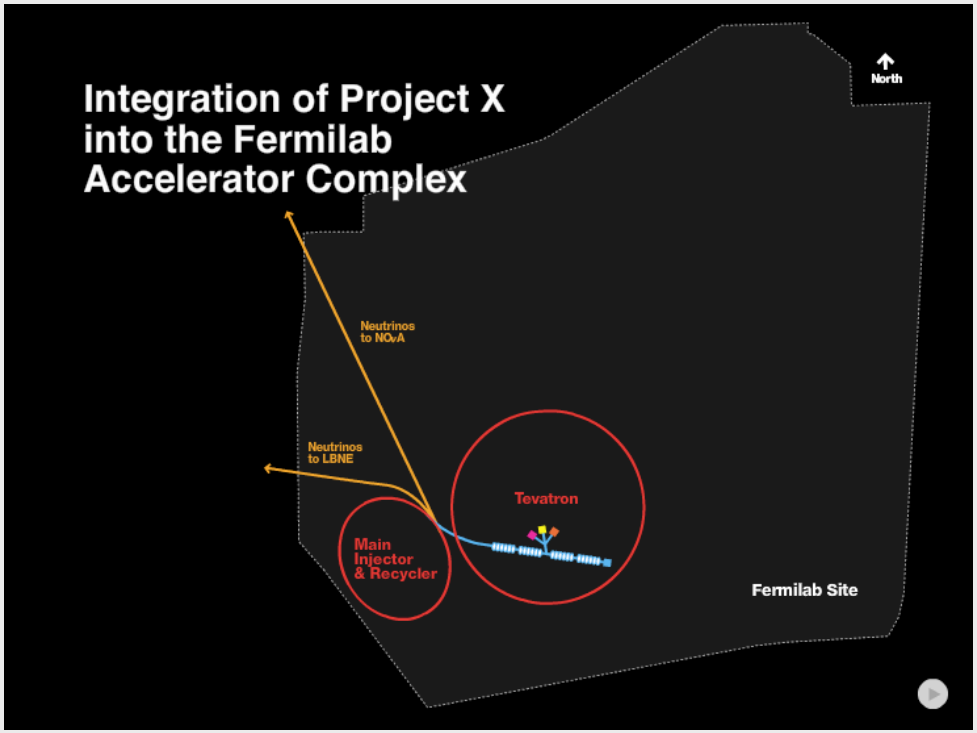
And on the Civil Construction

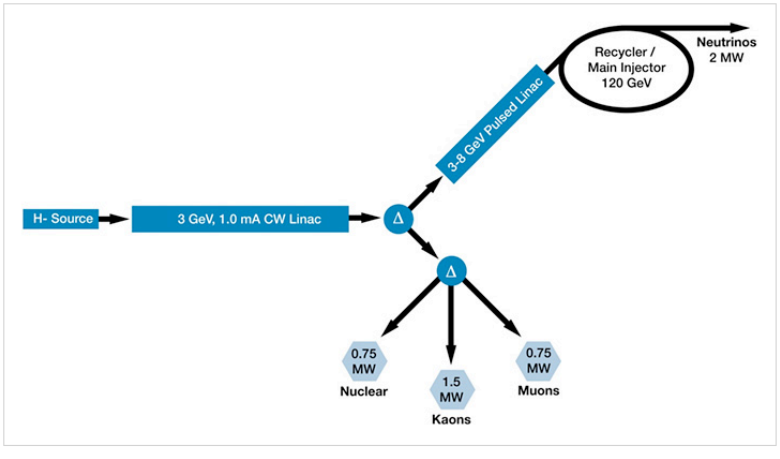
Outline

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

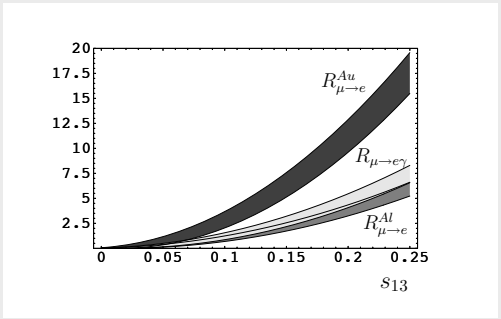
Upgrades at Project X

- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- Can drive next generation experiments in intensity frontier physics: rare processes, neutrinos
- Potential to upgrade Mu2e by *x100*
  - *study new physics*
  - *set stronger limit*





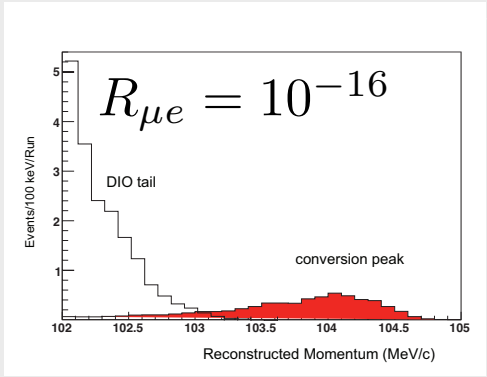
Upgrade Plans...



Signal?

Yes

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

Upgrade Issues

- To go to higher Z, we need to look at shorter lifetimes (e.g. Au, ~73 nsec) but would then be swamped by Radiative Pion Capture.
- So how do we make a beam with all the pions gone? Basically make beam circulate until pions disappear.
- Would also be very good to reduce momentum spread so we can stop muons in a better-defined location (think surface beam)
  - *FFAG(PRISM/PRIME)*
  - *Helical Cooling Channel*
  - *Other?*
- There is a lot of overlap with muon collider/neutrino factory world and much work has been done (see, for example, NuFact conference series)

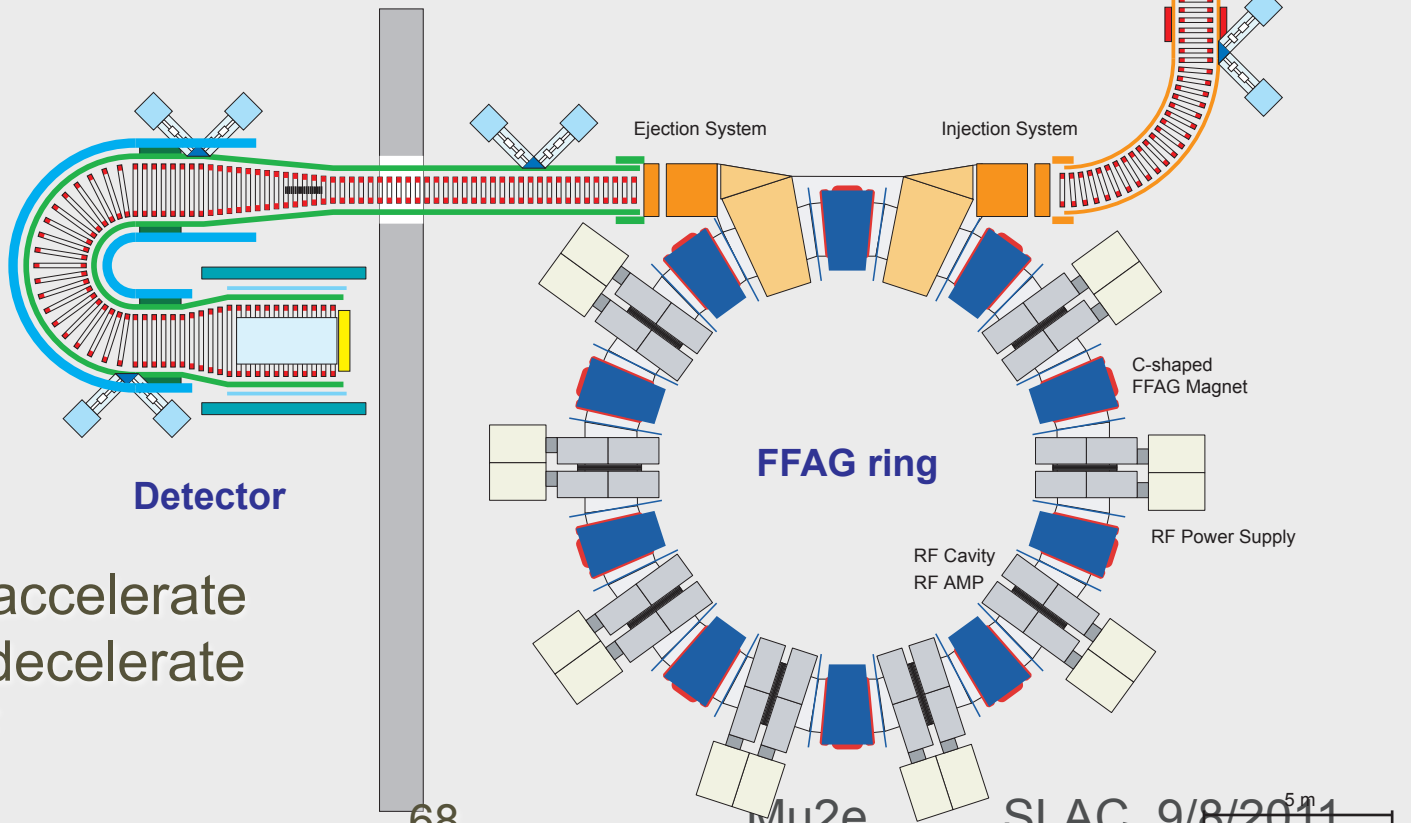
FFAG

PRISM=Phase Rotated Intense Slow Muon source

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- muon intensity: 10^{11}~10^{12} /sec
- central momentum: 68 MeV/c
- narrow momentum width by phase rotation
- pion contamination : 10^{-20} for 150m

From Yoshi Kuno



Phase rotation = accelerate slow muons and decelerate fast muons by RF

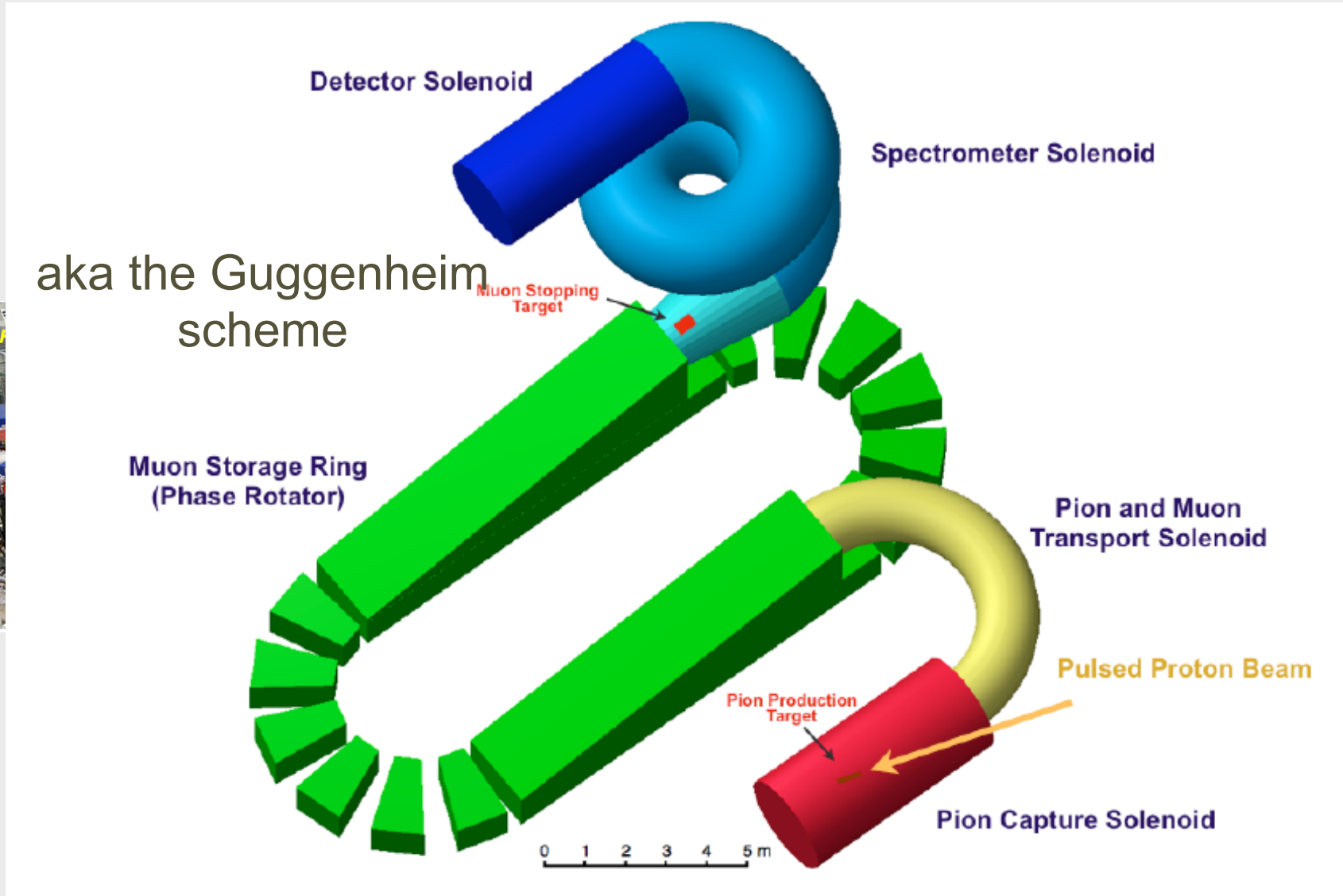
FFAG

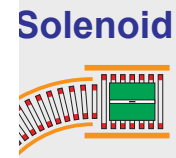
PRISM=Phase Rotated Intense Slow Muon source

$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$

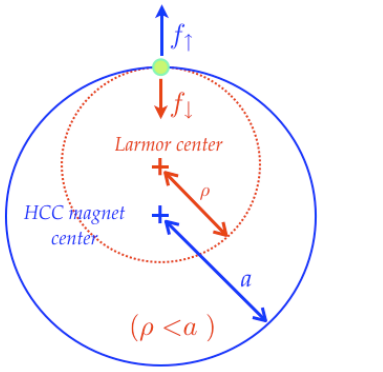
-
-
-
-

aka the Guggenheim scheme

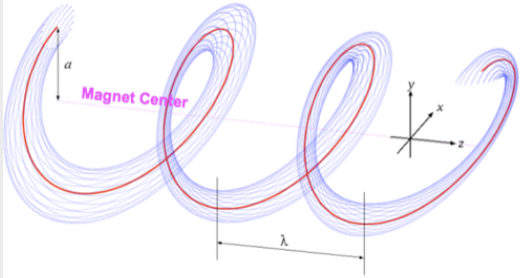




Helical Cooling Channel



Projectile in transverse (x-y) plane



Particle motion in helical magnet

Larmor motion in pure solenoid

$$f_\downarrow = -\frac{e}{m_\mu} p_\varphi \cdot b_z$$
$$\rho = \frac{p_\varphi}{b_z}$$

Radial equation of motion with helical dipole

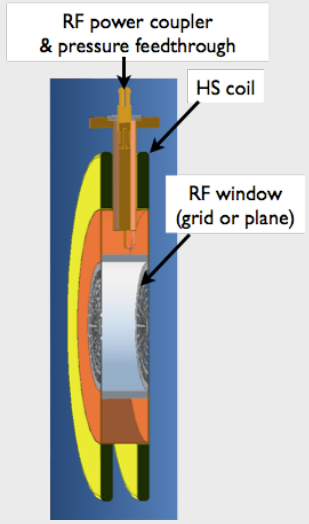
$$f = f_\uparrow + f_\downarrow$$
$$= \frac{e}{m_\mu}(p_z b_\varphi - p_\varphi b_z)$$

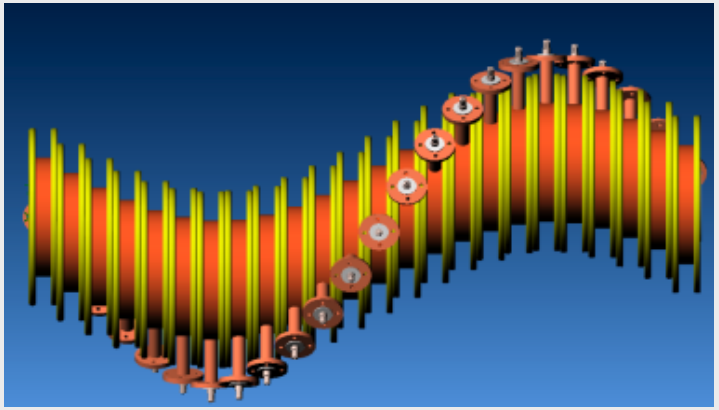
$k = \frac{2\pi}{\lambda}$ HCC wavenumber

$\kappa = ka = \frac{p_\perp}{p_z}$ HCC pitch

Equation of motion for reference particle

$$p(a) = \frac{\sqrt{1+\kappa^2}}{k}\left(b_z - \frac{1+\kappa^2}{\kappa} b_\varphi\right)$$





Bullet Points

- Physics Motivations are clear with or without a signal, and we expect this will be a flagship Project X experiment
- Every upgrade scheme has significant technical problems, both in the detector technology and the muon beam formation
- The best way to go is to join Mu2e to learn about the issues and use knowledge and experience to design upgrades of the experiment from the proton beam on

Conclusions

- Mu2e will 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 and*
  - *Provide important information either complementing LHC results or probing up to 10^4 TeV mass scales*
- With upgrades, we could extend the limit by up to two orders of magnitude or 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?