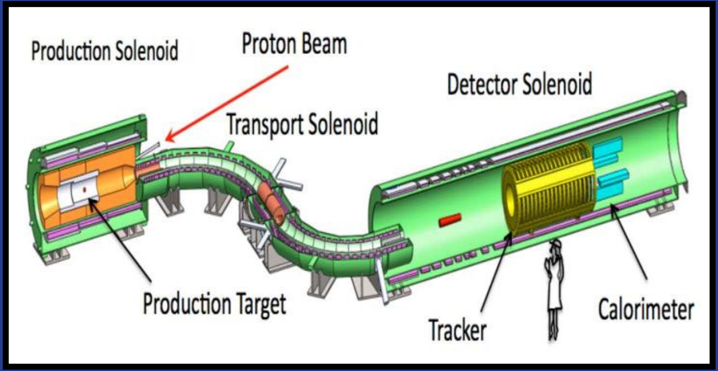
The Mu2e Experiment at Fermilab



Xth International Conference on Hyperons, Charm and Beauty Hadrons

Wichita, KS USA

Andrew Norman, Fermilab

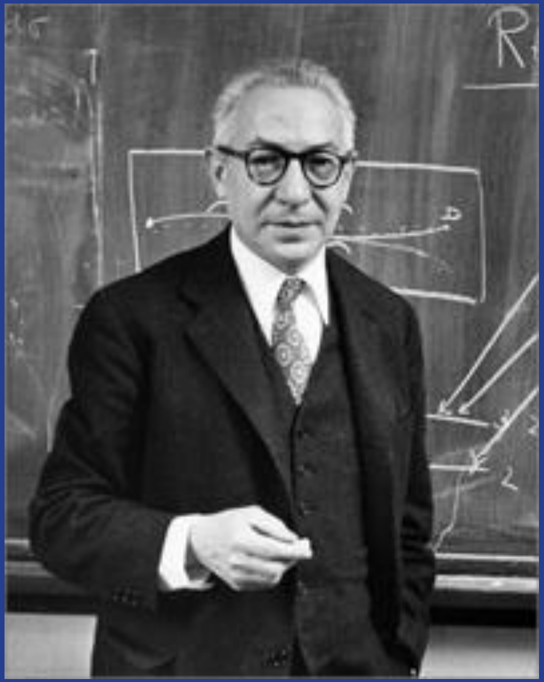
For the Mu2e Collaboration

U.S. DEPARTMENT OF ENERGY

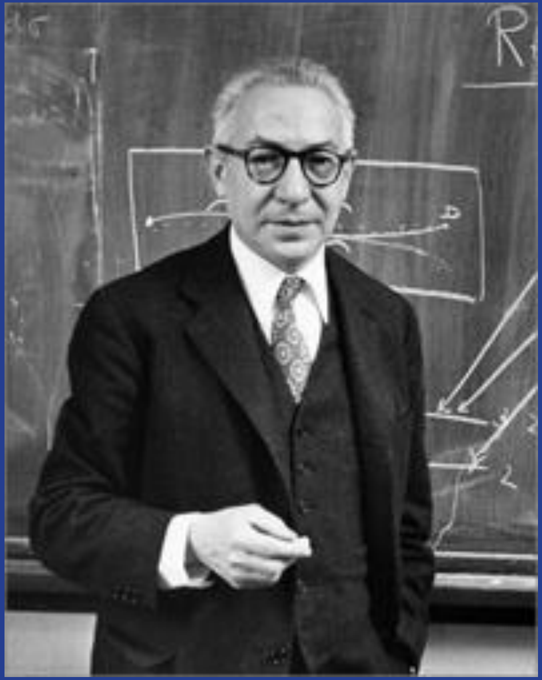
Fermilab

A muon talk at a heavy flavor conference?

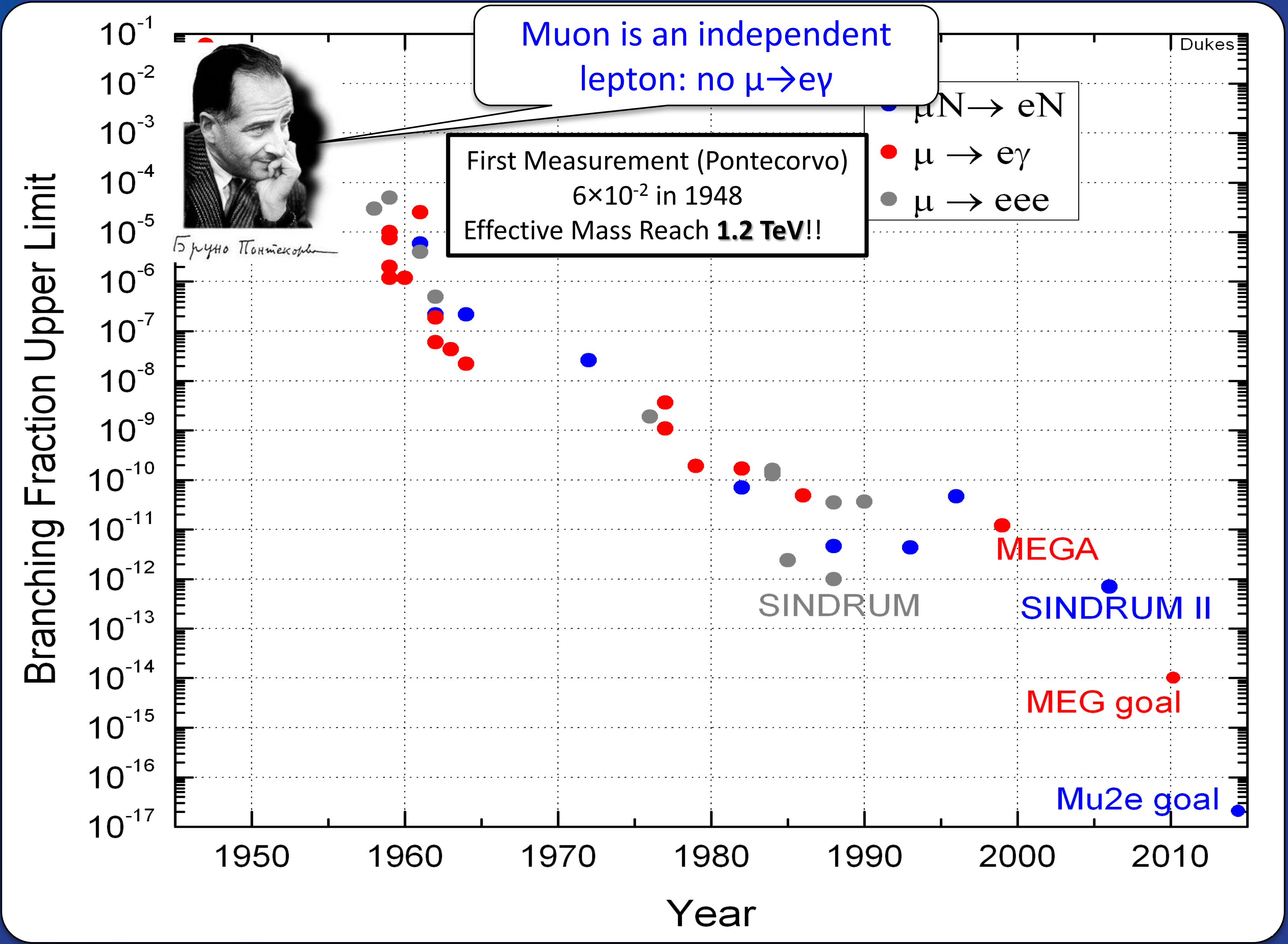
"Who ordered that?"
—I.I.Rabi

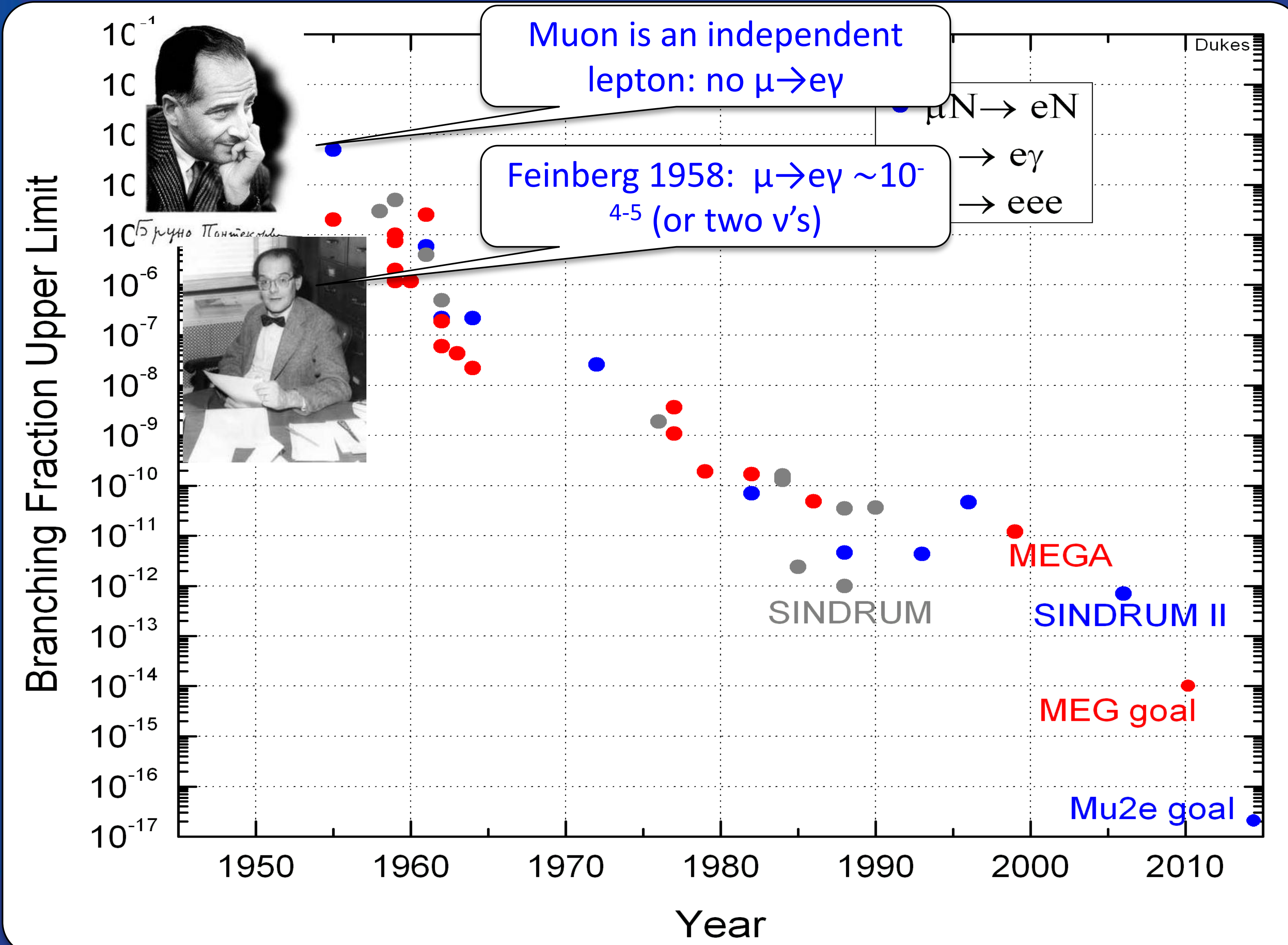


“Who ordered that?”



- When the μ was discovered it was logical to think of the μ as just an excited electron
  - So we would expect:
    - BR($\mu \rightarrow e\gamma$)≈10^{-4}
  - That is, unless another ν, in an intermediate vector boson loop canceled it out. (Feinberg, 1958)
  - Same as GIM mechanism!
- Introduced the notion of lepton flavor


Muon is an independent lepton: no μ→eγ
First Measurement (Pontecorvo)
6×10-2 in 1948
Effective Mass Reach **1.2 TeV**!!
μN→ eN
μ → eγ
μ → eee
Dukes
Branching Fraction Upper Limit
Year
SINDRUM
MEGA
SINDRUM II
MEG goal
Mu2e goal
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
10-16
10-17
1950
1960
1970
1980
1990
2000
2010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μN→ eN
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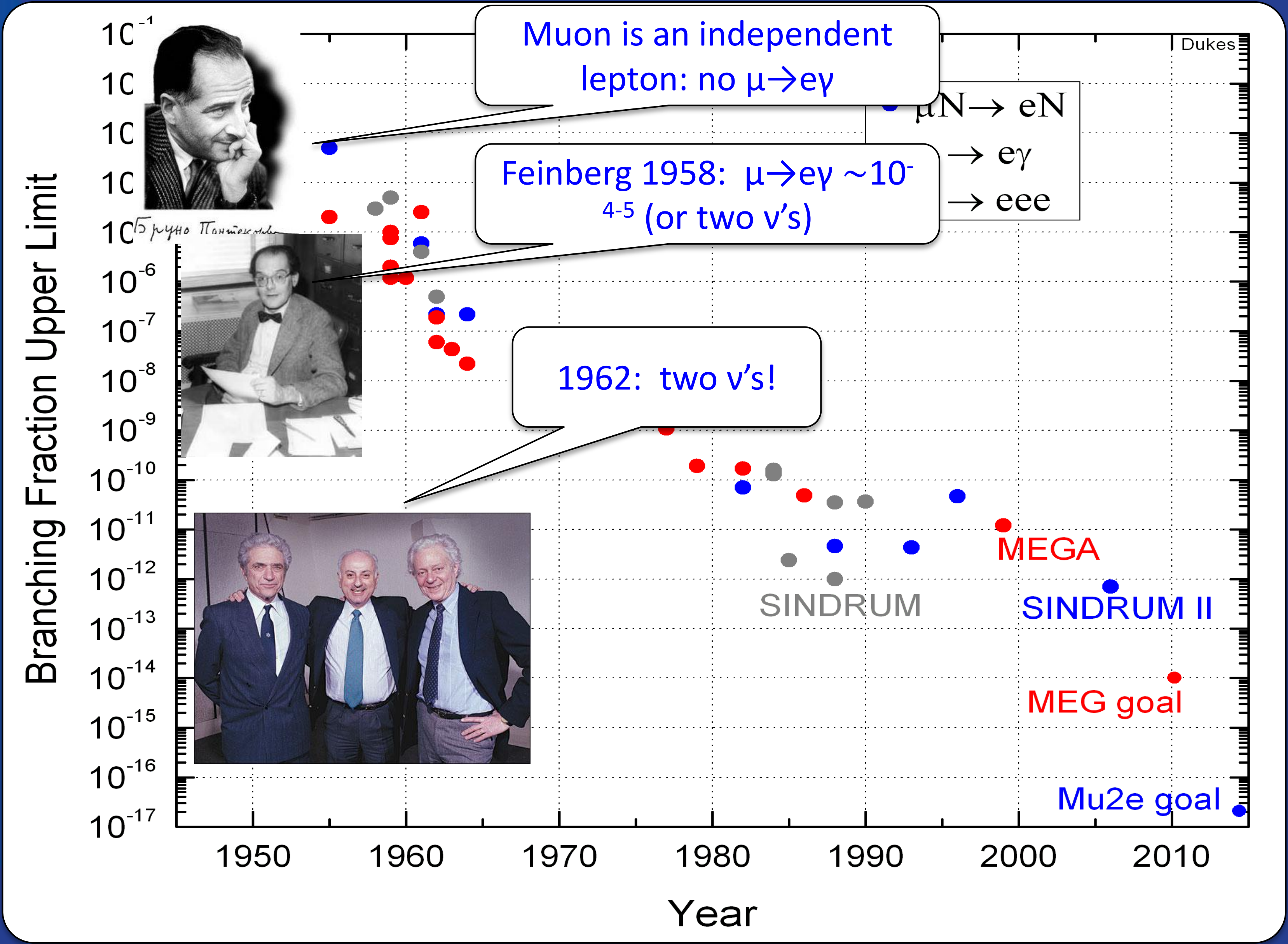

Muon is an independent lepton: no μ→eγ
Feinberg 1958: μ→eγ ~10-4-5 (or two ν's)
1962: two ν's!
μN→ eN
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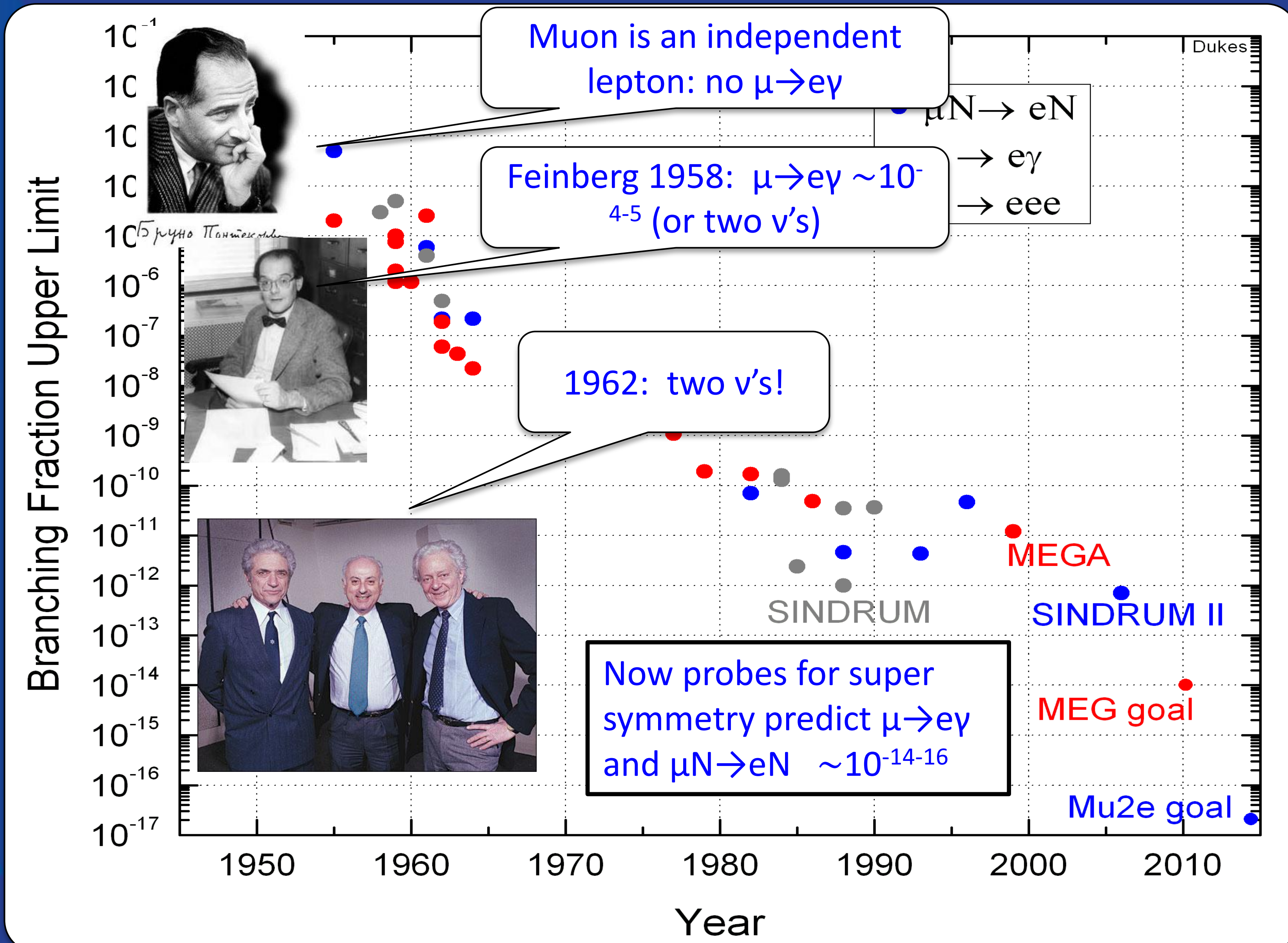
Muon is an independent lepton: no μ→eγ
Feinberg 1958: μ→eγ ~10-4-5 (or two ν's)
1962: two ν's!
Now probes for super symmetry predict μ→eγ and μN→eN ~10-14-16
μN→ eN
→ eγ
→ eee
Dukes
MEGA
SINDRUM
SINDRUM II
MEG goal
Mu2e goal
Branching Fraction Upper Limit
Year
1950
1960
1970
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10-6
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10-8
10-9
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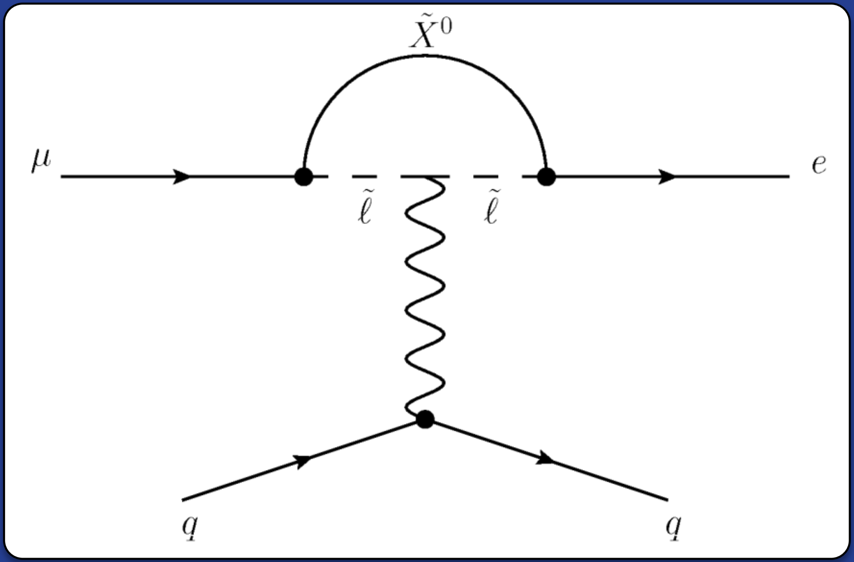
10-11
10-12
10-13
10-14
10-15
10-16
10-17

Why Precision Measurements & Ultra-Rare Processes?

- We want to access physics beyond the standard model
  - This means access to High and Ultra-High Energy interactions
  - We get to these energies through loops
  - Getting at Loops means making precision measurements and looking for ultra-rare decays
- Ideally we start with processes that are forbidden or highly suppressed in the standard model
  - Any observation becomes proof of non-SM physics



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- Flavor Changing Neutral Currents
  - FCNC in quark sector
    - $B_s \rightarrow \mu\mu$, $b \rightarrow s\gamma$, $K \rightarrow \pi\nu\nu$
    - Allowed but HIGHLY suppressed in Standard Model
    - Can receive LARGE enhancements in SUSY and other beyond-SM physics
  - FCNC in charged lepton sector
    - $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu N \rightarrow e N$ (Lepton Flavor Violating)
    - No SM amplitudes (except via ν loops)
    - Permitted in beyond-SM models, and have extreme reach in energy

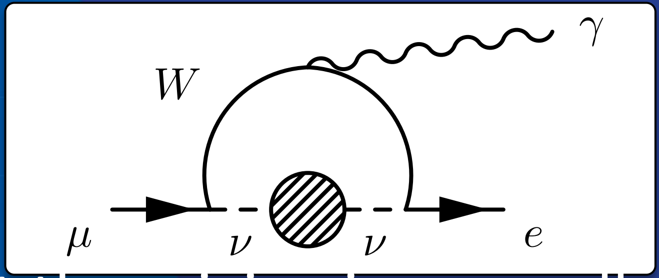
Lepton Mixing in the Standard Model

- We have three generations of leptons:

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

No SM couplings between generation!

- In the standard model Lagrangian there is no coupling to mixing between generations
- But we have explicitly observed *neutrino oscillations*
- *Thus charged lepton flavor is **not** conserved.*
- Charged leptons must mix through neutrino loops



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W} \right|^2$$

$$\leq 10^{-54}$$

- But the mixing is so small, it's effectively forbidden

Charged Lepton Flavor Violation (CLFV) Processes with μ's

- There are three basic channels to search for μ-CLFV in:

$$\mu^+ \to e^+\gamma$$

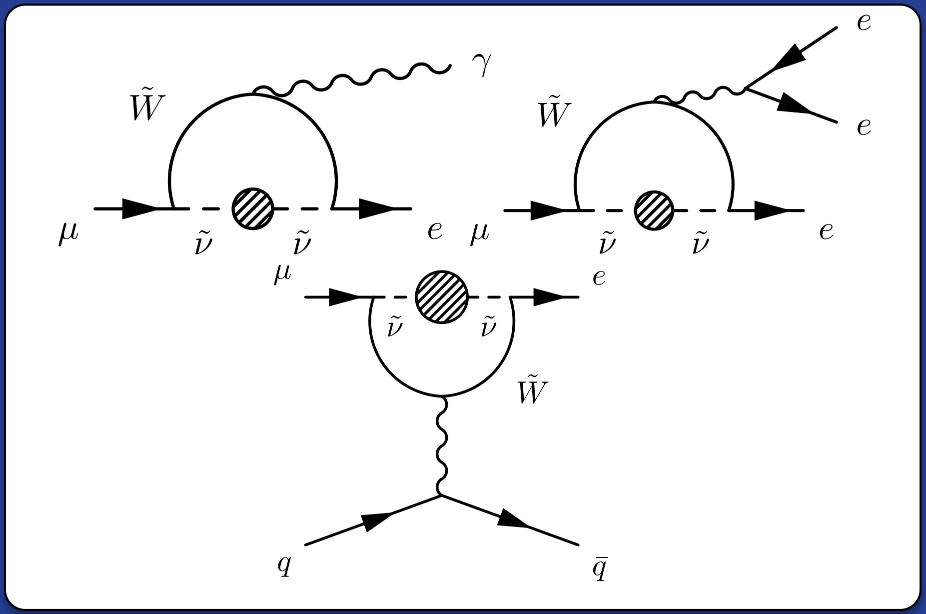
$$\mu^+ \to e^+e^+e^-$$

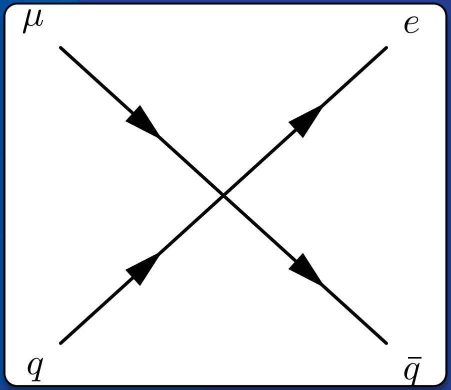
$$\mu^- N \to e^- N$$

- If loop like interactions dominate we expect a ratio of these rates:

  ≈ 400 to 2 to 1

- New physics for these channels can come from loop level





- For μN→eN and μ→eee we also can have contact terms

If contact terms dominate then μN→eN can have rates 200 times that of μ→eγ

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  ≈ 400 to 2 to 1

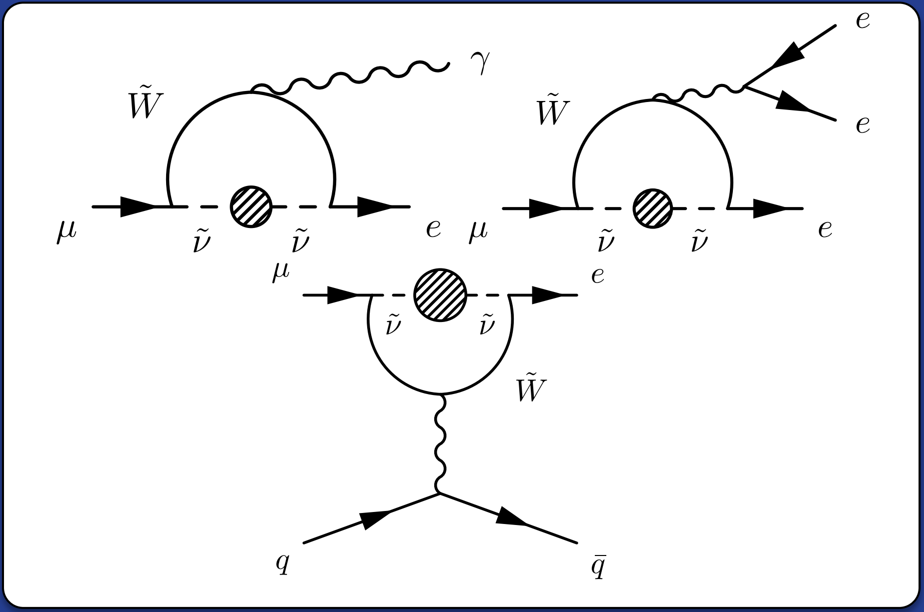
Note: μ→eγ and μ→eee have *experimental* limitations (resolution, overlap, accidentals)

Ultimately Limits the measurement of:

$Br(\mu \to e\gamma) \approx 10^{-14}$

No such limits on μN→eN channel

- New physics for these channels can come from loop level



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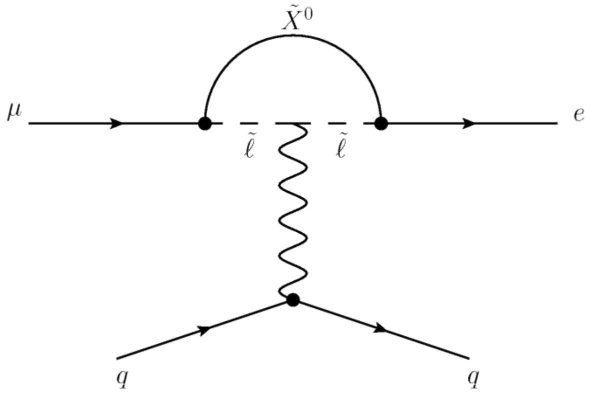
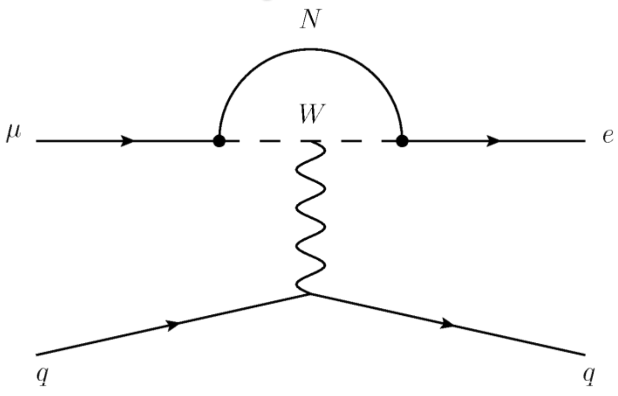
Beyond the Standard Model

- The CLFV process can manifest in the μN→eN channel in many models with large branching fractions:

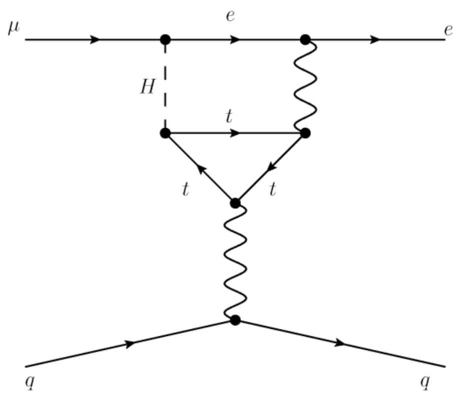
Loops



SUSY



Heavy Neutrinos

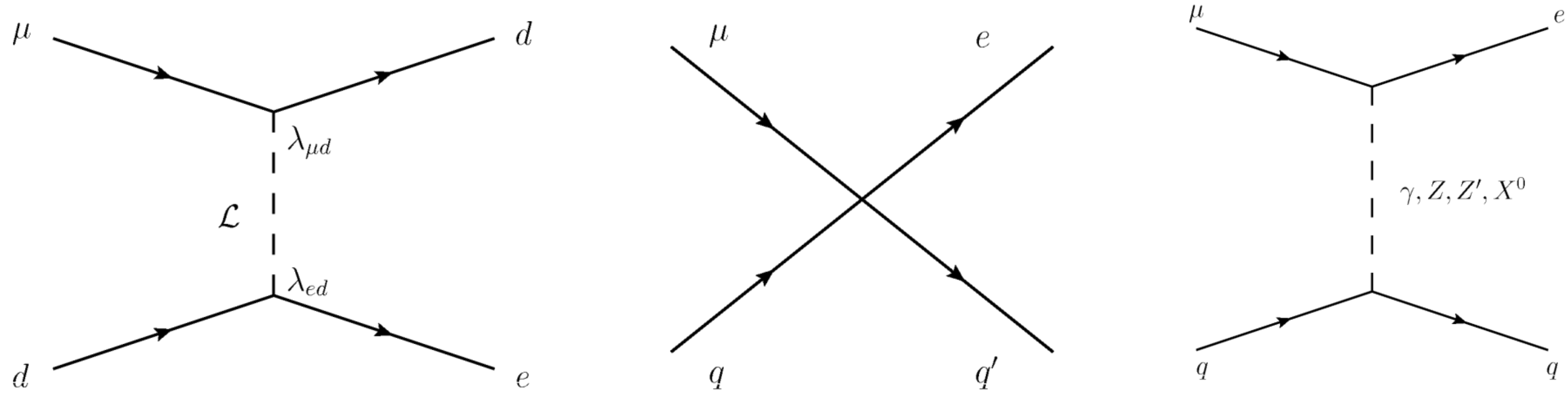


Second Higgs Doublet

Beyond the Standard Model

- The CLFV process can manifest in the μN→eN channel in many models with large branching fractions:

Contact Terms



Leptoquarks

Compositeness

Anomalous Heavy Couplings

General CLFV Lagrangian

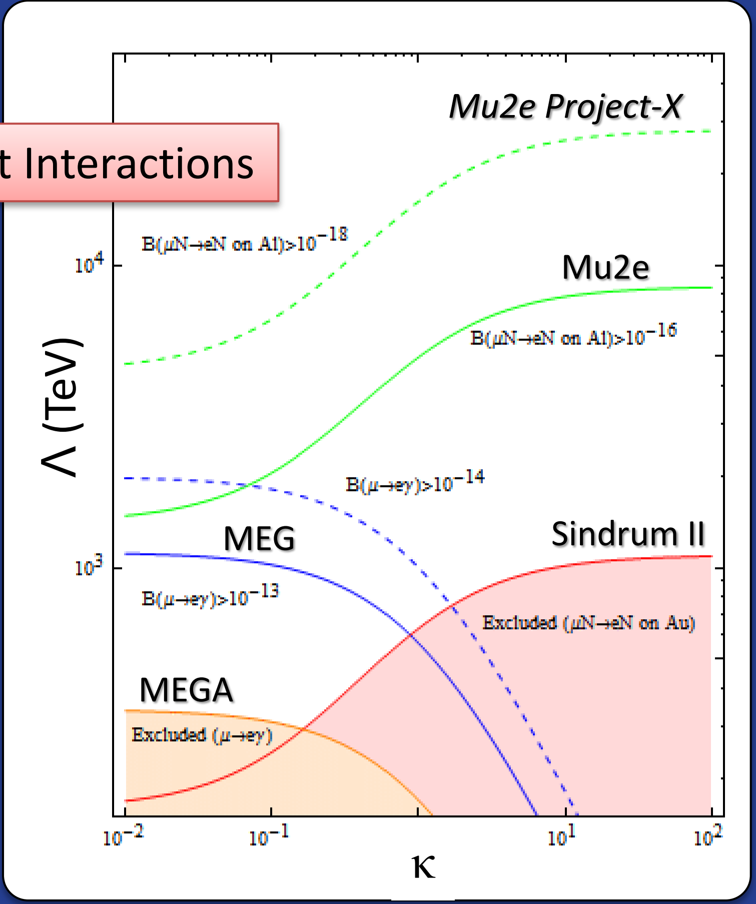
- Recharacterize these all these interactions together in a model independent framework:

Loops

Contact Interactions

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

  - Splits CLFV sensitivity into
    - Loop terms
    - Contact terms
  - Shows dipole, vector and scalar interactions
  - Allows us to parameterize the effective mass scale ¤ in terms of the dominant interactions
  - The balance in effective reach shifts between favoring ¹N!eN and ¹!e° measurements .
  - For contact term dominated interaction (large κ) the sensitivity in Λ, reaches upwards of 10^4 TeV for the coherent conversion process



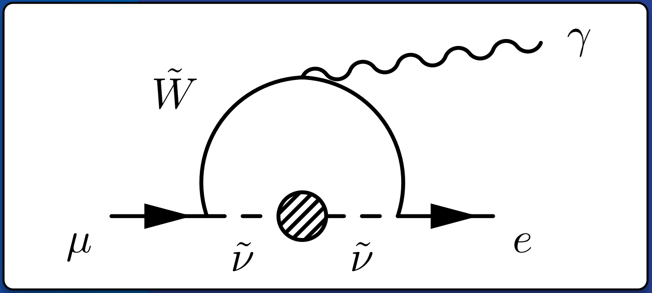
Experimental Limits vs. SU(5) SUSY-GUT

SUSY predictions for CLFV processes are only a few orders of magnitude below current experimental limits

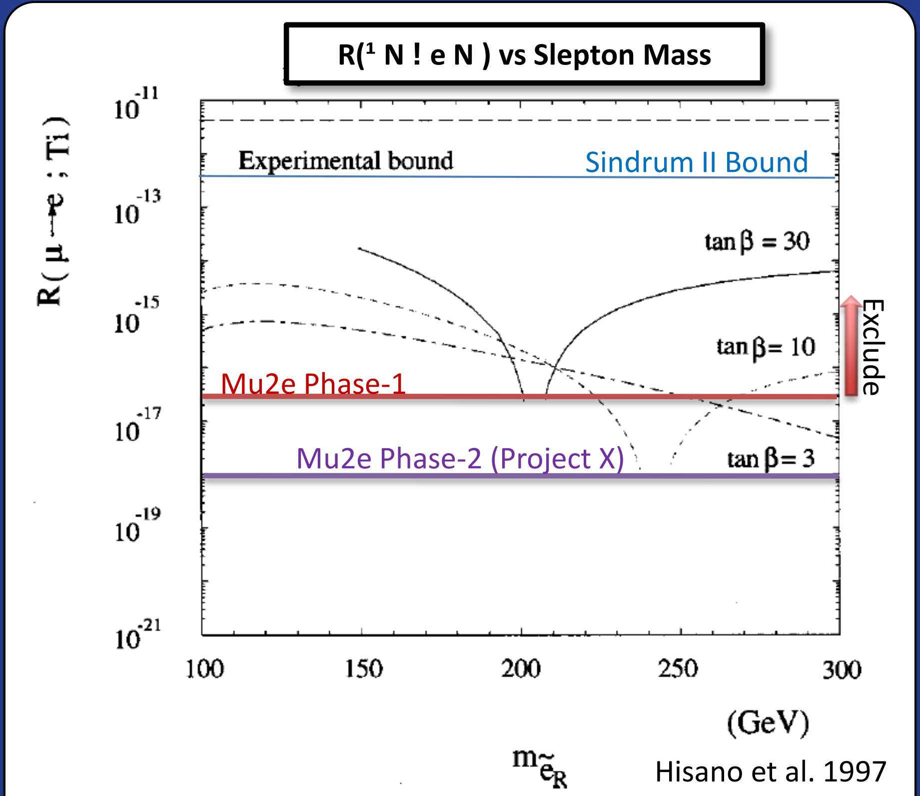
Process	Current Limit	SUSY-GUT level
$\mu N \rightarrow e N$	**7×10^{-13}** W. Bertl, et al EPJ C47(06)337	**10^{-16}**
$\mu \rightarrow e \gamma$	**2.4×10^{-12}** J. Adam, et al PRL 107(11)171801	**10^{-14}**
$\tau \rightarrow \mu \gamma$	**4.5×10^{-8}** K. Hayasaka, et al PL B666(08)16	**10^{-9}**

μN→eN Sensitivity to SUSY

- Rates are not small because they are set by the SUSY mass scale



- For low energy SUSY like we would see at the LHC:
  Br(μN→eN) ~10^{-15}
- Makes μN→eN compelling, since for Mu2e this would mean observation of
  ≈O(40) events [0.5 bkg]



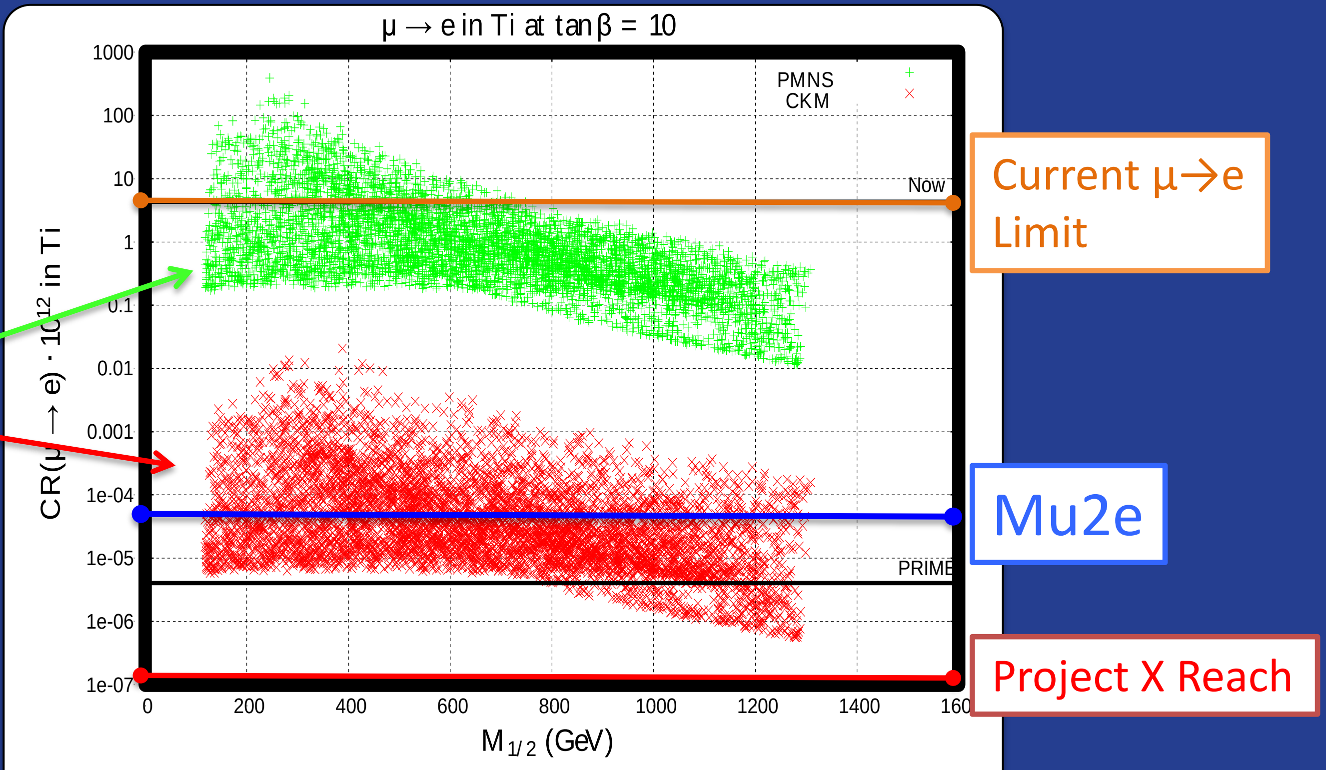
A $2x10^{-17}$ single event sensitivity, can exclude large portions of the available SUSY parameter spaces

Tests of SUSY Frameworks

μ→e measurement can distinguish between PMNS and MFV mixing structures in SUSY frameworks

Neutrino-Matrix Like (PMNS)

Minimal Flavor Like (CKM)



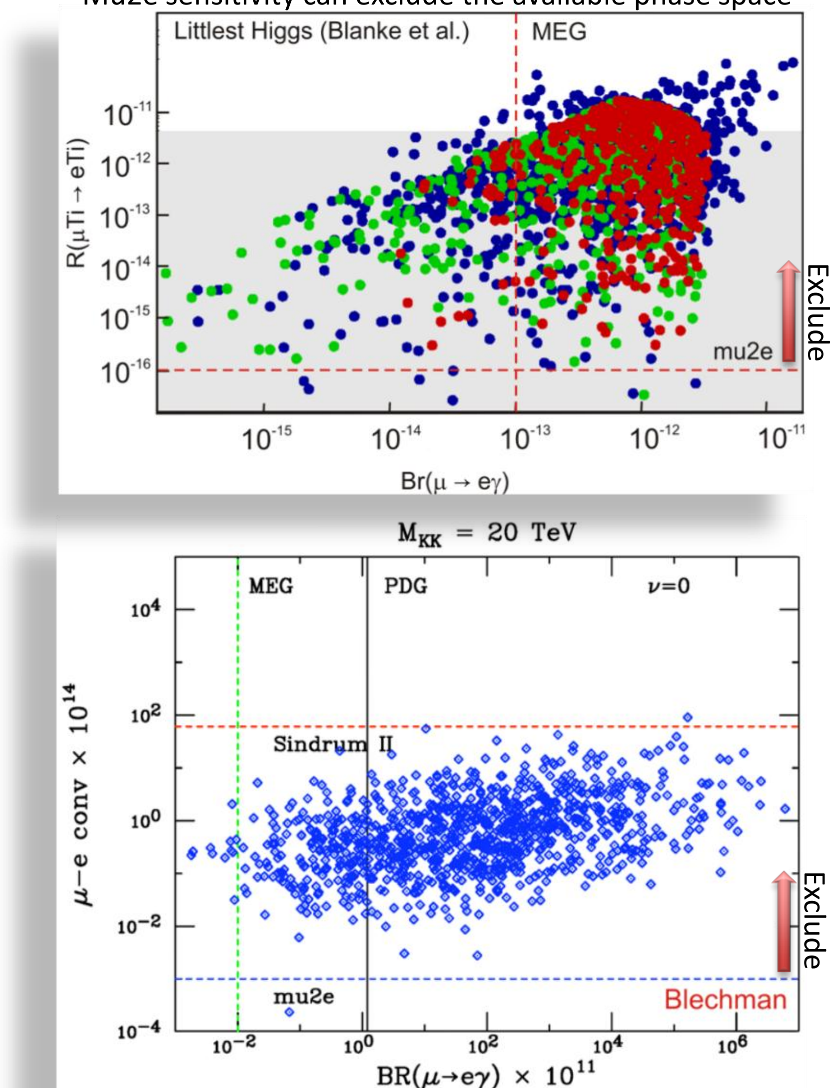
L.Calibbi, A.Faccia, A.Masiero Hep-ph/0605139

Example: neutrino masses via the seesaw mechanism, analysis is performed in an SO(10 framework). Different predictions for μe conversion with mixing structure.

μN→eN, μ→eγ, g-2 Work Together

- Knowing μN→eN , μ→eγ allow us to exclude SUSY phase space
- Also knowing the g-2 results allows us to then over constrain SUSY models
- In some cases this permits us to make strong, testable predictions for our models in terms of Br(μ→eγ) & R(μN→eN)

Mu2e sensitivity can exclude the available phase space



Randall-Sundrum

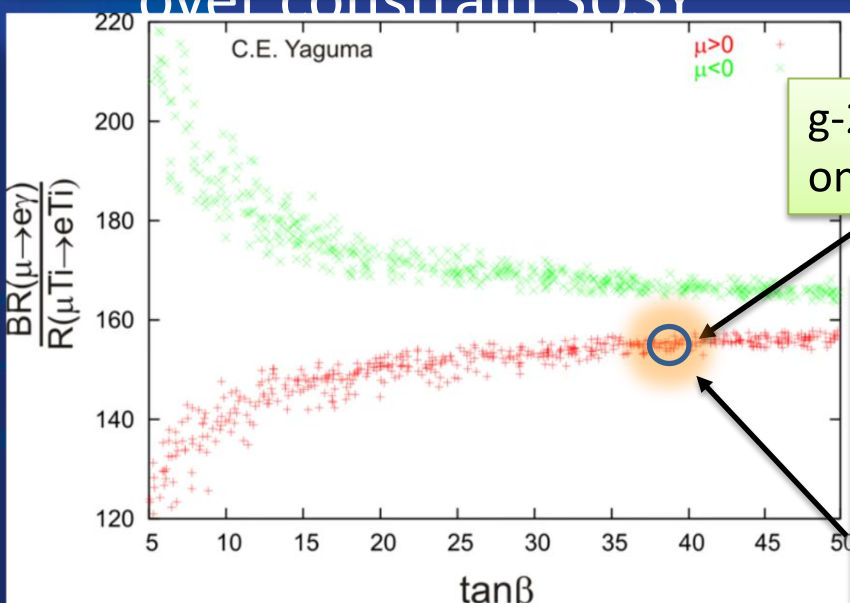
μN→eN, μ→eγ, g-2 Work Together

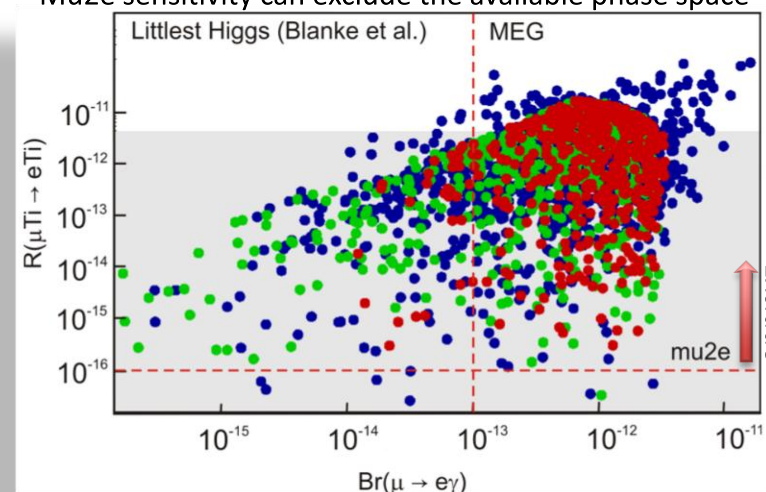
Example:

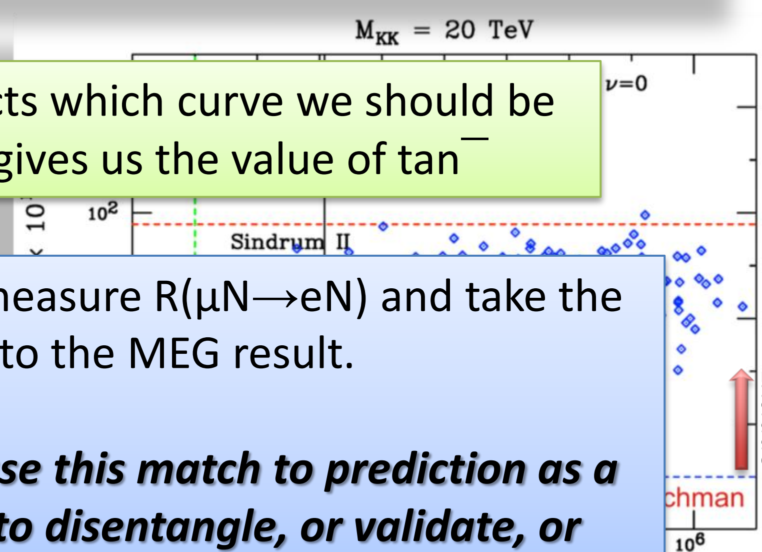
- From LHC we have the SUSY masses
- From g-2 we know tanβ
- From g-2 we know also know μ>0
- Combining these we get an a priori PREDICTION for:

$$\frac{Br(\mu \to e\gamma)}{R(\mu N \to eN)}$$

under MSSM/MSUGRA







g-2 selects which curve we should be on, and gives us the value of tan¯

We measure R(μN→eN) and take the ratio to the MEG result.

We use this match to prediction as a way to disentangle, or validate, or interpret manifestations of SUSY

MSSM/msugra/seesaw

SUSY

Many search modes have large effects for some models

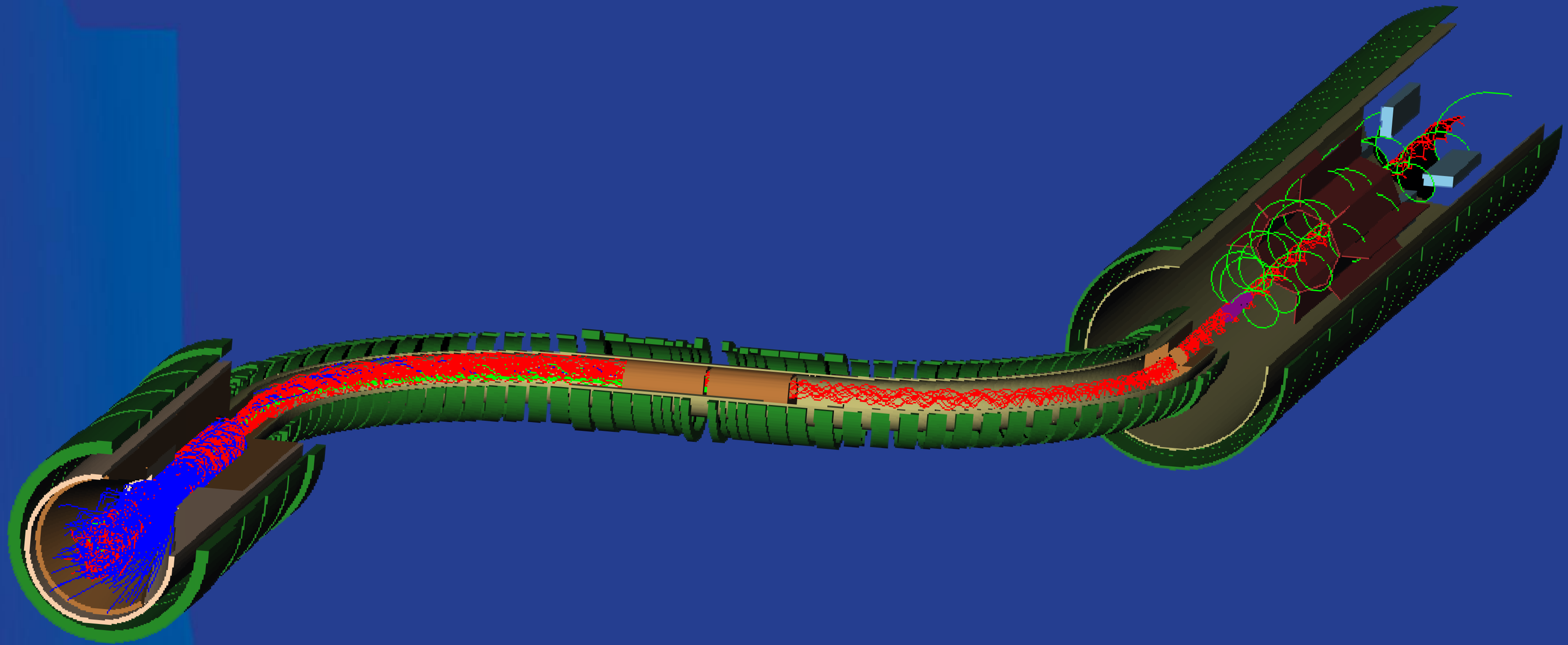
But only:

- μ→eγ
- 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]



Ordering up μN→eN at 10^{-16}

MAKING THE MEASUREMENT

The $\mu N \rightarrow eN$ measurement at $Br(10^{-17})$ (in a nutshell)

- Stop ~O(5×10^{10}) μ^- per pulse on a target (Al, Ti, Au)
- Wait 700ns (to let prompt backgrounds clear)
- Look for the coherent conversion of a muon to a mono-energetic electron:

$$E_e = M_\mu - N_{recoil} - (B.E.)_\mu^{1S}$$
$$= 104.96 \text{ MeV (on } {}^{27}\text{Al})$$

- Report the rate relative to nuclear capture

$$\mathcal{R} = \frac{\Gamma(\mu^- N \rightarrow e^- N)}{\Gamma(\mu^- N(Z) \rightarrow \nu_\mu N(Z-1)d}$$

- *If we see a signal, it's compelling evidence for physics beyond the standard model!*

μN→eN in Detail

Muonic Atom

- Start with a series of target foils
  - For Mu2E these are Al or Ti
- Bring in the low energy muon beam
  - We stop ≈ 50% of μ's
  - Stopped muons fall into the atomic potential
  - As they do they emit x-rays
- Muons fall down to the 1S state and a captured in the orbit
  - Muonic Bohr Radius

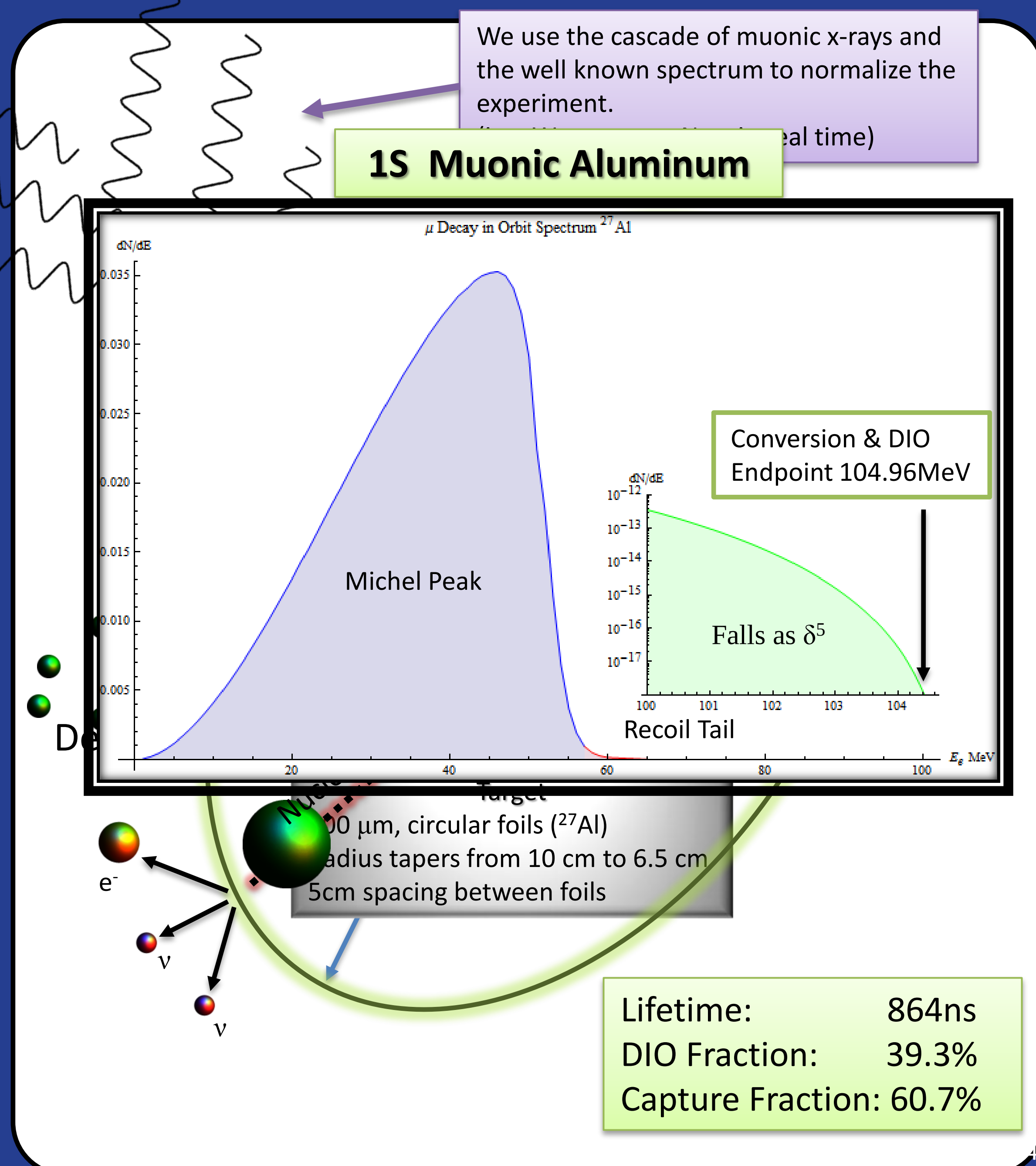
$$\langle r_\mu \rangle = \frac{n^2 \hbar}{m_\mu z e^2} \approx 19.6 \text{ fm (Al)}$$

  - Nuclear Size

$$R \approx 1.2 A^{1/3} \text{fm} = 3.6 \text{ fm (Al)}$$

  - Provides large overlap in the muon's wavefunction with the nucleous's
  - For Z > 25 the muon is "inside" the nucleous
- Once captured 3 things can happen
  - **Decay in Orbit**:

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$



Muonic Atom

- Start with a series of target foils
  - We stop ≈ 50% of μ's
- Bring in the low energy muon beam
  - We stop ≅ 50% of μ's
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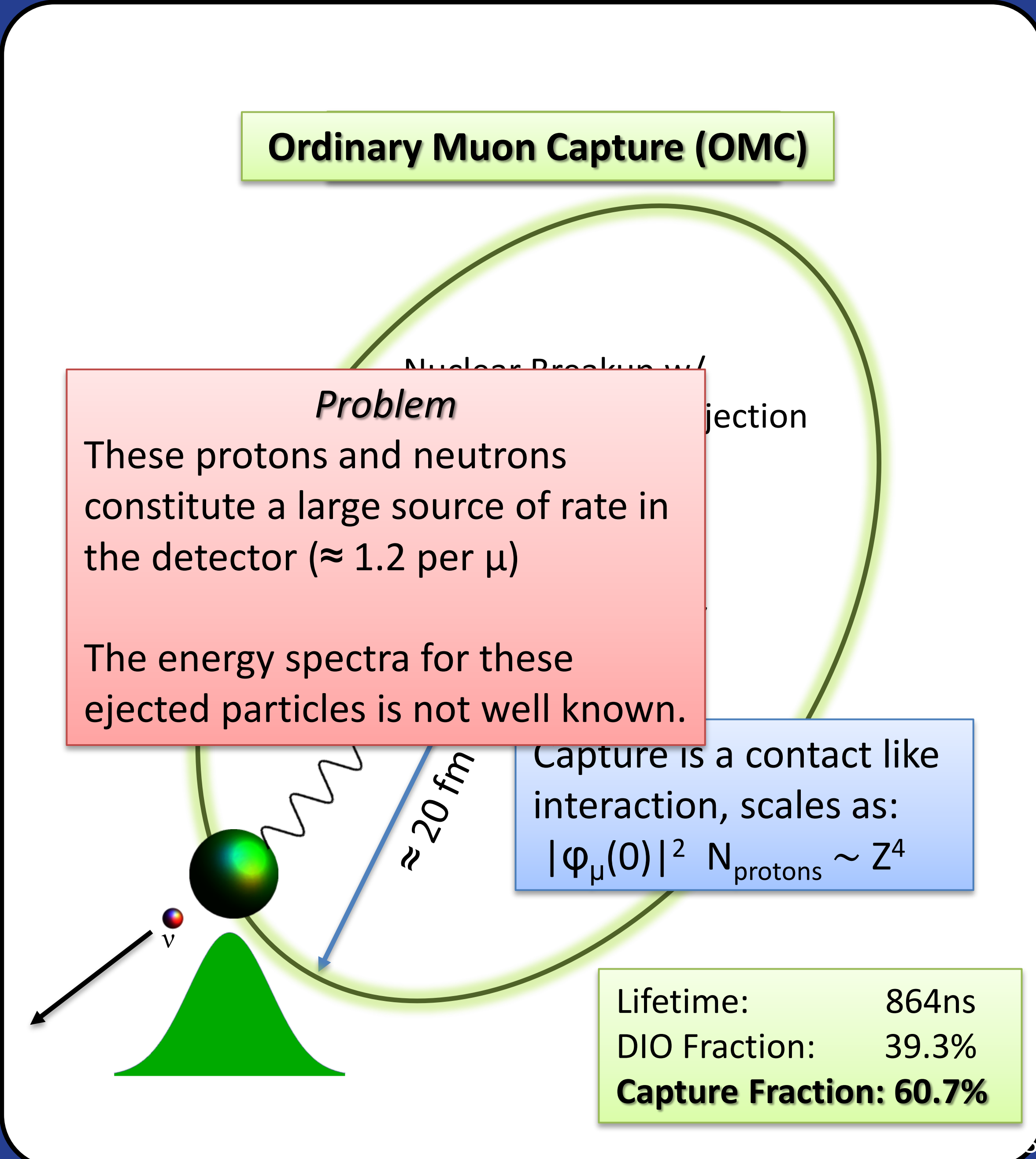
  - Decay in Orbit:
  - **Nuclear Capture**:

$$\mu^- N(Z) \to \nu N(Z-1)$$



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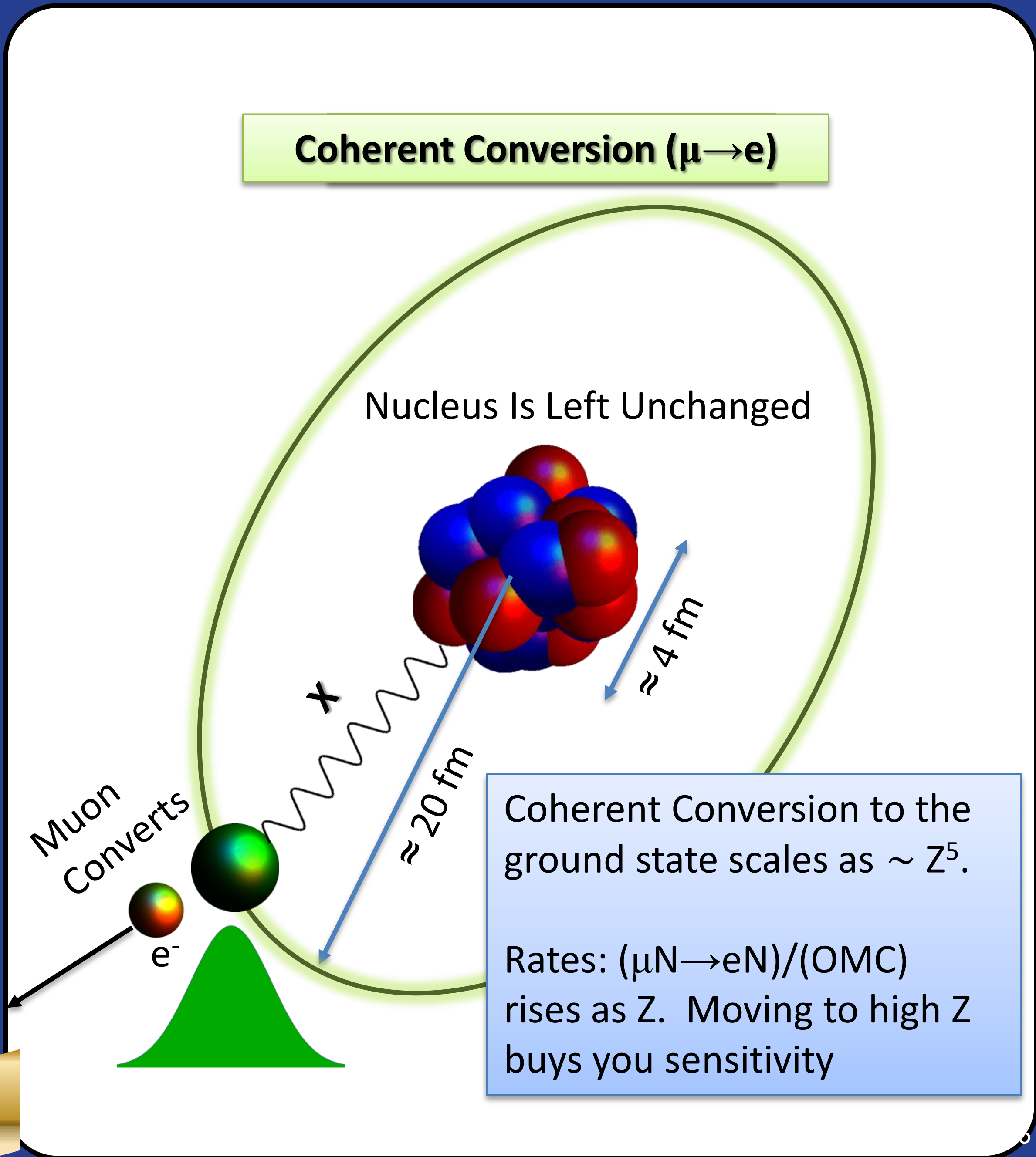
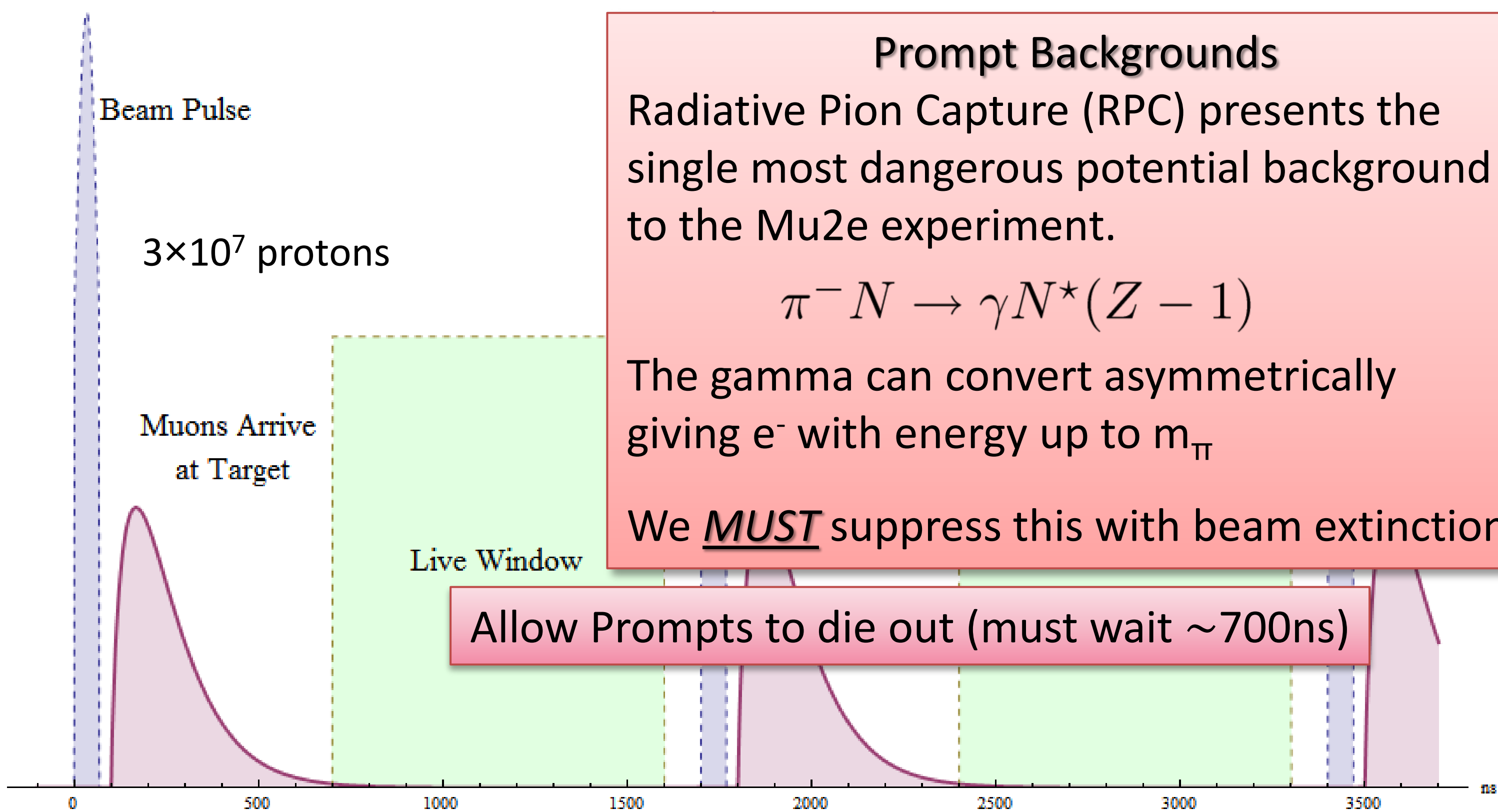
  - For Z > 25 the muon is “inside” the nucleus
- Once captured 3 things can happen
  - Decay in Orbit
  - Nuclear Capture
  - **New Physics! i.e. μ N → e N**

$E_e \approx 104.96$ MeV



Beam Structure

- μ's are accompanied by prompt e, π's, ….
- These cause dangerous backgrounds (RPC)
- Must limit our beam extinction, and detector live window



Prompt Backgrounds

Radiative Pion Capture (RPC) presents the single most dangerous potential background to the Mu2e experiment.

$$\pi^- N \rightarrow \gamma N^\star (Z-1)$$

The gamma can convert asymmetrically giving e^- with energy up to m_π

We ***MUST*** suppress this with beam extinction

Allow Prompts to die out (must wait ~700ns)

Beam Structure

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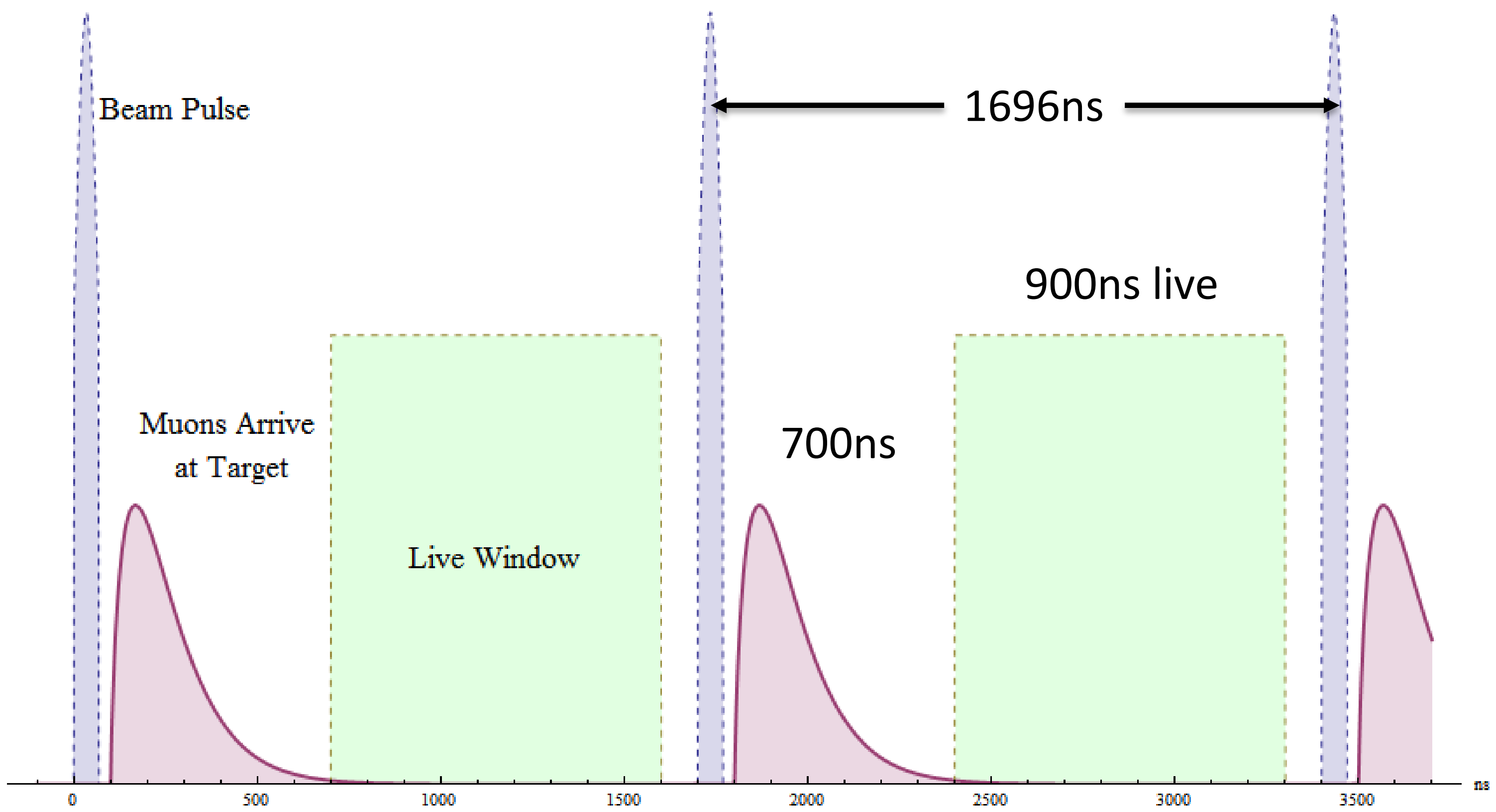
The spill cycle time is set by the muonium capture time



Total Backgrounds

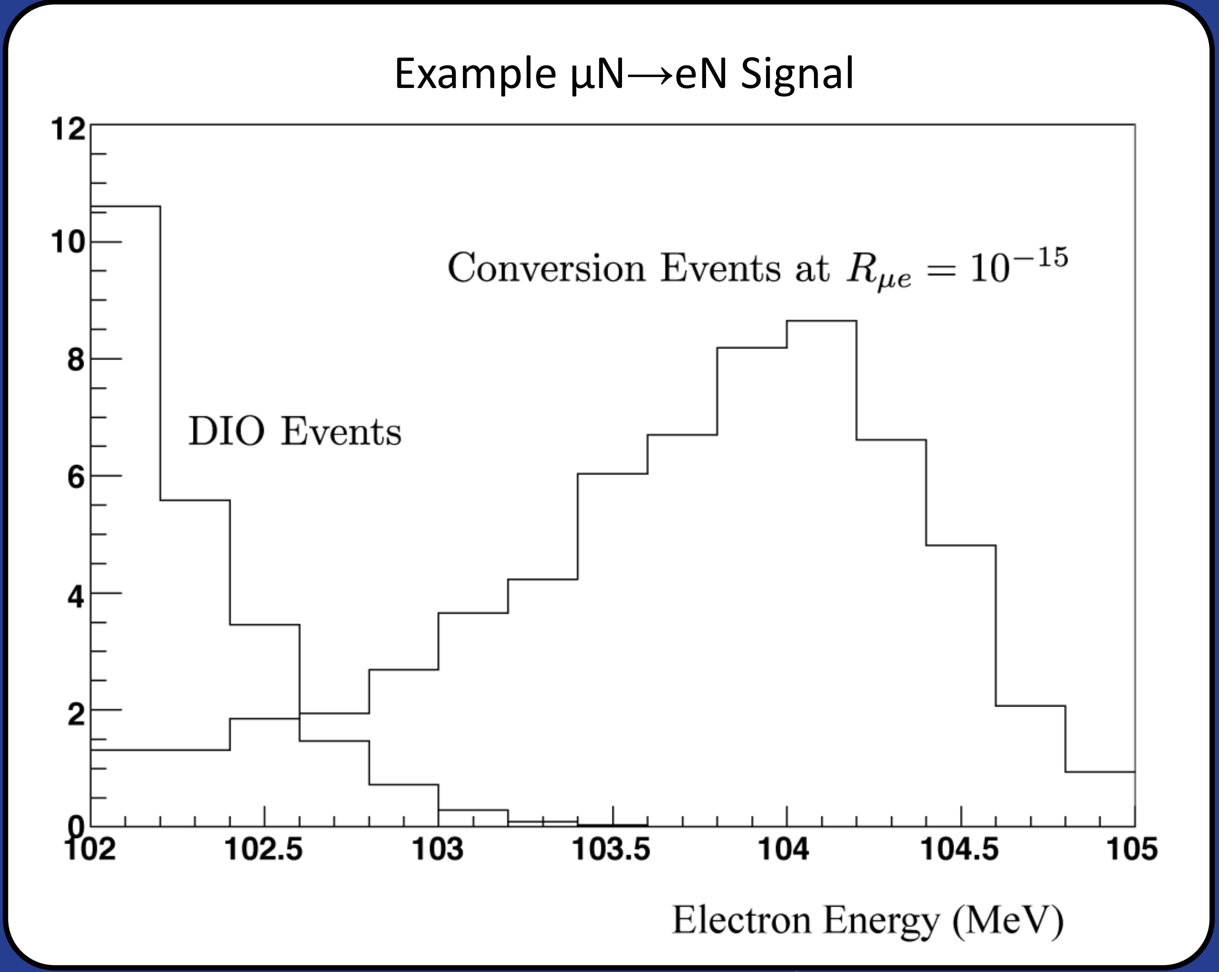
- Total expected background for SES $10^{-17} \approx 0.41$ evts
- Largest Background
  - Decay in Orbit (DIO)

Background	Bkg Est.	Err Est.	Notes
Muon Decay-in-orbit	0.22	±0.06	Acceptance and energy loss modeling, spectrum calculation; reco algorithm
$\bar{p}$ Induced	0.10	±0.05	Cross-section, modeling
Cosmic Ray	0.05	± 0.013	Monte Carlo Stats.
Rad Pion Capture	0.003	±0.007	Acceptance and energy loss modeling
μ decay in flight	0.01	± 0.003	
π decay in flight	0.003	± 0.0015	
Beam electrons	0.0006	± 0.0003	
Total	0.41	±0.08	

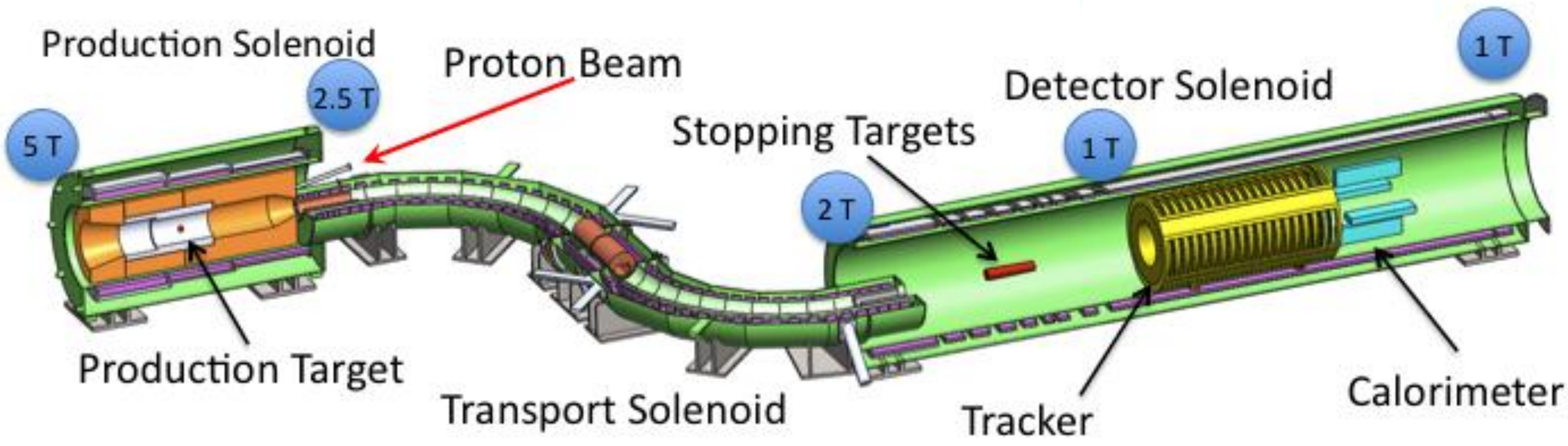
Signal Estimates

- For $R_{\mu e} = 10^{-15}$
  40 events / 0.41 bkg
  (LHC SUSY)

- For $R_{\mu e} = 10^{-16}$
  4 events / 0.41 bkg



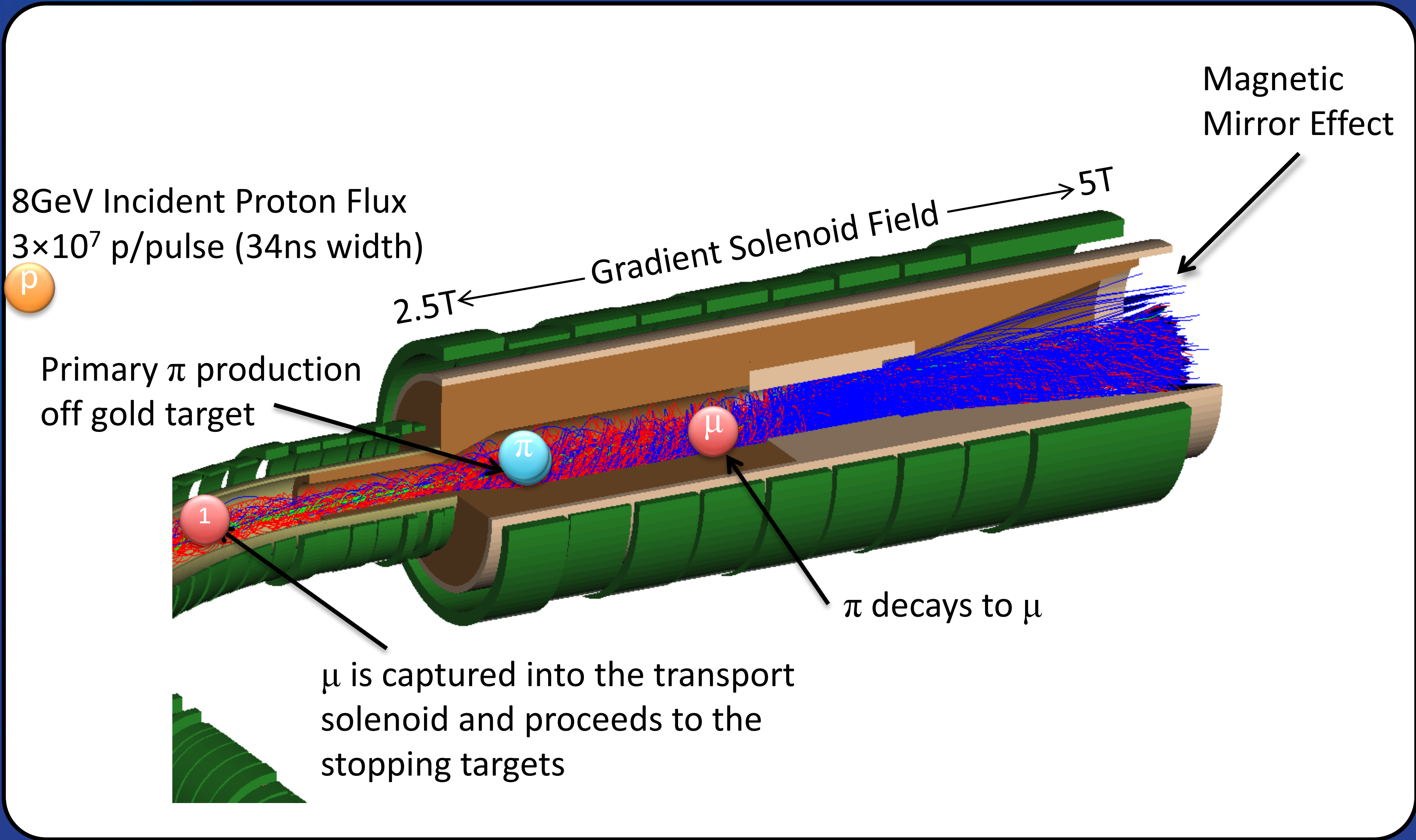
Observed electron energy is shifted down to 104 MeV due to energy loss in stopping target and smeared by detector resolution



Who ordered this?

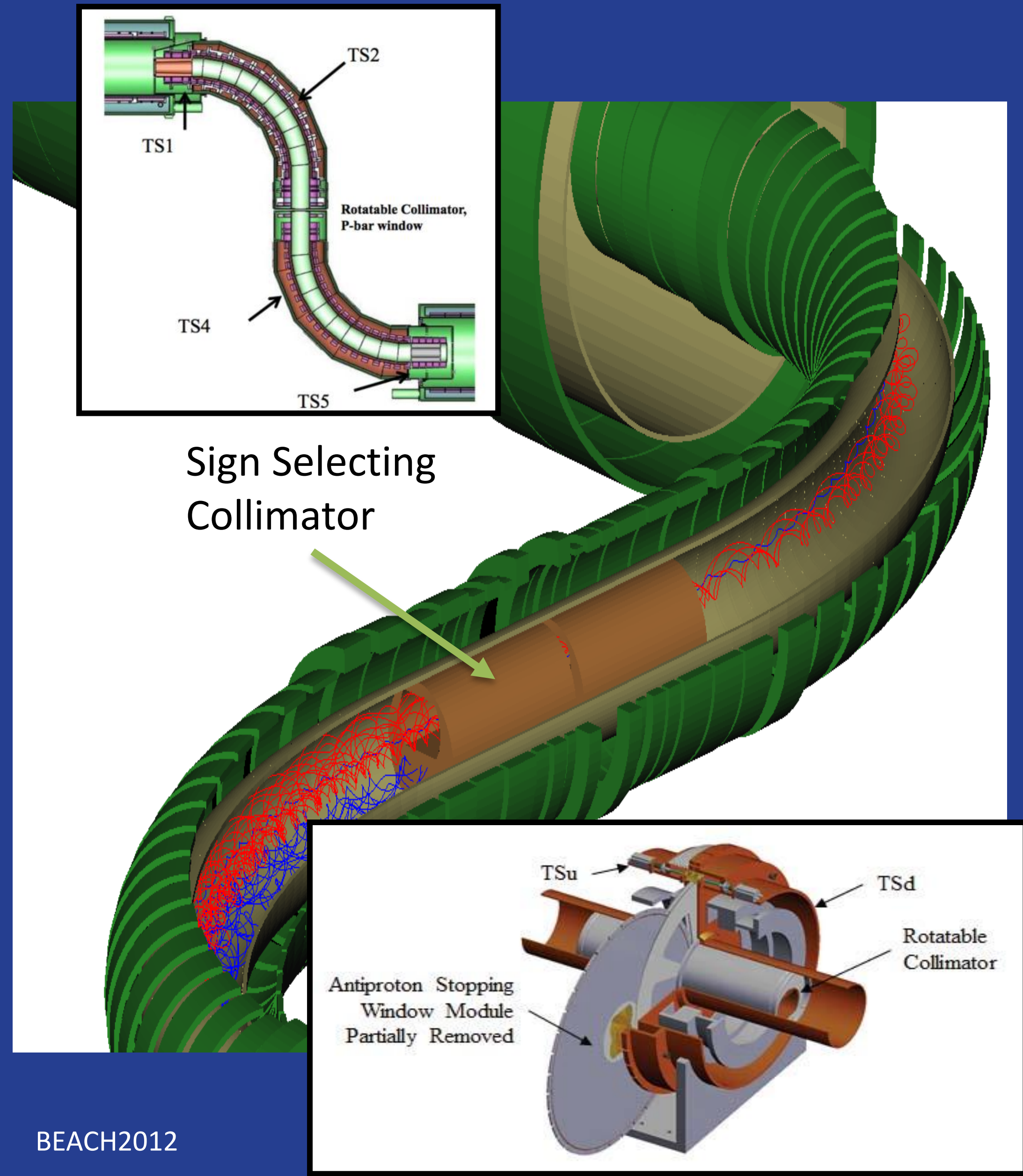
THE MU2E DETECTOR IN DETAIL

Production Solenoid

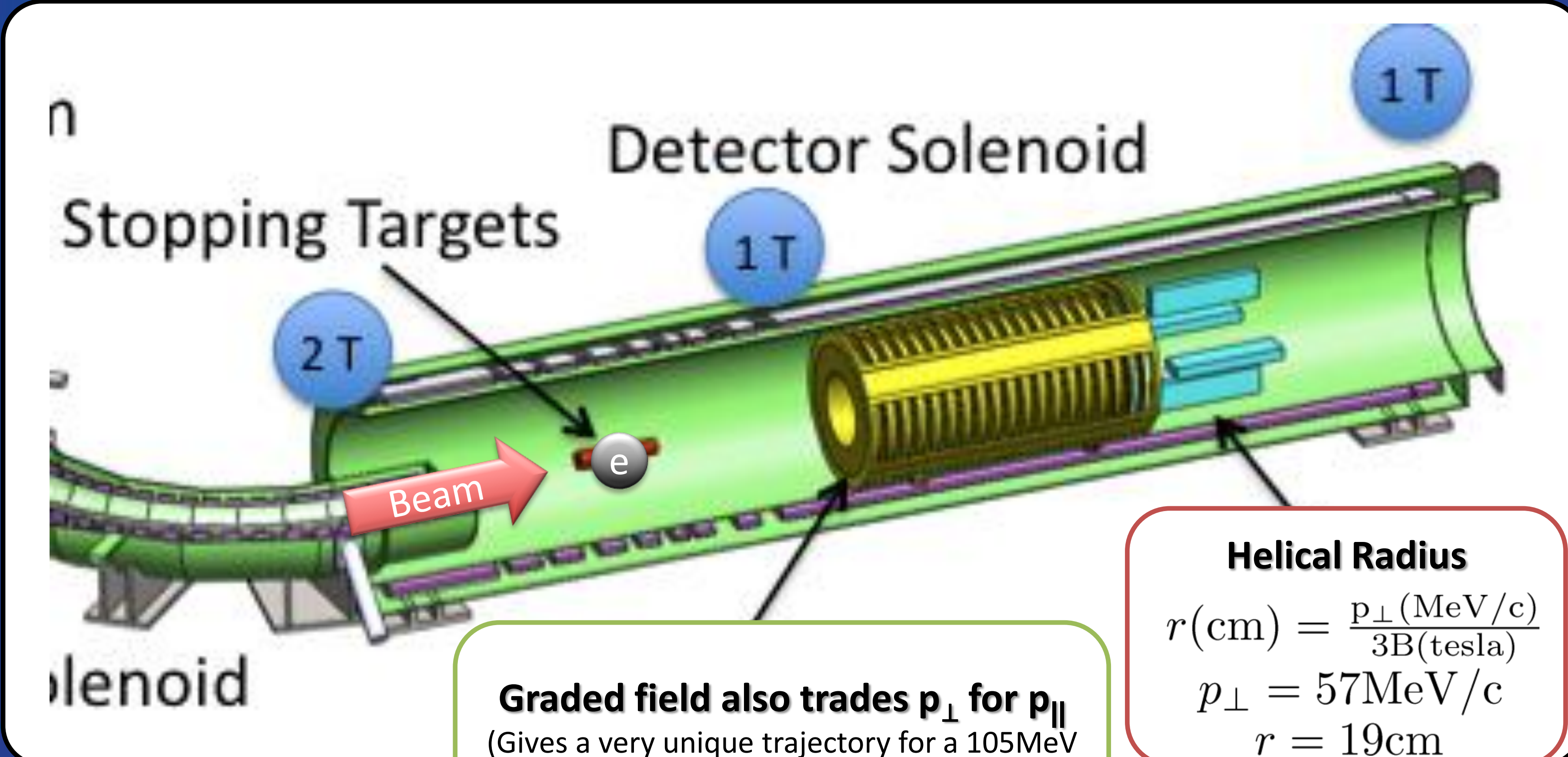


Transport Solenoid

- Designed to minimize beam background rates from the production target
- Removes anti-protons from the beam line in a Be foil
- Sign selects the muon beam
  - Collimator blocks the positives after the first bend
  - Negatives are brought back on axis by the second bend
  - Allows for momentum selection of the beam



The Detector



Helical Radius

$$r(\text{cm}) = \frac{p_\perp(\text{MeV/c})}{3B(\text{tesla})}$$

$$p_\perp = 57\text{MeV/c}$$

$$r = 19\text{cm}$$

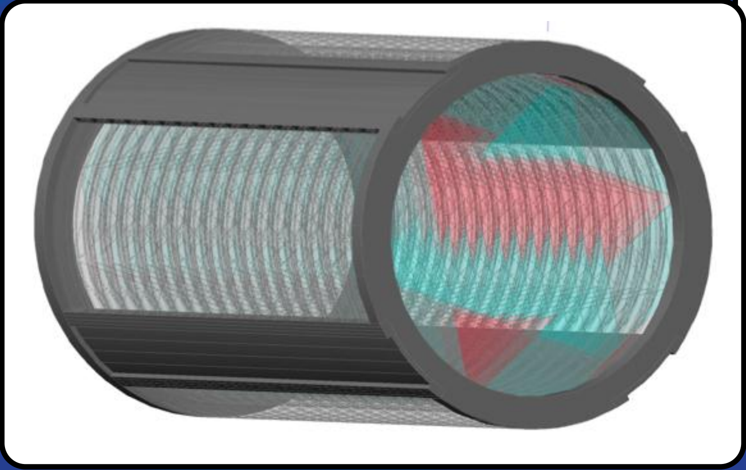
Graded field also trades $p_\perp$ for $p_{||}$

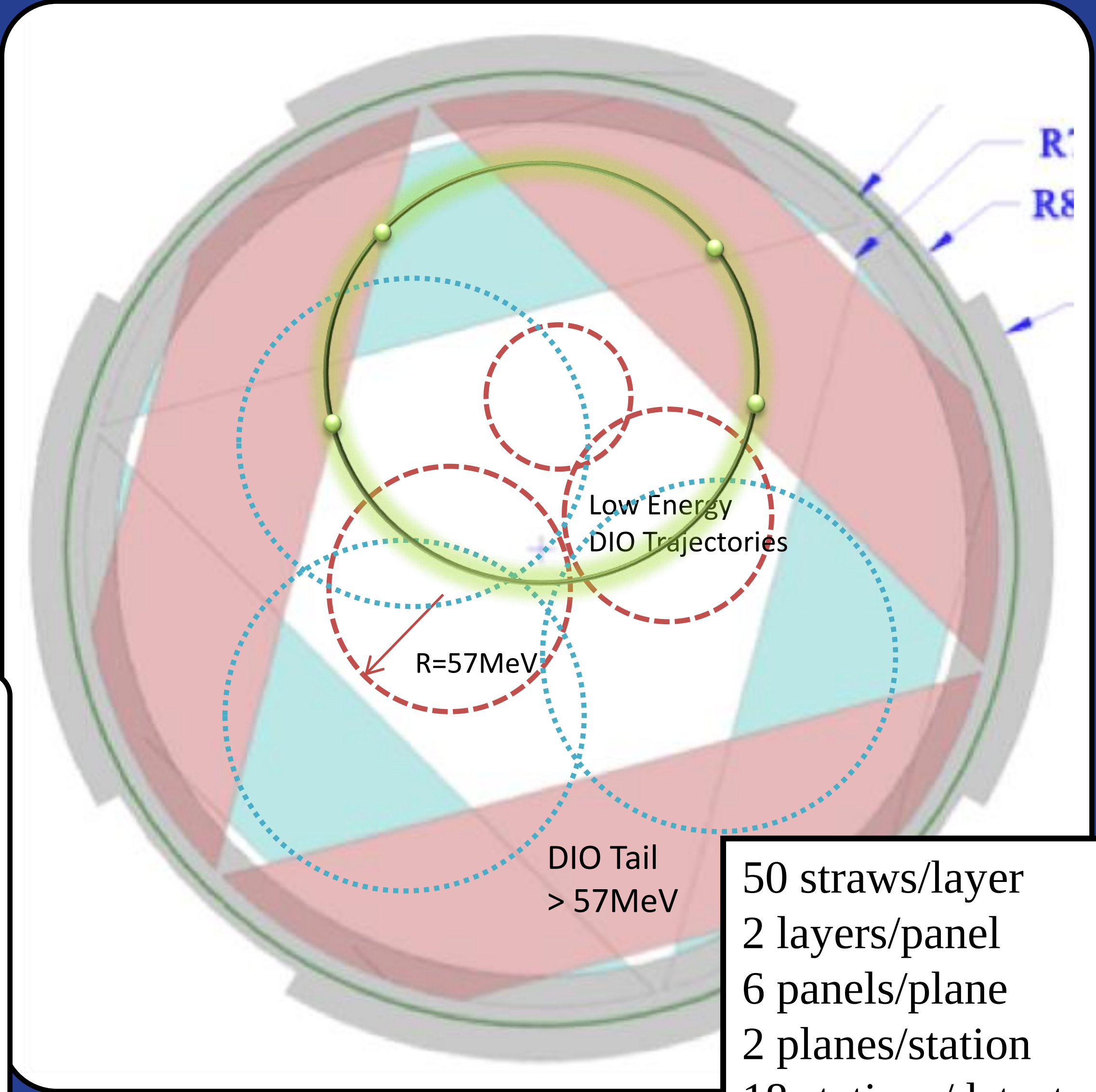
(Gives a very unique trajectory for a 105MeV e from the target region – suppresses background from upstream sources)

- The detector … k for the helical trajectories o…
- Each component is optimized to resolve signal from the *Decay in Orbit* Backgrounds

Straw Tracker (In Vacuum)

- Geometry is optimized for reconstruction of 105MeV helical trajectories
- Extremely low mass
- DIO tracks miss the senstive regions don't contribute to rate





50 straws/layer
2 layers/panel
6 panels/plane
2 planes/station
18 stations/detector
21,600 straws

Conclusions

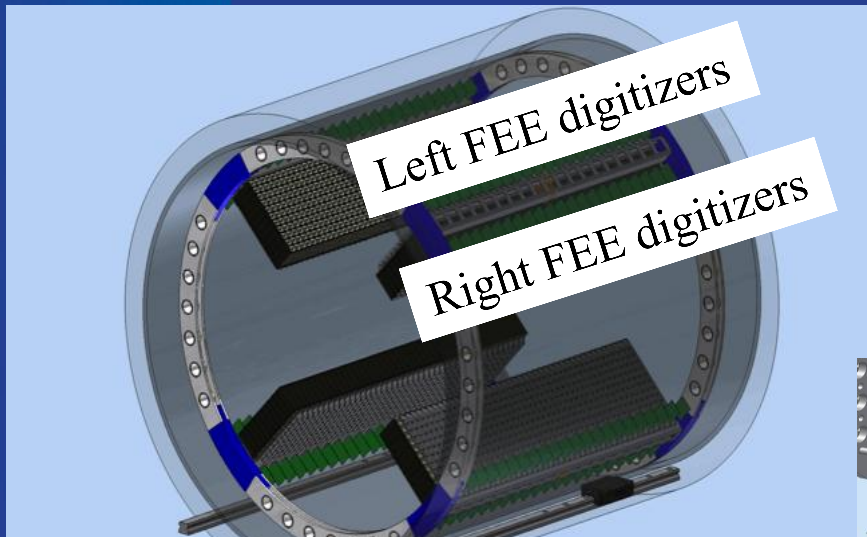
- Mu2e is unique in that it can push down the current limits on $R_{\mu e}$ by more than four orders of magnitude
- This gives the experiment real discovery potential of physics beyond the standard model
- Mu2e has the ability to complement LHC results or probe beyond the LHC to 10^4 TeV mass scales

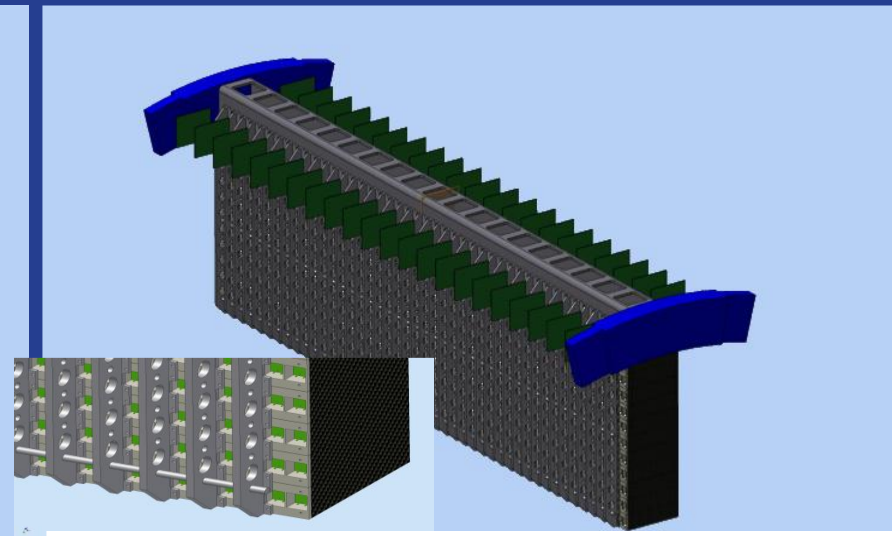
Mu2e received CD-1 on July 11th!

Project-X

ADDITIONAL MATERIAL

Calorimeter





Crystal	LYSO	$PbWO_4$
Density (g/cm^3)	7.28	8.28
Radiation length (cm) X_0	1.14	0.9
Molière radius (cm) R_m	2.07	2.0
Interaction length (cm)	20.9	20.7
dE/dx (MeV/cm)	10.0	13.0
Refractive Index at λ_{max}	1.82	2.20
Peak luminescence (nm)	402	420
Decay time τ (ns)	40	30, 10
Light yield (compared to NaI(Tl)) (%)	85	0.3, 0.1
Light yield variation with temperature(% / °C)	-0.2	-2.5
Hygroscopicity	None	None