Charged Lepton Flavor Violation:

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

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CWRU, Cleveland IL

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What is CLFV?

- a transition among μ , e , τ that doesn't conserve lepton family number
 - muon decay: $\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$ has two neutrinos
 - CLFV is seen in (for example) $\mu \rightarrow e \gamma$ or $\mu \rightarrow 3e$ with NO neutrinos; both being searched for (MEG, Mu3e)
 - similar τ decays: $\tau \rightarrow \mu, e + X$ (and no neutrinos)
 - in K system, $K_L \rightarrow \mu e$ and charged B , K to dileptons
 - $H \rightarrow \mu, e, \tau + X$

Two Ways to Look at CLFV

$$\mathcal{L} = \sum_n \frac{\text{couplings}}{\Lambda^n}$$

1. What is the mass scale of new physics?
 - Muon Lifetime and Size of G_F told us about a mass scale M_W ;
2. What are the symmetries and flavor structure of new physics?
 - the mass scale is not everything; you don't know the couplings or the sizes of mixing angles

Family number: not a fundamental symmetry

- family number is not a symmetry of Lagrangian like charge
 - quark family number is violated in weak decays in the CKM matrix
 - we know it's violated in neutral leptons: neutrino oscillations (PMNS matrix)
- but we've never seen it in charged leptons. Most “natural” new physics models predict we should have seen it already, even if small. Why haven't we?

How It Seems With Single Measurements

Muon Processes

- Decay Experiments:
 - $\mu \rightarrow e\gamma$
 - oldest studied, most powerful limits, and the best experiment so far: MEG at PSI. Back-to-back, limited by resolution and accidentals
 - $\mu \rightarrow eee$
 - ambitious and unique, in planning at PSI
- Conversion Experiment:
 - $\mu N \rightarrow eN$
 - three experiments upcoming at FNAL and JPARC

What is Muon to Electron Conversion?

- Muon converts to an electron in the field of a nucleus:

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

no neutrinos

- Effectively zero Standard Model background
 - a signal is new physics
- Experiments to be discussed can measure a signal with SES of $\sim 3 \times 10^{-17}$, discovery at 2×10^{-16}
 - typical predictions for EWSB $\sim 10^{-15}$

How Small is Our SES?

- Pretty Rare: let us know if this happens to you!
You can immediately join the experiment

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

Neutrinos and Mu2e

- Neutrino Oscillations are the only Standard Model background (except neutrino oscillations are not in the Standard Model)

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

- nobody understood why $\mu \rightarrow e \gamma$ wasn't 10^{-4} until we hypothesized two neutrinos ($\nu_\mu \neq \nu_e$)
- linkage of CLFV to oscillations, see-saw, Majorana vs. Dirac are getting more interest

Contributions to μe Conversion

Supersymmetry

rate $\sim 10^{-15}$

Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$

Leptoquark

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

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) ;

Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:[10.1146/annurev.nucl.58.110707.171126](https://doi.org/10.1146/annurev.nucl.58.110707.171126) ;

de Gouvea and Vogel, arXiv:1303.4097v2

Effective Lagrangian

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

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

1) Mass Reach to $\sim 10^4$ TeV for unit coupling, x10 in mass scale for dim-6

2) Mu2e and MEG-II are complementary in loop-dominated physics.

3) These are discovery experiments

Mu2e, g-2, and $\mu \rightarrow e \gamma$

Yaguna,
hep-ph/0502014v2
MSSM w mSUGRA

- Need:

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

to allow discrimination among different models

$$M_H = \sqrt{2} |\mu|$$

CLFV and Tau Processes

- Advantage:
 - Beyond SM rates can be orders of magnitude higher than in the corresponding muon channel
- Disadvantage
 - τ 's hard to produce:
 - $\sim 10^{11} \tau/\text{yr}$ vs $\sim 10^{11} \mu/\text{sec}$ in muon experiments

SM $\sim 10^{-14}$?

τ 's help pin down models; e.g. Cheng-Sher Ansatz $\sqrt{m_i m_j}$

Combine LHC/Direct

$$Y_{l_i l_j}^2 + Y_{l_j l_i}^2 = \text{constant} \quad (\mathcal{P} \text{ can make mixing asymmetric})$$

Lepton Flavor Violating Higgs Decays

Harnik, Kopp, Zupan, [arXiv:1209.1397](https://arxiv.org/abs/1209.1397)

- all $H \rightarrow l_i l_j$ consistent with zero
- muon experiments much better in $e\mu$ modes
- colliders unique in τ , can't make in low-energy μ beams

Collider or Muon Beam?

- 1st/2nd generation processes (“solar”)
 - *Muon experiments orders of magnitude better than colliders in muon-electron processes because we can make beams*
- 2nd/3rd, 1st/3rd (“atmospheric and θ_{13} ”)
 - *can’t make τ beams, so colliders best there*
 - *B^* , K^* , $b \rightarrow sll$, $b \rightarrow ll$ and $b \rightarrow s\gamma$ puzzles: lepton universality*
 - pp or e^+e^- both have contributions depending on channel; e.g. CLFV Higgs decays or τ CLFV (ATLAS/CMS, LHCb, and BELLE-II or BES-III; don’t overlook e^+e^- and B mesons)

Measuring 10^{-17} in Collider Units

- The captured muon is in a 1s state and the wave function overlaps the nucleus (*picture ~ to scale*)
- We can turn this into an effective luminosity
- Luminosity = density x velocity

$$|\psi(0)|^2 \times \alpha Z = \frac{m_\mu^3 Z^4 \alpha^4}{\pi} = 8 \times 10^{43} \text{ cm}^{-2} \text{ sec}^{-1}$$

- Times 10^{10} muons/sec X 2 μsec lifetime
- **Effective Luminosity of $10^{48} \text{ cm}^{-2} \text{ sec}^{-1}$**
 - vs HL-LHC at $\sim 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$ without pile-up

CLFV and the LHC

LHC inverse problem

Experimental Signal

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

- A Single Mono-energetic Electron
 - muon falls into 1s state in “stopping target”
- Nucleus coherently recoils off outgoing electron
- If $N = \text{Al}$, $E_e \sim 105. \text{ MeV} \sim m_\mu$
 - electron energy depends on Z
 - physics in Z -dependence of rate

very low energies for
HEP!

Mu2e: x10,000 improvement

- World's most intense muon beam:
 - 10^{10} μ /sec at detector under construction
 - Superconducting solenoid system to form muon beam
 - Efficient muon collection; see $\sim 10^{18}$ muons
- Have to reduce backgrounds to take advantage of statistics
 - Pulsed Beam reduces a background
 - And a high-resolution spectrometer to make muon-related backgrounds small

Backgrounds and Design

	<i>source</i>	<i>scales with</i>	<i>solution</i>
Intrinsic Backgrounds	decay-in-orbit	# of muons	detector resolution
Beam	radiative pion capture	closeness to beam pulse	pulsed beam
Running Time	cosmic ray	live time	veto system

Decay-In-Orbit: usually not background

- Peak and Endpoint of free muon decay spectrum is at

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

- Detector will be insensitive to electrons at this energy
- Recall *signal* at $105 \text{ MeV} \gg 52.8 \text{ MeV}$

Michel=free muon decay

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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Decay-in-Orbit Shape

Szafron 10.5506/APhysPolB.46.2279: Radiative Corrections

Czarnecki: 10.1016/j.physletb.2015.12.008 many other papers

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Radiative Pion Capture

- Need π 's to make μ 's
- Sometimes those π 's live long enough to make it to the stopping target
- They can then undergo radiative pion capture (RPC):
 - $\pi N \rightarrow \gamma N'$ and the γ converts to e^+e^- in the Al.
 - $\pi N \rightarrow \gamma N'$ and the γ internally converts
- Sometimes the e^- is at the signal energy

SINDRUM-II Results

- Effectively constant beam
 - 51 MHz (**~20 nsec**) repetition rate, ~0.3 nsec pulse
- Small time separation between signal and prompt pion backgrounds
 - bottom plot is first half of **20 nsec**, top plot is 2nd half
 - delay lowers background

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

Pulsed Beam Structure

π backgrounds

signal window

- Wait out pion backgrounds, then open signal window
- Can't “restart the clock” with out-of-pulse protons
- Need 10^{-10} in-pulse/out-of-pulse ratio (**extinction**)
 - will measure and monitor during experiment

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Actual Experiments: Mu2e/COMET

mu2e.fnal.gov

4.6T $\longrightarrow$ B-field gradient $\longrightarrow$ 1T

Mu2e

Production

Transport

Detector

- Target protons at 8 GeV inside superconducting solenoid at 8kW: shielding a challenge
- Capture muons and guide through S-shaped region to Al stopping target

Detector Layout

finding electron track and momentum determination: highest precision, needed to reject decay-in-orbit

tracker

beam stop

stopping
target

calorimeter

- 1) PID separation of $\pi/\mu/e$
- 2) Seed for Track Finder
- 3) Standalone Trigger

Why Annular?

- Reduces beam activity and a background
 - don't want initial “flash” of activity from proton pulse, or remnant muon beam in detector (only $\sim 1/2$ of muon beam stops in target)
 - eliminates all but a tiny number of decay-in-orbit background
 - $p \sin\theta \sim qBR$ in solenoid, Michel e^- at small radius
 - so we're not rejecting 10^{18} ; only $\sim 10^5$ even reconstructed
- COMET uses a different method; not annular
 - advantages and disadvantages

Straw Tube Tracker

- 15 microns of Kapton (human hair = 10–80 microns)
- ~1 meter long straws, 5 mm diameter with a central gold-plated tungsten wire
- ~20,000 straws in a vacuum of 10^{-4} Torr

Calorimeter

- Two CsI crystal disks
 - hole, as in tracker, for passage of muon beam
 - distance chosen such that if signal electron goes down hole, hits next disk

“module 0”:
51 crystals

Backgrounds and Design

	<i>source</i>	<i>scales with</i>	<i>solution</i>
Intrinsic Backgrounds	decay-in-orbit	# of muons	detector resolution
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Cosmic Ray Background

- At 10^{-17} there's a lot of rare backgrounds; here's one that is surprising but not too rare: $\sim 1/\text{day}$

- the experiment needs a 99.99% efficient veto (3/4 layers)
- in an environment with 10^{10} neutrons/cm²/sec from proton pulse

CR Veto Details

Neutron Rates

- Veto systems are never totally hermetic
 - even with 26 km of veto counters, area of a large house (~3000 ft²) (extrusions completed)
- Simulated 250 experiment live-times in targeted regions

targeted simulations here, for example

Tracker/Calorimeter/ CRV Test Beam Results

- Energy and time response of 3X3 CsI crystal array
- PE yields of CRV scintillation counters read out by SiPMs
- Tracker Resolution measured and modeled at level of charge cluster formation
- *Measured resolutions and properties in the simulations*

arXiv: 1709.06587, submitted to NIM

DOI: 10.1088/1748-0221/12/05/P05007

Beam Under Construction

diagnostic absorber near g-2/Mu2e split:
is the beam as expected and does the
extinction work?

checking polarity now!
(before we turn on)

Mu2e Solenoid

Coil modules at ASG

R. Bernstein (FNAL)

~1 of 75
km of
cable and
spares
(cable
complete)

B9

at General Atomics
splice between solenoids

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Beginning Production

- Ramping up production and cold tests

~204 scientists
from
US, Italy, Russia,
Germany

production solenoid here

transport solenoid here

Mu2e Expected

90% CL $\sim 8 \times 10^{-17}$

$5\sigma \sim 2 \times 10^{-16}$

x10000 better than SINDRUM-II

Mu2e

typical SUSY at 10^{-15} : 40 events vs 0.4 bkg

Background Estimates

Process	Expected Number
Cosmic Ray Muons	0.25 ± 0.026
DIO	0.14 ± 0.09
RPC	0.025 ± 0.003
Antiprotons	0.047 ± 0.024
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam Electrons	$< 5 \times 10^{-4}$
Total	0.46 ± 0.10

Mu2e Schedule

Construction underway now;
setting up factories

COMET

- Stage I: (2021)
 - x100 better than SINDRUM-II
- Stage II
 - x10,000 better
 - same reach as Mu2e
- Important differences:
 - C- vs S- for transport
 - 2nd bend in detector solenoid: charge/ momentum selects, (save that info for later)

COMET

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DeeMe

- DeeMe at J-PARC $\mu N \rightarrow e N$ with a 2×10^{-14} SES, **x10** improvement
- **production target and conversion target are the same: not like Mu2e or COMET**

Calibration Spectra (μ^+ data)

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

- Closely related to $\theta_{\nu 2\beta}$ best done at Mu2e
- or a leptoquark (not shown), ...

- <https://doi.org/10.1103/PhysRevD.95.115010>, <https://arxiv.org/pdf/1611.00032.pdf>, <https://arxiv.org/pdf/1705.07464.pdf>, Geib et al., Physics Letters B 764 (2017) 157–162 or <https://arxiv.org/abs/1609.09088> discusses relation to $\theta_{\nu 2\beta}$

Mu2e Summary

- $\mu^- Al \rightarrow e^- Al$
 - SES $\sim 3 \times 10^{-17}$
 - 90% CL $\sim 8 \times 10^{-17}$
 - 5σ discovery $\sim 2 \times 10^{-16}$
 - Run for 3 years; physics data starting 2022
- Upgrades in intensity and changes in material already under examination

Mu2e Upgrades

- Next Step in cLFV Program:

Upgrades and Z-Dependence

- Different Operators have different Z-dependence
 - Combine depending on the particular model
- Z penguins
- γ penguins
- dipole
- scalar

Lepton flavor violating $\mu - e$ conversion rate for various nuclei
 M. Koike et al., J.Phys. G29 (2003) 2051-2054
 DOI: [10.1088/0954-3899/29/8/401](https://doi.org/10.1088/0954-3899/29/8/401)

Relationship to Neutrino Oscillations (neutral lepton flavor violation)

- want as high a Z as possible

Choice of Z for Upgrade

- What Sets Material Choice? Lifetime:

$$\tau_{\mu}(\text{Al}) = 864 \text{ ns}$$

$$\tau_{\mu}(\text{Ti}) = 338 \text{ ns}$$

$$\tau_{\mu}(\text{Au}) = 74 \text{ ns}$$

Mu2e Upgrades

- Studies for x10 improvement with Ti look promising and will be continued; EOI written (1307.1168 and EOI at 1802.02599)
- We need detector and solenoid improvements
 - may need new production solenoid to handle lower energy beam and higher power.
- FNAL PIP-II natural for both pulsed and non-pulsed CLFV, could do $\mu^- N \rightarrow e^\pm N$, $\mu \rightarrow e \gamma$, $\mu \rightarrow 3e$, $\mu^- e^- \rightarrow e^- e^-$ at one facility

What I Hope You'll Remember

- Any signal is unambiguously new physics. We need multiple measurements to understand sort out the nature of the signal (or limits)
 - CLFV, neutrinos, $g-2$, EDMs, kaon decays, $0\nu 2\beta$, dark matter, collider CLFV are tightly linked and models have to fit *all* the data.
- The experiments are challenging theory and getting better fast, with upgrades on the way.
 - within next 5-10 years: muons improve by 10^4 , $\times 10$ in mass scale; Run-II data; e^+e^- and LHCb will probe τ , B, and charm sectors. Kaon system continues to be incisive and unique.

Conclusions

- Mu2e will:
 - Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude, x10 in mass reach ($R_{\mu e} < 8 \times 10^{-17}$ @ 90% C.L.)
 - Discover unambiguous proof of new physics or
 - Set powerful constraints on a wide variety of models
- Mu2e will therefore both complement LHC results and independently probe up to 10^4 TeV/c²
 - COMET and DeeMe in progress; MEG upgrade underway
- Upgrades already under consideration with a new muon CLFV program being mapped out

NOvA and miniBooNE at Neutrino 2018

(I am a NOvA collaborator but not miniBooNE)

Summary of NOvA Results

- over 4σ ν_e appearance
- analyzed our first $\bar{\nu}$ data and in a joint analysis ($\nu_\mu + \nu_e$ and $\bar{\nu}_\mu + \bar{\nu}_e$) we see:
 - a preference for the normal hierarchy at 1.8σ , exclusion of IH at the $\delta_{CP} = \pi/2$ point at $> 3\sigma$
- reject maximal mixing at 1.8σ and prefer the upper octant solution at similar level

ELECTRON NEUTRINO AND ANTINEUTRINO APPEARANCE

- On the neutrino beam we observe 58 events and expect 15 background interactions:
 - 11 beam, 3 cosmic background and < 1 wrong sign background.
- For the antineutrino beam we observe 18 and expect 5.3 background interactions:
 - 3.5 beam background, < 1 cosmic background and 1 wrong sign background.

$> 4\sigma$ evidence of electron antineutrino appearance

ALLOWED OSCILLATION PARAMETERS

- Best fit: Normal Hierarchy
 $\delta_{CP} = 0.17\pi$
 $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
 $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3} \text{ eV}^2$

Prefer NH by 1.8σ
 Exclude $\delta = \pi/2$ in the IH at > 3σ

miniBooNE

- Excess of events at low energy
- Combined with LSND (3.8σ) total significance 6.1σ

miniBooNE

R. T. Thornton - Recent Results from MiniBooNE

Parameter Space

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_e \text{ or } \nu_\mu \rightarrow \nu_e$$

- MiniBooNE ν and $\bar{\nu}$ are **CONSISTENT** with LSND in L/E and appearance probability
- Simple 2ν fit
 - Best fit at maximum mixing
 - But 1σ region is large
 - Hints at more complicated model

- For more information
 - [arxiv:1805.12028](https://arxiv.org/abs/1805.12028)
 - July 27 W&C Talk

note
 $\Delta m^2 > .01$:
 difficult
 to
 combine
 with
 solar,
 atmo. at
 $\Delta m^2 \sim 10^{-3}$
 or less,
 leading to
 sterile?

R. T. Thornton - Recent Results from MiniBooNE

$$(\Delta m^2, \sin^2 2\theta) = (0.041 \text{ eV}^2, 0.958)$$

$$\chi^2/ndf = 19.5/15.4 \text{ (prob. = 20.1\%)}$$

Short-Baseline Neutrino (SBN) Program

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- **MicroBooNE:** what is the MiniBooNE excess? Is it electrons or photons? (Eberly, this conf.)
- **ICARUS + MicroBooNE + SBND:** Is there definitive evidence for sterile neutrinos in the currently allowed parameter space?

COMET Progress

Chen Wu, Tau 2016
and
Y. Kuno, priv. comm

- Extinction measured $\sim 10^{-11}$
- Prototype Target
- Coil winding for capture solenoid
- Transport Solenoid in Hall
- 14 Coils of Detector Solenoid wound

Target prototype

Al stabilized SC wire

Coil winding

Detector Solenoid

COMET Remaining

- Production Solenoid cable procured, but one has to then design a solenoid shielding system that will withstand heat and radiation
 - dumping up to 56 kW (Stage II) in a superconducting solenoid
 - design still underway
 - then needs construction
- Negotiation over running time with T2K
 - ~150 days live-time needed for Stage 1 (x100 improvement)
- Available schedules out-of-date, but Stage 1 ~ 2021

http://j-parc.jp/researcher/Hadron/en/pac_1707/PAC24thMinutes_final_draft.pdf

DeeMe HV Switching

- Since the detector is so “close” to the production target, the detector has to be turned off near the beam flash
- HV switching on a MWPC

DeeMe Status

- Depends on J-PARC H-line construction (different from COMET, DeeMe in Materials Science section)

Summary

- There is a competitive merit of physics in searching for μ -e conversion at sensitivity of 10^{-14} in timely manner.
- **It is important to maximize the potential of major discovery at J-PARC.**
- DeeMe, yet another mu-e conversion search with totally different method from COMET and Mu2e, creates harmonious diversity for J-PARC.
- DeeMe has already acquired **Stage-2 Approval from muon-PAC of KEK/IMSS.**
- Construction of **detector system has completed** with Grant-in-Aid for Scientific Research of Japan (Basic Science S, 2012–2016).
- An **integration test of the whole detector system** including DAQ had **successfully** performed. A **DIO measurement** had done at the same time, and analysis is ongoing.
- The **Detector system is ready** for the physics data taking.
- We are hoping to start soon after the completion of the beamline construction. No beam-time conflicts with T2K, KOTO or whatever the physics programs with the main ring of J-PARC.
- Meanwhile, we are keeping collaboration activities with detector improvements and by-product research.

Mu2e and COMET: High-Level Differences

- COMET Staging has obvious advantages for learning as you go
- Charge Symmetry of Detector:
 - Mu2e: charge symmetric, e^+e^- the same
 - 2nd Bend in COMET Stage II momentum selects ~ 105 MeV e^- only
 - Mu2e needs hole, COMET does not

Effect of Charge-Symmetry Choice

- Backgrounds
 - many background sources of e^- (RPC!) produce equal e^+e^-
 - Mu2e can measure them with e^+ *in situ*
 - *look “inside the box”, no blinding needed since e^+*
- Physics (next topic)
 - Mu2e can simultaneously measure $\mu^- N \rightarrow e^+ N'$, different/unique physics
 - COMET would have to reverse field, not trivial: separate runs

Pulsed vs. “Steady” Beam

- Decay expts, $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ want a steady beam: PSI
- need to minimize backgrounds from coincidences of two decays
- $(\text{Rate})^2$ bkg vs $\text{Rate}(\text{signal})$
- muon-electron conversion wants a pulsed beam: FNAL/J-PARC
- Many pion-induced backgrounds after proton pulse
- Take advantage of 26 nsec lifetime to “wait it out”

DC optimizes in rate

R. Bernstein (FNAL)

Pulsed optimizes
in time

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Beam Flash

- After proton beam strikes target, “flash” of photons and electrons, and many electrons hit stopping target and detector
- Large neutron flux as well that would deaden detectors
- By waiting:
 - activity from beam flash is over
 - And pion backgrounds have decayed by $\sim 10^{11}$
- This early flash has implications for Mu2e and especially for potential upgrades