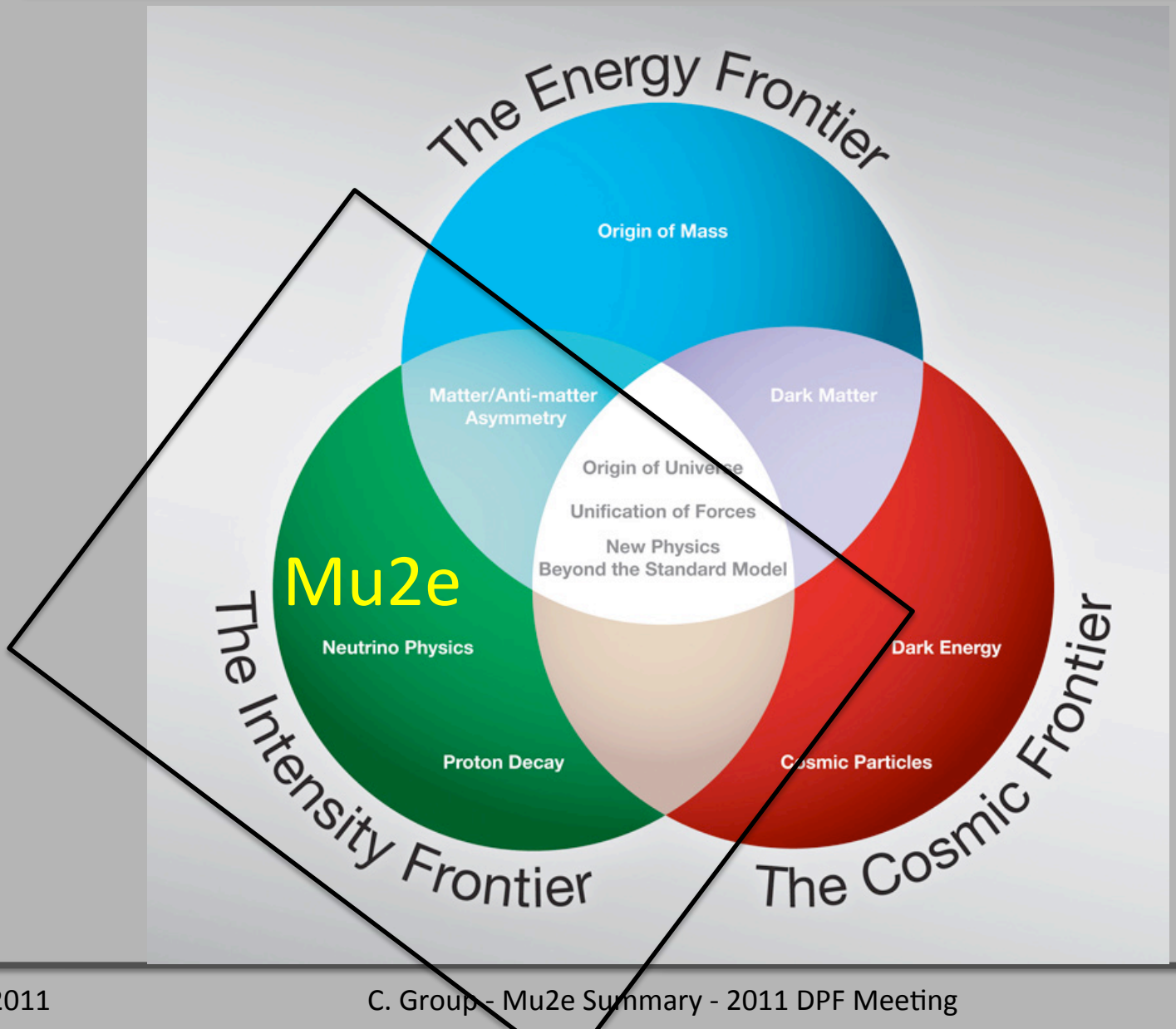
2011 DPF Meeting

Summary and Status of the Mu2e Experiment at Fermilab

Craig Group
(University of Virginia and Fermilab)
...on behalf of the Mu2e collaboration.

The Frontiers of Particle Physics



The Intensity Frontier!

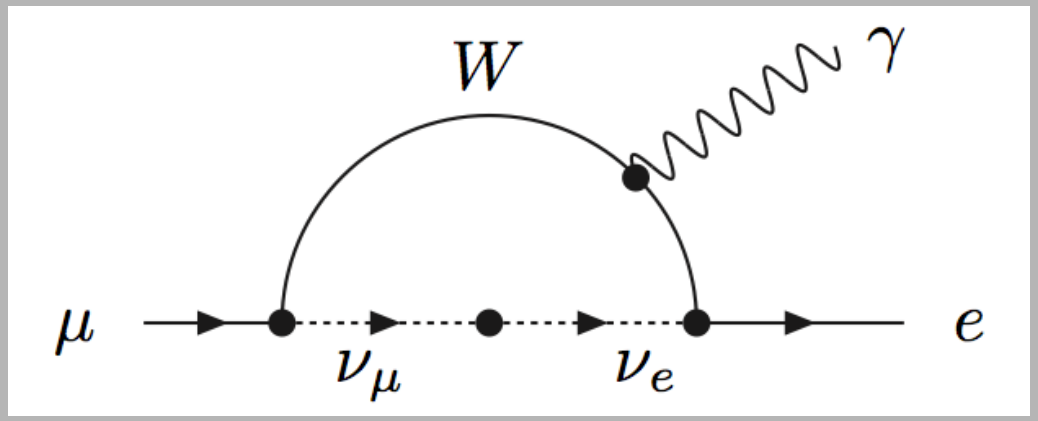
- One can probe the properties of the universe by looking for extremely rare processes
- Complementary alternative to using higher energies
- The medium-term future of accelerator-based particle physics on US soil is the intensity frontier:
  - Neutrino experiments (NOvA, LBNE, MINOS, MINERvA, and others…)
  - Precision measurements (g-2)
  - Rare decays (Mu2e, MEG, COMET, and others)

Charged Lepton Flavor Violation (CLFV)

- Neutrinos have mass!

  → individual lepton numbers are not conserved!

- Therefore, Lepton Flavor Violation occurs in Charged Leptons!

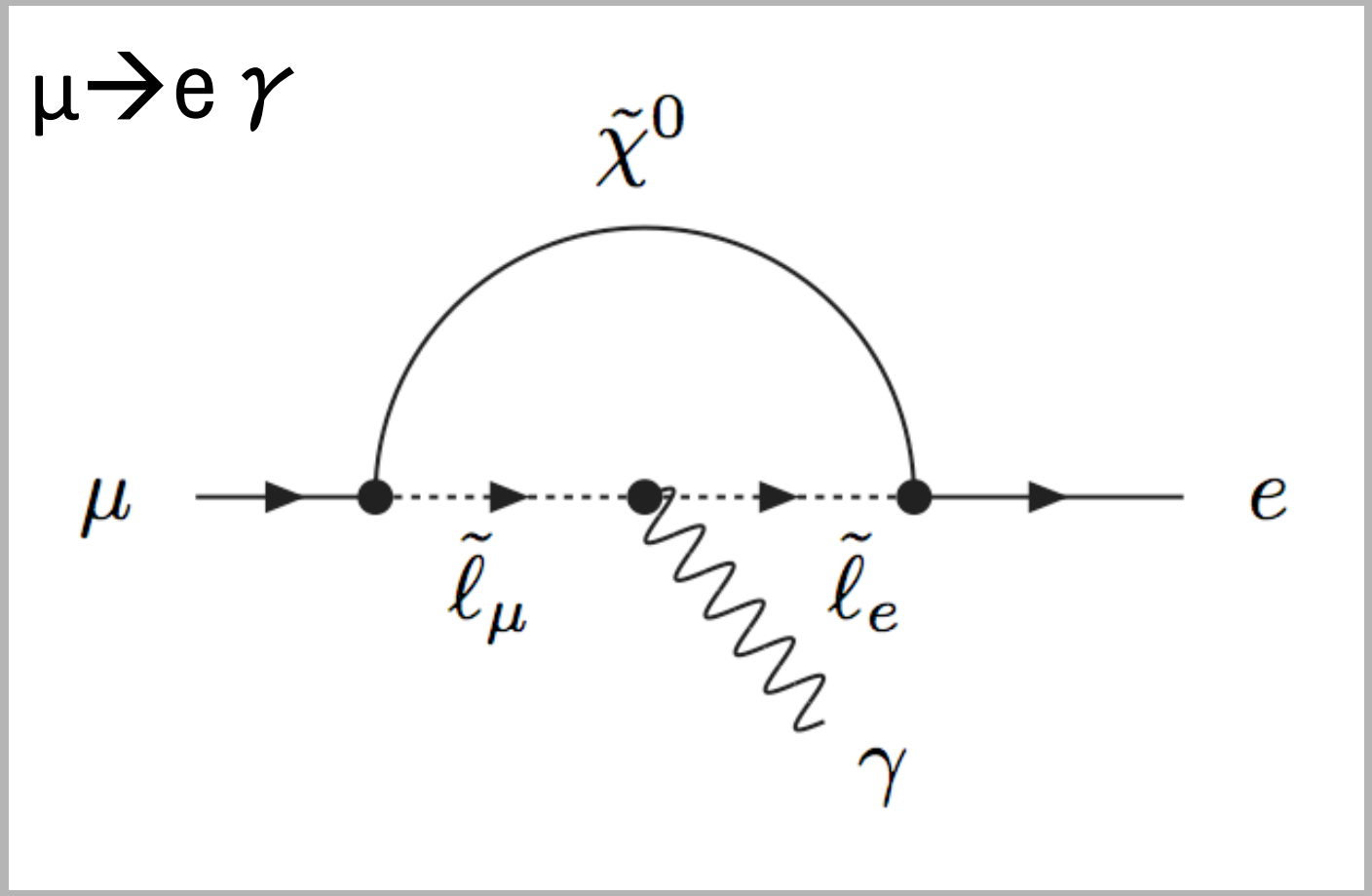


NO PHYSICS BACKGROUND! Observation is unambiguous sign of new physics!

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

Searching for CLFV

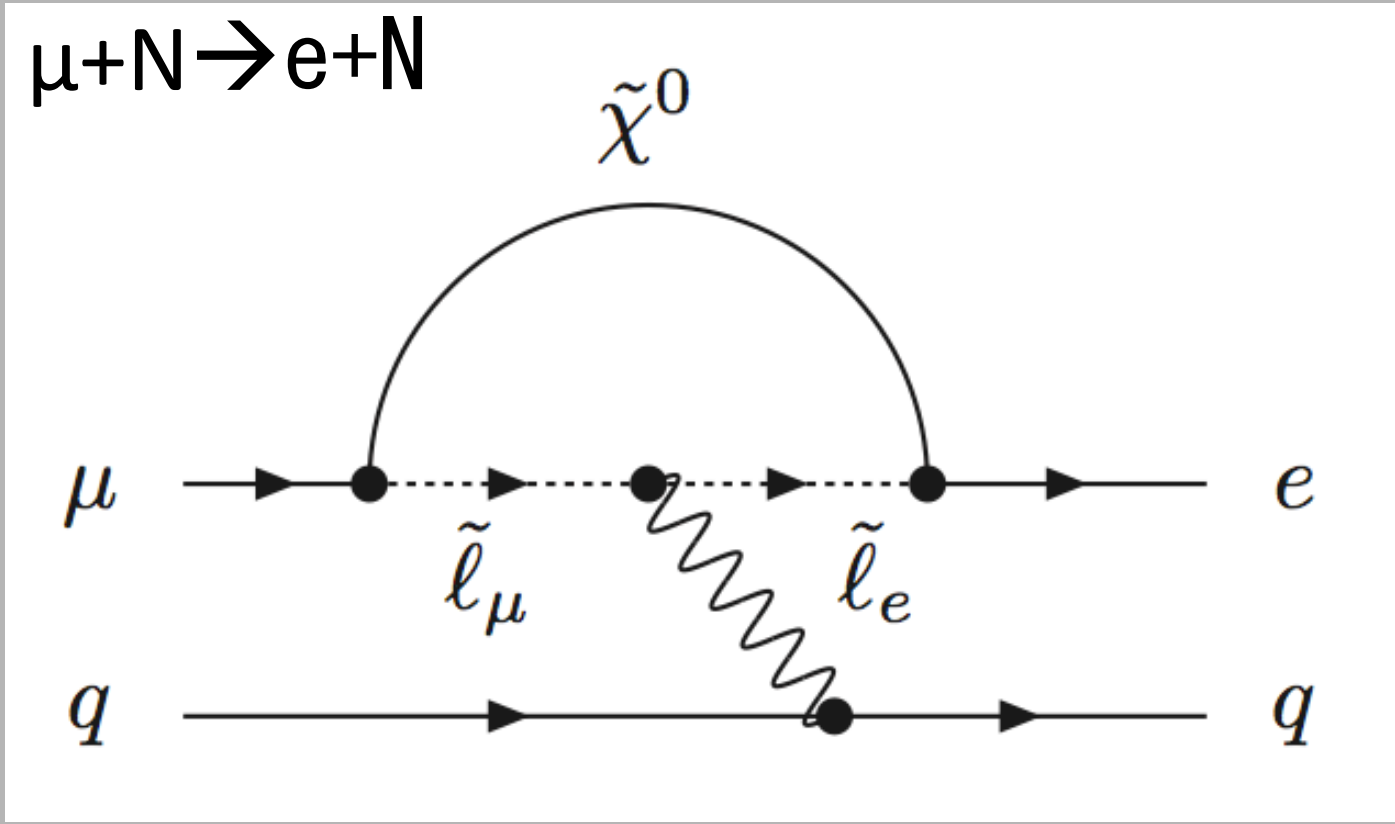
Can look for muon decaying into an electron plus a photon:



Experiments: MEGA, MEG, and others…

Searching for CLFV

In the presence of a nucleus (N):



The electron is mono-energetic in CM frame!

Experiments:Mu2e, SINDRUM II, TRIUMF, COMET, and others…

Mu2e

Experiment with preliminary approval that is proposed to begin data taking in 2018 at Fermilab.

- Goal: Search for $\mu^- N \rightarrow e^- N$
  - Measure ratio:

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

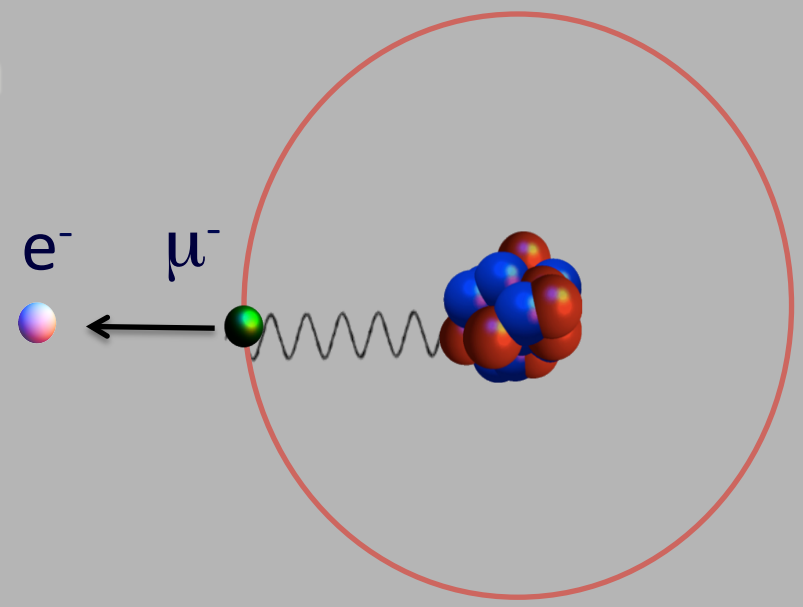
  - With sensitivity to R at 90% C.L. of $6*10^{-17}$
    - → 4 orders of magnitude better than current limits
    - → Need more than 10^{17} stopped muons!
      - -- $3.6*10^{20}$ protons on target (2 year run – $2x10^7$ s)
    - → Need to keep background small and well understood

Experimental Signature

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

- A single monoenergetic electron
- If N = Al, E_e = 105. MeV

  (Electron E depends on Z)
- Nucleus coherently recoils off outgoing electron, no breakup

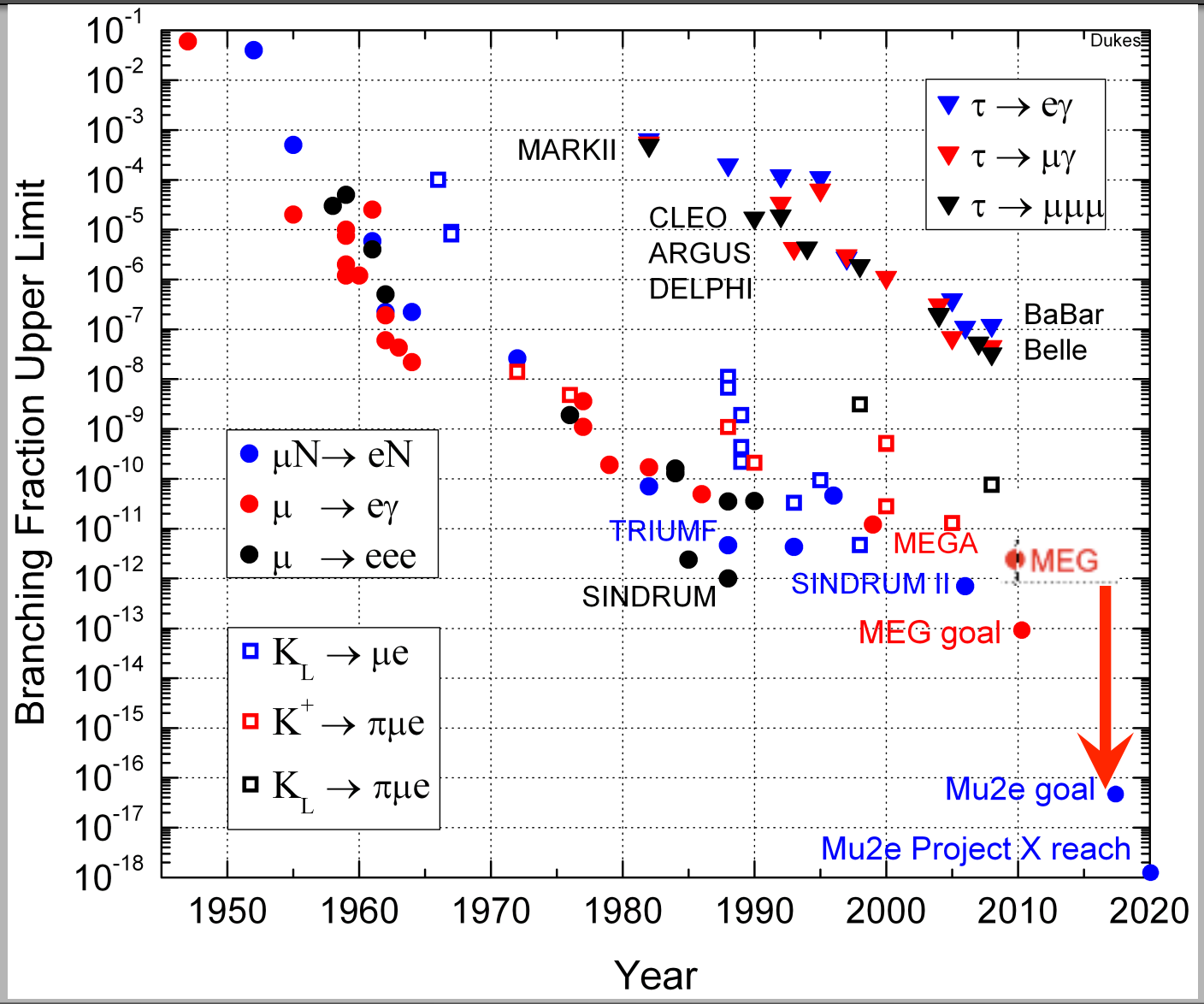


Background Processes

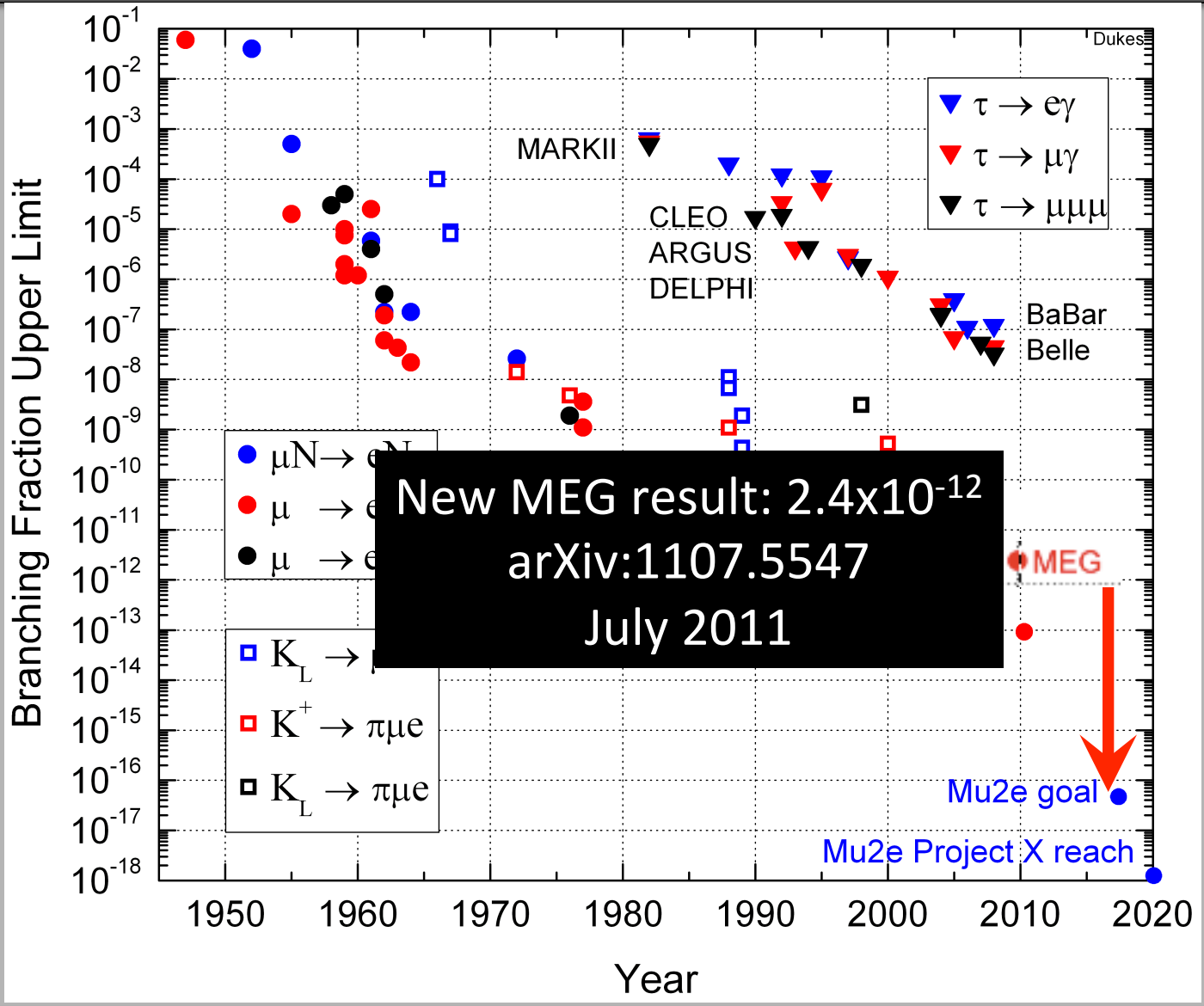
- Signal is a single 105 MeV e-.
- Many possible sources of background events:
  - Muon decay in Coulomb orbit (DIO)
  - Radiative muon/pion capture
    - →Photon produced that can convert asymmetrically
  - Beam electrons can scatter in target
  - Muon/pion decay in flight
  - Antiprotons and other late arriving particles
  - Cosmic-ray induced electrons

These can all be controlled
and none produce a sharp peak at 105 MeV!

History of CLFV Searches



History of CLFV Searches

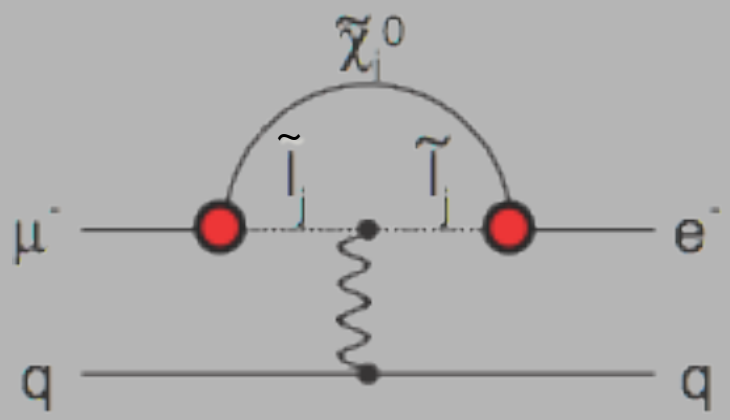


CLFV from SUSY

Access to SUSY through loops.

Supersymmetry

rate ~ 10^{-15}



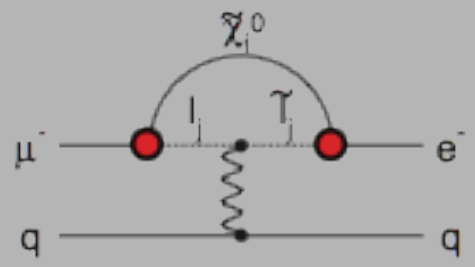
In Mu2e, a signal of Terascale physics at LHC implies:

$$\sim \frac{\textbf{40 signal events}}{\textbf{0.2 background events}}$$

Other "new physics" also provide Mu2e signal

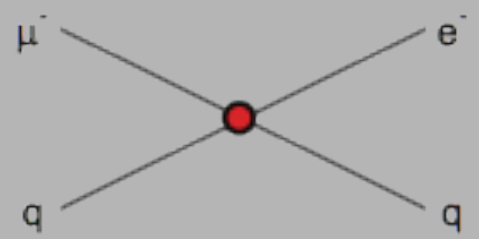
Supersymmetry

rate ~ 10^{-15}



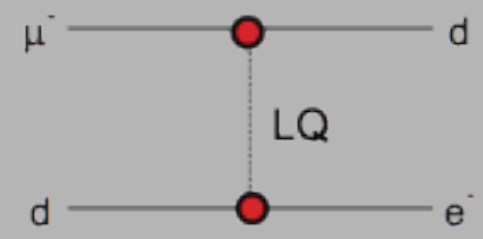
Compositeness

Λ_c ~ 3000 TeV



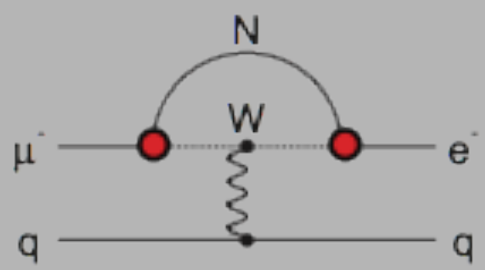
Leptoquark

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



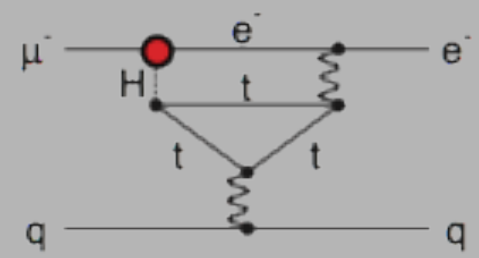
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



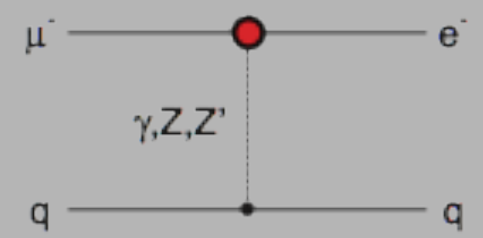
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



Marciano, Mori, and Roney , Ann. Rev. Nucl. Sci. 58

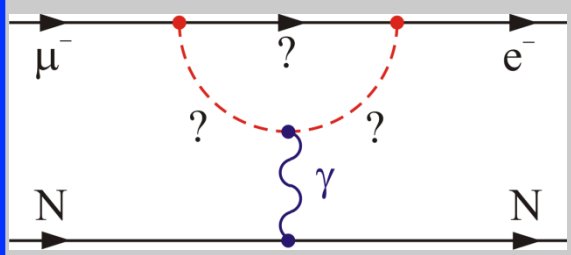
CLFV in $\mu^+ \rightarrow e^+\gamma$ and $\mu^- N \rightarrow e^- N$

Model independent effective CLFV Lagrangian

$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L$$

Mass scales probed ~10,000 times that probed directly by LHC

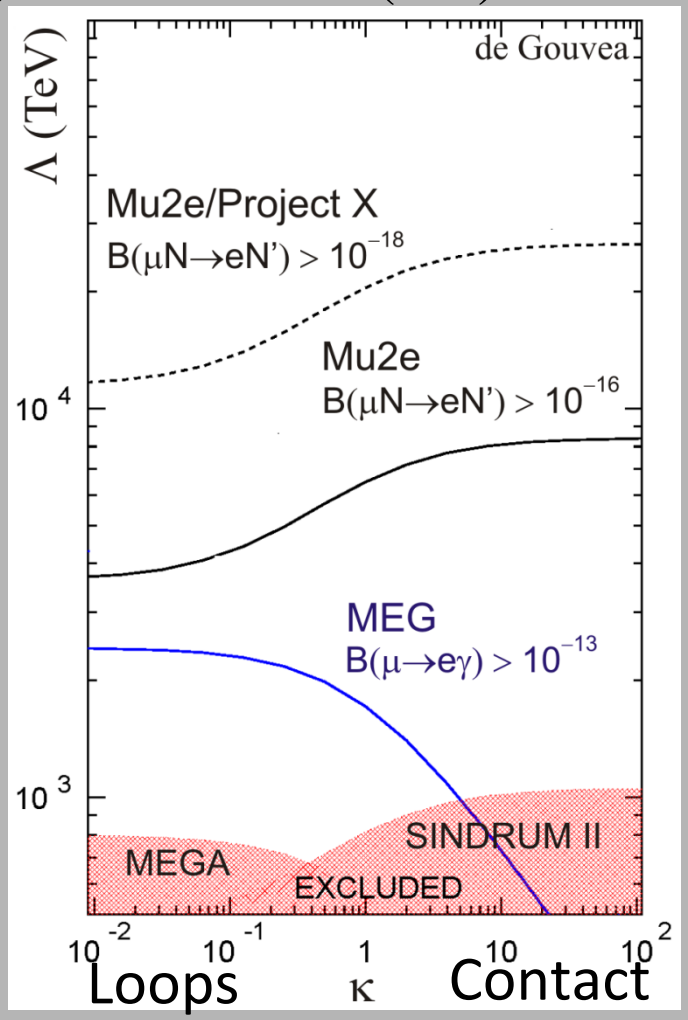
Loops



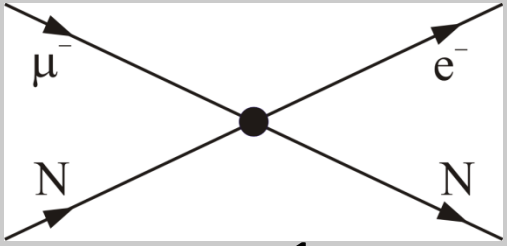
$\kappa << 1$

magnetic moment type operator

$\mu \rightarrow e\gamma$ rate ~300X $\mu N \rightarrow eN$ rate



Contact Interactions



$\kappa >> 1$

four-fermion interaction

$\mu N \rightarrow eN >> \mu \rightarrow e\gamma$ rate

Constraints on new physics

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

Neutrino-Matrix Like (PMNS)

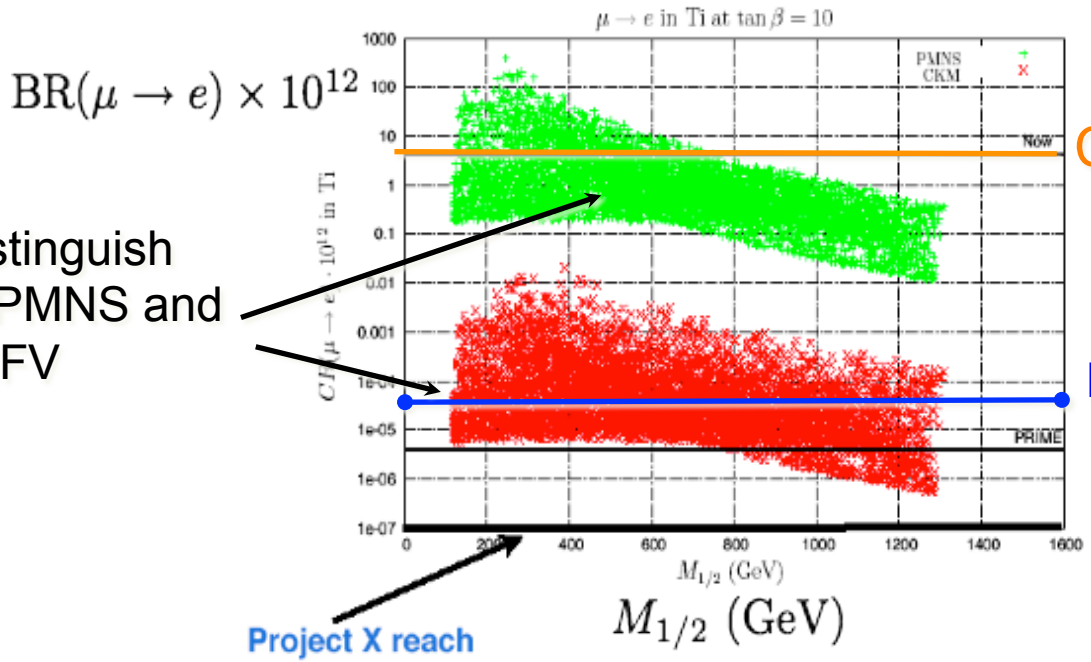
Minimal Flavor Violation(CKM)

$\tan\beta = 10$

Current limits

Mu2e

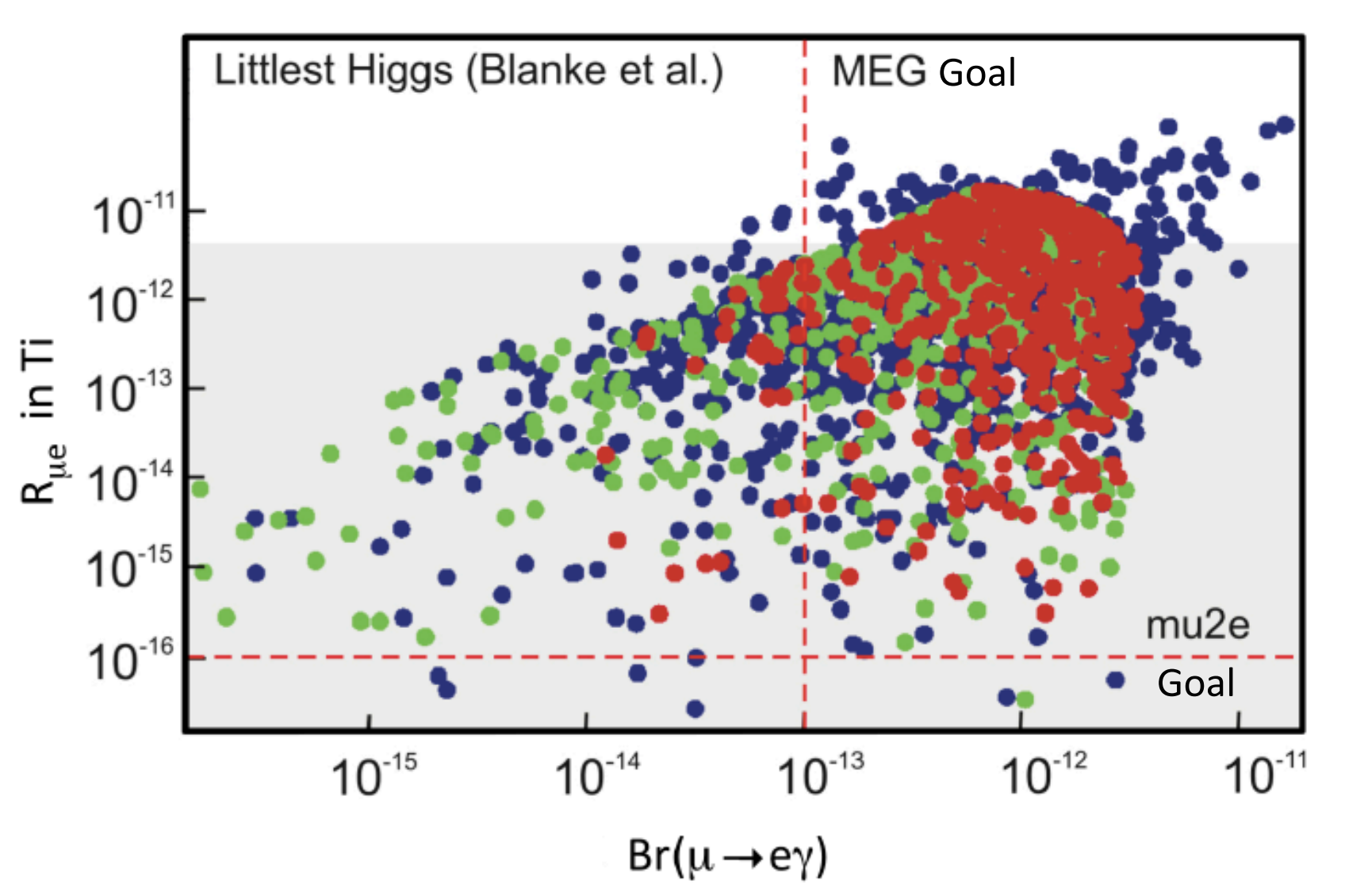
Can distinguish between PMNS and MFV



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

Complementarity between Lepton Flavor Violation (LFV) and LHC experiments

Constraints on new physics



Mu2e Beyond the LHC

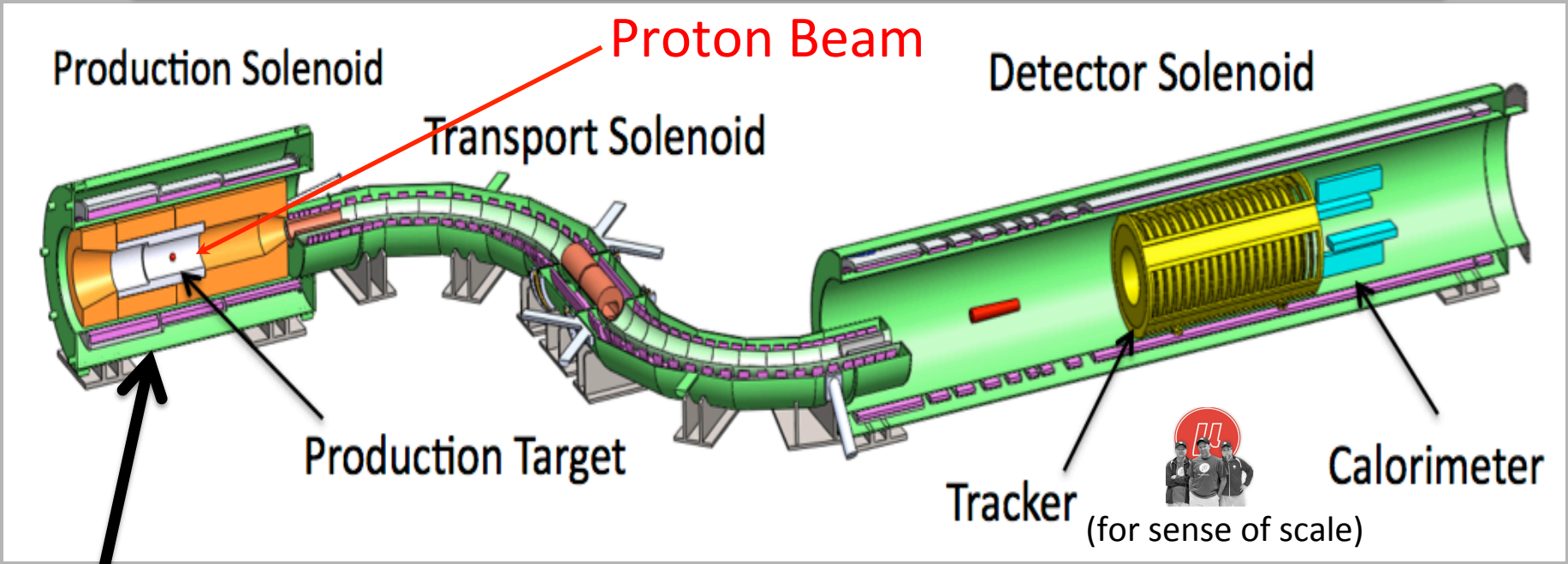
Provides information about flavor structure of new physics even if it is not easily accessible at the LHC.

A null result at the proposed sensitivity will severely constrain new physics models.

CLFV is predicted at observable rates for Mu2e in many models of new physics.

Mu2e can probe mass scales up to 10^4 TeV, far beyond the direct reach of the LHC.

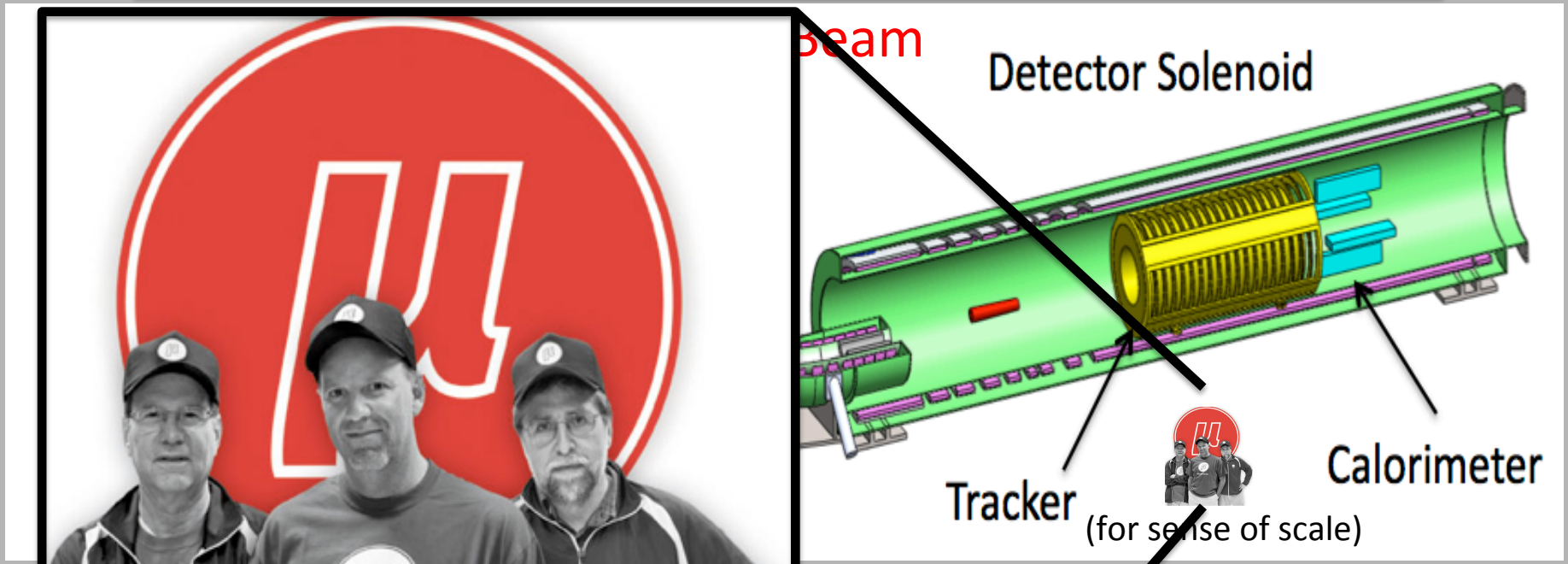
The Mu2e Experiment



1)

- Proton beam hits production target in Production Solenoid.
- Pions captured and accelerated towards Transport Solenoid by graded field.
- Pions decay to muons.

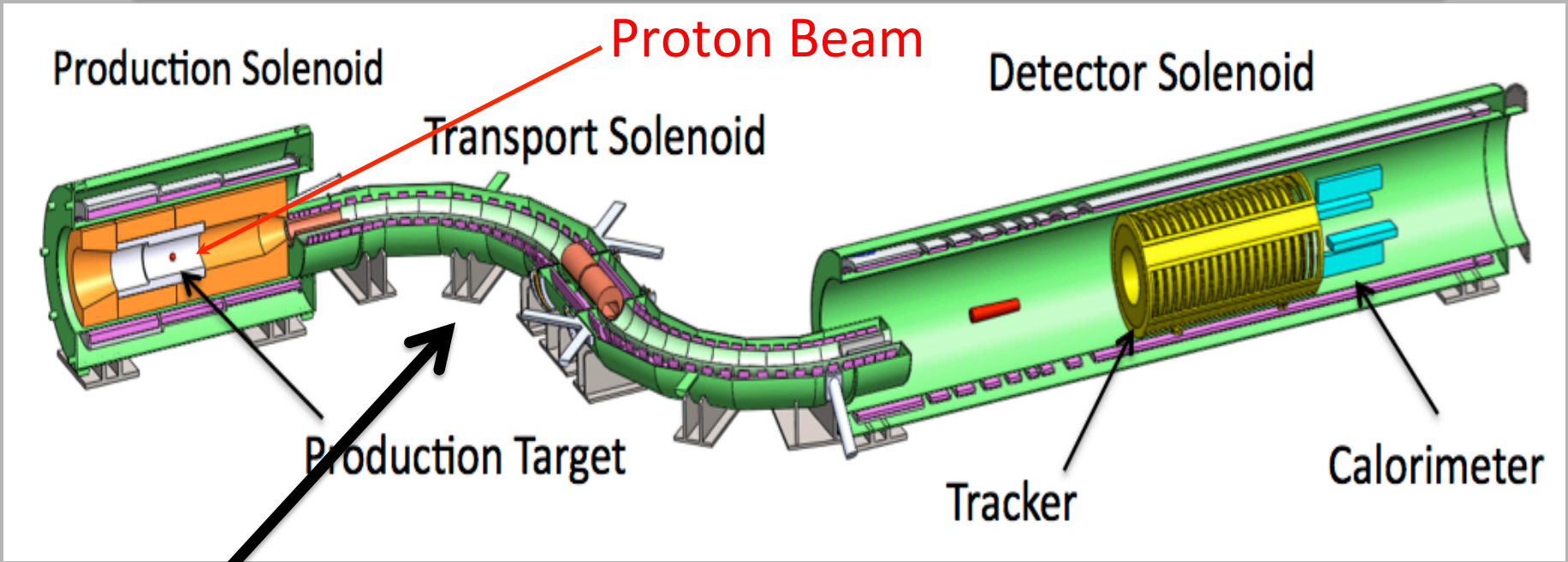
The Mu2e Experiment



Courtesy of Symmetry Magazine.

- duction target in Production
- ccelerated towards Transport
- eld.

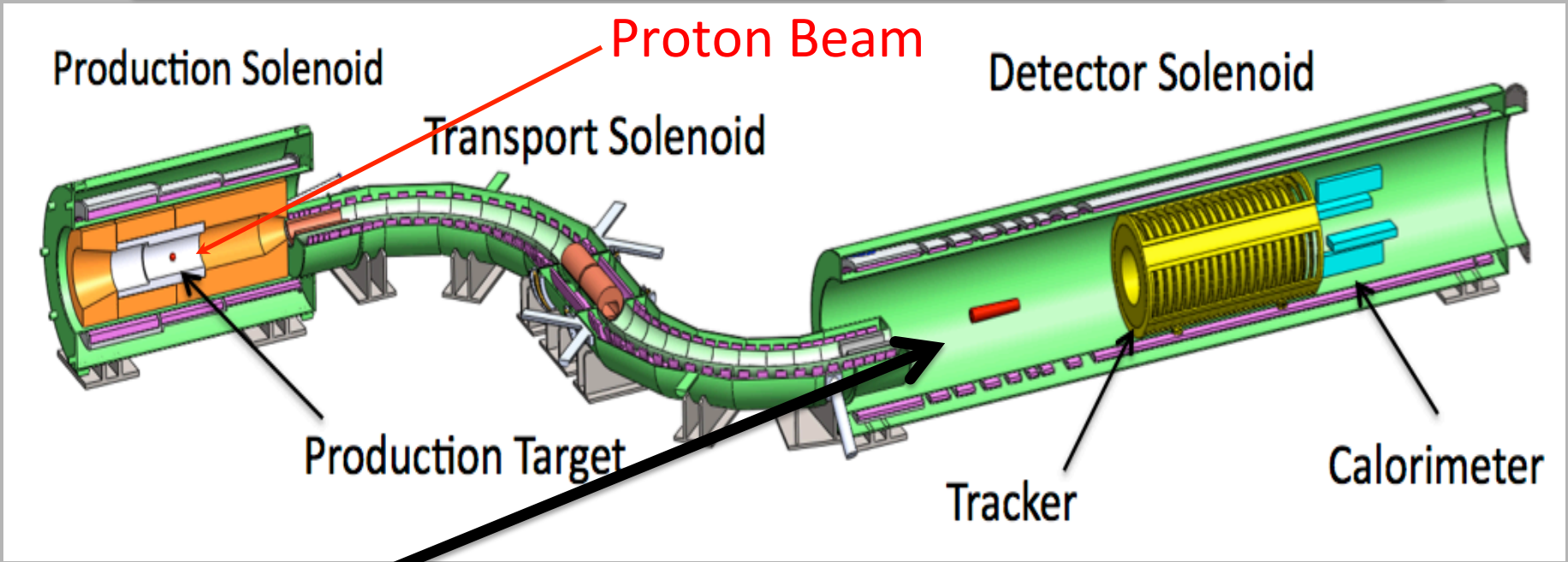
The Mu2e Experiment



2)

- Transport solenoid performs sign and momentum selection.
- Eliminates high energy negative particles, positive particles and line-of-sight neutrals.

The Mu2e Experiment



3)

- Muons stop in target and decay.
- Conversion electron trajectory measured in tracker, validated in calorimeter.
- Cosmic Ray Veto surrounds Detector Solenoid.

Sensitivity Goal

Current limits: $R_{\mu e} = \frac{\mu^- Au \rightarrow e^- Au}{\mu^- Au \rightarrow \text{capture}} < 7\text{x}10^{-13}$ (SINDRUM II)

Mu2e goal: $R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow \text{capture}} < 6\text{x}10^{-17}$ (90% c.l.)

X10000 improvement over current best limit!

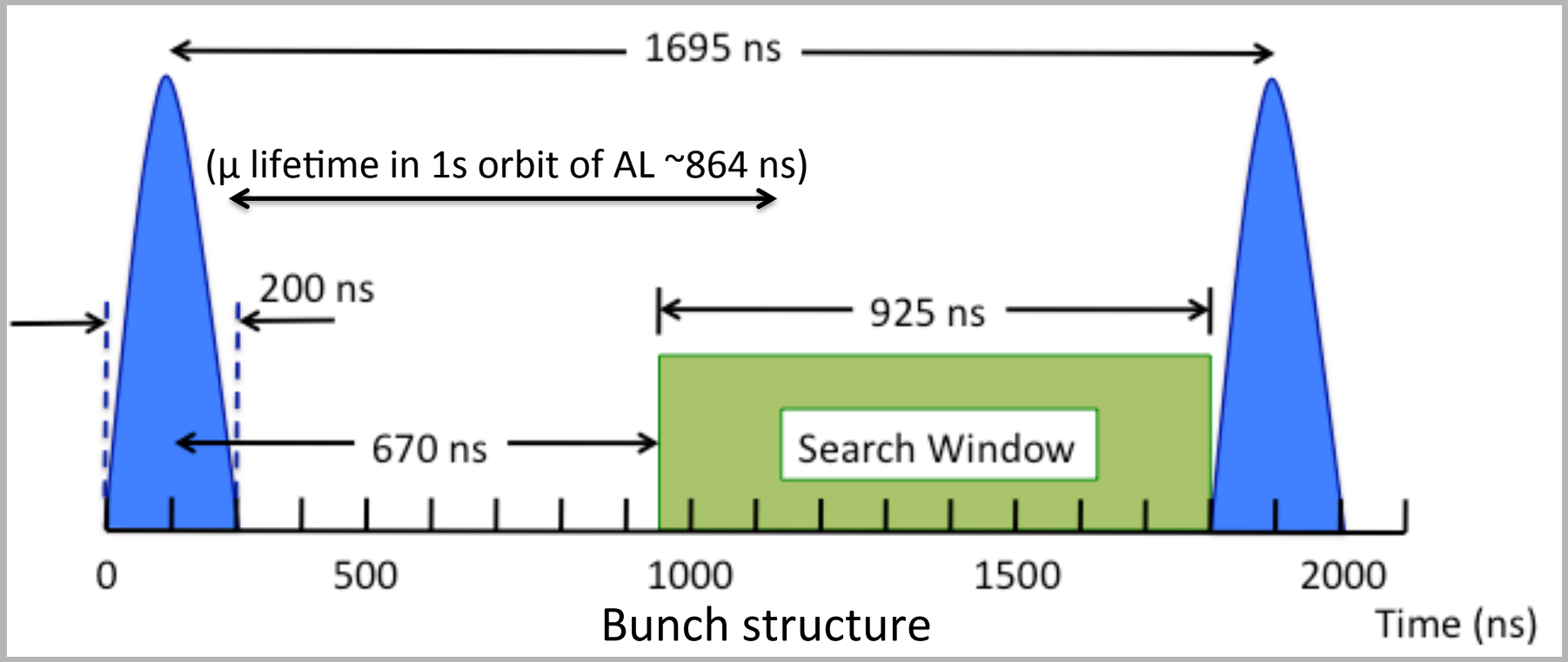
How:

- Improved efficiency for producing and stopping muons
  - Production target in gradient field*
  - Mu2e will stop 50 billion muons per second!
  - Expect to stop 21 muons per 10,000 proton on target.
- Reduced backgrounds and detector occupancy due to pulsed beam
  - Single event sensitivity! <0.2 bkg events expected in 2-year run

* Djilkibaev, Lobashev *et. al.*

4 Orders-of-Magnitude?

- We have the best accelerator setup in the world for this measurement! Ideal pulse spacing…

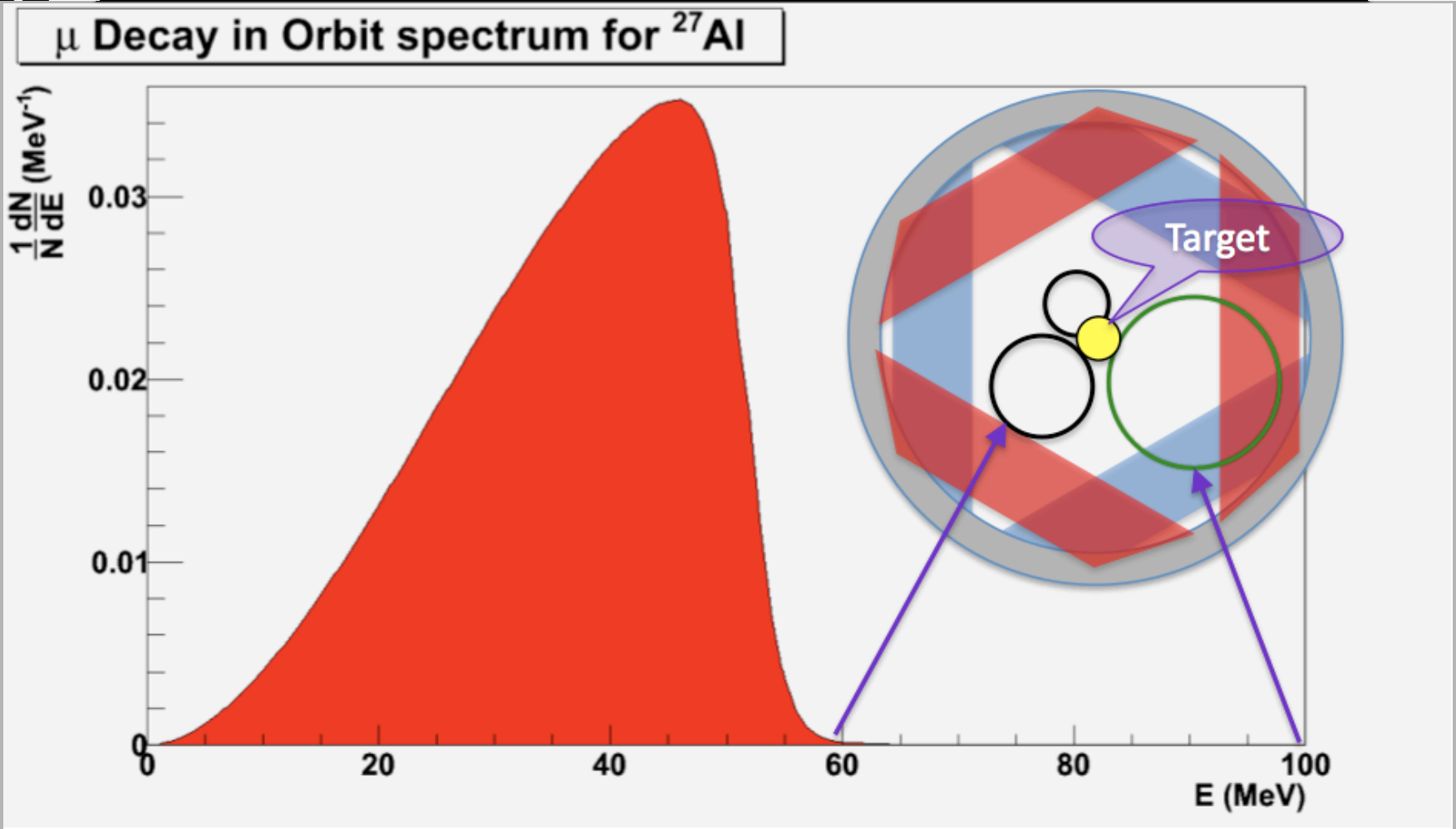


Bunch structure

Extinction level of 10^{-10} between bunches is crucial!

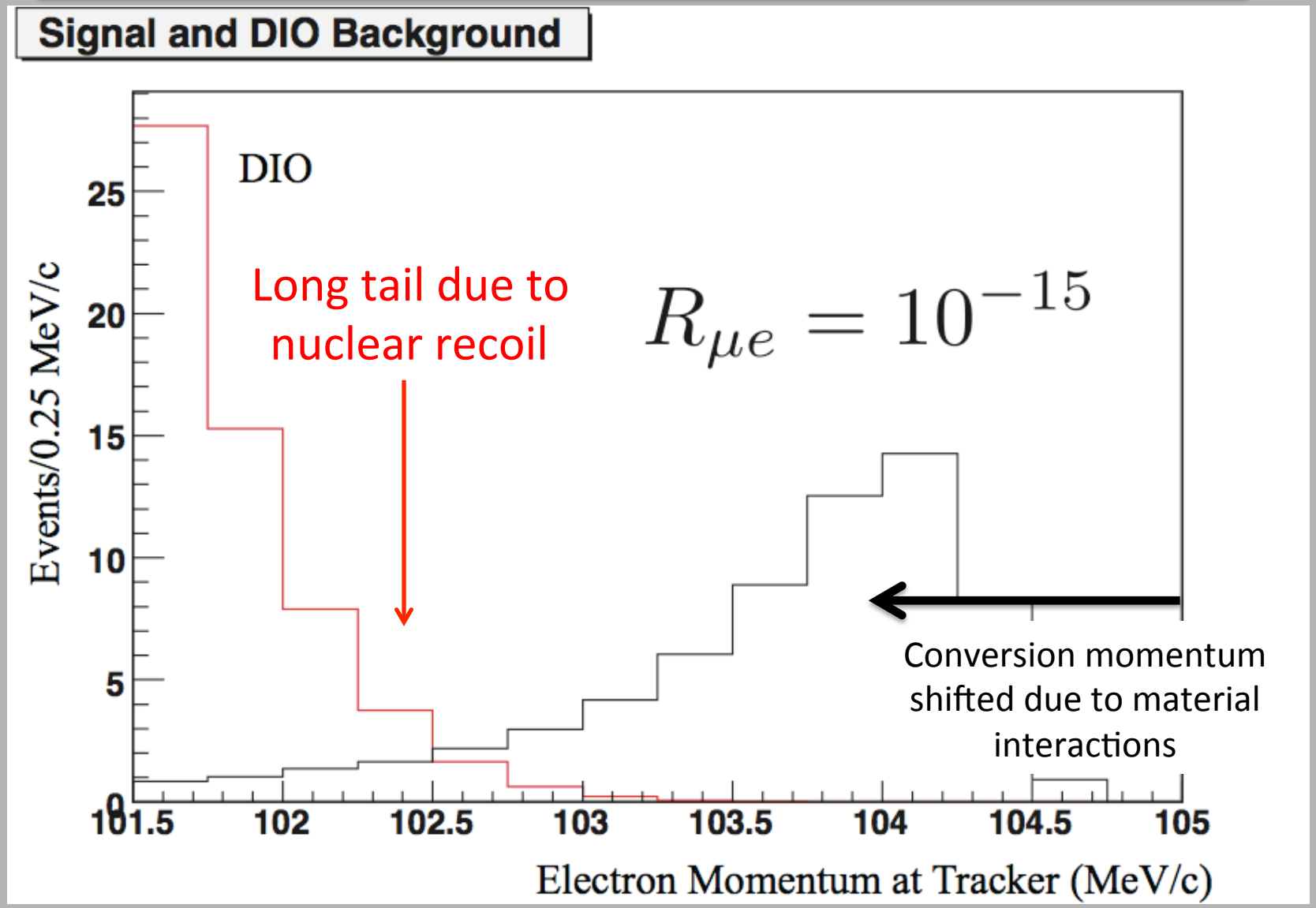
(Removes 'prompt' backgrounds!)

4 Orders-of-Magnitude?

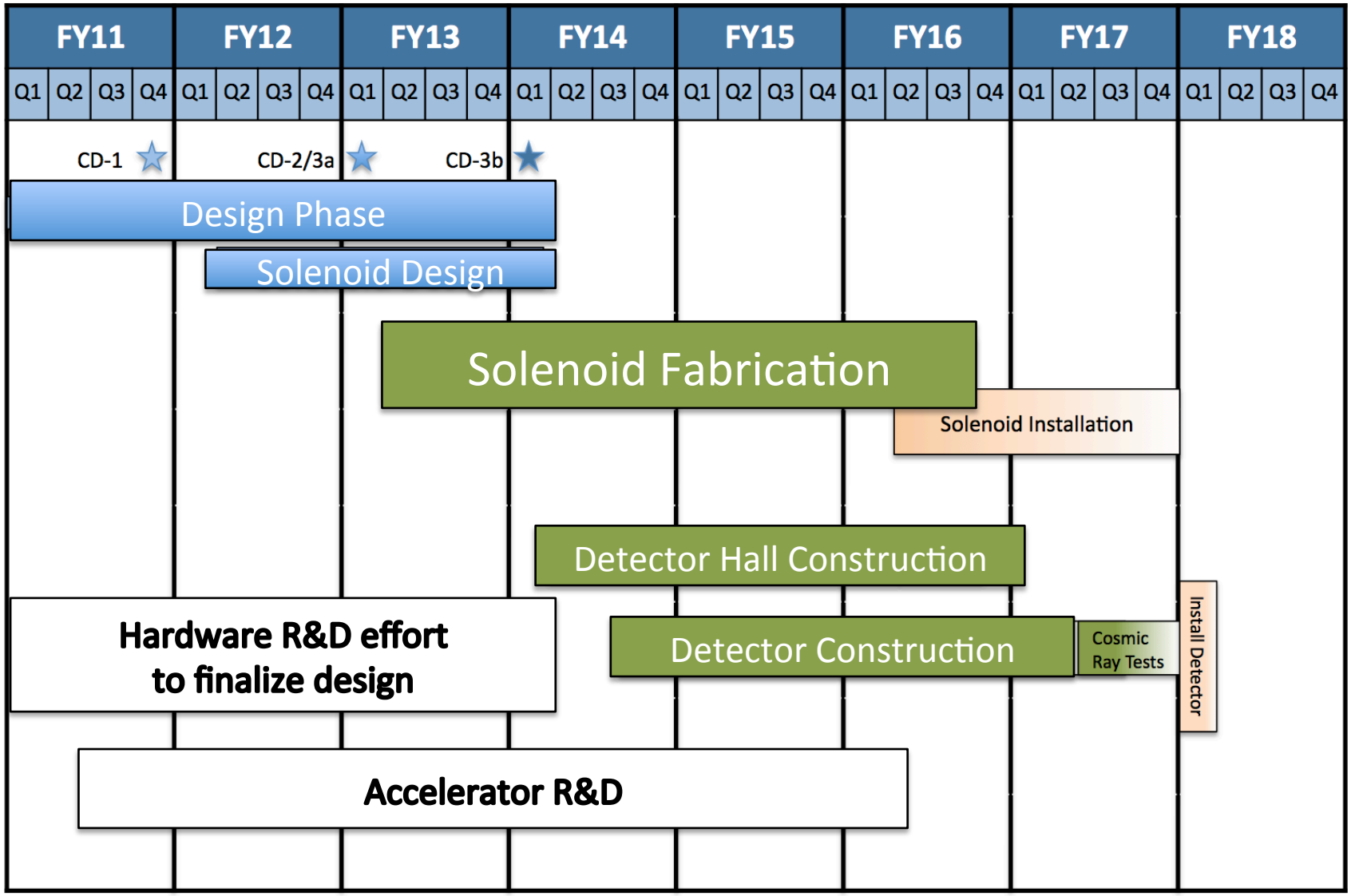


→ Straw tracker designed such that no acceptance for lower-energy electrons from muon decay in orbit.

4 Orders-of-Magnitude?



Mu2e Schedule



The Mu2e Collaboration

Boston University
Brookhaven National Laboratory
Cal Tech
University of California, Berkeley
University of California, Irvine
City University of New York
Duke University
Fermilab
University of Houston
University of Illinois, Urbana-Champaign
Institute for Nuclear Research, Moscow
JINR, Dubna, Russia
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
Northwestern University
INFN Frascati
INFN Pisa, Università di Pisa, Pisa, Italy
University of Massachusetts
INFN Lecce, Università del Salento, Italy
Rice University
Syracuse University
University of Virginia
College of William and Mary
University of Washington, Seattle

~120 collaborators

Summary

- The intensity frontier and flavor physics may well reveal a sign of exotic physics!
- Mu2e will improve sensitivity by 4 orders-of-magnitude relative to past CLFV searches.
- Mu2e will provide complementary information relative to the LHC and is sensitive to mass scales many orders of magnitude higher than can be directly probed at colliders.

Backup

CDR

Conceptual Design Report

March 2011

DRAFT

The Mu2e Project

Fermilab

Mu2e Review Status

- Mu2e received mission-need approval from DOE in November 2009.
- From our Mission Need Statement:
  - "A muon-to-electron conversion experiment at Fermilab could provide an advance in experimental sensitivity of four orders of magnitude."
- We have a complete set of requirements designed to meet this goal:
  →Describes what each major system component must achieve
- We have a conceptual design that we believe satisfies these requirements.
- Mu2e had a successful Independent Design Review on May 3rd and 4th
- Two more reviews later this Summer…

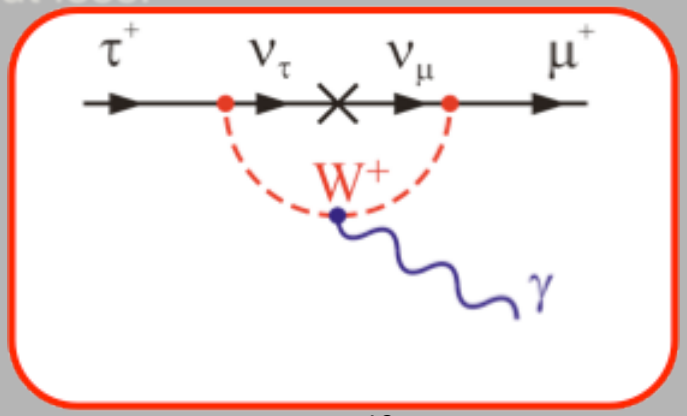
Goal: Approved conceptual design by end of 2011

Possible Scenarios

- We see something the first year!
  - Change target to better constrain the new physics rule out some backgrounds.
- See something with two years of data:
  - Plan for intensity upgrade
  - New targets…
- Don't see anything:
  - Intensity upgrade to Project X for sensitivity improvement of two additional orders-of-magnitude.

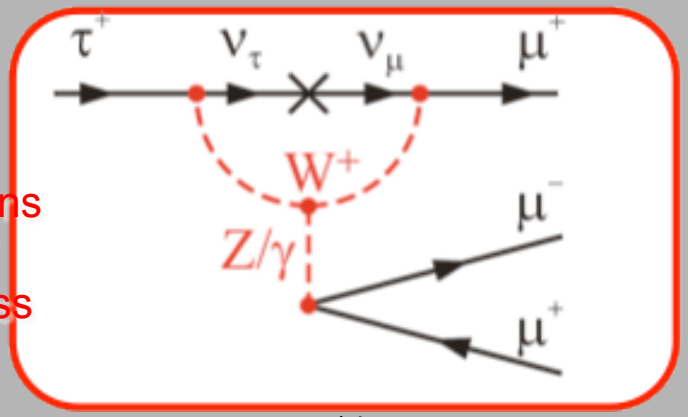
CLFV and Tau Decays

τ processes also suppressed in Standard Model but less:



SM ~ 10^{-40}

Smaler GIM Cancellations because of large τ mass



SM ~ 10^{-14}

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

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)

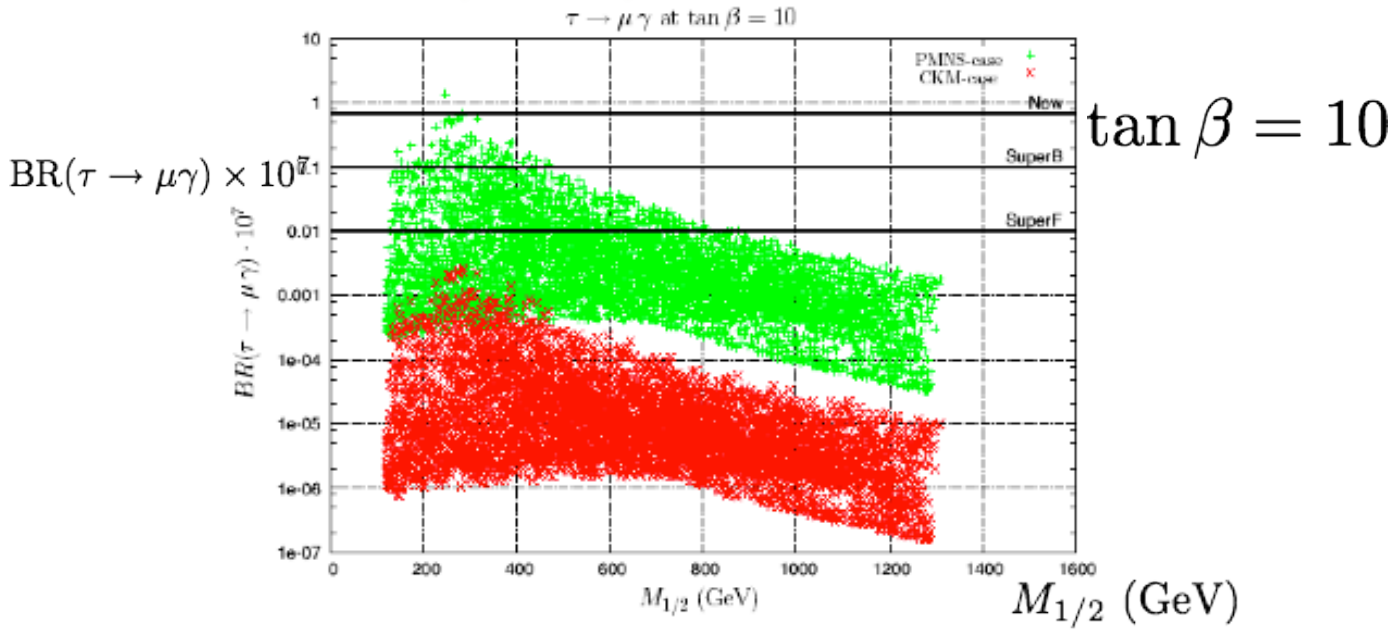
also $e \rightarrow \tau$ at electron-ion collider?
M. Gonderinger, M. Ramsey-Musolf, arXiv:1006.5063v1

Supersymmetry in Tau LFV

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

Neutrino-Matrix Like (PMNS)

Minimal Flavor Violation(CKM)



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

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