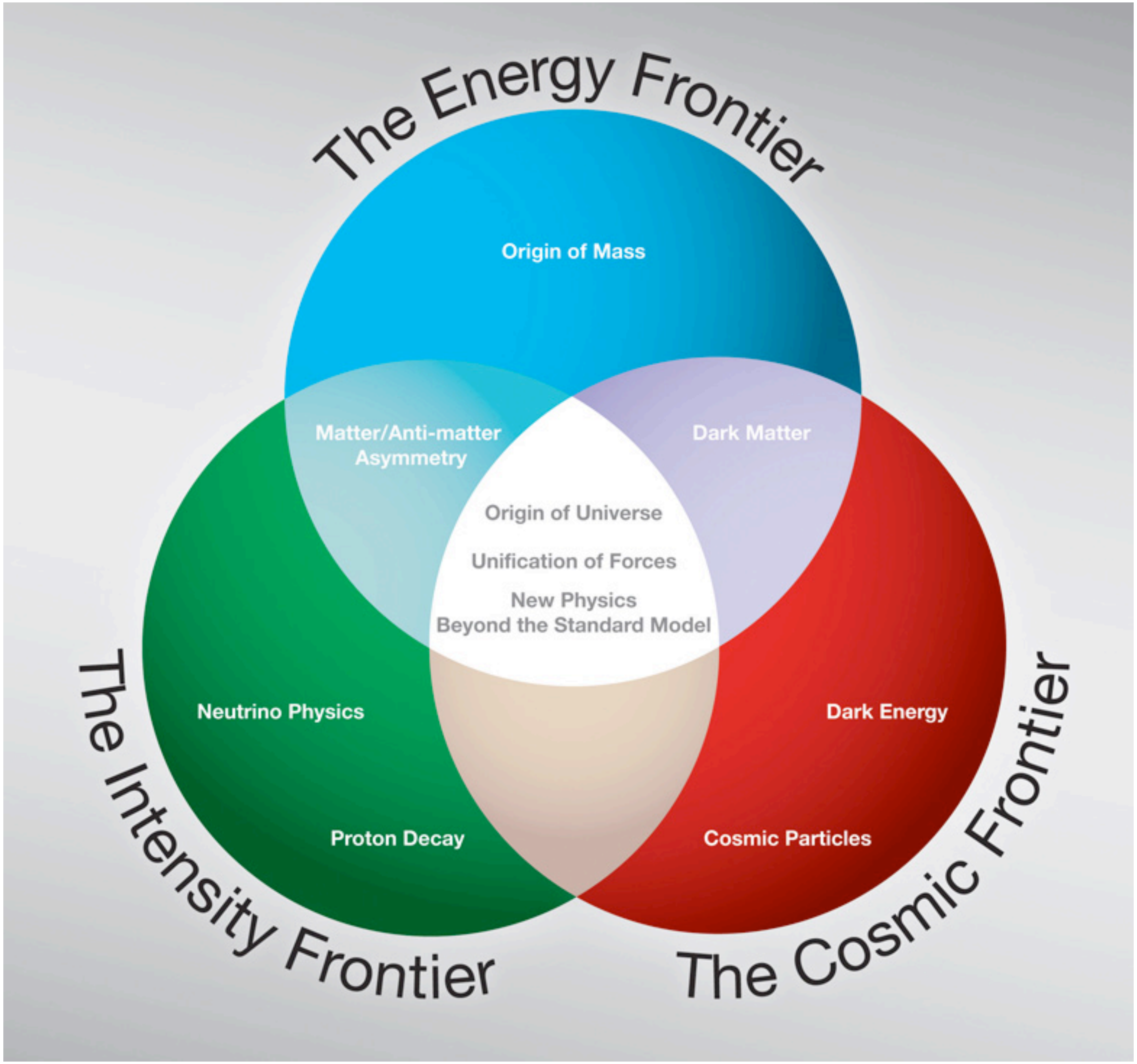
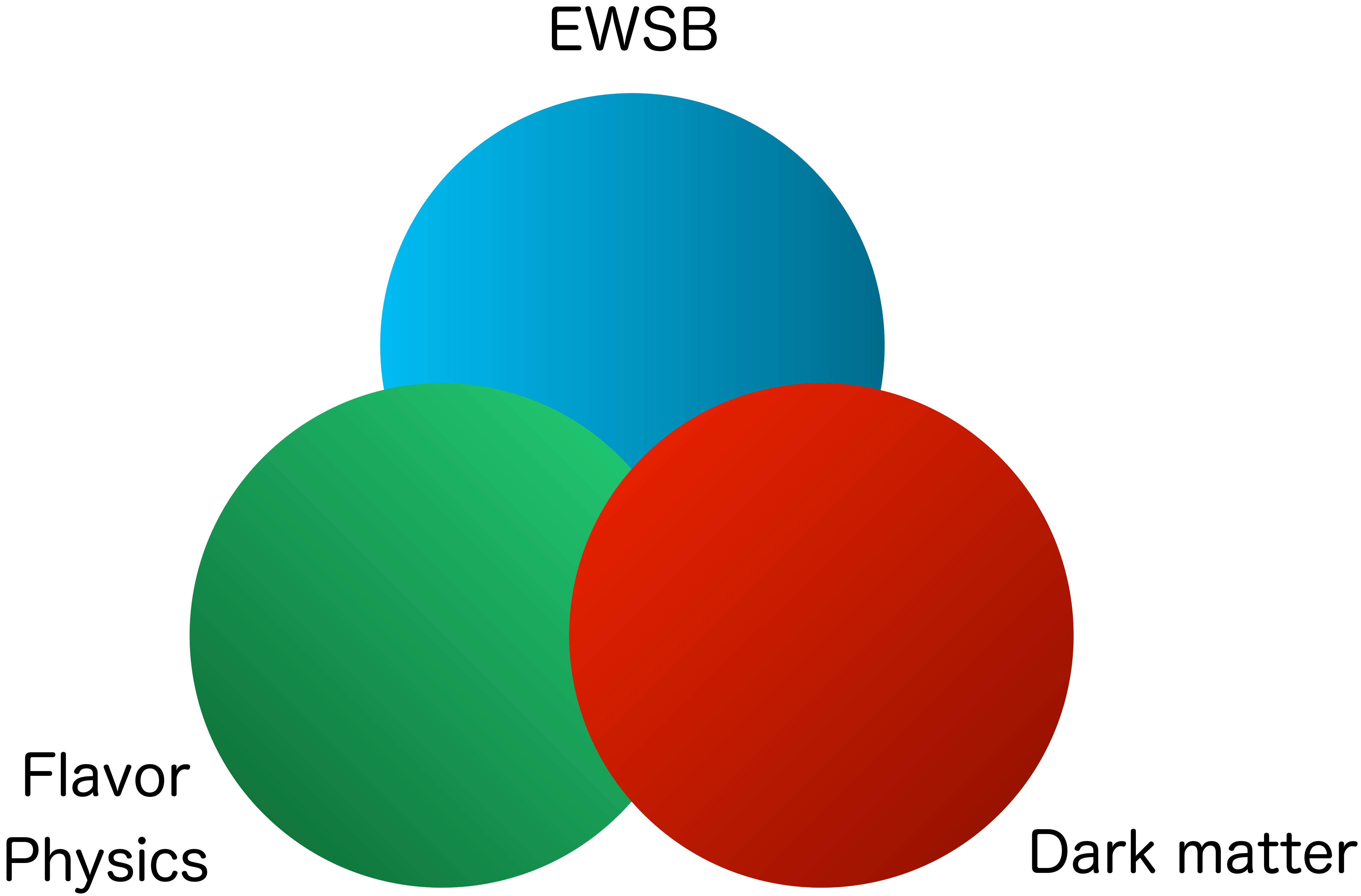
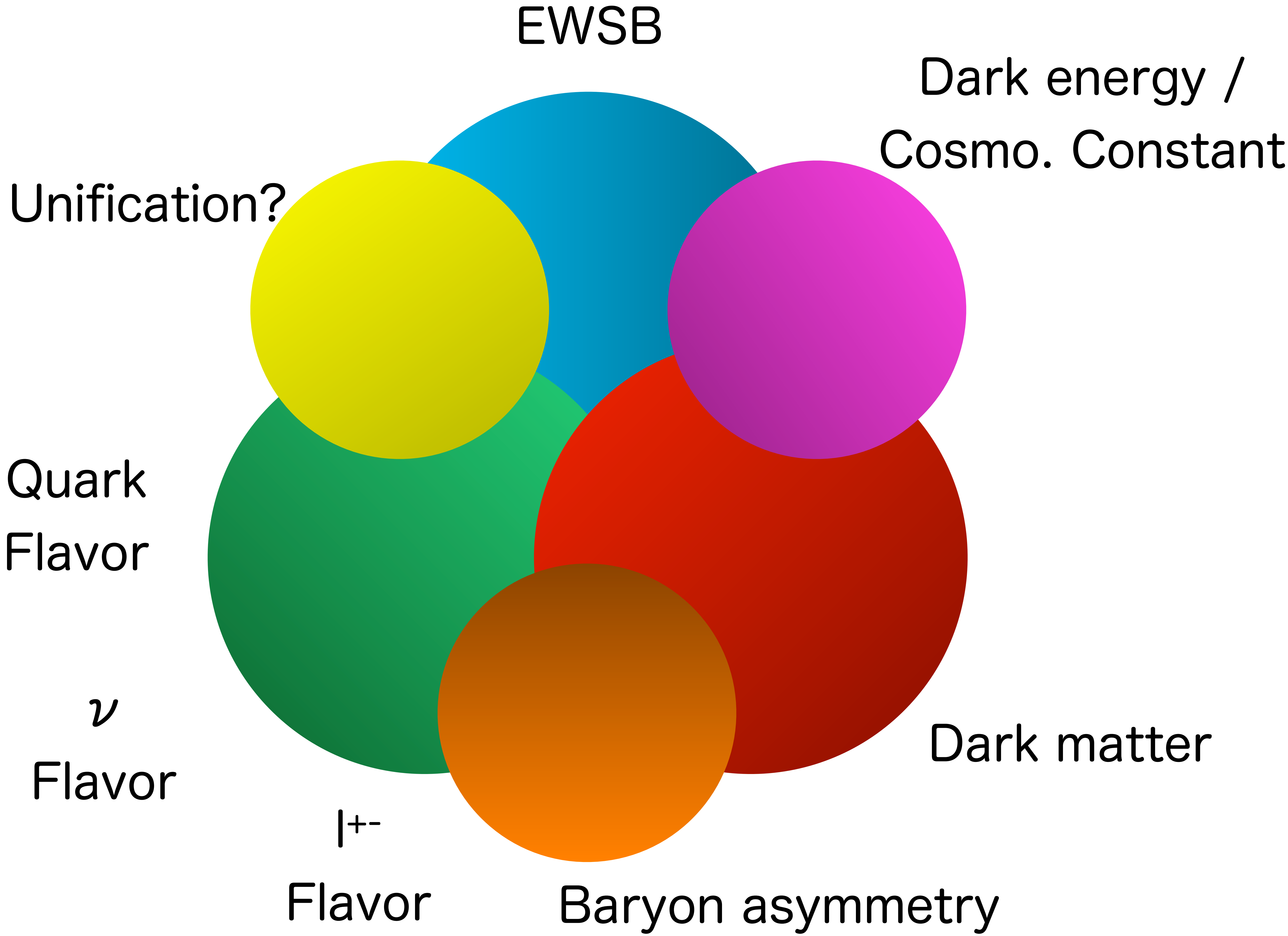
# Muon Physics Summary

Graham Kribs


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier


EWSB
Flavor
Physics
Dark matter


EWSB
Dark energy / Cosmo. Constant
Unification?
Quark Flavor
$\nu$ Flavor
$l^{+-}$ Flavor
Baryon asymmetry
Dark matter

Flavor Physics

50+ years of heroic measurements have precisely characterized flavor sector of SM
(masses & mixings of q & l).

Yet, we are no closer to an "origin" or "theory" of flavor.

Flavor Physics

Dark matter

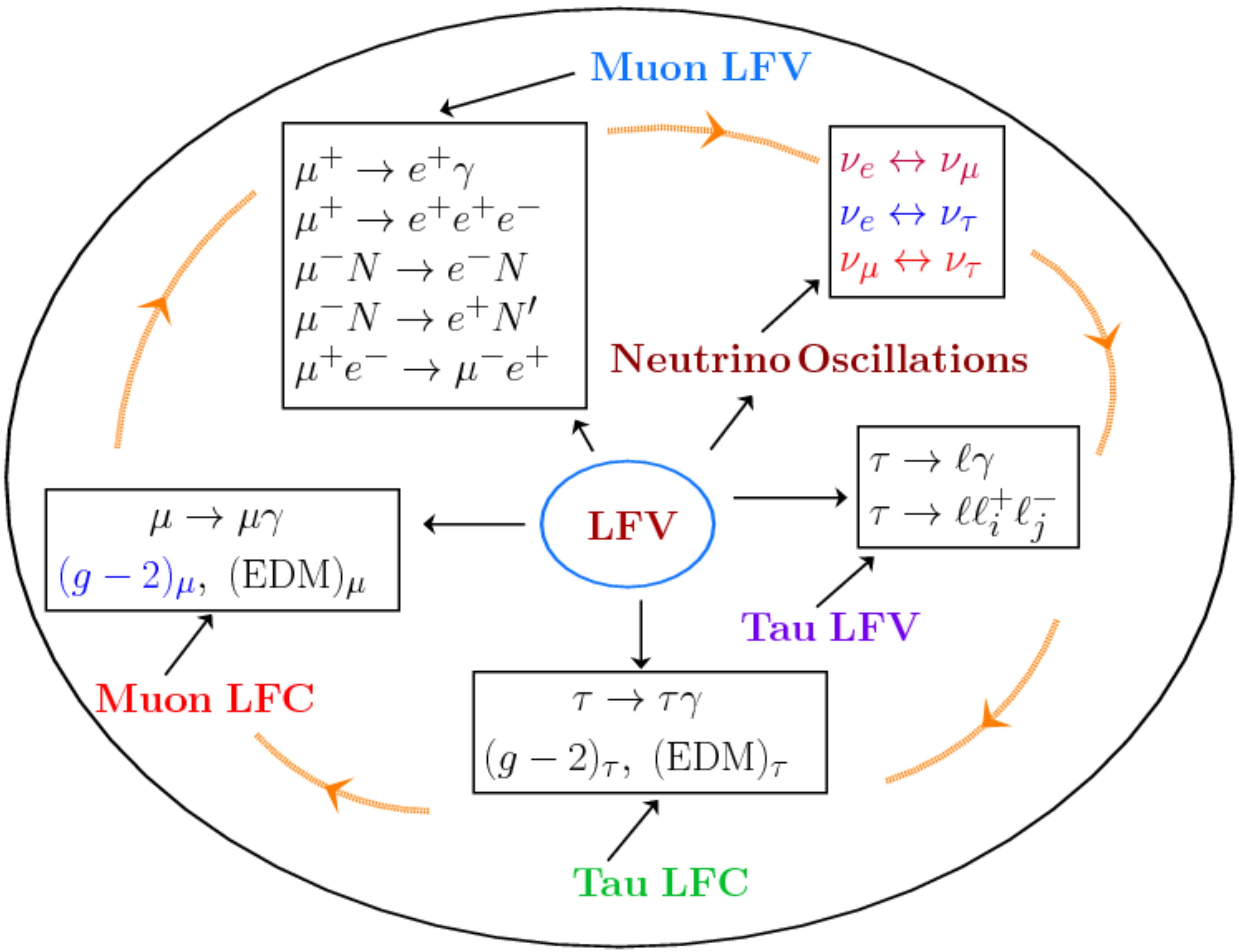
1 event* would rock our world!

e.g. $\mu$ -> e transition

e.g. direct detection nuclear recoil

*(in principle)

# Lepton Flavor Physics: The Big Picture




Babu

# Muon flavor-conserving puzzles

# Muon (g-2) Anomaly

$$a_\mu = (g_\mu - 2)/2$$

$$a_\mu(\text{Expt}) = 116\,592\,089\,(54)(33) \times 10^{-11}$$

BNL E821 (2006)

$$a_\mu(\text{SM}) = 116\,591\,802\,(42)(26)(02) \times 10^{-11}$$

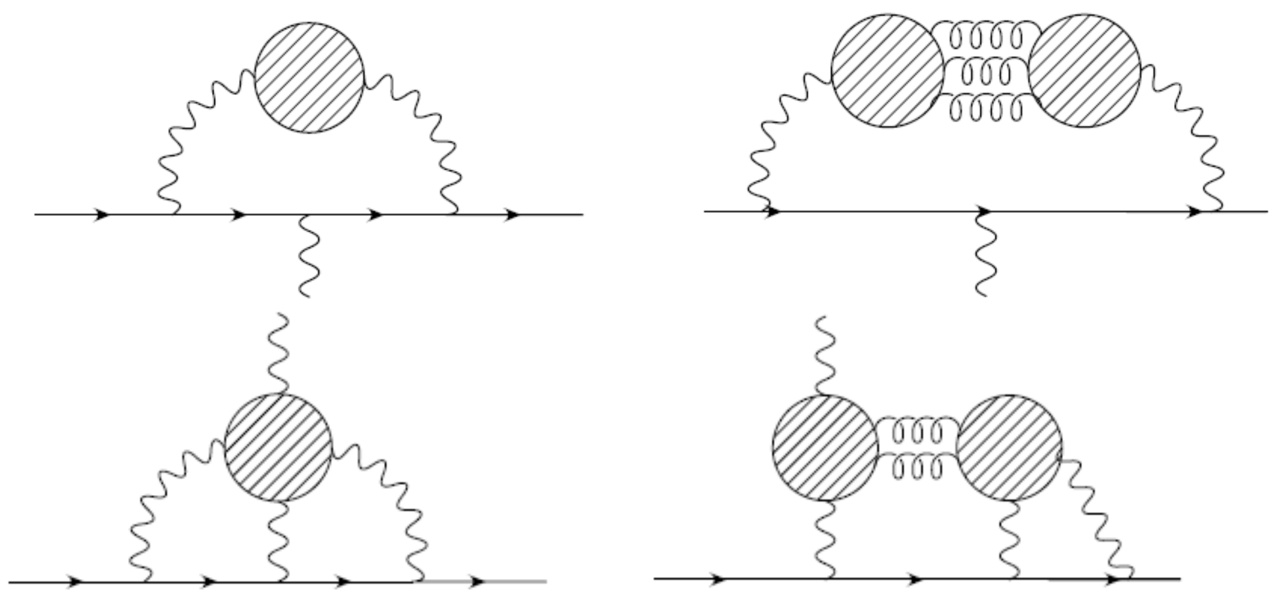
$$\Rightarrow \quad \Delta a_\mu = 287(80) \times 10^{-11}$$

$3.6\sigma$ discrepancy

10th orderr QED contributions now fully evaluated

(T. Aoyama et. al., 2012)

Major theory uncertainty in hadronic vacuum polarization



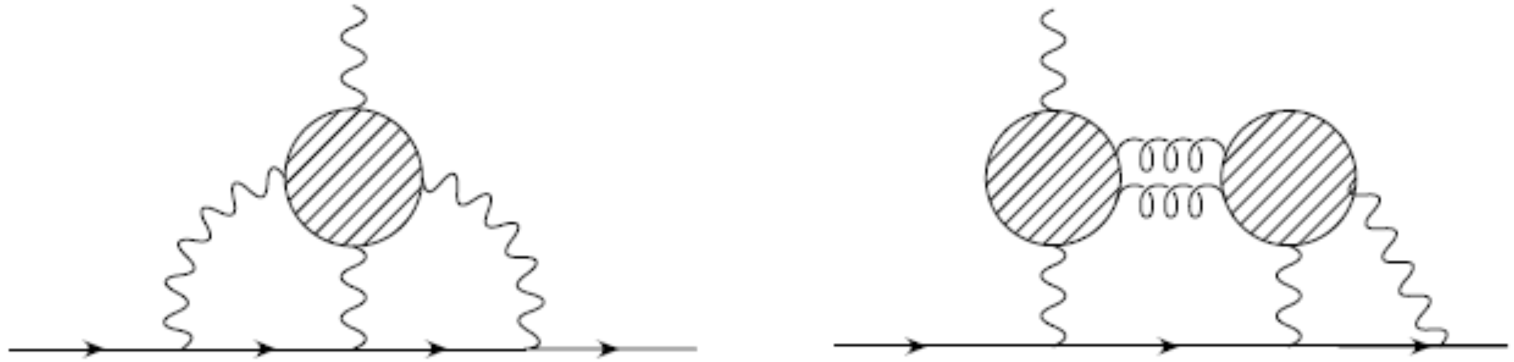
$$a_\mu(\text{HVP}) = (692.3 \pm 4.2) \times 10^{-10}$$

$$= (701.5 \pm 4.7) \times 10^{-10}$$

$(\tau \to$ hadrons data)

$$a_\mu(\text{HLbL}) = 105\,(26) \times 10^{-11}$$

Babu



$a_\mu$(HLbL)

## Models

- See INT workshop (Seattle, Feb. 2011), http://www.int.washington.edu/PROGRAMS/11-47w/
- Low energy effective theories, $\chi$PT, ...
- Operator product expansion constraints
- holographic QCD (extra-dimensions)
- Schwinger-Dyson (out-lier)
- Glasgow Consensus, $a_\mu(\mathrm{HLbL}) = 10.5 \pm 2.6 \times 10^{-10}$
- $\pi \to \gamma^* \gamma$ (KLOE, lattice, ...)
- Model errors not systematically improveable

Blum 2011

# Preliminary Lattice Calculations for HLbL

## $a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

- $a_\mu(\mathrm{HLbL}) = (-15.7 \pm 2.3) \times 10^{-5}$ (lowest non-zero mom, $e = 1$)
- HLBL amplitude depends strongly on $m_\mu$ ($m_\mu^2$ in models)
- Magnitude 5-10 times bigger, sign opposite from models
- models not expected to be accurate in this regime
- Check subtraction is working by varying $e = 0.84, 1.19$
  - HLbL amplitude ($\sim e^4$) changes by $\sim 0.5$ and 2 ✓
  - while unsubtracted amplitude stays the same ✓

## $a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

- Easy to lower muon mass (muon line is cheap)
- Try $m_\mu \approx 190$ MeV
- $a_\mu(\mathrm{HLbL}) = (-2.2 \pm 0.8) \times 10^{-5}$ (lowest non-zero mom, $e = 1$). Right direction...

## $a_\mu(\mathrm{HLbL})$ in 2+1f lattice QCD+QED (PRELIMINARY)

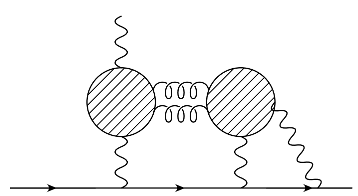
Signal may be emerging in the model ballpark:

- $F_2(0.18\ \mathrm{GeV}^2) = (0.142 \pm 0.067) \times (\frac{\alpha}{\pi})^3$
- $F_2(0.11\ \mathrm{GeV}^2) = (0.038 \pm 0.095) \times (\frac{\alpha}{\pi})^3$
- $a_\mu(\mathrm{HLbL/model}) = (0.084 \pm 0.020) \times (\frac{\alpha}{\pi})^3$

Lattice size $24^3$, $m_\pi = 329$ MeV, $m_\mu \approx 190$ MeV

model value/error is "Glasgow Consensus" (arXiv:0901.0306 [hep-ph])

## HLbL systematic error



"Disconnected" diagrams (quark loops connected by gluons) not calculated yet (not suppressed).

Several possibilities,

1. Use multiple valence quark loops (qQED)
2. Re-weight in $\alpha$ (T. Ishikawa) or dynamical QED in HMC
3. "$\not{A}$ source" (see Izubuchi's talk) (no subtraction)

## HLbL systematics

Need to address

- Finite volume
- $q^2 \to 0$ exptrap
- $m_q \to m_{q,\mathrm{phys}}$
- $m_\mu \to m_{\mu,\mathrm{phys}}$
- excited states/"around the world" effects
- $a \to 0$
- QED renormalization
- ...

Blum 2012

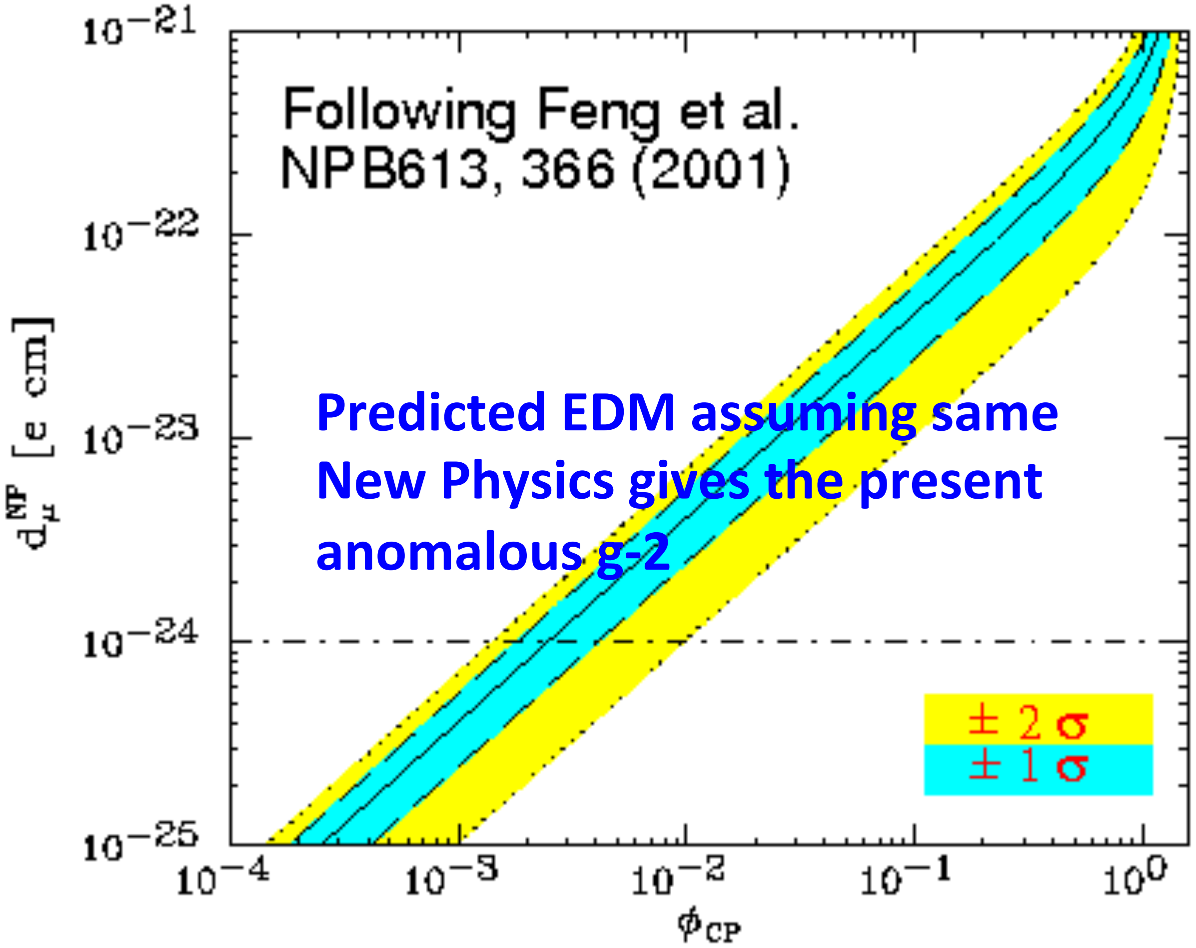
## Summary/Outlook

- Demanding, but straightforward calculation
- Early HLbL lattice calculation encouraging
- Intermediate lattice calculations to check models (four-point, $\pi \to \gamma^* \gamma$, chiral susceptibility, ...)
- Optimistic lattice+models+expt can reach 10% goal in $\sim$ 5 years (INT WS on HLbL, Feb. 2011)
- White papers, prospects for lattice QCD:
  - USQCD white-paper (http://www.usqcd.org/collaboration.html)
  - Fundamental physics at the Intensity Frontier white-paper (arXiv:1205.2671 [hep-ex])
- Expected precision
  - E989: 0.14 PPM (factor of 3-4 better than E821)
  - SM theory, HVP: 0.3% (factor of 2)
  - SM theory, HLbL 10% or better (?)
  - Same central values, $a_\mu$ discrepancy $\to$ 5-8 $\sigma$

Blum 2012

# Muon EDM (entangled with g-2!)

$$\vec{\omega} = -\frac{e}{m}\left\{a\vec{B} + \left(\frac{1}{1-\gamma^2} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

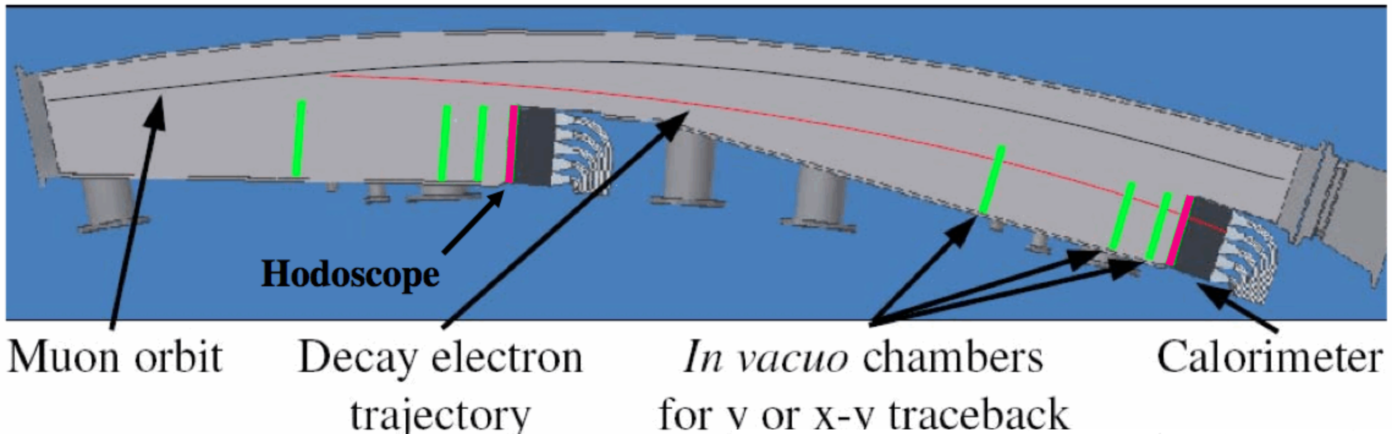


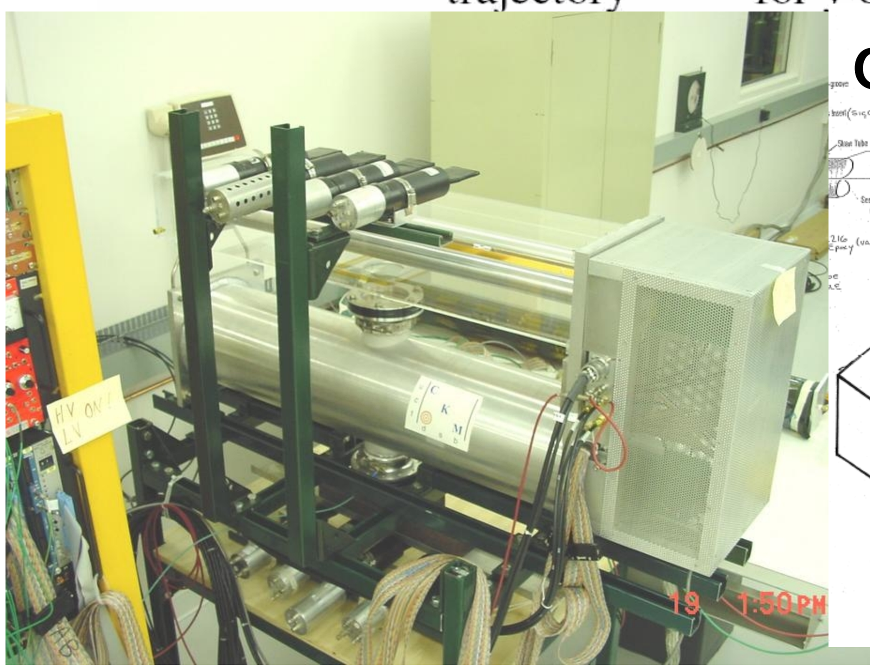

$$d_\mu^{\mathrm{NP}} \simeq 3\times 10^{-22}\left(\frac{a_\mu^{\mathrm{NP}}}{3\times 10^{-9}}\right)\tan\phi_{CP}$$

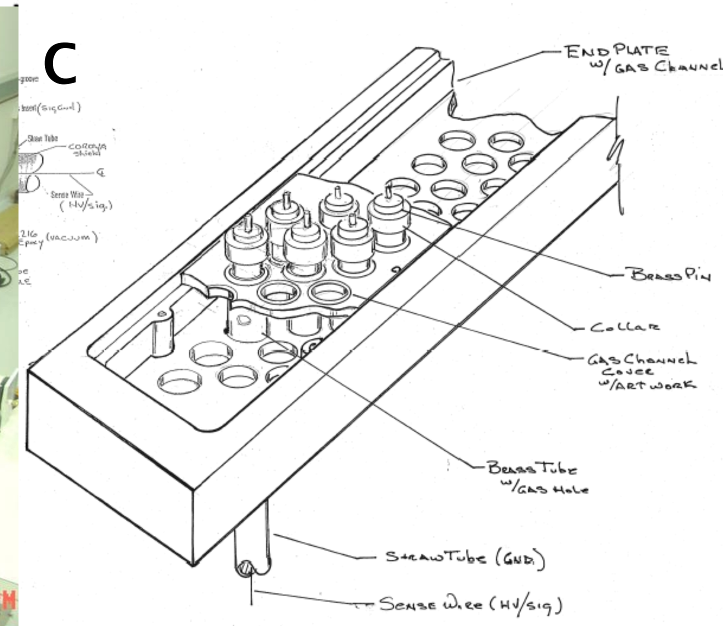
where $\phi_{CP}$ is a $CP$ violating phase.

Lancaster

# *In situ* measurement in E989 FNAL g-2






B. Casey - FNAL

Installing in vacuo tracking chambers

- Track muons for better understanding of $a_\mu$ systematics

- Push $d_\mu$ limits down to $10^{-21}$ e·cm range

Polly (IFW 2011)

# J-PARC Muon EDM beyond $10^{-21}$

Parasitic EDM has intrinsic limitation at ~ $10^{-21-22}$

To go below this : use so-called **“Frozen Spin” technique**
- judicious E and B to cancel magnetic moment contribution

$$\omega = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

Radial E-field without any residual vertical field.

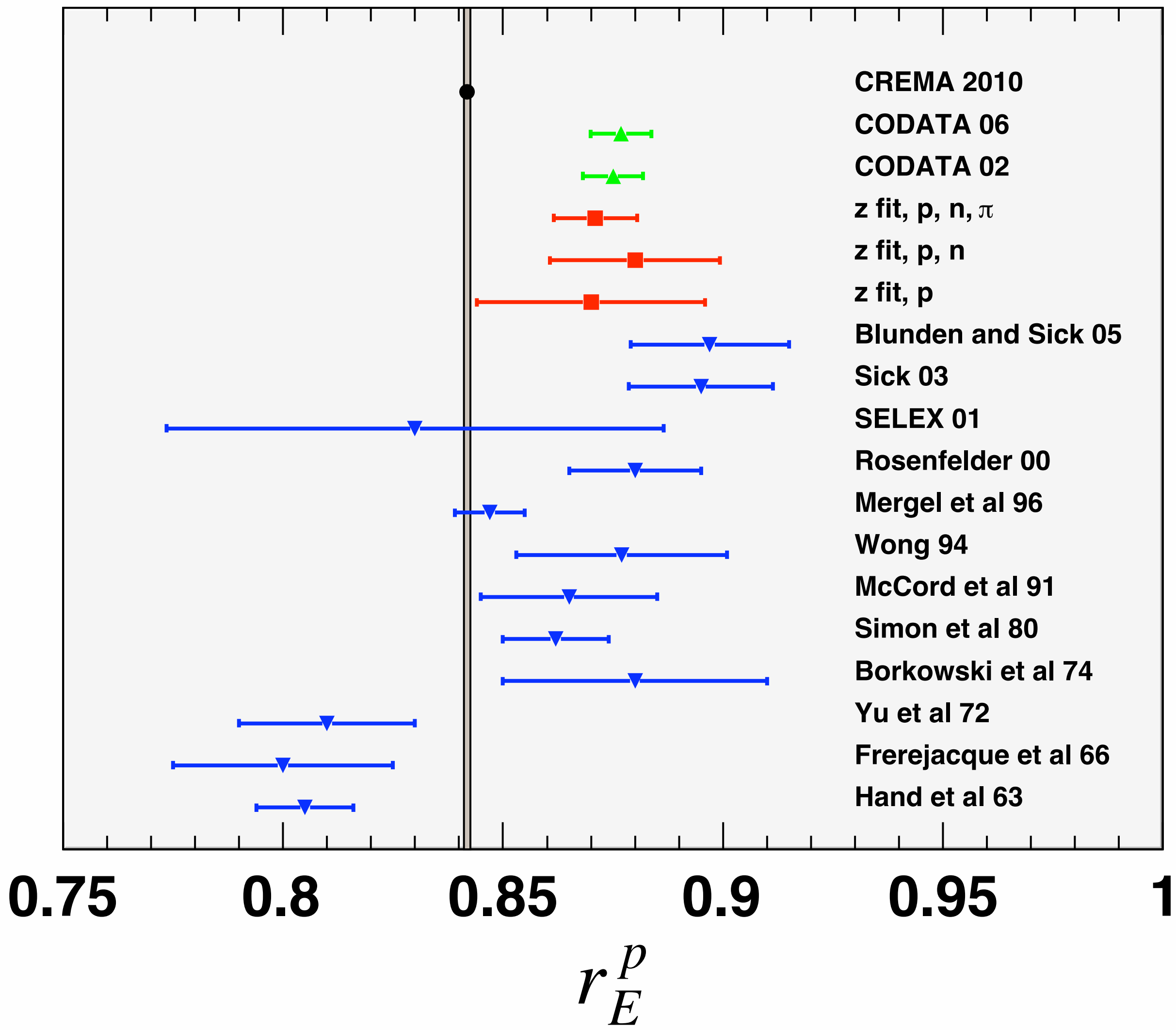
**LOI to J-PARC in 2003 to use dedicated 11m FFAG ring with sensitivity @ $10^{-24}$**
Proof of principle proposed at PSI (2006-2010) with 42cm ring with sensitivity @ $5\text{x}10^{-23}$
- challenging .....

J-PARC PAC / IPNS favours nEDM (E33) experiment over µEDM although nEDM has not yet got stage-1 approval.

Lancaster

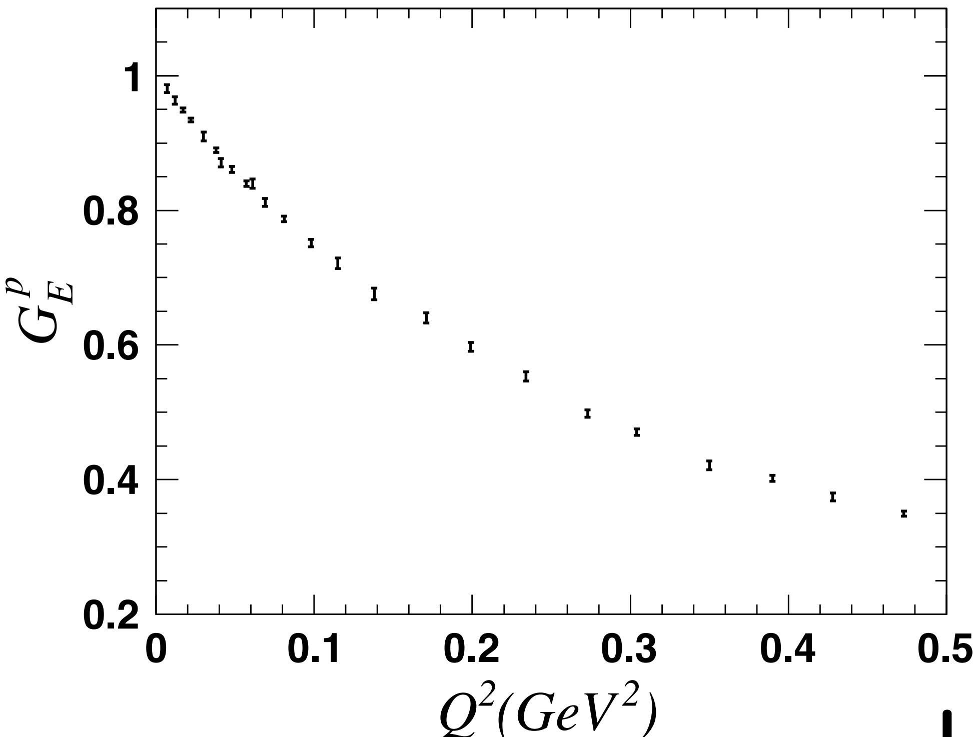
# Proton Charge Radius Puzzle

# the proton radius puzzle




- inferred from muonic H
- inferred from electronic H
- extraction from e p, e n scattering, ππNN data (this talk)
- previous extractions from e p scattering (as tabulated in PDG)

$$G_E'(0) \equiv \frac{1}{6}(r_E^p)^2 + \frac{\alpha}{3\pi m_p^2}\log\frac{m_p}{\lambda}$$




Hill

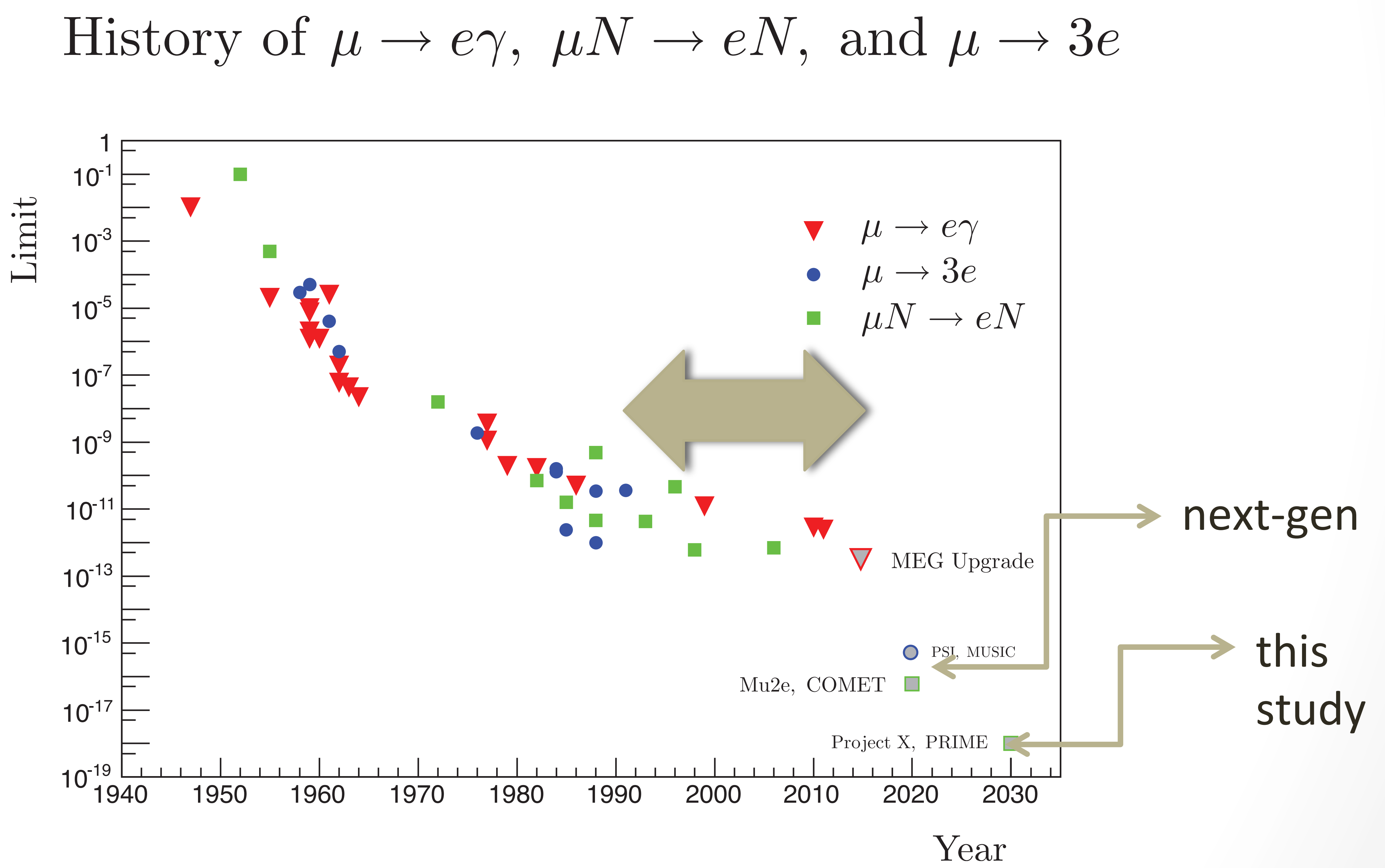
| | $(g\text{-}2)_\mu$ | $r_E^p$ |
|---|---|---|
| significance | 3.6σ e+e-<br>2.4σ τ | 5σ H spectroscopy<br>1σ - 5σ ep scattering |
| hadronic uncertainties | hadronic vac. pol,<br>light-by-light | charge radius,<br>two-photon exchange |
| new physics/SUSY interpretation | ≈✓ ? | ? |

The proton radius is still a puzzle.

Hill

# Muon LFV

# Muon LFV history



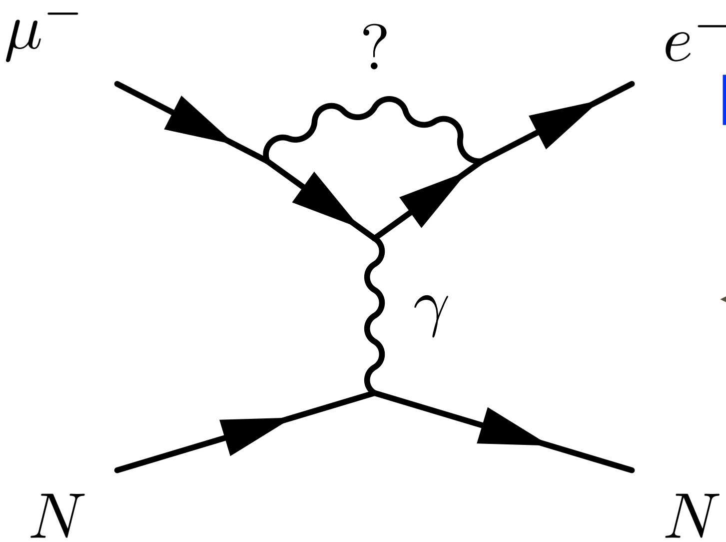

Bernstein

# Muon LFV for Dummies (like me)

- Very generically, "loops" and contact-terms

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

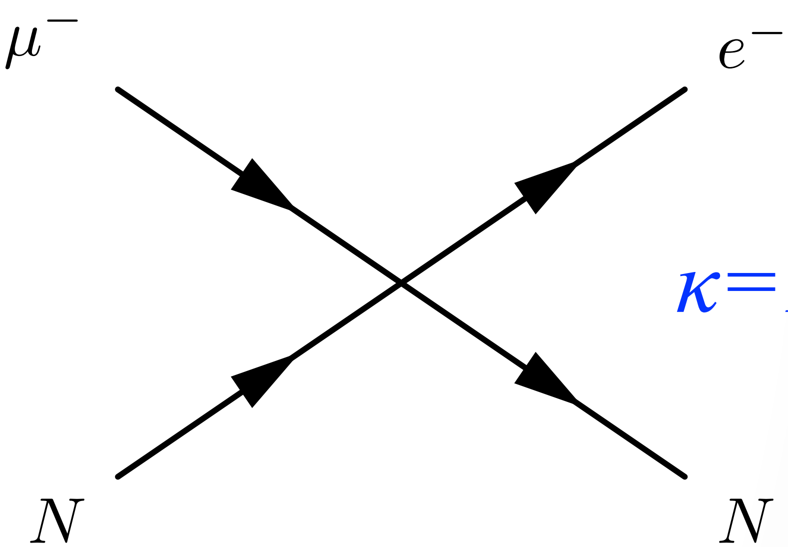
**"Loops"**




mass scale $\Lambda$

$\kappa$

**"Contact Terms"**




$\kappa=1$

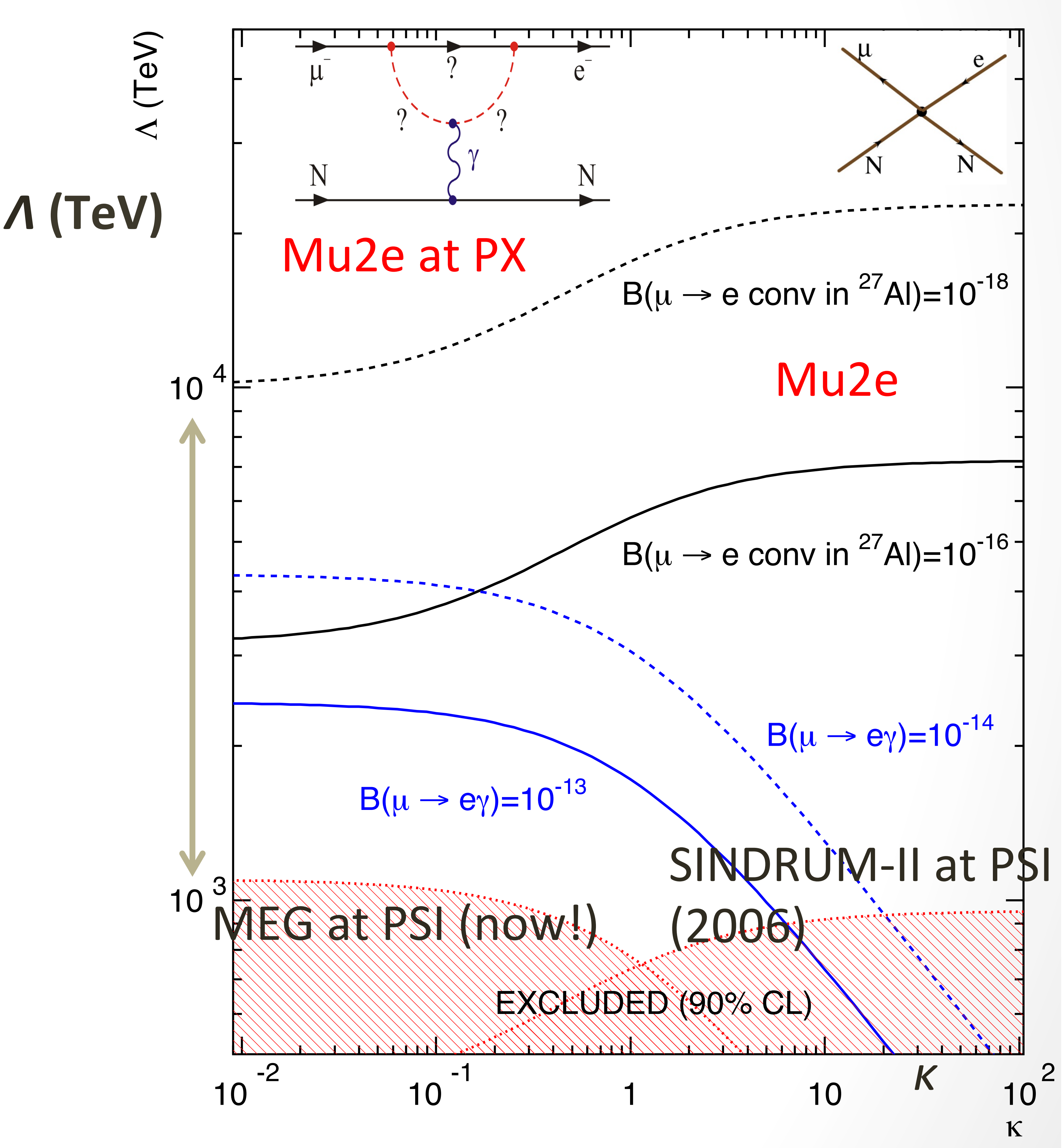
Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

New Particles at High Mass Scale (leptoquarks, heavy *Z*,...)

Does not produce μ→eγ

Bernstein



Λ (TeV)
Λ (TeV)
μ⁻
e⁻
?
N
N
γ
μ
e
N
N
Mu2e at PX
B(μ → e conv in 27Al)=10-18
Mu2e
B(μ → e conv in 27Al)=10-16
B(μ → eγ)=10-14
B(μ → eγ)=10-13
SINDRUM-II at PSI (2006)
MEG at PSI (now!)
EXCLUDED (90% CL)
10 4
10 3
10 -2
10 -1
1
10
10 2
K
κ


Bernstein

# Muon LFV

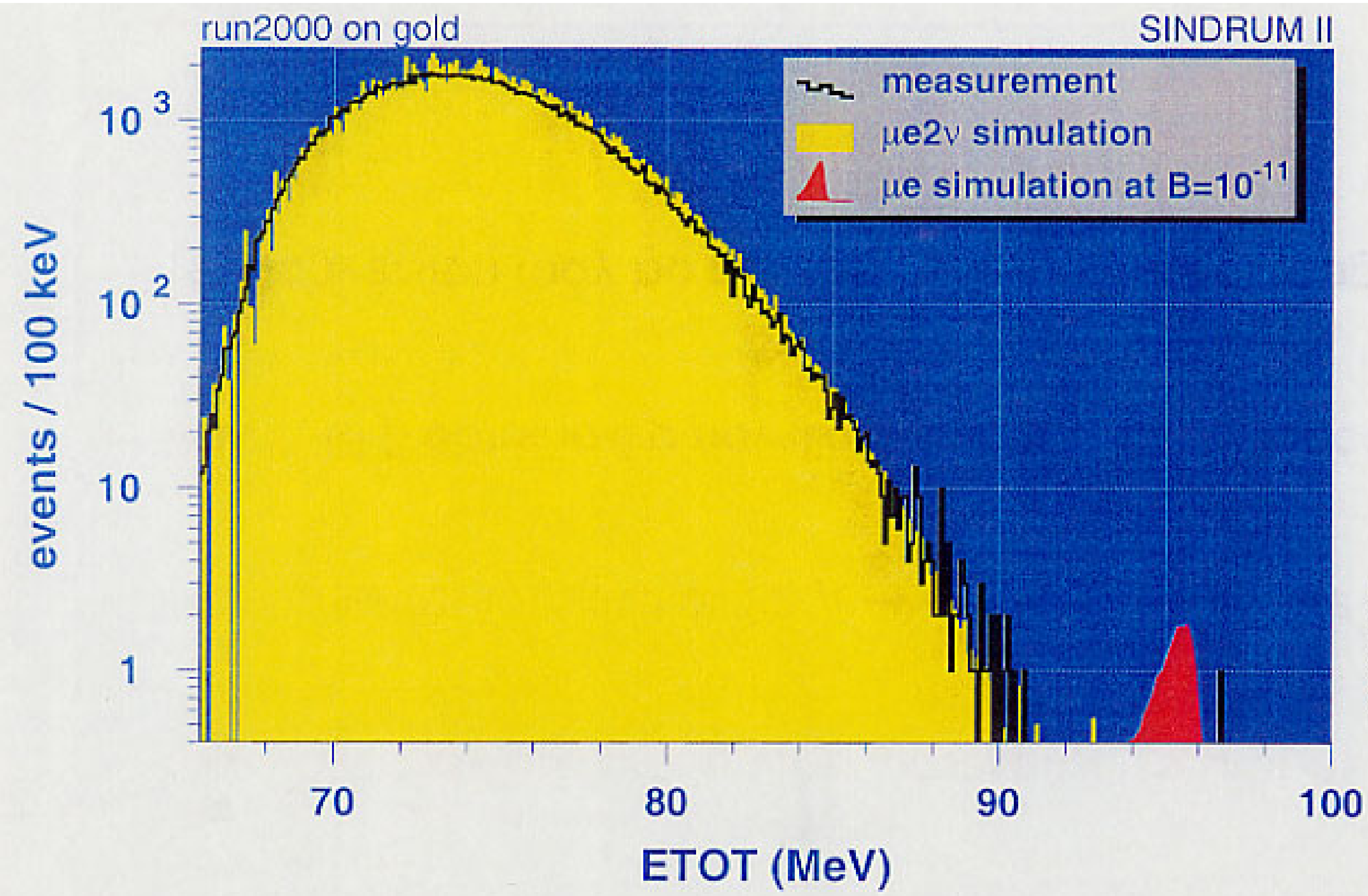
# Where are we now?

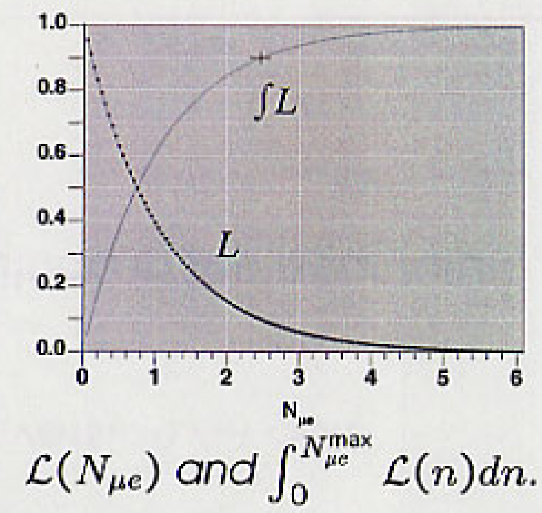
# $\mu \to e\gamma$ @ MEG

- MEG searches for $\mu^+ \to e^+\gamma$ with an unprecedented sensitivity.
- Five times tighter upper limit on $\mathcal{B}(\mu^+ \to e^+\gamma)$ was set with data 2009+2010.
  - New limit: $\boldsymbol{\mathcal{B}(\mu^+ \to e^+\gamma) < 2.4\times10^{-12}}$ **(90% C.L.)**
- MEG will be exploring the branching ratio region of $O(10^{-13})$ with data 2011 and 2012.
- Other physics analyses besides $\mu^+ \to e^+\gamma$ search analysis are also in progress.
- R&D work on MEG upgrade aiming at sensitivity of $O(10^{-14})$ is in progress.

Ootani (Moriond 2012)

# μ -> e conversion @ SINDRUM II




$\mathcal{L}(N_{\mu e})$ and $\int_0^{N_{\mu e}^{max}} \mathcal{L}(n)dn.$

| | |
|---|---|
| $\mu^-$ stops | $4.4 \pm 0.3 \times 10^{13}$ |
| $f_{cap} \times \Omega \times \epsilon_{tot}$ | 7.0% |
| single event sensitivity | $3.3 \pm 0.2 \times 10^{-13}$ |
| 90% C.L. limit | 2.45 events |

In the likelihood analysis of the energy distribution a flat background from cosmic rays and radiative pion capture was allowed.

Result: $B_{\mu e}^{gold} < 8 \times 10^{-13}$ 90% C.L.

Van der Schaaf (NOON03 2003)

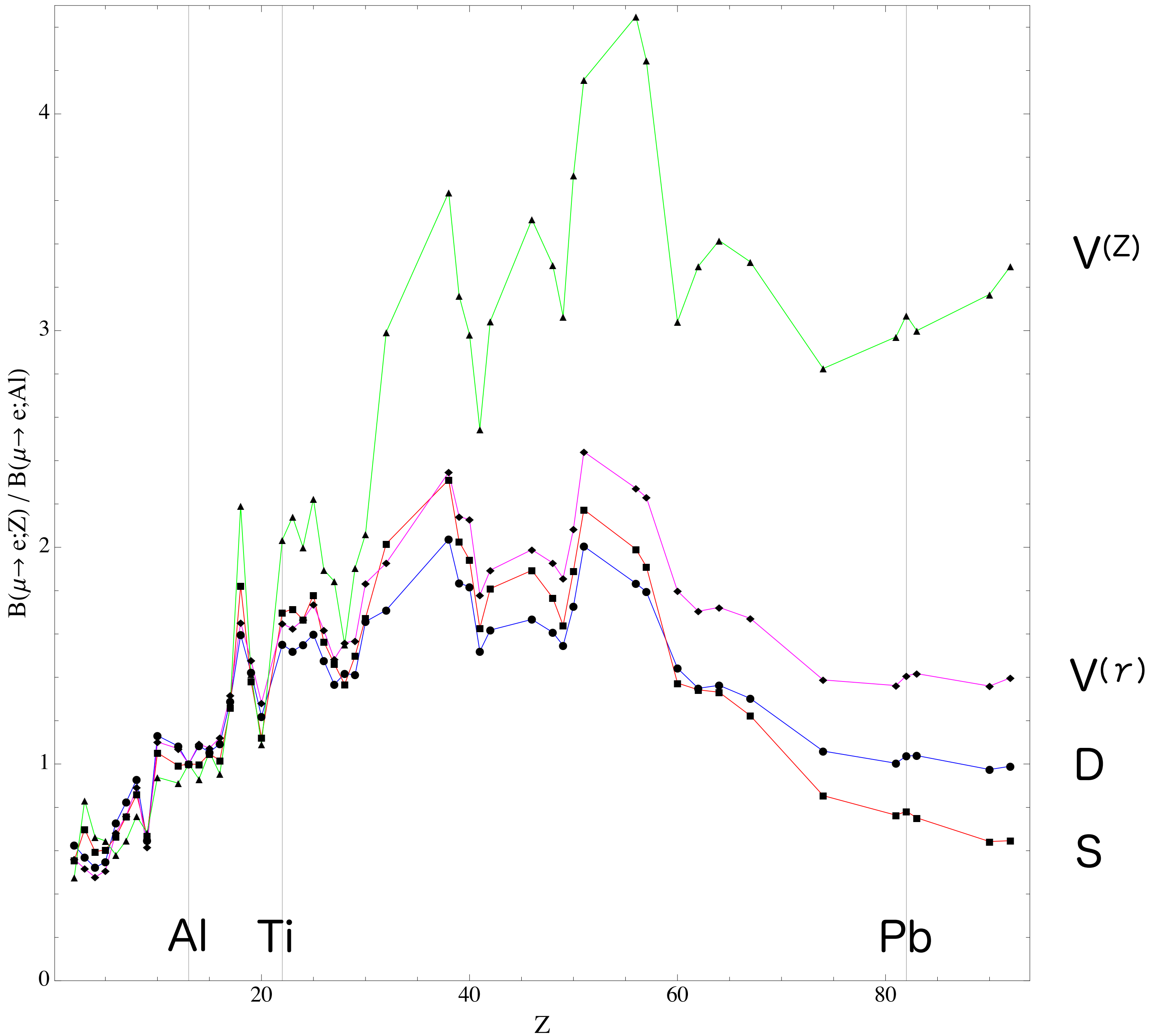
# μ -> 3e @ SINDRUM II

- Current <1.0e-12 at 90% CL:
  Bellgardt et al., Nuclear Physics B 299 (1998)

Muon LFV

What could be out there?

# Target Nuclei Dependence




Cirigliano, Kitano, Koike, Tuzon (0904.0957)

# Coherent versus Incoherent Rates

**For coherent μ−e conversion, only the vector and scalar parts are needed (the axial and pseudoscalar nucleon currents couple to the nuclear spin and for J=0 nuclei they contribute only to incoherent transitions).**

**The total incoherent *μ-e conversion* strength is obtained by summing over the partial transition ME for all accessible final states induced by the multipole operators as**

**Nuclear structure calculations have been performed by using:**

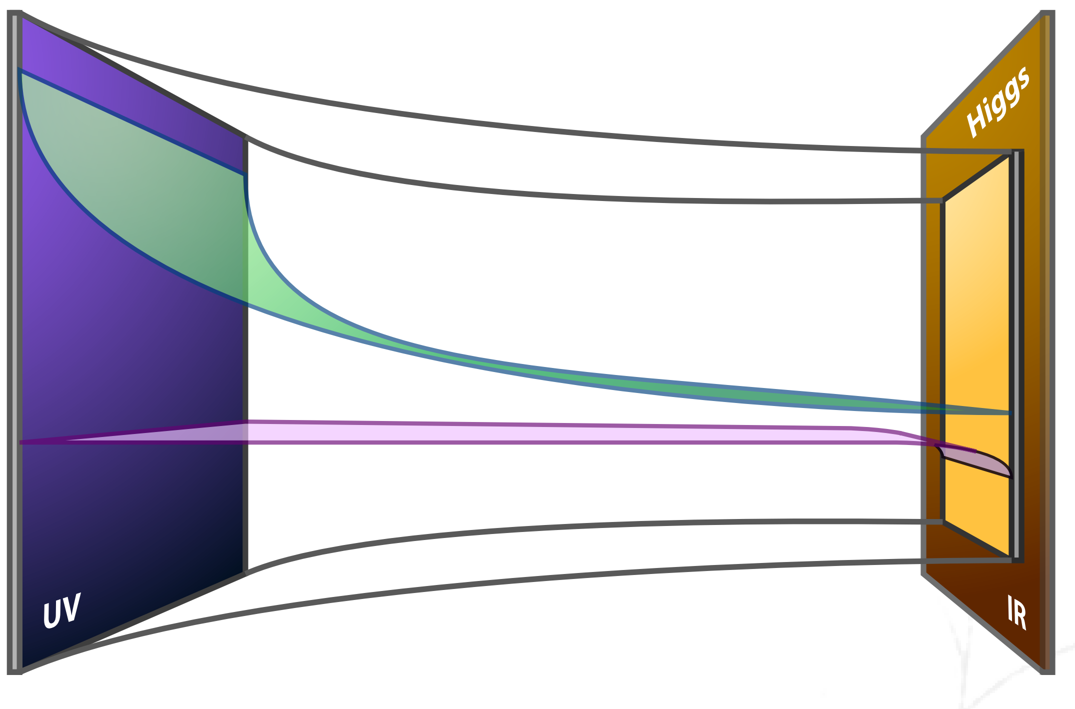
(i) Shell Model,
(ii) Various QRPA methods
(iii) Relativistic Fermi Gas Model (use of the Lindhard function)

**The results, in some important channels, are model dependent**

| Mechanism | $S_A$(coh) | $S_V$(coh) | $M^2_{coh}$ | $S_A$(inc) | $S_V$(inc) | $M^2_{inc}$ | $M^2_{tot}$ | $\eta$(%) |
|---|---|---|---|---|---|---|---|---|
| $\gamma$ exchange | 0.000 | 64.60 | 64.60 | 0.000 | 1.54 | 1.54 | 66.13 | 97.7 |
| $W$ exchange | 0.002 | 512.10 | 512.11 | 2.94 | 10.42 | 19.26 | 531.36 | 96.4 |
| SUSY $Z$ exchange | 6.71 | 392.36 | 412.47 | 116.72 | 10.61 | 360.76 | 773.23 | 53.3 |

Kosmas

# RS Model with Anarchic Flavor




Anarchic Flavor in RS

For an interesting model, we want...

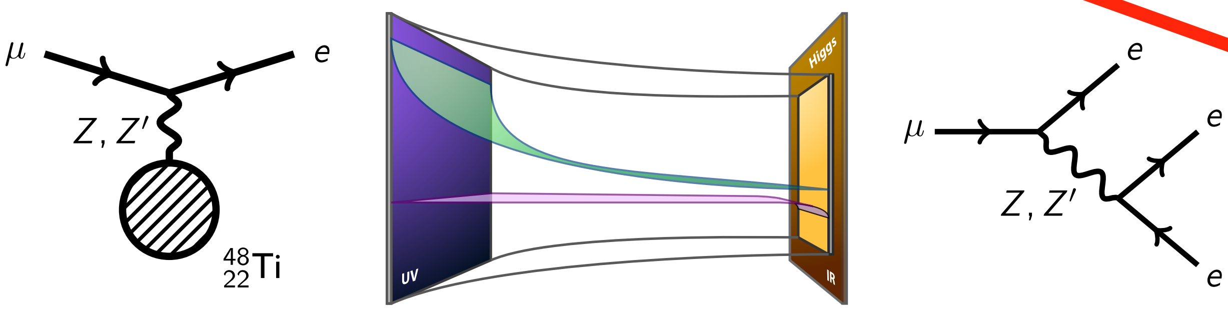
- $Y^*_{ij} = Y_* Ⓐ_{ij}$ is an ancharic matrices with $\mathcal{O}(1)$ numbers.
$\Rightarrow$ The mass hierarchy is determined by the wave function localization.

- $M_{kk}$ is not too heavy. $\Rightarrow$ KK modes can be seen at LHC.

Tsai

# Lepton Flavor Violation : Tree

Two dominant parmeters



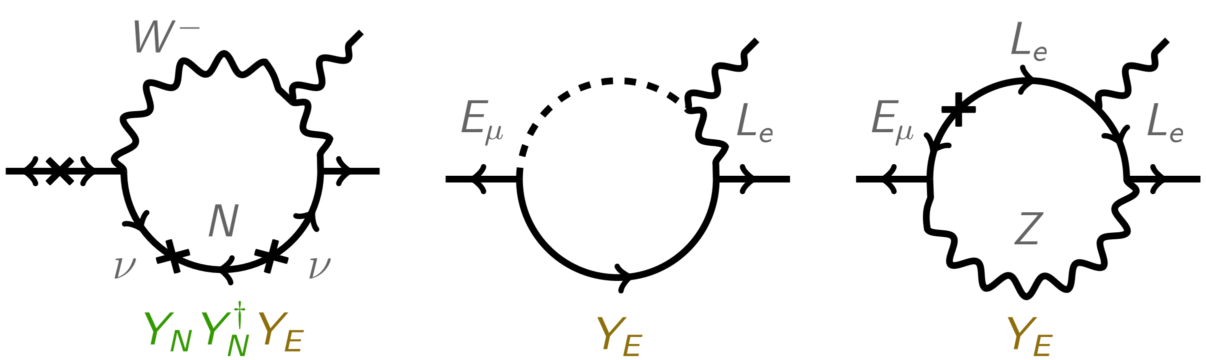

$\mathcal{M}_{\text{tree}} \sim \left(\frac{1}{M_{KK}}\right)^2 \left(\frac{1}{Y_*}\right)$ WHY $Y_*^{-1}$ ?

To increase $Y_*$ while fixing the SM mass spectrum, need to

$\Rightarrow$ push fermion profiles towards UV

$\Rightarrow$ less overlap with non-universal part of the gauge boson

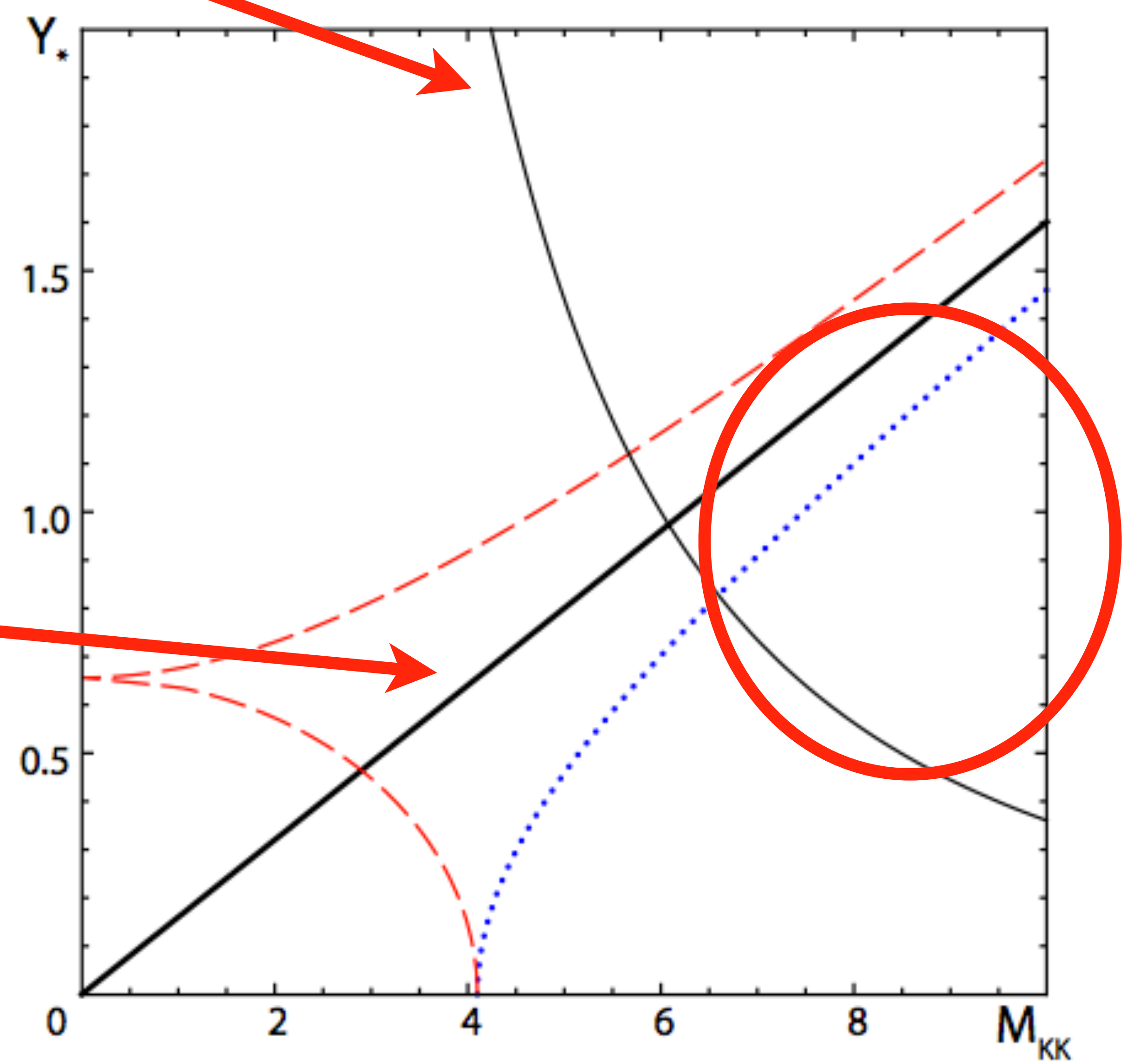
# Leading order $\mu \to e\,\gamma$




Two types of diagrams with $Y^3$ and $Y$ carry arbitrary relative signs

Defined $aY_*^3 = \sum_{k,\ell} a_{k\ell} Y_{ik} Y^\dagger_{k\ell} Y_{\ell j}$ and $bY_* = \sum_{k,\ell} b_{k\ell} Y_{k\ell}$

$$\mathcal{M}_{\text{loop}} = \left(aY_*^3 \pm bY_*\right) \times (\text{loop factor, charge,...})$$




(a) Minimal model

Tsai

# Supersymmetry with an R-symmetry

## *MSSM*

| | L | | | R | | |
|---|---|---|---|---|---|---|
| L | $m^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ |
| L | $m_{ij}^2$ | $m^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ |
| L | $m_{ij}^2$ | $m_{ij}^2$ | $m^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ |
| R | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m^2$ | $m_{ij}^2$ | $m_{ij}^2$ |
| R | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m^2$ | $m_{ij}^2$ |
| R | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m_{ij}^2$ | $m^2$ |

## *MRSSM*

| | L | | | R | | |
|---|---|---|---|---|---|---|
| L | $m^2$ | $m_{ij}^2$ | 0 | 0 | 0 | 0 |
| L | $m_{ij}^2$ | $m^2$ | 0 | 0 | 0 | 0 |
| L | 0 | 0 | $m^2$ | 0 | 0 | 0 |
| R | 0 | 0 | 0 | $m^2$ | $m_{ij}^2$ | 0 |
| R | 0 | 0 | 0 | $m_{ij}^2$ | $m^2$ | 0 |
| R | 0 | 0 | 0 | 0 | 0 | $m^2$ |

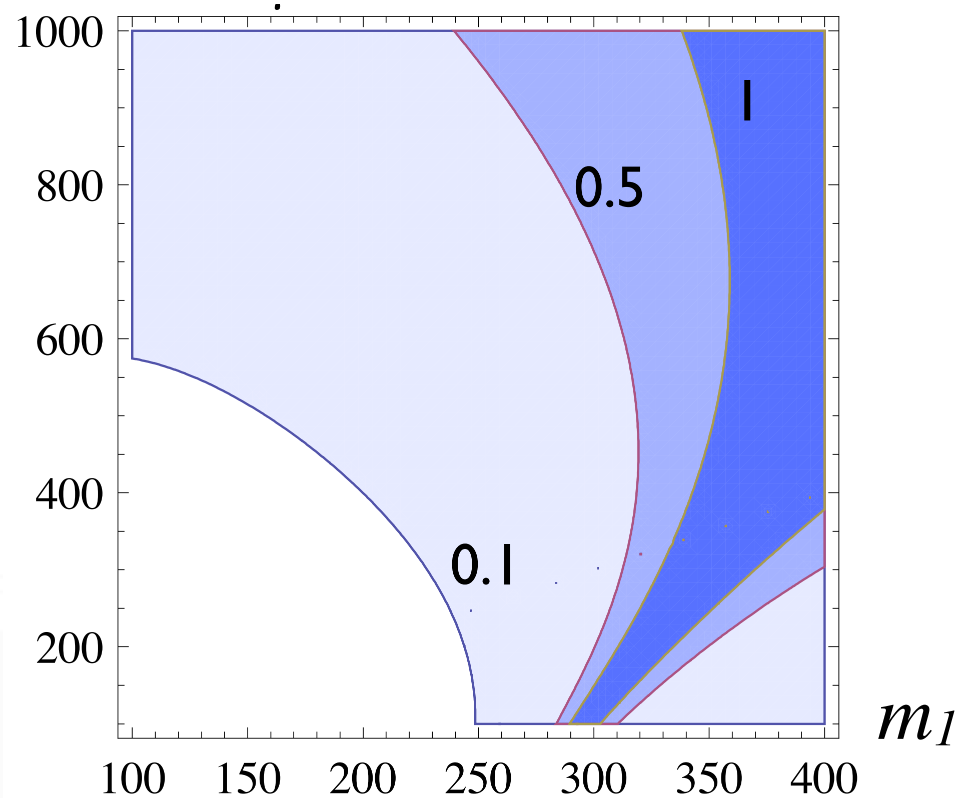
*LR mixing forbidden in MRSSM*

*Current limits on $m_{ij}^2$ is much more relaxed, potentially solving the lepton flavor problem*

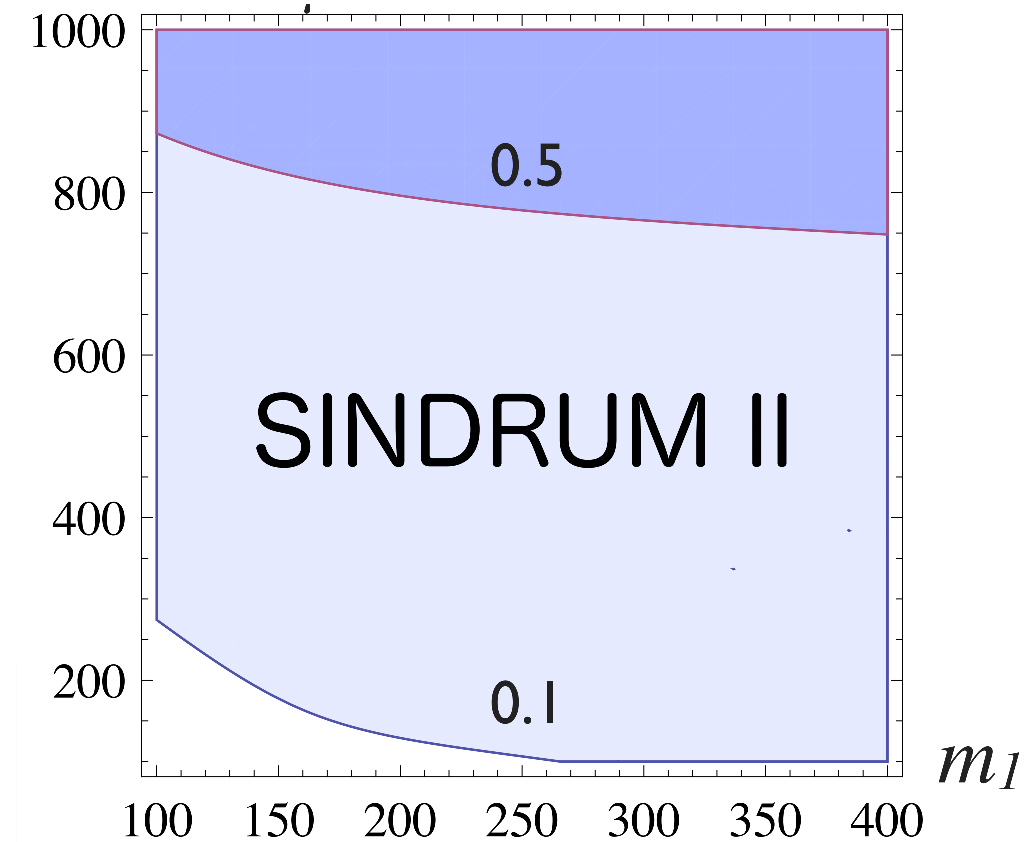
*Project X will be able to determine whether the MRSSM is a solution*

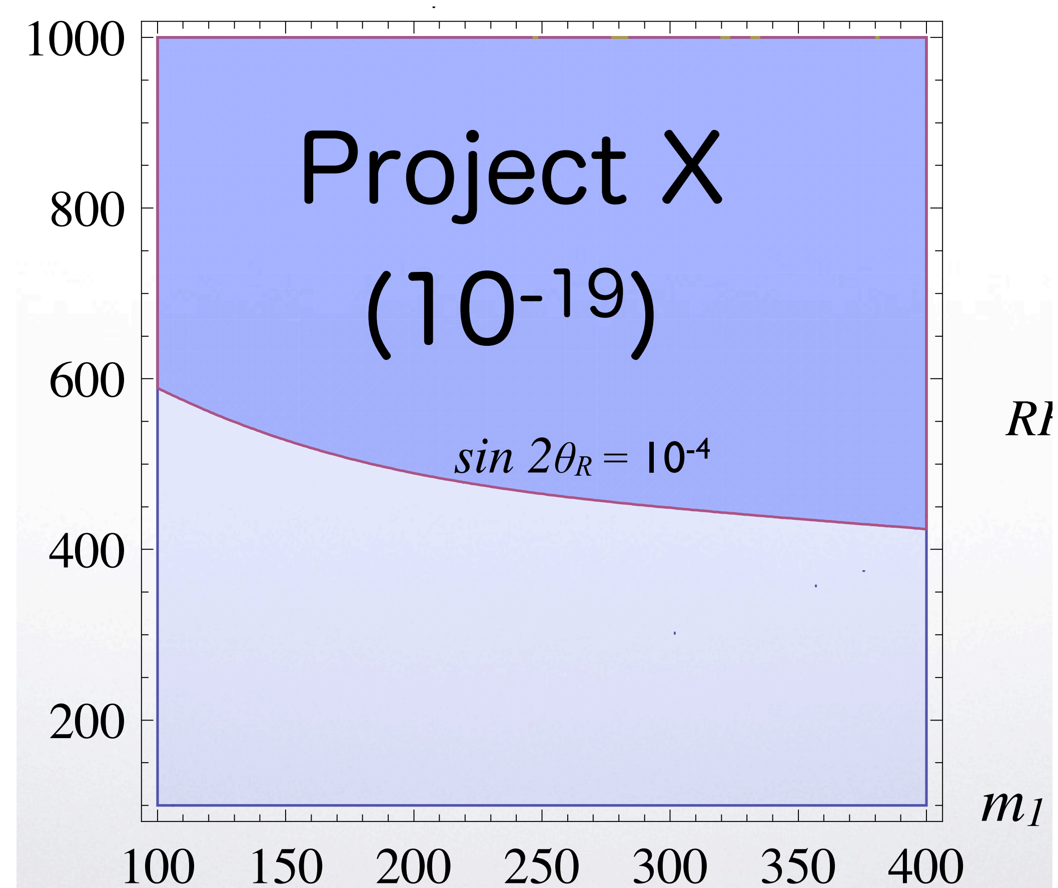
Fok

## $\mu \to e\gamma$




## $(\mu \to e)$




*If Project X does not find any $\mu \to e$ conversion events, the flavor problem persists and cannot be explained by the MRSSM*

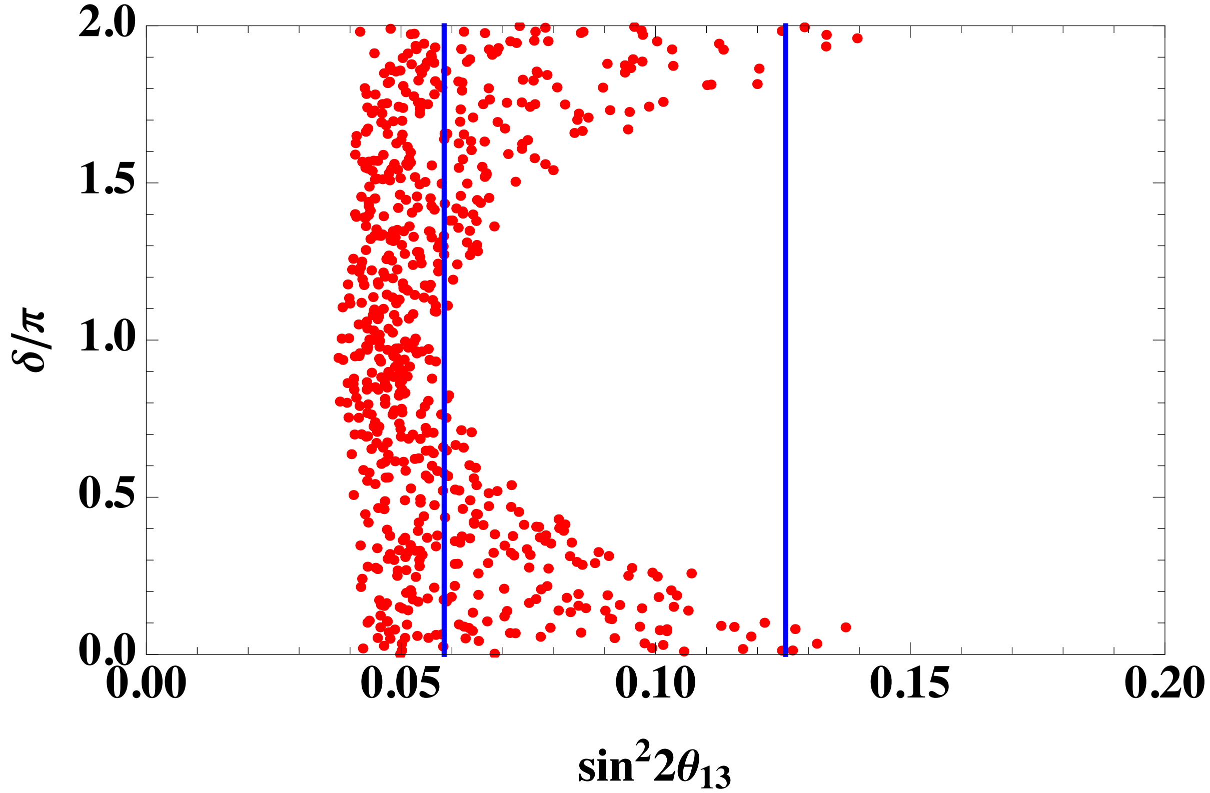
Fok

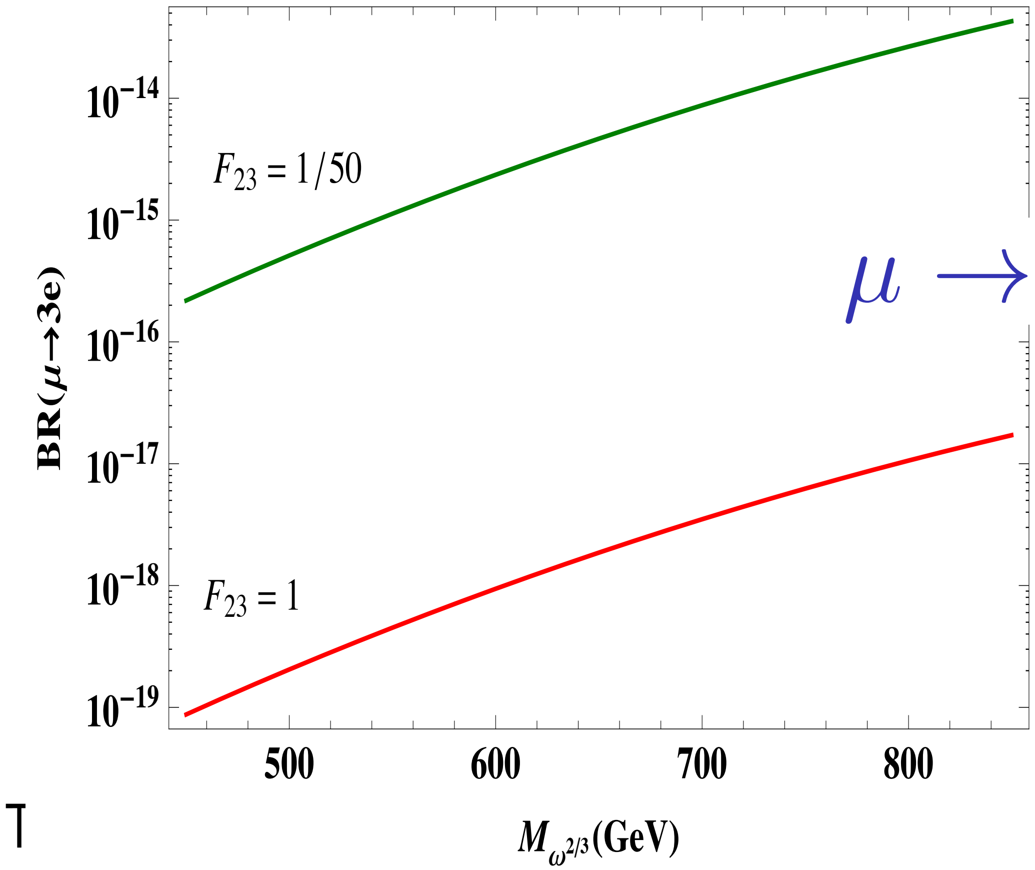
# Neutrino Mass from Leptoquarks

- Two–loop neutrino mass model via leptoquarks
  - Predictions
    $\theta_{13}$, mass hierarchy
  - Low-energy phenomena
    $\mu \to e\gamma$, $\mu \to 3e$, $\mu - e$ conversion in nuclei, muon $g-2$

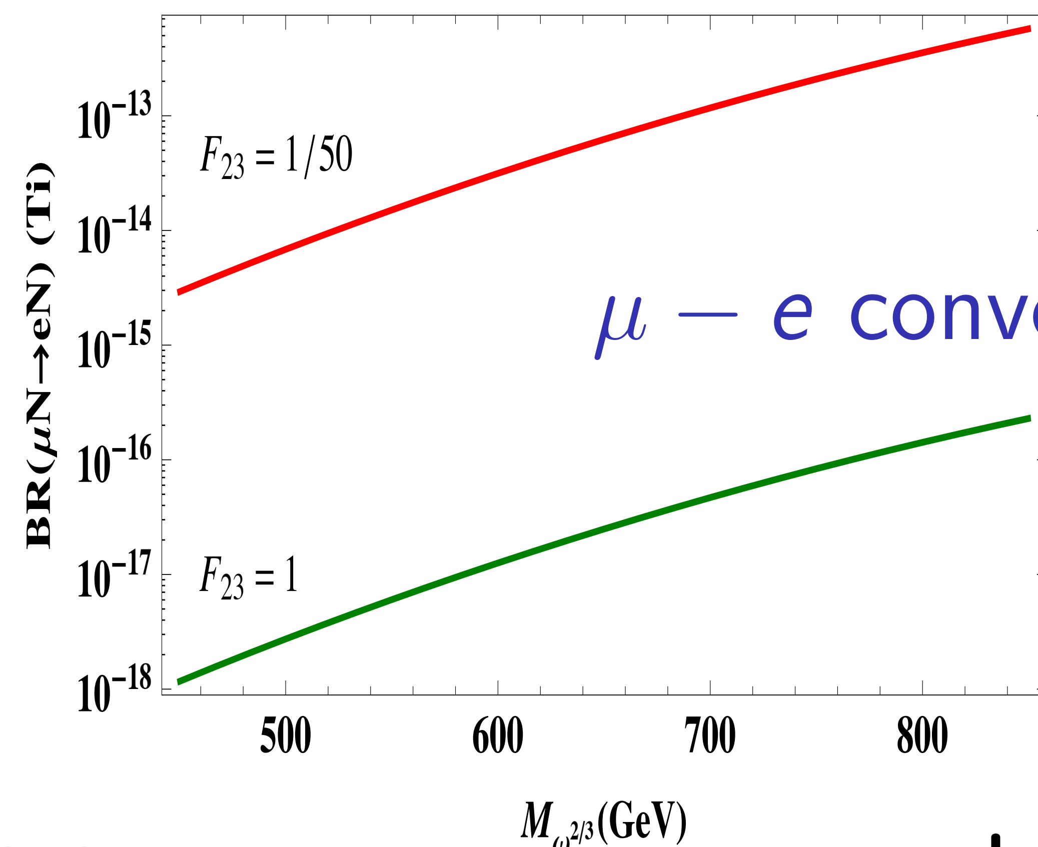
Julio

$w \gg 1$




$\mu \to 3e$

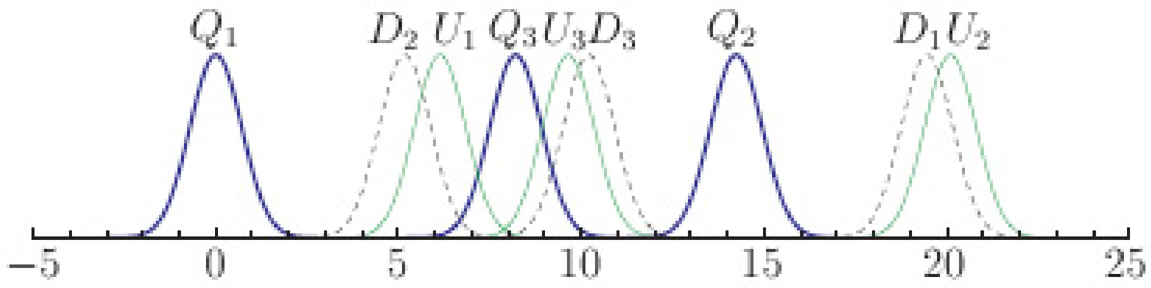



$\mu - e$ conversion

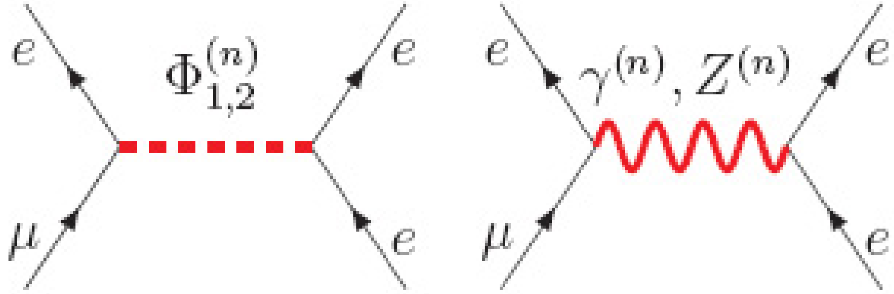
Julio

# Split Fermions in Extra Dimensions

- Flavor Problem ⇔ Geometry in extra dimension
- Split fermion model as an example:
  - Linear displacement between left-handed and right-handed fermions in the fifth dimension becomes exponentially suppressed 4D Yukawa.
  - A realistic configuration to fit quark masses and mixings



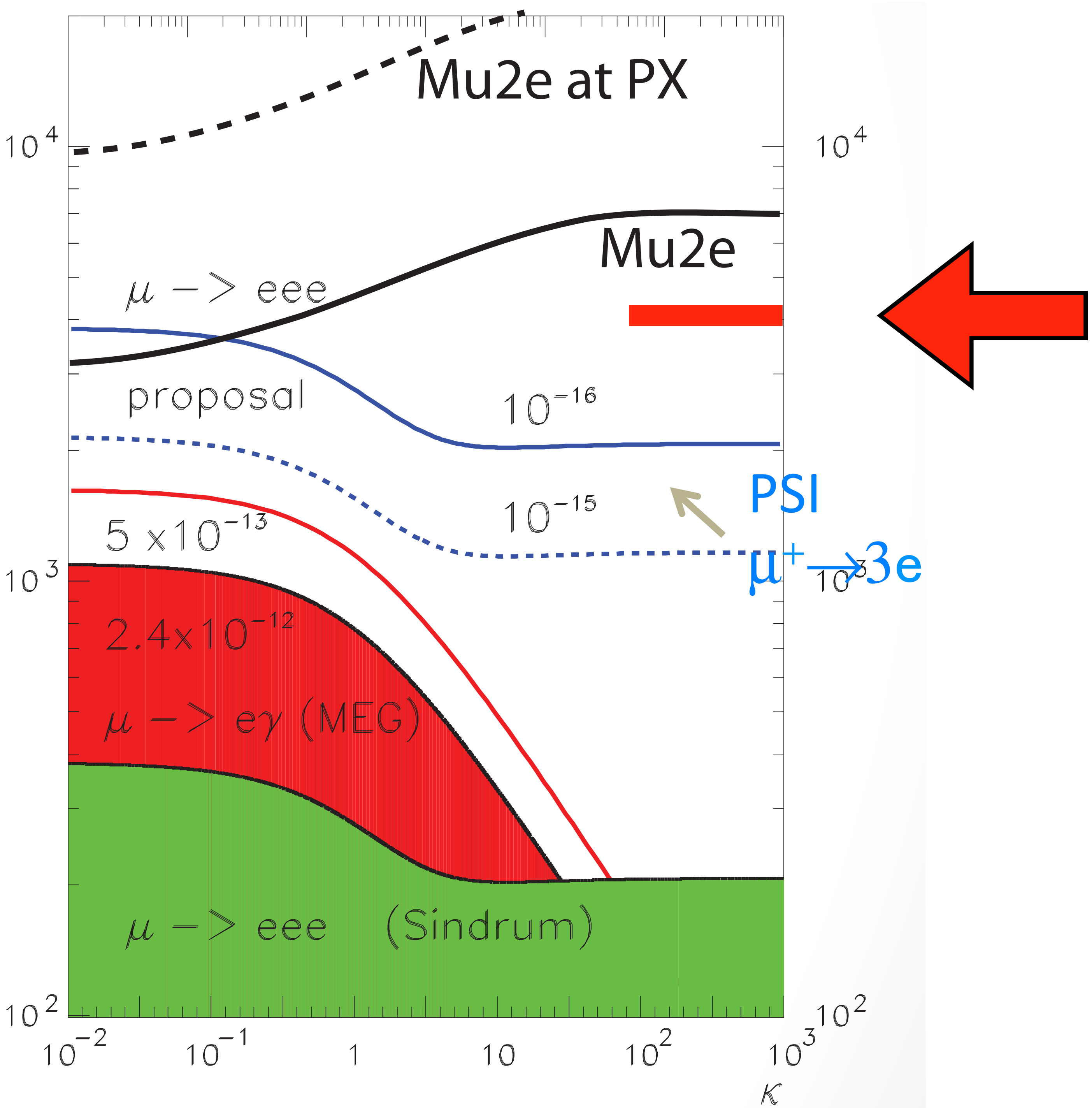

- tree-level LFV processes will be much larger than the loop induced ones, e.g. $Br(\mu \to 3e) \gg Br(\mu \to e\gamma)$.




Chang

## μ -> e conversion

## μ -> 3e



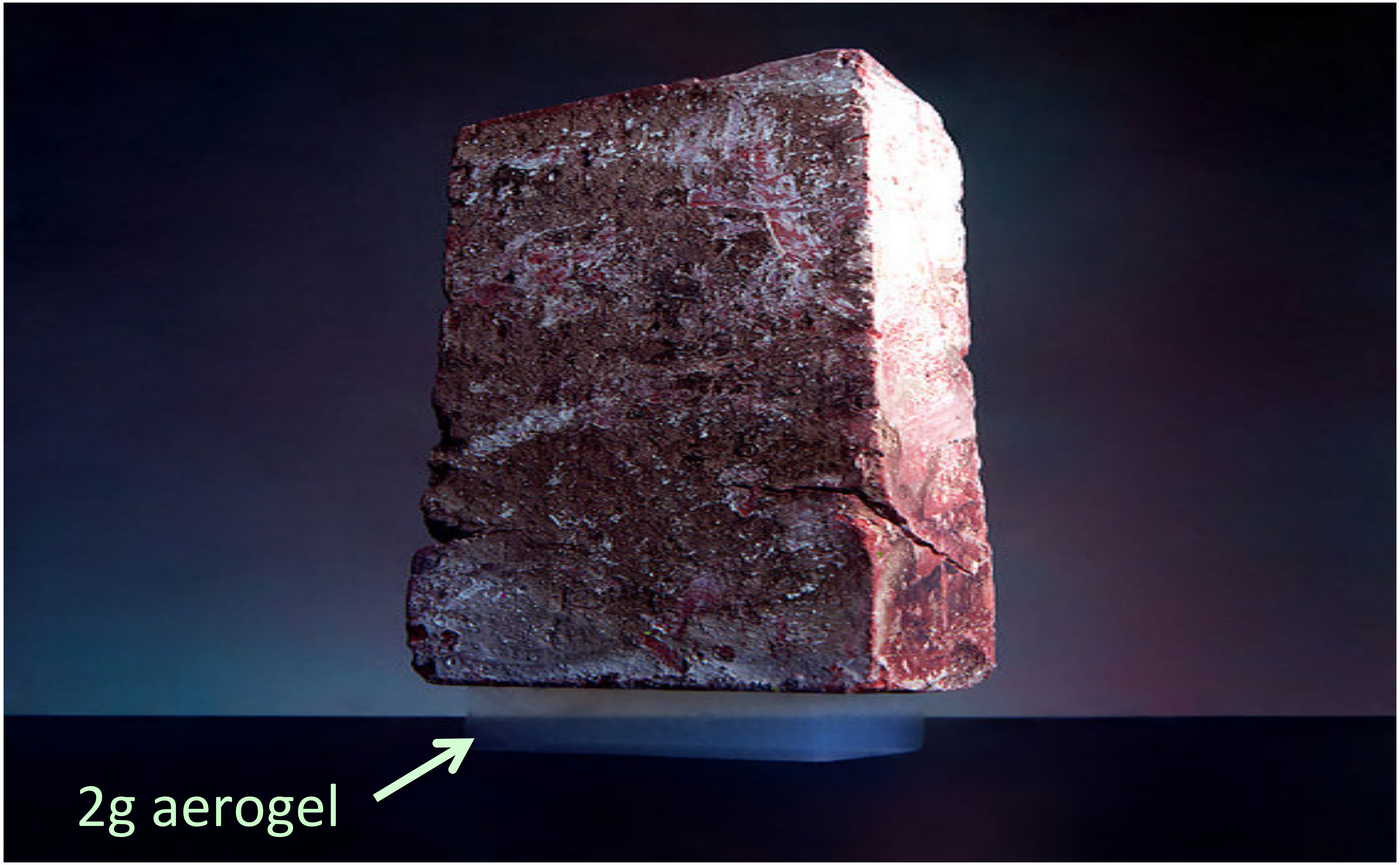

BR(μ -> 3e) ≈ $10^{-13}$

Chang

# Muon LFV

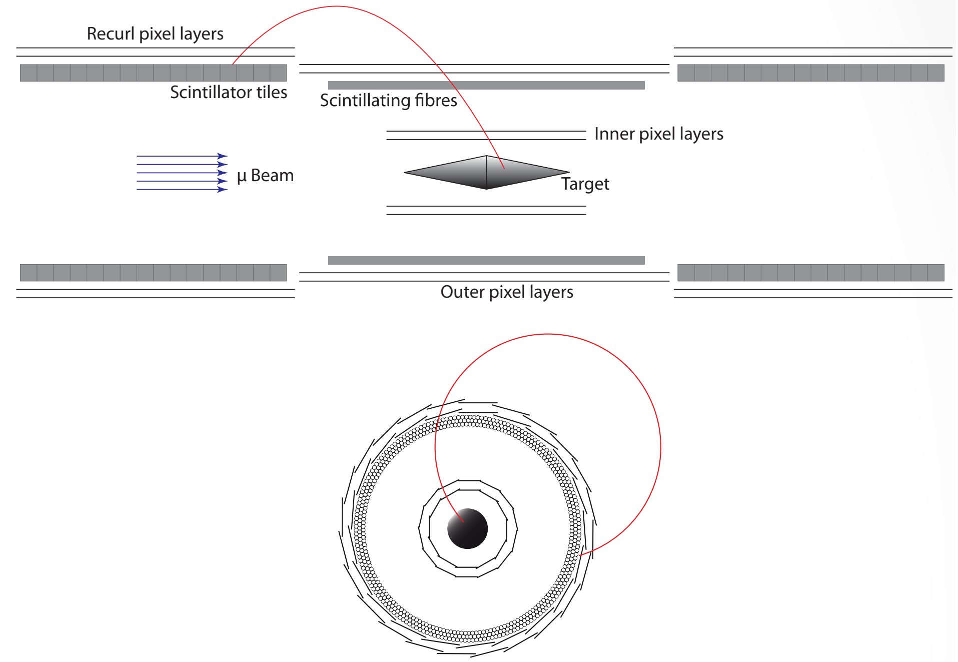
# Where should we be going?

# JPARC g-2 : Material R&D

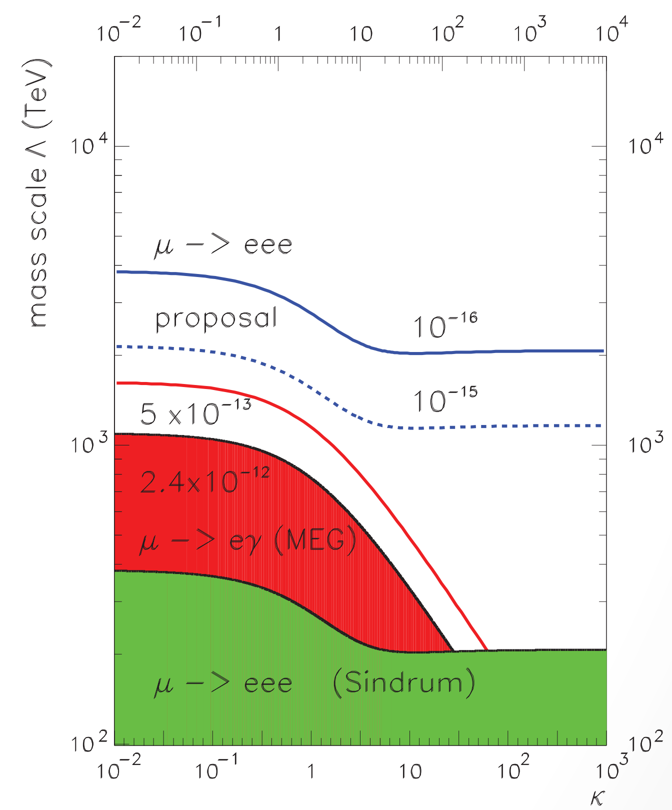



Lancaster

# $\mu^+ \to 3e$ at PSI: $10^{-15}$ to $10^{-16}$




- Current <1.0e-12 at 90% CL:
  Bellgardt et al., Nuclear Physics B 299 (1998)
- LOI to PSI:
  - Stopped $\mu^+$ beam with SciFi and Pixels
- $\mu^+ \to 3e$ shares much with $\mu^+ \to e\gamma$:
  - Accidentals and Resolution
    - Here, from $\mu^+ \to 3e\nu\bar{\nu}$ at BR= (3.4e−05) overlapping other decays
    - Bhabha scattering of positrons from regular Michel decay can yield a pair in combination with another decay
- Need high resolution tracker
  - Innovative pixel tracker
  - LOI at PSI:
    A novel experiment searching for the lepton flavour violating decay μ → eee




Bernstein

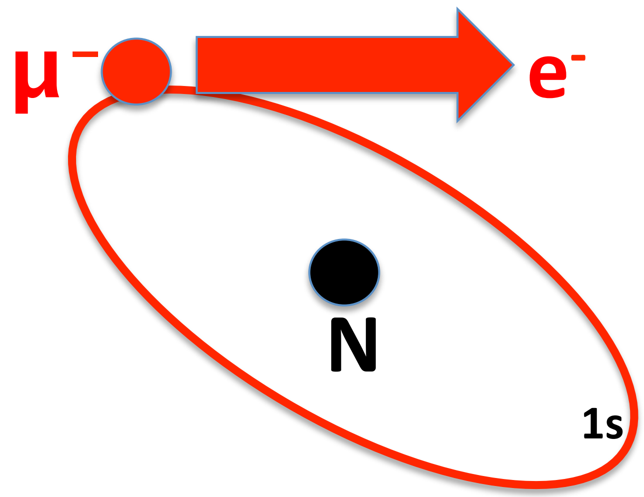
# $\mu$-> e $\gamma$ with converted $\gamma$

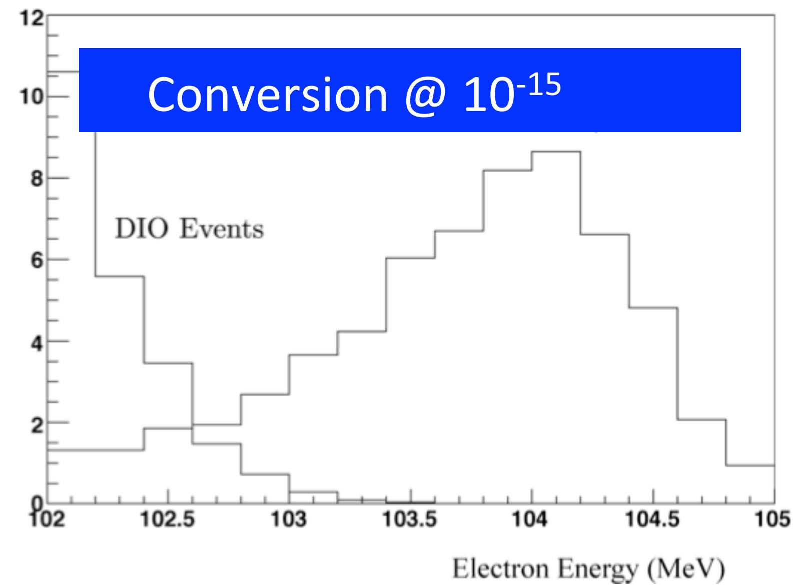
Fritz DeJongh

- Goal: Path to $10^{-16}$ sensitivity using
  - Intense stopped muons beams from Project-X
  - Monolithic pixel detectors
  - Time of flight
  - Calorimetry?
- Outline:
  - Conceptual design based on resolution estimates
  - Some initial simulation results
  - Can we move converter closer to muon stopping target?
    - To the limit: Use internal conversions?
  - Comments on $\mu$ -> *eee*
  - What's next toward Snowmass?

DeJongh

# J-PARC Muon to Electron Conversion




1. **COMET** : stage-1 approval with stage-2 expected with TDR in 2012.
   CDR BR sensitivity 6 x $10^{-17}$ in 2021.

2. **Phase-I COMET** : Beamline+1st $90^0$ for COMET has been recommended for inclusion in KEK budget. Sensitivity O(100) better than SINDRUM.

3. **DeeMe** : stage-1 approval from muon PAC but further R&D requested from IPNS PAC
   Would run in MLF without MR in H- line.
   Sensitivity O(100) better than SINDRUM.

Lancaster

# Mu2e @ Fermilab

## Mu2e Apparatus

**Production Solenoid**

- Production target
- Graded field

- Delivers ~ 0.0016 stopped $\mu^-$ per incident proton
- $10^{10}$ Hz of stopped muons

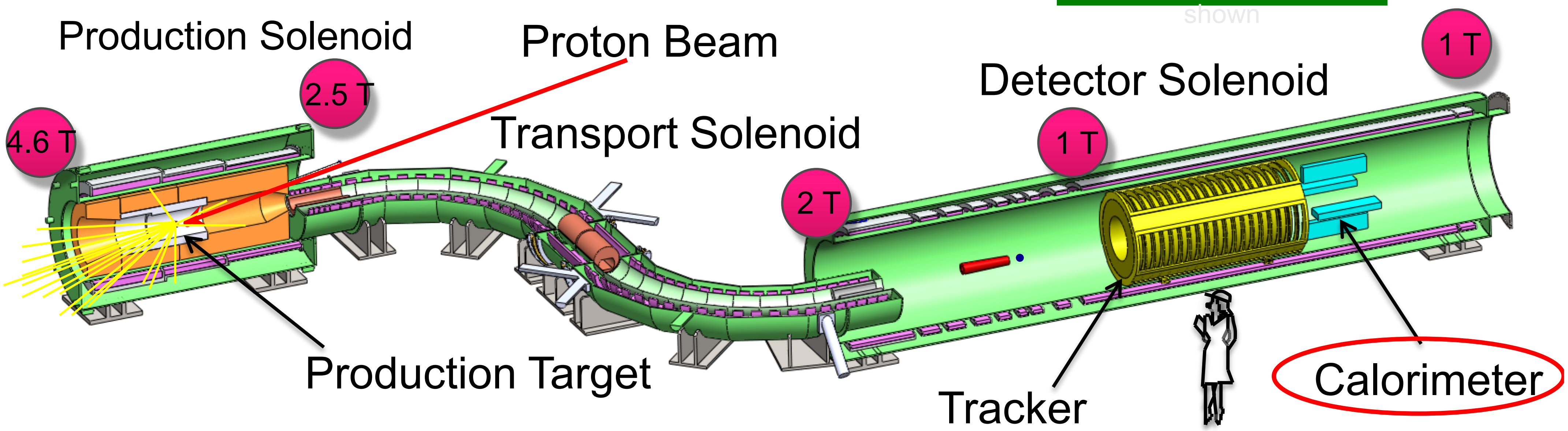
**Detector Solenoid**

- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to $10^{-4}$ Torr

**Transport Solenoid**

- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown




Hitlin

# Project X Advantages for μN -> eN

- *Beam Power*:
  - Aside from raw statistics, lets us solve other problems
- *Time Structure*
  - A problem in Mu2e/Booster Era is radiative pion capture
  - Too detailed for this talk, but "wait" for pions to decay
  - Beam at Mu2e is 200 nsec wide and that yields background since you can't wait forever!
  - PX can give O(10 nsec) beam widths, a huge improvement!
- *Lower Energy*
  - Another problem in Mu2e/Booster is antiproton production
    - Antiprotons wander down beamline (same charge as $\mu^-$), annhihilate, and make pions -> radiative pion capture
    - We're on a threshold for pbars, so slightly lower energy yields huge reduction
- *Can tradeoff the above to optimize sensitivity*

Bernstein

# An R&D plan

- It may be possible for the Mu2e calorimeter (tracker ???) to cope with initial Project X rates by shortening the signal integration time
  - It is straightforward to study the effect on energy resolution
- At 50x, it is likely that a new approach will be necessary
  - Something completely different
  - A crystal with a shorter scintillation decay time
    - There are candidates: $BaF_2$, $LABr_3$(Ce), $LaCl_3$(Ce), ……
    - Before these crystals can be employed in an HEP experiment, further R&D will be necessary
      - Crystals
        - » Size
        - » Production efficiency
        - » Impurities – radiation hardness
        - » Uniformity
      - Readout devices
        - » Spectral response
        - » Size
        - » Radiation hardness

Hitlin

# Summary

* FC: g-2, μ EDM, $R_p$, muonium
  FV: μN -> eN; μ->3e; μ -> e$\gamma$; $\mu^-$N -> $e^+$N',

* μ -> e transition probes lepton flavor sector 200 -> 1000 TeV now; experiments within ≈ 5 years can achieve 3000 -> 7000 TeV; PX would exceed $10^4$ TeV

* Rich set of experiments (μN -> eN; μ->3e; μ -> e$\gamma$) give complementary opportunities for probing new CLFV physics

* Observation of μ -> e transition would be huge! Many opportunities for pinning down origin of CLFV (experiments, targets, etc.)