Quark and Lepton Flavour -probing the PeV scale

IOP Sussex 2016

Purpose

(New) Physics up to PeV Scale

(Quarks – well covered)

Leptons

Charged Leptons

EDMs

Give a taste of the physics that can be done

Physics

Landscape

- We have discovered the 125 GeV Higgs
- We know neutrinos oscillate
- Seen gravitational waves

- Haven't yet seen any sign of SUSY
- CP in quark sector not enough for matter and antimatter asymmetry
- No understanding of neutrino mass

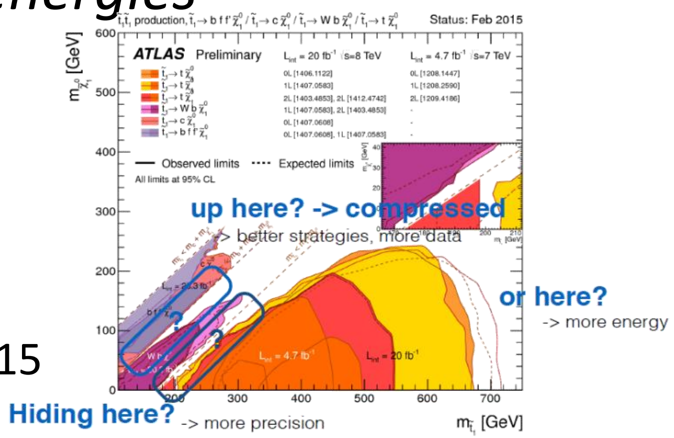
- Tantalizing hints of NP at HE, energy frontier and at lower energies
  - 2TeV, 750 GeV, g-2,…

Caveat: Scales

Physics

- Not all "new" experiments tell the same story
  - Explanations for g-2 probe ~1 TeV models
    - *Useful for SUSY*
  - cLFV/EDMS probe up PEV > scales
    - *Keep probing for SUSY at higher energies*
    - *(Split) SUSY PeV Scale 1308.3653*
  - Non zero θ_{QCD} can hide NP
    - *(no energy scale dim 4 operator*)

Weiler, EPS 2015



Anomalies

Physics

$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$
$2-3\sigma$	anomaly in $B \to K^*\mu^+\mu^-$ angular distributions
$2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$
$\sim 2.5\sigma$	non-zero $h \to \tau\mu$

Silvestrini: QCD? 1512.07157

Large number of modest tensions in large number of data!

Wolfgang Altmannshofer

SUSY to PeV

Physics

Altmannshofer et. al. 1308.3653

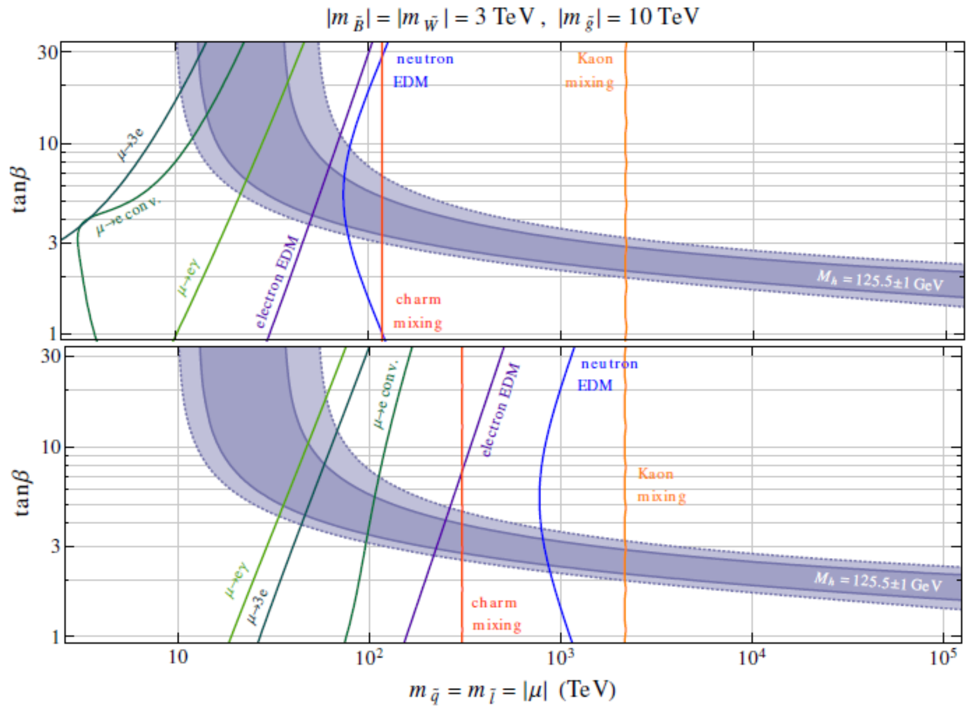


FIG. 1: Summary of various low energy constraints (left of the lines are the excluded regions) in the sfermion mass vs. $\tan\beta$ plane for the example of 3 TeV bino and wino and 10 TeV gluino, while fixing the mass insertion parameters to be $(\delta_A)_{ij} = 0.3$ when using the super-CKM basis. The dark (light) blue shaded band is the parameter space compatible with a Higgs mass of $m_h = 125.5 \pm 1$ GeV within 1σ (2σ). The upper (lower) plot gives the reach of current (projected future) experimental results collected in Tab. I.

Probes for NP

★★★ = Discovery Sensitivity

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
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.

arXiv:0909.1333[hep-ph]

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

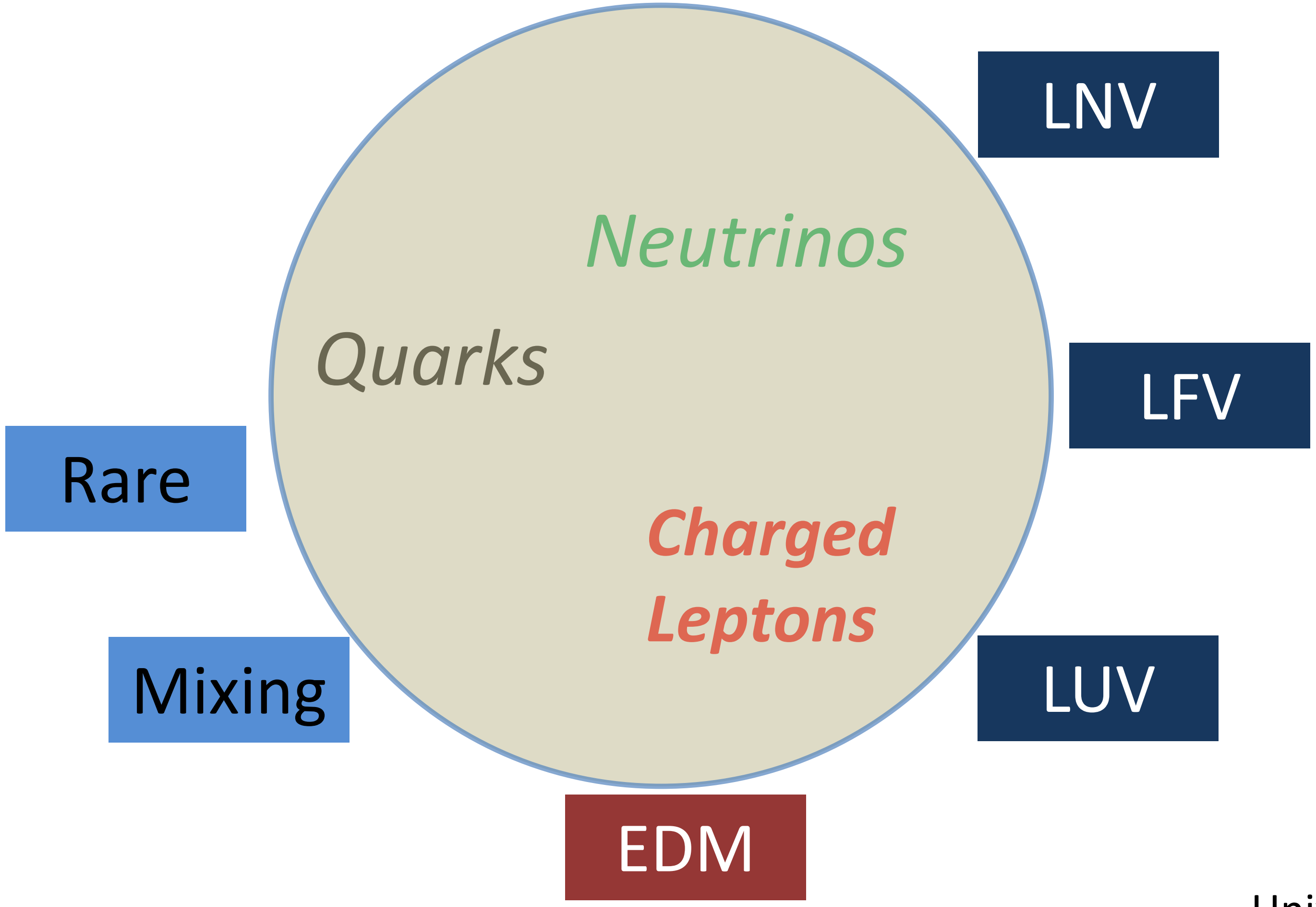
RH Currents
AC = *Agashe , Carone* hep-ph/0304229 (Abelian)
RVV2 = *Calibbi et al.* 0907.4069 (non-Abelian)
AKM = *Antusch et al.* 0708.128 (flavour symmetry)

δLL = (CKM LH currents)
FBMSSM = (flavour blind MSSM)
LHT = (Little Higgs with T parity)
RS = (Randall-Sundrum)

If New Physics has generic flavor violating couplings of $O(1)$, it has to be at extremely high scales

If there is New Physics at the TeV scale, it has to have a highly non-generic flavor structure

Probes for NP



Physics

Universality

Quarks

very SELECTED TOPICS

Overview

- Mixing
- Rare decays

  $K \to \pi \nu\nu$, $B \to \mu\mu$, …

Theory precision high

- R_K

Mixing

Rare

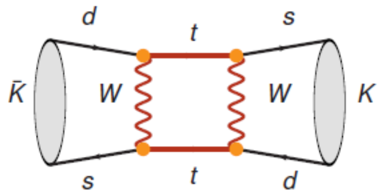
LUV

Quarks: *b,c,s*

Mixing

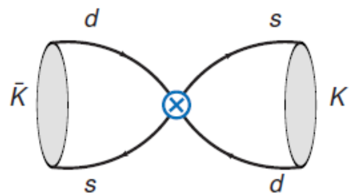
Example: CP Violation in Kaon mixing

- Standard Model amplitude is loop suppressed and CKM suppressed



$$\propto \frac{g^4}{16\pi^2} \frac{m_t^2}{M_W^4} (V_{td} V_{ts}^*)^2$$

- Generic New Physics amplitude only suppressed by New Physics scale



$$\propto \frac{1}{\Lambda_{NP}^2}$$

- CP Violation in Kaon Mixing can probe extremely high scales

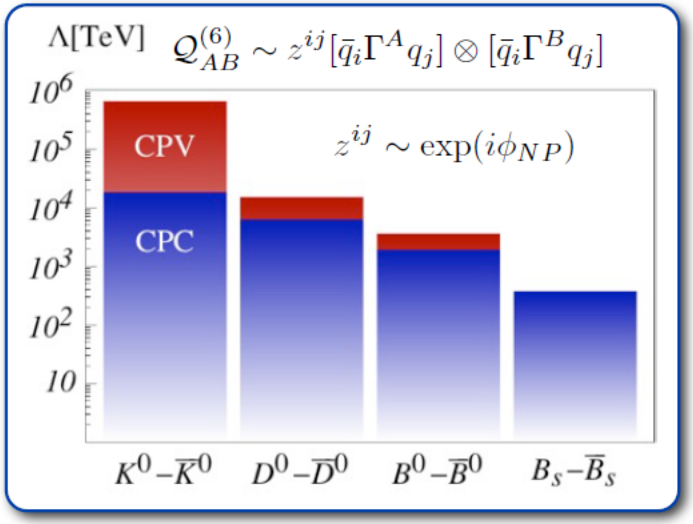
$$\Lambda_{NP} \sim \frac{M_W^2}{m_t} \frac{4\pi}{g^2} \frac{1}{|V_{td} V_{ts}^*|} \sim 10^4 \text{ TeV}$$

Mixing

NP in D-mixing

- CP violation in $\Delta F=2$ processes is the most sensitive probe of NP, reaching scales of $O(10^5)$ TeV

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\nu{\rm SM}} + \sum_{i,(d>4)} \frac{\mathcal{Q}_i^{(d)}}{\Lambda^{d-4}}$$



- CPV in D mixing gives best bound after ε_K

UTFit, 0707.0636
Isidori, Nir & Perez, 1002.0900
Lenz et al., 1203.0238
ETMC, 1207.1287

- How far can we push it?

Mixing

Quarks: *charm+*

Squark Masses

Altmannshofer et. al. 1308.3653

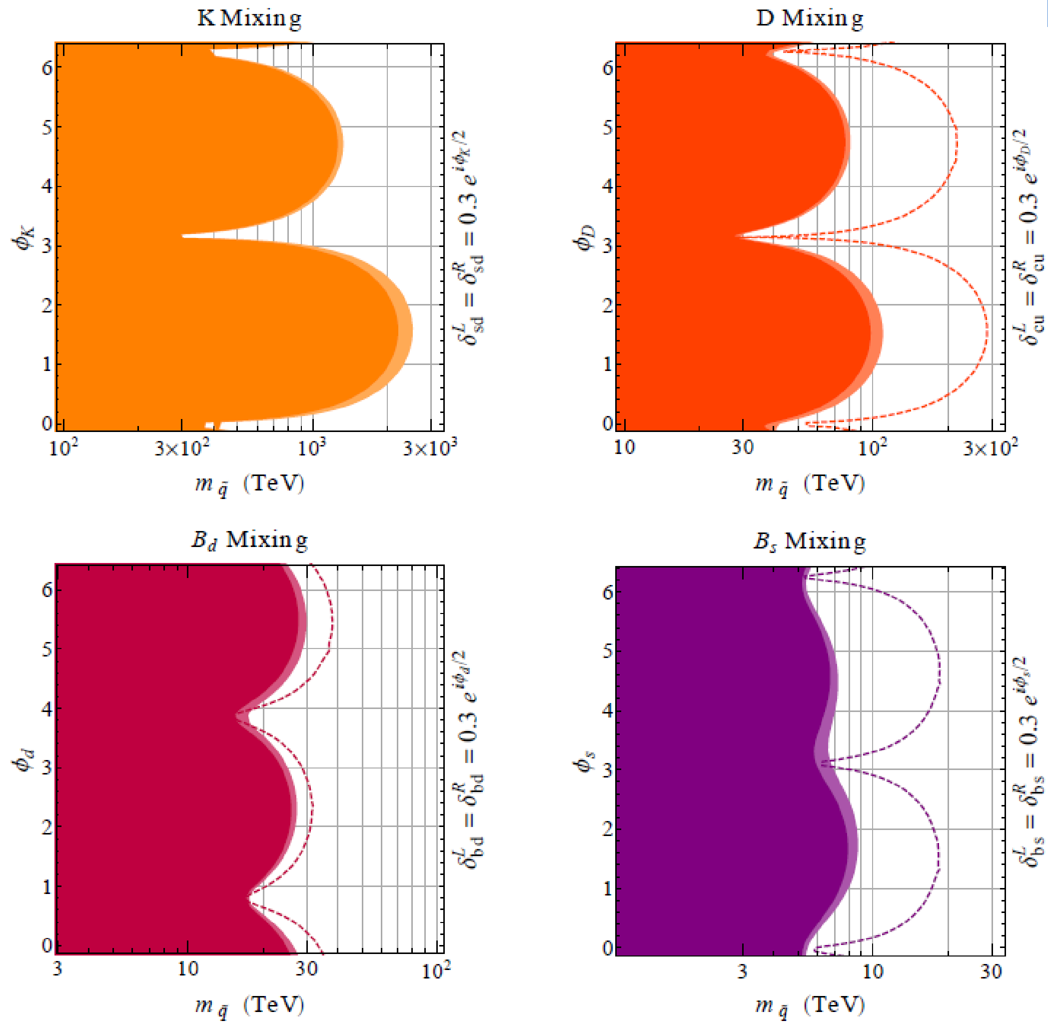
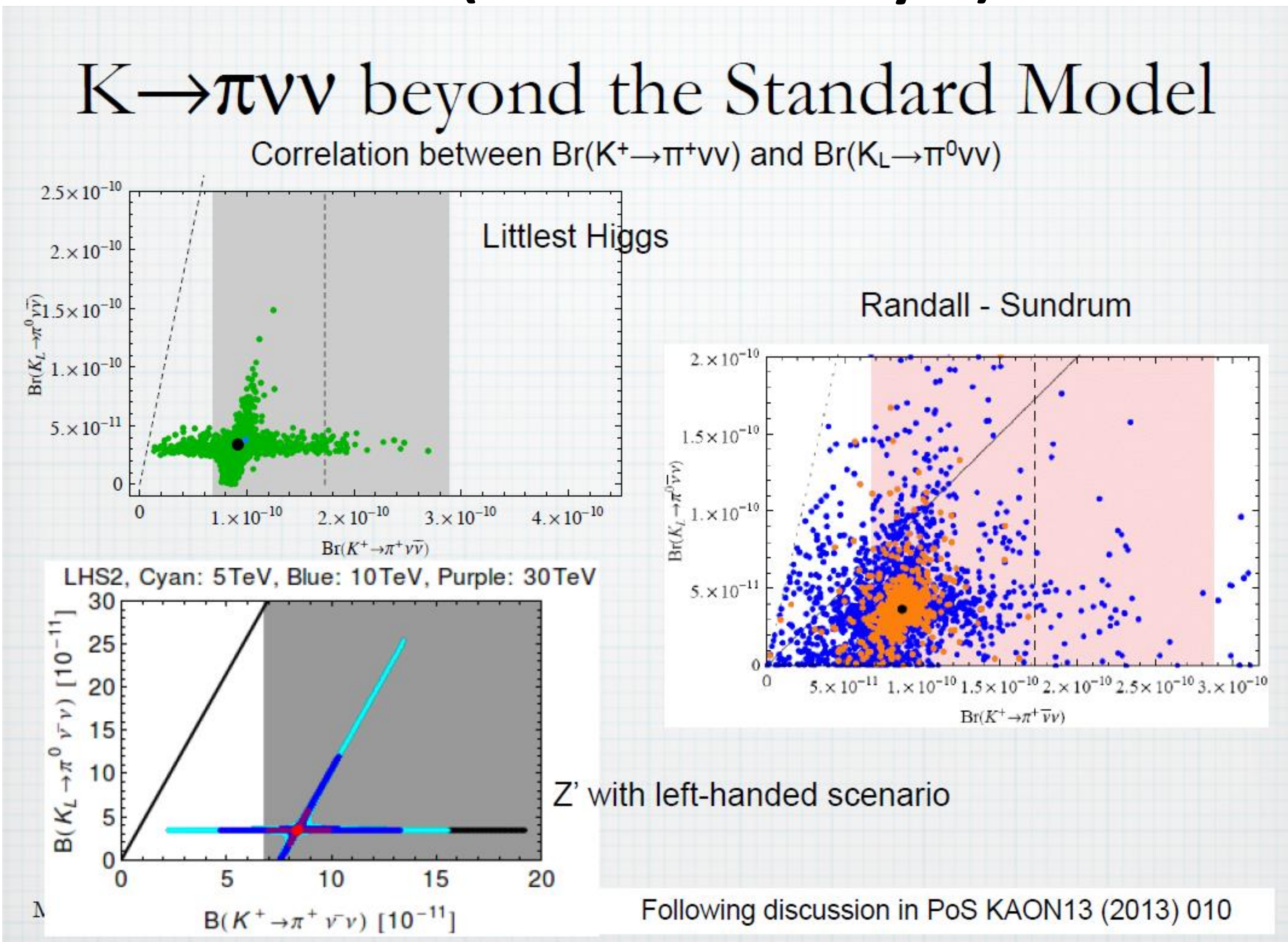


FIG. 7: Squark masses $m_{\tilde{q}}$ probed by meson oscillations as a function of the phase of the NP contribution ϕ_i. The gluino mass is fixed to $|m_{\tilde{g}}| = 3$ TeV. The dark (light) shaded regions are excluded at 95% (90%) C.L.. The dashed lines show the expected 95% C.L. constraints with future experimental improvements on CP violation in meson mixing (factor ~ 10 in D^0 mixing, factor ~ 2 in B_d mixing, and factor ~ 10 in B_s mixing).

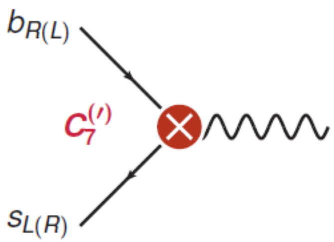
NP (rare decays)



b → s

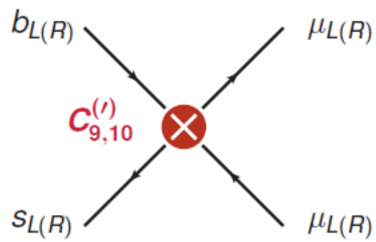
$$\mathcal{H}_{\text{eff}}^{b\to s} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{e^2}{16\pi^2} \sum_i \left(C_i \mathcal{O}_i + C_i' \mathcal{O}_i' \right)$$

magnetic dipole operators



$\propto 1/q^2$

semileptonic operators



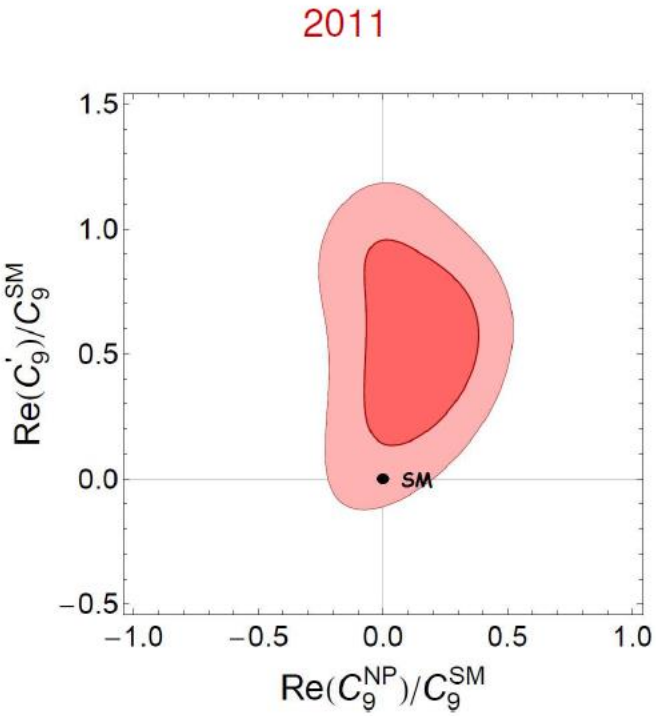
$\propto 1$

	$C_7,\ C_7'$	$C_9,\ C_9'$	$C_{10},\ C_{10}'$
$B \to (X_s, K^*)\ \gamma$	★		
$B \to (X_s, K, K^*)\ \mu^+\mu^-$	★	★	★
$B_s \to \phi\ \mu^+\mu^-$	★	★	★
$B_s \to \mu^+\mu^-$			★

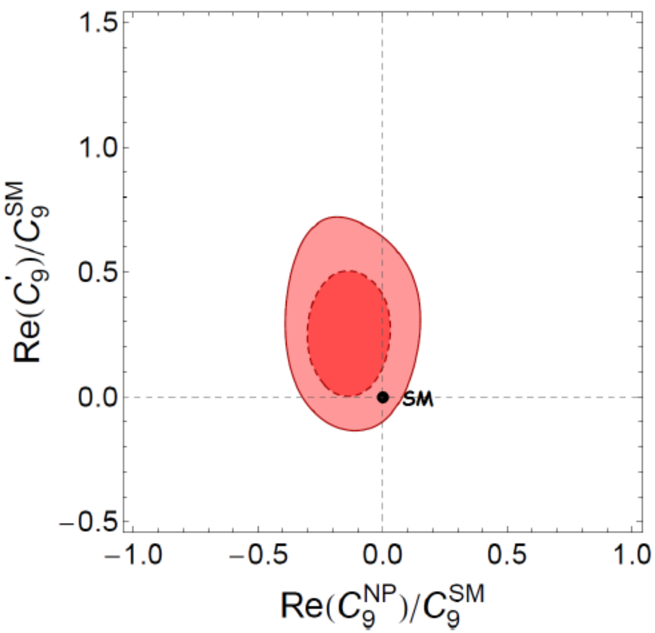
neglecting tensor operators (secretly dimension 8)

neglecting scalar operators (strongly constrained by $B_s \to \mu^+\mu^-$)

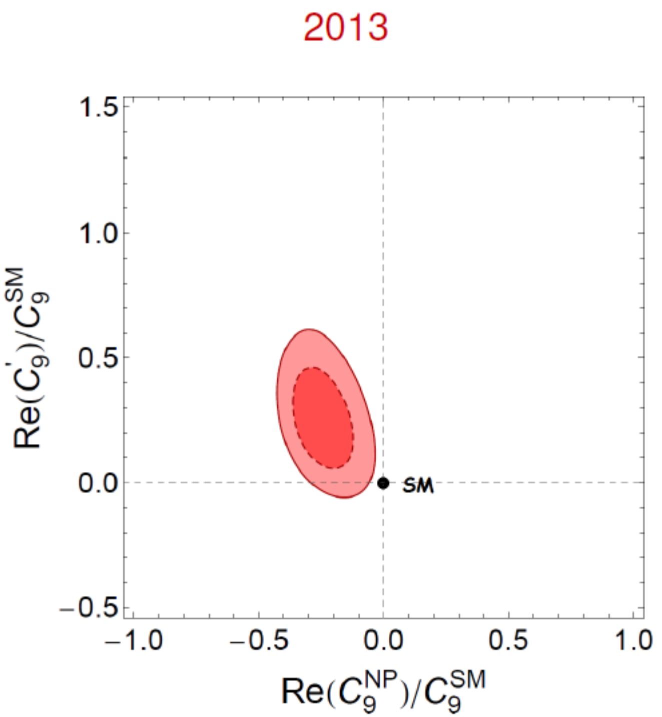
(Alonso, Grinstein, Martin Camalich '14)


2011
1.5
1.0
0.5
0.0
−0.5
−1.0
−0.5
0.0
0.5
1.0
SM
$\mathrm{Re}(C_9')/C_9^{\mathrm{SM}}$
$\mathrm{Re}(C_9^{\mathrm{NP}})/C_9^{\mathrm{SM}}$

2012

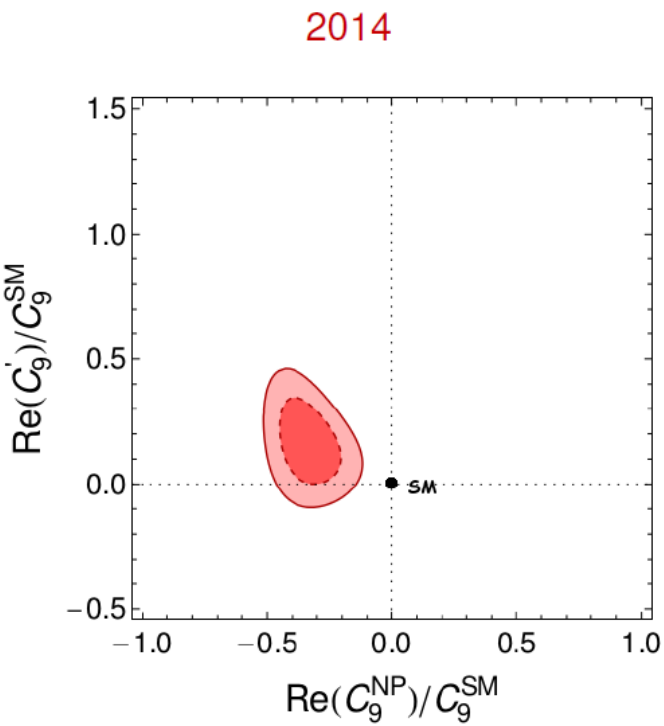


Quarks: *beauty*

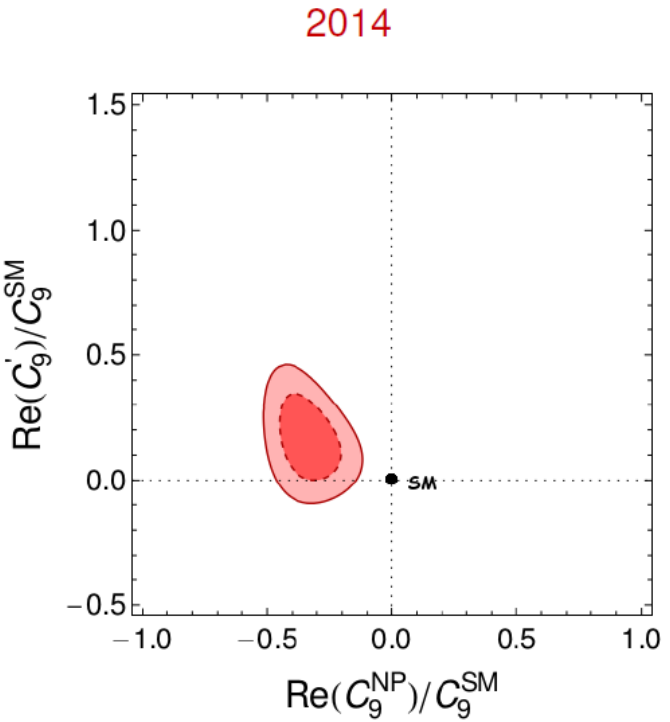


Quarks: *beauty*

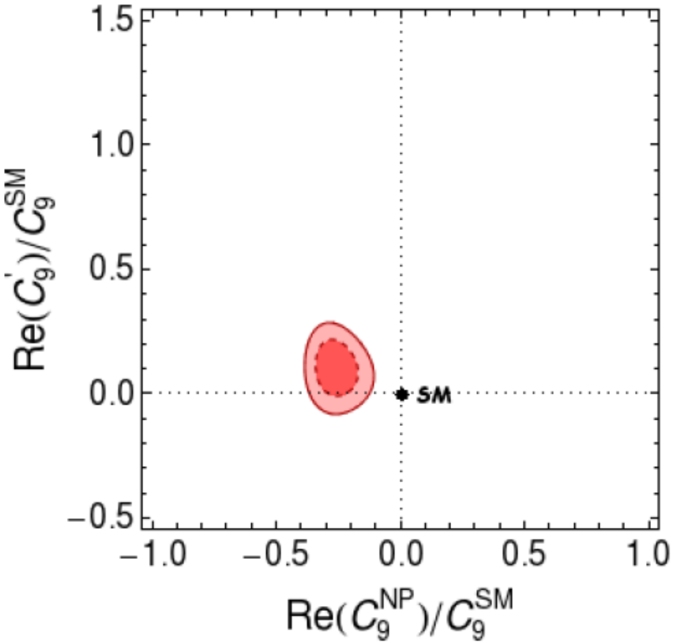
Quarks: *beauty*



Quarks: *beauty*



2015



Large number of measurements gives large trial factor

Global p-value

- $\Delta\chi^2 = 15.2$
- p-value: 12.4% (2.1% in the SM)

Many experimental improvements:
Theoretical uncertainties?

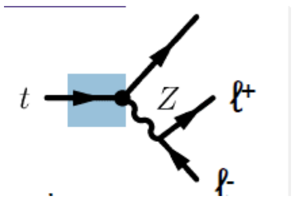
Quarks: *beauty*

FCNC

Quarks: *top*

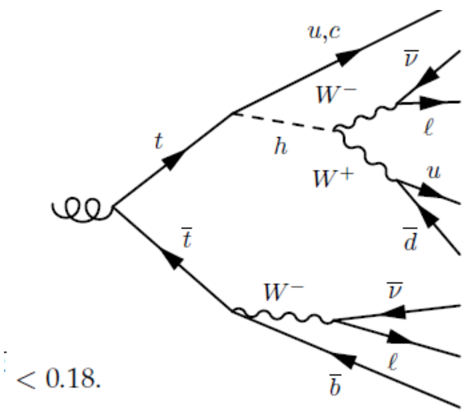
- FNCN top decays arxiv:1312.419

  t→qZ



- Multileptons (CMS) PAS TOP-13-017

Cirigliano / top quark
arxiv.org/pdf/1603.03049.pdf



- Top quark flavour violation can be tensioned against measurements from B&K physics and EDMs

Leptons

SELECTED TOPICS

another way to reach a PeV

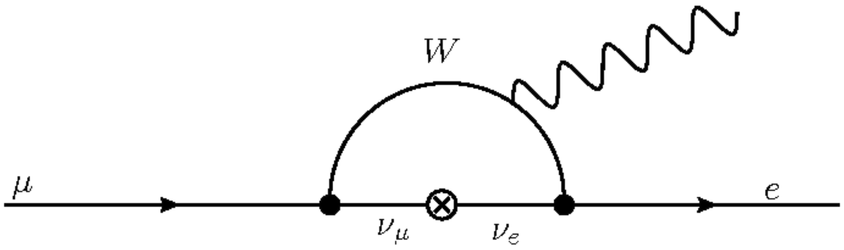
Many tests at different facilities

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	NA62
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	Belle II, LHCb
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

The most sensitive CLFV probes use muons

Neutrino Oscillations and CLFV

- Neutrinos oscillate, so lepton flavor is not conserved.
- Charged leptons *must* mix through neutrino loops.
    - But the mixing is so small, it's effectively forbidden.



- No Standard Model pollution! Observation is unambiguous evidence for new physics.

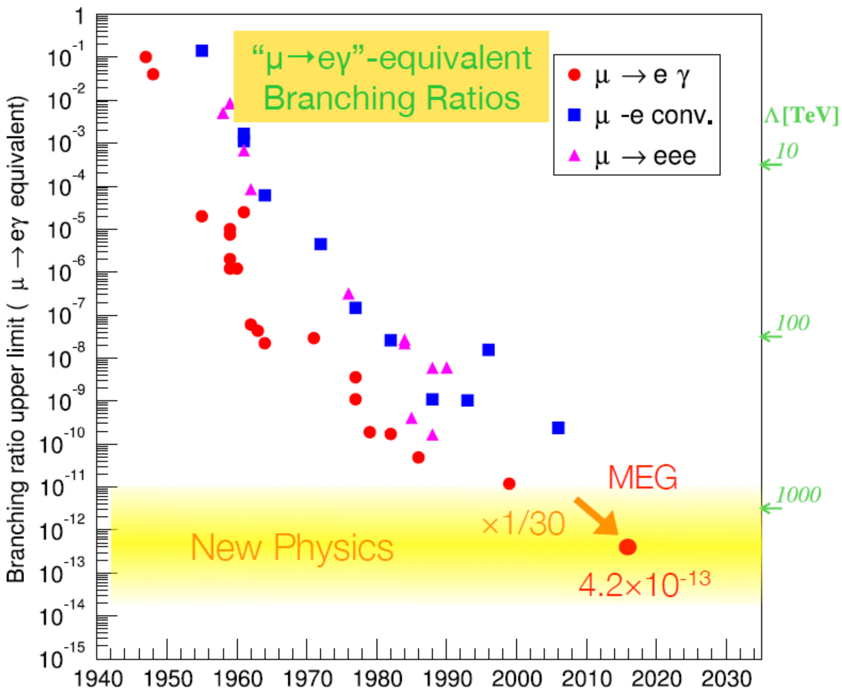
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W}\right|^2 \leq 10^{-54}$$

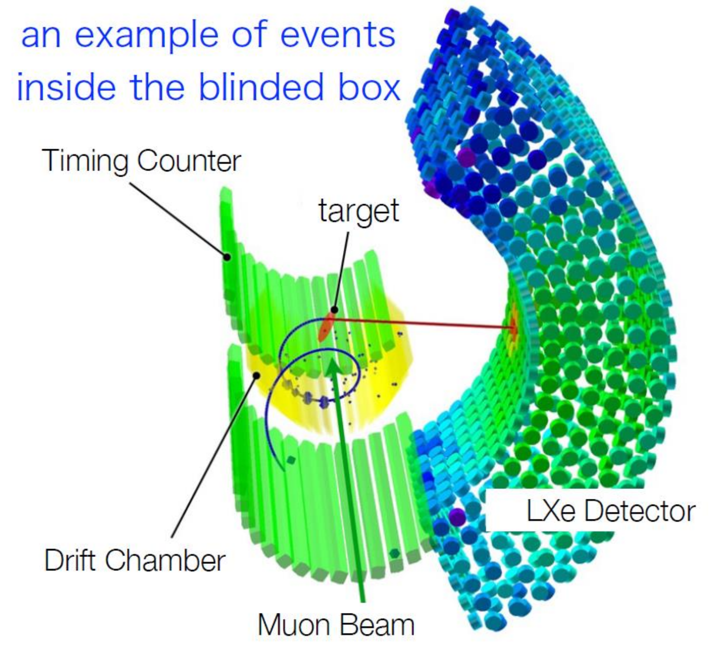
Experiments

mostly **MUONS AND EDMS**

g-2 COMET MEG mu2e mu3e srEDMs

Experiment: MEG





LFV

Experiment: mu2e

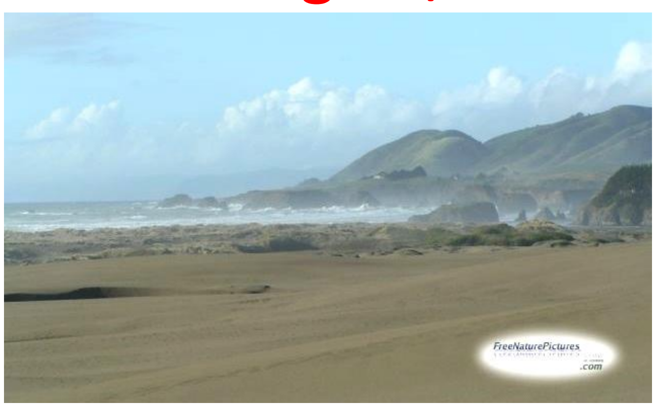
A search for Charged-Lepton Flavor Violation

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

LFV in the field of a nucleus (see COMET)

Use *current* Fermilab accelerator complex to reach a sensitivity 10 000 better than world's best

Data taking 20/21



Mu2e plans to use aluminum

Sensitivity goal requires ~10^{18} stopped muons

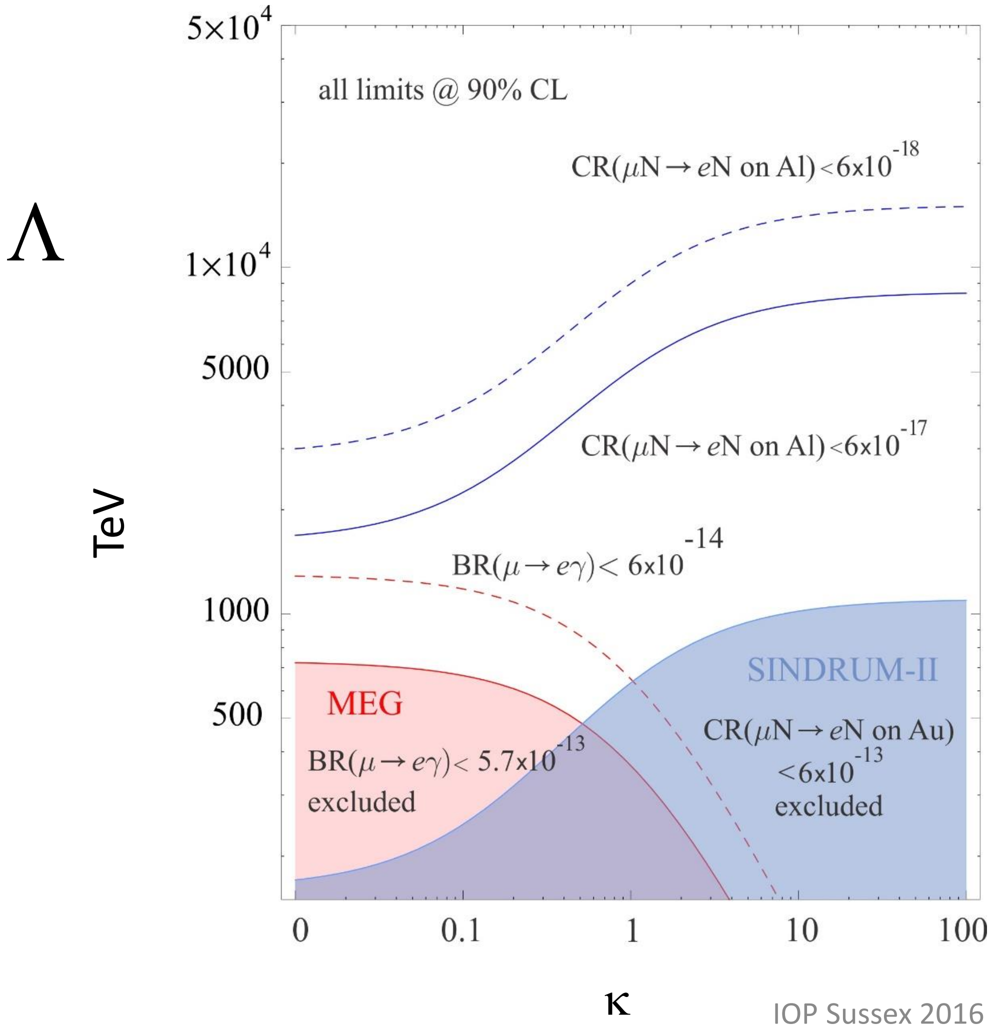
1,000,000,000,000,000,000

=number of stopped Mu2e muons

= number of grains of sand on earth's beaches

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

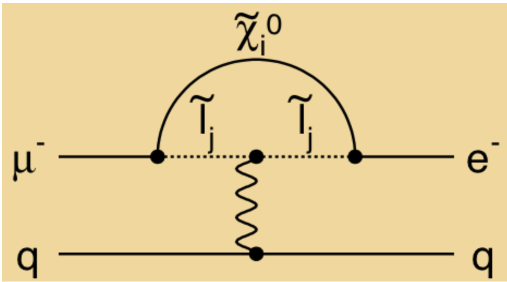
Magnetic moment op. contact term



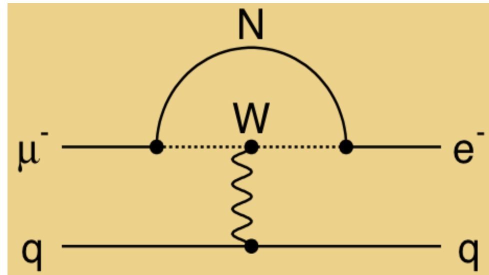
Mu2e extends beyond exisiting MEG for all BSM interaction types and conversion process has sensitivity to non-dipole BSM that MEG doesn't.

NP & μN → eN

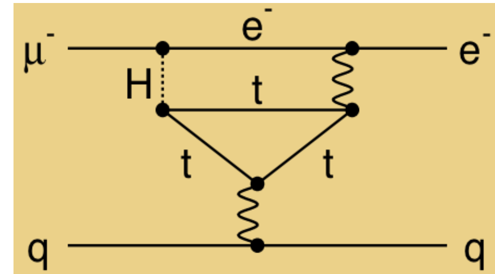
Loops



Supersymmetry

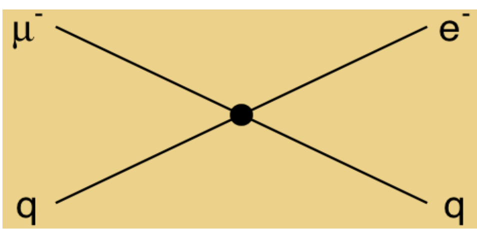


Heavy Neutrinos

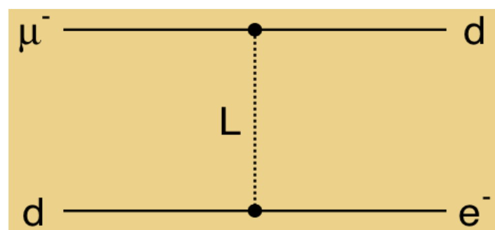


Two Higgs Doublets

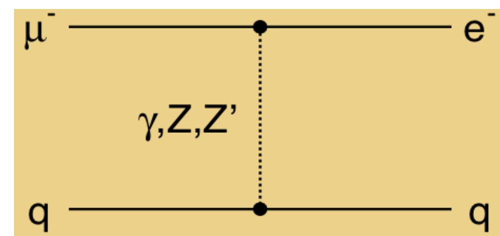
Contact Terms



Compositeness



Leptoquarks



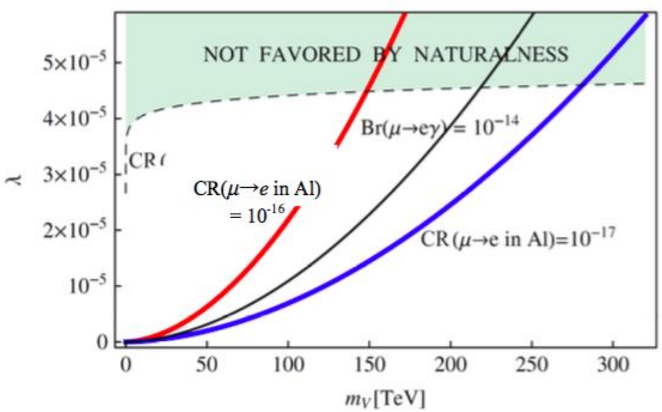
New Heavy Bosons /
Anomalous Couplings

μN → eN sensitive to wide array of New Physics models

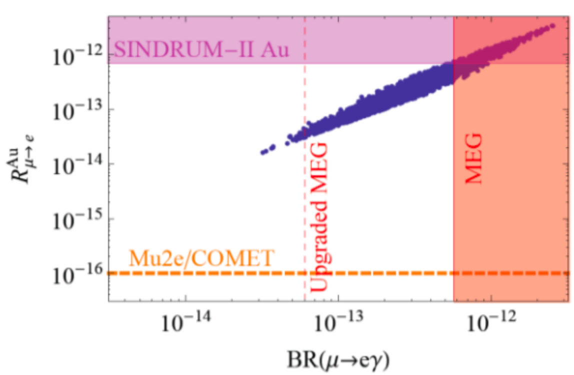
scalar leptoquarks

not excluded by LHC

Arnold et al, Phys. Rev **D88** 035009 (2013)



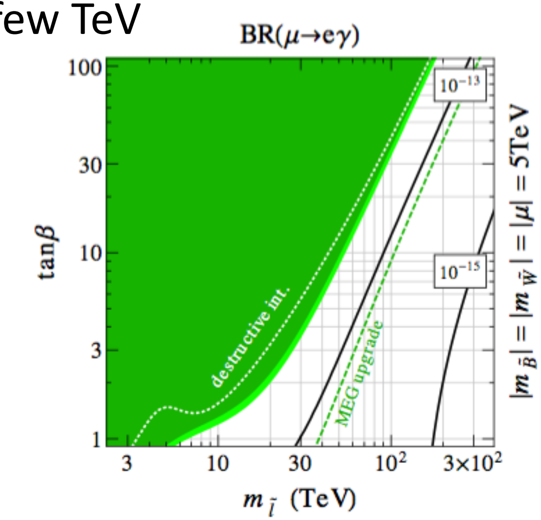
Scalar leptoquark mass [TeV]

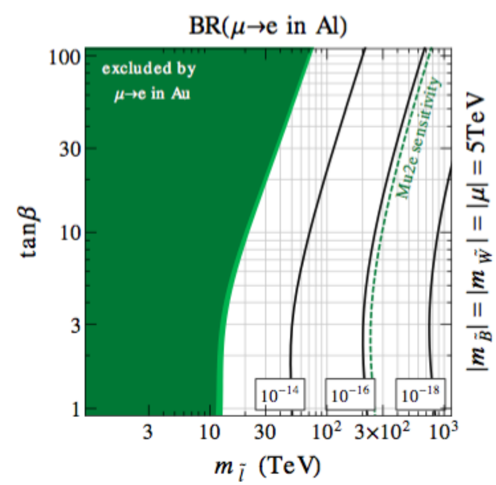


TeV-scale Left-right seesaw model

Split SUSY : Higgs mass

Sfermions not at TeV scale but: 100 – 1000 TeV with gauginos at a few TeV

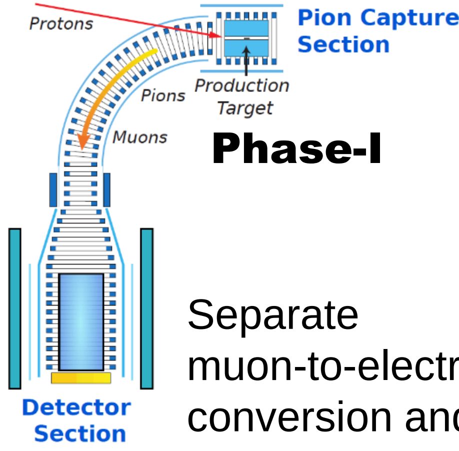




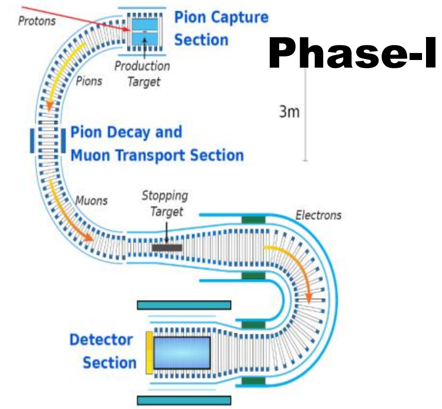
Many of the CLFV models have:
- effects too weak to see at LHC e.g. non-standard h (e mu) coupling
- physics at a scale beyond LHC e.g. **split SUSY** and physics of neutrino masses

COMET

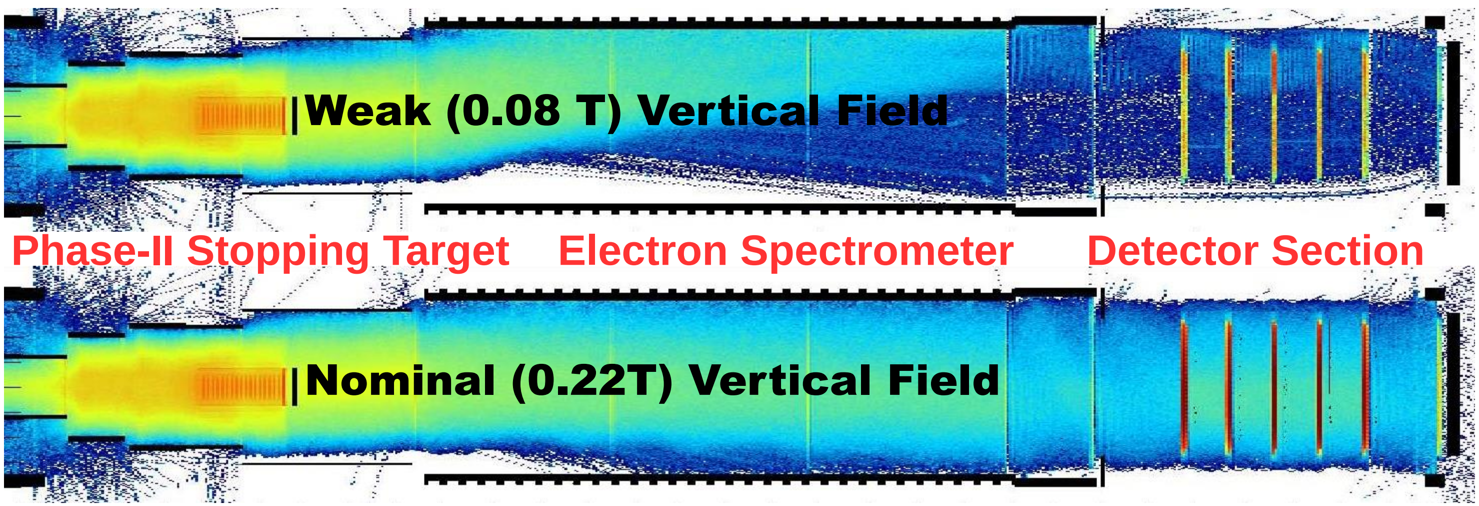
- Two-phase approach:
- physics and background
- studies with first 90° for
- Phase-I, full $O(10^{-17})$
- sensitivity for Phase-II
-



Separate muon-to-electron conversion and background study detectors



- Adjustable charge & momentum selection with vertical B-fields



Traject
of 105
- electrons
- from the
- muon-
- stopping
- target:

- similar momentum selection for muon beam (both phases)
- Intense 56 kW beam: full sensitivity after one year

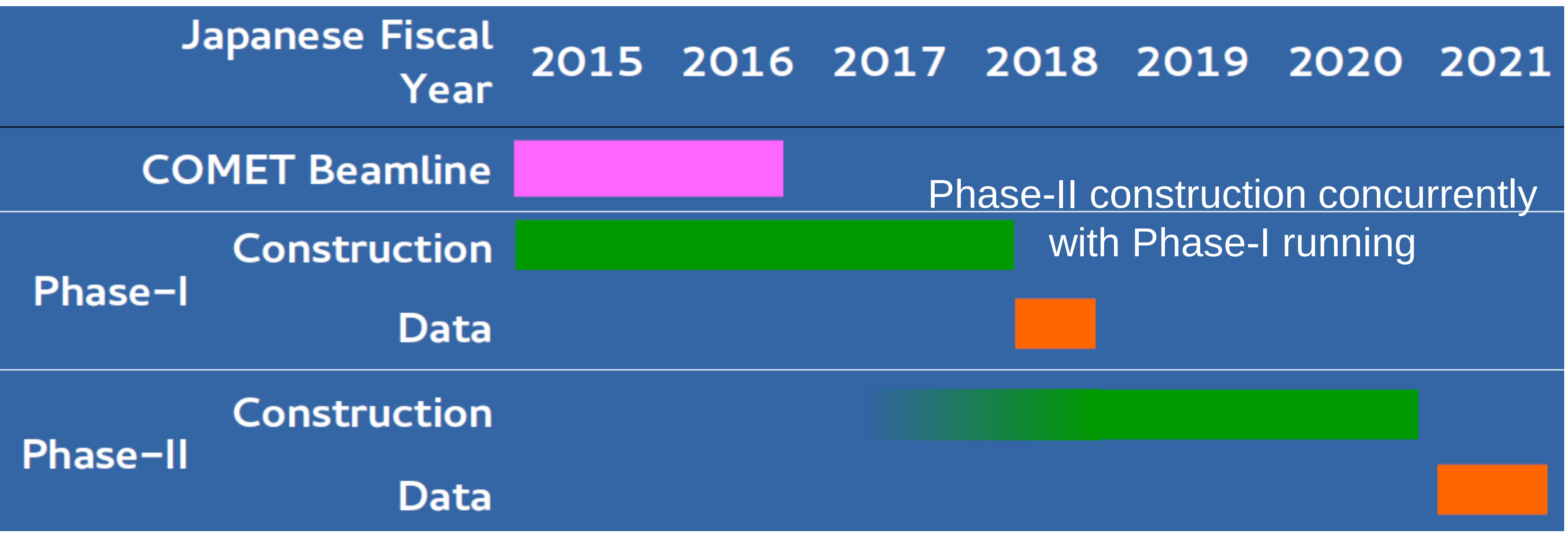
COMET Facility at J-PARC

LFV

Experiment: Comet

- COMET Building and Hall, Counting Rooms completed
- Phase-I Bent Solenoid installed and undergoing testing, detector solenoid almost complete
- System integration work ongoing

COMET: Schedule

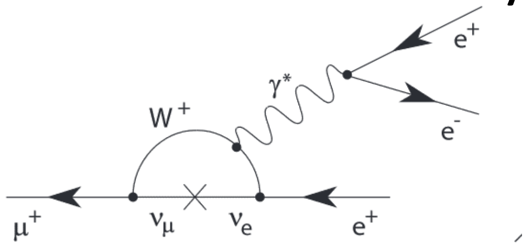


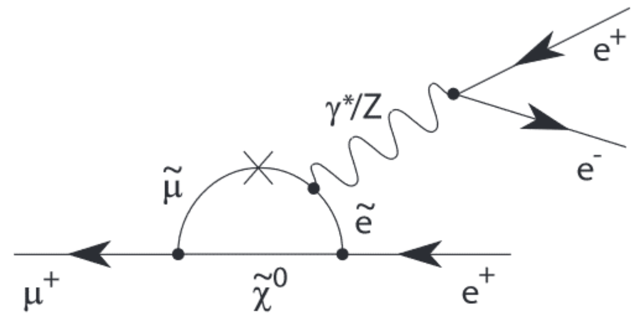
LFV

Experiment: mu3e

mu3e

- CFLV with $\mu \rightarrow eee$
- Look at 1 in 10^{16} decays

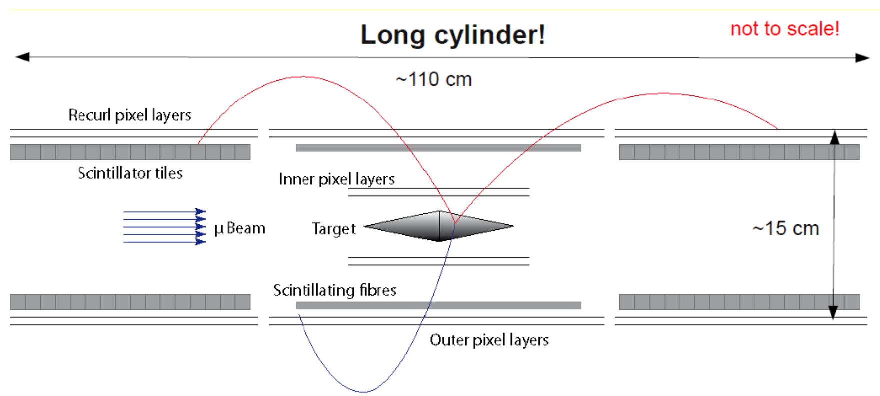




Heavily suppress $\mu \rightarrow ee e\nu\nu$

(over 16 orders magnitude

with kinematic cuts)



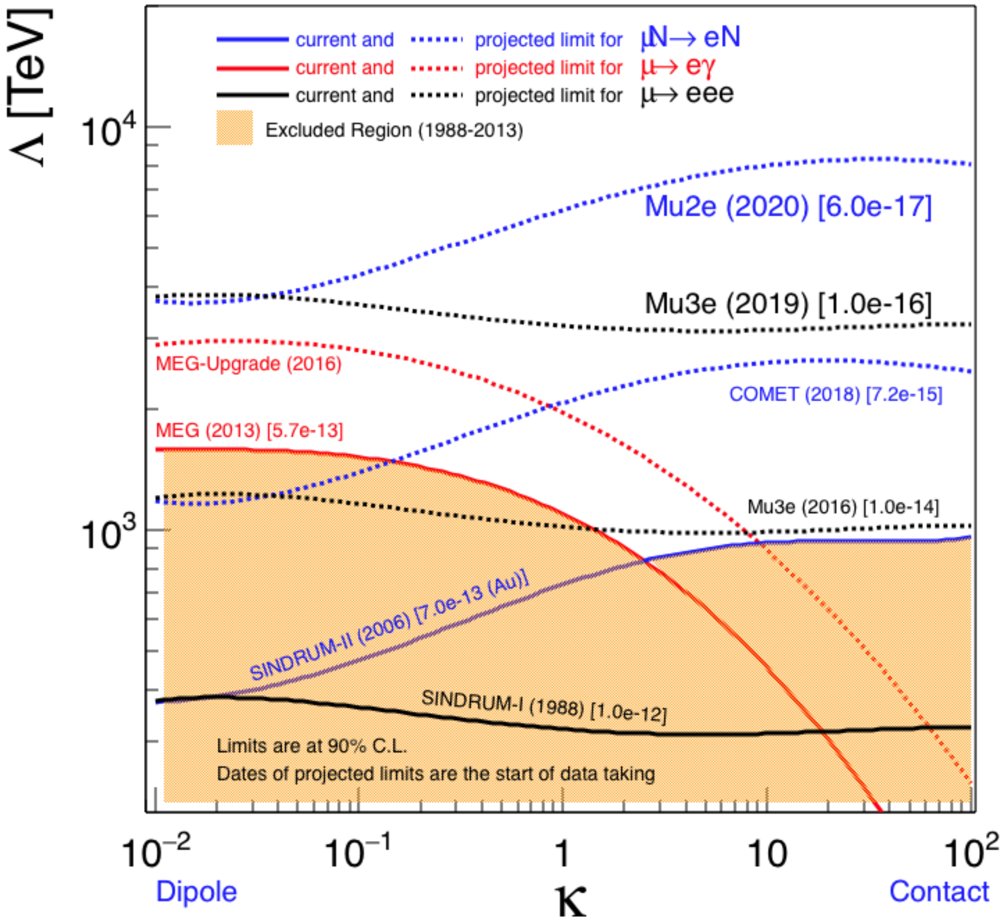
mu3e v mu2e

- leptogenesis models (with cLFV) there are big variations in the expected rates of the $\mu N \rightarrow eN$ and the $\mu \rightarrow eee$ decays.
  - If inverted neutrino mass hierarchy enhancement of $\mu \rightarrow eee$ decays
- If NP couples more strongly to leptons than to quarks, mu3e has unique sensitivity.
- More than event counting – if signal
  - Full reconstructed 3 electron state
- Access to dark photons (10 to 100 MeV)

LFV

Experiment: all

Putting it all together ....



Updated from A. de Gouvea, P. Vogel, arXiv:1303.4097

Race

We need all the results!

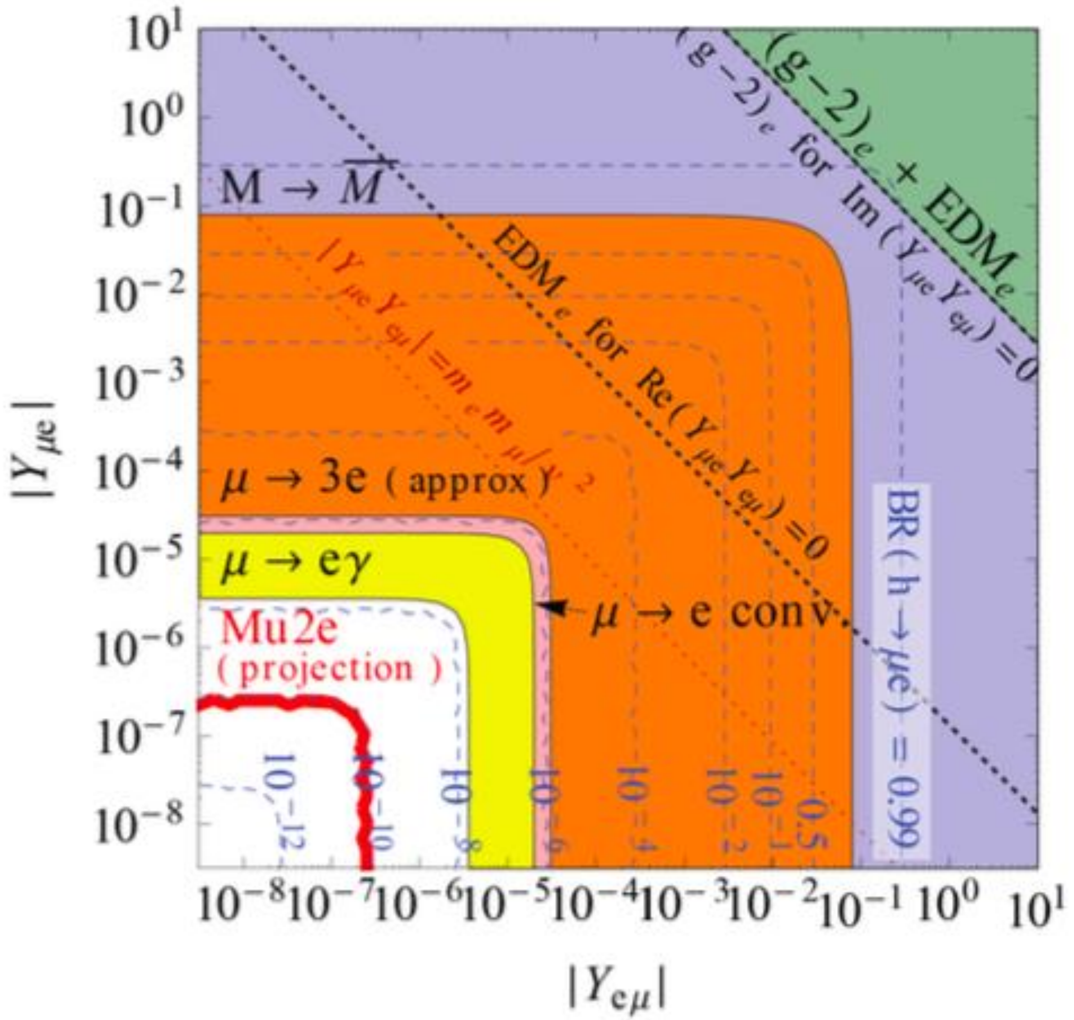
If you measure one (meg/muN-eN), m3e (e.g.) needed combination of λ,κ. *Need to measure more than one*

LFV

Experiment: all

Even sensitivity to **non-standard Higgs couplings** (new Higgs bosons)

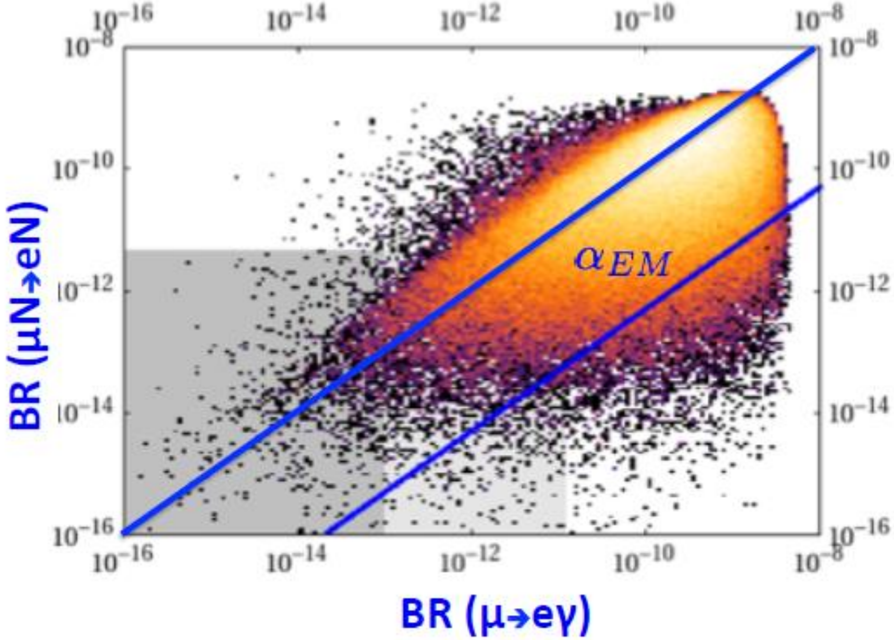
Harnik et al JHEP **3**, 26 (2013)



Sensitive down to BR ($h \to \mu e$) of 10^{-10} (cf current LHC limit of 3×10^{-4})

Many Model Dependent Relationships between observables

In general in BSM models $\frac{BR(\mu N \to eN)}{BR(\mu \to e\gamma)} = \mathcal{O}(\alpha_{EM})$ but not always...



e.g. "Littlest Higgs model" with T-parity (LHT)

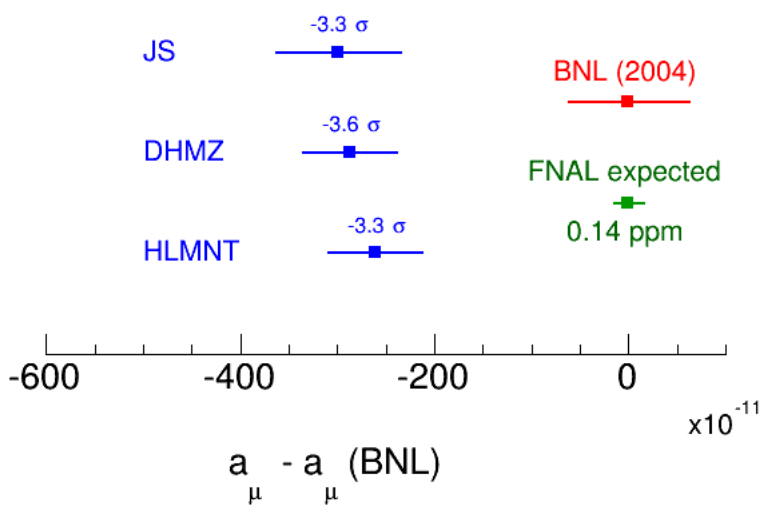
Experiment: g-2

NP

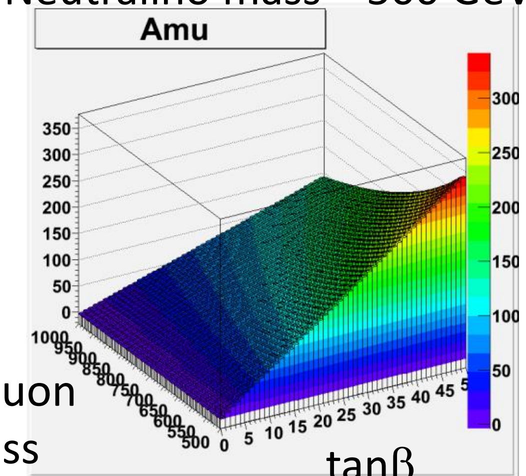
Experiment: g-2

g-2 does not probe flavour changing interactions but NP in loops….

Can address models: technicolor, SUSY, 2HDM, LHT, W', Z' (TeV range)



Neutralino mass = 500 GeV

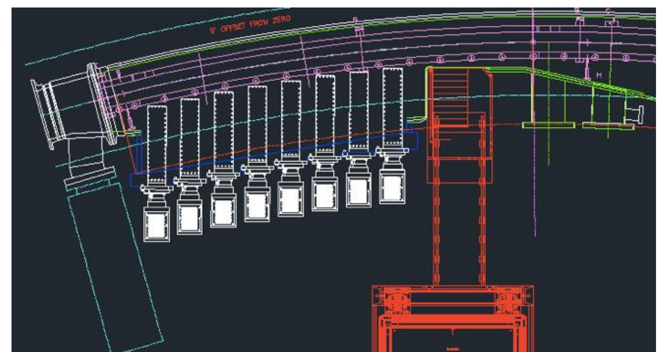


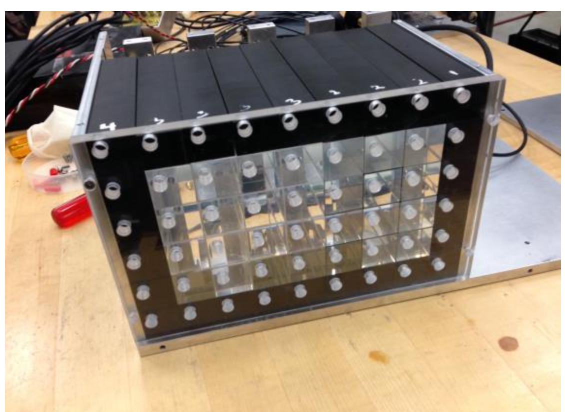
Smuon mass (Gev)

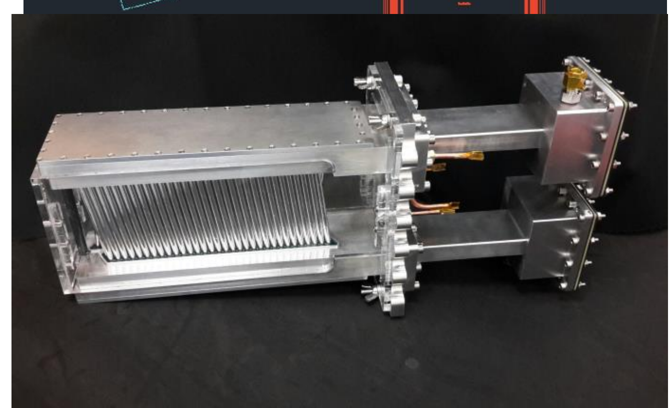
tanβ

By 2019 (First Data 2017)
5.5σ significance from the experimental improvement becomes 9.7σ evidence of NP

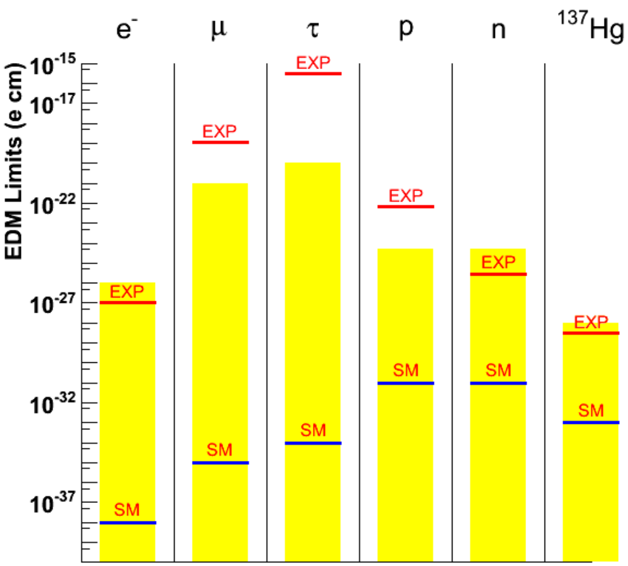
- Improvements from BNL
  - More muons/proton, less pions
  - Improved detectors (3 trackers, Calorimeters)
  - Better beam dynamics
  - Improved field uniformity
  - Improved modelling



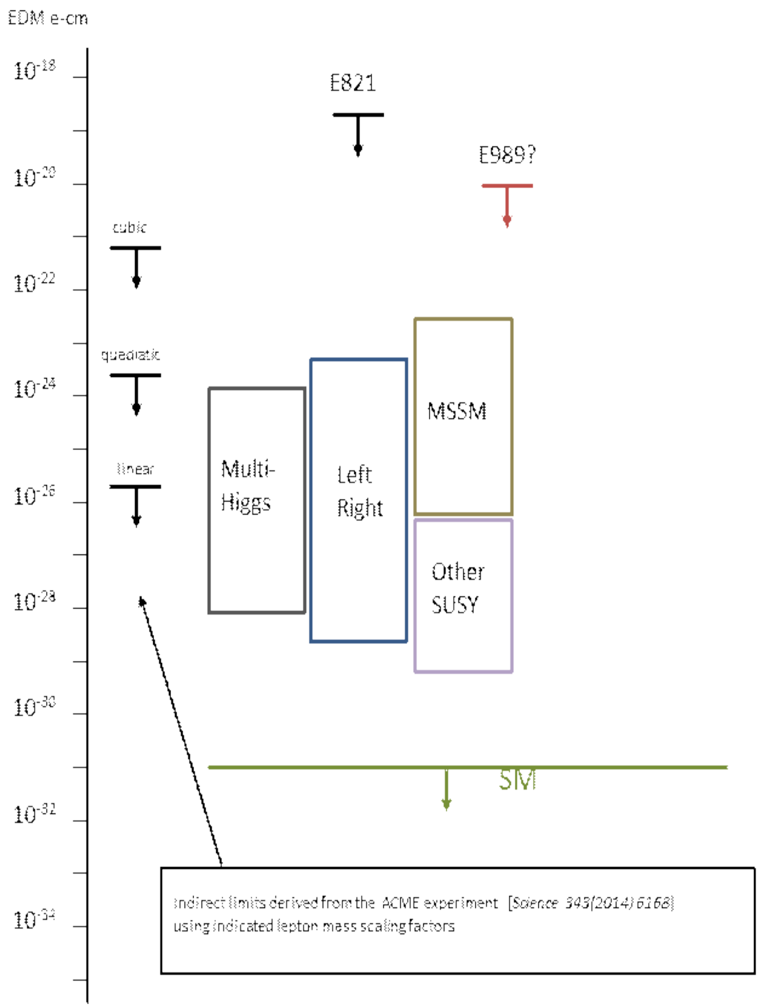


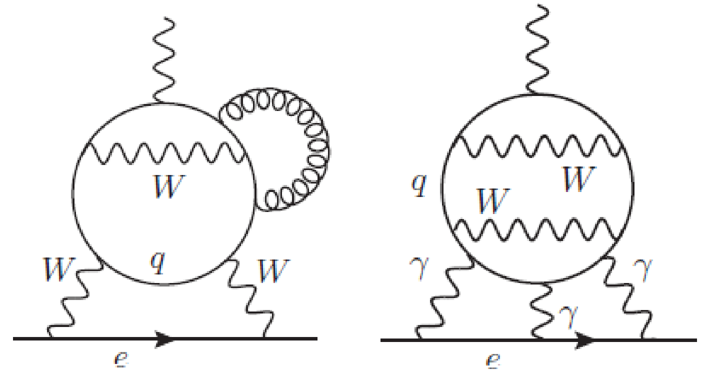


muEDM

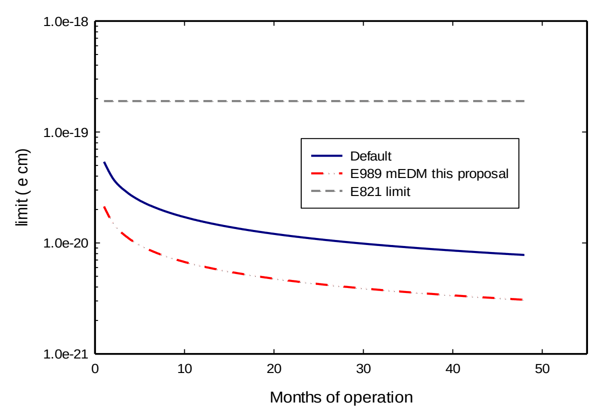


- Phase-I Part of g-2 experiment (first measurement)
- see anything in muons, sign of new physics
- $|d_e| < 10^{-29}$ e cm, the current results, for 2nd generation muons 10 orders of magnitude worse, $|d_\mu| < 1.8 \times 10^{-19}$ e cm
- *g-2@FNAL will get improve this by two orders of magnitude*





Examples of a 4-loop diagram, **the lowest order contributing to lepton EDMs in the Standard Model**, and 5-loop diagram



EDM

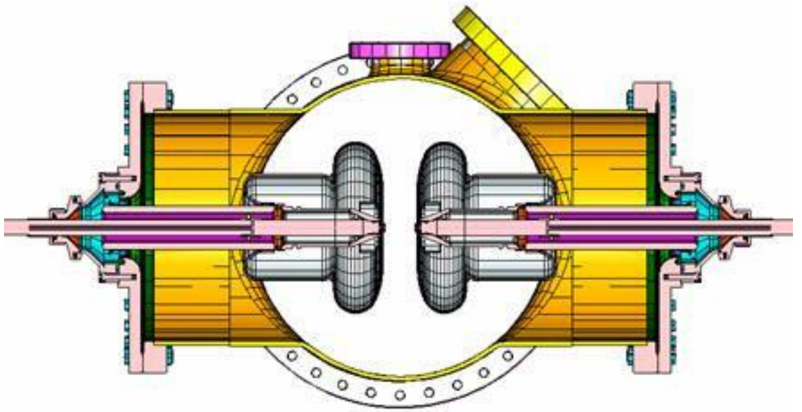
Experiment: srEDM

proton
storage ring
EDM

e(p)EDM

- Ideas from same original g-2 team
- pEDM "like" g-2 but ALL electric
  - Counter rotating beams enable huge cancellation of systematics
  - Study polarization of proto

2014 received P5 support under all scenarios

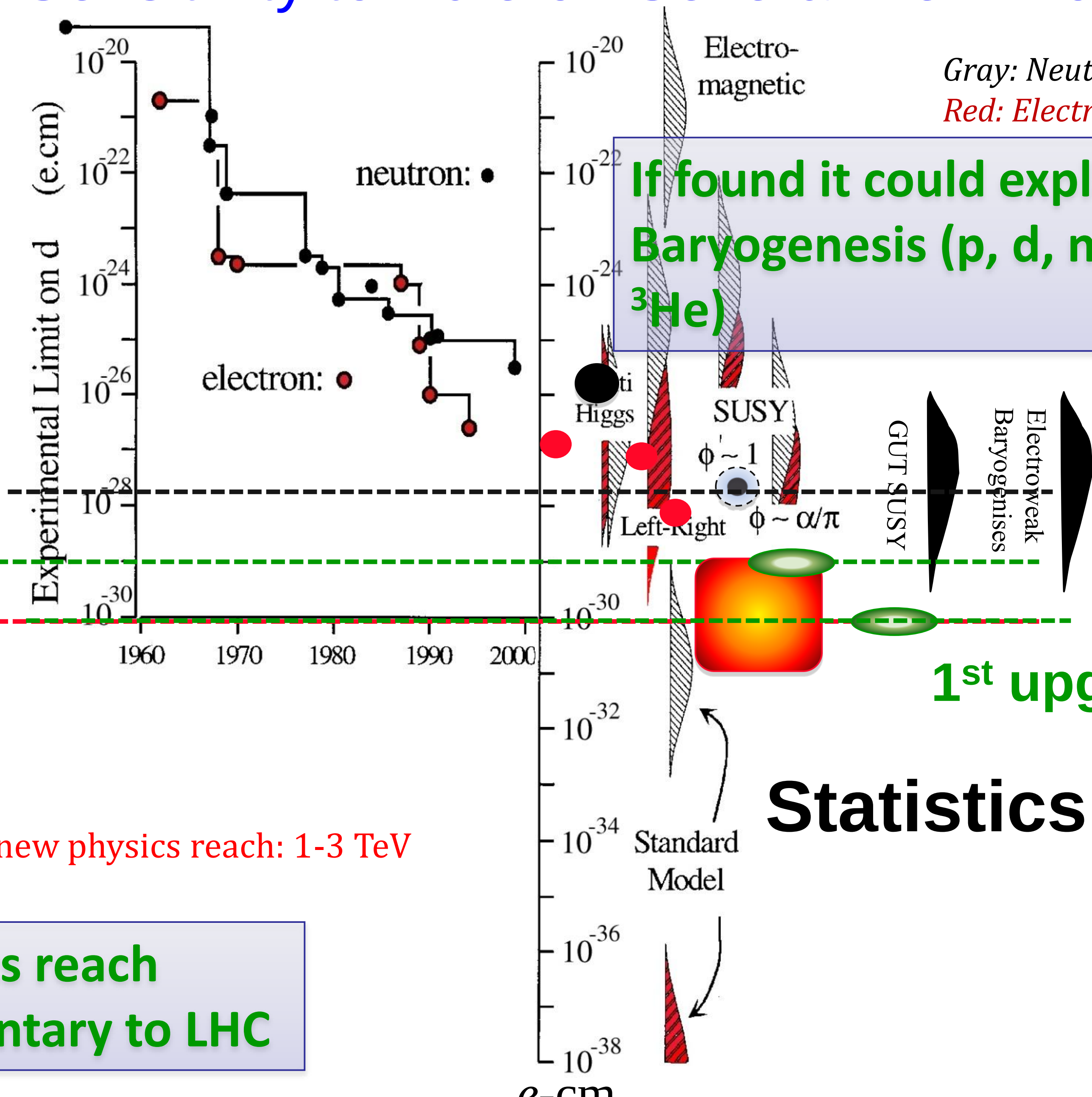


Sensitivity to Rule on Several New Models

Physics

Gray: *Neutron*
Red: *Electron*

n current
e current
n target
p, d target
e target



If found it could explain Baryogenesis (p, d, n, ^{3}He)

1^{st} upgrade

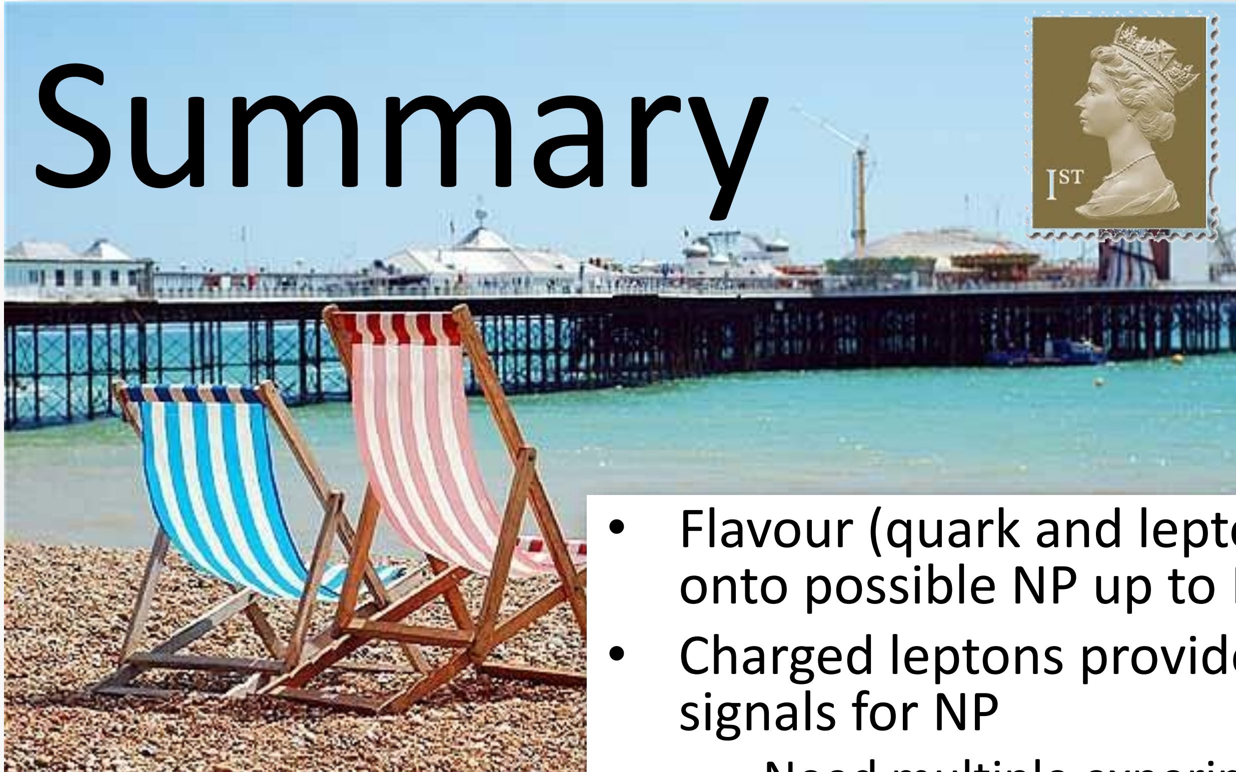
Statistics limited

Electron EDM new physics reach: 1-3 TeV

high physics reach
Complementary to LHC

J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

Summary



- Flavour (quark and lepton) provides wide vista onto possible NP up to PeV scale
- Charged leptons provide especially clean signals for NP
  - Need multiple experiments to interpret signals
- Fertile ground for theory
- Involvement for all: specialized experiments to GPD
  - Think creatively – its inspirational
- Exciting time competition to find new physics

Thanks…