Charged lepton flavor violation

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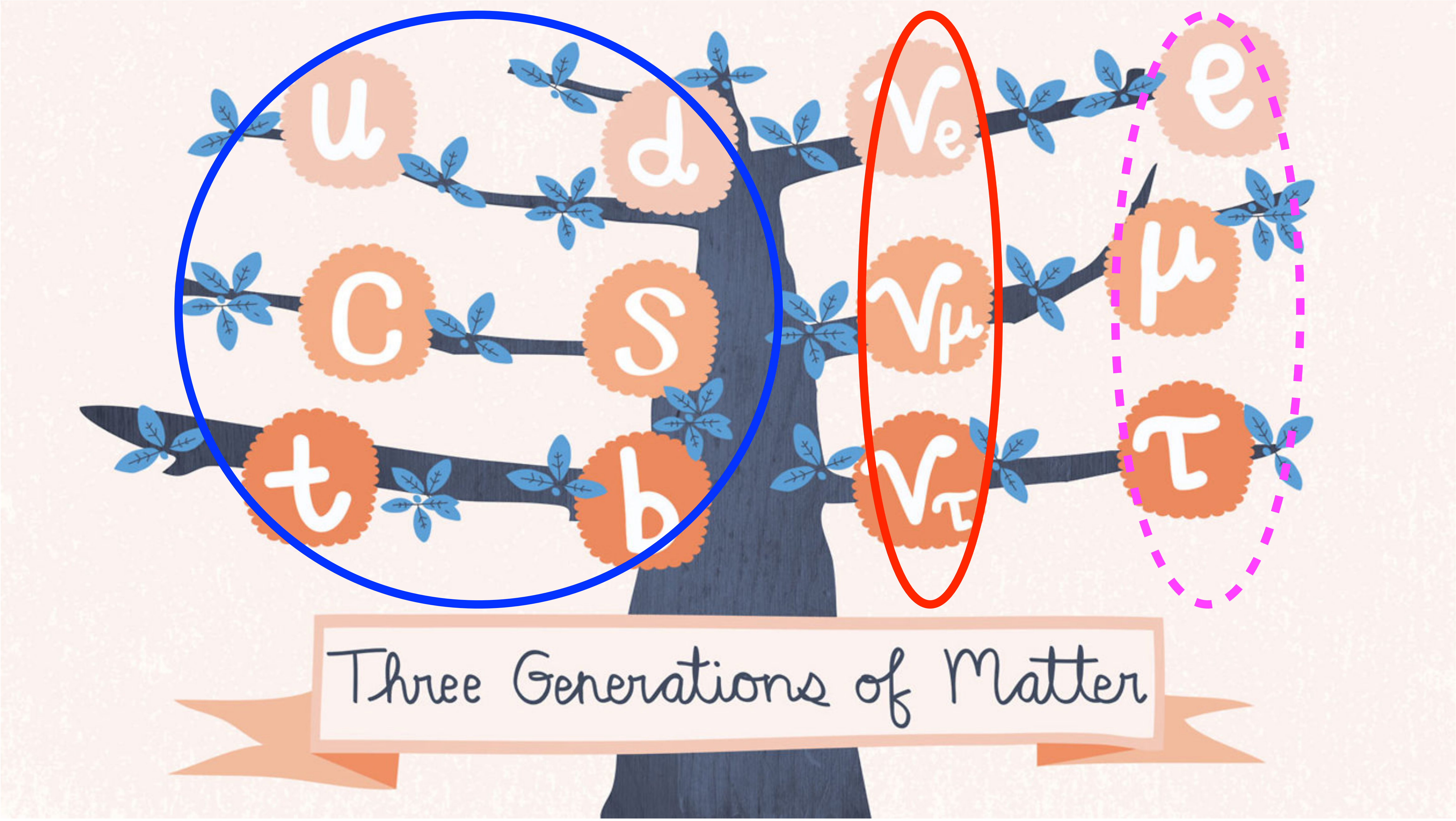
IPA 2018: Interplay between Particle and Astroparticle physics
8-12 Oct 2018, Cincinnati, OH, USA

Three Flavors

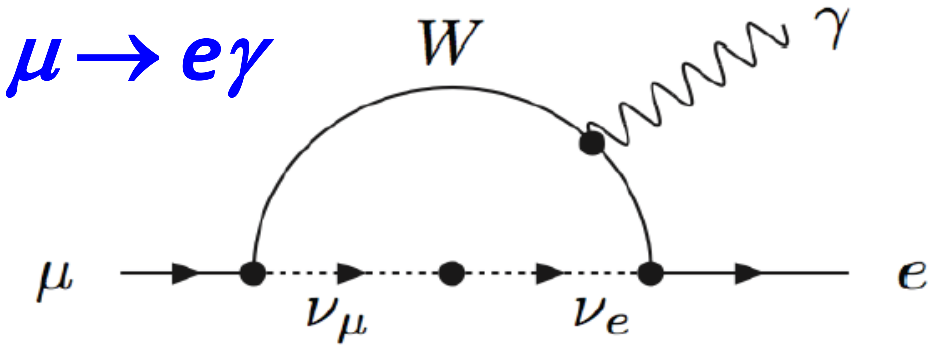


- Quark - mixing: NP 2008
- Neutrino - oscillations: NP 2002, 2015
- Charged lepton flavor violation: ?

Standard Model (SM)

- Lepton flavor violation (LFV)
  - not forbidden by SM gauge symmetry
  - most new models naturally include LFV vertex
- In SM, LF is conserved for zero degenerate ν masses
- Now we have clear indication that ν's have finite mass
  $\Rightarrow$ Lepton Flavor is violated in Nature: but by how much?
- SM extended to include finite ν mass and mixing predicts LFV

$\mu \to e\gamma$

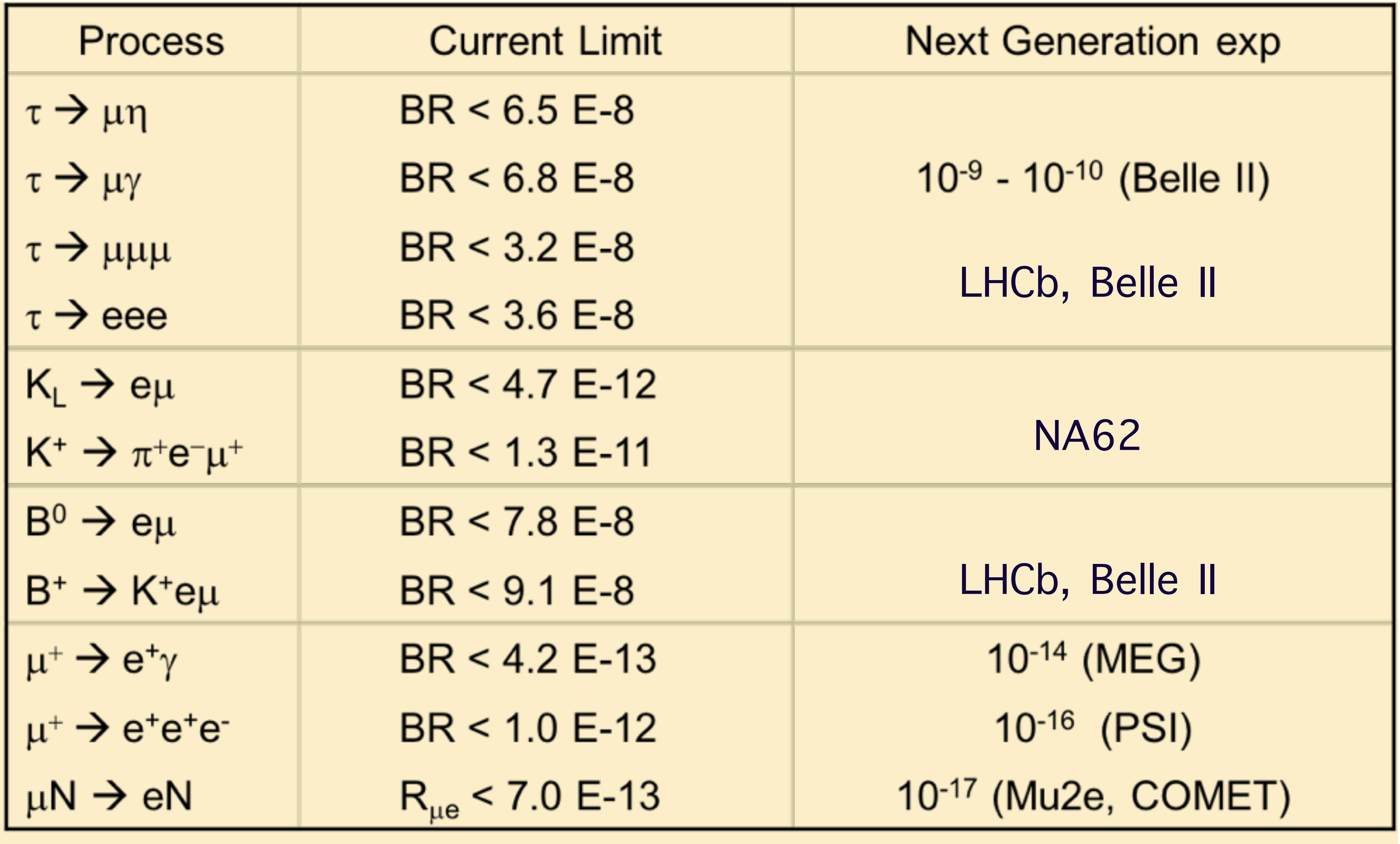


$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

... many orders below experimental sensitivity!

- Observation for LFV $\Rightarrow$ unambiguous signature of new physics

LFV processes

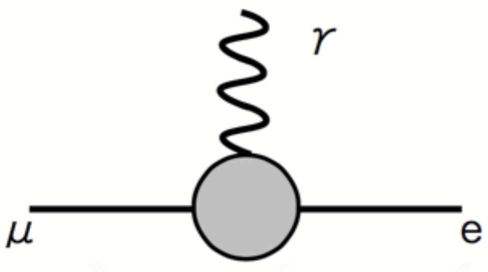


Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II) LHCb, Belle II
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	NA62
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	LHCb, Belle II
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

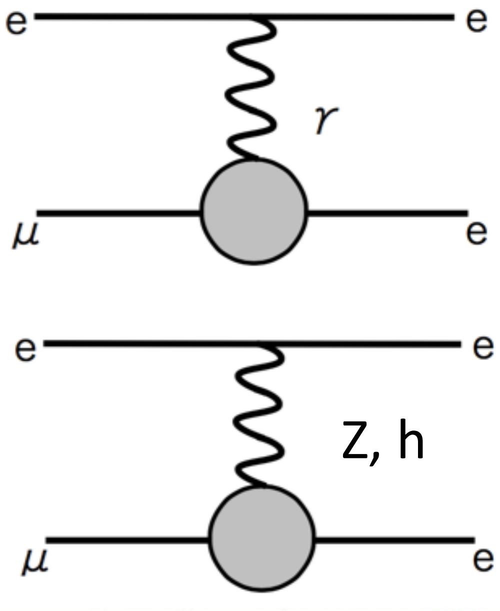
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to \text{all muon captures})}$$

Muon to electron processes

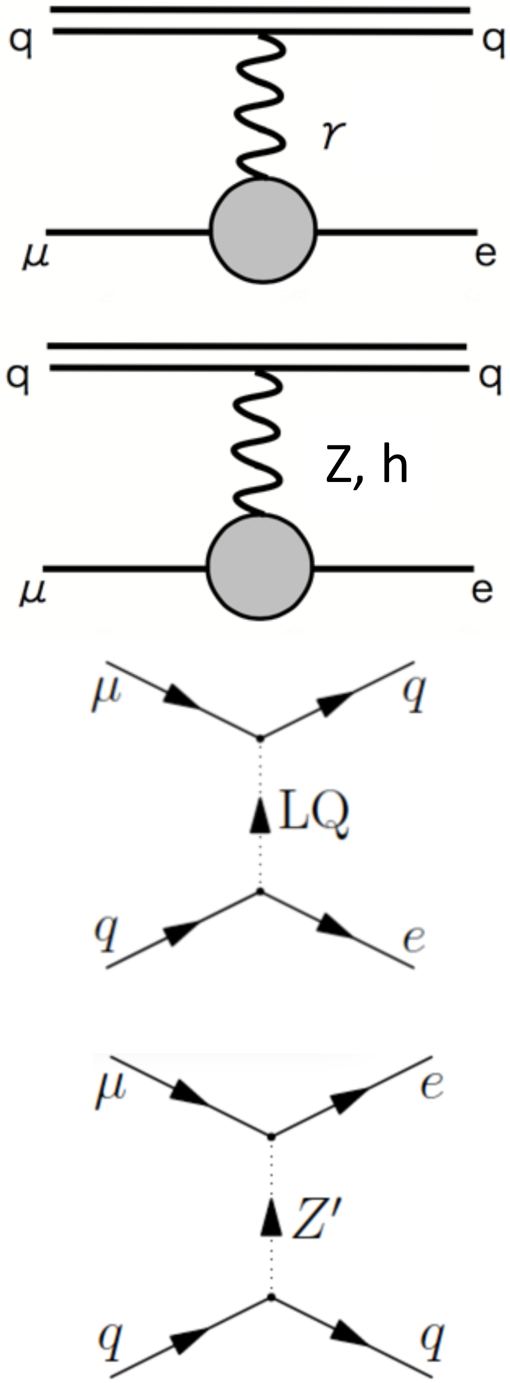
$\mu^+ \rightarrow e^+\gamma$



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

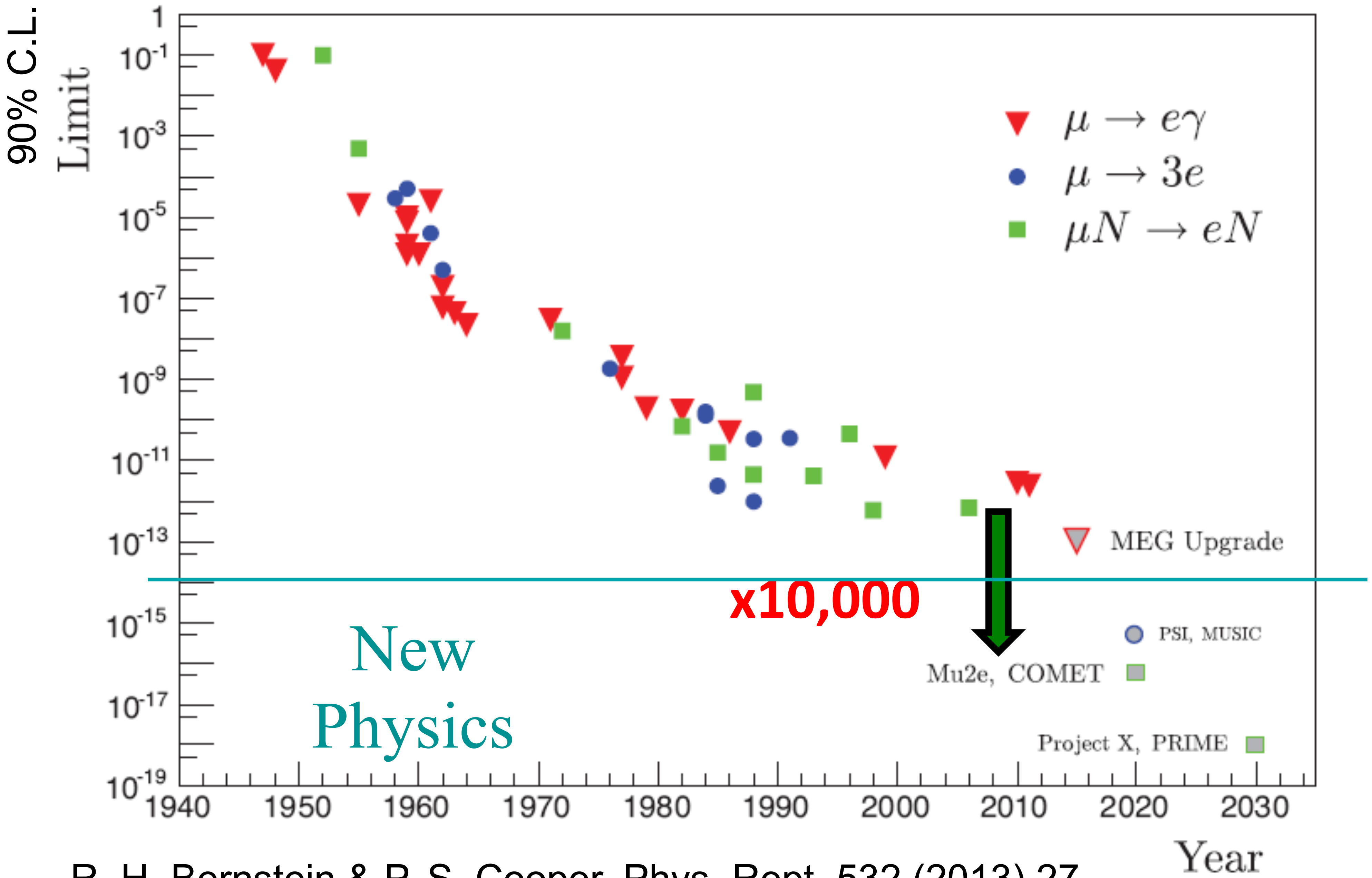


$\mu^- N \rightarrow e^- N$



Different channels offer complementary sensitivity.

Muon to electron processes



R. H. Bernstein & P. S. Cooper, Phys. Rept. 532 (2013) 27

Current best limits:

MEG-2016

BR($\mu \to e\gamma$) < 4.2 x 10^{-13}

SINDRUM-1988

BR($\mu \to 3e$) < 1 x 10^{-12}

SINDRUM-II 2006

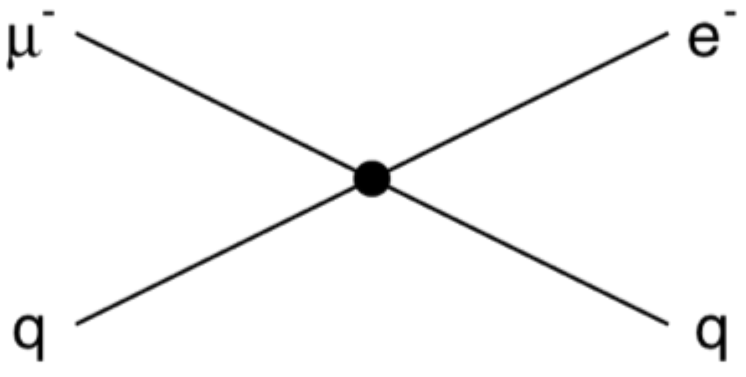
$R_{\mu e}$ < 7 x 10^{-13}

MU2E GOAL

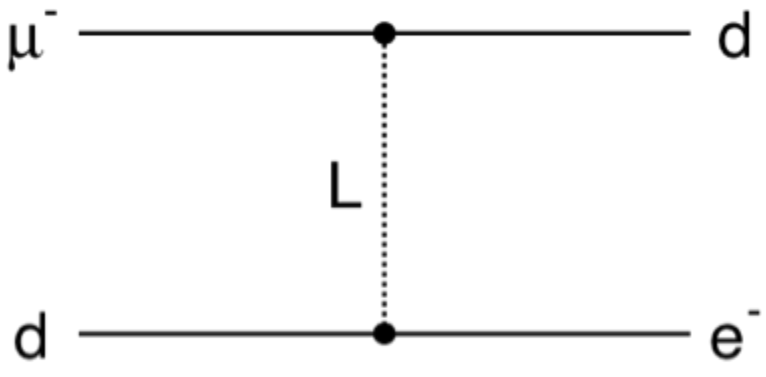
$R_{\mu e}$ = 6 x 10^{-17}

Beyond SM processes

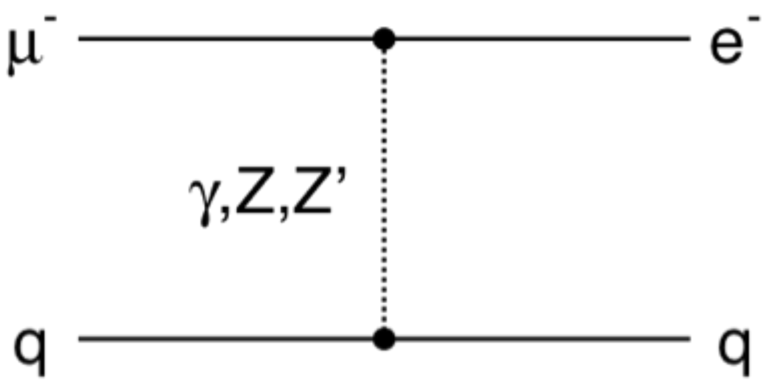
Tree level :



Compositeness

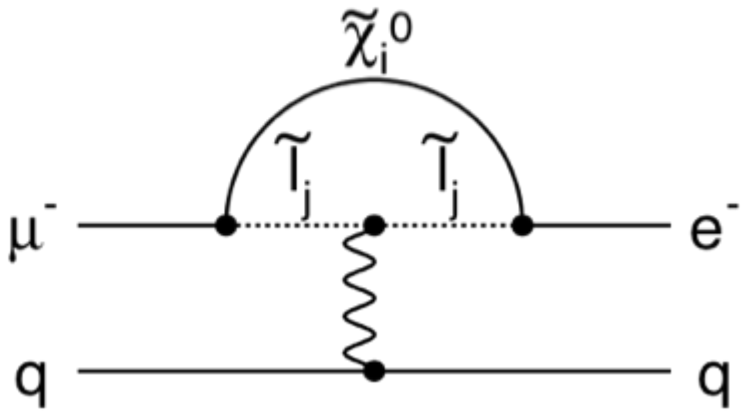


Leptoquarks

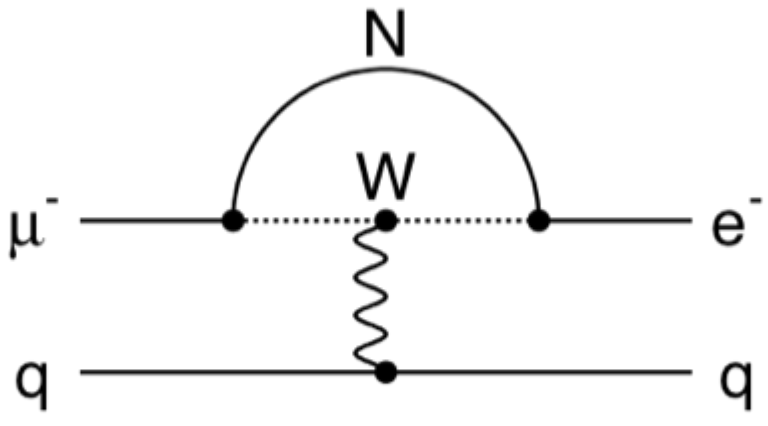


New Heavy Bosons / Anomalous Couplings

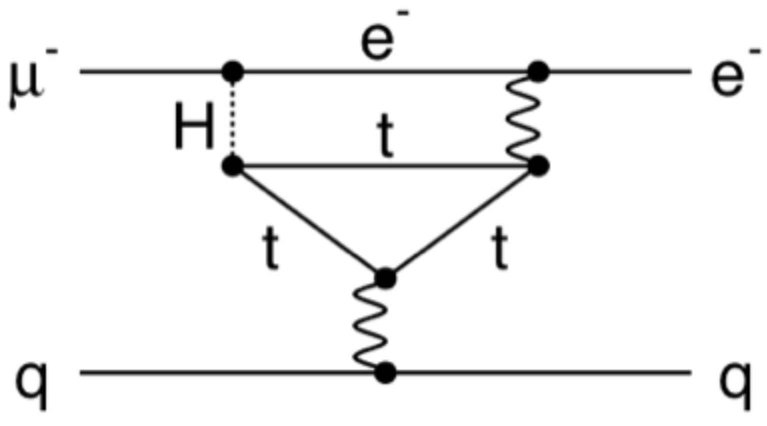
Loop induced :



Supersymmetry



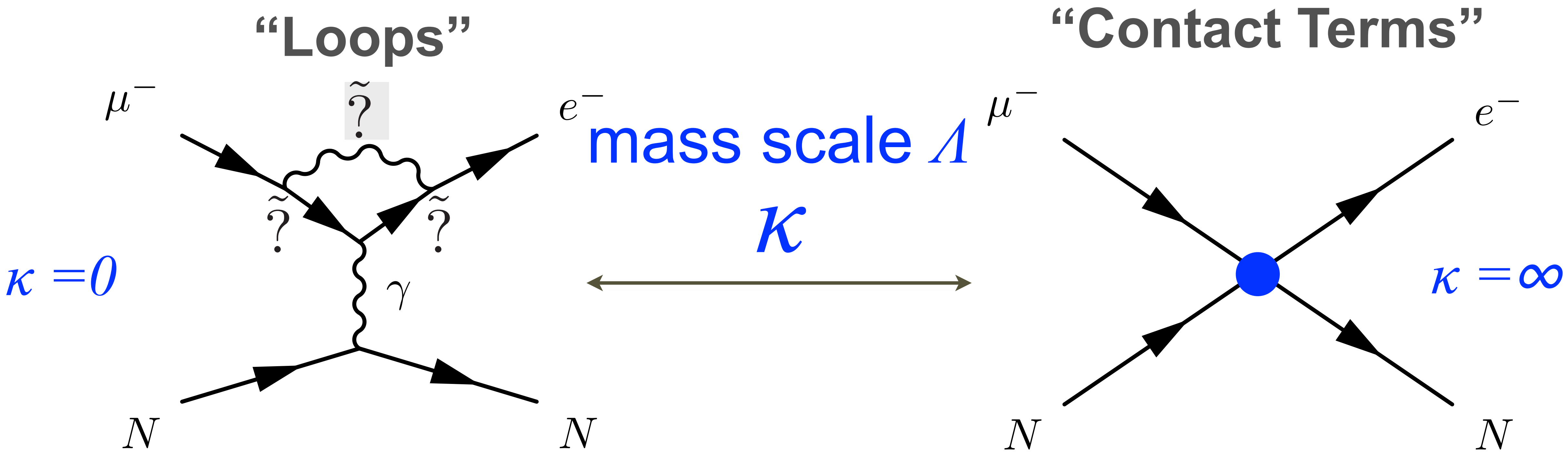
Heavy Neutrinos



Extended higgs models

Effective Lagrangian ($\mathscr{L}_{\mathrm{eff}}$)

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



"Loops"

"Contact Terms"

$\kappa = 0$

mass scale Λ

κ

$\kappa = \infty$

Supersymmetry, Heavy Neutrinos

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

Contributes to μ→eγ

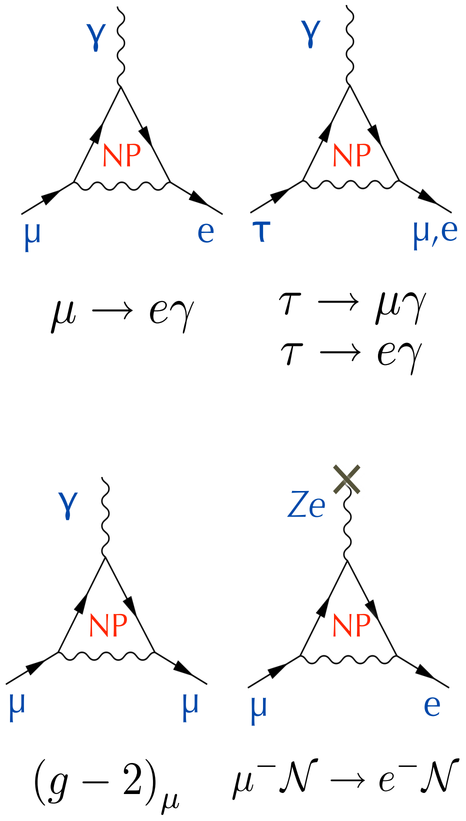
Does not produce μ→eγ

Scale of new physics

Discovery experiments probing ~10^4 TeV much beyond LHC

Loop induced :

$\kappa \ll 1$

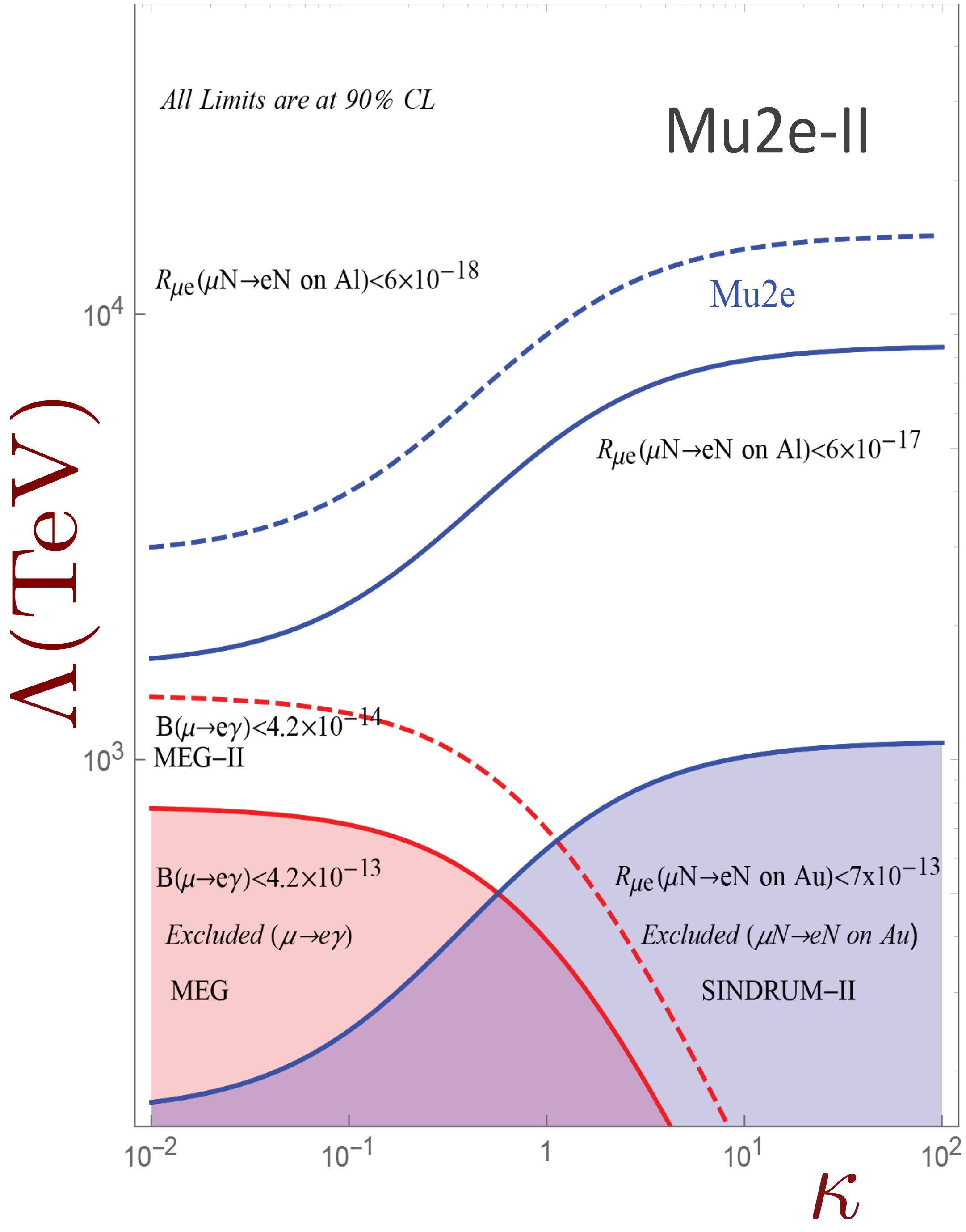


$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$

$(g-2)_\mu$

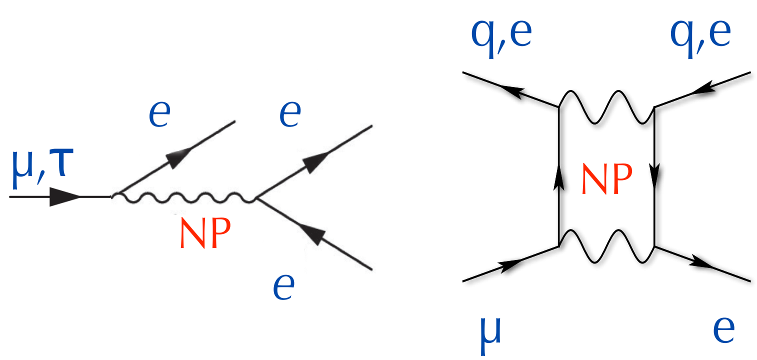
$\mu^- \mathcal{N} \to e^- \mathcal{N}$



Based on A. de Gouvêa, P. Vogel, Prog.Part.Nucl.Phys 71, 75-92 (2013)

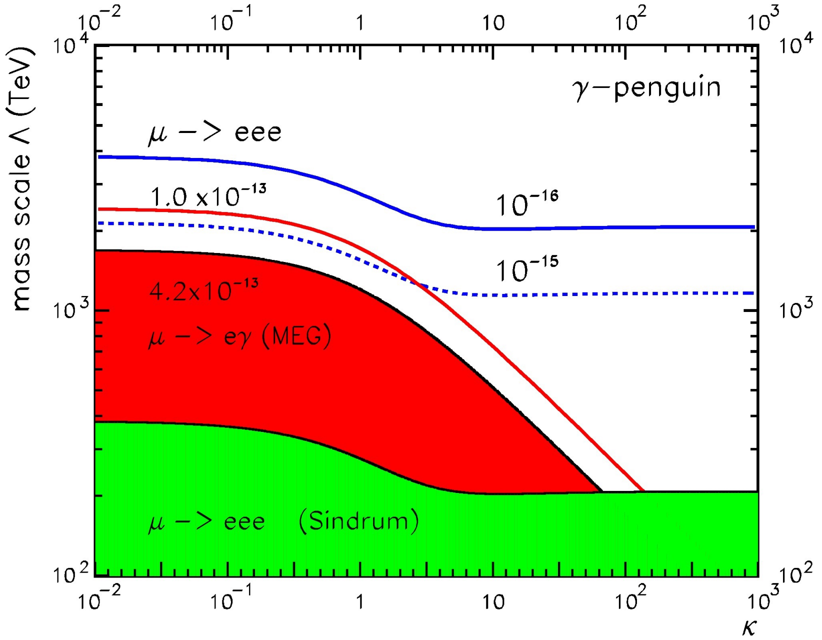
Tree level :

$\kappa \gg 1$



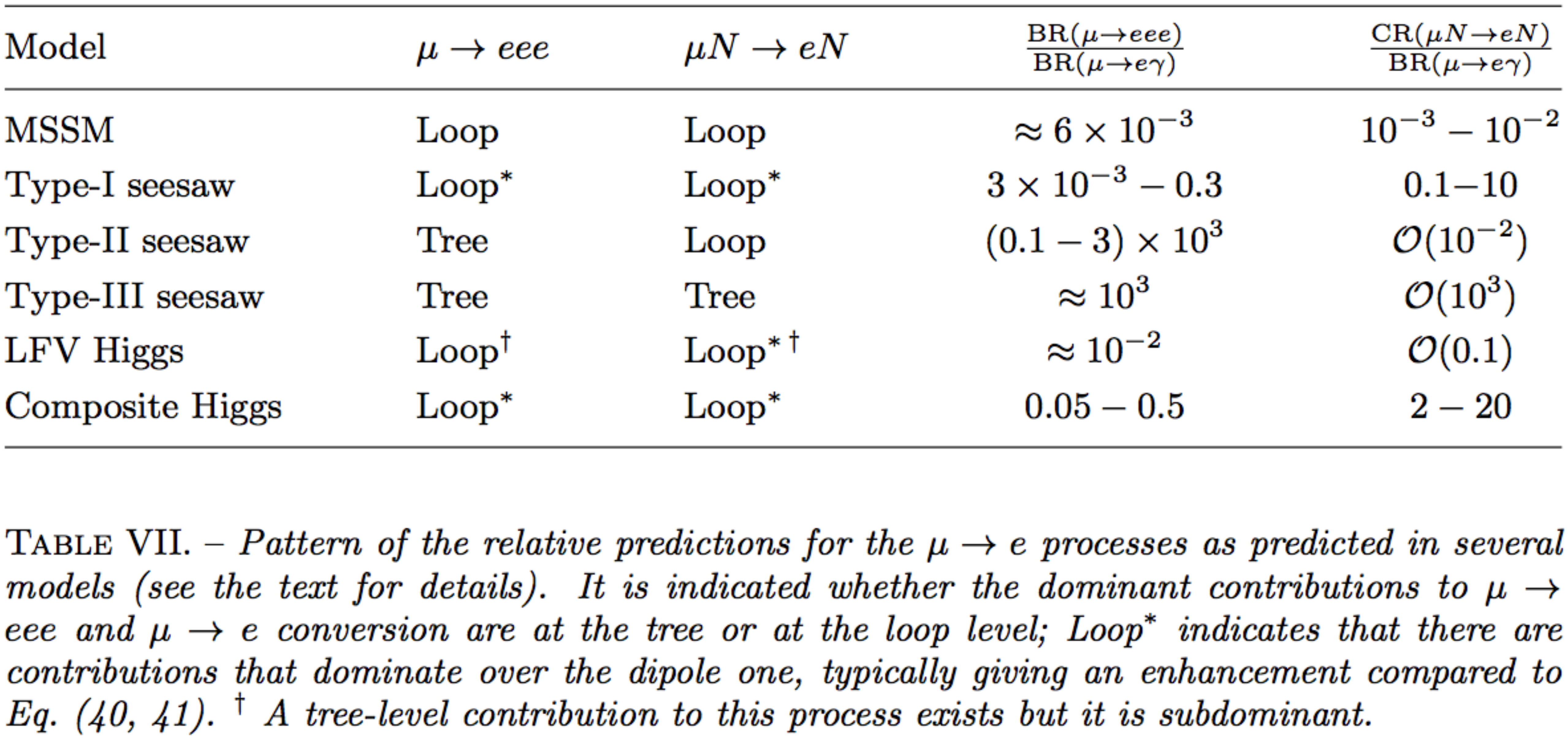
$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$



Disentangling the nature of LFV

Comparisons between channels are powerful model discriminants



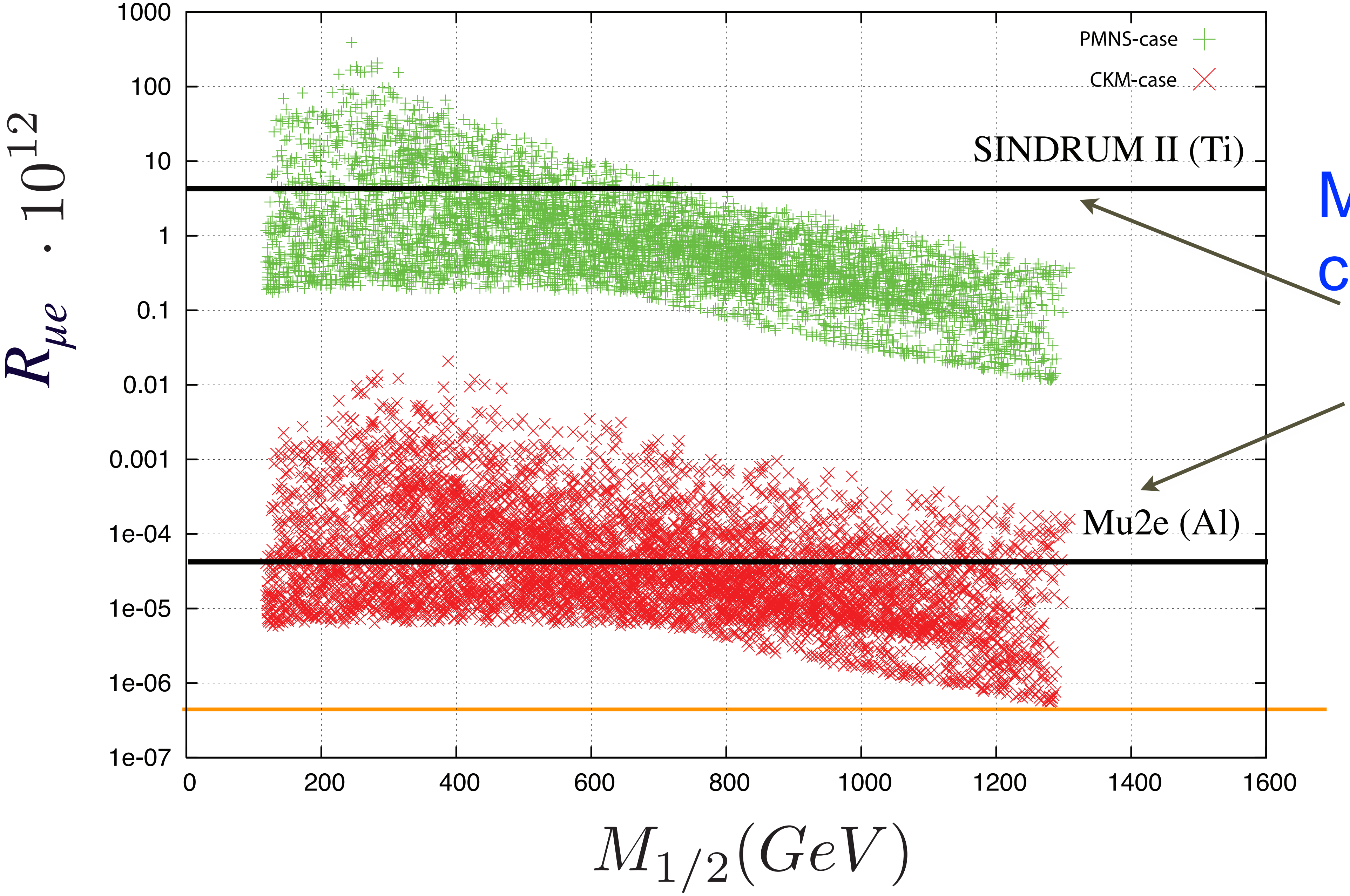
Model	$\mu \to eee$	$\mu N \to eN$	$\frac{\mathrm{BR}(\mu\to eee)}{\mathrm{BR}(\mu\to e\gamma)}$	$\frac{\mathrm{CR}(\mu N\to eN)}{\mathrm{BR}(\mu\to e\gamma)}$
MSSM	Loop	Loop	$\approx 6\times10^{-3}$	$10^{-3} - 10^{-2}$
Type-I seesaw	Loop*	Loop*	$3\times10^{-3} - 0.3$	0.1–10
Type-II seesaw	Tree	Loop	$(0.1-3)\times10^{3}$	$\mathcal{O}(10^{-2})$
Type-III seesaw	Tree	Tree	$\approx 10^{3}$	$\mathcal{O}(10^{3})$
LFV Higgs	Loop†	Loop$^{*\,\dagger}$	$\approx 10^{-2}$	$\mathcal{O}(0.1)$
Composite Higgs	Loop*	Loop*	$0.05 - 0.5$	$2 - 20$

TABLE VII. – *Pattern of the relative predictions for the $\mu \to e$ processes as predicted in several models (see the text for details). It is indicated whether the dominant contributions to $\mu \to eee$ and $\mu \to e$ conversion are at the tree or at the loop level; Loop* indicates that there are contributions that dominate over the dipole one, typically giving an enhancement compared to Eq. (40, 41).* † *A tree-level contribution to this process exists but it is subdominant.*

L. Calibbi and G. Signorelli,
Riv. Nuovo Cimento, 41 (2018) 71
arXiv:1709.00294v2[hep-ph]

Disentangling the nature of LFV

μ to e at $\tan\beta = 10$



Measurements can distinguish between structure of mass mixing matrix

Mu2e Upgrades

L. Calibbi, A. Faccia, A. Masiero, S. K. Vempati
Phys.Rev.D74:116002,2006,
arXiv:hep-ph/0605139v2

Disentangling the nature of LFV

- Mass of heavy neutrino in Type I Seasaw models:

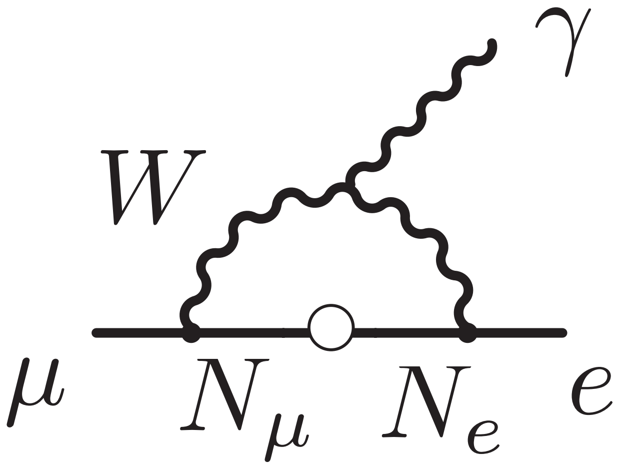
$$\boxed{\Gamma \propto \frac{\left|\sum_{N_i} U_{N_i\mu}U^*_{N_i e}\right|^2}{M_N^4}}$$

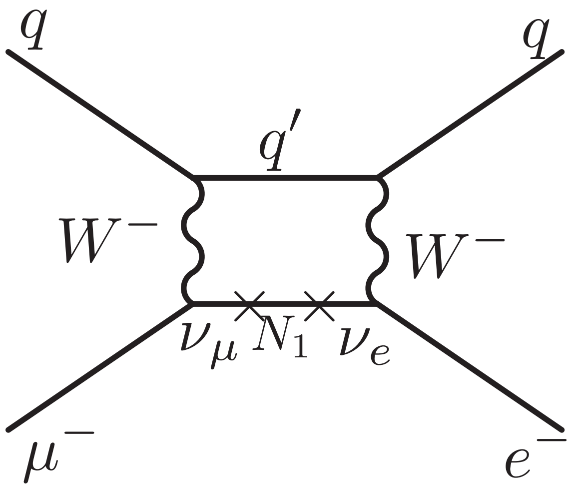
$$m_N \leq 6000\ \text{TeV} \left(\frac{10^{-16}}{R_{\mu e}}\right)^{1/4}$$

$$m_N \leq 300\ \text{TeV} \left(\frac{10^{-14}}{\text{BR}(\mu \to e\gamma)}\right)^{1/4}$$

$$m_N \leq 1000\ \text{TeV} \left(\frac{10^{-14}}{\text{BR}(\mu \to eee)}\right)^{1/4}$$

- Left diagram for μ → eγ, μN → eN, μ→eee; right only for μN → eN

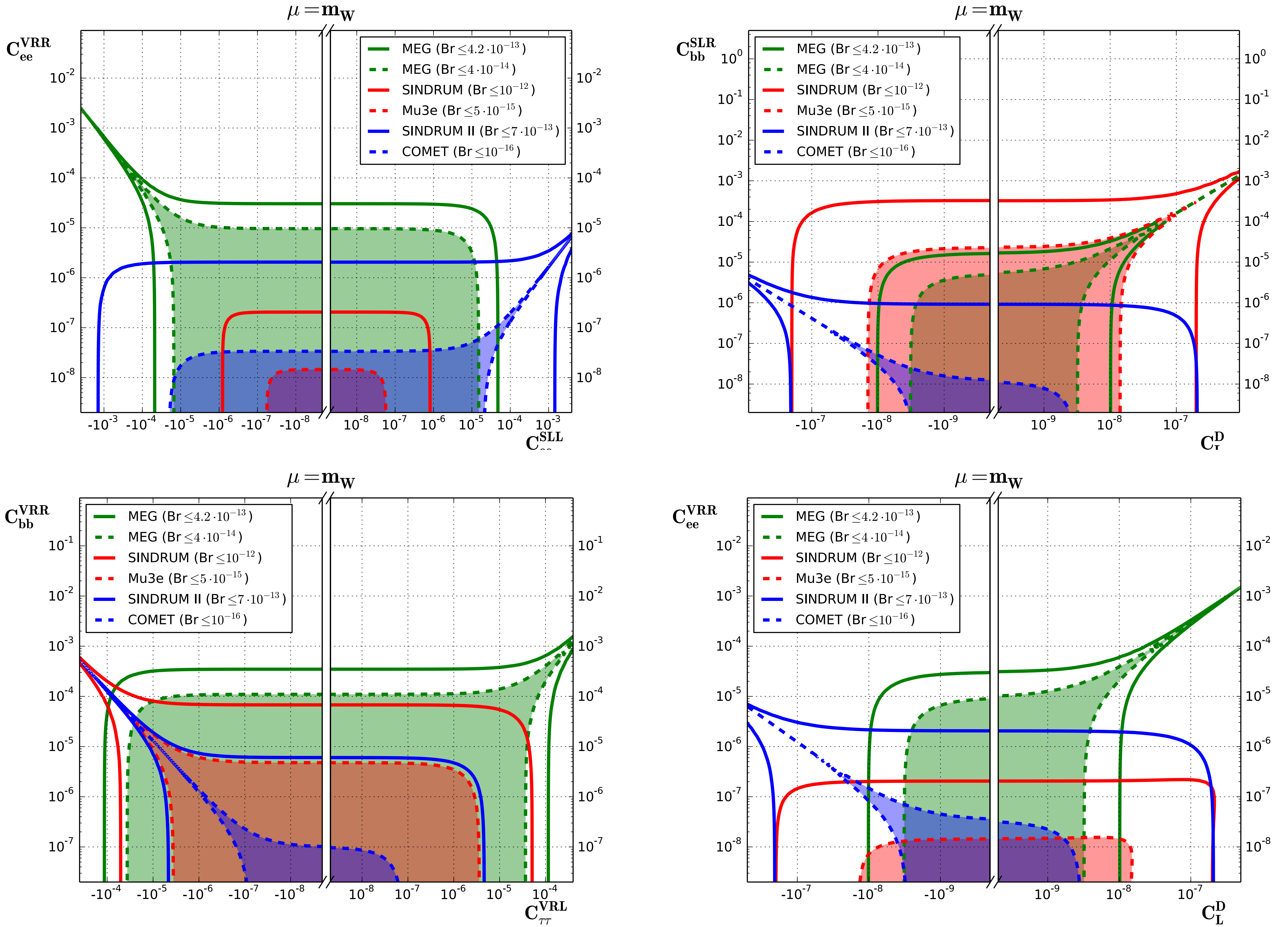




Rodrigo Alonso, Mikael Dhen, Belen Gavela, Thomas Hambye, JHEP01(2013)118, arXiv:1209.2679v2
D. N. Dinh, A. Ibarra, E. Molinaro, S. T. Petcov, JHEP08(2012)125, arXiv:1205.4671v4

Disentangling the nature of LFV

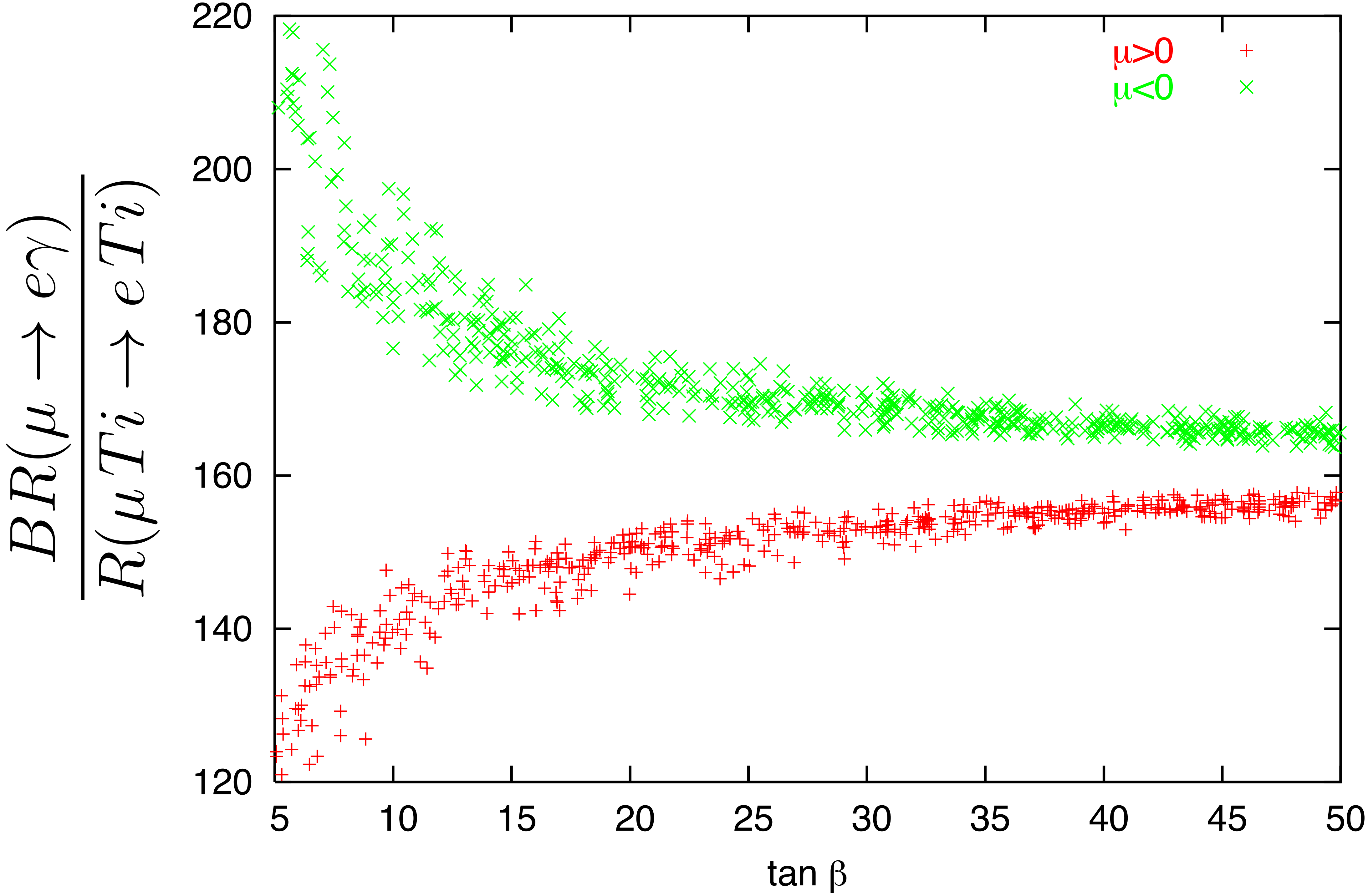
- Wilson coefficients for Vector (V), Scalar (S), Dipole (D) terms in $\mathscr{L}_{\text{eff}}$



Andreas Crivellin, Sacha Davidson, Giovanni Marco Pruna, Adrian Signer
JHEP05(2017)117, arXiv:1702.03020v3

Disentangling the nature of LFV

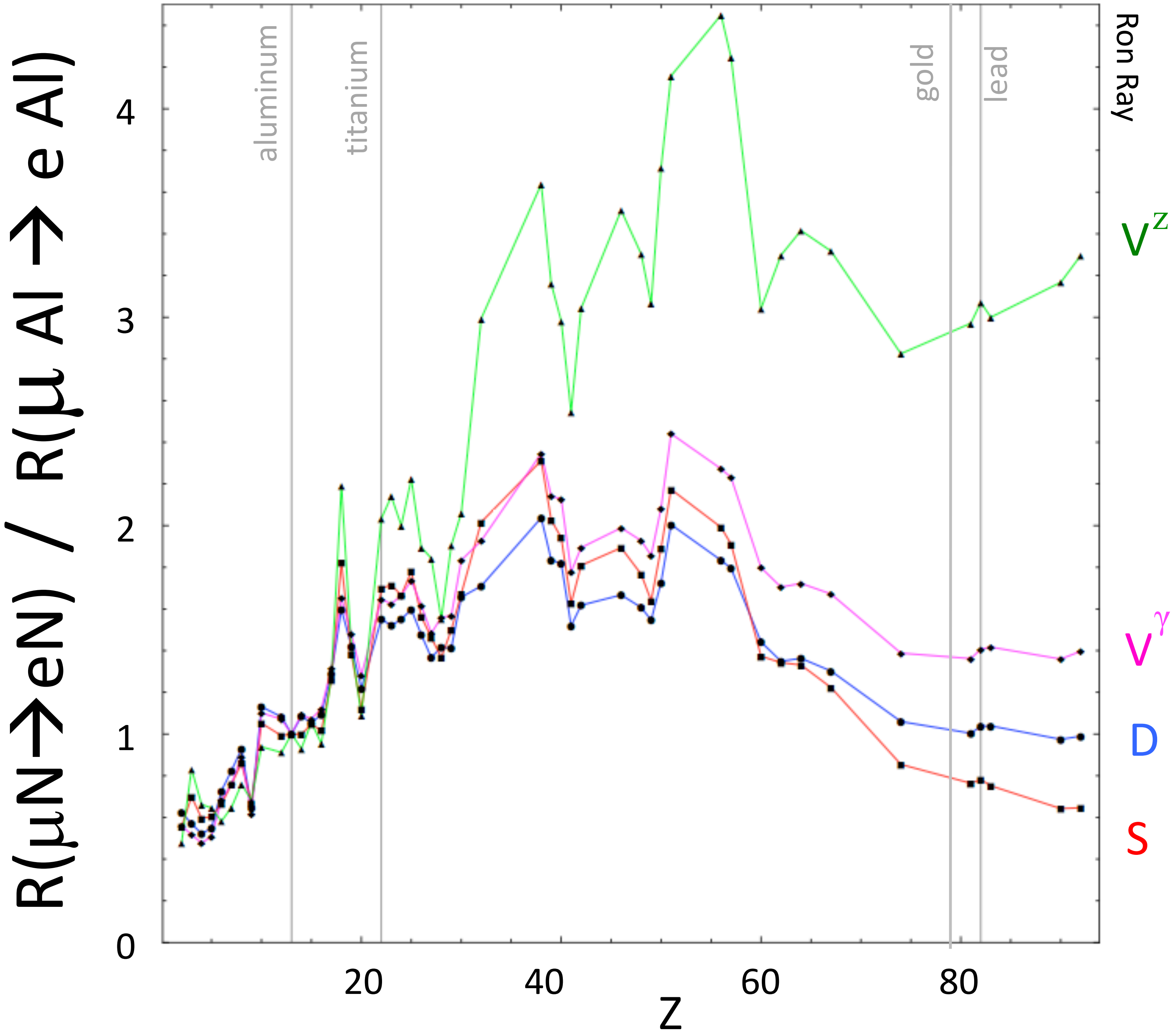
- Constraining sign(μ) in mSUGRA with seesaw induced neutrino masses



Carlos E. Yaguna, Int.J.Mod.Phys. A21 (2006) 1283-1289, arXiv:hep-ph/0502014v2

Disentangling the nature of LFV

- Z-dependence of μ to e conversion rates normalized to Aluminum (Z=13)



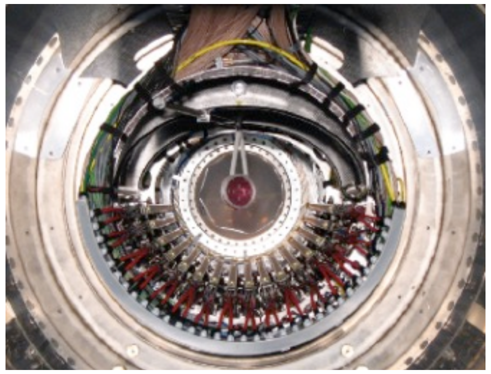
Vincenzo Cirigliano, Ryuichiro Kitano, Yasuhiro Okada, Paula Tuzon
Phys.Rev.D80:013002,2009, arXiv:0904.0957v1 [hep-ph]

Muon to electron experiments

	$\mu^+ \rightarrow e^+\gamma$	$\mu^- N \rightarrow e^- N$	$\mu^+ \rightarrow e^+e^+e^-$
	MEG (PSI)	Mu2e COMET (FNAL) (JPARC)	Mu3e (PSI)
Now:	4.2×10^{-13} (MEG, 2016)	7×10^{-13} (SINDRUM-II, 2006)	1×10^{-12} (SINDRUM, 1998)
Future:	4×10^{-14}	6×10^{-17}	1×10^{-14}
Timeframe:	2020	2023	2020

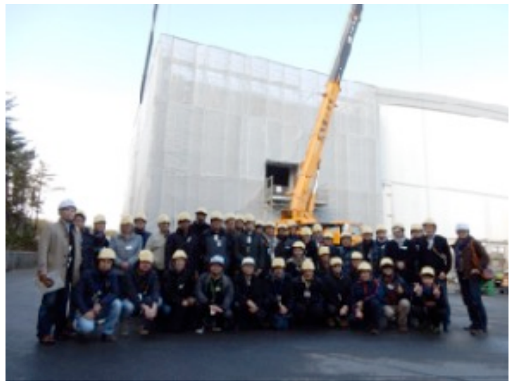
Mu3e @PSI

MEG Upgrade @PSI



Mu2e @FNAL

COMET @KEK

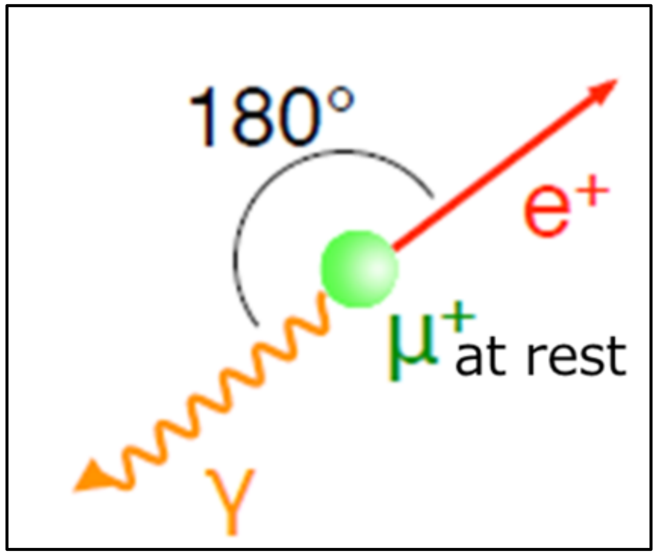


MEG experiment

Signal

Back-to-back eγ

$E_e = E_\gamma = m_\mu/2$

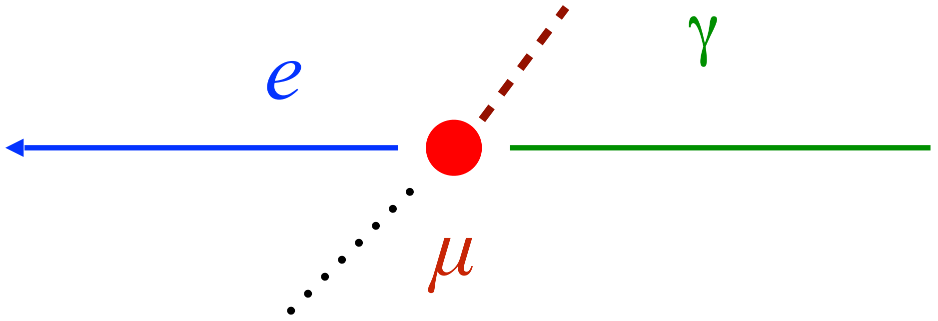


Keys to success:

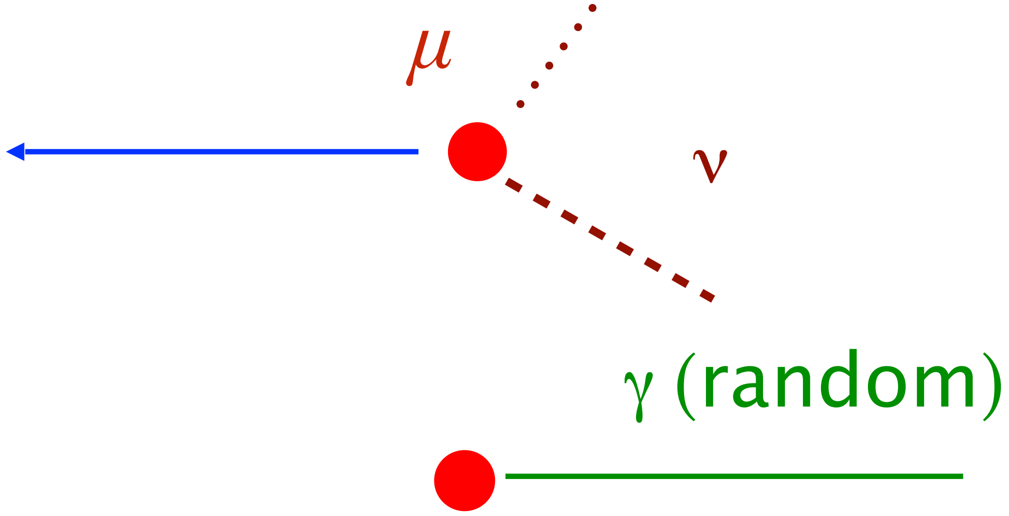
excellent energy, timing, angular resolutions, particularly ΔE_γ and $\Delta\theta_{e\gamma}$

Background

correlated $\mu \rightarrow e\,\gamma\,\nu\,\nu$



uncorrelated $\mu \rightarrow e\,\nu\,\nu$

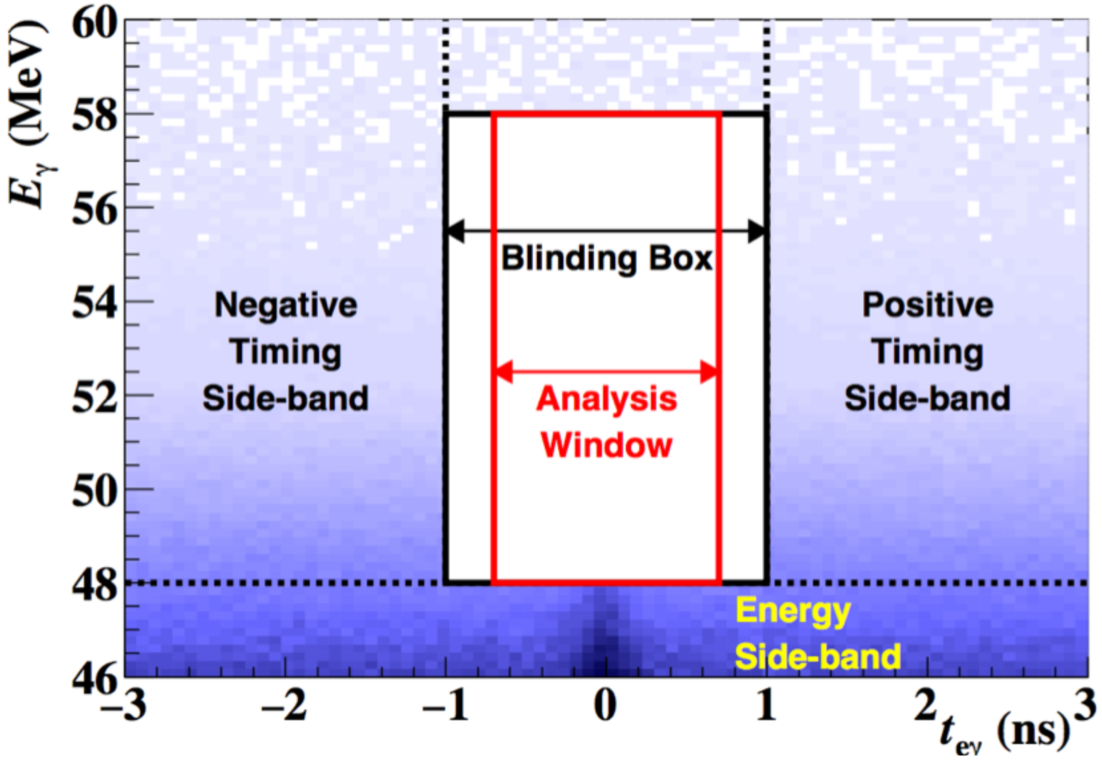


MEG results

- Published results uses full data set (2009-2013)
  - –~7.5 x 10^{14} stopped μ^+

Utilizes 5 variables

- E_e, E_γ
- $t_{e\gamma} = t_e - t_\gamma$
- $\theta_{e\gamma}$
- $\phi_{e\gamma}$



Blind Analysis

Full Likelihood fit to data

Best fit BF($\mu^+ \rightarrow e^+\gamma$) = -2.2 x 10^{-13}

BF($\mu^+ \rightarrow e^+\gamma$) < 4.2 x 10^{-13} @ 90% CL

(< 5.3 x 10^{-13} expected)

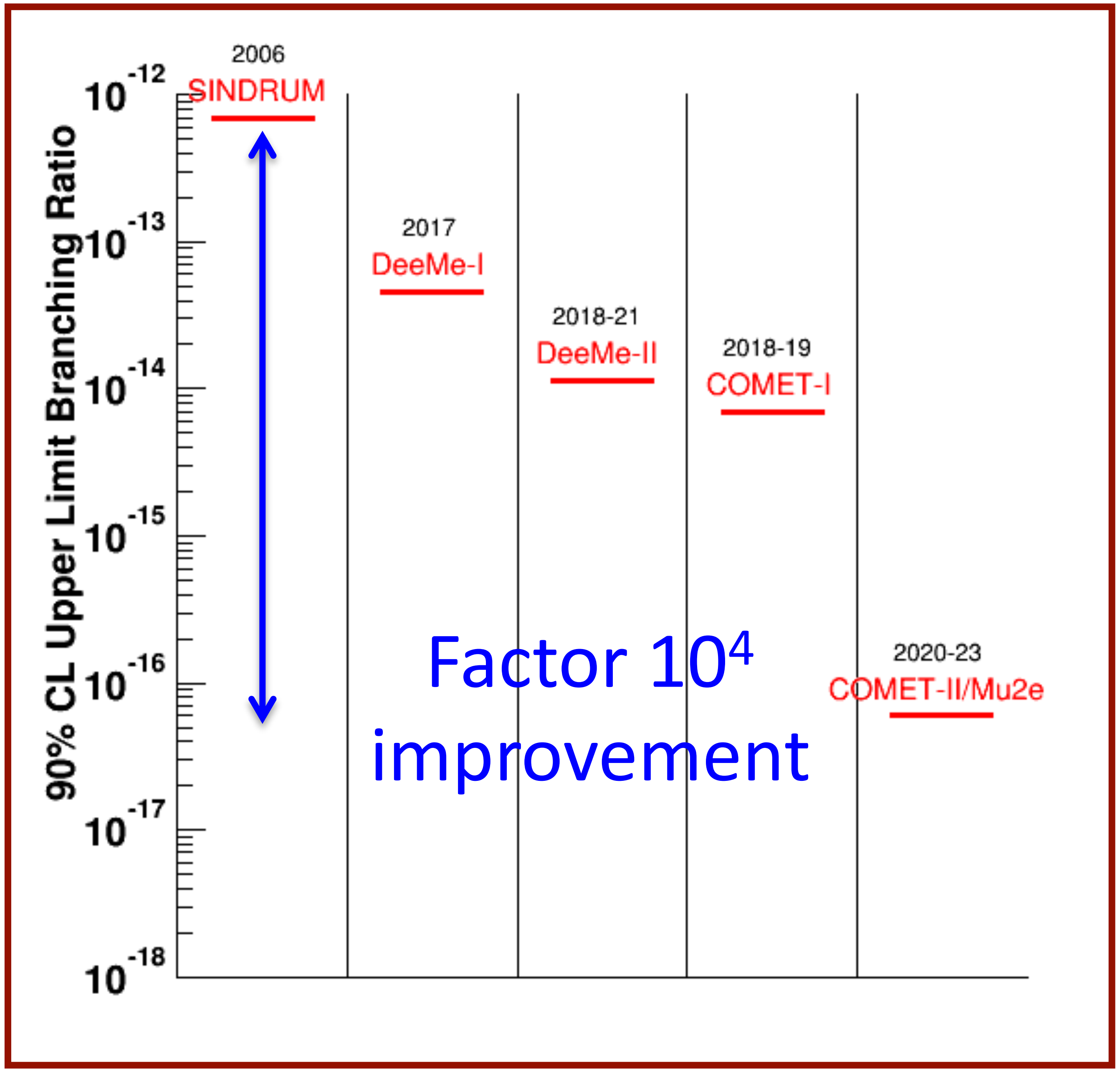
Eur. Phys. J. C76 (2016) 434 [arXiv:1605.05081]

Muon to electron conversion experiments

Current State-of-the-art (@ 90% CL) :

$$R_{\mu e} = \frac{\Gamma(\mu^- \mathrm{Au} \rightarrow e^- \mathrm{Au})}{\Gamma(\mu^- \mathrm{Au\ capture})} < 7 \times 10^{-13}$$

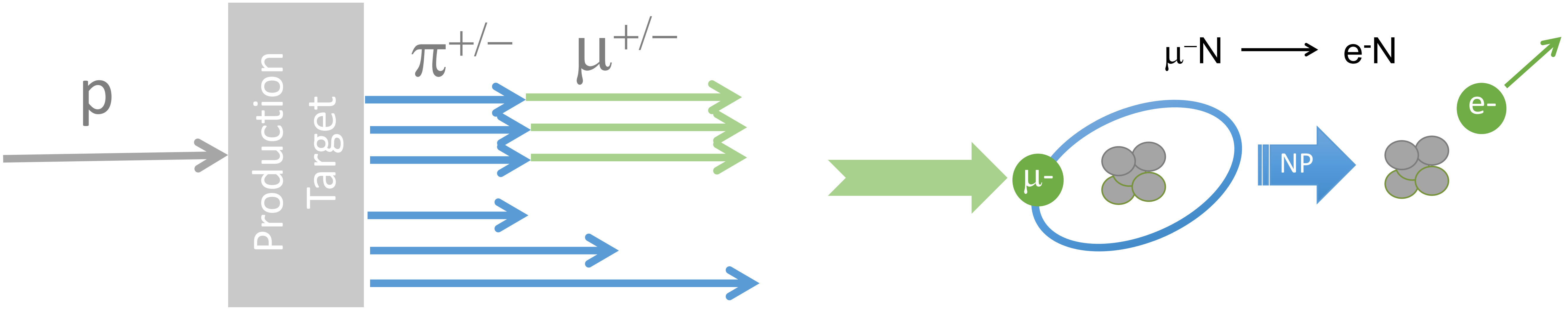
W. Bertl, et al. (SINDRUM-II) Eur. Phys. J. C47 (2006) 337.



Next generation experiments:

– DeeMee (J-PARC, 3 GeV)	x10
– Mu2e (Fermilab)	x10,000
– COMET (J-PARC, 8 GeV)	
• Phase-I	x10-100
• Phase-II	x10,000

Muon to electron conversion experiments

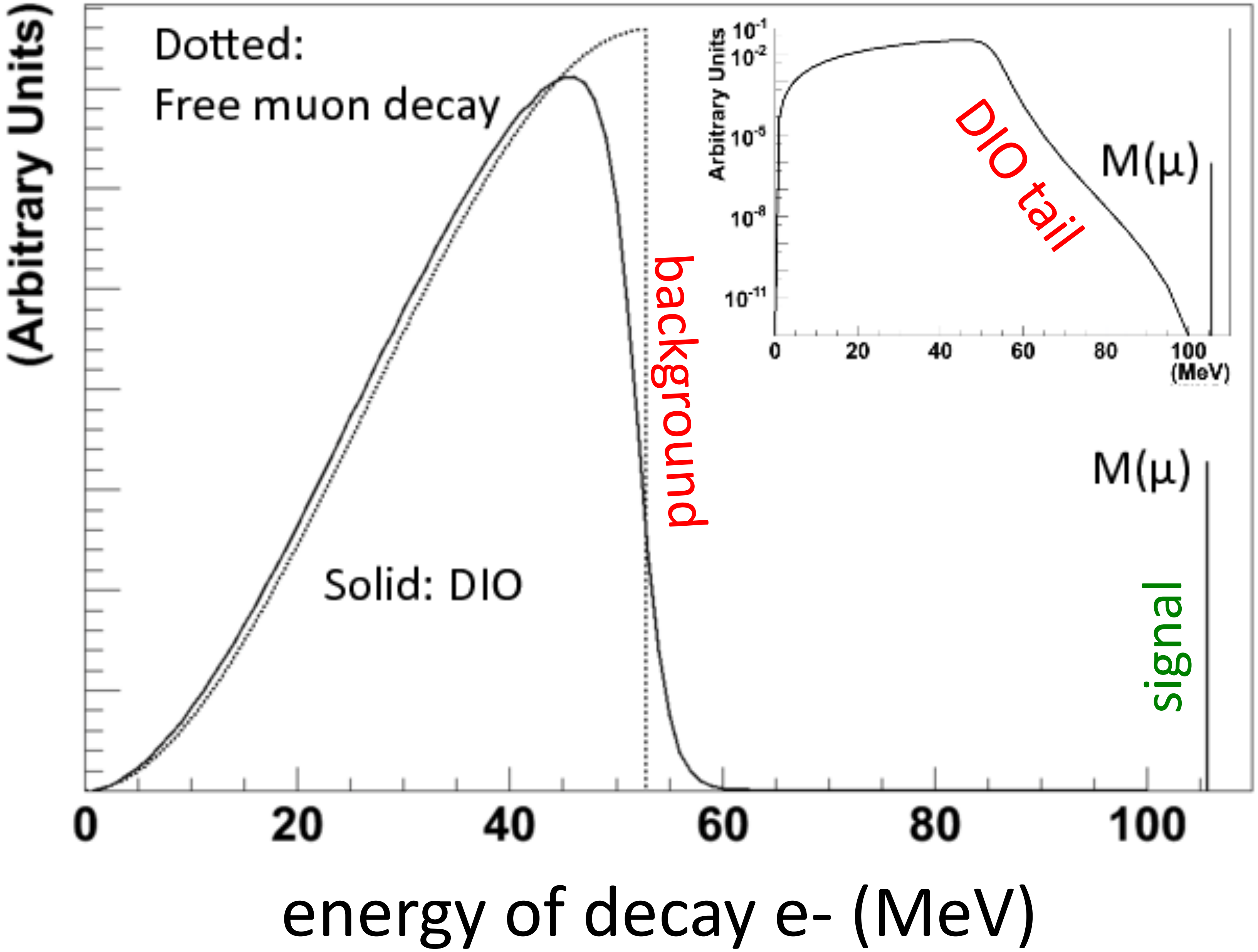


- Stopped μ^- is captured in atomic orbit
  - Quickly (~fs) cascades to 1s state

- Bohr radius ~20 fm (for aluminum)
  - Significant overlap of μ^- and N wavefunctions
  - Lifetime of the μ-atom ~few 100 ns for stopping targets of interest

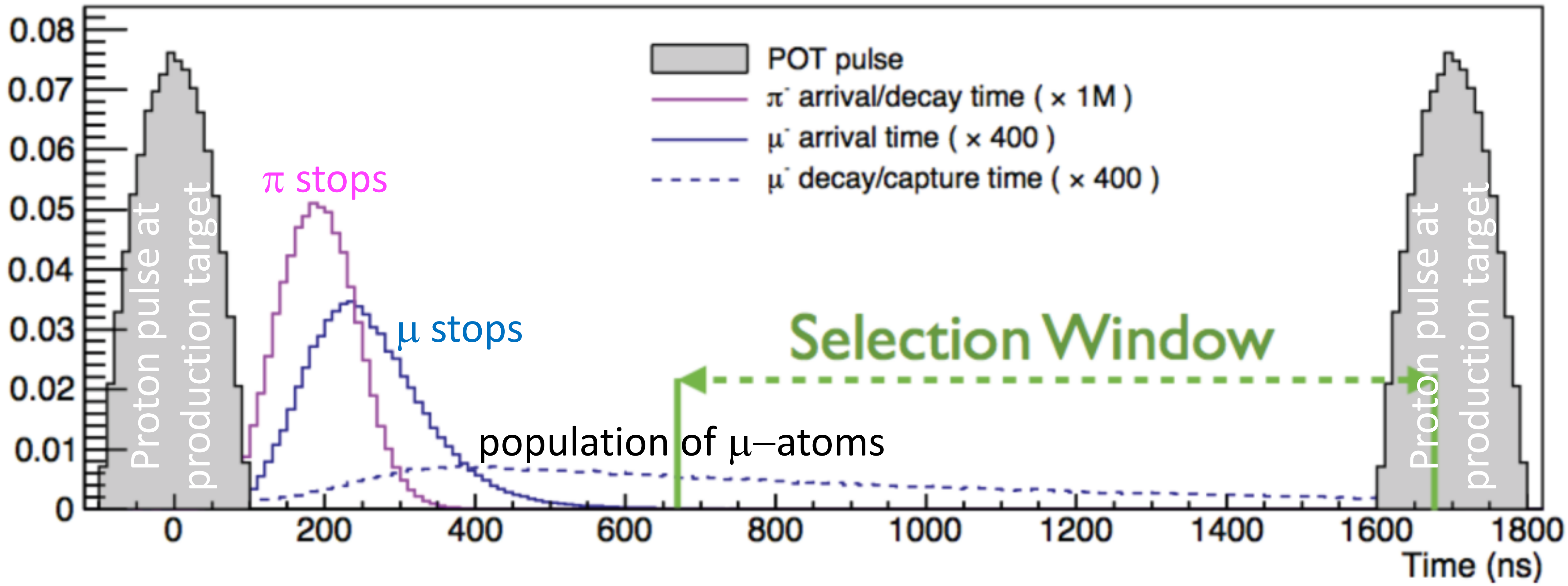
- Once in orbit, 3 things can happen
  - Decay : $\mu^- N(A,Z) \rightarrow e^- \nu\nu N(A,Z)$ (background) [39% in Al target]
  - Capture : $\mu^- N(A,Z) \rightarrow \nu N^*(A, Z-1)$ (normalization) [61% in Al target]
  - Conversion : $\mu^- N(A,Z) \rightarrow e^- N(A,Z)$ (signal) $E_e = m_\mu - E_{binding} - E_{recoil} = 104.9$ MeV [in Al]

Background from decay in orbit (DIO)



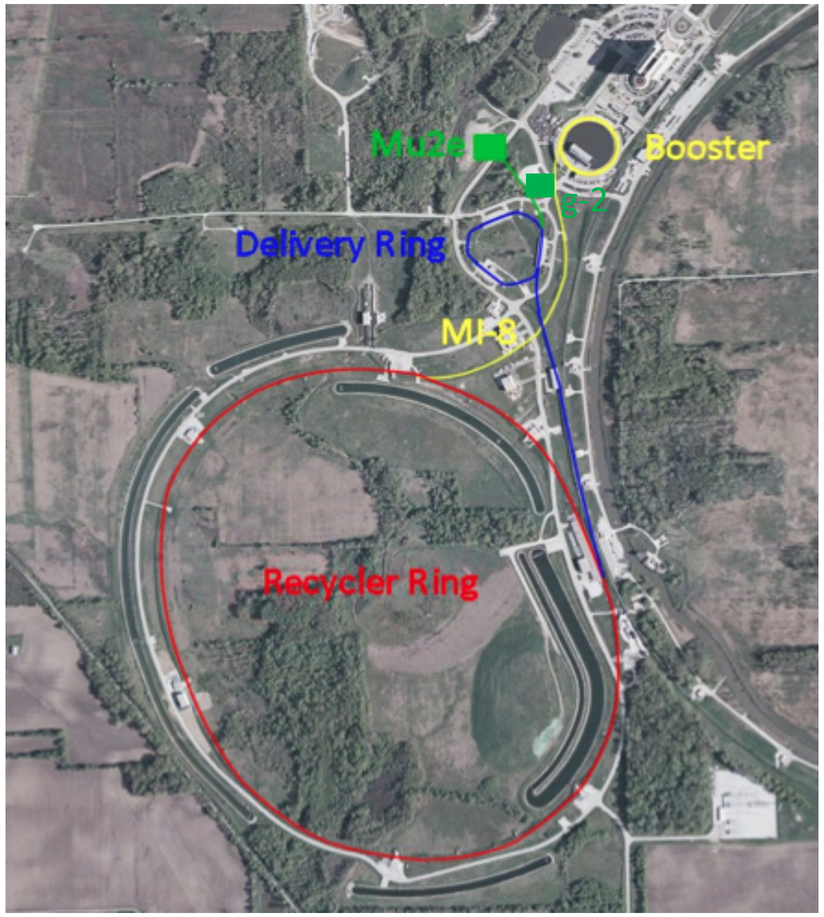
- E_e follows the Michel spectrum… but with a long tail from nuclear recoil $E_{max} = E_{\mu e}$
  - Requires excellent σ_p (<200 keV/c) & FWHM < 1 MeV/c to suppress

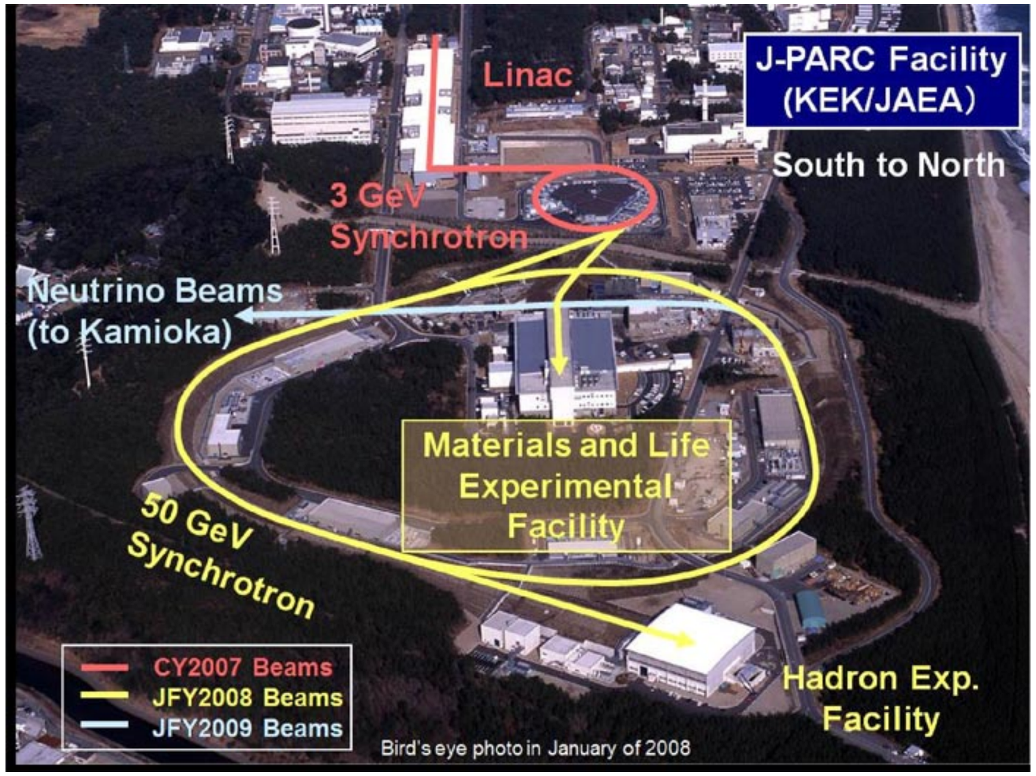
Background from radiative pion capture (RPC)



- Pions that survive to the stopping target are promptly captured on the nucleus
  - few% of the time, radiate γ with $E_\gamma \sim m_\mu$
  - Suppressed by 10^9-10^{10} with pulsed proton beam and utilizing a delayed search window while maintaining a high efficiency for signal (~50%)

Proton beams for Mu2e and COMET





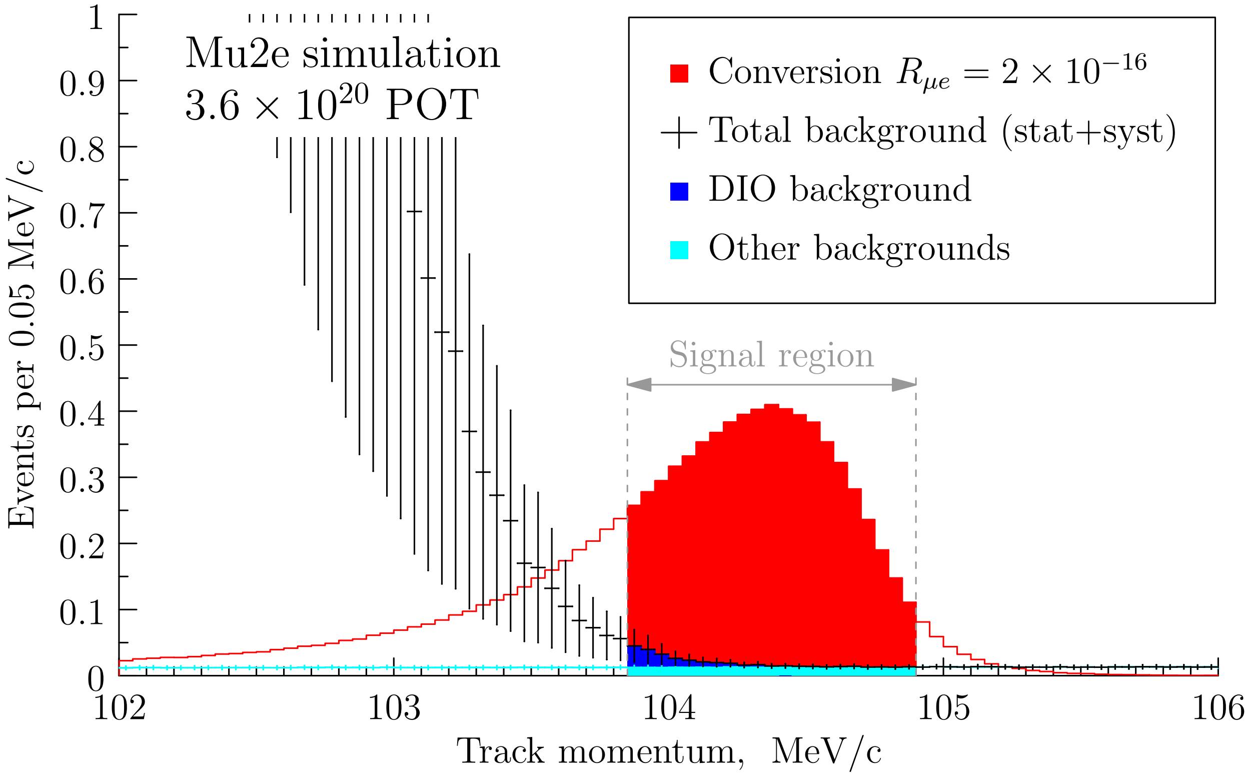
- 8kW of 8 GeV protons
  - 10^{10} stop μ^-/s
- Protons delivered in pulses
  - 4 x 10^7 protons per pulse
  - spaced by 1695 ns.
- Mu2e will run simultaneously with NOvA and short baseline neutrino experiments

- Utilize 8 GeV protons
  - Phase I : 3 kW ; $10^{8\text{-}9}$ stop μ^-/s
  - Phase II: 56 kW ; 10^{11} stop μ^-/s
- Protons delivered in pulses
  - spaced by 1100 ns.
- COMET will share beam time with T2K

Mu2e Sensitivity [COMET Phase II is similar]

Typical Signal [SUSY at 10^{-15}:]

40 events vs 0.4 bkg



Background compositions

Category	Source	Events
	μ Decay in Orbit	0.14
Intrinsic	Radiative μ Capture	<0.01
	Radiative π Capture	0.02
	Beam electrons	<0.01
	μ Decay in Flight	<0.01
Late Arriving Beam	π Decay in Flight	<0.01
	Anti-proton induced	0.04
Miscellaneous	Cosmic Ray induced	0.21
Total Background		0.41

(assuming 6.7E17 stopped muons in 6E7 s of beam time)

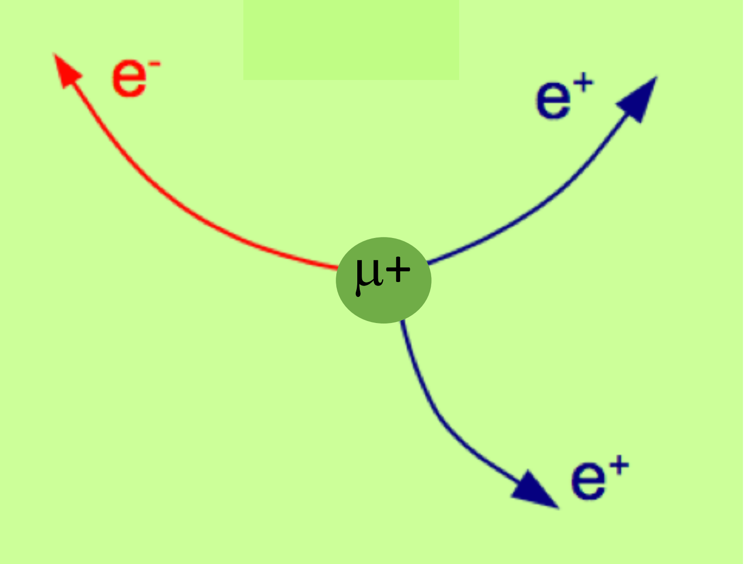
- Full Geant4 simulation and reconstruction, background overlaid with signal
- Discovery sensitivity accomplished with 3 years of running and suppressing backgrounds to < 0.4 event total: **2 x 10^{-16}** [5σ significance]
- Single event sensitivity **3 x 10^{-17}**
- Null signal upper limit **8 x 10^{-17} @ 90% C.L.**

Muon to three electrons experiment

Current State-of-the-art (@ 90% CL) :

$$BF(\mu^+ \rightarrow e^+e^+e^-) < 1 \times 10^{-12}$$

U. Bellgardt, et al. (SINDRUM) Nucl.Phys. B299 (1988) 1.



Next generation experiments:

- Mu3e (PSI)

• Phase Ia	x20
• Phase Ib	x400
• Phase II	x10,000

Muon to three electrons experiment

Signal

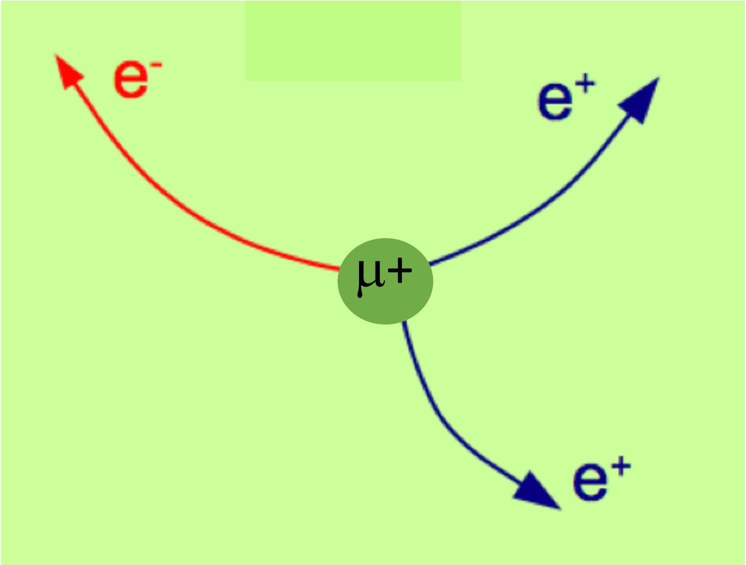
$\Sigma\, p = 0$

$E_e < m_\mu/2$

$\Sigma\, E_e = m_\mu$

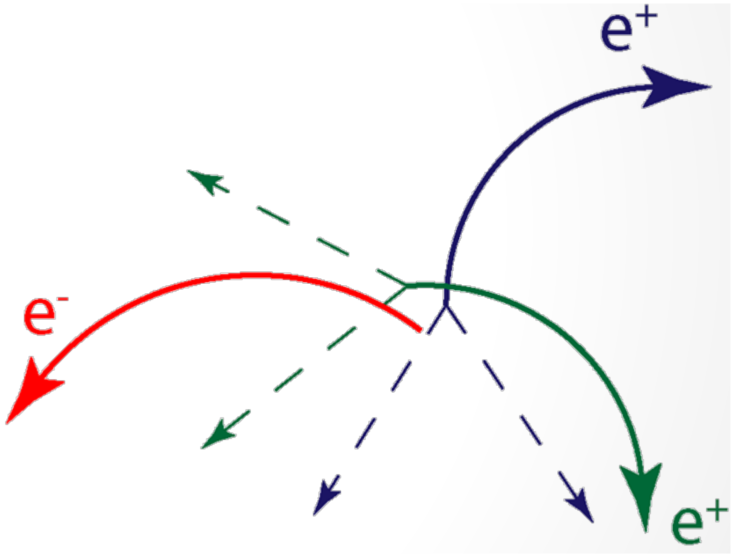
Common vertex

Co-incident in time



Backgrounds

- internal conversion of photon in radiative muon decays
- accidental photons followed by e^-e^+ pair-production

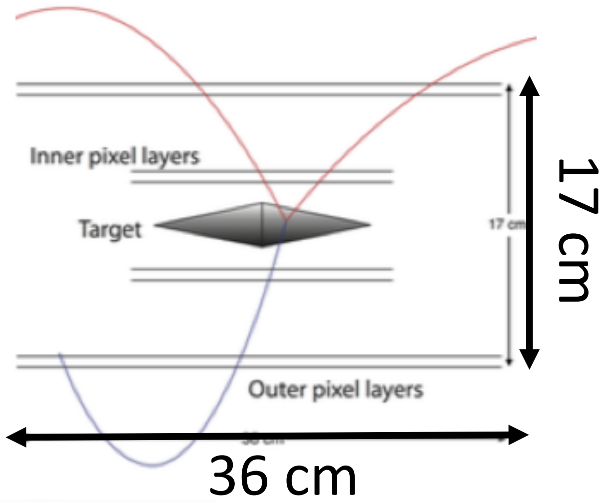


- **Keys to success:** excellent momentum, timing, and vertex resolutions

Phased construction progressively more sensitive

Phase-Ia

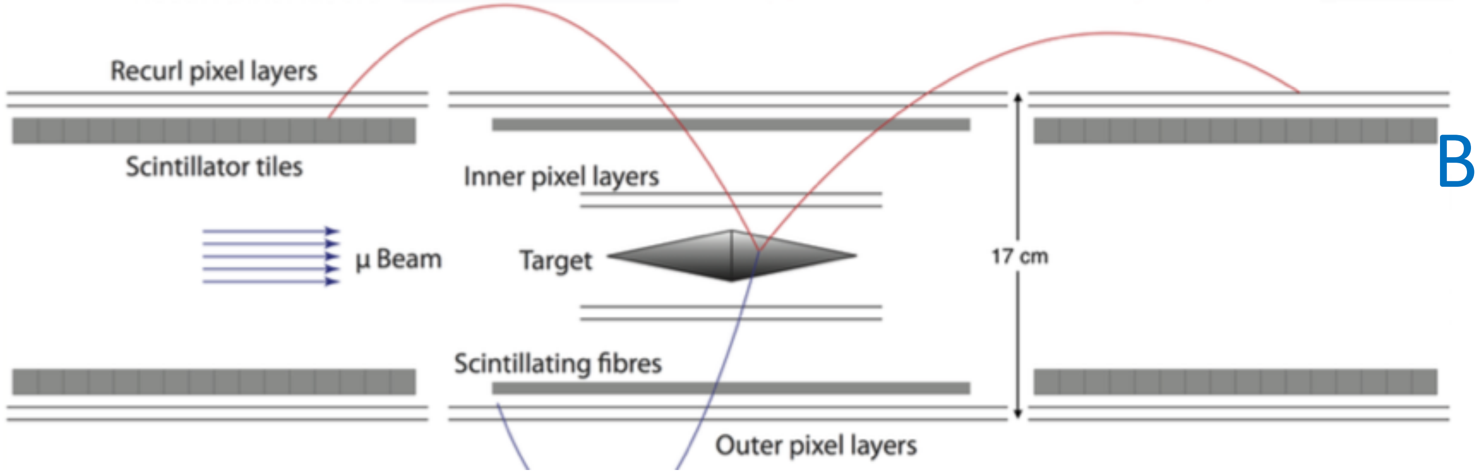
All inside 1T magnetic field



BF < 10^{-13} - 10^{-14}

10^{7} μ^{+}/s

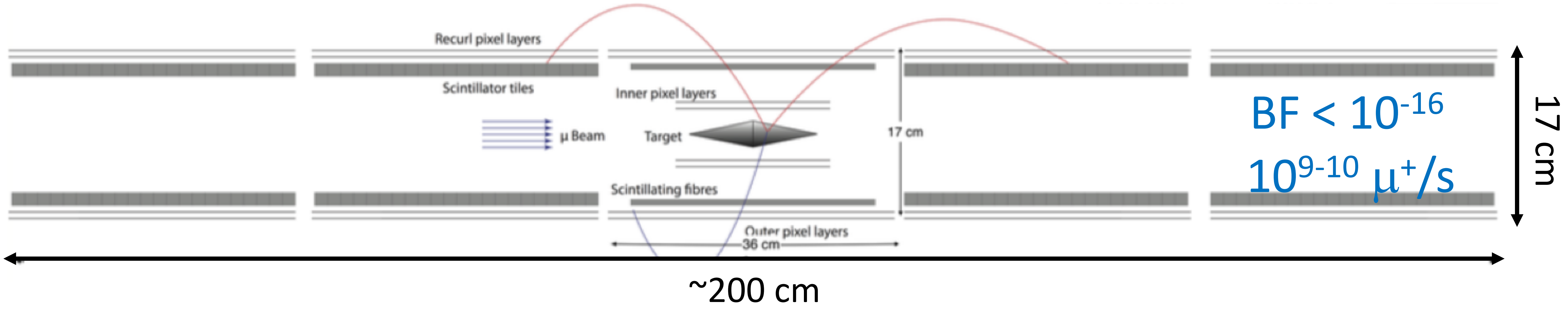
Phase-Ib



BF < 10^{-14} - 10^{-15}

10^{8} μ^{+}/s

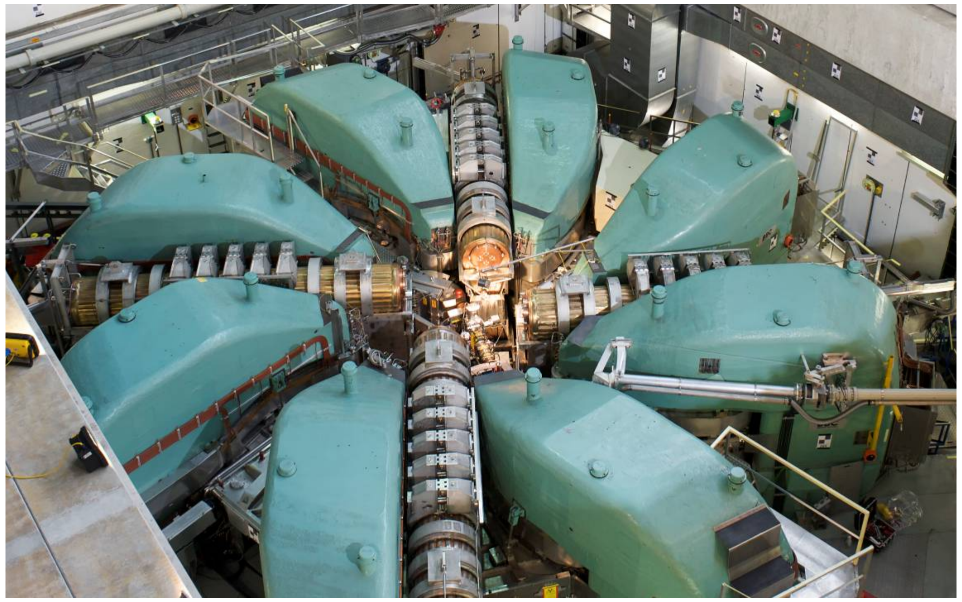
Phase-II



BF < 10^{-16}

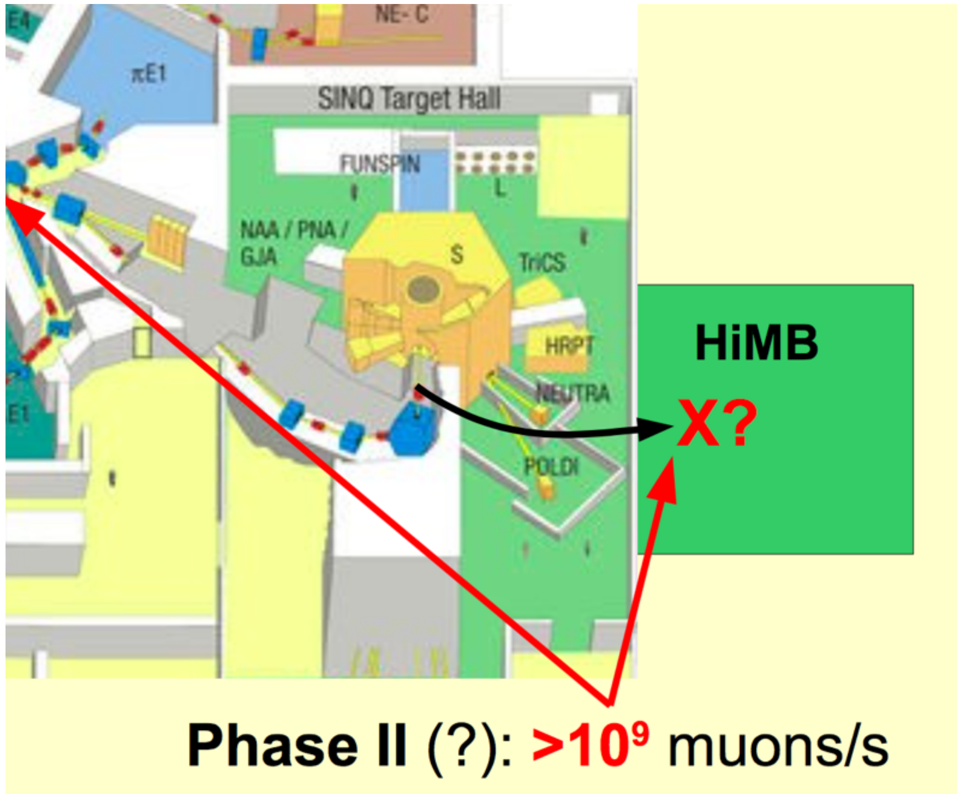
10^{9-10} μ^{+}/s

Mu3e beam @ PSI



Phase I cyclotron

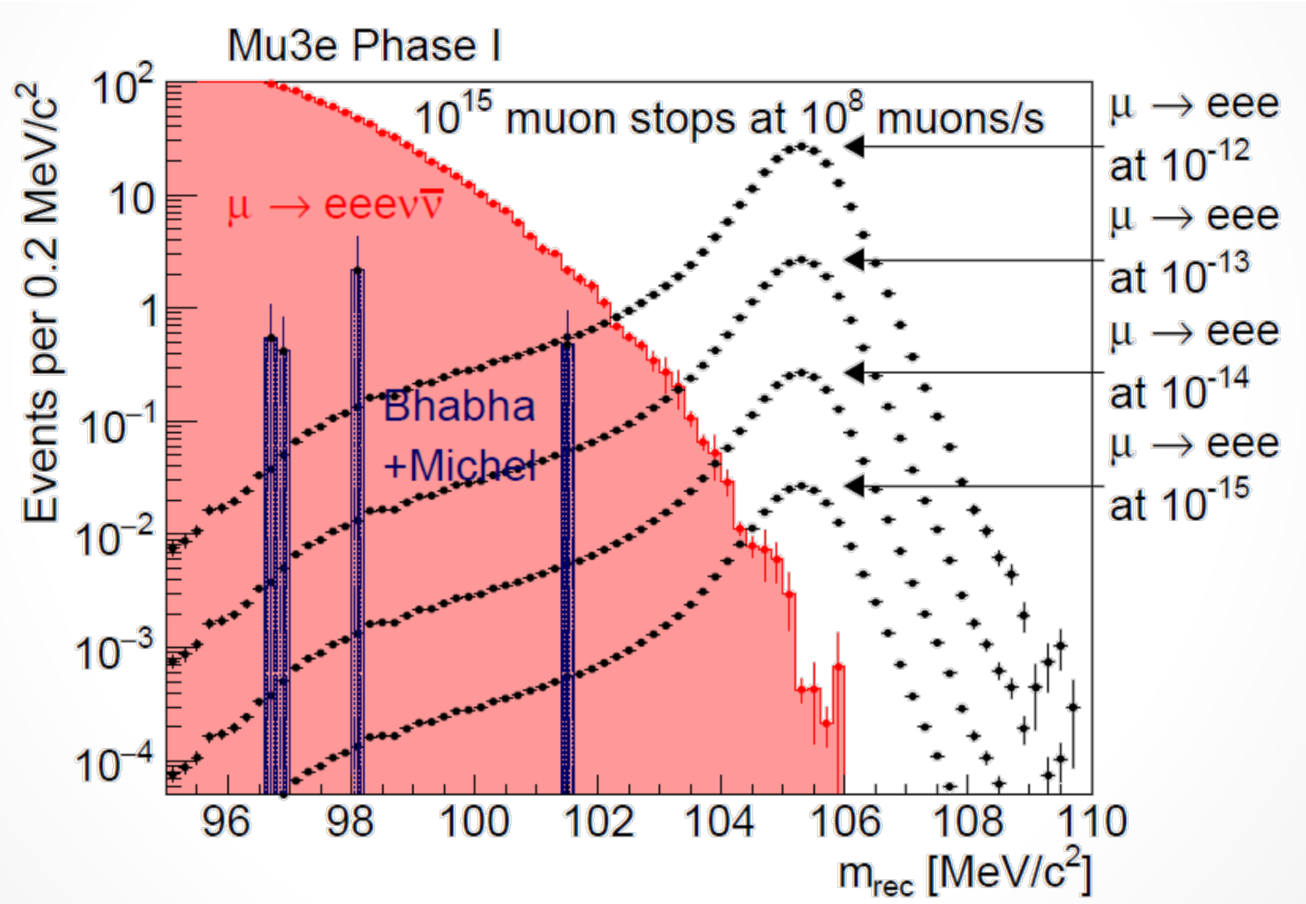
- 1.3 MW of 0.6 GeV protons
- DC muon beam using “surface” muons, $p_\mu \sim 28$ MeV/c
- Mu3e will use $10^7 - 10^8\ \mu^+/s$
- Utilizes same beam line as MEG

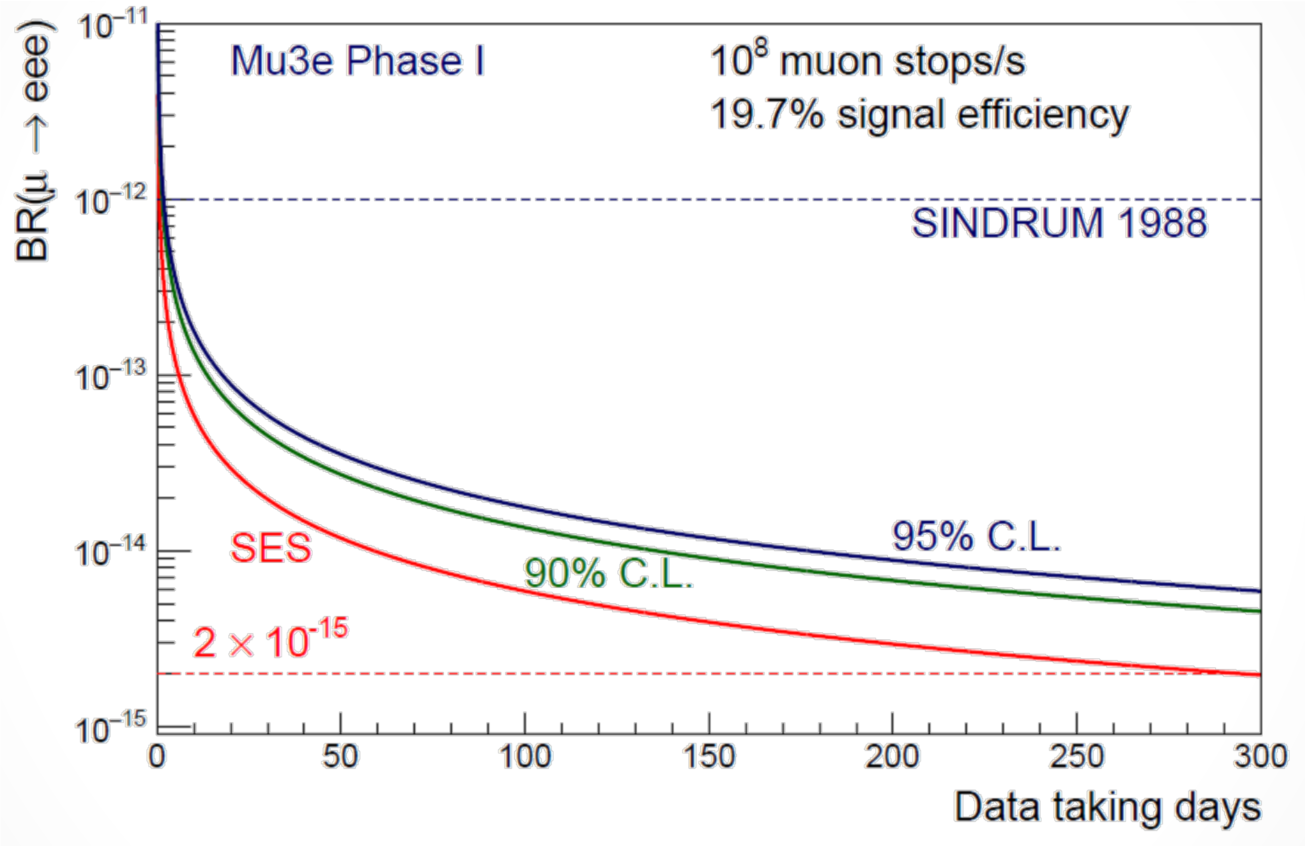


To achieve Phase-II sensitivity requires an upgraded facility at PSI: High Intensity Muon Beam

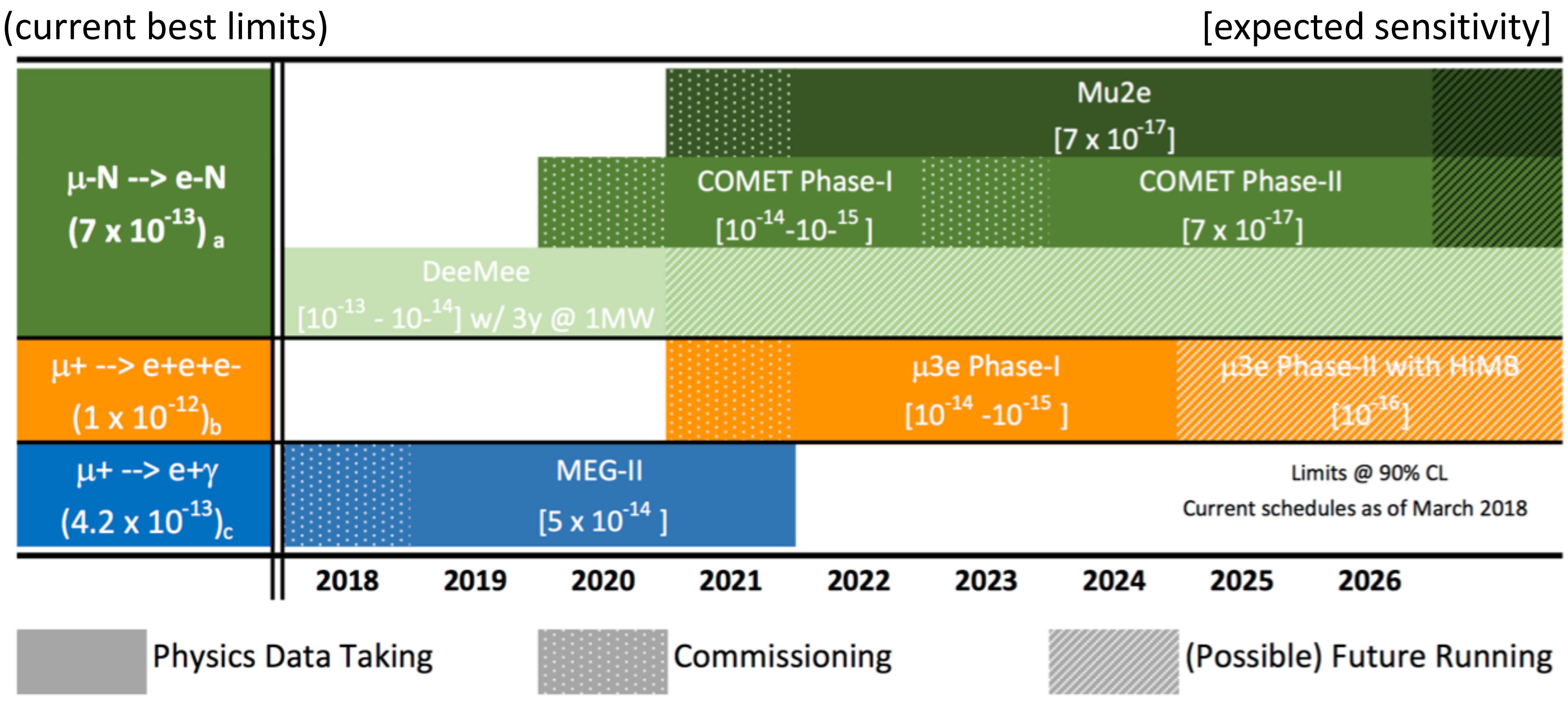
Mu3e projections

- **2019** Magnet delivery and detector **construction**
- **2020** Installation and **commissioning** at PSI
- **2021** Data taking at up to a few **10^8 μ/s**





Summary



- Exciting improvements in sensitivity of LFV
- Probe new physics up to 10000 TeV scale
- In case of null observation, further improve sensitivity with:
  - source intensity upgrade
  - detector improvements
- If signal is observed, distinguish models by studying:
  - target nuclei dependence
  - different final states
- Acknowledgements: Many thanks to Douglas Glenzinski & Robert Bernstein