Title: Experimental Overview of low-energy precision experiments

Date: Jun 12, 2017 09:30 AM

URL: http://pirsa.org/17060002

Abstract:

A Flavorful Tasting Menu

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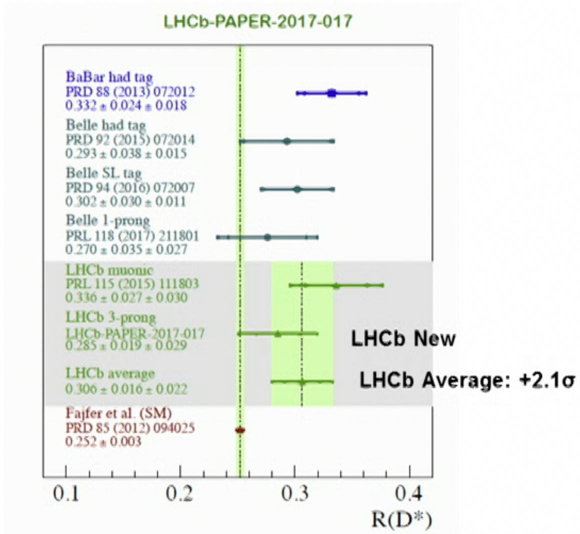
Hints of New Flavor Effects in B decays?

τ / μ Universality Violation?

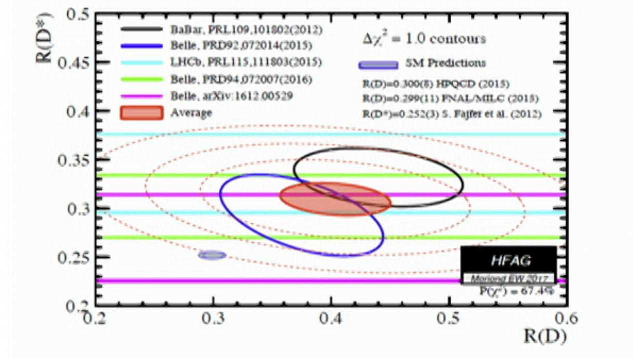
$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^*\tau\nu)_{\rm exp}/\mathcal{B}(B \to D^*\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D^*\ell\nu)_{\rm exp}/\mathcal{B}(B \to D^*\ell\nu)_{\rm SM}} = 1.28 \pm 0.08$$

$$R_{D}^{\tau/\ell} = \frac{\mathcal{B}(B \to D\tau\nu)_{\rm exp}/\mathcal{B}(B \to D\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D\ell\nu)_{\rm exp}/\mathcal{B}(B \to D\ell\nu)_{\rm SM}} = 1.37 \pm 0.18\ ,$$

Measuring R(D*) using 3-prong $\tau^- \to \pi^-\pi^+\pi^-(\pi^0)\nu$ decays;LHCb-PAPER-2017-017, in preparation



$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu}_l)} \text{ with } l = e, \mu$$

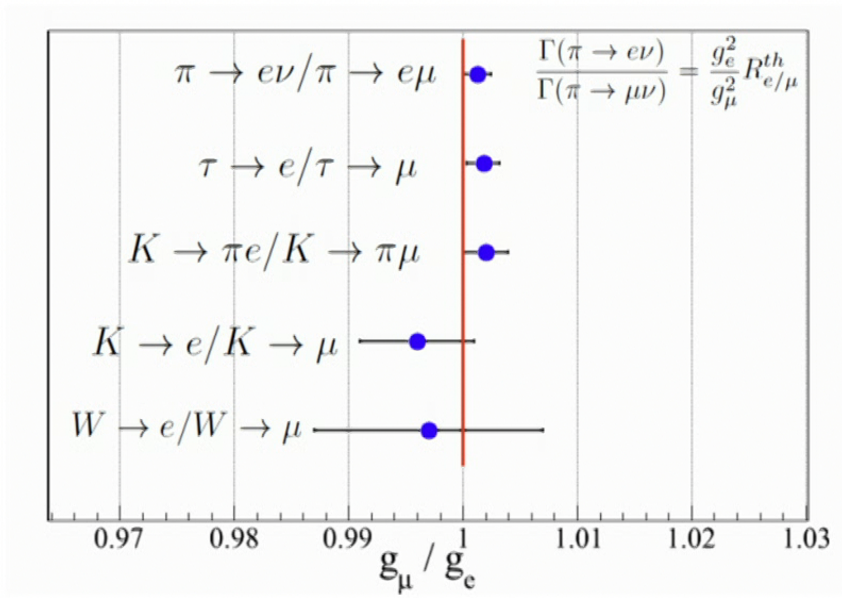


O(10-20%) effects?

e / μ Universality Violation?

$$R_K^{\mu/e} = \left.\frac{\mathcal{B}(B \to K\mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B \to Ke^+e^-)_{\rm exp}}\right|_{q^2\in[1,6]{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Compare with other e/μ Charged Current Universality tests at <0.1% level



More Universality Tests

$\frac{\tau \to e\nu\nu}{\mu \to e\nu\nu}$ for τ-μ Universality and $\frac{\tau \to \mu\nu\nu}{\mu \to e\nu\nu}$ for τ-e Universality

$\frac{\tau \to \pi\nu}{\pi \to \mu\nu}$ for τ-μ Universality and $\frac{\tau \to \pi\nu}{\pi \to e\nu}$ for τ-e Universality

	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to e}$	
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)	1.0044 (60)	

<O(0.2%) effects

Pich 2013, DB 1992

$\tau \to K/\pi \ \nu$ Radiative Corrections Alert!

Radiative corrections for $\tau \to \pi/K \ \nu$ (different from $K/\pi \to l\nu$ [1,2])
have only been done approximately $\delta R = (0.16 \pm 0.14)\%$ [3]

Pich 2013

1. W. Marciano, Phys. Rev. D 45, R721 (1992).
2. W.J. Marciano and A. Sirlin, Phys. Rev. Lett. 71 (1993) 3629
3. R. Decker and M. Finkemeier, Phys. Lett. B 334 (1994) 199; Nucl. Phys. B 438 (1995) 17; Nucl. Phys. B (Proc. Suppl.) 40 (1995) 453

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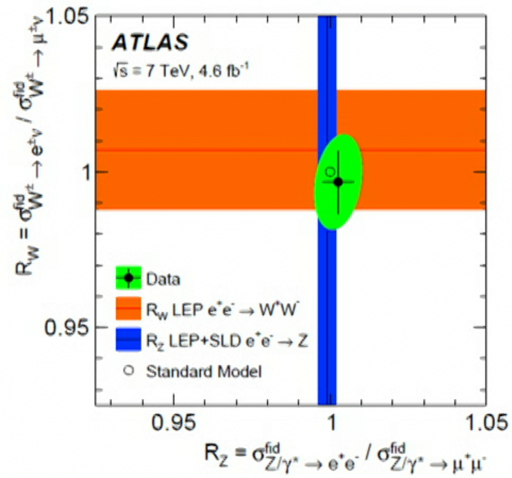
LHC ATLAS LFU Tests

CERN-EP-2016-272
12th December 2016

$$R_W = \frac{\sigma^{\text{fid,e}}_{W\to e\nu}/E^{e}_{W}}{\sigma^{\text{fid},\mu}_{W\to\mu\nu}/E^{\mu}_{W}} = \frac{\sigma^{\text{fid}}_{W\to e\nu}}{\sigma^{\text{fid}}_{W\to\mu\nu}} = \frac{BR(W\to e\nu)}{BR(W\to\mu\nu)}$$
$$= 0.9967 \pm 0.0004\,(\text{stat}) \pm 0.0101\,(\text{syst})$$
$$= 0.997 \pm 0.010\,.$$

$$R_Z = \frac{\sigma^{\text{fid,e}}_{Z\to ee}/E^{e}_{Z}}{\sigma^{\text{fid},\mu}_{Z\to\mu\mu}/E^{\mu}_{Z}} = \frac{\sigma^{\text{fid}}_{Z\to ee}}{\sigma^{\text{fid}}_{Z\to\mu\mu}} = \frac{BR(Z\to ee)}{BR(Z\to\mu\mu)}$$
$$= 1.0026 \pm 0.0013\,(\text{stat}) \pm 0.0048\,(\text{syst})$$
$$= 1.0026 \pm 0.0050\,.$$



Lepton Flavor Universality -- Experimental Summary:

- Possible big O(10-20%) τ/μ flavor universality-violation effects in $b \rightarrow c\tau\nu$ (~2-3 σ effects) not seen at O(0.2%) in other charged current current reactions involving e,μ,τ decays.
- Possible e/μ universality-violation effects in $b \rightarrow s\mu\mu$ neutral currents (~2 σ effects)

Theoretical Speculations:

- Lepton flavor universality-violating (LFU) effects are confined to 3rd generation
- Effects related to masses e.g. $m_\tau^2 / m_\mu^2 \sim 283$ (20% effect for $\tau \rightarrow$ 0.07% for μ)
- New flavor-changing couplings beyond SM or MFV?
- Lepton flavor-violating (LFV) couplings
- Models

  TeV scale with couplings O(1)

  Scalar leptoquarks, New Z', H^+...

Could precise measurements of 1st, 2nd generation decays be used to corroborate models?

Bordone, Buttazzo, Isidori, Monnard ArXiv:1705.10729

Special Role of $K \to \pi\nu\bar{\nu}$

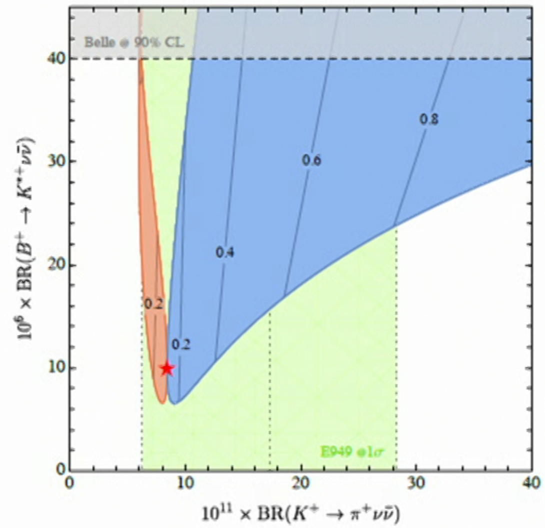
Third generation leptons ν_τ in final state

EFT approach to LFU violations based on $U(2)_q \times U(2)_l$ for first 2 generations
Third generation and rt-handed fermions: singlets

Correlation of $K^+ \to \pi^+\nu\bar{\nu}$

with $B^+ \to K^{*+}\nu\bar{\nu}$

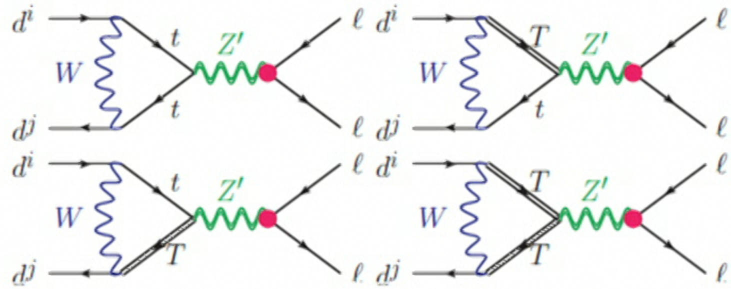
$B(K^+ \to \pi^+\nu\bar{\nu})$ [−30%, +100%]



Example: Effects of LFU violation on $K^+ \to \pi^+ \nu\bar{\nu}$

Kamenik, Soreq, Zupan arXiv:1704.06005v (2017)

Z' in b $\to s\mu\mu$ decays



$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i^\ell O_i^\ell + C_i'^\ell O_i'^\ell) + \text{h.c.}$$

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}(\gamma)) = (8.4 \pm 1.0) \times 10^{-11} \times \frac{1}{3} \sum_\ell \left| 1 + \frac{s_W^2 (C_9^{\ell,\rm NP} - C_{10}^{\ell,\rm NP})}{X_{\rm SM}} \right|^2,$$

$$R_K \to \quad C_9^{\mu,\rm NP} = -C_{10}^{\mu,\rm NP} \simeq 0.60(15)$$

$$\frac{B(K^+ \to \pi^+ \nu\bar{\nu})}{B(K^+ \to \pi^+ \nu\bar{\nu})_{SM}} \sim 1.09 - 1.28 \text{ (Possibly within reach of NA62)}$$

Flavor Vineyard Tasting Menu

Sample new Phyics delights — *1-1000 TeV Scales*

Exotic Searches LFV

LFV Processes Forbidden or out of Reach in the SM

Item	Today's Price (Future)
$K_L^0 \to \mu e, K \to \pi\mu e$	\$ <4.7 10^{-12}(10-12)
$\mu \to e\gamma$	\$ <4.3 10^{-13}(10-14)
$\mu \to 3e$	\$ < 10^{-12}(10-16)
$\mu^- N \to e^- N$	\$ <7.8 10^{-13}(10-16)

Other Exotics

Non-SM Processes

Item		Today's Price
$K^+ \to \pi^+ f$	"Axions"	\$< 10^{-10} (tba)
$\pi / K^+ \to e / \mu^+ \nu_H$	"Sterile Neutrinos"	\$ $\lvert U\rvert^2$

SM Allowed Processes

New Physics if deviations from well calculated predictions

Item	
$K_L^0 \to \mu^+ \mu^-$	\$ 10^{-8}: 6200 events
$K^+ \to \pi^+ \nu\bar{\nu}$	\$ 10^{-10}:7events (100)
$K_L^0 \to \pi^0 \nu\bar{\nu}$ CP violation	\$<5.1 10^{-8} (10-11)

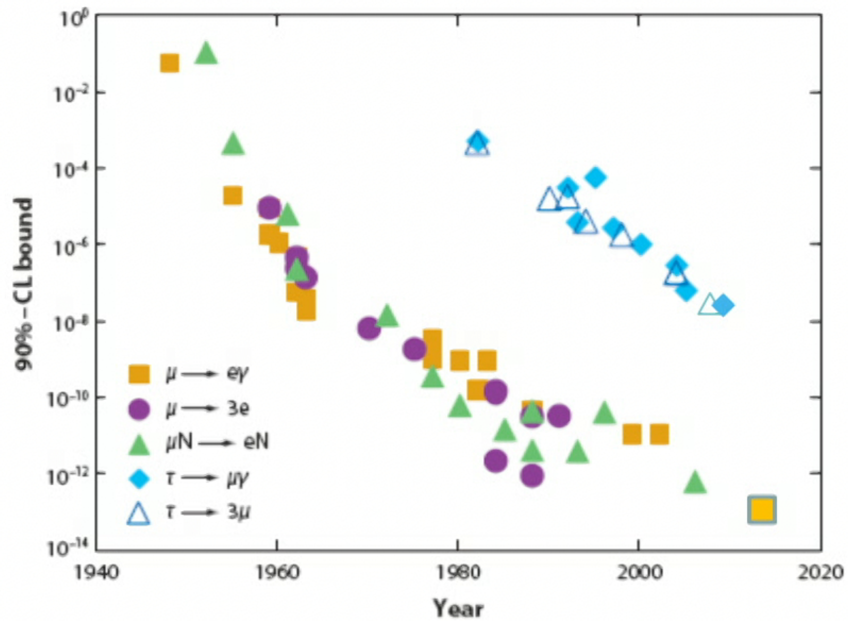
Lepton Flavor Universality

Violations of SM flavor universality

Item	
$\frac{\pi^+(K^+) \to e^+\nu}{\pi^+(K^+) \to \mu^+\nu}$	\$ 10^{-4}: 10^7 events;0.2% (0.1%)
$\frac{\tau \to e^+\nu\bar{\nu}}{\tau \to \mu^+\nu\bar{\nu}}$	\$ 0.2%(<0.2%)

History of Some Rare Decay Experiments

Lepton Flavor Violation



Based on Marciano, Mori, Roney 2010

90% CL

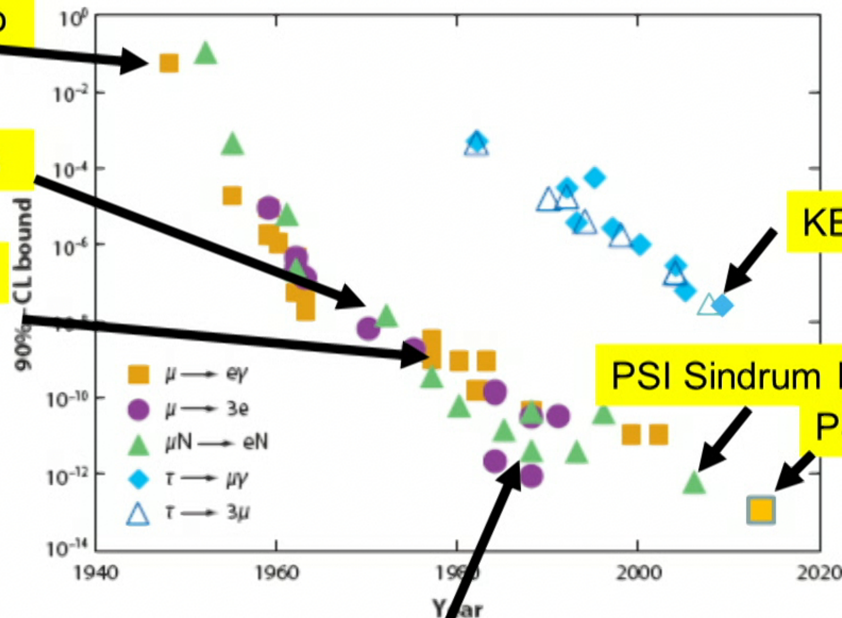
History of Some Rare Decay Experiments

Lepton Flavor Violation

Hincks, Pontecorvo

D.B. Thesis

μ->eγ 1977



KEK Belle

PSI Sindrum II (2006)

PSI MEG (2016)

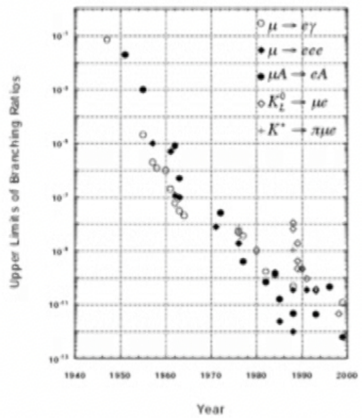
TRIUMF TPC (1987)

Based on Marciano, Mori, Roney 2010

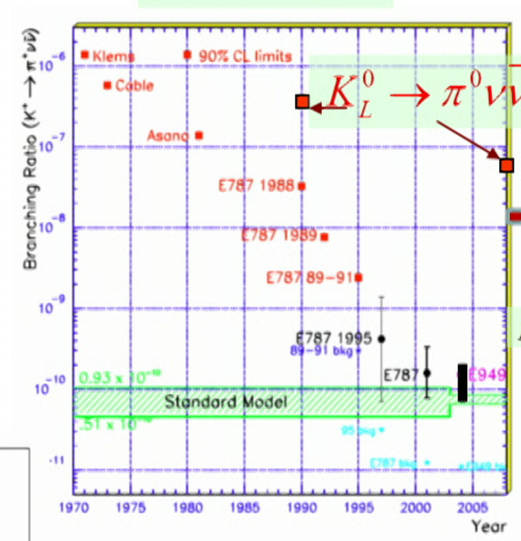
90% CL

Rare Decay Experiment Prospects

Lepton Flavor Violation



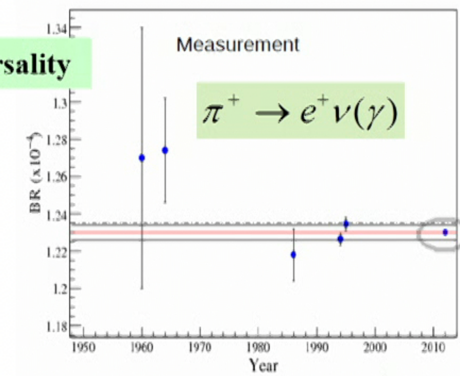
$K^+ \to \pi^+ \nu\bar{\nu}$



$K^+ \to \pi^+ \nu\bar{\nu}$

7 E949

Lepton Flavor Universality

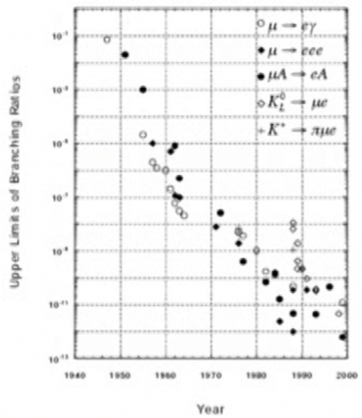


PIENU/PEN

TREK Ke2

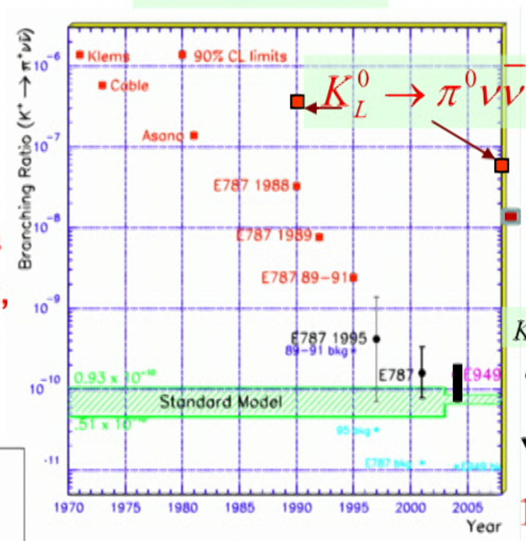
Rare Decay Experiment Prospects

Lepton Flavor Violation



MEG 4×10^{-13}->4×10^{-14}
Deeme, Mu2E, Comet, Mu3e 10^{-12}->10^{-16}

$K^+ \to \pi^+ \nu\bar{\nu}$



$K_L^0 \to \pi^0 \nu\bar{\nu}$

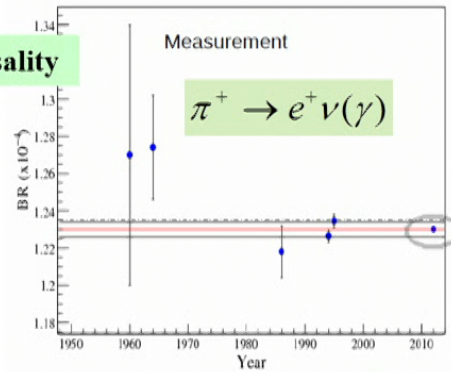
KOTO

$K^+ \to \pi^+ \nu\bar{\nu}$

7 E949

100 NA62

Lepton Flavor Universality



TREK Ke2

PIENU/PEN → **0.2%→<0.1% precision**

Flavor Vineyard Tasting Menu

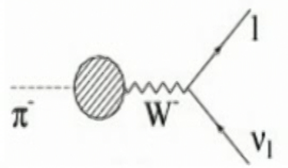
First Course

Delicious PIE$_{NU}$

Kinoshita (1959), **Marciano and Sirlin** (1976, 1995), Finkemeir (1995)

$\pi^+ \rightarrow e^+\nu$

Radiative Corrections; Inner Bremsstrahlung; and Structure-Dependent Radiation:



$$\Gamma(\pi \rightarrow l\bar{\nu}_l(\gamma)) = \frac{G_\mu^2 |V_{ud}|^2}{8\pi} f_\pi^2 m_\pi m_l^2 \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2 \left[1 + \frac{2\alpha}{\pi}\ln\left(\frac{m_Z}{m_\rho}\right)\right]_\gamma$$

$$\times \left[1 - \frac{\alpha}{\pi}\left\{\frac{3}{2}\ln\left(\frac{m_\rho}{m_\pi}\right) + C_1 + C_2\frac{m_l^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_l^2} + C_3\frac{m_l^2}{m_\rho^2} + \cdots\right\}\right]\left[1 + \frac{\alpha}{\pi}F(x)\right]$$

-4% for l=e

$\left[+\,\pi \;\; \text{Structure-dependent}\; \pi^+ \rightarrow e^+\nu\gamma \;\text{terms}\right]$

where $G_\mu = 1.16637(1)\times 10^{-5}\, GeV^{-2}$, $V_{ud} = 0.9738$

But, most factors cancel in the ratio

$$R^{th}_{e/\mu} = \frac{\Gamma\left(\pi \to e\nu + \pi \to e\nu\gamma\right)}{\Gamma\left(\pi \to \mu\nu + \pi \to \mu\nu\gamma\right)}$$

$$R^{th}_{e/\mu} = R^{0}_{e/\mu}\left\{1 + \frac{\alpha}{\pi}\left[F\left(\frac{m_e}{m_\pi}\right) - F\left(\frac{m_\mu}{m_\pi}\right) + C_2\frac{m_\mu^2}{m_\rho^2}\ln\frac{m_\rho^2}{m_\mu^2} + C_3\frac{m_\mu^2}{m_\rho^2}\right]\left(+SD_\pi\right)\right.$$

$8x10^{-8}$

F : kinematic factors

C_2=3.1 (Terent'ev)

C_3 : Small but
Model dependent
Marciano : 0 ± 10

Pure Structure Dependent (SD) $\pi \to e\nu\gamma$
corrections are not helicity suppressed
but are small and known for π decay:

$$\frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)} \qquad R^{th}_{e/\mu} = (1.2353 \pm 0.0001)\, x10^{-4}$$

PI E NU 2015

Possibly the most accurately calculated decay process involving hadrons . W. Marciano → V. Cirigliano

Current Result PIENU: $R^{\exp\pi}_{e/\mu} = 1.2344 \pm 0.0030x10^{-4}$ (±0.2%)

Future: PIENU, PEN <0.1%

$$\frac{K^+ \to e^+\nu(\gamma)}{K^+ \to \mu^+\nu(\gamma)} \qquad R^{th}_{K\to e/\mu} = (2.477 \pm 0.001)\, x10^{-5}$$

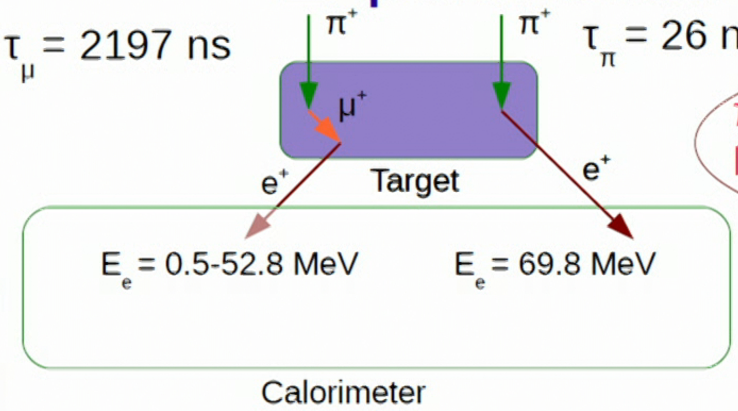
Finkemeier(1995)
Cirigliano, Rosell(2007)

Current Result NA62: $R^{\exp K}_{e/\mu} = 2.488 \pm 0.010x10^{-5}$ (±0.4%)

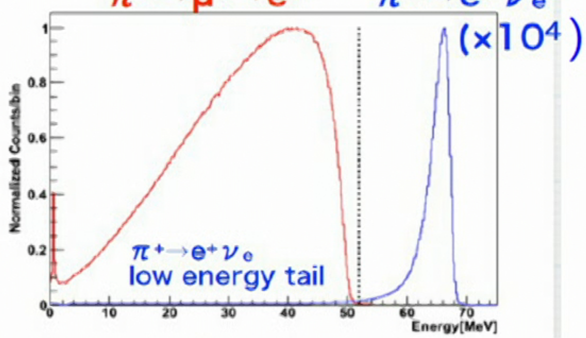
Future: NA62, TREK: 0.2%

Experimental Method

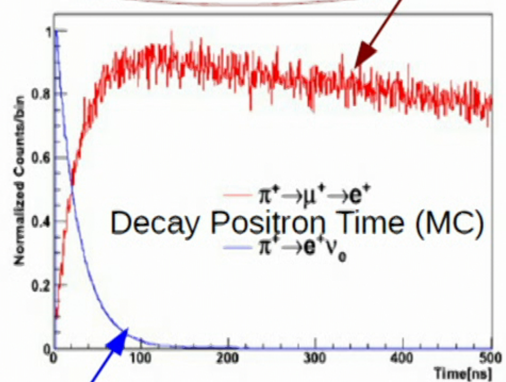
$\tau_\mu = 2197$ ns $\qquad \tau_\pi = 26$ ns



$\pi^+ \longrightarrow \mu^+ \longrightarrow e^+$:
$N_{PIMU} / (\tau_\mu - \tau_\pi) \times (e^{-t/\tau_\mu} - e^{-t/\tau_\pi})$



Decay Positron Energy (MC)



Decay Positron Time (MC)

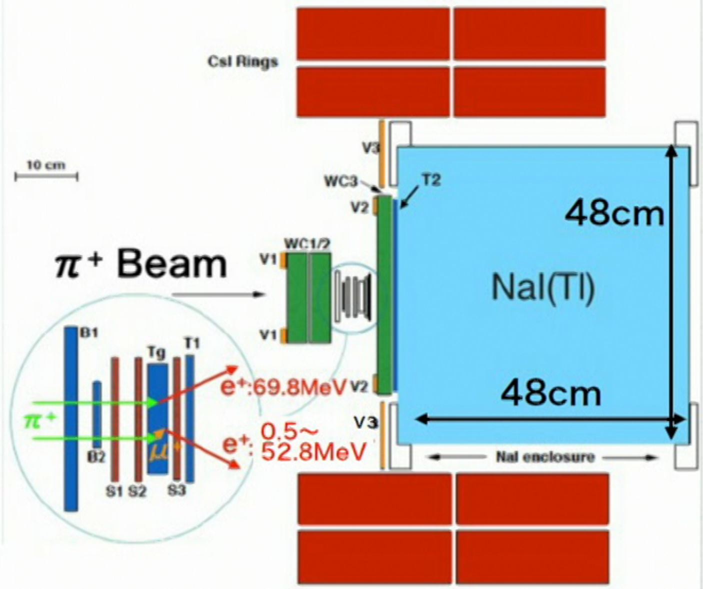
$\pi^+ \longrightarrow e^+$:
$(N_{PIE} / \tau_\pi)\, e^{-t/\tau_\pi}$

T. Sullivan HQL2016

PIENU Detector

π^+ beam:
- ~ 60 KHz on B1
- 75 ± 1 MeV / c
- $\pi^+ : \mu^+ : e^+ = 85 : 14 : 1$

Detector:
- Acceptance ~ 20%
- Energy Resolution 2.2% (FWHM) at 70 MeV
- 19 radiation lengths of NaI, 9 of CsI
- Pion and positron times obtained from fitting B1 and T1 waveforms, respectively
- Wire chambers & silicon strips for π^+ beam and decay e^+ tracking



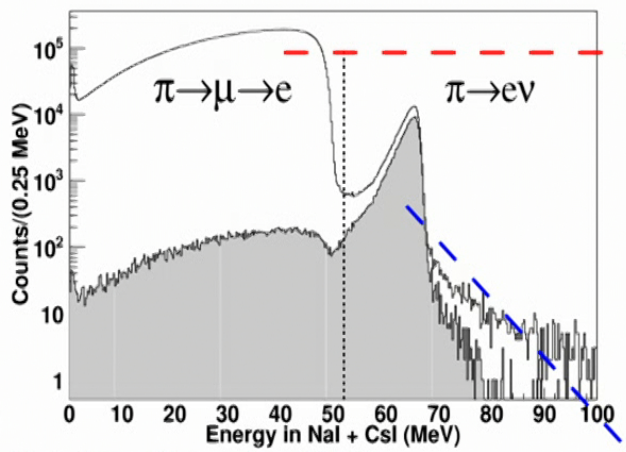
WC: Wire Chamber

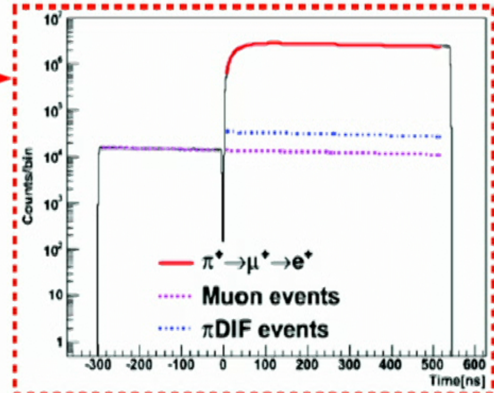
SS: Silicon Strip

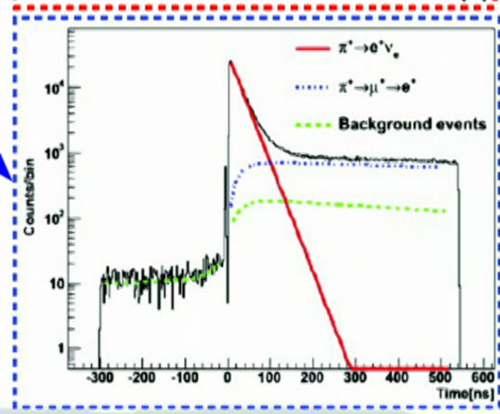
B1, B2, Tg, T1, T2: Plastic Scintillator

PI E NU

Raw Branching Ratio Extraction







- Data from November 2010
- 4.0×10^5 clean π —> e ν events
- Fitting time spectra simultaneously gives raw branching ratio:

$$R_{raw} = [1.1972 \pm 0.0022\ (stat) \pm 0.0005\ (syst)] \cdot 10^{-4}$$

T. Sullivan HQL2016

PI E NU 2015

Current Result PIENU: $R_{e/\mu}^{\exp \pi} = 1.2344 \pm 0.0030 x 10^{-4}$ $(\pm 0.2\%)$

$$R_{e/\mu}^{th} = \left(1.2353 \pm 0.0001\right) x 10^{-4}$$

Error	PIENU 2010	PIENU goal
Statistical	0.19%	0.07%
Time Spectrum	0.04%	0.04%
Tail Correction	0.12%	0.06%
Others	0.07%	0.04%
Total	0.24%	< 0.1%

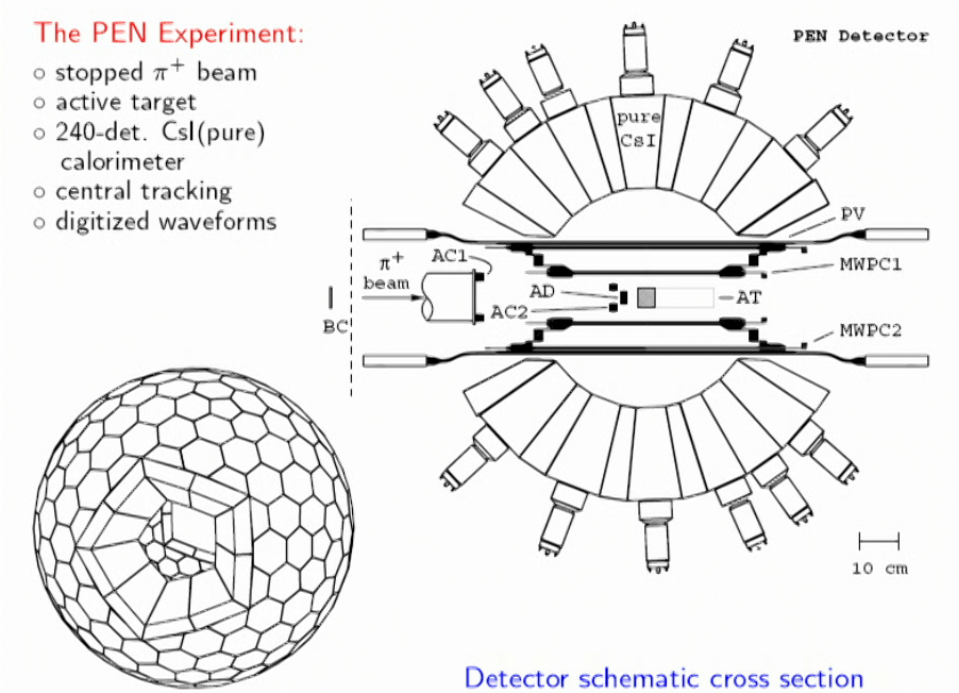
$\pi^+ \to e^+\nu$ at PSI

Precision Goal: 0.05%

PI Beta Spectrometer: 12 X0 pure CsI

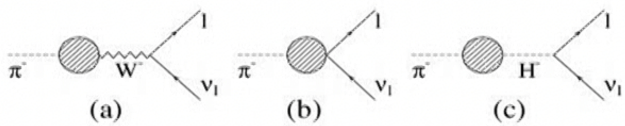
Previously measured

$\pi^+ \to \pi^0 e^+\nu, \pi^+ \to e^+\nu\gamma$



$\pi^+ \to e^+\nu$: Sensitivity to High Mass Scales

New Pseudoscalar interaction



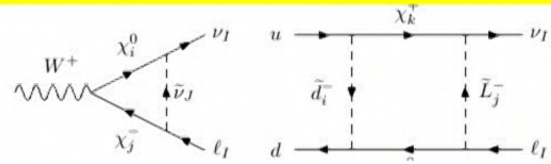
$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m^2_\pi}{m_e(m_d + m_u)}$$

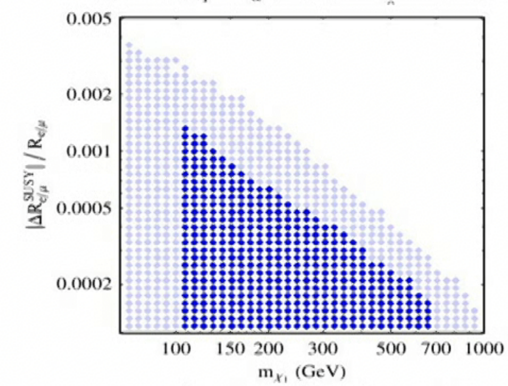
$$\sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3$$

0.1 % measurement→Λ~1000 TeV

Assuming non-SM Higgs' couplings. Marciano…

R-parity violating SUSY





Lowest chargino mass

Ramsey-Musolf…

Others :

- **-Leptoquarks**
- **-Excited gauge bosons**
- **-Compositeness**
- **-SU(2)xSU(2)xSU(2)xU(1)**
- **-..**.

Campbell and Marbury (2003), Marciano

Scalar Interactions:
$\pi \to e\nu$ *vs*. Super-allowed β Decay

$$\left.\begin{cases} CKM \text{ Unitarity: } |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978 \pm 0.00055 \\ R_{e/\mu} = \dfrac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(\pi^+ \to \mu^+\nu)} = 1.2344(23)x10^{-4}\ (now\ \ 0.2\% \to < 0.1\%) \end{cases}\right\} 0.1\% \text{ Precision}$$

Constraining new Physics?

Direct Constraints

$R_{e/\mu}$: $\Lambda_A \sim 20TeV,\ \Lambda_P \sim 1000TeV\,(!)$

$SM: \frac{G_\mu}{\sqrt{2}} \sim \frac{\pi}{2\Lambda_{SM}^2};\ \Lambda_{SM} \sim 440GeV$

Unitarity: $\Lambda_V \sim 20TeV,\ \Lambda_S \sim 17\ TeV$

Induced Current Constraints

$R_{e/\mu}$: $\Lambda_V \sim 2TeV,\ \Lambda_S \sim 60TeV\,(!)$

Unitarity: $\Lambda_A \sim 2TeV$

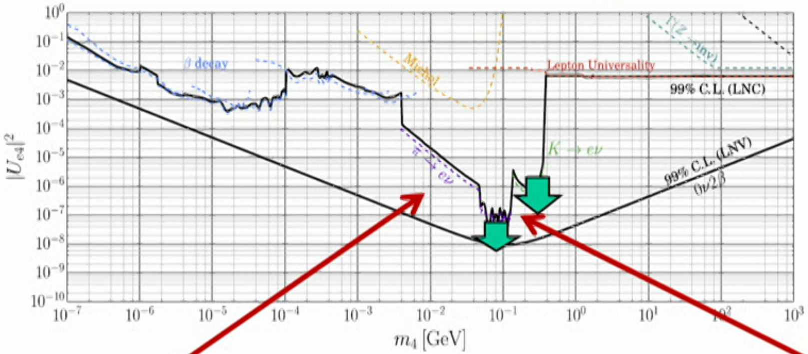
Loops 

e.g. A induces V

P induces S

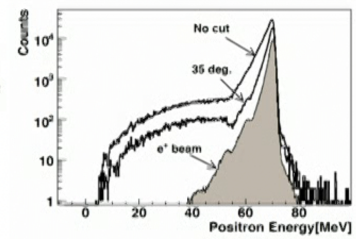
$|U_{ei}|^2$ vs Mass

De Gouvêa and Kobach, PRD93 (2016) 033005



Heavy Neutrinos Coupled to Electrons $\pi \rightarrow e\nu_H$

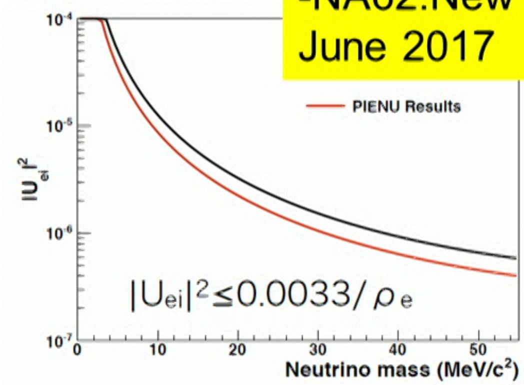
$$\frac{\Gamma(\pi \to e\nu_i)}{\Gamma(\pi \to e\nu_e)} = |U_{ei}|^2 \rho_e$$



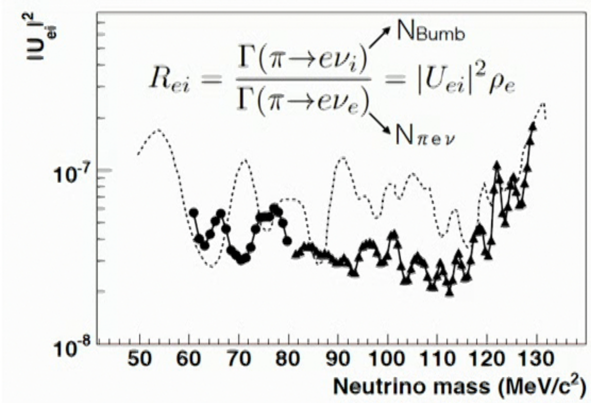
- -PIENU: Expect ~3x improvement
- -NA62:New results June 2017

PIENU

2015 Branchir



PIENU Peak Search



M.Aoki et al, Phys.Rev.D 84 052002 (2011)

Majorons or **New Vector Bosons coupled to neutrinos**

$$\pi \to e\nu X$$

Sensitivity to Majorons

- Nambu-Goldstone bosons (Majorons) occur in gauge models with spontaneously broken global B-L symmetry.
- In the presence of Majorons M, the expected branching ratio is slightly higher.

Majoron-neutrino coupling

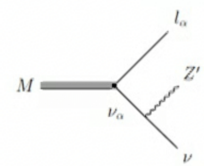
$$\frac{\Gamma(\pi\to eL^0)/\Gamma(\pi\to\mu L^0)}{\Gamma(\pi\to e\nu)/\Gamma(\pi\to\mu\nu)} = 1 + 157.5 g_M^2$$

G.B.Gelmini and M.Roncadelli., Phys.Lett. 99B 411 (1981)

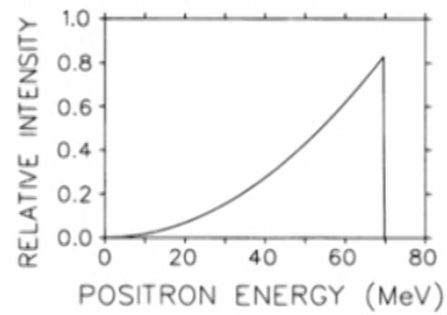
- L^0: final states of ν, νM, and $\nu\,\chi$ (very light Higgs particle).
- Previous result: $g_M^2<3\times10^{-5}$ This result: $g_M^2<2.1\times10^{-5}$

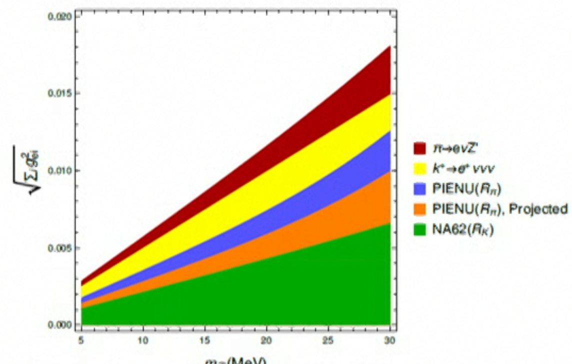
(90% C.L.)

11



$$g_{\alpha i} Z'_\mu \bar{\nu}_i \gamma^\mu \nu_\alpha$$





Bakhti, Farzan arXiv:1702.04187 2017

Non-unitary Neutrino mixing matrix, CP violation, non-FU….

Escrihuela et al. arXiv: 1612.07377

$$N = N^{NP} U = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

$$\sum_{i=1}^{3} |V_{ui}|^2 = \frac{1}{\alpha_{22}^2 + |\alpha_{21}|^2} = 0.9999 \pm 0.0006.$$

$$R_\pi = \frac{\Gamma(\pi^+ \to e^+ \nu)}{\Gamma(\pi^+ \to \mu^+ \nu)} = \frac{\alpha_{11}^2}{\alpha_{22}^2 + |\alpha_{21}|^2}.$$

	One parameter (1 d.o.f.)		All parameters 6 d.o.f.	
	90% C.L.	3σ	90% C.L.	3σ
Neutrinos + charged leptons				
α_{11}	0.9974	0.9963	0.9961	0.9952
α_{22}	0.9994	0.9991	0.9990	0.9987
α_{33}	0.9988	0.9976	0.9973	0.9961
$\lvert\alpha_{21}\rvert$	1.7×10^{-3}	2.5×10^{-3}	2.6×10^{-3}	4.0×10^{-3}
$\lvert\alpha_{31}\rvert$	2.0×10^{-3}	4.4×10^{-3}	5.0×10^{-3}	7.0×10^{-3}
$\lvert\alpha_{32}\rvert$	1.1×10^{-3}	2.0×10^{-3}	2.4×10^{-3}	3.4×10^{-3}
Neutrinos only				
$\lvert\alpha_{21}\rvert$	2.6×10^{-2}	3.6×10^{-2}	-	-
$\lvert\alpha_{32}\rvert$	1.5×10^{-2}	2.0×10^{-2}	-	-

$$R_{\tau/P} = \frac{\Gamma(\tau^- \to P^- \nu_\tau)}{\Gamma(P^- \to \mu^+ \nu_\mu)} \propto \left|\frac{g_\tau}{g_\mu}\right|^2 = \frac{\alpha_{33}^2 + |\alpha_{32}|^2 + |\alpha_{31}|^2}{\alpha_{22}^2 + |\alpha_{21}|^2}$$

$$M_W = \frac{A_0}{s_W (1 - \Delta r)^{1/2}} \qquad A_0 = \left(\frac{\pi \alpha \sqrt{\alpha_{11}^2 (\alpha_{22}^2 + |\alpha_{21}^2|)}}{\sqrt{2} G_\mu} \right)^{1/2}$$

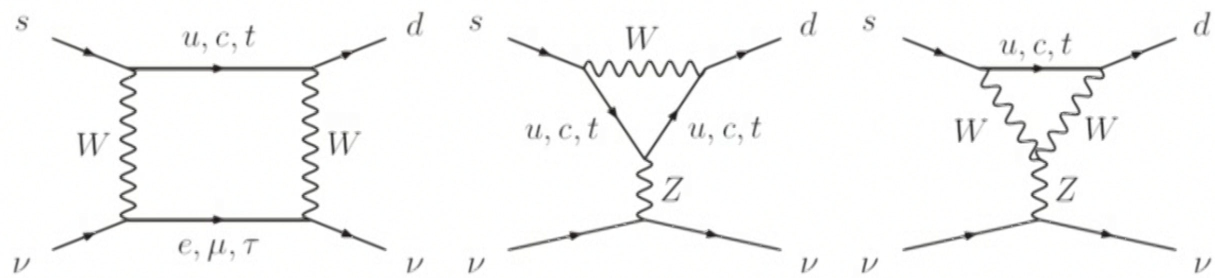
Flavor Vineyard Tasting Menu

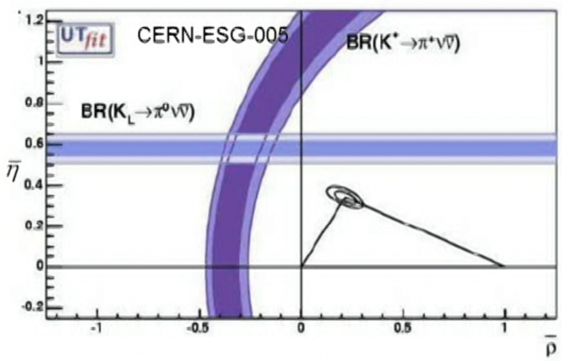
2nd Course

Nutritious K(aons)

$K^+ \to \pi^+ \nu\bar{\nu}$ in the Standard Model

The $K \to \pi\nu\bar{\nu}$ decays are the most precisely predicted FCNC decays





A single effective operator $(\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L \gamma_\mu \nu_L)$

Dominated by top quark

(charm significant, but controlled)

Hadronic matrix element shared with Ke3

Remains clean in most New Physics models

$$B_{SM}(K^+ \to \pi^+ \nu\bar{\nu}) = (8.4 \pm 1.0) \text{ x } 10^{-11}$$

$$B_{SM}(K_L^0 \to \pi^0 \nu\bar{\nu}) = (3.4 \pm 0.6) \text{ x } 10^{-11}$$

Expect total SM theory error ≤6%.

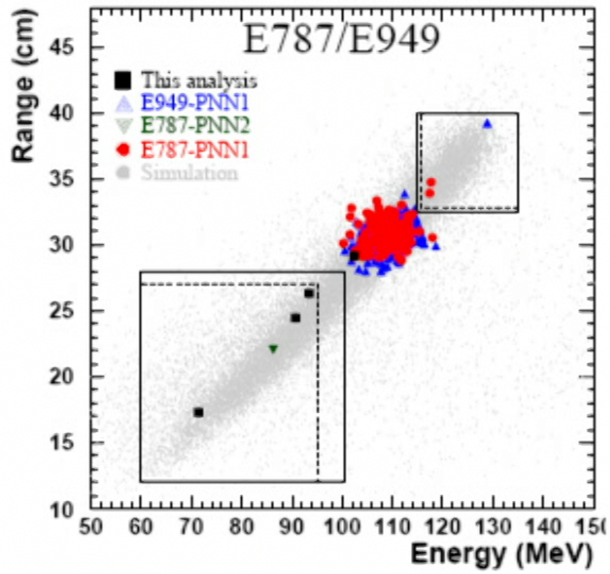
30% deviation from the SM would be a 5σ signal of NP

A. J. Buras, D. Buttazzo, R. Knegjens, ArXiv:1507.08672v2

BNL E787/E949 $K^+ \rightarrow \pi^+ \nu\bar{\nu}$

$$\mathrm{BR}(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 1.73^{+1.15}_{-1.05}\, x10^{-10}$$

7 events observed



Phys.Rev. D79 (2009) 092004

The NA62 Experiment for $K^+ \to \pi^+ \nu \bar{\nu}$

Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna (JINR), Fairfax, Ferrara, Florence, Frascati, Glasgow, Liverpool, Louvain-la-Neuve, Mainz, Merced, Moscow (INR), Naples, Perugia, Pisa, Prague, Protvino (IHEP) , Rome I, Rome II, San Luis Potosi, SLAC, Sofia, TRIUMF, Turin, Vancouver (UBC)

The NA62 detector

NA62 physics data taking started in June 2015

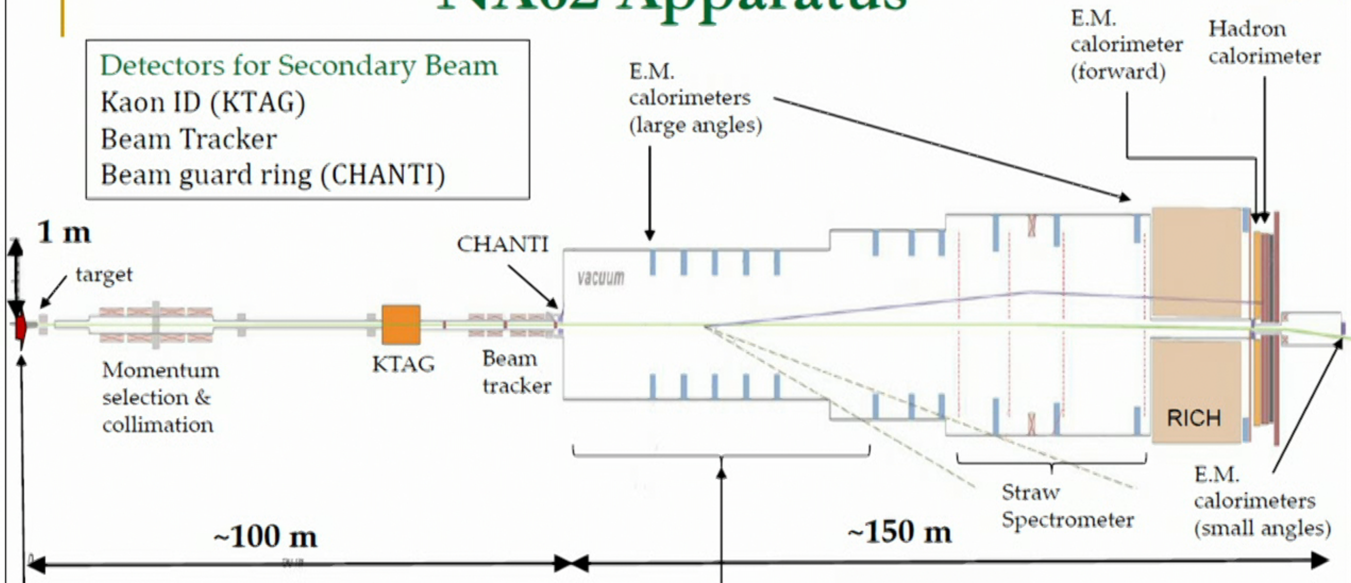
- Primary goal:
  10% precision BR($K^+ \to \pi^+ \nu \bar{\nu}$)

- Requirements:
  - Statistics: O(100) events
  - K decays (2 years) 10^{13}, Signal acceptance ~ 10%
  - Systematics: <10% precision background measurement
  - >10^{12} background rejection (<20% background)

- Technique:
  - K Decay – in – flight

NA62 Apparatus

Detectors for Secondary Beam
Kaon ID (KTAG)
Beam Tracker
Beam guard ring (CHANTI)



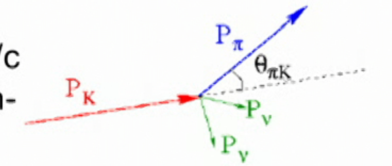
SPS proton	Secondary Beam	Kaon Decay
400 GeV	75 GeV/c, $\Delta p/p \sim 1\%$	~5 MHz
10^{12} p/s	X,Y Divergence < 100 μrad	$4.5 \times 10^{12}/year$
3.5 s spill	K(6%), π(70%), p(23%)	60 m length
	Total rate: 750 MHz	10^{-6} mbar vacuum
	Beam size: 6.0 × 2.7 cm²	

Detectors for decay products
Charged particle tracking
Charged particle time stamping
Photon detection
Particle ID

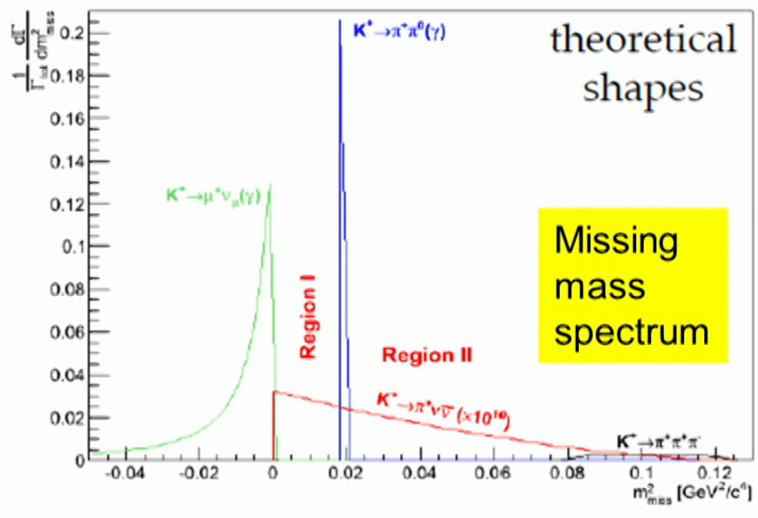
In operation 2015-2018

$K^+ \to \pi^+ \nu \bar{\nu}$

75 GeV/c decay in-flight

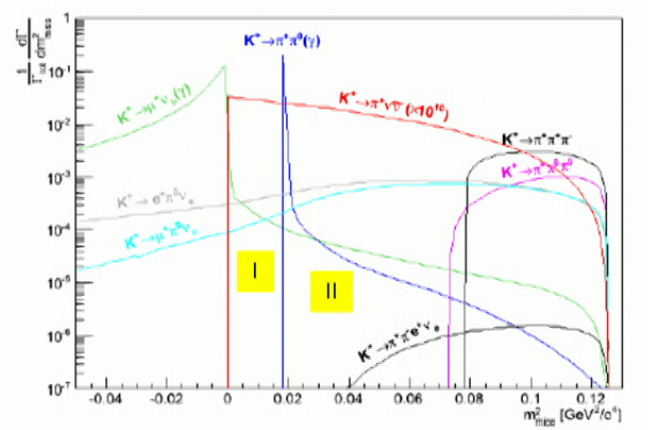


$$m^2_{miss} = (P_K - P_{\pi^+})^2$$



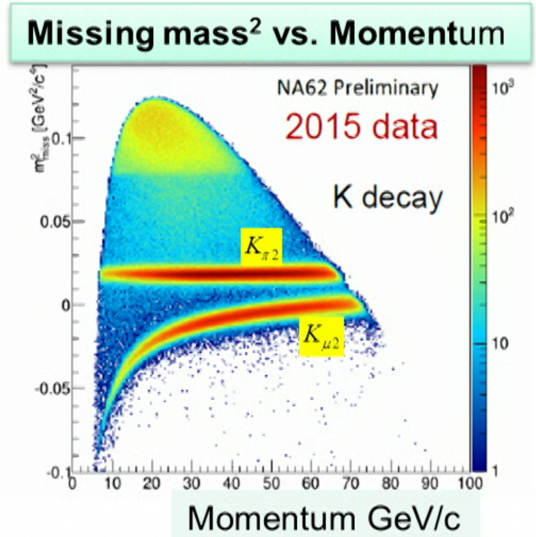
Suppress backgrounds by 12 orders of magnitude:

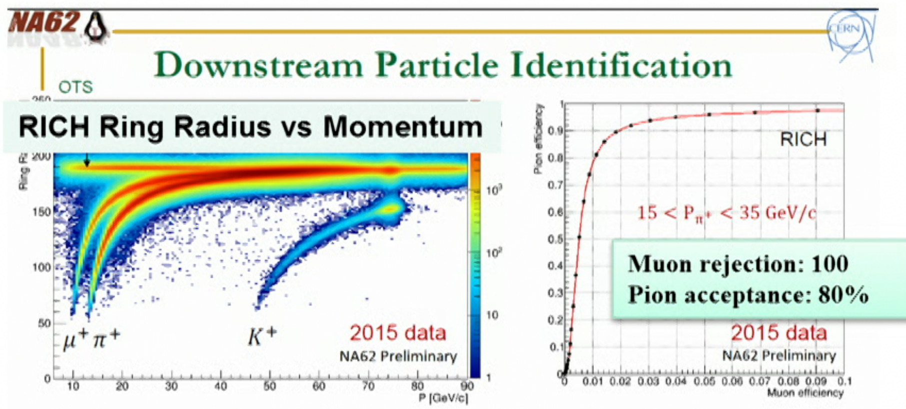
- High resolution kinematics
- RICH particle ID
- High precision LKr calorimeter
- Muon filter calorimeters
- ~4π Photon Vetos



NA62 $K^+ \to \pi^+ \nu \bar{\nu}$

- NA62 commissioned and tested to nominal intensity in 2015
- Operations in 2016-2018
- Preliminary study of data quality
  - Physics sensitivity in line with design
  - Studies ongoing for exotics sensitivity





M. Mirra 2016

NA62 physics programme

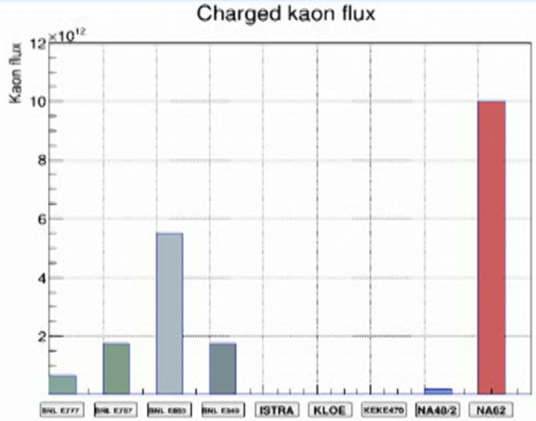
- **Standard Kaon Physics Precision:**
  - 10% precision BR($K^+ \to \pi^+ \nu\bar{\nu}$) measurement
  - Measurements of the BR of all the main K decay modes
  - χPT studies: $K^+ \to \pi^+\gamma\gamma$, $K^+ \to \pi^+\pi^0 e^+ e^-$, $K^+ \to \pi^{0(+)}\pi^{0(-)} l^+ \nu$
  - Precision measurement of $R_K = \Gamma(K^+ \to e^+\nu_e)/(K^+ \to \mu^+\nu_\mu)$

- **LFV with kaons:**
  - $K^+ \to \pi^+\mu^\pm e^\mp$, $K^+ \to \pi^-\mu^+ e^+$, $K^+ \to \pi^- l^+ l^+$

- **Heavy neutrino searches**
  - $K^+ \to l^+ \nu_h$
  - ν_h from K, D decays and $\nu_h \to \pi l$
- **Pion decay:**
  - $\pi^0 \to 3/4\gamma$, $\pi^0 \to invisible$

- **Dark sector:**
  - long living dark photon, produced by $\pi^0/\eta/\eta/\Phi/\varrho/\omega$, decaying in l^+l^-
  - long living axion, produced in a beam-dump configuration, decaying in $\gamma\gamma$

NA62: kaon factory



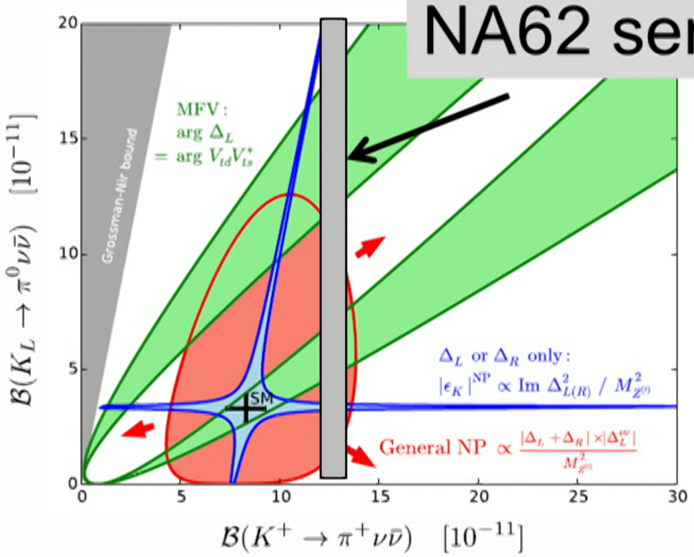
- Excellent particle veto efficiency
- Excellent momentum resolution
- Particle ID efficiency
- High kaon flux

Mode	Present	Expected
R_K $\frac{K^+\to e^+\nu}{K^+\to \mu^+\nu}$	0.4%	0.2%
$K^+\to\pi^+\gamma\gamma$	<500 events	10^5 events
$K^+\to\pi^0\pi^0 e^+\nu$	66000	$O(10^6)$
$K^+\to\pi^0\pi^0\mu^+\nu$	66000	$O(10^5)$

Mode	BSM Physics	90% CL present limit	NA62
$K^+\to\pi^+\mu^+e^-$	LFV	$1.3*10^{-11}$	$10^{-12}/10^{-13}$
$K^+\to\pi^+\mu^-e^+$	LFV	$5.2*10^{-10}$	$10^{-12}/10^{-13}$
$K^+\to\pi^-\mu^+e^+$	LNV	$5*10^{-10}$	$10^{-12}/10^{-13}$
$K^+\to\pi^-e^+e^+$	LNV	$6.4*10^{-10}$	10^{-12}
$K^+\to\pi^-\mu^+\mu^+$	LNV	$1.1*10^{-9}$	$10^{-12}/10^{-13}$
$K^+\to\mu^-\nu e^+e^+$	LFV/LNV	$2*10^{-8}$	10^{-12}
$K^+\to e^-\nu\mu^+\mu^+$	LFV/LNV	No data	10^{-12}
$K^+\to\pi^+X^0$	New particle	$5.9*10^{-11}, m_{X_0} = 0$	10^{-12}
$K^+\to\pi^+\chi\chi$	New particle	-	10^{-12}
$K^+\to\pi^+\pi^+l^-\nu$	$\Delta S \neq \Delta Q$	$1.2*10^{-8}$	10^{-11}
$K^+\to\pi^+\gamma$	Angular momentum	$2.3*10^{-9}$	10^{-12}
$K/D\to l\nu_h$, $\nu_h\to\pi l$	Heavy neutrino		
$\pi^0\to$ invisible, $\pi^0\to 3/4\gamma$, $\pi^0\to U\gamma$			
Dark sector: long living dark photon, long living ALPs			

Venelin Kozhuharov

New Physics Sensitivity of $K^+ \to \pi^+ \nu\bar{\nu}$



Andrzej J. Buras, Dario Buttazzo and Robert Knegjens arXiv:1507.08672 (2015)

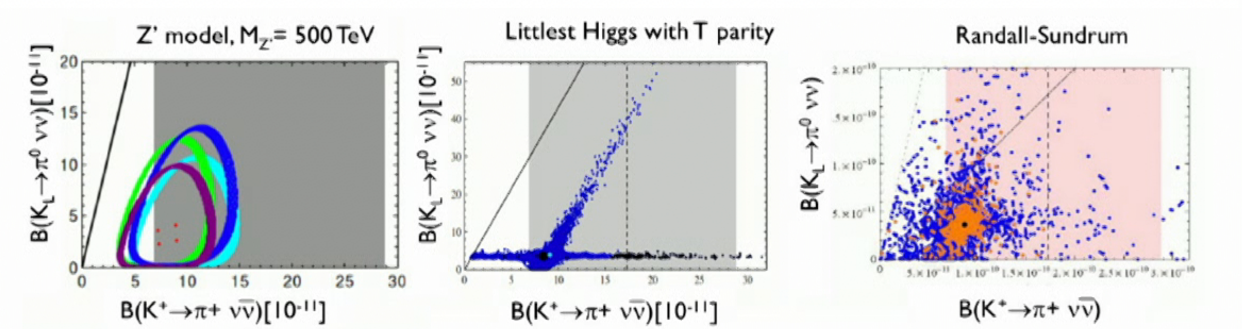
- Minimum flavor violation models
- Supersymmetric models
- Littlest Higgs (LH) model without/with T-parity
- Randall-Sundrum models
  -general LH, RH couplings
- Partial compositeness
- Models in which ε_K constraint applies

Other potential correlations of $K^+ \to \pi^+ \nu\bar{\nu}$ with

$$K_L^0 \to \mu\mu,\ \varepsilon'/\varepsilon,\ B \to K(K^*)\mu\mu$$

$K^+ \to \pi^+ \nu\nu$ sensitive to NP contribution

- Simplified Z, Z' models
  Buras et al., JHEP 1511 (2015) 166
- Littlest Higgs with T-parity
  Blanke et al., EPJ C76 (2016) no.4, 182
- Custodial Randall-Sundrum
  Blanke et al, JHEP 0903 (2009) 108
- MSSM non-MFV
  Tanimoto, Yamamoto, PTEP 2015 no.5, 053B07
  Isidori et al., JHEP 0608 (2006) 064

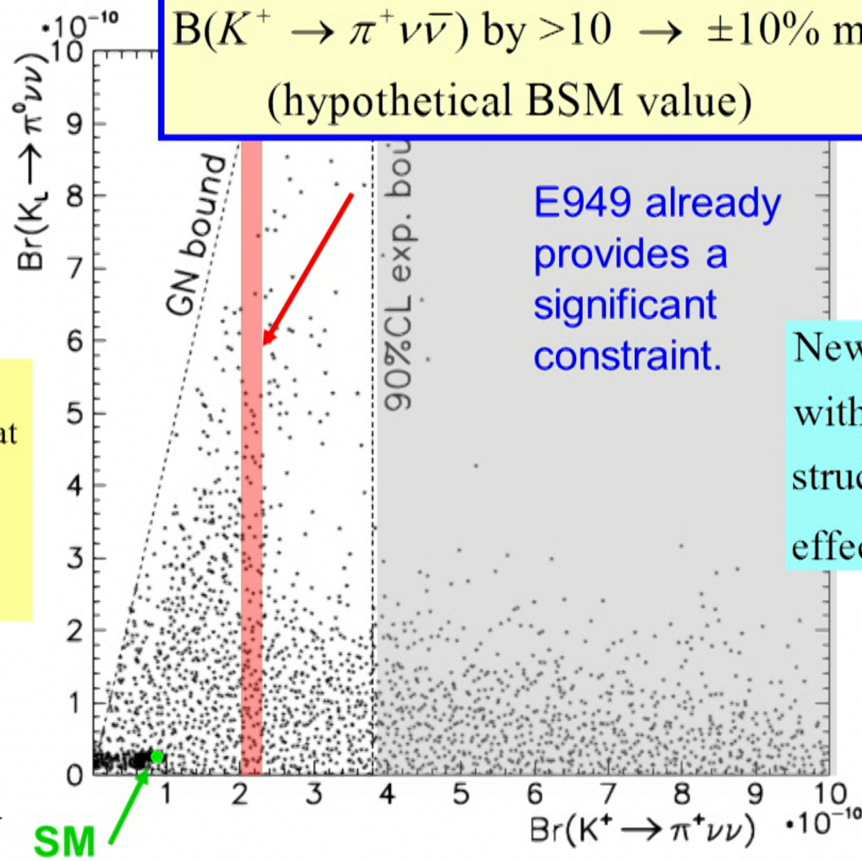


General MSSM with R-parity

NA62 will improve the sensitivity of $B(K^+ \to \pi^+ \nu\bar{\nu})$ by >10 $\to$ ±10% measurement (hypothetical BSM value)

Buras et al, NP B714,103(2005)

Points from a scan of MSSM parameters that satisfy experimental constraints except $B(K^+ \to \pi^+ \nu\bar{\nu})$



New Physics models with generic flavor structure induce large effects in $K^+ \to \pi^+ \nu\bar{\nu}$.

R Parity: $R = (-1)^{2j+3B+L}$

link.springer.com/content/pdf/10.1007/JHEP03(2012)090

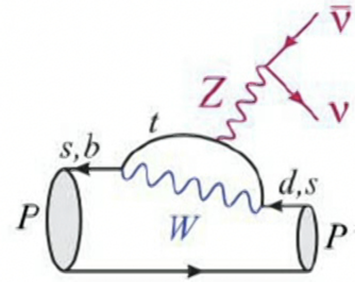
Kamenik and Smith (2012)

"FCNC portals to the dark sector"

Dark Sector Decays $K / B \to \pi^+ XX$ compete with SM Decays $K / B \to \pi \nu \bar{\nu}$

Operator Dimensional Analysis

$$\frac{m_I^{n-6}}{\Lambda^{n-4}} \approx \frac{g^2}{M_W^2}\frac{g^2}{16\pi^2}\left|V_{tI}V_{tJ}\right|$$



K decays Highly sensitive for low dimension operators

	$n=5$	$n=6$	$n=7$	$n=8$	$n=9$
$s \to d$	$3.3 \cdot 10^7$ TeV	130 TeV	2.0 TeV	0.25 TeV	0.07 TeV
$b \to d$	$1.3 \cdot 10^5$ TeV	26 TeV	1.5 TeV	0.37 TeV	0.16 TeV
$b \to s$	$2.7 \cdot 10^4$ TeV	12 TeV	0.9 TeV	0.25 TeV	0.11 TeV

Constraints on Vector-liike fermions from $K^+ \to \pi^+ \nu\bar{\nu}$

Ishiwata,Ligeti,Wise JHEP10(2015)027

Flavor-changing neutral-current processes provide the most important constraints 10 TeV

$$\begin{aligned}\mathcal{H} &= c_\nu \sum_i (\bar{s}_L \gamma_\mu d_L)(\bar{\nu}_{iL}\gamma^\mu \nu_{iL}) + c'_\nu \sum_i (\bar{s}_R \gamma_\mu d_R)(\bar{\nu}_{iL}\gamma^\mu \nu_{iL}) \\ &= \frac{c_{\nu,V}}{2} \sum_i (\bar{s}\gamma_\mu d)(\bar{\nu}_{iL}\gamma^\mu \nu_{iL}) + \frac{c_{\nu,A}}{2} \sum_i (\bar{s}\gamma_\mu \gamma_5 d)(\bar{\nu}_{iL}\gamma^\mu \nu_{iL})\end{aligned}$$

$$|c_{\nu,V}^{(a)}| = \eta_{Zd}^{(a)} \frac{|\lambda_1 \lambda_2|}{2M^2}$$

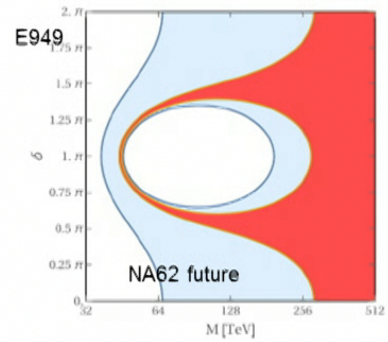
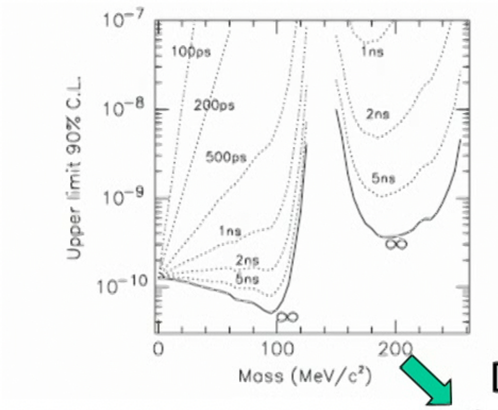


Figure 1. Constraints from $K^+ \to \pi^+\nu\bar{\nu}$ on vector-like fermions in the $M/\sqrt{\eta_{Zd}^{(a)}|\lambda_1\lambda_2|}$ vs. $\delta = \arg\left(c_{\nu,V}^{(a)}/c_{\nu,V}^{(\mathrm{SM})}\right)$. The currently allowed 1σ region is blue-shaded, corresponding to $0.8 < |1 + c_{\nu,V}^{(a)}/c_{\nu,V}^{(\mathrm{SM})}|^2 < 3.6$, whereas a future 10% measurement in agreement with the SM, $0.9 < |1 + c_{\nu,V}^{(a)}/c_{\nu,V}^{(\mathrm{SM})}|^2 < 1.1$, would constrain M and δ to the red-shaded region.

Vector-like quarks are hypothetical spin 1/2 particles that transform as triplets under the colour gauge group and whose left- and right-handed components have the same colour and electroweak quantum numbers.

BNL E949

$K^+ \to \pi^+ A', A' \to invisible$



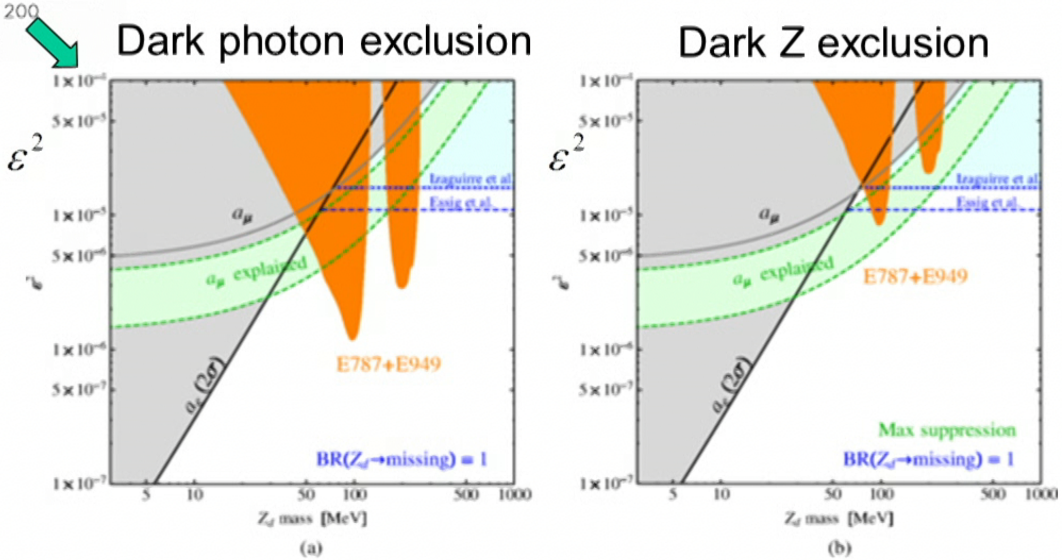
$K^+ \to \pi^+ A'$

PRD 79 (2009) 092004

$\pi^0 \to invisible$ <2.7x10^{-7}

PRD 72 (2005)

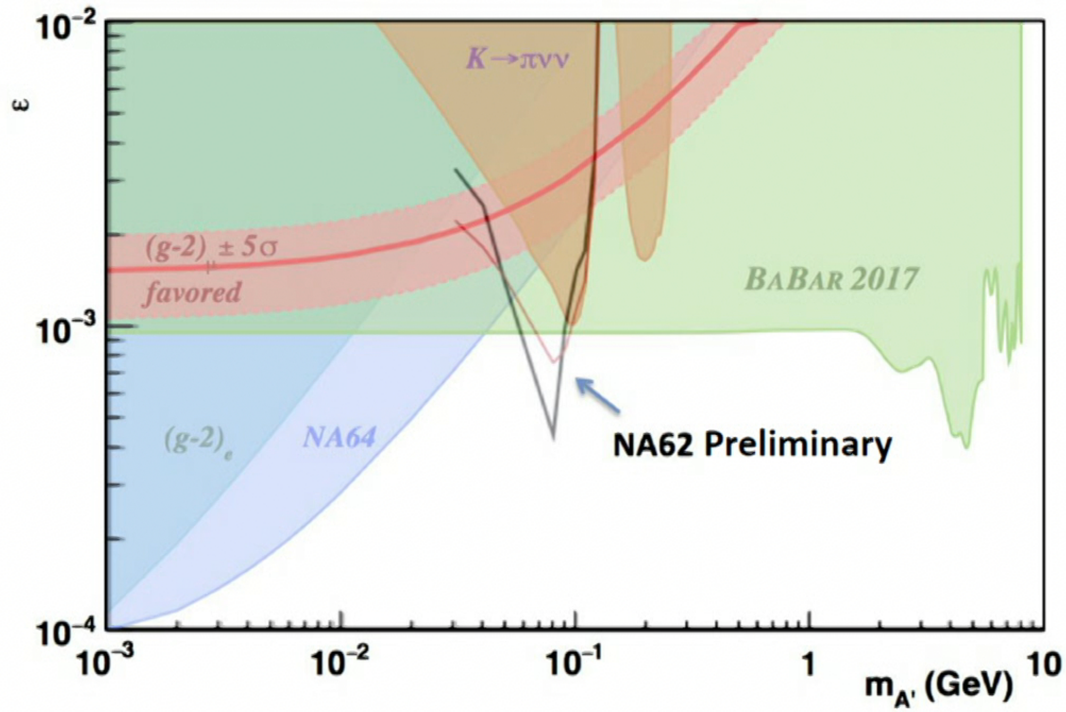
H. Davoudiasl, H. Lee, and W.J. Marciano Phys. Rev. D 89, 095006 (2014)



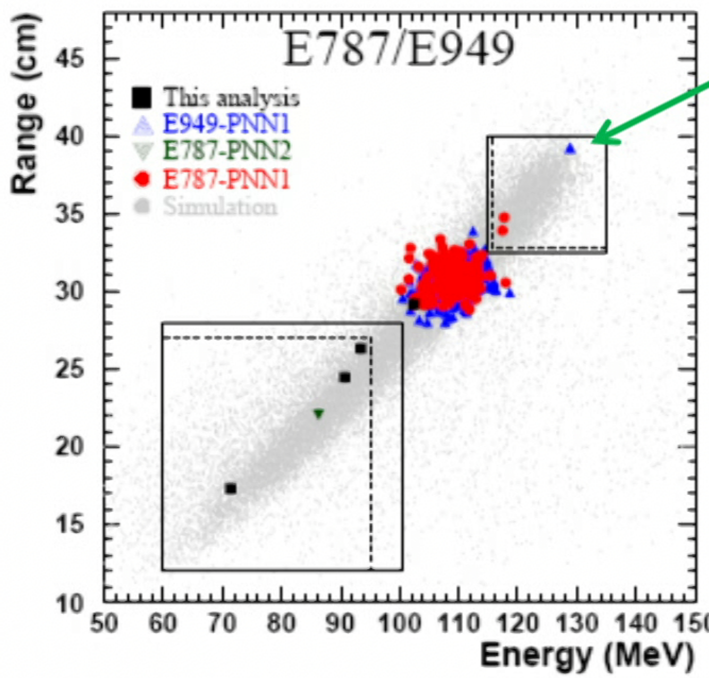
Search for invisible vector bosons

Slide

- Current experimental limits, 2016A dataset corresponding to **$1.5x10^{10}$** K^+ decays (3% of $5x10^{11}$ collected in 2016A)



E787/E949 $K^+ \to \pi^+ \nu \bar{\nu}$ Data



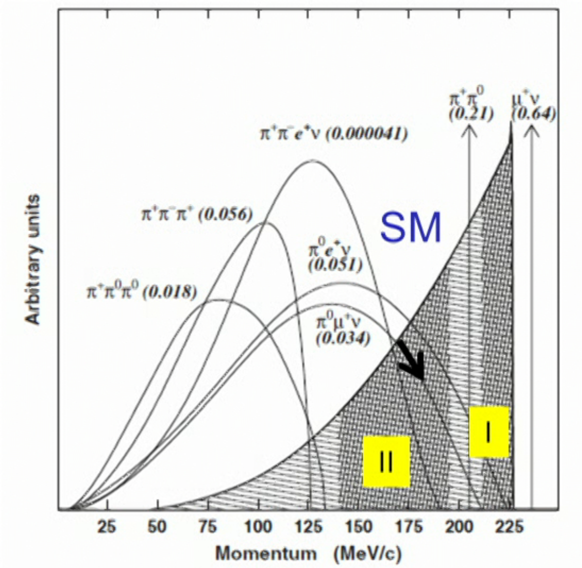
One event consistant wth $K^+ \to \pi^+ f$

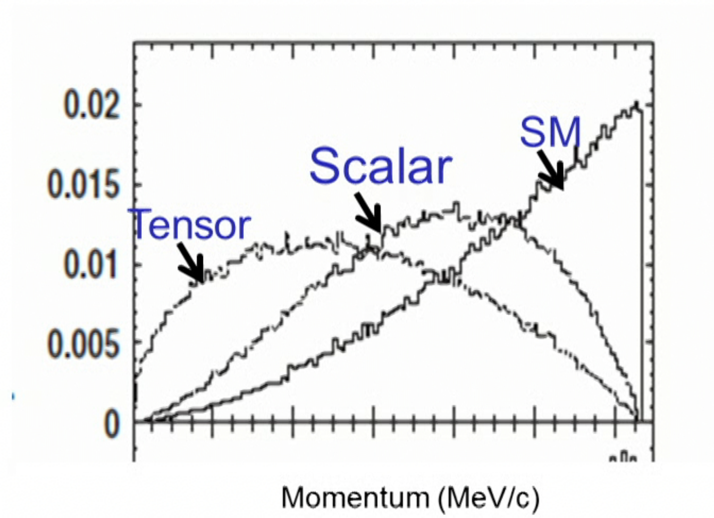
$Br(K^+ \to \pi^+ f) < 5.9x10^{-11} (90\% c.l.)$

NA62 may improve on the search for $K^+ \to \pi^+ f$ by 10x

$K^+ \to \pi^+ \nu \bar{\nu}$ Spectrum Measurement

Spectrum shape could indicate non-(V-A) interactions
e.g. scalar/tensor would shift spectrum from region I to region II

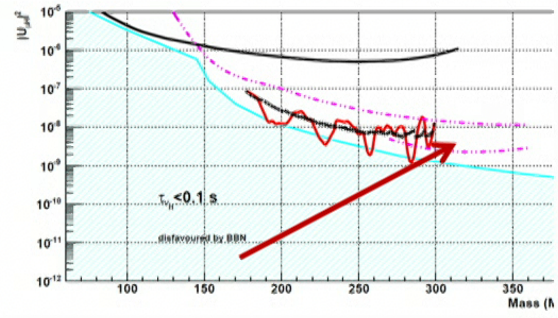


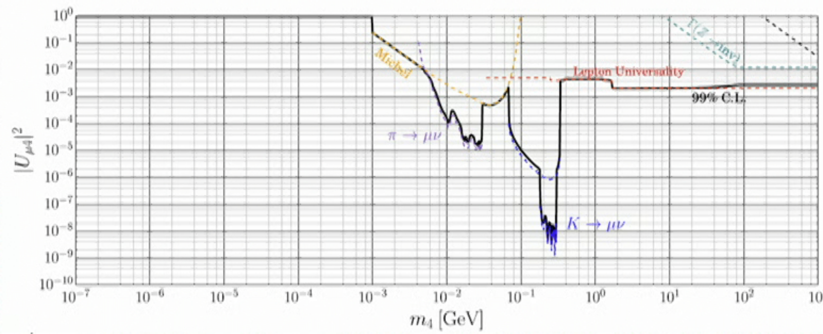


$\left|U_{\mu i}\right|^2$ vs Mass

Heavy Neutrinos Coupled to Muons

BNL E949 (2015)





De Gouvêa and Kobach, PRD93 (2016) 033005

E949 recently used the same data to search for $K^+ \to \mu^+ \nu\nu\bar{\nu}$ [SM < O(10^{-16})]

Br($K^+ \to \mu^+ \nu\nu\bar{\nu}$)< 2.4 x$10^{-6}$ **Phys.Rev. D94 (2016) no.3, 032012**

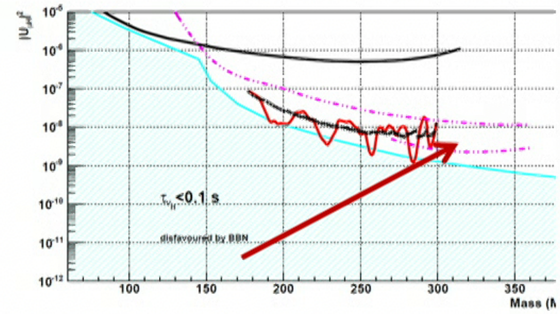
New Physics possibilities: Neutrino-neutrino interactions

Six fermion interactions

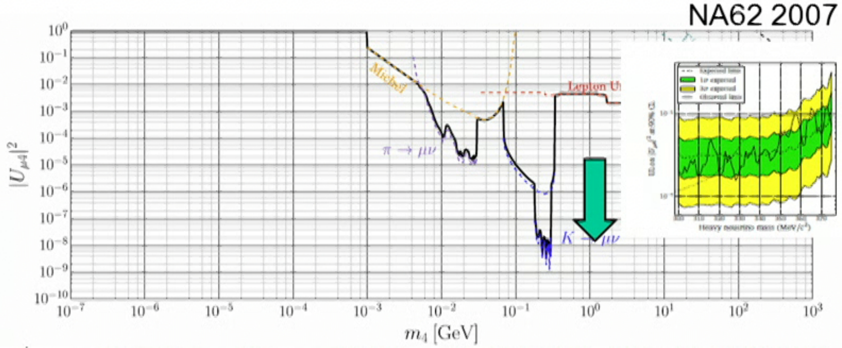
$|U_{\mu i}|^2$ vs Mass

Heavy Neutrinos Coupled to Muons

BNL E949 (2015)



NA62 2007



De Gouvêa and Kobach, PRD93 (2016) 033005

E949 recently used the same data to search for $K^+ \to \mu^+ \nu\nu\bar{\nu}$ [SM < O(10^{-16})]

Br($K^+ \to \mu^+ \nu\nu\bar{\nu}$)< 2.4 x$10^{-6}$ **Phys.Rev. D94 (2016) no.3, 032012**

New Physics possibilities: Neutrino-neutrino interactions

Six fermion interactions

Coming Soon:
NA62: 100x
improvement

Babette Döbrich (CERN)

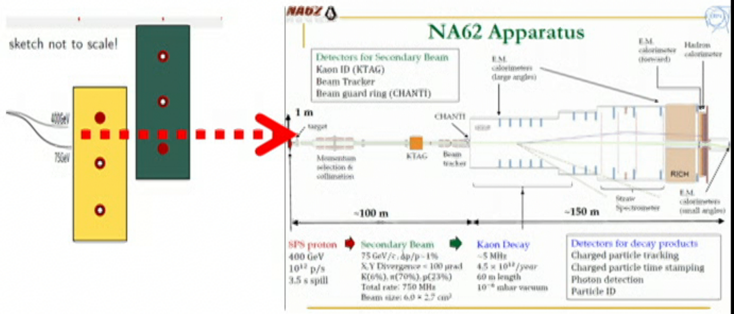
arxiv:1512.03069

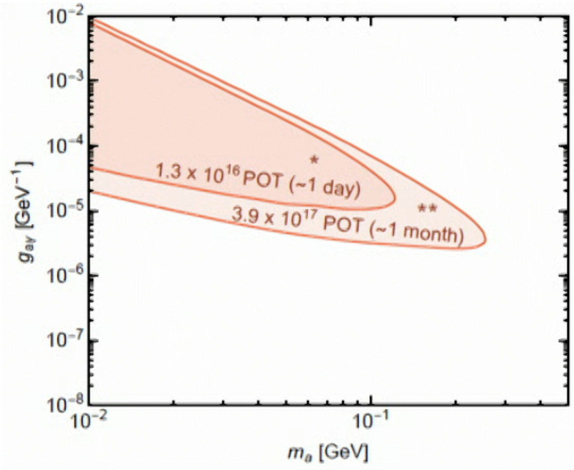
Idea to Search for axion-like particles with NA62

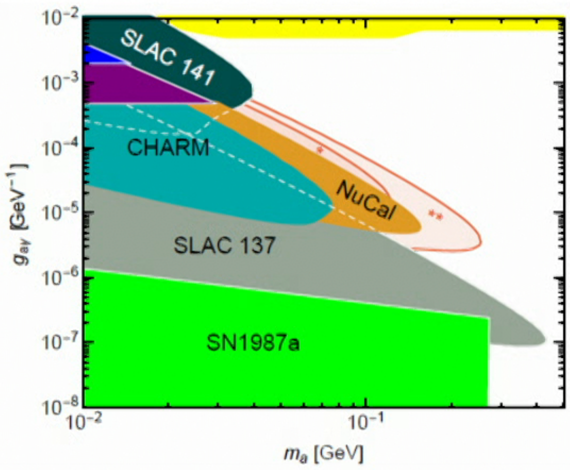
400 GeV p into closed target dump

Look for $a \to \gamma\gamma$ in LAr Calorimeter

- decay length $\gamma\beta\tau$, ALP lifetime $\Gamma = \tau^{-1} = g^2_{a\gamma} m_a^3/(64\pi)$







Flavor Vineyard Tasting Menu

3rd Course

Flavor Violation

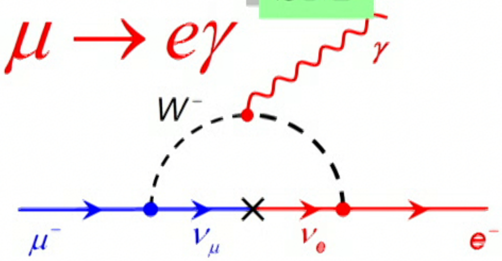
(Could be painful!)

Lepton Flavor Violation

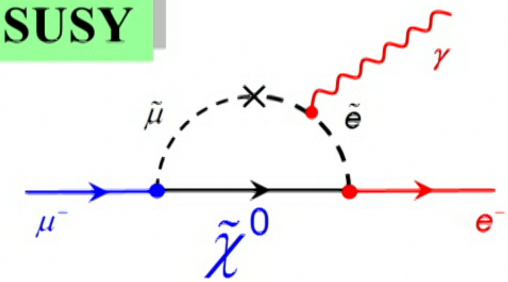
Neutrino oscillations→ lepton family numbers not conserved

SM

$\mu \rightarrow e\gamma$



SUSY



$$BR(\mu^- \rightarrow e^-\gamma)\big|_{SM} \propto \frac{m_\nu^4}{m_W^4} \approx 10^{-54}$$

Petcov '77, Marciano-Sanda '77

$$BR(\mu^- \rightarrow e^-\gamma)\big|_{SUSY} \approx 10^{-5}\,\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\bar{m}^2_{\tilde{\ell}}}\left(\frac{100\ \text{GeV}}{m_{SUSY}}\right)^4 \tan^2\beta \quad \approx 10^{-13}$$

- Observation means new physics.
- Some SUSY models predict BR(μ → eγ) near the experimental limit (always!). CLFV may also be observable at the LHC

$$\text{Sensitivity to new physics} \sim \frac{1}{M_H^4} \ \text{with } M_H \sim 1-100\ \text{TeV}$$

LFV -- Prospects

Mu2E, Comet, $\mu \to 3e$ μ rates increase by 10^3

Belle II τ rates increase by 10x

process	present limit	future	
$\mu \to e\gamma$	$<5.7 \times 10^{-13}$	$<10^{-14}$	MEG at PSI
$\mu \to eee$	$<1.0 \times 10^{-12}$	$<10^{-16}$	Mu3e at PSI
$\mu N \to eN$ (in Al)	none	10^{-14}-10^{-16}	Mu2e / COMET

Deeme

$\tau \to e\gamma$	$<1.1 \times 10^{-7}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \to eee$	$<3.6 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \to \mu\gamma$	$<4.5 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB
$\tau \to \mu\mu\mu$	$<3.2 \times 10^{-8}$	$<10^{-9}$ - 10^{-10}	superKEKB/LHCb

Model discriminating power by Measuring different processes.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)}$$

$$\frac{C_{\text{NP}}}{\Lambda^2} O_{ij}^{(6)} \rightarrow \frac{C_{\mu e}}{\Lambda^2} \overline{e}_L \sigma^{\rho\nu} \mu_R \Phi F_{\rho\nu}$$

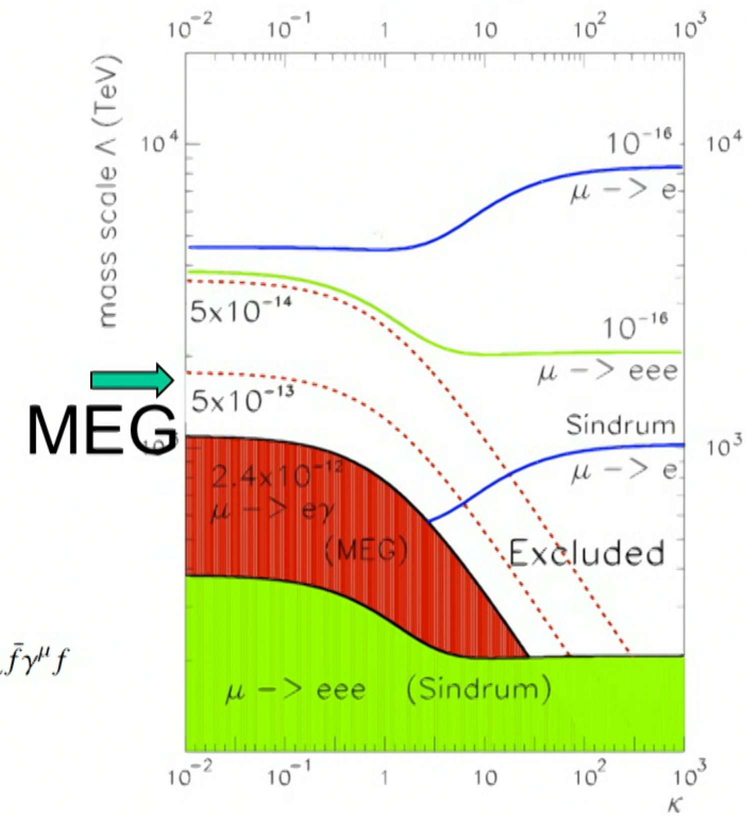
$$\Lambda > 2 \times 10^5 \,\text{TeV} \times (C_{\mu e})^{\frac{1}{2}} \,.$$

Two operators:

$$\mathcal{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2} \bar{\mu}_R \gamma_\mu e_L \bar{f} \gamma^\mu f$$

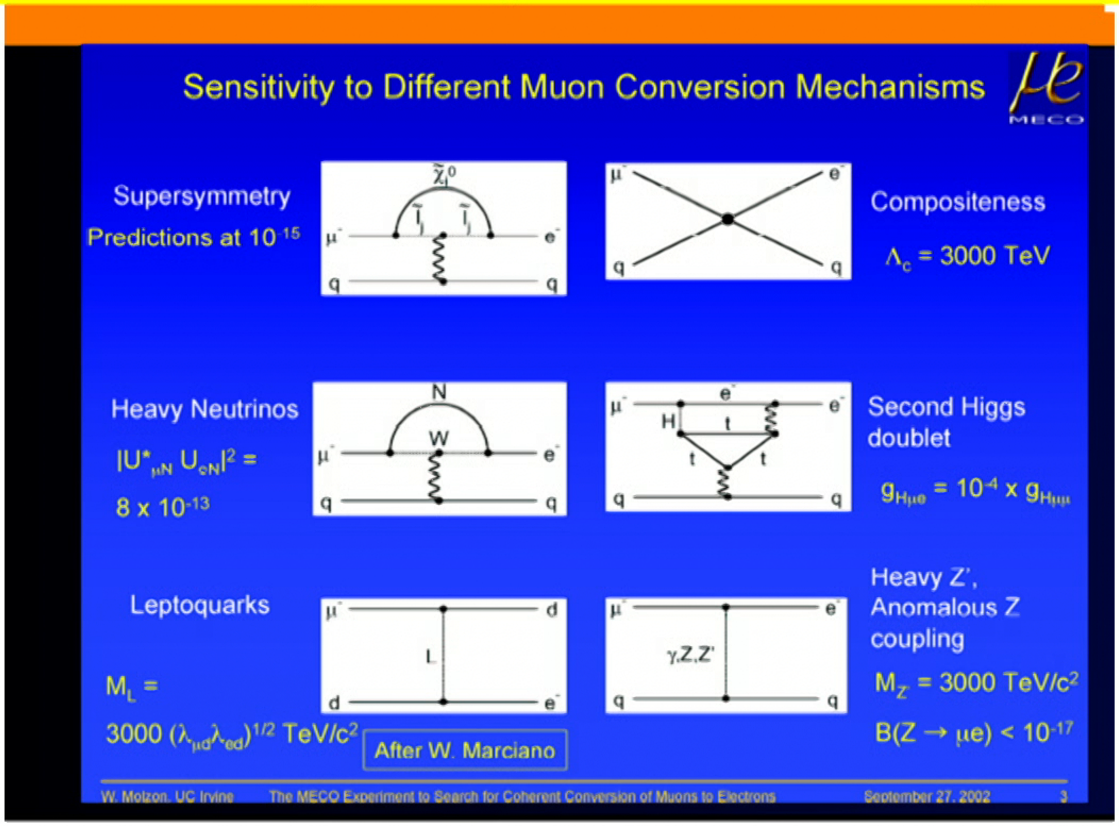
κ controls relative strength of dipole vs vector operator

De Gouvea, Vogel



There may also be important connections between models for CLFV, g-2, and neutrino mass generation e.g. via Seesaw

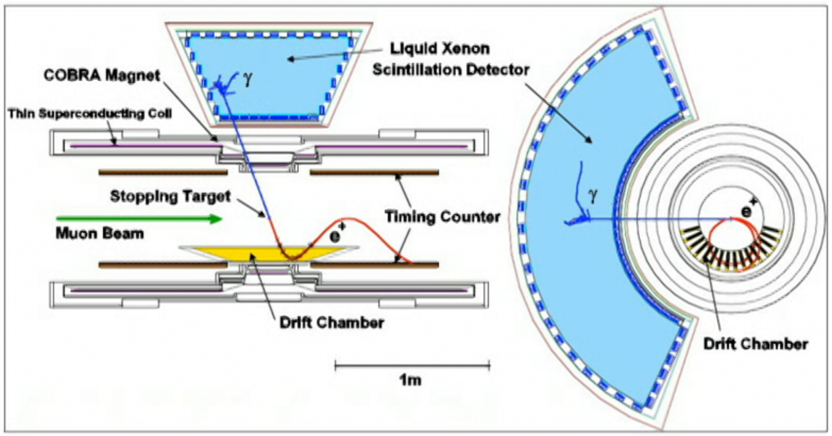
$\mu - e$ Conversion is particularly sensitive to a wide array of models



KUNO

MEG Experiment at PSI

$\mu \rightarrow e\,\gamma$



Variable	Foreseen	Obtained	Upgrade Scenario
ΔE_γ (%)	1.2	1.7	1.0
Δt_γ (ps)	43	67	≤ 67
γ position (mm)	4-6	4-6	~ 2
γ efficiency (%)	> 40	63	70
ΔP_e (keV)	200	306	≤ 130
e^+ angle (mrad)	$5(\varphi), 5(\theta)$	$8.7(\varphi), 9.4(\theta)$	$\leq 4(\varphi), \leq 5(\theta)$
Δt_{e^+} (ps)	50	107	30
e^+ efficiency (%)	90	40	≥ 85
$\Delta t_{e\gamma}$ (ps)	65	122	80

- 3×10^7 μ/sec, 100% duty factor
- LXe for efficient γ detection
- Solenoidal magnetic spectrometer

- Proposal (1999): goal $<2\times10^{-14}$
- 2016 Result*: $<4.2\times10^{-13}$
- New goal (~2020): $<6\times10^{-14}$

*Baldini A. et al, et al., Eur. Phys. J. C (2016) 76.

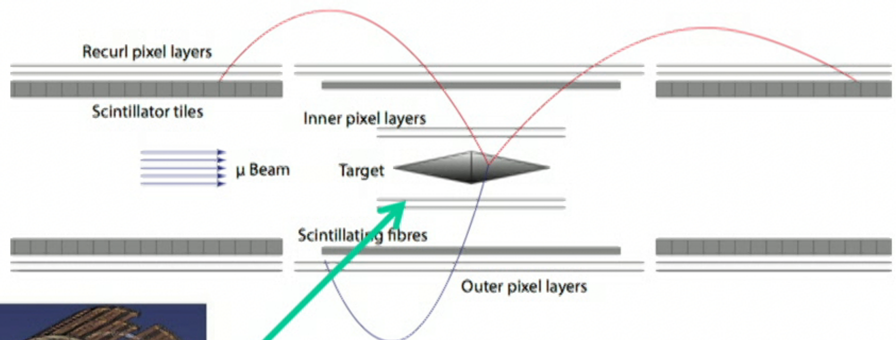
S. Ritt

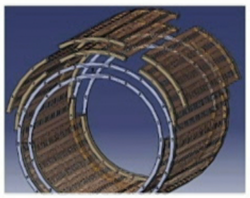
Niklaus Berger

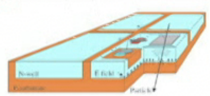
$\mu \rightarrow 3e$ at PSI: Goal $<10^{-16}$

Mu3e proposal

- Phase I uses MEG beamline to provide ~ 10^8 μ^+/s to get to 10^{-15}
- Phase II assumes construction of new high intensity beam at PSI spallation neutron source to reach 10^{-16}



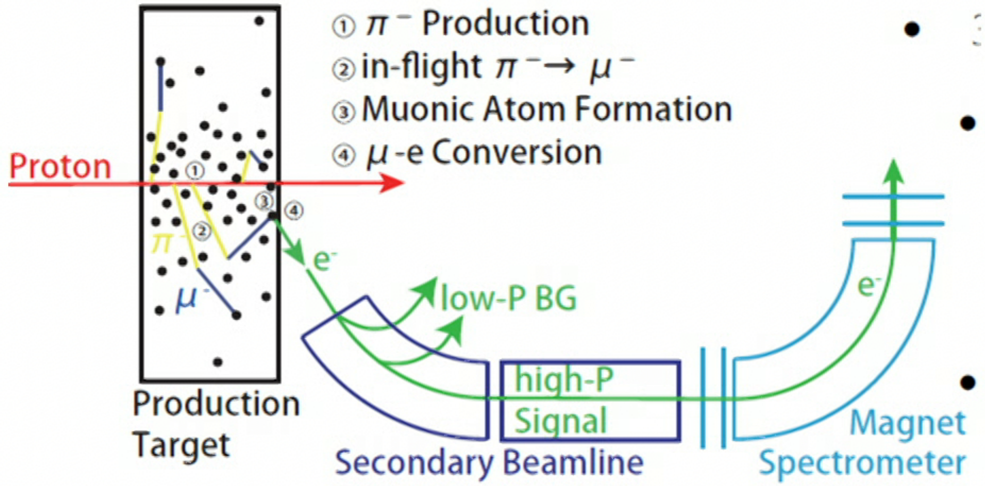




50μm Monolithic active pixel (MAP) detectors

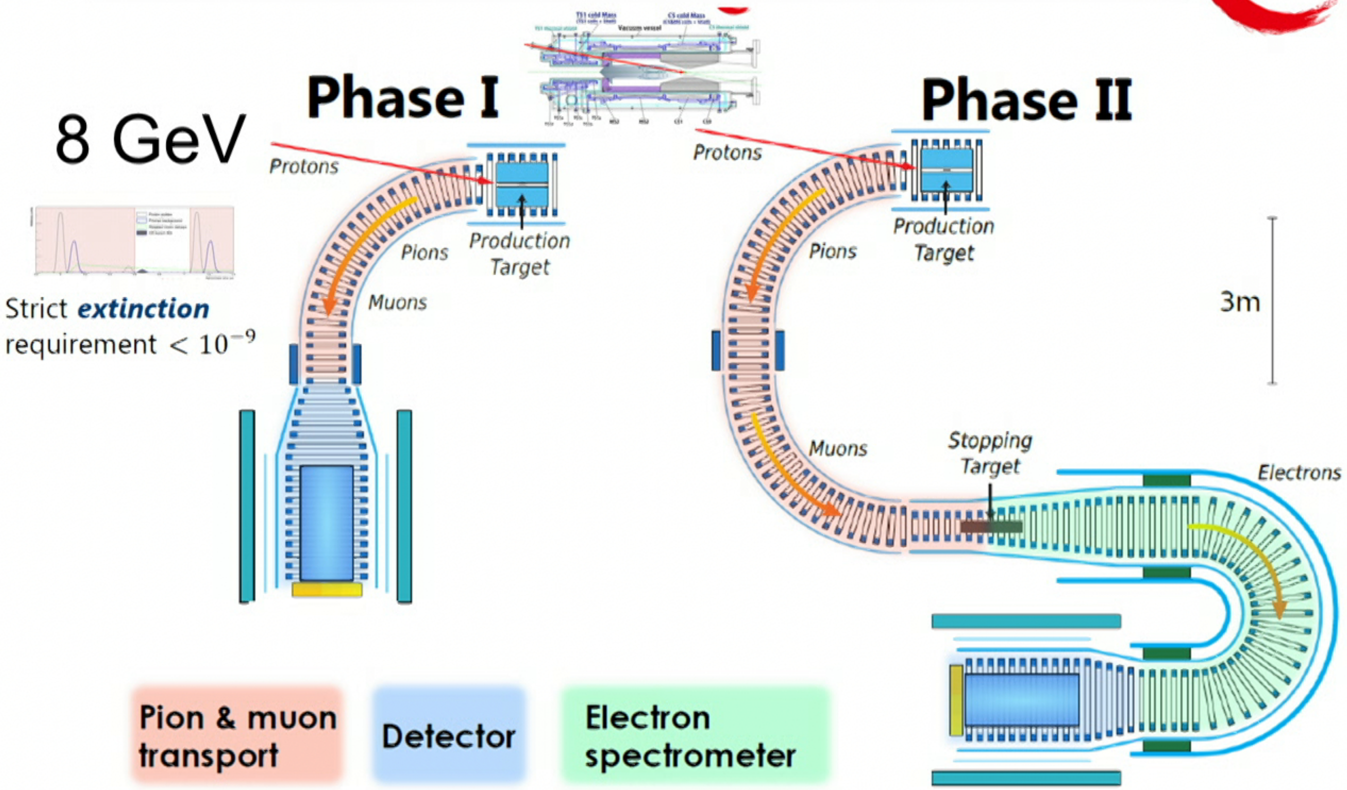
DeeMe

JPARC RCS
Aoki et al.



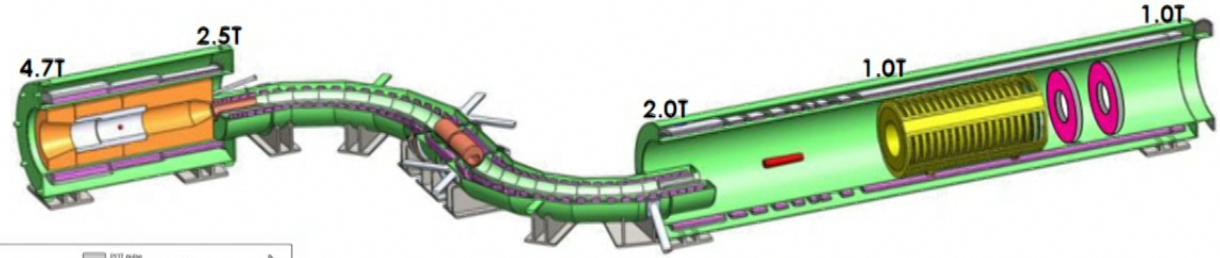
$\mu - e$ 1 year S.E.S.
1.2×10^{-13} [Carbon target]
2.1×10^{-14} [SiC target]

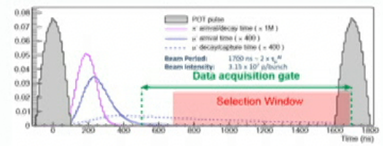
COMET, Phase I and II



Fermilab

Mu2e: Overview

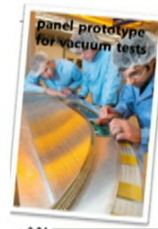




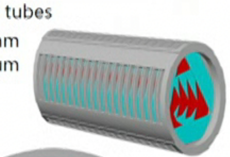
6.8×10^{17} stopped muons.

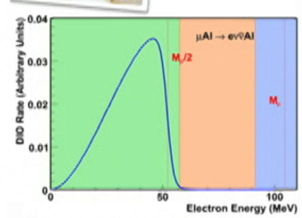
Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	0.001 ± <0.001
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.092 ± 0.020
	Total	0.37 ± 0.10

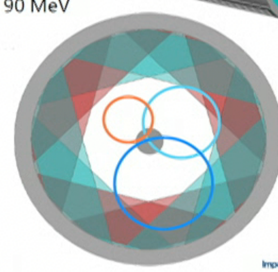
Mu2e Tracker



- Tracker made from straw tubes
- Minimum radius of 380mm corresponds to momentum of ~ 60MeV
- 'Complete' tracks need momentum > 90 MeV







Imperial College

Fermilab

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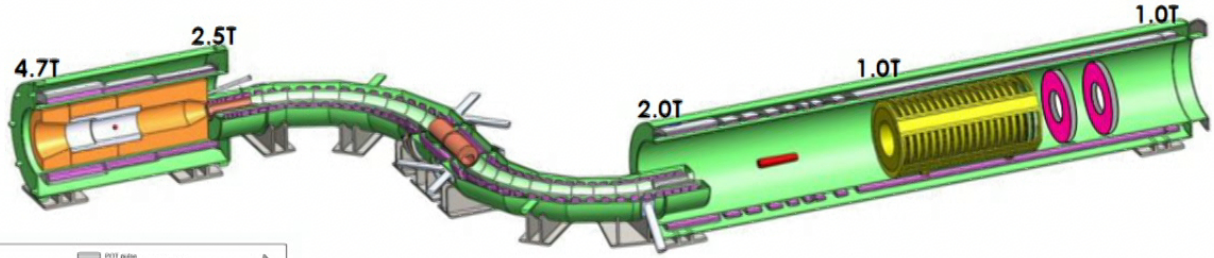

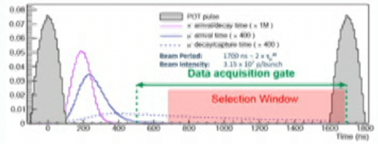

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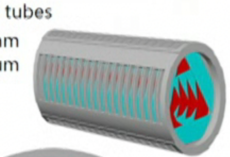

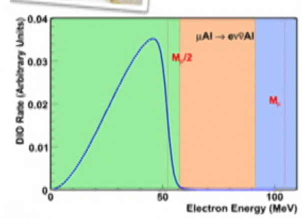

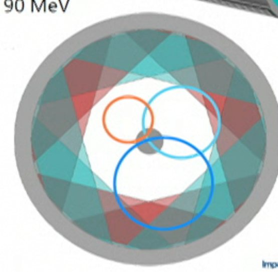

Imperial College

Flavor Vineyard Tasting Menu

(Sweet Stuff !)

Coffee/Dessert/Discussion

- **Rare μ, π and K decays have unique and important roles to play in the search for new physics including exotic effects like *Flavor Universality and Lepton Flavor Violations* --- unique sensitivity to very high mass scales**

- **New π/K/B results soon from PIENU,PEN and NA62, LHCb**

- **Significant prospects for currently developing and running rare decay experiments involving muons, pions (π^0), and kaons – NA62, KOTO, MEG, DeeMe, COMET, Mu2E, Mu3E, …and B decays: Belle II, LHCb, ATLAS/CMS….**