Neutron Lifetime & CKM Unitarity: The Standard Model & Beyond

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Outline

I. CKM unitarity: the NP & BSM context
II. CKM unitarity: status
III. CKM unitarity: BSM implications
IV. Summary

I. NP & BSM Context

Fundamental symmetries and neutrinos in NP in light of the LHC

Scientific Questions

2007 NSAC LRP:

- What are the masses of neutrinos and how have they shaped the evolution of the universe?
- Why is there more matter than antimatter in the present universe?
- What are the unseen forces that disappeared from view as the universe cooled?

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Four Components **

EDM searches: BSM CPV, Origin of Matter	<i>0vββ decay searches:</i> Nature of neutrino, Lepton number violation, Origin of Matter
Electron & muon prop's &	Radioactive decays & other
interactions:	tests
SM Precision Tests, BSM	SM Precision Tests, BSM
"diagnostic" probes	"diagnostic" probes

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The BSM Context: NP & the LHC

What are the BSM interactions and what is the associated mass scale?

♦ Are fundamental interactions "natural" ?



Scalar fields are a simple

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Scalar fields are theoretically problematic



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$$H^{0} \qquad \qquad \Delta m^{2} \sim \lambda \Lambda^{2}$$

Discovery of a (probably) fundamental 125 GeV scalar :

Is it telling us anything about Λ ? Naturalness?

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Discovery of a (probably) fundamental 125 GeV scalar :

 $m_h^2 \sim \lambda v^2 \& G_F \sim 1/v^2$: what keeps G_F "large"?

LHC Implications

- Weak scale BSM physics (e.g., SUSY) is there but challenging for the hadronic collider
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Opportunity for precision tests: weak decays





Pair production of squarks





$$\begin{split} \tilde{q} &\to q + \tilde{\chi}_1^0 \\ \tilde{q} &\to q' + \tilde{\chi}^{\pm} \to \ell + \nu + q' + \tilde{\chi}_1^0 \end{split}$$

Final state:
$$2j + E_T$$
, $2j + \ell + E_T$

No exclusion yet (jets analysis): is sub-TeV SUSY hiding here?

If so, will it show up in precision tests ?





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CMS: SUS-13-012-pas





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Opportunity for SM-suppressed processes: EDMs...

Probing Heavy Scale: EDMs & Precision Tests

BSM Signal ~
$$(v/\Lambda)^2$$



LHC (lack of) Indications ?

ATLAS Exotics Searches* - 95% CL Exclusion						ATL			
00	1011L1 2014						$\int \mathcal{L} dt = (1.0 - 20.3) \text{fb}^{-1}$	$\sqrt{s} = 7, 8$ lev	
	Model	ℓ,γ	Jets	ET	∫£dt[fb	⁻¹] Mass limit		Reference	
Extra dimensions	$\begin{array}{l} \text{ADD } G_{\text{KK}} + g/q \\ \text{ADD non-resonant } \ell\ell \\ \text{ADD odd } \rightarrow \ell q \\ \text{ADD odd } \rightarrow \ell q \\ \text{ADD Odd } A$	$- 2e, \mu$ 1 e, μ - 2 μ (SS) ≥ 1 e, μ 2 e, μ 2 e, μ 2 e, μ - 1 e, μ 2 γ	1-2j - 1j 2j - 2j/1J 4b ≥ 1b,≥ 1J -	Yes - - - Yes - Yes - Yes - Yes Yes	4.7 20.3 20.3 20.3 20.3 20.3 20.3 20.3 4.7 20.3 19.5 14.3 5.0 4.8	Mo 4.37 TeV Ma 5.2 TeV Gase mass 2.68 TeV Gase mass 1.23 TeV Gase mass 590-710 GeV Gase mass 590-710 GeV Gase mass 2.0 TeV Mass R ⁻¹ 4.71 TeV <td>$\begin{array}{l} n-2 \\ n-3\text{HzZ} \\ n-6 \\ n-6, M_D-1.5\text{TeV}, \text{non-rot BH} \\ n-6, M_D-1.5\text{TeV}, \text{non-rot BH} \\ k/M_{PT}-0.1 \\ k/M_{PT}-0.1 \\ k/M_{PT}-0.1 \\ k/M_{PT}-1.0 \\ k/M_{PT}-1.0 \\ BR=0.925 \end{array}$</td> <td>1210.4491 ATLAS-CONF-2014-030 1311.2006 to be submitted to PRD 1308.4075 1406.4254 1406.4254 1406.4123 1208.2880 ATLAS-CONF-2014-005 ATLAS-CONF-2013-052 1209.2555 ATLAS-CONF-2013-052</td>	$\begin{array}{l} n-2 \\ n-3\text{HzZ} \\ n-6 \\ n-6, M_D-1.5\text{TeV}, \text{non-rot BH} \\ n-6, M_D-1.5\text{TeV}, \text{non-rot BH} \\ k/M_{PT}-0.1 \\ k/M_{PT}-0.1 \\ k/M_{PT}-0.1 \\ k/M_{PT}-1.0 \\ k/M_{PT}-1.0 \\ BR=0.925 \end{array}$	1210.4491 ATLAS-CONF-2014-030 1311.2006 to be submitted to PRD 1308.4075 1406.4254 1406.4254 1406.4123 1208.2880 ATLAS-CONF-2014-005 ATLAS-CONF-2013-052 1209.2555 ATLAS-CONF-2013-052	
Gauge bosons	$\begin{array}{l} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{SSM} W' \to \ell\nu \\ \operatorname{EGM} W' \to WZ \to \ell\nu \ell'\ell' \\ \operatorname{EGM} W' \to WZ \to qq\ell\ell \\ \operatorname{LRSM} W_R^{\prime} \to t\overline{b} \\ \operatorname{LRSM} W_R \to t\overline{b} \end{array}$	2 e, μ 2 τ 1 e, μ 3 e, μ 2 e, μ 1 e, μ 0 e, μ	- - 2j/1J 2b,0-1j ≥1b,1J	- Yes Yes - Yes J -	20.3 19.5 20.3 20.3 20.3 14.3 20.3	Z' mass 2.0 TeV Z' mass 1.9 TeV W' mass 3.28 TeV W' mass 1.52 TeV W' mass 1.59 TeV W' mass 1.50 TeV W' mass 1.50 TeV W' mass 1.51 TeV W' mass 1.64 TeV		1405.4123 ATLAS-CONF-2013-066 ATLAS-CONF-2014-017 1406.4456 ATLAS-CONF-2014-039 ATLAS-CONF-2013-050 to be submitted to EPJC	
C	CI qqqq CI qqℓℓ CI uutt	 2 е, µ 2 е, µ (SS	2j)≥1 b,≥1	- - j Yes	4.8 20.3 14.3	Λ 7.8 Tel Λ Λ 3.3 TeV	7 η = +1 21.8 ΤθV ημ = -1 C = 1	1210.1718 ATLAS-CONF-2014-030 ATLAS-CONF-2013-051	
мa	EFT D5 operator (Dirac) EFT D9 operator (Dirac)	0 e, μ 0 e, μ	1-2j 1 J,≤1j	Yes Yes	10.5 20.3	M, 731 GeV M, 2.4 TeV	at 90% CL for $m(\chi) < 80$ GeV at 90% CL for $m(\chi) < 100$ GeV	ATLAS-CONF-2012-147 1309.4017	
ΓO	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e,μ,1 τ	≥2j ≥2j 10,1j	-	1.0 1.0 4.7	LQ mass 860 GeV LQ mass 885 GeV LQ mass 534 GeV	$\begin{array}{c} \beta = 1 \\ \beta = 1 \\ \beta = 1 \end{array}$	1112.4828 1203.3172 1303.0526	
Heavy quarks	Vector-like quark $TT \rightarrow Ht + X$ Vector-like quark $TT \rightarrow Wb + X$ Vector-like quark $TT \rightarrow Zt + X$ Vector-like quark $BB \rightarrow Zb + X$ Vector-like quark $BB \rightarrow Wt + X$	1 e,µ 1 e,µ 2/≥3 e,µ 2/≥3 e,µ 2 e,µ (SS	≥ 2 b, ≥ 4 ≥ 1 b, ≥ 3 ≥2/≥1 b ≥2/≥1 b ≥2/≥1 b	j Yes j Yes – – j Yes	14.3 14.3 20.3 20.3 14.3	T mass 790 GeV T mass 670 GeV T mass 735 GeV B mass 755 GeV B mass 720 GeV	T in (T,B) doublet iscepin singlet T in (T,B) doublet B in (B,Y) doublet B in (T,B) doublet	ATLAS-CONF-2013-018 ATLAS-CONF-2013-060 ATLAS-CONF-2014-036 ATLAS-CONF-2014-036 ATLAS-CONF-2013-051	
Excited fermions	Excited quark $q^* \rightarrow q\gamma$ Excited quark $q^* \rightarrow qg$ Excited quark $b^* \rightarrow Wt$ Excited lepton $\ell^* \rightarrow \ell\gamma$	1 γ - 1 or 2 e, μ 2 e, μ, 1 γ	1 j 2 j 1 b, 2 j or 1	– – IjYes –	20.3 20.3 4.7 13.0	te* mass 3.5 TeV q* mass 4,09 TeV b* mass 870 GeV I* mass 2.2 TeV	only u* and d*, $\Lambda - m(q^*)$ only u* and d*, $\Lambda - m(q^*)$ left-handed coupling $\Lambda - 2.2$ TeV	1309.3230 to be submitted to PRD 1301.1583 1308.1364	
Other	LSTC $a_T \rightarrow W\gamma$ LRSM Majorana ν Type III Seesaw Higgs triplet $H^{++} \rightarrow \ell\ell$ Mutti-charged particles Magnetic monopoles	1 e, μ, 1 γ 2 e, μ 2 e, μ 2 e, μ 2 e, μ (SS -	- 2j) - - - -	Yes - - - -	20.3 2.1 5.8 4.7 4.4 2.0	By mass D80 GeV N ⁰ mass 1.5 TeV H** mass 245 GeV H** mass 409 GeV multi-barged particle mass 409 GeV monopole mass 862 GeV	$m(W_R) - 2$ TeV, no mixing $ V_e =0.055$, $ V_p =0.063$, $ V_r =0$ DY production, $BR H^{++} \rightarrow \ell\ell_r^2 = 1$ DY production, $ q = 4a$ DY production, $ q = 1g_O$	to be submitted to PLB 1203.5420 ATLAS-CONF-2013-019 1210.5070 1301.5272 1207.6411	
¹⁰ Mass scale [TeV]									

LHC Implications

- Weak scale BSM physics (e.g., SUSY) is there but challenging for the hadronic collider
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- We are thinking about the problem incorrectly (cosmological constant???)

Naturalness is a misleading guide & there may be new ultralight degrees of freedom: Intensity frontier

New Light States ?

- "Dark" gauge bosons
- *Macroscopic (spin-dependent) forces*





The BSM Context: NP & the LHC

What are the BSM interactions and what is the associated mass scale?

♦ Are fundamental interactions "natural" ?

Weak decays provide an invaluable window into possible answers

II. CKM Unitarity: Status

Weak Decays: CKM Unitarity



Includes theory error

CKM Unitarity & V_{ud}

$$\begin{aligned}
d \to u \ e^{-} \ \overline{v}_{e} \\
s \to u \ e^{-} \ \overline{v}_{e} \\
b \to u \ e^{-} \ \overline{v}_{e}
\end{aligned}$$

$$\begin{pmatrix}
u \ c \ t
\end{pmatrix} \begin{pmatrix}
V_{ud} \ V_{us} \ V_{ub} \\
V_{cd} \ V_{cs} \ V_{cb} \\
V_{td} \ V_{ts} \ V_{tb}
\end{pmatrix} \begin{pmatrix}
d \\
s \\
b
\end{pmatrix}$$

$$\begin{aligned}
\beta - decay \\
n \to p \ e^{-} \ \overline{v}_{e} \\
A(Z,N) \to A(Z-1,N+1) \ e^{+} \ v_{e} \\
\pi^{+} \to \pi^{0} \ e^{+} \ v_{e}
\end{aligned}$$

$$\begin{aligned}
\frac{G_{F}^{\beta}}{G_{F}^{\mu}} = |V_{ud}| \left(1 + \Delta r_{\beta} - \Delta r_{\mu}\right)
\end{aligned}$$

Latest Results from UCNA

$A_0 = 0.11972(55)_{stat}(98)_{syst}$

Mendenhall, et al Phys. Rev. C **87**, 032501 (2013)







Thanks: B. Filippone



Two approaches:

K_{I3} decays:

$$d\Gamma(K_{\ell 3}^{+}) = \frac{G_{\mu}^{2} m_{K}^{5}}{128\pi^{3}} S_{\rm EW} C(t) |V_{us}|^{2} |f_{+}^{K}(0)|^{2} \left[1 + \frac{\lambda_{+}^{K} t}{m_{\pi}^{2}}\right]^{2} \left[1 + 2\Delta_{SU(2)}^{K} + 2\Delta_{EM}^{K\ell}\right]$$

K₁₂ decays:

$$|V_{ud}|^2 + |V_{us}|^2 = |V_{ud}|^2 \left[1 + \frac{|V_{us}|^2}{|V_{ud}|^2}\right]$$

$$\frac{\Gamma_{K_{\ell 2}}}{\Gamma_{\pi_{\ell 2}}} = \frac{|V_{us}|^2}{|V_{ud}|^2} \frac{f_K^2}{f_\pi^2} \frac{m_K (1 - m_\ell^2 / m_K^2)^2}{m_\pi (1 - m_\ell^2 / m_\pi^2)^2} \left(1 + \delta_{\rm EM}\right)$$

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 χPT

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Two approaches:

K_{I3} decays:





 $f_K/f_{\pi} = 1.198(2)_{\text{stat}} \begin{pmatrix} +6\\ -8 \end{pmatrix}_{\text{syst}} = 1.197(7),$



 $f_+(0) = 0.959(5),$

$$|V_{us}/V_{ud}| \times f_K/f_{\pi} = 0.2758(5).$$

 $|V_{us}|f_+(0) = 0.2163(5),$

CKM Unitarity



III. CKM Unitarity: BSM Implications

$$d \rightarrow u \ e^{-} \ \overline{v}_{e}$$
$$s \rightarrow u \ e^{-} \ \overline{v}_{e}$$
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$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$\frac{G_F^{\beta}}{G_F^{\mu}} = |V_{ud}| \left(1 + \Delta r_{\beta} - \Delta r_{\mu}\right)$$
BSM physics



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Next generation: ~ 10⁻⁴ *precision*

Pion Leptonic Decay

$$R_{e/\mu} = \frac{\Gamma[\pi^- \to e^- \bar{\mathbf{v}}_e(\gamma)]}{\Gamma[\pi^- \to \mu^- \bar{\mathbf{v}}_\mu(\gamma)]} = \frac{m_e^2}{m_\mu^2} \left[\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2} \right]^2 \left\{ 1 + \frac{\alpha}{\pi} \left[F(\frac{m_e}{m_\pi}) - F(\frac{m_\mu}{m_\pi}) + C_{QCD}^{e-\mu}(\mu) \right] + \Delta_{NEW}^{e-\mu} \right\}$$

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SUSY: RPV or loops R-M, Su, Tulin



Probing Slepton Universality



π_{ℓ^2} & β Decay: Diagnostic Tool



Bauman, Erler, R-M

π_{ℓ^2} & β Decay: Diagnostic Tool



Bauman, Erler, R-M

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π_{ℓ^2} & β Decay: Diagnostic





π_{ℓ^2} & β Decay: Diagnostic





Bauman, Erler, R-M









Pair production of squarks





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Pair production of squarks





CKM Unitarity Tests









Pair production of squarks



CKM Unitarity Tests







Effective Operators

 \diamond What if $\Lambda_{BSM} >> E_{LHC}$?

Effective Operators

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left[\left(1 + \delta_\beta \right) \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_L \, \bar{e} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d + \tilde{\epsilon}_L \, \bar{e} \gamma_\mu (1 + \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_R \, \bar{e} \gamma_\mu (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma^\mu (1 + \gamma_5) d \right. \\ \left. + \left. \epsilon_S \, \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} d \right. \\ \left. + \left. \epsilon_S \, \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \right. \\ \left. - \left. \epsilon_P \, \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \gamma_5 d \right. \\ \left. - \left. \epsilon_P \, \bar{e} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma_{\mu\nu} (1 - \gamma_5) \nu_\ell \cdot \bar{u} \sigma^{\mu\nu} (1 - \gamma_5) d \right. \\ \left. + \left. \epsilon_T \bar{e} \sigma$$

$$\varepsilon \sim C (V/\Lambda)^2$$

Effective Operators: LHC & Weak Decays



V. Cirigliano et al, 1303.6953

Effective Operators: LHC & Weak Decays



V. Cirigliano et al, 1303.6953

Worldwide Radioactivity

$$d \rightarrow u e^{-} \overline{v}_{e}$$
$$s \rightarrow u e^{-} \overline{v}_{e}$$
$$b \rightarrow u e^{-} \overline{v}_{e}$$

$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



Summary

- Precision tests of weak decays can provide unique and powerful diagnostic probes of BSM physics, complementing what we may learn from the energy frontier
- Tests of CKM unitarity and lepton universality with ~ 10⁻⁴ precision could uncover "footprints" of BSM interactions that so far have evaded the LHC and address key open questions at the NP/HEP interface
- Achieving a robust value of the neutron lifetime with $\delta \tau_n < 1s$ is an essential step in this program