Neutron Lifetime & CKM Unitarity: The Standard Model & Beyond

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U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

ACFI Neutron Lifetime Workshop, September 2014

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*	*$0\nu\beta\beta$ decay searches:* *Nature of neutrino, Lepton number violation, Origin of Matter*
Electron & muon prop's & interactions: *SM Precision Tests, BSM "diagnostic" probes*	*Radioactive decays & other tests* *SM Precision Tests, BSM "diagnostic" probes*

*** 2012 NSAC Subcommittee Report*

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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 in Particle Physics

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Scalar fields are a simple

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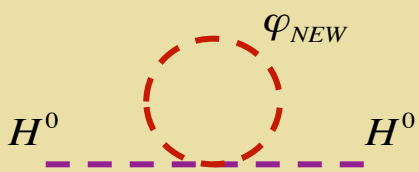
Scalar fields are theoretically problematic



$\Delta m^2 \sim \lambda \Lambda^2$

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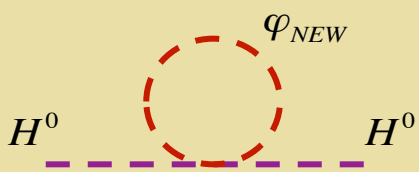

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Discovery of a (probably) fundamental 125 GeV scalar :

Is it telling us anything about Λ ? Naturalness?

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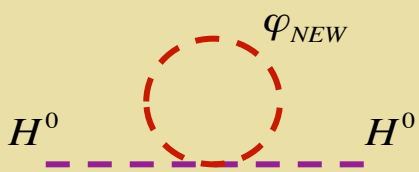

$\Delta m^2 \sim \lambda \Lambda^2$

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*
- *SUSY is there but a bit heavy (some fine tuning)*
- *We are thinking about the problem incorrectly (cosmological constant???)*

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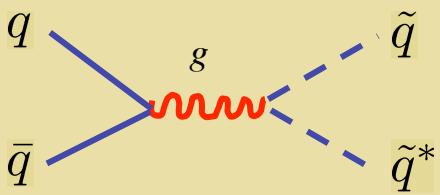
Opportunity for precision tests: weak decays

LHC BSM Challenge: Light but Compressed ?

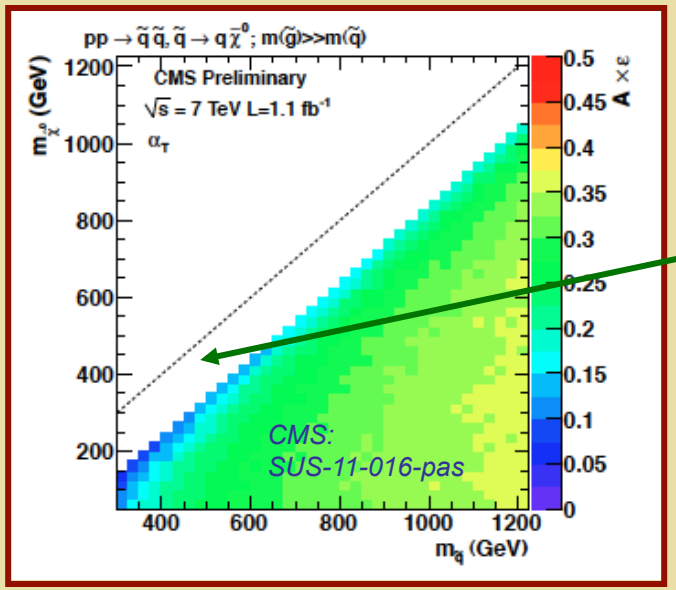
Pair production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$

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

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$



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If so, will it show up in precision tests ?

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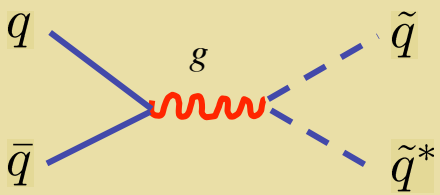

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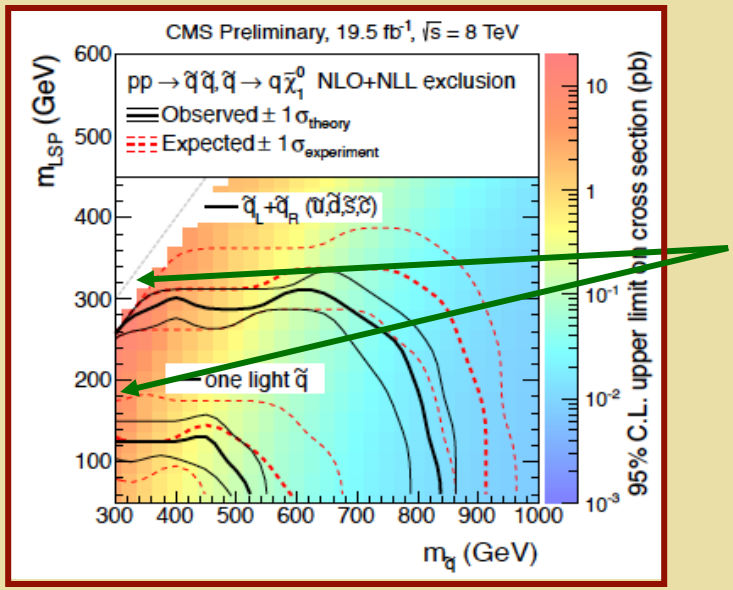

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CMS: SUS-13-012-pas

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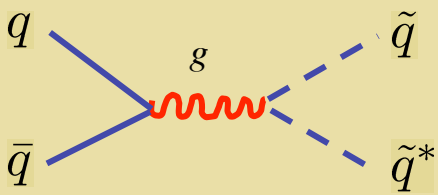

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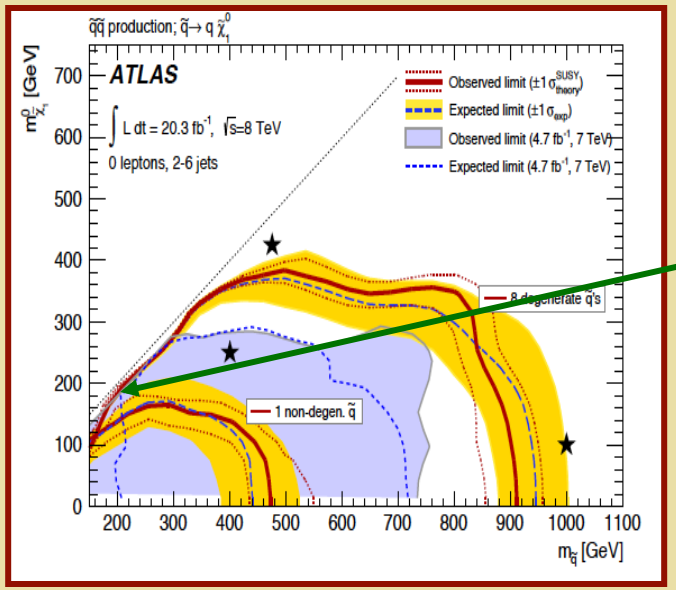

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ATLAS: 1405.7875

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Opportunity for SM-suppressed processes: EDMs…

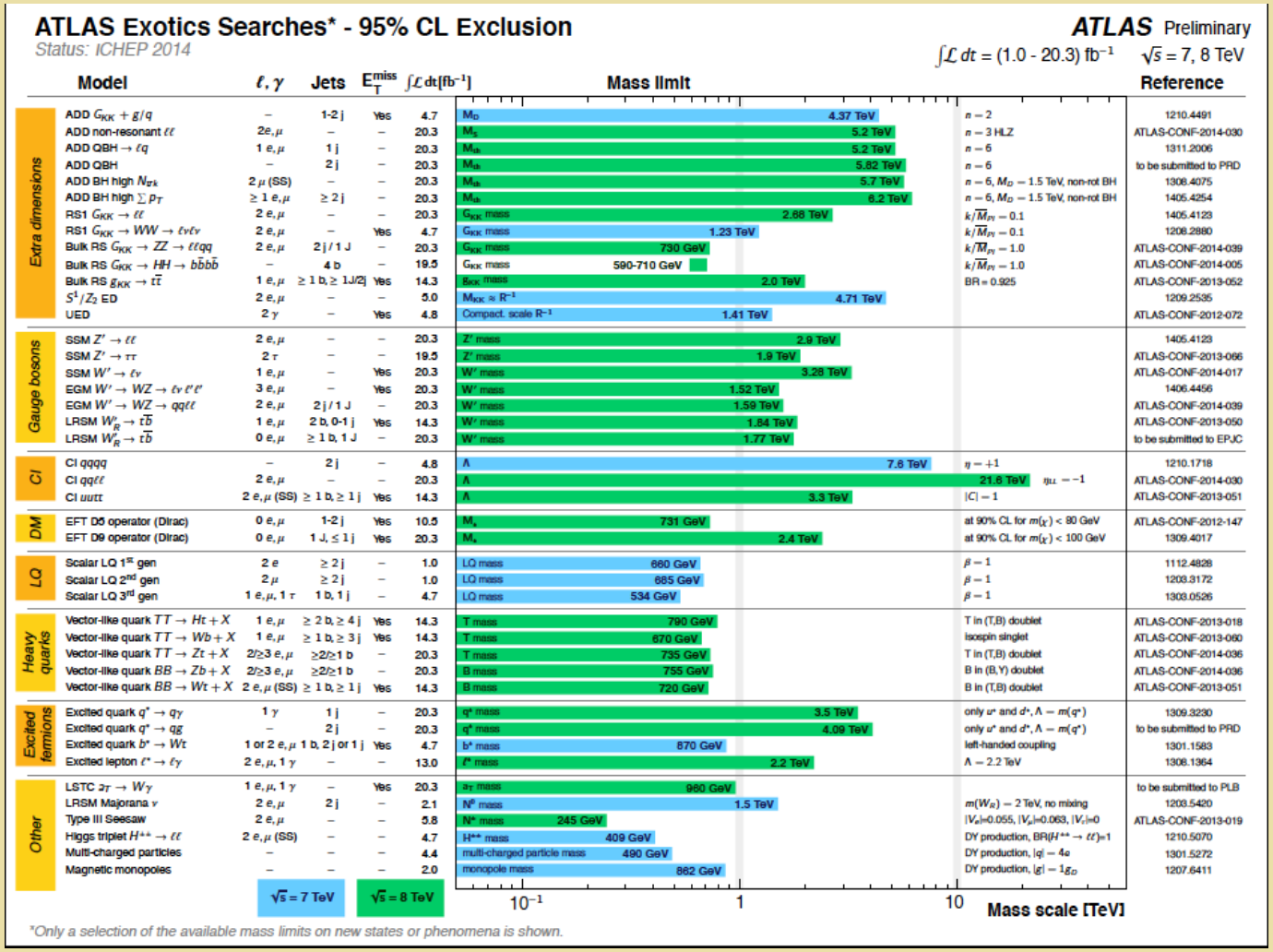
Probing Heavy Scale: EDMs & Precision Tests

BSM Signal $\sim (\upsilon / \Lambda)^2$

BSM Probe :

θ_{QCD} & *BSM CPV*	*EDM*
BSM "diagnostic"	*Weak Decays*

LHC (lack of) Indications ?



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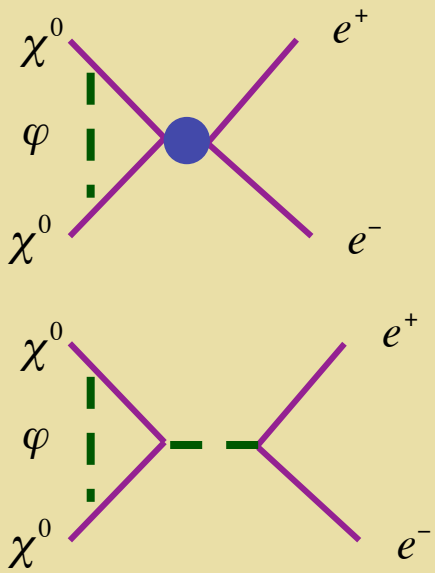
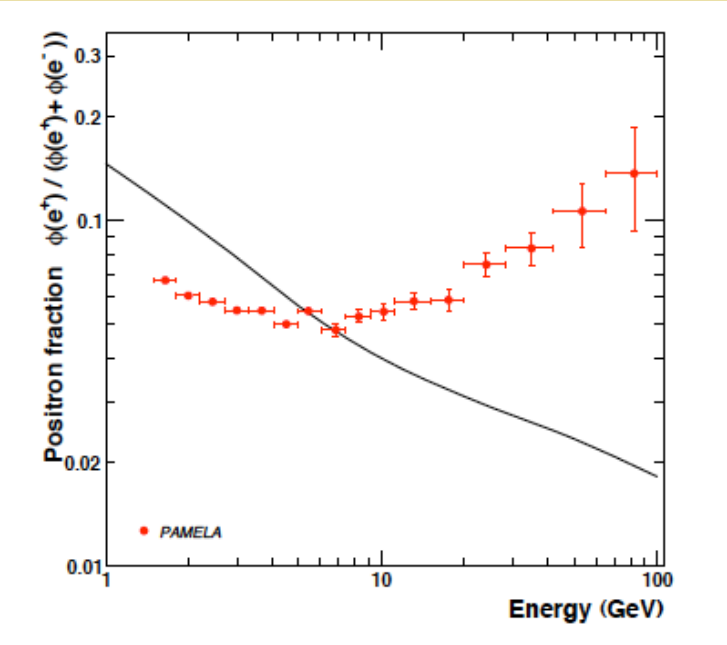
Naturalness is a misleading guide & there may be new ultralight degrees of freedom: Intensity frontier

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

$$d \rightarrow u\, e^- \bar{\nu}_e$$
$$s \rightarrow u\, e^- \bar{\nu}_e$$
$$b \rightarrow u\, e^- \bar{\nu}_e$$

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

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad \text{SM}$$

$$0.9999 \pm 0.0006 \quad \text{Expt}$$

0.9492 ± 0.0005

0.0507 ± 0.0004

0.00001 ± 0.000007

Includes theory error

CKM Unitarity & V_{ud}

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β-decay

$$n \rightarrow p\, e^- \bar{\nu}_e$$

$$A(Z,N) \rightarrow A(Z-1,N+1)\, e^+ \nu_e$$

$$\pi^+ \rightarrow \pi^0\, e^+ \nu_e$$

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

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τ_n + asym

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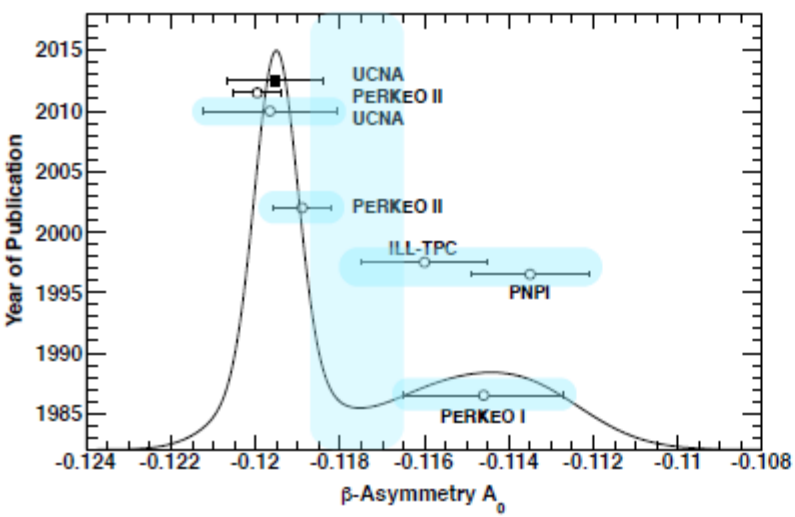
$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \cdots$$

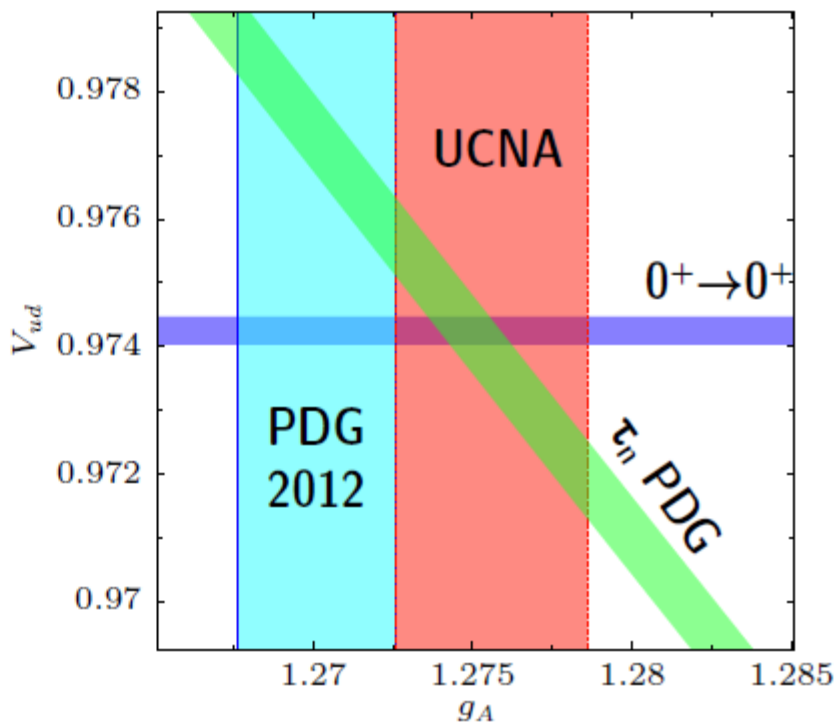
Latest Results from UCNA

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

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

Systematic	corr. (%)	unc. (%)
Polarization	+0.67	±0.56
$\Delta_{backscattering}$	+1.36	±0.34
Δ_{angle}	−1.21	±0.30
Energy reconstruction		±0.31
Gain fluctuation		±0.18
Field non-uniformity	+0.06	±0.10
ϵ_{MWPC}	+0.12	±0.08
Muon veto efficiency		±0.03
UCN-induced background	+0.01	±0.02
$\sigma_{statistics}$		±0.46
Theory contributions		
Recoil order [19–21]	−1.71	
Radiative [22]	−0.10	





Thanks: B. Filippone

Weak decays

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

SM theory input

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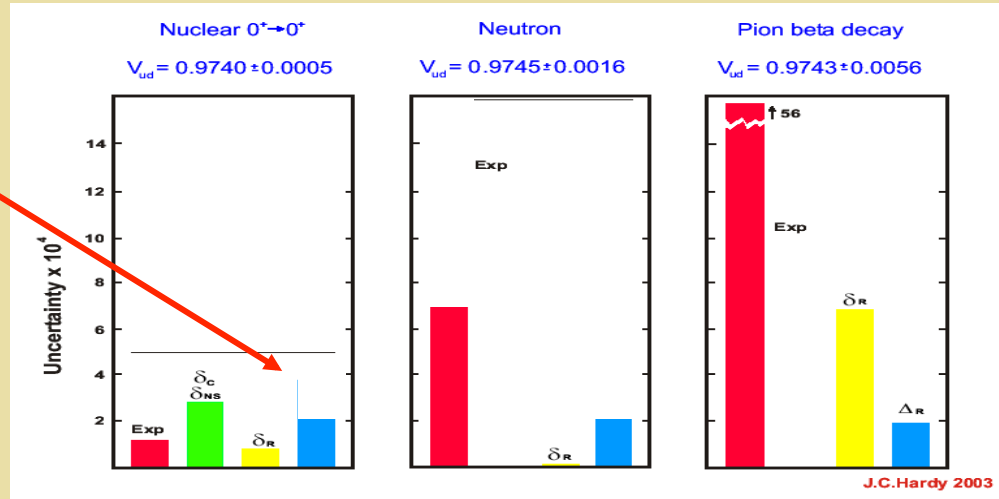

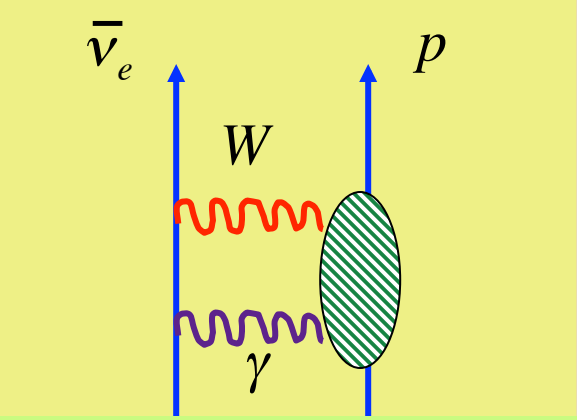

Recent Marciano & Sirlin

$$M_{W\gamma} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi}\left[\ln\left(\frac{M_Z^2}{\Lambda^2}\right) + C_{\gamma W}(\Lambda)\right]$$

Weak decays: kaons & V_{us}

Two approaches:

K_{l3} decays:

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

K_{l2} decays:

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

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

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χPT

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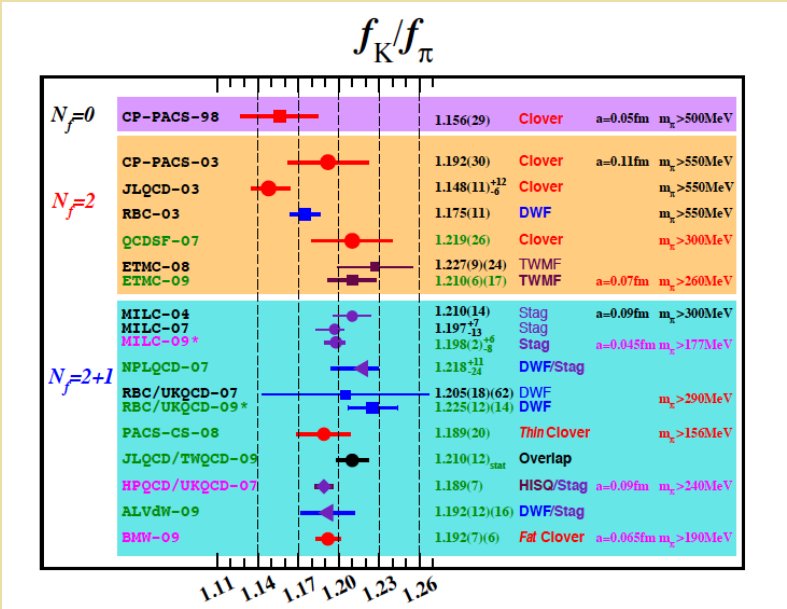
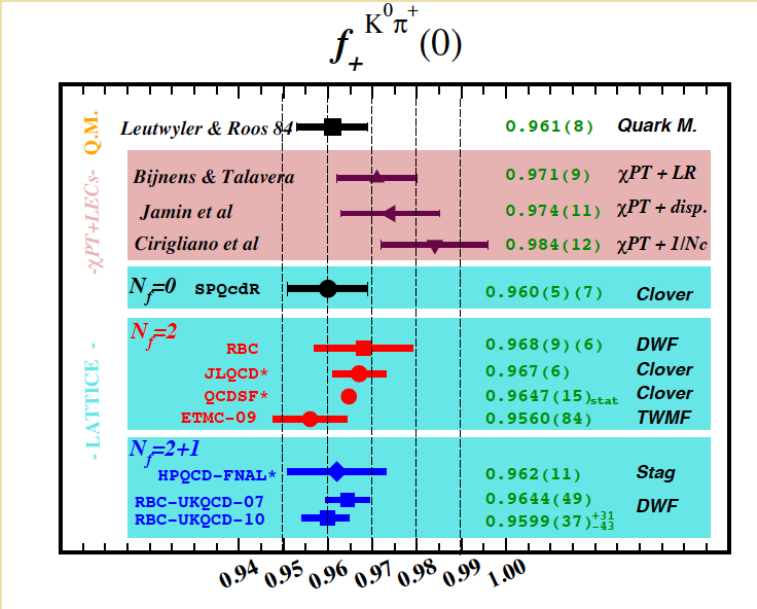
LQCD

χPT

Weak decays: kaons & V_{us}

Antonelli et al, 1005.2323





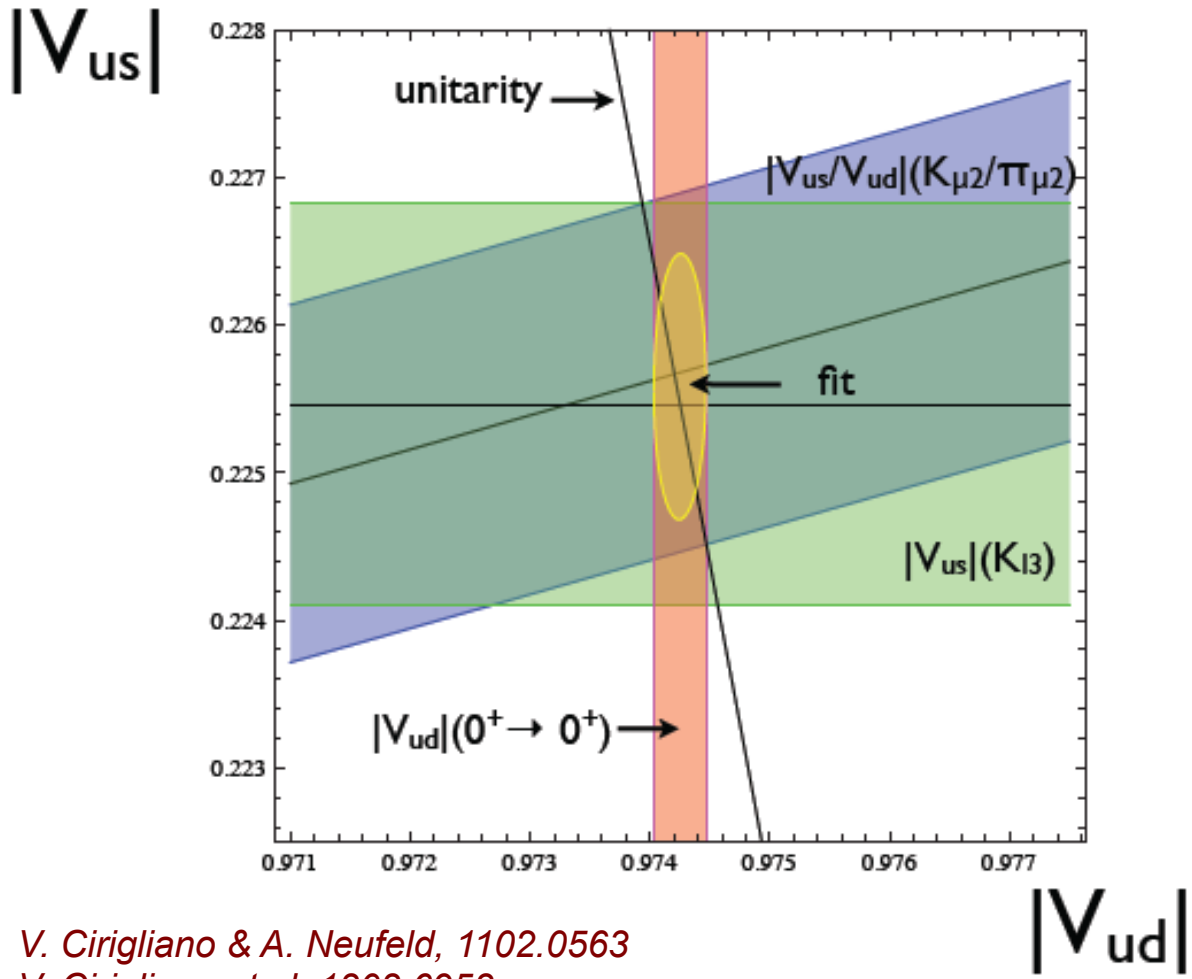
$$f_K/f_\pi = 1.198(2)_{\rm stat}(^{+6}_{-8})_{\rm syst} = 1.197(7),$$

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

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

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

CKM Unitarity



V. Cirigliano & A. Neufeld, 1102.0563
V. Cirigliano et al, 1303.6953

III. CKM Unitarity: BSM Implications

CKM Unitarity & BSM Physics

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BSM physics

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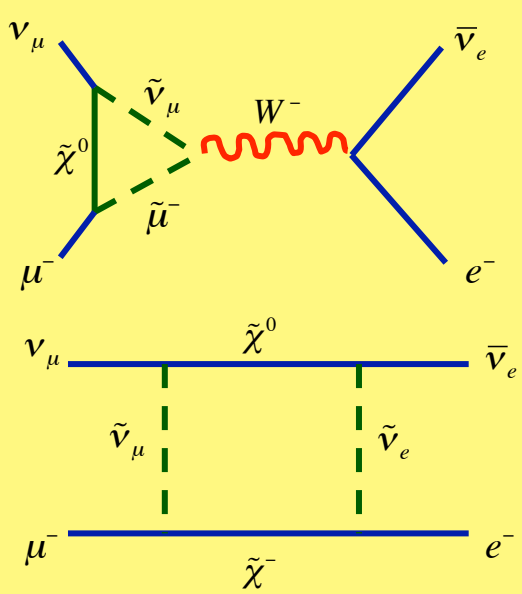


$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.001$$

$+ \cdots$

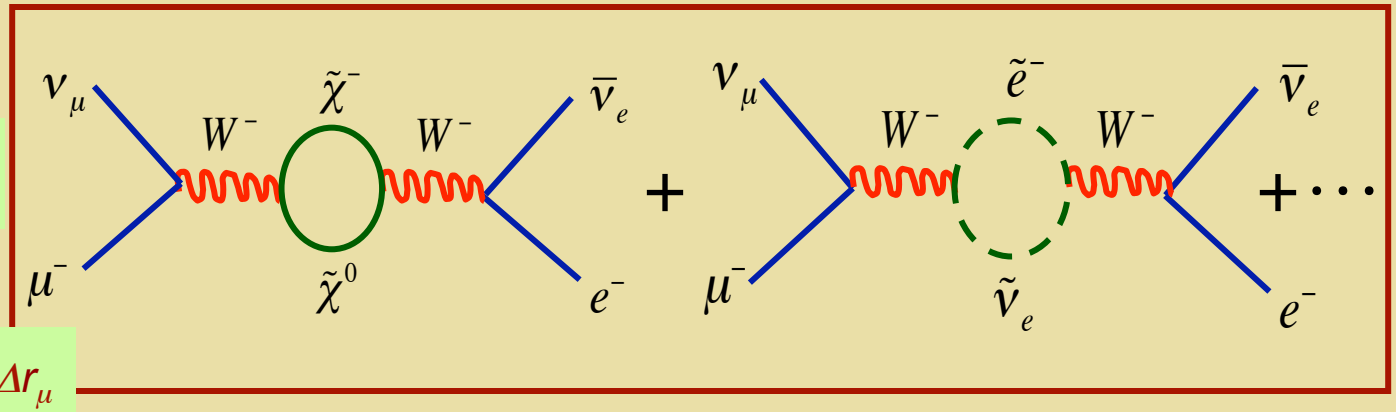
SUSY

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

BSM physics

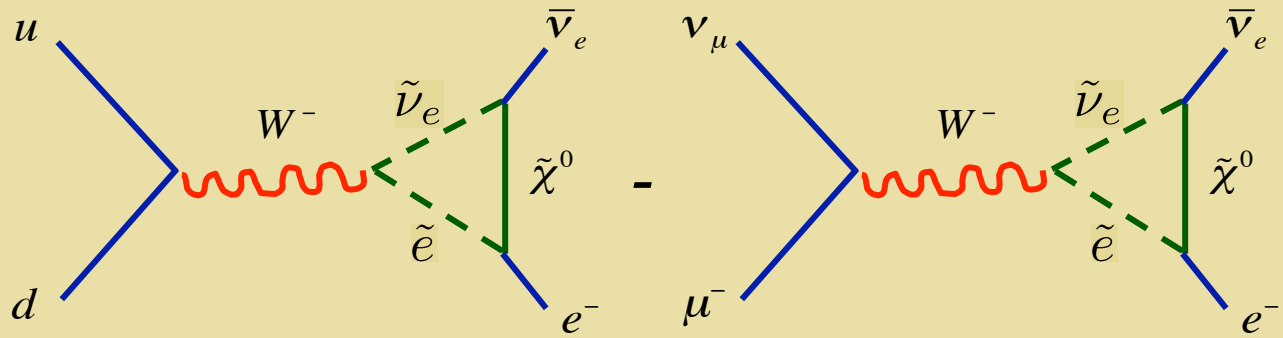
CC: SUSY Radiative Corrections

Propagator

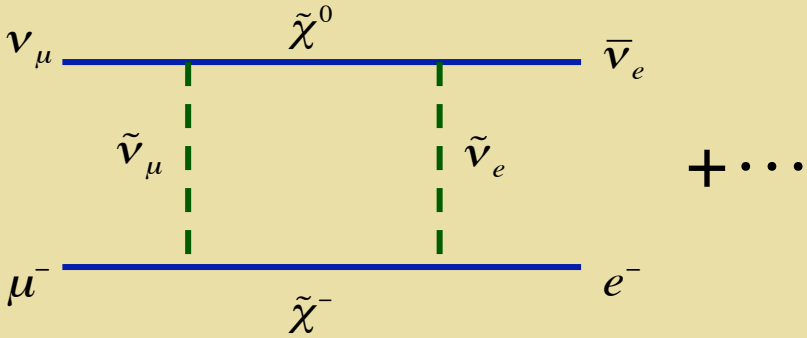


Cancel from $\Delta r_\beta - \Delta r_\mu$

Vertex & External leg



Box



Bauman, Erler, Kurylov & RM

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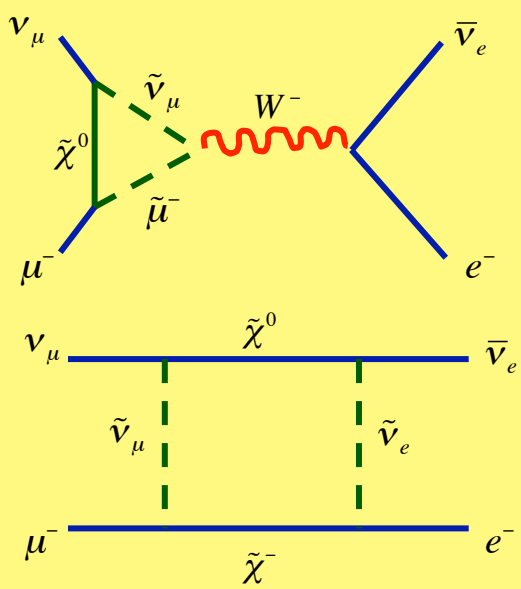

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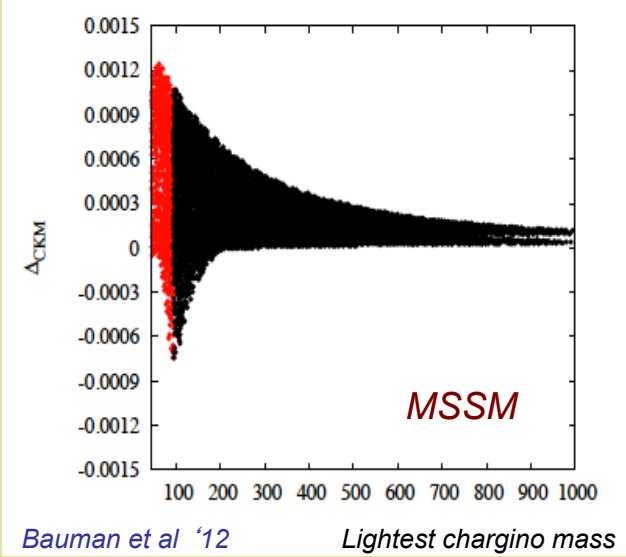
SUSY

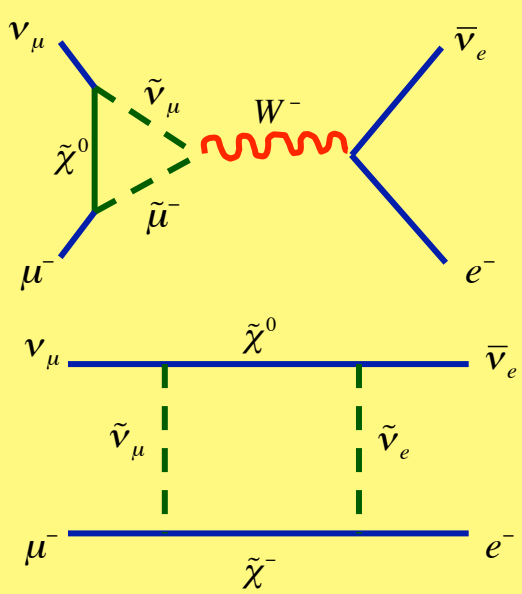
CKM Unitarity



CKM Unitarity & BSM Physics

$$d \to u\, e^- \bar{\nu}_e$$
$$s \to u\, e^- \bar{\nu}_e$$
$$b \to u\, e^- \bar{\nu}_e$$

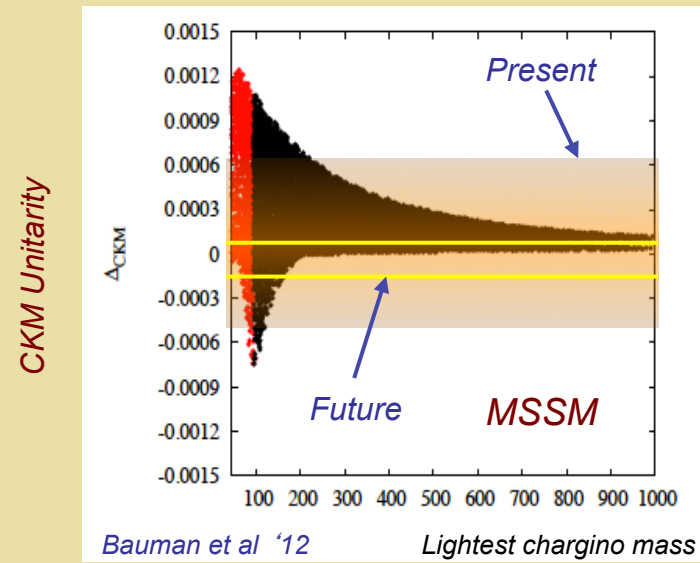
$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$\frac{\delta O^{SUSY}}{O^{SM}} \sim 0.001$$

$+ \cdots$

SUSY



Next generation: ~ 10^{-4} precision

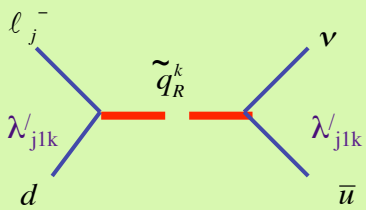
Pion Leptonic Decay

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

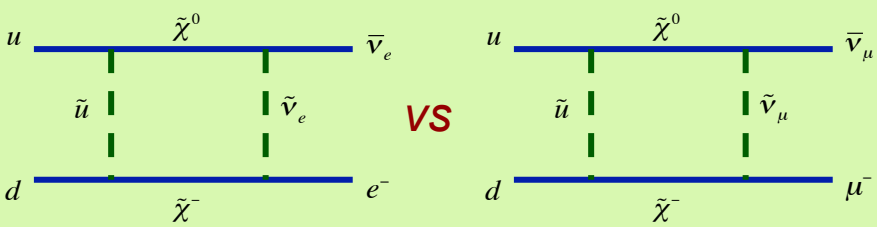
Pion Leptonic Decay

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

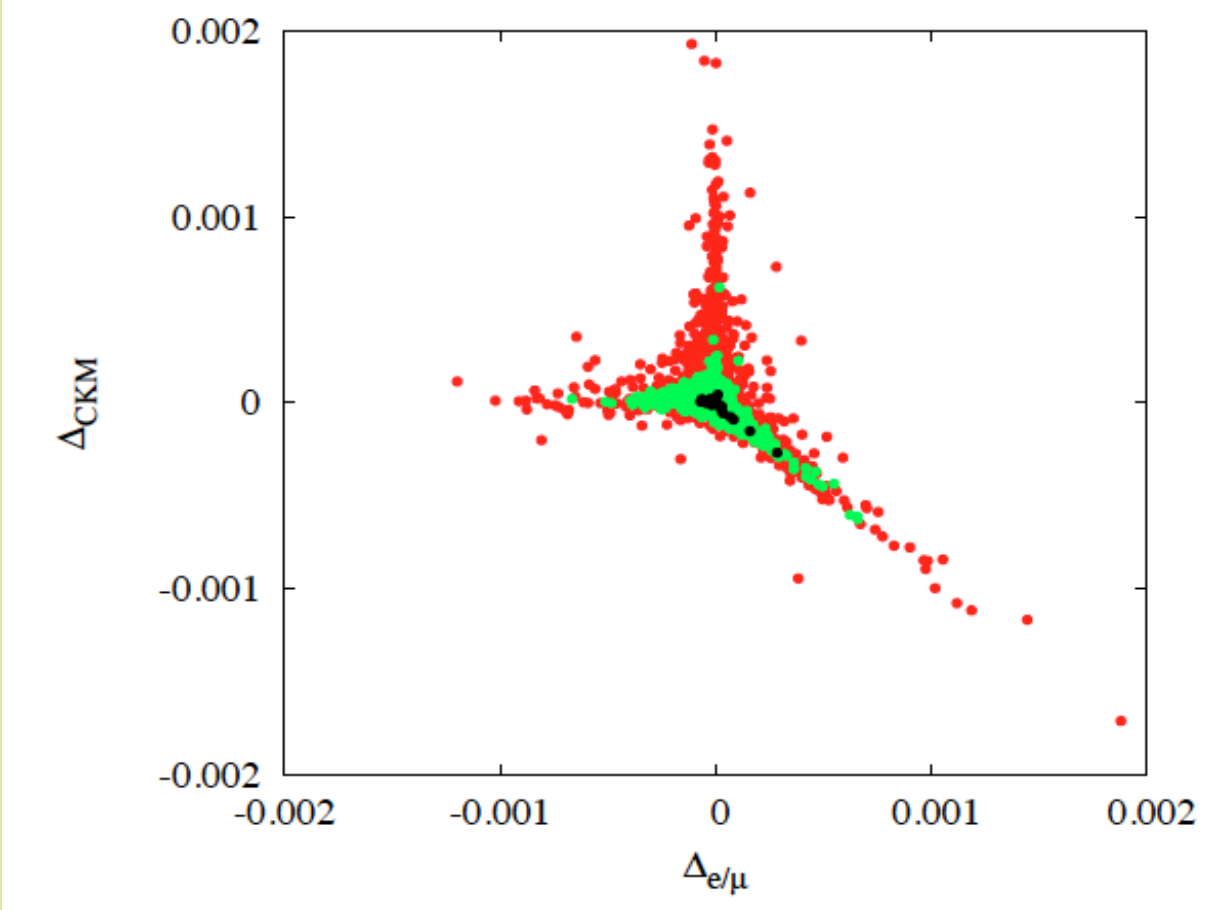
SUSY: RPV or loops *R-M, Su, Tulin*



Probing Slepton Universality

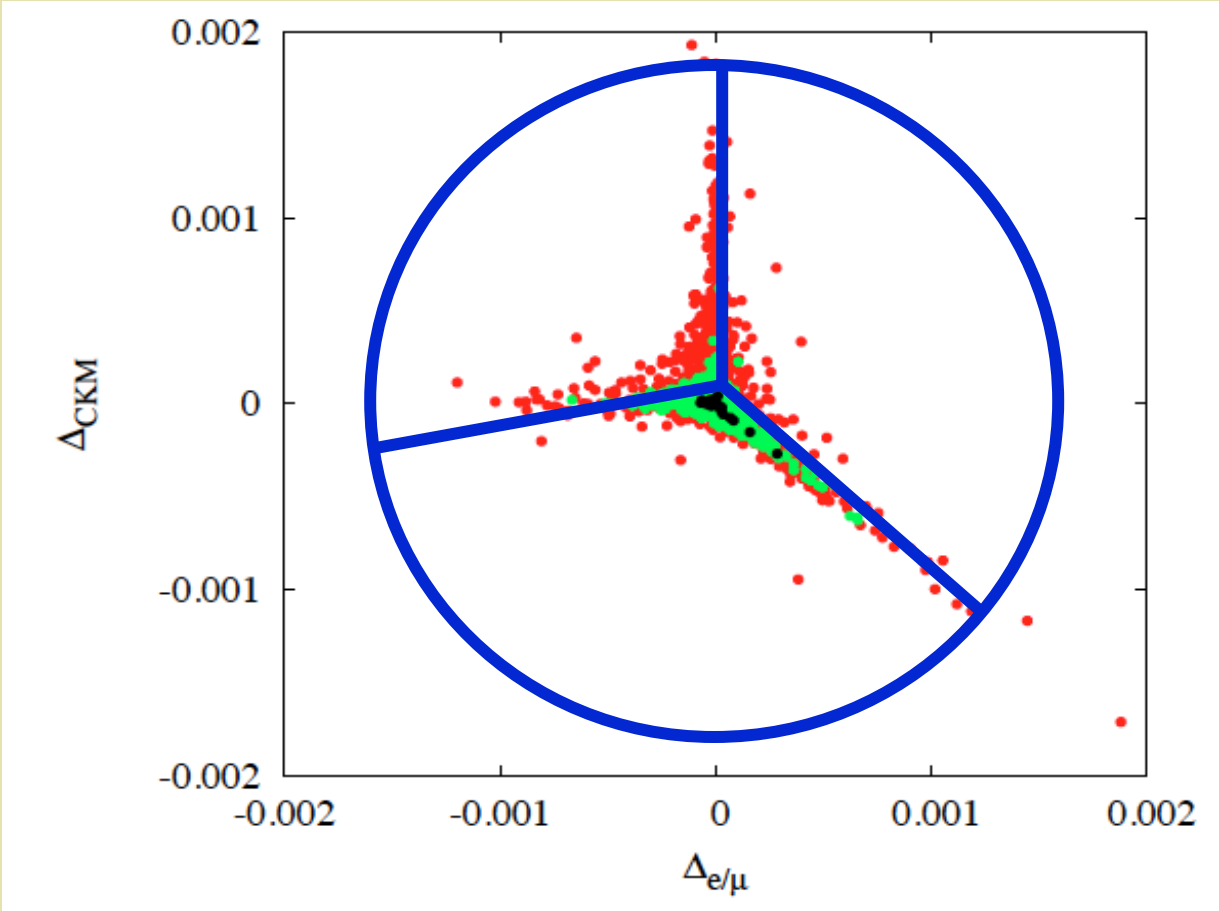


$\pi_{\ell 2}$ & β Decay: Diagnostic Tool



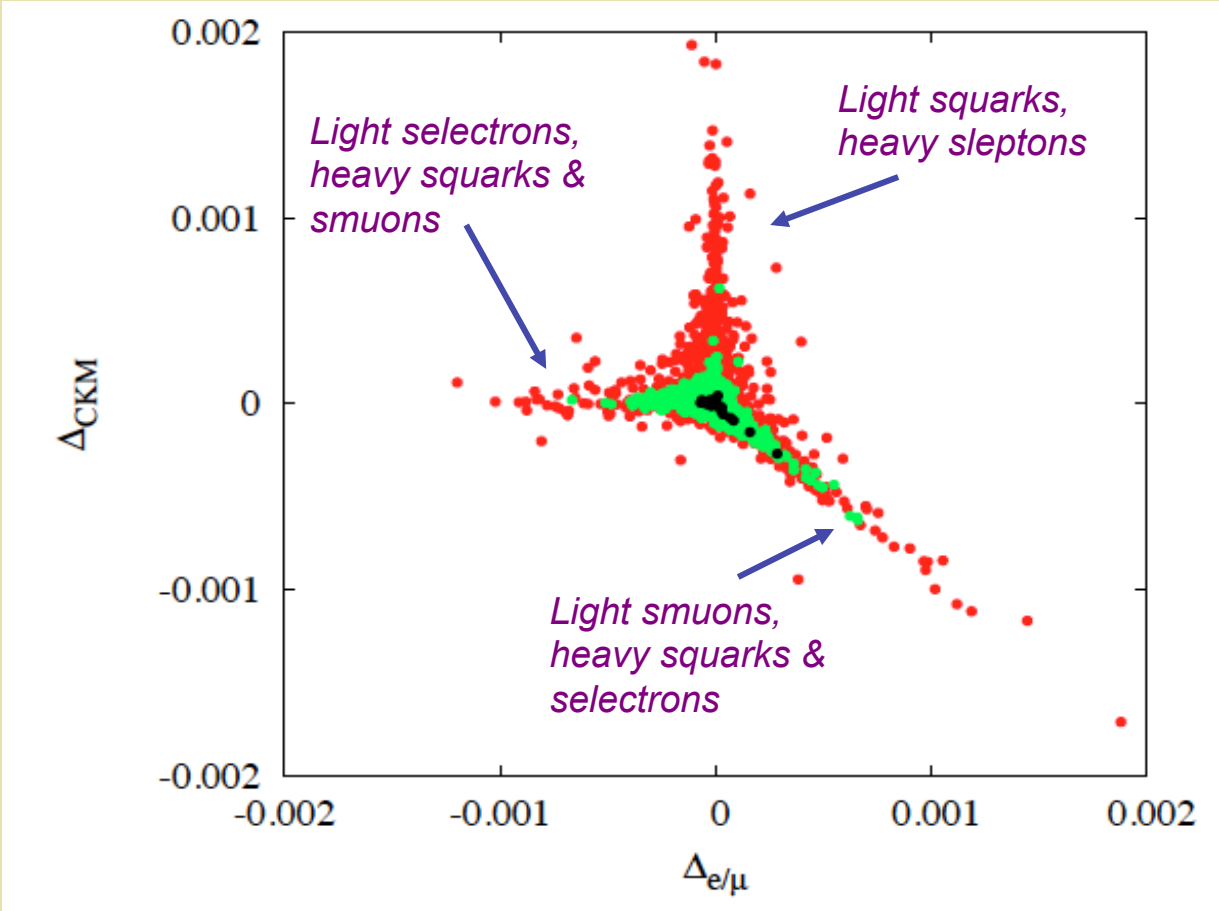
Bauman, Erler, R-M

$\pi_{\ell 2}$ & β Decay: Diagnostic Tool



Bauman, Erler, R-M

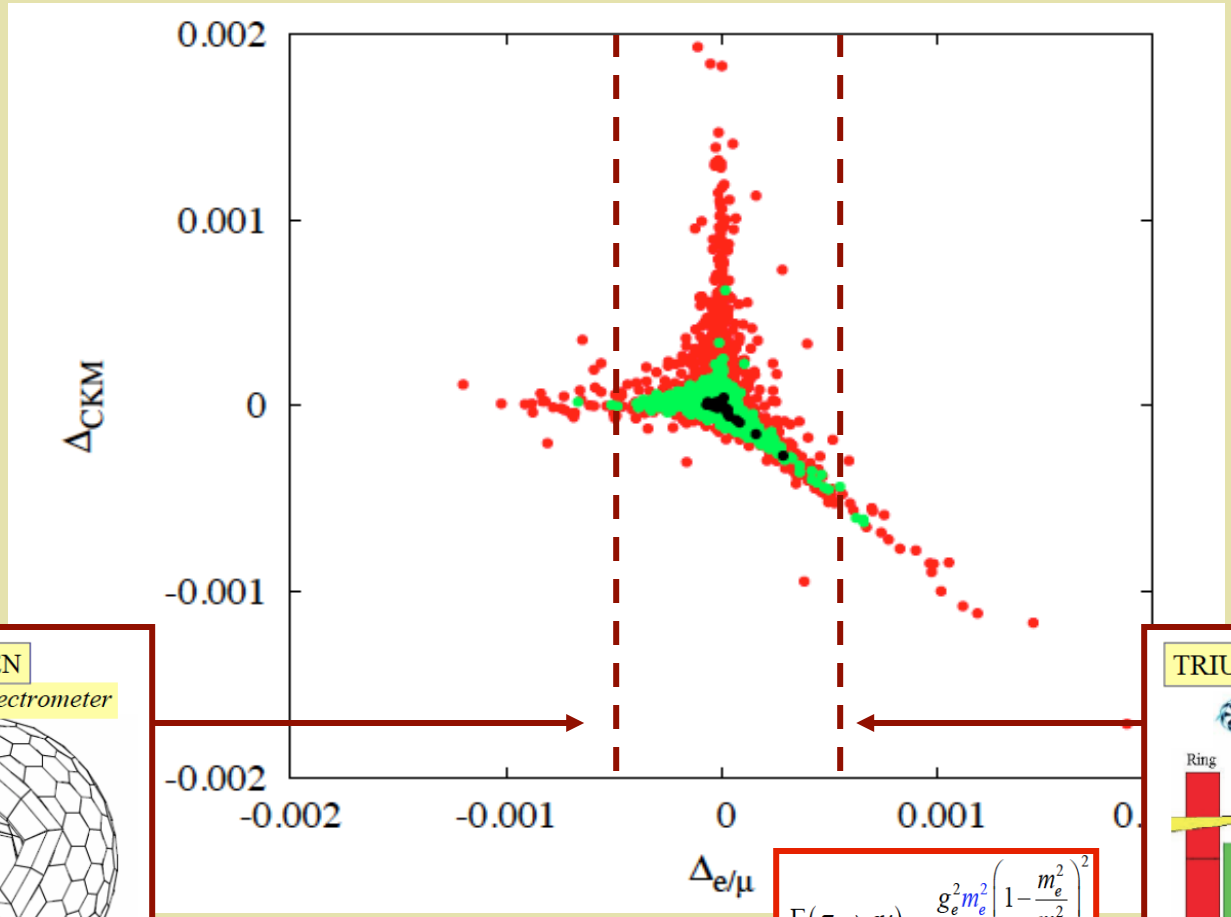
$\pi_{\ell 2}$ & β Decay: Diagnostic Tool



Bauman, Erler, R-M

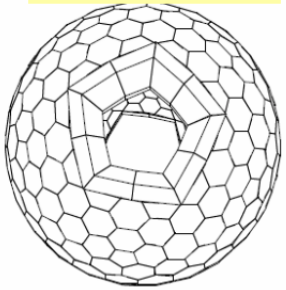
$\pi_{\ell 2}$ & β Decay: Diagnostic T

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2 m_e^2 \left(1 - \frac{m_e^2}{m_\pi^2}\right)^2}{g_\mu^2 m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2}$$

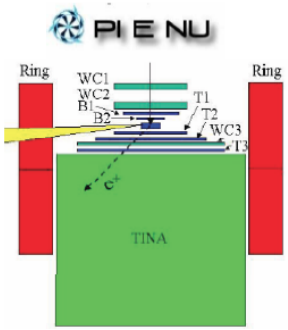


PSI PEN

PIBETA Spectrometer



TRIUMF PIENU

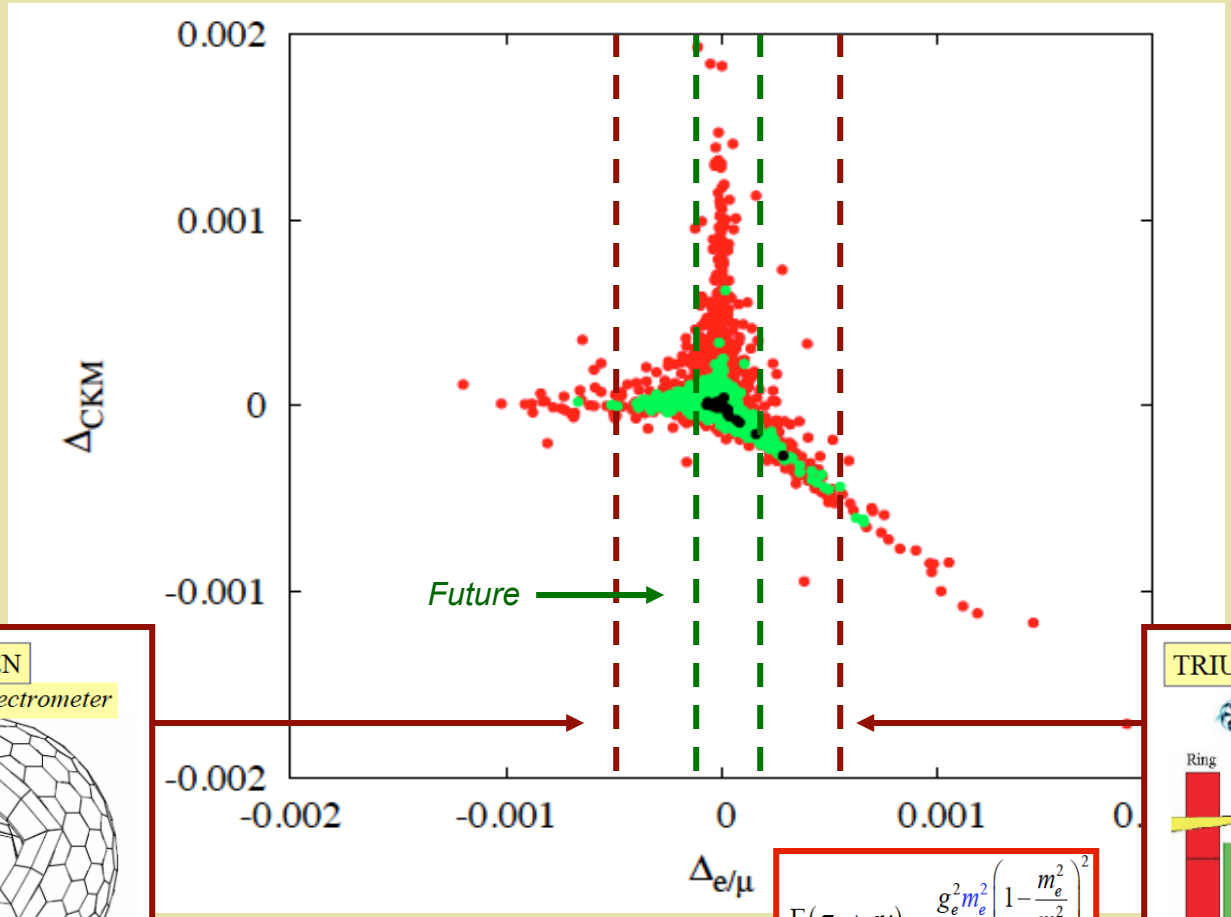


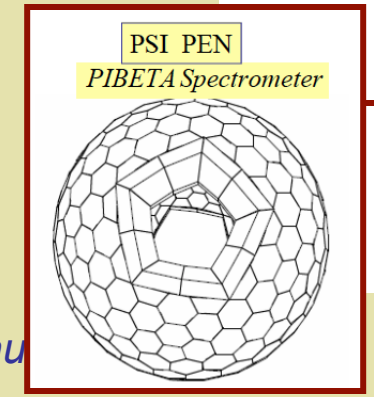
$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2 m_e^2 \left(1 - \frac{m_e^2}{m_\pi^2}\right)^2}{g_\mu^2 m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2}$$

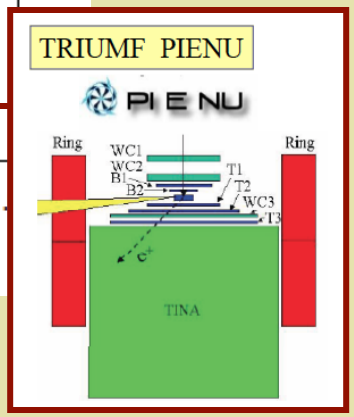
Bau

$\pi_{\ell 2}$ & β Decay: Diagnostic T

$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2 m_e^2 \left(1 - \frac{m_e^2}{m_\pi^2}\right)^2}{g_\mu^2 m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2}$$



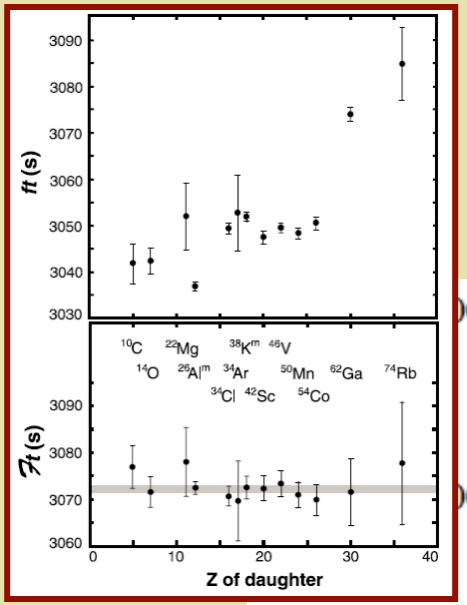




$$\frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)} = \frac{g_e^2 m_e^2 \left(1 - \frac{m_e^2}{m_\pi^2}\right)^2}{g_\mu^2 m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2}$$

Bau

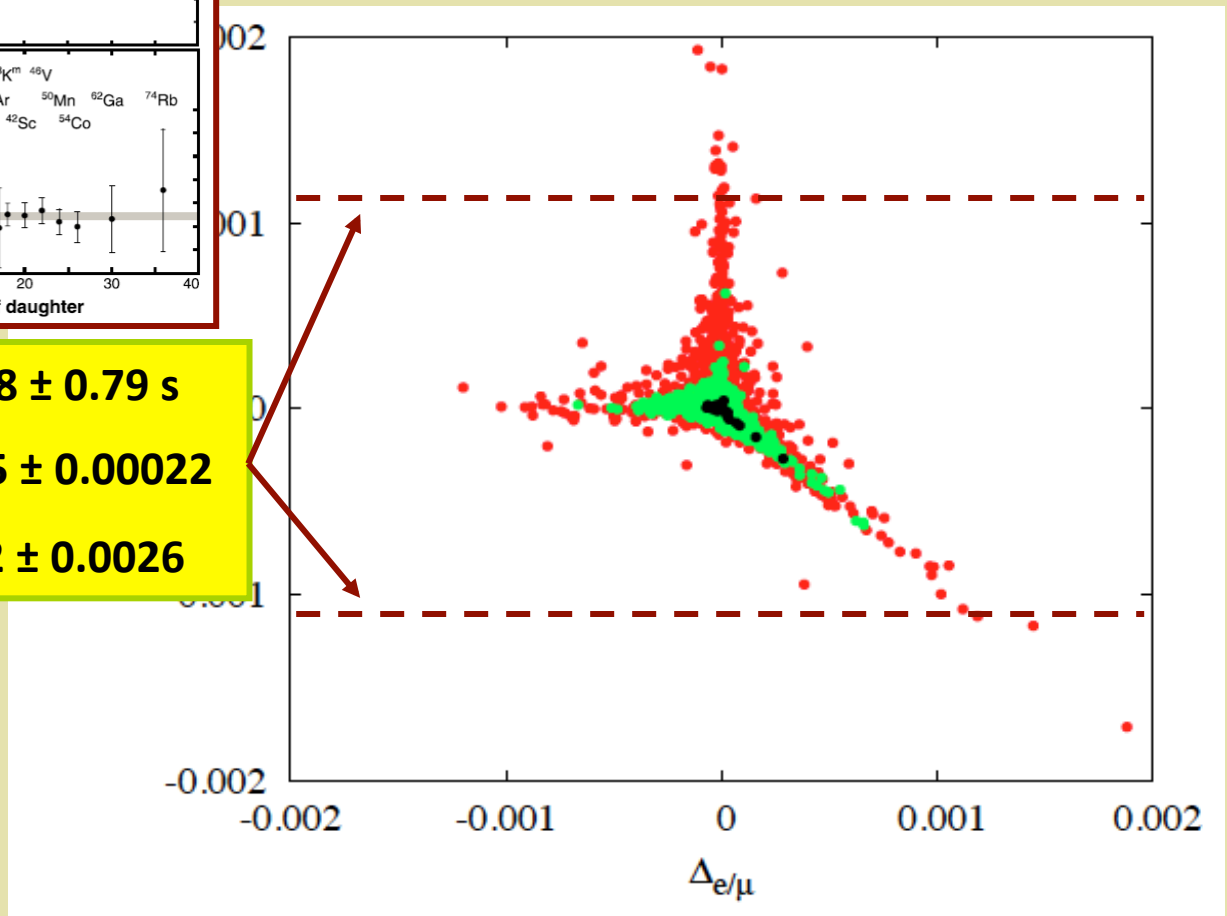
β Decay: Diagnostic Tool



***Ft* = 3072.08 ± 0.79 s**

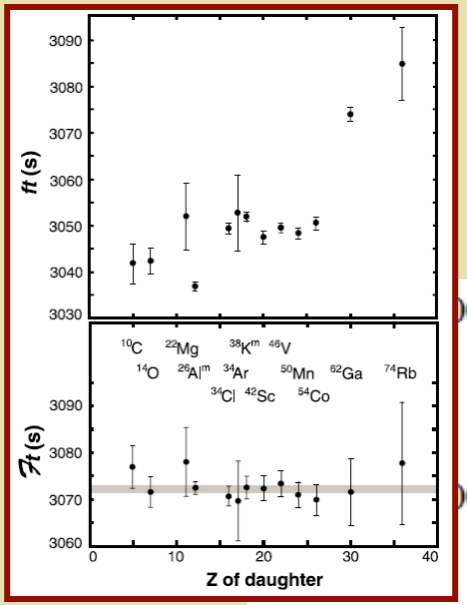
V_{ud} = 0.97425 ± 0.00022

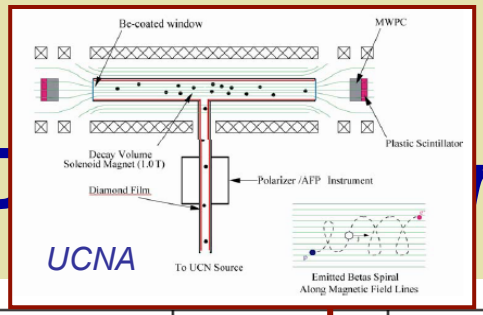
b_F = -0.0022 ± 0.0026

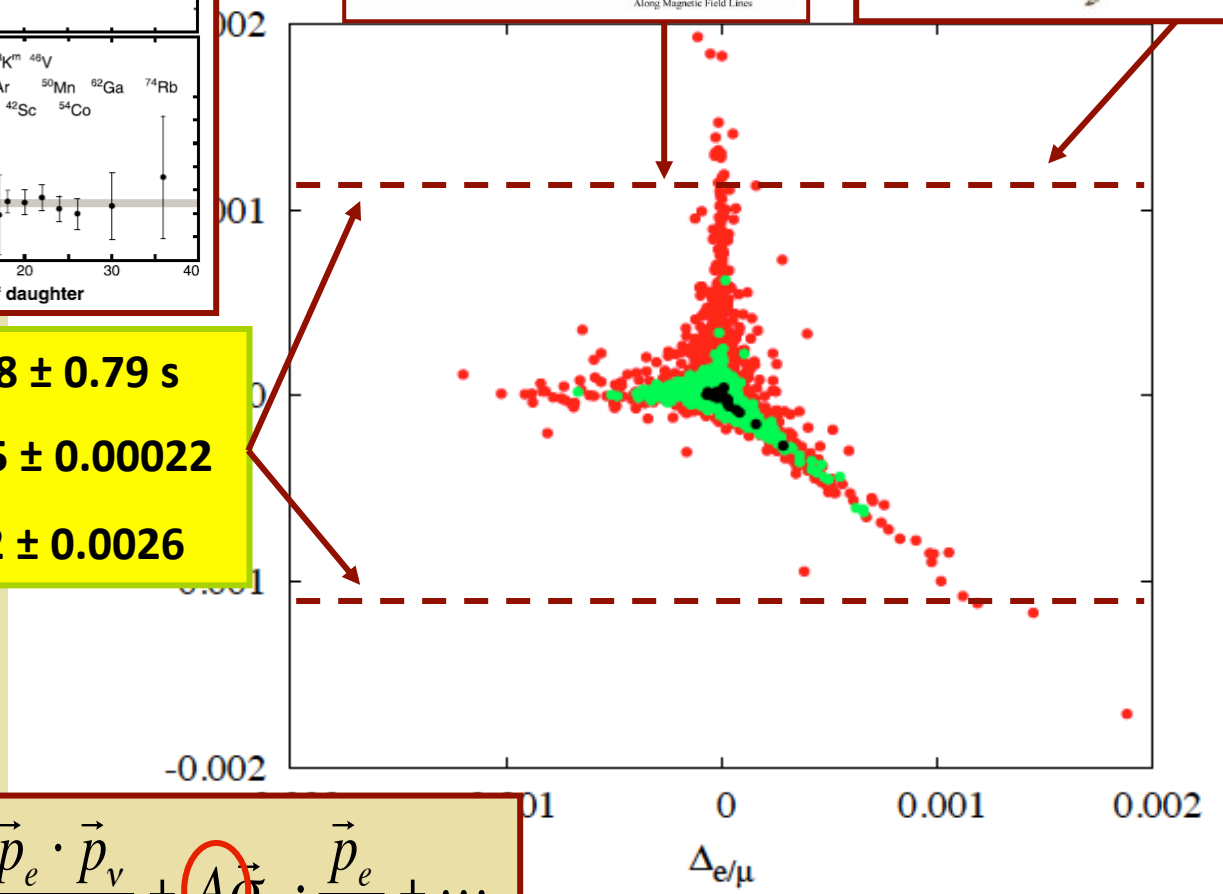


Bauman, Erler, R-M

β D n







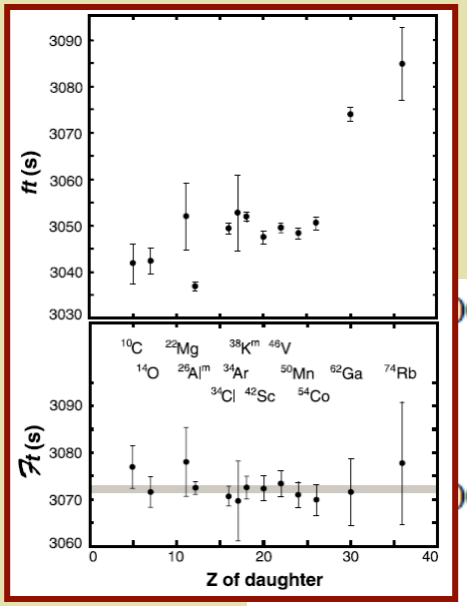
Ft **= 3072.08 ± 0.79 s**

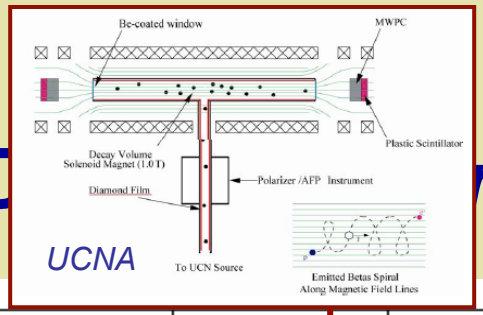
V_{ud} = 0.97425 ± 0.00022

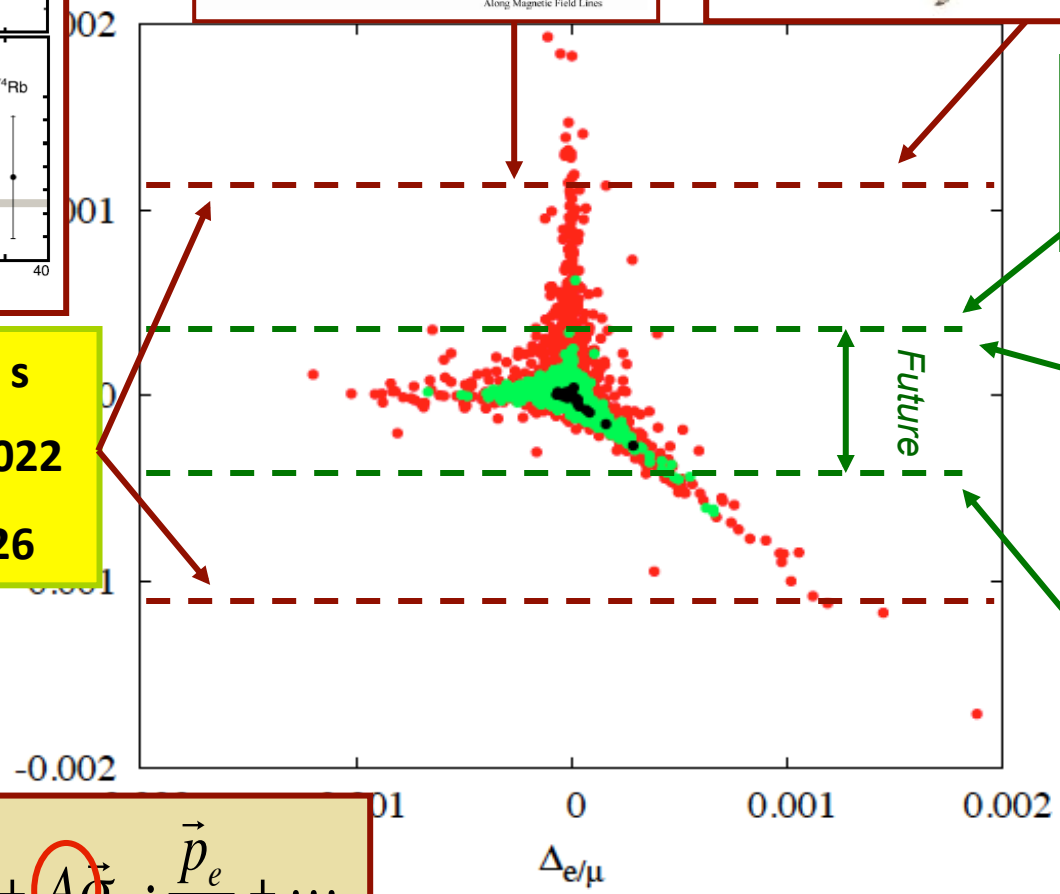
b_F = -0.0022 ± 0.0026

$$dW \propto 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\vec{\sigma}_n \cdot \frac{\vec{p}_e}{E_e} + \cdots$$

β D n







Ft **= 3072.08 ± 0.79 s**

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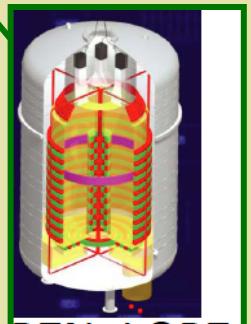
PERC

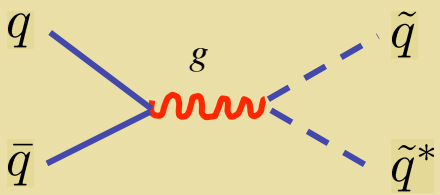
LANL lifetime



PENeLOPE
TUM

LHC BSM Challenge: Light but Compressed ?

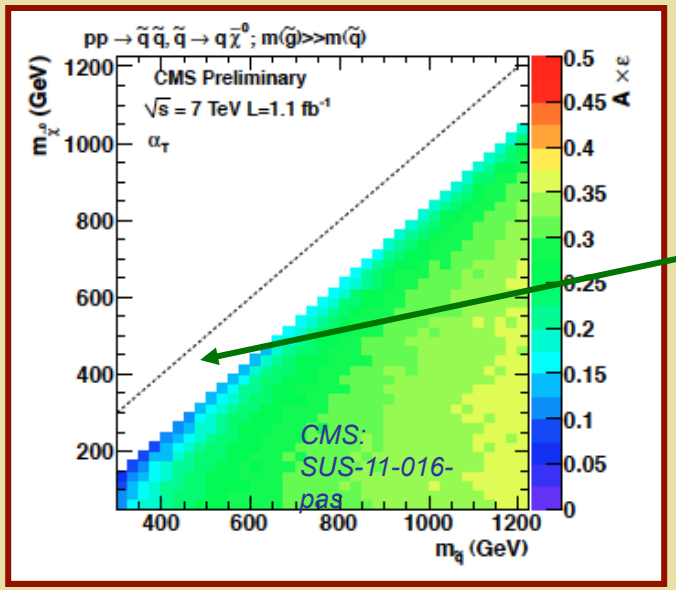
Pair production of squarks



$$\tilde{q} \to q + \tilde{\chi}_1^0$$

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

Final state: 2j + $\not{E}_T$, 2j + ℓ + $\not{E}_T$

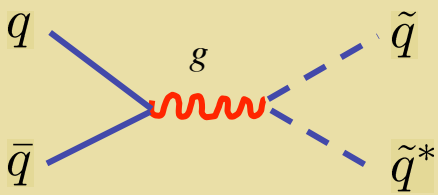


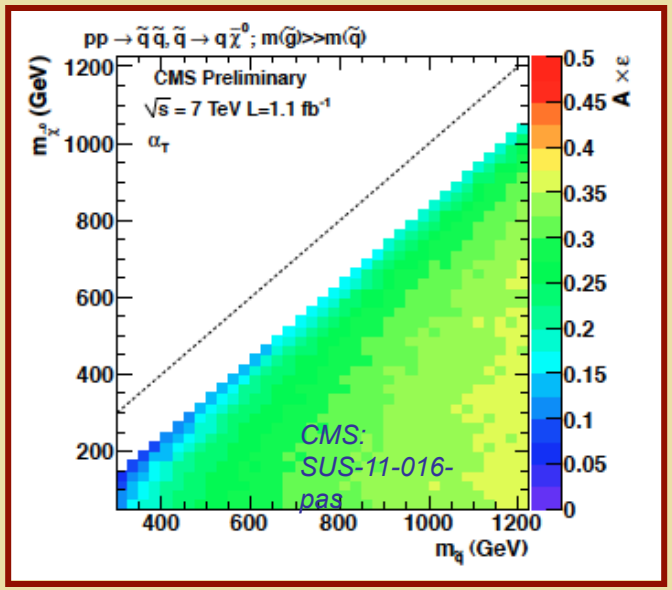
No exclusion yet (jets analysis): is sub-TeV SUSY hiding here?

If so, will it show up in precision tests ?

LHC BSM Challenge: Light but Compressed ?

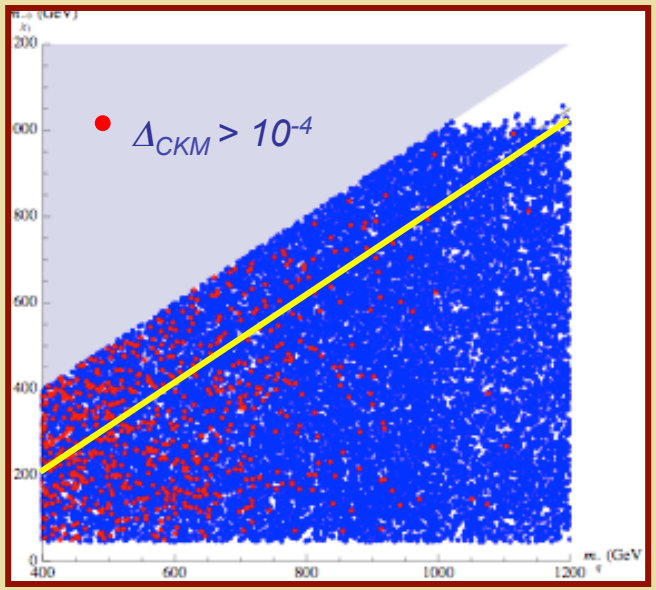
Pair production of squarks





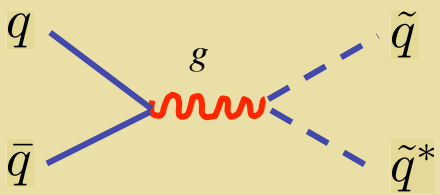
CKM Unitarity Tests

Bauman, Pitschmann, Erler, R-M preliminary



LHC BSM Challenge: Light but Compressed ?

Pair production of squarks



CKM Unitarity Tests

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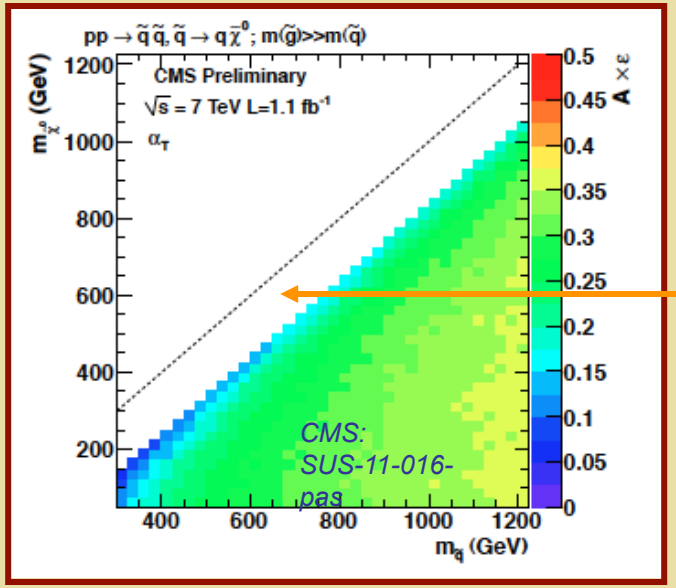
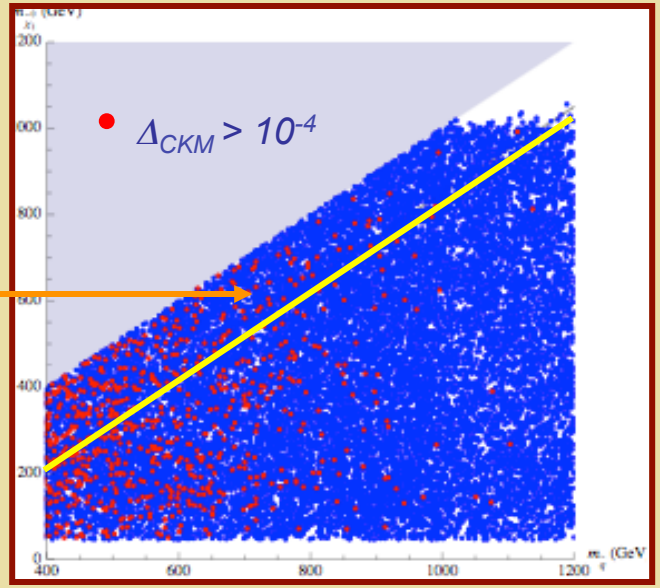




Effective Operators

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

Effective Operators

$$
\begin{aligned}
\mathcal{L}_{\rm CC} \;=\; & -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[\Big(1+\delta_\beta\Big)\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \;\; \epsilon_L\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L\;\; \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \;\; \epsilon_R\;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \;+\; \tilde{\epsilon}_R\;\; \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \;\; \epsilon_S\;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d \;+\; \tilde{\epsilon}_S\;\; \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
& - \;\; \epsilon_P\;\; \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \;-\; \tilde{\epsilon}_P\;\; \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
& + \;\; \epsilon_T\; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \;+\; \tilde{\epsilon}_T\; \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d + \text{h.c.}
\end{aligned}
$$

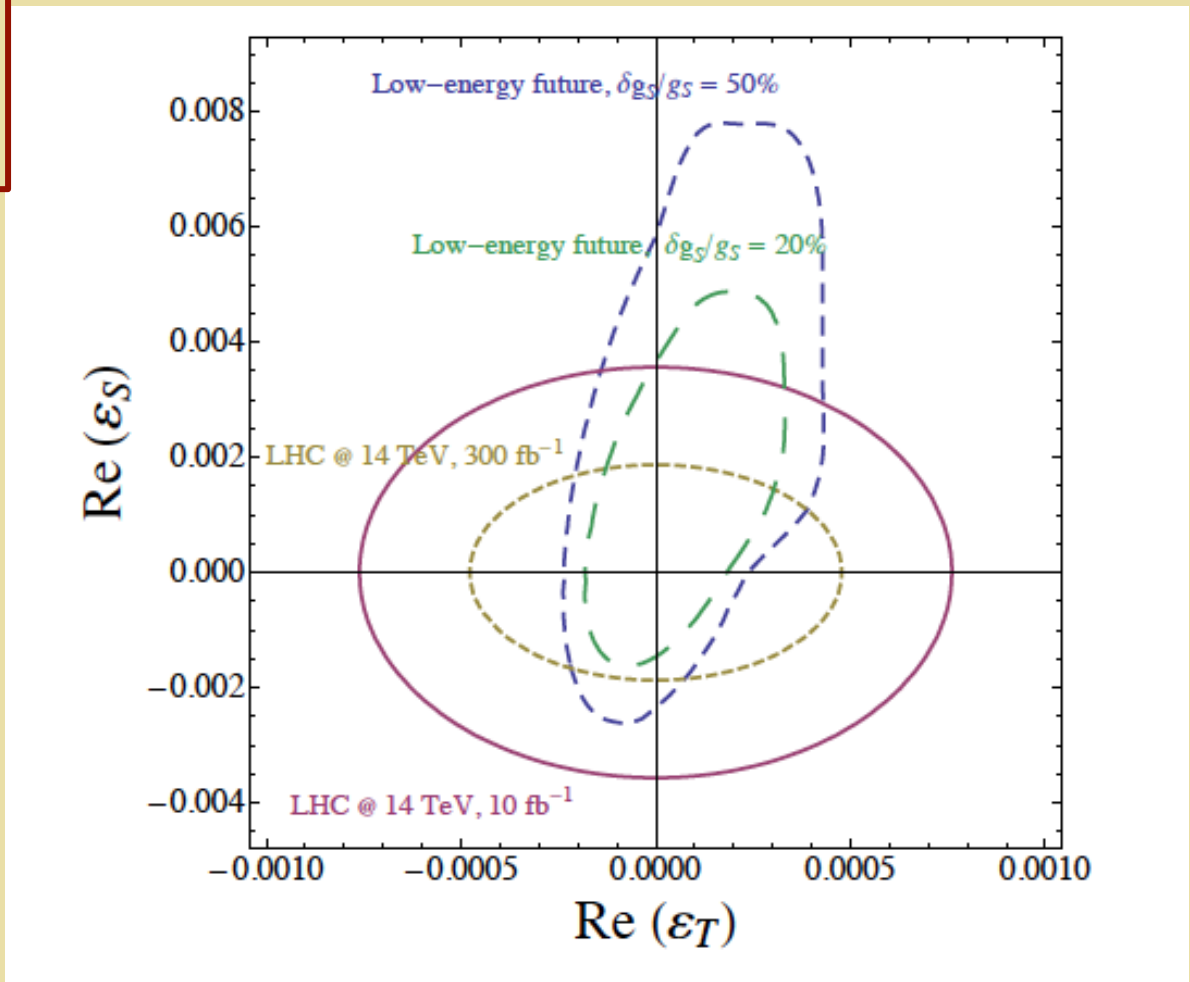
$$\varepsilon \sim C\,(\,v/\Lambda\,)^2$$

V. Cirigliano et al, 1303.6953

Effective Operators: LHC & Weak Decays

0.1% on

- *Neutron B, b*
- *^{6}He b*



V. Cirigliano et al, 1303.6953

Effective Operators: LHC & Weak Decays

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- *Neutron B, b*
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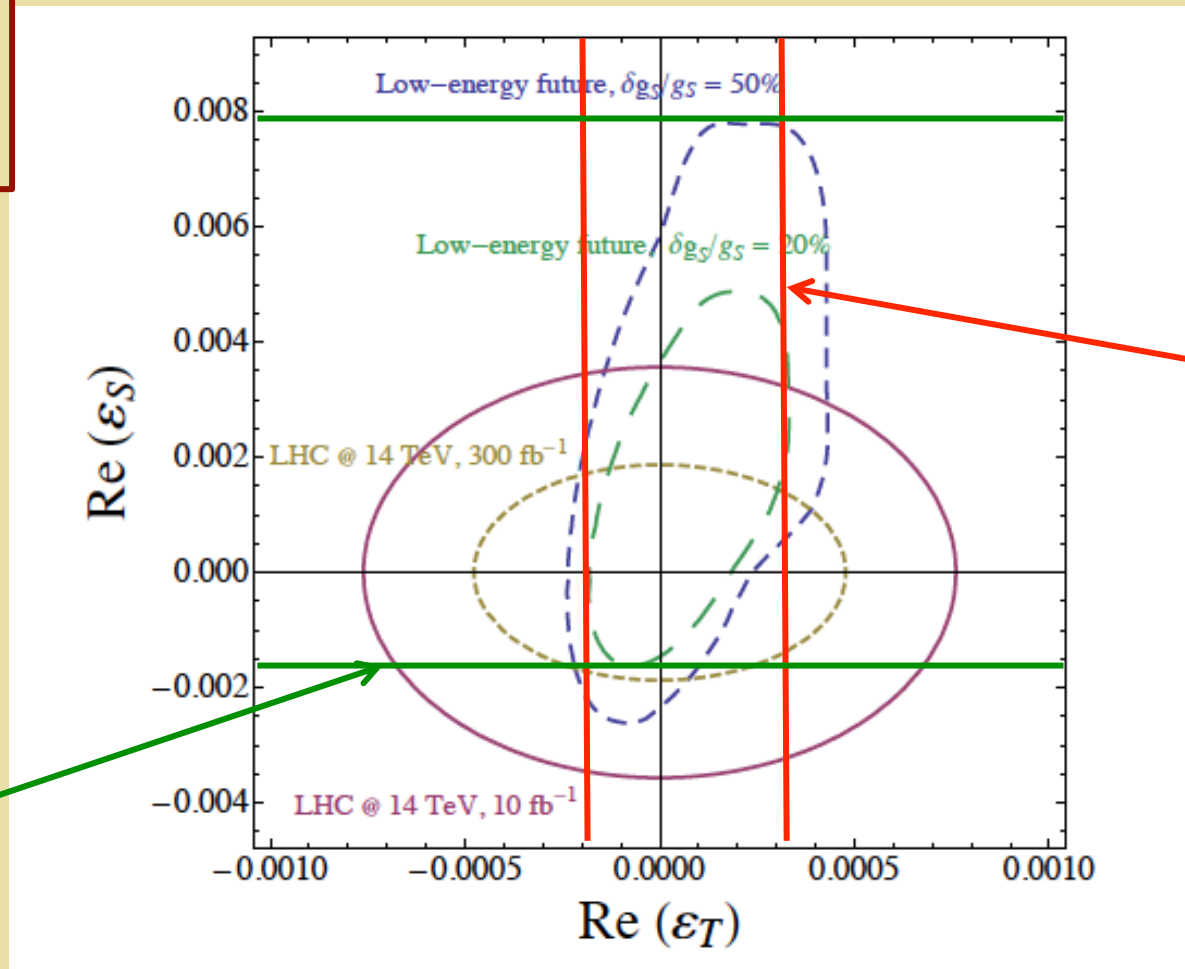

Λ ~ 30 TeV

Λ ~ 10 TeV : Comparable to $0^+ \to 0^+$

V. Cirigliano et al, 1303.6953

Worldwide Radioactivity

$$d \rightarrow u\, e^{-}\, \bar{\nu}_e$$

$$s \rightarrow u\, e^{-}\, \bar{\nu}_e$$

$$b \rightarrow u\, e^{-}\, \bar{\nu}_e$$

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

★ *neutron*

★ *nuclei*

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*