(New) Nucleon Matrix Elements for New Physics Searches

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Symmetry Tests with Neutrons

"Windows" on New Physics

Some examples…

- Searches for new sources of CP violation: *namely, permanent electric dipole moment (EDM); time-dependent EDMs as probes of ultralight (axion-like) dark matter*

→ Note Session E talks on Aug. 1: S. Syritsyn, C. Roccia

Today

- Searches for new S, T degrees of freedom & … in beta-decay
- Searches for baryon number violation: esp. quark probes of Majorana dynamics

Effective Field Theory & New Physics

Enter a "Model Independent" Analysis Framework

Suppose new physics enters at an energy scale $E > \Lambda$

Then for $E < \Lambda$ we can extend the SM as per

$$\mathcal{L}_{\rm SM} \Longrightarrow \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{D-4}} \mathcal{O}_i^D \ ,$$

Symmetries guide their construction [Weinberg, 1979]

Here assume SM electroweak symmetry [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010]

New physics can enter as (i) new operators or as (ii) modifications of c_i for operators in the SM

cf. non-V-A tests with tests of CKM unitarity

Other searches involve new operators exclusively

[Note Session E talk Aug. 3 on cLFV: G. Pruna]

Theoretical Framework for β Decay

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{1}{\Lambda_i^2} O_i \Longrightarrow \mathcal{L}_{\rm SM} + \frac{1}{v^2}\sum_i \hat{\alpha}_i O_i \,,$$

with $\hat{\alpha}_i = v^2/\Lambda_i{}^2$. [Buchmuller & Wyler, 1986; Grzadkowski et al., 2010; Cirigliano, Jenkins, González-Alonso, 2010; Cirigliano, González-Alonso, Graesser, 2013]

Radiative correction*!

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

*[Sirlin, 1974, 1978, 1982; Marciano & Sirlin, 1986, 2006; Czarnecki, Marciano, & Sirlin, 2004]

Note right-handed neutrinos appear explicitly

QCD (hadron matrix elements) play a key role!

n,p!

Theoretical Framework

Connecting to Lee and Yang....

$$\mathcal{H}_{int} = (\bar{\psi}_p\psi_n)(C_S\bar{\psi}_e\psi_\nu - C'_S\bar{\psi}_e\gamma_5\psi_\nu) + (\bar{\psi}_p\gamma_\mu\psi_n)(C_V\bar{\psi}_e\gamma^\mu\psi_\nu - C'_V\bar{\psi}_e\gamma^\mu\gamma_5\psi_\nu)$$
$$-(\bar{\psi}_p\gamma_\mu\gamma_5\psi_n)(C_A\bar{\psi}_e\gamma^\mu\gamma_5\psi_\nu - C'_A\bar{\psi}_e\gamma^\mu\psi_\nu) + (\bar{\psi}_p\gamma_5\gamma_\mu\psi_n)(C_P\bar{\psi}_e\gamma_5\psi_\nu - C'_P\bar{\psi}_e\psi_\nu)$$
$$+\frac{1}{2}(\bar{\psi}_p\sigma_{\lambda\mu}\psi_n)(C_T\bar{\psi}_e\sigma^{\lambda\mu}\psi_\nu - C'_T\bar{\psi}_e\sigma^{\lambda\mu}\gamma_5\psi_\nu) + h.c.$$

The terms appear in a one-to-one map....

$$\begin{aligned}
C_i &= \frac{G_F^{(0)}}{\sqrt{2}} V_{ud}\,\bar{C}_i \\
\bar{C}_V &= g_V\,(1+\delta_\beta+\epsilon_L+\epsilon_R+\tilde{\epsilon}_L+\tilde{\epsilon}_R) \\
\bar{C}'_V &= g_V\,(1+\delta_\beta+\epsilon_L+\epsilon_R-\tilde{\epsilon}_L-\tilde{\epsilon}_R) \\
\bar{C}_A &= -g_A\,(1+\delta_\beta+\epsilon_L-\epsilon_R-\tilde{\epsilon}_L+\tilde{\epsilon}_R) \\
\bar{C}'_A &= -g_A\,(1+\delta_\beta+\epsilon_L-\epsilon_R+\tilde{\epsilon}_L-\tilde{\epsilon}_R) \\
\bar{C}_S &= g_S\,(\epsilon_S+\tilde{\epsilon}_S) \\
\bar{C}'_S &= g_S\,(\epsilon_S-\tilde{\epsilon}_S) \\
\bar{C}_P &= g_P\,(\epsilon_P-\tilde{\epsilon}_P) \\
\bar{C}'_P &= g_P\,(\epsilon_P+\tilde{\epsilon}_P) \\
\bar{C}_T &= 4\,g_T\,(\epsilon_T+\tilde{\epsilon}_T) \\
\bar{C}'_T &= 4\,g_T\,(\epsilon_T-\tilde{\epsilon}_T)\ .
\end{aligned}$$

The "QCD parts" are now clearly identified; note, e.g., in n decay

$$\langle p(p_p)|\,\bar{u}\,d\,|n(p_n)\rangle = g_S(q^2)\;\bar{u}_p(p_p)\,u_n(p_n)$$

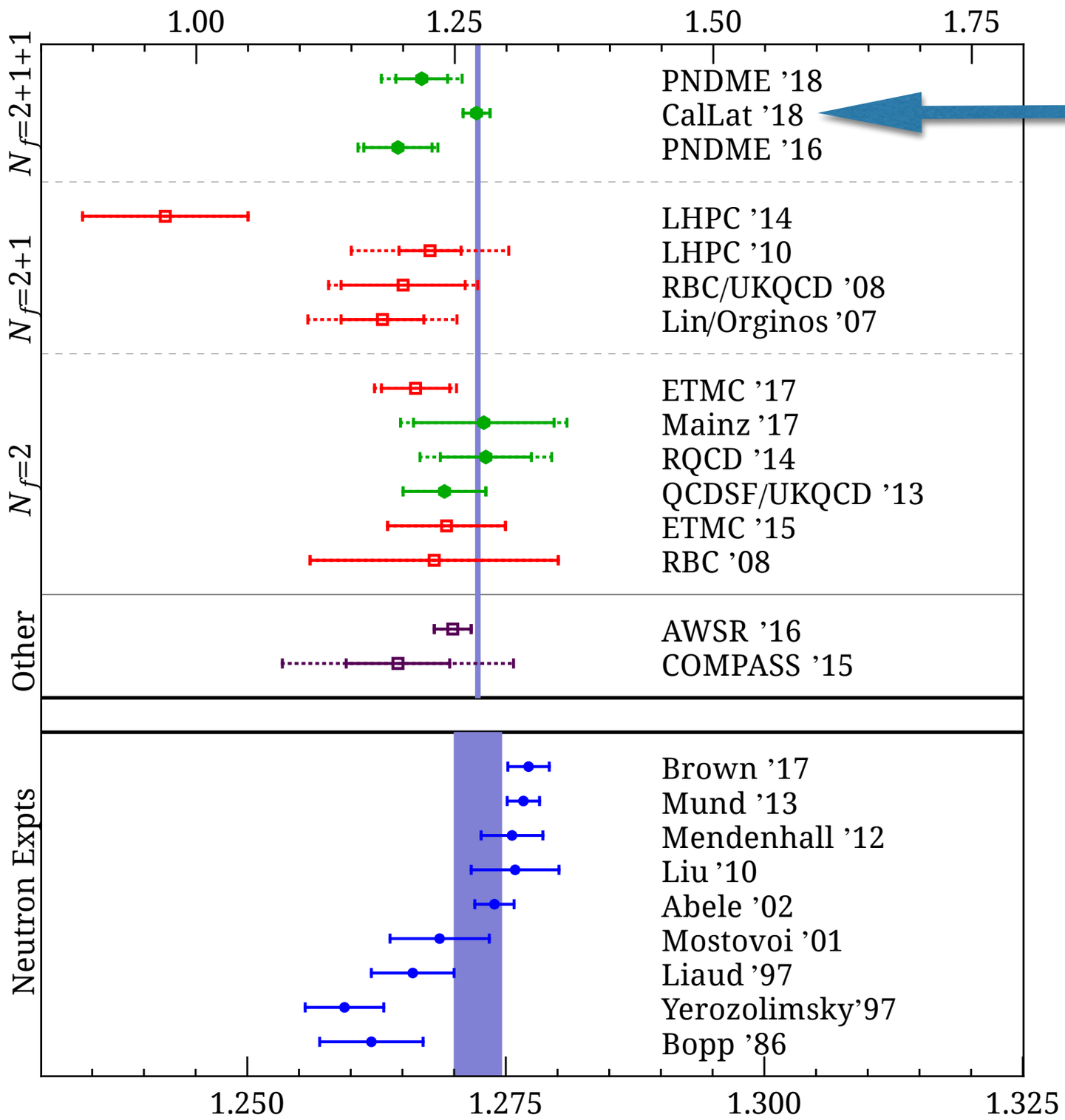
★ **Enter lattice QCD....**

[Bhattacharya et al., 2012]

Summary Snapshot

Nucleon axial isovector charge

g_A [Gupta et al. [PNDME '18], 1806.09006]



!!

[Chang et al. [CalLat], Nature 558, 91 (2018), 1805.12130]

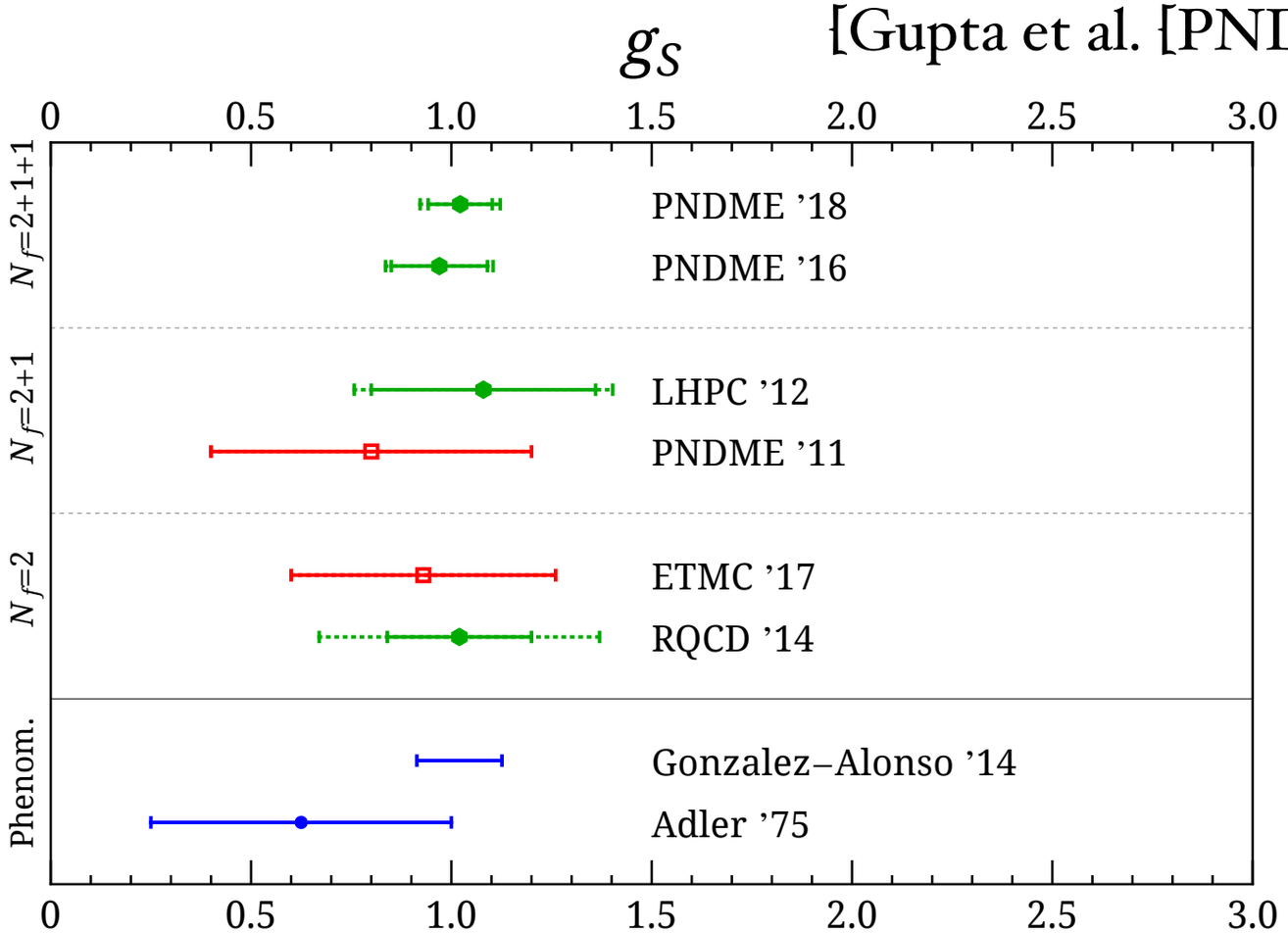
Recent g_A result of 1% precision in agreement w/ expt!

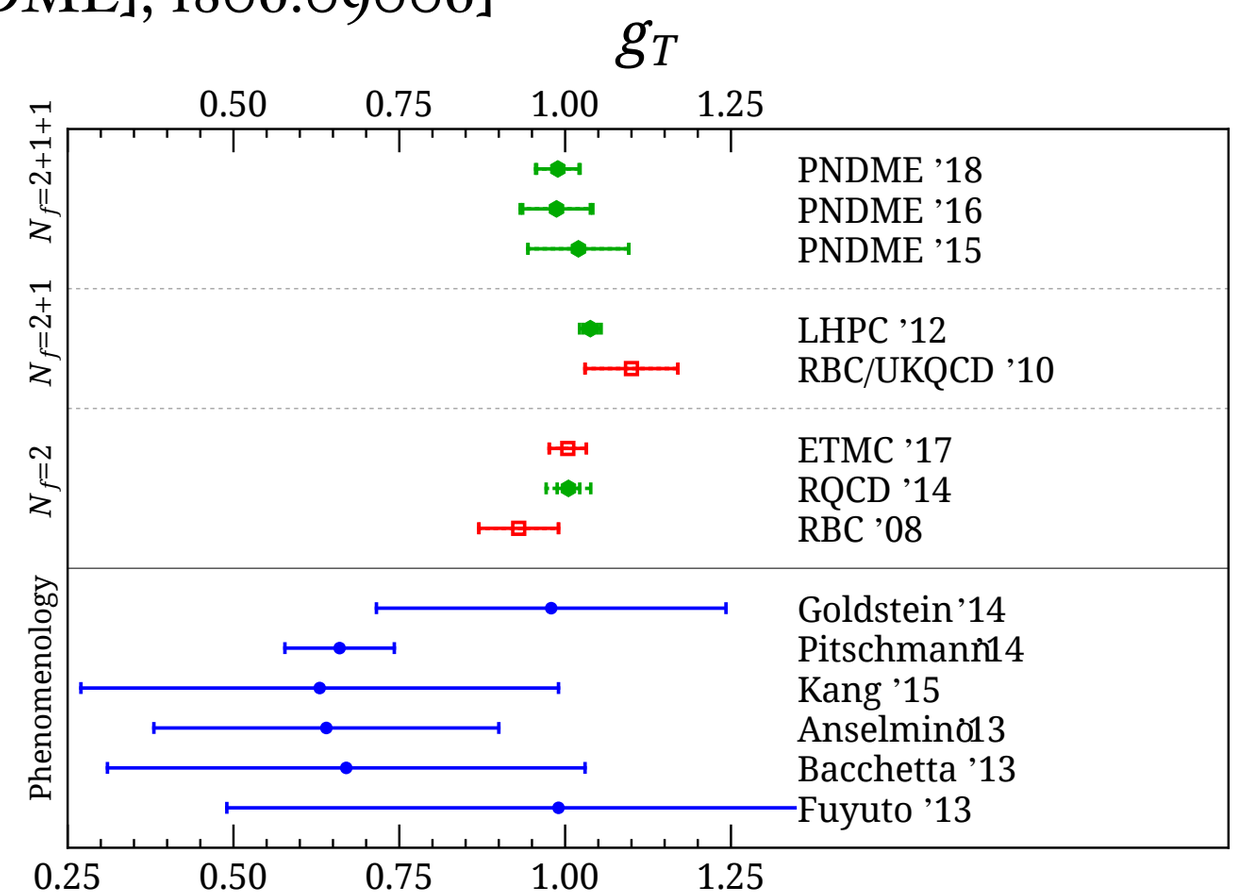
"Deep dive" by PNDME '18 reveals no serious disagreements

Summary Snapshots

Nucleon scalar and tensor isovector charges

[Gupta et al. [PNDME], 1806.09006]





Act to sharpen constraints on non-V-A currents from decay correlation measurements (esp. b)

Decay Correlations

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \frac{\vec{J}}{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e\,E_\nu} \right] + \ldots \right\}$$

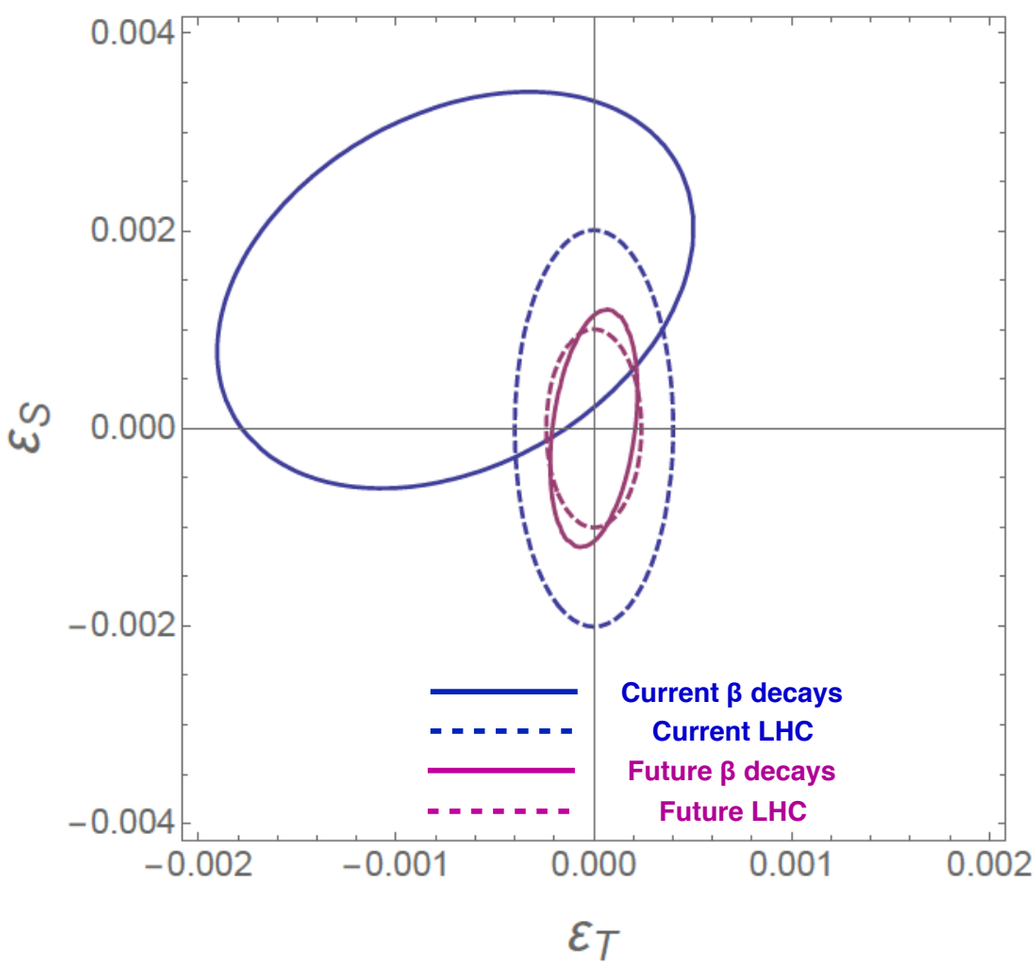
[Jackson, Treiman, Wyld, 1957]

If $J \neq 1/2$

$$b = \frac{2\gamma}{1+3\lambda^2}\left[g_S\,\mathrm{Re}(\epsilon_S) - 12\lambda\, g_T\,\mathrm{Re}(\epsilon_T) \right],$$

$$b_\nu = \frac{-2\gamma}{1+3\lambda^2}\left[g_S\,\mathrm{Re}(\epsilon_S)\,\lambda - 4 g_T\,\mathrm{Re}(\epsilon_T)\,(1-2\lambda) \right]$$

$$B(E_e) = B_0 + b_\nu m_e / E_e$$

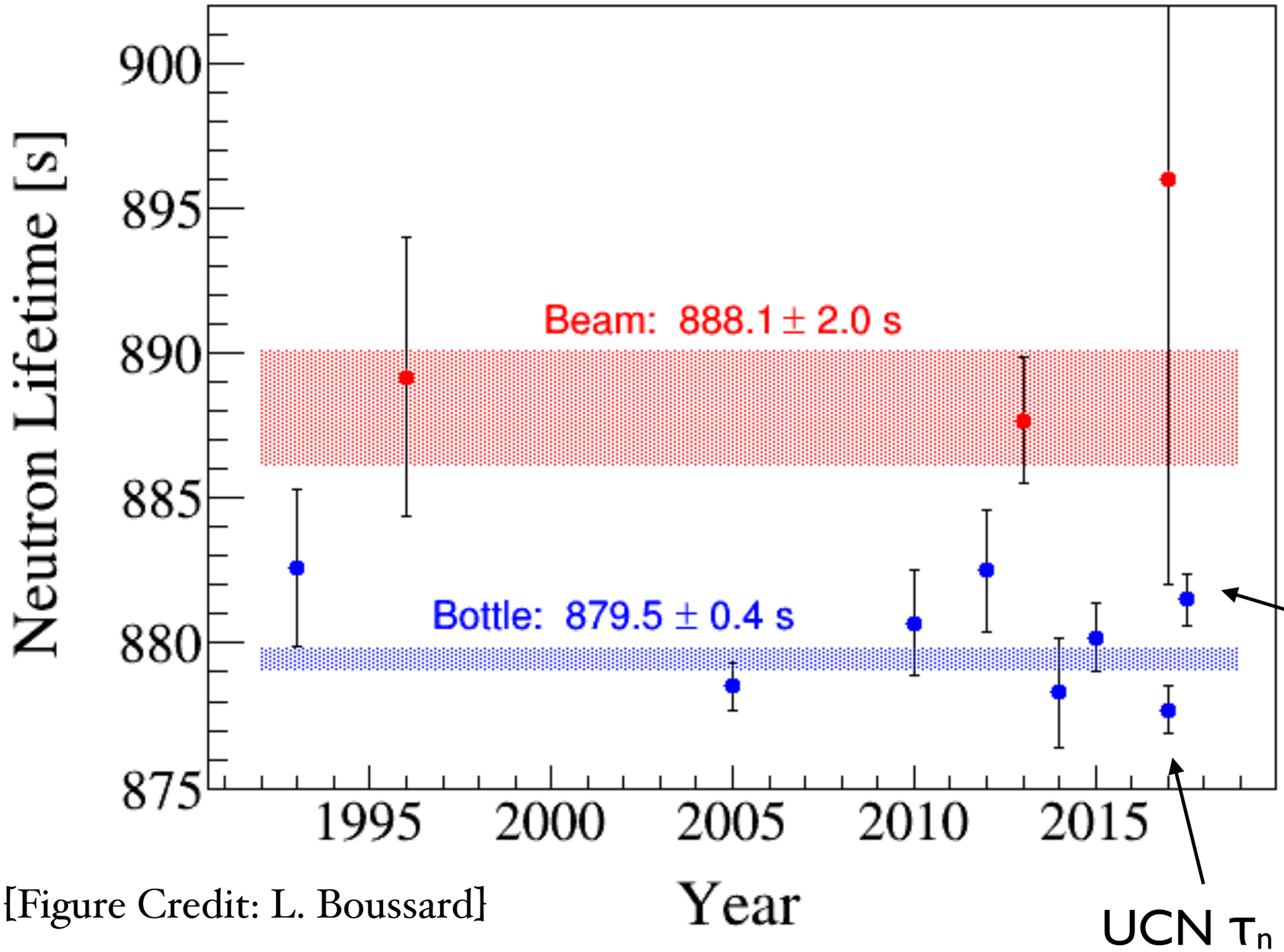


Comparison assumes $\Lambda_{BSM} > 13$ TeV

[Gupta et al. [PNDME], 1806.09006; current β decay from Gonzalez-Alonso et al, 1803.08752]

Analysis & forecast neglect second class currents [SG & Plaster, 2013]

The Neutron Lifetime Puzzle



(8.6 s, 4σ)

Count **protons** that appear

Serebrov

Count **neutrons** that persist

[Figure Credit: L. Boussard]

What if neutrons also decay invisibly?

[Recall early suggestion: Z. Berezhiani & "mirror neutrons"]

Possible Dark Decays

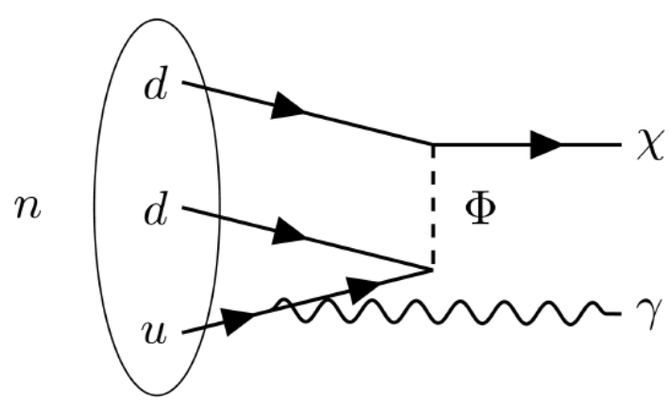
Modeled to solve the n lifetime puzzle

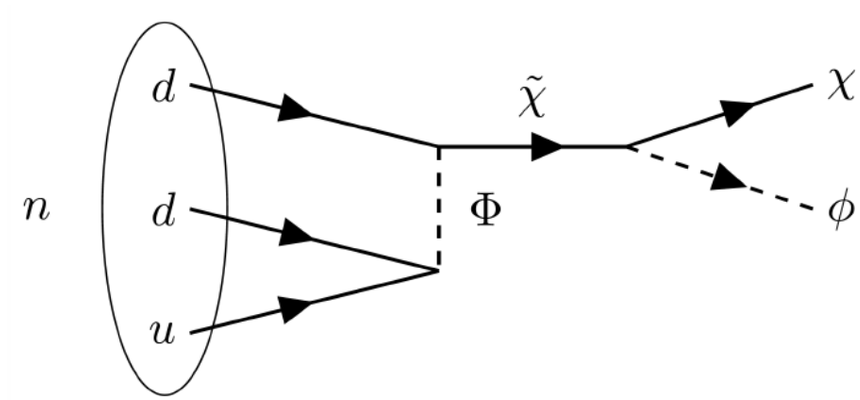
[Fornal & Grinstein, PRL, 2018]

Thus $\tau_n^{beam} = \tau_n^{bottle} / Br(n \rightarrow p + \text{anything})$

★ Visible Invisible ~99%

$$\mathcal{L}_1^{\text{eff}} = \bar{n}\left(i\partial\!\!\!/ - m_n + \frac{g_n e}{2m_n}\sigma^{\mu\nu}F_{\mu\nu}\right)n$$
$$+ \bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \varepsilon(\bar{n}\chi + \bar{\chi}n)$$

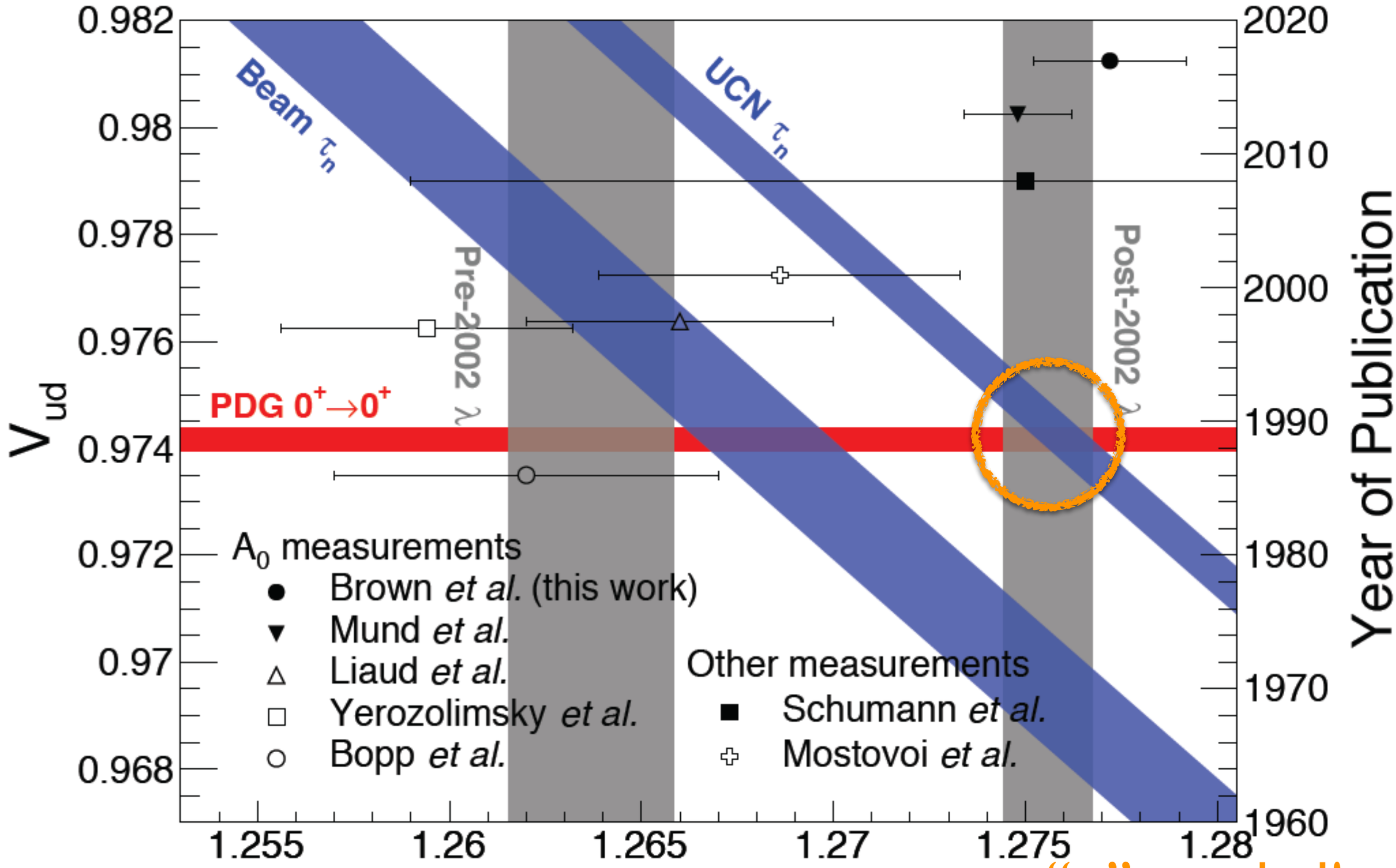




Enter Φ = (3, 1, -1/3) and χ a SM singlet

Select χ mass window to avoid **proton decay** & nuclear constraints

Status of V_{ud}



[Figure Credit: M. A. P. Brown]

[Czarnecki, Marciano, Sirlin, PRL 2018]

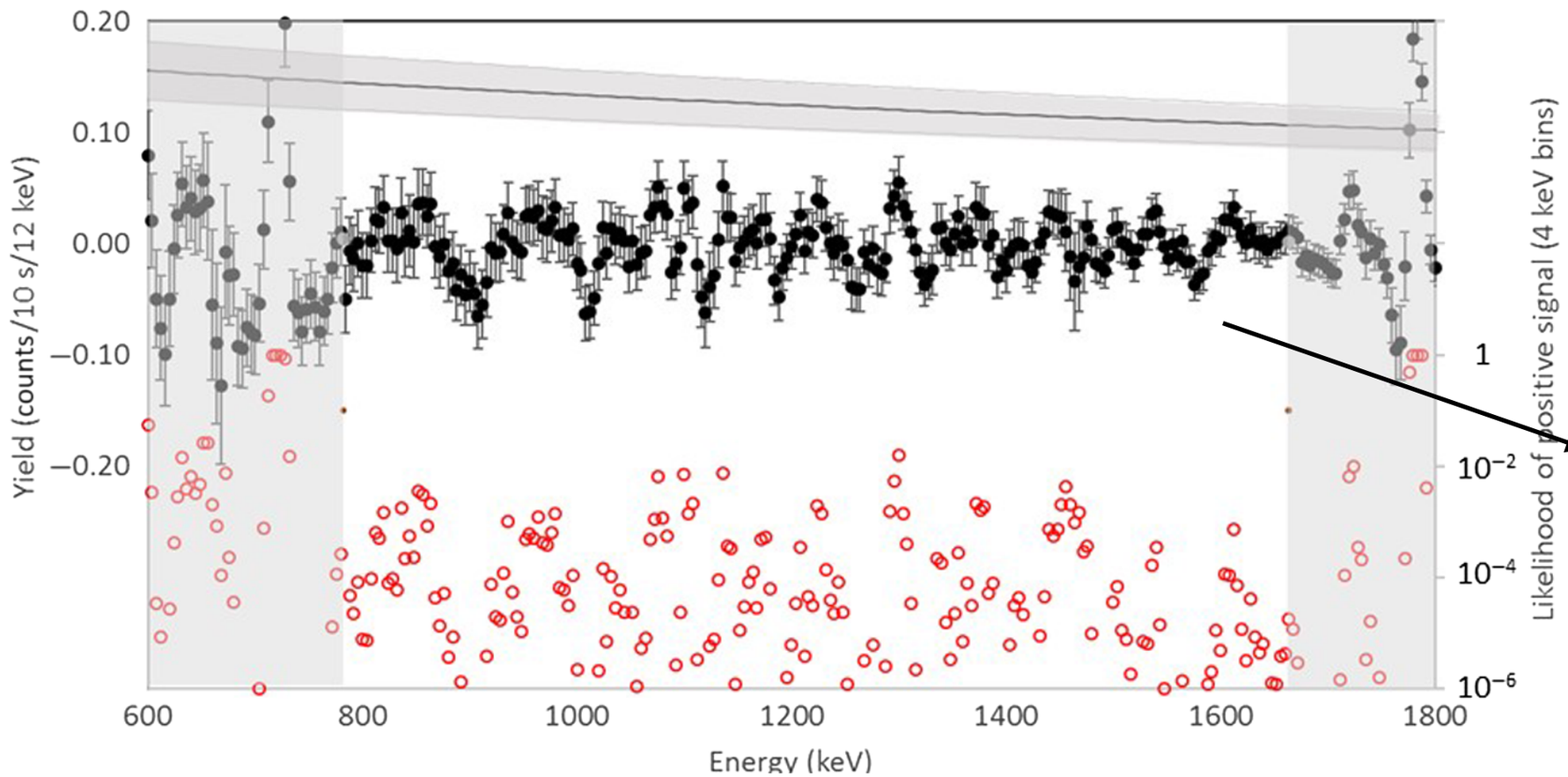
suggests no "χ" needed!

But note most recent bottle τ_n

Dark Aftermaths?

Particular models are now excluded

as explanations of the **entire** anomaly



expected yield $n \to \chi\gamma$

data

[Tang et al., PRL, 2018]

These models also run afoul of the existence of 2 $M_\odot$ neutron stars (unless χ is self-interacting or heavy)

[McKeen et al., 2018; Baym et al., 2018, Motta et al., 2018]

B-L Violation with Quarks

in collaboration with Xinshuai Yan

Origins of the Neutrino Mass

The Majorana mass and 0 ν ββ decay

A neutrino can have a Majorana mass if B-L symmetry is broken

(Enter the Weinberg operator $(v_{\underline{weak}}^2/\Lambda_{new})\ \nu_L^T\, C\, \nu_L$)

→ Or (and) the neutrino could have a Dirac mass

(Enter the right-handed neutrino & the Higgs mechanism)

But only B-L violation permits 0 ν ββ decay

However, 0 ν ββ decay need not mediated by the exchange of a light Majorana ν (other sources could act); though its observation would show it effectively exists

[Schechter & Valle, 1982]

Mechanisms of 0ν ββ decay

Why the energy scale of B-L violation matters

If it is generated by the Weinberg operator, then SM electroweak symmetry yields $m_\nu = \lambda v_{\rm weak}^2/\Lambda$. If $\lambda \sim 1$ and $\Lambda \gg v_{\rm weak}$, then naturally $m_\nu \ll m_f$!
N.B. if $m_\nu \sim 0.2$ eV, then $\Lambda \sim 1.6 \times 10^9$ GeV!

Alternatively it could also be generated by higher dimension $|\Delta L| = 2$ operators, so that m_ν is small just because $d \gg 4$ and Λ need not be so large.

[EFTs: Babu & Leung, 2001; de Gouvea & Jenkins, 2008 and many models]

Can we establish the scale of $\mathcal{B} - \mathcal{L}$ violation in another way?

N.B. searches for same sign dilepton final states at the LHC also constrain the higher dimension ("short range") operators. [Helo, Kovalenko, Hirsch, and Päs, 2013]

Here we consider B-L violation in the quark sector: via n-$\bar{\text{n}}$ transitions

Neutron-Antineutron Transitions

Can be realized in different ways

Enter searches for

- neutron-antineutron oscillations (free n's & in nuclei)

"spontaneous"
& thus sensitive to
environment

$$\mathcal{M} = \begin{pmatrix} M_n - \mu_n B & \delta \\ \delta & M_n + \mu_n B \end{pmatrix}$$

$$P_{n\to\bar{n}}(t) \simeq \frac{\delta^2}{2(\mu_n B)^2}\left[1 - \cos(2\mu_n B t)\right]$$

- dinucleon decay (in nuclei)
  (limited by finite nuclear density)
- neutron-antineutron conversion (NEW!)

[SG & Xinshuai Yan, arXiv:1710.09292, PRD 2018 (also arXiv:1602.00693, PRD 2016)]

Effective Lagrangian

Neutron interactions with B-L violation & electromagnetism

$$\mathcal{L}_{\rm eff} \supset -\frac{1}{2}\mu_n \bar{n}\sigma^{\mu\nu} n F_{\mu\nu} - \frac{\delta}{2} n^T C n - \frac{\eta}{2} n^T C \gamma^\mu \gamma^5 n j_\mu + \text{h.c.}$$

$[\, Q e j^\nu = \partial_\mu F^{\mu\nu} \,]$

magnetic moment

$n \to \bar{n}$ conversion

"spontaneous" → $n \to \bar{n}$ oscillation

[SG & Xinshuai Yan, arXiv: 1710.09292, PRD 18]

Since the quarks carry electric charge, a BSM model that generates neutron-antineutron oscillations can also generate conversion (here $e^- n \to e^- \bar{n}$)

Patterns of $|\Delta B|=2$ Violation?

Minimal scalar-fermion models give connections

[SG & Xinshuai Yan, arXiv: 1808.nnnn]

Note such models of $n \to \bar{n}$ oscillation without p decay

[Arnold, Fornal, Wise, PRD, 2013]

Enter new scalars X_i that respect SM gauge symmetry and interactions $X_iX_jX_k$ or $X_iX_jX_kX_l$ — cf. "hidden sector" searches: possible masses are limited by experiment

Here products of different new scalars give $n \to \bar{n}$ oscillation and $n\bar{n}$ conversion ($e^- p \to e^+ \bar{p}$, …), and thus can predict $\pi^-\pi^- \to e^-e^-$!

Summary

- The long-standing g_A problem in LQCD appears to have been finally solved!
- The possibility of light, dark physics in neutron decay has generated intense interest — with no end as yet!

- The energy scale of B-L violation speaks to different explanations as to why the neutrino is light (A “TeV scale” mechanism could also generate B-L violation in the quark sector)

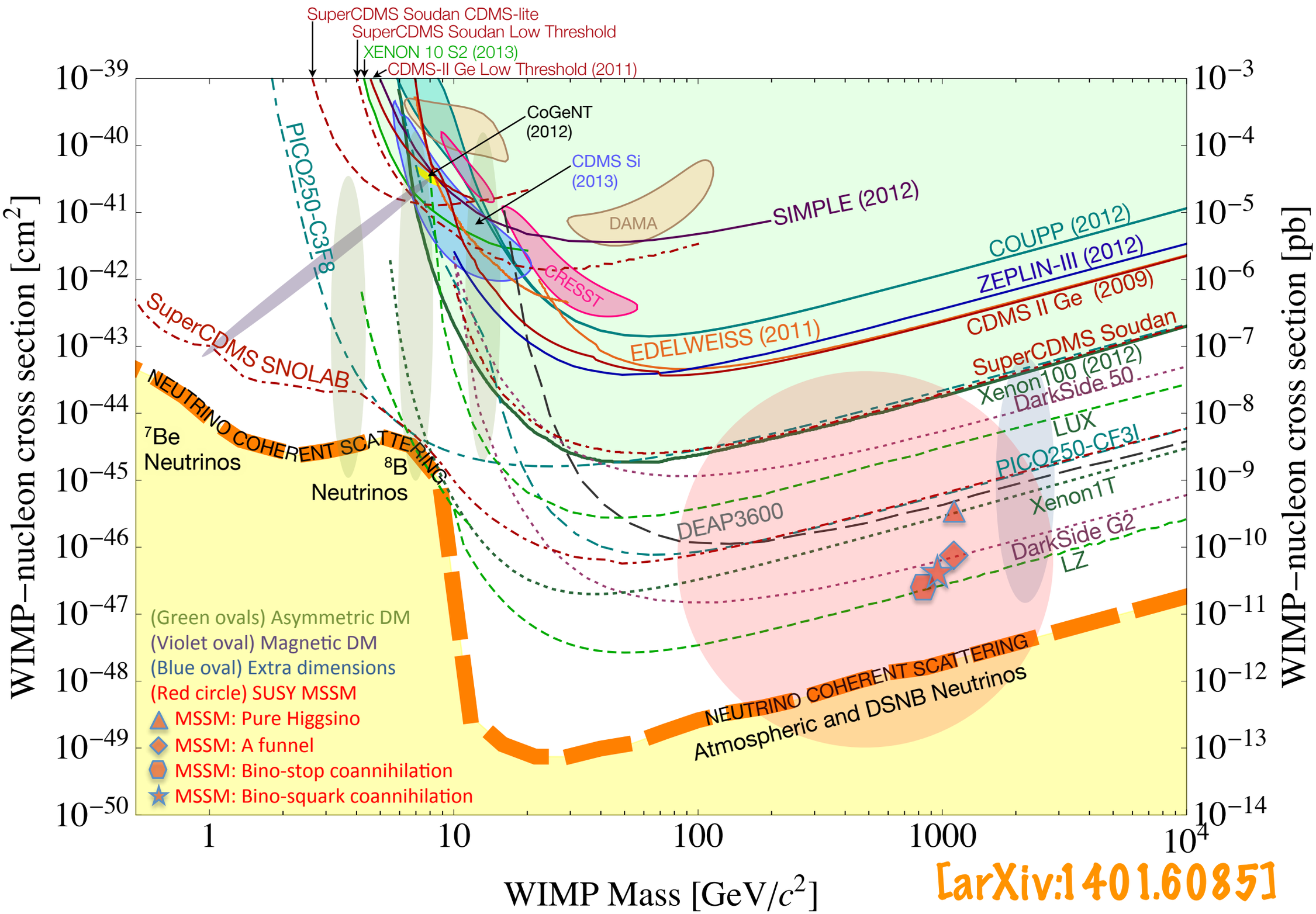
- We have noted neutron-antineutron conversion, i.e., neutron-antineutron transitions as mediated by an external current (as via scattering)

- Experiments with intense low-energy electron beams, e.g., can also be used to search for B-L violation & help solve the ν mass puzzle

Backup Slides

Direct Detection: Dark Matter "WIMPs"

Limits rely on local DM density and velocity distribution



[arXiv:1401.6085]

Theoretical Framework

Fixing the Fermi constant

$G_F^{(0)}/\sqrt{2} = g^2/8M_W^2$ is fixed from muon decay

$$\mathcal{L}_{\mu\to e\bar{\nu}_e\nu_\mu} = -4\,G_F^{(0)}\,(1+\delta_\mu+\epsilon_\mu)\;\bar{e}_L\gamma_\mu\nu_{eL}\cdot\bar{\nu}_{\mu L}\gamma^\mu\mu_L \;+\; \text{h.c.}$$

[van Ritbergen & Stuart, 2000]

[N.B. MuLan expt, Chitwood, 2007]

$$G_\mu \equiv G_F^{(0)}(1+\delta_\mu+\epsilon_\mu)$$

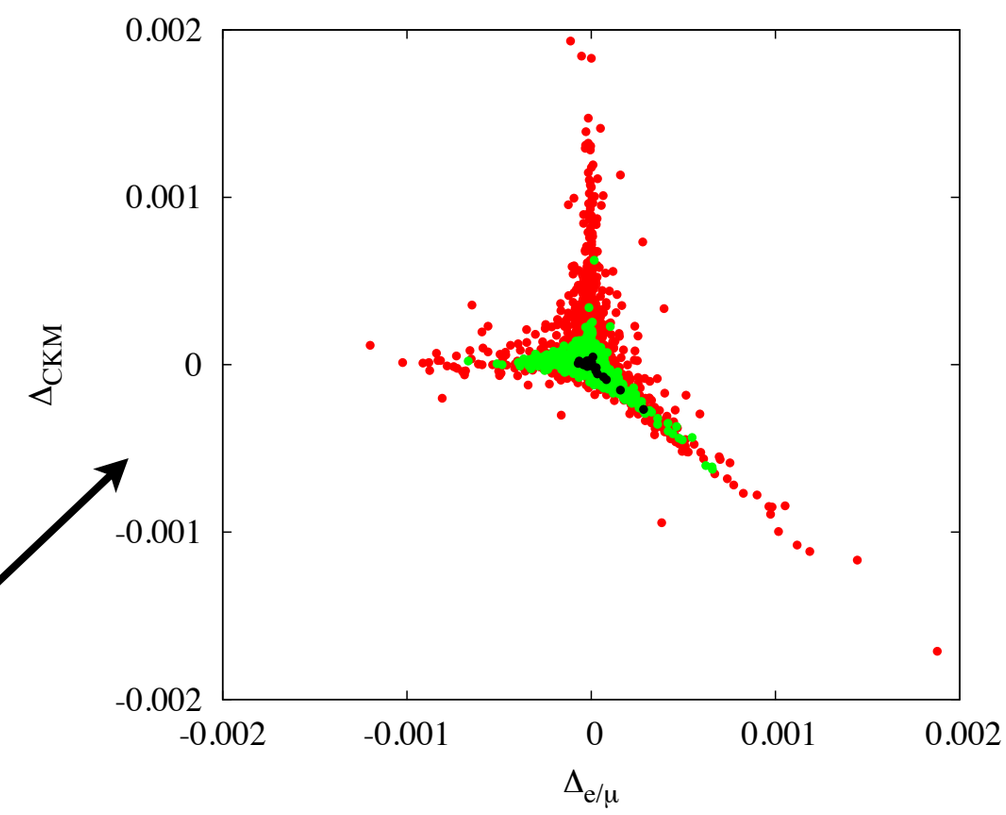
New physics!

Thus testing CKM unitarity probes weak universality!

Also each extracted V_{ij} can contain BSM effects

N.B. explicit studies in the MSSM...

[Kurylov & Ramsey-Musolf, 2002; Bauman, Erler, Ramsey-Musolf, 2012]



n - n̄ Transitions & Spin

Spin can play a role in a "mediated" process

A neutron-antineutron **oscillation** is a spontaneous process & thus the spin does not ever flip

However,

$$\mathcal{O}_4 = \psi^T C \gamma^\mu \gamma_5 \psi \, \partial^\nu F_{\mu\nu} + \text{h.c.}$$

$n(+) \to \bar{n}(-)$ occurs directly because the interaction with the current flips the spin.

This is concomitant with $n(p_1, s_1) + n(p_2, s_2) \to \gamma^*(k)$, for which only $L = 1$ and $S = 1$ is allowed via angular momentum conservation and Fermi statistics. [Berezhiani and Vainshtein, 2015]

Here $e + n \to \bar{n} + e$, e.g., so that the experimental concept for "$n\bar{n}$ conversion" would be completely different.

Neutron-Antineutron Conversion

Different mechanisms are possible

* n-$\bar{n}$ conversion and oscillation could share the same "TeV" scale BSM sources
  → Then the quark-level conversion operators can be derived noting the quarks carry electric charge

* n-$\bar{n}$ conversion and oscillation could come from different BSM sources
  → Then the neutron-level conversion operators could also be different

Note studies of scattering matrix elements of Majorana dark matter [Kumar & Marfatia, PRD, 2013]

Theoretical Framework

On non "V-A" currents

$$\mathcal{L}^{\rm eff} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[\Big(1+\delta_\beta\Big)\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

$$+ \quad \epsilon_L\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d + \tilde{\epsilon}_L\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

$$+ \quad \epsilon_R\, \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d + \tilde{\epsilon}_R\, \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$+ \quad \epsilon_S\, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \tilde{\epsilon}_S\, \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d$$

$$- \quad \epsilon_P\, \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d - \tilde{\epsilon}_P\, \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+ \quad \epsilon_T\, \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \tilde{\epsilon}_T\, \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d$$

$$+ \quad \text{h.c.}\ .$$

ϵ_S , ϵ_T enter in linear order!

"most visible"

$$R_\pi \equiv \Gamma(\pi \to e\nu[\gamma])/\Gamma(\pi \to \mu\nu[\gamma]).$$

$\epsilon_L + \epsilon_R$	CKM unitarity
$\epsilon_L - \epsilon_R,\ \ \epsilon_P,\ \ \tilde{\epsilon}_P$	R_π
ϵ_S	$b,\ B\ \ [a,\ A]$
ϵ_T	$b,\ B\ \ [a,\ A],\ \ \pi \to e\nu\gamma$
$\tilde{\epsilon}_{\alpha\neq P}$	R_π