New CP Tests in Low Energy QCD

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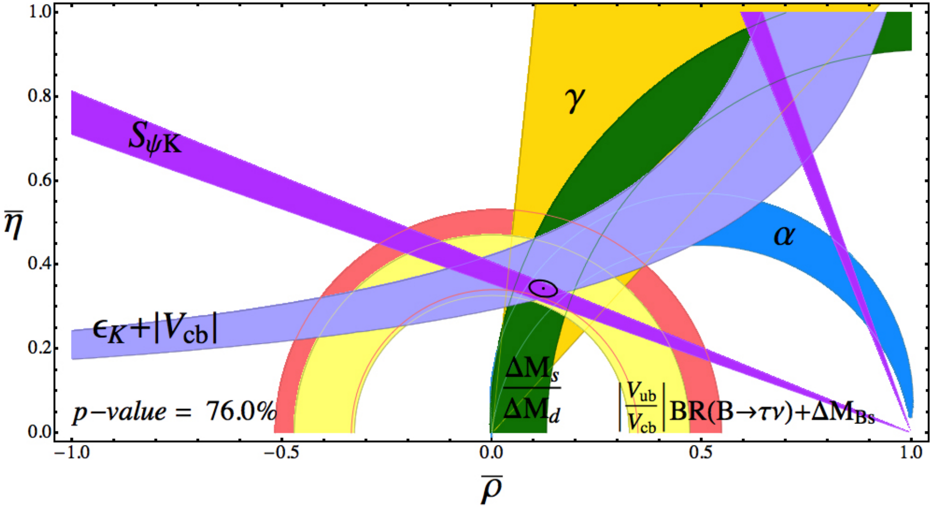
Known Flavor and CP Violation are CKM-like



[2013 update (th+exp) of Laiho, Lunghi, van de Water, arXiv:0910.2928]

Evidence for New CP Phases:

We live in a known Universe of matter.

Confronting the observed ^{2}H abundance with big-bang nucleosynthesis yields a **baryon asymmetry**

$$\eta = n_{\rm baryon}/n_{\rm photon} = (5.96 \pm 0.28) \times 10^{-10}$$ [Steigman, 2012]

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, 1967]

But the SM cannot explain it! [Farrar and Shaposhnikov, 1993; Gavela et al., 1994; Huet and Sather, 1995.]

One Reason: CP violation in the SM is special: it appears only if

$$\begin{aligned} J_{CP} &= (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_u^2)(m_s^2 - m_d^2) \\ &\times \; {\rm Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \neq 0 \end{aligned}$$

Now ${\rm Im}(V_{tb} V_{td}^* V_{cd} V_{cb}^*) \sim 3 \times 10^{-5}$ [Jarlskog, 1985] so that

$$n_{\rm baryon}/n_{\rm photon} \sim J_{CP}/T_c^{12} \sim 1 \times 10^{-19} \; (!)$$

Ergo to explain the BAU there must be sources of CP violation beyond the CKM matrix.

What's Next?!

We can

i) continue to test the **relationships** that a single CP-violating parameter entails to higher precision

– as well as –

ii) continue to make "null" tests.
e.g., EDMs, as they are inaccessibly small in the (C)KM model. Beta-decay correlations also give T-odd "null" tests.

Limits on permanent EDMs of nondegenerate systems and T-odd correlations in β-decays probe new sources of CP violation. All these observables necessarily involve spin.

Here we consider the possibility of new null tests of CP violation — without spin!

CP-odd Observables

Enter Dalitz studies of $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$.

Connects to studies in untagged B-meson decays — breaking the mirror symmetry of the Dalitz plot breaks CP!

[SG, SG and Jusak Tandean, 2003]

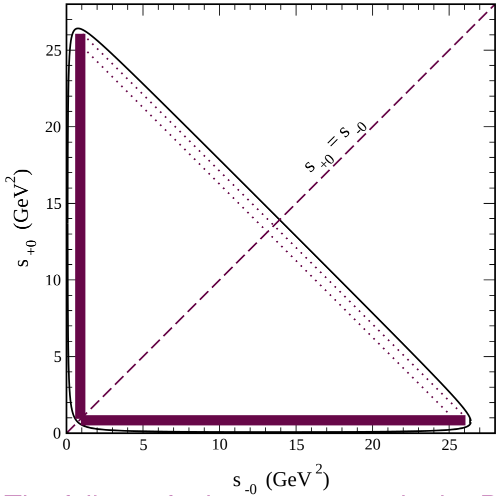
T-odd Correlations

Such can only be motion-reversal odd; they are not true tests of T.
In β decay, the mimicking FSI are electromagnetic and can be computed.

In *radiative* β-decay we can form a T-odd correlation from momenta alone: $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, so that we probe new physics sources which are not constrained by EDM limits. [SG and Daheng He, 2012, 2013]

Here we probe CP violation under the CPT theorem.

Dalitz Studies of CP Violation in $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$



The failure of mirror symmetry in the Dalitz plot in η or η' decay (or of the **untagged** decay rate in B, $\bar{B}$ or D, $\bar{D}$ decay) to $\pi^+\pi^-\pi^0$ signals the presence of CP violation.

Anatomy of CP Violation in $\Gamma(M_{C=+} \to \pi^+\pi^-\pi^0)$

The breaking of **mirror symmetry** can be realized in two disjoint ways. To see this, let

$$CP|\pi^0\rangle = -|\pi^0\rangle \quad , \quad CP|\pi^+\rangle = \eta_\pi|\pi^-\rangle \, ,$$

Working in the rest frame of the two pions coupled to angular momentum l,

$$P\Big|\left[\pi_1(\boldsymbol{p})\,\pi_2(-\boldsymbol{p})\right]_l \pi_3(\boldsymbol{p}')_l\Big\rangle = -\Big|\left[\pi_1(\boldsymbol{p})\,\pi_2(-\boldsymbol{p})\right]_l \pi_3(\boldsymbol{p}')_l\Big\rangle \, ,$$

$$C\Big|\left[\pi^+(\boldsymbol{p})\,\pi^-(-\boldsymbol{p})\right]_l \pi^0(\boldsymbol{p}')_l\Big\rangle = (-1)^l\Big|\left[\pi^-(-\boldsymbol{p})\,\pi^+(\boldsymbol{p})\right]_l \pi^0(\boldsymbol{p}')_l\Big\rangle \, .$$

It follows that

$$CP\Big|\left[\pi^+(\boldsymbol{p})\,\pi^-(-\boldsymbol{p})\right]_l \pi^0(\boldsymbol{p}')_l\Big\rangle = (-1)^{l+1}\Big|\left[\pi^-(-\boldsymbol{p})\,\pi^+(\boldsymbol{p})\right]_l \pi^0(\boldsymbol{p})_l\Big\rangle \, ,$$

$$CP\Big|\left[\pi^-(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})\right]_l \pi^+(\boldsymbol{p}')_l\Big\rangle = -\Big|\left[\pi^+(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})\right]_l \pi^-(\boldsymbol{p}')_l\Big\rangle \, .$$

The resonance content of the Dalitz plot distinguishes the various 3π final states.

Anatomy of CP Violation in $\Gamma(M_{\mathrm{C}=+} \to \pi^+\pi^-\pi^0)$

C-odd, P-even

This can be generated by $s - p$ interference of $\left|[\pi^+(\boldsymbol{p})\,\pi^-(-\boldsymbol{p})]_l \pi^0(\boldsymbol{p}')_l\right\rangle$ final states of 0^- meson decay.
It is linear in a CP-violating parameter.
This contribution **cannot** be generated by $\bar{\theta}_{\mathrm{QCD}}$!
"C violation" [Lee and Wolfenstein, 1965; Lee, 1965, Nauenberg, 1965; Bernstein, Feinberg, and Lee, 1965]

C-even, P-odd

This can be generated by the interference of amplitudes which distinguish $\left|[\pi^-(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})]_l\,\pi^+(\boldsymbol{p}')_l\right\rangle$ from $\left|[\pi^+(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})]_l\,\pi^-(\boldsymbol{p}')_l\right\rangle$ as in, e.g., $B \to \rho^+\pi^-$ vs. $B \to \rho^-\pi^+$. "CP-enantiomers" [SG, 2003]
This possibility is not accessible in $\eta \to \pi^+\pi^-\pi^0$ decay (but in η' decay, yes). Thus a "left-right" asymmetry in $\eta \to \pi^+\pi^-\pi^0$ decay tests C-invariance, too.

Searching for a Broken Mirror

The population asymmetry (or left-right asymmetry) across the mirror line of the Dalitz plot is

$$\mathcal{A}_{3\pi} \equiv \frac{\Gamma_{3\pi}\left[s_{+0}>s_{-0}\right] - \Gamma_{3\pi}\left[s_{+0}<s_{-0}\right]}{\Gamma_{3\pi}\left[s_{+0}>s_{-0}\right] + \Gamma_{3\pi}\left[s_{+0}<s_{-0}\right]}$$

Currently, in $\eta \to \pi^+\pi^-\pi^0$:
$A_{\rm LR} = (+0.09 \pm 0.10\ {}^{+0.09}_{-0.14}) \times 10^{-2}$

[Ambrosino et al. [KLOE], 2008]

The background reduction associated with boosted η decay at the JEF should help control systematics.

A "charge asymmetry" in $B, \bar{B} \to \rho^\pm\pi^\mp$ has also been reported by BaBar.

To understand what we constrain we must turn to an operator analysis. This is in progress.

To illustrate, we review recent work in the analysis of β-decay....

Effective Operator Analysis for β Decay

The Lee-Yang Hamiltonian [Lee and Yang, 1956; note also Gamow and Teller, 1936]

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

can be recovered in an EFT framework by writing the dimension-6 quark-level operators which can appear [Buchmüller and Wyler, 1986; Grzadkowski et al., 2010] (include those mediated by ν_R: [Cirigliano, Gonzalez-Alonso, and Graesser, 2013]) after EWSB as

$$\mathcal{L}^{\rm eff} = \mathcal{L}_{SM} + \sum_i \frac{1}{\Lambda_i^2} O_i$$

and then matching to the nucleon-level EFT.

There is a one-to-one map between the Lee-Yang parameters and the EFT.

[Cirigliano, Gonzalez-Alonso, and Graesser, 2013]

EFT methods have also been used to classify P-odd, T-odd operators in the nucleon sector [e.g., de Vries et al., 2013]; one wants to follow a similar path here....

T-odd Correlations

In neutron β decay, triple product correlations are spin dependent.
Major experimental efforts have recently been concluded.

D term [Mumm et al., 2011; Chupp et al., 2012]

D probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \boldsymbol{p}_\nu)$ and is T-odd, P-even.
$D = [-0.94 \pm 1.89(\text{stat}) \pm 0.97(\text{sys})] \times 10^{-4}$ (best ever!)
D_{FSI} is well-known (N^3LO) and some $10\times$ smaller. [Callan and Treiman, 1967; Ando et al., 2009]
D limits the phase of C_A/C_V...

R term [Kozela et al., 2009; Kozela et al., 2012]

Here the transverse components of the electron polarization are measured.

R probes $\boldsymbol{J} \cdot (\boldsymbol{p}_e \times \hat{\boldsymbol{\sigma}})$ and is T-odd, P-odd.
N probes $\boldsymbol{J} \cdot \hat{\boldsymbol{\sigma}}$ and gives a non-zero check.

$R = 0.004 \pm 0.012(\text{stat}) \pm 0.005(\text{sys})$
R limits the imaginary parts of scalar, tensor interactions...

In contrast, in radiative β-decay one can form a T-odd correlation from momenta alone, $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$, so that the spin does not enter.

Anomalous interactions at low energies

What sort of interaction gives rise to a $\mathbf{p}_\gamma \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$ correlation at low energy?

Harvey, Hill, and Hill: Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ makes the baryon vector current anomalous and gives rise to "Chern-Simons" contact interactions (containing $\varepsilon^{\mu\nu\rho\sigma}$) at low energy.

[Harvey, Hill, and Hill (2007, 2008)]

In a chiral Lagrangian with nucleons, pions, and a complete set of electroweak gauge fields, the requisite terms appear at N^{2}LO in the chiral expansion. [Hill (2010); note also Fettes, Meißner, Steininger (1998) (isovector)]

Integrating out the $W^\pm$ yields

$$-\frac{4c_5}{M^2}\frac{eG_F V_{ud}}{\sqrt{2}}\varepsilon^{\sigma\mu\nu\rho}\bar{p}\gamma_\sigma n\bar{\psi}_{eL}\gamma_\mu\psi_{\nu_e L}F_{\nu\rho}\,,$$

which can infere with (dressed by a bremsstrahlung photon)

$$\frac{G_F V_{ud}}{\sqrt{2}}g_V\bar{p}\gamma^\mu n\bar{\psi}_e\gamma_\mu(1-\gamma_5)\psi_{\nu_e}\,,$$

Thus the weak vector current can mediate parity violation, too.

Radiative β-Decay

In $n(p_n) \to p(p_p) + e^-(l_e) + \overline{\nu}_e(l_\nu) + \gamma(k)$ decay the interference of the c_5 term with the leading $V - A$ terms yields

$$|\mathcal{M}|^2_{c_5} = 256 e^2 G_F^2 |V_{ud}|^2 \mathrm{Im}\,(c_5\, g_V) \frac{E_e}{l_e \cdot k} (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu + \ldots \,,$$

neglecting corrections of radiative and recoil order.
Note EMIT II limits $\mathrm{Im}\, g_V < 7 \cdot 10^{-4}$ (68%CL). [Mumm et al., 2011; Chupp et al., 2012]
First row CKM unitarity yields $\mathrm{Im}\, g_V < 2 \cdot 10^{-2}$ (68%CL).
Defining $\xi \equiv (\mathbf{l}_e \times \mathbf{k}) \cdot \mathbf{l}_\nu$, we form an asymmetry:

$$\mathcal{A}(\omega_{\min}) \equiv \frac{\Gamma_+(\omega_{\min}) - \Gamma_-(\omega_{\min})}{\Gamma_+(\omega_{\min}) + \Gamma_-(\omega_{\min})} \,,$$

where $\Gamma_\pm$ contains an integral of the spin-averaged $|\mathcal{M}|^2$ over the region of phase space with $\xi \gtrless 0$, respectively, neglecting corrections of recoil order.

Results

Table: T-odd asymmetries in units of $\mathrm{Im}\,[g_V(c_5/M^2)]\,[\mathrm{MeV}^{-2}]$ for neutron, $^{19}\mathrm{Ne}$, and $^{35}\mathrm{Ar}$ radiative β decay.

$\omega_{\min}(\mathrm{MeV})$	$\mathcal{A}^{\mathrm{HHH}}(n)$	$\mathrm{BR}(n)$	$\mathcal{A}^{\mathrm{HHH}}(^{19}\mathrm{Ne})$	$\mathrm{BR}(^{19}\mathrm{Ne})$
0.01	-5.61×10^{-3}	3.45×10^{-3}	-3.60×10^{-2}	4.82×10^{-2}
0.05	-1.30×10^{-2}	1.41×10^{-3}	-6.13×10^{-2}	2.82×10^{-2}
0.1	-2.20×10^{-2}	7.19×10^{-4}	-8.46×10^{-2}	2.01×10^{-2}
0.3	-5.34×10^{-2}	8.60×10^{-5}	-0.165	8.86×10^{-3}

Limits on $\mathrm{Im}(c_5)$ come only from the empirical radiative β decay BR: $|\mathrm{Im}(c_5/M^2)| < 12\,\mathrm{MeV}^{-2}$ **at 68% C.L.**

In constrast the Lee-Yang Hamiltonian yields ($C_i^{(\prime)} \equiv G_F V_{ud}\tilde{C}_i^{(\prime)}/\sqrt{2}$)

$$|\mathcal{M}|^2_{\mathrm{T-odd,LY}} = 16e^2 G_F^2 |V_{ud}|^2 M \mathbf{I}_\nu \cdot (\mathbf{l}_e \times \mathbf{k}) \frac{1}{l_e \cdot k} \mathrm{Im}[\tilde{C}_T(\tilde{C}_S'^* + \tilde{C}_P'^*) + \tilde{C}_T'(\tilde{C}_S^* + \tilde{C}_P^*)]$$

With $\mathrm{Im}\,\mathcal{C}_{\mathrm{LY}} \equiv \mathrm{Im}[\tilde{C}_T(\tilde{C}_S'^* + \tilde{C}_P'^*) + \tilde{C}_T'(\tilde{C}_S^* + \tilde{C}_P^*)]$, we have for $\omega^{\min} = 0.3\,\mathrm{MeV}$, in units of $\mathrm{Im}\,\mathcal{C}_{\mathrm{LY}}$

$$\mathcal{A}^{\mathrm{LY}}(n) = 5.21\times10^{-6} \quad ; \quad \mathcal{A}^{\mathrm{LY}}(^{19}\mathrm{Ne}) = 4.53\times10^{-7} \quad ; \quad \mathcal{A}^{\mathrm{LY}}(^{35}\mathrm{Ar}) = 8.63\times10^{-7}$$

These asymmetries are negligible cf. to $\mathrm{Im}(c_5)$.

Electromagnetic Simulation of T-Odd Effects

We first compute $\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}}$ and then the asymmetry. We work in $\mathcal{O}(\alpha)$ and in **leading recoil order**.

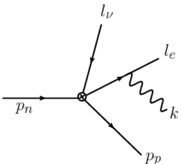
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{tree}}|^2 + \mathcal{M}_{\mathrm{tree}} \cdot \mathcal{M}^*_{\mathrm{loop}} + \mathcal{M}_{\mathrm{loop}} \cdot \mathcal{M}^*_{\mathrm{tree}} + \mathcal{O}(\alpha^2)$$

$$\overline{|\mathcal{M}|^2}_{\mathrm{T-odd}} \equiv \frac{1}{2}\sum_{\mathrm{spins}} |\mathcal{M}|^2_{\mathrm{T-odd}} = \frac{1}{2}\sum_{\mathrm{spins}} (2\mathrm{Re}(\mathcal{M}_{\mathrm{tree}} i \mathrm{Im}\mathcal{M}^*_{\mathrm{loop}}))$$

Note “Cutkosky cuts” [Cutkosky, 1960]

$$\mathrm{Im}(\mathcal{M}_{\mathrm{loop}}) = \frac{1}{8\pi^2}\sum_n \int d\rho_n \sum_{s_n} \mathcal{M}_{fn}\mathcal{M}^*_{in} = \frac{1}{8\pi^2}\int d\rho_n \sum_{s_n} \mathcal{M}_{fn}\mathcal{M}_{ni}$$

There are many cancellations. At tree level



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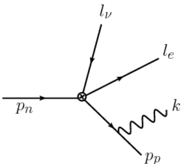
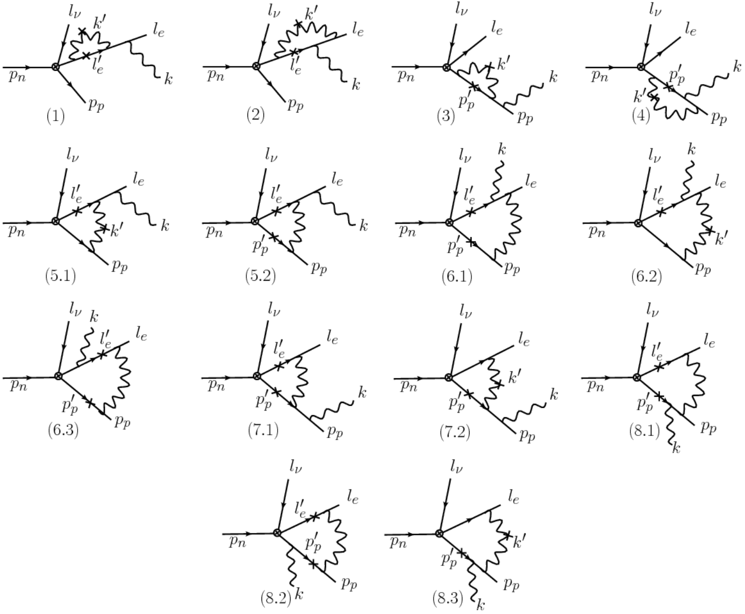


(02)

The Family of Two-Particle Cuts in $\mathcal{O}(e^3)$



Results

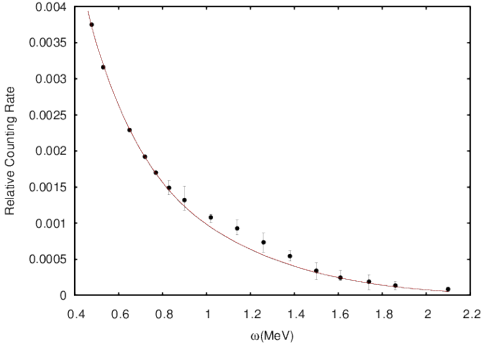
Table: Asymmetries from SM FSI in various weak decays. The range of the opening angle between the outgoing electron and photon is chosen to be $-0.9 < \cos(\theta_{e\gamma}) < 0.9$.

$\omega_{\rm min}$(MeV)	$\mathcal{A}^{\rm FSI}(n)$	$\mathcal{A}^{\rm FSI}(^{19}{\rm Ne})$	$\mathcal{A}^{\rm FSI}(^{35}{\rm Ar})$
0.01	1.76×10^{-5}	-2.86×10^{-5}	-8.35×10^{-4}
0.05	3.86×10^{-5}	-4.76×10^{-5}	-1.26×10^{-3}
0.1	6.07×10^{-5}	-6.40×10^{-5}	-1.60×10^{-3}
0.3	1.31×10^{-4}	-1.14×10^{-4}	-2.55×10^{-3}

The computation of the nuclear FSI proceeds similarly; the final results depend on the Z of the daughter.

The SM asymmetries are sufficiently small as to be negligible for present purposes.

Very little data exist. ^{6}He decay offers a proof-of-principle experiment?



Data from the 1960's.

For ^{6}He β-decay (GT!):

$\omega_{\rm min}$(MeV)	$A_\xi{}^{\rm SM}$
0.01	7.00×10^{-5}
0.05	1.14×10^{-4}
0.1	1.52×10^{-4}
0.2	2.13×10^{-4}
0.3	2.63×10^{-4}
0.4	3.07×10^{-4}
0.5	3.45×10^{-4}
0.6	3.79×10^{-4}
0.7	4.07×10^{-4}

Now we turn to models which can generate $\mathrm{Im}\, c_5$.

its relic density need not be fixed by thermal freezeout, and its stability need not be guaranteed by a discrete symmetry.

What mechanisms then are operative and how do we discover them?

Some possibilities...

- Its stability may be guaranteed by a hidden gauge symmetry.

  E.g., dark matter can possess a hidden U(1) symmetry. If the gauge mediator is massless, dark matter can have a **millicharge**.

  [B. Holdom, PLB 1986; Pospelov, Ritz, arXiv:0810.1502; Fox, Poppitz, arXiv:0811.0399 ...]

- Its relic density may be related to Ω_B.

  If so, dark matter ought be **asymmetric.**

  [Nussinov, PLB 1985; Barr, Chivukula, Farhi, PLB 1990; Harvey and Turner, PRD 1990; Ellis et al., NPB 1992. Ryttov and Sannino, arXiv:0809.0713 [hep-ph]; Kaplan, Luty, Zurek, arXiv:0901.4117 [hep-ph].]

Hidden Sector Models

Many variants exist....

Hermetic

Dark matter which is neutral under all SM gauge interactions. Suppose it possesses an exact hidden U(1). DM (here a hidden sector stau) is self-interacting and thus subject to observational constraints... e.g., $\alpha_\chi < 10^{-7}$ for $M_\chi \sim 1$ GeV.

[Feng, Kaplinghat, Tu, Yu, arXiv:0905.3039; Feng, Tu, Yu, arXiv:0808.2328]

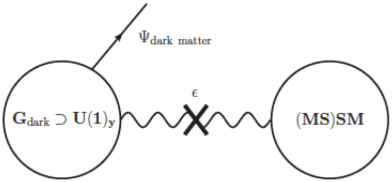
Models with Abelian Connectors

Astrophysical anomalies prompts models which mix with $U(1)_Y$.

[Essig, Schuster, Toro, 2009; Arkani-Hamed, Finkbeiner, Slatyer, Weiner, 2009; Baumgart, Cheung, Ruderman, Wang, Yavin, 2009]

Models with non-Abelian Connectors

[Baumgart, Cheung, Ruderman, Wang, Yavin, 2009; SG and He, arXiv:1302.1862]



[Baumgart et al., 2009]

Let A' be the gauge field of a massive dark U(1)$'$ gauge group

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{\epsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} - \frac{1}{4} F'^{,\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\,\mu} A'_{\mu}$$

With $A_\mu \to \tilde{A}_\mu = A_\mu - \epsilon A'_\mu$, the A' gains a tiny electric charge ϵe.

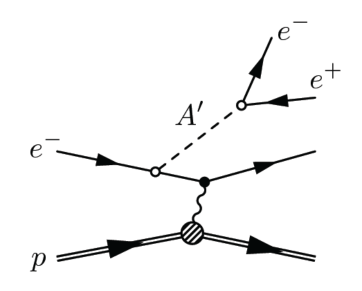
[Holdom, 1986]

The A' can be discovered in fixed-target experiments....

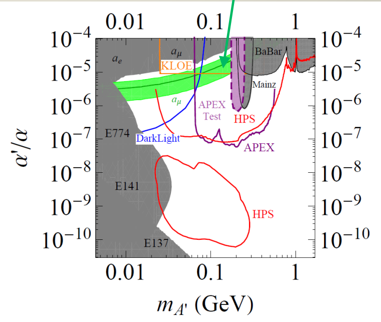
[Bjorken, Essig, Schuester, Toro, arXiv:0906.0580]

New Opportunity: Search for A’ at JLab

Search for new forces mediated by ~100 MeV vector boson A’ with weak coupling to electrons:



g – 2 preferred!



Irrespective of astrophysical anomalies:

- New ~GeV–scale force carriers are important category of physics beyond the SM
- Fixed-target experiments @JLab (FEL + CEBAF) have unique capability to explore this!

Jefferson Lab   Va. Tech. Physics Colloquium, Dec. 3, 2010   Thomas Jefferson National Accelerator Facility   GHP2011, R. D. McKeown   Slide 27   27

[R. McKeown, GHP 2011, April APS] [Note M. Pospelov for $g-2$ connection.]

Non-Abelian Kinetic Mixing with a Hidden Sector

Consider an operator Φ which transforms under the adjoint rep of a non-Abelian dark group. Then $\mathrm{tr}(\Phi F_{\mu\nu})\mathrm{tr}(\tilde{\Phi}\tilde{F}_{\mu\nu})$ can connect the sectors.

[Baumgart et al., 2009]

This operator should become more important at low energies.

We model this as (noting the hidden local symmetry model of QCD)

[Bando, Kugo, Uehara, Yamawaki, Yanagida, 1985]

$$\begin{aligned}\mathcal{L}^{\pm}_{mix} &= -\frac{1}{4}\rho^{+\,\mu\nu}\rho^{-}_{\mu\nu} - \frac{1}{4}\rho'^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \frac{\epsilon}{2}\left(\rho^{+\,\mu\nu}\rho'^{-}_{\mu\nu} + \rho^{-\,\mu\nu}\rho'^{+}_{\mu\nu}\right) \\ &+ \frac{g_\rho}{\sqrt{2}}(\rho^{+}_{\mu}J^{+\,\mu} + \rho^{-}_{\mu}J^{-\,\mu})\,.\end{aligned}$$

Under $\tilde{\rho}^{\pm}_{\mu} = \rho^{\pm}_{\mu} - \epsilon\rho'^{\pm}_{\mu}$, the baryon vector current couples to $\rho'^{\pm}$....

One can hope to detect the ρ' through its possible CP-violating effects.

A Tale of Two Models

The notion of new physics in QCD is vintage. [Okun, 1980; Bjorken, 1979; Gupta, Quinn, 1982]
Note much more recent "quirk" models:
quirks are charged under "infracolor" and are supposed to have mass $M_Q \sim 100 - 1000$ GeV, with $M_Q > \Lambda \Longrightarrow$ macroscopic strings!
The two sectors connect via

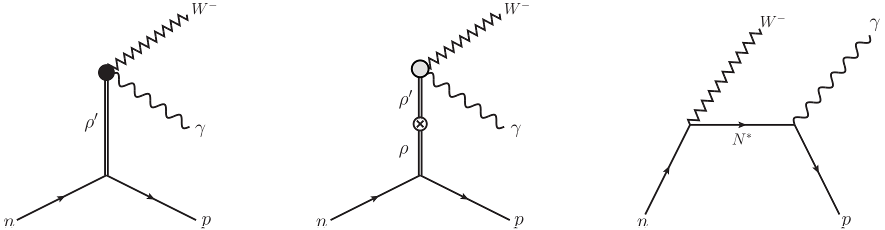
$$\mathcal{L}_{\rm eff} \sim \frac{g^2 g'^2}{16\pi^2 M_Q^4} F_{\mu\nu}^2 F'^2_{\mu\nu}$$

[Kang and Luty, arXiv:0805.4642]

For $M_Q \gtrsim 100$ GeV, weaker than the weak interactions!
Expect collider signatures only!
In our model we suppose hidden quarks crudely comparable to m_q in mass but with $\Lambda' < \Lambda$ and thus $m_{\rho'} < m_\rho$
Expect collider effects to be hidden under hadronization uncertainties!
Expect low-energy signatures only!
New physics can be an emergent low-energy feature... to be discovered at the Intensity Frontier!

Radiative β decay revisited

The low-energy constant c_5 can be generated in different ways....



The first graph mediates radiative decay in the physical ρ basis, an experimental limit on the asymmetry translates as
$\mathrm{Im}(c_5/M^2) = 2\epsilon \mathrm{Im}\epsilon g^2_{\rho^0}/(16\pi^2 m^2_{\rho'})$.
Note that one could include a $\mathrm{U}(1)_Y$ portal also....

This would yield, e.g., a composite dark-matter candidate with a magnetic moment.

T-odd correlations in beta-decay (and the population asymmetry in $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$) offer constraints on new CP-violating phases, which are complementary to those from EDMs.

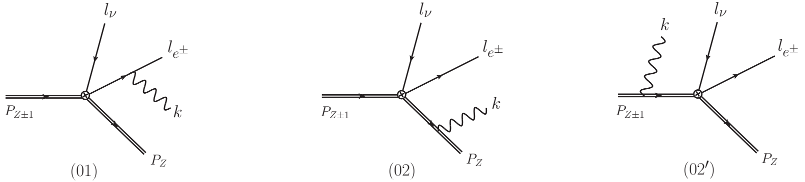
The study of a spin-independent T-odd correlation coefficient is also possible via radiative β decay and allows access to CP-violating effects associated with a "strong" hidden sector.

The BSM extension of the Harvey, Hill, and Hill ($\propto \epsilon_{\mu\nu\delta\sigma}$) interaction can also be tested in other ways at JLab. E.g., one can study parity-violating pion electroproduction at near threshold energies, namely, the $\xi = \mathbf{q} \cdot (\mathbf{p}_{\pi^+} \times \mathbf{p}_{\pi^-})$ correlation in $ep \to e\pi^+\pi^- p$. This would probe the neutral-current analog ($\mathrm{Im} c_4$ after Hill, 2010) to our CC study in β-decay.

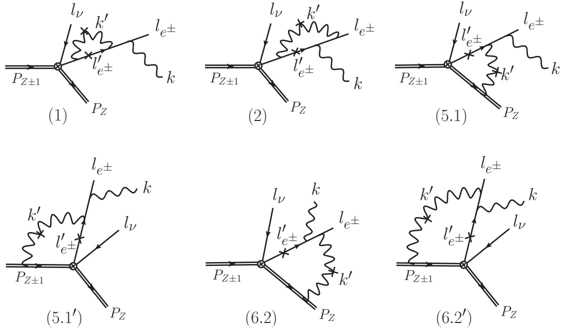
Backup Slides

The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

At tree level...

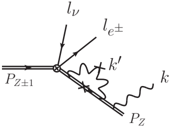


At loop level... $\gamma - e$ family:

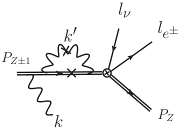


The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

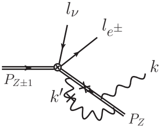
$\gamma - p$ family:



(3)



(3′)



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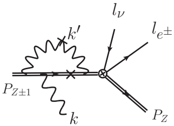
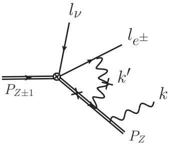
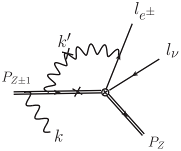


(4′)



(7.2)



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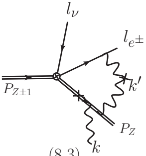
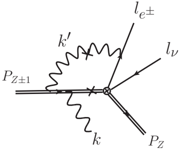


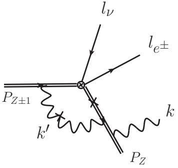
(8.3)



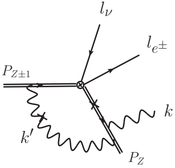
(8.3′)

The Family of Nuclear Two-Particle Cuts in $\mathcal{O}(e^3)$

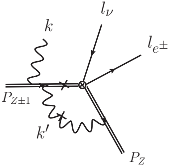
$e - p - \gamma$ family:



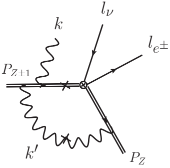
(9.1)



(9.2)



(10.1)



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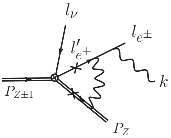

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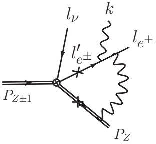
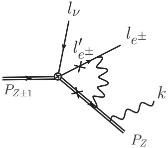
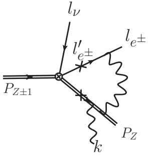


(6.1)

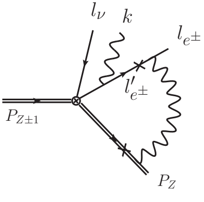


(7.1)

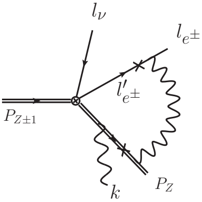


(8.1)

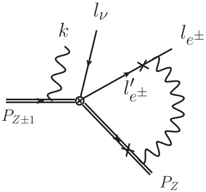
$e - p$ family:



(6.3)



(8.2)



(8.2′)

The final results depend on the Z of the daughter.

$\mathcal{A}_\xi^{\rm SM}$ is proportional to $(1 - \lambda^2)$, with $\lambda = g_A/g_V = 1.267$ for neutron β decay.

The observed quenching of the Gamow-Teller strength in nuclear decays can also suppress $\mathcal{A}_\xi^{\rm SM}$. One can use the lifetime or the β asymmetry to infer $\lambda^{\rm eff}$.

Note shell-model calculations determine $g_A^{\rm eff} = q g_A$ where $q \approx 0.75$.

[Wildenthal, Curtin, and Brown (1983); Martínez-Pinedo et al. (1996)]

A Common Origin for Baryonic and Dark Matter?

One can connect the origin of baryonic and dark matter in different ways.
i) Dark and ordinary matter can carry a common quantum number.
ii) Net "baryon number" is zero, with $n_B = -n_D$. [Davoudiasl and Mohapatra, arXiv:1203.1247]
Dynamically, there are also many possibilities....
i) **A baryon asymmetry is formed and transferred to dark matter.** [DB Kaplan, PRL 1992; ... DE Kaplan, Luty, Zurek, PRD 2009]
A B-L asymmetry generated at high T is transferred to DM which carries a B-L charge.
The relic density is set by the BAU and **not** by thermal freeze-out.
Thus $n_{\rm DM} \sim n_{\rm B}$ and $\Omega_{\rm DM} \sim (M_{\rm DM}/M_{\rm B})\Omega_{\rm B}$. Note $M_{\rm DM} \sim 5 - 15$ GeV.
ii) **A dark matter asymmetry is formed and transferred to the baryon sector.** [Shelton and Zurek, arXiv:1008.1997; Davoudiasl et al., arXiv:1008.2399; Haba and Matsumoto, arXiv:1008.2487; Buckley and Randall, arXiv:1009.0270.]
iii) **Dark matter and baryon asymmetries are formed simultaneously.** [Blennow et al, arXiv:1009.3159; Hall, March-Russell, and West, arXiv:1010.0245]
Many models contain $\gamma - \gamma'$ mixing....

Asymmetric Dark Matter: Experimental Signatures

ADM models can give distinctive collider signatures.

E.g. long-lived metastable states, new charged states at the weak scale, and/or colored states at a TeV.

Direct detection signals can arise from the interactions which i) eliminate the symmetric DM component or ii) transfer the asymmetry.

The latter can be realized through magnetic moment or charge radius couplings.

Both interactions can give rise to anomalous nuclear recoils....

[Bagnasco, Dine, and Thomas, PLB 1994; Barger, Keung, Marfatia, arXiv:1007.4345; Banks, Fortin, and Thomas, arXiv:1007.5515]

The models we consider can generate EDM signals within the reach of planned experiments.

[Hall, March-Russell, and West, arXiv:1010.0245]

A magnetic Faraday effect can also discover dark matter if it possesses a magnetic moment... and establish asymmetric dark matter.

[SG, 2008, 2009]