CP Violation, Baryon Oscillations, and Baryogenesis

work with David McKeen, arXiv:1512.05359
and in progress with Kyle Aitken, David McKeen, Thomas Neder
See also Seyda Ipek, David McKeen, A.E.N., arXiv:1407.8193
Akshay Ghalsasi, David McKeen, A.E.N., arXiv:1508.05392
Seyda Ipek, John March-Russell, arXiv:1604.00009

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CPV beyond the Standard Model

- Needed to produce early universe asymmetry of 10^{-8} between quarks and anti-quarks? (***baryogenesis***)
  - Effects of CKM phase in early universe highly suppressed by small mixing angles and mass differences.
    - non standard CPV

      or

    - non standard enhancement of standard CPV

Particle Oscillations

- quantum interference due to coherent superposition of particles with slightly different masses
  - production conserves some *approximate* symmetry
- Observed in neutrinos (lepton flavor oscillations), neutral K,D,B mesons (particle-anti-particle oscillations)
  - masses must be near degenerate-
    - wave packet propagation must be similar enough so spatial separation does not occur over an oscillation time
    - oscillation time must not be too fast or too slow or oscillations not observable

CPV in Oscillations

- CP Violation: amplitude depends on CP odd phase in Hamiltonian and CP even phase in propagation
  - $|A(i \rightarrow f)|^2 \neq |A(i_{CP} \rightarrow f_{CP})|^2$
  - **without decays**, CPV in oscillations requires oscillations between 3 states
    - (this kind of CPV has not yet been observed)
    - increasing hints of CPV in ν flavor oscillations

Oscillations among 2 states can only violate CP when they are unstable

$$\text{CPT}:Prob(A \to A) = Prob(\bar{A} \to \bar{A})$$

$$\text{Unitarity}:Prob(A \to A) + Prob(A \to \bar{A}) = 1$$

$$Prob(\bar{A} \to \bar{A}) + Prob(\bar{A} \to A) = 1$$

$$\text{So } Prob(\bar{A} \to A) = Prob(A \to \bar{A})$$

CPV in oscillations of unstable states

- Only requires 2 oscillating states
- Observed in neutral kaon anti-kaon and neutral B meson-anti-B meson oscillations
- Large effect possible when oscillation and decay rates comparable

$O(1)$!

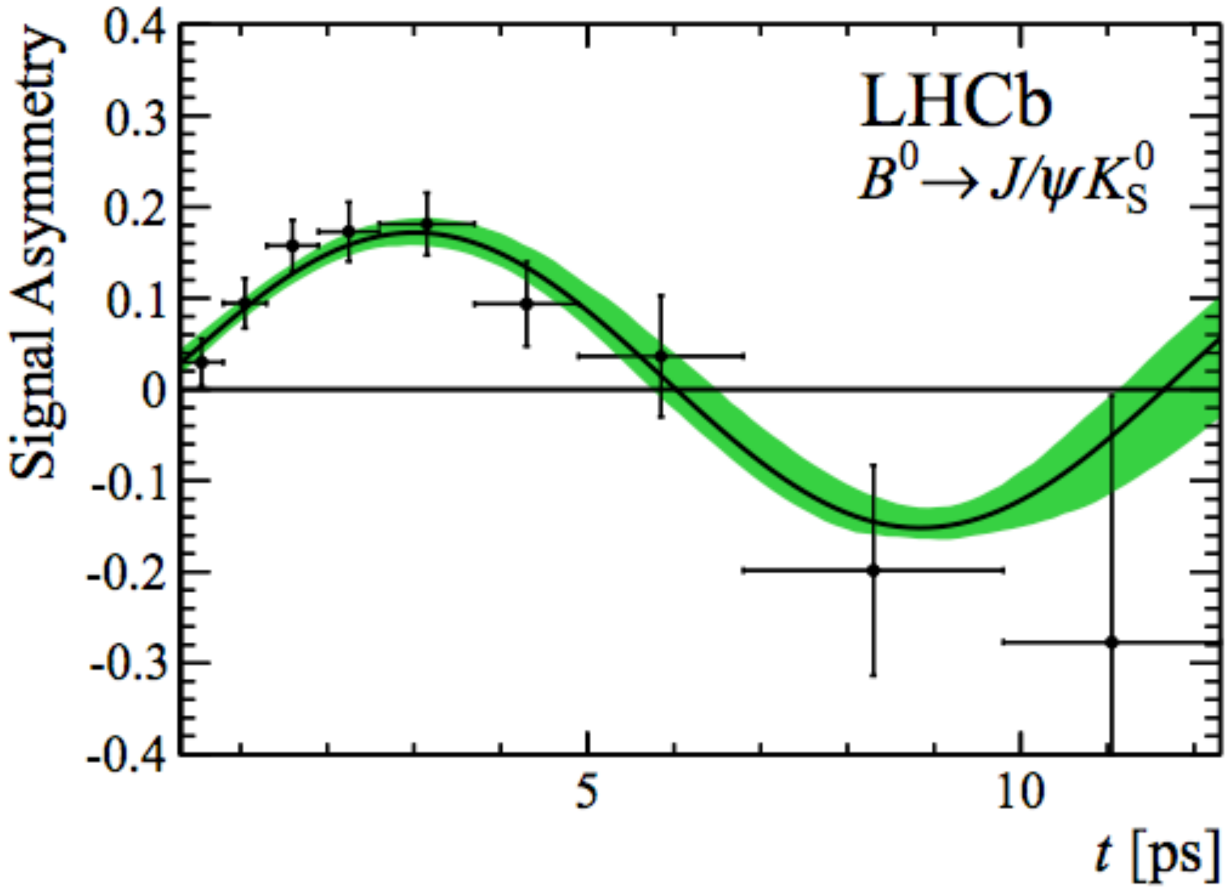


Figure 2: Time-dependent asymmetry $(N_{\bar{B}^0} - N_{B^0})/(N_{\bar{B}^0} + N_{B^0})$. Here, N_{B^0} ($N_{\bar{B}^0}$) is

Pseudo-Dirac Fermion Oscillation: Two state system, similar to neutral mesons

- pseudo-Dirac fermions have 4 states, but mix in 2 x 2 blocks:
- Charge+, spin ↑ can oscillate into Charge -, spin ↑
- Charge+, spin ↓ can oscillate into Charge -, spin ↓
- Rotational invariance (in rest frame) guarantees that these 2 x 2 blocks have same effective Hamiltonian

CPT and rotation constraints

- CPT: exchanges spin↑ particle in initial state with spin ↓ anti particle in final state
- can rotate spin
- H_{eff} must have form: $\begin{pmatrix} m_D - i\Gamma/2 & m_{12} - i\Gamma_{12}/2 \\ m_{12}^* - i\Gamma_{12}^*/2 & m_D - i\Gamma/2 \end{pmatrix}$
- Can work in basis with m_{12} real
- looks exactly like neutral meson H_{eff}
- CPV phase difference between m_{12} and Γ_{12}

CPV in Fermion particle—anti-particle oscillations

- Requires a *Pseudo Dirac Fermion:* massive, carries *approximately* conserved charge, can *oscillate* into own anti-particle as well as decay, requires common final state in decays of particle and anti-particle
  - fermion particle-anti-particle oscillations have never been observed
  - SM candidates: **neutron, other neutral baryons**
  - BSM candidates: Mesino, pseudo-Dirac gluino, neutralino

Neutron Oscillations

- Dim 9 ΔB=2 operator $\frac{1}{\Lambda^5} uddudd$
- Oscillations between equal energy states at rate which is *linear in operator*
- free neutron oscillation rate bound: τ>10^8 s
- Bound neutrons, or neutrons in an external field: split in n $\bar{\text{n}}$ energies→*rate is quadratic in operator.* 10^8 s→10^{40} s
  - comparable *(marginally stronger)* bounds on operator from dinucleon decay (SuperKamiondande)
  - Λ >~ PeV $\langle \bar{n} | \frac{1}{\Lambda^5} uddudd | n \rangle < 10^{-25} eV$

CPV in neutron oscillations?

$$H = \begin{pmatrix} m_n - \frac{i}{2}\Gamma_n & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & m_n - \frac{i}{2}\Gamma_n \end{pmatrix}$$

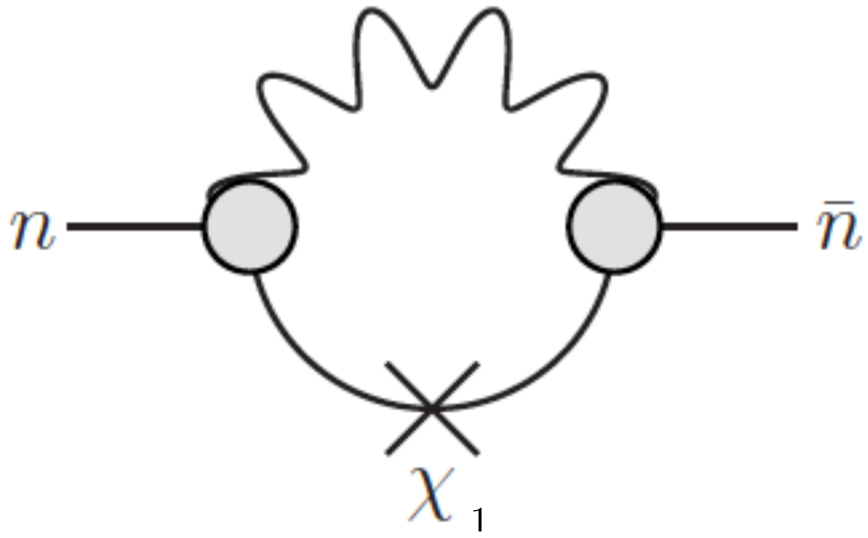
$$\frac{P_{|n\rangle \to |\bar{n}\rangle}}{P_{|\bar{n}\rangle \to |n\rangle}} - 1 = \frac{2\Im\left(M_{12}\Gamma_{12}^*\right)}{\left|M_{12}\right|^2 - \left|\Gamma_{12}\right|^2/4 - \Im\left(M_{12}\Gamma_{12}^*\right)}$$

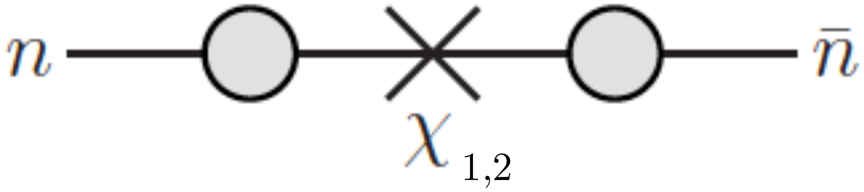
Origin of M_{12} $\quad \frac{1}{\Lambda^5} uddudd$

Origin of Γ_{12} $\quad \cancel{\frac{1}{\Lambda^8} udduud\ell\bar{\nu}}$ $\quad$ or new fermion(s) χ

938 MeV Neutral Majorana Fermion?

- Proton stability: $m_p - m_e < M\chi$
- $M\chi < m_n \rightarrow \Gamma_{12} > 0$
- Z_2 subgroup of baryon number→stable dark matter candidate if $M\chi < m_p + m_e$





$$\Gamma_{12} = \frac{\mu^2 m_n^2 m_\chi}{16\pi}\left(1 - \frac{m_\chi^2}{m_n^2}\right)^3 \quad << \quad M_{12} \sim \left(\frac{\kappa g y}{m_\phi^2}\right)^2 \frac{m_\chi}{m_n^2 - m_\chi^2}$$

Do not expect to see CPV in n $\bar{\text{n}}$ oscillations

- Restrictive Kinematics: $\Delta M = M_n - M_\chi < \text{MeV}$ (proton stability)

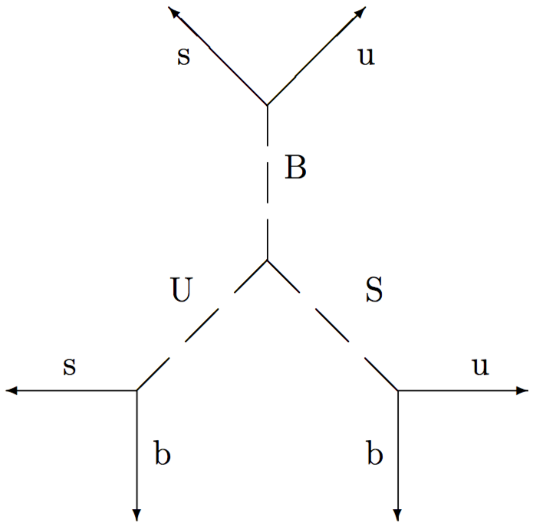
$$\frac{P_{|n\rangle \to |\bar{n}\rangle}}{P_{|\bar{n}\rangle \to |n\rangle}} - 1 \propto \frac{|\Gamma_{12}|}{|M_{12}|} \lesssim 10^{-14} \left(\frac{\Delta M}{1 \text{ MeV}} \right)^4$$

Other neutral baryons?

- What constraints on baryon violating operators containing heavy flavors?
- For $\Delta B=2$, $\Delta s=1,2,3$ operators dinucleon decay into 1,2,3 kaons is almost as constraining as neutron oscillations.
- $\Delta B=2$, $\Delta s=4$: $\overline{\Xi}^0$-Ξ^0 oscillations? $\Omega^- \to \overline{p}\,K$? Not looked for.
- $\Delta B=2$, $\Delta c=2$, $\Delta b=2$: heavy flavor baryon oscillations $bcd \to \overline{b}\,\overline{c}\,\overline{d}$
  - not looked for
- Conceivable to look for oscillations of neutral charmed baryons at Belle II

Constraints from weak flavor violation

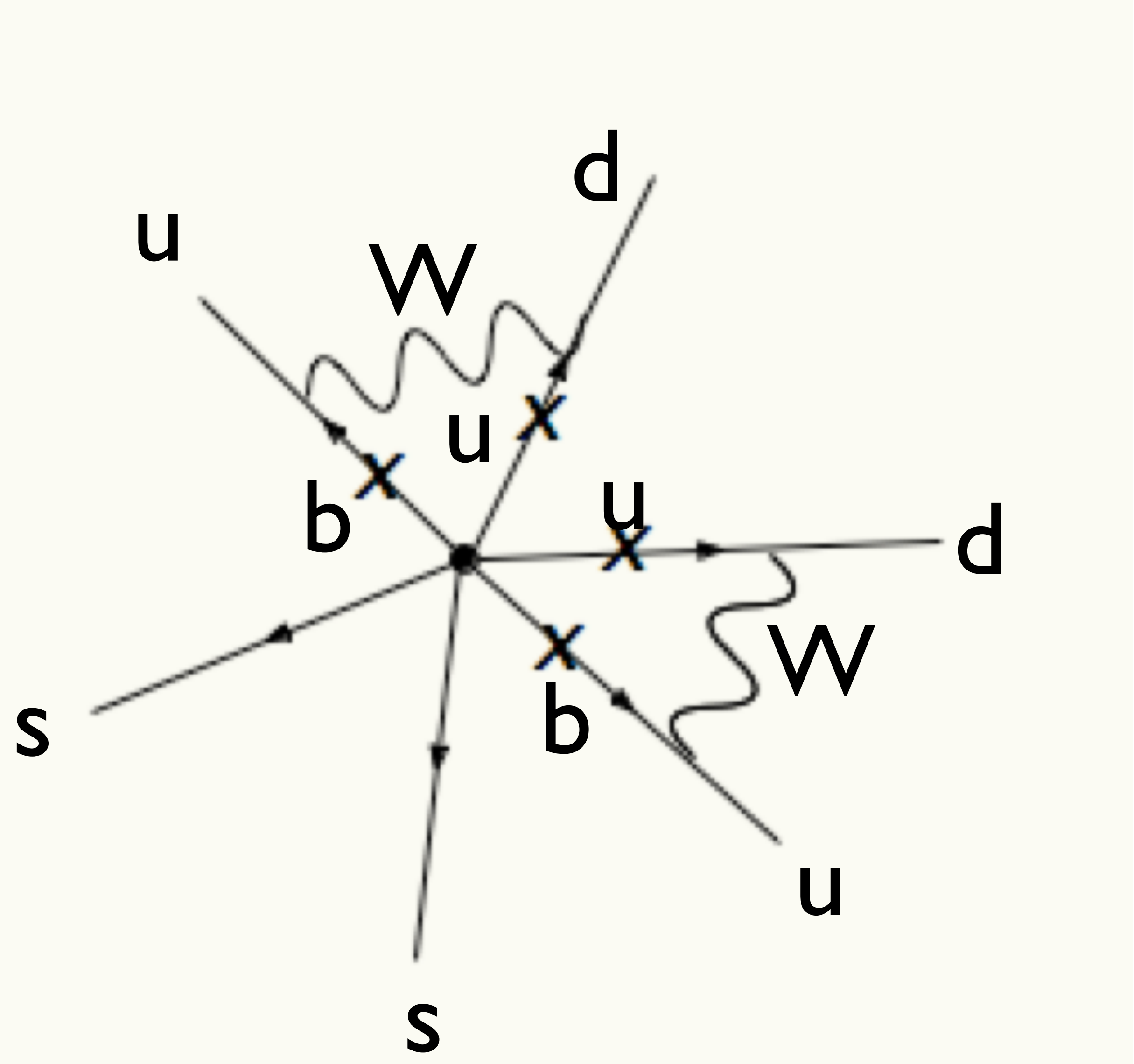
- Do constraints from n $\bar{n}$ make other flavors of $\Delta B=2$ unobservable?
- operators involving right-handed (SU(2) singlet) quarks much less constrained
- Kuzmin (1996) bsu→$\bar{b}\bar{s}\bar{u}$ baryon oscillations from RPV could be as fast as decay!



Di-nucleon decay constraints

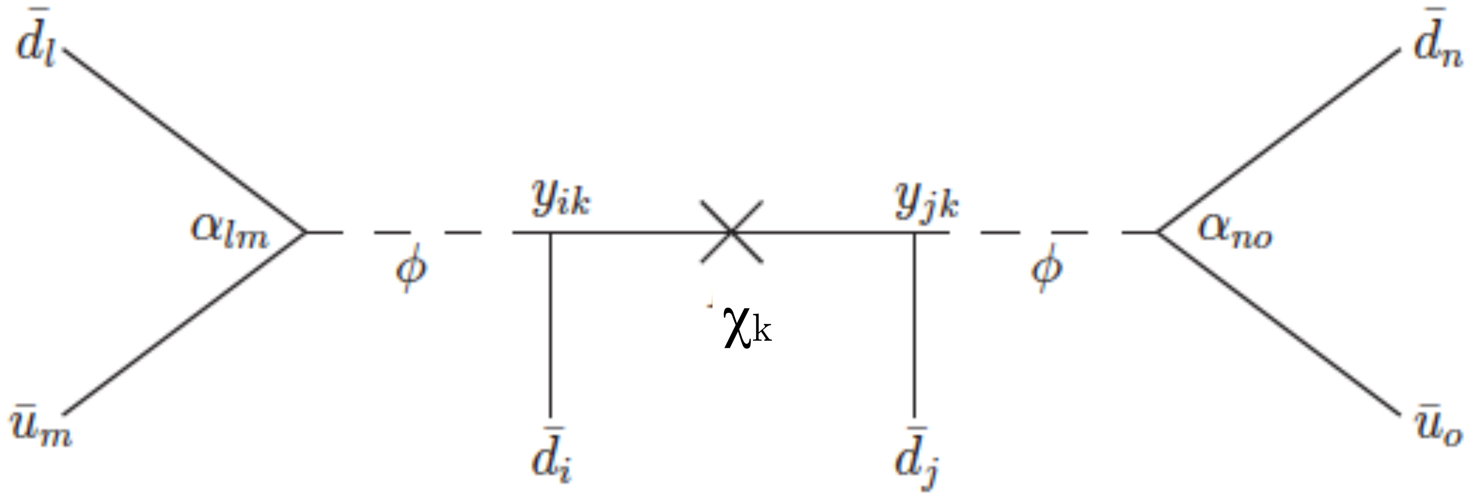
$$\frac{1}{\Lambda^5} busbus \rightarrow \left(\frac{g^2 V_{ub} V_{ud} m_b \Lambda_{QCD}}{16\pi^2 M_W^2}\right)^2 \left(\frac{1}{\Lambda^5} dusdus\right)$$

- dinucleon→ kaons constraints similar to neutron oscillation constraints
- bus baryon allowed to oscillate at ~10^{18} faster rate than neutron: 10^{-10} s



Model for CPV in heavy flavor baryon oscillation

- same model as in "mesino oscillation" model arXiv:1508.05392, different parameters (χ lighter than heavy flavor baryon)
  - "RPV SUSY-lite"
  - New particles:
    - Neutral Majorana fermions χ_i, $i=1,2,\ldots$, mass~few GeV
    - charge $-1/3$ colored scalar ϕ, *mass >~650 GeV*
    - *low energy effective theory:* $\frac{\alpha_{ij} y_{k\ell}}{m_\phi^2} \bar{d}_i \bar{u}_j \bar{d}_k \chi_\ell$



Dinucleon decay constraints on combinations of α_{11}, α_{21}, y_{1k}, y_{2k}

CPV in heavy flavor oscillations

- oscillation rate in neutral heavy flavor baryons could be 10^{-2}—10^{-3} times decay rate, when 2 weak interactions required to convert operator to one producing dinucleon decay
- Γ_{12} not kinematically suppressed, could be ~ 10^{-1} M_{12}
- could this be CPV be observable, and directly related to baryogenesis?

Baryogenesis?

- CPV in Baryon oscillations fulfills 2/3 Sakharov conditions
- Heavy flavor baryons out of equilibrium in early universe via long lived χ decay when early universe has temperature between ~1 and 200 MeV
- Some of the baryons will undergo CPV oscillations before they decay.

Summary

$$\frac{\alpha_{ij} y_{k\ell}}{m_\phi^2} \bar{d}_i \bar{u}_j \bar{d}_k \chi_\ell$$

- Low energy effective theory with neutral Majorana fermions χ with baryon violating couplings for heavy flavored quarks
- stability of matter→ lightest χ satisfies $m_p - m_e < M_\chi$
- stable dark matter candidate if lightest χ satisfies $M_\chi < m_p + m_e$
- $n\ \bar{n}$ oscillations consistent with heavy flavor baryon oscillations with $\tau \sim 10^{-10}$ s
- CPV in heavy flavor baryon oscillations (requires at least one χ to be lighter than the heavy flavor baryon (need Γ_{12})
- Low energy baryogenesis? (requires 1 long lived χ)