M 07 OCT 2015 C. Lee, LANL

"CP-Violating flavor oscillations in EWB"

based on work in progress w/ V. Cirigliano & E. Passemar

1106.0747 w/ VC & S. Tulin

0912.3523 + M.J. Ramsey-Musolf

This morning $\not{CP}$.

One of Sakharov : 1) $\not{B}$

2) $\not{C}$, $\not{CP}$

3) arrow of time or ~~th eq.~~ (or ~~CPT~~)

almost ~~th~~ 50 yrs (1967).

1), 2) exist in SM but not enough $\not{CP}$.

3) could've existed in SM (EWPT) but $m_H = 125$ GeV $\Rightarrow$ no 1st order PT.

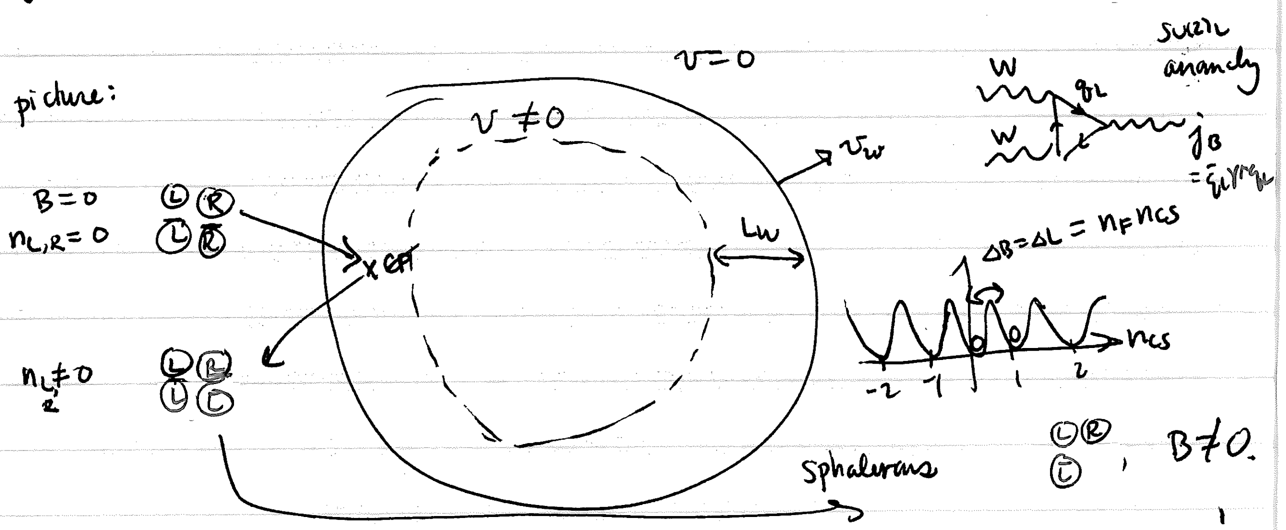
Need BSM.

I will focus on EWB, on improving the theory of quantum transport in which $O(10-100)$ uncertainties existed in literature.

3 min

Construct toy model of scalars exhibiting ~~some~~ the key qualitative features of EWB. (loosely based on stops $\tilde{t}_{L,R}$ in MSSM $\Rightarrow$ QCD.)

Big picture:



Lots of complicated physics

1) non-PT sphaleron rate
2) bubble wall dynamics
3) 1^{st} vs. 2^{nd} order PT
* 4) transport theory:

$$\frac{\partial \rho_B}{\partial t} \sim \Gamma_{sph} \frac{\partial n_L}{\partial t}$$

↳ evolution eqs. in non-eq. bkgd.?

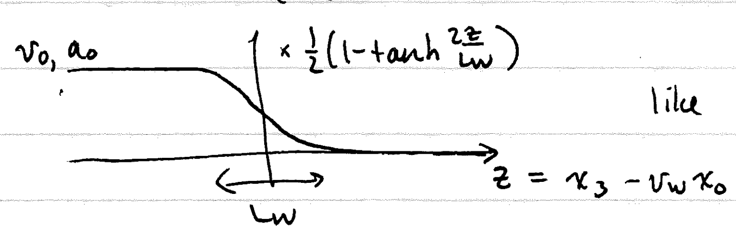
I want to give a flavor, intuitive picture for non-eq $\not{CP}$ transport.

8 min

Consider the model $\Phi = \begin{pmatrix}\phi_L \\ \phi_R\end{pmatrix}$

$$\mathcal{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi - \Phi^\dagger M^2(x) \Phi + \mathcal{L}_{int}$$

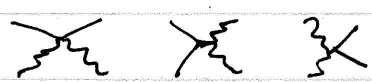
where $M^2(x) = \begin{pmatrix} m_L^2 & v(x) e^{-ia(x)} \\ v(x) e^{ia(x)} & m_R^2 \end{pmatrix}$ (like $\tilde{t}_{L,R}$ interacting w/ Higgs vev)



like planar bubble wall

$\mathcal{L}_{int} = -\frac{1}{2} \Delta^2 \Phi^\dagger y \Phi$ $\quad y = \begin{pmatrix} y_L & 0 \\ 0 & y_R \end{pmatrix}$ → defines "flavor" or "interaction" basis

↓ real scalar acting as thermal bath (try gauge boson)



13 min

Mass basis: $\phi = \begin{pmatrix}\phi_1 \\ \phi_2\end{pmatrix} = U^\dagger \Phi$

$$U = \begin{pmatrix} \cos\theta & -\sin\theta\, e^{-ia} \\ \sin\theta\, e^{ia} & \cos\theta \end{pmatrix}(x)$$

$$\tan 2\theta = \frac{2v(x)}{m_L^2 - m_R^2}$$

$$m^2 = U^\dagger M^2 U = \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \qquad m_{1,2}^2 = \frac{1}{2}(m_L^2 + m_R^2) \pm \frac{1}{2}\sqrt{(m_L^2 - m_R^2)^2 + 4v^2}$$

$\nearrow -\frac{1}{2} A^2 \phi^\dagger Y \phi \qquad Y = U^\dagger y U = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix}$

$$\mathcal{L} = \partial_\mu \phi^\dagger \partial^\mu \phi - \phi^\dagger m^2 \phi + \mathcal{L}_{int}$$
$$- \phi^\dagger \Sigma^\mu \partial_\mu \phi + \partial_\mu \phi^\dagger \Sigma^\mu \phi - \phi^\dagger \Sigma^\mu \Sigma_\mu \phi$$

$$\Sigma_\mu = U^\dagger \partial_\mu U$$
$$= \begin{pmatrix} 0 & -e^{ia} \\ e^{ia} & 0 \end{pmatrix} \partial_\mu \theta + \begin{pmatrix} i \sin^2\theta & \frac{i}{2} \sin 2\theta e^{-ia} \\ \frac{i}{2} \sin 2\theta e^{ia} & -i \sin^2 \theta \end{pmatrix} \partial_\mu a.$$

17 min

Derive transport eqs. for particle densities from correlation functions

$$\tilde{G} = \begin{pmatrix} G^t & -G^< \\ G^> & -G^{\bar{t}} \end{pmatrix}(x,y) = \begin{pmatrix} \langle T \phi(x) \phi^\dagger(y) \rangle & -\langle \phi^\dagger(y) \phi(x) \rangle \\ \langle \phi(x) \phi^\dagger(y) \rangle & -\langle \bar{T} \phi(x) \phi^\dagger(y) \rangle \end{pmatrix}$$

Schwinger-Dyson:

$$\tilde{G}(x,y) = \tilde{G}^{(0)}(x,y) + \int d^4z\, d^4w\, \tilde{G}^0(x,z) \tilde{\Pi}(z,w) \tilde{G}(w,y)$$

Eqs of motion for $G^{\gtrless}$:

$$\left[\partial_x^2 + m^2(x) + 2\Sigma_\mu(x)\partial_x^\mu + \Sigma_\mu \Sigma^\mu(x) + \partial_x^\mu \Sigma_\mu(x)\right] G^{\gtrless}(x,y) = -i \int d^4z \left[\tilde{\Pi}(x,z) \tilde{G}(z,y)\right]^{\gtrless}$$

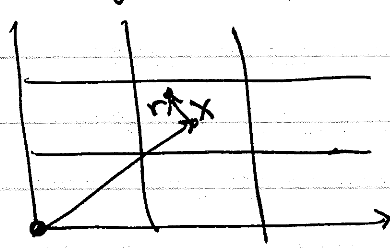
sim. for y (Rest of this talk I am just going to unpack this eq.)

want distributions in momentum space:

21 min

Wigner transform

$$G(k;X) \equiv \int d^4r\, e^{ik\cdot r}\, G\left(X + \frac{r}{2}, X - \frac{r}{2}\right)$$



Solve for k distribution in each X box.

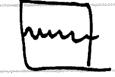
Wigner transforms obey complicated eqs with infinite number of derivatives in k and X.

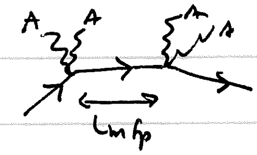
Need power counting scheme.

25 min

Expand in 3 ϵ's:

$$\epsilon_W \sim \frac{L_{int}}{L_W} \qquad \text{where } L_{int} \sim \frac{1}{|\vec{k}|} \sim \frac{1}{T}$$





$$\epsilon_{coll} \sim \frac{L_{int}}{L_{mfp}} \qquad \epsilon_{coll} \sim y_{LR} \quad \text{(pert. th.)}$$

$$\epsilon_{osc} \sim \frac{L_{int}}{L_{osc}} \qquad L_{osc} \sim \frac{1}{\omega_1 - \omega_2} \sim \frac{|\vec{k}|}{\Delta m^2}$$

27 min

$\mathcal{O}(\epsilon^0)$: $\quad (k^2 - \bar{m}^2)\, G^{\gtrless}(k;X) = 0 \qquad \bar{m}^2 = \frac{m_1^2 + m_2^2}{2}$

"constraint eq"

$$\Rightarrow \quad G^{\gtrless}(k;X) = 2\pi\, \delta(k^2 - \bar{m}^2)\, F^{\gtrless}(\vec{k},X)$$

↳ so far arbitrary

(actually $m_{11}^2 = m_1^2$, $m_{22}^2 = m_2^2$)

$$F^{>} = \theta(k^0)\left[\mathbb{1} + f(\vec{k};X)\right] + \theta(-k^0)\, \bar{f}(\vec{k};X)\big]$$

$$F^{<} = \theta(k^0)\, f(\vec{k};X) + \theta(-k^0)\left[\mathbb{1} + \bar{f}(-\vec{k};X)\right]$$

(commutation rels.)

In eq., $f = n_B = \frac{1}{e^{\omega_k/T} - 1}$.

30 min

$\mathcal{O}(\epsilon^1)$: "kinetic eqs." tell us how f's evolve.

We get:

$$\left\{\begin{aligned} &(u \cdot \partial_X + \vec{F} \cdot \vec{\nabla}_{\vec{k}})\, f(\vec{k};X) = -\left[i\omega_{\vec{k}} + u \cdot \Sigma,\, f_m\right] + \mathcal{C}[f,\bar{f}] \\ &(u \cdot \partial_X + \vec{F} \cdot \vec{\nabla}_{\vec{k}})\, \bar{f} = +\left[i\omega_{\vec{k}} - u \cdot \Sigma,\, \bar{f}_m\right] + \mathcal{C}[\bar{f}, f] \end{aligned}\right.$$

(leave out)

where $u^\mu = \left(1, \frac{\vec{k}}{\omega_{\vec{k}}}\right) \qquad \vec{F} = -\vec{\nabla}_X \bar{\omega}_{\vec{k}}$

planar →

$$v_{rel}\, \partial_z f = -\left[i\omega_{\vec{k}} + v_{rel}\, \Sigma_z,\, f\right] + \mathcal{C}[f,\bar{f}]$$

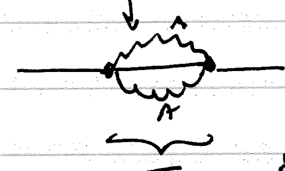
$$v_{rel}\, \partial_z \bar{f} = \left[i\omega_{\vec{k}} - v_{rel}\, \Sigma_z,\, f\right] + \mathcal{C}[\bar{f}, f]$$

where $v_{rel} = \frac{k_z}{\bar{\omega}_k} - v_W$.

33 min

Collision term:

$$\mathcal{C}[f,\bar f] = \int_0^\infty \frac{dk^0}{2\pi}\,\frac{1}{2}\left(\{\Pi^>(k,X)\,;\,G^<(k,X)\} - \{\Pi^<(k,X)\,,\,G^>(k,X)\}\right)$$



$\phi A \to \phi A$ scattering

or $\phi\phi^\dagger \leftrightarrow AA$ pair annihilation/creation.

not going to write more explicitly here.

35 min

Make sense of physical meaning of kin eq:

$$f = \begin{pmatrix} f_{11} & f_{12} \\ f_{21} & f_{22} \end{pmatrix} = P_0\,\mathbb{1} + \vec{P}\cdot\vec{\sigma} \qquad \sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\bar f = \bar P_0\,\mathbb{1} + \vec{\bar P}\cdot\vec{\sigma} \qquad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

(Bloch decomposition)

write $\frac{1}{V_{rel}}\mathcal{C} = -D_0\,\mathbb{1} - \vec{\sigma}\cdot\vec{D}$

kin eq $\Rightarrow$

$$\partial_z P_0 = -D_0[P,\bar P] \qquad \partial_z \bar P_0 = -D_0[\bar P, P]$$

$$\partial_z \vec{P} = (\vec{B}_0 + \vec{B}_\Sigma)\times\vec{P} - \vec{D}[P,\bar P]$$

$$\partial_z \vec{\bar P} = -(\vec{B}_0 - \vec{B}_\Sigma)\times\vec{\bar P} - \vec{D}[\bar P, P]$$

$$\vec{B}_0 = \begin{pmatrix} 0 \\ 0 \\ \frac{\omega_1-\omega_2}{V_{rel}} \end{pmatrix} \qquad \vec{B}_\Sigma = \begin{pmatrix} 2\sin a\,\theta' + \sin 2\theta\,\cos a\,a' \\ -2\cos a\,\theta' + \sin 2\theta\,\sin a\,a' \\ 2\sin^2\theta\,a' \end{pmatrix}$$

Like spin precession in mag. field

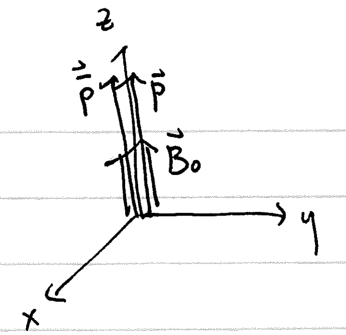
here P_0 ~ total occupation #

P_3 ~ L–R asymmetry

$P_{1,2}$ ~ off-diagonal correlations in flavor space

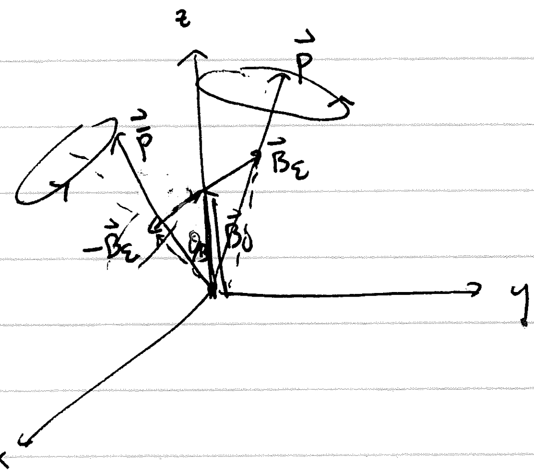
42 min

Equil:

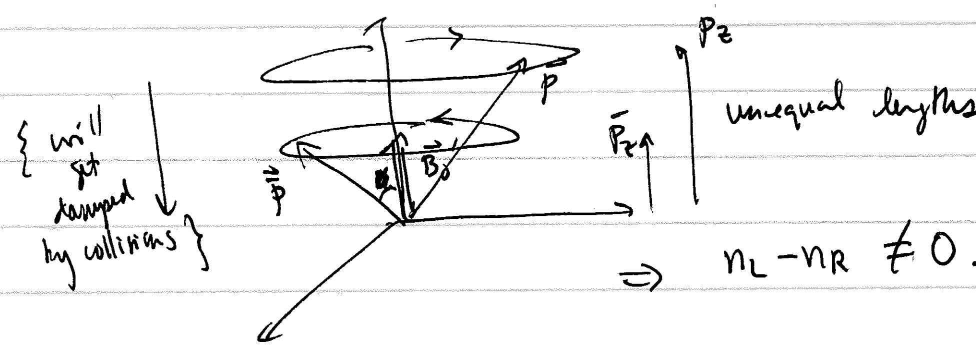


$\rightarrow$ no precession

during EWPT:
(in wall)



after:



$\Rightarrow \; n_L - n_R \neq 0.$

largest effect when $\theta_B \sim 1$ $\qquad L_W \sim L_{osc}$
"non-adiabatic"

previous lit assumed $\theta_B \ll 1$, not always true,
missed large ~~CP~~ flav-osc. source.

50 min.

---

extra: take $\vec{B}_{\not{E}} \times \vec{p} \rightarrow \begin{pmatrix} B_x \\ B_y \\ 0 \end{pmatrix} \times \begin{pmatrix} 0 \\ 0 \\ n_B(w_1) - n_B(w_2) \end{pmatrix}$

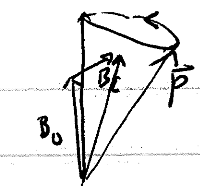
$\quad\;\; \sim\epsilon \quad \sim\epsilon$

$+ \begin{pmatrix} 0 \\ 0 \\ B_z \end{pmatrix} \times \begin{pmatrix} p_x \\ p_y \\ 0 \end{pmatrix}$

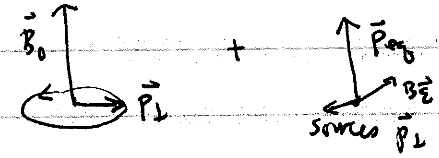
For $\theta_B \sim 1 \longrightarrow \mathcal{O}(100)$ enhancement of $n_L - n_R$.

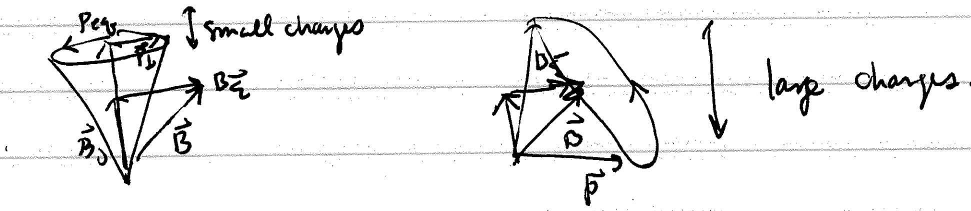
Under study:
- simplify to diffusion eqs.
- realistic pheno.

exact: $v_{rel}\,\partial_z \vec{p} = (\vec{B}_0+\vec{B}_\Sigma)\times\vec{p}$



approx: $\vec{B}_0\times \begin{pmatrix}p_x\\p_y\\0\end{pmatrix} + \vec{B}_\Sigma\times\begin{pmatrix}0\\0\\n_B(\omega_1)-n_B(\omega_2)\end{pmatrix}$





$$(\underset{\downarrow\,\epsilon}{\vec{B}_0} + \underset{\downarrow\,\epsilon}{\vec{B}_\Sigma})\times \underset{\downarrow\,\epsilon}{\delta\vec{p}}$$

Conclusions / future:

- new possibly dominant source for $\not{CP}$ in EWB
- simplification to diffusion eqs. (retaining flav. osc.)
- realistic models (incl. fermions)

55 min.