Baryon Oscillations and CP Violation

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Outline

- CP & neutron oscillations
- How to engineer CPV in neutron oscillation
- Heavy flavor baryon oscillations and CPV
- Contribution to the baryon asymmetry of the Universe

See also talk by Vainshtein
Vainshtein & Berezhiani, Gardner (& Jafari, & Yan)

(DM & Ann Nelson 1512.05359)

Neutron Oscillation Lagrangian

The general Lagrangian containing neutron bilinear

$$\mathcal{L} = \bar{n} i \gamma^\mu \partial_\mu n + \mathcal{L}_B + \mathcal{L}_{\not{B}}$$

with B-preserving

$$-\mathcal{L}_B = \bar{n}\left(m_n P_L + m_n^* P_R\right) n$$

and B-violating terms

$$-\mathcal{L}_{\not{B}} = \bar{n}^c\left(\delta_1 P_L + \delta_2^* P_R\right) n + \bar{n}\left(\delta_2 P_L + \delta_1^* P_R\right) n^c$$

In terms of 2-comp., LH Weyl spinors

$$\xi \ \ (B=+1)\,, \ \ \eta \ \ (B=-1)$$

$$n = \begin{pmatrix} \xi \\ \eta^\dagger \end{pmatrix} = \begin{pmatrix} \xi \\ i\sigma^2 \eta^* \end{pmatrix}$$

$$\mathcal{L} = \xi^\dagger i \bar{\sigma}^\mu \partial_\mu \xi + \eta^\dagger i \bar{\sigma}^\mu \partial_\mu \eta + \mathcal{L}_B + \mathcal{L}_{\not{B}}$$

$$-\mathcal{L}_B = m_n \eta \xi + \text{h.c.}$$

$$-\mathcal{L}_{\not{B}} = \delta_1 \xi\xi + \delta_2 \eta\eta + \text{h.c.}$$

How does this behave wrt CP?

See also talk by Vainshtein
Vainshtein & Berezhiani, Gardner (& Jafari, & Yan)

(DM & Ann Nelson 1512.05359)

Neutron Oscillation Lagrangian

$$\xi \underset{C}{\longleftrightarrow} \eta$$

$$m_n \underset{C}{\longrightarrow} m_n, \;\; \delta_1 \underset{C}{\longleftrightarrow} \delta_2$$

$$\xi \underset{P}{\longleftrightarrow} \eta^\dagger$$

$$m_n \underset{P}{\longleftrightarrow} m_n^*, \;\; \delta_1 \underset{P}{\longleftrightarrow} \delta_2^*$$

$$\xi \underset{CP}{\longleftrightarrow} \xi^*, \;\; \eta \underset{CP}{\longleftrightarrow} \eta^*$$

$$m_n \underset{CP}{\longleftrightarrow} m_n^*, \;\; \delta_{1,2} \underset{CP}{\longleftrightarrow} \delta_{1,2}^*$$

$$\mathcal{L} = \xi^\dagger i\bar{\sigma}^\mu \partial_\mu \xi + \eta^\dagger i\bar{\sigma}^\mu \partial_\mu \eta + \mathcal{L}_B + \mathcal{L}_{\not B}$$

$$-\mathcal{L}_B = m_n \eta\xi + \text{h.c.}$$

$$-\mathcal{L}_{\not B} = \delta_1 \xi\xi + \delta_2 \eta\eta + \text{h.c.}$$

3 phases, 2 fields, naively can't remove all but can rotate to remove δ_1 or δ_2

$$\xi \to \cos\theta\xi + \sin\theta\eta, \;\; \eta \to -\sin\theta\xi + \cos\theta\eta$$

(Ipek, DM, & Nelson)

Neutron Oscillation Hamiltonian

Express fields in terms of creation/annihilation operators

$$\xi_\alpha = \sum_s \int \frac{d^3p}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_p}} \left[x^s_{p\,\alpha} a^s_p e^{-ip\cdot x} + y^s_{p\,\alpha} b^{s\,\dagger}_p e^{ip\cdot x} \right]$$

$$\eta_\alpha = \sum_s \int \frac{d^3p}{(2\pi)^{3/2}} \frac{1}{\sqrt{2E_p}} \left[x^s_{p\,\alpha} b^s_p e^{-ip\cdot x} + y^s_{p\,\alpha} a^{s\,\dagger}_p e^{ip\cdot x} \right]$$

$$|n; p, s\rangle = a^{s\,\dagger}_p |0\rangle, \;\; |\bar{n}; p, s\rangle = b^{s\,\dagger}_p \| 0\rangle$$

Can then compute Hamiltonian

$$-\langle i; p, s| \int d^3x\, \mathcal{L} |j; p', s'\rangle\Big|_{p\to 0} = (2\pi)^3\, \delta^{(3)}\left(p - p'\right) H^{ss'}_{ij}$$

$$H = \begin{pmatrix} m_n & \frac{\delta_1^* + \delta_2}{2} \\ \frac{\delta_1 + \delta_2^*}{2} & m_n \end{pmatrix} \delta^{ss'}$$

Remaining phase can be removed by rephasing states

Neutron Oscillation Hamiltonian

Can easily incorporate B fields, decays in this

$$\mathcal{L} \supset (\mu_n - i d_n) F_{\mu\nu} \eta \sigma^{\mu\nu} \xi + \text{h.c.}$$

$$H = \begin{pmatrix} m_n \delta^{ss'} - (\mu_n B - d_n E)\cdot\sigma & M_{12}\delta^{ss'} \\ M_{12}^* \delta^{ss'} & m_n \delta^{ss'} + (\mu_n B - d_n E)\cdot\sigma \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_n & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_n \end{pmatrix} \delta^{ss'}$$

$$M_{12} = \delta_1^* + \delta_2$$

Gives transition probs.

$$\Delta \equiv 2\sqrt{\mu_n^2 B^2 + H_{12} H_{21}}$$

$$P_{|n\rangle \to |\bar{n}\rangle} = \frac{2\left|H_{21}\right|^2}{\left|\Delta\right|^2} \left(\cosh \frac{\Delta\Gamma t}{2} - \cos \Delta m t \right) e^{-\Gamma_n t}$$

$$H_{12,21} = M_{12,21} - \frac{i}{2}\Gamma_{12,21}$$

CPV is, e.g.,

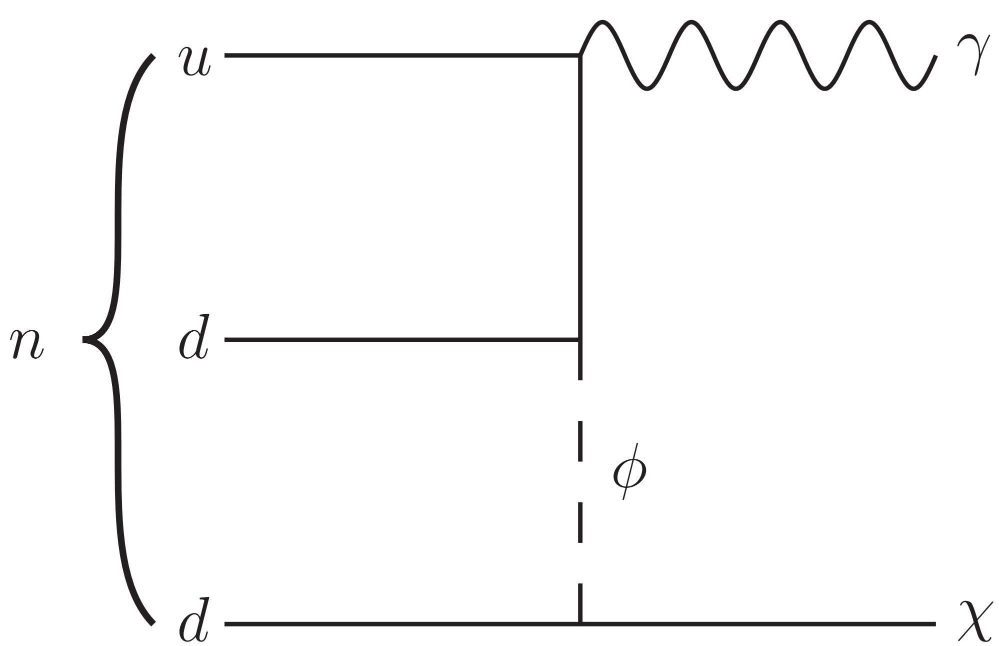
$$\frac{P_{|n\rangle \to |\bar{n}\rangle}}{P_{|\bar{n}\rangle \to |n\rangle}} - 1 = \frac{2\text{Im}\left(M_{12}\Gamma_{12}^*\right)}{\left|M_{12}\right|^2 - \left|\Gamma_{12}\right|^2/4 - \text{Im}\left(M_{12}\Gamma_{12}^*\right)}$$

CPV in Neutron Oscillations

Is measurable CPV possible? Need Γ_{12}

$n \to \bar{p} e^+ \nu_e, \ \bar{n} \to p e^- \bar{\nu}_e$ dim-12, 3 body, so extremely suppressed

Need to consider new state lighter than neutron



$$m_p - m_e < m_\chi < m_p + m_e$$

$$\mathcal{L} \supset g\phi \bar{u}\bar{d} + y\phi^* \bar{d}\chi + m_\chi \chi\chi + \text{h.c.}$$

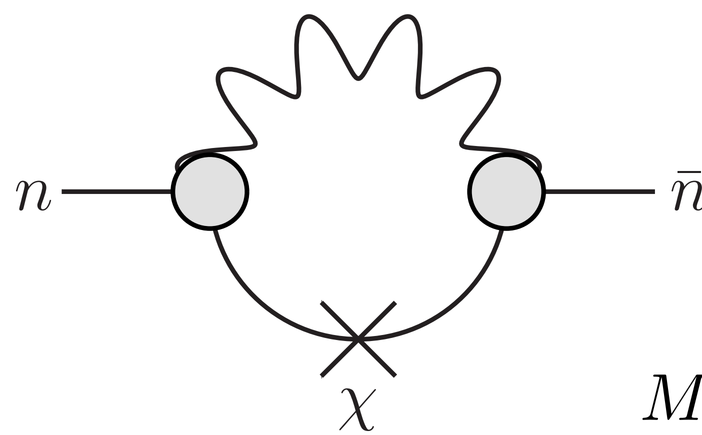
guarantees stability of $\chi, \ p$

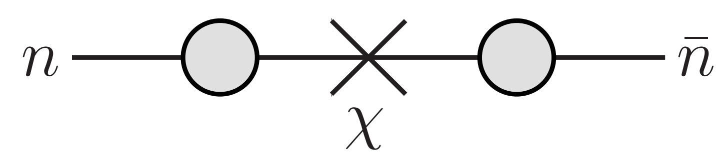
Z_2 subgroup of B number preserved

CPV in Neutron Oscillations

Is measurable CPV possible? Need Γ_{12}

$$\mathcal{L} \supset g\phi\bar{u}\bar{d} + y\phi^*\bar{d}\chi + m_\chi\chi\chi + \text{h.c.}$$





$$\Gamma_{12} \sim \left(\frac{egy\Lambda^3_{\text{QCD}}}{m^2_\phi m^2_n}\right)^2 \frac{m^2_n m_\chi}{16\pi}\left(1 - \frac{m^2_\chi}{m^2_n}\right)^3$$

$$\sim 10^{-47}\ \text{GeV}\left(\frac{10^8\ \text{GeV}}{m_\phi/\sqrt{gy}}\right)^4\left(\frac{\Delta M}{1\ \text{MeV}}\right)^3$$

$$M_{12} \sim \left(\frac{\Lambda^3_{\text{QCD}}gy}{m^2_\phi}\right)^2 \frac{m_\chi}{m^2_n - m^2_\chi}$$

$$\sim 10^{-33}\ \text{GeV}\left(\frac{10^8\ \text{GeV}}{m_\phi/\sqrt{gy}}\right)^4\left(\frac{1\ \text{MeV}}{\Delta M}\right)$$

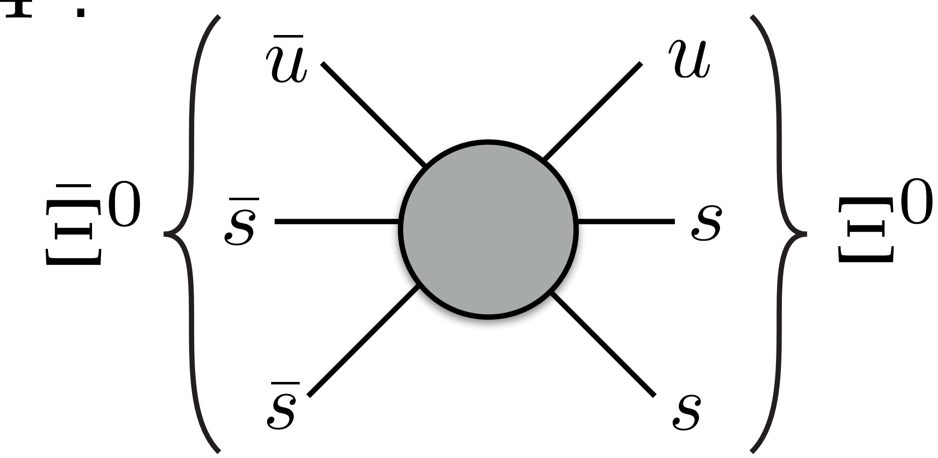
So $\dfrac{P_{n\to\bar{n}}}{P_{\bar{n}\to n}} - 1 \propto \dfrac{|\Gamma_{12}|}{|M_{12}|} \lesssim 10^{-14}\left(\dfrac{\Delta M}{1\ \text{MeV}}\right)^4$

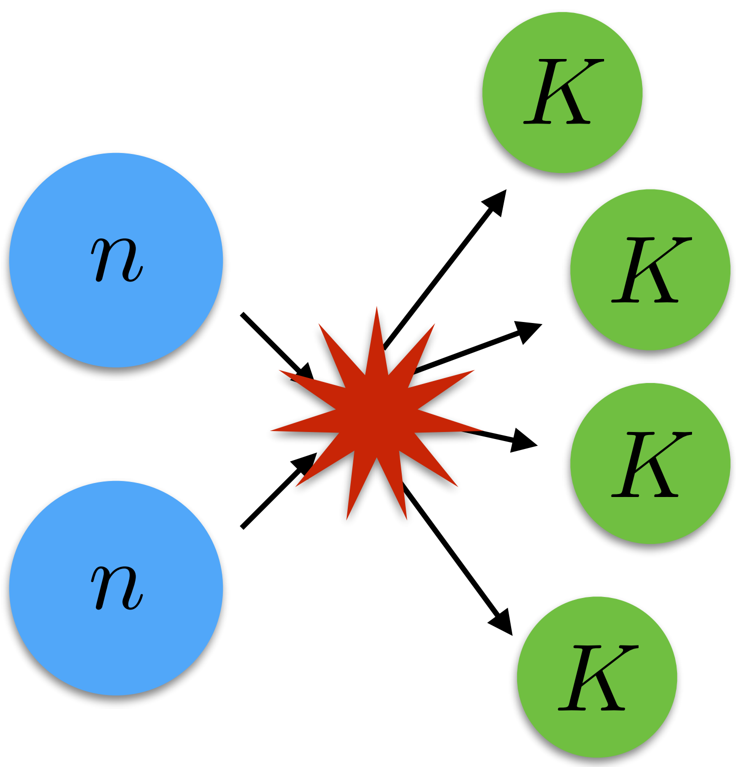
Oscillations also suppressed by $\dfrac{|M_{12}|}{\Gamma_n} \lesssim 10^{-5}$

(Aitken, DM, Neder, & Nelson)

Heavy Flavor Oscillations

What if $\Delta B = 2$ operators had $\Delta S = 4$?





is kinematically forbidden!

$$2m_N < 4m_K$$

Dominant constraints could be from colliders

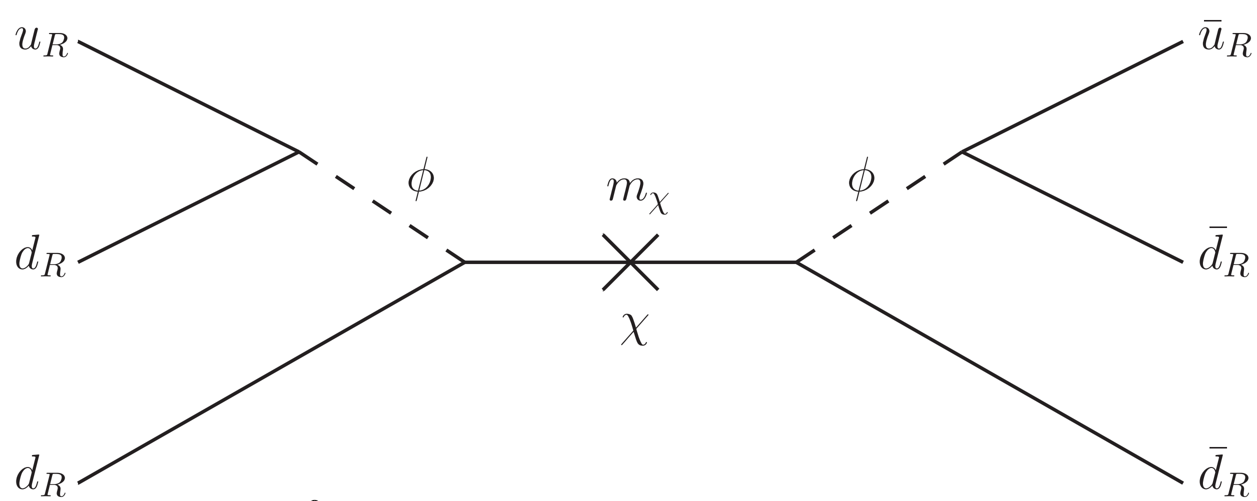
$\Gamma_{12},\ M_{12}$ could be much larger

Kuzmin ('96)

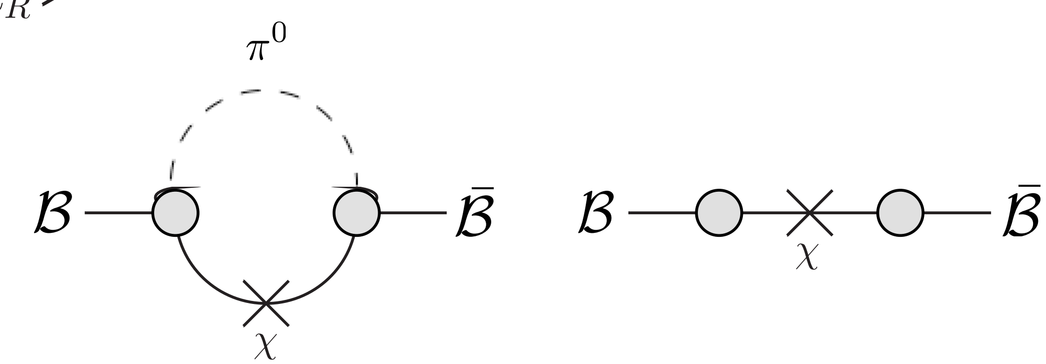
(Aitken, DM, Neder, & Nelson)

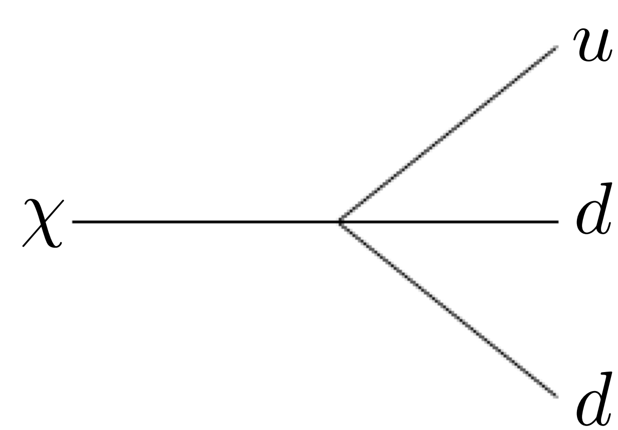
Heavy Flavor Oscillation Model

$$\mathcal{L}_{\rm int} \supset -g^*_{ud}\phi^*\bar{u}_R d^c_R - y_{id}\phi\bar{\chi}_i d^c_R + \text{H.c.}$$



Same model as described by Nelson but different regime: $m_\chi \ll m_\phi$





long-lived

$$\Gamma_\chi \propto \frac{m_\chi^5}{m_\phi^4}$$

$$\left|\frac{\Gamma_{12}}{M_{12}}\right|_1 \sim 4\pi\left(\frac{\Delta m_{\mathcal{B}1}}{m_{\mathcal{B}}}\right)^2 \simeq 0.1\left(\frac{\Delta m_{\mathcal{B}1}}{500\text{ MeV}}\right)^2\left(\frac{5\text{ GeV}}{m_{\mathcal{B}}}\right)^2$$

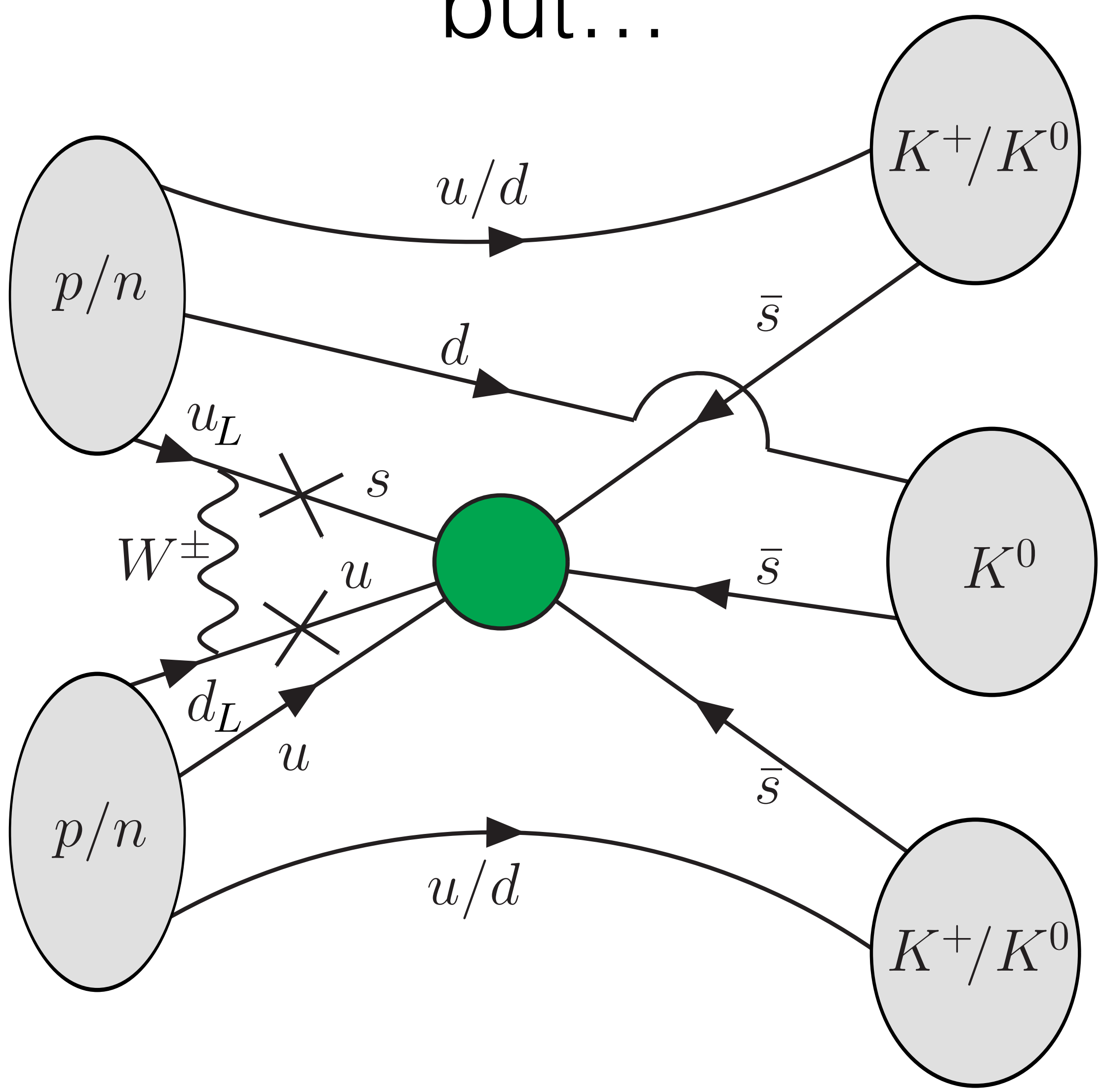
$$|M_{12}|_i \sim \frac{\kappa^2}{2\Delta m_{\mathcal{B}i}}\left|\frac{g^*_{ud}y_{id'}}{m_\phi^2}\right|^2 \simeq 8\times10^{-16}\text{ GeV}\left(\frac{500\text{ MeV}}{\Delta m_{\mathcal{B}i}}\right)\left(\frac{600\text{ GeV}}{m_\phi/\sqrt{|g^*_{ud}y_{id'}|}}\right)^4$$

Need 2 χ_i for phase diff.

Including weak interactions

What if $\Delta B = 2$ operators had $\Delta S = 4$?

but…



Chirally suppressed. Matching:

$$C_{\mathcal{B}\mathcal{B}}(q_R q_R q_R)^2 \to \left(4\pi f_\pi^3\right)^2 \operatorname{tr} B \tilde{C}_{\mathcal{B}\mathcal{B}} B + \ldots,$$

Combine with strangeness changing operators

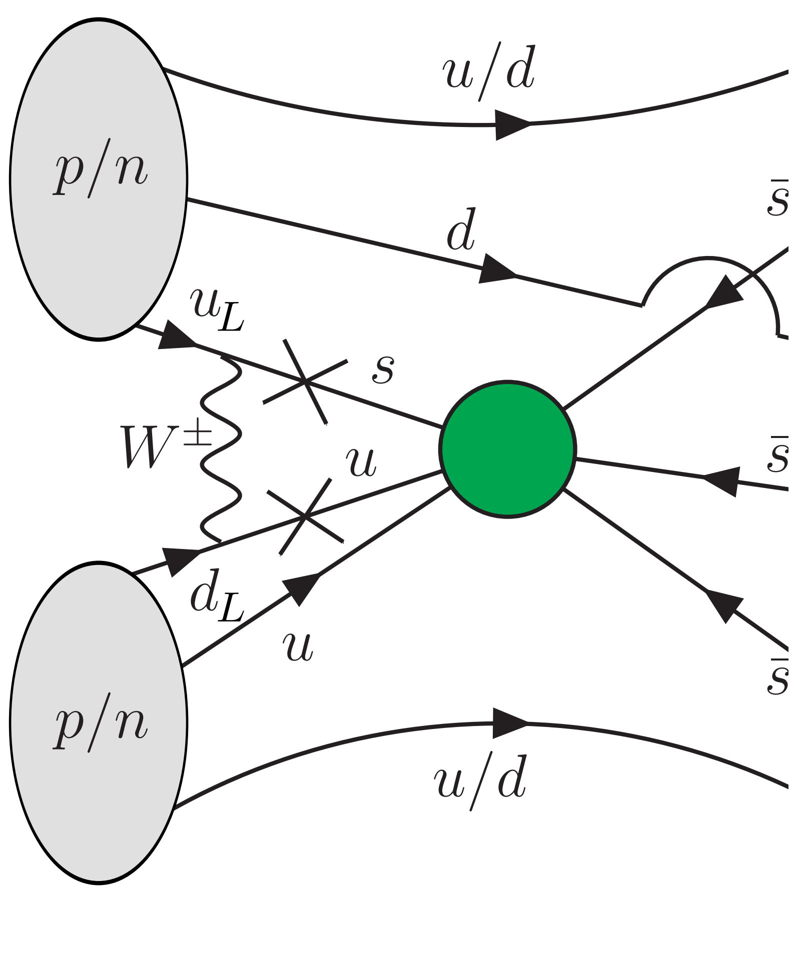
$$\underbrace{\frac{G_F}{\sqrt{2}} V_{us} V_{ud}^*}_{10^{-8}} f_\pi^2 \left(4\pi f_\pi^3\right)^2 \operatorname{tr} B \tilde{C}_{\mathcal{B}\mathcal{B}} \xi^\dagger h \xi B + \ldots$$

Can estimate constraints on heavy flavor transition amplitudes from n osc./DND

Heavy Flavor Oscillations

What if $\Delta B = 2$ operators had $\Delta S = 4$? $2m_N < 4m_K$

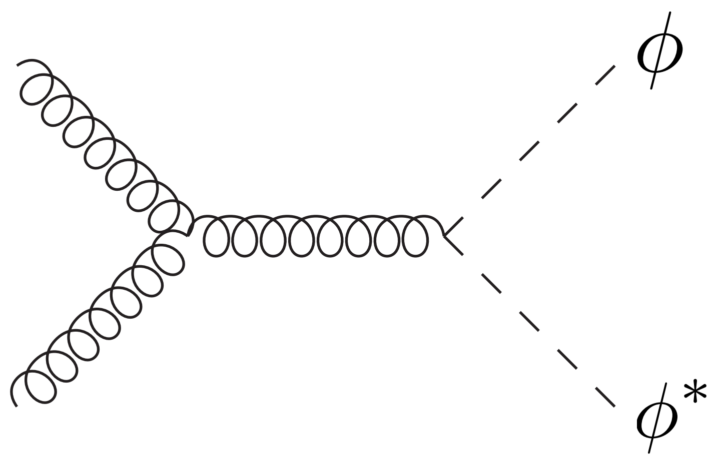
but…

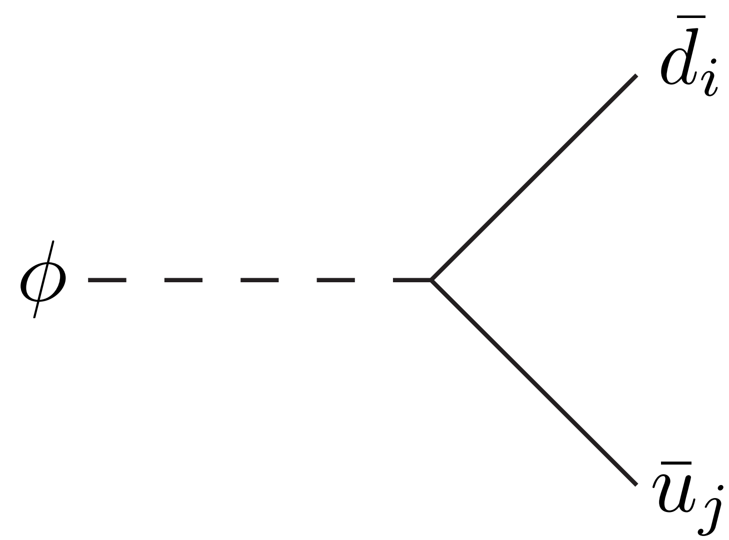


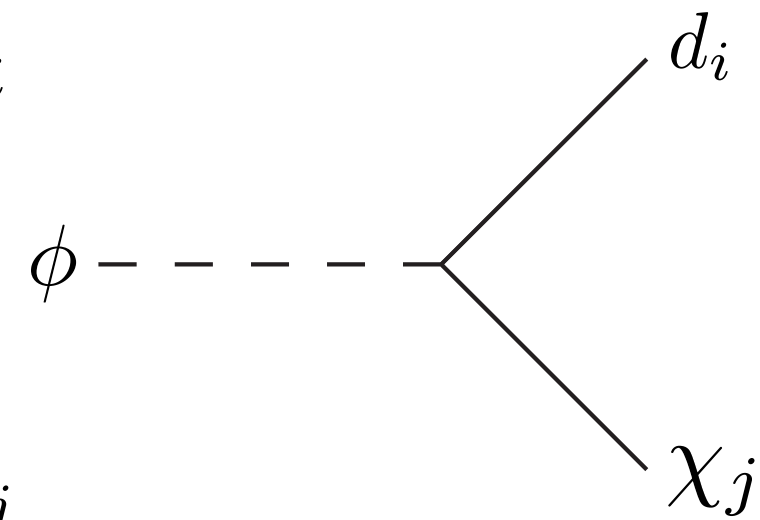
Operator	$\mathcal{B}$	Weak insertions required	Measured Γ (GeV) [22]	Limits on $\delta_{\mathcal{BB}}$ = Dinucleon decay
$(udd)^2$	n	None	$(7.477 \pm 0.009) \times 10^{-28}$	10^{-33}
$(uds)^2$	Λ	None	$(2.501 \pm 0.019) \times 10^{-15}$	10^{-30}
$(uds)^2$	Σ^0	None	$(8.9 \pm 0.8) \times 10^{-6}$	10^{-30}
$(uss)^2$	Ξ^0	One	$(2.27 \pm 0.07) \times 10^{-15}$	10^{-22}
$(ddc)^2$	Σ_c^0	Two	$(1.83^{+0.11}_{-0.19}) \times 10^{-3}$	10^{-17}
$(dsc)^2$	Ξ_c^0	Two	$(5.87^{+0.58}_{-0.61}) \times 10^{-12}$	10^{-16}
$(ssc)^2$	Ω_c^0	Two	$(9.5 \pm 1.2) \times 10^{-12}$	10^{-14}
$(udb)^2$	Λ_b^0	Two	$(4.490 \pm 0.031) \times 10^{-13}$	10^{-13}
$(udb)^2$	Σ_b^{0*}	Two	$\sim 10^{-3*}$	10^{-13}
$(usb)^2$	Ξ_b^0	Two	$(4.496 \pm 0.095) \times 10^{-13}$	10^{-10}
$(dcb)^2$	$\Xi_{cb}^{0\,\dagger}$	Two	$\sim 10^{-12\dagger}$	10^{-17}
$(scb)^2$	$\Omega_{cb}^{0\,\dagger}$	Two	$\sim 10^{-12\dagger}$	10^{-14}
$(ubb)^2$	$\Xi_{bb}^{0\,\ddagger}$	Four	$\sim 10^{-13\ddagger}$	>1
$(cbb)^2$	$\Omega_{cbb}^{0\,\dagger}$	Four	$\sim 10^{-12\dagger}$	>1

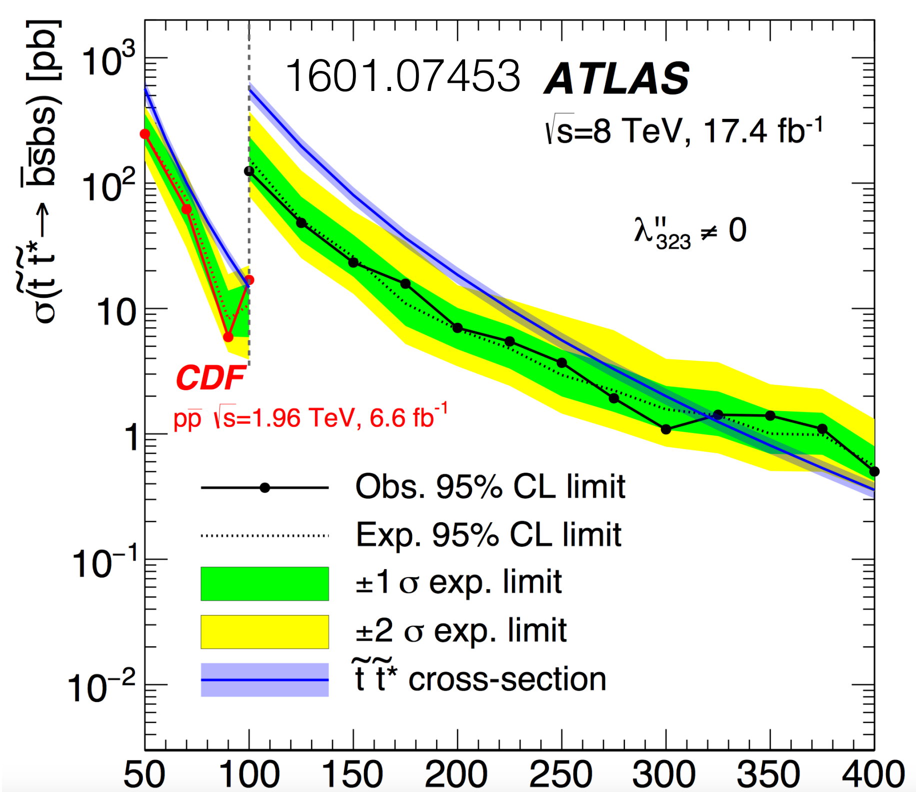
Collider constraints

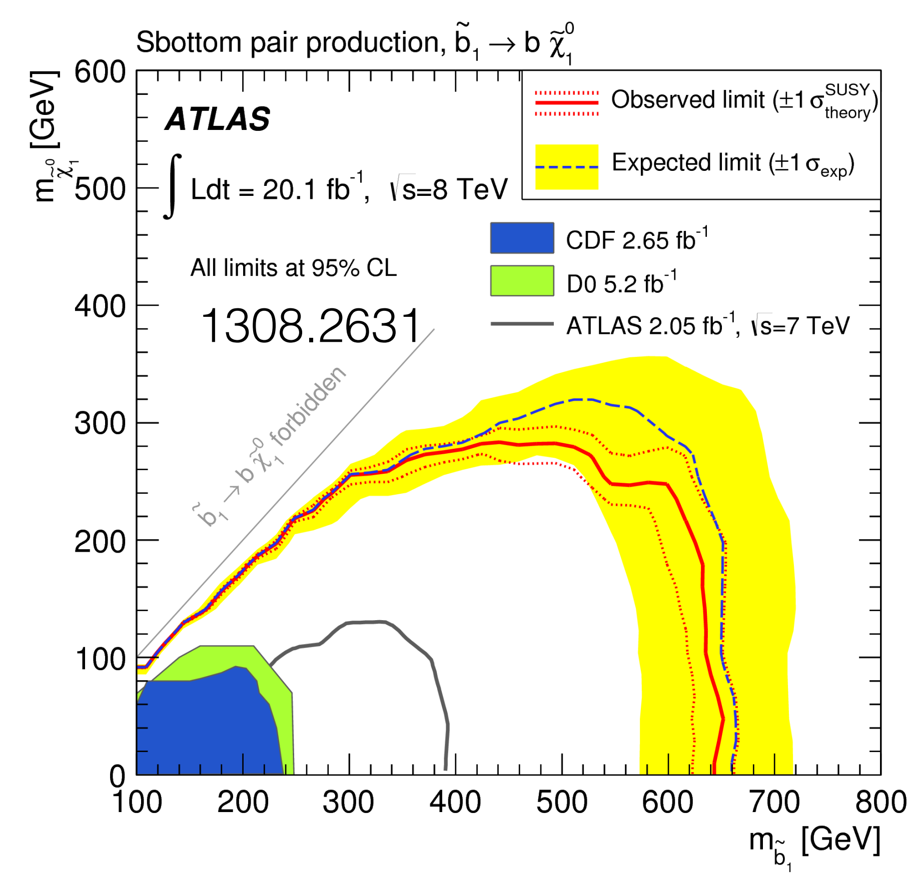
Produce color triplet scalars easily





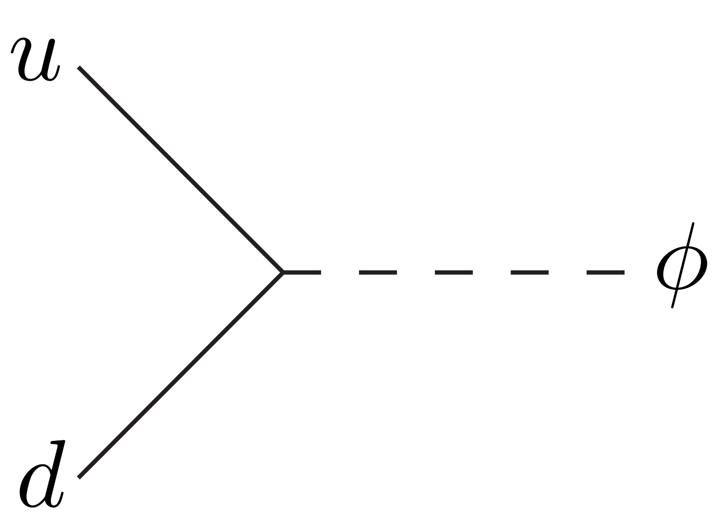


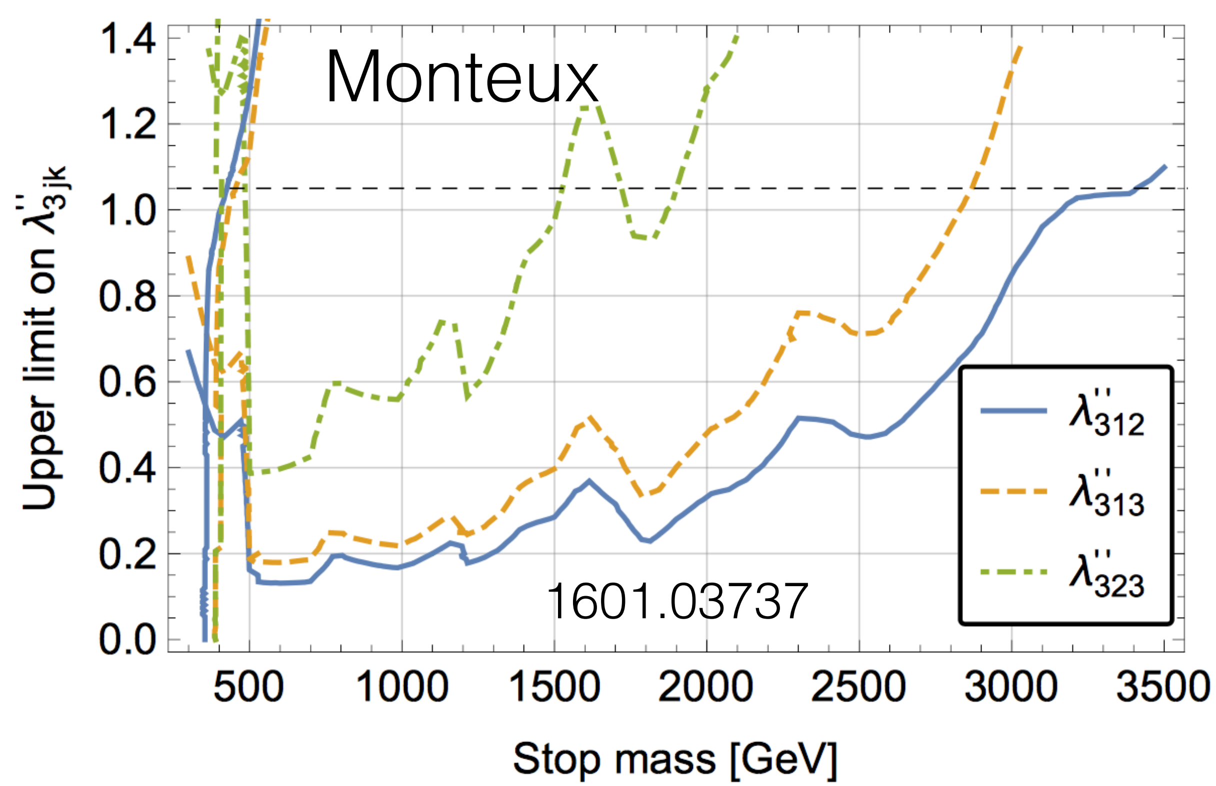




Collider constraints

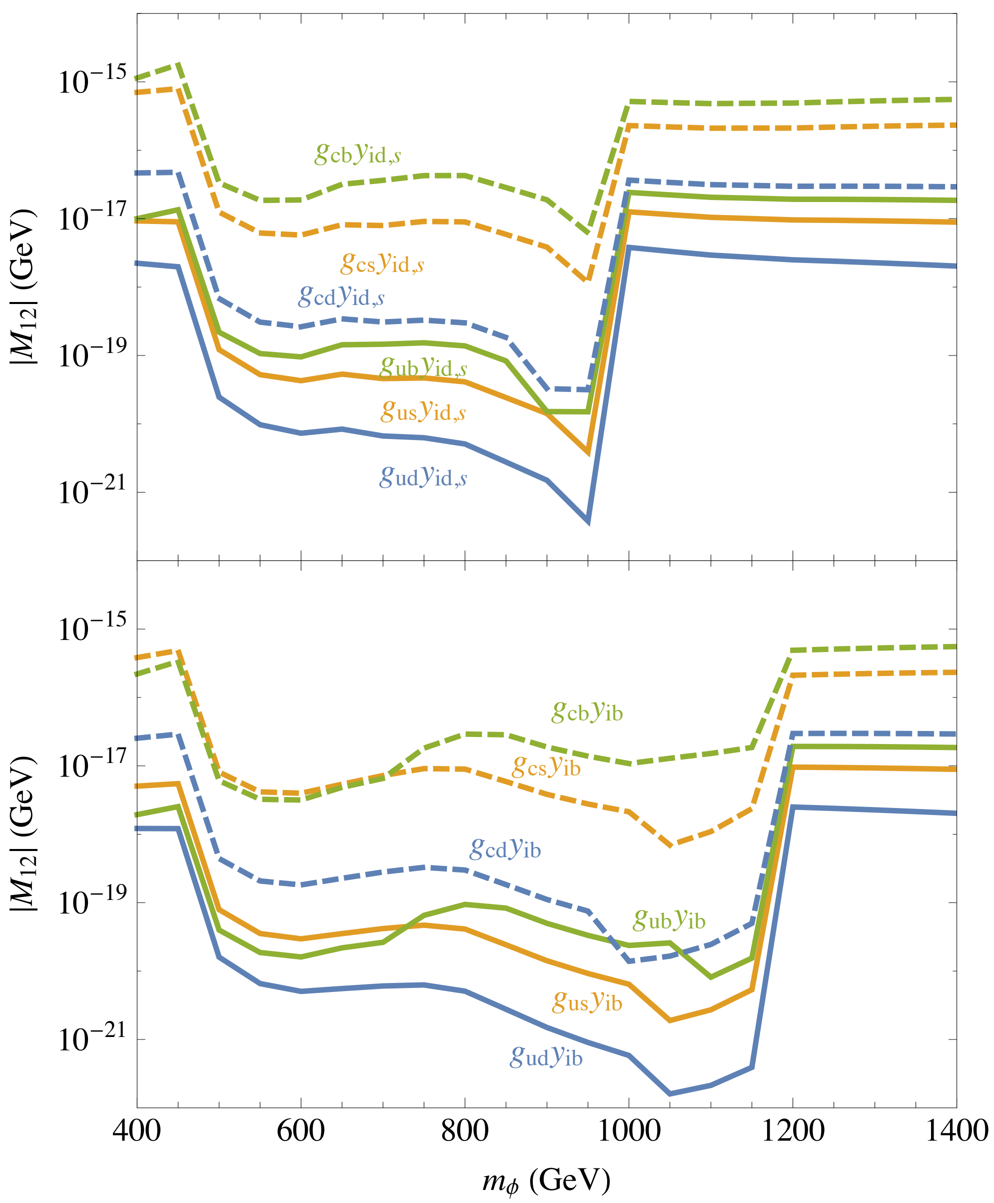
Also produced through “RPV” coupling





Resonant production is important!

Collider constraints



Scan over scalar masses

$$\Delta m = 200 \text{ MeV}$$

		Weak insertions	Measured	Limits on $\delta_{BB} = M_{12}$ (GeV)	
Operator	$\mathcal{B}$	required	Γ (GeV) [22]	Dinucleon decay	Collider
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Production in the early Universe

Need a way to produce the baryons out of equilibrium

Simplest possibility is long-lived χ_3

Same as in model described by Nelson, similar to post-sphaleron scenario of Babu, Dev, Mohapatra

In this case, decoherence is important

Boltzmann equations for radiation, long-lived fermion, heavy B

$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = \Gamma_{\chi_3}\rho_{\chi_3}$$

$$\frac{d\rho_{\chi_3}}{dt} + 3H\rho_{\chi_3} = -\Gamma_{\chi_3}\rho_{\chi_3}$$

$$\frac{dn}{dt} + 3Hn = -i\left(\mathcal{H}n - n\mathcal{H}^\dagger\right) - \frac{\Gamma_\pm}{2}\left[O_\pm, \left[O_\pm, n\right]\right]$$
$$- \langle\sigma v\rangle_\pm \left(\frac{1}{2}\left\{n, O_\pm \bar{n} O_\pm\right\} - n_{\rm eq}^2\right) + \frac{1}{2}\frac{\Gamma_{\chi_3}\rho_{\chi_3}}{m_{\chi_3}}{\rm Br}_{\chi_3\to\mathcal{B}}$$

Need density matrix

$$n = \begin{pmatrix} n_{\mathcal{B}\mathcal{B}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} \end{pmatrix}, \quad \bar{n} = \begin{pmatrix} n_{\bar{\mathcal{B}}\bar{\mathcal{B}}} & n_{\mathcal{B}\bar{\mathcal{B}}} \\ n_{\bar{\mathcal{B}}\mathcal{B}} & n_{\mathcal{B}\mathcal{B}} \end{pmatrix}$$

Tulin, Yu, Zurek

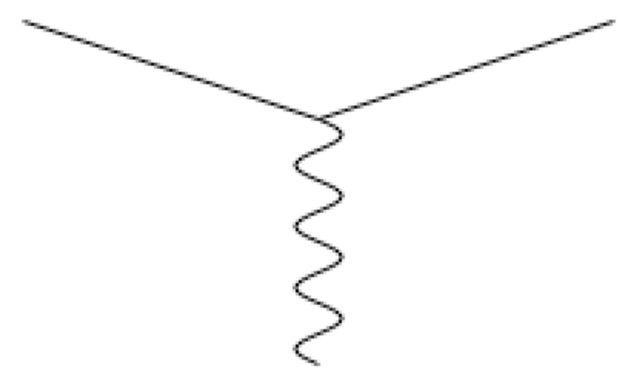
Change of variables to symmetric/asymmetric components

$$\Sigma \equiv n_{\mathcal{B}\mathcal{B}} + n_{\bar{\mathcal{B}}\bar{\mathcal{B}}}, \;\; \Delta \equiv n_{\mathcal{B}\mathcal{B}} - n_{\bar{\mathcal{B}}\bar{\mathcal{B}}}, \;\; \Xi \equiv n_{\mathcal{B}\bar{\mathcal{B}}} - n_{\bar{\mathcal{B}}\mathcal{B}}, \;\; \Pi \equiv n_{\mathcal{B}\bar{\mathcal{B}}} + n_{\bar{\mathcal{B}}\mathcal{B}}.$$

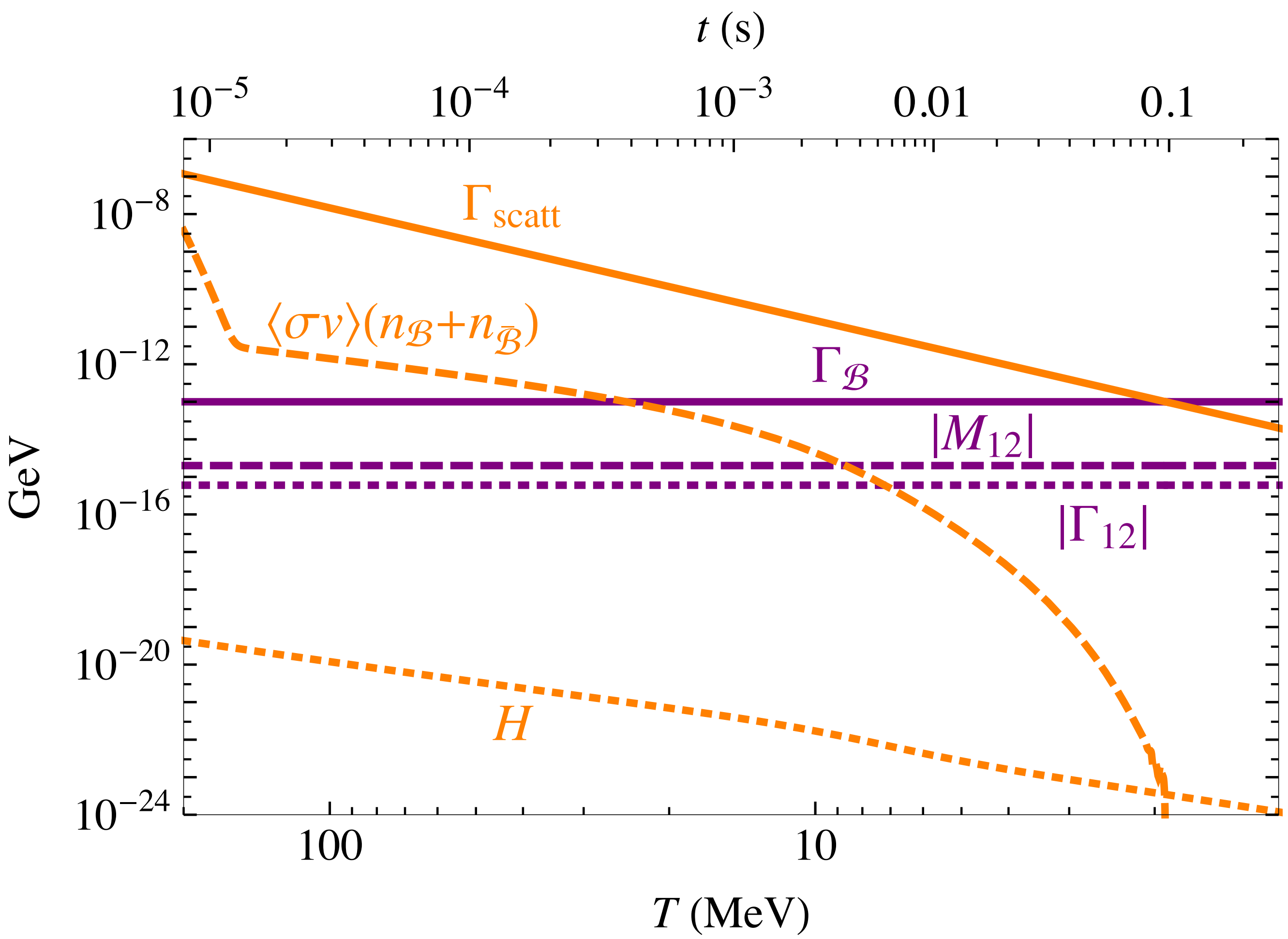
$$\begin{aligned}
\left(\frac{d}{dt} + 3H\right)\Sigma &= \frac{\Gamma_{\chi_3}\rho_{\chi_3}}{m_{\chi_3}}{\rm Br}_{\chi_3\to\mathcal{B}} - \Gamma_{\mathcal{B}}\Sigma - \left({\rm Re}\,\Gamma_{12}\right)\Pi + i\left({\rm Im}\,\Gamma_{12}\right)\Xi \\
&\quad - \frac{1}{2}\Big[\left(\langle\sigma v\rangle_+ + \langle\sigma v\rangle_-\right)\left(\Sigma^2 - \Delta^2 - 4n_{\rm eq}^2\right) \\
&\quad + \left(\langle\sigma v\rangle_+ - \langle\sigma v\rangle_-\right)\left(\Pi^2 - \Xi^2\right)\Big], \\
\left(\frac{d}{dt} + 3H\right)\Delta &= -\Gamma_{\mathcal{B}}\Delta + 2i\left({\rm Re}\,M_{12}\right)\Xi + 2\left({\rm Im}\,M_{12}\right)\Pi, \\
\left(\frac{d}{dt} + 3H\right)\Xi &= -\left(\Gamma_{\mathcal{B}} + 2\Gamma_- + \langle\sigma v\rangle_+\Sigma\right)\Xi \\
&\quad + 2i\left({\rm Re}\,M_{12}\right)\Delta - i\left({\rm Im}\,\Gamma_{12}\right)\Sigma, \\
\left(\frac{d}{dt} + 3H\right)\Pi &= -\left(\Gamma_{\mathcal{B}} + 2\Gamma_- + \langle\sigma v\rangle_+\Sigma\right)\Pi \\
&\quad - 2\left({\rm Im}\,M_{12}\right)\Delta - \left({\rm Re}\,\Gamma_{12}\right)\Sigma.
\end{aligned}$$

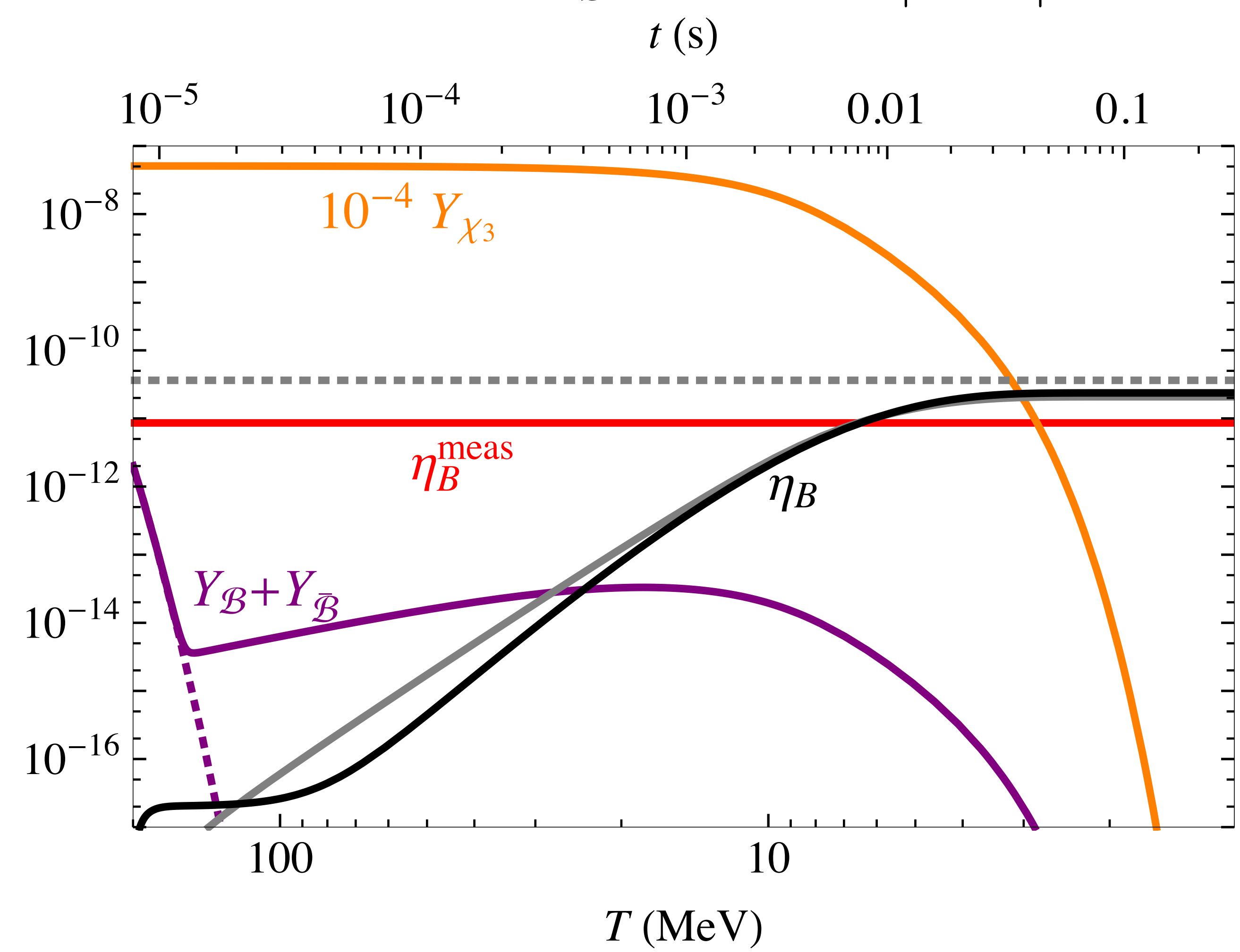
Decoherence due to

$$\frac{i\mu}{4}\bar{\mathcal{B}}\left[\gamma^\nu, \gamma^\rho\right]\mathcal{B}F_{\nu\rho}.$$



Baryon asymmetry calculation: Ω_{cb} $\quad \frac{|M_{12}|}{\Gamma_{\mathcal{B}}} = 10^{-2}, \quad \left|\frac{\Gamma_{12}}{M_{12}}\right| = 0.3$





Sudden decay approx:

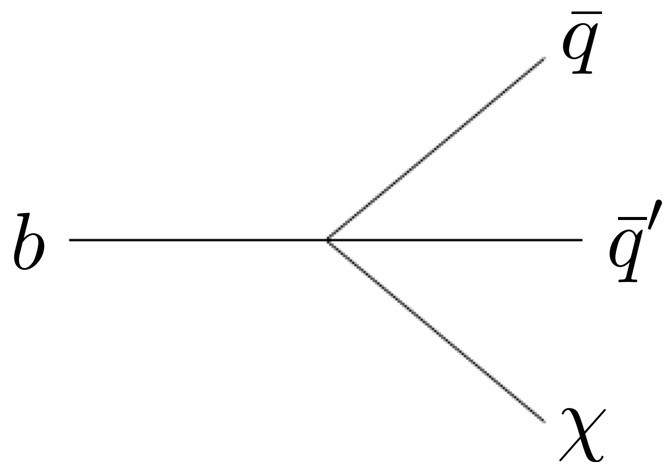
$$\eta_B \simeq \frac{\pi^3}{3\zeta(3)}\sqrt{\frac{\pi g_*(T_{\rm dec})}{10}}\frac{\Gamma_{\mathcal{B}}\epsilon}{\sigma m_{\chi_3}\Gamma_{\chi_3}M_{\rm Pl}}$$

$$= 9\times 10^{-11}\left[\frac{g_*(T_{\rm dec})}{50}\right]^{1/2}\left(\frac{m_{\mathcal{B}}}{5\ {\rm GeV}}\right)^2\left(\frac{\Gamma_{\mathcal{B}}}{10^{-13}\ {\rm GeV}}\right)$$

$$\times\left(\frac{8\ {\rm GeV}}{m_{\chi_3}}\right)\left(\frac{10^{-22}\ {\rm GeV}}{\Gamma_{\chi_3}}\right)\left(\frac{\epsilon}{10^{-5}}\right).$$

Can get observed asymmetry!

Probing this scenario



$$\Gamma_{b\to\bar{\chi}\bar{q}_i\bar{q}_j} \sim \frac{1}{60\,(2\pi)^3}\frac{m_b \Delta m^4}{\Lambda_b^4}$$

$$\textbf{meson} \to \textbf{baryon} + \chi_i[+\textbf{meson(s)}],$$

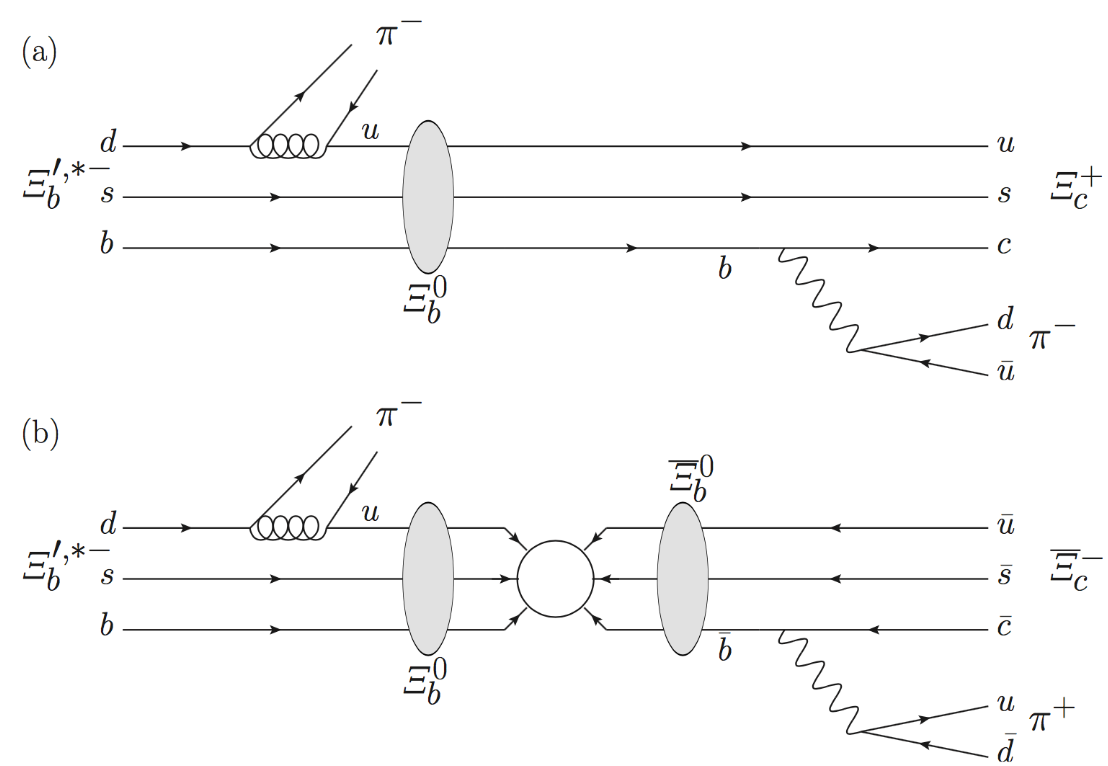
$$\textbf{baryon} \to \textbf{meson(s)} + \chi_i.$$

branchings can be $\mathcal{O}(10^{-3})$

Search for baryon-number-violating $\boldsymbol{\Xi_b^0}$ oscillations

LHCb collaboration [1708.05808]

$$P_{\mathcal{B}\to\bar{\mathcal{B}}} \sim \frac{|M_{12}|^2}{\Gamma_{\mathcal{B}}^2} \sim 10^{-5}$$



Further work in progress…

Conclusions

Having measurable CPV in baryon oscillations requires common final states for baryon & antibaryon

In the neutron system, this is very constrained

Heavy baryons are less constrained and could exhibit a large degree of CPV

This could be relevant to baryon asymmetry of the Universe