Neutron-antineutron oscillation as a probe of baryogenesis

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Collaboration with
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Baryon asymmetry

Baryogenesis is an attempt to answer the question of why matter exists in the Universe

$$\eta_B^{\text{obs}} = (6.20 \pm 0.015) \times 10^{-10}$$

Planck collaboration (2018)

$$\eta_B \equiv \frac{n_B}{n_\gamma}$$

Three conditions: Sakharov conditions

- Baryon number (B) violation
- C and CP violation
- Out-of-equilibrium dynamics

In the Standard Model (SM):

√ Sphalerons
√ CKM matrix
√ Electroweak transition

$\eta_B \approx 10^{-19}$ X

Out-of-equilibrium dynamics and C and CP violation:
Can be connected to B violation in a given model

Need Beyond SM (BSM) physics to explain the baryon asymmetry
How can baryogenesis be probed experimentally?

Search for B violation

Neutron-antineutron oscillation

$$n \to \overline{n}$$

$$\Delta B = -2$$

Proton decay

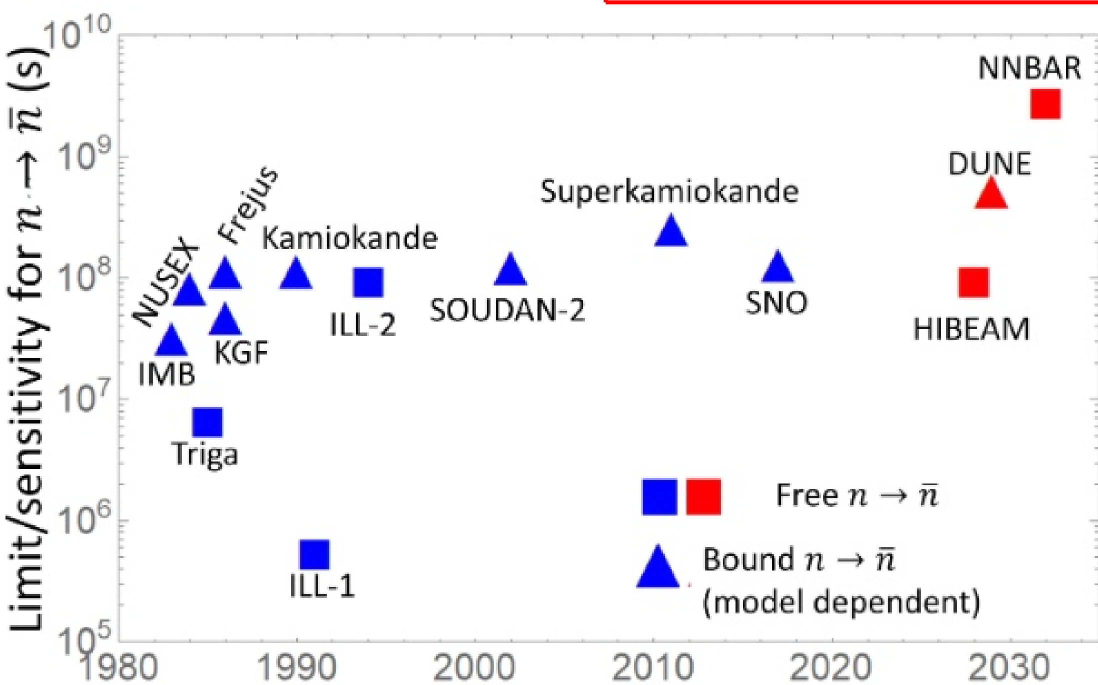
$$p \to X$$

$$\Delta B = -1$$

Dinucleon decay

$$n\,n \to X$$

$$\Delta B = -2$$



Addazi et al (2020)

Future:

- ▲ DUNE (bound):

  $\tau_{n\overline{n}} \sim 7 \times 10^{8}$ s

- ■ NNBAR (free):

  $\tau_{n\overline{n}} \sim 3 \times 10^{9}$ s

Exciting future prospects!
Connect to theory?

Effective field theory (EFT)

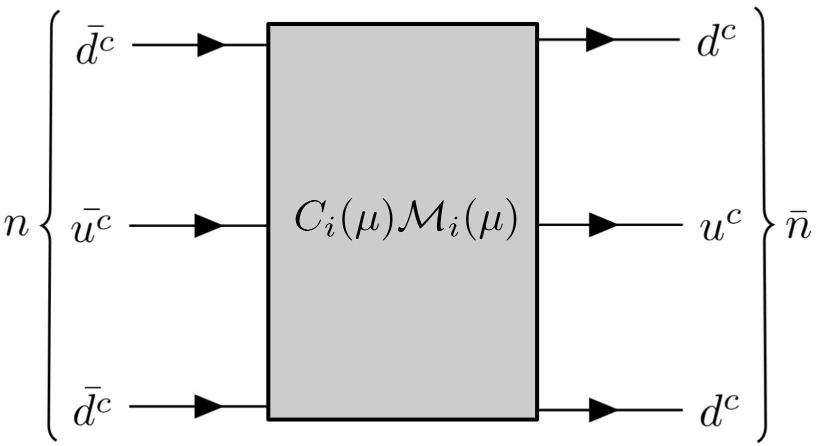
Neutron-antineutron oscillations can be realized by dimension 9 operators

$$\tau_{n\text{-}\bar{n}}^{-1} = \langle \bar{n} | \mathcal{L}_{\text{eff}}^{\bar{n}\text{-}n} | n \rangle = \Big| \sum_i C_i(\mu) \mathcal{M}_i(\mu) \Big|$$

Rinaldi et al (2019)

$$\text{Wilson coefficient: } C_i \propto \frac{1}{\Lambda^5}$$

$$\Lambda = \text{New Physics (NP) scale}$$



Early Universe reaction rate is obtained from the operator and quark number density.

A differential equation for the baryon asymmetry is then obtained:

Deppisch et al (2018)

$$\Gamma_W = \frac{f(n_d, n_u)}{n_\gamma} \frac{T^{14}}{\Lambda^{10}} \quad \Rightarrow \quad \boxed{zH \frac{d\,\eta_{\Delta B}}{d\,z} = -\Gamma_W \eta_{\Delta B}}$$

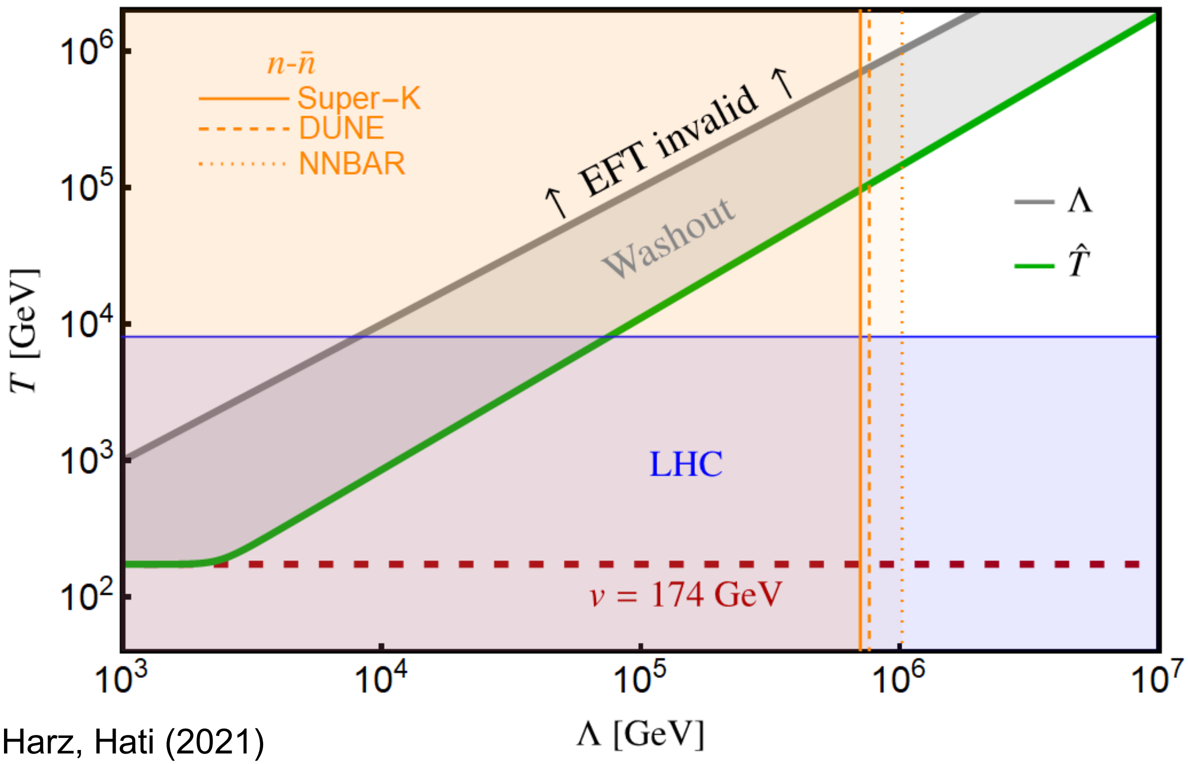
RHS contains only a term with a minus sign: the effect is a washout of the baryon asymmetry

Baryogenesis: effective washout

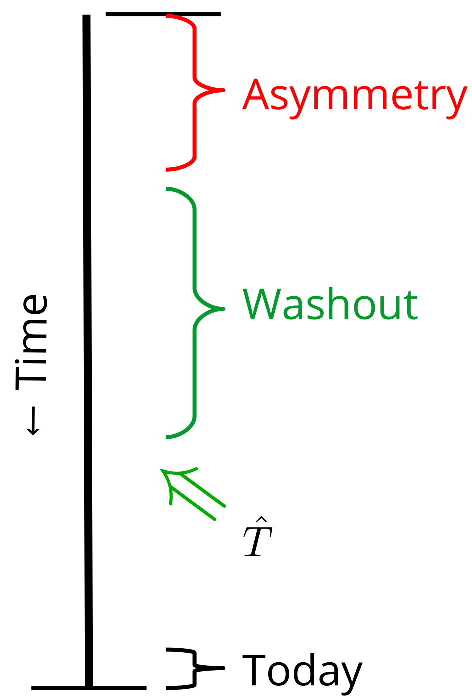
Washout: B violating process that reduces or removes B asymmetry

A baryon asymmetry can be created at a high scale but later washed out

Can be estimated by comparing width to Hubble rate $\Gamma_W \sim H$



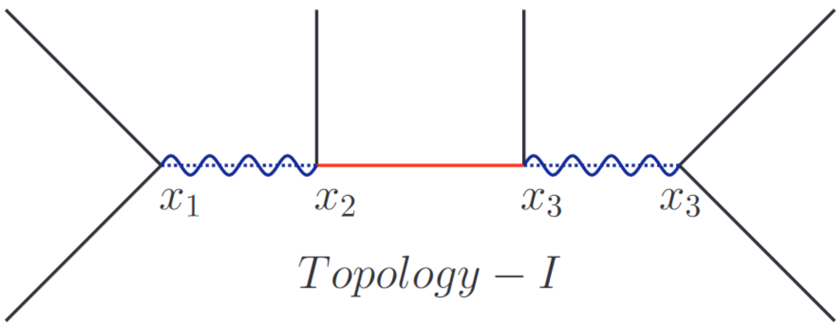
KF, Harz, Hati (2021)

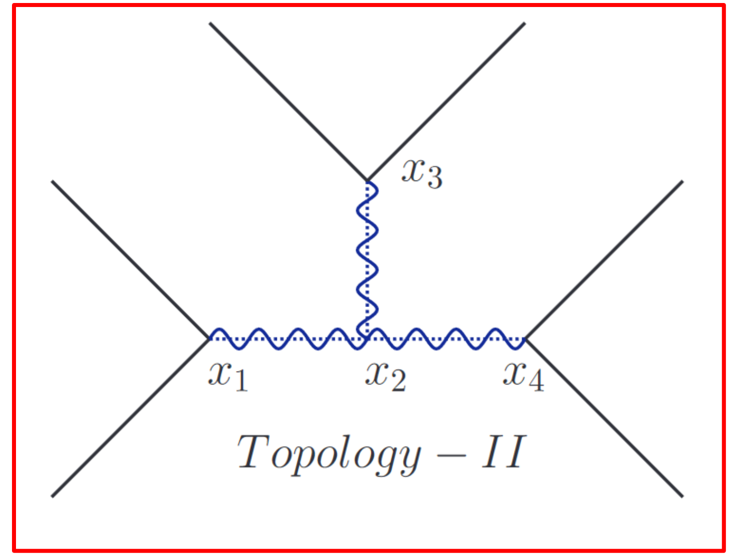


Simplified model

Motivation: This EFT formalism does not account for CP violation or a hierarchy of scales

Grojean et al (2018)





$$\mathcal{L} \supset f^{dd} X_{dd} d_R d_R + f^{ud} X_{ud} u_R d_R + \lambda v' X_{dd} X_{ud} X_{ud} + \text{h.c.}$$

Field	Spin	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	B
X_{dd}	0	$(6, \overline{3})$	1	$+\frac{2}{3}$	$-\frac{2}{3}$
X_{ud}	0	$(6, \overline{3})$	1	$-\frac{1}{3}$	$-\frac{2}{3}$

Very common in GUTs, e.g. $SO(10), E_6$

Babu et al (2012), Aulakh et al (2005), London et al (1986) + ….

Diquarks in SO(10)

Different breaking routes to the SM gauge group.

$$\boxed{SO(10) \xrightarrow{G_{PS},\ G_{LR},\ \ldots} G_{SM}}$$

$$G_{PS} = SU(2)_L \times SU(2)_R \times SU(4)_c$$
$$G_{LR} = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
$$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$$

From the representation 126 of SO(10):

$G_{\rm PS}$	$G_{\rm LR}$	$G_{\rm SM}$
$(\mathbf{1},\mathbf{3},\overline{\mathbf{10}})$	$(1,1,3,+2)$	$(\mathbf{1},\mathbf{1},\mathbf{0}) \oplus (1,1,+1) \oplus (1,1,+2)$
	$(\bar{3},1,3,+\frac{2}{3})$	$(\bar{3},1,-\frac{2}{3}) \oplus (\bar{3},1,+\frac{1}{3}) \oplus (\bar{3},1,+\frac{4}{3})$
	$(\bar{\mathbf{6}},\mathbf{1},\mathbf{3},-\frac{\mathbf{2}}{\mathbf{3}})$	$(\bar{\mathbf{6}},\mathbf{1},-\frac{\mathbf{4}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\mathbf{1},-\frac{\mathbf{1}}{\mathbf{3}}) \oplus (\bar{\mathbf{6}},\mathbf{1},+\frac{\mathbf{2}}{\mathbf{3}})$

$$X_{dd} \sim (6,1,-\tfrac{2}{3}),\ X_{uu} \sim (6,1,\tfrac{4}{3}),\ X_{ud} \sim (6,1,\tfrac{1}{3}),\ \xi \sim (1,1,0)$$

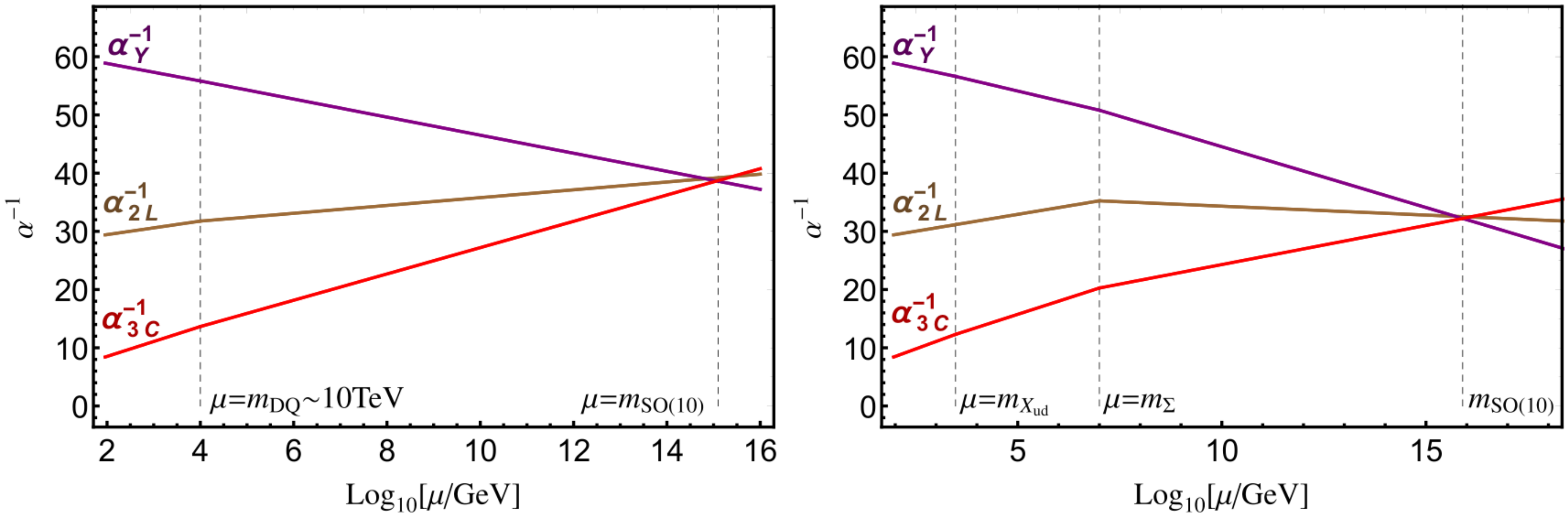
Where ξ breaks the B-L symmetry:

$$\mathcal{L} \supset \lambda \xi X_{dd} X_{ud} X_{ud} \to \lambda v' X_{dd} X_{ud} X_{ud}$$

Unification in SO(10)

RGE running: $\mu \frac{\partial g_i}{\partial \mu} = \frac{b_i}{16\pi^2} g_i^3$

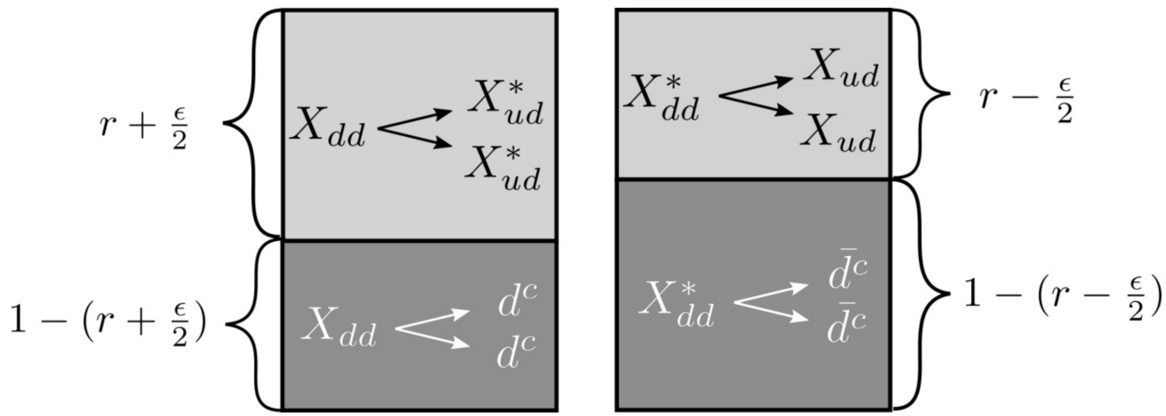
Assuming intermediate symmetries in the breaking chain are all close to $m_{SO(10)}$

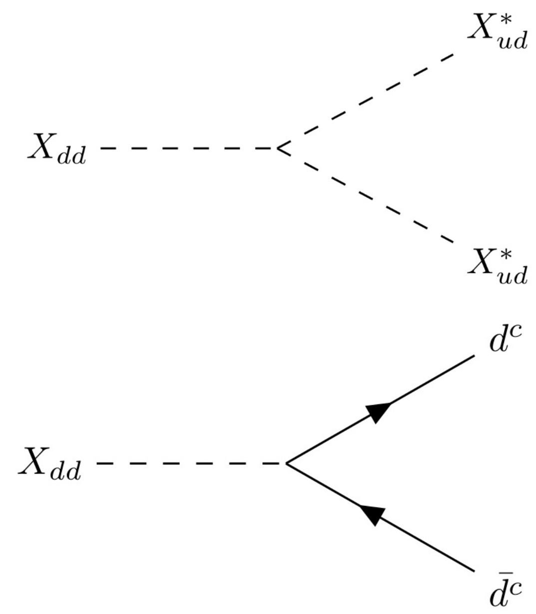


Two scenarios: *Left:* Two copies of $\Delta \sim (1,3,0)$ at $m_\Delta \sim m_{X_{ud}} \sim \mathcal{O}(\mathrm{TeV})$. Babu et al (2012)

Right: Intermediate scale $\Sigma \sim (6,3,\frac{1}{3})$ at $m_\Sigma \sim \mathcal{O}(10^4\ \mathrm{TeV})$, and $\mathrm{m}_{X_{ud}} \sim \mathcal{O}(\mathrm{TeV})$.

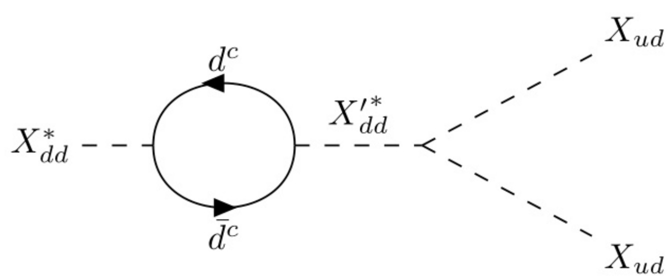
CP violation





The total decay width of X_{dd} and X_{dd}^* are the same. CP violation arises from different branching ratios of X_{dd} and X_{dd}^* into X_{ud} +X_{ud} / d^c + $\bar{d}^c$.

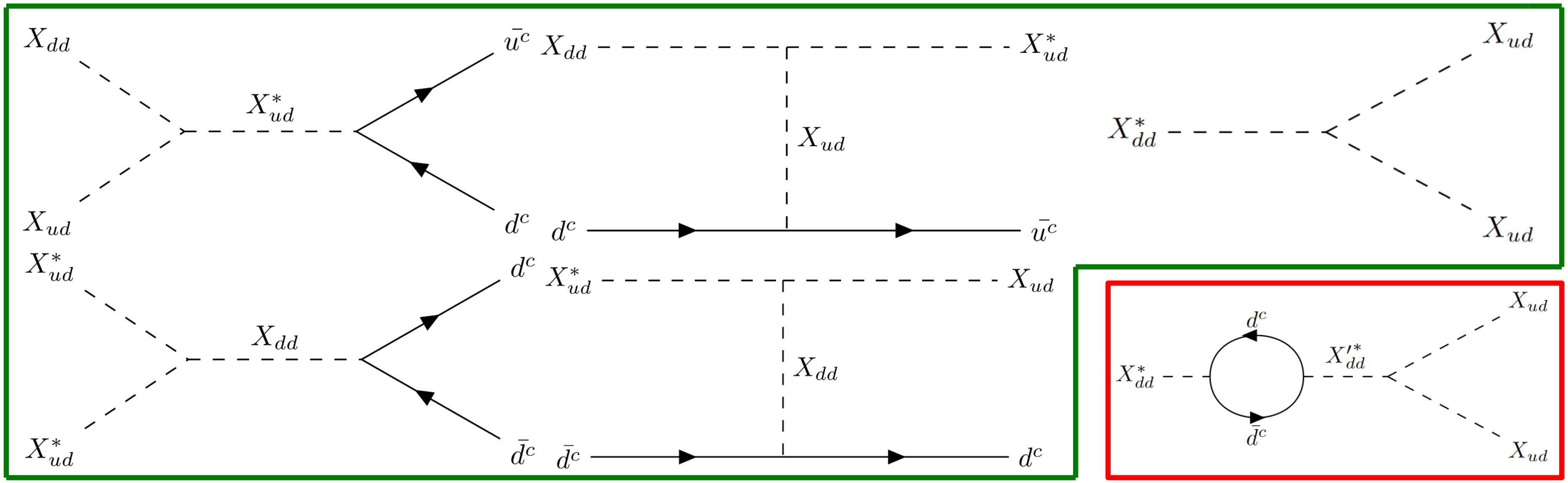
The difference in branching ratios comes from loop diagrams involving X_{dd}', which in turn comes from a field (6,1,-2/3) from the representation 54 of SO(10) mixing with the one from 126.

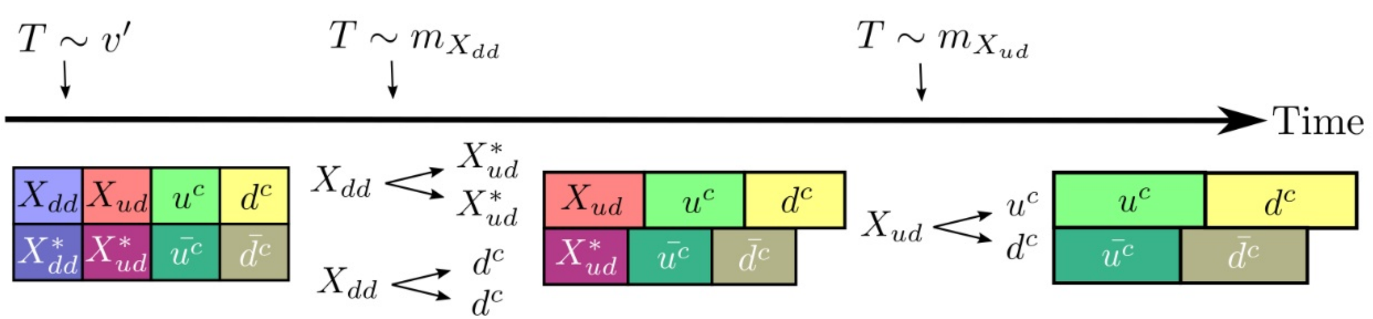


Baryogenesis

$$\frac{d\eta_{\Delta B}}{dT} = \epsilon \times D(\eta_{X_{dd}} - \eta^{\mathrm{eq}}_{X_{dd}}) - \eta_{\Delta B} W$$

$m_{X_{dd}} > 2m_{X_{ud}}$

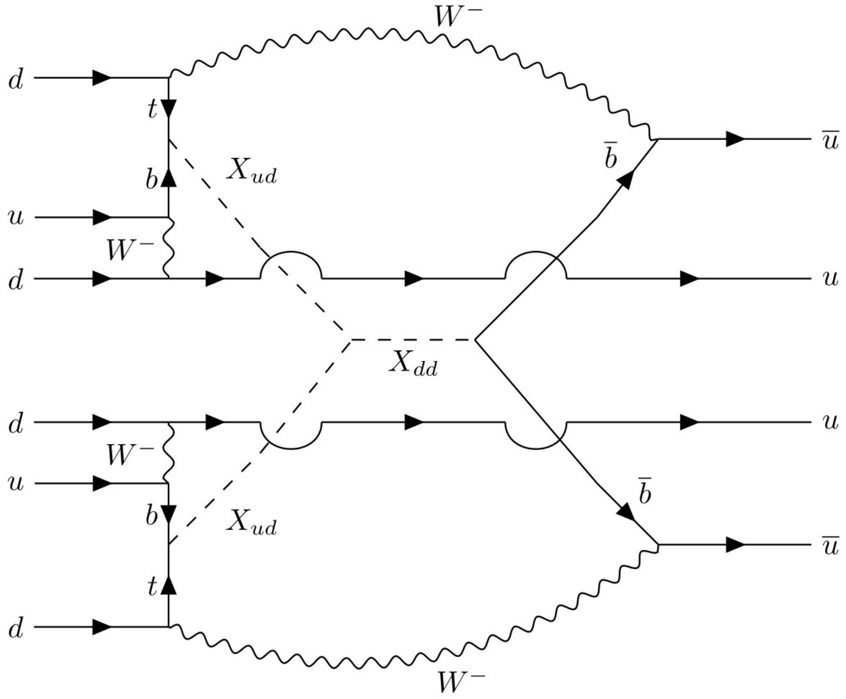




Dinucleon decay, meson oscillations

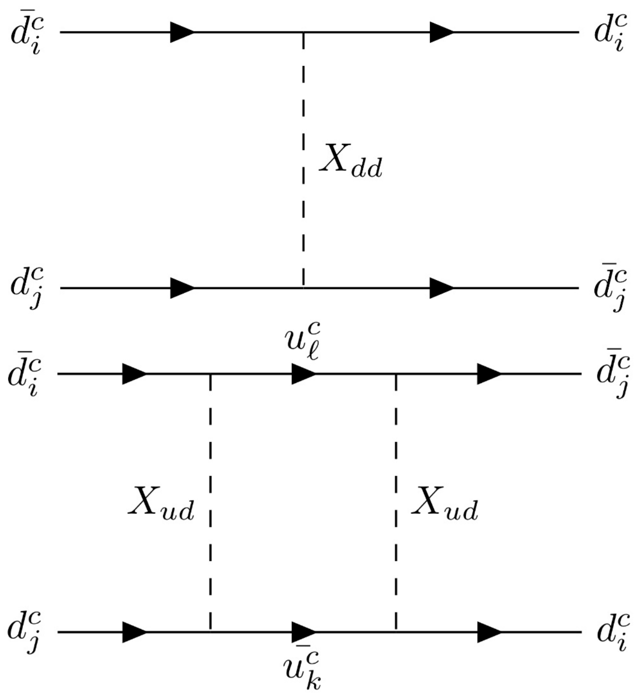
Dinucleon decay:

- Large uncertainties in nuclear matrix elements
- Fewer loops than neutron-antineutron oscillations for 3rd gen
- Generally low constraints



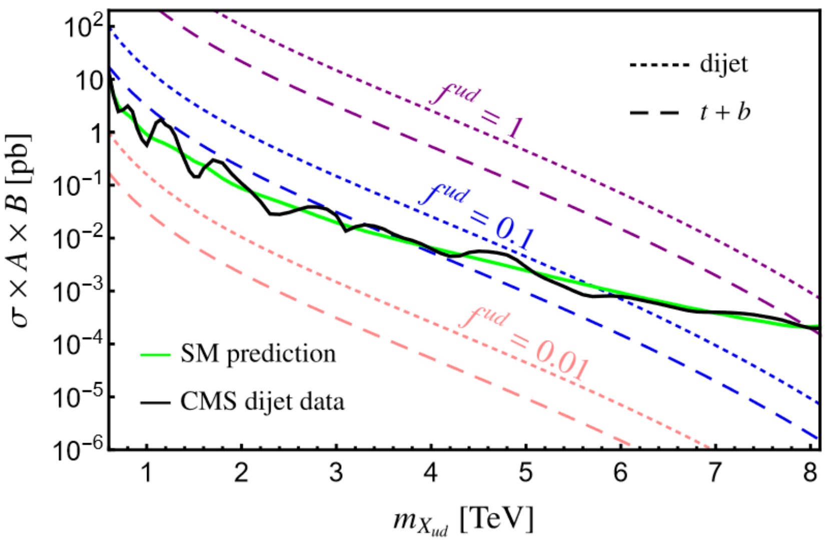
Meson oscillations:

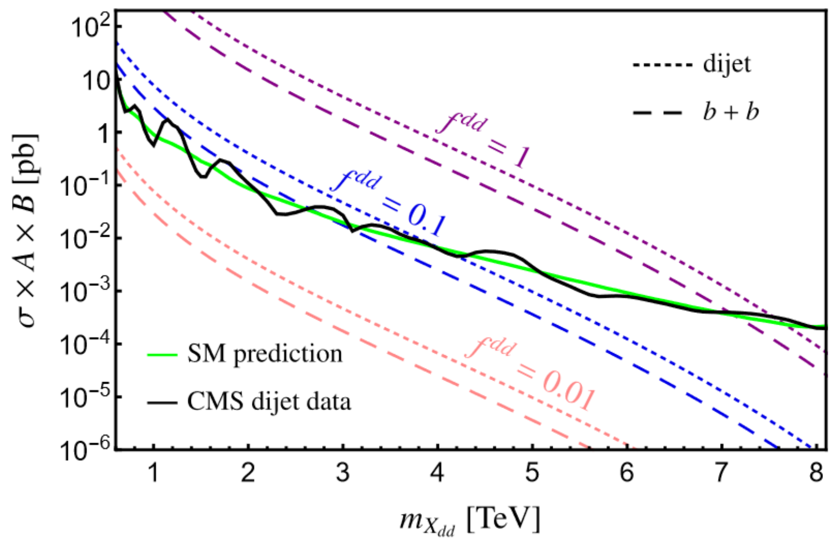
- Tree- or loop-level oscillations depending on the diquark
- Kaon oscillations the most sensitive
- Generally low constraints (compared to neutron-antineutron oscillations)



LHC

KF, Harz, Hati (2021)





CMS Collaboration (2018)

The LHC provides a good complementarity to low-scale observables

LHC does not directly probe the B-violating mechanism

Two benchmark scenarios:

High-scale:

$$m_{X_{dd}} \sim 10^{14}\ \text{GeV} \gg m_{X_{ud}} \sim 10^{4}\ \text{GeV}$$

Low-scale:

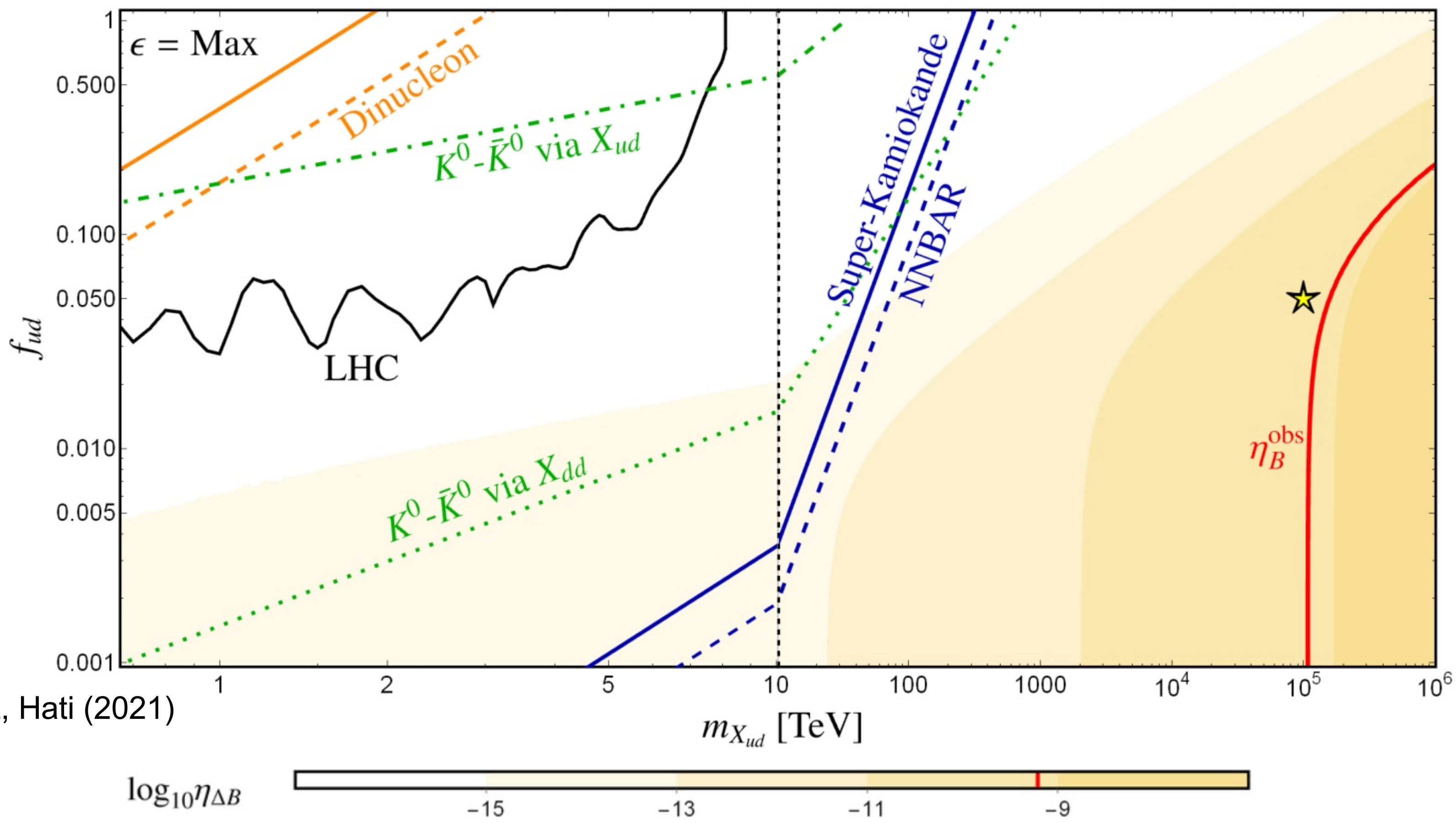
$$10^{9}\ \text{GeV} \gtrsim m_{X_{dd}}, m_{X_{ud}} \gtrsim 10^{3}\ \text{GeV}$$

$$m_{X_{dd}} = 3 m_{X_{ud}}$$

Low-scale baryogenesis

$$\mathcal{L}_{\text{eff}}^{n\text{-}\bar{n}} = \frac{f_{ud}^2 f_{dd} \lambda v'}{m_{X_{dd}}^2 m_{X_{ud}}^4} \mathcal{O}_{RRR}^{n\text{-}\bar{n}}$$

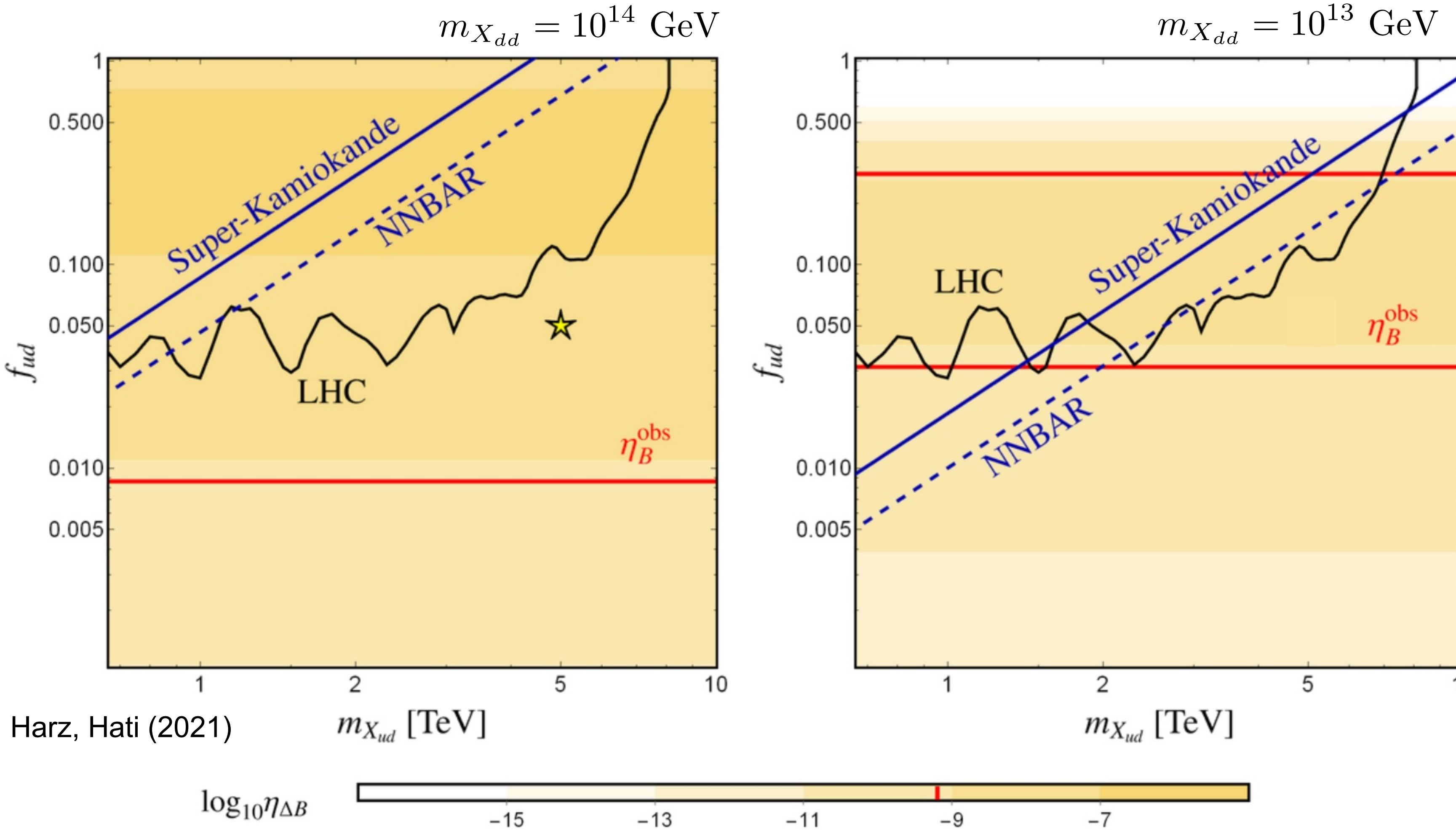
$m_{X_{dd}} = 3 m_{X_{ud}}$



KF, Harz, Hati (2021)

Agrees with the EFT, the washout is big even with an additional CP-violation source.
A small mass hierarchy leads to baryogenesis being out of reach for experiments.

High-scale baryogenesis

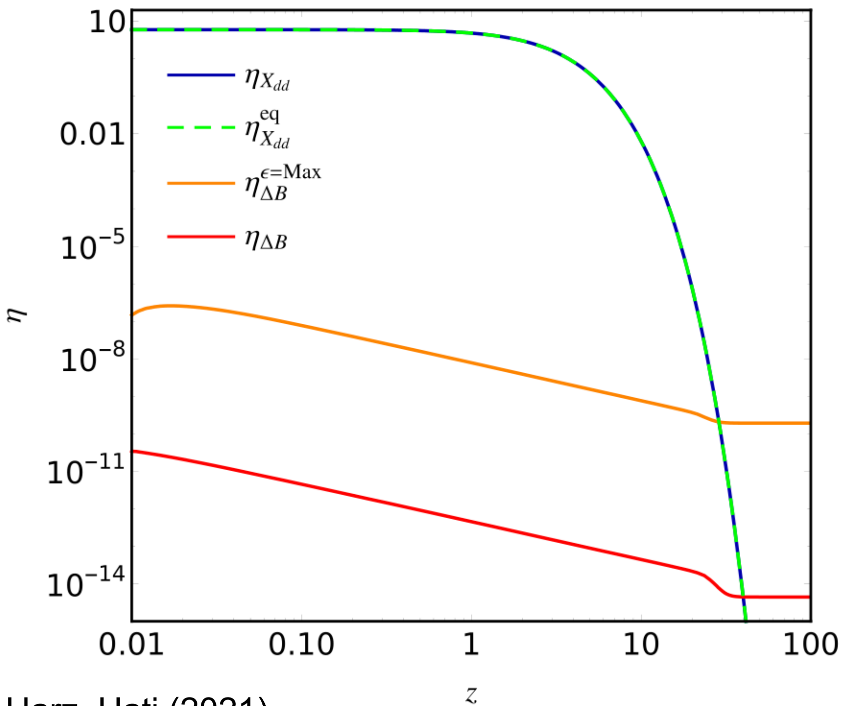


KF, Harz, Hati (2021)

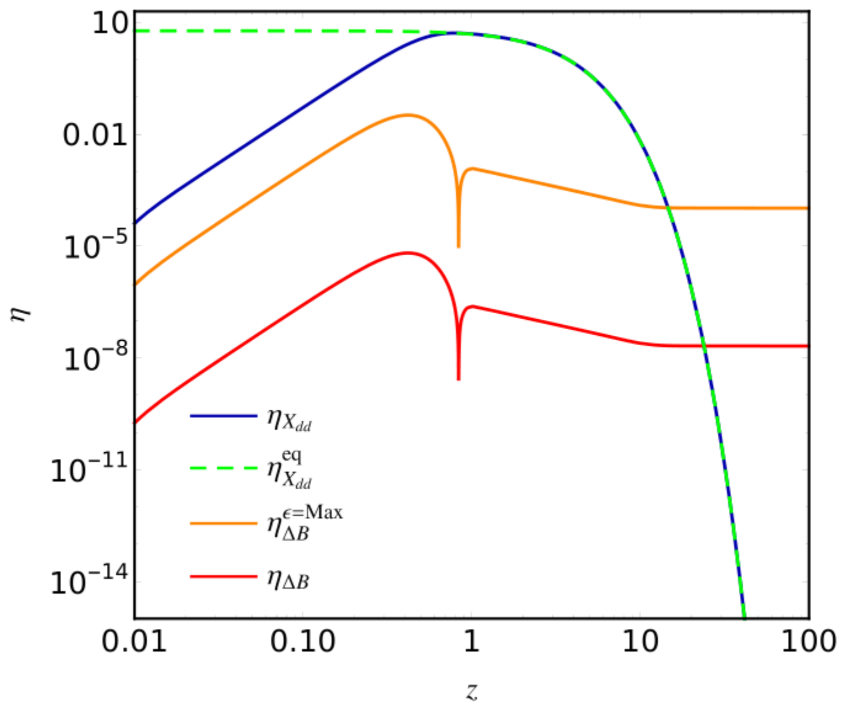
EFT breaks down due to mass hierarchy. Regions of parameter space that can be probed by both LHC and neutron-antineutron oscillations result in successful baryogenesis.

Evolution of baryon asymmetry

Low scale



High scale



KF, Harz, Hati (2021)

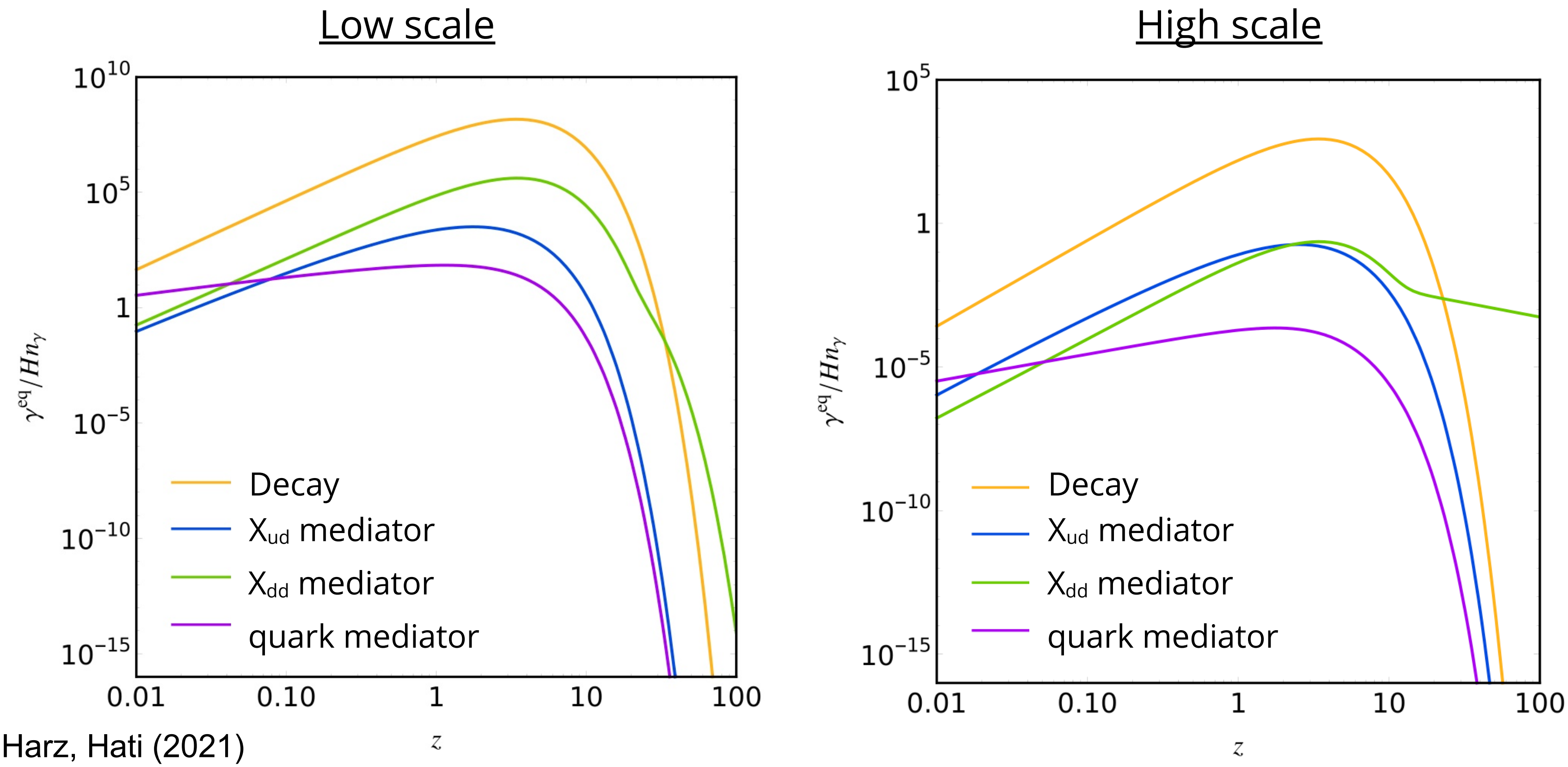
$$z = m_{X_{dd}}/T$$

$$\eta_X = n_X/n_\gamma$$

$$\eta_B^{\mathrm{obs}} = (6.20 \pm 0.015) \times 10^{-10}$$

Baryon asymmetry freezes out at z ~ 10 – 40 in both scenarios. The observed baryon asymmetry is exceeded at this benchmark point for maximum CP violation in the low scale case and for different magnitudes of CP violation in the high scale case.

Rates for benchmark points



KF, Harz, Hati (2021)

In both cases, the X_{dd} mediated scattering is the dominant washout apart from inverse decay. In the high scale case, this washout channel does not vanish until much after the other processes do, however its effect is negligable after z ~ 40.

Conclusion

- Neutron-antineutron oscillation experiments will probe B-violation by two units to an unprecedented sensitivity in the near future

- A potential neutron-antineutron oscillation discovery could have far reaching implications for GUT baryogenesis

- To study the overlap of neutron-antineutron oscillation and baryogenesis it is useful to go beyond the EFT to a simplified model

Thank you