Probing baryogenesis using neutron-antineutron oscillations

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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

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

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

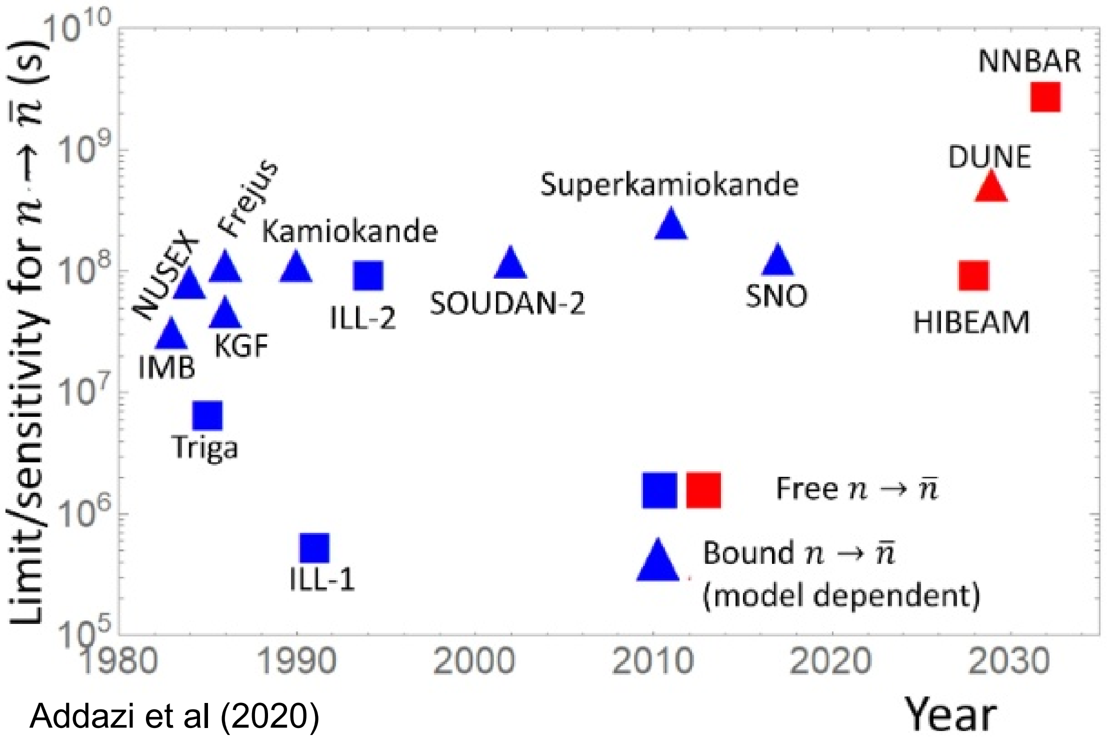
$$p \to X$$

$$\Delta B = -1$$

Dinucleon decay

$$nn \to X$$

$$\Delta B = -2$$



Addazi et al (2020)

Future:

▲ DUNE (bound):

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

■ NNBAR (free):

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

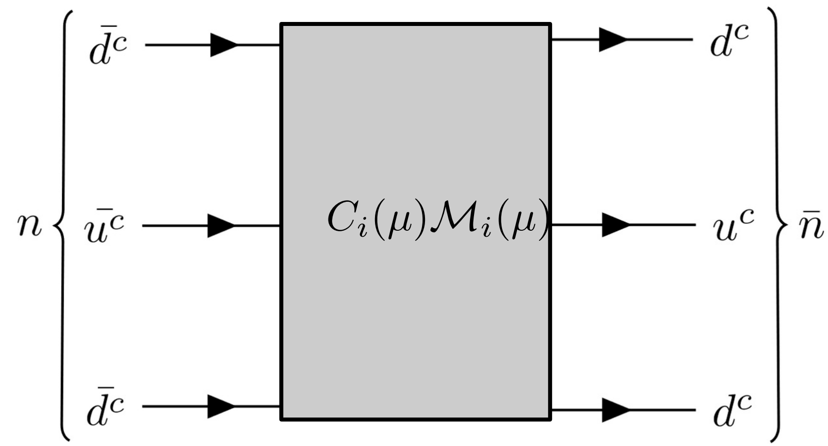
Exciting future prospects!
Connect to theory?

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)

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

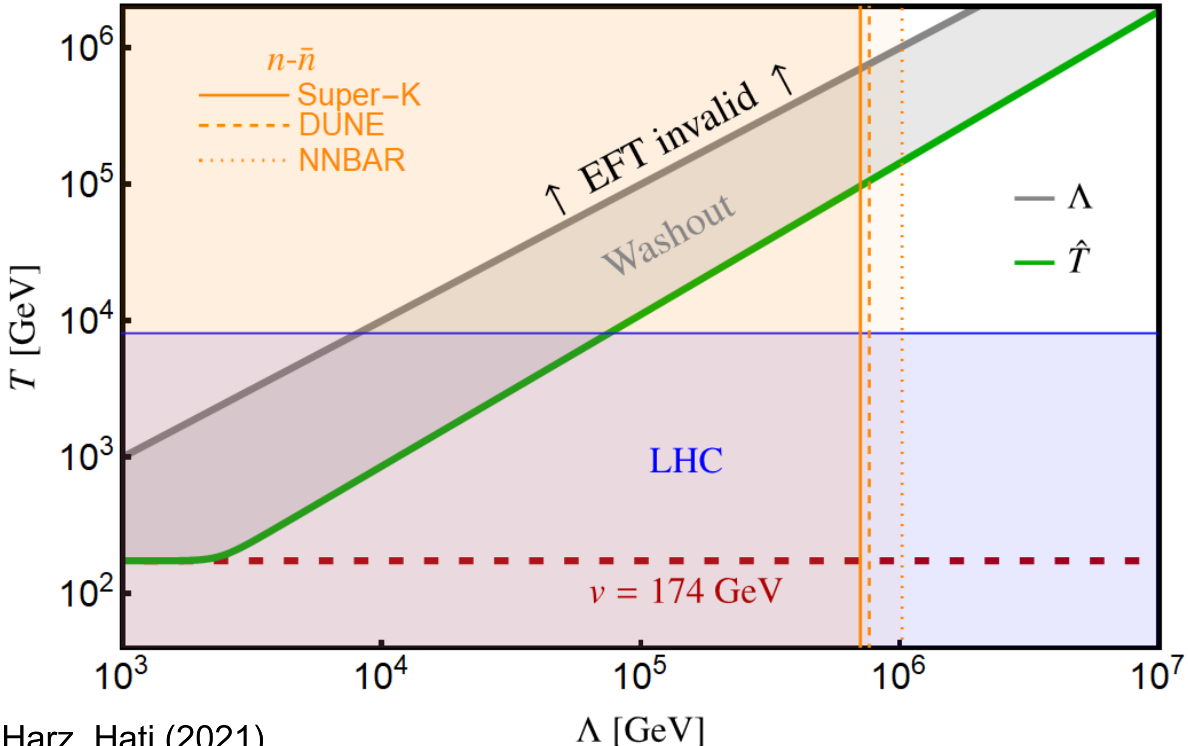
RHS contains only a term with a minus sign: the effect is a washout of the baryon asymmetry

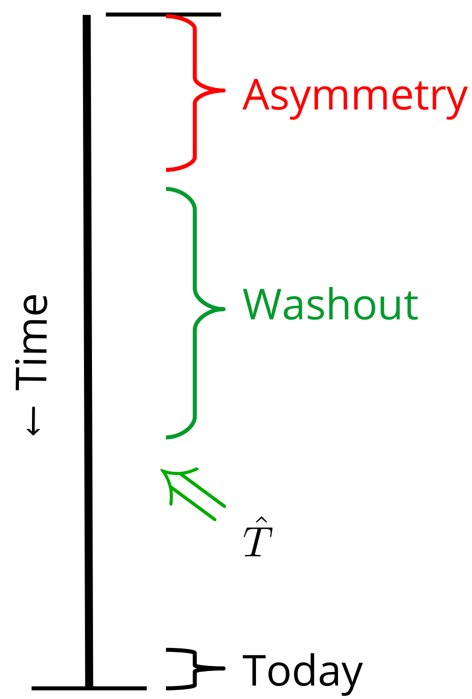
Baryogenesis: effective washout

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 $\Gamma_W \sim H$



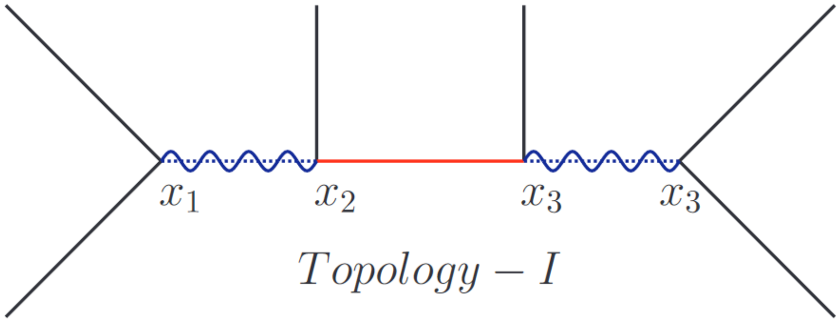


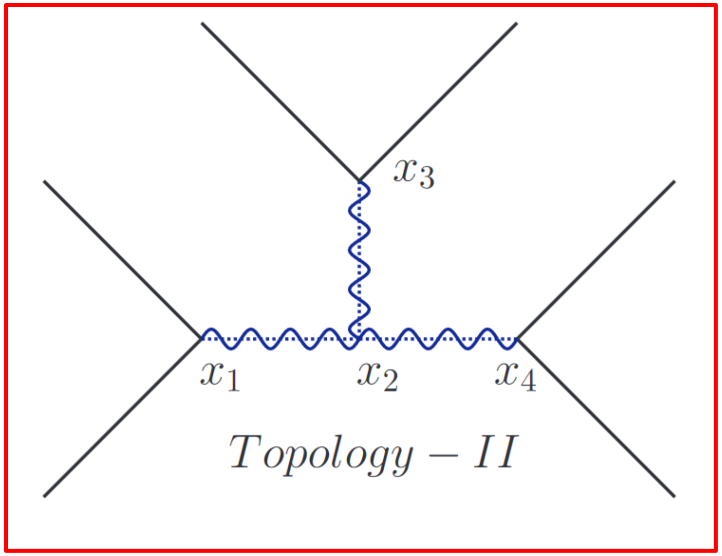
KF, Harz, Hati (2021)

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) + ….

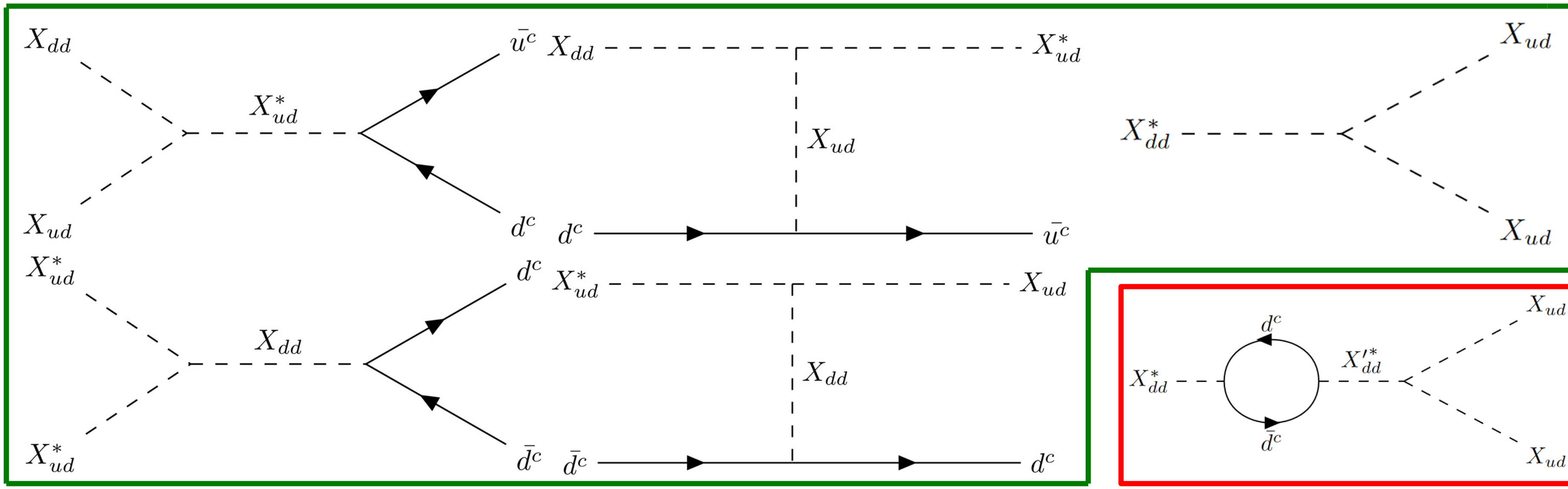
SFB 1258 Neutrinos Dark Matter Messengers

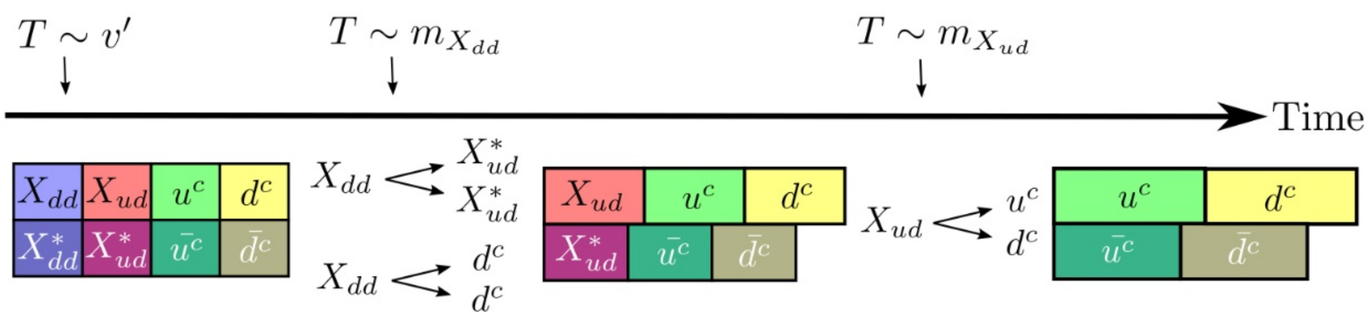
Emmy Noether-Programm DFG

Baryogenesis

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

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

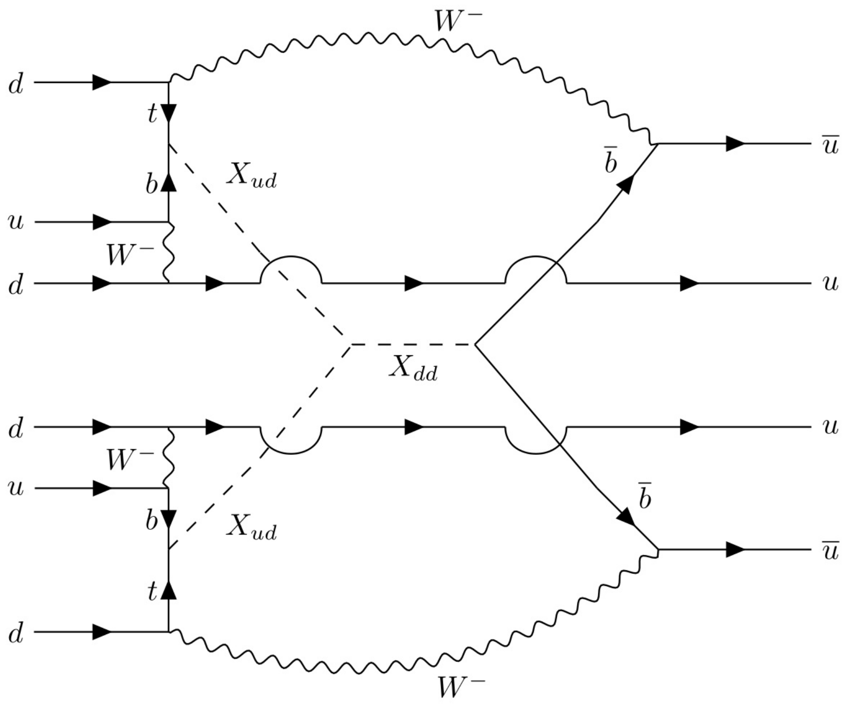




Dinucleon decay, meson oscillations

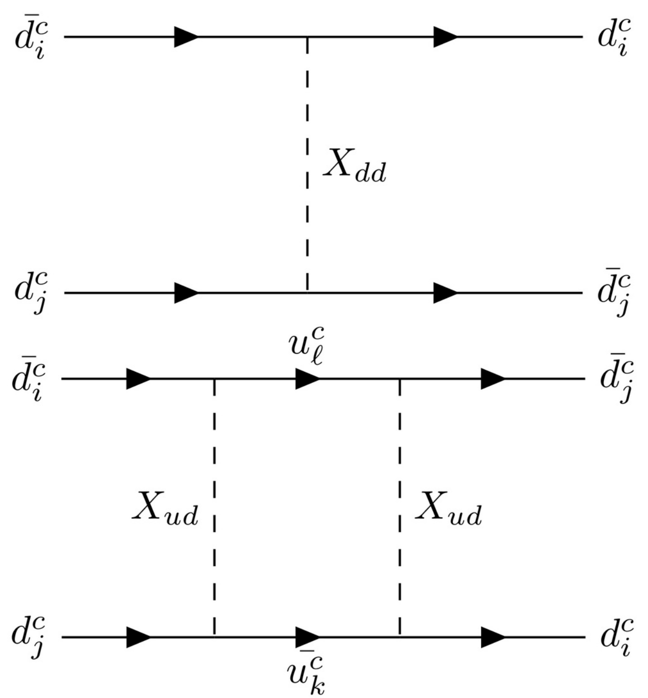
Dinucleon decay:

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



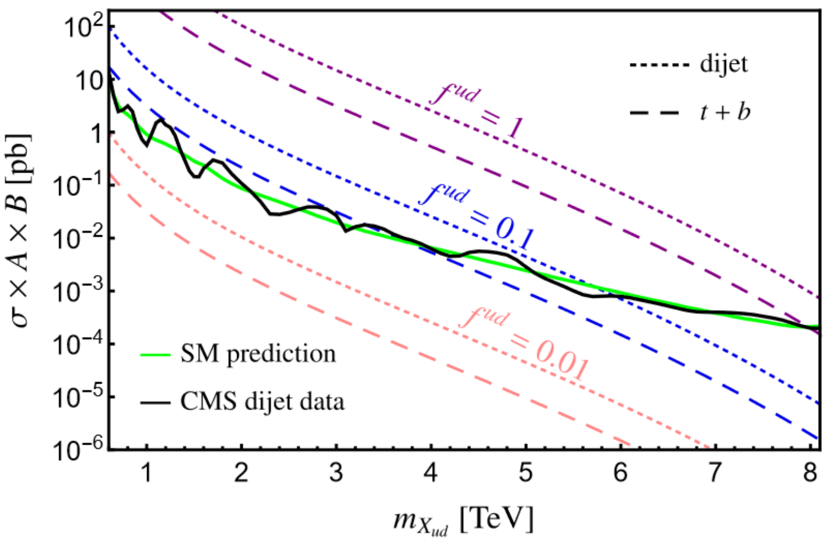
Meson oscillations:

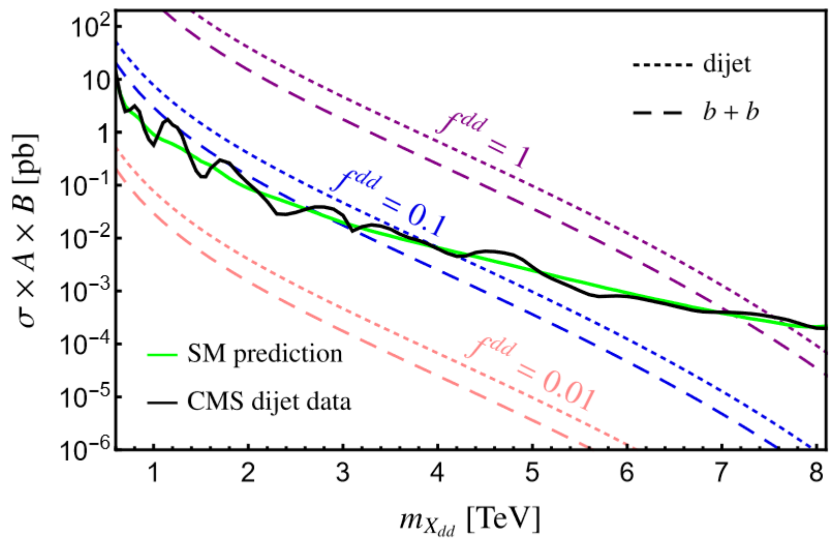
- Tree- or loop-level oscillations depending on the diquark
- Kaon oscillations the most sensitive
- Generally low constraints (compared to neutron-antineutron oscillations)



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:

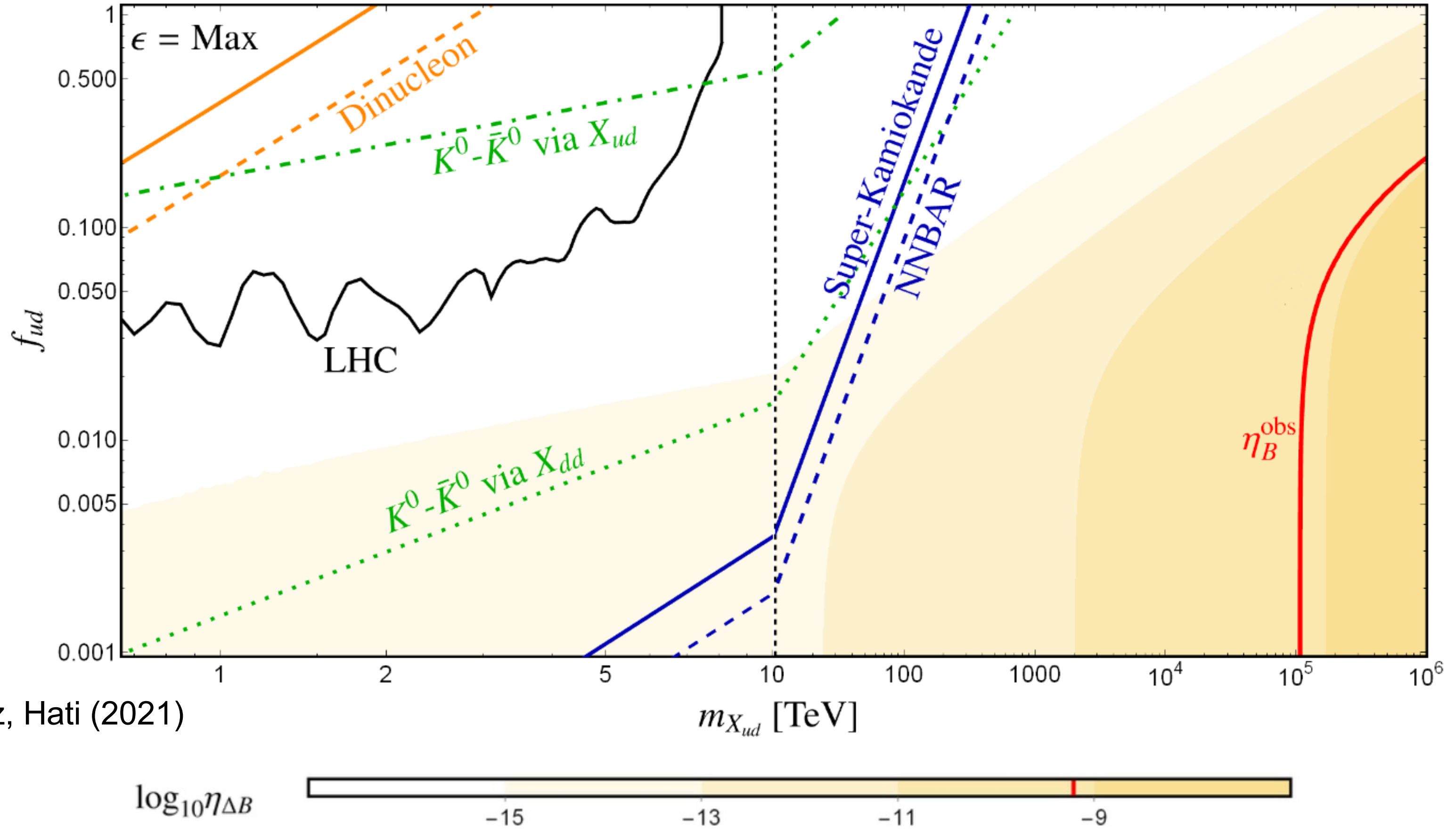
$$10^{9}\ \text{GeV} \gtrsim m_{X_{dd}}, m_{X_{ud}} \gtrsim 10^{3}\ \text{GeV}$$

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

Low-scale baryogenesis

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

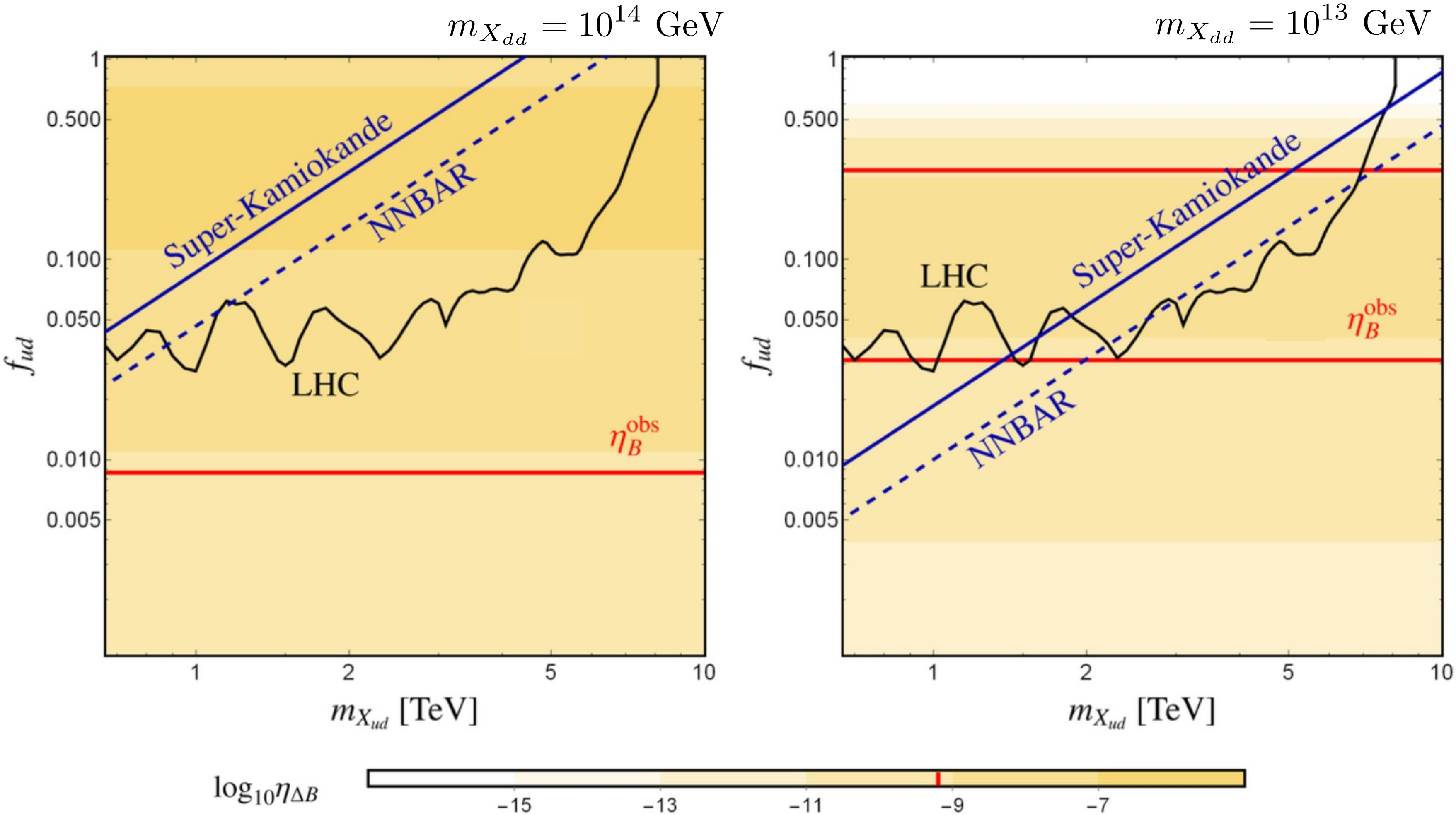
$m_{X_{dd}} = 3 m_{X_{ud}}$



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



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.

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

Thanks for listening