Probing baryogenesis using neutron-anti-neutron oscillation

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Based on
arXiv:2008:XXXX

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Baryon asymmetry

Baryogenesis deals with the question of why matter exists in the Universe

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

Planck collaboration (2018)

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

Baryon asymmetry of the Universe (BAU): There are more baryons than anti-baryons

Three conditions: Sakharov conditions

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

In the Standard Model (SM):

$$\left.\begin{array}{l}\surd\ \text{Sphalerons}\\ \surd\ \text{CKM matrix}\\ \surd\ \text{Electroweak transition}\end{array}\right\} \eta_B \approx 10^{-19}\ \text{X}$$

$\Longrightarrow$ Need Beyond SM (BSM) physics to explain the BAU

How can baryogenesis be probed experimentally?

Search for B violation

B violation:

Experimental searches are relatively model-independent

Would provide a clear sign of BSM physics

Neutron-anti-neutron oscillation

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

$$\Delta B = -2$$

Proton decay

$$p \to X$$

$$\Delta B = -1$$

Dinucleon decay

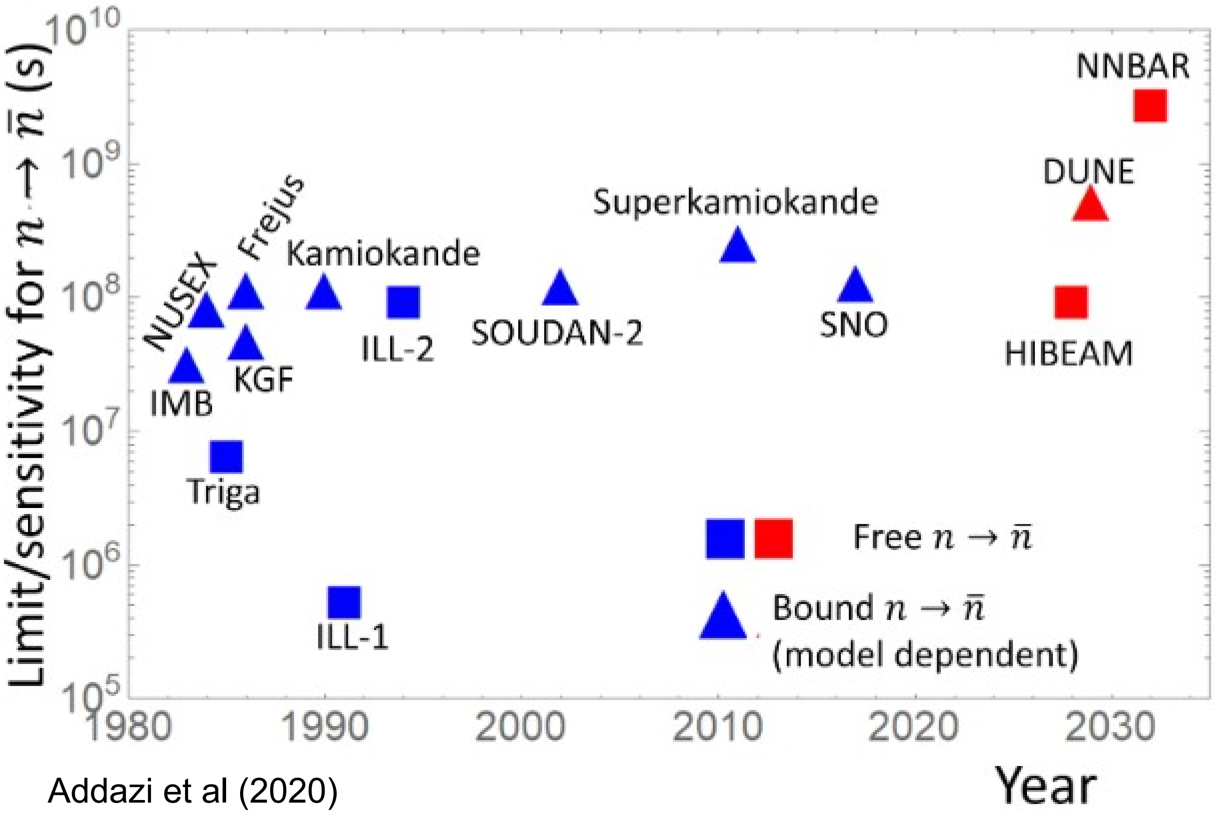
$$n\,n \to X$$

$$\Delta B = -2$$

Out-of-equilibrium dynamics and C and CP violation:

Can be connected to B violation in a given model

Neutron-anti-neutron oscillation



Addazi et al (2020)

See also other talks @ ICHEP 2020

ORNL/ESS (Broussard)
MicroBooNE/DUNE (Hwa)
MURMUR (Stasser)

Current:

▲ **Bound:**

$$\tau_{n\bar{n}} \geq 2.7 \times 10^8 \text{ s}$$

Super-Kamiokande collaboration (2011)

■ **Free:**

$$\tau_{n\bar{n}} \geq 0.86 \times 10^8 \text{ s}$$

ILL, Baldo-Ceolin et. al (1994)

Future:

▲ **DUNE (bound):**

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

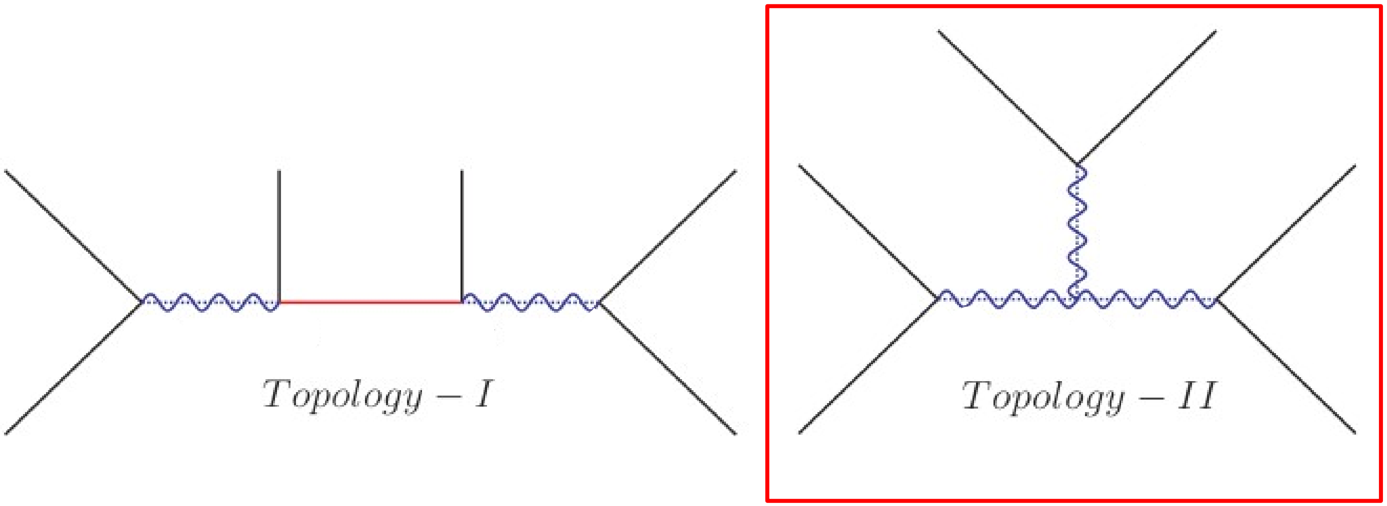
■ **NNBAR (free):**

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

Exciting future prospects

Effective field theory (EFT)

Neutron-anti-neutron oscillation can be realized at tree level by dim 9 operators



$$\left.\begin{aligned} \mathcal{L}_{\mathrm{WET}}^{\bar{n}n} &= \sum_i C_i \mathcal{O}_i + \mathrm{h.c.} \\ \mathcal{O}_1 &= (\psi P_R \psi^c)(\psi P_R \psi^c)(\psi P_R \psi^c) \end{aligned}\right\} \quad \begin{aligned} \tau_{n\bar{n}}^{-1} &= \langle \overline{n} | \mathcal{L}_{\mathrm{WET}}^{n\overline{n}} | n \rangle = \left| C_1(\mu) \mathcal{M}_1(\mu) \right| \\ \mathcal{M}_i(\mu) &= \langle \overline{n} | \mathcal{O}_i(\mu) | n \rangle \end{aligned}$$

Rinaldi et al (2019)

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

$\boxed{\Lambda = \text{New Physics (NP) scale} \rightarrow \text{encodes all the effects of heavy NP.}}$

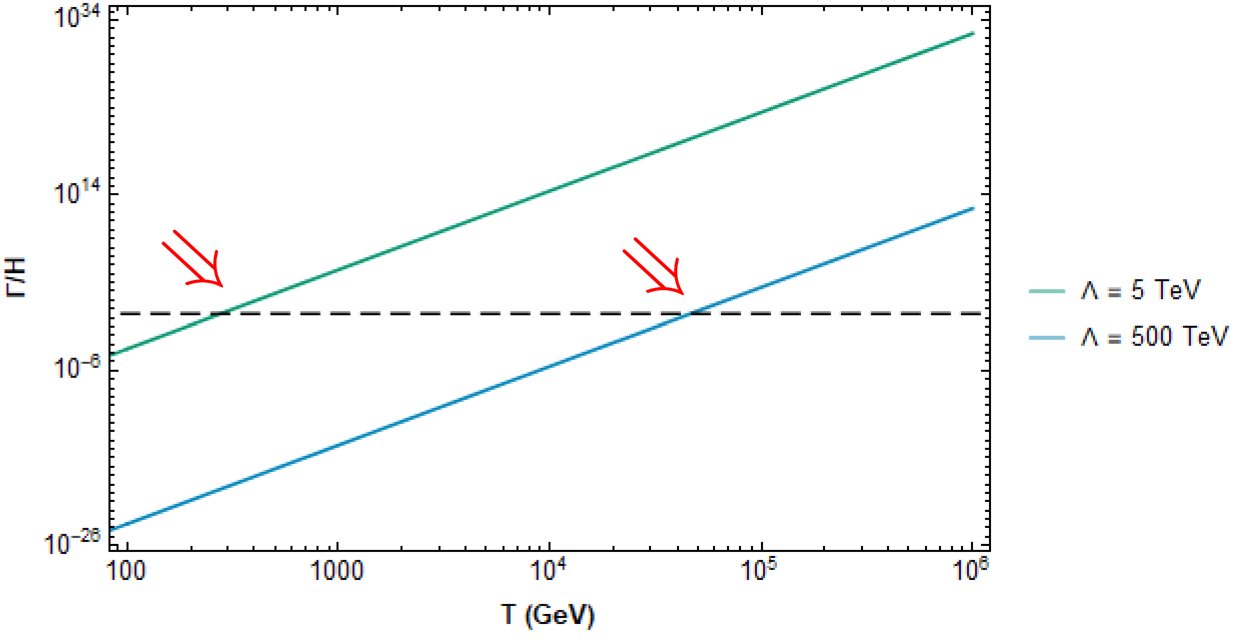
Baryogenesis: effective washout

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

Washout: B violating process that removes B asymmetry → Reduces η_B

Deppisch et al (2018)

Can be estimated by comparing width to Hubble rate $\Gamma \sim H, \quad \Gamma \propto \left|C_i \mathcal{M}_i\right|^2 \propto \left|\frac{1}{\Lambda^5}\right|^2$



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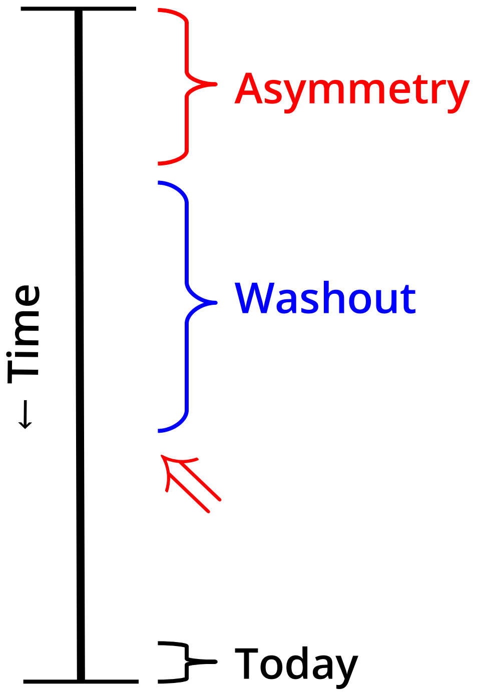


Diquarks

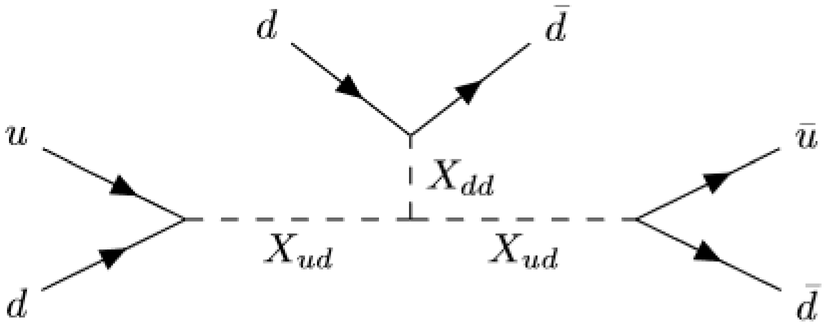
$$\mathcal{L} \supset f^{dd} X_{dd} d_R d_R + f^{ud} X_{ud} u_R d_R + \lambda v_{B-L} X_{dd} X_{ud} X_{ud} + \text{h.c.} \qquad m_{X_{dd}} > m_{X_{ud}} > m_d$$

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	$-\frac{1}{3}$	$-\frac{2}{3}$

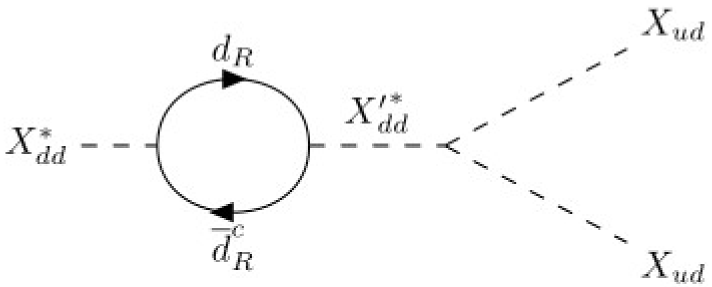
Very common in GUTs, e.g. $SO(10), E_6$

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

Neutron-anti-neutron oscillation

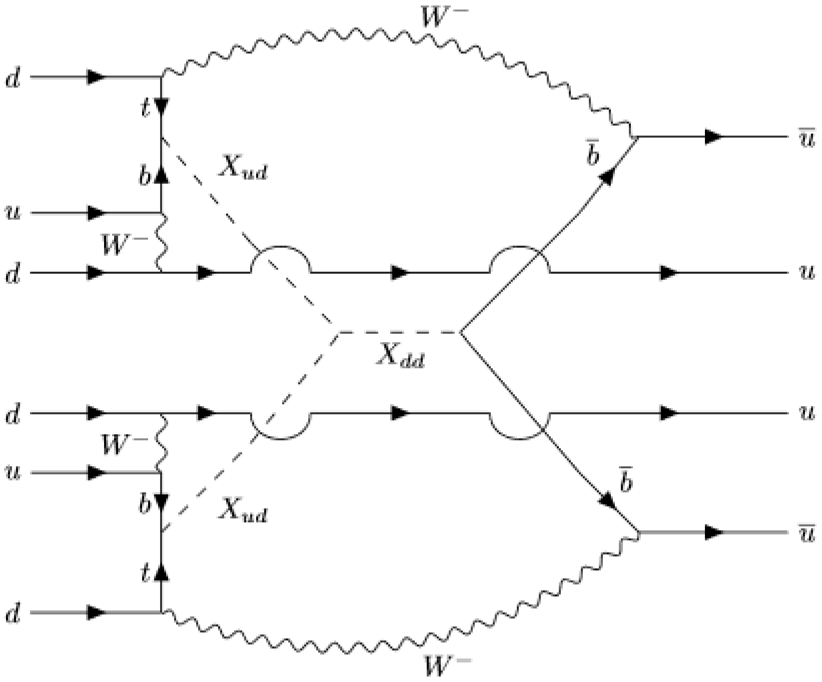


CP violation/B violation/out-of-equilibrium



Dinucleon decay

Dinucleon decay can occur with 3rd generation quarks at two-loop level, while neutron-anti-neutron oscillation requires three loops.



$$nn \to \pi^0\pi^0$$

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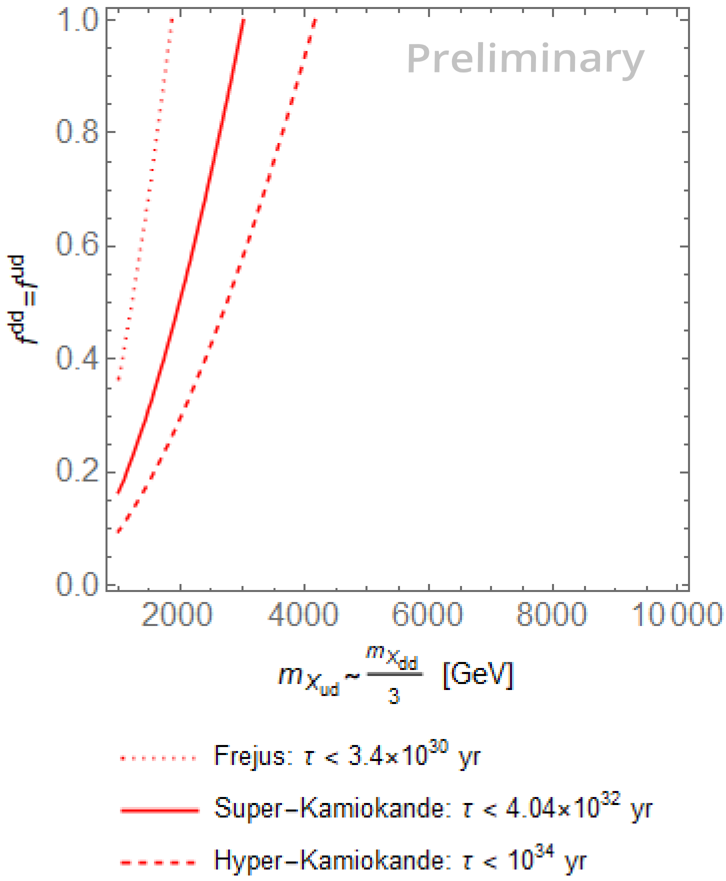


LHC

Puts constraints on diquark couplings to 3rd gen quarks

LHC is already probing (5-10) TeV range

Excellent complementarity to n-n̄ oscillation/ dinucleon decay

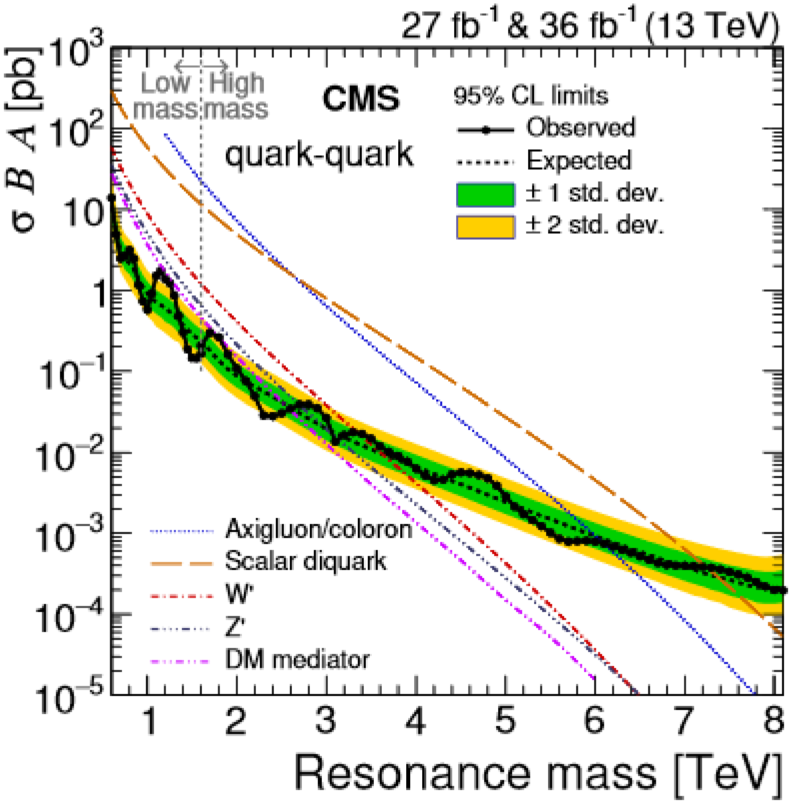
$$\mathcal{L} \supset f^{ud} X_{ud} u_R d_R$$

$$\text{For } f^{ud} = 1.0,\ m_{X_{ud}} \lesssim 5.4 \text{ TeV disfavored}$$

$$\text{For } f^{ud} = 0.3,\ m_{X_{ud}} \lesssim 4.7 \text{ TeV disfavored}$$

$\text{For } \sqrt{s} = 8 \text{ TeV}$

Chivukula et al (2018)
Pascual-Dias et al (2020) + ….



CMS Collaboration (2018)

Asymmetry generation

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

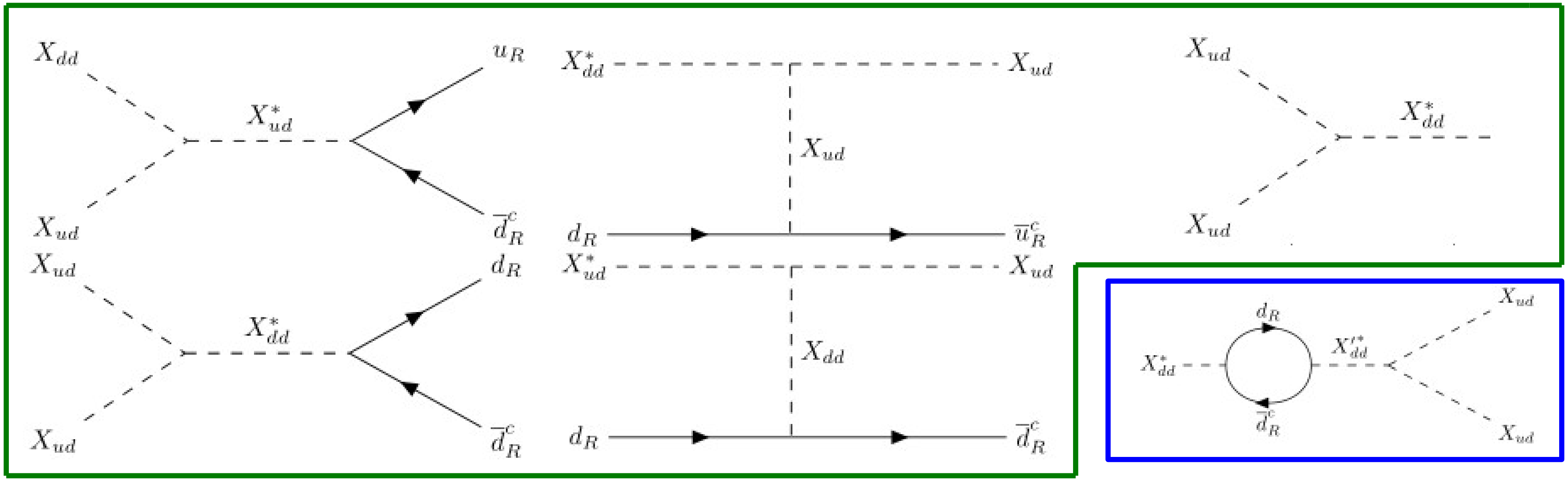
CP asymmetry: $\epsilon \sim \frac{\Gamma(X^*_{dd} \to X_{ud}X_{ud}) - \Gamma(X_{dd} \to X^*_{ud}X^*_{ud})}{\Gamma(X^*_{dd} \to X_{ud}X_{ud}) + \Gamma(X_{dd} \to X^*_{ud}X^*_{ud})}$

$$W = \frac{T}{m_{X_{dd}}}\frac{\Gamma}{H}$$

Decay: $D \sim \Gamma(X^*_{dd} \to X_{ud}X_{ud})$

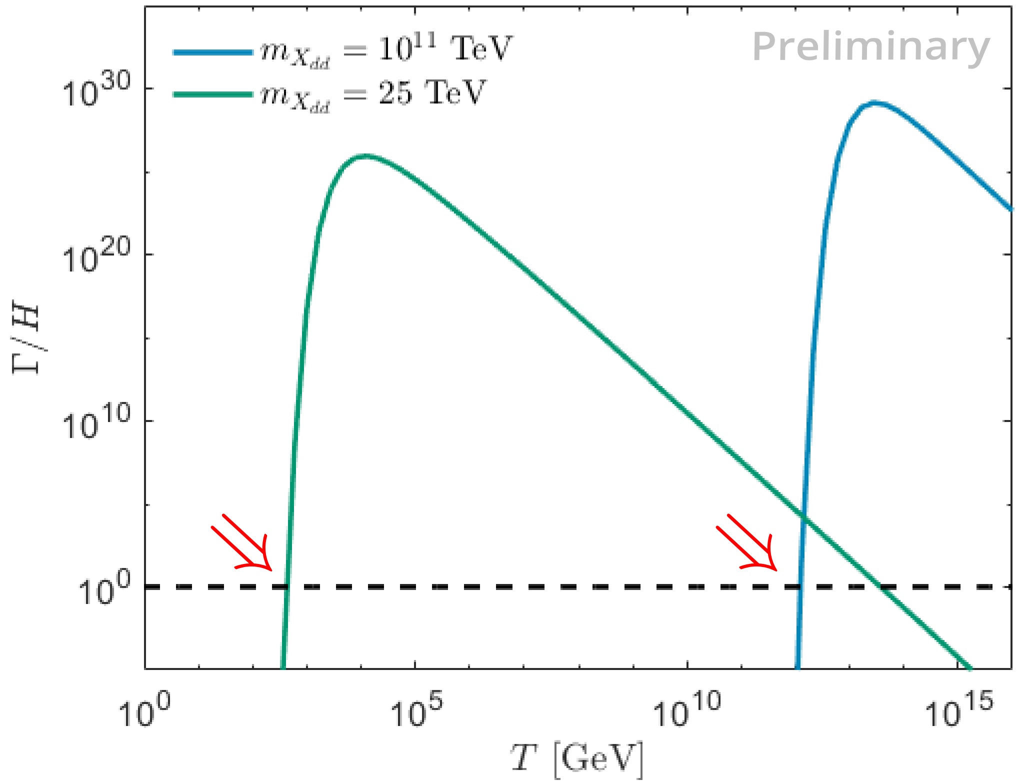
$$\eta_i \equiv \frac{n_i}{n_\gamma}$$

Washout: $W \sim \Gamma(X_{dd}X_{ud} \to u_R\overline{d}^c_R) + \Gamma(\dots) + \&\text{c.}$



Washout

Washout is strong when $\Gamma > H$ $\quad$ $W = \frac{T}{m_{X_{dd}}} \frac{\Gamma}{H}$



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Using couplings of order one and

$$m_{X_{ud}} = 5 \text{ TeV}$$

$$v_{B-L} = (6/5) m_{X_{dd}}$$

Two benchmark scenarios:

TeV scale

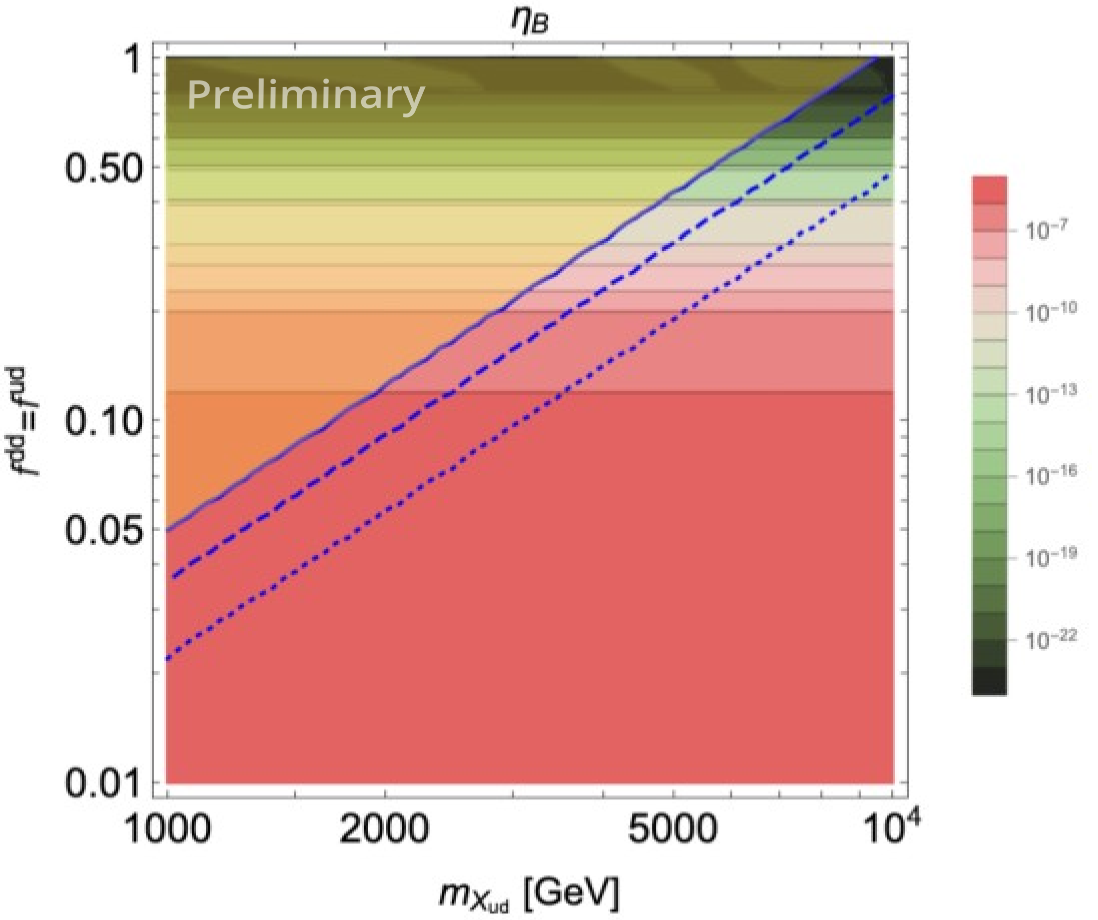
$$m_{X_{dd}} > m_{X_{ud}} \gg m_d$$

High scale

$$m_{X_{dd}} \gg m_{X_{ud}} \gg m_d$$

Washout roughly agrees with the EFT approach

Results for high scale baryogenesis



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Benchmark:

$m_{X_{dd}} = 10^{14}$ GeV $\epsilon = 1$

$\lambda v_{B-L} = 6 \times 10^{14}$ GeV

A signal @ DUNE/NNBAR would disfavor high scale baryogenesis for a large part of the parameter space

Results for TeV scale baryogenesis

Observable dinucleon decay rate requires large couplings
→ too strong washout → underabundance

An observation of a dinucleon signal can rule out TeV scale baryogenesis

However, for smaller values of couplings,
TeV scale baryogenesis can still work

Benchmark:

$$m_{X_{dd}} = 50 \times m_{X_{ud}}$$

$$v_{B-L} = (6/5) \times m_{X_{dd}}$$

$$\epsilon = 1$$

Blue areas: correct or higher abundance

$$\mathcal{L} \supset \lambda v_{B-L} X_{dd} X_{ud} X_{ud}$$

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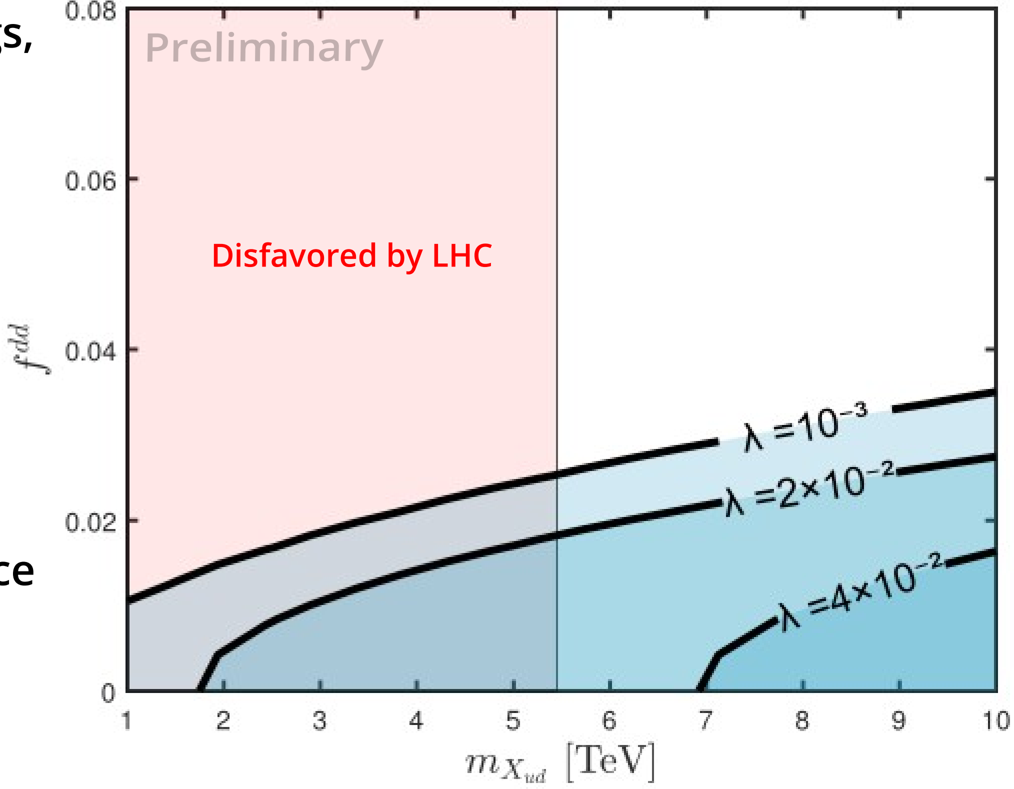


Conclusion

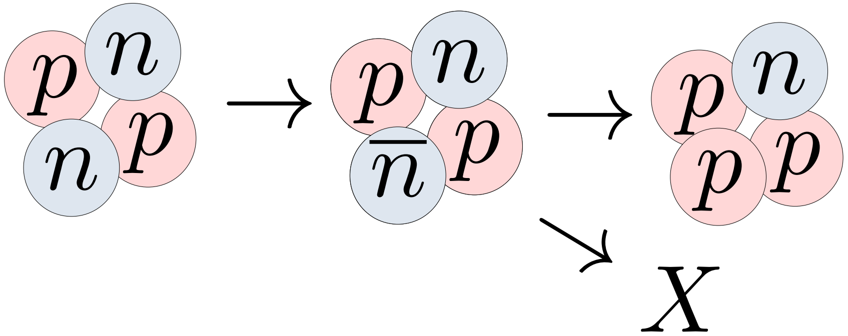
- Interplay of diquark searches at the LHC with neutron-anti-neutron oscillation or dinucleon decay has excellent prospects to probe baryogenesis
- For high scale baryogenesis a large part of the parameter space would be disfavored by a signal @ DUNE/NNBAR
- TeV scale baryogenesis would be disfavored by an observation of a dinucleon signal
- For smaller values of couplings (nonobservable at experiments), TeV scale baryogenesis is still feasible
- There are bright experimental future prospects @ DUNE/NNBAR, therefore it is timely to study neutron-anti-neutron oscillation

Thanks for listening

Backup: Indirect vs Direct

Neutron-anti-neutron oscillation

Indirect search:
(bound)



Direct search:
(free)