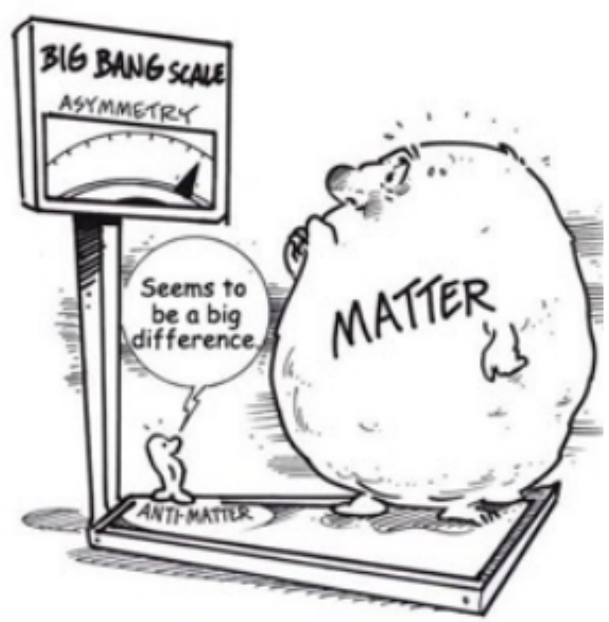
Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Physik Department T70
Technical University of Munich

Probing baryogenesis using synergy between $n - \bar{n}$ oscillation and collider searches



Chandan Hati

Based on arXiv:2009:XXXX
in collaboration with

Kåre Fridell and Julia Harz

c.hati@tum.de

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES
DESY THEORY WORKSHOP
22 - 25 September 2020
DESY Virtual Theory Forum 2020
DESY Hamburg, Germany
DESY.

22 Sept 2020

Beyond Standard Model: Direction

The only laboratory evidence of BSM physics so far:

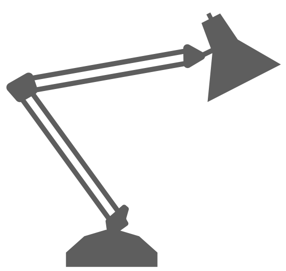
neutrino oscillations => neutrino masses

Amongst the other strong motivations: observed baryon asymmetry of the Universe

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

Planck collaboration (2018)

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



Why baryon number violation (BNV)?

- ★ Many reasons to believe: Baryon number can be a broken symmetry of nature
  Approximate conservation of BN in SM; “Accidental” global symmetry at perturbative level
- ★ BNV in SM by non-perturbative processes
  Sphalerons; B-L conserved in SM, not B,L separately
- ★ Generic BNV in BSM theories, eg, GUT
- ★ BNV a Sakharov condition for baryogenesis
- ★ BNV can give nontrivial hints towards understanding neutrino mass

Why $n - \bar{n}$ oscillation ?

If B is violated, important to determine the selection rules: B=1 (p-decay) or B=2 $(n - \bar{n})$?

$(n - \bar{n})$ oscillation can be closely connected to neutrino mass physics when combined with quark-lepton unification e.g. Pati-Salam Model, SO(10), E6 etc

$n - \bar{n}$ oscillation EFT and the topologies

$$\mathcal{L}^{\bar{n}n}_{\text{WET}} = \sum_i C_i \mathcal{O}_i + \text{h.c.}$$

$$\mathcal{O}_1 = (\psi P_R \psi^c)(\psi P_R \psi^c)(\psi P_R \psi^c)$$

$$\tau^{-1}_{n\bar{n}} = \langle \bar{n} | \mathcal{L}^{n\bar{n}}_{\text{WET}} | n \rangle = \left| C_1(\mu) \mathcal{M}_1(\mu) \right|$$

$$\mathcal{M}_i(\mu) = \langle \bar{n} | \mathcal{O}_i(\mu) | n \rangle$$

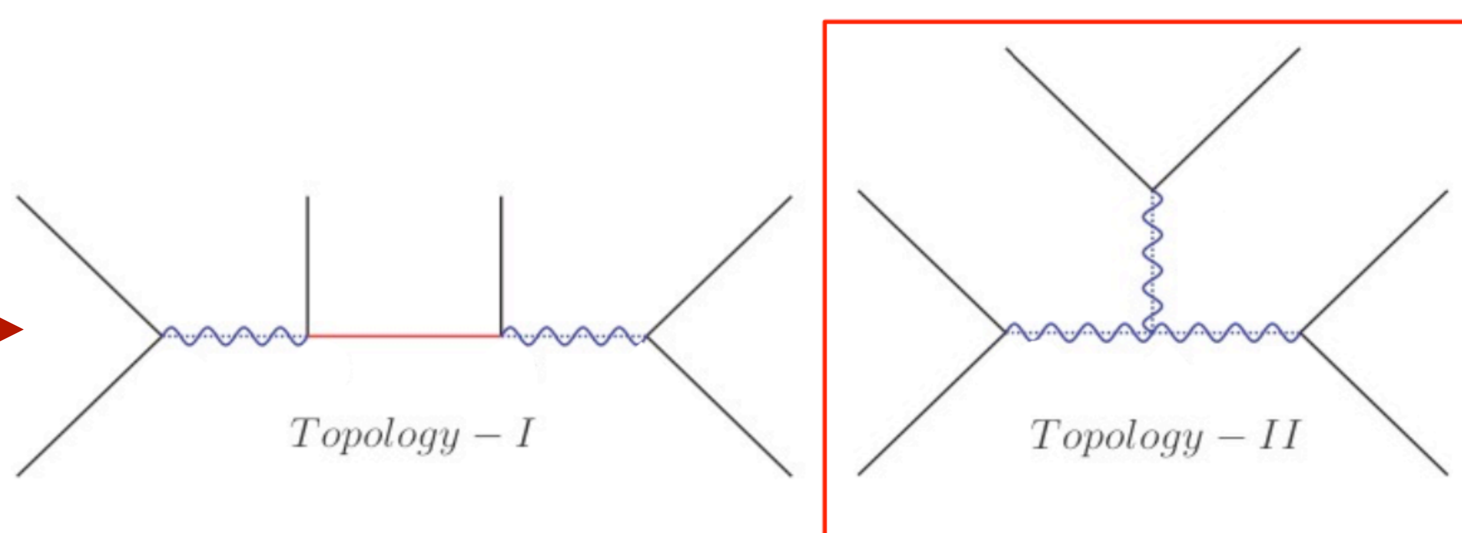
Rinaldi et al (2019)

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

Λ = New Physics (NP) scale $\rightarrow$ encodes all the effects of heavy NP.

Can such an observable probe the baryogenesis mechanism ?

Grojean et al PRL 2018 ++ →



→ corresponds to BNV scattering at high scale

Mohapatra-Marshak (1980)

Babu-Mohapatra (2012) ++

$n - \bar{n}$ oscillation: experimental status

Current:

▲ **Bound:**

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

Super-Kamiokande collaboration (2011)

■ **Free:**

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

ILL, Baldo-Ceolin et. al (1994)

Future:

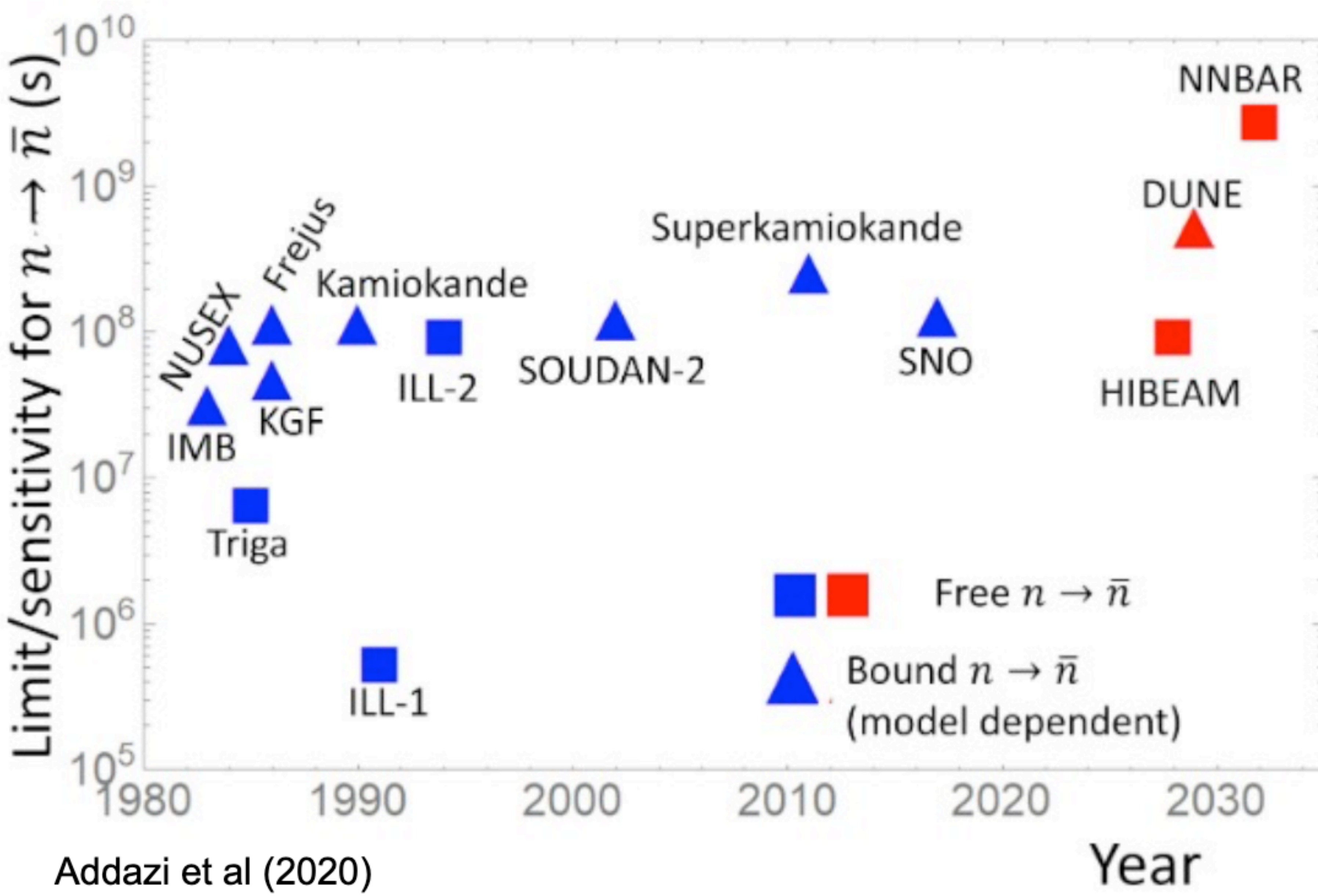
▲ **DUNE (bound):**

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

■ **NNBAR (free):**

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

Exciting future prospects



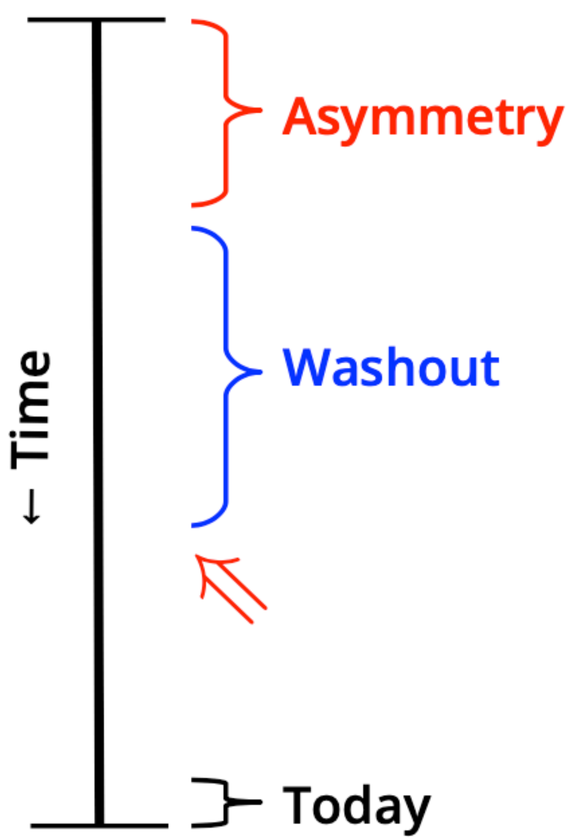
Addazi et al (2020)

Baryogenesis: effective washout

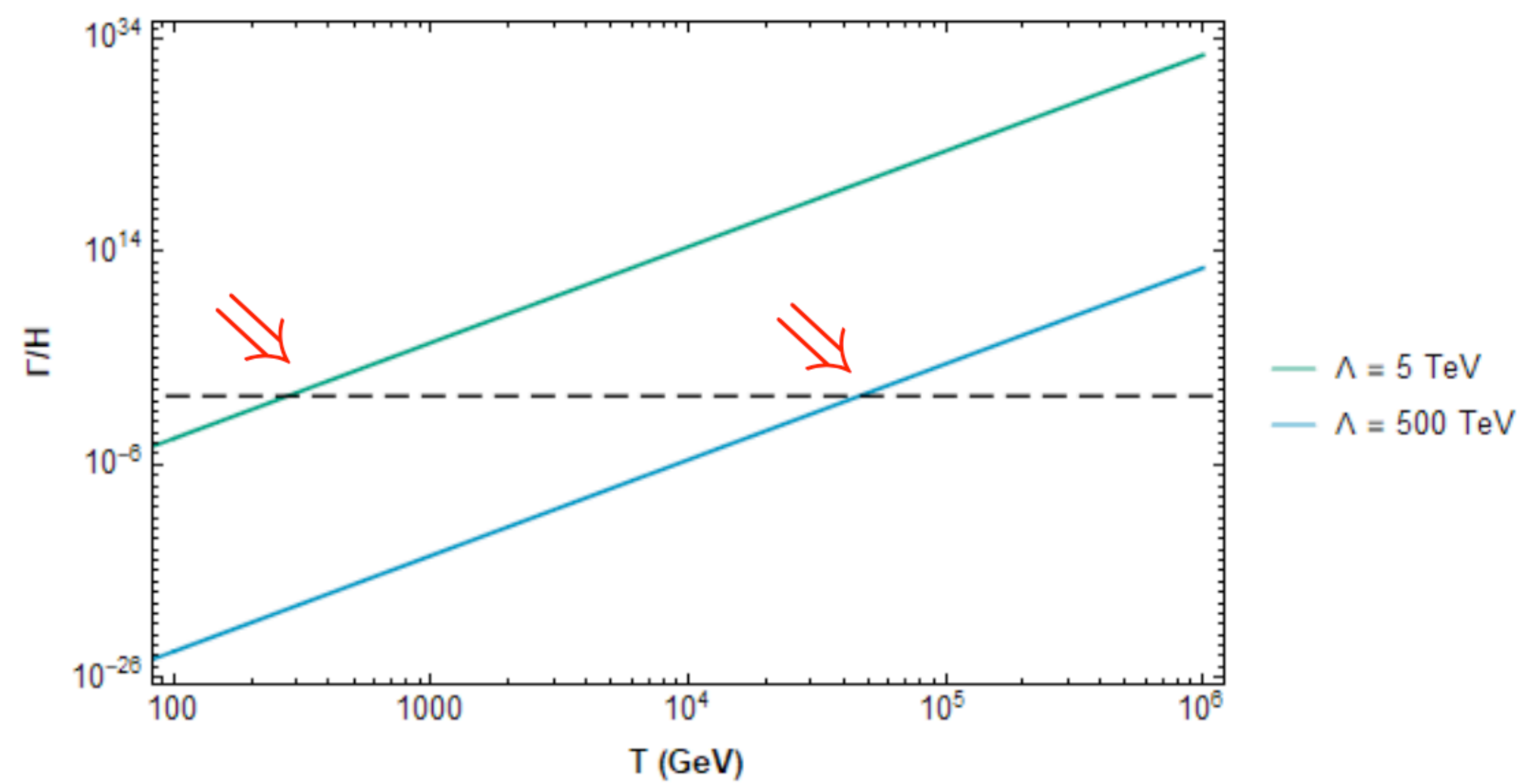
A baryon asymmetry can be injected at a high scale but can be subjected to wash out at late time

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

Out of equilibrium temperature: compare width to Hubble rate $\Gamma \sim H, \quad \Gamma \propto \left|C_i \mathcal{M}_i\right|^2 \propto \left|\frac{1}{\Lambda^5}\right|^2$



Fridell, Harz, CH: arXiv:2009:XXXX



Diquarks and a simplified model of $B-L$ violating trilinear coupling

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

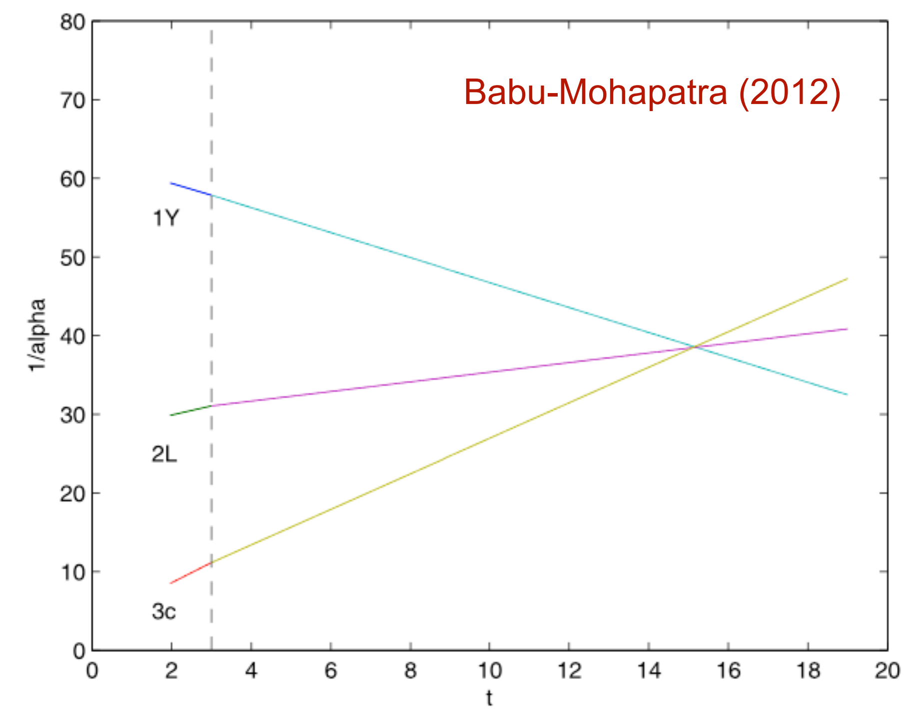
Field	Spin	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	B
X_{dd}	0	$(6,\bar{3})$	1	$+\frac{2}{3}$	$-\frac{2}{3}$
X_{ud}	0	$(6,\bar{3})$	1	$-\frac{1}{3}$	$-\frac{2}{3}$

For various UV completions see e.g.

Babu et al (2012),

Aulakh et al (2005),

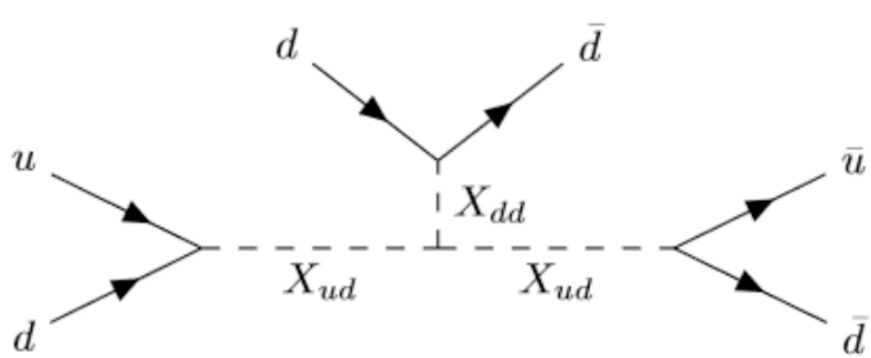
London et al (1986) + ...



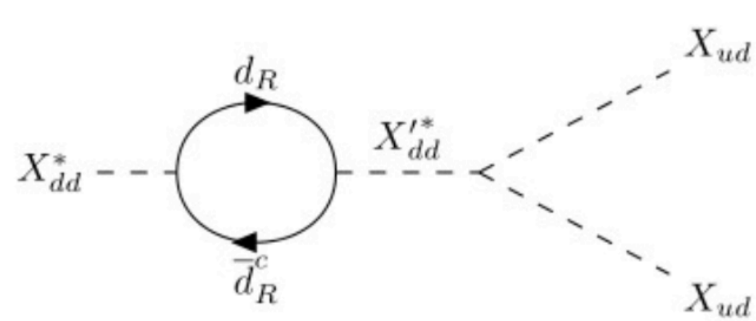
TeV scale diquarks are theoretically well-motivated

e.g. non-SUSY $SO(10)$ unification requires TeV scale X_{ud} and GUT scale X_{dd} and v_{B-L}

Neutron-anti-neutron oscillation



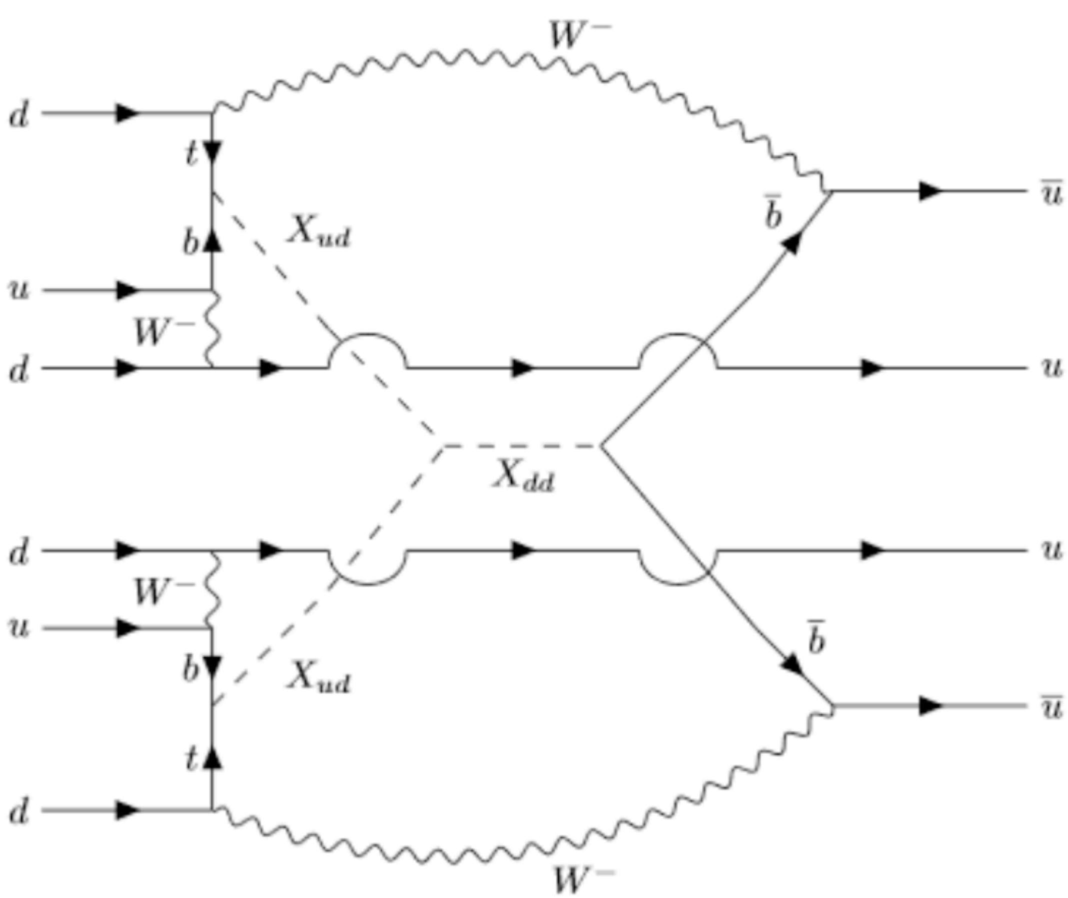
CP violation/B violation/out-of-equilibrium



$n-\bar{n}$ @ tree level requires first generation couplings

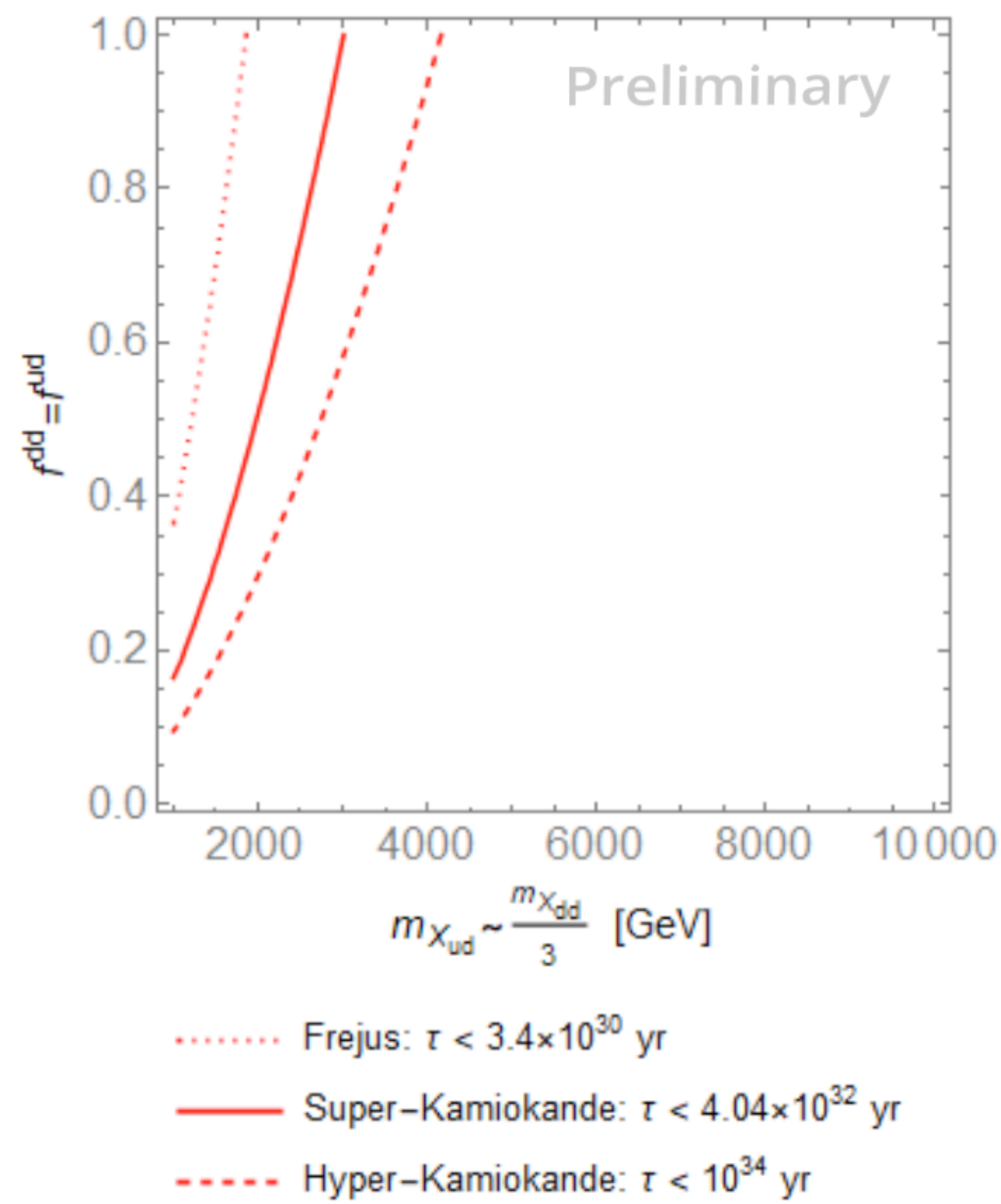
Loop effects and dinucleon decay

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



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

Fridell, Harz, CH: arXiv:2009:XXXX



Diquark searches @ LHC

Single production: $ud \to X_{ud} \to tj$

resonance peaks above SM background

Pair production: $gg \to X_{ud}\bar{X}_{ud}$ $\quad q\bar{q} \to X_{ud}\bar{X}_{ud}$

$ttjj$ **final states, relatively low energy reach @ LHC**

Mohapatra et al (2007)
Chen et al (2009)
Gogoladze et al (2010)
Han et al (2010)
Berger et al (2010)
Chivukula et al (2018)
Pascual-Dias et al (2020) + ...

Constraints on diquark couplings to 3rd gen quarks

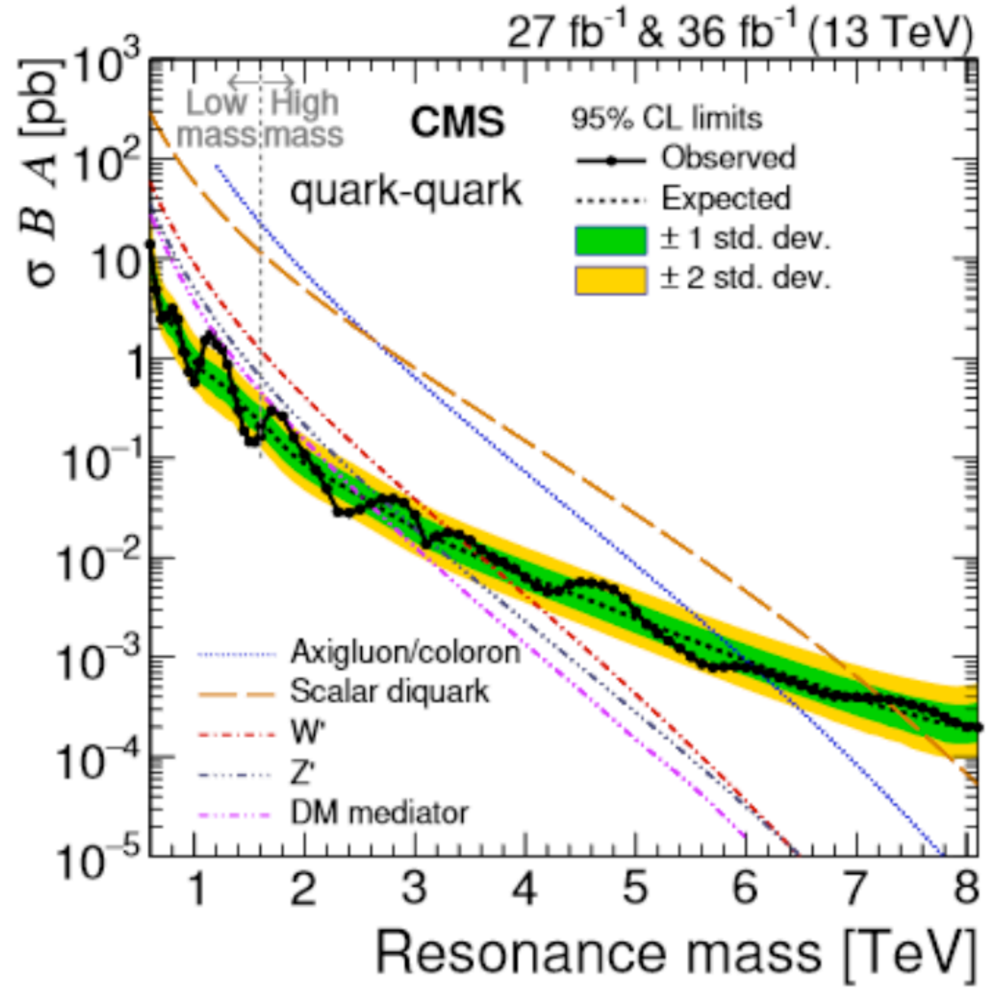
LHC is already probing (5-10) TeV range

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

with $\sqrt{s}$ = 8 TeV data Gogoladze et al (2010)

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

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



CMS Collaboration (2018)

Excellent complementarity to $n - \bar{n}$ oscillation/ dinucleon decay

Will improving b tagging play a major role in future limits?

Results for high scale scenario using Boltzmann equations

$$\Delta B = 0: D_d^0 = [X_{dd} \leftrightarrow d^c d^c]$$

$$S_s^0 = [X_{dd}\bar{d}^c \overset{d^c}{\underset{s}{\longleftrightarrow}} X_{ud}\bar{u}^c] \quad S_{t_a}^0 = [X_{dd}u^c \overset{d^c}{\underset{t}{\longleftrightarrow}} d^c X_{ud}] \quad S_{t_b}^0 = [X_{dd}X_{ud}^* \overset{d^c}{\underset{t}{\longleftrightarrow}} d^c\bar{u}^c]$$

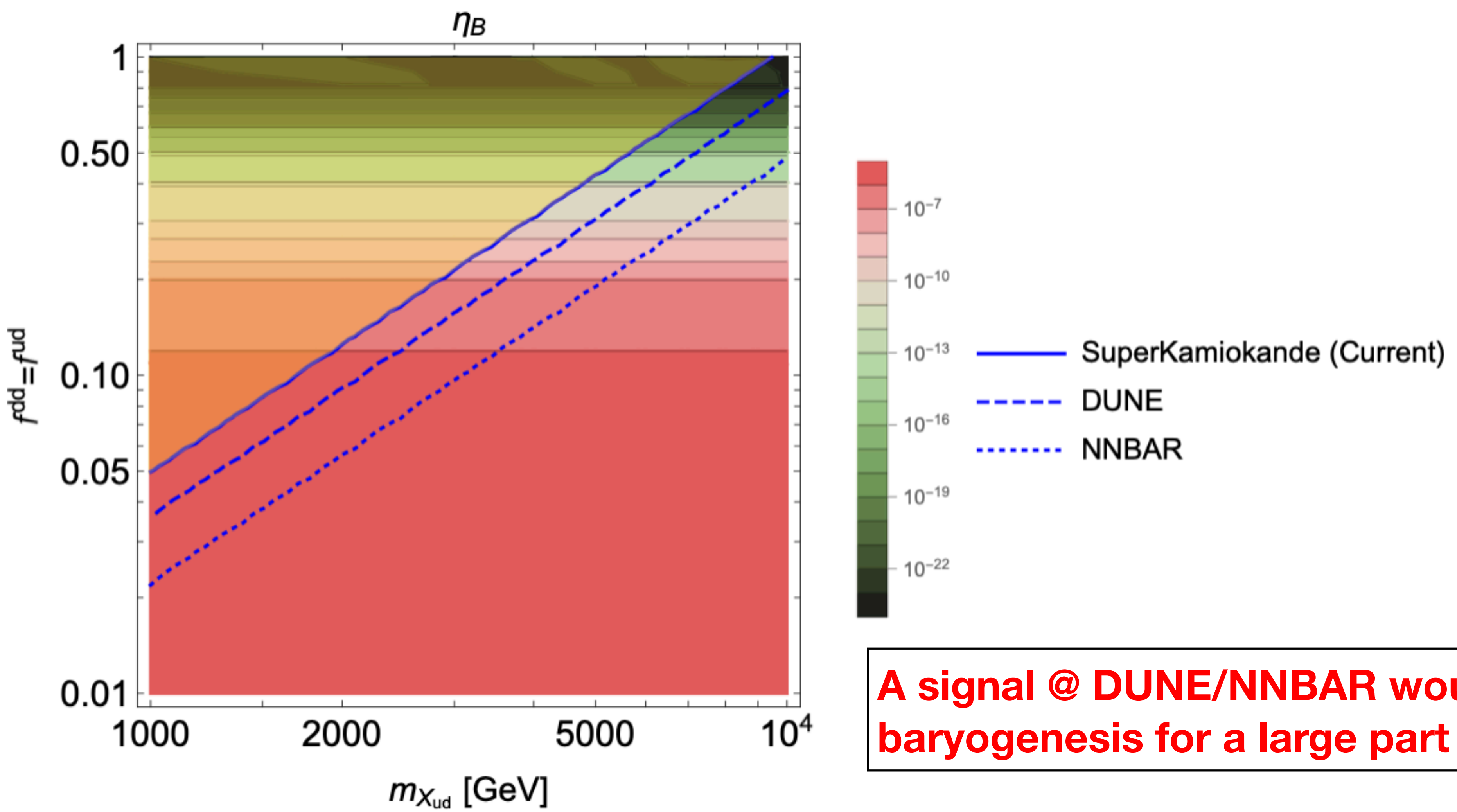
$$\Delta B = 2: D_d = [X_{dd} \leftrightarrow X_{ud}^* X_{ud}^*]$$

$$X_s = [X_{ud}^* X_{ud}^* \overset{X_{dd}}{\underset{s}{\longleftrightarrow}} d^c d^c] \quad X_t = [X_{ud}^* \bar{d}^c \overset{X_{dd}}{\underset{t}{\longleftrightarrow}} X_{ud} d^c]$$

$$S_s = [X_{dd}X_{ud} \overset{X_{ud}^*}{\underset{s}{\longleftrightarrow}} \bar{d}^c\bar{u}^c] \quad S_{t_a} = [X_{dd}u^c \overset{X_{ud}^*}{\underset{t}{\longleftrightarrow}} X_{ud}^*\bar{d}^c] \quad S_{t_b} = [X_{dd}d^c \overset{X_{ud}^*}{\underset{t}{\longleftrightarrow}} X_{ud}^*\bar{u}^c]$$

Full technical details of multi-mode decay Boltzmann equation @

Fridell, Harz, CH: arXiv:2009:XXXX



Benchmark:

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

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

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

Results for TeV scale baryogenesis using Boltzmann equations

Observable dinucleon decay rate requires large couplings

→ too strong washout → under-abundance

An observation of a dinucleon signal can potentially threaten TeV scale baryogenesis

Caveats:

- **post-sphaleron baryogenesis**
- **smaller couplings with non-observable dinucleon decay rates**

Benchmark:

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

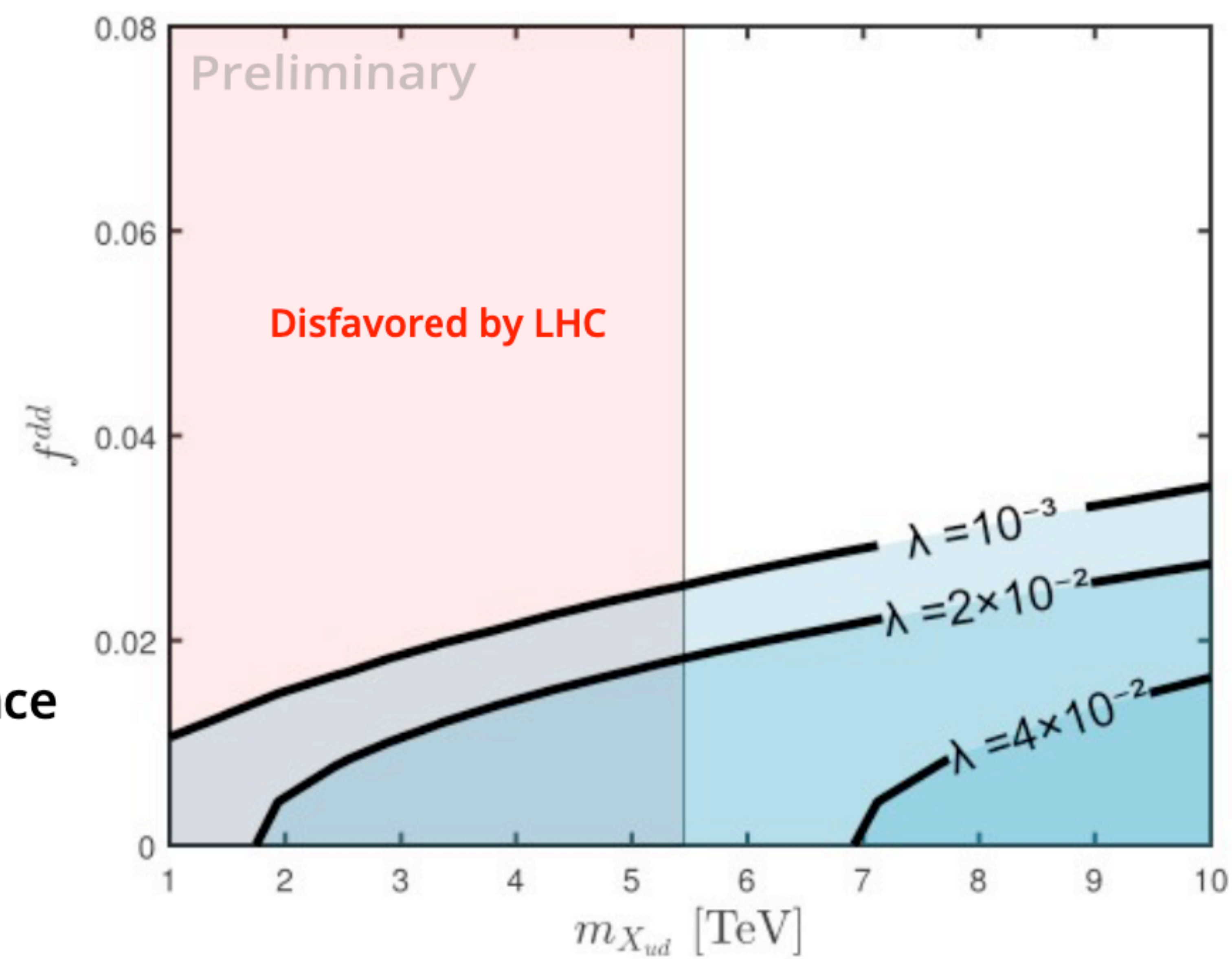
$$v_{B-L} = (6/5) \times m_{X_{dd}}$$

$$\epsilon = 1$$

Blue areas: correct or higher abundance

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

Fridell, Harz, CH: arXiv:2009:XXXX



Concluding remarks

- There are bright experimental future prospects @ DUNE/NNBAR, therefore it is timely to study $n - \bar{n}$ oscillation

- Interplay of diquark searches at the LHC with $n - \bar{n}$ oscillation or dinucleon decay has excellent prospects to probe baryogenesis

- For high scale baryogenesis a large part of the parameter space would be disfavoured by a signal @ DUNE/NNBAR

- TeV scale baryogenesis would be disfavoured by an observation of a dinucleon signal

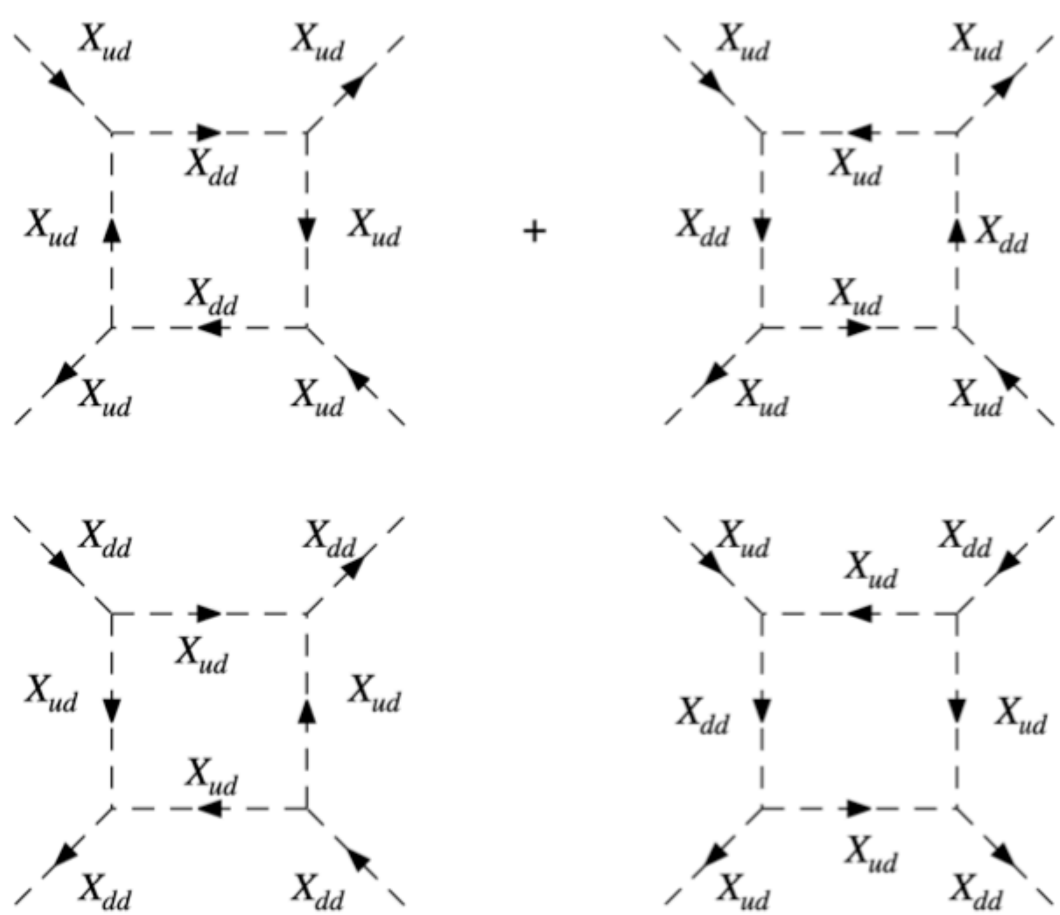
- For smaller values of couplings (non-observable at experiments), TeV scale baryogenesis is still feasible

Backup-I

$$\tau_{n\text{-}\bar{n}}^{-1} = 1.52 \times 10^{18} \left| \sum_{i=1,2,3,5} \frac{\mathcal{M}_i(\mu)}{(\mathrm{GeV})^6} \left[\left(\frac{C_i(\mu)}{(\mathrm{TeV})^{-5}} \right) - \left(\frac{C_i^P(\mu)}{(\mathrm{TeV})^{-5}} \right) \right] \right|_{\mu=\mu_{\mathrm{NP}}} \times 10^{-9}\ \mathrm{s}^{-1}$$

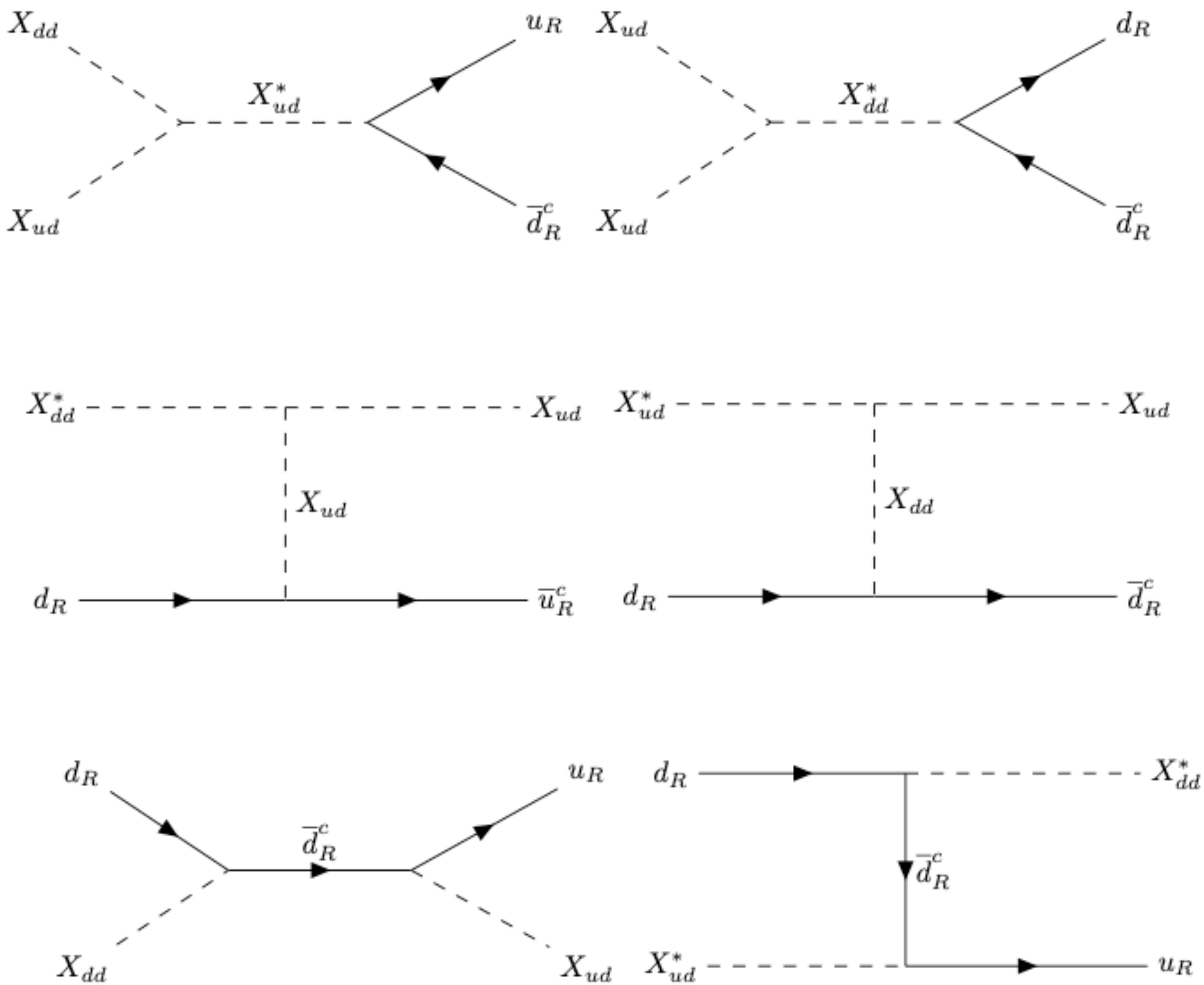
$$= 1.52 \times 10^{18} \left| \sum_{i=1,2,3,5} U_i'(\mu, 2\,\mathrm{GeV}) \frac{\mathcal{M}_i(2\,\mathrm{GeV})}{(\mathrm{GeV})^6} \left[\left(\frac{C_i(\mu)}{(\mathrm{TeV})^{-5}} \right) - \left(\frac{C_i^P(\mu)}{(\mathrm{TeV})^{-5}} \right) \right] \right|_{\mu=\mu_{\mathrm{NP}}} \times 10^{-9}\ \mathrm{s}^{-1}$$

VACUUM PRESERVING COLOUR



Backup-II

Some relevant scattering processes



Backup-III

Constraints from neutral meson oscillations

$$H_{\text{eff}} = C_1 \mathcal{O}_1 = C_1 \left(\bar{d}_i \gamma^\mu P_{R(L)} d_j\right) \left(\bar{d}_i \gamma_\mu P_{R(L)} d_j\right)$$

$$\Delta_M = 1 + \frac{\langle M | H_{\text{eff}}^{\text{NP}} | \overline{M} \rangle}{\langle M | H_{\text{eff}}^{\text{SM}} | \overline{M} \rangle}$$

$$\left| \frac{f_{dd}^{22} f_{dd}^{11}}{m_{X_{dd}}^2} \right| \lesssim 2.4 \times 10^{-7}\ \text{TeV}^{-2}$$
$$\left| \frac{f_{dd}^{33} f_{dd}^{11}}{m_{X_{dd}}^2} \right| \lesssim 3.6 \times 10^{-7}\ \text{TeV}^{-2}$$
$$\left| \frac{f_{dd}^{33} f_{dd}^{22}}{m_{X_{dd}}^2} \right| \lesssim 7.9 \times 10^{-6}\ \text{TeV}^{-2}$$