Low Temperature Baryogenesis

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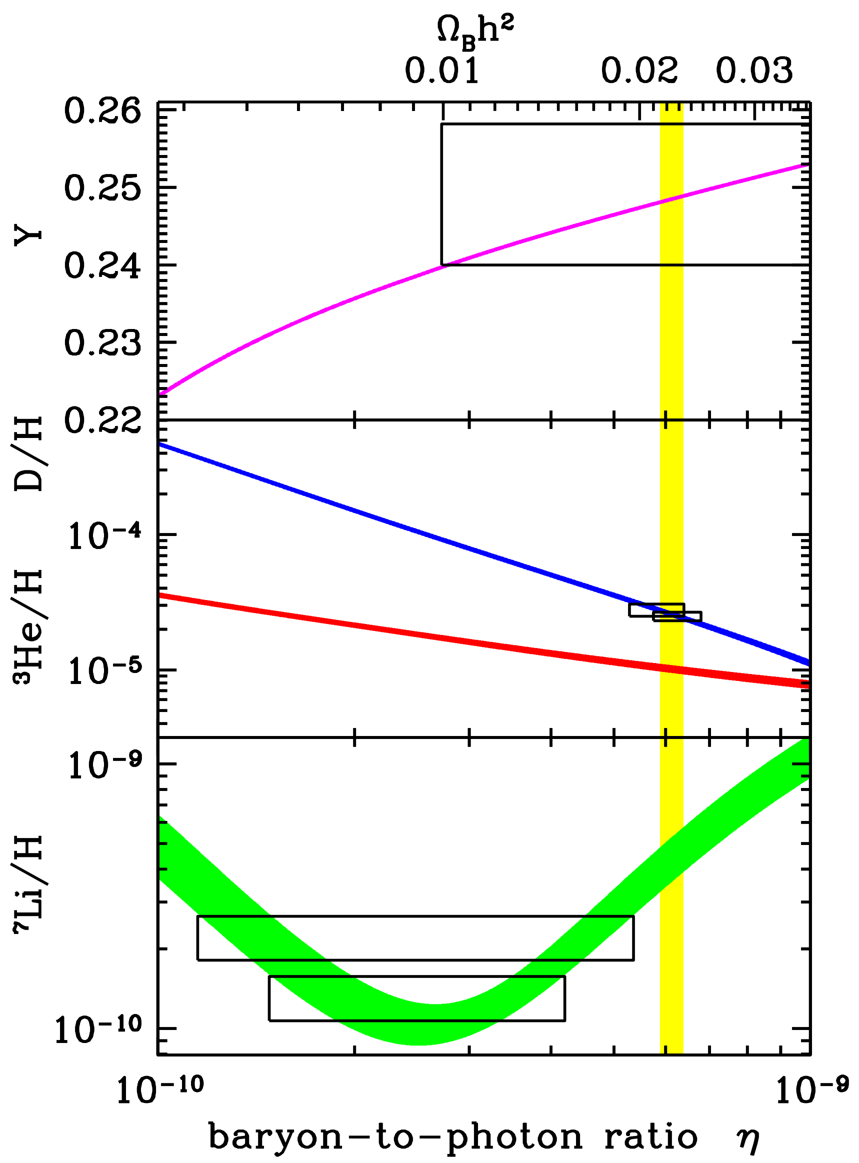
11TH WORKSHOP
Flavor Symmetries and Consequences in Accelerators and Cosmology

Baryogenesis

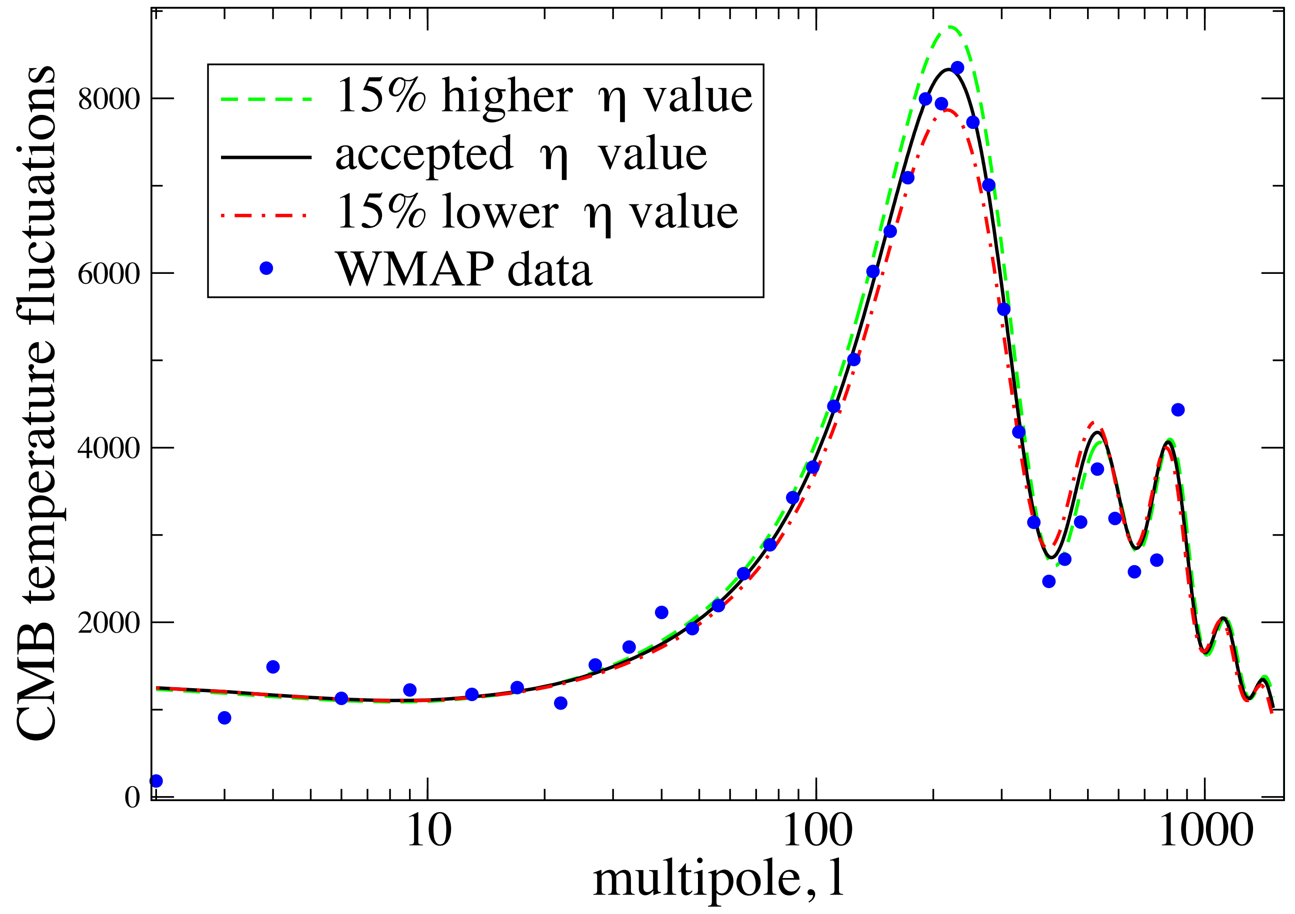
What is the origin of the baryon asymmetry ?

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma}$$

BBN



CMB



$$\eta = (6.12 \pm 0.04) \times 10^{-10}$$

mostly from Planck CMB data

Baryogenesis and the Standard Model

- B Violation: SM non perturbative source of B+L violation at high temperatures $T_{\rm EW}$ ✓

- C and CP violation: not enough CP violation in the SM

  Figure of merit: Jarlskog invariant, normalized by the $T_{\rm EW}$

$$J = det[m_u^2, m_d^2] = (m_t^2 - m_c^2)\ldots.(m_s^2 - m_d^2)\, K$$

← CKM factor

$$\frac{J}{(100\ \mathrm{GeV})^{12}} \simeq 10^{-20}$$

✗

- Non equilibrium: electroweak phase transition should be strong first order. But m_h is too heavy. ✗

Baryogenesis Beyond the Standard Model

- Various attempts in supersymmetric extensions of the SM
  - MSSM and light spectrum
  - Affleck-Dine
  - …
- Leptogenesis:
  - Typically a high scale mechanism
  - Low scale leptogenesis possible: e.g. talks by *Julia Harz, Alessandro Granelli*
  - Signals: LFV, potentially displaced vertices, enhancements of ν-less double β decays.

Low Temperature Baryogenesis

Generic Ideia:

A new particle decays out of equilibrium *after the sphaleron decoupling* and before BBN

Its decays violate B and CP fulfilling the Sakharov conditions

Babu, Mohapatra, Nasri , hep-ph/0606144

Kohri, Mazumdar, Sahu, 0905.1625

Allhaverdi, Datta, Sinha, 1005.2804

Allahverdi, Loc, Osinski, 2212.11303

Dangers:

Proton decay

$n\bar{n}$ oscillations

Flavor bounds

⋮

Low Temperature Baryogenesis and Displaced Vertices

If a particle N decays to generate the asymmetry its lifetime satisfies

$$\tau_N > H^{-1}(T \simeq m_N) \quad \Rightarrow \quad c\tau_N > 20 \text{ mm} \left(\frac{\text{GeV}}{m_N}\right)^2$$

Window of interest:

$$\tau_{\text{sphaleron}} \,(10^{-12}\ s) < \tau_N < \tau_{\text{BBN}}$$

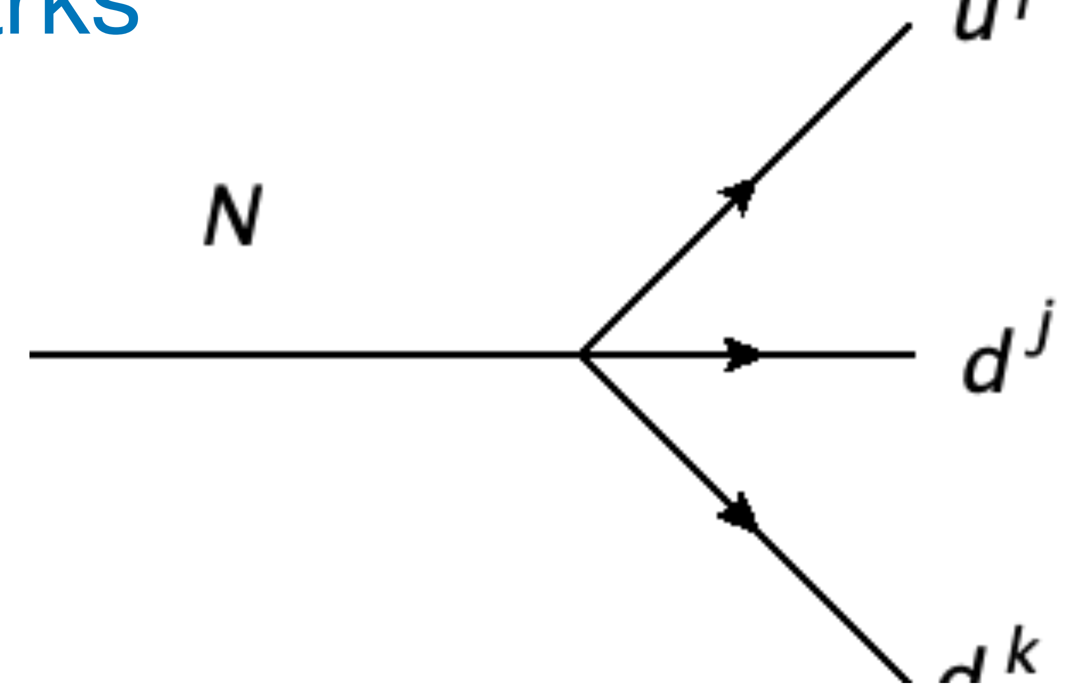
Connection between Low Temperature Baryogenesis and LLP with $0.1 \text{ mm} \lesssim c\tau_N \lesssim 200 \text{ m}$

Opportunity for DV at the LHC as well as MATUSLA, CODEX-b, ANUBIS, …

A Low Temperature Baryogenesis Model

Pedro Bittar, GB, 21410.00957

- 3 Majorana fermions N_1, N_2, N_3 + 1 Complex scalar Φ
- Out of equilibrium decays: $N_\alpha \to$ quarks



$$\mathscr{L}_{\text{eff.}} = \frac{\kappa_\alpha^{ijk}}{M_X^2} \left(\overline{N}_\alpha^c u_R^i\right) \left(\bar{d}_R^{c\,j} d_R^k\right) + \xi_{\alpha\beta} \overline{N}_\alpha^c \Phi N_\beta + \text{h.c.}$$

$i, j, k = 1,2,3$ generation indices

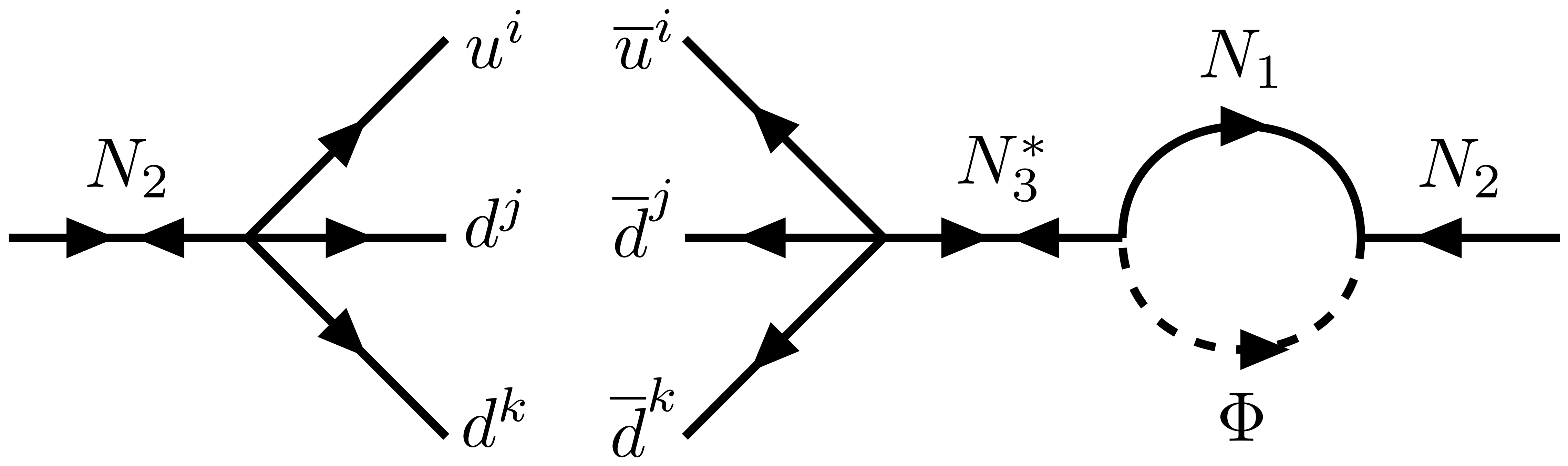
M_X UV scale

$\alpha, \beta = 1,2,3$ Majorana flavor indices

A model of Low Temperature Baryogenesis

- Assume: $m_{N_1} \lesssim m_\Phi < m_{N_2} < m_{N_3}$

$\Rightarrow$ CP Violation from N_2 decay



<u>Baryon Asymmetry:</u>

$$Y_{\Delta B} = Y_2\, \epsilon_{CP}\, \mathrm{Br}(N \to udd')$$

with Y_2 the N_2 yield.

UV Completion

Integrate in a scalar diquark X in the $(\mathbf{3},\mathbf{1})_{2/3}$ of the SM:

$$\mathscr{L}_X = \lambda_{\alpha i}\, X^\dagger\, \overline{N^c_\alpha}\, u^i_R + \lambda'_{jk}\, X\, \overline{d^c_R}^j\, d^k_R + \mathrm{h.c.}$$

- No proton decay as long as $m_N \gtrsim 1\ \mathrm{GeV}$ and N does not mix with neutrinos *Arnold, Fornal, Wise, 1212.4556*
- Color antisymmetry $\Rightarrow$ flavor antisymmetry of λ'_{jk} $\Rightarrow$ we can write $\lambda'_{jk} = \epsilon_{jk\ell}\,\lambda'_\ell$

  Or only 3 independent λ' couplings

$\Rightarrow$ No $n\bar{n}$ oscillations at tree level

- No tree level $K^0 - \overline{K^0}$ or $B^0 - \overline{B^0}$ mixing

  At one loop, they are suppressed if one of the 3 couplings is suppressed. E.g. $\lambda'_{bs} < \lambda'_{db}, \lambda'_{ds}$

Bounds

- $D^0 - \overline{D^0}$ mixing

$$\sqrt{|\mathrm{Re}(\lambda^*_{\alpha u}\lambda_{\alpha c})^2|}\left(\frac{2\mathrm{TeV}}{M_X}\right) \leq 2.9\times 10^{-2}$$

(dominated by $\alpha = 3$)

- Bounds from $pp \to K^+K^+$ (from $O^{16} \to C^{14}K^+K^+$)

$$|\lambda_{\alpha u}\lambda'_{ds}|\left(\frac{2\ \mathrm{TeV}}{M_X}\right)^2\left(\frac{200\ \mathrm{GeV}}{m_{N_\alpha}}\right)^2 < 1.5\times 10^{-6}$$

$\Rightarrow$ choose $\lambda_{\alpha u} \ll \lambda_{\alpha c}, \lambda_{\alpha c}$

so λ'_{ds} not suppressing N production

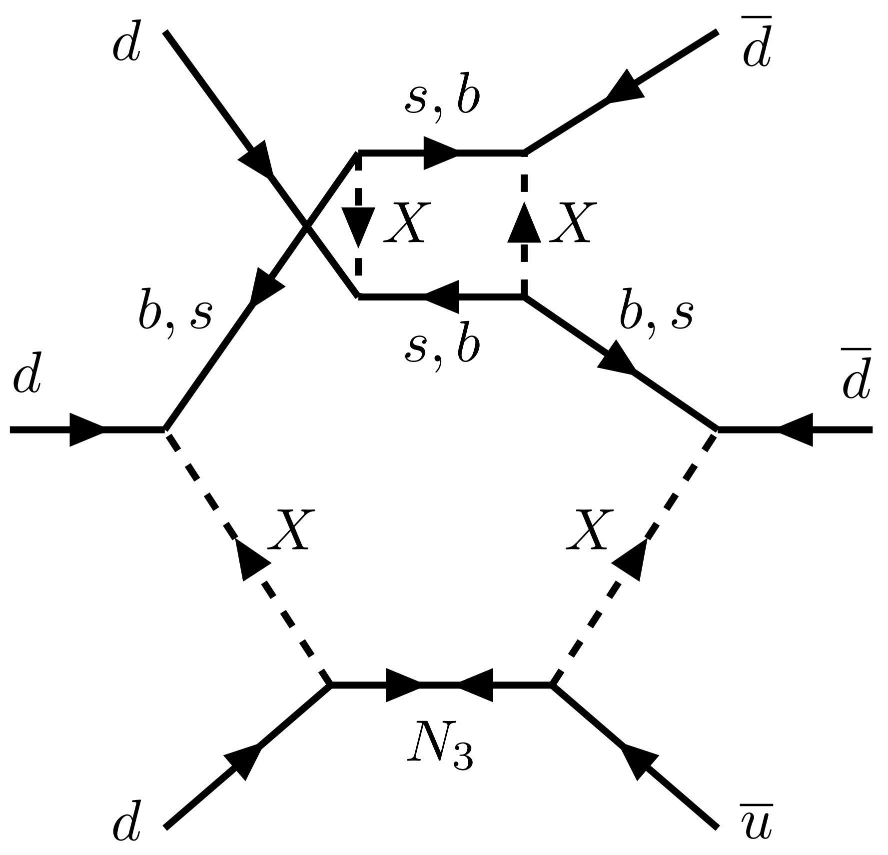
$$\kappa_\alpha^{cjk} \simeq \kappa_\alpha$$

Bounds

- Λ^0 oscillations impose weak bounds on M_X:

$$|\kappa_1| \lesssim 10^{-1} \left(\frac{m_{N_1}}{5 \ \ \mathrm{GeV}}\right)^{1/2} \left(\frac{M_X}{2 \ \ \mathrm{TeV}}\right)^2 \quad (\Lambda^0\bar{\Lambda}^0 \text{ oscillation})$$

- $n\bar{n}$ oscillations: dim 9 operator → 2 loops



$$\tau_{n-\bar{n}} \simeq 8.6 \times 10^7 s \times \left(\frac{(0.09)^6}{|\lambda_{3u}|^2 |\lambda'_{ds}|^4}\right)\left(\frac{200 \ \mathrm{GeV}}{m_{N_3}}\right)\left(\frac{M_X}{2 \ \mathrm{TeV}}\right)^6$$

- Neutron EDM: CP violating phases only contribute at 3 loop level *Giudice, Gripaios, Sundrum, 1105.3161*

Bounds

All constraints satisfied by

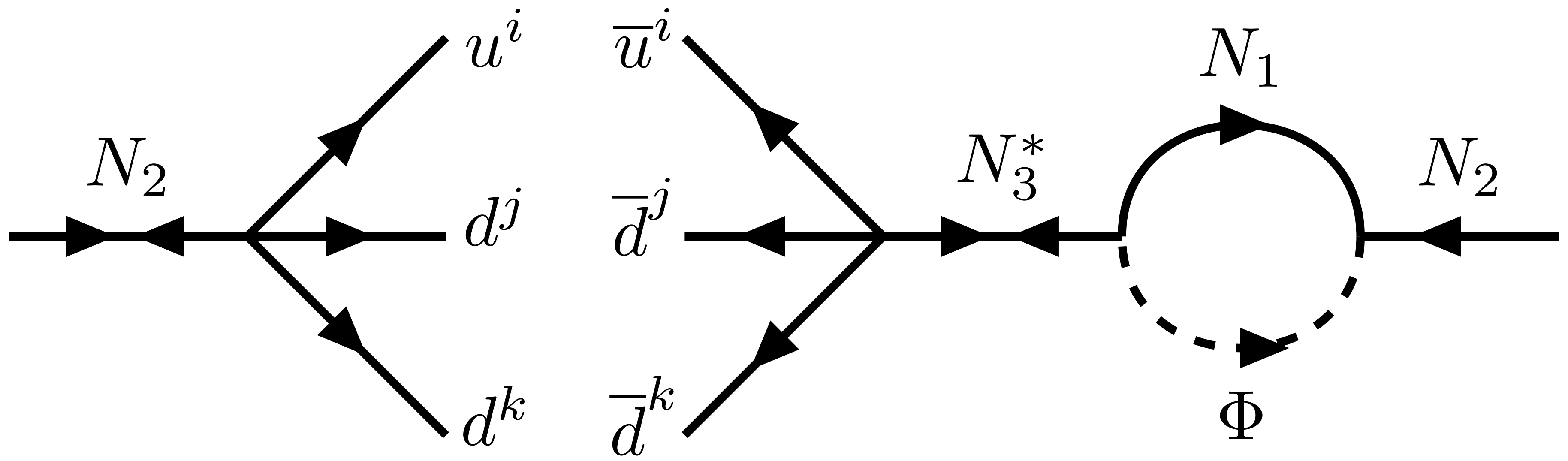
$$\lambda'_{ds} < 0.3, \qquad \lambda'_{db} < 0.3, \qquad \lambda'_{sb} < 0.11,$$

$$\lambda_{\alpha u} < 1.5 \times 10^{-6}, \quad \lambda_{\alpha c} < 1, \quad \lambda_{\alpha t} < 1,$$

Back to the baryon asymmetry

$$Y_{\Delta B} = Y_2 \, \epsilon_{\rm CP} \, {\rm Br}(N \to udd')$$

CP Violati:on



$$\epsilon_{\rm CP} \simeq \frac{3}{8\pi} \frac{m_{N_1}}{m_{N_3}} \frac{|\kappa_2 \xi_{12}^* \xi_{13} \kappa_3^*| \sin\delta}{|\kappa_2|^2} \sqrt{1 - \frac{(m_{N_1}^2 + m_\Phi^2)}{m_{N_2}^2}}$$

with δ the phase of $\kappa_2^{ijk} \xi_{12}^* \xi_{13} \kappa_3^{ijk*}$

and we assume $\kappa_\alpha^{cjk} \simeq \kappa_\alpha \gg \kappa_\alpha^{ujk}$ to satisfy bounds from dinucleon $pp \to K^+ K^+$

Baryon Asymmetry

- N_2 Yield:

$$Y_2 = \frac{n_{N_2}}{s}$$

- Processes to consider

Annihilation $N_2 u \leftrightarrow dd'$ and decay $N_2 \rightarrow udd'$

For $m_{N_2} \simeq 100\ \mathrm{GeV}$, and annihilation suppressed by HDO, N_2 freeze out can be relativistic

$$m_{N_2} < T_{\mathrm{FO}} < M_X$$

Imposing $\Gamma_{\mathrm{ann.}} \simeq H(T_{\mathrm{FO}})$

$$T_{FO} \simeq 280\ \mathrm{GeV} \left(\frac{M_X}{2\mathrm{TeV}}\right)^{4/3} \left(\frac{10^{-6}}{\kappa_2}\right)^{2/3}$$

Baryon Asymmetry

Using the relativistic yield (i.e. no Boltzmann suppression) we have

$$Y_2 = \frac{45\,\zeta(3)}{2\pi^4}\frac{g_{N_2}}{g_{*,s}(T_{\rm FO})}$$

Branching Ratio $N_2 \to udd'$: vs. 2 body decay $N_2 \to N_1\Phi$

$$\Gamma_{N_2\to udd'} \simeq \frac{3\,|\kappa_2|^2}{192\pi^3}\frac{m_{N_2}^5}{M_X^4} \qquad \simeq \qquad \Gamma_{N_2\to N_1\Phi} \simeq \frac{m_{N_2}\,|\xi_{12}|^2}{\pi}$$

for efficient generation of asymmetry: B violating 3 body decay should not be too small

but 2 body should be comparable or $\epsilon_{\rm CP}$ is suppressed

Baryon Asymmetry

Br($(N_2 \to udd')$) (*cont.*)

$$\Gamma(N_2 \to udd') \simeq \Gamma(N_2 \to N_1\Phi) \quad \Rightarrow \quad \frac{|\xi_{12}|}{|\kappa_2|} \approx \frac{1}{8\sqrt{3}\pi}\left(\frac{m_{N_2}}{M_X}\right)^2$$

$$\frac{Y_{\Delta B}}{Y_{\Delta B}^{\exp}} \simeq \left(\frac{m_{N_2}}{100\ \mathrm{GeV}}\right)^2 \frac{\kappa_3 \xi_{13} \sin\delta}{3\times 10^{-2}} \frac{m_{N_1}}{m_{N_3}} \sqrt{1 - \frac{m_{N_1}^2 + m_\Phi^2}{m_{N_2}^2}}$$

With $Y_{\Delta B}^{\exp} = 8.7 \times 10^{-11}$ *(Planck)*

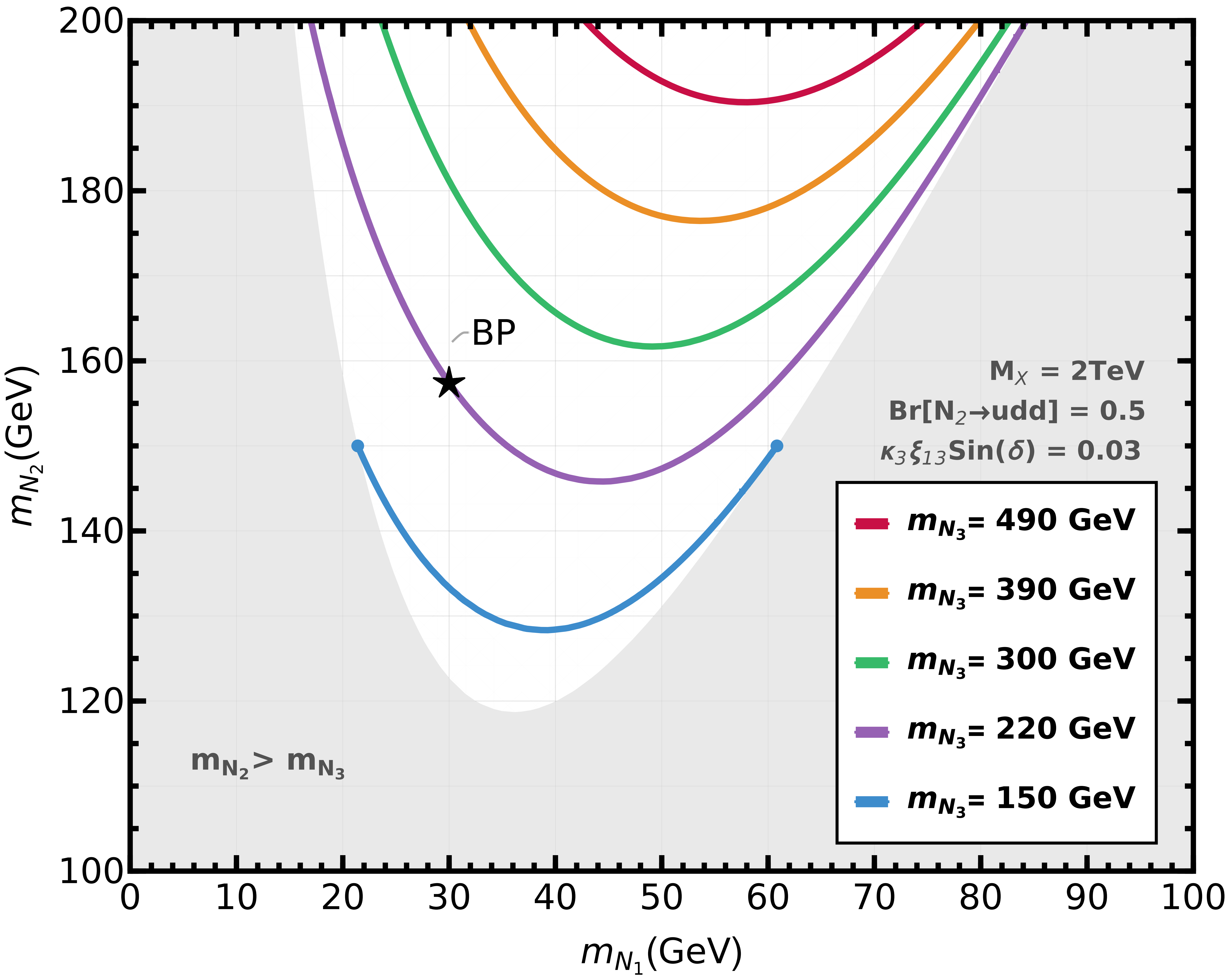
Baryon Asymmetry

Imposing $Y_{\Delta B} = Y_{\Delta B}^{\rm exp}$

E.g.

With $M_X = 2$ TeV

Using $\mathrm{Br}(\mathrm{N}_2 \to \mathrm{udd}') = 0.5$



Phenomenology

LHC bounds on diquark X

ATLAS and CMS on $(\mathbf{3},\mathbf{1})_{2/3}$ exclude $0.50\ \mathrm{TeV} < M_X < 0.77\ \mathrm{TeV}$ $@\,95\,\%\,\mathrm{CL}$

Recast by *Diaz, Saha, London (2006.13385)* using bounds on resonant production and flavor:

For our purposes, choosing $M_X = 2\ \mathrm{TeV}$ and

$$\left.\begin{array}{l}\lambda'_{ds} = 0.30 \\ \lambda'_{sb} = 0.12\end{array}\right]$$

Consistent with both constraints from flavor and direct searches

Phenomenology

N_α production and Monojet bounds

- N_α production dominated by monojet channels

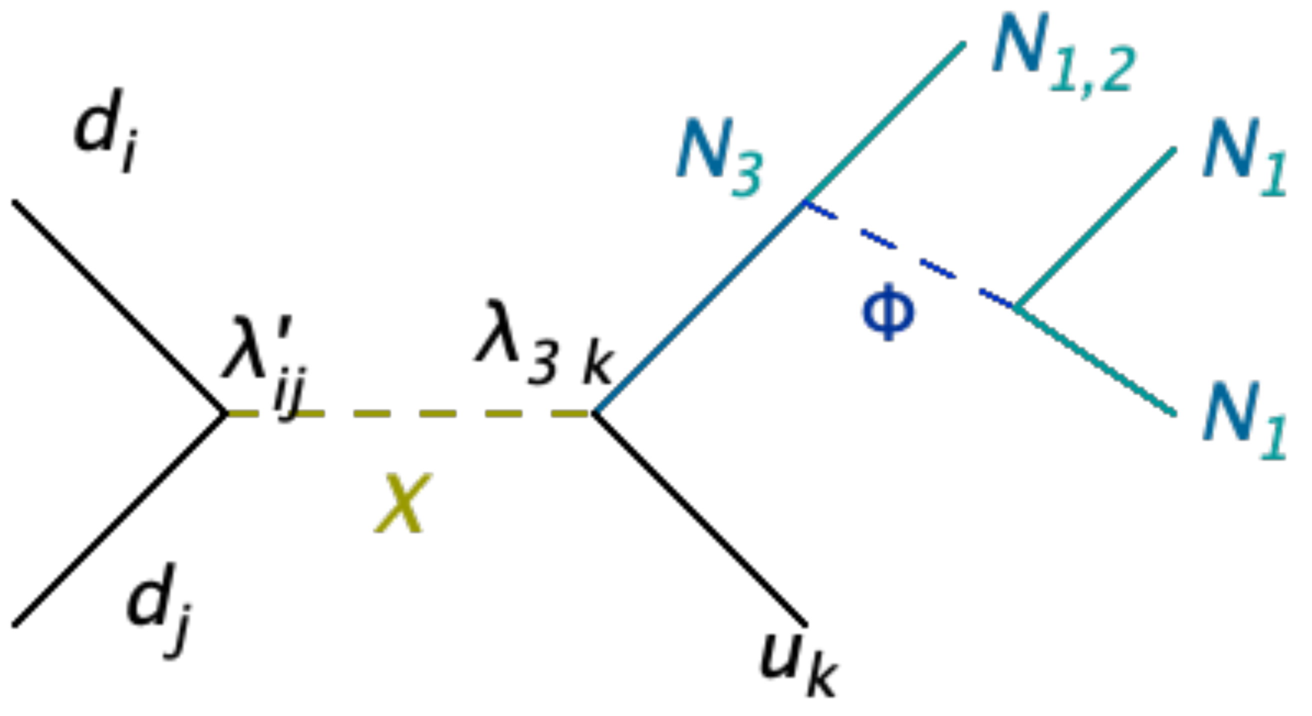
But $\kappa_3 \sim \lambda'_{ij} \lambda_{3k}$ cannot be suppressed in order to get $Y_{\Delta B}$ right

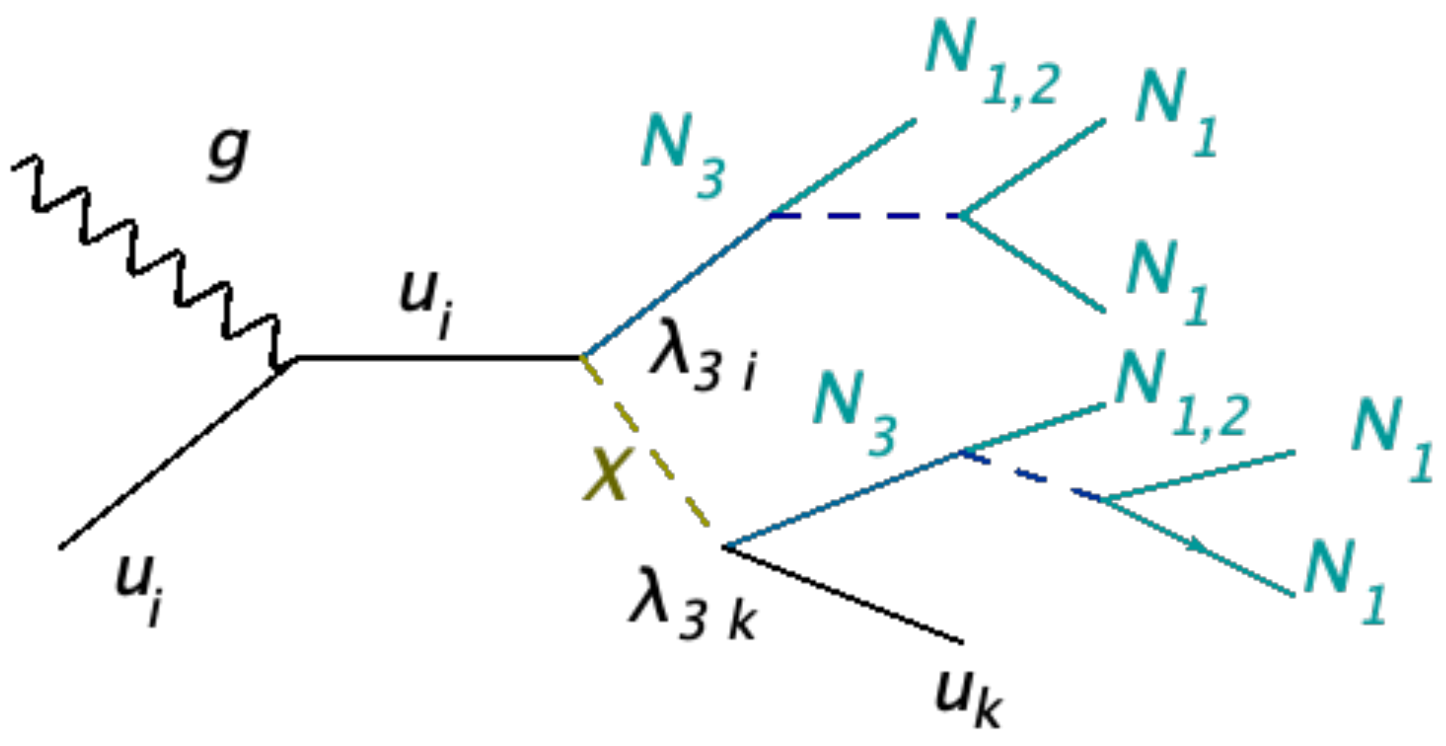
So production dominated by N_3 which decays promptly $N_3 \to N_1, N_2 + \Phi \to N_1, N_2 + N_1 + N_1$

Jet + 3N's or Jet + 6N's $\Rightarrow$ Potentially more than one DV + jet

Phenomenology

Topology of DV events





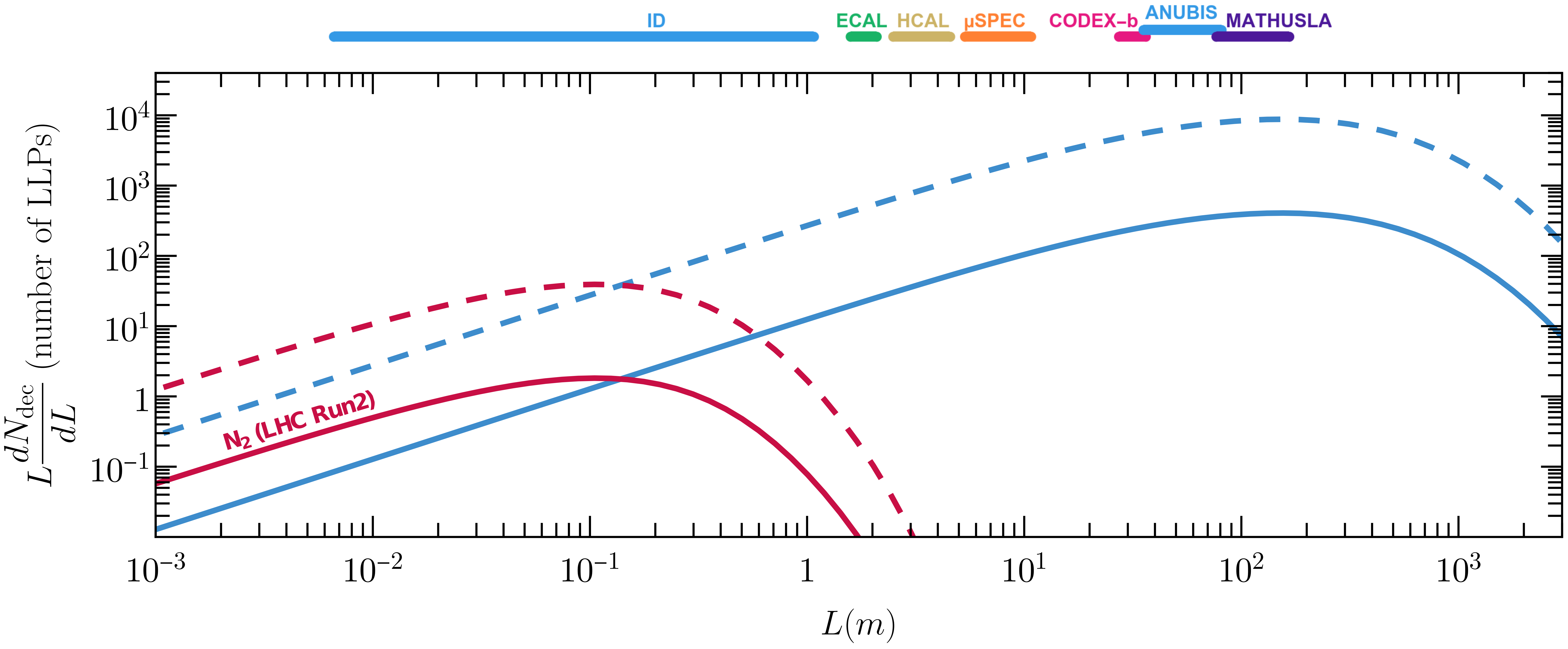
- N_3 dominates production and decays promptly
- N_2 has displaced vertices typical inside the LHC detectors. Need to balance HDO with 2 body
- But N_1 only decays through the HDO suppressed by $M_X \Rightarrow$ decays typically outside the detectors

These diagrams dominate and have a Jacobian peak at $E_J \simeq \dfrac{M_x}{2}$ $\Rightarrow$ hight p_T events

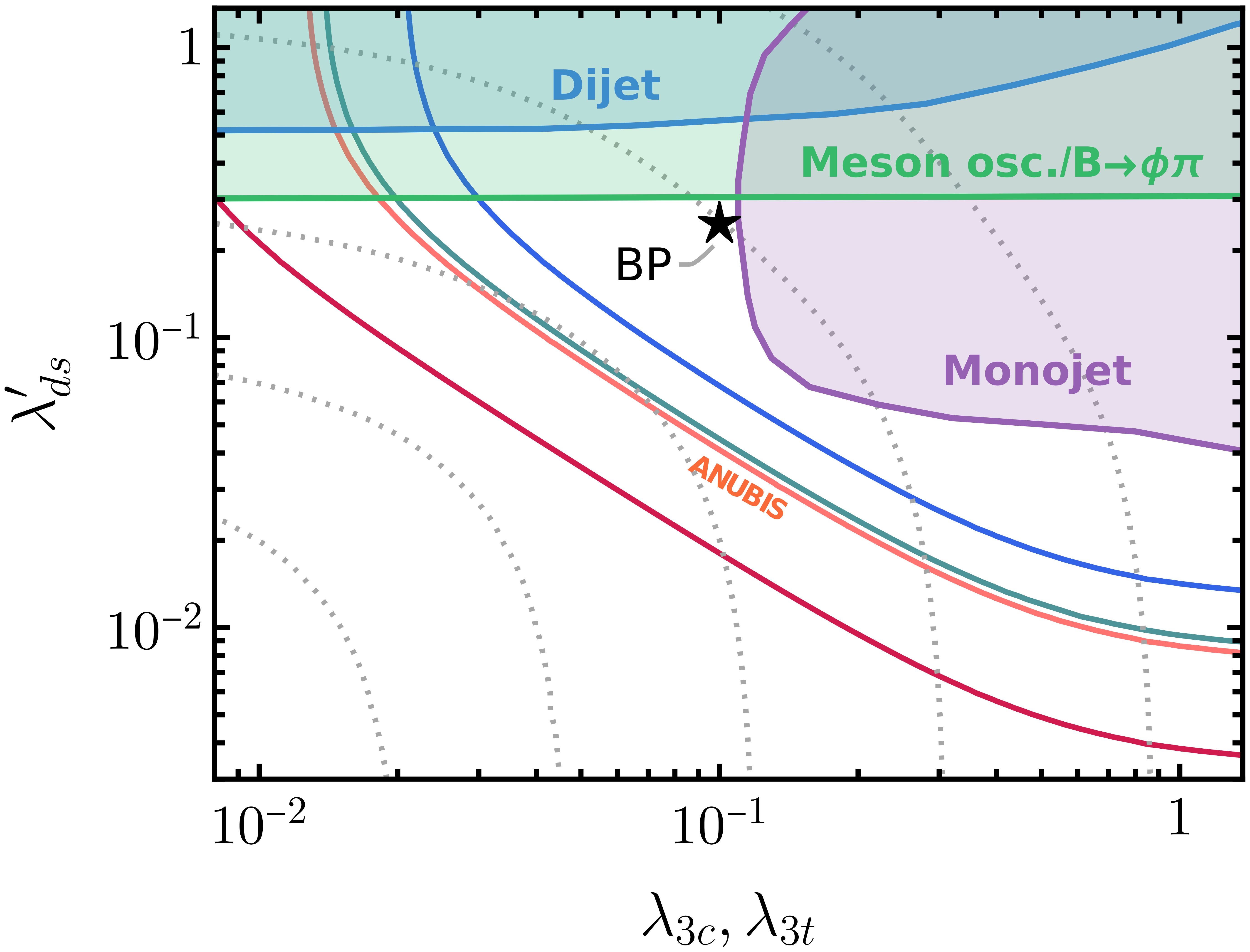
Distribution of Displaced Vertices

Imposing that $\tau_{\text{sphaleron}} < \tau_N < \tau_{\text{BBN}}$

- N_3 decays promptly
- N_2 decays inside the LHC
- N_1 decays outside the LHC



Constraints and Reach



Spontaneous Breaking of Baryon Number

Pedro Bittar, Gabriel Massoni Salla and G.B., 2410.00964

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\overline{N_B} i \not{\partial} N_B + \frac{1}{2}\overline{\chi_a} i\not{\partial}\chi_a - \frac{1}{2}M_a\overline{\chi^c_a}\chi_a$$
$$- \frac{\kappa_B}{\Lambda^2}(\overline{N^c_B}u_R)(\overline{d^c_R}d_R) - \xi_a\overline{N^c_B}\Phi\chi_a + h.c.$$
$$+ |\partial^\mu\Phi|^2 - \lambda_\Phi\left(|\Phi|^2 - \frac{f_B^2}{2}\right)^2$$
$$+ \Delta\mathcal{L}^{(1)}_{\not{B}} + \Delta\mathcal{L}^{(2)}_{\not{B}}.$$

	Q_L	u_R	d_R	N_B	$\chi_{2,3}$	Φ	H
$SU(3)_c$	3	3	3	–	–	–	–
$SU(2)_L$	2	–	–	–	–	–	2
$U(1)_Y$	1/6	2/3	−1/3	–	–	–	1/2
$U(1)_B$	1/3	1/3	1/3	−1	0	1	0

$\langle \Phi \rangle = f_B \Rightarrow$ spontaneous B braking

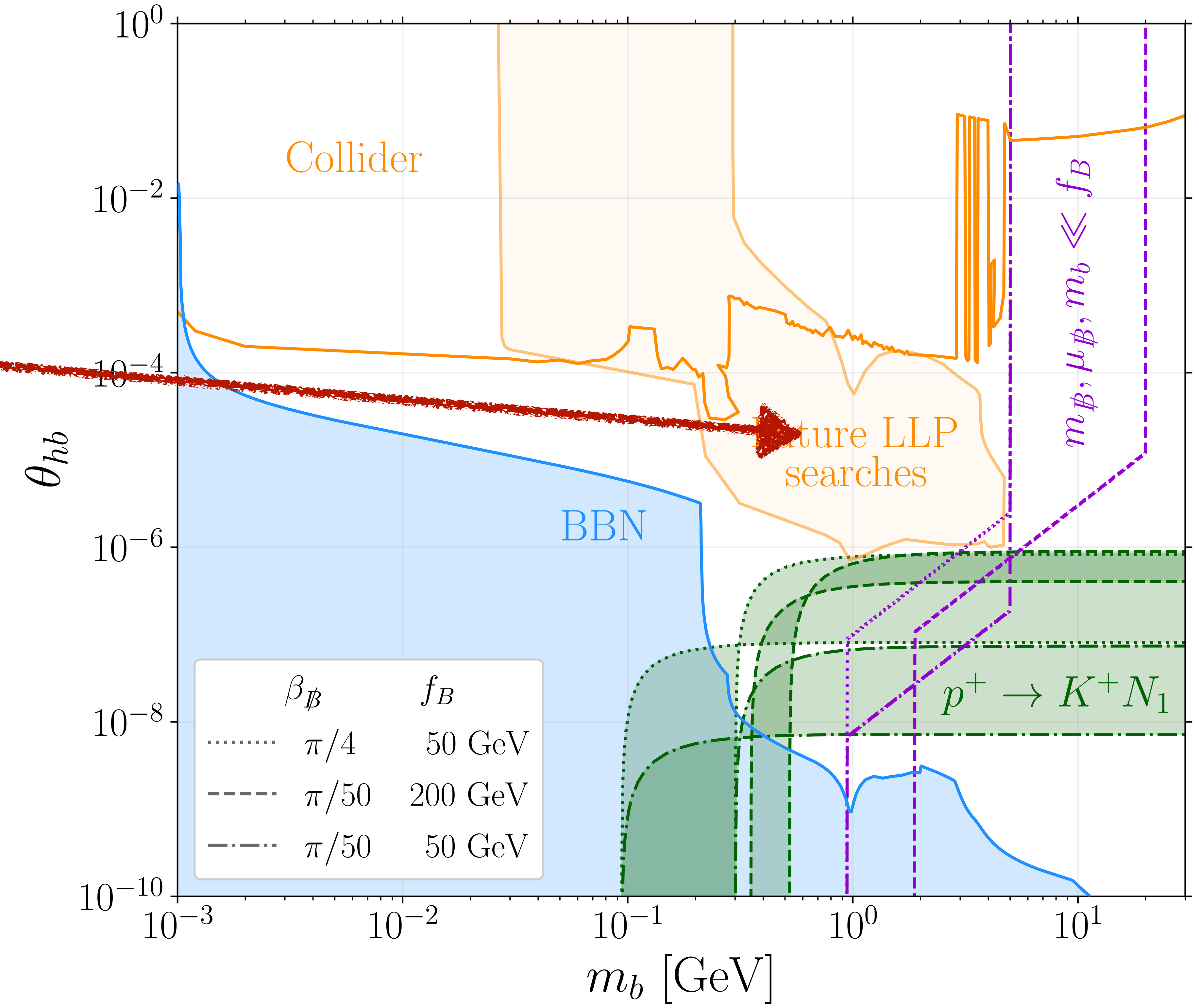
$N_B, \chi_2, \chi_3 \rightarrow N_1, N_2, N_3$ with phenomenology as before

Plus a light pNGB, the *bajoron*

Spontaneous Breaking of Baryon Number

Bajoron parameter space is already constrained

Future searches could almost close it



Summary

- Low Temperature Baryogenesis models are viable and testable

- Connection between LTB and largely displaced vertices

Requiring that $\tau_{\text{sphaleron}} < \tau_N < \tau_{\text{BBN}}$

$\Rightarrow$ pattern of DV at the (HL-)LHC, as well as in proposed MATHUSLA, CODEX-b, ANUBIS

- Extensions of the basic framework to accommodate spontaneous B violation

$\Rightarrow$ Bajoron phenomenology