

# Dark Matter Induced Nucleon Decay Signals in Mesogenesis

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JB, G. Elor: 2301.04165 (Submitted to PRL)

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# CPV from the Meson Systems

There's more matter than anti-matter:

$$\frac{n_B - n_{\bar{B}}}{s} \sim 8 \times 10^{-11}$$

How? **Sakharov** says:

1.  $C$  and  $CP$  violation:  
 $B$ -meson oscillation
2. Baryon-number violation:  
Store anti-baryon number in dark sector state
3. Out-of-equilibrium:  
Late decay of a heavy scalar



# Model Structure

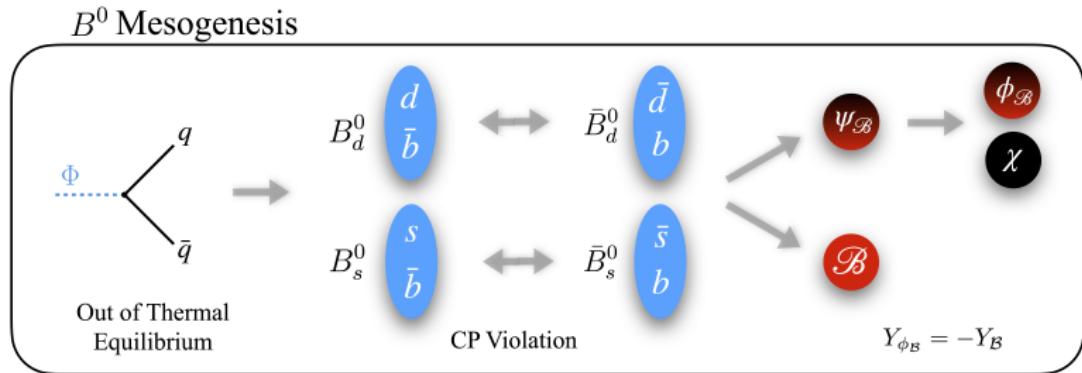
Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_B$	$Z_2$
$Y$	3	1	-1/3	2/3	1
$\psi_B$	1	1	0	-1	1
$\phi_B$	1	1	0	-1	-1
$\xi$	1	1	0	0	-1

Two DM particles

Integrate out TeV-scale  $Y$  to get EFT:

$$\mathcal{L} = \frac{y_{u_a d_b} y_{\psi d_c}}{M_Y^2} \epsilon_{ijk} \left( u_{R,a}^i d_{R,b}^j \right) \left( \psi_B d_{R,c}^k \right) - y_d \bar{\psi}_B \phi_B \xi + \text{h.c.}$$

# $B^0$ Mesogenesis Mechanism



Elor, Escudero, Nelson: PRD 99, 035031 (2019)

Asymmetry tied to observables:

- ▶ Need sufficient  $B$  CP violation
- ▶ Need sufficient branching to  $\psi_{\mathcal{B}}$

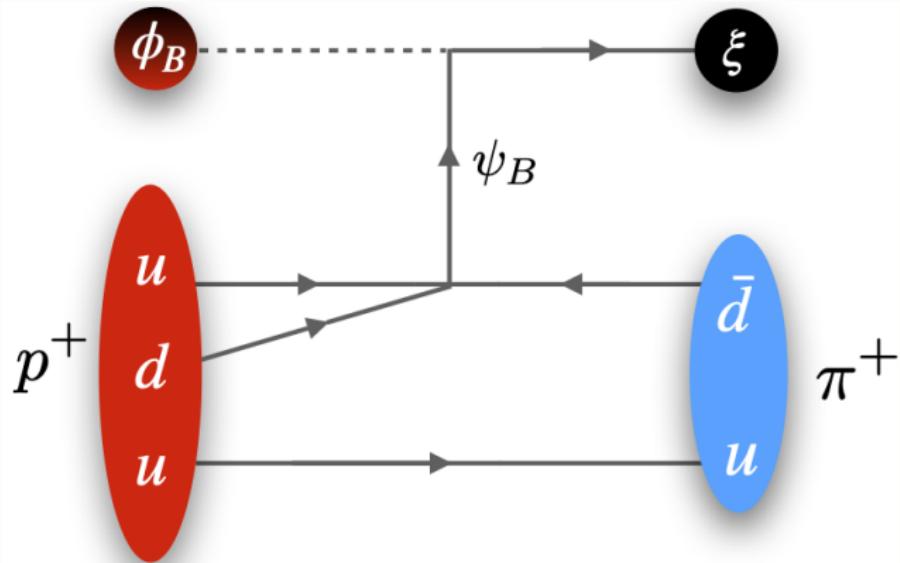
# Other Observables

Asymmetry given by:

$$Y_{\mathcal{B}} = \frac{n_{\mathcal{B}} - n_{\bar{\mathcal{B}}}}{s} = 8.7 \times 10^{-11} \frac{\text{Br}(B \rightarrow \psi_{\mathcal{B}} \mathcal{B}_{\text{SM}})}{10^{-2}} \sum_{q=s,d} \alpha_q \frac{A_{SL}^q}{10^{-4}}$$

- ▶  $A_{SL}^q$ : CP asymmetry in  $\overset{(-)}{B}_q \rightarrow \ell^\mp + X$   
Constrained by LHC,  $B$  factories
- ▶ Exotic  $B$  decays at  $B$  factories
- ▶ Indirect effects on  $B^0$  oscillation/CP violation  
e.g.  $\phi_{1,2}^{d,s}$ ,  $\Delta M_{d,s}$ ,  $\Delta \Gamma_{d,s}$
- ▶ Direct production of  $Y$  @ LHC

# Can We Detect Dark Matter?



Induced Nucleon Decay!

# Modeling IND

- ▶ Amplitude written in terms of  $N \rightarrow \pi, K$  form factors

$$\mathcal{A} \propto W_0(q^2) - i \frac{\not{q}}{m_N} W_1(q^2)$$

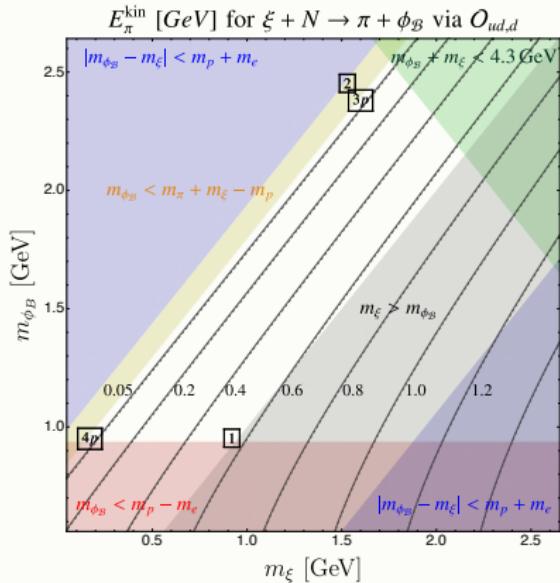
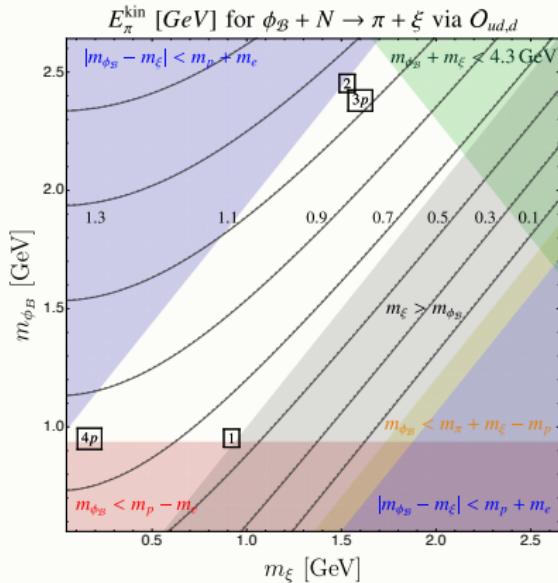
- ▶ Calculated on the lattice at  $q^2 = 0, 1 \text{ GeV}^2$

Yoo et. al.: PRD105, 074501 (2022)

- ▶ 3 choices of  $udd$  operator

$$(u_R d_R) d_R, \quad (u_R d_R) s_R, \quad (u_R s_R) d_R$$

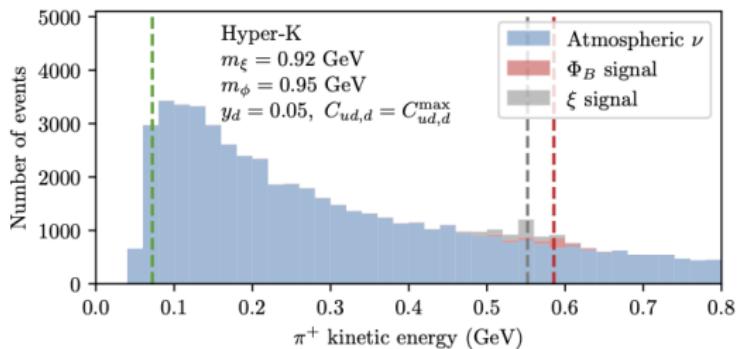
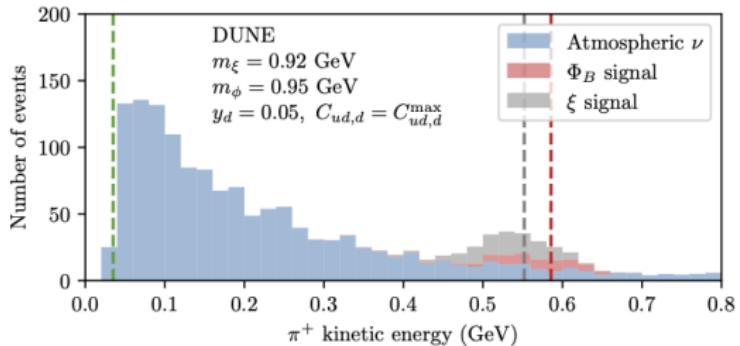
# Parameter Space: $\pi$ Channel



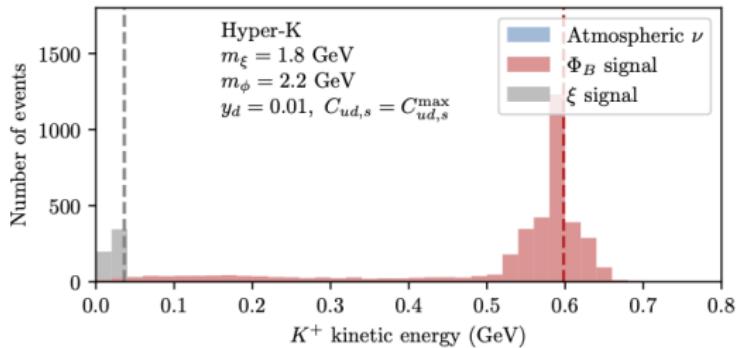
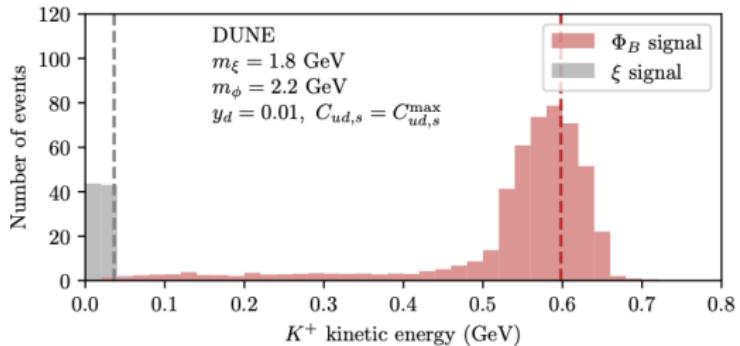
# Can We Simulate?

- ▶ Hacked together simulation in **GENIE v3.06**  
Based on existing nucleon decay module
- ▶ Event generation of model points **by request**  
<https://github.com/jberger7/Generator-IND>
- ▶ Why GENIE?
  - ▶ Standard tool in  $\nu$  experiment
  - ▶ Includes important **nuclear effects**
  - ▶ Get full kinetic energy **distributions!**
- ▶ Allowed meson FS:  $\pi$ ,  $K$ ,  $D^0$

# Kinematic Distributions: $\pi$ Channel



# Kinematic Distributions: K Channel



# Event Counts

Benchmark and Meson	Bkg. DUNE	$y_d(C_{ud,d}/C_{ud,d}^{\max})$ DUNE sens.	Bkg. Hyper-K	$y_d(C_{ud,d}/C_{ud,d}^{\max})$ Hyper-K sens.
1 $\pi^+$	118	0.019	9452	0.020
2 $\pi^+$	14	0.007	2323	0.0090
3p $\pi^+$	584	0.021	13835	0.015
4p $\pi^+$	600	0.040	15653	0.029
1 $K^+$	0	0.0016	0	0.00061
2 $K^+$	0	0.00038	0	0.00014
3k $K^+$	0	0.00063	0	0.00023
4k $K^+$	0	0.0010	0	0.00038

Min. solar model, 10 years running,  $m_{\psi_B} = 4 \text{ GeV}$

# Backup

# Fixed kinetic energy

- ▶ In nucleon rest frame: Fixed meson K.E.

$$E_{\phi_B N \rightarrow \xi M}^{\mathcal{M}, \text{kin}} = \frac{m_{\mathcal{M}}^2 - m_\xi^2 + (m_N + m_{\phi_B})^2}{2(m_N + m_{\phi_B})} - m_{\mathcal{M}}$$

- ▶ Smeared by nucleon motion:

$$p_{\mathcal{M}} \lesssim p_F \approx 240 \text{ MeV} \quad (\text{Argon})$$

- ▶ Hydrogen in water: no smearing!
- ▶ Ideally: simulate this process!

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# Parameter Space

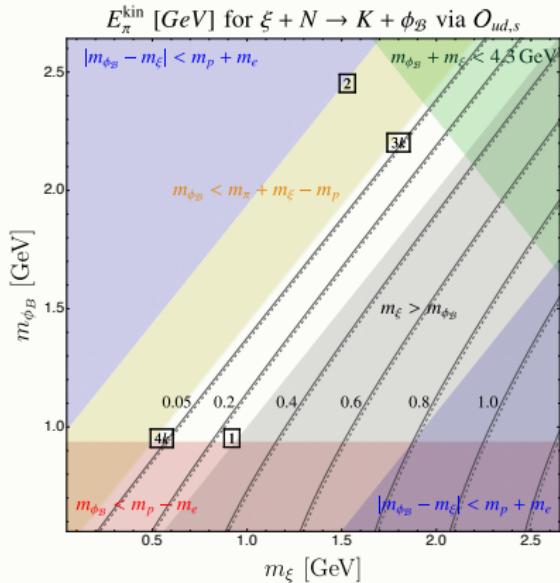
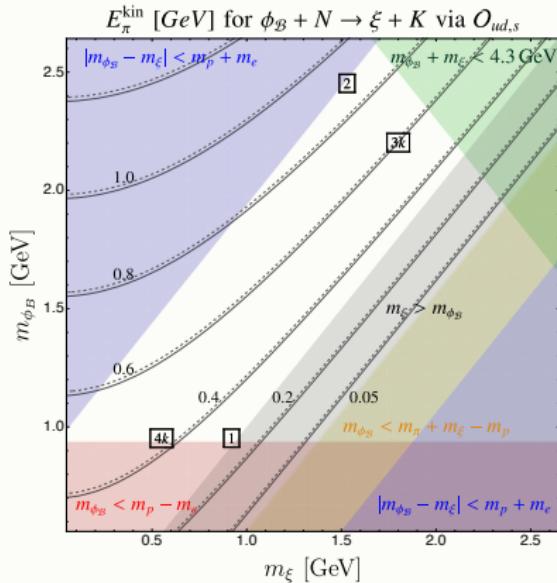
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- ✓  $B \rightarrow \mathcal{B}_{\text{SM}} \psi_{\mathcal{B}}$ :  $m_{\psi_{\mathcal{B}}} < m_B - m_p \simeq 4.34 \text{ GeV}$
- ✓  $\psi_{\mathcal{B}} \rightarrow \xi + \phi_{\mathcal{B}}$ :  $m_{\psi_{\mathcal{B}}} > m_\xi + m_{\phi_{\mathcal{B}}}$
- ✗  $\phi_{\mathcal{B}} + \xi \rightarrow \mathcal{B}_{\text{SM}}$ :  $|m_{\phi_{\mathcal{B}}} - m_\xi| < m_p + m_e \simeq 938.8 \text{ MeV}$
- ✗  $\mathcal{B}_{\text{SM}} \rightarrow \phi_{\mathcal{B}}, \xi$ :  $m_{\phi_{\mathcal{B}}}, m_\xi < m_p - m_e$
- ✓  $\phi_{\mathcal{B}} + \bar{\phi}_{\mathcal{B}} \rightarrow \xi + \bar{\xi}$ :  $m_{\phi_{\mathcal{B}}} > m_\xi$

# Benchmarks

Benchmark	$m_{\phi_B}$ [GeV]	$m_\xi$ [GeV]
1	0.95	0.92
2	2.45	1.53
3p	2.38	1.6
3k	2.2	1.8
4p	0.95	0.17
4k	0.95	0.55

# Parameter Space: K Channel

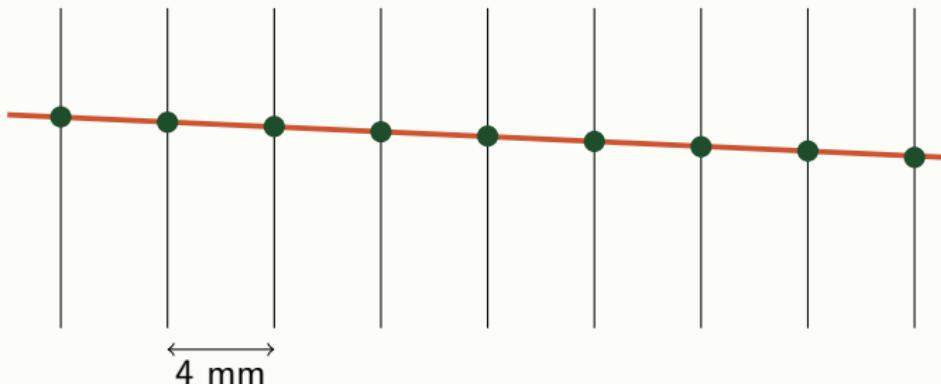


# Backgrounds: Atmospheric $\nu$

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- ▶ Trickiest background: atmo  $\nu$  NC  
with  $\nu + N \rightarrow \nu + n + \pi$
- ▶ Also: CC,  $p$  FS with missed particles
- ▶ Bkg: events with only  $\pi$  above threshold
- ▶  $K$  background extremely tiny
- ▶ Model  $\nu$  scattering in GENIE using Bartol fluxes at Soudan (DUNE) and Kamioka (Super-K/Hyper-K)

# DUNE Thresholds



- ▶ Charged particles: cross 10 wires
- ▶ Unstable particles: energetic decay products

# Water Cherenkov Thresholds

- ▶ Charged & heavy: require  $\beta > 1/n$  for Cherenkov radiation
- ▶  $e$  &  $\gamma$ : 3.5 MeV
  - Super-Kamiokande: PRD94, 052010 (2016)
- ▶ Unstable particles: energetic decay products
- ▶  $\mu^\pm$  vs.  $\pi^\pm$ : challenging to distinguish
  - For Cherenkov: assume no distinction

A bit crude... but need experimental input for more!