Baryogenesis and dark matter from CPV in B meson oscillations

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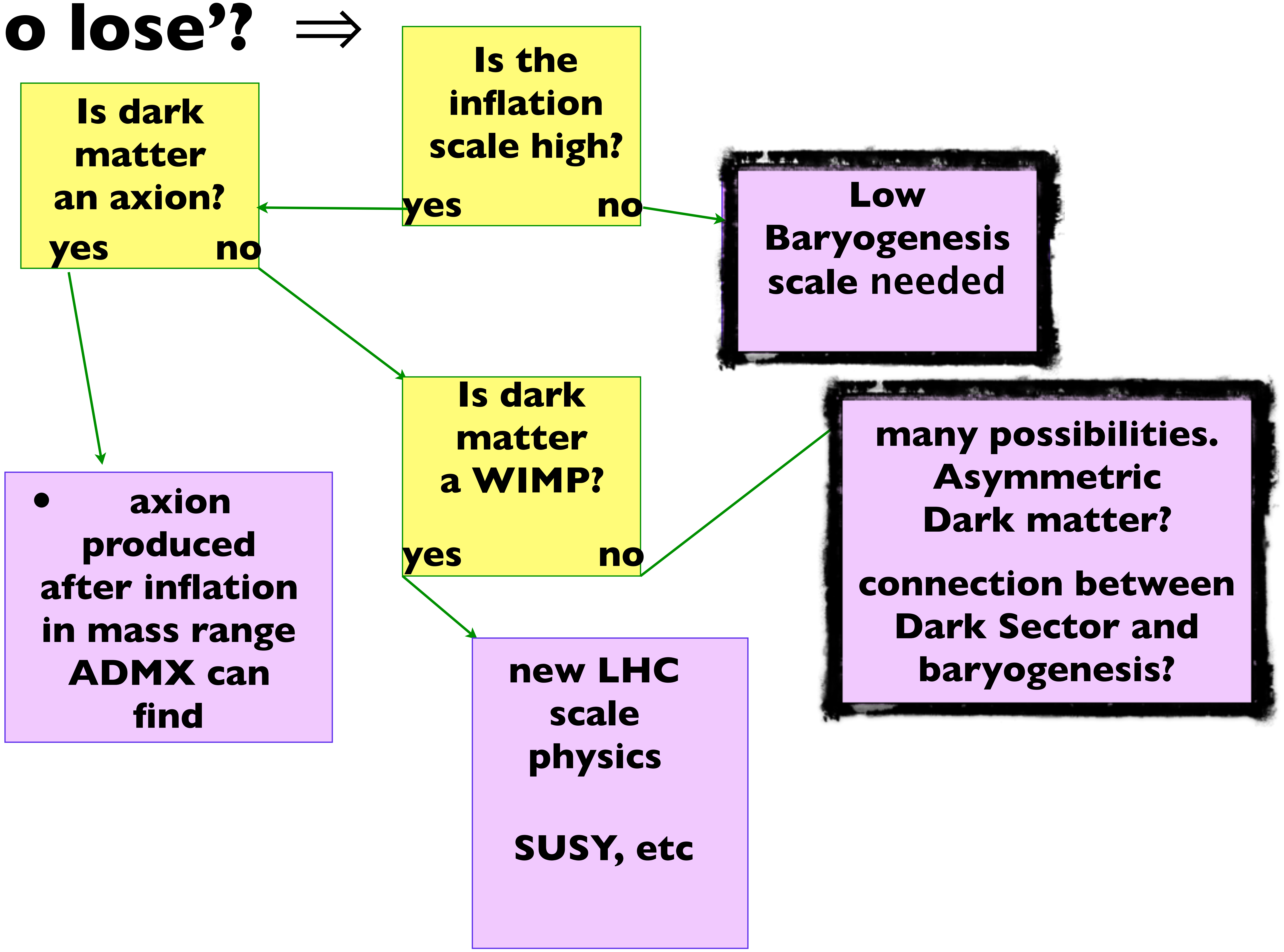
Ipek, McKeen, AEN, arXiv:1407.8193
Ghalsasi, McKeen, AEN, arXiv:1508.05392
McKeen, AEN, arXiv:1512.05359
Aitken, McKeen, Neder, AEN, arXiv:1708.01259
Elor, Escudero, AEN, arXiv:1810.00880
AEN, Xiao, arXiv:1901.08141
Elor, Alonso Alvarez, AEN, Xiao, in progress

focus of this talk

Cosmology ‘no lose’? ⇒



Is the inflation scale high?
yes no

Is dark matter an axion?
yes no

Low Baryogenesis scale needed

- axion produced after inflation in mass range ADMX can find

Is dark matter a WIMP?
yes no

many possibilities. Asymmetric Dark matter?

connection between Dark Sector and baryogenesis?

new LHC scale physics

SUSY, etc

Why ‘post sphaleron’ baryogenesis is compelling

- Consistent with wide range of cosmology/inflation models.
  - No high temperature required (avoids many cosmological issues, e.g. gravitino over production, axion isocurvature perturbations)
  - Electroweak baryogenesis requires 1st order weak transition, CPV in Higgs sector—very constrained by electric dipole moment of electron, mass of Higgs.
  - High scale Leptogenesis requires very high postinflation reheat temperature
  - Many high scale models with scalars have isocurvature perturbation constraints

Inflation’s end and reheating

- reheat temp T_r set by time at which inflaton dumps its energy into radiation (simple model: set by inflaton lifetime)
- $t^{-1} \sim \Gamma \sim H \sim T_r^2/M_{pl}$
- T_r typically assumed to be very high, ~ 10^{12} GeV, but could be as low as 4 MeV
    - lower bound set by nucleosynthesis, ν abundance (N_{eff})
    - upper bound set by energy density during inflation

Cosmology with low reheat scale: Either

- “Early matter domination”— postinflation energy density dominated by late (.01 s) decaying particle

or

- “slow reheating” inflaton decays late (.01 s)
- thermalized radiation dominated universe never hotter than ~10 MeV
- economical picture: inflation→something→B hadrons+…
- something could be oscillating Inflaton or modulus or …
- could decay to top or Higgs or weak bosons—always gives B hadrons decaying out of equilibrium
- could CPV in B oscillations/decays yield BAU and dark matter?

sufficient CPV at low energy

- Baryogenesis at low scales requires departure from thermal equilibrium at low scales, very weak couplings
- CPV requires new phase, quantum mechanics, effects usually very small (loop effects)
- CPV effects can be large in particle oscillations
- oscillations require near degeneracy (e.g. particle-antiparticle)

CPV from particle/anti particle Oscillations

- CPV requires common final state between particle and antiparticle
- Charge asymmetry requires $m_{12} \neq 0$, $\Gamma_{12} \neq 0$, $\arg(m_{12}\Gamma_{12}^*) \neq 0$
- *maximum effect:* $\Delta\Gamma \sim \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) \sim O(1)$
- theory: $\Delta\Gamma < \Delta m, \Gamma$

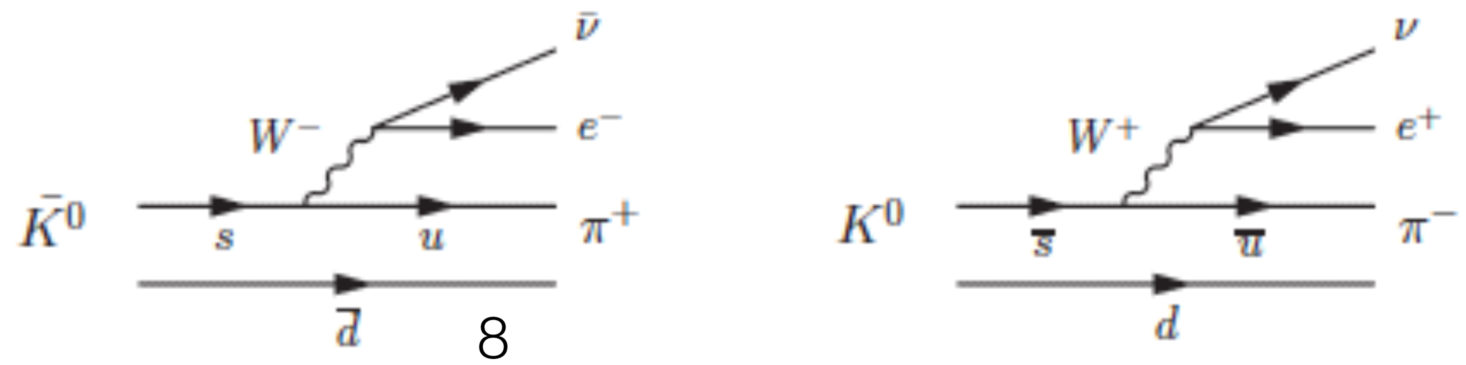
$$H = \begin{pmatrix} m - i\frac{\Gamma}{2} & m_{12} - \frac{i}{2}\Gamma_{12} \\ m_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - i\frac{\Gamma}{2} \end{pmatrix}$$

  - *Kaons:* $\Delta\Gamma \sim \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$,
  - B^0_d: $\Delta\Gamma << \Delta m \sim \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$ *(theory)*
  - B^0_s: $\Delta\Gamma << \Gamma << \Delta m$, $\arg(m_{12}\Gamma_{12}^*) << 1$ *(theory)*
  - D^0: $\Delta\Gamma \sim \Delta m < \Gamma$, $\arg(m_{12}\Gamma_{12}^*) << 1$

Effects of charge asymmetry

$$H = \begin{pmatrix} m - i\frac{\Gamma}{2} & m_{12} - \frac{i}{2}\Gamma_{12} \\ m_{12}^* - \frac{i}{2}\Gamma_{12}^* & m - i\frac{\Gamma}{2} \end{pmatrix}$$

- rate(particle→antiparticle)≠rate(antiparticle→particle)
- start with equal amounts of particles and antiparticles (e.g.K^0 $\bar{K}^0$)
- semileptonic charge asymmetry: flavor asymmetry in decays
- *kaon semileptonic asymmetry* a_{sl}^K: more e^+ than e^- ⇒ more $\bar{s}$ than s decays.

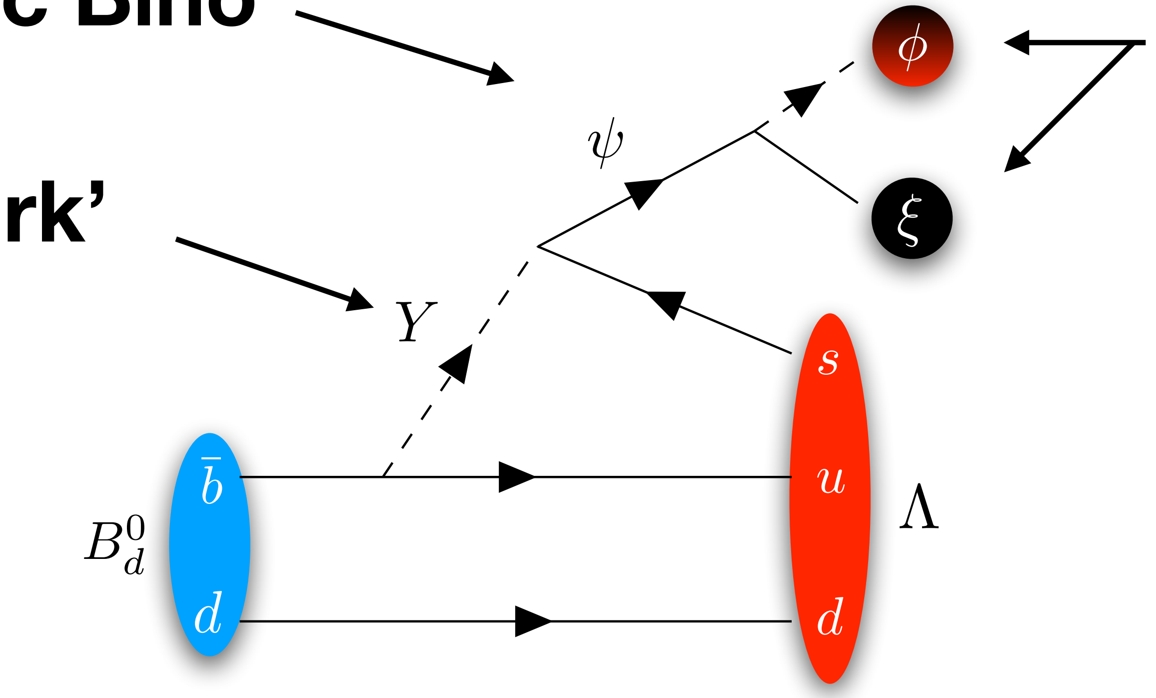


meson CPV

- B mesons oscillate and decay in CPV violating way
- Dark matter and baryon production from charge asymmetry in decay
- Currently embedding mechanism in $U(1)_R$ SUSY with $\bar{U}\bar{D}\bar{D}$ in superpotential

‘light Dirac Bino’

‘squark’



Dark matter—carries Z_2 and anti baryon number. (chiral superfield added to SUSY) Currently exploring whether could be right handed neutrino (sterile sneutrino carries baryon number)

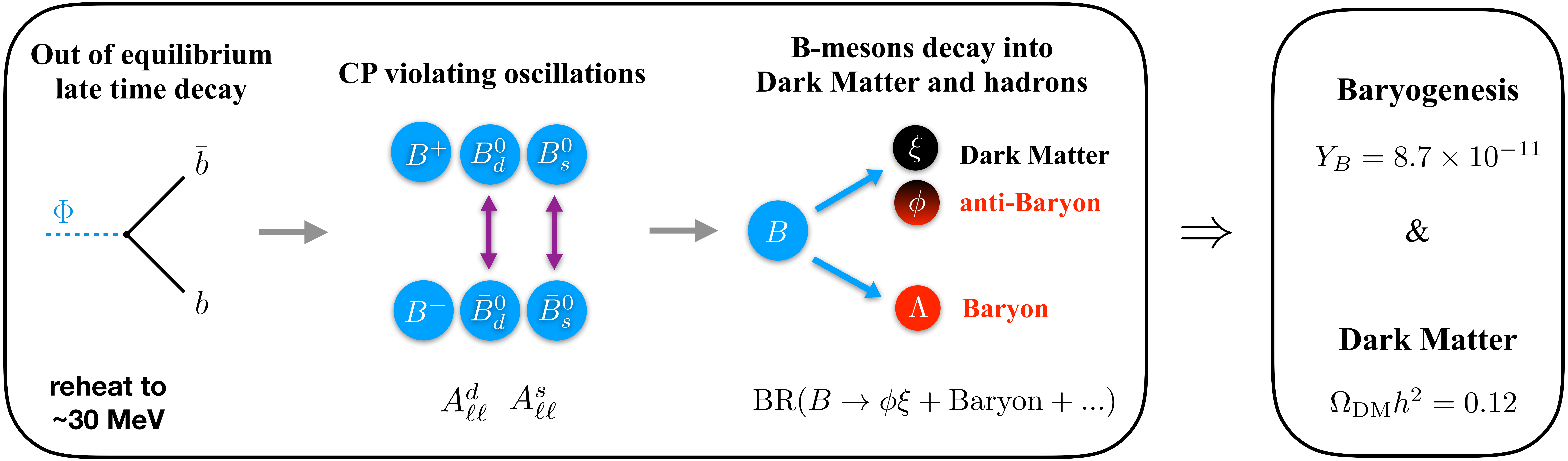
Decay kinematics: $m_\phi + m_\xi \ < \ m_\psi$

DM stability: $|m_\xi - m_\phi| \ < \ m_p + m_e$

Neutron star stability: $m_\psi \ > \ m_\phi \ > \ 1.2\,\mathrm{GeV}$

adequate decay rate: $m_\psi < m_B - m_\Lambda$

Summary of Baryon/DM production mechanism



Out of equilibrium late time decay

reheat to ~30 MeV

CP violating oscillations

$A_{\ell\ell}^d$ $A_{\ell\ell}^s$

B-mesons decay into Dark Matter and hadrons

Dark Matter

anti-Baryon

Baryon

$\mathrm{BR}(B \to \phi\xi + \mathrm{Baryon} + ...)$

Baryogenesis

$Y_B = 8.7 \times 10^{-11}$

&

Dark Matter

$\Omega_{\rm DM} h^2 = 0.12$

Essential new particles

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	$+1$	$11-100\,\mathrm{GeV}$
Y	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
ψ	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
ξ	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

VERY weakly coupled "reheaton" decays out of equilibrium to $b\bar{b}$

"squark"

"Light Dirac Bino"

Dark matter Majorana fermion

Dark matter charged scalar

} Can be superpartners

$$\mathcal{L} \supset y_d \bar{\psi}\phi\xi + y_{ub} Y^* \bar{u}\bar{b} + y_{\psi s} Y \bar{\psi}\bar{s} + \mathrm{h.c.}$$

$U(1)_R$ SUSY and dark sector

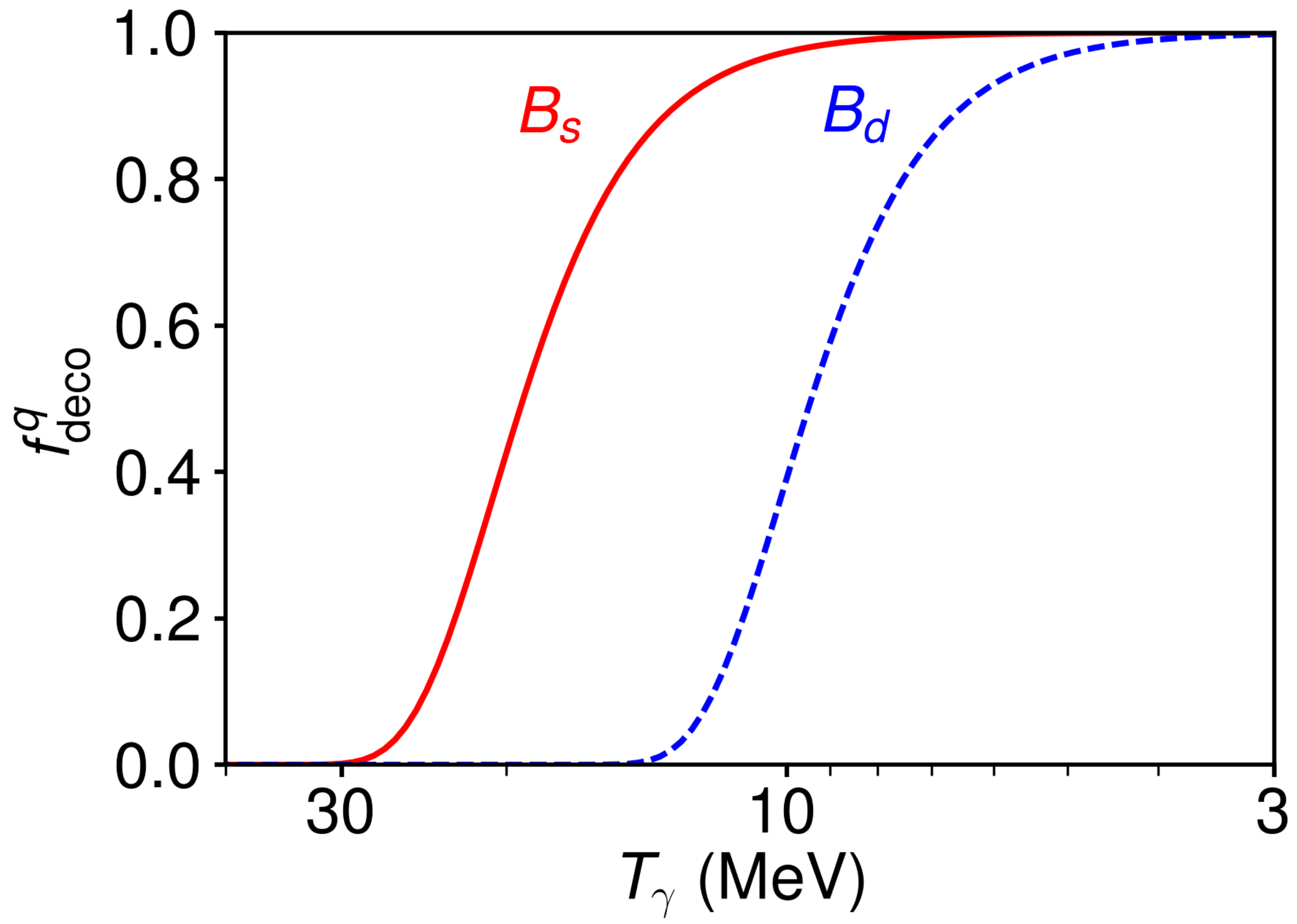
- With extended Higgs sector and Dirac gauginos, can extend R parity to a $U(1)_R$
- $\overline{u}_i\overline{d}_j\overline{d}_k$ in superpotential: Baryon number + $U(1)_R$ breaks to $U(1)_{RB}$
- all superpartners carry baryon number! none of usual ones are stable.
- can add dark matter supermultiplet—single chiral superfield, coupled to "right handed Bino"
- no constraints from neutron oscillations
- small breaking of $U(1)_R$ from anomaly mediation ⇒ weak constraints from neutron oscillations

B mesons in early universe

- b quarks quickly hadronize, mostly into mesons
- mesons decay, annihilate, scatter off e^+, e^- , γ   (charge radius)
  - (annihilation numerically unimportant)
- neutral mesons oscillate and decohere due to scattering off e+, e^-, model via decoherence function
  - At 10-30 MeV

Decoherence mostly affects B_d

$$f^q_{\rm deco} = e^{-\Gamma\left(e^\pm B^0_q \to e^\pm B^0_q\right)/\Delta m_{B_q}}$$



Early Universe Boltzmann equations

Reheating of universe to ~ 10 MeV from reheaton decay:

Hubble parameter:

$$H^2 \equiv \left(\frac{1}{a}\frac{da}{dt}\right)^2 = \frac{8\pi}{3m_{Pl}}\left(\rho_{\rm rad} + m_\Phi n_\Phi\right)$$

$$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$
$$\frac{d\rho_{\rm rad}}{dt} + 4H\rho_{\rm rad} = +\Gamma_\Phi m_\Phi n_\Phi$$

Production and decay of B mesons

$$\frac{dn_B}{dt} + 3Hn_B = \Gamma_\Phi {\rm Br}_{\Phi\to B} n_\Phi - \Gamma_B n_B - \langle\sigma v\rangle n_B^2$$

Production of B-mesons from reheaton decay

B meson decays

B meson annihilations

(numerically negligible)

Production and annihilation of dark matter

$$\frac{dn_\xi}{dt} + 3Hn_\xi \; = -\langle\sigma v\rangle_\xi \left(n_\xi^2 - n_{{\rm eq},\xi}^2\right) + 2\,\Gamma_\Phi^B\, n_\Phi$$

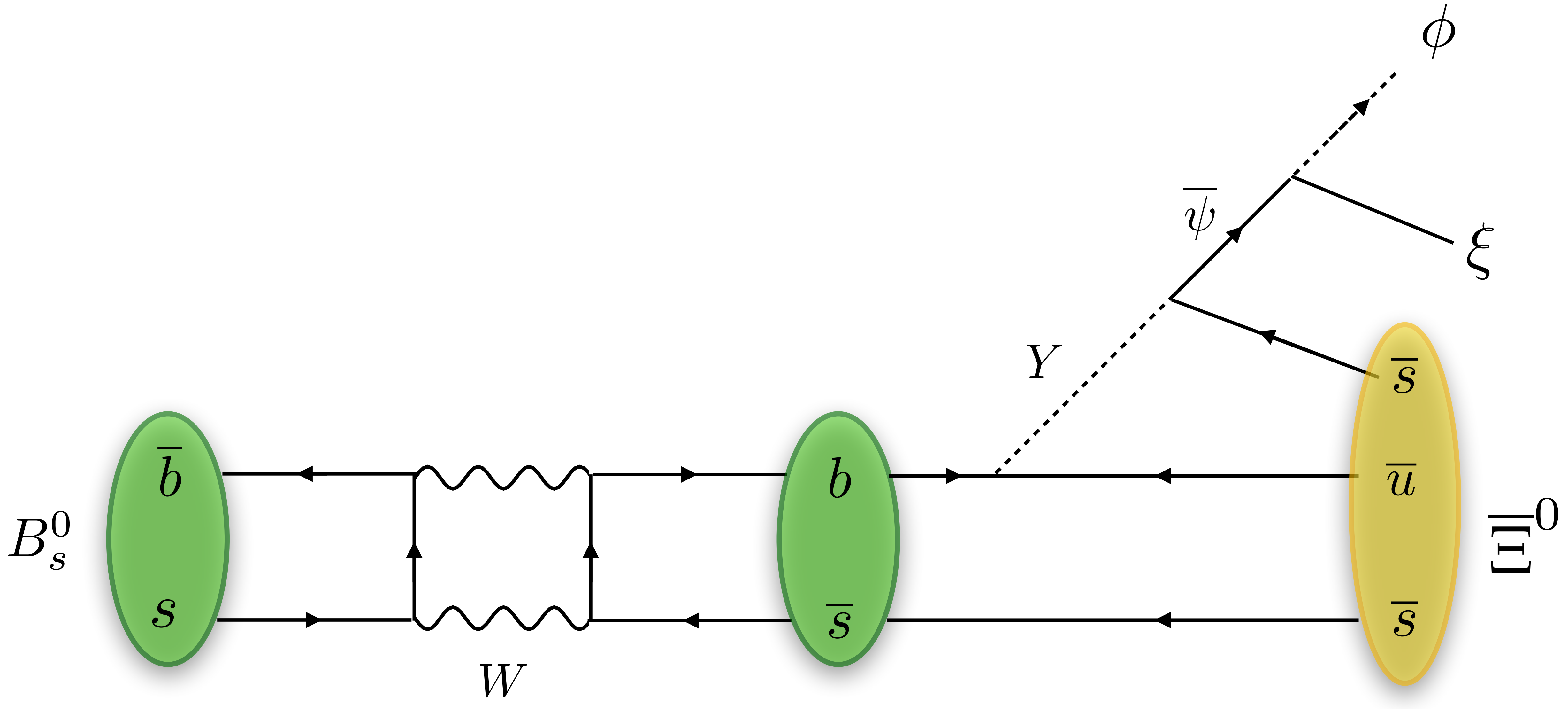
$$\frac{dn_\phi}{dt} + 3Hn_\phi = -\langle\sigma v\rangle_\phi (n_\phi n_{\phi^\star} - n_{{\rm eq},\phi} n_{{\rm eq},\phi^\star}) \; + \Gamma_\Phi^B\; n_\Phi \times \left[1 + \sum_q A_{\ell\ell}^q\, {\rm Br}(\bar b \to B_q^0)\, f_{\rm deco}^q\right]$$

$$\frac{dn_{\phi^\star}}{dt} + 3Hn_{\phi^\star} = -\langle\sigma v\rangle_\phi (n_\phi n_{\phi^\star} - n_{{\rm eq},\phi} n_{{\rm eq},\phi^\star}) \; + \Gamma_\Phi^B\, n_\Phi \times \left[1 - \sum_q A_{\ell\ell}^q\, {\rm Br}(\bar b \to B_q^0)\, f_{\rm deco}^q\right]$$

Dark matter asymmetry=Baryon asymmetry

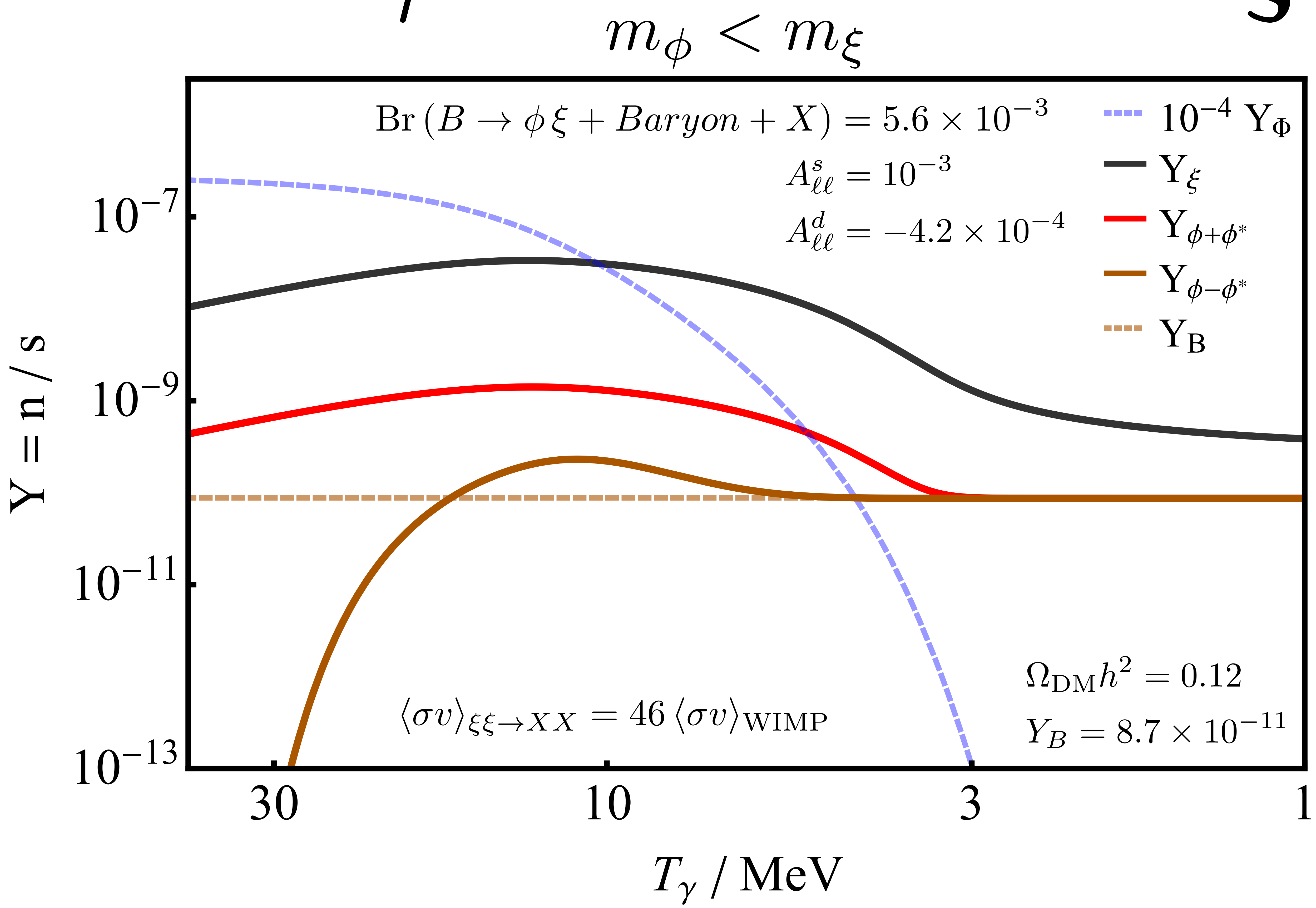
$$\frac{d(n_\phi - n_{\phi^\star})}{dt} + 3\,H(n_\phi - n_{\phi^*}) \; = \; 2\,\Gamma_\Phi^B \sum_q {\rm Br}(\bar b \to B_q^0)\, A_{\ell\ell}^q\, f_{\rm deco}^q\, n_\Phi$$

Is Standard model CPV sufficient?



- SM charge asymmetry in B_d is negative (wrong sign)
- SM charge asymmetry in B_s is positive (but small)
- Decoherence effects much larger for B_d (because they oscillate more slowly) so asymmetry from B_s dominates
- Detailed computations—not quite. Still need some small new contribution to B_s mixing (can make consistent with B CPV observations)

$\mathbf{m}_\phi < \mathbf{m}_\xi$



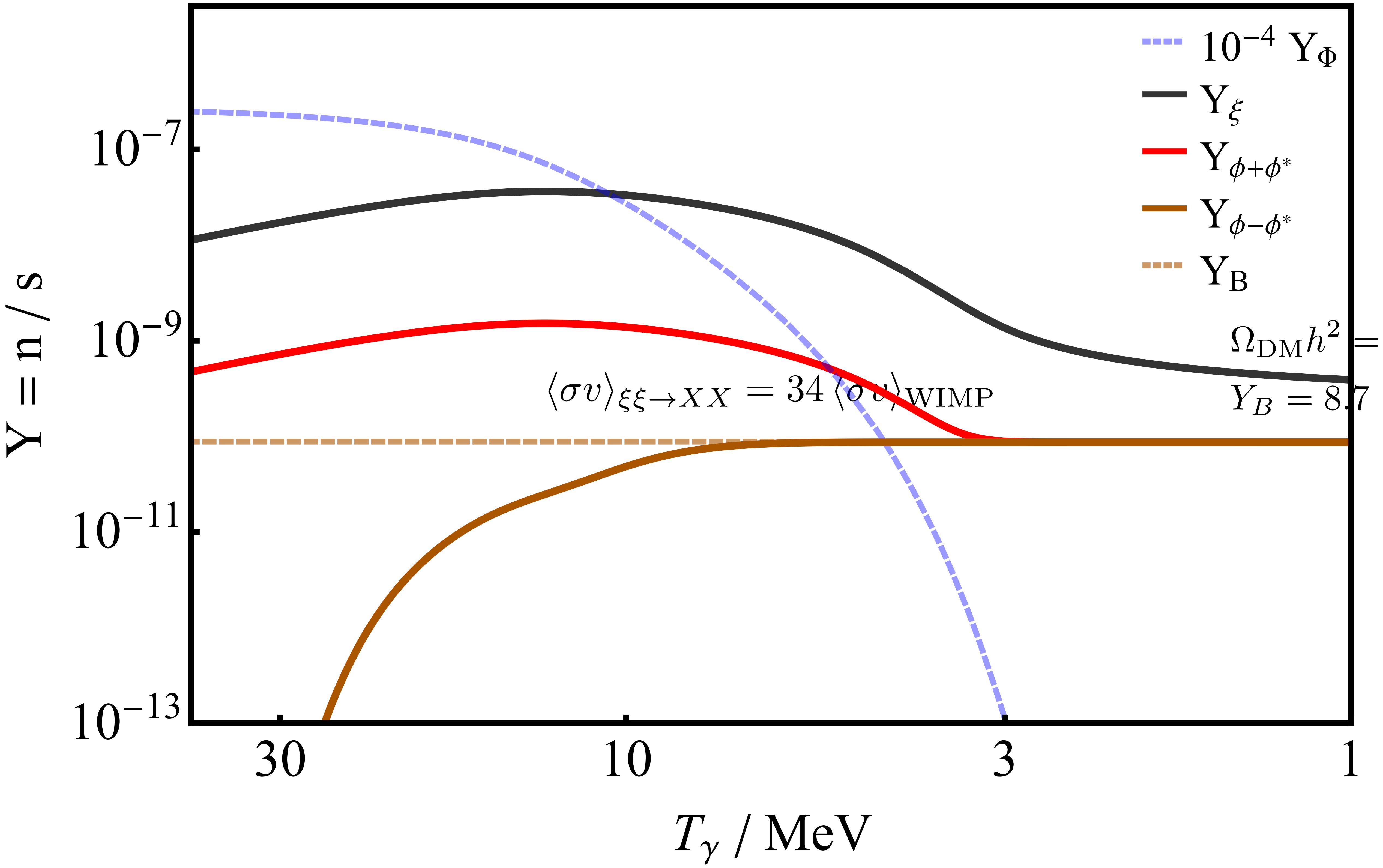
$\mathbf{m}_\xi < \mathbf{m}_\phi$

$$m_\xi < m_\phi$$

$$\mathrm{Br}\,(B \to \phi\,\xi + Baryon + X) = 5.6 \times 10^{-3}$$

$$A^s_{\ell\ell} = 10^{-4}$$

$$A^d_{\ell\ell} = 10^{-4}$$

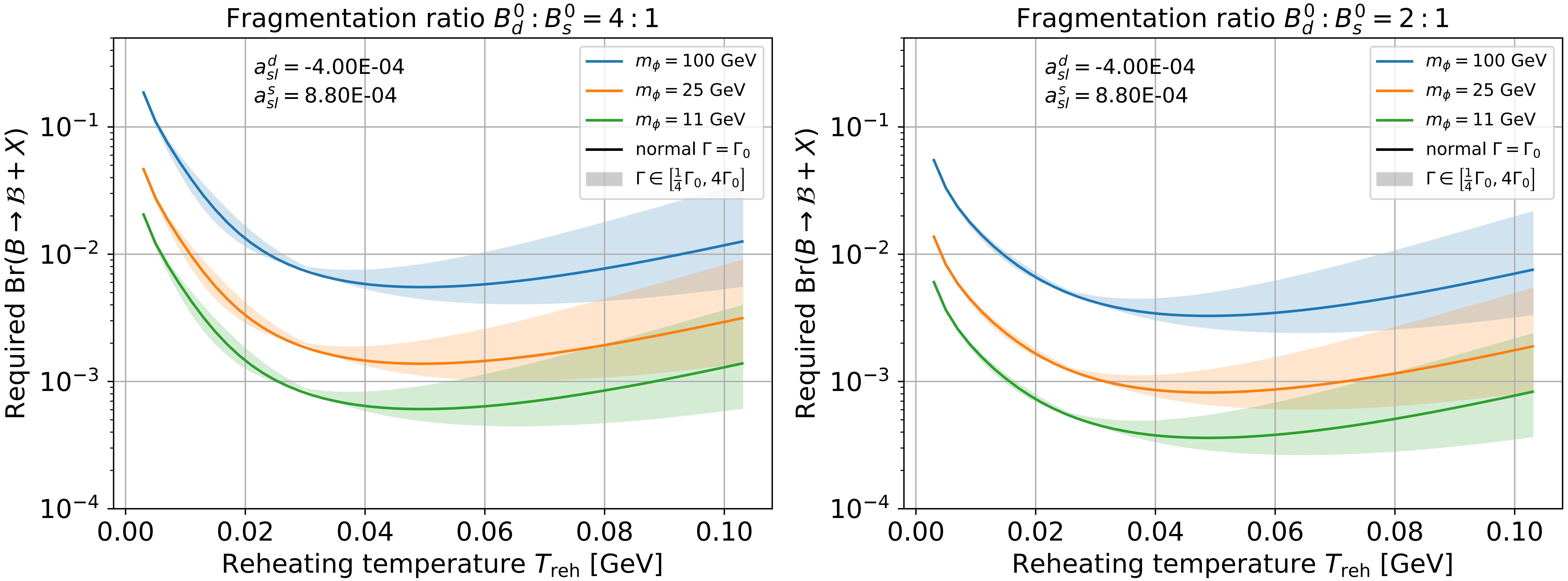


$\langle\sigma v\rangle_{\xi\xi\to XX} = 34\,\langle\sigma v\rangle_{\mathrm{WIMP}}$

$\Omega_{\mathrm{DM}}h^2 = 0.12$

$Y_B = 8.7 \times 10^{-11}$

Results


Fragmentation ratio $B_d^0 : B_s^0 = 4 : 1$
Fragmentation ratio $B_d^0 : B_s^0 = 2 : 1$
$a_{sl}^d =$ -4.00E-04
$a_{sl}^s =$ 8.80E-04
$m_\phi = 100$ GeV
$m_\phi = 25$ GeV
$m_\phi = 11$ GeV
normal $\Gamma = \Gamma_0$
$\Gamma \in [\frac{1}{4}\Gamma_0, 4\Gamma_0]$
Required Br($B \to \mathcal{B} + X$)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.00
0.02
0.04
0.06
0.08
0.10
Reheating temperature T_{reh} [GeV]

lower bound on new B physics

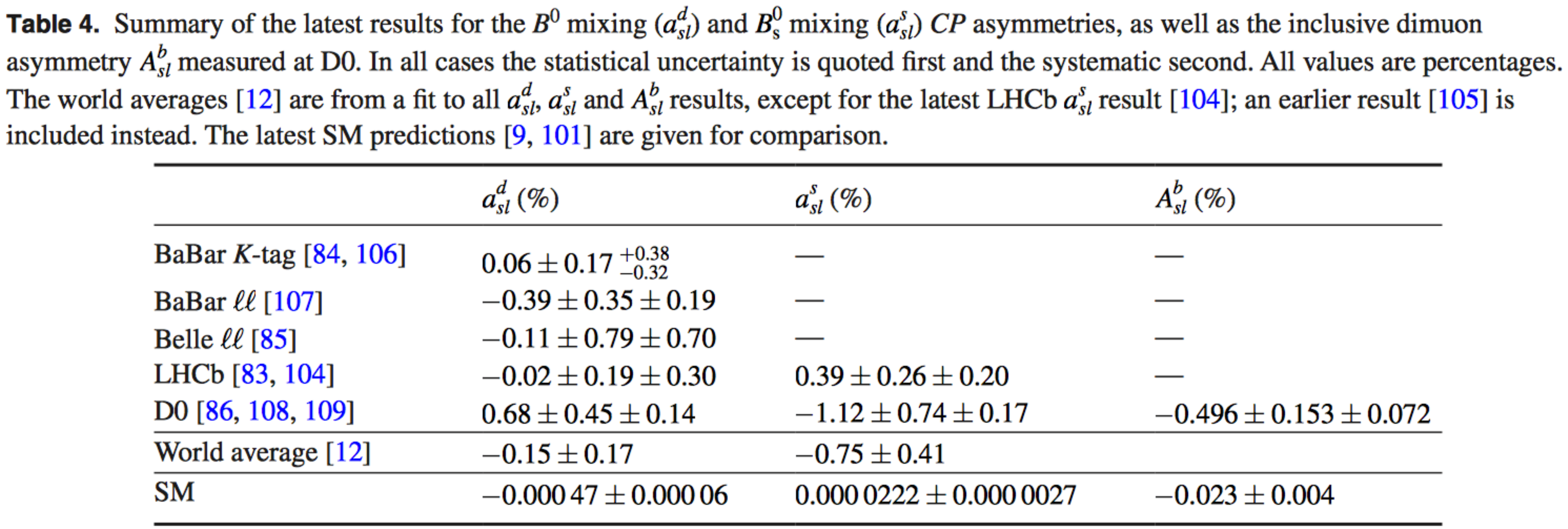


Table 4. Summary of the latest results for the B^0 mixing (a_{sl}^d) and B_s^0 mixing (a_{sl}^s) *CP* asymmetries, as well as the inclusive dimuon asymmetry A_{sl}^b measured at D0. In all cases the statistical uncertainty is quoted first and the systematic second. All values are percentages. The world averages [12] are from a fit to all a_{sl}^d, a_{sl}^s and A_{sl}^b results, except for the latest LHCb a_{sl}^s result [104]; an earlier result [105] is included instead. The latest SM predictions [9, 101] are given for comparison.

	a_{sl}^d (%)	a_{sl}^s (%)	A_{sl}^b (%)
BaBar *K*-tag [84, 106]	$0.06 \pm 0.17\,^{+0.38}_{-0.32}$	—	—
BaBar $\ell\ell$ [107]	$-0.39 \pm 0.35 \pm 0.19$	—	—
Belle $\ell\ell$ [85]	$-0.11 \pm 0.79 \pm 0.70$	—	—
LHCb [83, 104]	$-0.02 \pm 0.19 \pm 0.30$	$0.39 \pm 0.26 \pm 0.20$	—
D0 [86, 108, 109]	$0.68 \pm 0.45 \pm 0.14$	$-1.12 \pm 0.74 \pm 0.17$	$-0.496 \pm 0.153 \pm 0.072$
World average [12]	-0.15 ± 0.17	-0.75 ± 0.41	
SM	$-0.000\,47 \pm 0.000\,06$	$0.000\,0222 \pm 0.000\,0027$	-0.023 ± 0.004

- Interesting observables:
  - semileptonic charge asymmetry a_{sl}^d (asymmetry between b and $\bar{b}$ quarks at time of decay)
  - ($\bar{b}\to$diquark + dark matter) ⇒B meson → Baryon+ dark matter+ mesons
  - BAU $\propto$ ($f_d\, a_{sl}^d + f_s\, a_{sl}^s$)Br (B meson → Baryon+ dark matter+…)
    - $f_{d,s}$=fraction of b quarks which hadronize as $B_{d,s}$ mesons times decoherence function

Experimental Prospects:

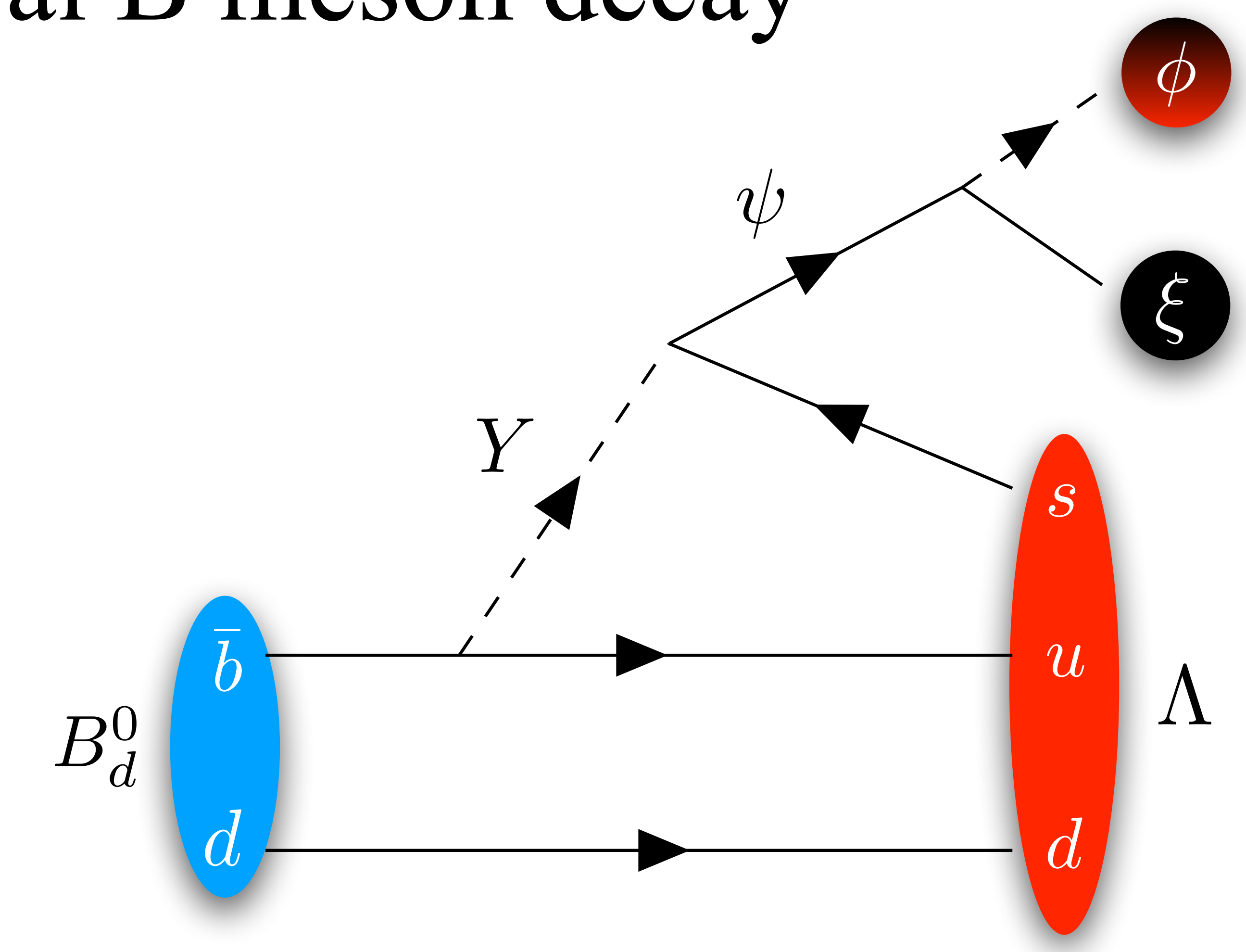
B Meson Decays

$$\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 5 \times 10^{-4} - 0.1$$

$$\mathrm{Br}(B \to \xi\phi + \mathrm{Baryon}) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\ \mathrm{GeV}}\right)^4 \left(\frac{1\ \mathrm{TeV}}{m_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4$$

- Direct searches for charged and neutral B meson decay

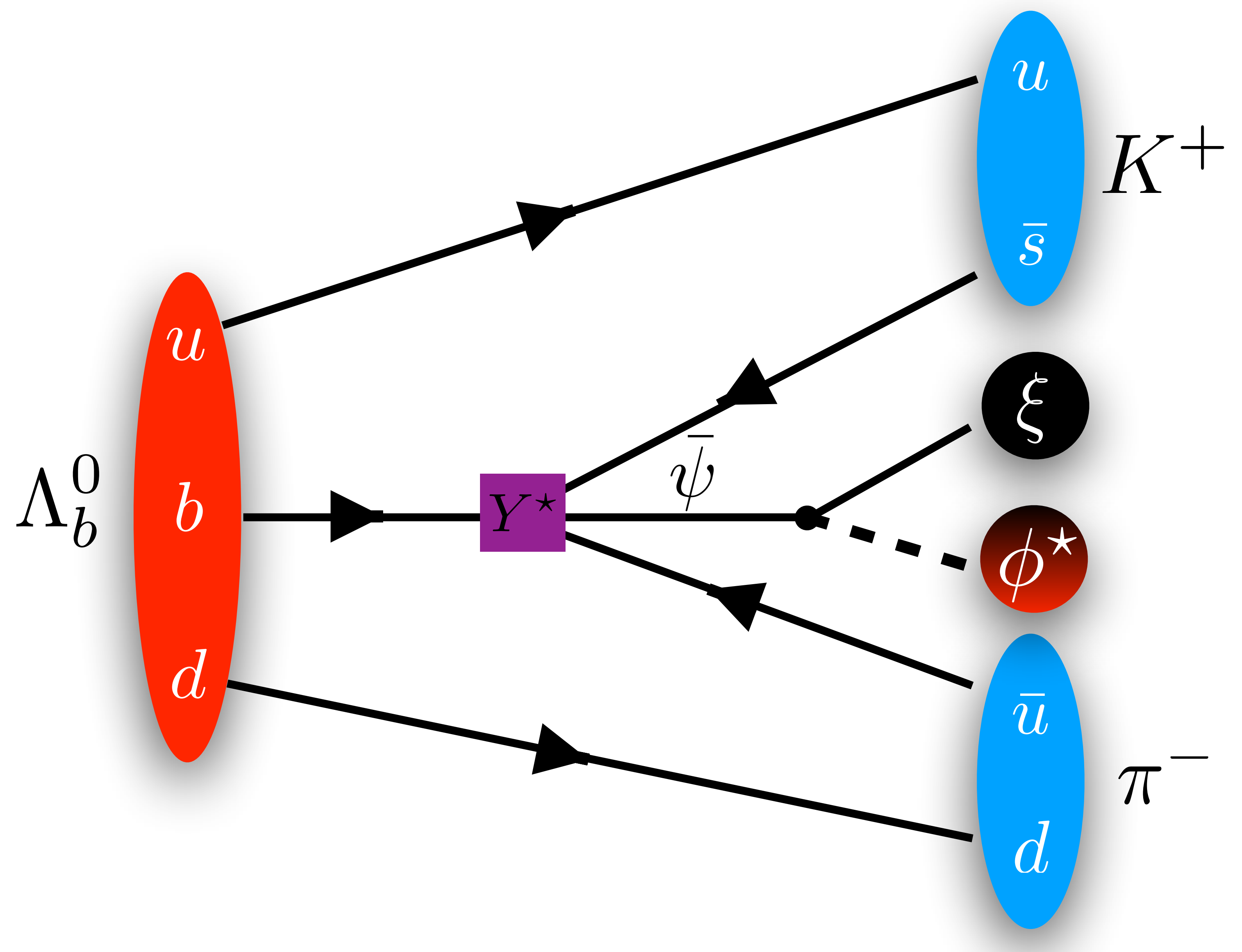
Belle-II, possibly old constraints from
BaBar and Belle data



Experimental Prospects:

Exotic b-flavored baryon decays

Operator	Initial State	Final state	ΔM (MeV)
$\psi\, b\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4163.95
	B_s	$\psi + \Xi^0\,(uss)$	4025.03
	B^+	$\psi + \Sigma^+\,(uus)$	4089.95
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\psi\, b\, u\, d$	B_d	$\psi + n\,(udd)$	4340.07
	B_s	$\psi + \Lambda\,(uds)$	4251.21
	B^+	$\psi + p\,(duu)$	4341.05
	Λ_b	$\bar{\psi} + \pi^0$	5484.5
$\psi\, b\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.76
	B_s	$\psi + \Omega_c\,(css)$	2671.69
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.36
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2
$\psi\, b\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.60
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.02
	B^+	$\psi + \Lambda_c\,(dcu)$	2992.86
	Λ_b	$\bar{\psi} + \overline{D}^0$	3754.7



$$\mathrm{Br}(\Lambda_b^0 \to \mathrm{Mesons} + \mathrm{DM})$$

Summary

- Baryogenesis is strong motivation for (new) CPV in heavy flavors
- Search for dark matter in B meson decays to Baryon+ X+ missing
- Baryogenesis with dark matter and no baryon # violation (similar to ‘hylogenesis’)
- Other model (with no dark matter): search for baryon violating heavy flavor baryon oscillations, baryon violating heavy flavor hadron decays, long lived fermion decaying to 3 quarks

Out of equilibrium late time decay

reheat to ~10 MeV

CP violating oscillations

$A_{\ell\ell}^d \quad A_{\ell\ell}^s$

B-mesons decay into Dark Matter and hadrons

Dark Matter

anti-Baryon

Baryon

$\mathrm{BR}(B \to \phi\xi + \mathrm{Baryon} + \ldots)$

Baryogenesis

$Y_B = 8.7 \times 10^{-11}$

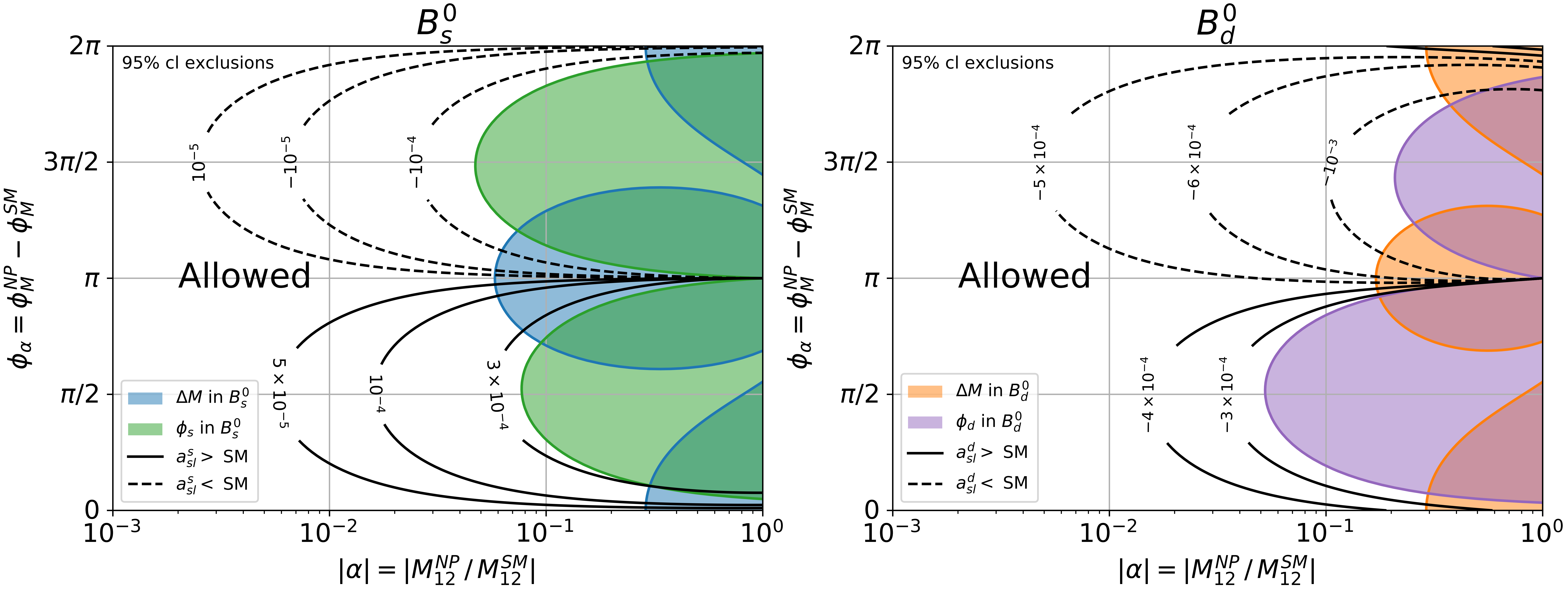
&

Dark Matter

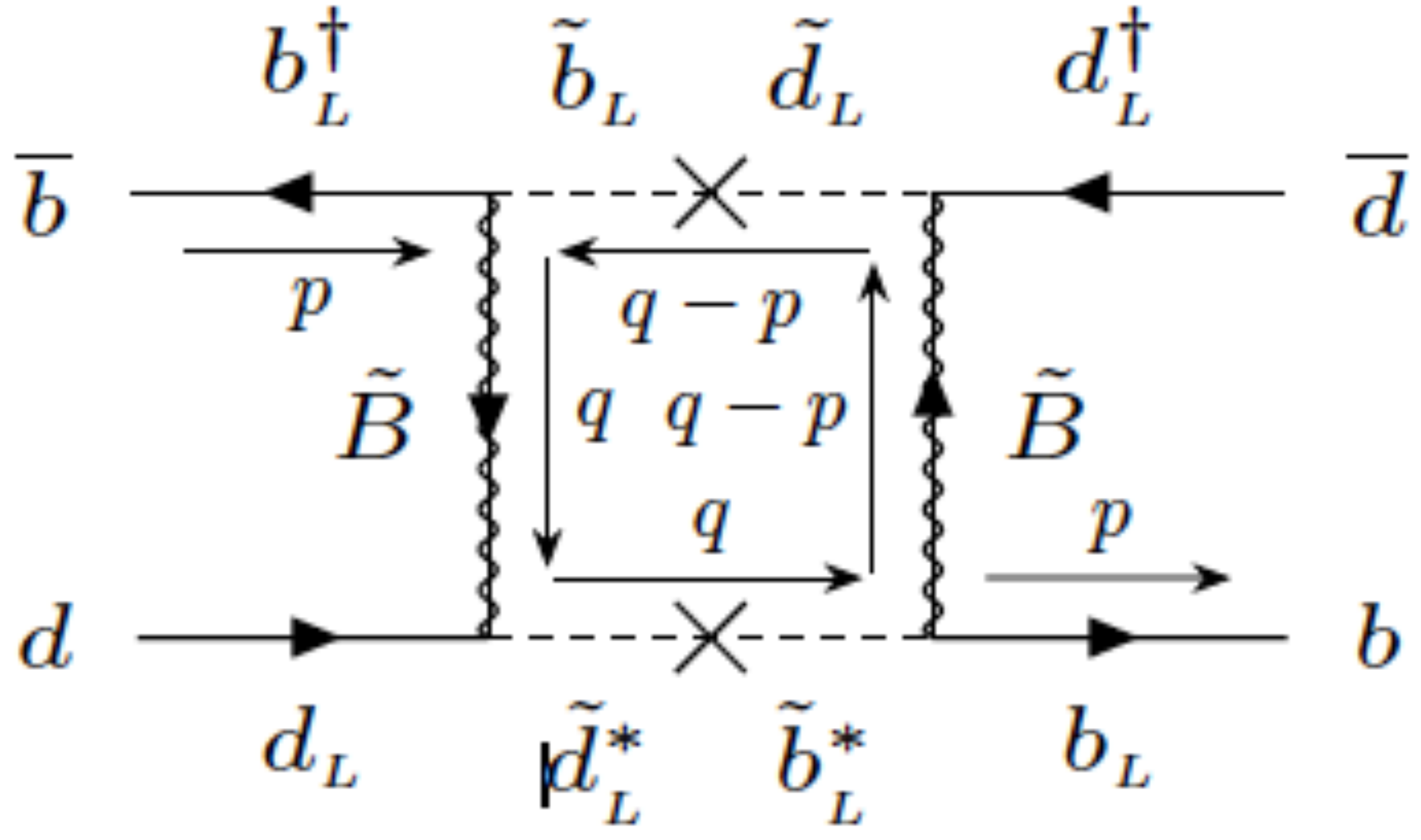
$\Omega_{\mathrm{DM}} h^2 = 0.12$

Backups

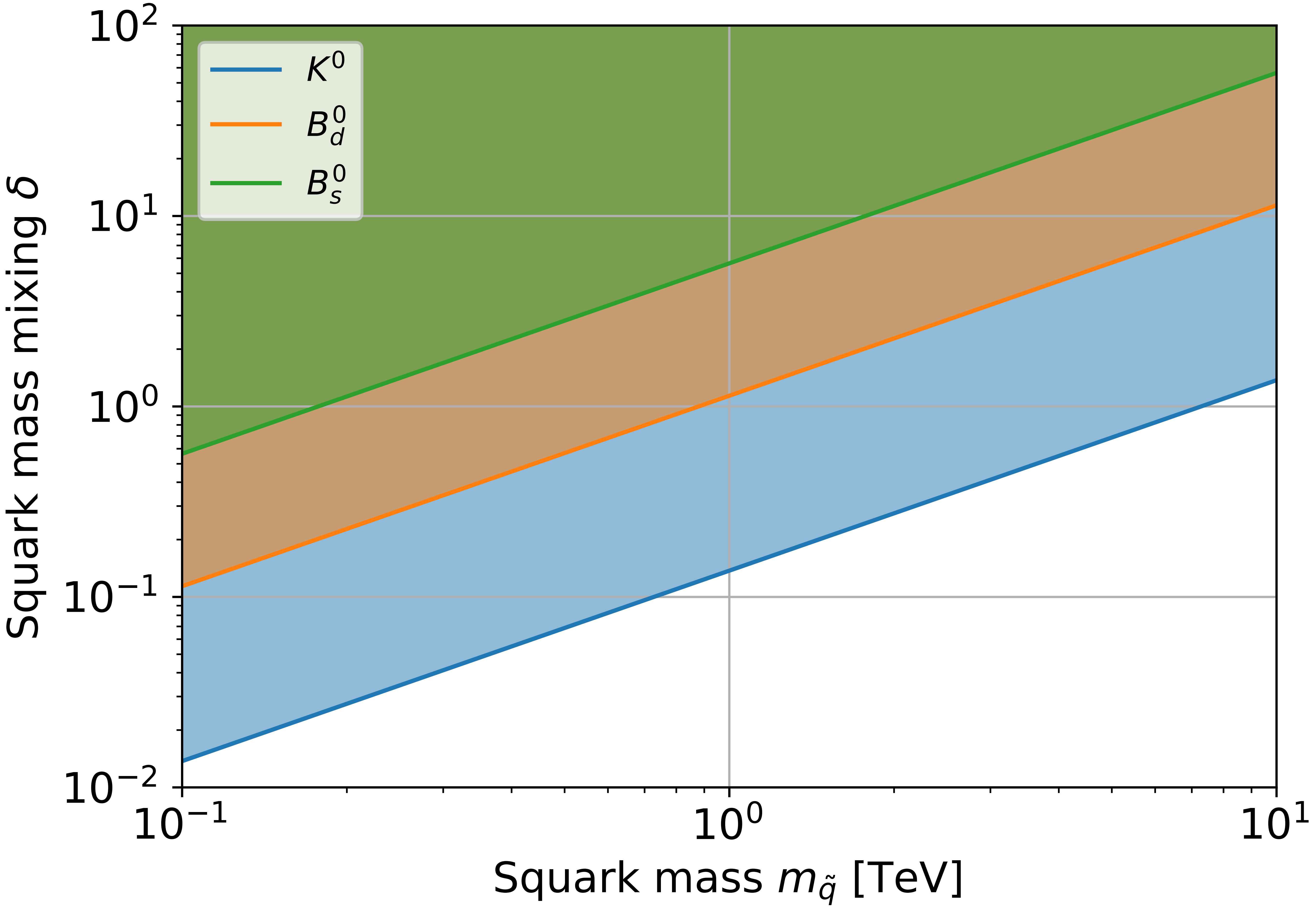
Constraints on semileptonic asymmetry



New contribution to CPV in B mixing



Flavor constraints on SUSY with light Dirac Bino



CPV in oscillations of unstable states

- Only requires 2 oscillating states
- Observed in neutral kaon anti-kaon and neutral B meson-anti-B meson oscillations
- Large effect possible when oscillation and decay rates comparable

$\mathcal{O}(1)$!

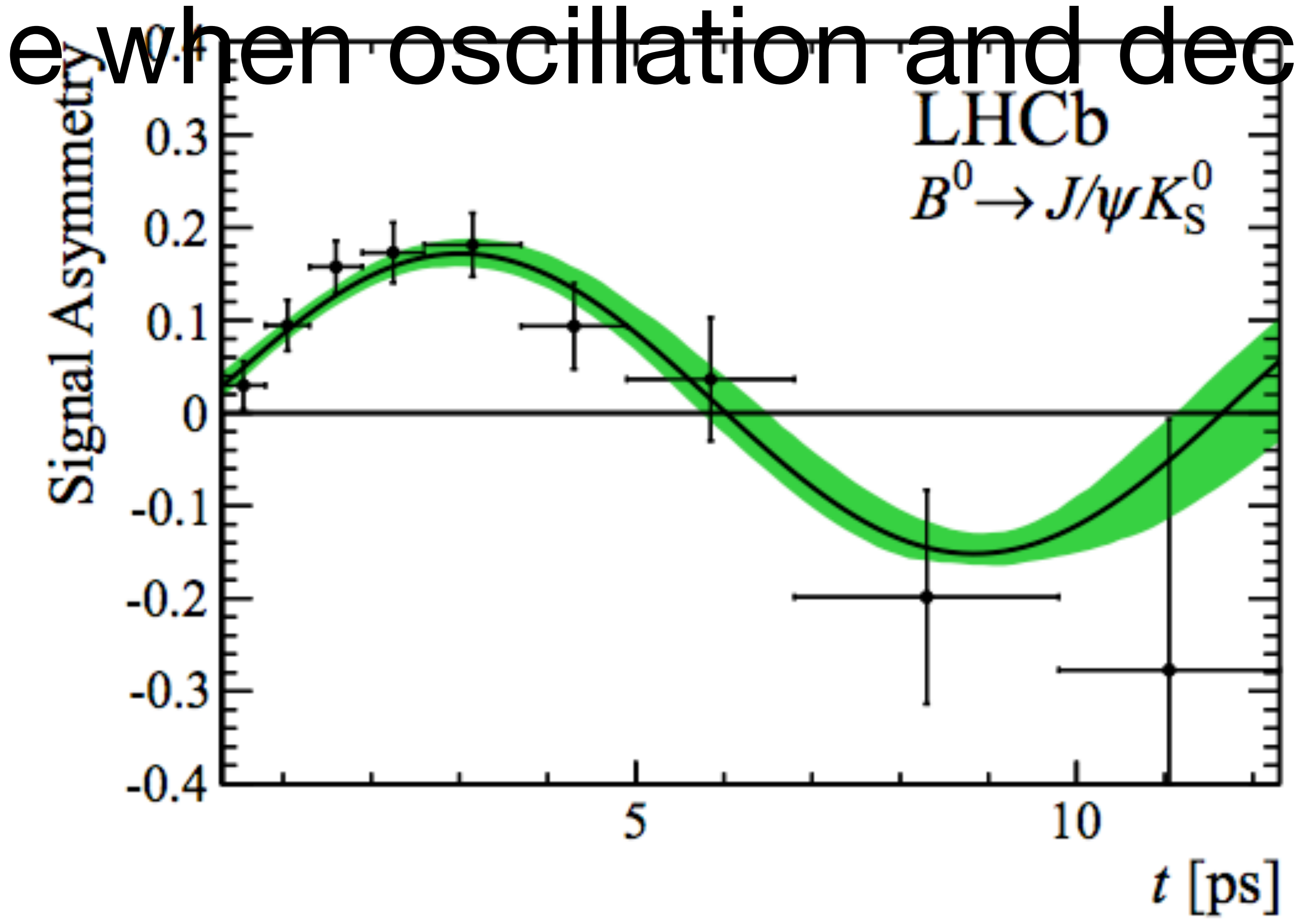
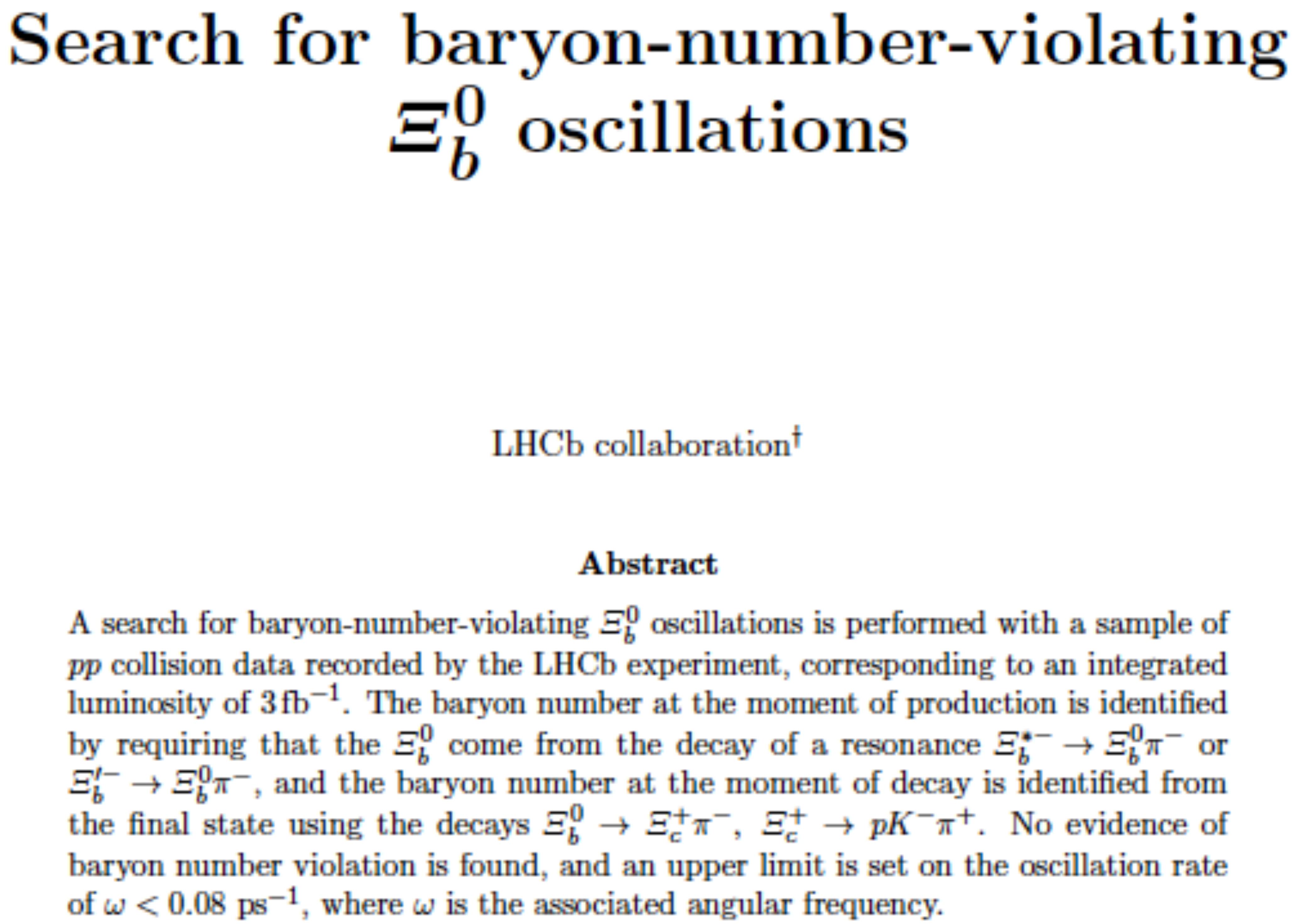


Figure 2: Time-dependent asymmetry $(N_{\overline{B}^0} - N_{B^0})/(N_{\overline{B}^0} + N_{B^0})$. Here, N_{B^0} ($N_{\overline{B}^0}$) is the number of $B^0 \to J/\psi K^0_S$ decays with a B^0 ($\overline{B}^0$) flavour tag. The data points are obtained with the *sPlot* technique, assigning signal weights to the events based on a fit to the reconstructed mass distributions. The solid curve is the signal projection of the PDF. The green shaded band corresponds to the one standard deviation statistical error.



Search for baryon-number-violating Ξ_b^0 oscillations

LHCb collaboration†

Abstract

A search for baryon-number-violating Ξ_b^0 oscillations is performed with a sample of *pp* collision data recorded by the LHCb experiment, corresponding to an integrated luminosity of 3 fb^{-1}. The baryon number at the moment of production is identified by requiring that the Ξ_b^0 come from the decay of a resonance $\Xi_b^{*-} \to \Xi_b^0 \pi^-$ or $\Xi_b^{\prime -} \to \Xi_b^0 \pi^-$, and the baryon number at the moment of decay is identified from the final state using the decays $\Xi_b^0 \to \Xi_c^+ \pi^-$, $\Xi_c^+ \to p K^- \pi^+$. No evidence of baryon number violation is found, and an upper limit is set on the oscillation rate of $\omega < 0.08$ ps^{-1}, where ω is the associated angular frequency.

0.08 ps^{-1}~5 x 10^{-14} GeV

Γ~4.5 x 10^{-13} GeV

(Dinucleon decay bound~ 10^{-10} GeV)

Possible Dark Sectors

$$\langle\sigma v\rangle_{\text{dark}} \simeq 25\,\langle\sigma v\rangle_{\text{WIMP}}\ \min[m_\phi, m_\xi]/\text{GeV}$$

- Annihilation into sterile neutrinos (massive, SM singlets)

Add dark sector particles charged under Lepton number

$$m_\xi > m_\phi$$

$$\mathcal{L} \quad \subset \quad y_N\,\phi\bar{\Psi}N_R + \text{h.c.}$$

$$\langle\sigma\,v\rangle_{\phi^\star\phi\to NN} \;=\; y_N^4\,\frac{m_N^2}{8\pi m_{\Psi'}^4}\left[1+\frac{m_\phi^2}{6m_N^2}v^2\right]$$

$$m_\phi > m_\xi$$

$$\mathcal{L} \quad \subset \quad y_N\,\xi\Phi^{'}N_R + \text{h.c.}$$

$$\langle\sigma\,v\rangle_{\xi\xi\to NN} \;=\; y_N^4\,\frac{m_N^2}{32\pi m_{\Phi'}^4}\left[1+\frac{2m_\xi^2}{3m_N^2}v^2\right]$$

Note: s-wave suppressed cross sections so that CMB constraints are alleviated.

Make sterile neutrino very heavy and we can consider annihilation to SM neutrinos (through mixing). But we do not expect a detectable signal given the required annihilation rate.

Possible Dark Sectors

$$\langle \sigma v \rangle_{\text{dark}} \simeq 25 \, \langle \sigma v \rangle_{\text{WIMP}} \; \min[m_\phi, m_\xi]/\text{GeV}$$

- Additional dark sector states carrying baryon number $B = 1/3$

$$\mathcal{L} \;\supset\; \kappa \, \phi \mathcal{A}^3 + \kappa' \, \phi \phi^* \mathcal{A} \mathcal{A}^* \;+\; \text{h.c.} \qquad \phi + \phi^* \leftrightarrow \mathcal{A} + \mathcal{A}^*$$

$$\Omega_{\text{DM}}/\Omega_b = 5.36 \qquad \longrightarrow \qquad m_{\mathcal{A}} \sim \frac{5}{3} m_p \sim 1.6 \, \text{GeV}$$

Example Model

MSSM, R Symmetry, and Dirac Gauginos

GE with A. Nelson, G. Alvarez, and H. Xiao (in progress)

Superpartners and SM particles have different charge under an unbroken R-symmetry. We can identify this with Baryon number. → Superpartners as dark baryons.

Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
Φ	0	0	0	$+1$	$11 - 100\,\mathrm{GeV}$
Y	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
ψ	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
ξ	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

Example Model

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	Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
	Φ	0	0	0	$+1$	$11-100\,\mathrm{GeV}$
MSSM Squark	$\tilde{d}_R$	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
	ψ	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
	ξ	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
	ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

Example Model

MSSM, R Symmetry, and Dirac Gauginos

GE with A. Nelson, G. Alvarez, and H. Xiao (in progress)

Superpartners and SM particles have different charge under an unbroken R-symmetry. We can identify this with Baryon number. → Superpartners as dark baryons.

	Field	Spin	Q_{EM}	Baryon no.	$\mathbb{Z}_2$	Mass
	Φ	0	0	0	$+1$	$11 - 100\,\mathrm{GeV}$
MSSM Squark	$\tilde{d}_R$	0	$-1/3$	$-2/3$	$+1$	$\mathcal{O}(\mathrm{TeV})$
Dirac Bino	$\begin{bmatrix}\tilde{B}\\ \lambda_s^\dagger\end{bmatrix}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
	ξ	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
	ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

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Dirac Bino	$\begin{bmatrix}\tilde{B}\\ \lambda_s^\dagger\end{bmatrix}$	$1/2$	0	-1	$+1$	$\mathcal{O}(\mathrm{GeV})$
New dark sector chiral multiplet	ξ	$1/2$	0	0	-1	$\mathcal{O}(\mathrm{GeV})$
	ϕ	0	0	-1	-1	$\mathcal{O}(\mathrm{GeV})$

Details of SUSY Embedding

Want SUSY embedding of:

$$\mathcal{L} \subset -y_{ub} Y^* \bar{u} b^c - y_{\psi s} Y \bar{\psi} s^c + \text{h.c.} \quad \text{and} \quad \mathcal{L} \subset -y_d \bar{\psi}\phi\xi$$

- Y/Squark-Quark Couplings:

$$\begin{aligned} W = {} & y_u \mathbf{Q}\mathbf{H}_u\mathbf{U}^c - y_d \mathbf{Q}\mathbf{H}_d\mathbf{D}^c - y_e\mathbf{L}\mathbf{H}_d\mathbf{E}^c + \mu_u \mathbf{H}_u\mathbf{R}_d + \mu_d\mathbf{R}_u\mathbf{H}_d \\ & + \lambda_u^t \mathbf{H}_u\mathbf{T}\mathbf{R}_d + \lambda_d^t\mathbf{R}_u\mathbf{T}\mathbf{H}_d + \lambda_d^s \mathbf{S}\mathbf{R}_u\mathbf{H}_d \\ & + \frac{1}{2}\lambda''_{ijk}\mathbf{U}^c_i\mathbf{D}^c_j\mathbf{D}^c_k \longrightarrow \mathcal{L} \supset \lambda''_{113}\left(\tilde{d}_R^* u_R^\dagger b_R^\dagger + \tilde{u}_R^* d_R^\dagger b_R^\dagger + \tilde{b}_R^* u_R^\dagger d_R^\dagger\right) \end{aligned}$$

- Y/Squark-Quark-Dirac Gaugino: from usual gauge interaction

$$\begin{aligned} \mathcal{L}_{\text{gauge}} \supset {} & -\sqrt{2}g(\phi T^a \psi^\dagger)\lambda^{a\dagger} + \text{h.c.} \\ \Rightarrow {} & -\sqrt{2}g(\tilde{d}_R d_R^\dagger \tilde{B}^\dagger) \end{aligned}$$

- Dark Matter: $W \supset \int \mathrm{d}^2\theta \, (y_s \mathbf{S}\mathbf{\Phi}\mathbf{\Phi} + m_\Phi \mathbf{\Phi}\mathbf{\Phi})$

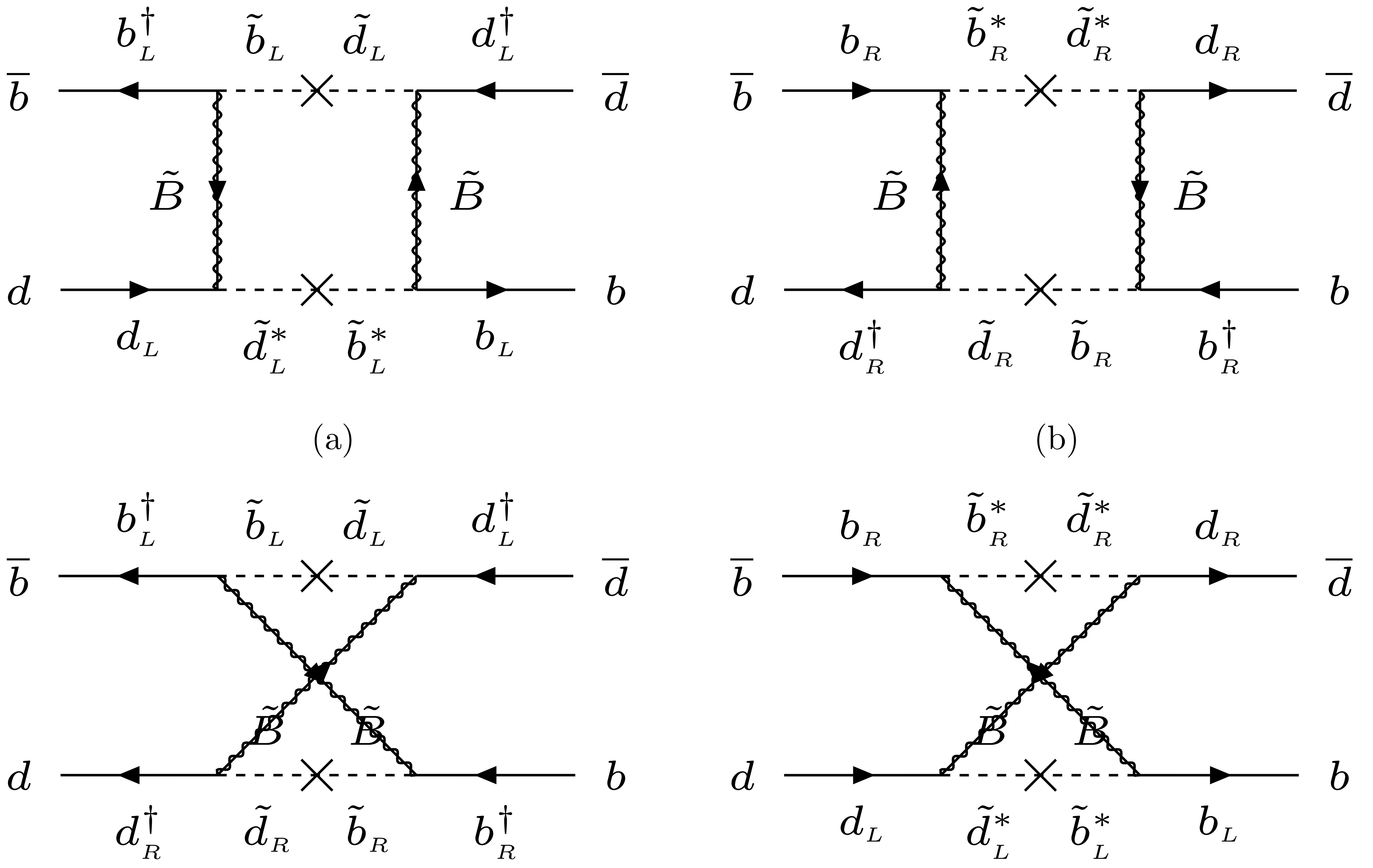
$$\mathbf{\Phi} = \phi^* + \sqrt{2}\theta^\alpha \xi_\alpha + \theta^2 F_\Phi$$

$$\mathbf{S}(y^\mu) = \phi_s + \sqrt{2}\lambda_s^\alpha \theta_\alpha + \theta^\alpha\theta_\alpha F_s$$

Model: MSSM + R Symmetry + Dirac Gauginos

GE with A. Nelson, G. Alvarez, and H. Xiao (to appear)

- Contribution to oscillation asymmetry:



(a) (b)

Collider Constraints

- Collider searches $\mathrm{Br}(B \to \xi\phi + \mathrm{Baryon}) = 10^{-4} - 10^{-2}$

$$\mathcal{L} \supset -g_{us} Y^\star \bar{u} s^c - y_{\psi b} Y \bar{\psi} b^c + \mathrm{h.c.}$$

$$\Gamma_{b\to\phi\xi\bar{u}\bar{d}} \sim \frac{m_b \Delta m^4}{60(2\pi)^3}\left(\frac{g_{ud} y_{\psi b}}{m_Y^2}\right) \simeq 2\times 10^{-15}\,\mathrm{GeV}\left(\frac{m_b - m_\psi}{2\,\mathrm{GeV}}\right)^4 \left(\frac{1.2\,\mathrm{TeV}}{m_Y/\sqrt{y_{\psi b} g_{ud}}}\right)^4$$

$$\mathrm{Br}(B \to \xi\phi + \mathrm{Baryon}) \simeq 6\times 10^{-3}\left(\frac{\Delta m}{2\ \mathrm{GeV}}\right)^4 \left(\frac{1.2\ \mathrm{TeV}}{m_Y/\sqrt{g_{us} y_{\psi b}}}\right)^4$$

$Y \to b\psi$ sbottom searches directly apply

$Y \to \bar{u} s$ Y searched for in dijet resonances

➡ $1.2\,\mathrm{TeV} < m_Y < 7\,\mathrm{TeV}$

Parameters

Parameter	Description	Range	Benchmark Value	Constraint?
m_Φ	Inflaton mass	$11 - 100$ GeV	15 GeV	$\rho_\Phi/\rho_{\rm rad} < 10^{-3}$ at $T = 3.5\,\text{MeV}$
Γ_Φ	Inflaton width	$10^{-21} > \Gamma_\Phi/\text{GeV} > 10^{-21}$	10^{-22} GeV	Decay between $3.5\,\text{MeV} < T < 50\,\text{MeV}$
m_ψ	Dirac fermion mediator	$1.5\,\text{GeV} < m_\psi < 4.4\,\text{GeV}$	3.3 GeV	Lower limit from $m_\psi > m_\phi + m_\xi$
m_ξ	Majorana dark matter	$0.3\,\text{GeV} < m_\xi < 3.1\,\text{GeV}$	1.0 and 1.8 GeV	$\lvert m_\xi - m_\phi\rvert < m_p - m_e$
m_ϕ	Scalar dark matter	$1.2\,\text{GeV} < m_\phi < 4\,\text{GeV}$	1.5 and 1.3 GeV	$\lvert m_\xi - m_\phi\rvert < m_p - m_e$
y_d	Yukawa for $L = y_d \phi \xi \psi$		0.3	
$\text{Br}(B \to \xi\phi)$	Br of $B \to \text{ME} + \text{Baryon}$	$10^{-2} - 10^{-5}$	1×10^{-4}	Is there any?
$A_{\ell\ell}^d$	Lepton Asymmetry B_d	Positive and $< 10^{-3}$	0	$A_{\ell\ell}^d = -0.0021 \pm 0.0017$ [8]
$A_{\ell\ell}^s$	Lepton Asymmetry B_s	Positive and $< 5 \times 10^{-3}$	10^{-3}	$A_{\ell\ell}^s = -0.0006 \pm 0.0028$ [8]
$\langle\sigma v\rangle_\phi^{\rm SM}$	Annihilation Xsec for ϕ		$4.4 \times 10^{-25}\,\text{cm}^3/s$	
$\langle\sigma v\rangle_\xi^{\rm SM}$	Annihilation Xsec for ξ		$2.1 \times 10^{-22} \times v^2\,\text{cm}^3/s$	

- Limit on inflation width comes from living in a regime where we can neglect B oscillations compared to decays

$$\frac{\Delta n_B \Gamma_B}{\Delta n_B^2 \langle\sigma v\rangle} = \frac{\Gamma_B^2}{\Gamma_\Phi \langle\sigma v\rangle n_\Phi(t)} \frac{1}{\text{Br}_{\Phi\to B}}$$

- We assume no decoherence between B mesons and the plasma. For instance elastic scattering rate for $e^\pm B_0 \to e^\pm B_0$

$$\Gamma \equiv \langle\sigma v\rangle n_e \simeq \sigma(E = 3T)\, n_e(T) \sim 3 \times 10^{-13}\,\text{GeV} \left(\frac{T}{10\,\text{MeV}}\right)^5 \left(\frac{\langle r_{B_0}^2\rangle}{0.187}\right)^2$$

Will be higher then Hubble Rate: $H \sim 4 \times 10^{-17} \left(\frac{T}{10\,\text{MeV}}\right)^2$ GeV

Dark Matter Cross Sections

$$\sigma v_{\phi^\star \phi \to \xi\xi} = \frac{y_d^4 \left(m_\xi + m_\psi\right)^2 \left(m_\phi^2 \left(m_\phi - m_\xi\right)\left(m_\xi + m_\phi\right)\right)^{3/2}}{2\pi m_\phi^6 \left(-m_\xi^2 + m_\psi^2 + m_\phi^2\right)^2}$$

$$\begin{aligned}\sigma v_{\xi\xi \to \phi^\star \phi} = {}& \frac{v^2 y_d^4 \left(m_\xi - m_\phi\right)\left(m_\xi + m_\phi\right)}{48\pi \sqrt{m_\xi^4 - m_\xi^2 m_\phi^2} \left(m_\xi^2 + m_\psi^2 - m_\phi^2\right)^4} \left[6 m_\xi m_\psi^5 + m_\psi^4 \left(9 m_\xi^2 - 6 m_\phi^2\right)\right. \\ & + 8 m_\xi m_\psi^3 \left(m_\xi^2 - m_\phi^2\right) + m_\psi^2 \left(-8 m_\xi^2 m_\phi^2 + 5 m_\xi^4 + 3 m_\phi^4\right) \\ & \left. + 2 m_\xi m_\psi \left(m_\phi^2 - m_\xi^2\right)^2 + 3 \left(m_\xi^3 - m_\xi m_\phi^2\right)^2 + 3 m_\psi^6\right]\end{aligned}$$

$$\sigma v_{\xi\xi \to \phi^\star \phi}\big|_{m_\phi = 0} = \frac{v^2 y_d^4 \left(2 m_\xi^5 m_\psi + 5 m_\xi^4 m_\psi^2 + 8 m_\xi^3 m_\psi^3 + 9 m_\xi^2 m_\psi^4 + 6 m_\xi m_\psi^5 + 3 m_\xi^6 + 3 m_\psi^6\right)}{48\pi \left(m_\xi^2 + m_\psi^2\right)^4}$$