B-Mesogenesis: Baryogenesis and Dark Matter from B Mesons

Miguel Escudero Abenza
miguel.escudero@tum.de

Based on:

arXiv:1810.00880, PRD 99, 035031 (2019)
with: Gilly Elor & Ann Nelson
arXiv:2101.02706
with: Gonzalo Alonso-Álvarez & Gilly Elor

Munich Dark Matter Meeting
24-02-2021

Unterstützt von / Supported by
Alexander von Humboldt
Stiftung / Foundation

B-Mesogenesis: Baryogenesis and Dark Matter from B Mesons

arXiv:1810.00880 Elor, Escudero & Nelson

1) **Baryogenesis and Dark Matter are linked**

2) **Baryon asymmetry directly related to B-Meson observables**

3) **Leads to unique collider signatures**

4) **Fully testable at current collider experiments**

arXiv:2101.02706 Alonso-Álvarez, Elor & Escudero

Precision Cosmology

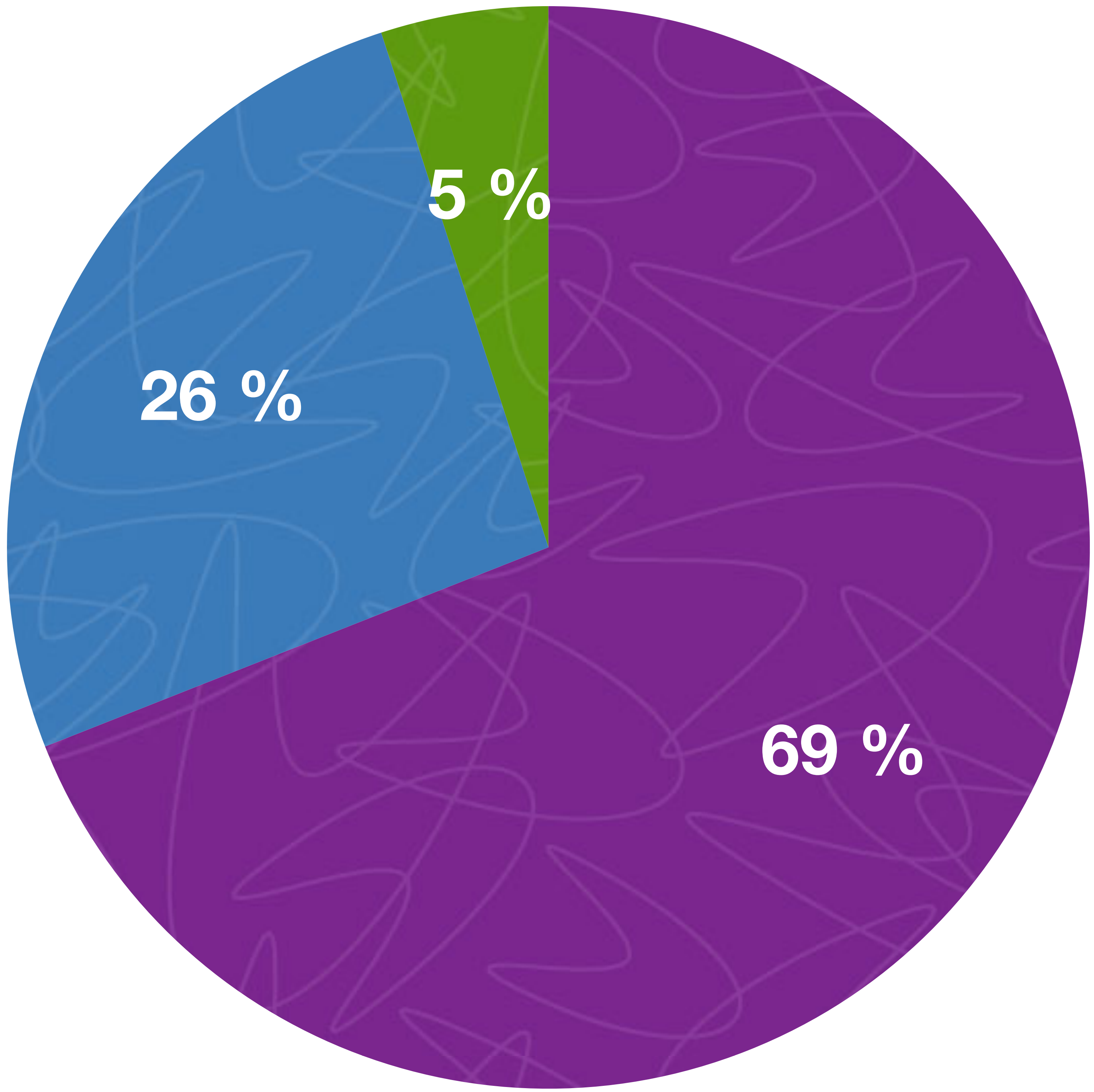
Planck 2018 1807.06209

$$\Omega_b h^2 = 0.02237(15)$$

Baryonic Matter

Dark Matter

$$\Omega_{\rm cdm} h^2 = 0.1200(12)$$



Dark Energy

$$\Omega_\Lambda = 0.6847(73)$$

Theoretical Understanding?

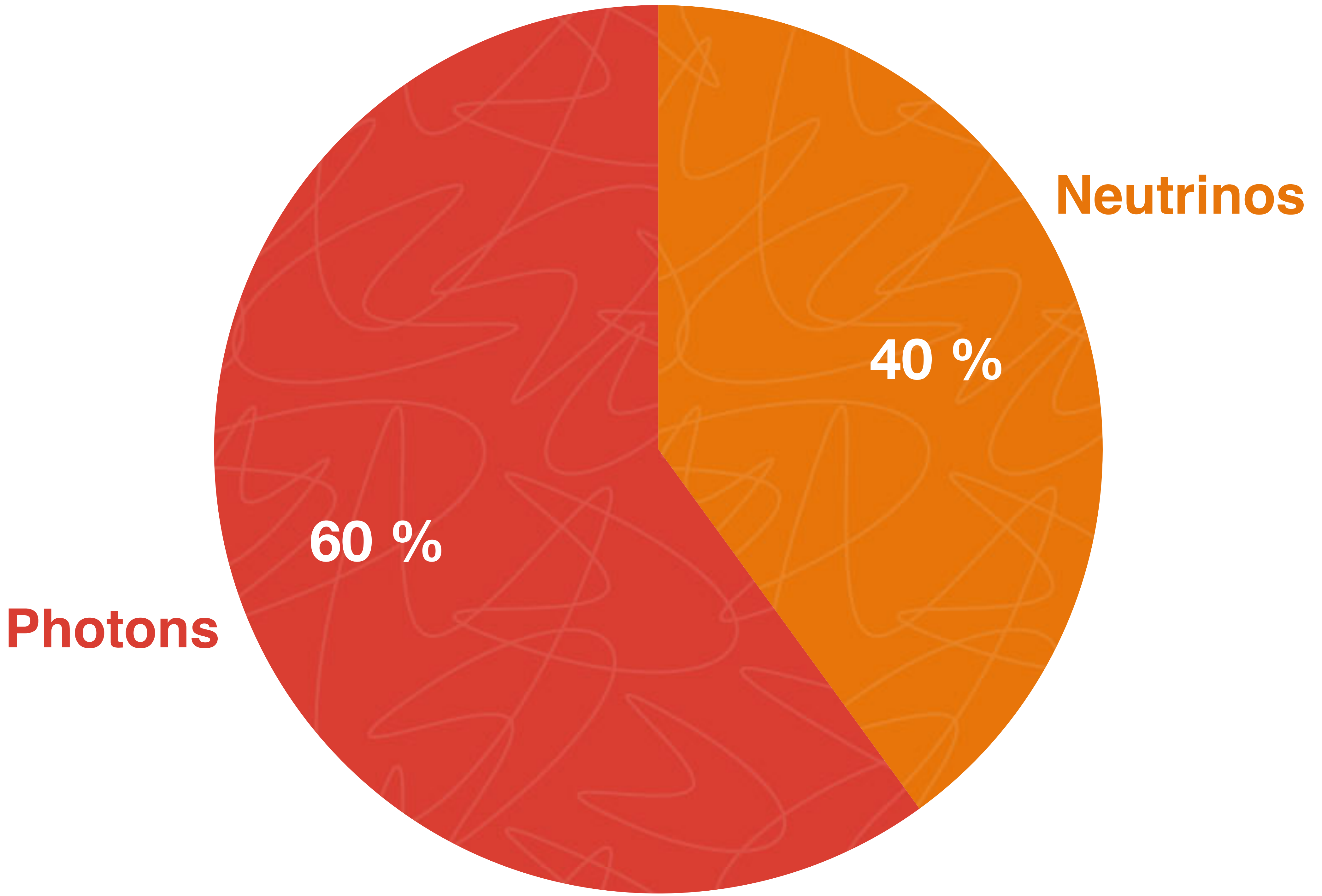
Motivating Question:

What fraction of the Energy Density of the Universe comes from Physics Beyond the Standard Model?

99.85%!

Standard Model Prediction:

We should be living in a Radiation Dominated Universe!



Theoretical Understanding?

Dark Energy Current data is consistent with a Cosmological constant

Dark Matter
The CMB anisotropies clearly motivate a particle description
Many candidates: WIMPS, Axions, Sterile Neutrinos ...
Existing experimental constraints on the various possibilities

Baryons
We observe a Universe with only matter and no antimatter
Small number of Baryons per photon point towards a primordial asymmetry:

$$\frac{n_B}{n_\gamma} = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6 \times 10^{-10}$$ **CMB & BBN**

Outline

1) B-Mesogenesis
   1) C/CP violation
   2) Out of equilibrium
   3) Baryon number violation?

2) A Minimal Model & Cosmology

3) Implications for Collider Experiments

4) Dark Matter Phenomenology

5) Summary and Outlook

Baryogenesis

The Three Sakharov Conditions (1967):

1) C and CP violation

2) Out of equilibrium

3) Baryon number violation

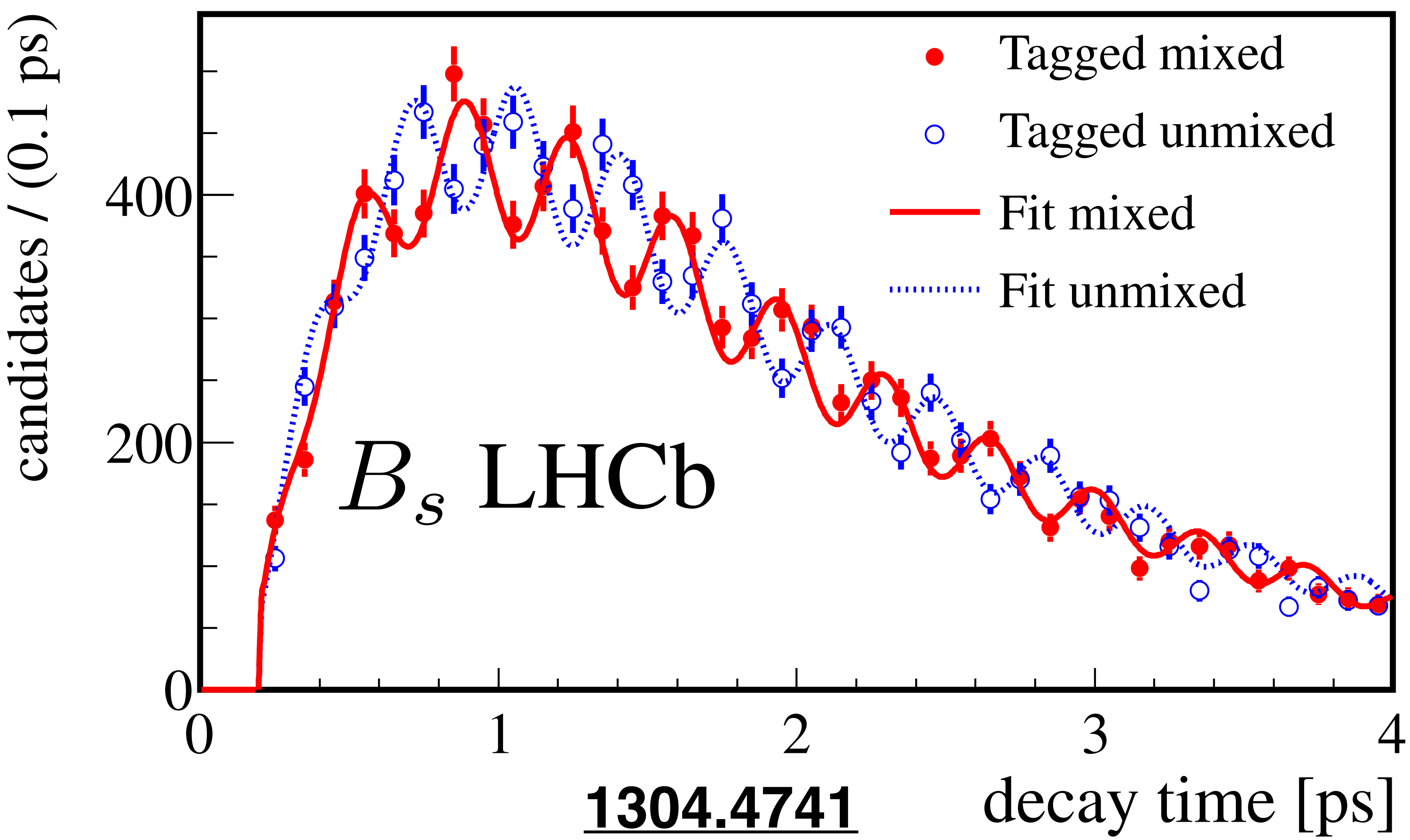
Baryogenesis from B Mesons

1) C and CP violation

Neutral and CP violating oscillating systems in the SM:

Kaons and D mesons cannot decay into baryons $m_{K^0} < 2m_p$ $m_{D^0} < 2m_p$

Neutral B Mesons are the perfect system: $m_B \simeq 5.3\,\mathrm{GeV}$

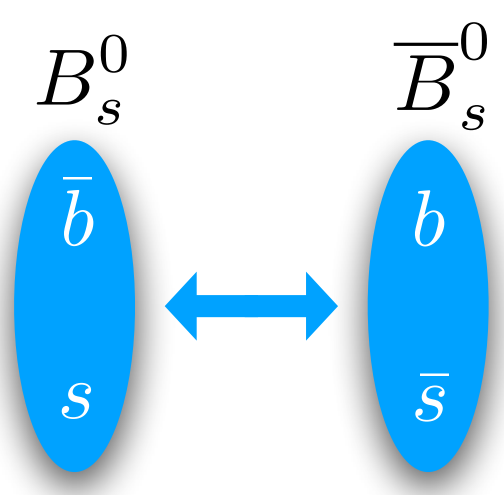


1304.4741

$\tau_B = 1.52\,\mathrm{ps}$

$t_{\mathrm{osc}}/\tau_B|_{\mathrm{B_s}} = 8.56$

$t_{\mathrm{osc}}/\tau_B|_{\mathrm{B_d}} = 0.24$



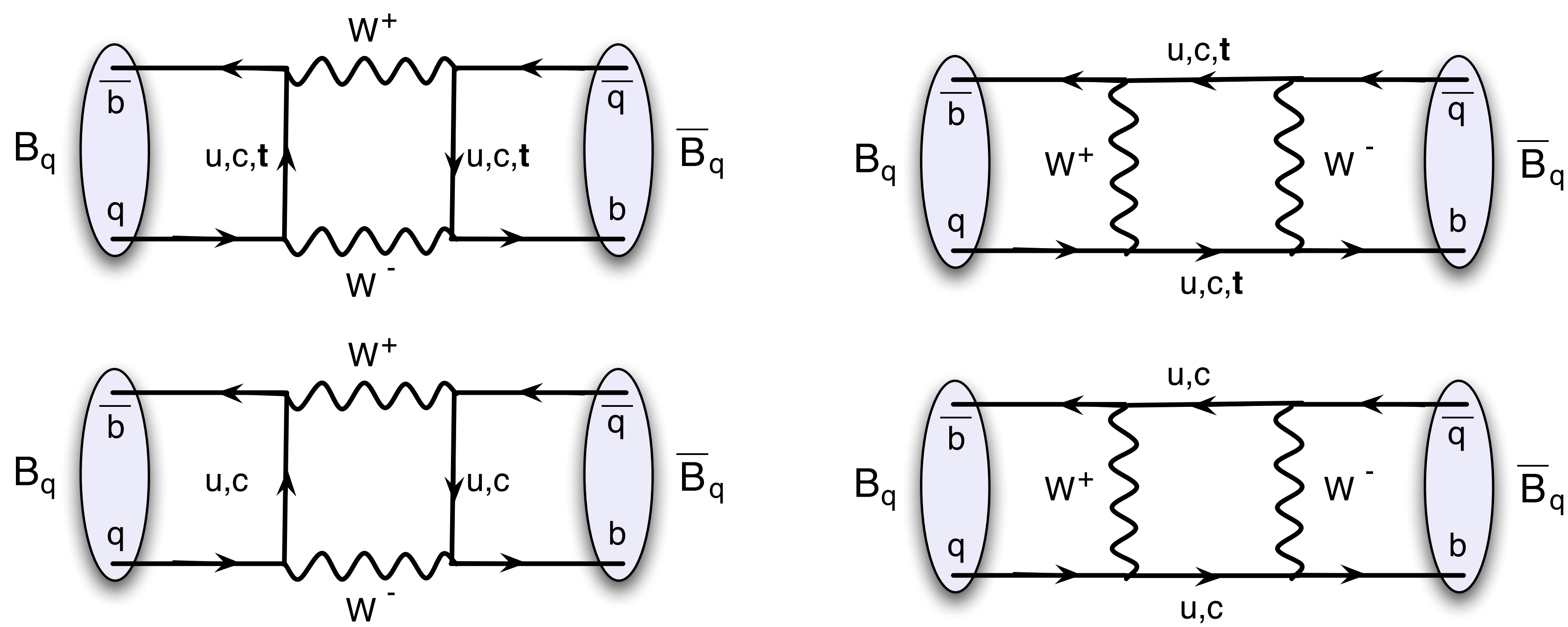
Baryogenesis from B Mesons

1) CP violation in the Meson System

SM: Box Diagrams

$M_{12} \propto$

$\Gamma_{12} \propto$



CP violating mixing requires a relative phase between Γ_{12} and M_{12}

BSM?

***Z′* models (even at tree level), Leptoquarks etc ...**

see *e.g.* Nir 9911321

Baryogenesis from B Mesons

CP violation in the neutral B-meson system

The key quantity: the semileptonic asymmetry,

$$A_{\rm SL}^q = {\rm Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right) = \frac{\Gamma(\overline{B}_q^0 \to B_q^0 \to f) - \Gamma(B_q^0 \to \overline{B}_q^0 \to \bar{f})}{\Gamma(\overline{B}_q^0 \to B_q^0 \to f) + \Gamma(B_q^0 \to \overline{B}_q^0 \to \bar{f})}$$

Standard Model

Lenz & Tetlalmatzi-Xolocotzi 1912.07621

$$A_{\rm SL}^d|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$$

$$A_{\rm SL}^s|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$$

small because ($m_b/m_t)^2$ is small

Measurements

$$A_{\rm SL}^d = (-2.1 \pm 1.7) \times 10^{-3}$$

$$A_{\rm SL}^s = (-0.6 \pm 2.8) \times 10^{-3}$$

World averages (HFLAV)

- **Plenty of BSM models that can enlarge the asymmetries up to 10^{-3}: SUSY, Extradim, LR, 2HDM, new generations, Leptoquarks, Z' models (see e.g. 1511.09466, 1402.1181).**

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

- **Require the presence of an out of equilibrium particle that dominates the energy density of the Universe and reheats it to a temperature of**

$$T_{RH} = \mathcal{O}(10\,\mathrm{MeV})$$

- **This particle should be very weakly coupled, with lifetimes**

$$\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$$

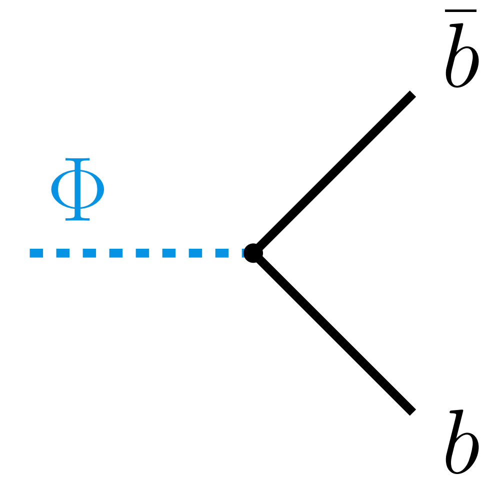
- **The decays don't spoil BBN or the CMB provided** $T_{RH} > 5\,\mathrm{MeV}$

de Salas *et al*. 1511.00672
Hasegawa *et al*. 1908.10189

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

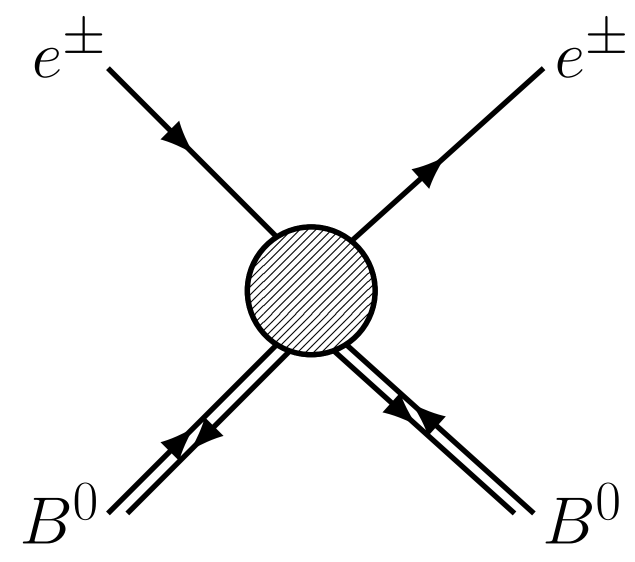
- **Scalar particle with** $M_\Phi \in 11 - 100\,\mathrm{GeV}$ **and** $\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$ **generically decays into b-quarks**



- **b-quarks hadronize at** $T < T_{\mathrm{QCD}} \sim 200\,\mathrm{MeV}$

- **Coherent oscillations in the B⁰ system are maintained in the early Universe for temperatures:**

$$T \lesssim 20\,\mathrm{MeV}$$



Baryogenesis and DM from B Mesons

3) Baryon number violation?

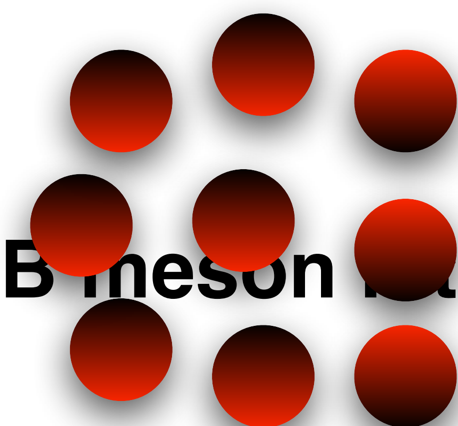
- **Baryon number is conserved in our scenario:** $\Delta B = 0$

  In a similar spirit to *Hylogenesis* by Davoudiasl, Morrissey, Sigurdson, Tulin 1008.2399

- **We make Dark Matter an anti-Baryon and generate an asymmetry between the two sectors thanks to the CP violating oscillations and subsequents decays of B-mesons.**

- **Require a new decay mode of the B meson into DM and a visible Baryon!**

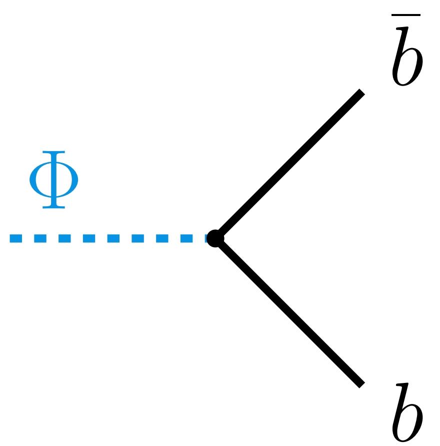
Visible Sector (Baryons)



Dark Sector (anti-Baryons)

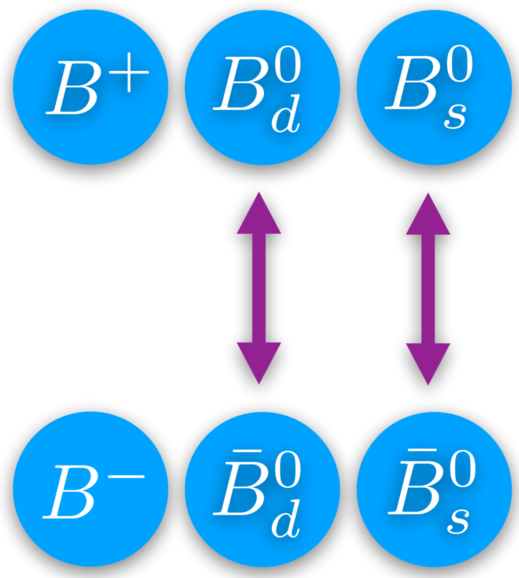
A Summary of the Mechanism

Out of equilibrium late time decay



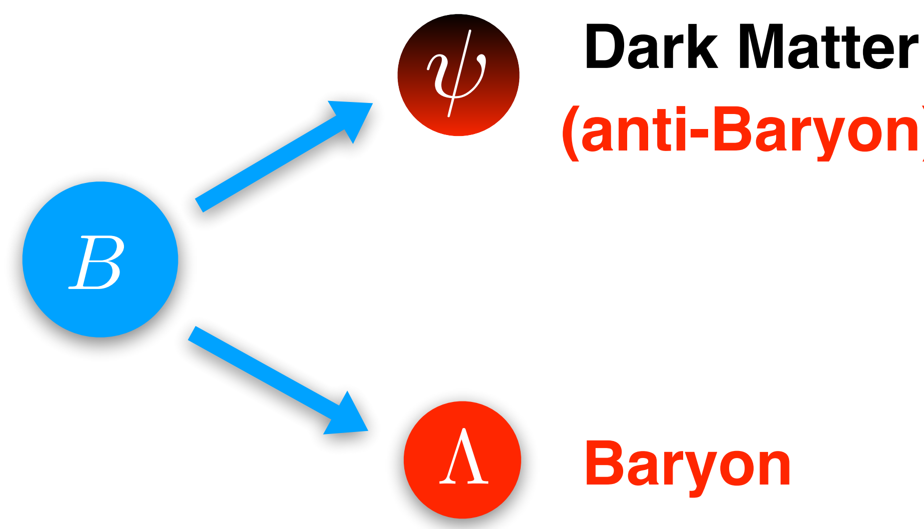
$T_R \sim 15\,\mathrm{MeV}$

CP violating oscillations



$A_{\mathrm{SL}}^d \;\; A_{\mathrm{SL}}^s$

B-mesons decay into Dark Matter and hadrons



$\mathrm{Br}\left(B \to \psi + \mathcal{B} + \mathcal{M}\right)$

Baryogenesis and **Dark Matter**

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

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

With:

$$Y_B \simeq 8.7 \times 10^{-11} \, \frac{\mathrm{Br}(B \to \psi + \mathcal{B} + \mathcal{M})}{10^{-2}} \sum_q \alpha_q \, \frac{A_{\mathrm{SL}}^q}{10^{-4}}$$

New B-Meson decay

$$\mathcal{L} \supset -y_{ub}\, Y^* \,\bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c}$$

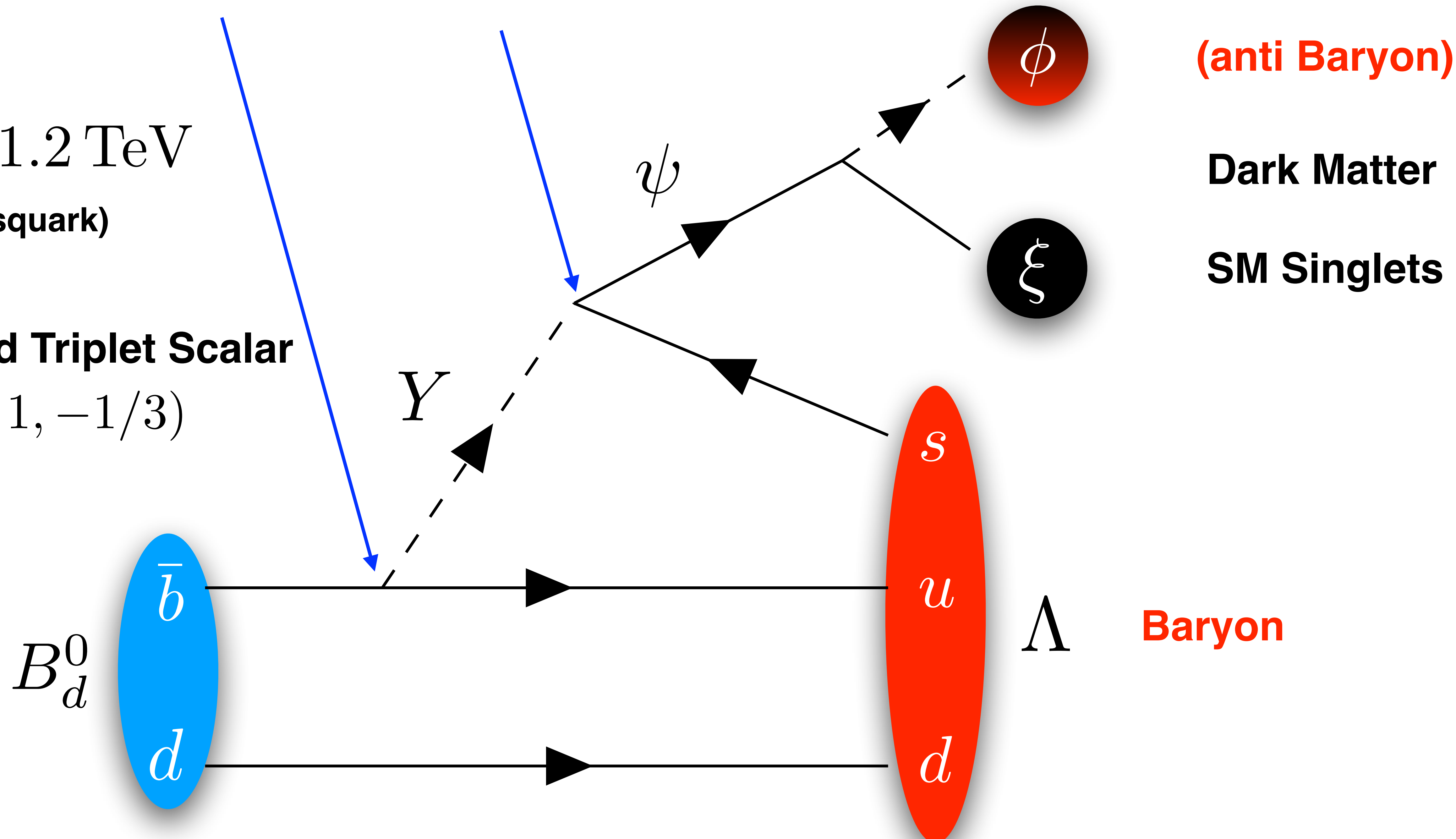
$$1\,\text{GeV} \lesssim m_{\phi,\xi} \lesssim 2.5\,\text{GeV}$$

$$M_Y > 1.2\,\text{TeV}$$

(4-jet/squark)

Y: Colored Triplet Scalar

$$Y \sim (3, 1, -1/3)$$



$$\text{Br}\,(B \to \psi + \text{Baryon} + \mathcal{M}) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\,\text{GeV}}\right)^4 \left(\frac{1.6\,\text{TeV}}{M_Y}\,\frac{\sqrt{y_{ub} y_{\psi s}}}{0.6}\right)^4$$

The Boltzmann Equations

Universe's Evolution

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

Late time Decay and Radiation

$$\frac{dn_\Phi}{dt} + 3Hn_\Phi = -\Gamma_\Phi n_\Phi$$

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

DM evolution

$$\frac{dn_\xi}{dt} + 3Hn_\xi = -\langle\sigma v\rangle_\xi \left(n_\xi^2 - n_{{\rm eq},\xi}^2\right) + 2\,\Gamma_\Phi^B\, n_\Phi \qquad \Gamma_\Phi^B = \Gamma_\Phi \times {\rm Br}\left(B \to \psi + {\rm Baryon} + \mathcal{M}\right)$$

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

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

Baryon asymmetry:

$$n_\mathcal{B} = n_\phi - n_{\phi^\star}$$

$$\frac{n_\mathcal{B}}{dt} + 3Hn_\mathcal{B} = 2\Gamma_\Phi n_\Phi \sum_q {\rm Br}\left(\bar b \to B_q^0\right) f_{\rm deco}^q\, A_{\rm SL}^q\, {\rm Br}\left(B \to \psi + {\rm Baryon} + \mathcal{M}\right)$$

- **Baryon asymmetry directly related to the CP violation in the B^0 system and to the new decay of B mesons to a visible Baryon and missing energy.**
- **We take into account the decoherence of the B^0 system in the early Universe.**

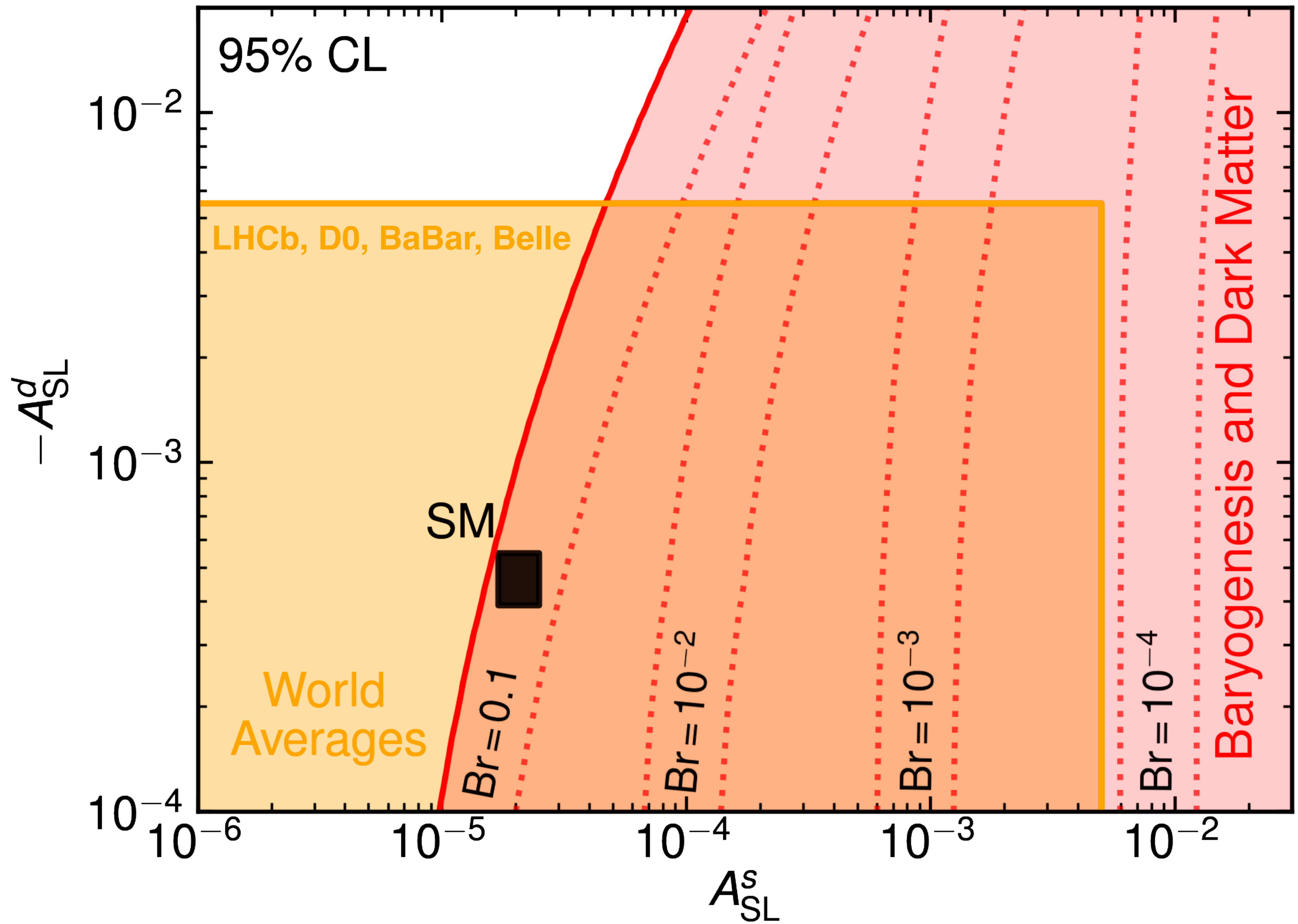
Collider Signatures

1) CP violation in B Meson decays

2) New B Meson decay into ME and a Baryon

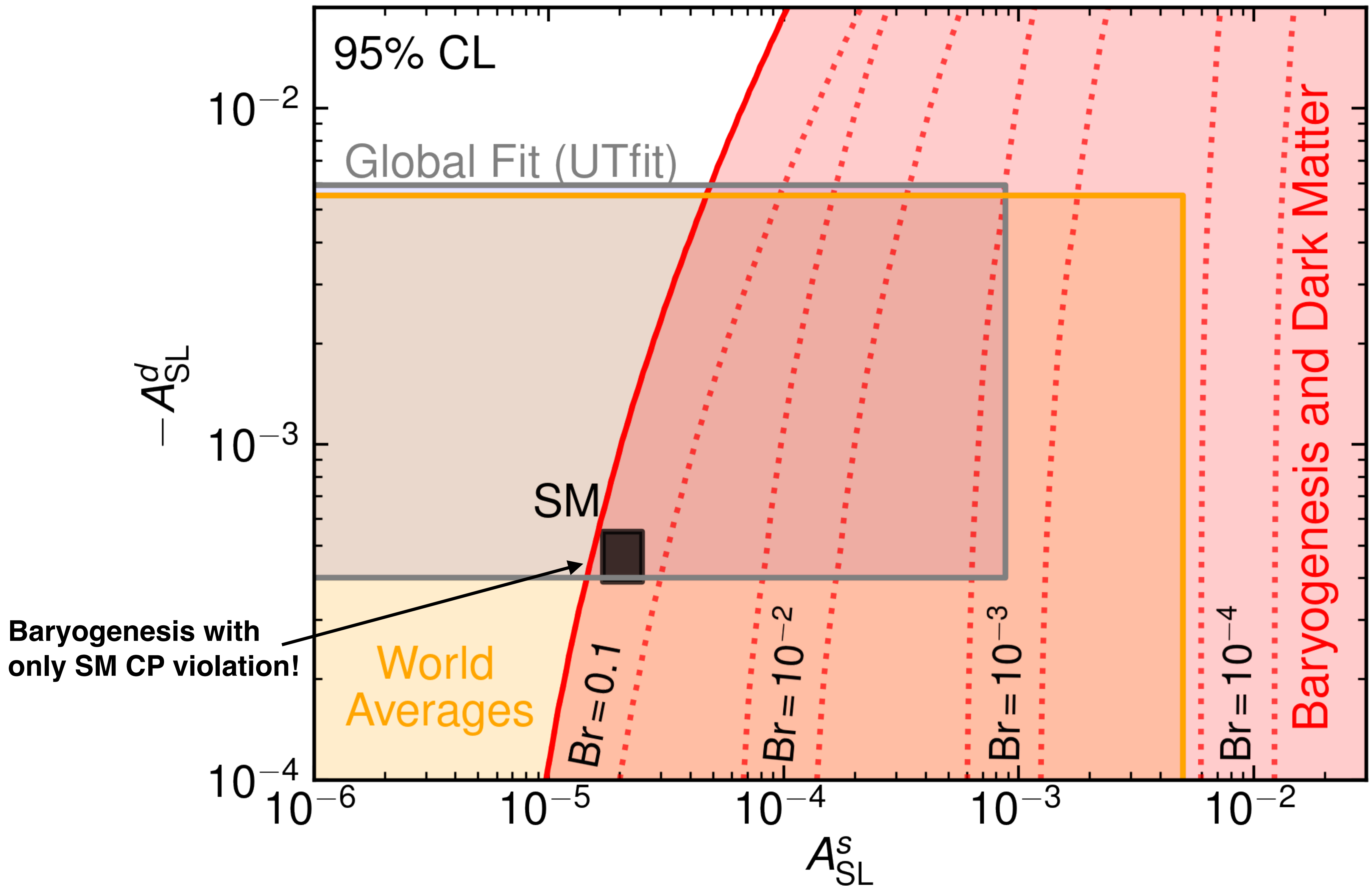
3) New TeV colored scalar

Parameter Space



Measured A_{SL} imply: $\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \gtrsim 10^{-4}}$

Parameter Space



Global fits suggest $\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \gtrsim 10^{-3}}$

Implications for Collider Experiments

1) New Decay mode of the B meson into ME and a Baryon

$$\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \gtrsim 10^{-4}}$$

2) CP violation in neutral B mesons

$$\boxed{A_{\mathrm{SL}}^{q} > 10^{-5}}$$

3) New TeV colored triplet scalar

$$\boxed{M_Y < 10\,\mathrm{TeV}}$$

Any room for a new decay mode?

Targeted decay modes are very constrained/well measured:

B-Factories $\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu) < 10^{-5}$

LHC $\mathrm{Br}(B_s^0 \to \mu^+ \mu^-) = (2.7 \pm 0.6) \times 10^{-9}$

But our decay mode has not been targeted!

$$B \to \psi + \mathrm{Baryon} + \mathcal{M}$$

What about the total width of B-Mesons?

Theory: $\Gamma^b_{\mathrm{SM}}/\Gamma^b_{\exp} = 0.86 \pm 0.19$ **Lenz et al. 1305.5390**

Constraint: $\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \lesssim 40\,\%$

Measurement: $\mathrm{Br}\left(B \to p/\bar{p} + \mathrm{anything}\right) = (8.0 \pm 0.4)\,\%$

Most stringent current constraint: $\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \lesssim 10\,\%}$

Future Searches

Baryogenesis Requires:

$$\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \gtrsim 10^{-4}}$$

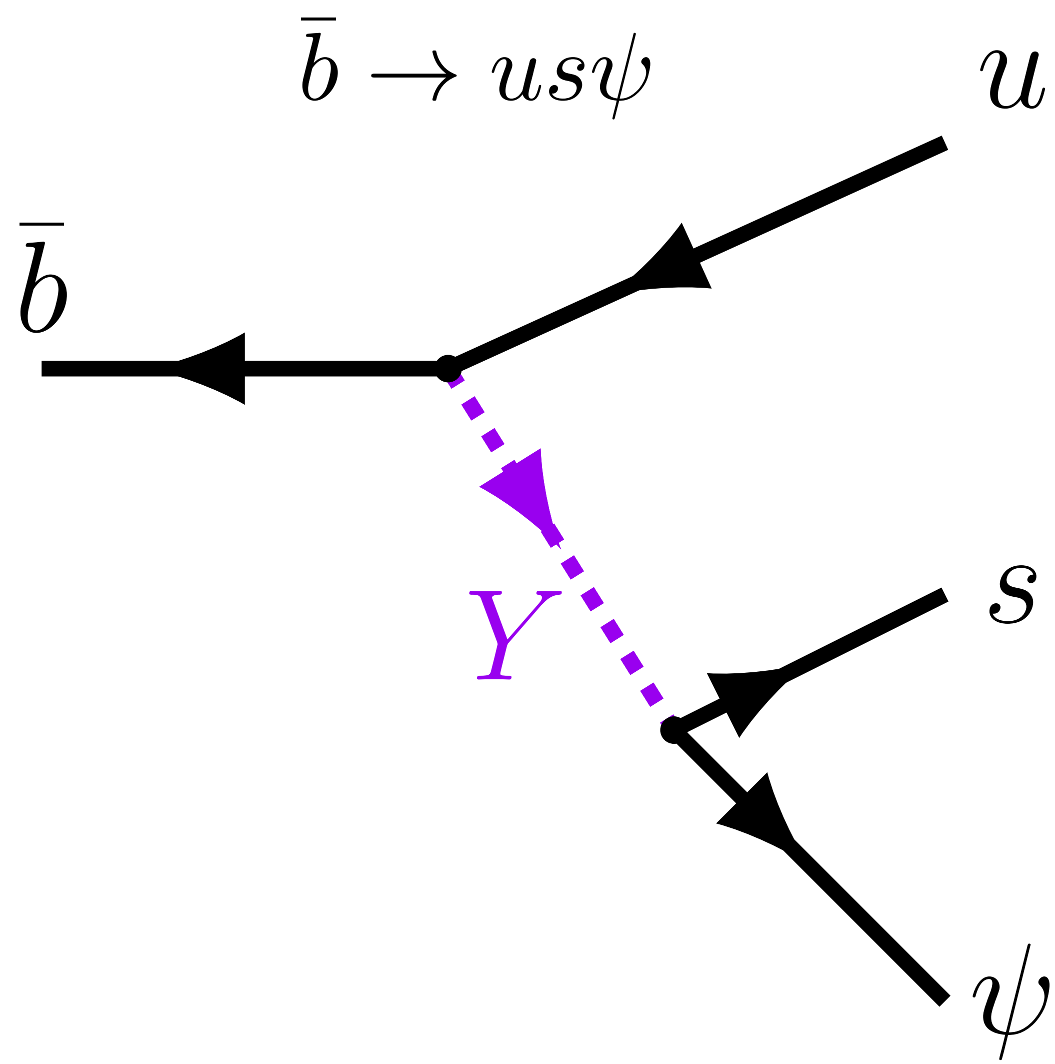
B-factories expected sensitivity: **(given that $\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu) < 10^{-5}$)**

$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon}\right) \gtrsim 10^{-5}$$

Ongoing searches with BaBar, Belle and Belle-II data!

The mechanism should be fully testable!

New Force Carrier



Y: Colored Triplet Scalar

$$Y \sim (3, 1, -1/3)$$

$$Y \sim (3, 1, 2/3)$$

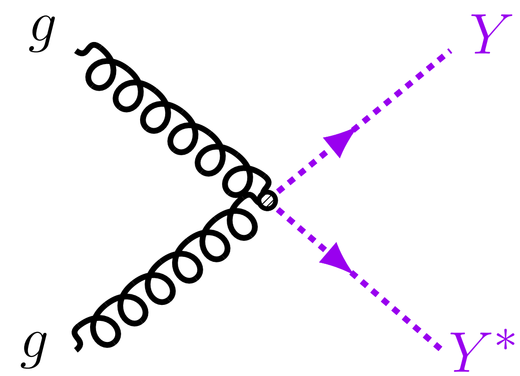
Same Quantum Numbers as a SUSY squark!

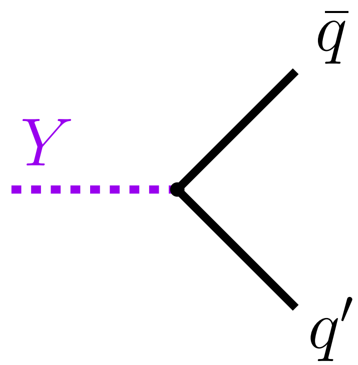
$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2\,\mathrm{GeV}}\right)^4 \left(\frac{1.6\,\mathrm{TeV}}{M_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.6}\right)^4$$

Perturbativity requires: $\boxed{M_Y < 10\,\mathrm{TeV}}$

Squark Searches

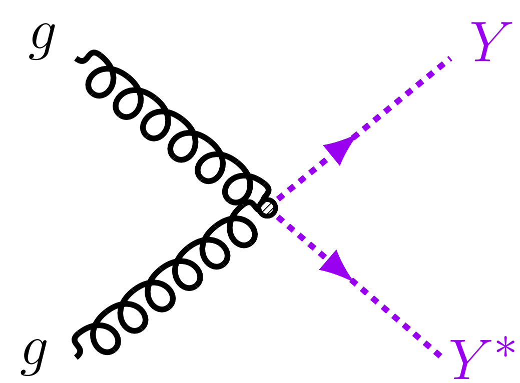
Production | **Decay** | **Signature** | **Constraint**

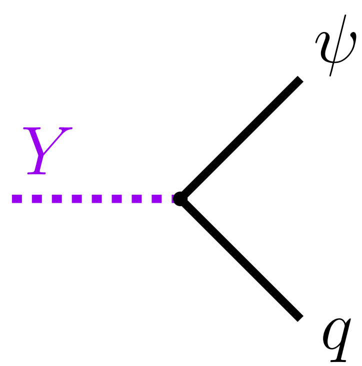




4 jets

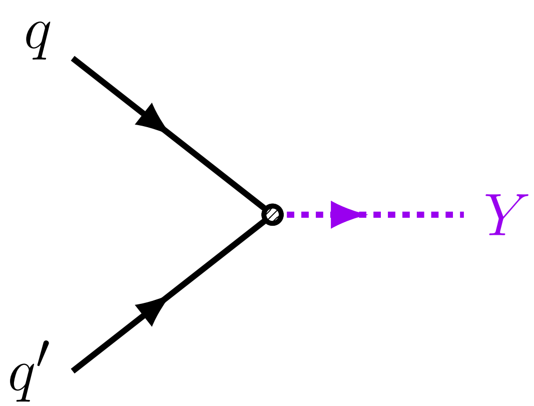
M_Y > 0.5 TeV
1710.07171 (ATLAS)

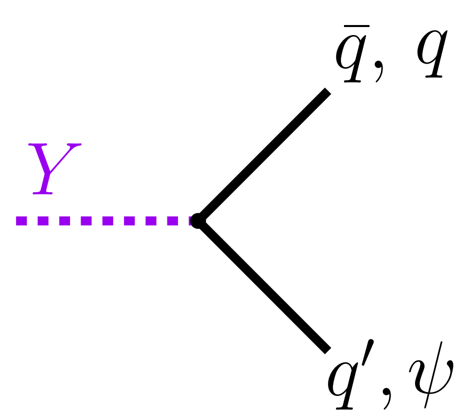




2 jets+ME

M_Y > 1.2 TeV
1908.04722 (CMS)
2010.14293 (ATLAS)





2 jets

M_Y > 1-7 TeV
1806.00843 (CMS)

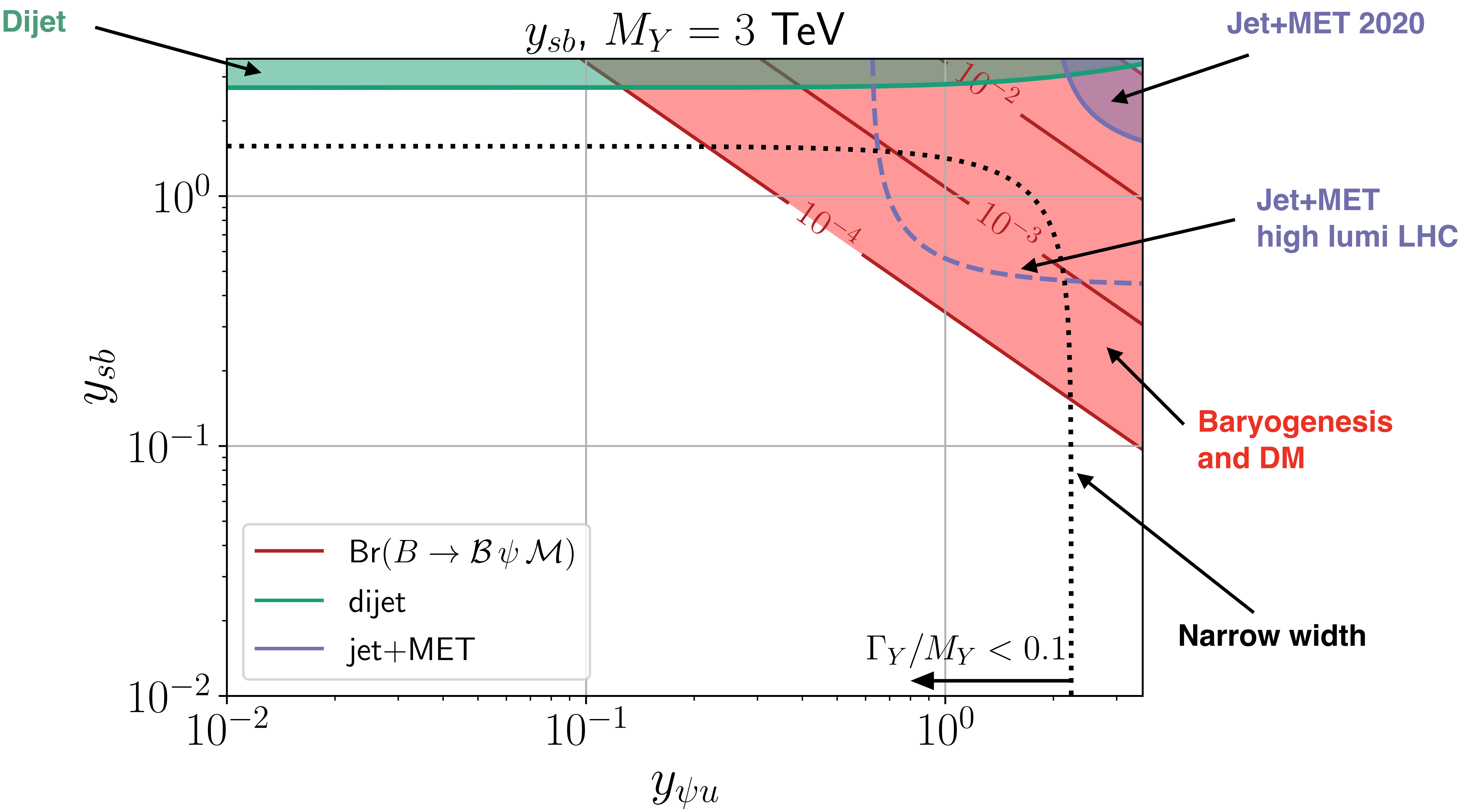
Monojet

M_Y > 1-7 TeV
1711.03301 (ATLAS)

We have recasted results from dijet and jet+MET searches

Bounds depend upon combinations of $y_{qq'} \times y_{q\psi}$

Squark Searches



LHC 2020: $\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \lesssim 0.1$

ATLAS & CMS have a great potential to detect the Y particle

Collider Complementarity

1) Parameter Space of B-Mesogenesis:

$$\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \times A_{\mathrm{SL}}^{q} \gtrsim 5 \times 10^{-7}}$$

2) As of today we know:

$$\boxed{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \times A_{\mathrm{SL}}^{q} \lesssim 10^{-4}}$$

BaBar
Belle

Belle II

LHCb

ATLAS
CMS

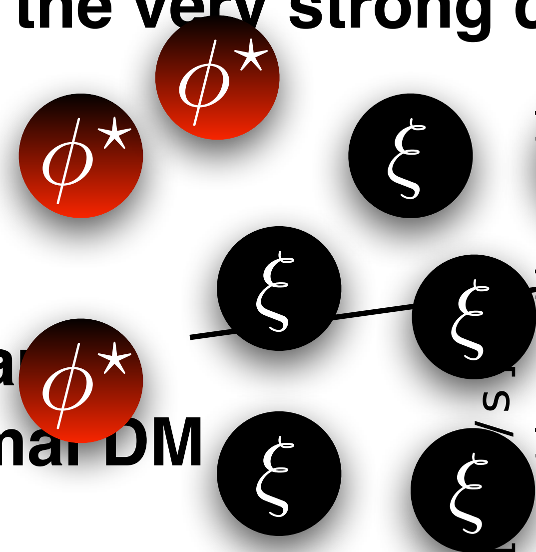
B-Mesogenesis can be fully tested at collider experiments!

Dark Matter Phenomenology

- **Relic abundance obtained with:**

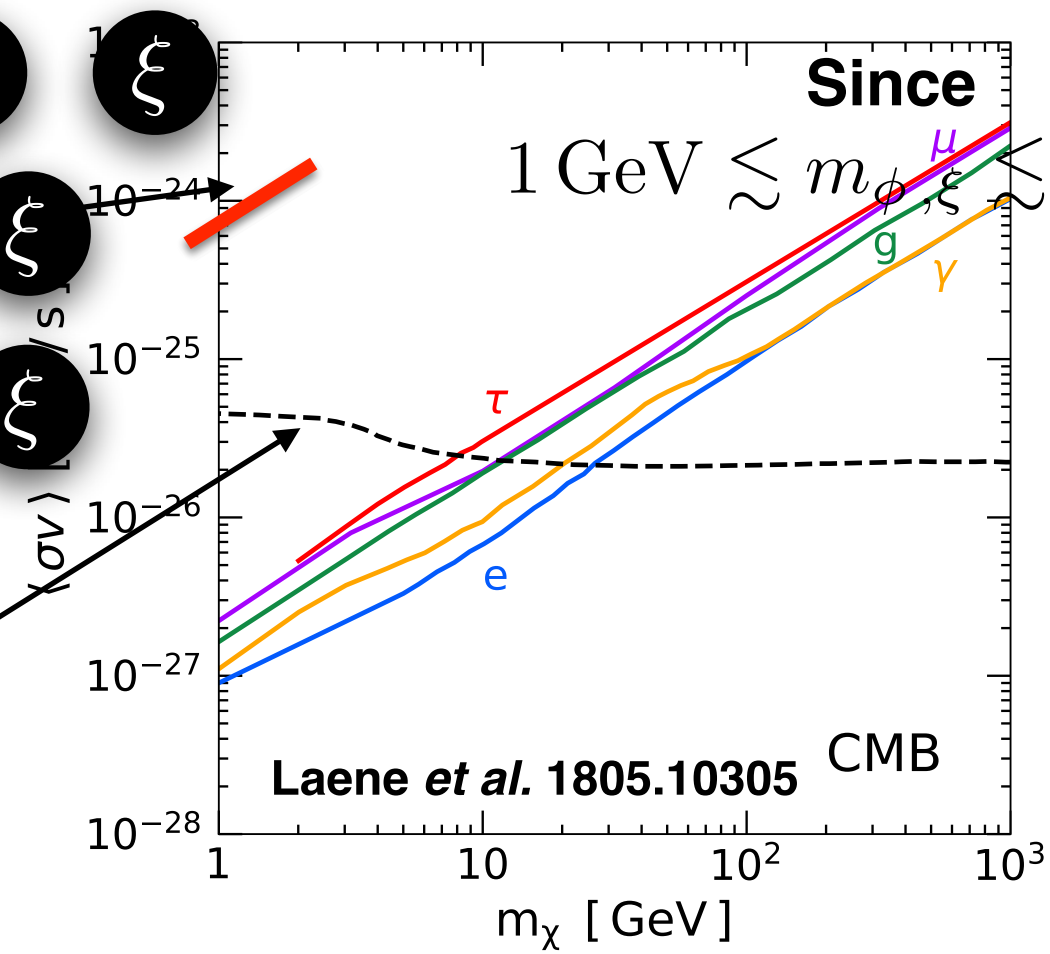
$$\Omega_{\rm DM} h^2 = 0.12 \quad \longrightarrow \quad \langle \sigma v \rangle_{\rm dark} \simeq 25 \, \langle \sigma v \rangle_{\rm WIMP} \, \min[m_\phi, m_\xi]/\mathrm{GeV}$$

- **What kind of Dark Sector could allow for such cross sections but being compatible with the very strong constraints from the CMB observations?**



Our scena… Non-thermal DM

Thermal relic



Laene *et al.* 1805.10305

Since

$$1\,\mathrm{GeV} \lesssim m_{\phi,\xi} \lesssim 2.5\,\mathrm{GeV}$$

Possible Dark Sectors

1) Annihilation into Sterile Neutrinos

0711.4866 Pospelov, Ritz, Voloshin

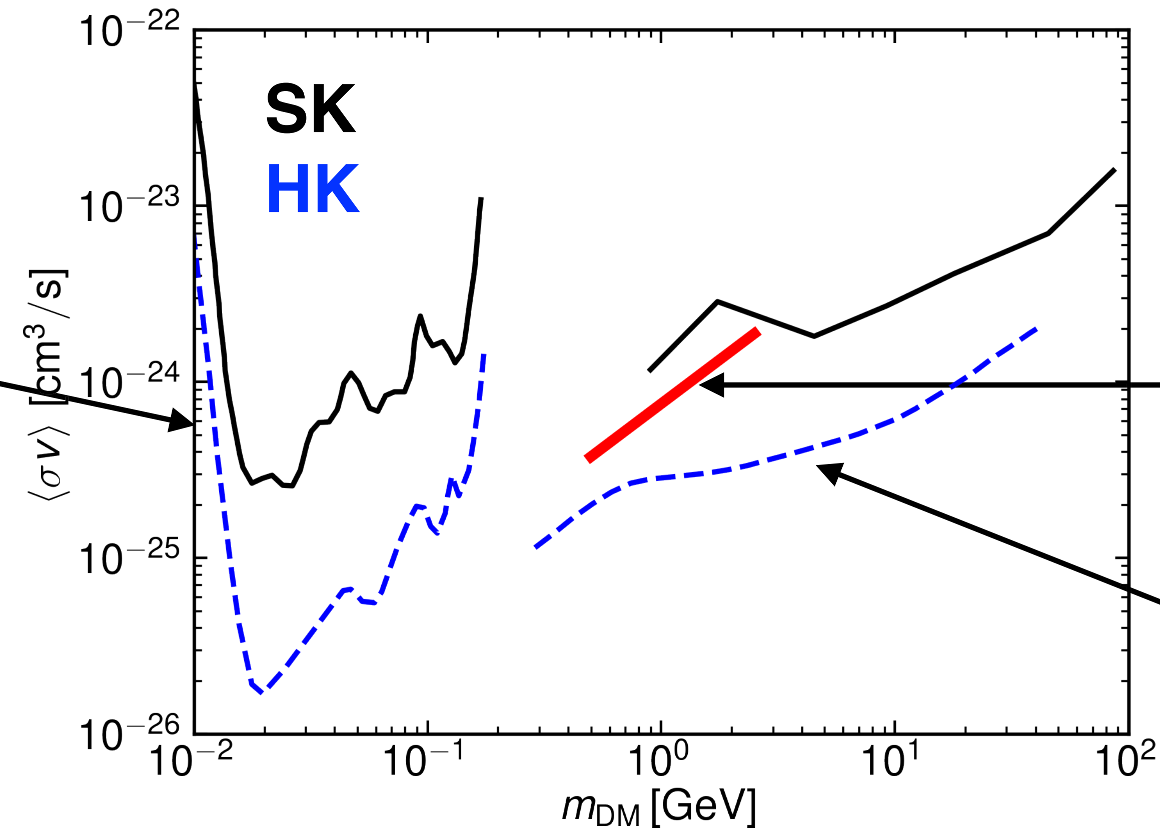
The annihilation can be predominantly p-wave: **1607.02373 Escudero, Rius, Sanz**

2) Annihilation into Active Neutrinos

González-Macias, Illana and Wudka, 1506.03825,1601.05051, Blennow et. al. 1903.00006

Constraints on dark matter annihilating to neutrinos are mild

Olivares-Del Rio, Boehm, Paloromes-Ruiz, Pascoli 1711.05283



Our scenario: Non-thermal DM

Bell, Dolan, Robles 2005.01950

Possible Dark Sectors

1) Annihilation into Sterile Neutrinos

0711.4866 Pospelov, Ritz, Voloshin

The annihilation can be predominantly p-wave: 1607.02373 Escudero, Rius, Sanz

2) Annihilation into Active Neutrinos

González-Macias, Illana and Wudka, 1506.03825,1601.05051, Blennow et. al. 1903.00006

Constraints on dark matter annihilating to neutrinos are mild

3) Additional particles carrying baryon number

$$\phi^\star + \phi \to \mathcal{A} + \mathcal{A}^\star$$
$$\phi + \mathcal{A} \to \mathcal{A}^\star + \mathcal{A}^\star$$

- **New scalar Baryon with B = 1/3:** $\mathcal{A}$
- **Is automatically stable!**
- **Which in order to get** $\Omega_{\rm DM}/\Omega_b = 5.36$ **will require** $m_{\mathcal{A}} \sim \frac{5}{3} m_p \sim 1.6\,{\rm GeV}$
- **Gives an understanding of the observed Dark Matter to Baryon energy density ratio**

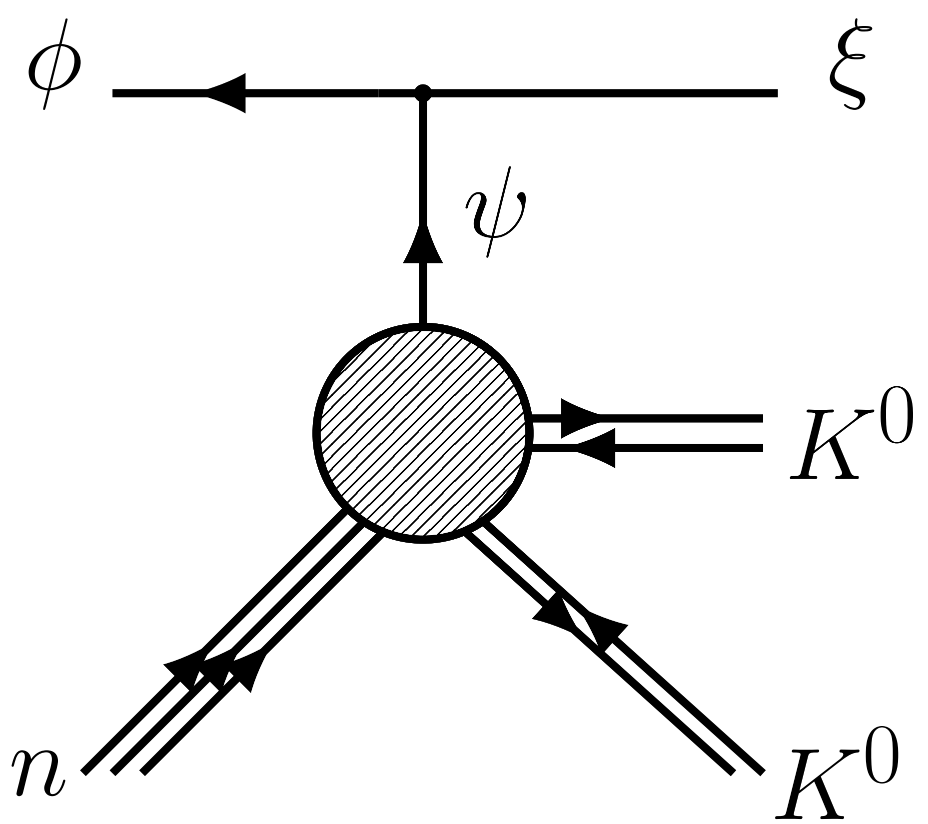
No Direct Detection Signatures

No direct coupling between the dark matter and light quarks

Coupling to light quarks can be generated through weak loops:

$$u\, s\, b\, \psi \to f_\pi^2 G_F V_{tb} V_{ts}^\star\, u\, s\, s\, \psi \sim 10^{-8}\, u\, s\, s\, \psi$$

These processes are possible and could be searched for at Super-Kamiokande:



But the rate is tiny, hence unobservable

see 1008.2399 by Davoudiasl, Morrissey, Sigurdson & Tulin

Summary

Baryogenesis and Dark Matter from B Mesons:

- **Which actually relates the CP violation in the B^0 system to Baryogenesis**
- **Baryon number is conserved and hence Dark Matter is anti-Baryonic**

Distinct experimental signatures:

- **Positive leptonic asymmetry in B meson decays** $A_{\mathrm{SL}}^{q} > 10^{-5}$
- **Neutral and charged B mesons decay into baryons and missing energy**

$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \gtrsim 10^{-4}$$

Ongoing search for this process at BaBar/Belle and Belle-II!

B-factories should test this scenario given the constraints on other missing energy channels:

$$\mathrm{Br}(B^+ \to K^+ \bar{\nu}\nu) < 10^{-5}$$

We expect the mechanism to be testable at current collider experiments!

Outlook

Theory

- Are the flavor anomalies ($b \to s\mu^+\mu^-$) in B-decays related to our required positive semileptonic asymmetry?

- Are there other possibilities for the dark sector?
    - Fractionally Charged Antibaryonic Dark Matter
    - Other Detection Methods

- What kind of UV theory contains our required heavy colored scalar plus our dark matter particles at the GeV scale?

E.g.: SUSY, 1907.10612 Alonso-Álvarez, Elor, Nelson, Xiao

Outlook

Improved QCD and Flavor Predictions

- **Exclusive Decays**

  It is very important to relate $\bar{b} \to \psi u d$ **to** $B \to \psi + \mathrm{Baryon}$

  We performed a rather rough phase space calculation

  A QCD sum rule or Lattice calculation would be very valuable

- **Also b-flavored baryon decays e.g.** $\Lambda_b \to \bar{\psi} + \overline{D}^0$ **,** $\Lambda_b \to \xi + \phi^\star$
- **This scenario can alter** Γ_{12}^q **via** $b \to \bar{\psi}\psi s$

Experiment

- **How well will BaBar/Belle/Belle-II constraint or measure?**

$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon}\right)$$

The B-Mesogenesis Team

Gonzalo Alonso
Heidelberg→McGill

Gilly Elor
UW→Mainz

Ann Nelson
1958-2019

Thank You!