B-Mesogenesis: Baryogenesis and Dark Matter from B Mesons

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Based on:

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

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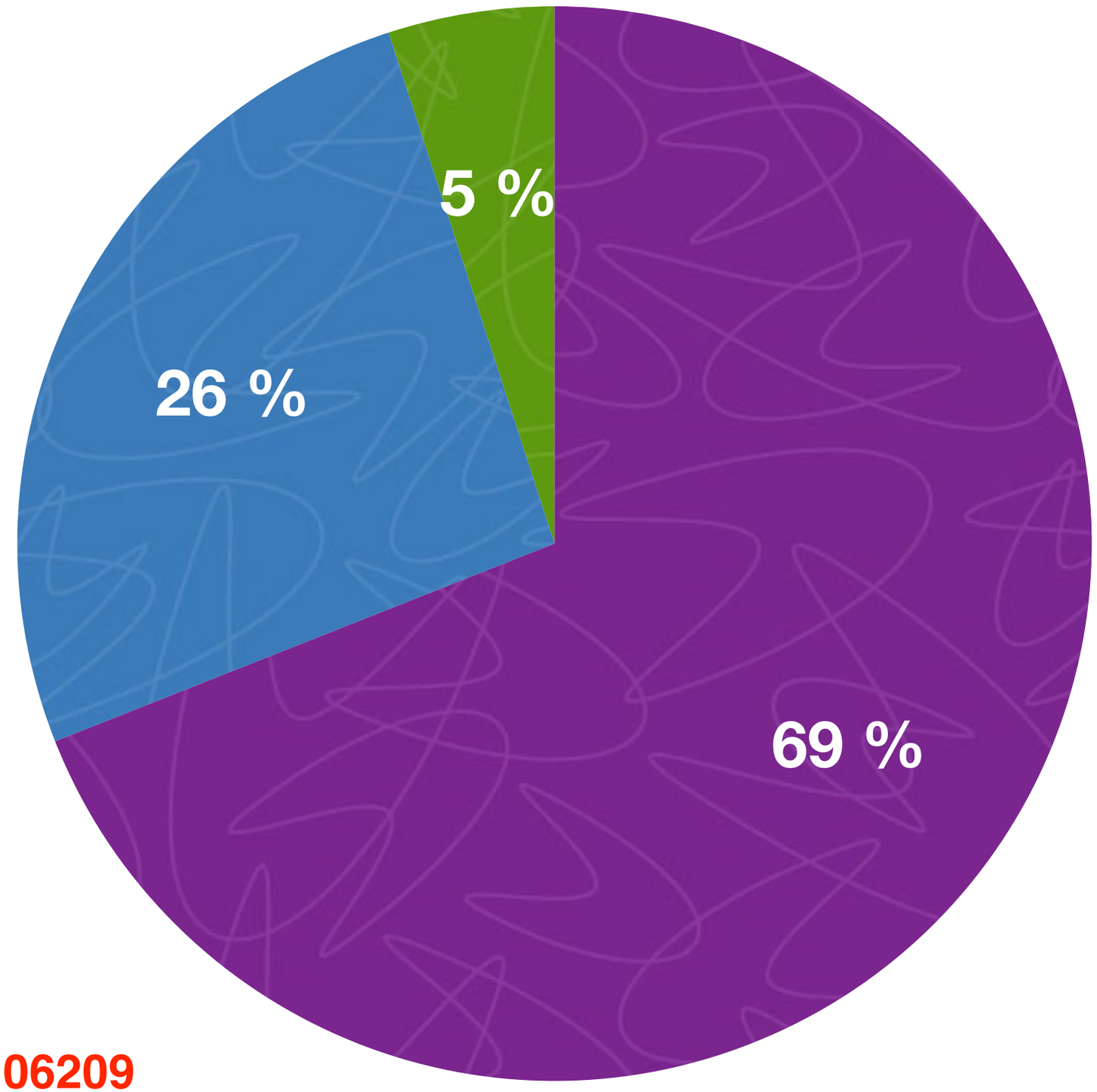
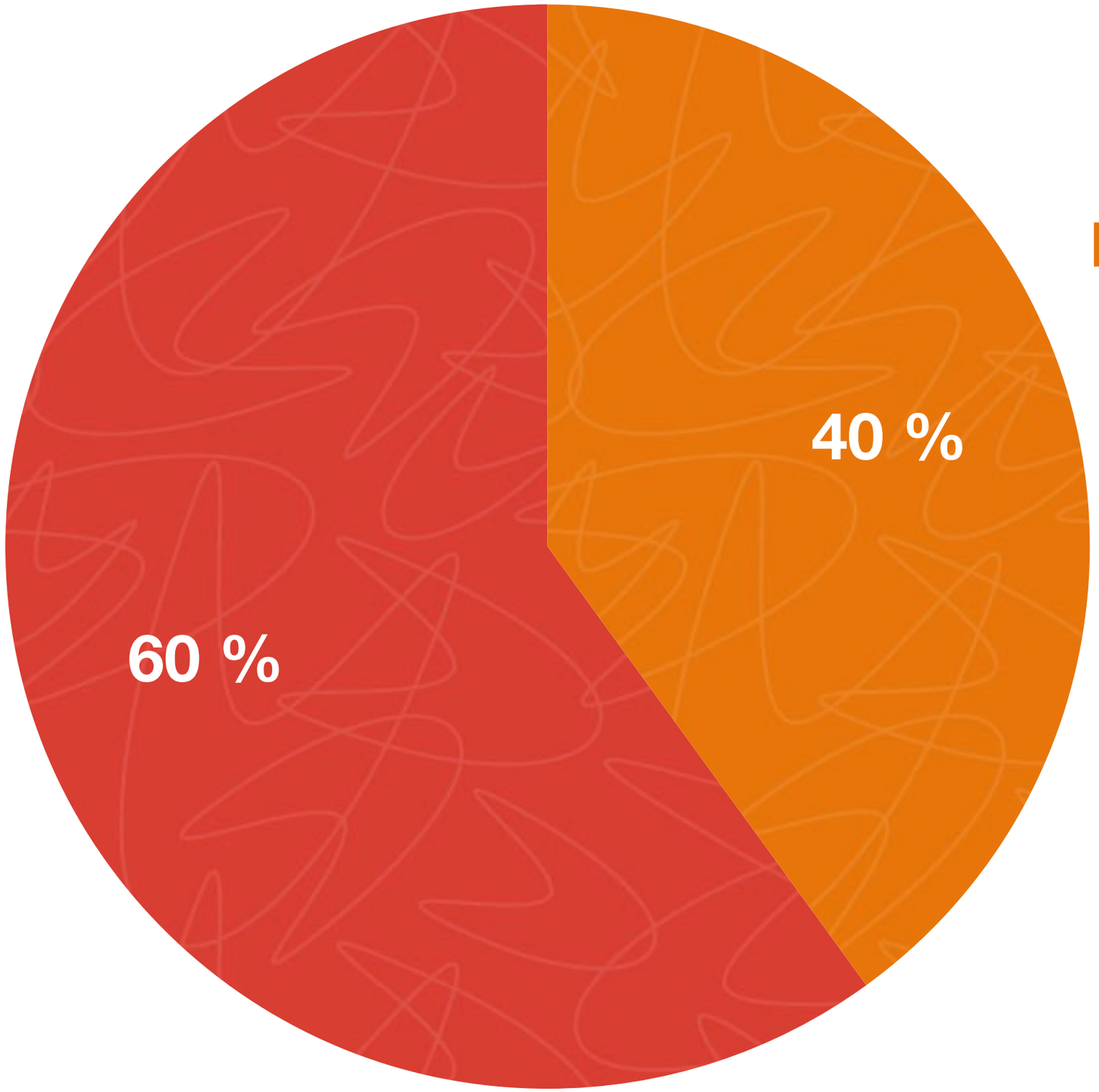
The Universe



Planck 2018 1807.06209

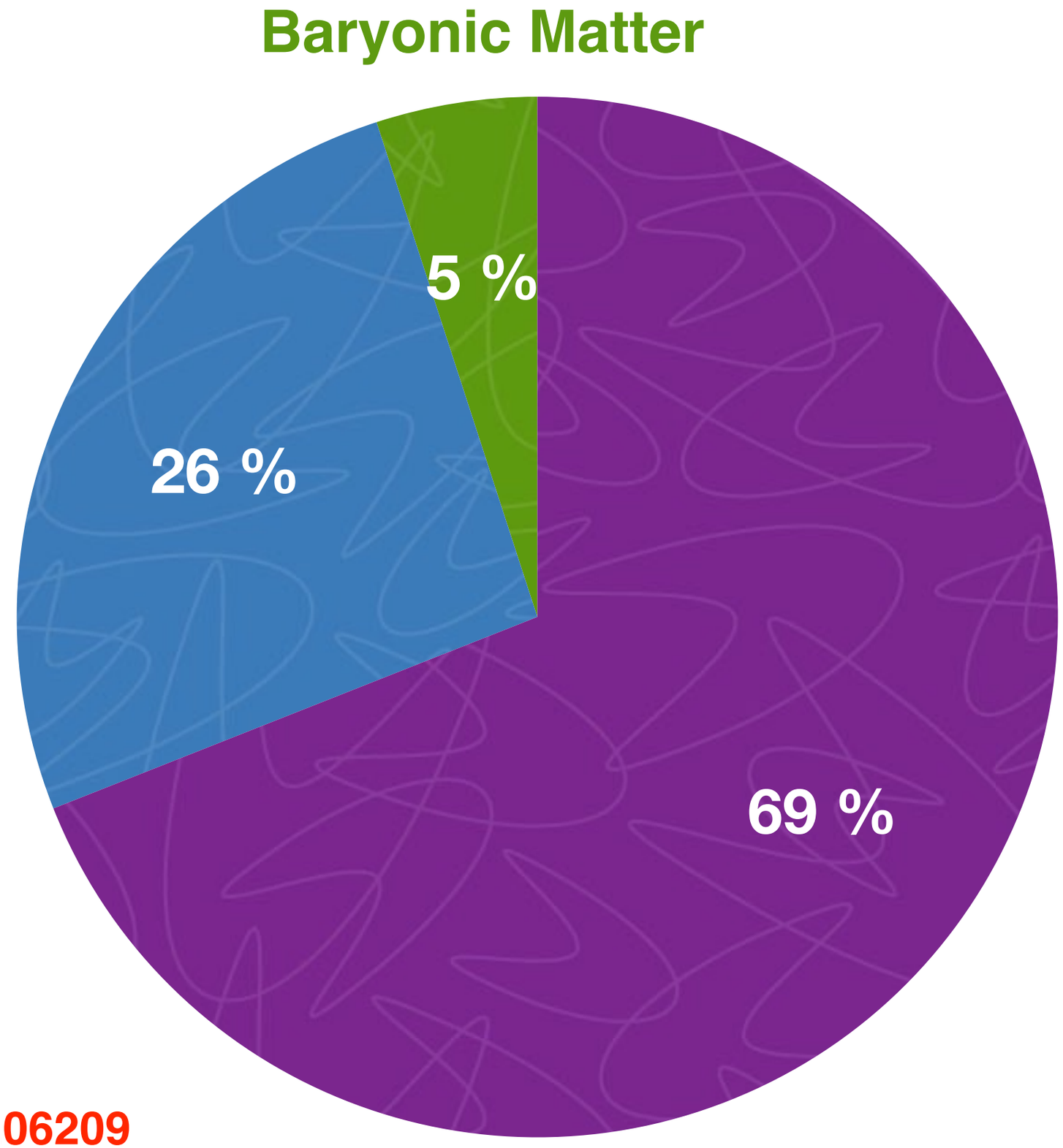
Standard Model Prediction:



Neutrinos

Photons

The Universe



Planck 2018 1807.06209

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

Outline

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

2) A Minimal Model

3) Implications for Collider Experiments
    1) CP violation in B^0 mesons
    2) New decay mode of B mesons into DM and a Baryon

4) Summary and Outlook

-1) Dark Matter Phenomenology

Baryogenesis

The Three Sakharov Conditions (1967):

1) C and CP violation

2) Out of equilibrium

3) Baryon number violation

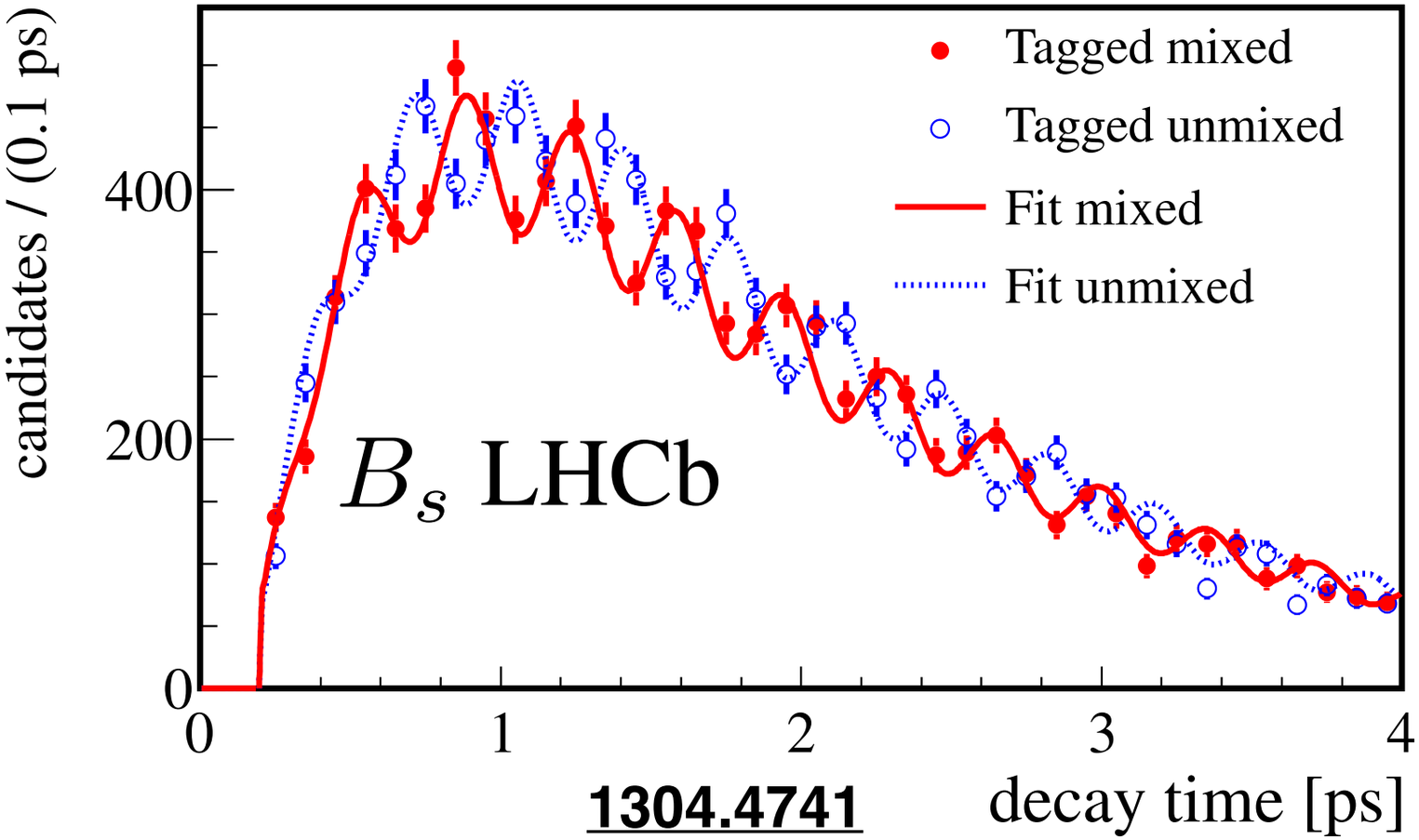
Baryogenesis from B Mesons

1) C and CP violation

Neutral and CP violating oscillating systems in the SM:

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

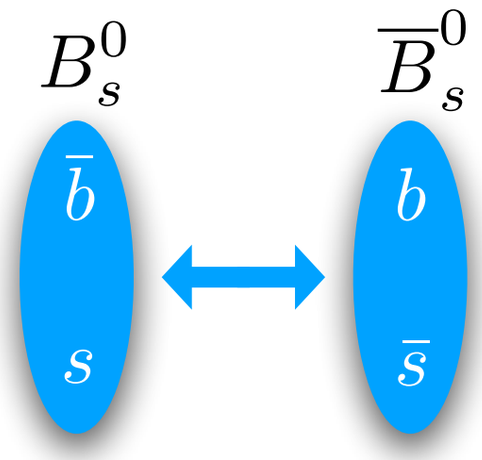
Neutral B Mesons are the perfect system: $m_B \simeq 5.3\,\mathrm{GeV}$



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

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

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

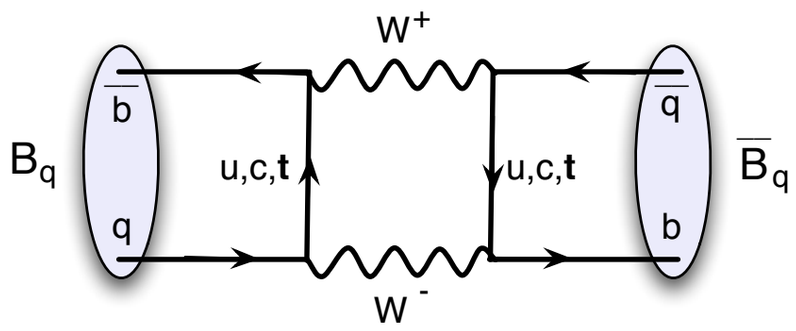


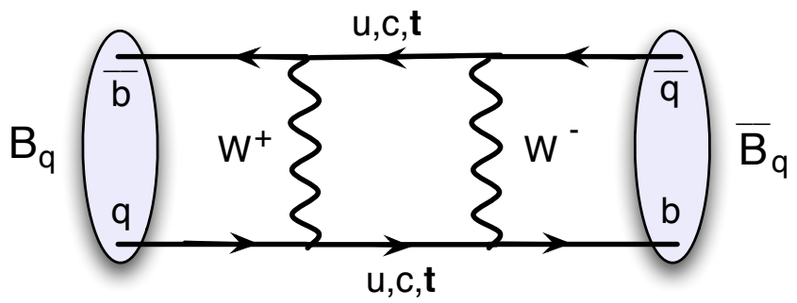
Baryogenesis from B Mesons

1) CP violation in the Meson System

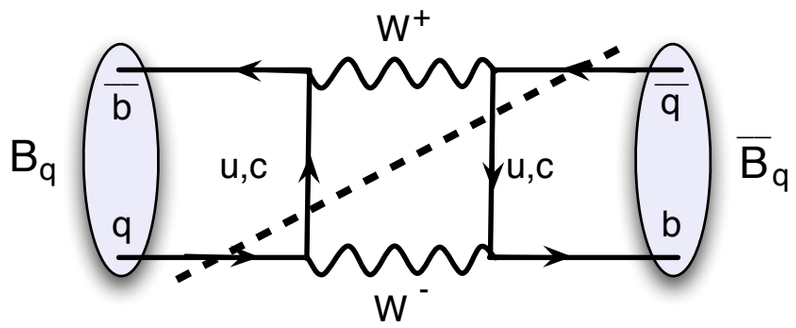
SM: Box Diagrams

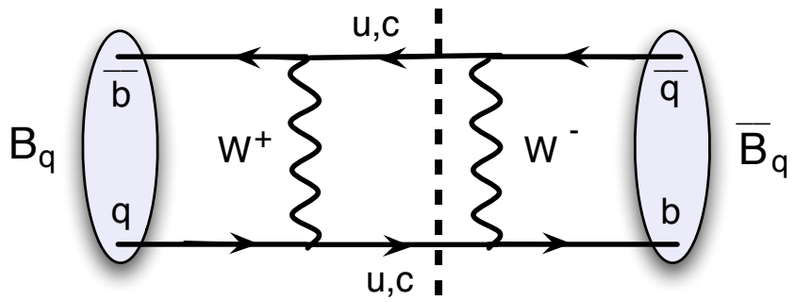
$$M_{12} \propto$$





$$\Gamma_{12} \propto$$





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).**
- **The SM asymmetries are not too small, remember that $\eta_B = (n_B - n_{\bar{B}})/n_\gamma = 6 \times 10^{-10}$**

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**

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

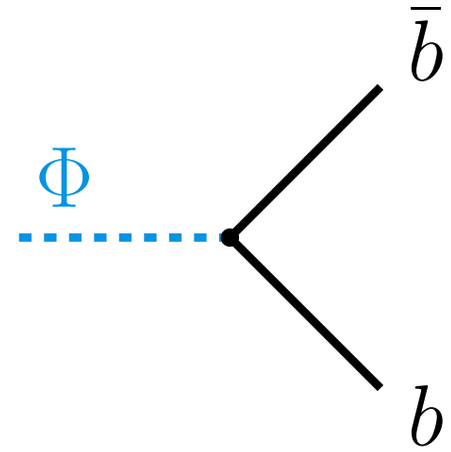
- **The decays don't spoil BBN or the CMB provided** $T_{RH} > 5\,\mathrm{MeV}$

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

Baryogenesis from B Mesons

2) Out of equilibrium and production of B Mesons

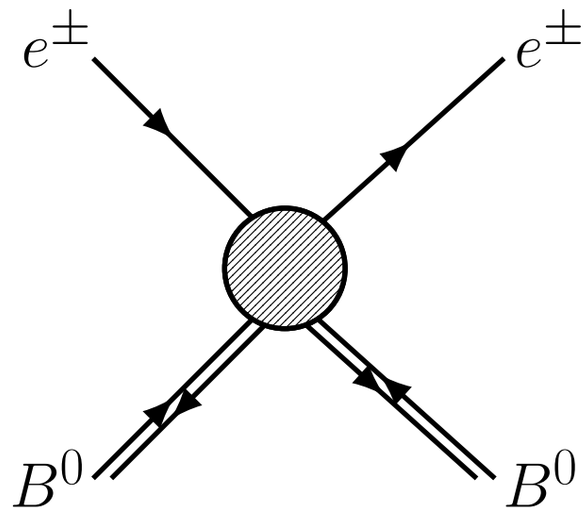
- **Scalar particle with** $M_\Phi \in 11 - 100\,\mathrm{GeV}$ **and** $\tau_\Phi = \mathcal{O}(10^{-3}\,\mathrm{s})$ **generically decays into b-quarks**



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

- **Coherent oscillations in the B^0 system are maintained in the early Universe for temperatures:**

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



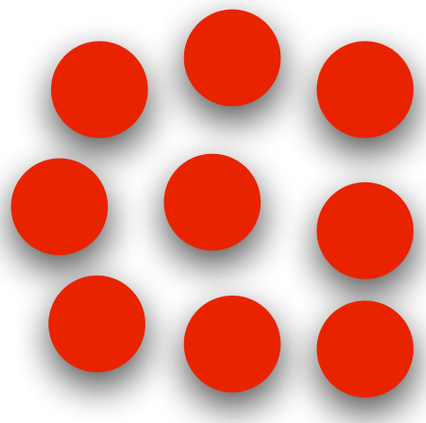
Baryogenesis and DM from B Mesons

3) Baryon number violation?

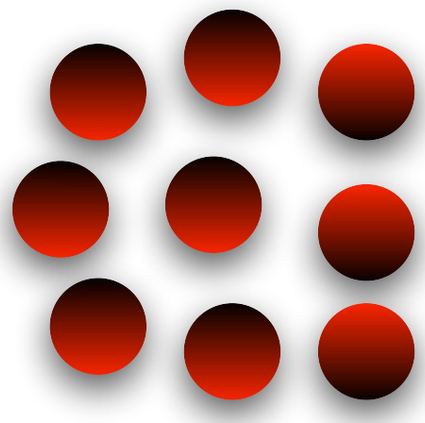
- **Baryon number is conserved in our scenario:** $\Delta B = 0$

  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.**



Visible Sector (Baryons)

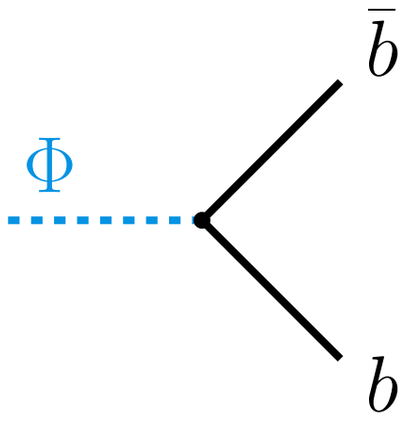


Dark Sector (anti-Baryons)

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

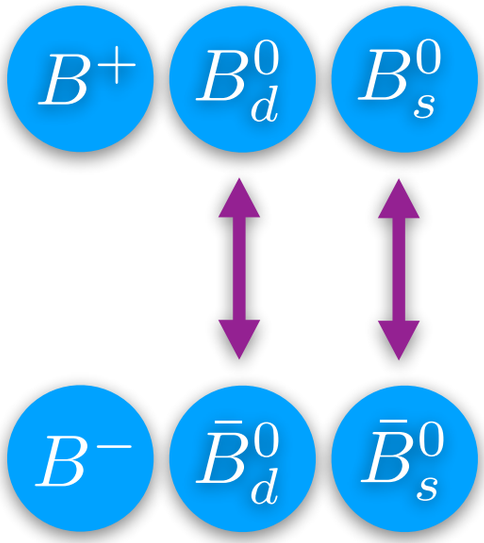
A Summary of the Mechanism

Out of equilibrium late time decay



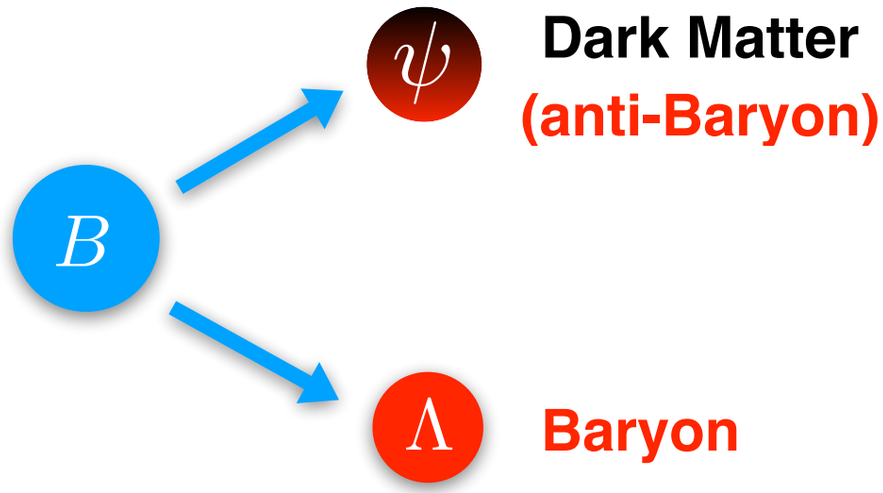
$T_R \sim 15\,\mathrm{MeV}$

CP violating oscillations



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

B-mesons decay into Dark Matter and hadrons



Dark Matter (anti-Baryon)

Baryon

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

Baryogenesis

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

and

Dark Matter

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

With:

$$Y_{\mathcal{B}} \simeq 8.7 \times 10^{-11}\, \frac{\mathrm{Br}(B \to \psi + \mathcal{B} + \mathcal{M})}{10^{-3}} \sum_q \alpha_q\, \frac{A_{\mathrm{SL}}^q}{10^{-3}}$$

New B-Meson decay

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

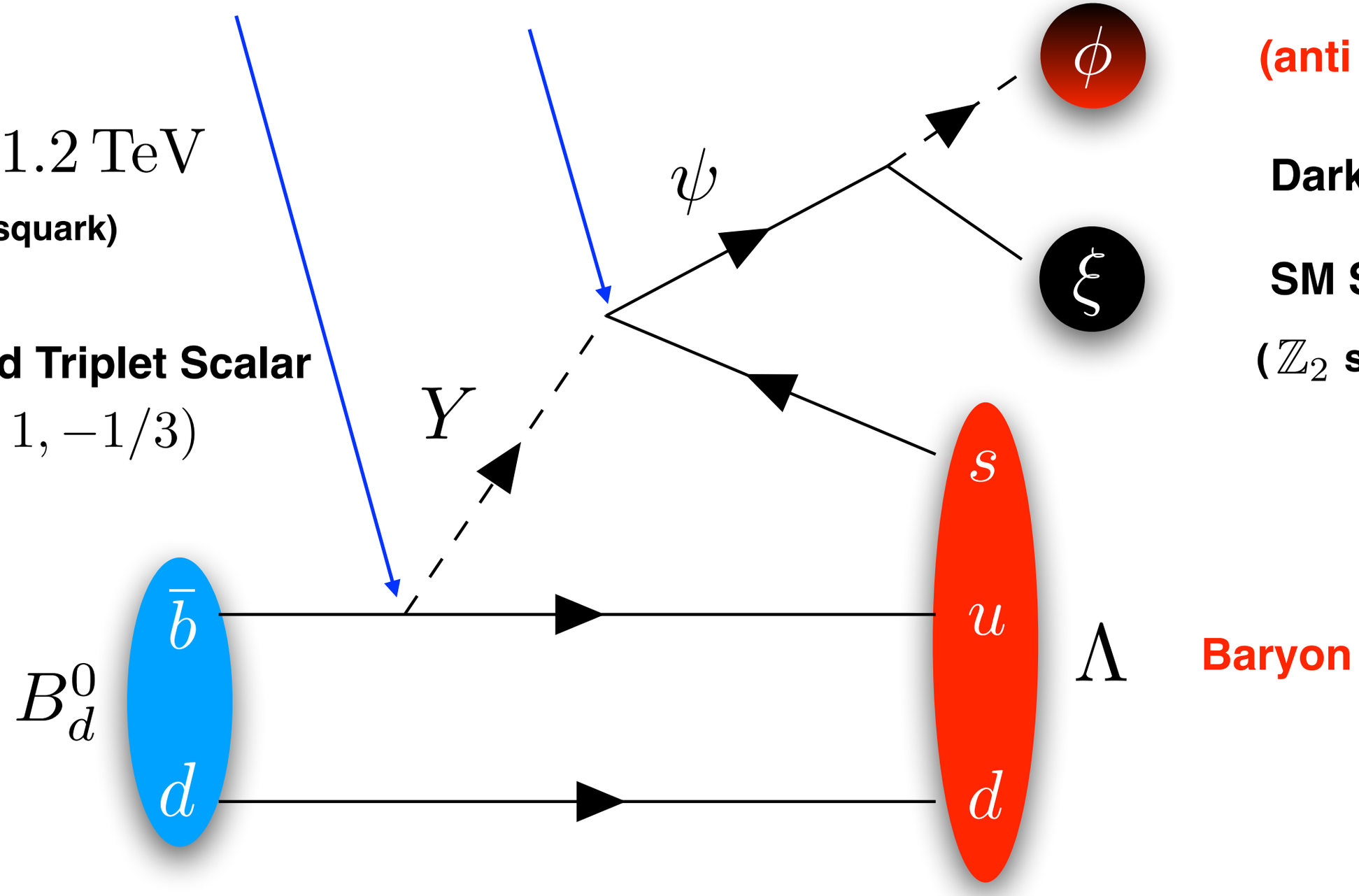
$$1\,\text{GeV} \lesssim m_{\phi\,,\xi} \lesssim 2.5\,\text{GeV}$$

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

(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.**

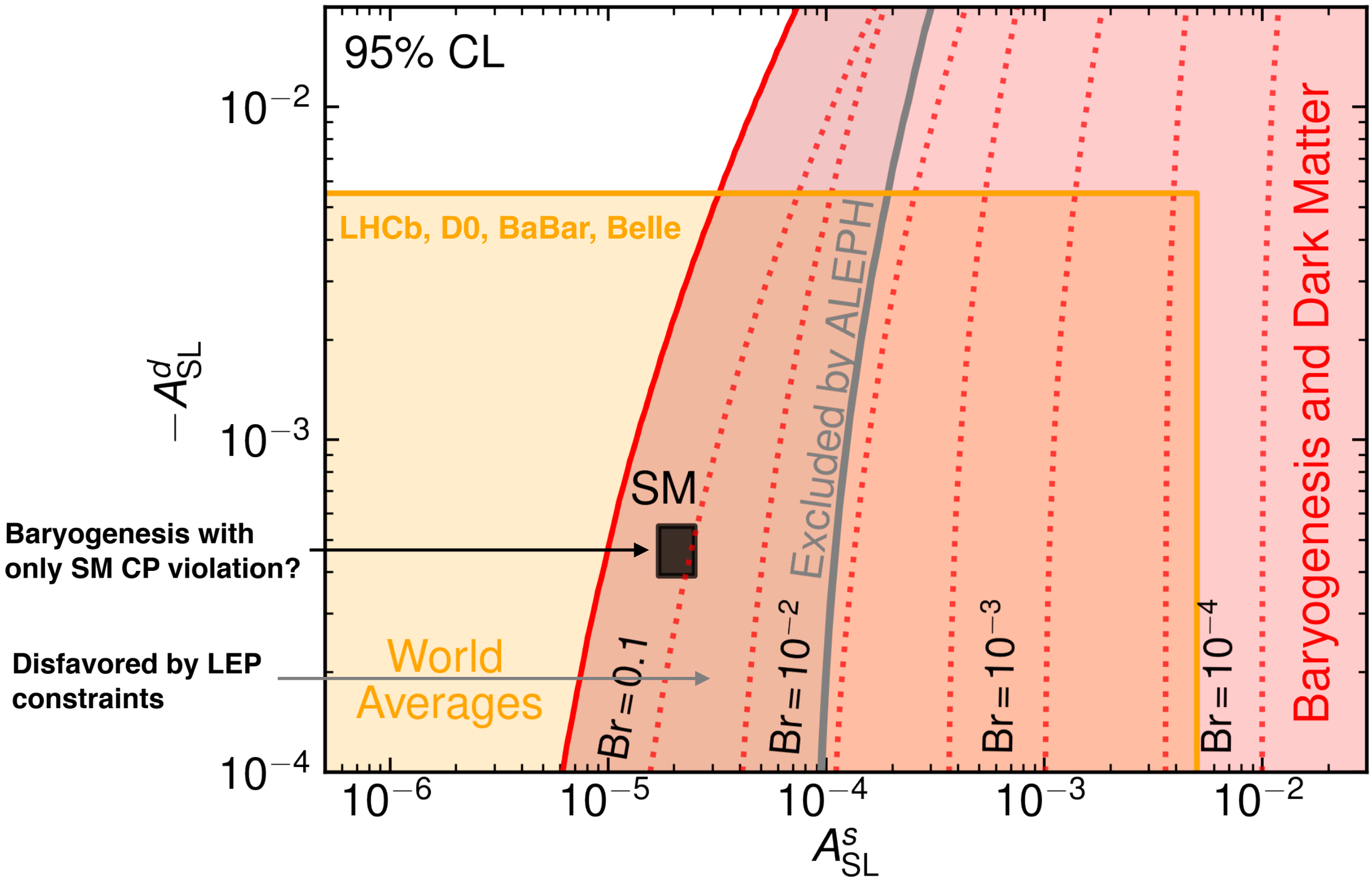
Collider Signatures

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:

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

Implications for Collider Experiments

1) CP violation in neutral B mesons

$$A_{\rm SL}^q > 10^{-4}$$

2) New Decay mode of B mesons into ME and a Baryon

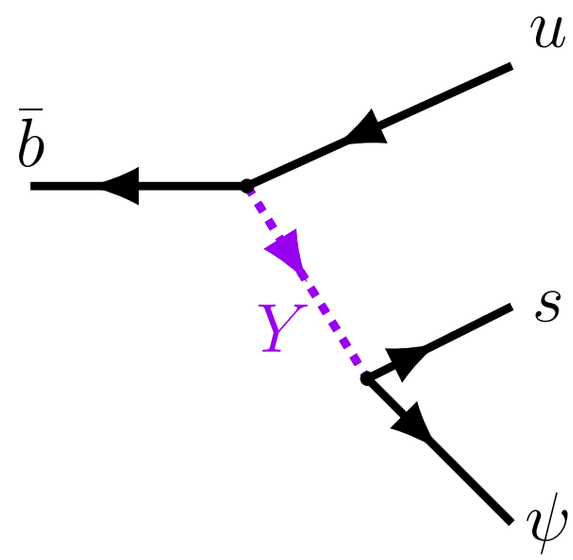
$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \gtrsim 10^{-4}$$

3) New TeV colored triplet scalar

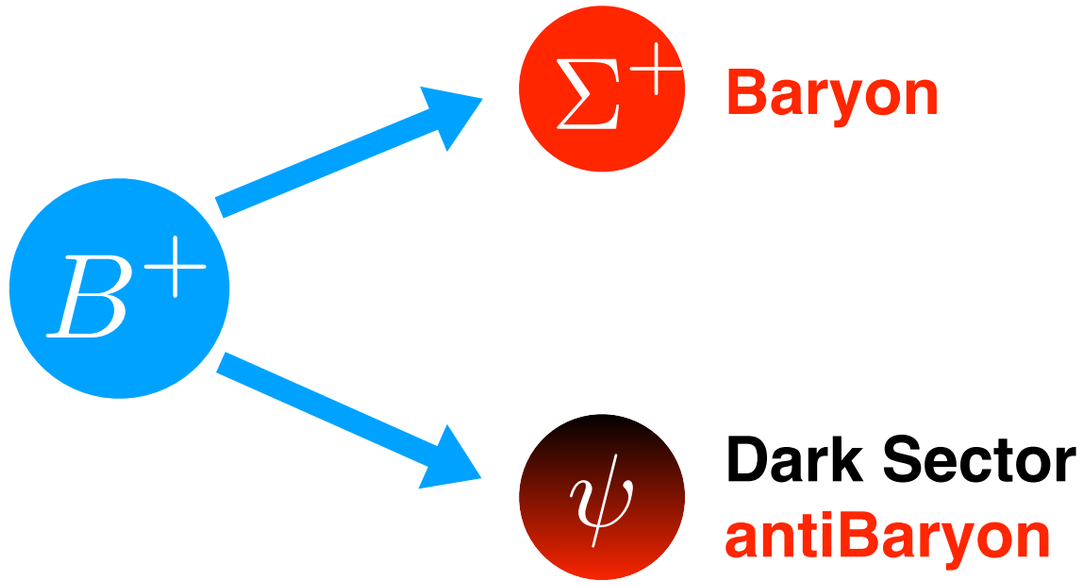
$$M_Y < 10\,\mathrm{TeV}$$

A close look at the new decays

1) Parton level decay:



2) It is a 2-Body decay



3) Parameter space is: $0.94\,\mathrm{GeV} < m_\psi < 4.34\,\mathrm{GeV}$

4) 4 Flavourful variations exist: (All work equally well for Baryogenesis)

$\psi\, b\, u\, d$	$\psi\, b\, u\, s$	$\psi\, b\, c\, d$	$\psi\, b\, c\, s$
$B_d \to \psi + n\,(udd)$	$B_d \to \psi + \Lambda\,(usd)$	$B_d \to \psi + \Lambda_c + \pi^-\,(cdd)$	$B_d \to \psi + \Xi_c^0\,(csd)$
$B_s \to \psi + \Lambda\,(uds)$	$B_s \to \psi + \Xi^0\,(uss)$	$B_s \to \psi + \Xi_c^0\,(cds)$	$B_s \to \psi + \Omega_c\,(css)$
$B^+ \to \psi + p\,(duu)$	$B^+ \to \psi + \Sigma^+\,(uus)$	$B^+ \to \psi + \Lambda_c\,(dcu)$	$B^+ \to \psi + \Xi_c^+\,(csu)$
$\Lambda_b \to \bar{\psi} + \pi^0$	$\Lambda_b \to \bar{\psi} + K^0$	$\Lambda_b \to \bar{\psi} + \overline{D}^0$	$\Lambda_b \to \bar{\psi} + D^- + K^+$

5) Baryogenesis only cares about $\mathrm{Br}\left(\bar{b} \to \psi u d\right)$ (Inclusive)

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 $\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = (2.8 \pm 0.3) \times 10^{-9}$

But our decay mode has not been targeted!

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

There is no available search for B mesons decaying into a Baryon, missing energy and any number of mesons

Constraints on these decays

Ways to constrain these new decay modes:

0) Total width of B mesons: Lenz et al. 1305.5390 $\mathrm{Br}\,(B \to \psi + \mathrm{Baryon} + \mathcal{M}) \lesssim 40\,\%$

1) Inclusive measurements involving Baryons (ARGUS, CLEO & BaBar)

$$\mathrm{Br}\,(B \to \psi + \mathrm{Baryon} + \mathcal{M}) \lesssim 10\,\%$$

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

2) Direct exclusive searches at B factories

sensitivity should be $\mathrm{Br}(B \to \psi + \mathrm{Baryon}) \sim 10^{-6} - 10^{-5}$

given that $\mathrm{Br}(B \to K\bar{\nu}\nu) \sim 10^{-6} - 10^{-5}$

There are ongoing searches at BaBar, Belle and Belle-II Echenard et al. Strube et al. (results in July)

3) Searches for resonances at LHCb $\mathrm{Br} \sim 10^{-7} - 10^{-5}$ Cid Vidal et al. 2106.12870

4) Searches for b-flavor baryon decays LHCb $\mathrm{Br} \sim 10^{-5}$ Cid Vidal et al. 2106.12870

→ **5) At ALEPH! Inclusive search for missing energy in b decays** hep-ex/0010022

→ **6) Indirectly at ATLAS and CMS** by constraining the mediator that should be M < 10 TeV

$$\mathrm{Br}\,(B \to \psi + \mathrm{Baryon} + \mathcal{M}) \lesssim 4 \times 10^{-3}$$

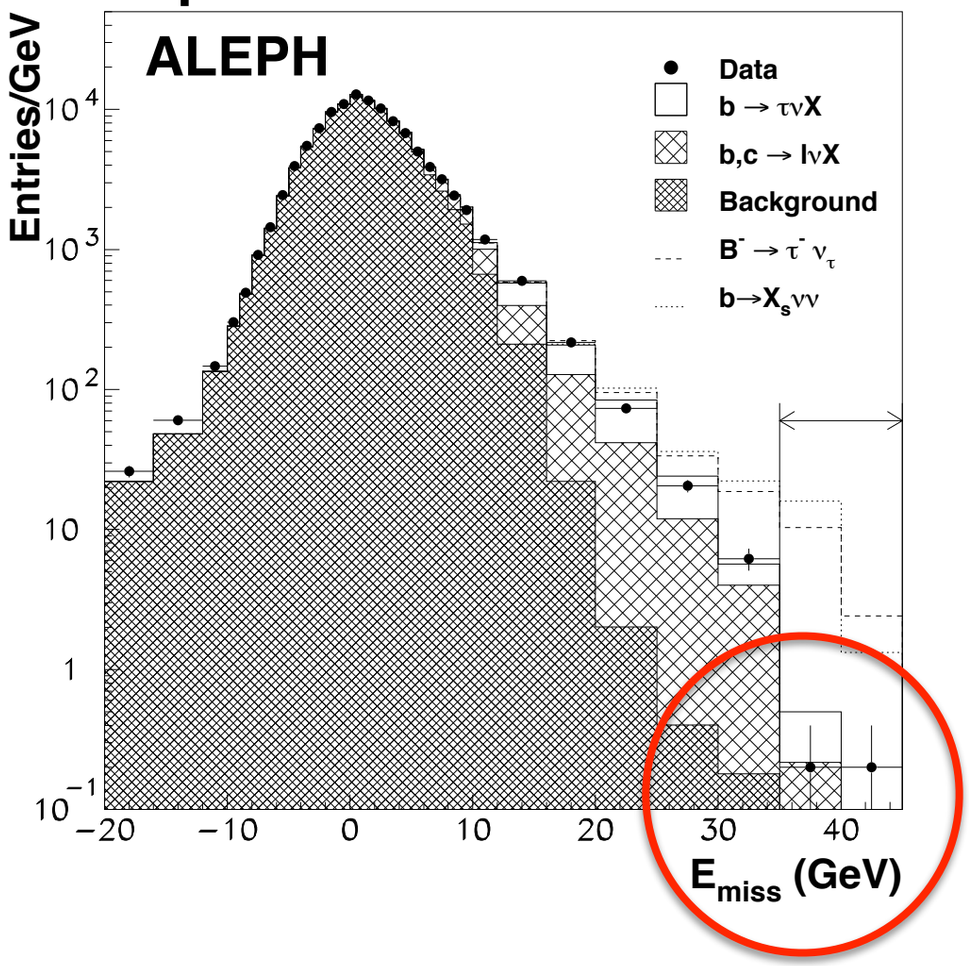
Inclusive Searches

ALEPH

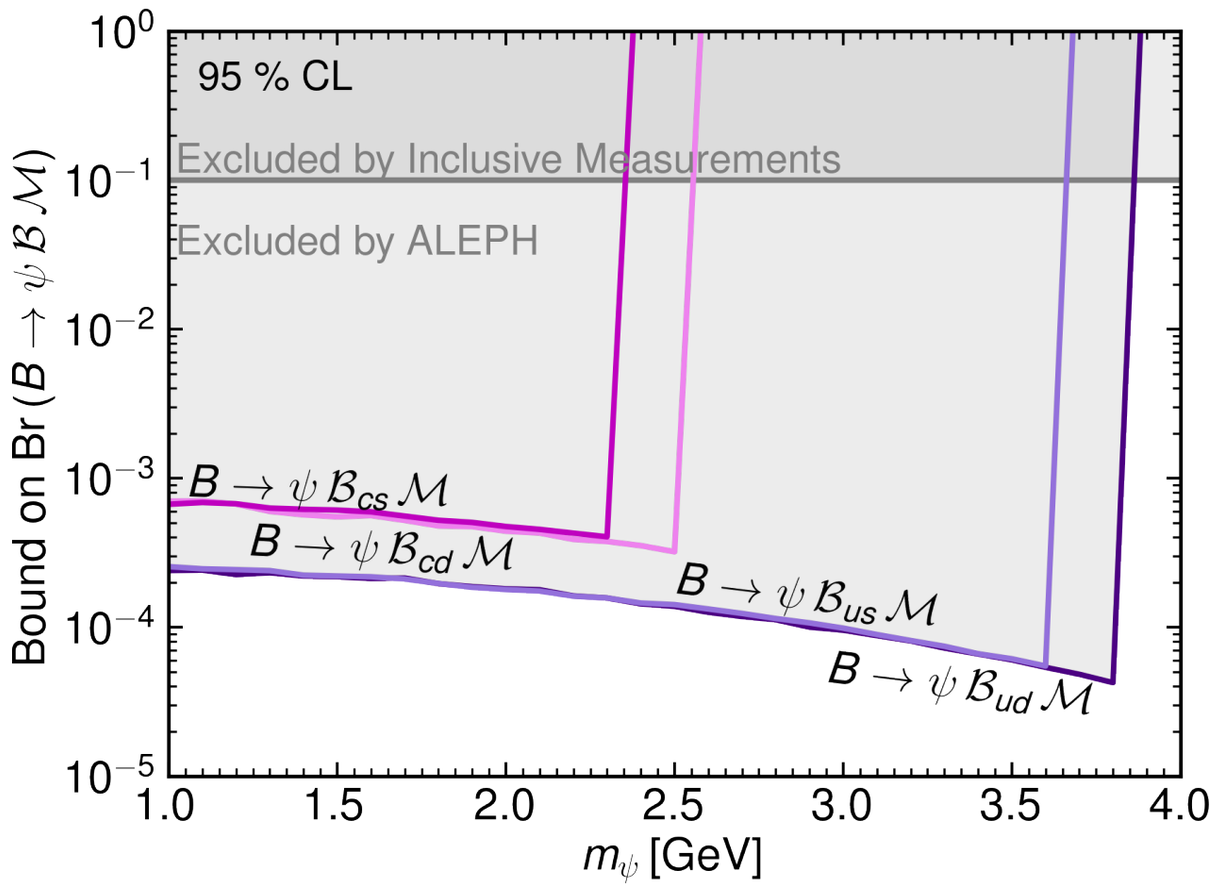
Our Referee has pointed out that ALEPH performed a generic search on b-hadron decays with large missing energy. Used to constrain $B \to \tau\nu$ and $b \to s\bar{\nu}\nu$ decays.

see Grossman, Ligeti and Nardi hep-ph/9510378

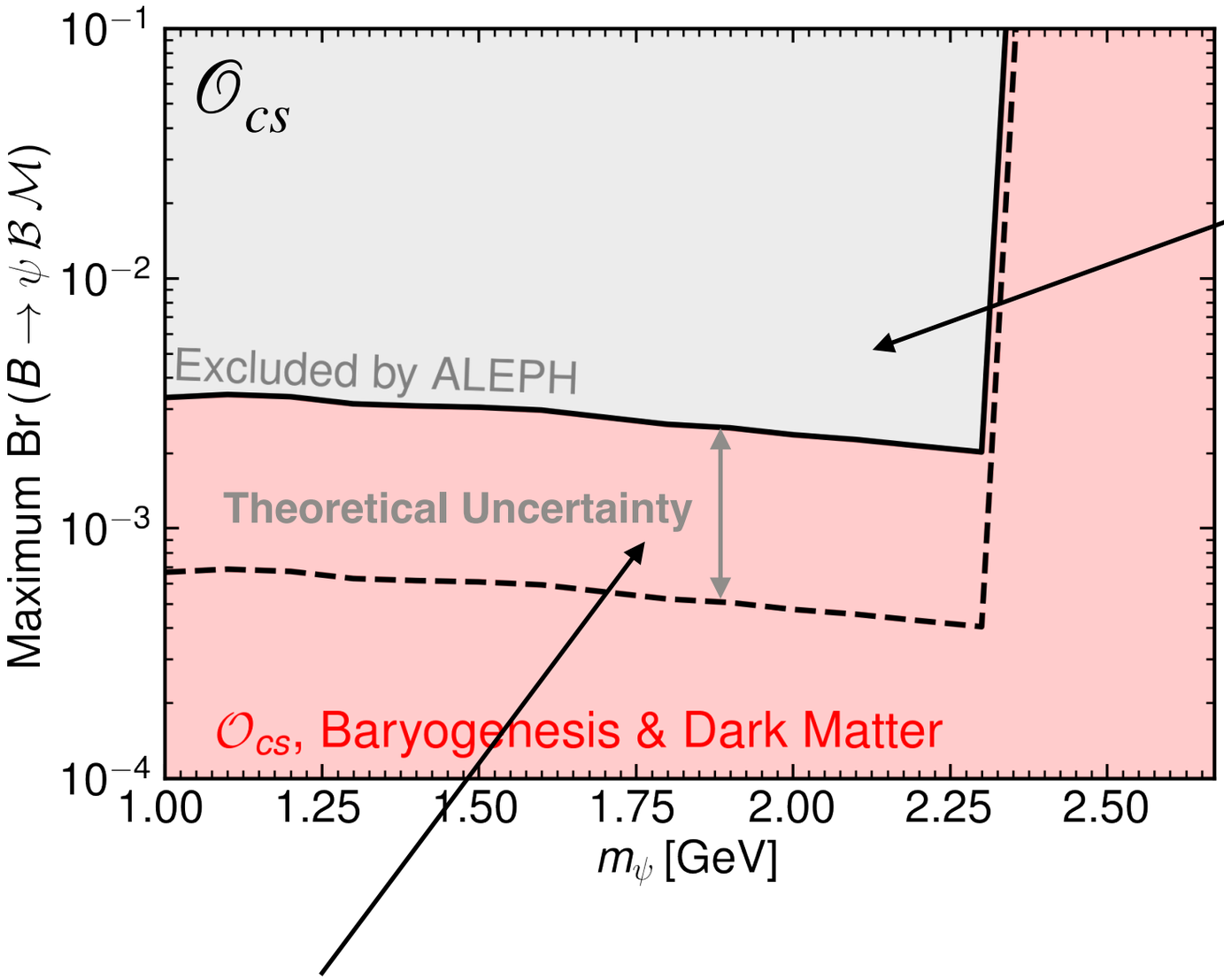
hep-ex/0010022



Our recast shows that:



ALEPH Constraints



Large missing energy at LEP from b decays

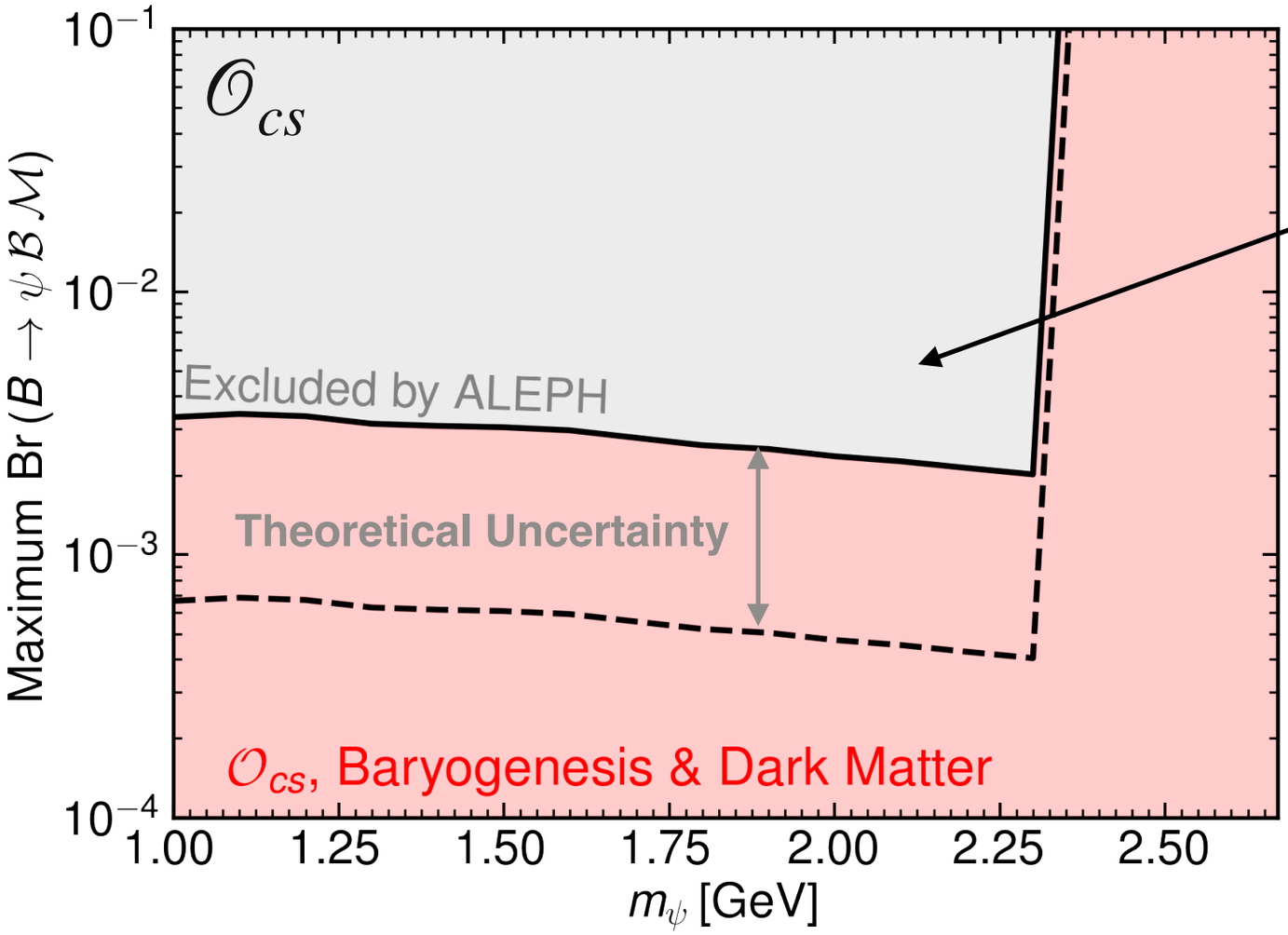
Important Uncertainty:

The missing energy spectrum in $\bar{b} \to \psi u d$ decays

We have calculated the missing energy spectrum at the parton level and without QCD corrections. A proper calculation including QCD corrections and the b momentum in the B meson would likely relax the constraints by a significant factor

In fact, the $b \to s\bar{\nu}\nu$ bound originally derived by Grossman, Ligeti and Nardi hep-ph/9510378, was later relaxed by a factor of 3 due to these effects! (see erratum of hep-ph/9510378)

Parameter Space



Large missing energy at LEP from b decays

Another possibility:

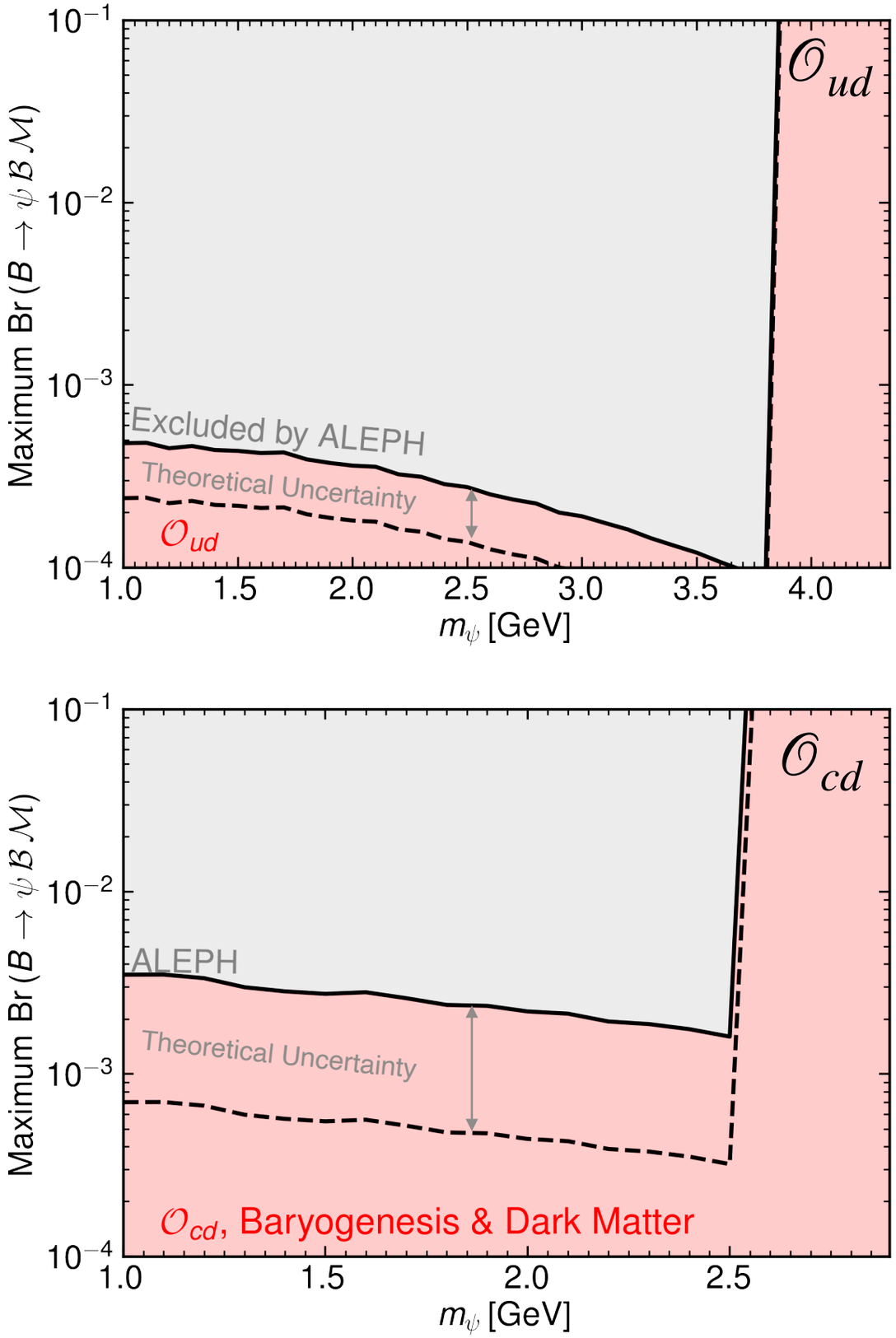
One can constrain exclusive 2-body decays, $B \to \psi \mathcal{B}$ to the $\mathrm{Br} \sim 10^{-4}$ level without theoretical uncertainties 😃

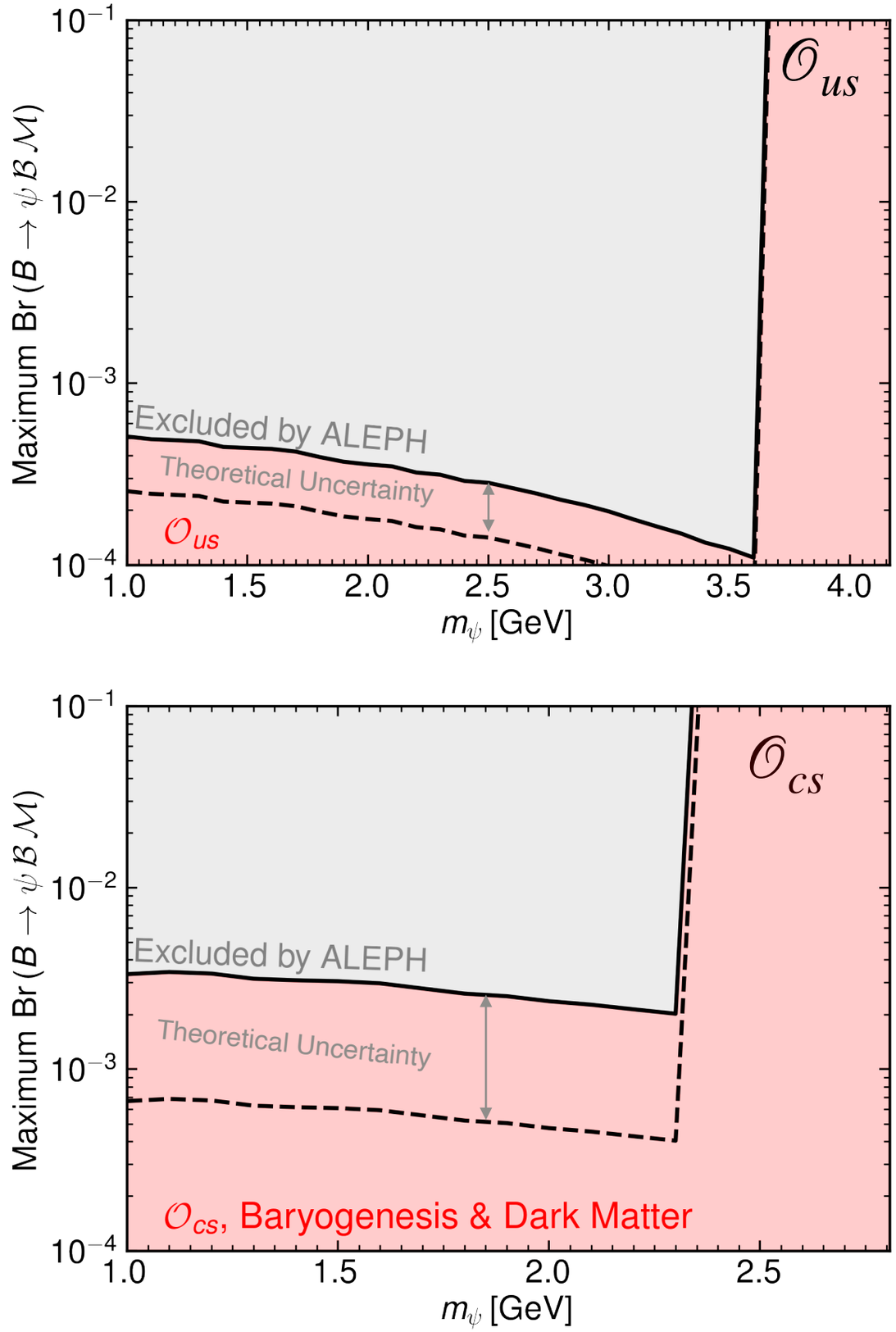
The problem is then that Baryogenesis only cares about $\bar{b} \to \psi u d$ and one expects many mesons in the final state

for instance, we know that:

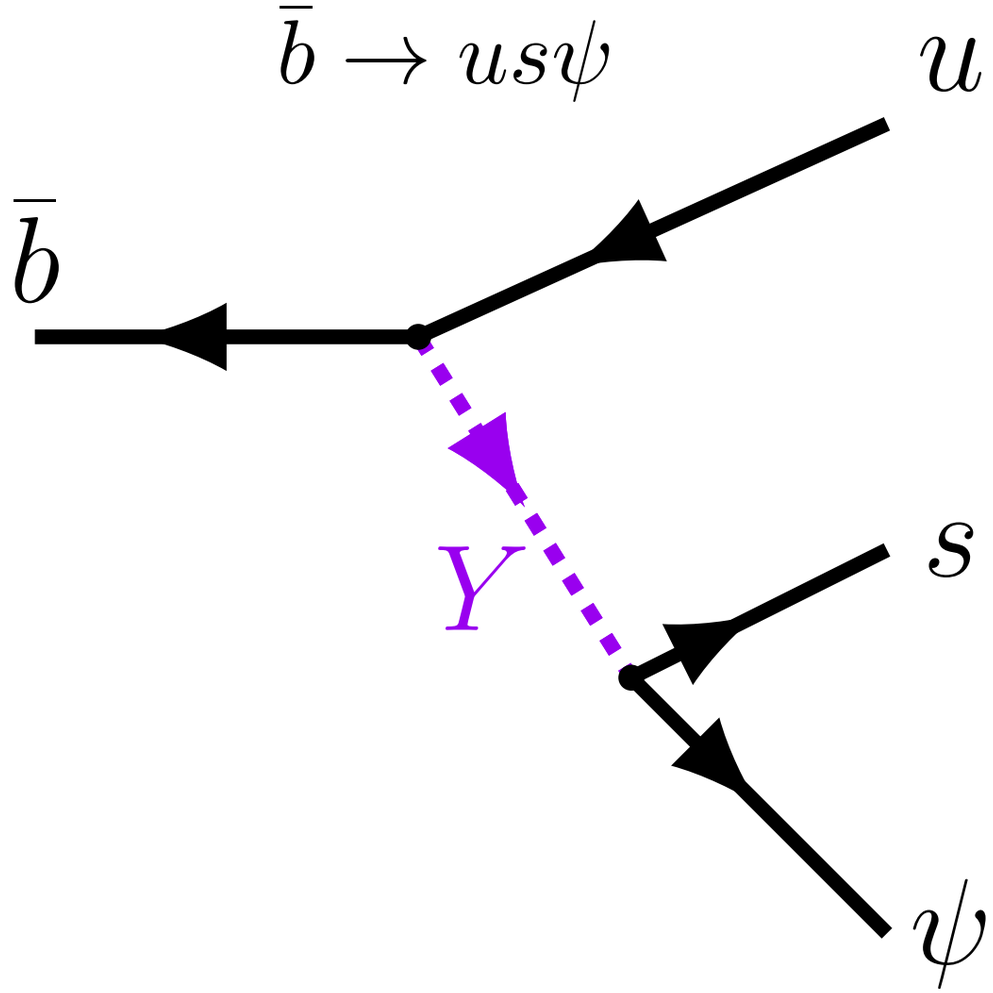
$$\frac{\mathrm{Br}(B^0 \to p\bar{p}K^+\pi^-)}{\mathrm{Br}(B^0 \to p\bar{p})} \simeq 500$$

Parameter Space





New Force Carrier



Y: Colored Triplet Scalar

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

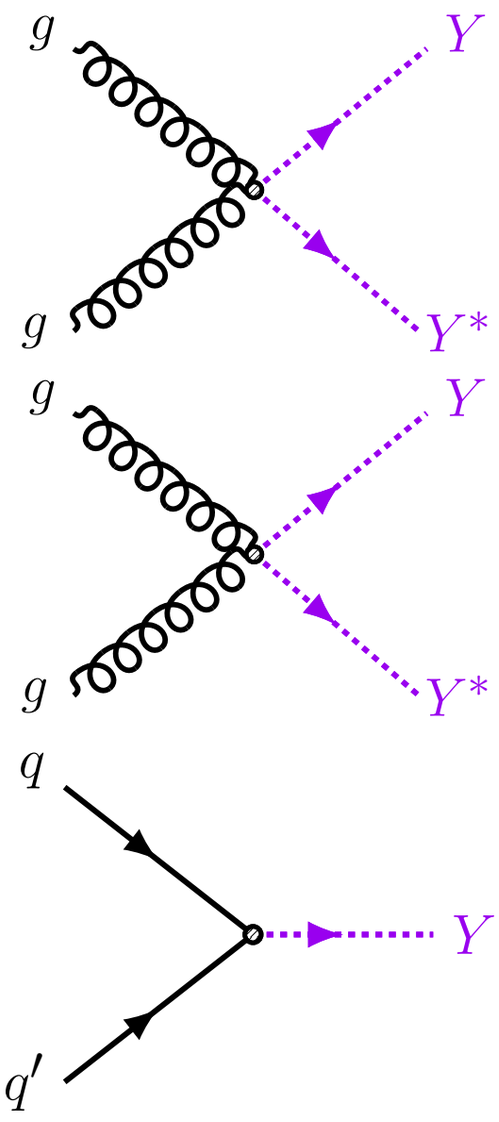
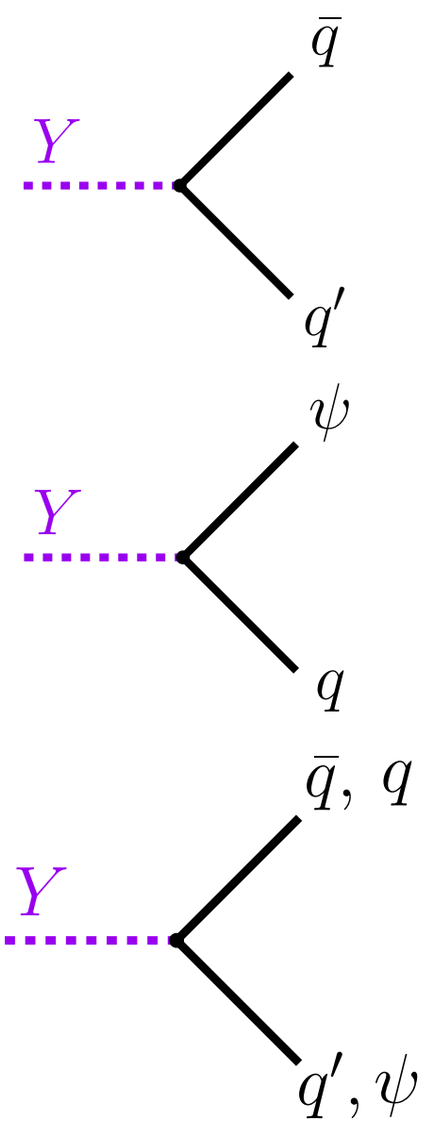
$$Y \sim (3, 1, 2/3)$$

Same Quantum Numbers as a SUSY squark!

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

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

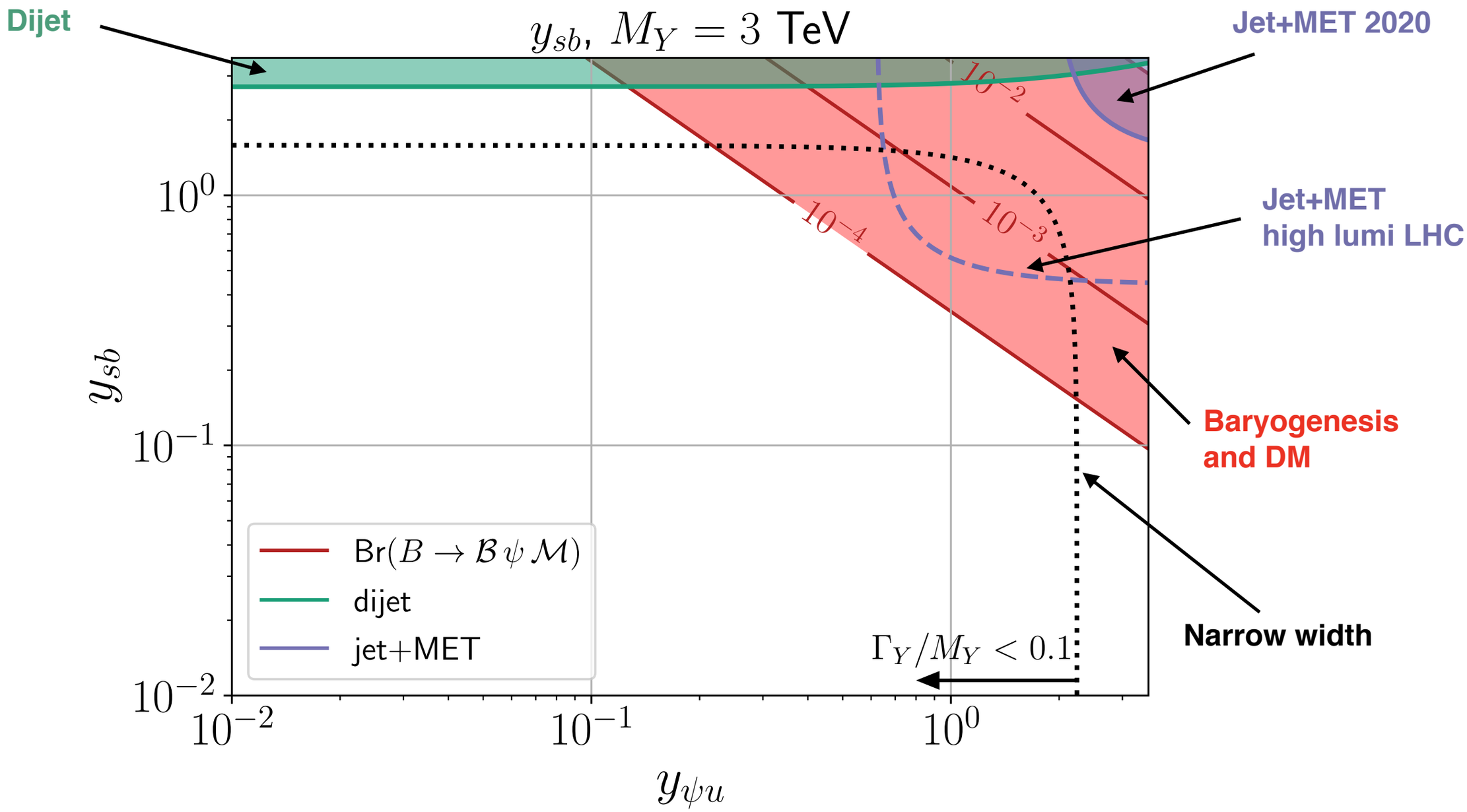
Squark Searches

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	$M_Y > 1\text{-}7$ TeV 1806.00843 (CMS)
		Monojet	$M_Y > 1\text{-}7$ TeV 1711.03301 (ATLAS)

We have recasted results from dijet and jet+MET searches

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

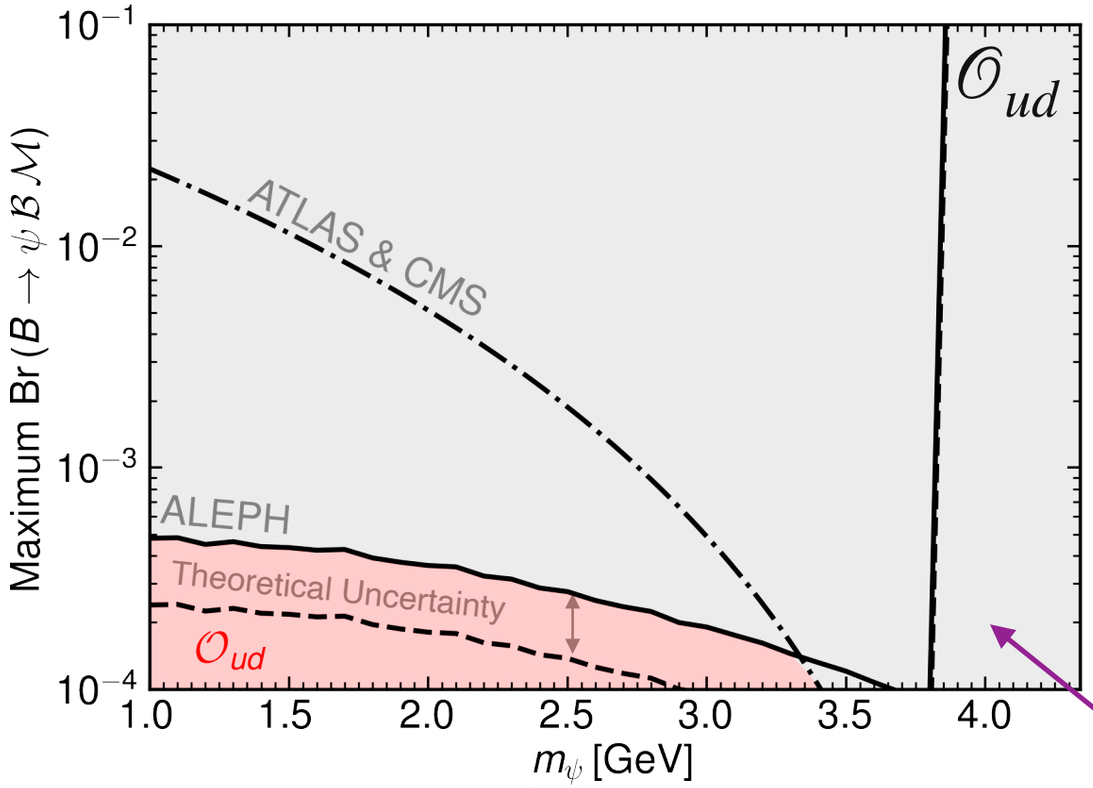
Squark Searches

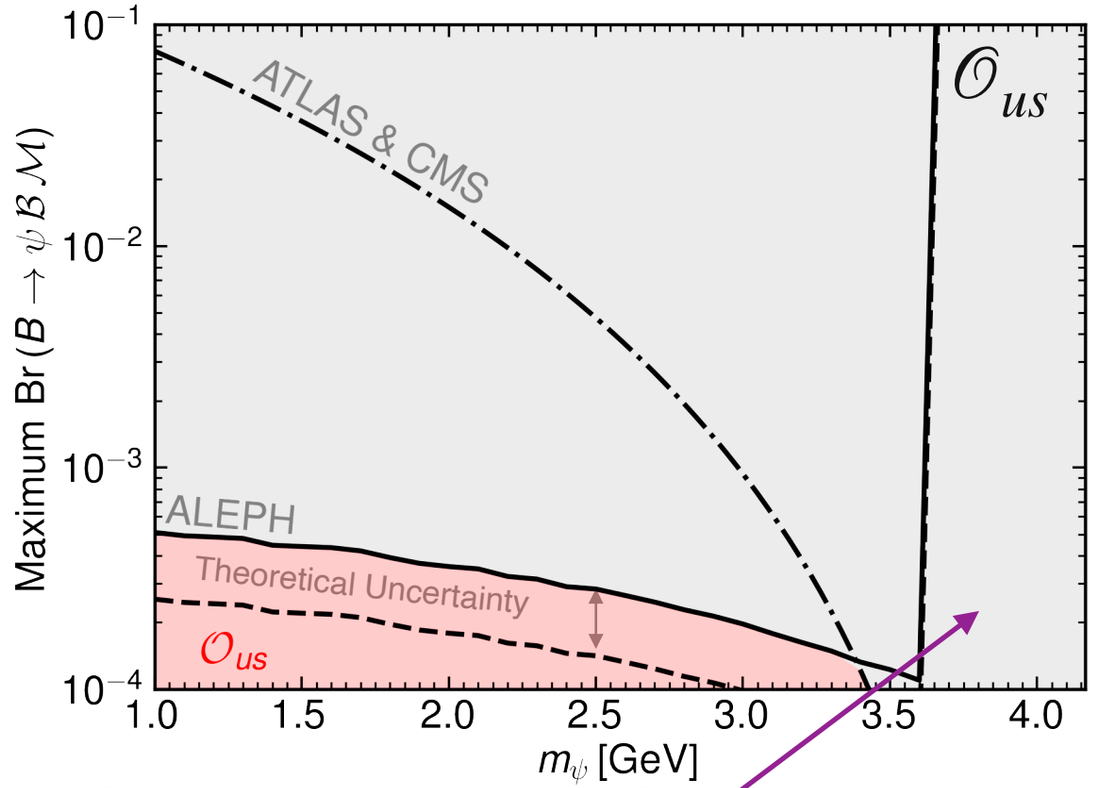


LHC 2020: $\mathrm{Br}\,(B \to \psi + \mathrm{Baryon} + \mathcal{M}) \lesssim 0.1$

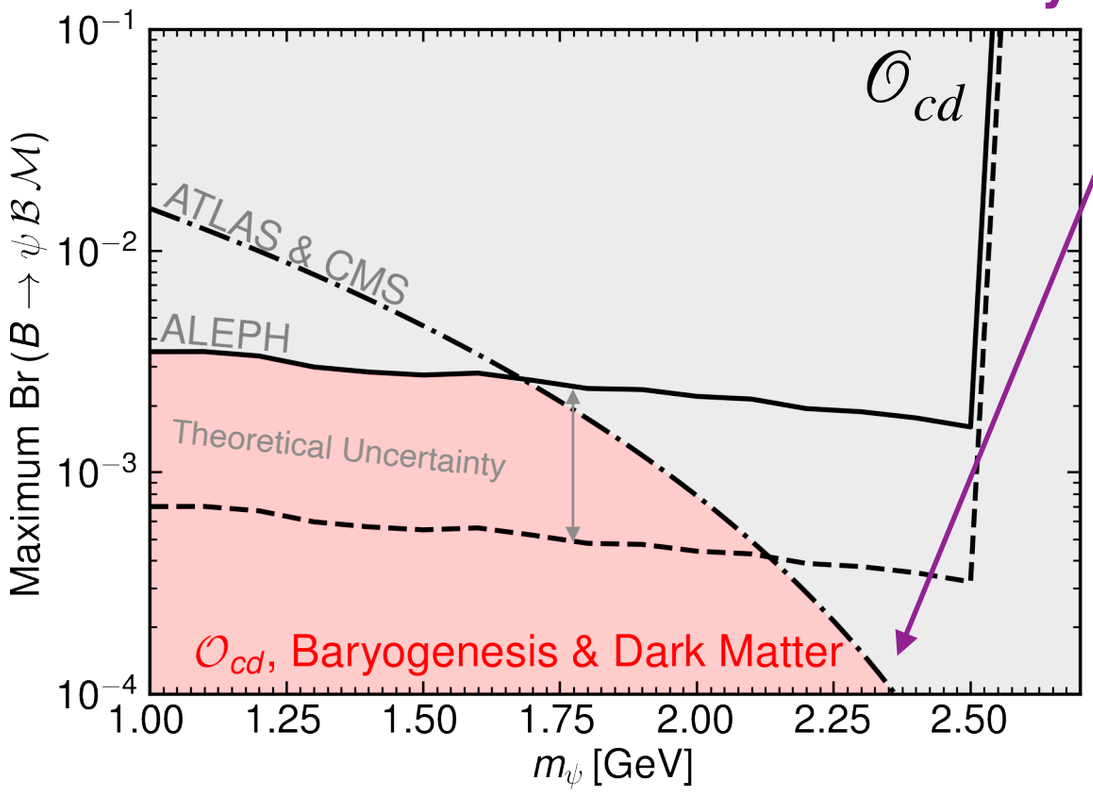
ATLAS & CMS have a great potential to detect the Y particle

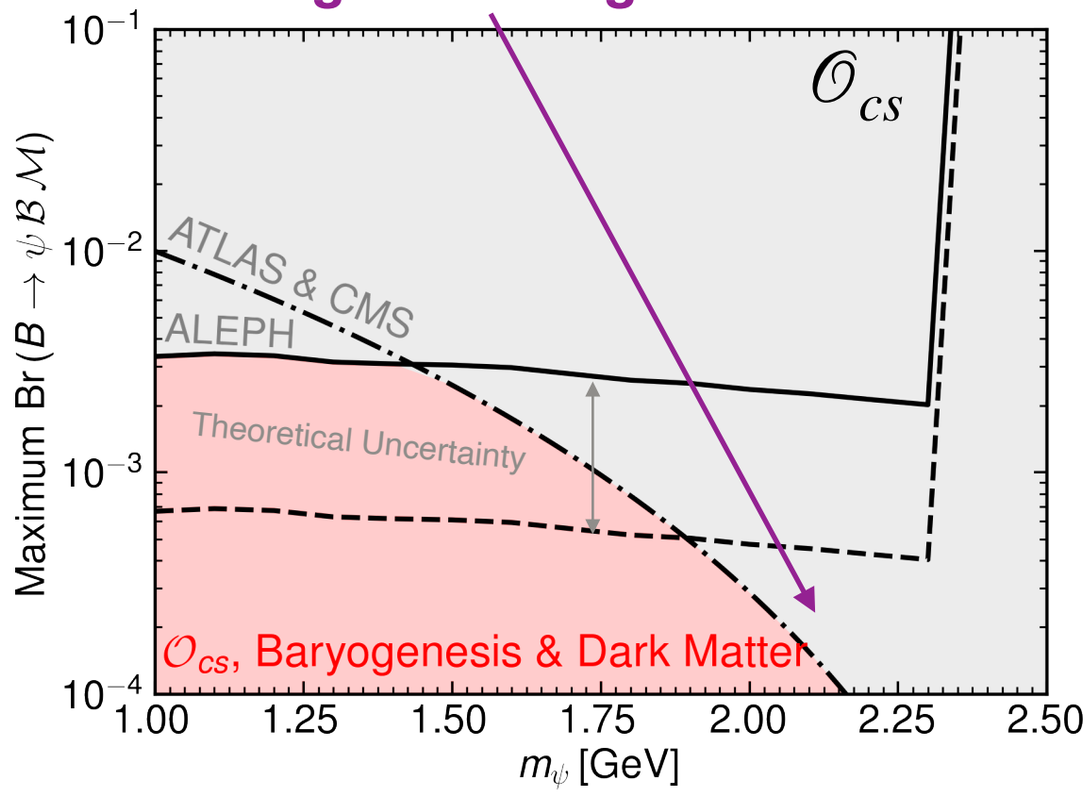
Parameter Space



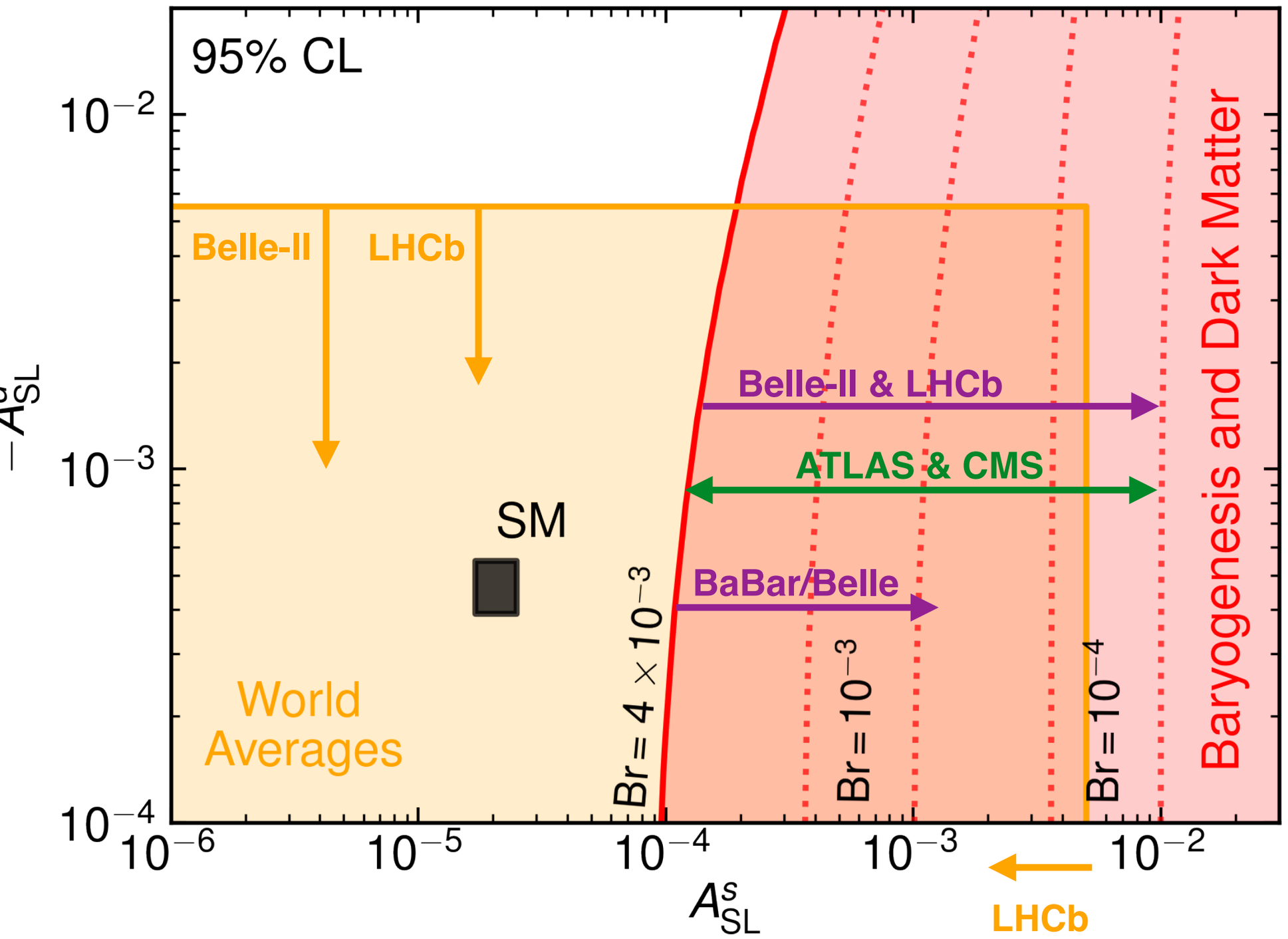


LHC constraints are key to constrain the high mass region





The B-Mesogenesis Parameter Space



Signatures

- **CP violation**
- **New b decays**
- **High pT jets and missing energy**

Arrows indicate projections for 2025

Conclusion: **B-Mesogenesis will be tested within 4 years!**

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** $A_{\rm SL}^q > 10^{-4}$
- **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 these processes at BaBar/Belle and Belle-II!

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

$$\mathrm{Br}(B \to K \bar{\nu} \nu) \sim 10^{-6} - 10^{-5}$$

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?**

- **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

- **New b decays**

  It is very important to relate $\bar{b} \to \psi u d$ (Inclusive) **to** $B \to \psi + \text{Baryon}$ (Exclusive)

  We performed a rather rough phase space calculation

  A QCD sum rule or Lattice calculation would be very valuable

  A precision calculation of the missing energy spectrum would be useful too

- **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 new** $b \to \psi \bar{\psi} d$ **decays**

Experiment

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

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

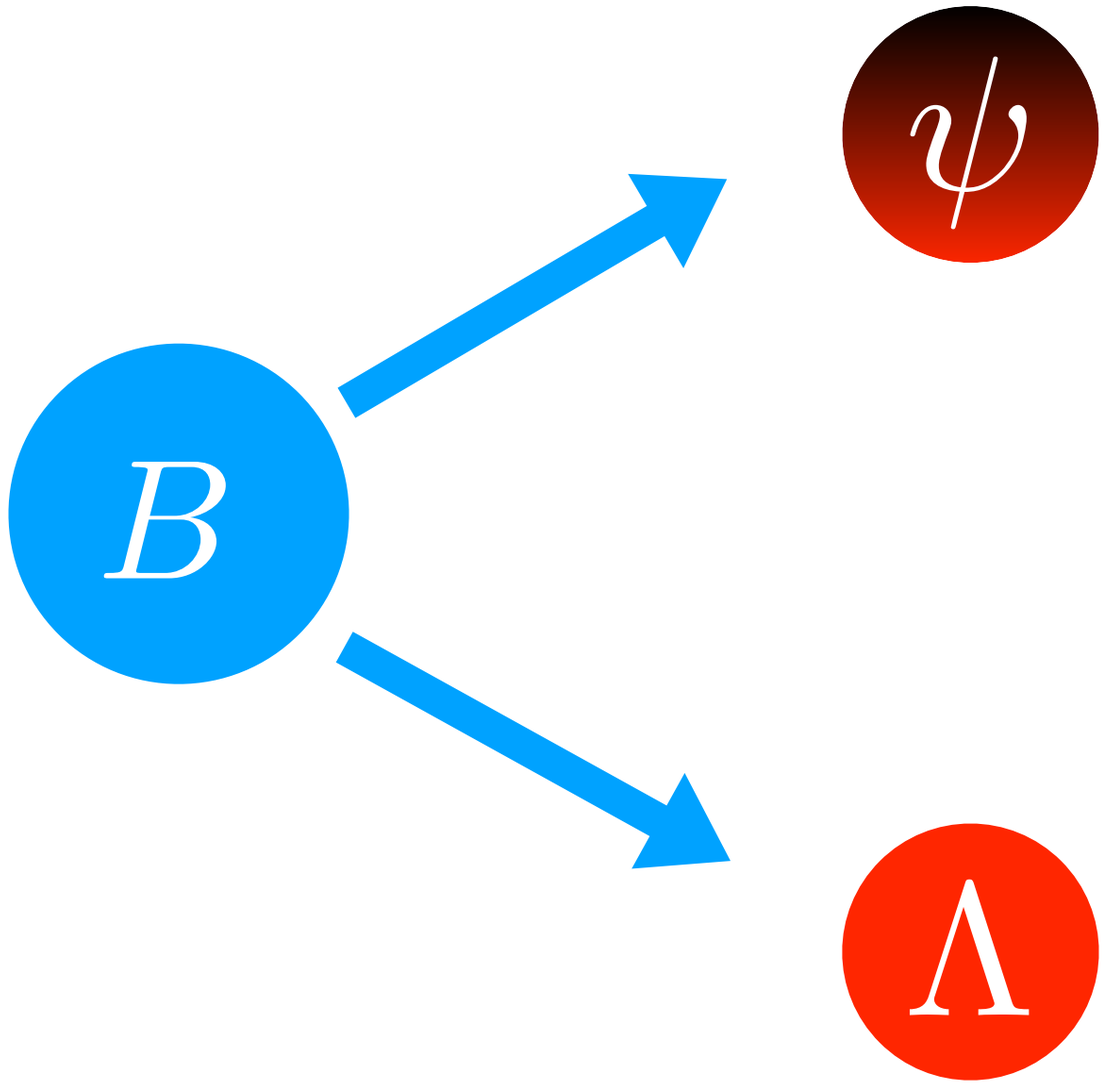
The B-Mesogenesis Team

Thank You!

Gonzalo Alonso
McGill

Gilly Elor
Mainz

Ann Nelson
1958-2019



Some References

Theory

Baryogenesis from Oscillations of Charmed or Beautiful Baryons
Aitken, McKeen, Nelson and Neder, 1708.01259

Baryogenesis and Dark Matter from B Mesons
Elor, Escudero and Nelson, 1810.00880

A Supersymmetric Embedding of B-Mesogenesis
Alonso-Álvarez, Elor, Nelson and Xiao, 1907.10612

Experiment

Collider Implications of B-Mesogenesis:
Alonso-Álvarez, Elor and Escudero, 2101.02706

LHC-b sensitivity to the relevant decays:
Xabier Cid Vidal et al. 2106.12870