Collider Implications of B-Mesogenesis

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Based on:

arXiv:1810.00880, PRD 99, 035031 (2019)
with: Gilly Elor & Ann Nelson
arXiv:2101.02706, PRD 104, 035028 (2021) [Editor suggestion]
with: Gonzalo Alonso-Álvarez & Gilly Elor

Physics of the Flavourful Universe
22-09-2021

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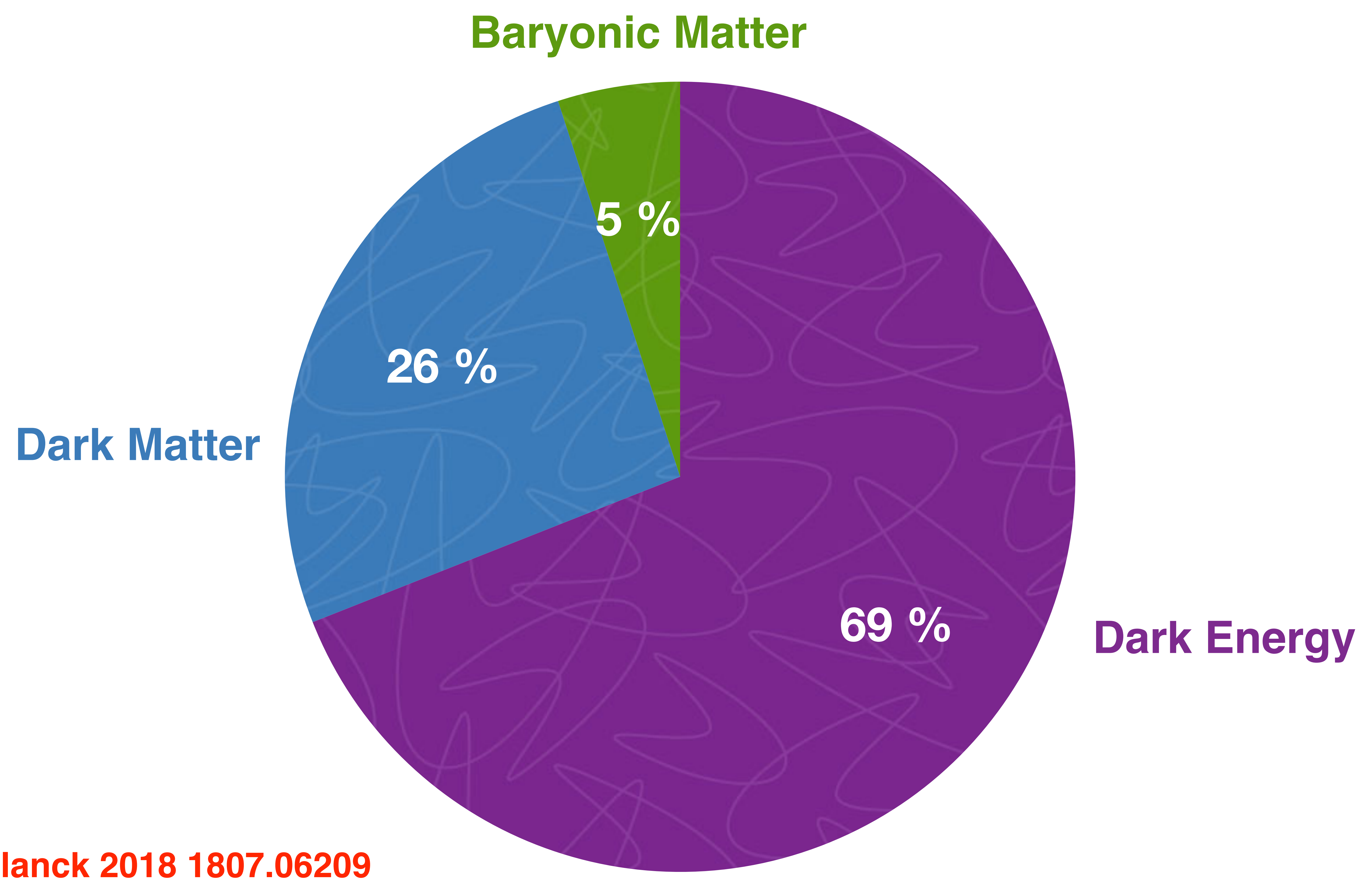
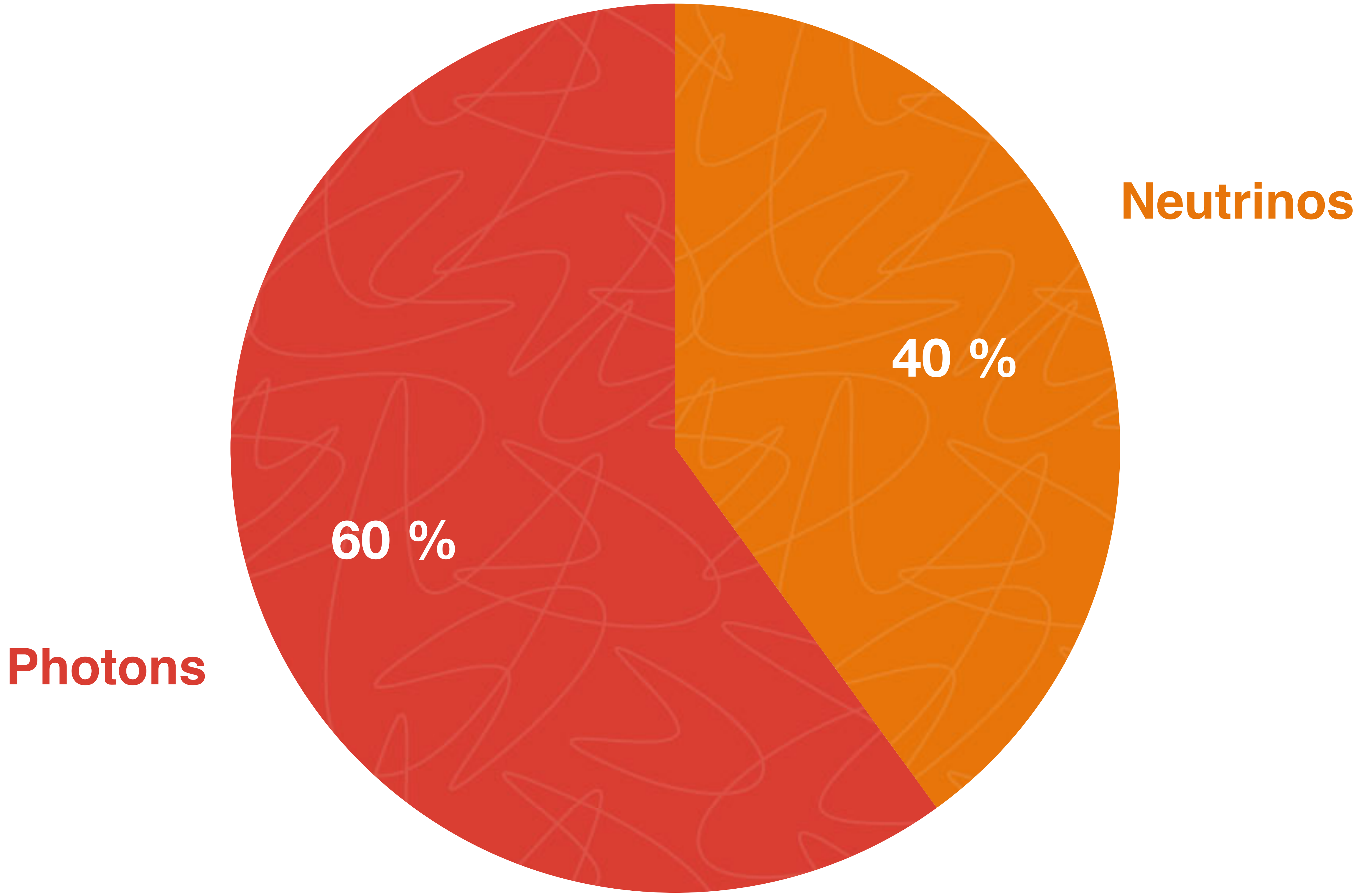
The Universe

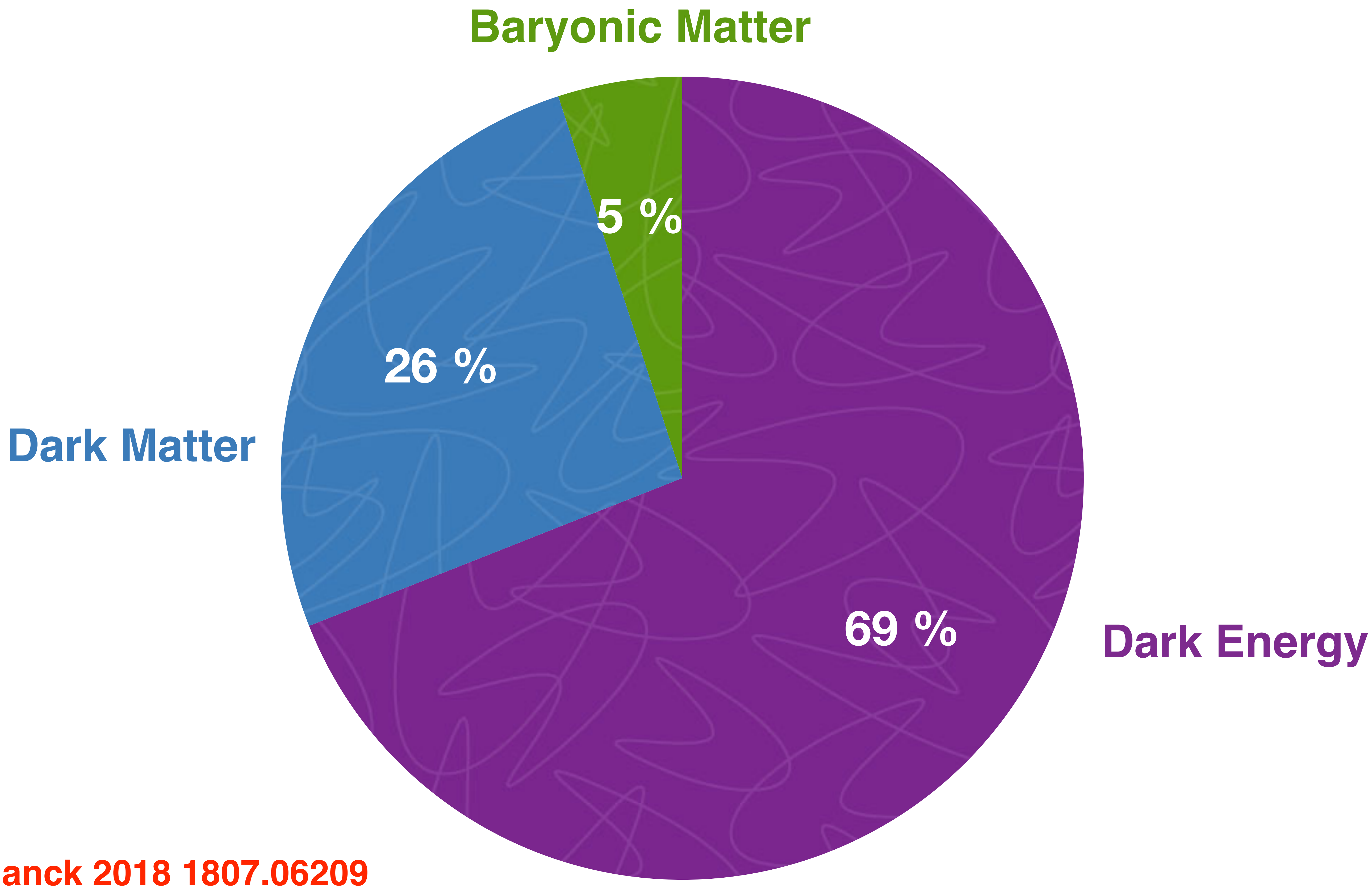


Planck 2018 1807.06209

SM Prediction:



The Universe



Planck 2018 1807.06209

B-Mesogenesis: Baryogenesis and Dark Matter from B Mesons

<u>arXiv:1810.00880</u> **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

<u>arXiv:2101.02706</u> **Alonso-Álvarez, Elor & Escudero**

Outline

1) **B-Mesogenesis**

2) **Collider Implications:**

   a) **CP violation in the B meson system**
   b) **Missing Energy decays of B mesons**
   c) **High pT jets + Missing Energy**

3) **Conclusions**

Why Baryogenesis with B-Mesons?

1) B-Mesons are heavy

B-Mesons can decay into baryons $m_B > 2m_p$

2) Large CP violation in the neutral B mesons:

Already in the SM, the mixing induced CP asymmetry is:

$$|A_{\rm CP}| \simeq 10^{-5} - 10^{-3}$$

and we want to explain a Universe with $\dfrac{n_b - n_{\bar{b}}}{n_\gamma} \simeq 6 \times 10^{-10}$

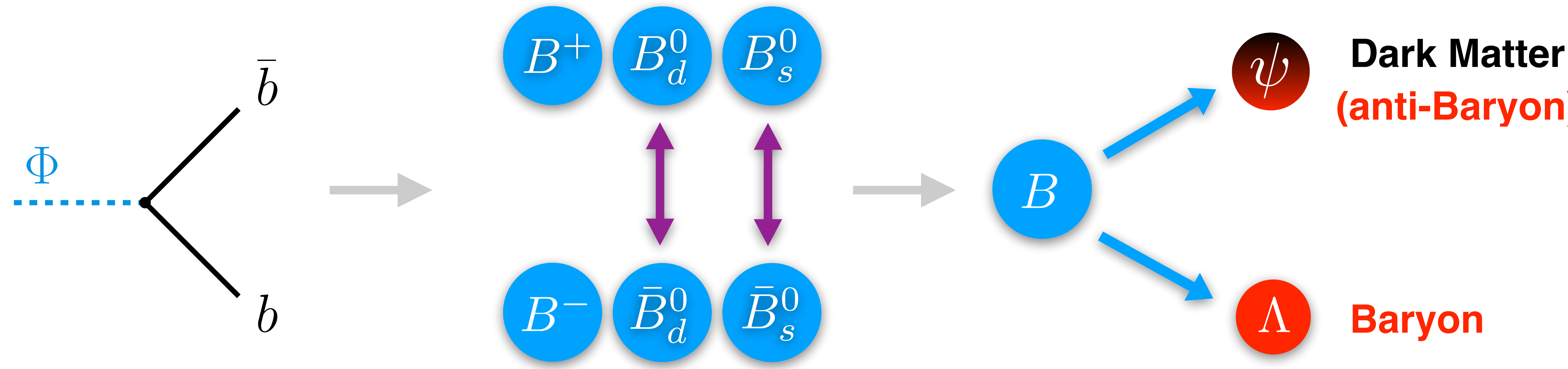
3) Some of its decays are fairly unconstrained!

Back in 2018: $\text{BR}(B \to \text{Baryon} + \text{missing energy}) \lesssim 10\,\%$

As of today: $\text{BR}(B \to \text{Baryon} + \text{missing energy}) \lesssim 0.5\,\%$

B-Mesogenesis

Out of equilibrium late time decay — **CP violating oscillations** — **B-mesons decay into Dark Matter and hadrons**



$T_R \sim 15\,\mathrm{MeV}$ — $A_{\mathrm{SL}}^d \;\; A_{\mathrm{SL}}^s$ — $\mathrm{Br}\,(B \to \psi + \mathcal{B} + \mathcal{M})$

Baryogenesis and **Dark Matter**

$$Y_B = 8.7 \times 10^{-11} \qquad \Omega_{\mathrm{DM}} h^2 = 0.12$$

With:

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

Distinctive Collider Signatures

1) Extra CP violation in B Meson decays

a) Semileptonic asymmetries

b) CP violation in tree level $b \to c\bar{c}s$ and $b \to \tau\bar{\tau}s$ decays

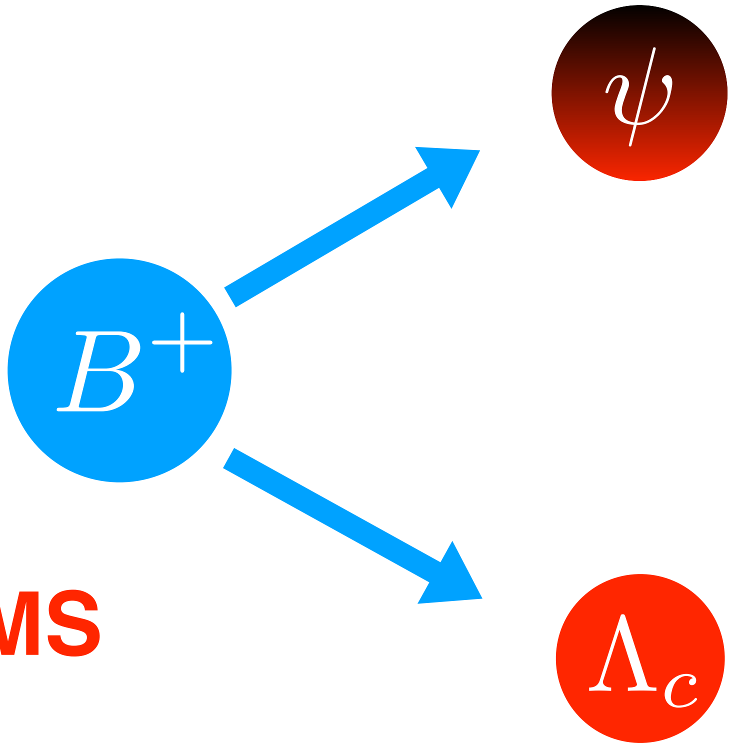
2) New B Meson decay into ME and a Baryon

a) Constraints from B-factories

b) Constraints from ALEPH

c) Sensitivity from LHCb

d) Indirect constraints from ATLAS & CMS



Indirect CP violation

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

$$A_{\rm SL}^d|_{\rm SM} = (-4.7 \pm 0.4) \times 10^{-4}$$
$$A_{\rm SL}^s|_{\rm SM} = (2.1 \pm 0.2) \times 10^{-5}$$

Lenz & Tetlalmatzi-Xolocotzi 1912.07621

Measurements

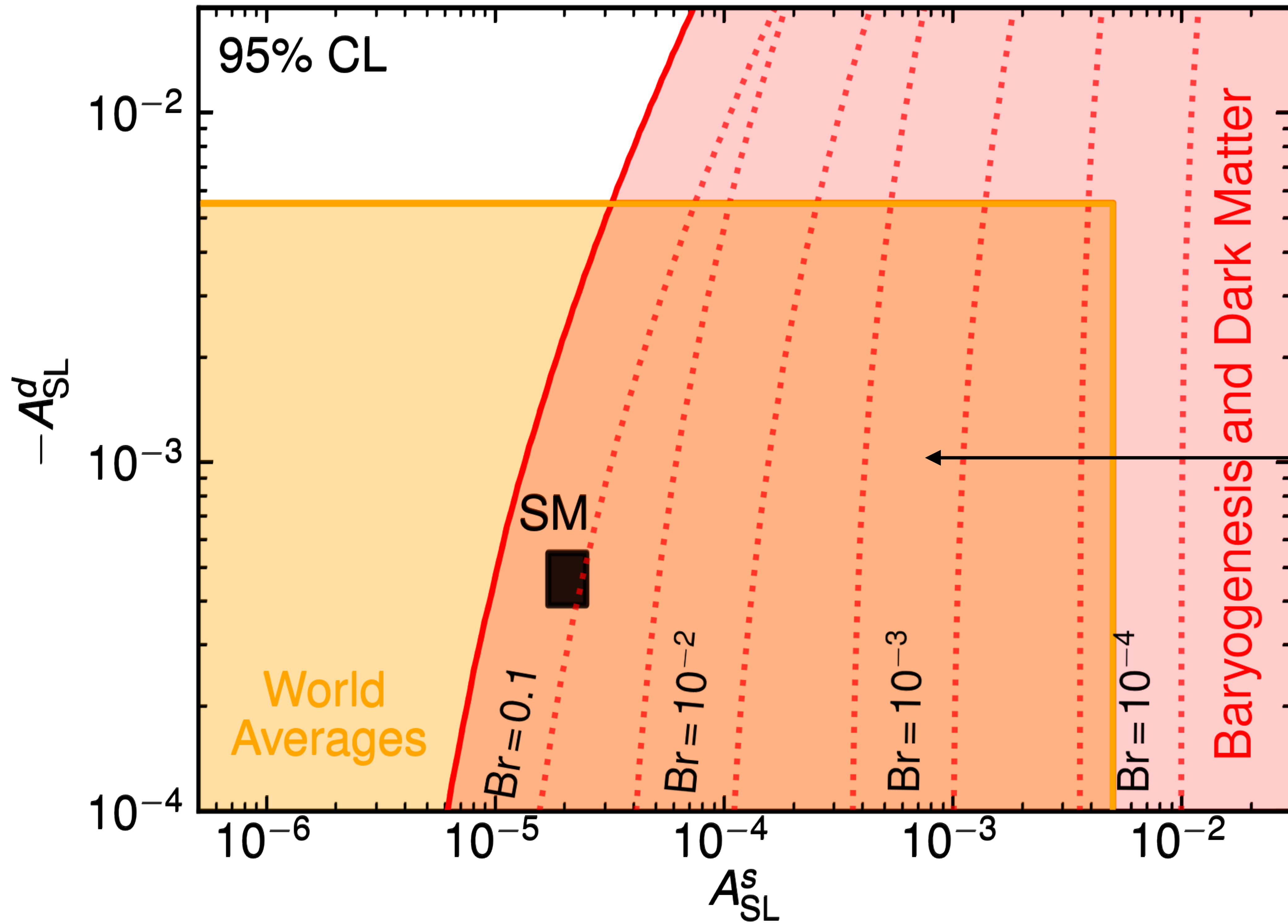
$$A_{\rm SL}^d = (-2.1 \pm 1.7) \times 10^{-3}$$
$$A_{\rm SL}^s = (-0.6 \pm 2.8) \times 10^{-3}$$

World averages (HFLAV)

Baryogenesis

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

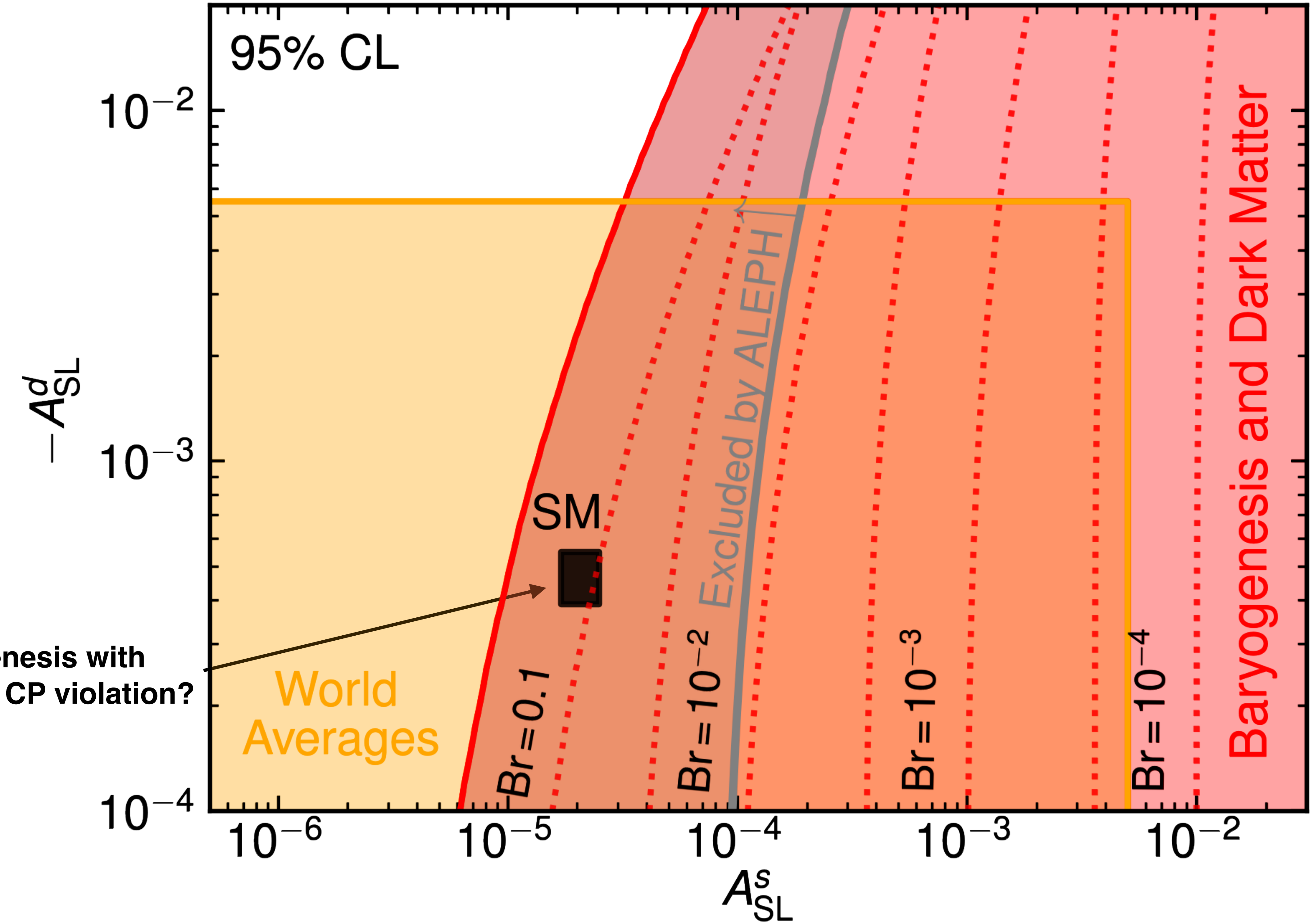
Parameter Space



The Bs Meson dominates the Baryon asymmetry because $\Delta M_s / \Delta M_d \sim 35$

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

Parameter Space



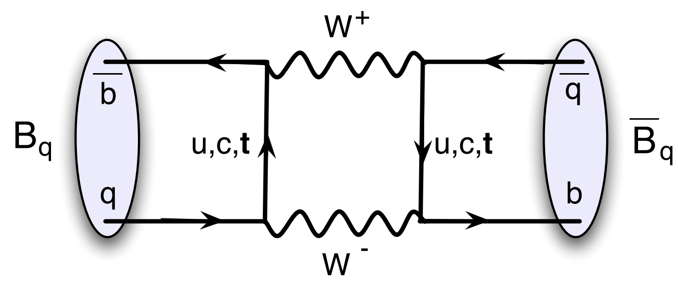
Baryogenesis with only SM CP violation?

ALEPH bound implies: $A_{\rm SL}^{q} > 10^{-4}$

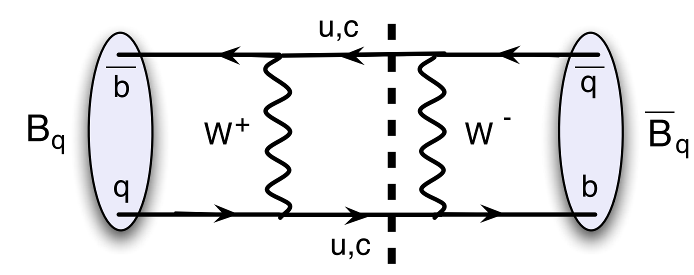
CP violation in mixing

- **Baryogenesis requires:** $A^q_{\rm SL} > 10^{-4}$
- **CP violation in mixing:** $\mathscr{H} = \mathscr{M} - i\Gamma/2$

SM: $M_{12} \propto$



$\Gamma_{12} \propto$



BSM: Many models can modify these quantities: *Z's* (even at tree level), Leptoquarks etc ...

- CP violation in mixing requires a relative phase between Γ^q_{12} and M^q_{12} $\quad A^q_{\rm SL} = -\frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi^q_{12}$
- The phase in M^q_{12} is constrained by interference between decay and mixing, in e.g. $B_s \to J/\psi\,\phi$

see Vladimir's talk this morning

- The phase in Γ^s_{12} is largely unconstrained. In the presence of modified $b \to c\bar{c}s$ decays can be as large as: $|A^q_{\rm SL}| \lesssim 1.5 \times 10^{-3}$

Lenz et al.
1912.07621
1910.12924

- Similar results expected for $b \to \tau\bar{\tau}s$ decays: $|A^s_{\rm SL}| \lesssim 10^{-3}$

Bobeth & Haisch
1109.1826

CP violation in mixing

- **Baryogenesis requires:** $A^q_{\rm SL} > 10^{-4}$

Conclusions:

- **Large CP asymmetries can arise beyond the Standard Model**
- **They require modifications to $b \to c\bar{c}s$ decays or $b \to \tau\bar{\tau}s$ decays**

Model Building:

- **$b \to c\bar{c}s$ decays can be altered by the same particle that triggers the $B \to \text{Baryon} + \psi$ decay Y ~ (3,1,-1/3):**

$$\mathscr{L}_{-1/3} = -\sum_{i,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi} + \mathrm{h.c.}$$

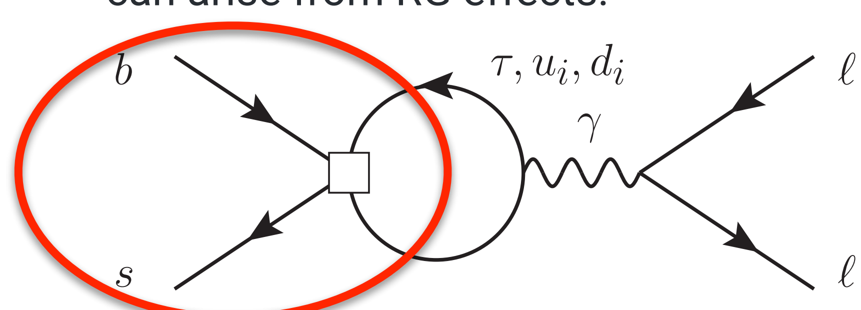
Connection with B-Anomalies?

- **RGE running can generate $C_9^{\rm univ}$!**

Taken from Peter's talk this morning:

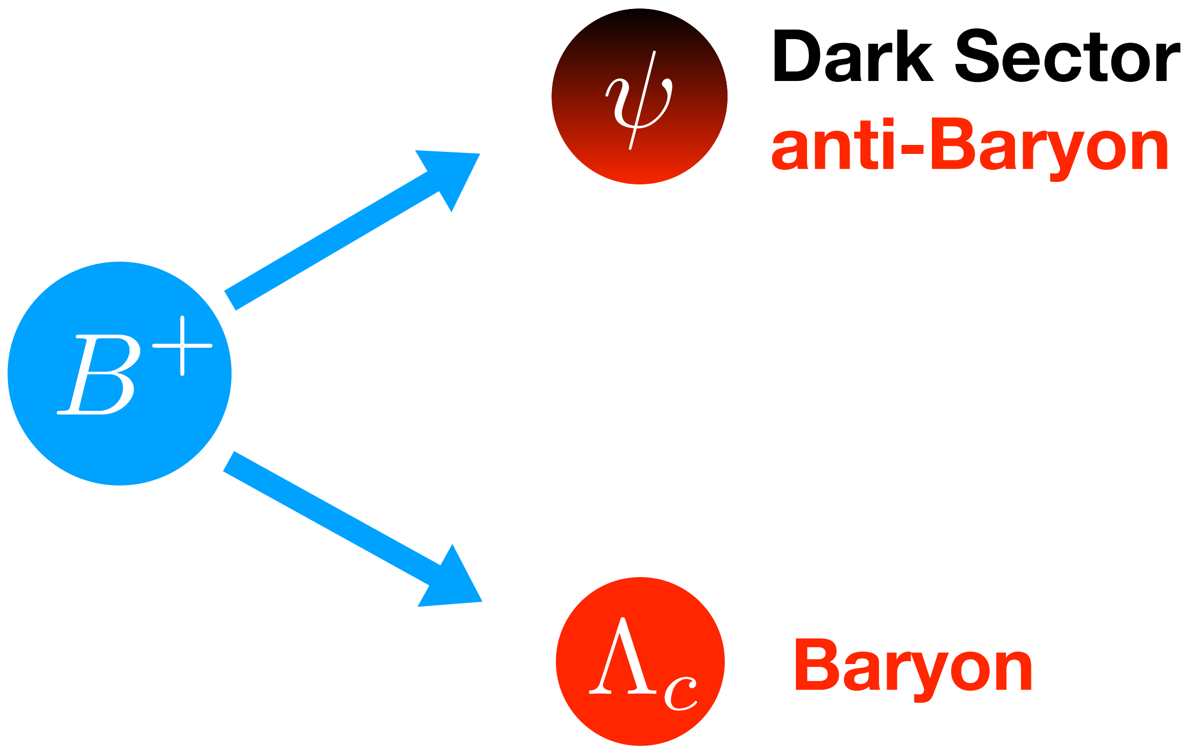
- Slight preference for **non-zero $C_9^{\rm univ.}$**
  - could be mimicked by hadronic effects
  - can arise from RG effects:

$A^q_{\rm SL} > 10^{-4}$ ⟷ **??**



Bobeth, Haisch, arXiv:1109.1826
Crivellin, Greub, Müller, Saturnino, arXiv:1807.02068

New B-Meson decay



Baryogenesis requires:

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

(Inclusive)

Parameter space is: $1.0\,\mathrm{GeV} < m_\psi < 4.0\,\mathrm{GeV}$

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

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

*Quarks are right handed

Constraints on the new Decays

1) Direct searches at B-factories

Sensitivity should be at the $\mathrm{Br} \sim 10^{-5}$ level given that $\mathrm{Br}(B \to K\bar{\nu}\nu) \sim 10^{-6} - 10^{-5}$

Indeed, first search using Belle data was released two weeks ago at PANIC and found:

Belle 2021 $\mathrm{Br}(B \to \psi + \Lambda) \lesssim 3 \times 10^{-5}$

Further searches under study for the rest of the operators at BaBar/Belle and Belle-II

2) Searches for b-decays with large missing energy at ALEPH

We recasted and old ALEPH search (hep-ex/0010022) for b-decays with large missing energy

Found relevant constraints in the range: $\mathrm{Br}(B \to \psi + \mathrm{Baryon} + \mathscr{M}) \lesssim 10^{-4} - 0.5\,\%$

3) Searches at LHCb for resonant B mesons and b-flavored Baryons

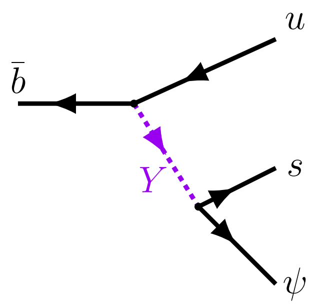
LHCb has recently been shown to be able to target our decays, Cid-Vidal et al. 2106.12870

Projected sensitivities at the level

$$\mathrm{Br}(B \to \psi + \mathrm{Baryon}^\star) \sim 10^{-7}$$
$$\mathrm{Br}(\Lambda_b^0 \to \psi + \mathrm{Mesons}) \sim 10^{-5}$$

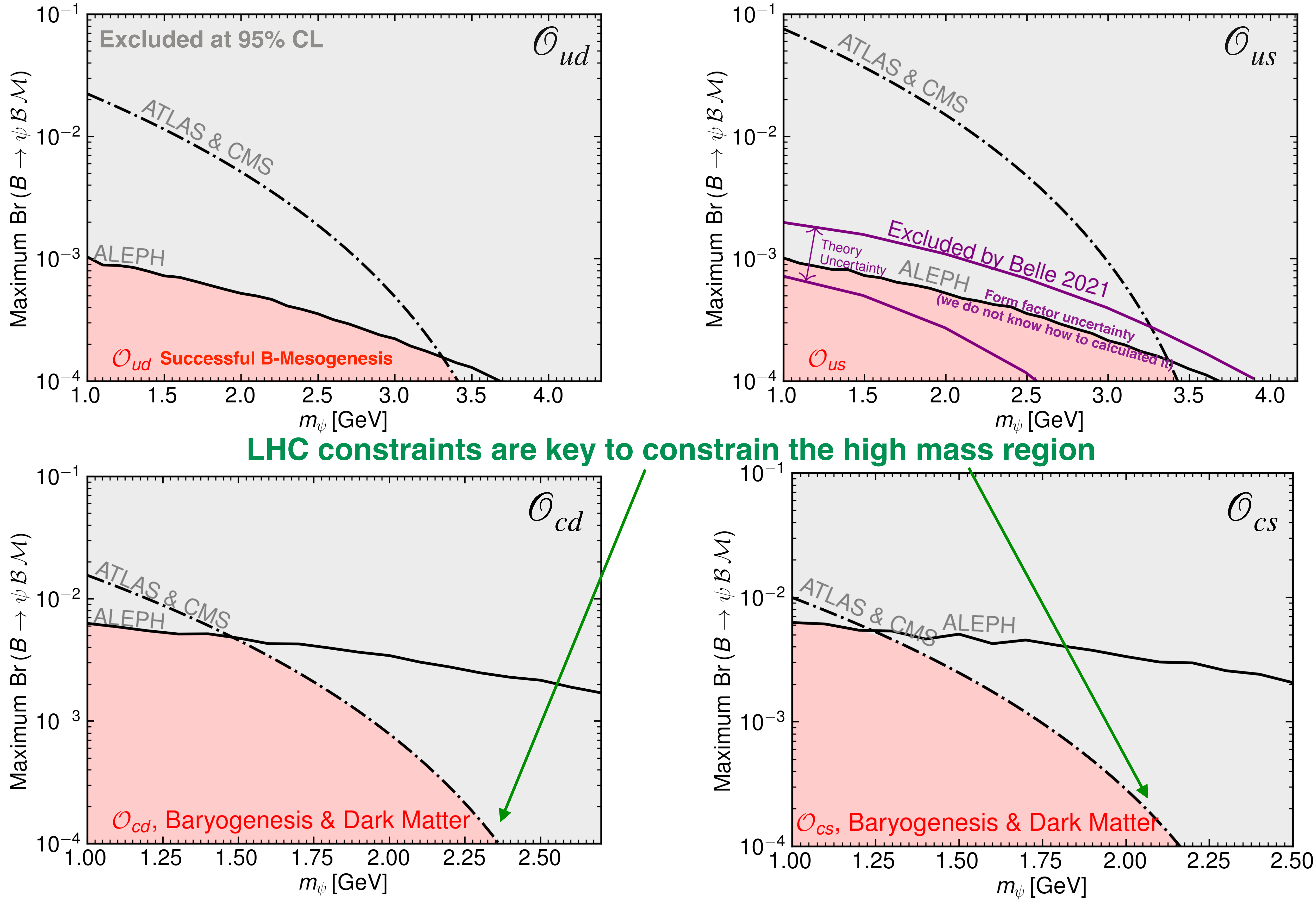
4) Indirect constraints from ATLAS & CMS on TeV-scale triplet scalars

ATLAS and CMS can constraint the mediator needed to trigger our decays

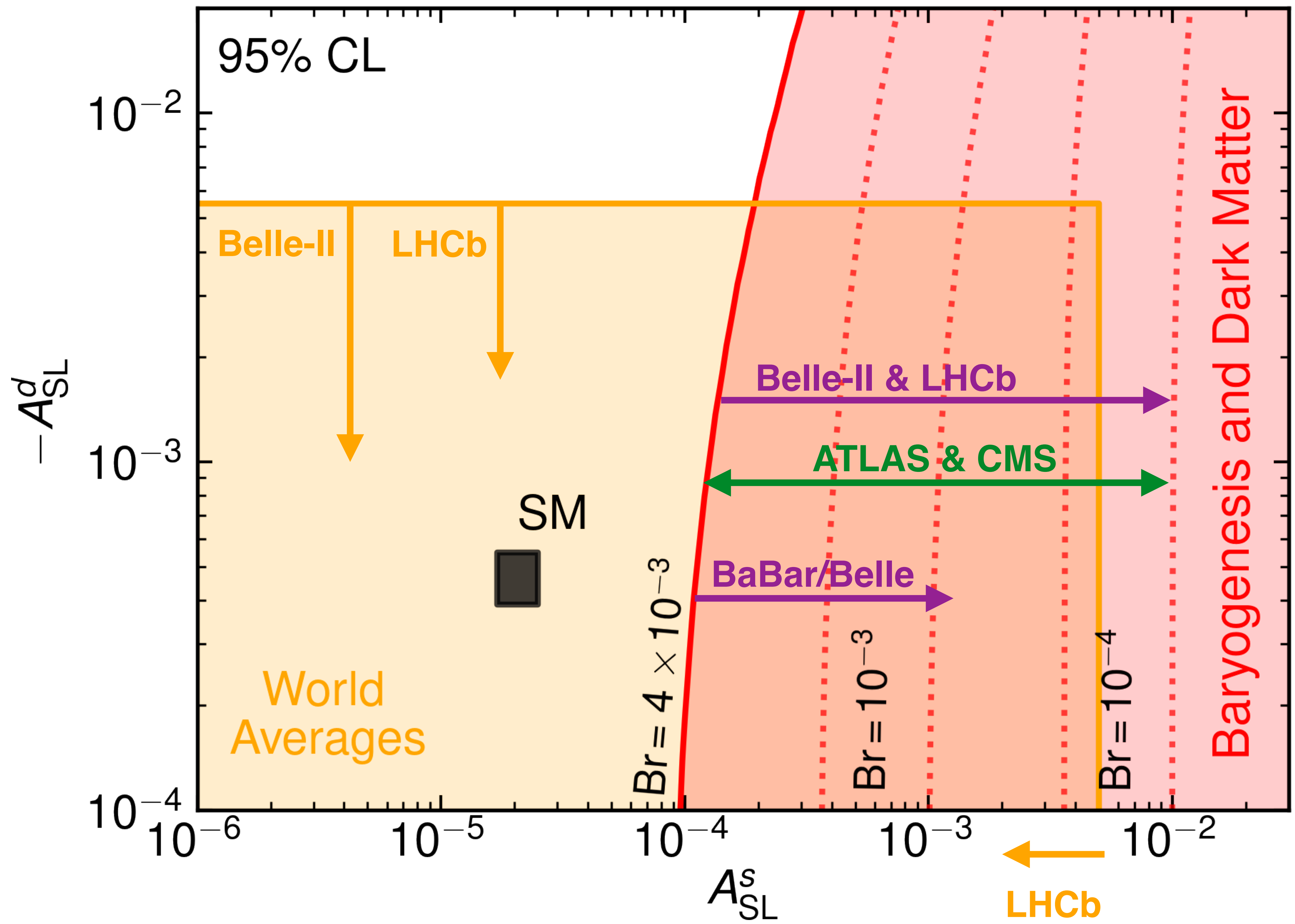


Our recast of various dijet [CMS-1806.00843] and jet+MET[1711.03301 (ATLAS)] renders complementary constraints at the level: $\mathrm{Br}(B \to \psi + \mathrm{Baryon} + \mathscr{M}) \lesssim 10^{-4} - 10\,\%$

Parameter Space



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**

Distinctive experimental signatures:

- **Neutral and charged B mesons decay into baryons and missing energy**

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

- **Positive leptonic asymmetry in B meson decays** $A^q_{\text{SL}} > 10^{-4}$

As of today we know:

$\text{Br}(B \to \psi + \text{Baryon} + \mathscr{M}) \lesssim 6 \times 10^{-3}$ **From ALEPH + ATLAS & CMS**

$\text{Br}(B \to \psi + \Lambda) < 3 \times 10^{-5}$ **From Belle 2021**

$A^q_{\text{SL}} \lesssim (2-3) \times 10^{-3}$ **From LHCb, ATLAS, CMS, BaBar & Belle**

B-Mesogenesis will be tested at current collider experiments!

Outlook

Theory/Model Building

Are the flavor anomalies in B-decays related to our required positive semileptonic asymmetry?

Given the relevance of $b \to c\bar{c}s$ and/or $b \to \tau\bar{\tau}s$ decays to our scenario

Flavor/QCD Pheno

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

This is critical in order to asses the power of searches at B-factories

Experiment

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

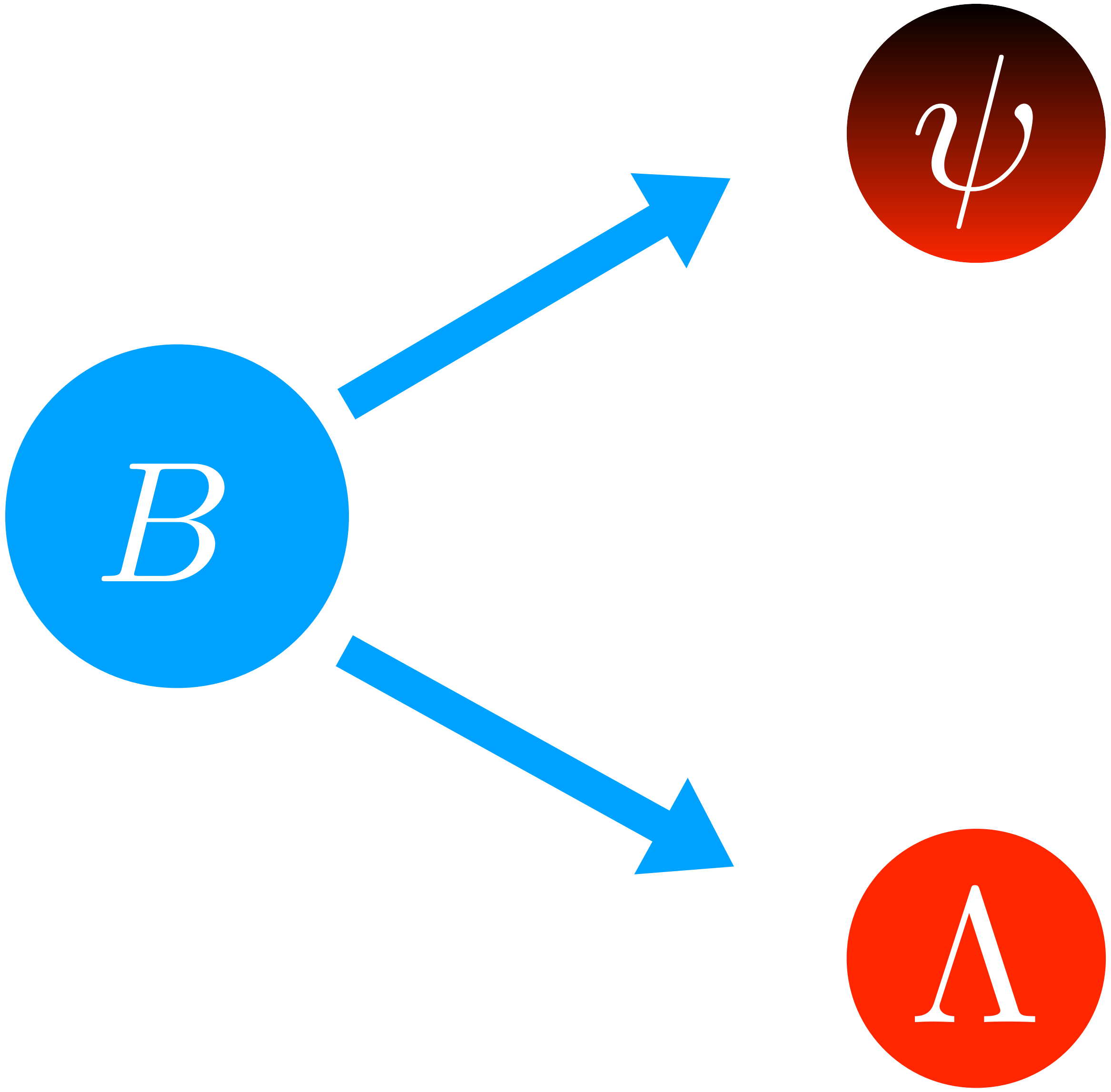
$$\mathrm{Br}\left(B \to \psi + \mathrm{Baryon}\right)$$

The rest of the B-Mesogenesis Team

Gonzalo Alonso (McGill)

Ann Nelson 1958-2019

Thank You!



Back Up

Constraints on the new Decays

4 Ways:

1) Direct searches at B-factories
2) Searches for b-decays with large missing energy at ALEPH
3) Searches at LHCb for resonant B mesons and b-flavored Baryons
4) Indirect constraints from ATLAS & CMS on TeV-scale triplet scalars

1) Direct searches at B-factories

B-factories should have sensitivities at the $\mathrm{Br} \sim 10^{-5}$ **level given that** $\mathrm{Br}(B \to K\bar{\nu}\nu) \sim 10^{-6} - 10^{-5}$

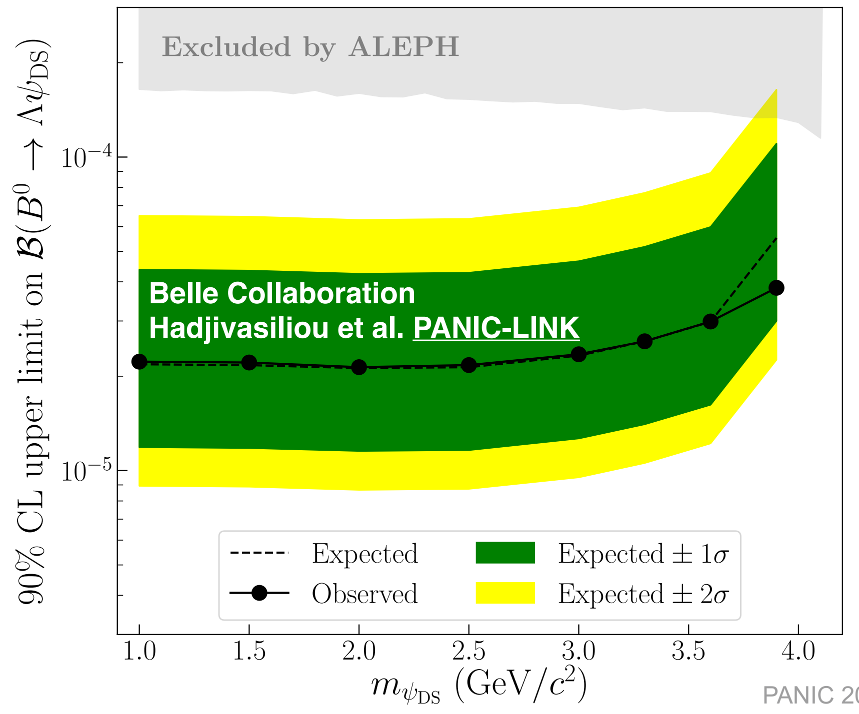
Recent search performed using Belle data:

Belle collaboration:

$$\mathrm{Br}(B \to \psi + \Lambda) \lesssim 3 \times 10^{-5}$$

The other channels remain to be searched for.
Analyses at BaBar, Belle and Belle-II on their way.

90% CL upper limits on $\mathcal{B}(B^0 \to \Lambda\psi_{\mathrm{DS}})$



PANIC 2021

Implications for the mechanism depend upon the rather uncertain and large ratio between exclusive (no mesons) and inclusive (any mesons)!

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

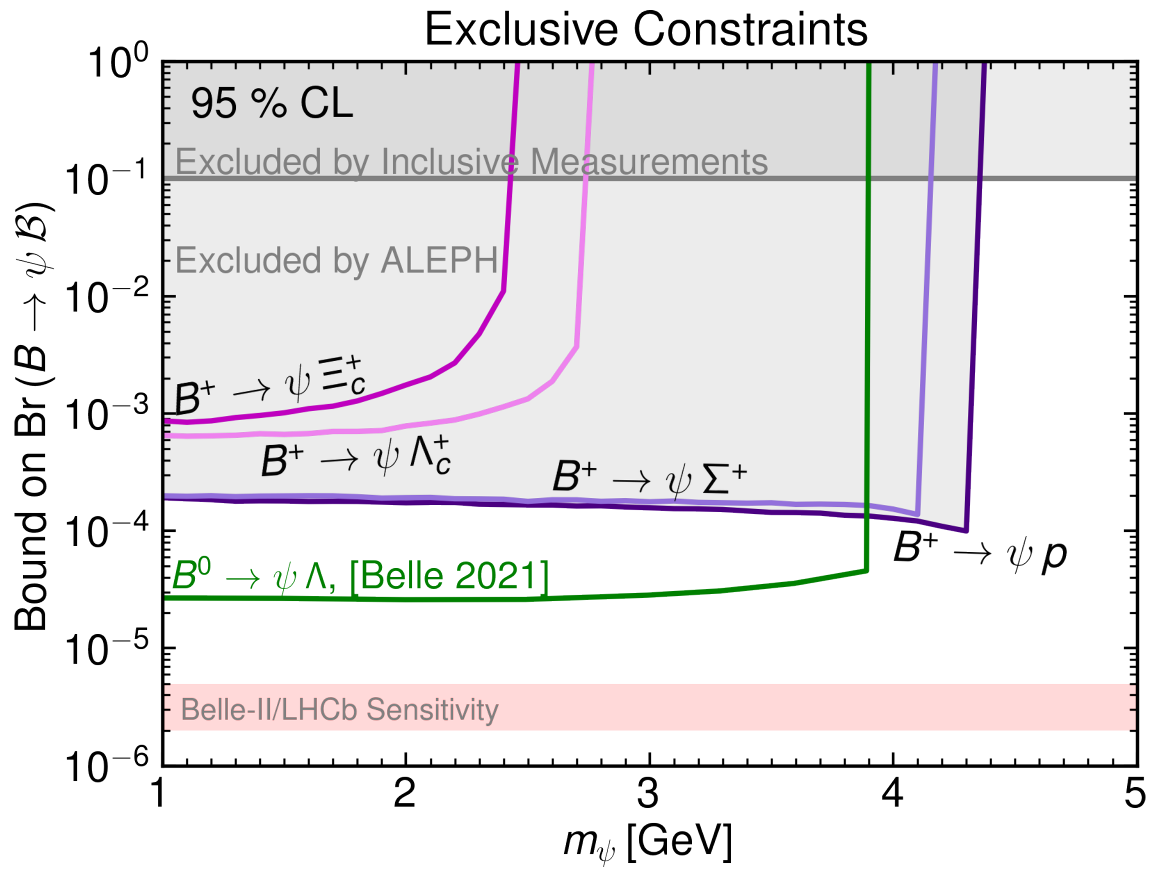
Constraints on the new Decays

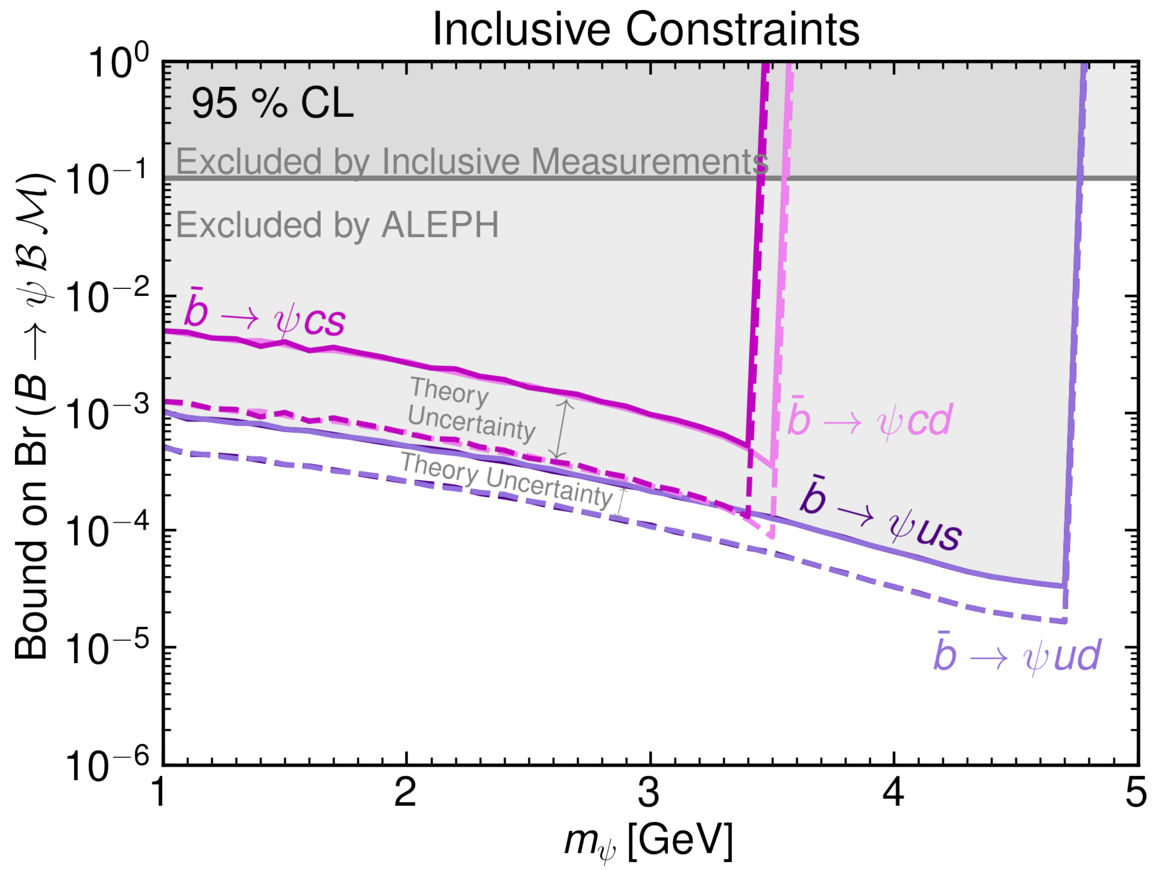
4 Ways:

1) **Direct searches at B-factories**
2) **Searches for b-decays with large missing energy at ALEPH**
3) **Searches at LHCb for resonant B mesons and b-flavored Baryons**
4) **Indirect constraints from ATLAS & CMS on TeV-scale triplet scalars**

2) Searches for b-decays with large missing energy at ALEPH

We have recasted the results from and old ALEPH search hep-ex/0010022 with $N_Z = 4 \times 10^6$





Constraints on the new Decays

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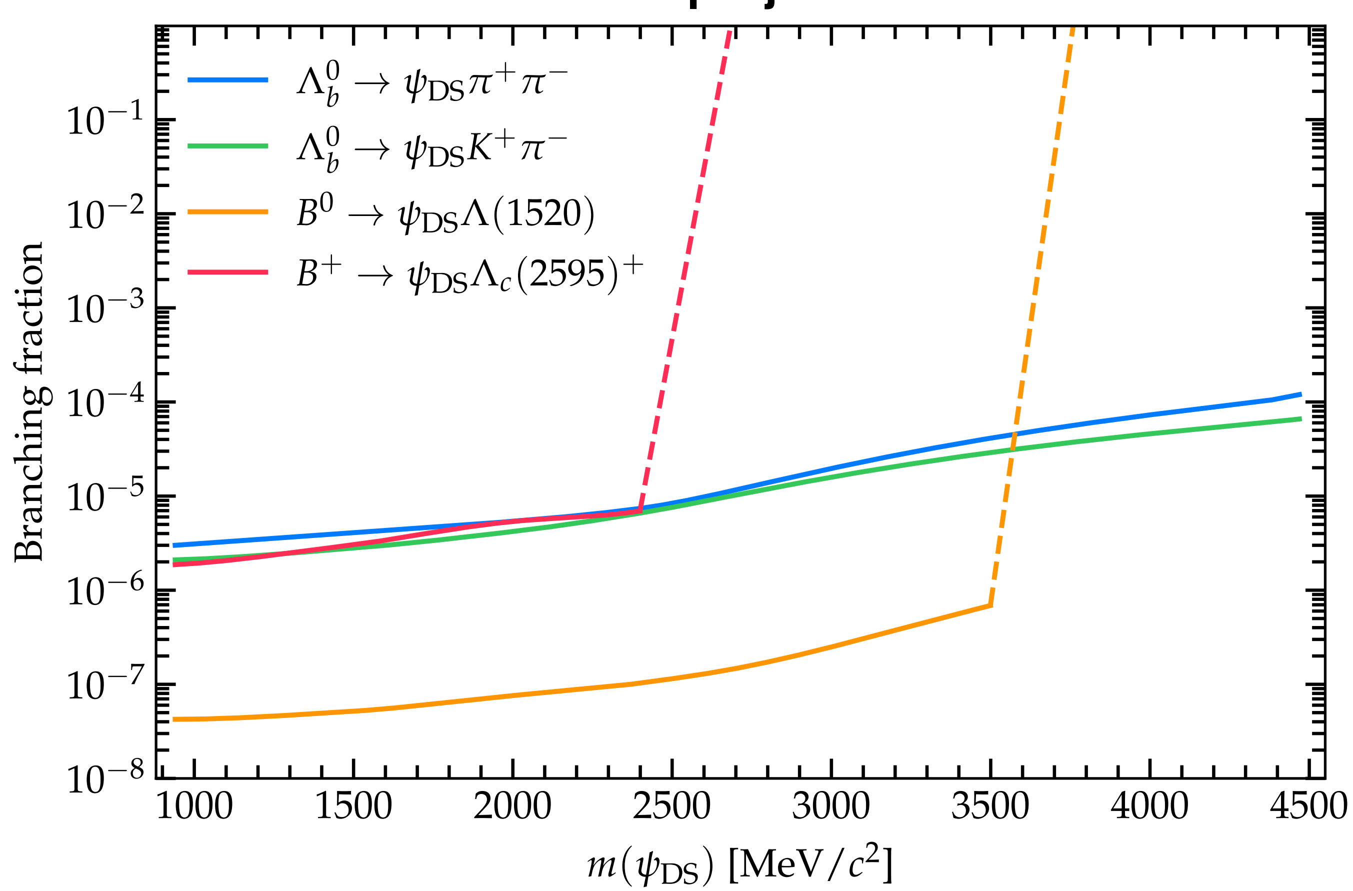
3) Searches at LHCb for resonant B mesons and b-flavored Baryons

Cid Vidal, Georgieva Chobanova, Martinez Santos et al. 2106.12870

LHCb has sensitivities at the $\mathrm{Br} \sim 10^{-7} - 10^{-4}$ **level**

LHCb projections from 2106.12870



Constraints on the new Decays

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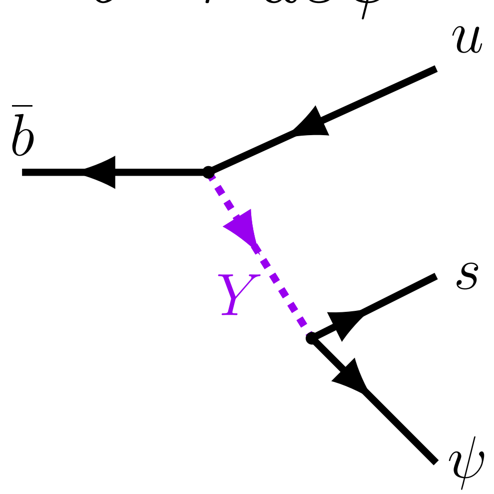
4) Indirect constraints from ATLAS & CMS on TeV-scale triplet scalars

4) Indirect constraints from ATLAS & CMS on TeV-scale triplet scalars

We need a colored triplet scalar Y to trigger the new decay mode of the b-quark

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

$$\bar{b} \to us\psi$$

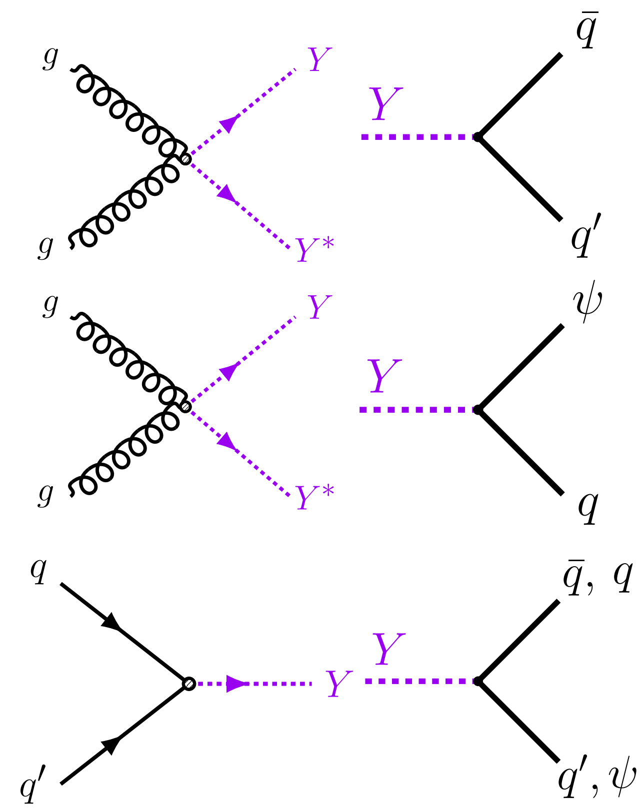


Y: Colored Triplet Scalar

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

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

Searches we considered:



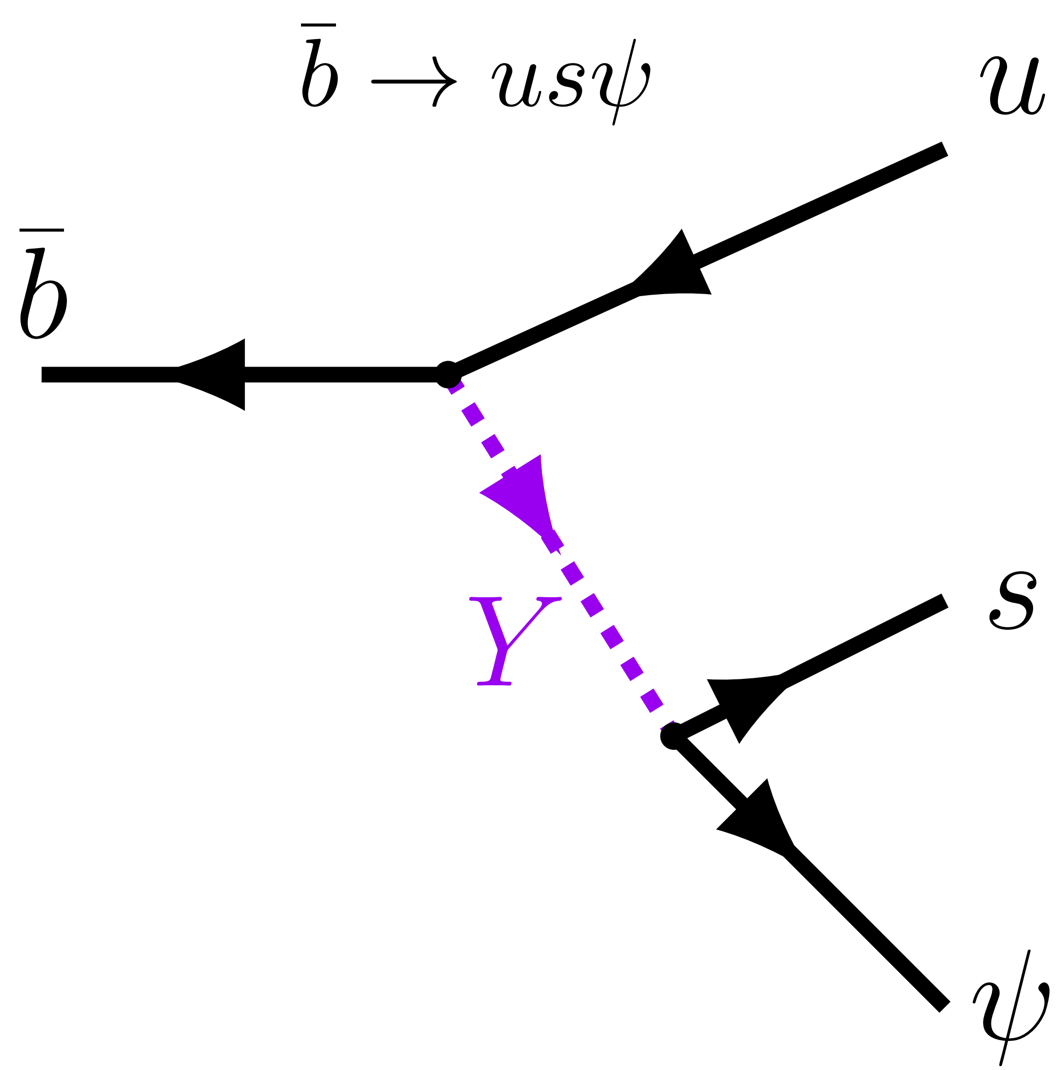
1710.07171 (ATLAS)

1908.04722 (CMS)
2010.14293 (ATLAS)

1806.00843 (CMS)
1711.03301 (ATLAS)

Our recast shows relevant constraints on the parameter space:

New Force Carrier



Y: Colored Triplet Scalar

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

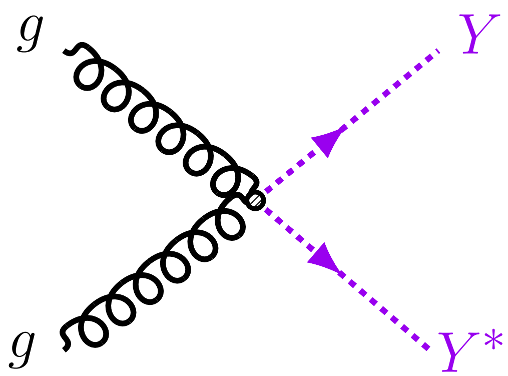
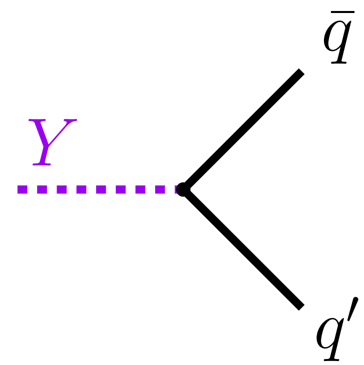
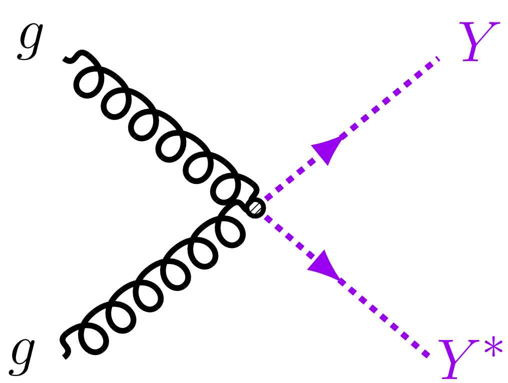
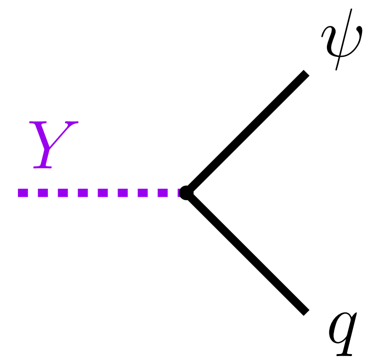
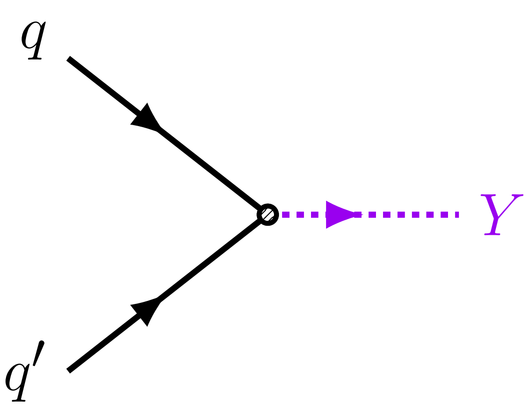
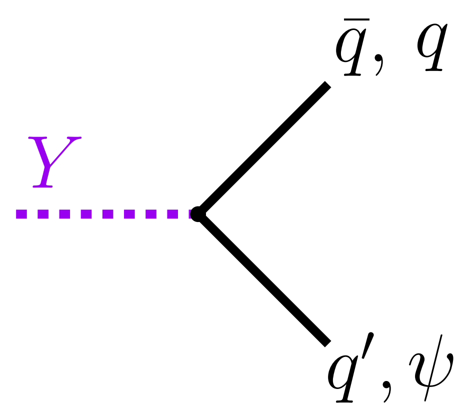
$$Y \sim (3, 1, 2/3)$$

Same Quantum Numbers as a SUSY squark!

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

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

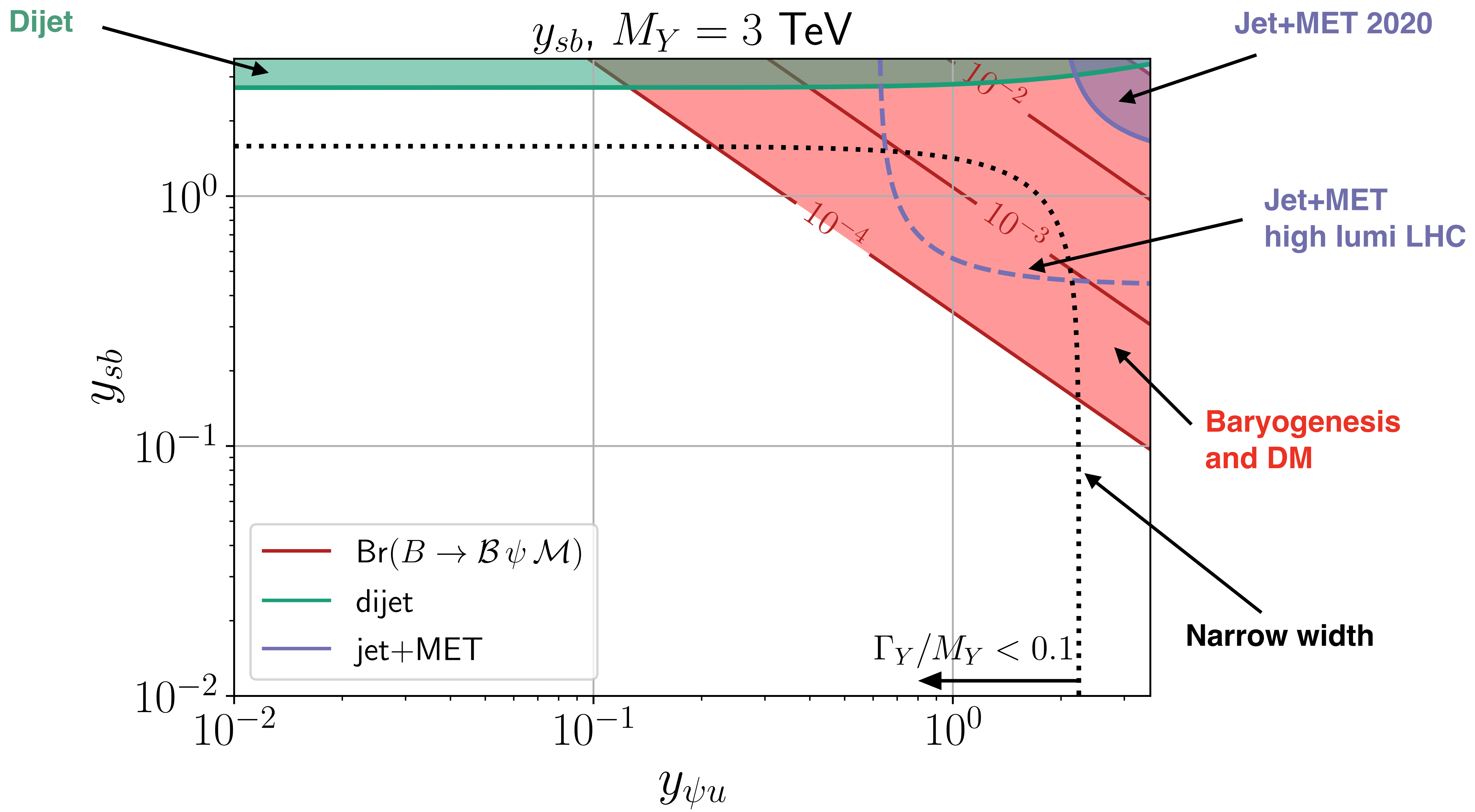
Squark searches

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

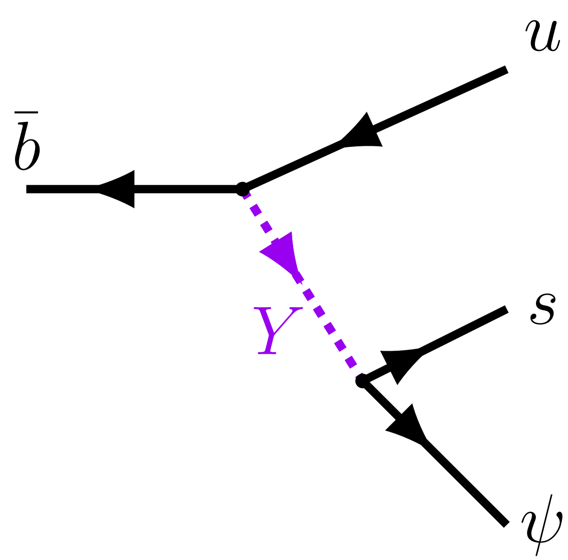


LHC 2020: $\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right) \lesssim 0.1$

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

Inclusive versus Exclusive

$\bar{b} \to \psi u d$



$B \to \psi + \text{Baryon}$

1) Lattice

2) Sum rules?

3) Vacuum insertion approximation?

4) Phase space considerations

REMARK ON BARYONIC DECAYS OF B MESONS

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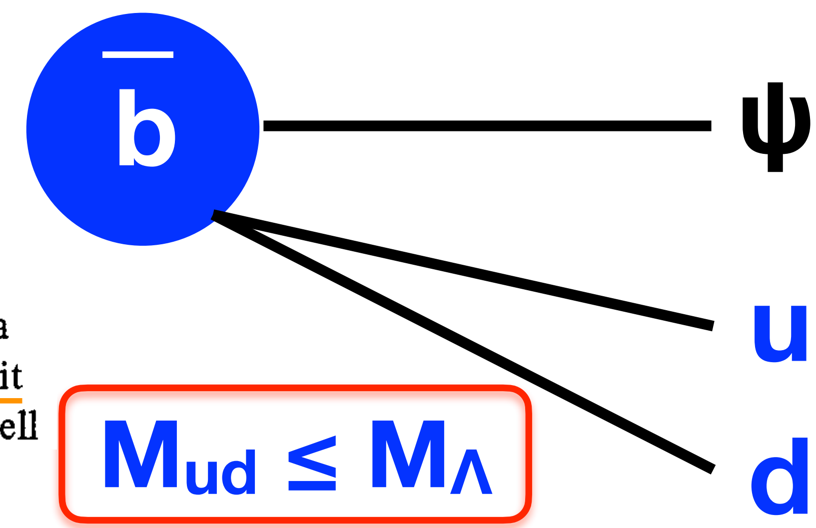
Received 28 August 1981

Bigi, Phys. Lett. B 106, 510 (1981)
see also Dunietz arXiv:hep-ph/9805287
also Hai-Yang Cheng hep-ph/0603003

energetic protons or lamdas. If B mesons possess a baryonic branching ratio of roughly ≈5–10%, as it was argued above, then such a procedure might well

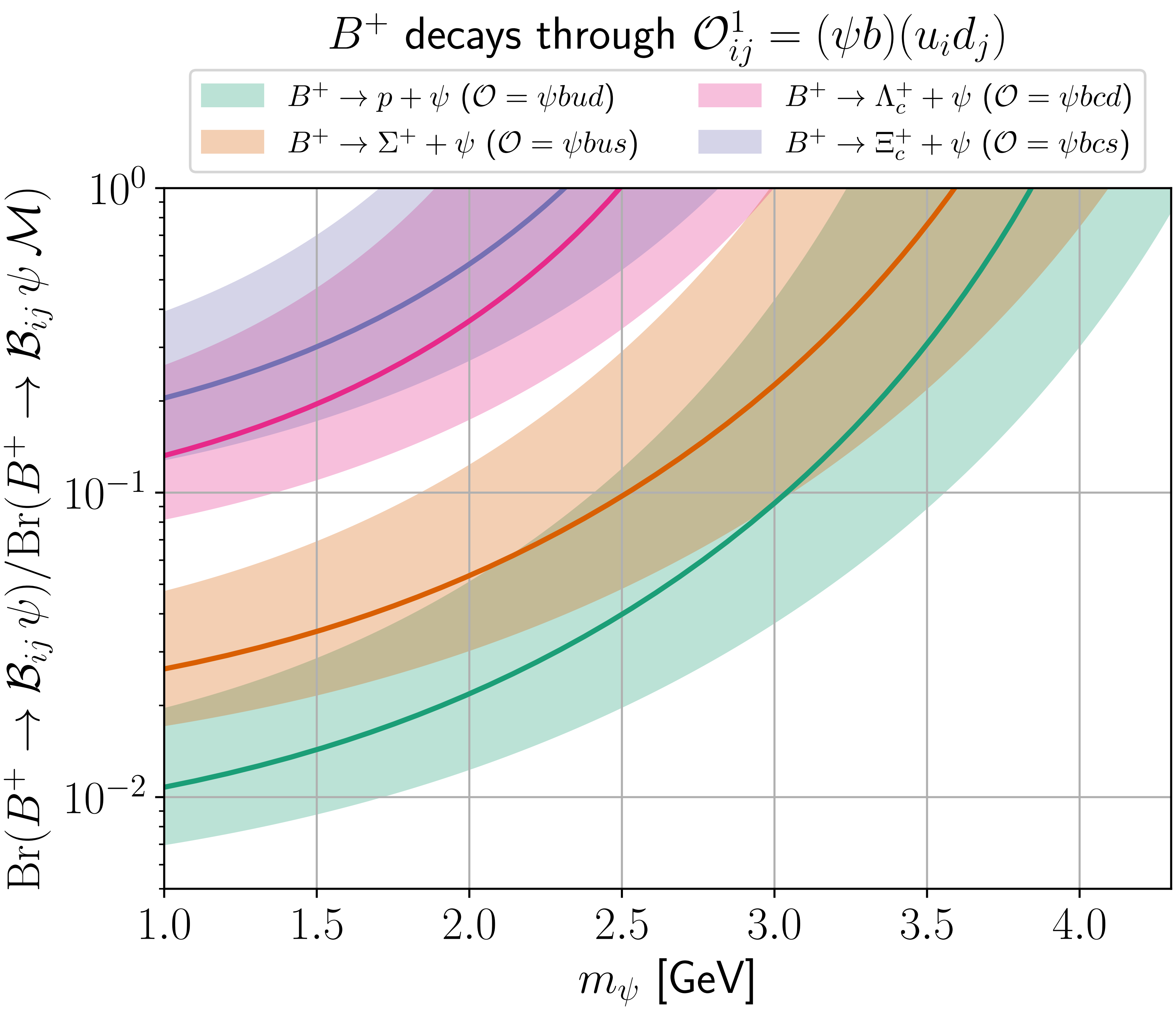


$M_{ud} \leq M_\Lambda$

M_{ud}

$$\frac{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon}\right)}{\mathrm{Br}\left(B \to \psi + \mathrm{Baryon} + \mathcal{M}\right)} \simeq \frac{\int_{(m_{q_i}+m_{q_j})^2}^{m^2_{\mathrm{Baryon}}} \frac{\partial \Gamma}{\partial M^2_{q_i q_j}} \, dM^2_{q_i q_j}}{\int_{(m_{q_i}+m_{q_j})^2}^{(m_b - m_\psi)^2} \frac{\partial \Gamma}{\partial M^2_{q_i q_j}} \, dM^2_{q_i q_j}},$$

Inclusive versus Exclusive



SM example:

$\mathrm{Br}(B_0 \to p\bar{p}) = (1.3 \pm 0.3) \times 10^{-8}$

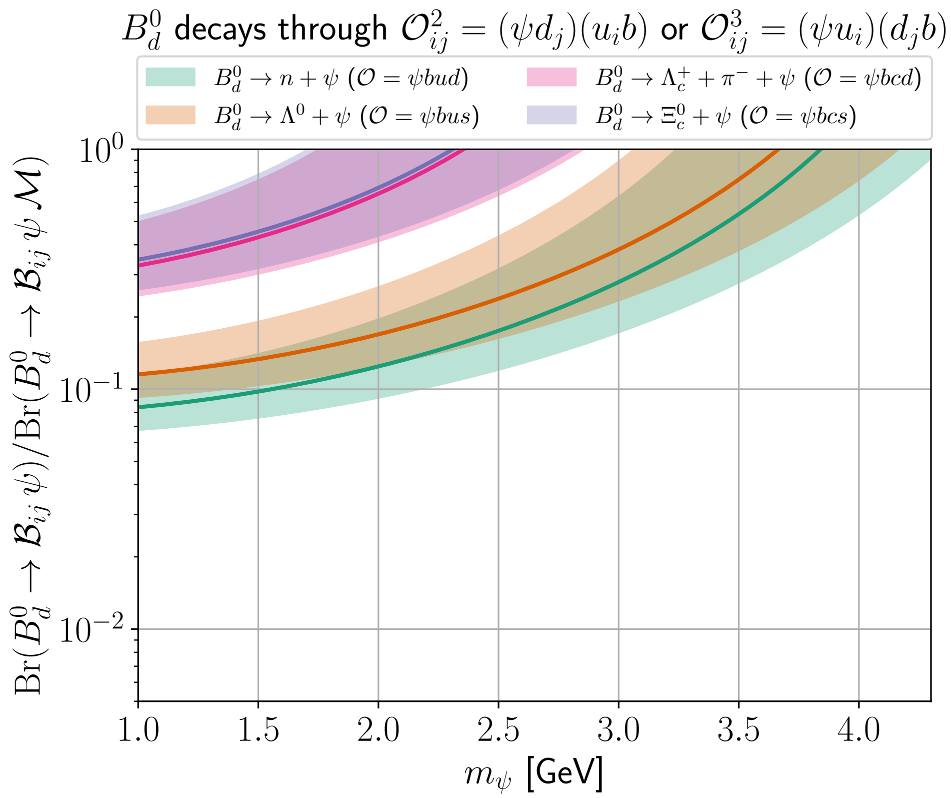
$\mathrm{Br}(B_0 \to p\bar{p}\pi^+\pi^-) = (2.9 \pm 0.2) \times 10^{-6}$

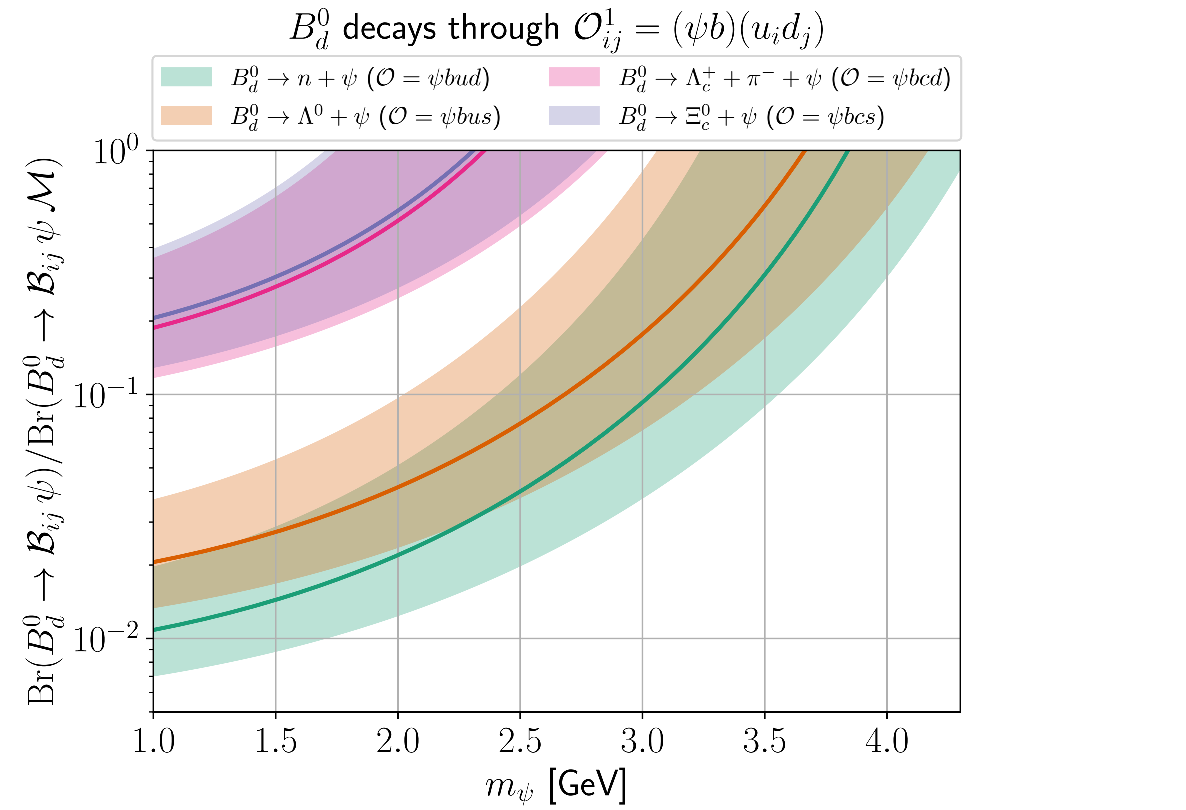
$\mathrm{Br}(B_0 \to p\bar{p}K^+\pi^-) = (6.3 \pm 0.5) \times 10^{-6}$

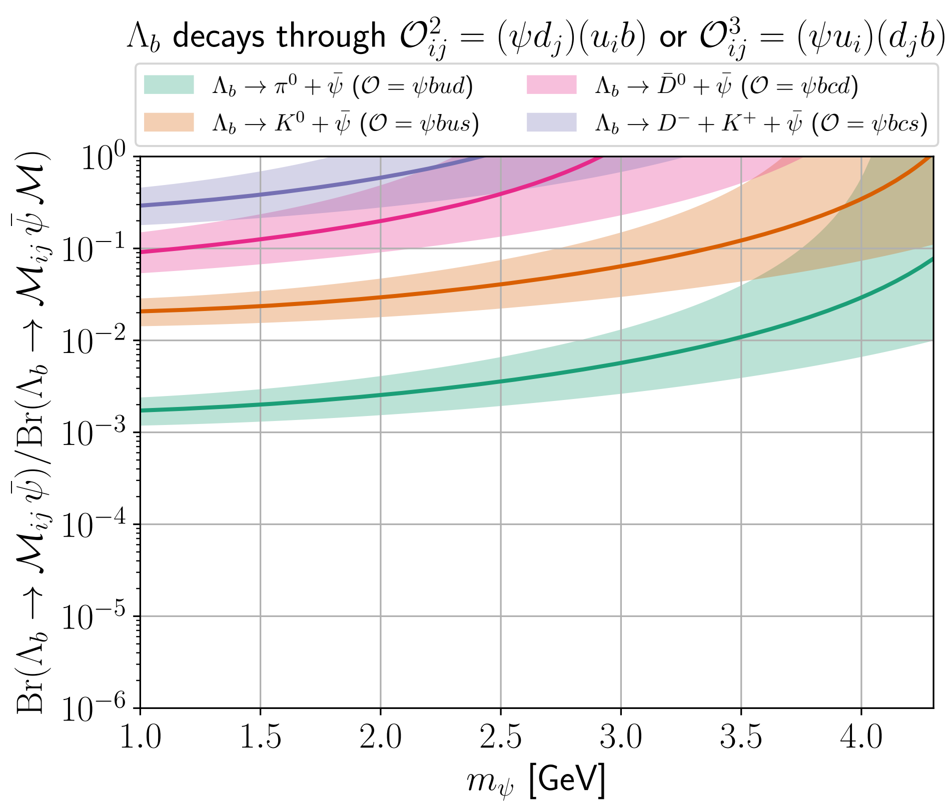
$\mathrm{Br}(B_0 \to p\bar{p}K_0) = (2.7 \pm 0.3) \times 10^{-6}$

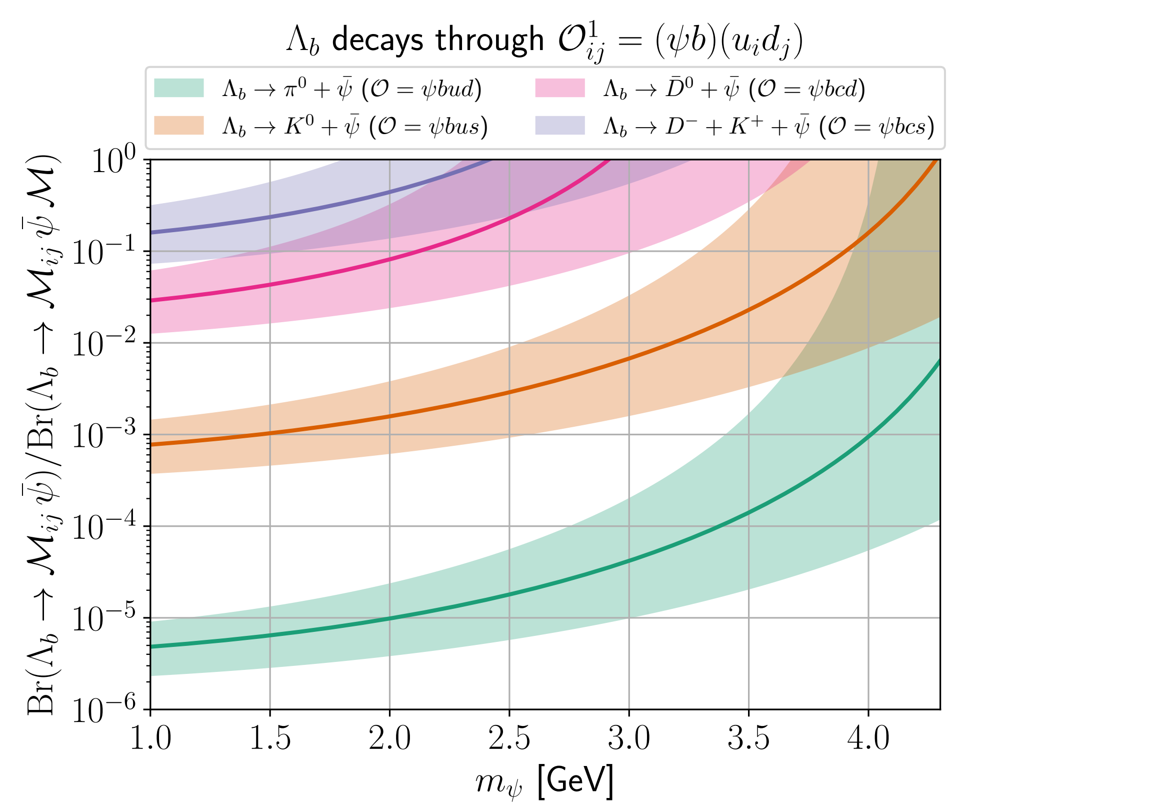
In general, it seems that we get at least ~1% of exclusive decays

Inclusive versus Exclusive





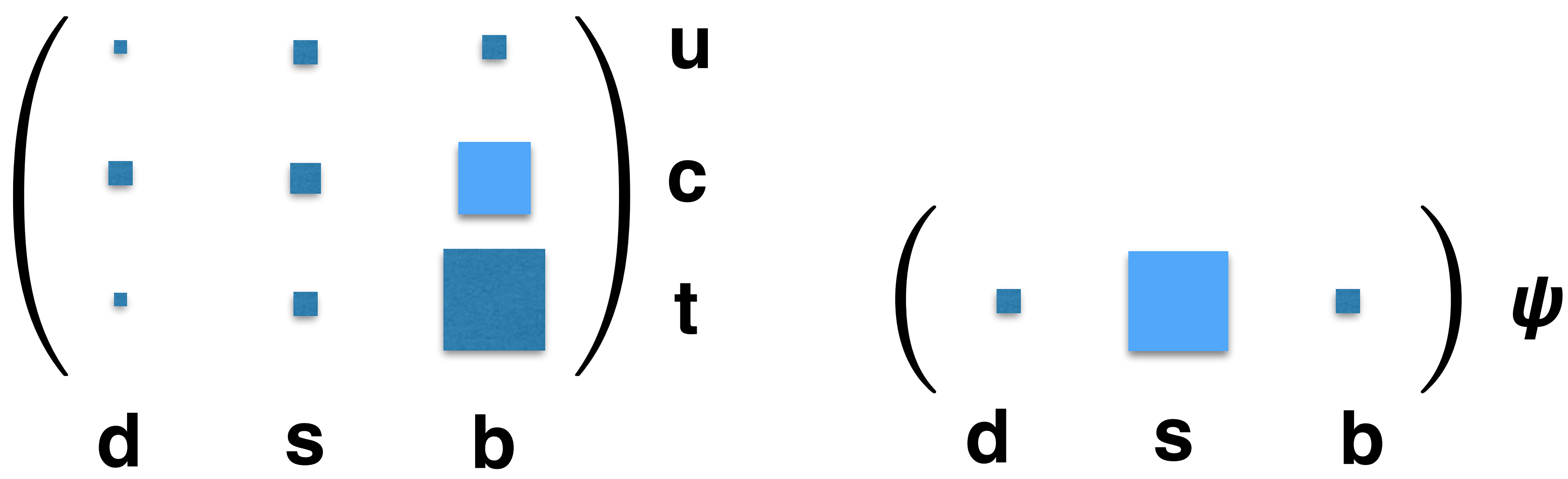




Flavor Structures

$$\mathcal{L} = -\sum_{u,\,d} y_{ud} Y^{\star} \bar{u}_R d_R^c - \sum_{d} y_{\psi d} Y \bar{\psi} d_R^c + \text{h.c.}$$

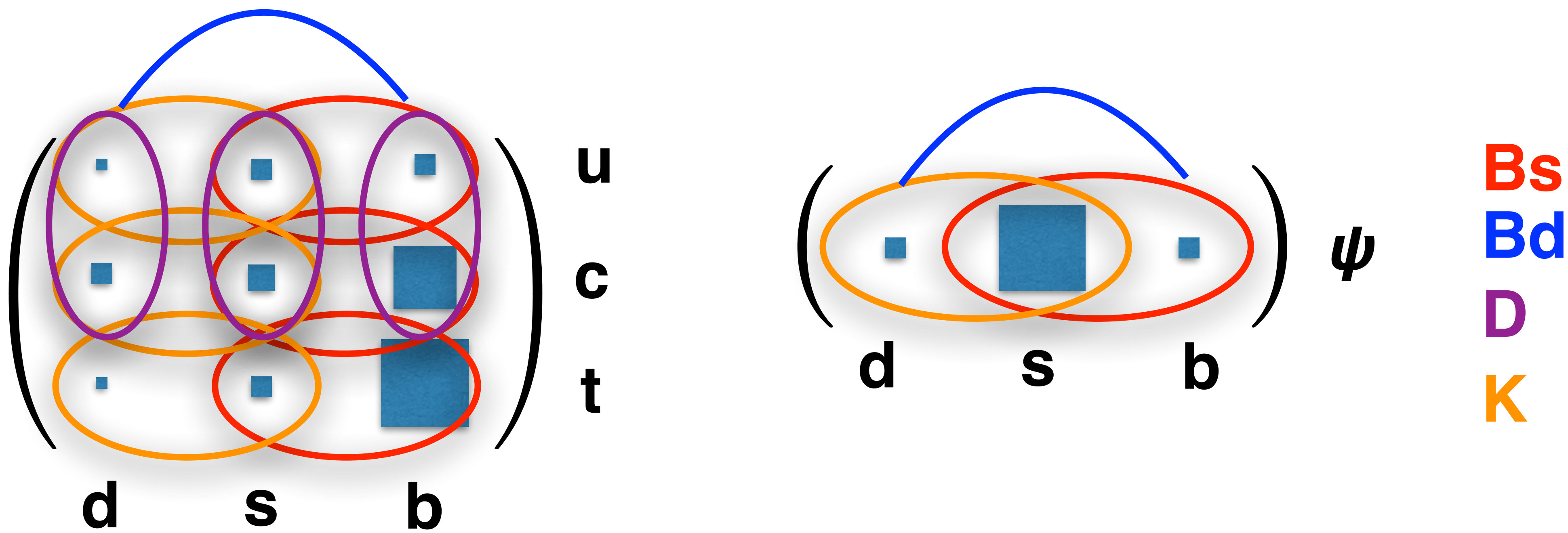
Flavor Mixing constraints do not directly probe the mechanism but shape the Y-quark and Y-Dark Matter coupling structure:



Example of viable Flavor structure
that gives the BR required for Baryogenesis
and satisfies all Flavor Mixing + Collider constraints

Flavor Structures

$$\mathcal{L}_{-1/3} = -\sum_{i,\,j} y_{u_i d_j} Y^\star \bar{u}_{iR} d^c_{jR} - \sum_k y_{\psi d_k} Y d^c_{kR} \bar{\psi} + \text{h.c.}$$



$$\mathcal{L}_{2/3} = -\sum_{i,\,j} y_{d_i d_j} Y^\star \bar{d}_{iR} d^c_{jR} - \sum_k y_{\psi u_k} Y u^c_{kR} \bar{\psi} + \text{h.c.}$$