Collider Implications of Baryogenesis and Dark Matter from B Mesons

Miguel Escudero Abenza
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Based on:

arXiv:1810.00880, PRD99, 035031 (2019)
with: Gilly Elor & Ann Nelson
arXiv:2004.XXXXX
with: Gilly Elor, Gonzalo Alonso-Álvarez, David McKeen

Stealth Physics at LHCb: 18-02-2020

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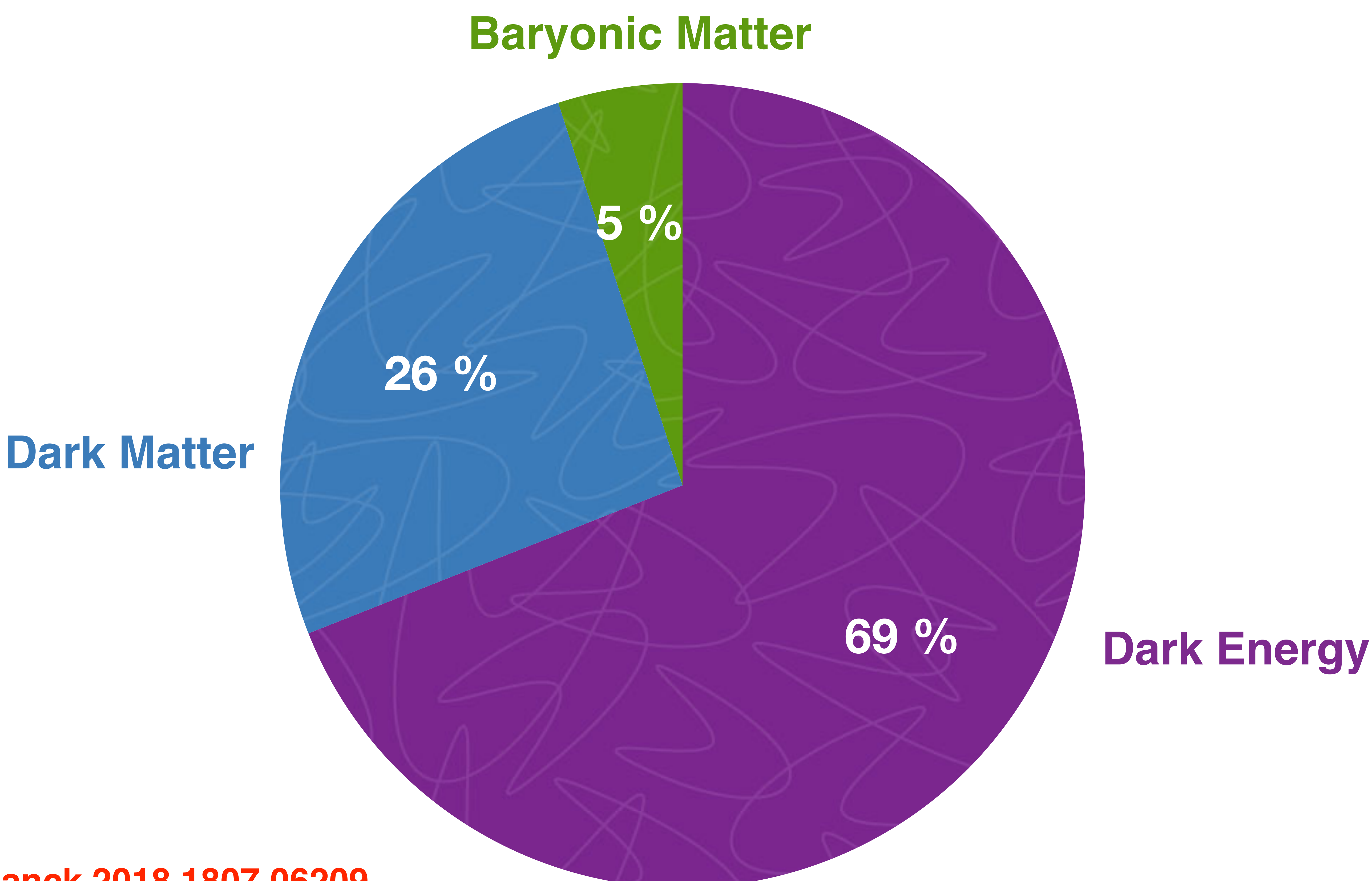
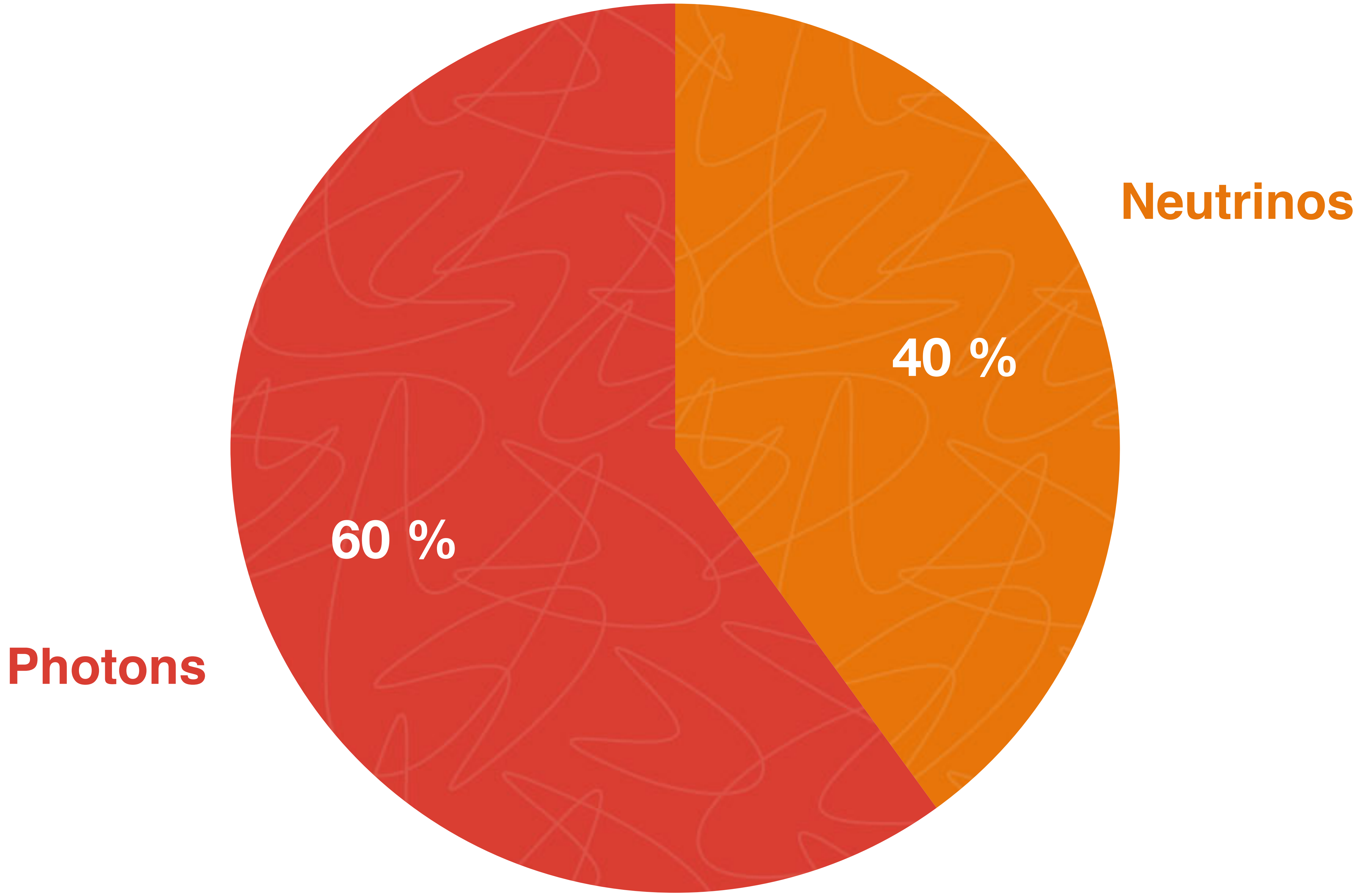
neutrinos, dark matter & dark energy physics

The Universe



Planck 2018 1807.06209

SM Prediction:



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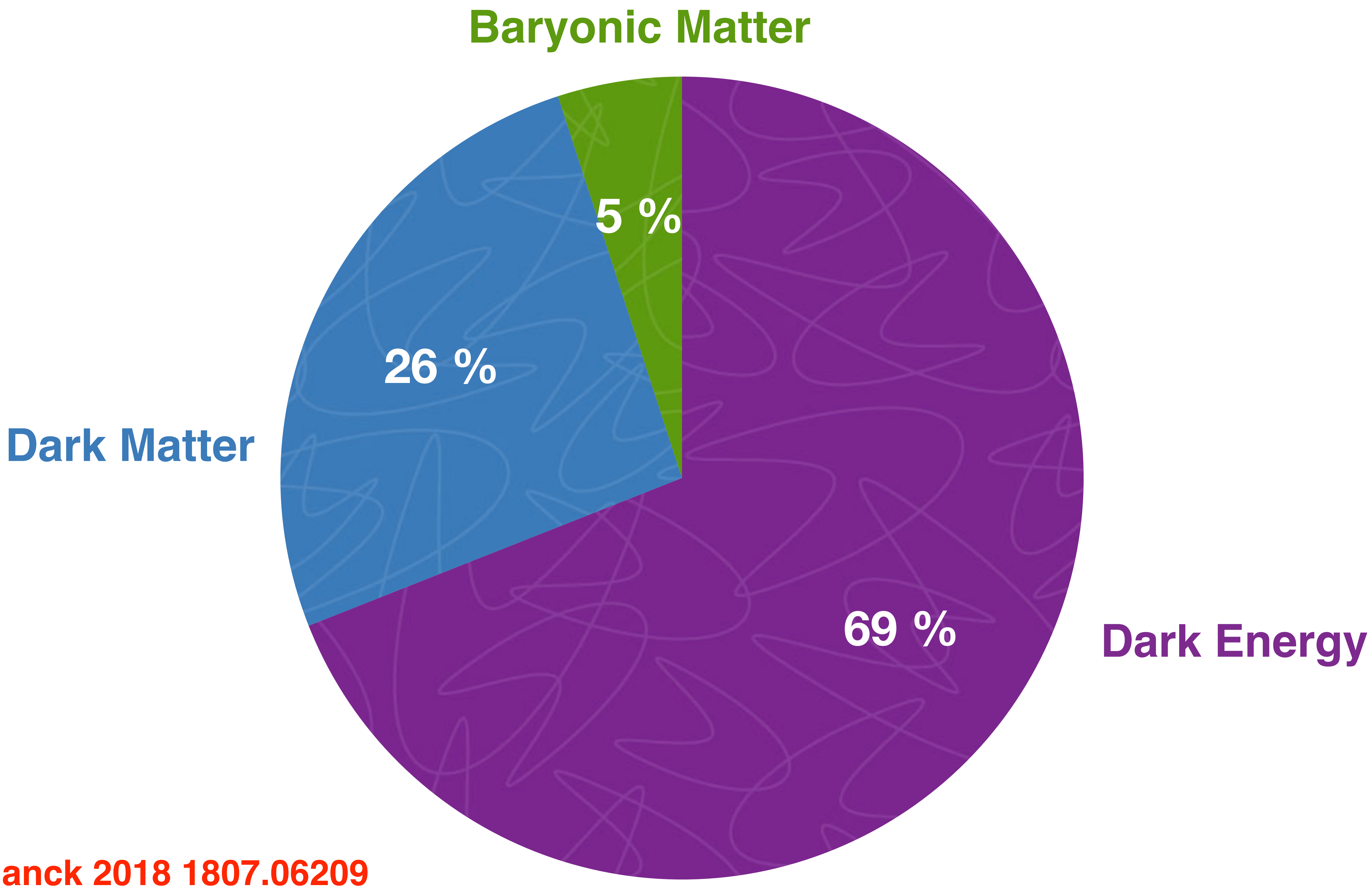

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Baryogenesis and Dark Matter from B Mesons

arXiv:1810.00880 Elor, Escudero & Nelson

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arXiv:1810.00880 Elor, Escudero & Nelson

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

3) **Leads to unique collider signatures**

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

Outline

1) Baryogenesis and DM from B Mesons

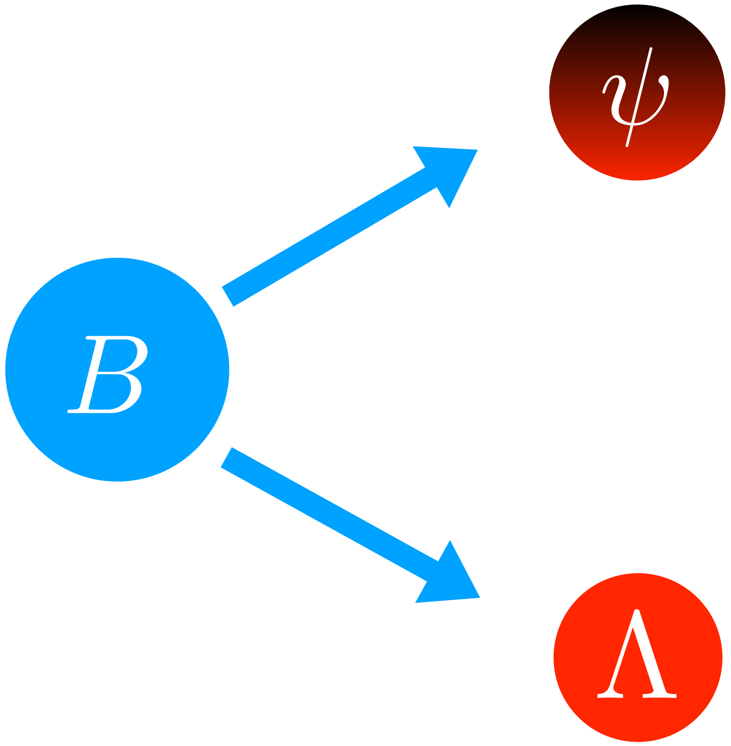
2) Collider implications

1) Direct CP violation in B Meson decays (LHCb/ATLAS/CMS)
2) Indirect CP violation in B mesons decays (LHCb/ATLAS/CMS/Belle-II)
3) Searches for heavy colored scalars (ATLAS/CMS)
4) Search for B meson decay into a baryon and ME (Belle-II/LHCb)
5) Search for b-flavored baryon decays into mesons and ME (LHCb)

3) Summary and Outlook

Baryogenesis and DM from B Mesons

1) New B Meson decay



B meson decay into a visible Baryon and missing energy at a rate:

$$\text{Br}(B \to \psi + \text{Baryon} + X) > 5 \times 10^{-4}$$

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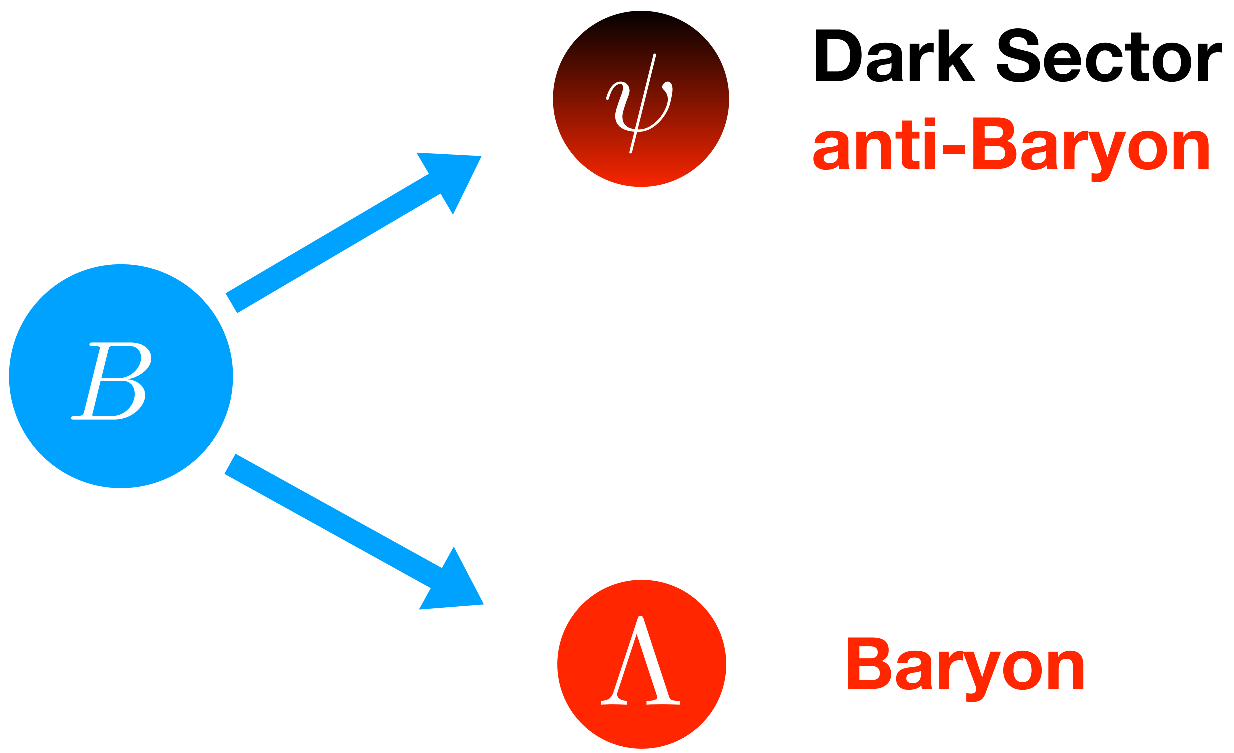

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Collider Implications:

1) **There should be a new force carrier**
2) **New decay mode that can be searched for!**

Baryogenesis from B Mesons

2) CP violation in the neutral B Meson system

Baryogenesis from B Mesons

2) CP violation in the neutral B Meson system

The key quantity: the semileptonic asymmetry,

$$A_{\ell\ell}^{q} = \mathrm{Im}\left(\frac{\Gamma_{12}^{q}}{M_{12}^{q}}\right) = \frac{\Gamma\left(B_q^0 \to f\right) - \Gamma\left(B_q^0 \to \bar{f}\right)}{\Gamma\left(B_q^0 \to f\right) + \Gamma\left(B_q^0 \to \bar{f}\right)}$$

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Standard Model

$$A_{\ell\ell}^{s}|_{\mathrm{SM}} = (2.22 \pm 0.27) \times 10^{-5}$$
$$A_{\ell\ell}^{d}|_{\mathrm{SM}} = (-4.7 \pm 0.6) \times 10^{-4}$$

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

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$$A_{\ell\ell}^s = (-0.6 \pm 2.8) \times 10^{-3}$$
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(World averages, HFLAV)

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Baryogenesis

$$A_{\ell\ell} > 10^{-5}$$

They should be Positive!

Parameter Space

Baryogenesis Requires:

$$A_{\ell\ell}^{d,\,s} \times \mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) > 5 \times 10^{-7}$$

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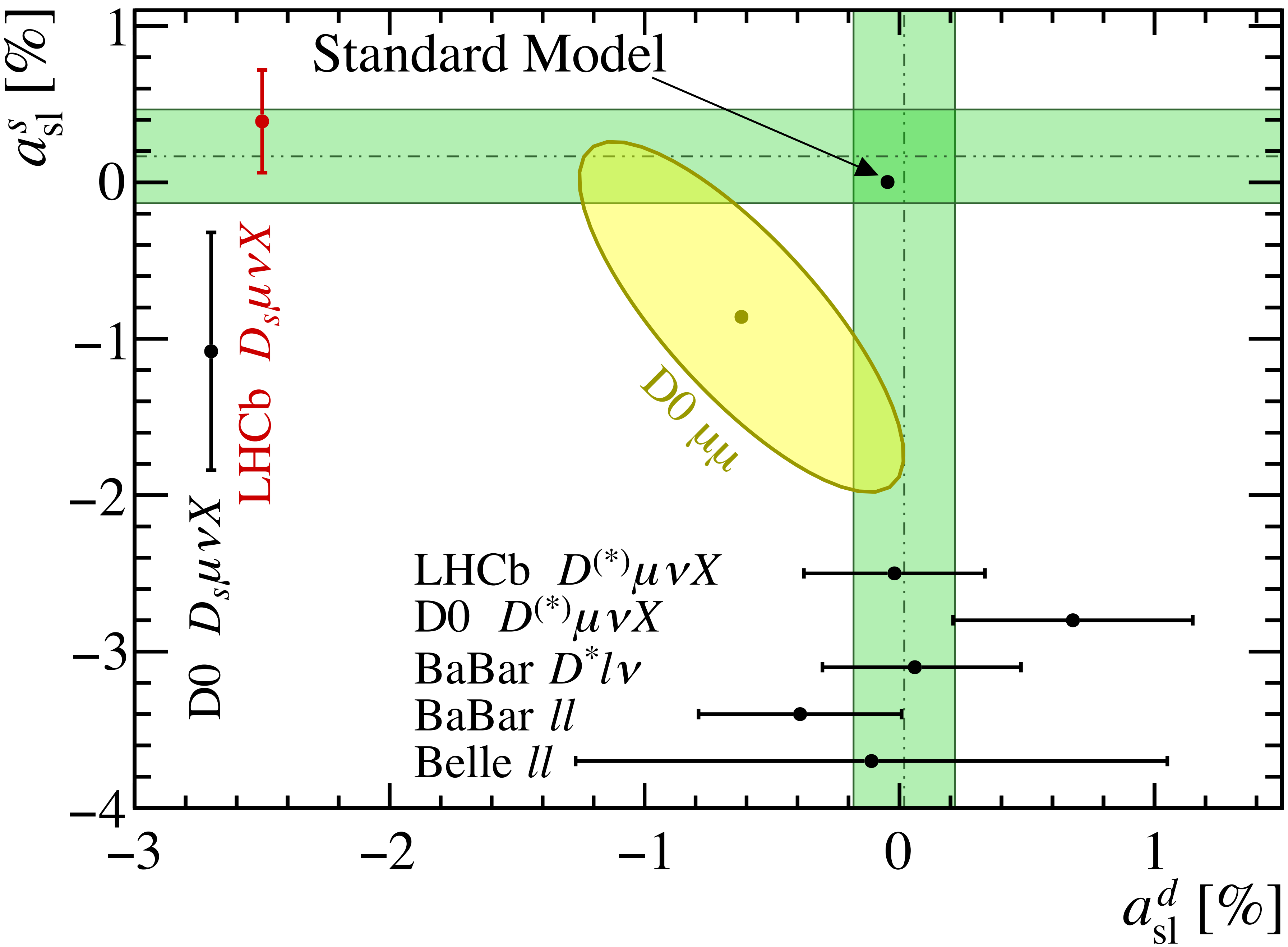
As of today we know:

$$A_{\ell\ell}^{d,\,s} \times \mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) \lesssim 10^{-4}$$

Indirect CP violation Searches

Lenz et al 1511.09466



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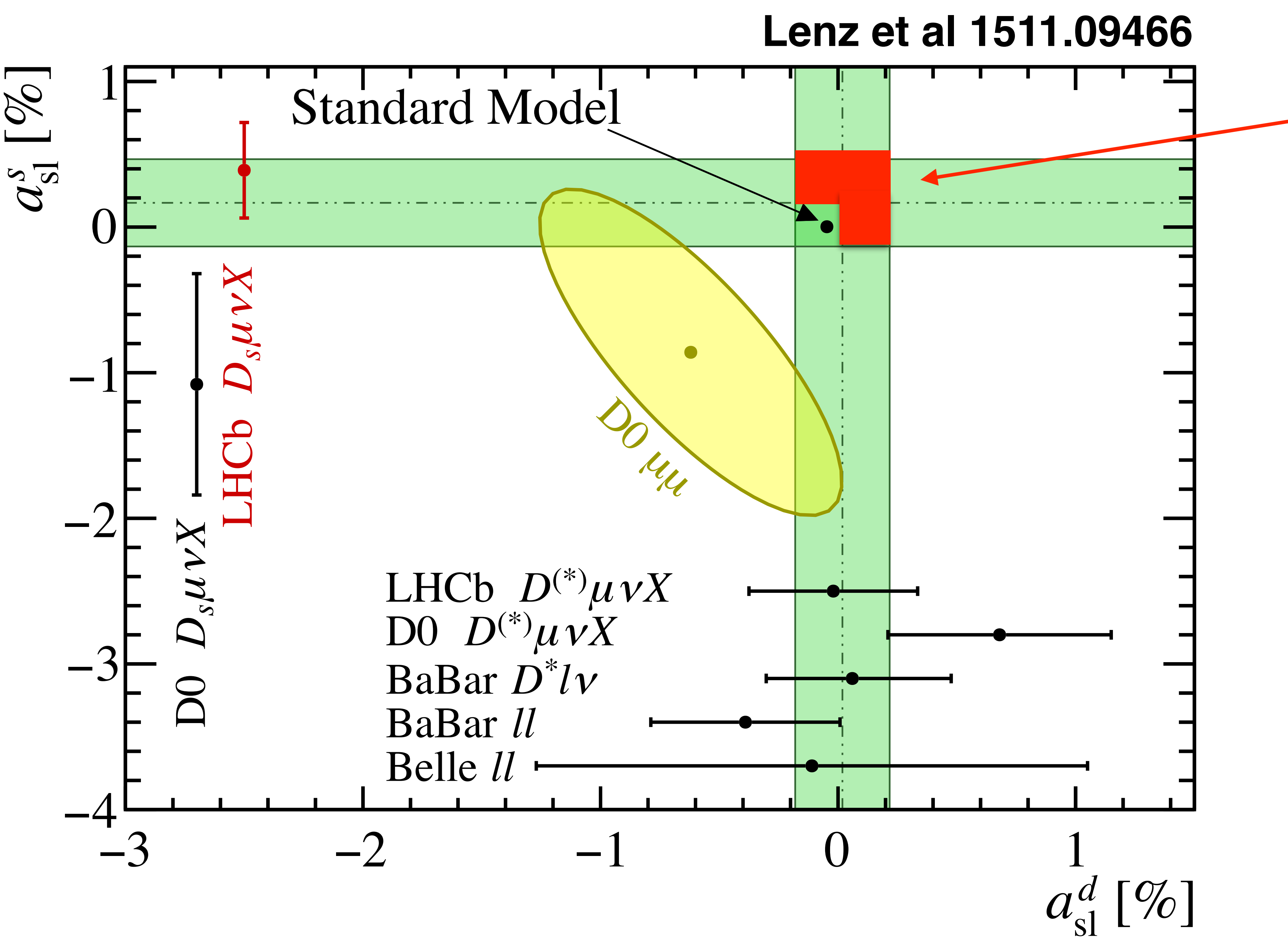

Baryogenesis

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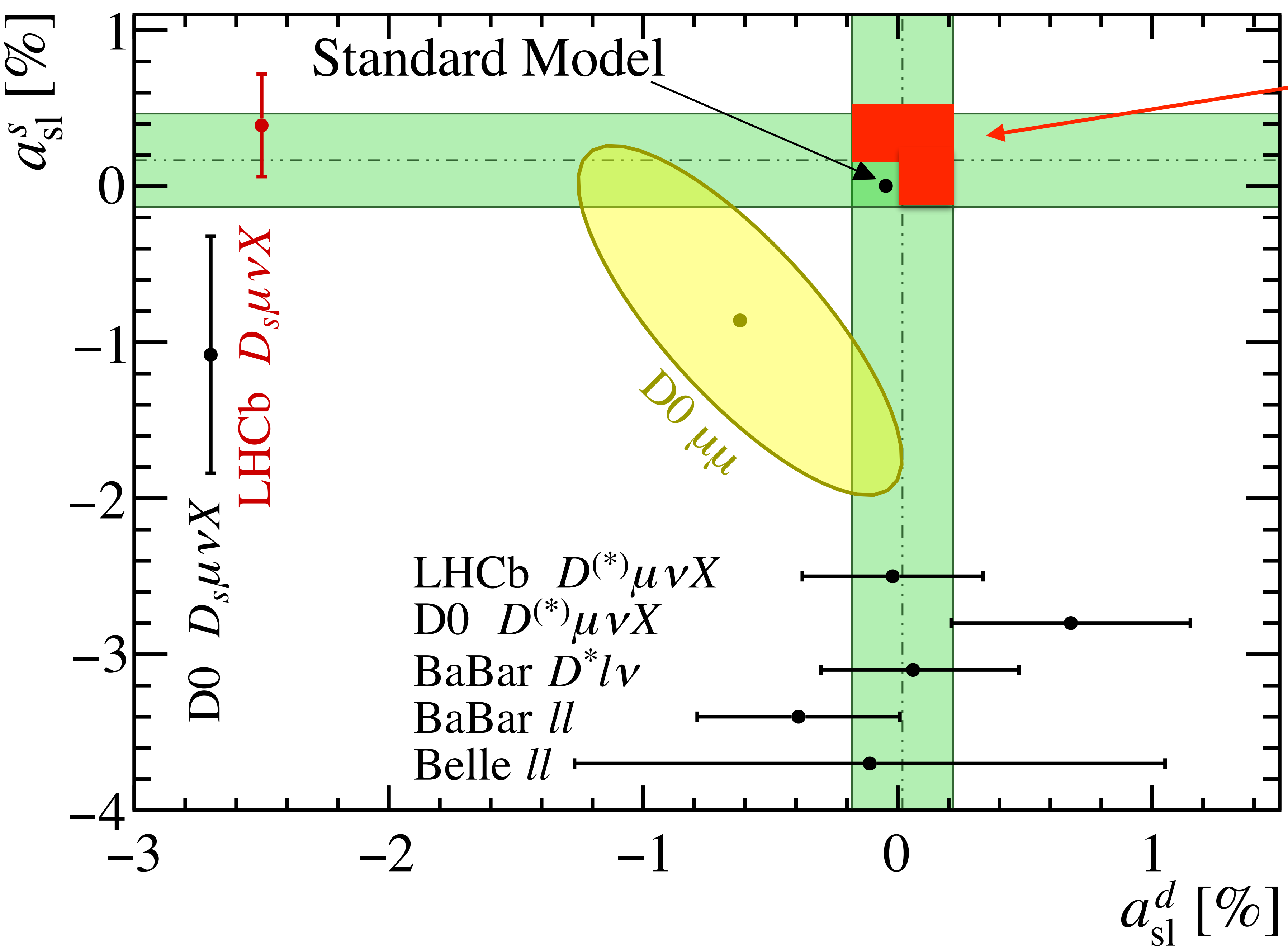


Baryogenesis

$$A_{\ell\ell}^{s,\,d} > 10^{-5}$$

Expected sensitivity:

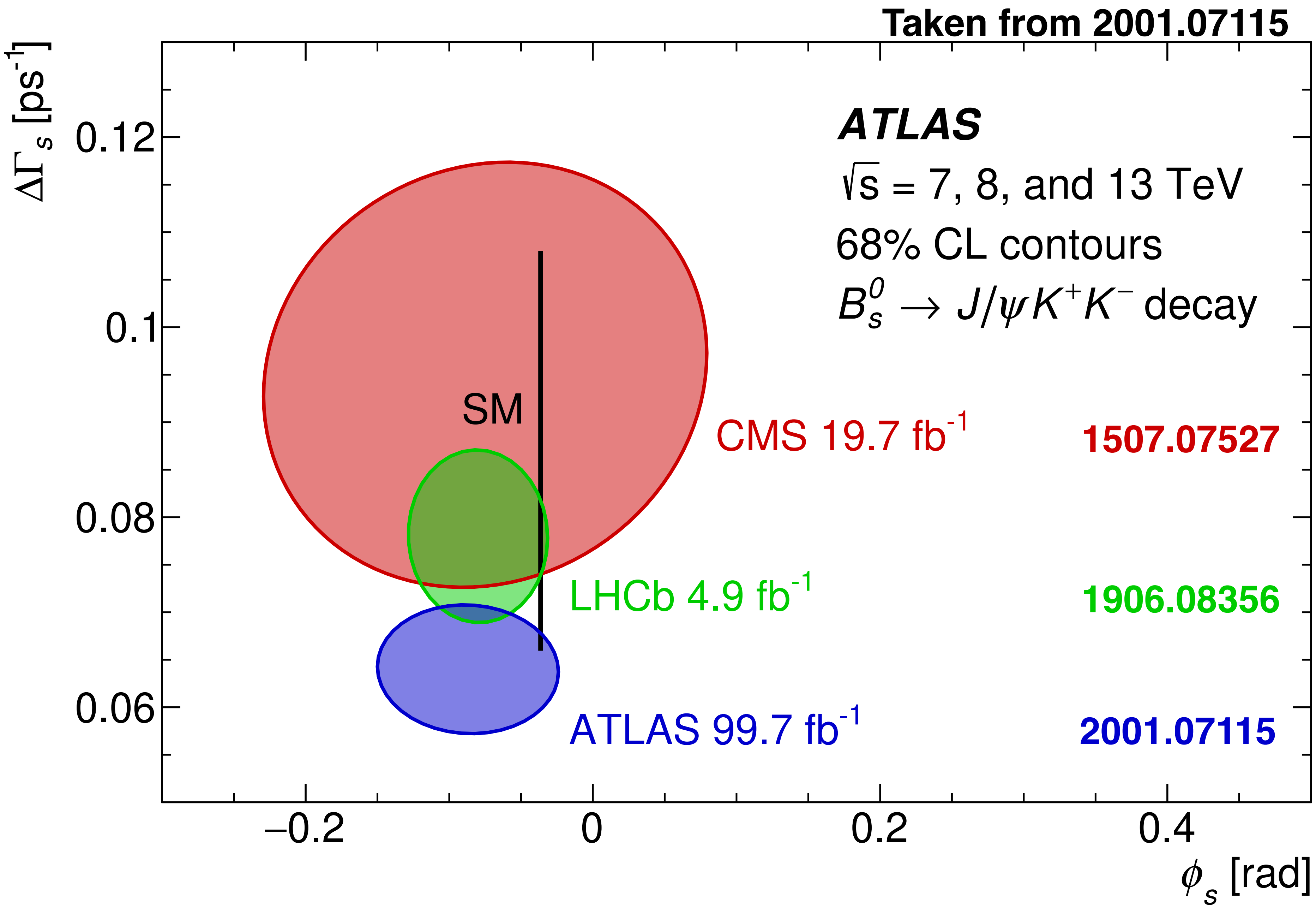
LHCb (50 fb^{-1})

$$A_{\ell\ell}^{s} \sim 5 \times 10^{-4}$$
$$A_{\ell\ell}^{d} \sim 5 \times 10^{-4}$$

Belle-II (50 ab^{-1})

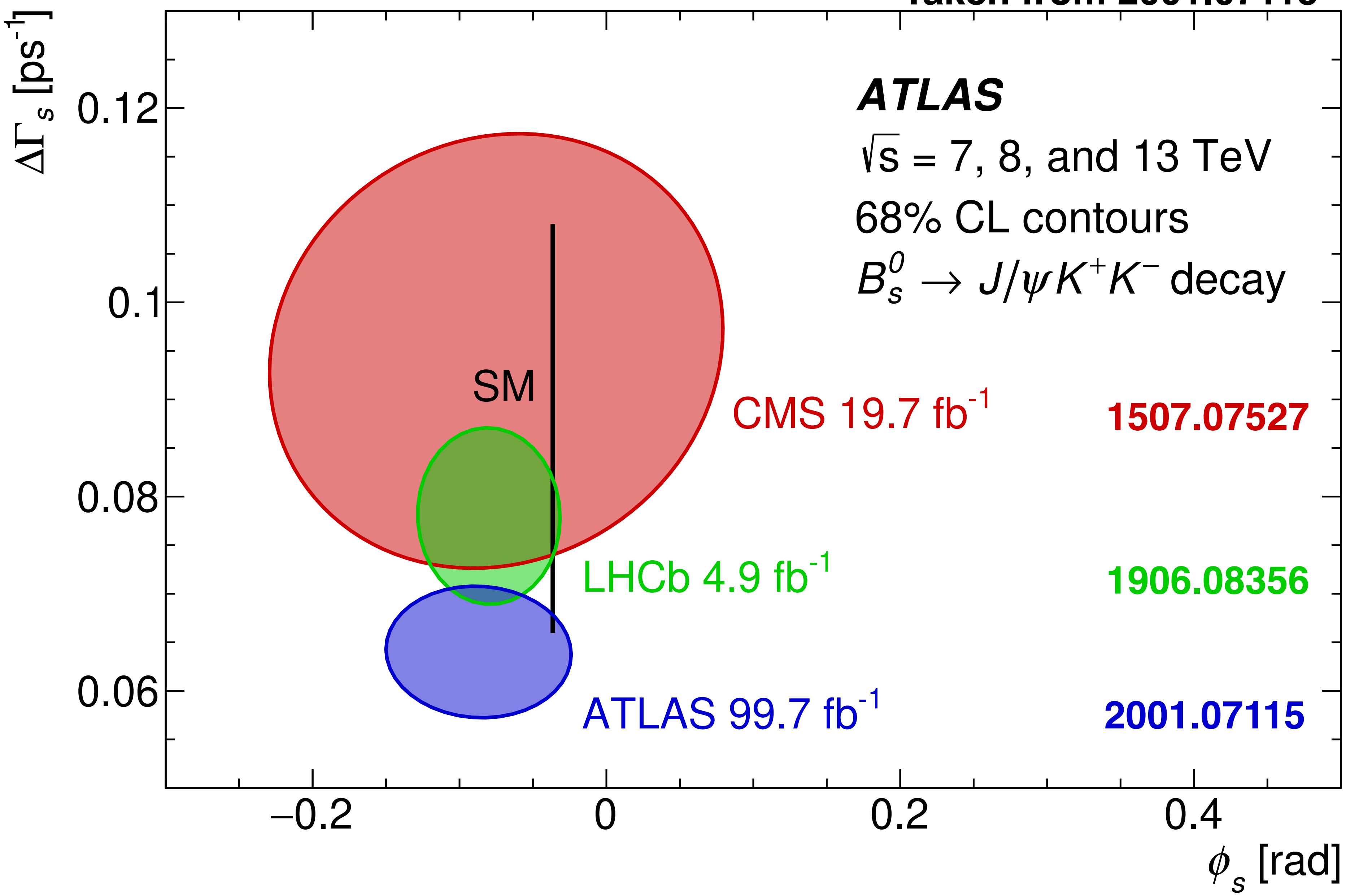
$$A_{\ell\ell}^{d} \sim 5 \times 10^{-4}$$

Direct CP violation Measurements



Direct CP violation Measurements

Taken from 2001.07115

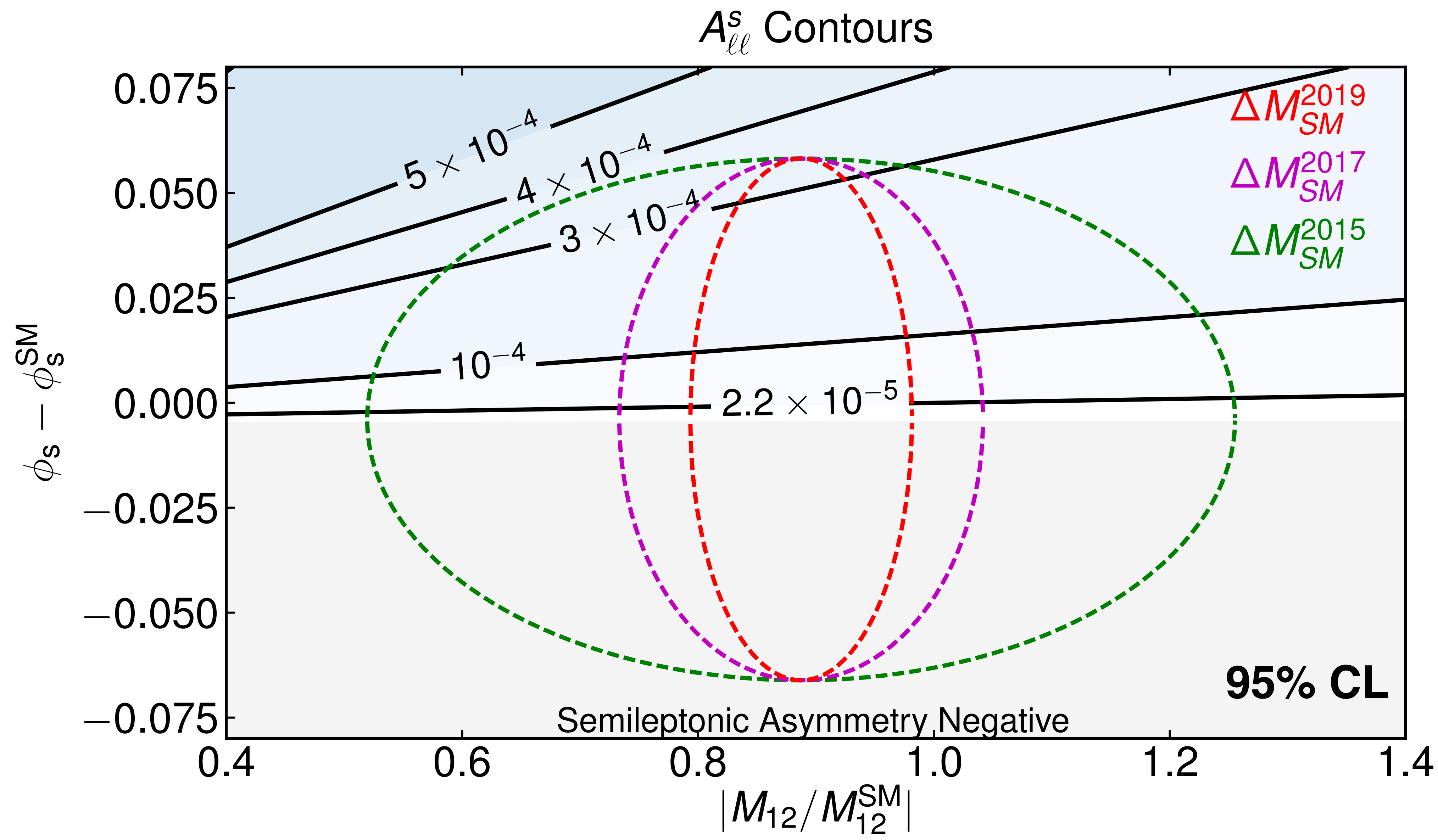


ϕ_s **Controls how large** $A^s_{\ell\ell}$ **could be**

$$A^s_{\ell\ell} \simeq 4 \times 10^{-3} \left| \frac{M_{12}^{\rm SM}}{M_{12}} \right| \sin(\phi_s)$$

Lenz et. al. 1712.06572

Direct CP violation Measurements



ϕ_s **from LHCb global fit 1906.08356.**

ΔM_s **from Lenz et al 1511.09466, 1712.06572, 1909.11087.**

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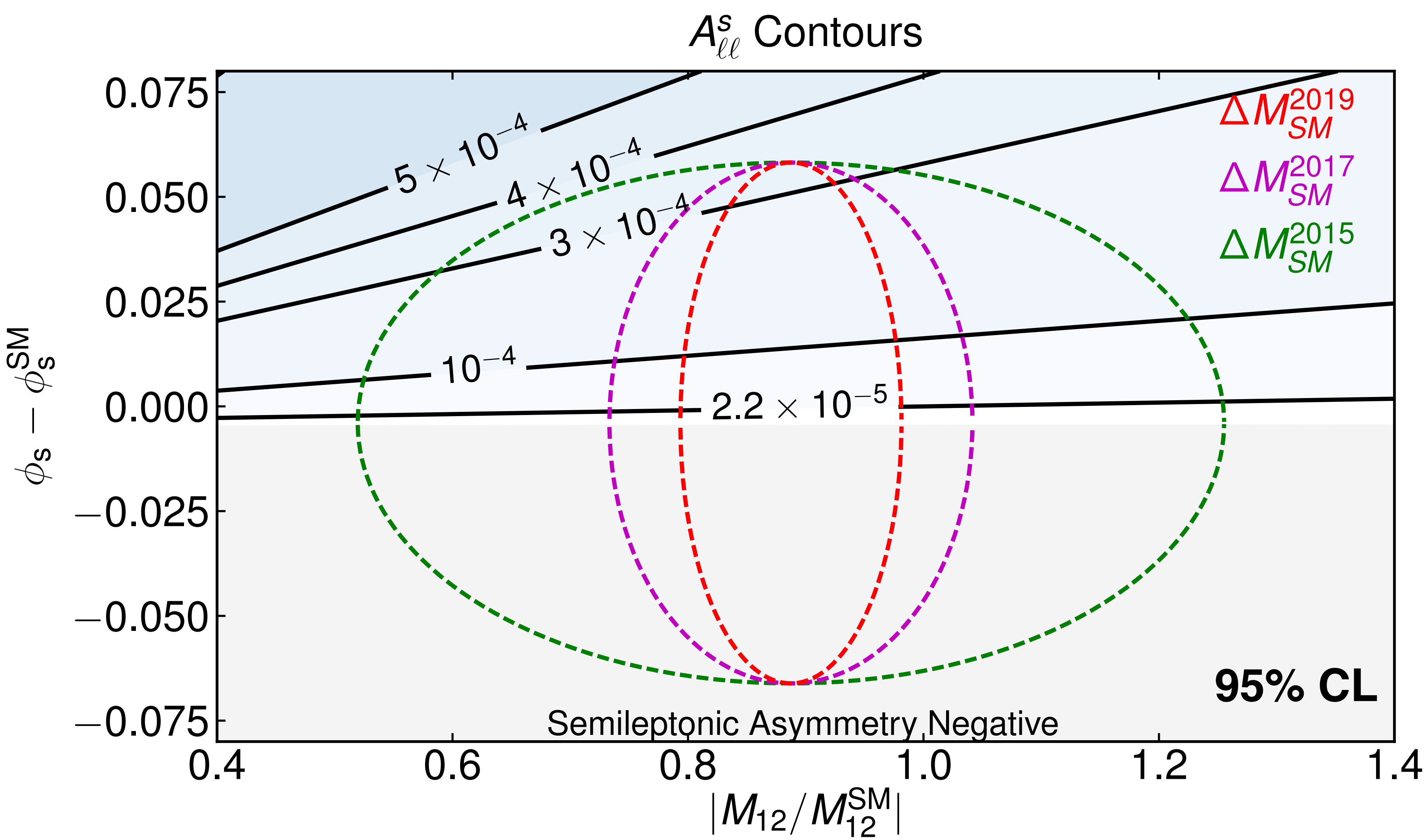

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Hence in the B_s system, due to direct CP violation measurements:

$$A^s_{\ell\ell} < 4 \times 10^{-4}$$ **at 95% CL**

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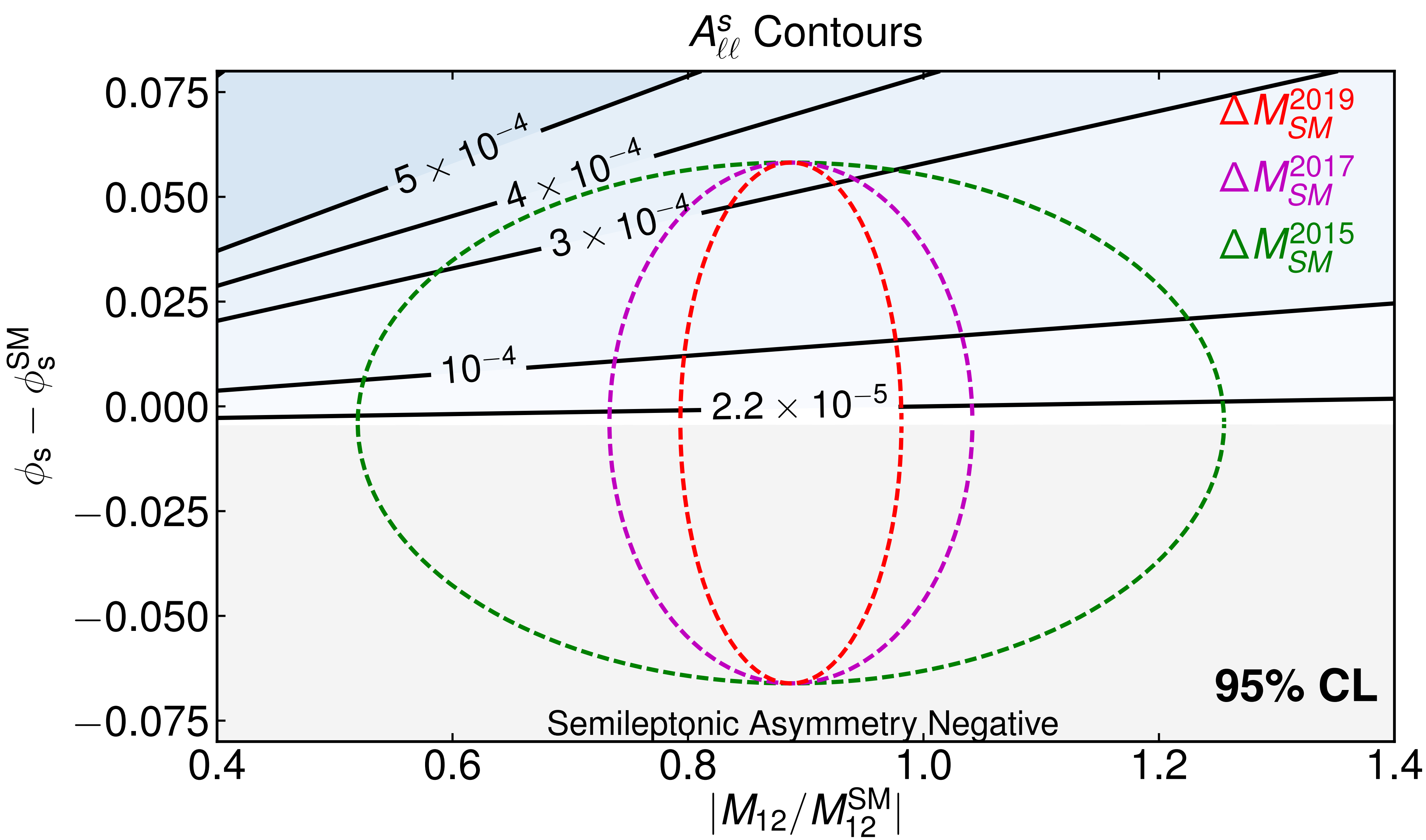

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Implying $$\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) > 10^{-3}$$

2004.XXXXX Alonso-Álvarez, Elor, Escudero, McKeen

Direct CP violation Measurements

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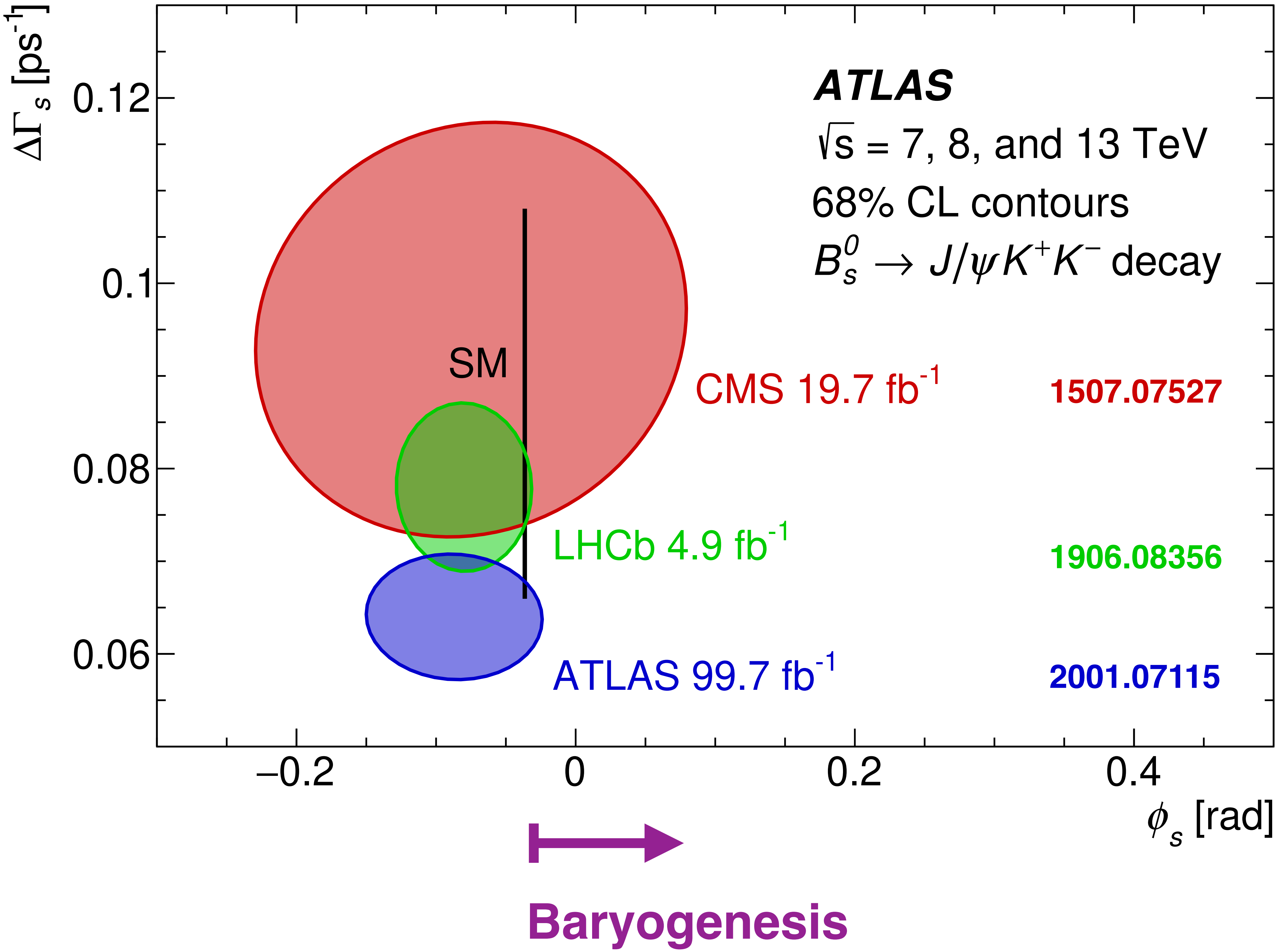
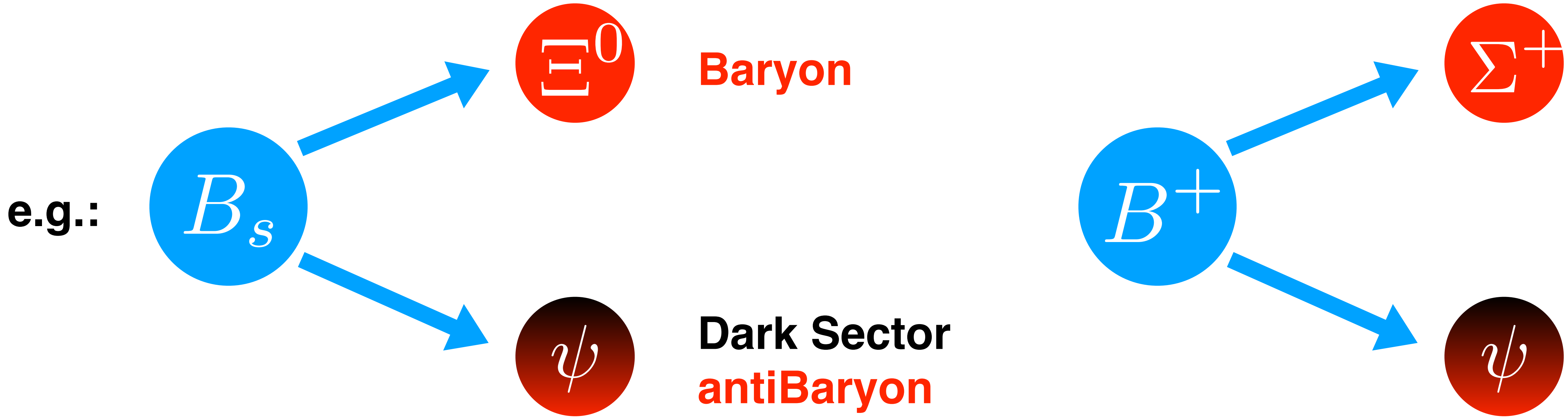


New B-Meson decay

1) It is a 2-Body decay



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3) 4 Flavourful variations exist:

$\psi\, b\, u\, s$	$\psi\, b\, u\, d$	$\psi\, b\, c\, s$	$\psi\, b\, c\, d$
$B_d \to \psi + \Lambda\,(usd)$	$B_d \to \psi + n\,(udd)$	$B_d \to \psi + \Xi_c^0\,(csd)$	$B_d \to \psi + \Lambda_c + \pi^-\,(cdd)$
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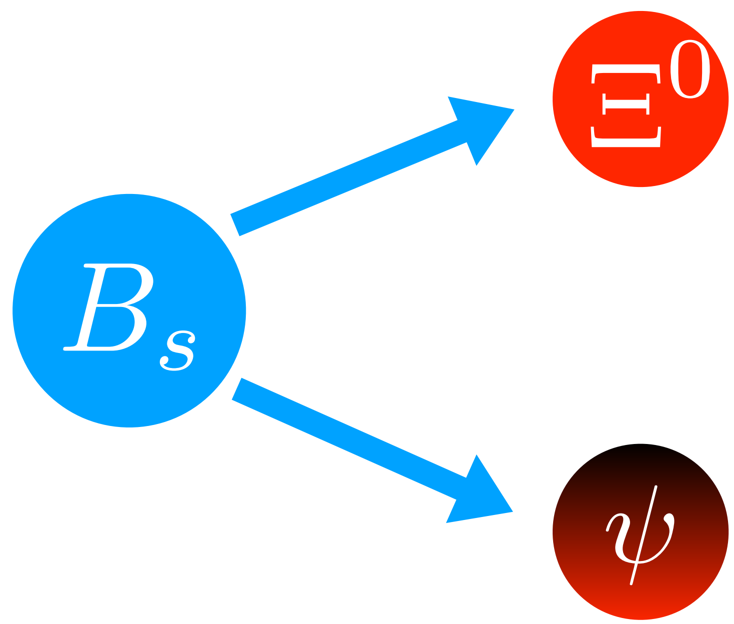
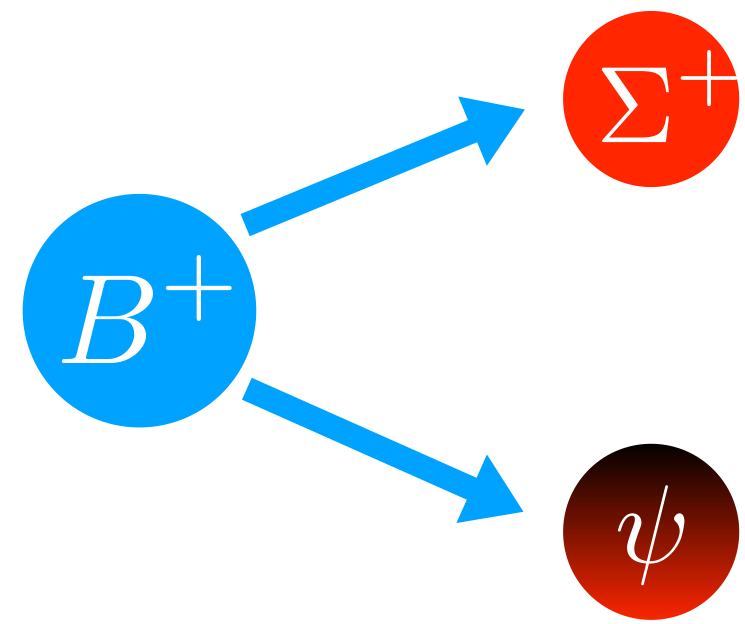


Baryon

Dark Sector
antiBaryon



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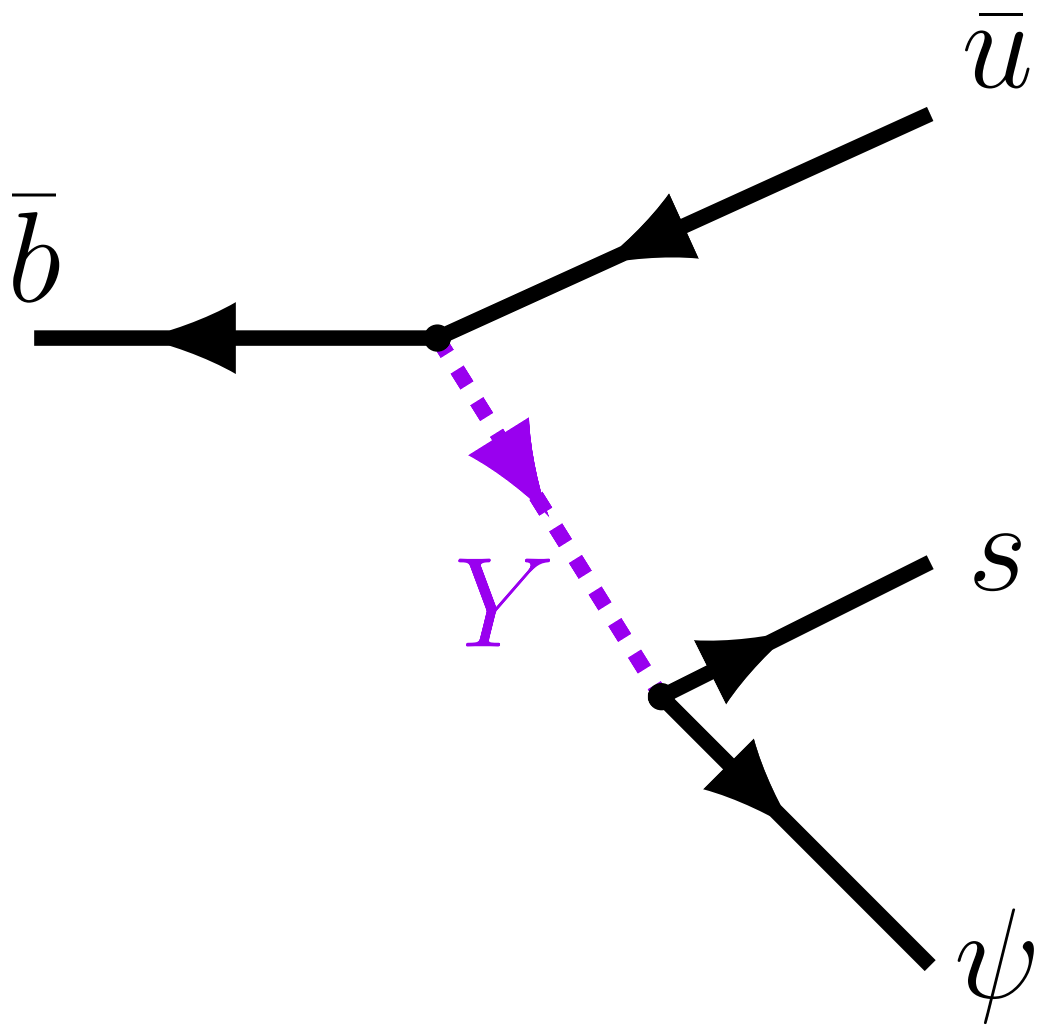
4) Emission of light mesons is likely, BR ~ 50%?

New Force Carrier



Y: Colored Triplet Scalar

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

Same Quantum Numbers as a SUSY squark!

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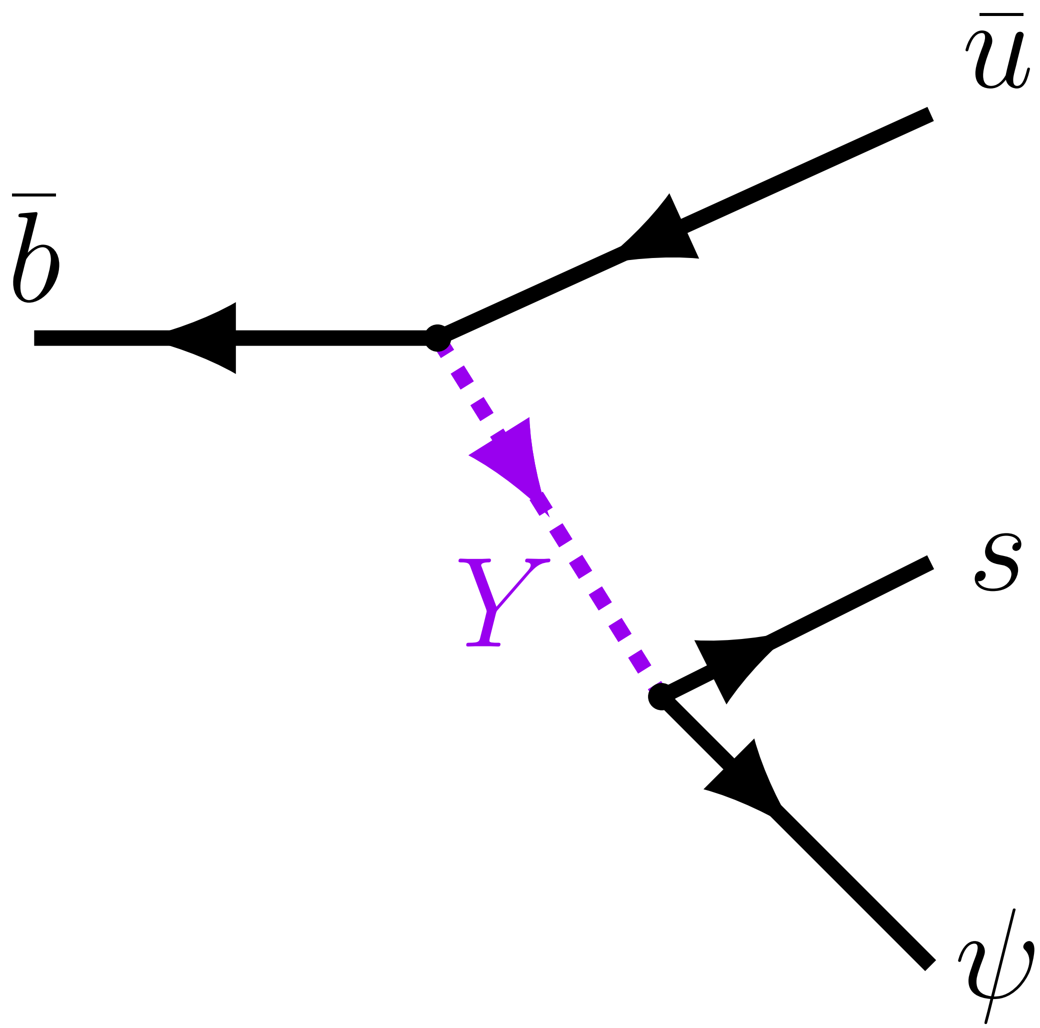

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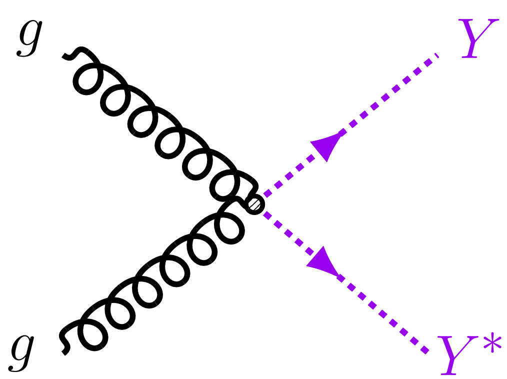
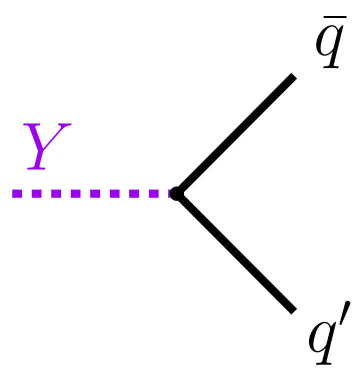
$$\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) \simeq 10^{-3} \left(\frac{m_B - m_\psi}{2 \ \mathrm{GeV}} \right)^4 \left(\frac{1.6 \ \mathrm{TeV}}{m_Y} \frac{\sqrt{y_{ub} y_{\psi s}}}{0.6} \right)^4$$

Squark Searches

Production	Decay	Signature	Constraint
		**4 jets**	**$m_Y > 0.5$ TeV** **1710.07171 (ATLAS)**

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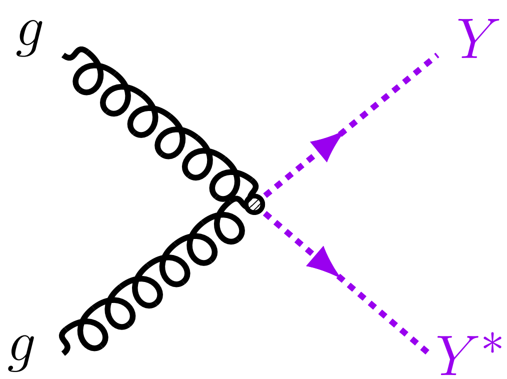
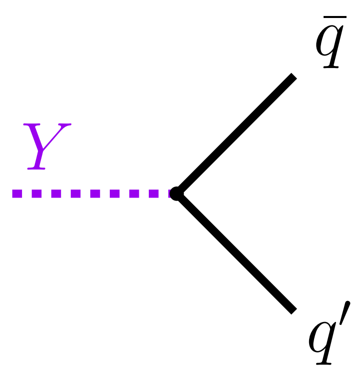
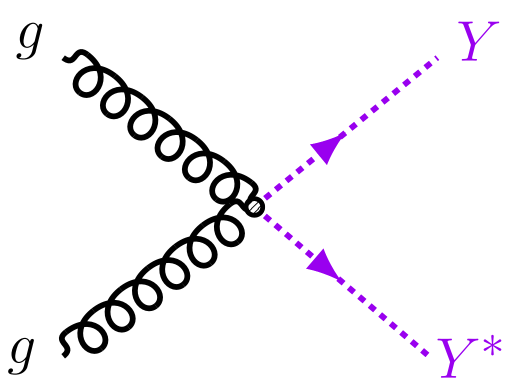
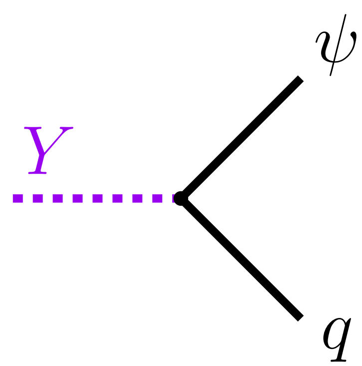
		**4 jets**	**$m_Y > 0.5$ TeV** **1710.07171 (ATLAS)**
		**2 jets+ME**	**$m_Y > 1.1$ TeV** **1908.04722 (CMS)**

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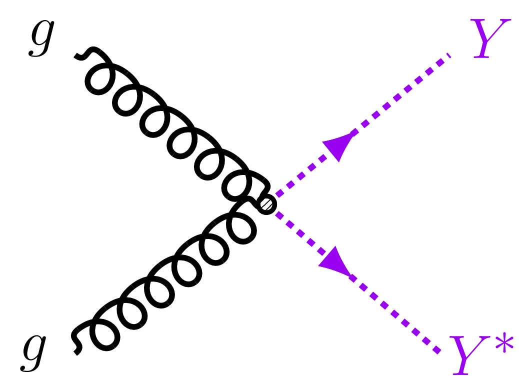
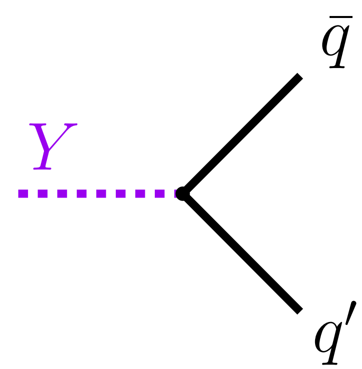
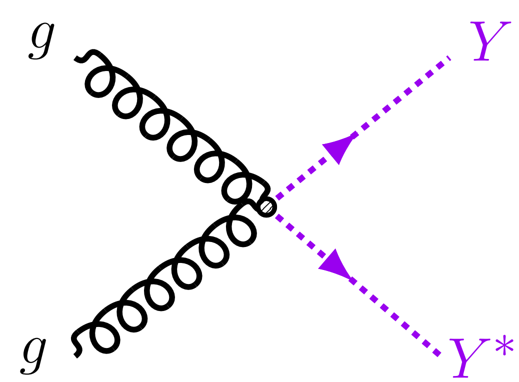
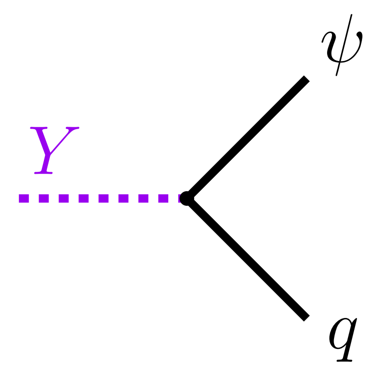
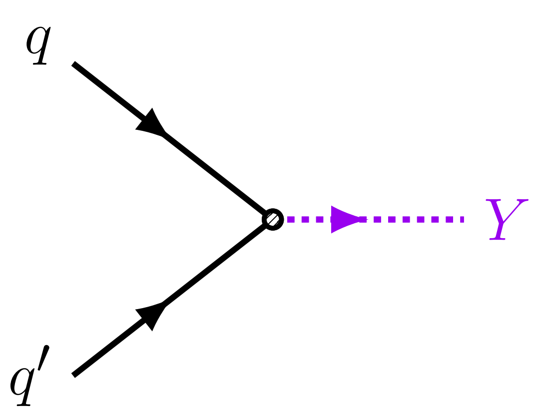
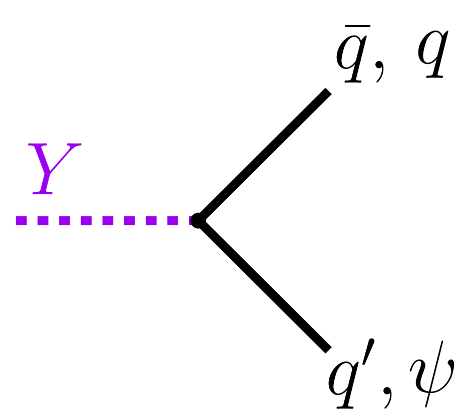
		**4 jets**	**m_Y > 0.5 TeV** **1710.07171 (ATLAS)**
		**2 jets+ME**	**m_Y > 1.1 TeV** **1908.04722 (CMS)**
		**2jets/Monojet**	**m_Y > 1-1.2 TeV** **for g ~ 0.6** **1708.01259** **(CMS + ATLAS recast)**

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

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What about the total width of B-Mesons?

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

Constraint: $\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) < 40\%$

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Measurement: $\mathrm{Br}(B^+ \to \bar{c} + X) = (97 \pm 4)\%$

Most stringent current constraint: $\mathrm{Br}(B \to \psi + \mathrm{Baryon} + X) < 10\%$

B Factories Reach

B meson decays into a Baryon plus Missing Energy

Direct search of $B \to \psi + \mathrm{Baryon} + X$ **(both charged and neutral)**

B-factories have a good handle on missing energy *e.g.*: $\mathrm{Br}(B \to K\nu\nu) < 10^{-5}$

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Naive sensitivity $\text{Br}(B \to \psi + \text{Baryon} + X) < 10^{-4}$

$\epsilon(\text{Kaon}) \sim 20\,\%$

$\epsilon(\text{Baryon}) \sim 2\,\%$

Baryogenesis requires $\text{Br}(B \to \psi + \text{Baryon} + X) > 10^{-3}$

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B meson decays into a Baryon plus Missing Energy

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Ongoing search at Belle-II and at BaBar!

Can LHCb target this decay?

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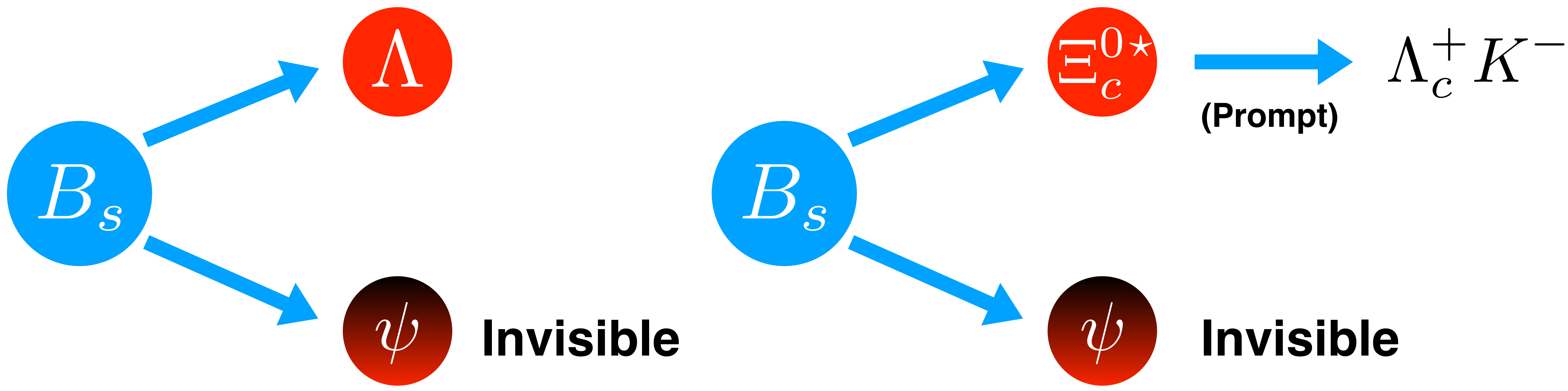


What are the backgrounds for this kind of processes?

Can they be triggered?

The oscillations could be useful (Poluektov and Morris 1911.12729)

LHCb reach to b-Baryons decays

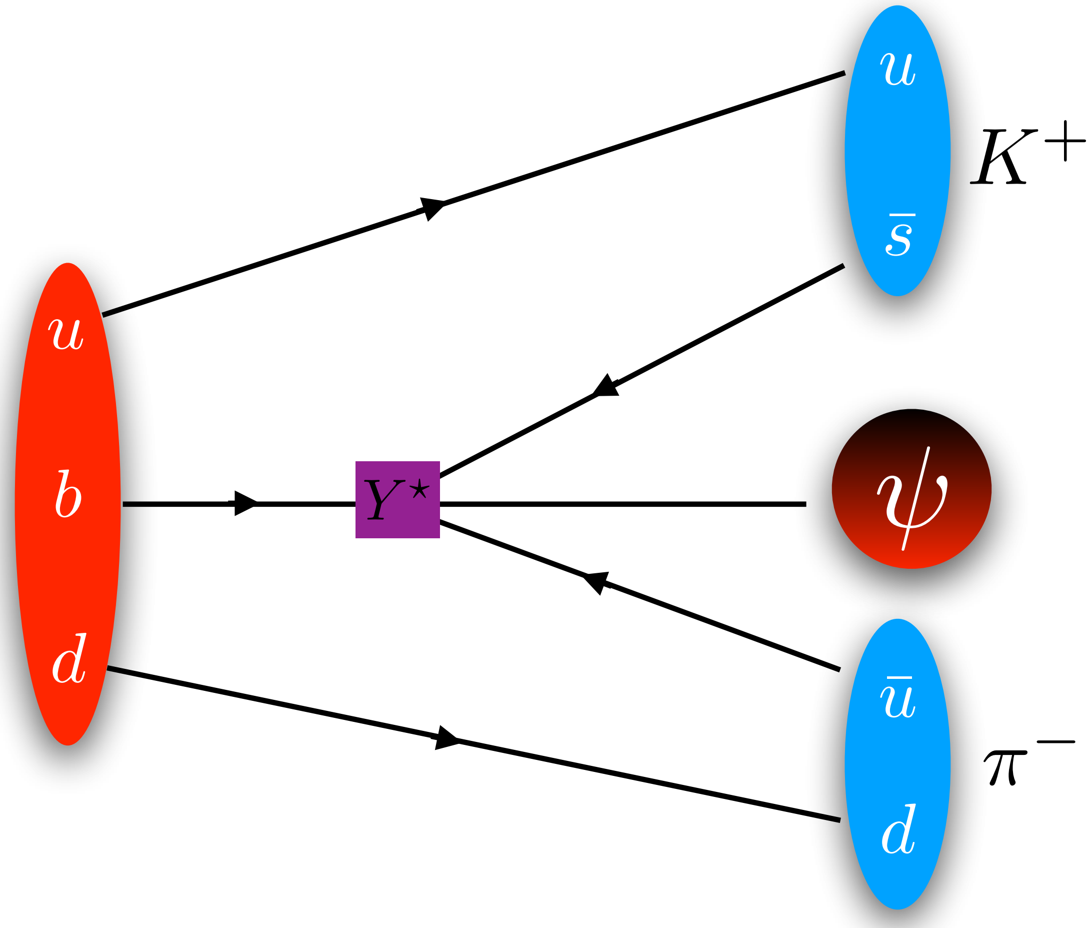
b-flavored Baryon decays into Mesons and Missing Energy

The heavy colored scalar *Y* can also trigger such decays at the same rate as B meson decays:

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

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

***e.g.*:** Λ_b^0



b-flavored baryons are not produced in B-factories

This search seems considerably challenging at hadron colliders

LHCb reach to b-Baryons decays

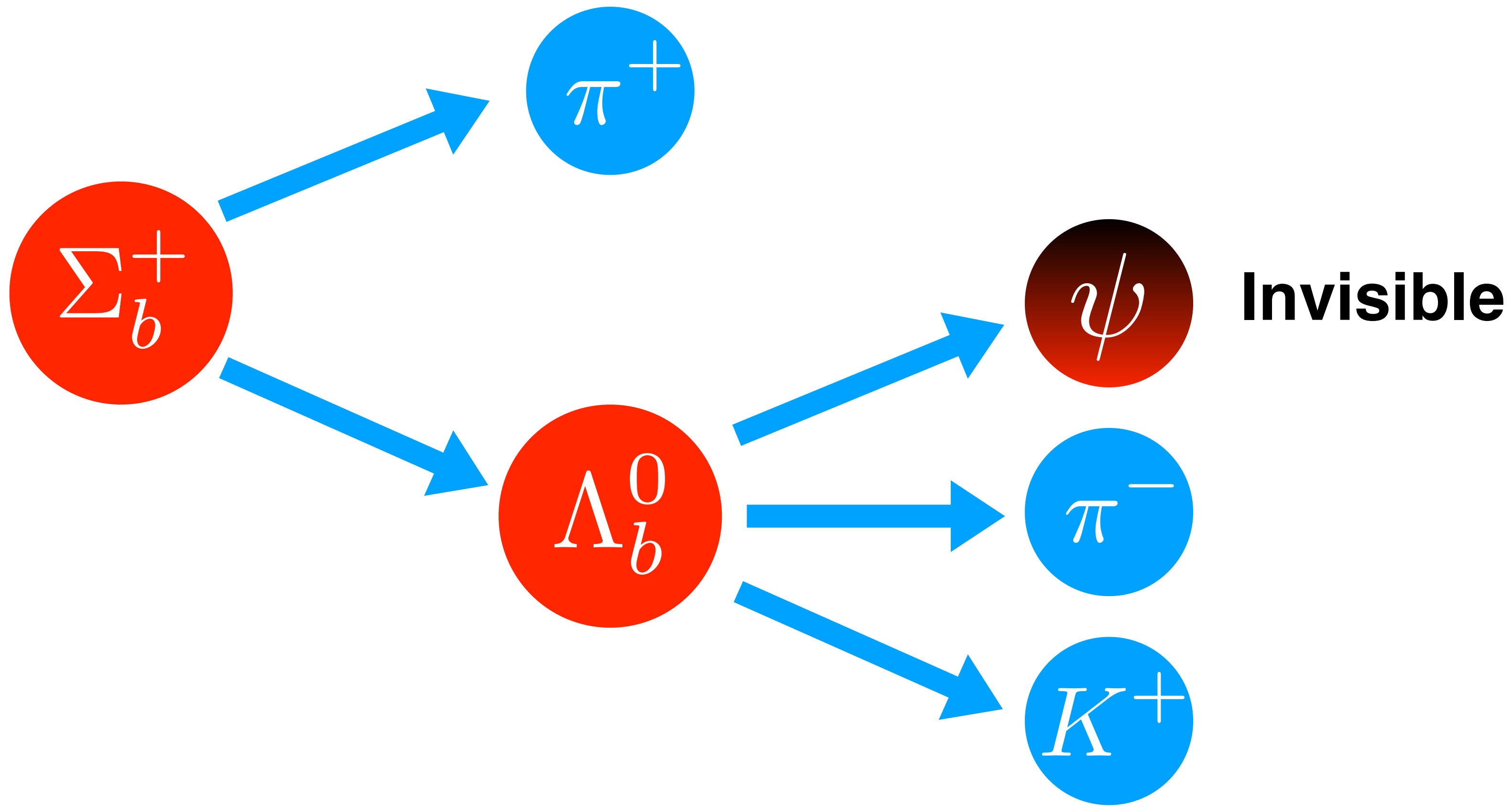
b-flavored Baryon decays into Mesons and Missing Energy

It might be feasible, see Stone & Zhang 1402.4205

The idea is to focus on baryons coming from other baryons

e.g.: $\Sigma_b^{\pm},\ \Sigma_b^{\pm\star} \to \Lambda_b + \pi^{\pm}$

By measuring E_Σ one could have a handle on the energy of Λ_b



Summary

Baryogenesis and Dark Matter from B-mesons:

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- **Positive leptonic asymmetry in B meson decays** $A_{\ell\ell}^{d\,s} > 10^{-5}$
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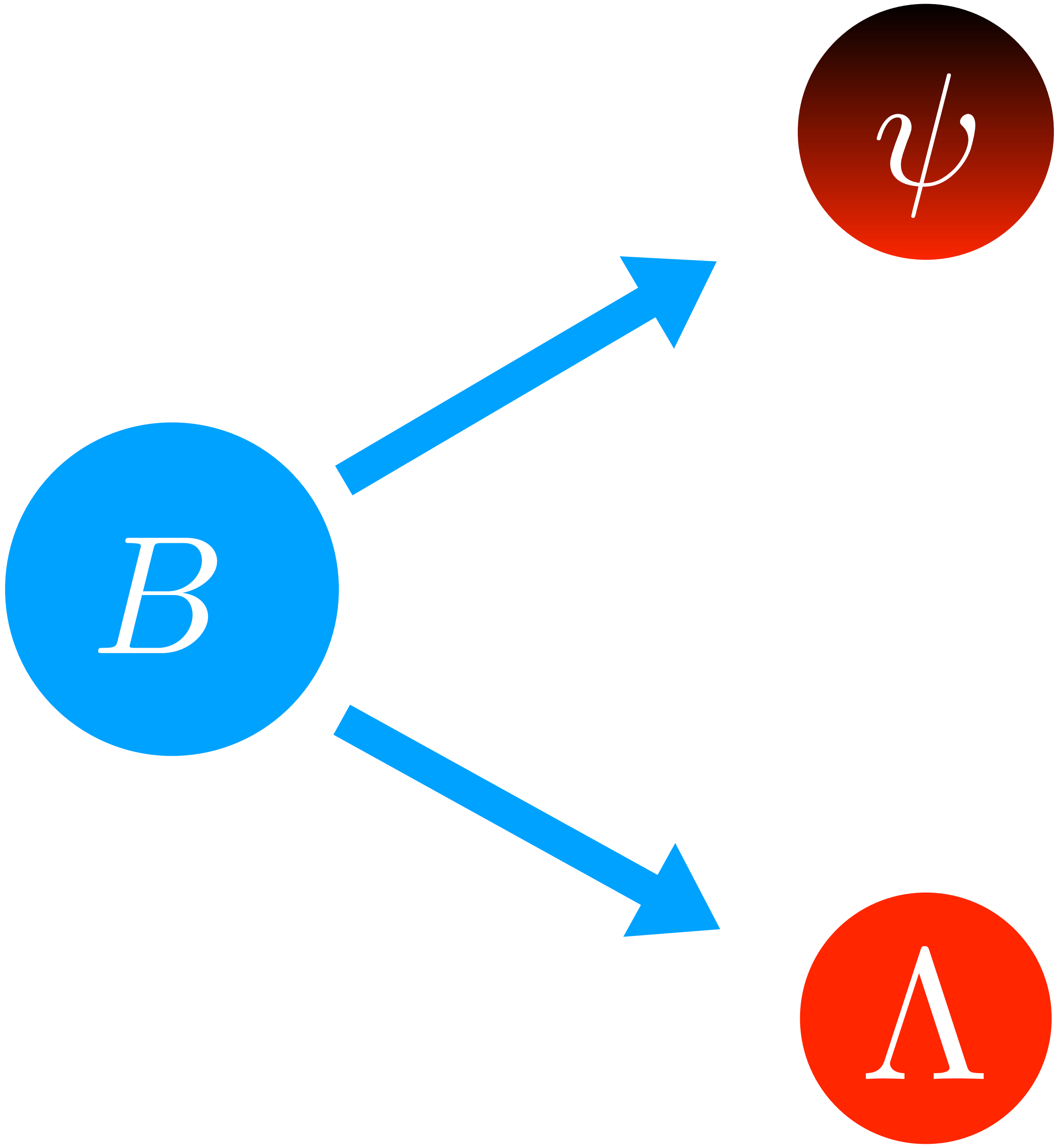
LHCb can contribute to test this mechanism:

- **Certainly in the CPV front.**
- **Can LHCb target invisible decays of B mesons and b-flavored baryons?**

Ann Nelson 1958-2019

Ann Nelson 1958-2019

Thank You!



Back Up

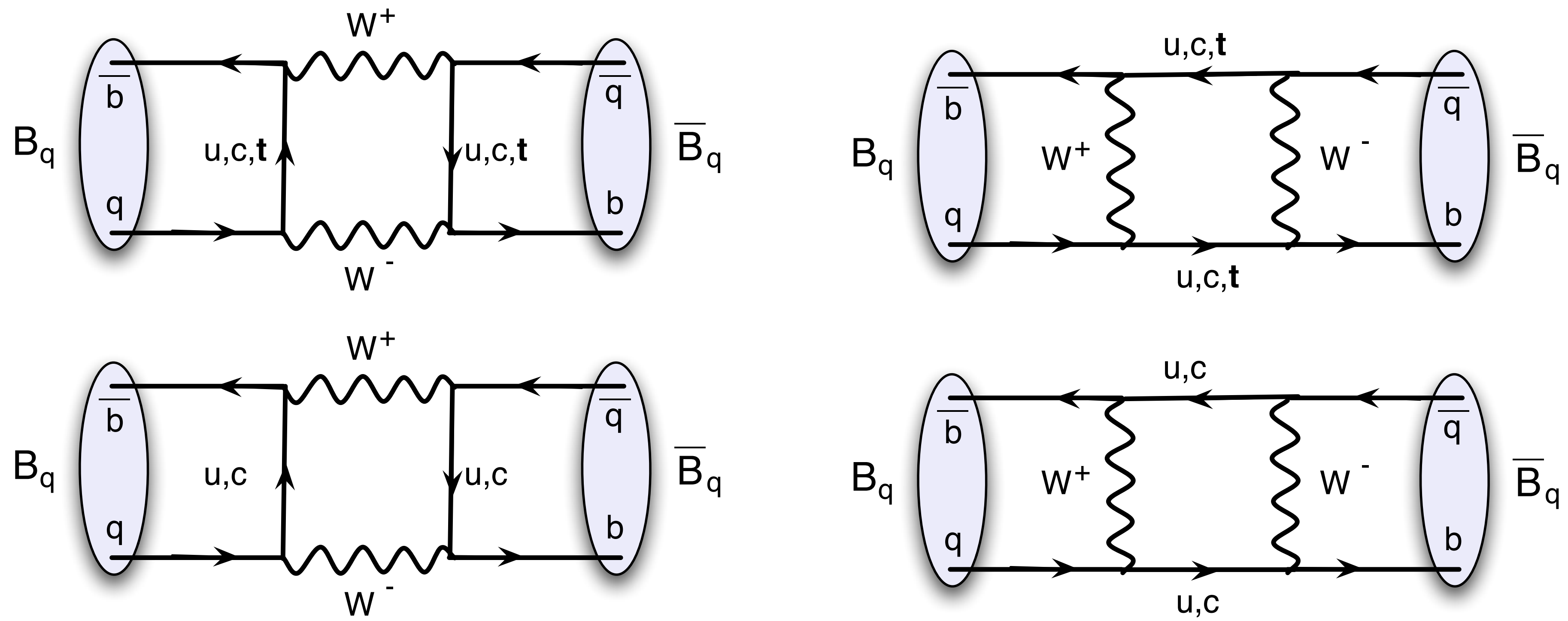
Baryogenesis from B Mesons

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

Oscillations could help

However, see Poluektov and Morris 1911.12729 for B0 mesons:

1) Decays of the type: Bs0 -> A + psi where A decays promptly

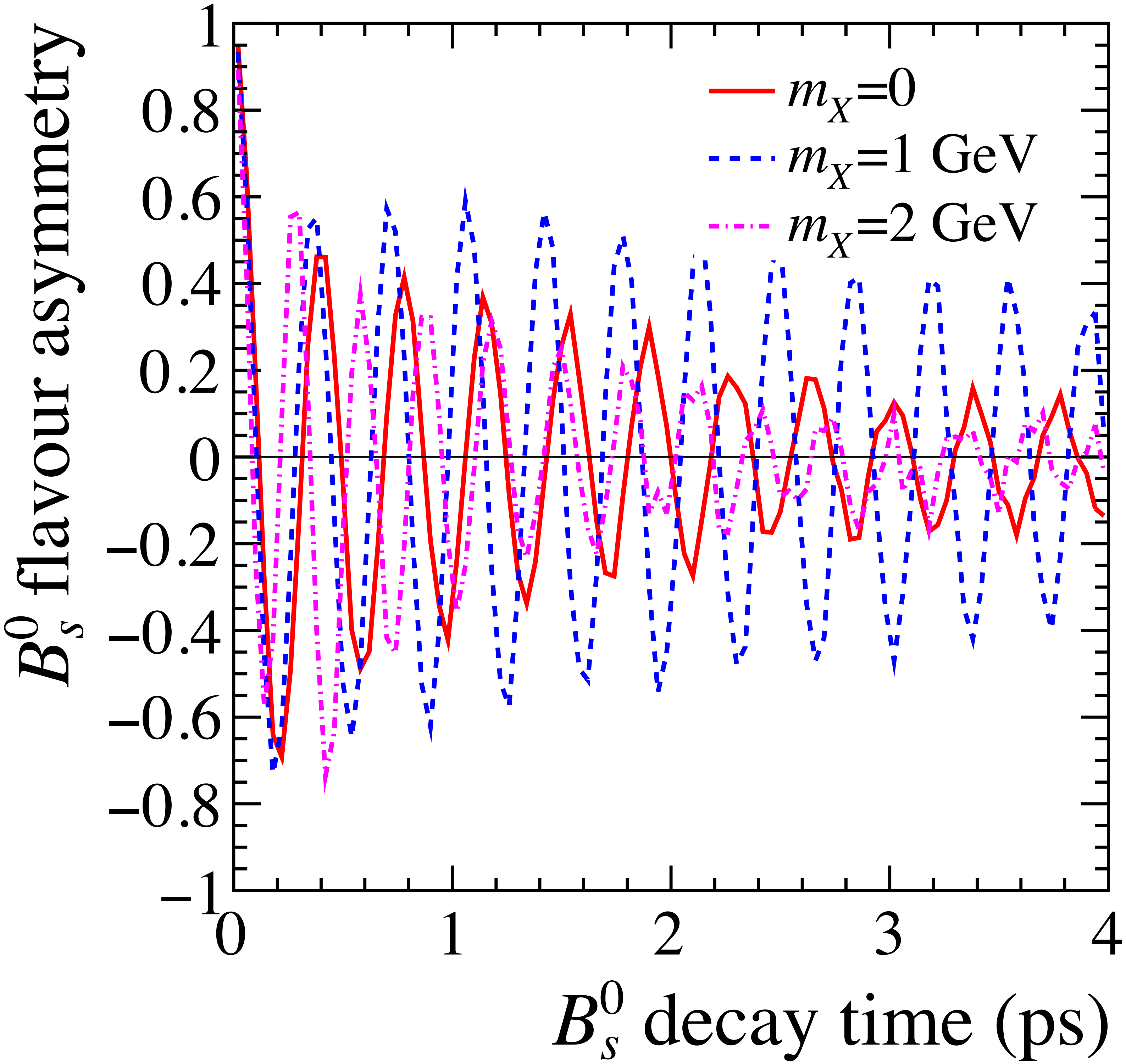
2) Then, if where not invisible pB could be reconstructed

3) (KEY) The momentum enters the calculation of the time of flight of B Mesons t = L M/pB

4) Then study the flavor asymmetry of A and Abar events until a resonance at GammaB is found. That will determine mpsi.

Oscillations could help

Poluektov and Morris 1911.12729



Back Up: Parameters

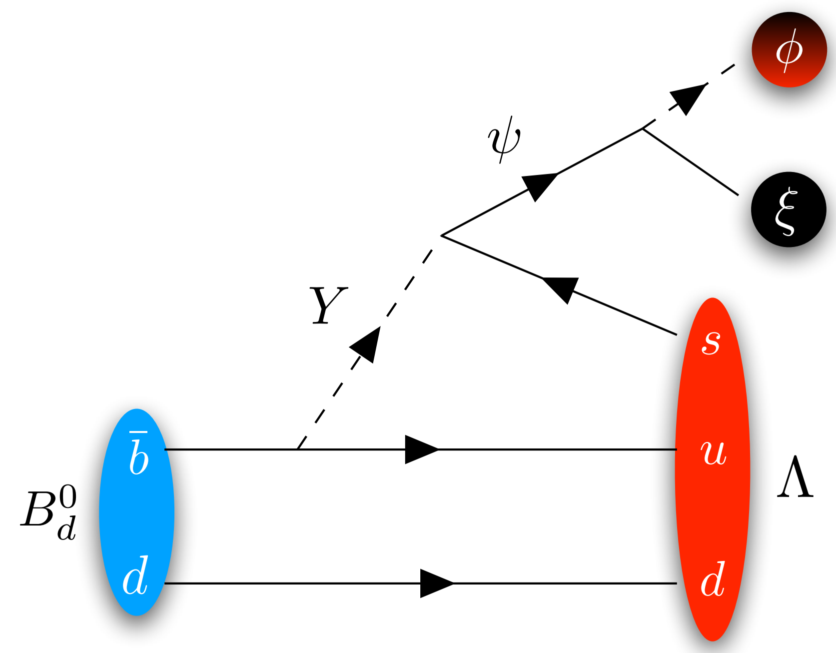
Parameter	Description	Range	Benchmark Value	Constraint
m_Φ	Φ mass	$11 - 100$ GeV	25 GeV	-
Γ_Φ	Inflaton width	$3 \times 10^{-23} < \Gamma_\Phi/\text{GeV} < 5 \times 10^{-21}$	10^{-22} GeV	Decay between $3.5\,\text{MeV} < T < 30\,\text{MeV}$
m_ψ	Dirac fermion mediator	$1.5\,\text{GeV} < m_\psi < 4.2\,\text{GeV}$	3.3 GeV	Lower limit from $m_\psi > m_\phi + m_\xi$
m_ξ	Majorana DM	$0.3\,\text{GeV} < m_\xi < 2.7\,\text{GeV}$	1.0 and 1.8 GeV	$\lvert m_\xi - m_\phi \rvert < m_p - m_e$
m_ϕ	Scalar DM	$1.2\,\text{GeV} < m_\phi < 2.7\,\text{GeV}$	1.5 and 1.3 GeV	$\lvert m_\xi - m_\phi \rvert < m_p - m_e$, $m_\phi > 1.2\,\text{GeV}$
y_d	Yukawa for $\mathcal{L} = y_d \bar{\psi} \phi \xi$		0.3	$< \sqrt{4\pi}$
$\text{Br}(B \to \phi\xi + ..)$	Br of $B \to \text{ME} + \text{Baryon}$	$2 \times 10^{-4} - 0.1$	10^{-3}	< 0.1 [5]
$A_{\ell\ell}^s$	Lepton Asymmetry B_d	$5 \times 10^{-6} < A_{\ell\ell}^d < 8 \times 10^{-4}$	6×10^{-4}	$A_{\ell\ell}^d = -0.0021 \pm 0.0017$ [5]
$A_{\ell\ell}^s$	Lepton Asymmetry B_s	$10^{-5} < A_{\ell\ell}^s < 4 \times 10^{-3}$	10^{-3}	$A_{\ell\ell}^s = -0.0006 \pm 0.0028$ [5]
$\langle \sigma v \rangle_\phi$	Annihilation Xsec for ϕ	$(6 - 20) \times 10^{-25}\,\text{cm}^3/\text{s}$	$10^{-24}\,\text{cm}^3/\text{s}$	Depends upon the channel [3]
$\langle \sigma v \rangle_\xi$	Annihilation Xsec for ξ	$(6 - 20) \times 10^{-25}\,\text{cm}^3/\text{s}$	$10^{-24}\,\text{cm}^3/\text{s}$	Depends upon the channel [3]

An Explicit Model

Minimal Particle Content

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

B-mesons decay into DM (missing energy) and a Baryon



Heavy Colored Triplet Scalar:

- $\mathcal{L} \supset -y_{ub}\, Y^*\, \bar{u}\, b^c - y_{\psi s}\, Y \bar{\psi}\, s^c + \text{h.c}$ $\quad m_Y > 1\,\text{TeV}$ **(4-jet/squark)**
- $\mathcal{H}_{eff} = \dfrac{y_{ub} y_{\psi s}}{m_Y^2} u\, s\, b\, \psi$ also possible $c\, s\, b\, \psi\,,\, u\, d\, b\, \psi\,,\, c\, d\, b\, \psi$
- $\Delta B = 0$ **operator induces new b-quark decay** $\bar{b} \to \psi u s$ **(CP and Baryon number conserving)**
- $\text{Br}(B \to \xi\phi + \text{Baryon}) \simeq 10^{-3} \left(\dfrac{m_B - m_\psi}{2\ \text{GeV}}\right)^4 \left(\dfrac{1\ \text{TeV}}{m_Y} \dfrac{\sqrt{y_{ub} y_{\psi s}}}{0.53}\right)^4$

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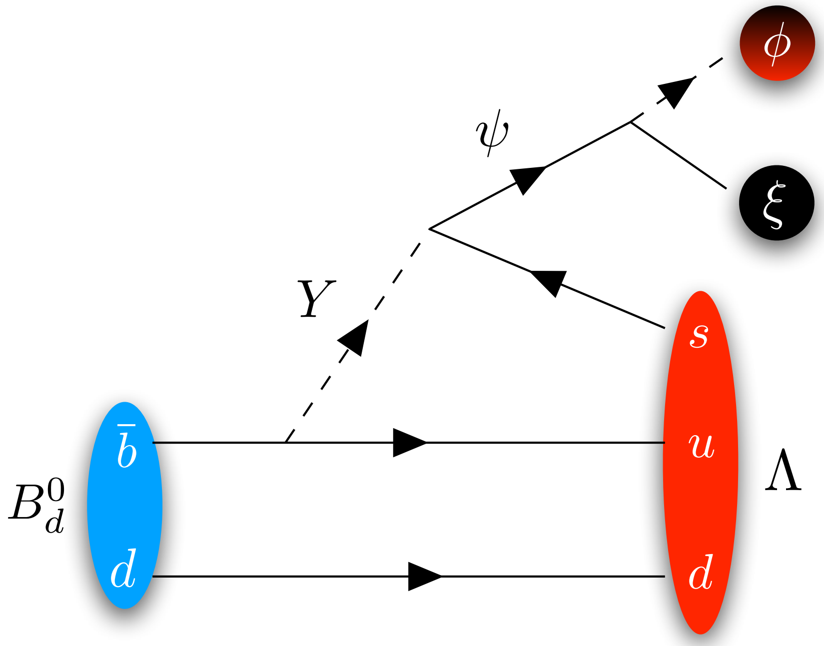

The Dark Sector:

ψ : **Dirac Dark Baryon**

- **For the b-quark decay to happen:** $m_\psi < m_B - m_{\text{Baryon}} < 4.3\,\text{GeV}$
- ψ **needs to have decays into other dark sector particles or will decay back to visible baryons and undo the Baryogenesis** $\tau(\psi \to p + \pi^-) \sim 10^4\,\text{years}$

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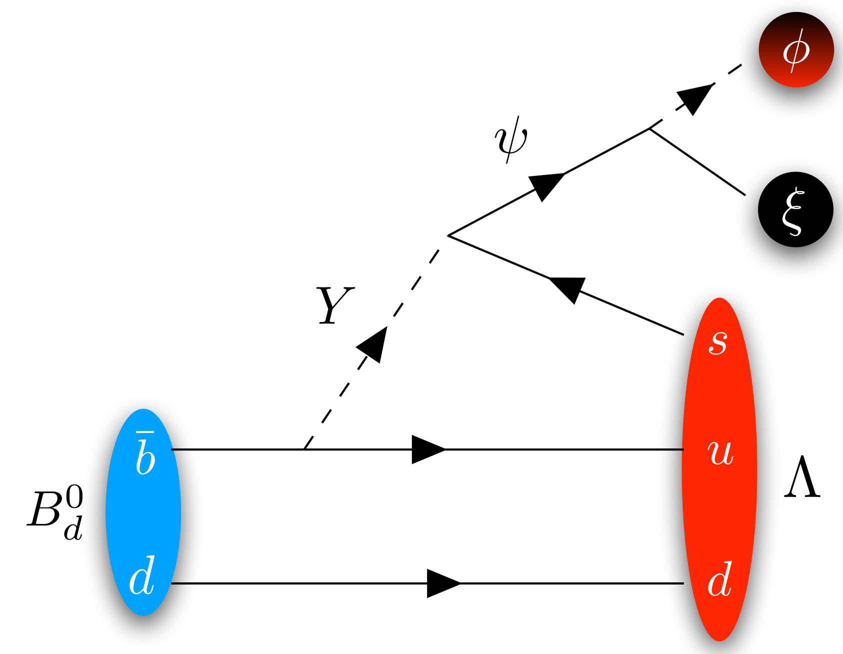


The Dark Sector:

ϕ : **Charged *Stable* Scalar anti-Baryon**

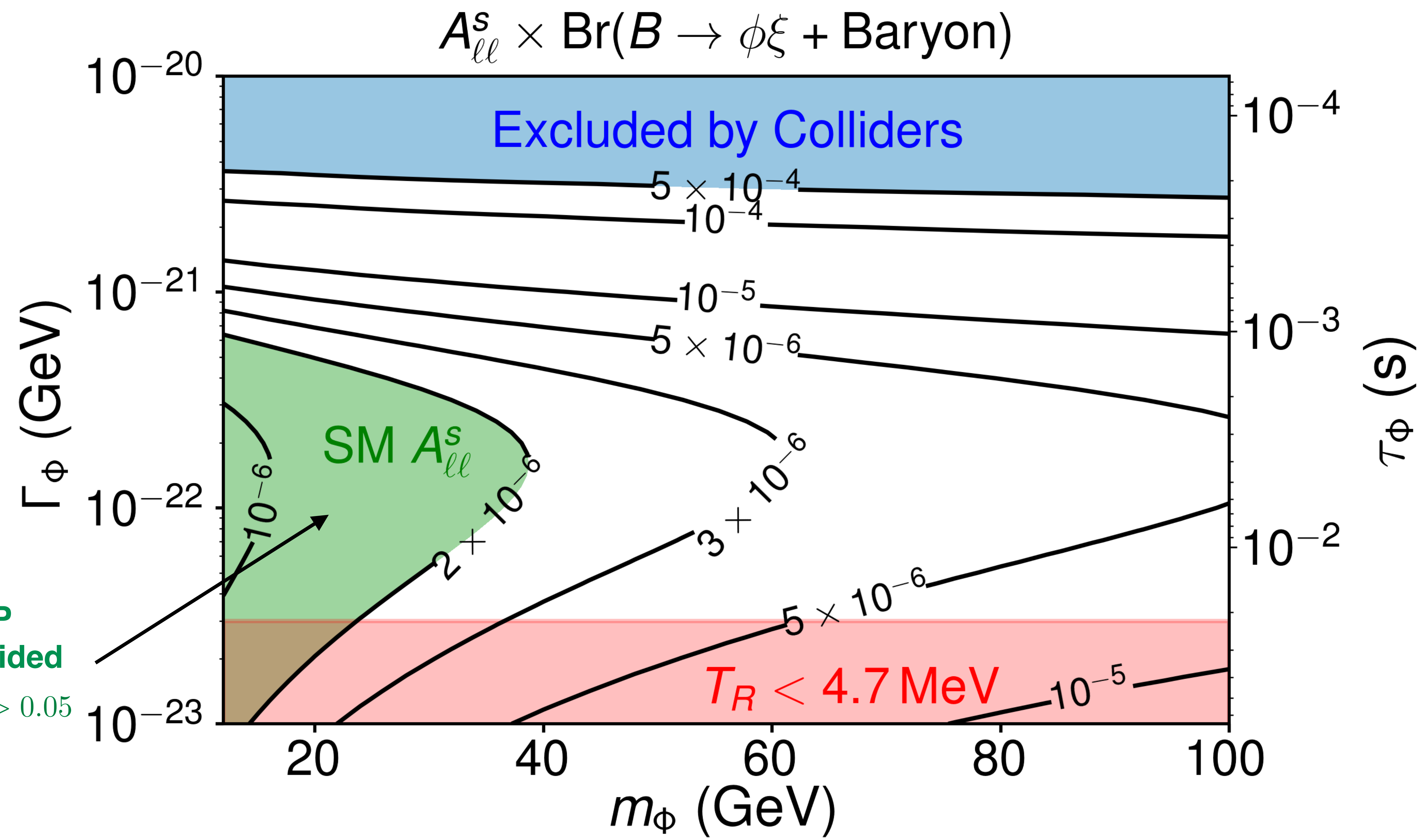
ξ : **Dark *Stable* Majorana Fermion**

- **Minimal Dark sector interaction** $\mathcal{L} \supset -y_d \bar{\psi} \phi \xi$ **with Z_2 symmetry**
- **Constraints:**
  - ***ψ -> $\phi\xi$* Decay*:*** $m_\phi + m_\xi < m_\psi < 4.3\,\text{GeV}$
  - **DM Stability:** $|m_\xi - m_\phi| < m_p + m_e$
  - **Neutron Star Stability:** $m_\psi > m_\phi > 1.2\,\text{GeV}$

McKeen, Nelson, Reddy, Zhou 1802.08244

Parameter Space $A^d_{\ell\ell} = 0$

All points correspond to $Y_B = 8.7 \times 10^{-11}$

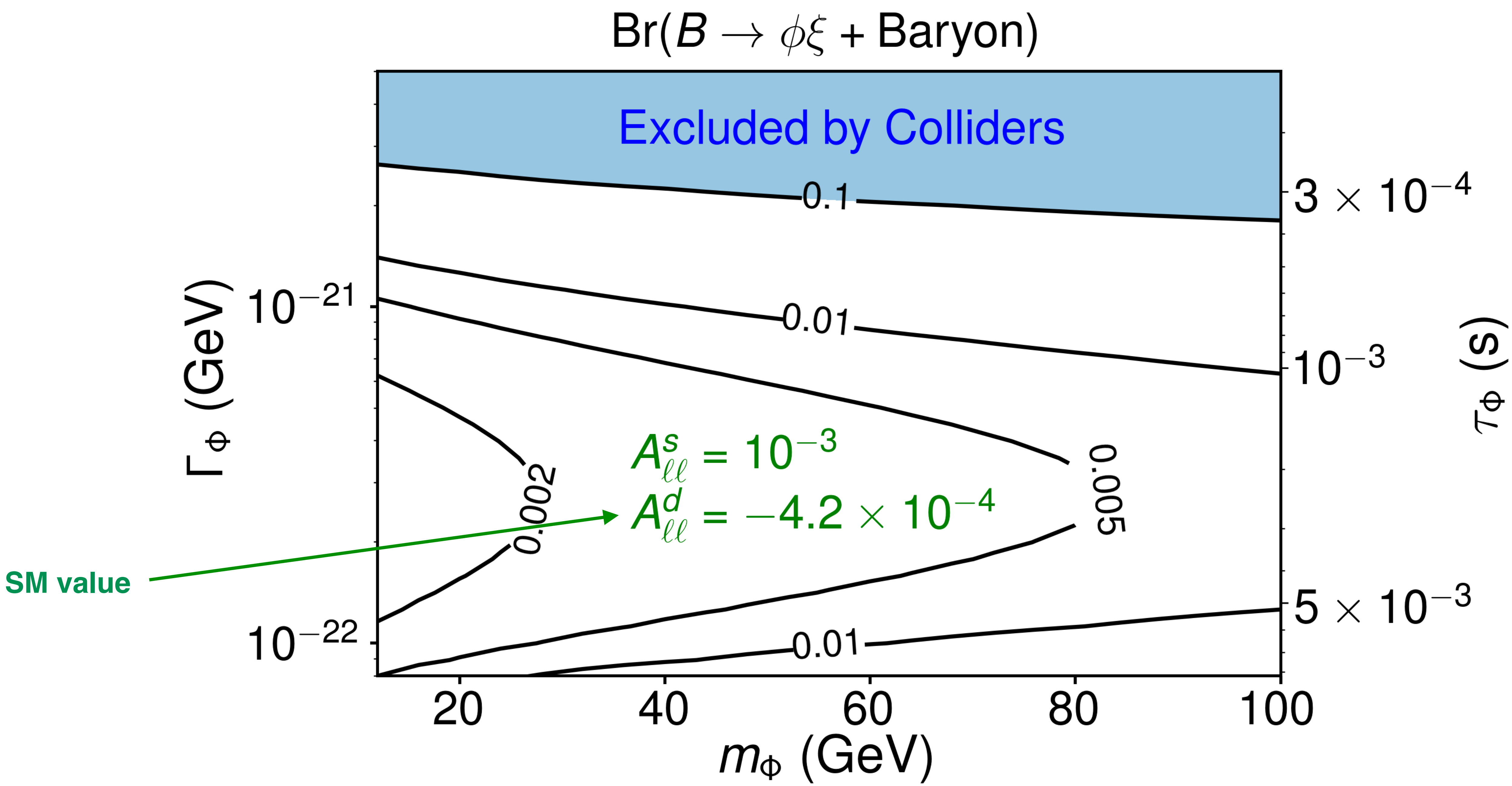


Baryogenesis can be achieved with just the CP violation in the SM! provided $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) > 0.05$ **and** $A^d_{\ell\ell} = 0$

Baryogenesis requires:

- $\mathrm{Br}(B \to \phi\xi + \mathrm{Baryon} + X) = 2 \times 10^{-4} - 0.1$
- $A^s_{\ell\ell} = 10^{-5} - 10^{-3}$

Parameter Space $A^d_{\ell\ell} = A^d_{\ell\ell}|_{\rm SM}$



- **Baryogenesis can take place even if one asymmetry is negative provided the other is positive and large enough.**

New B-Meson decay

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

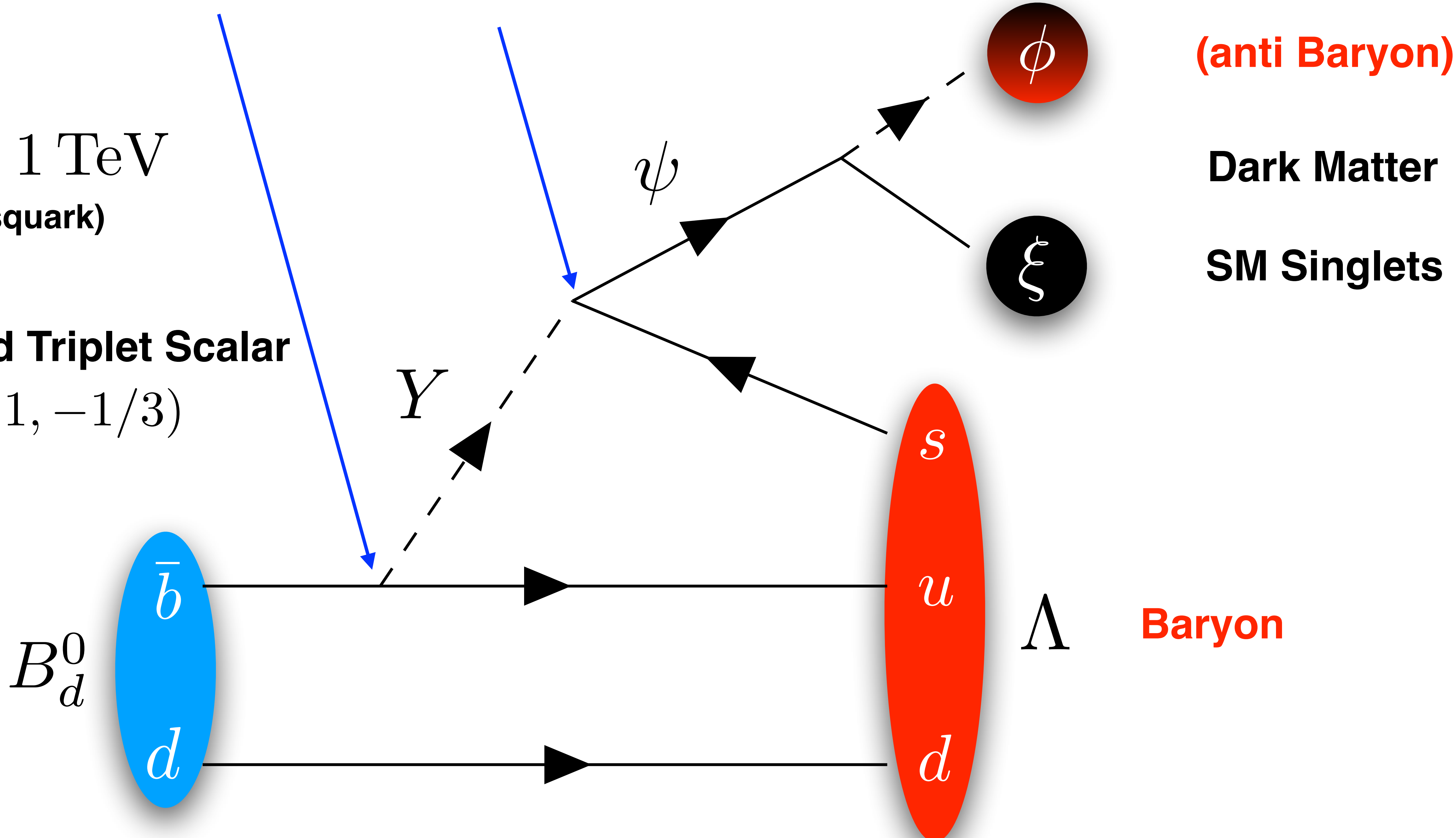
$$1.2\,\text{GeV} \lesssim m_{\phi,\,\xi} \lesssim 2.5\,\text{GeV}$$

$$m_Y > 1\,\text{TeV}$$

(4-jet/squark)

Y: Colored Triplet Scalar

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



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