Search for *B-Mesogenesis* at Belle II

Joint IJCLab IFJ-PAN Workshop 2024

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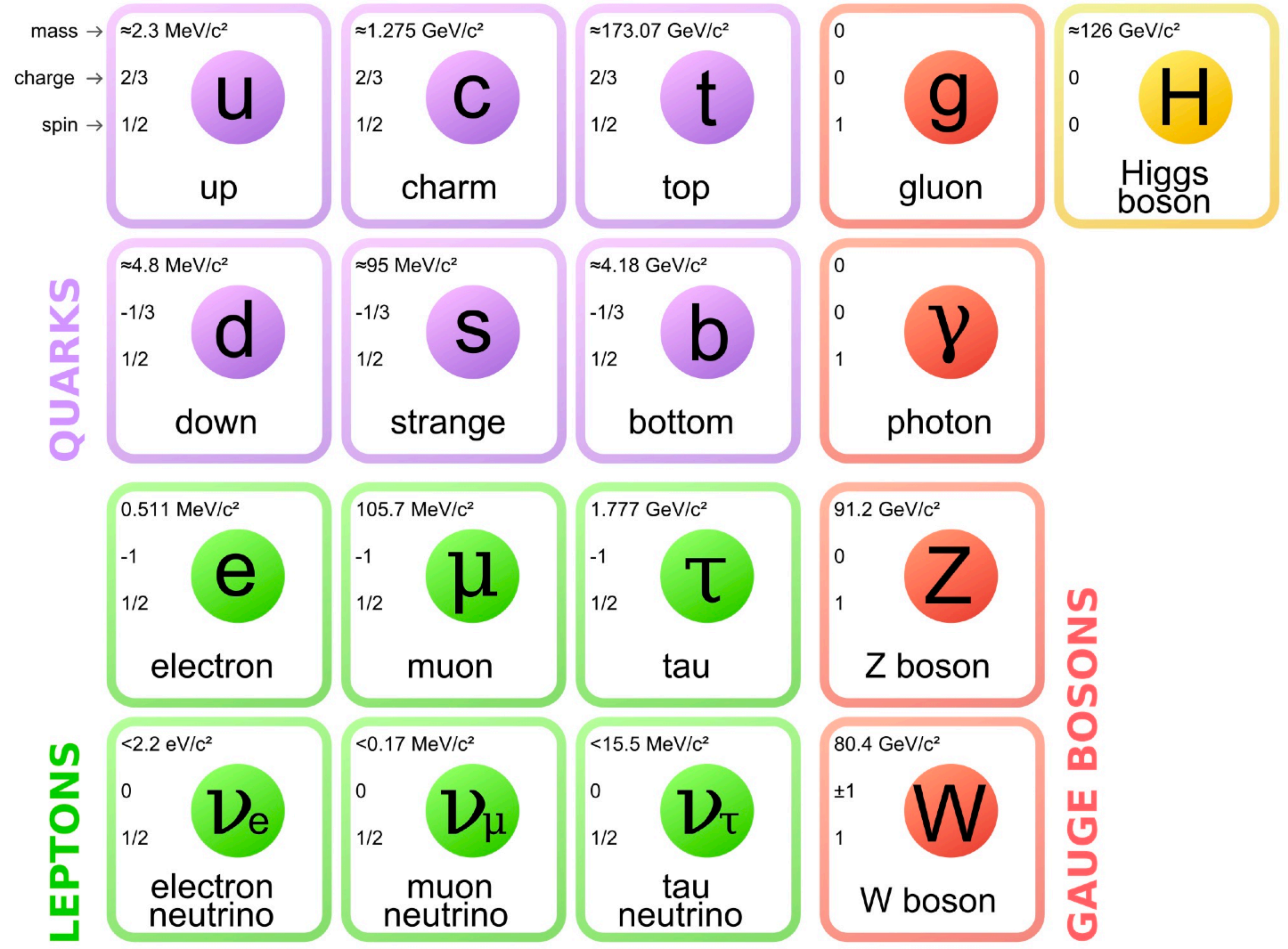
Belle II

The Standard Model and beyond

SM mysteries motivate models of New Physics

<u>Two of the remaining big questions:</u>

- **What is dark matter?**
- **Why is the Universe matter-dominated?**



What if we had a mechanism to simultaneously generate a baryon asymmetry, AND produce an abundance of dark matter in the early universe?

Baryogenesis

Any Baryogenesis mechanism needs:

- ☐ C and CP violation
- ☐ Baryon number violation
- ☐ Out-of-equilibrium interactions

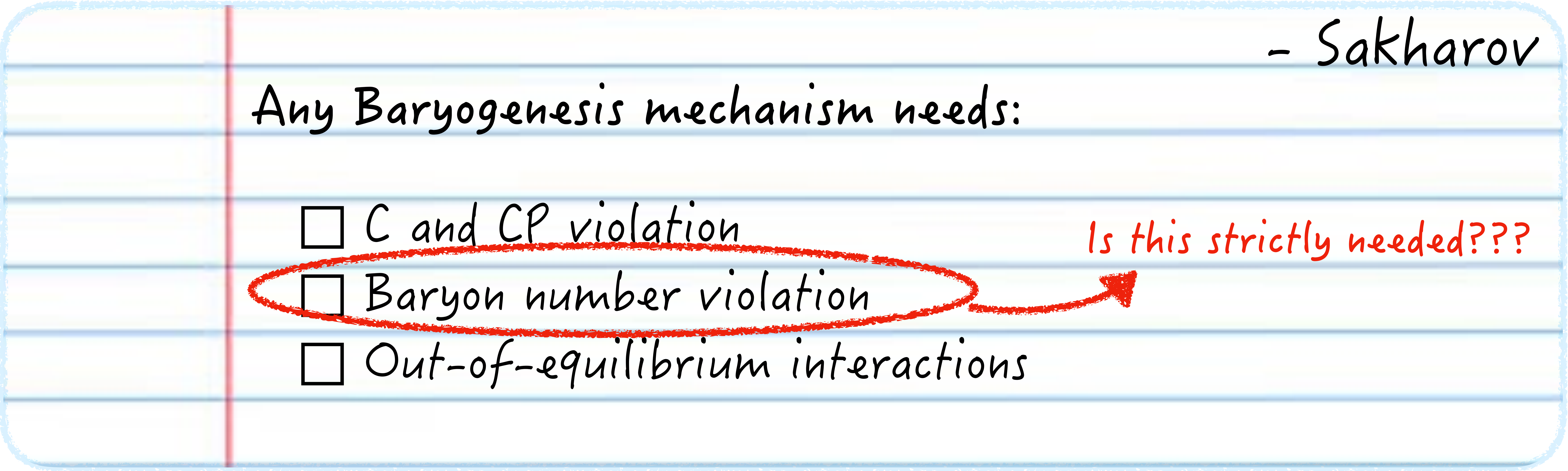
– Sakharov

Traditionally considered difficult to test for due to:

a) High temperature of early Universe

b) Lack of clear experimental signature

Baryogenesis



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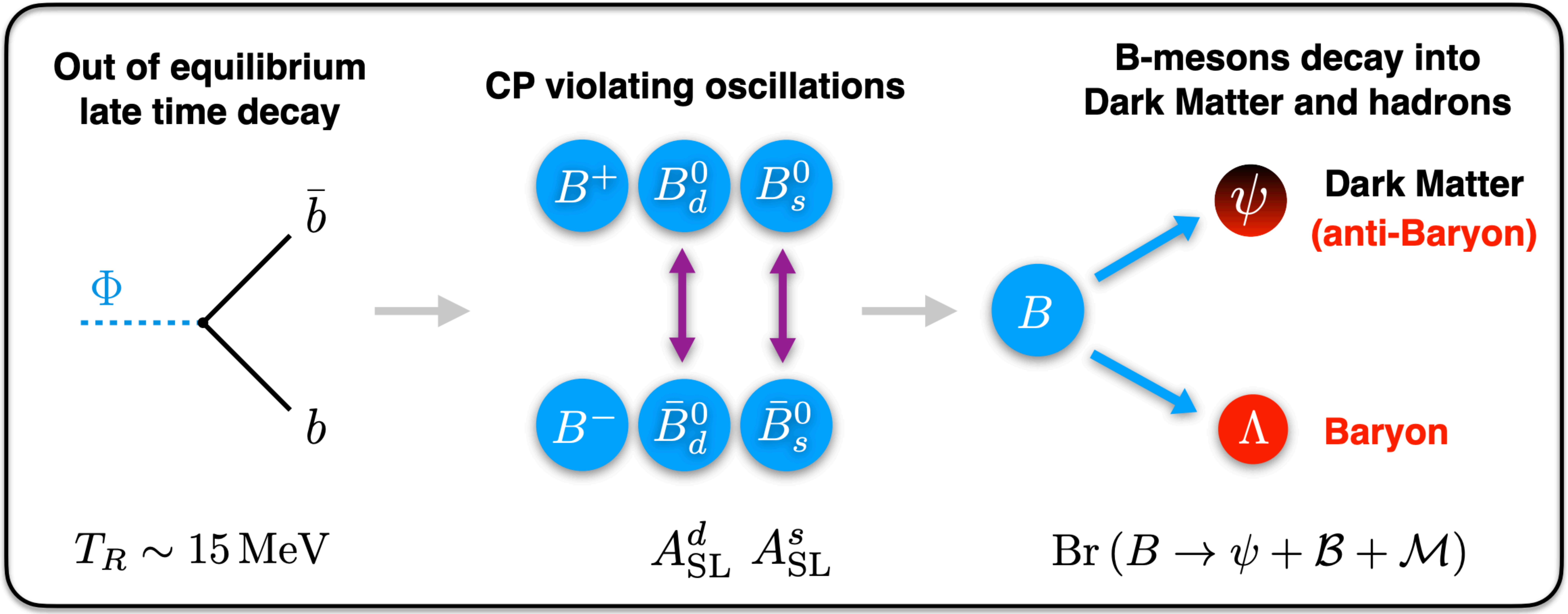
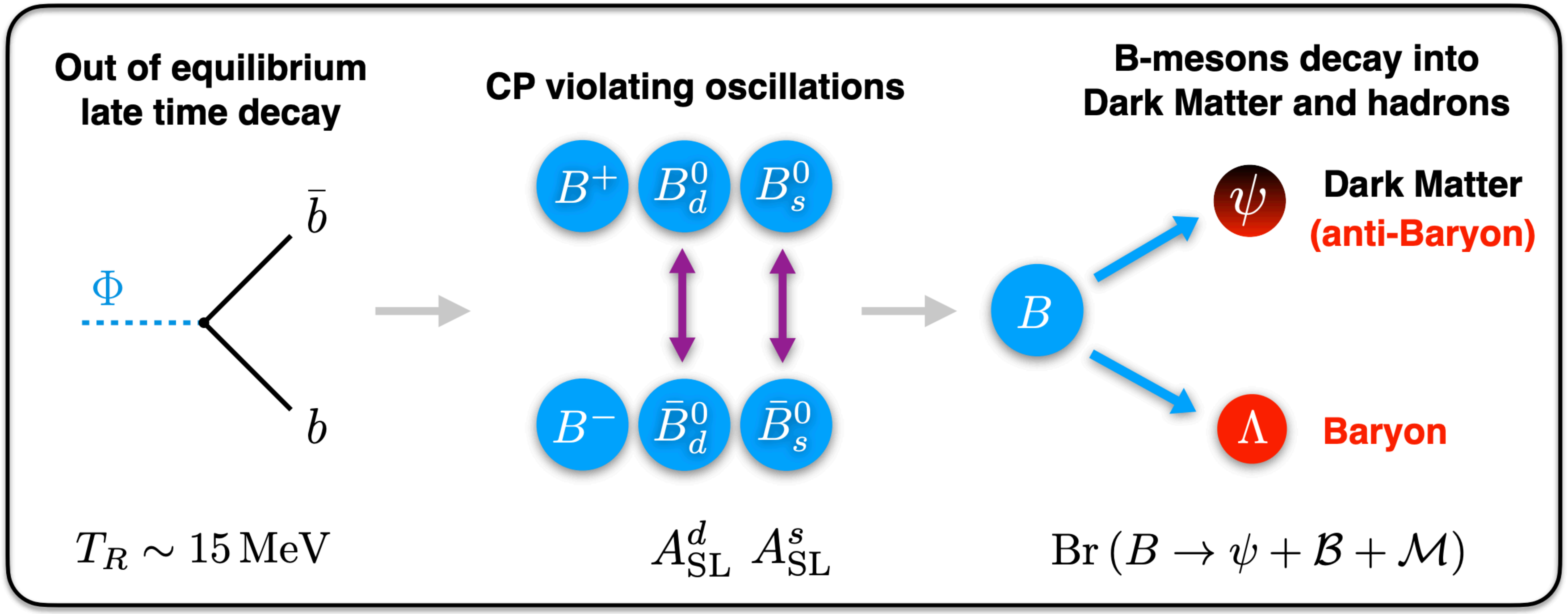
B-Mesogenesis

- B-*Mesogenesis* = baryogenesis + dark matter from B-mesons [arXiv:1810.00880]



B-Mesogenesis



[arXiv:1810.00880]

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Any Baryogenesis mechanism needs:

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- [ ] C and CP violation
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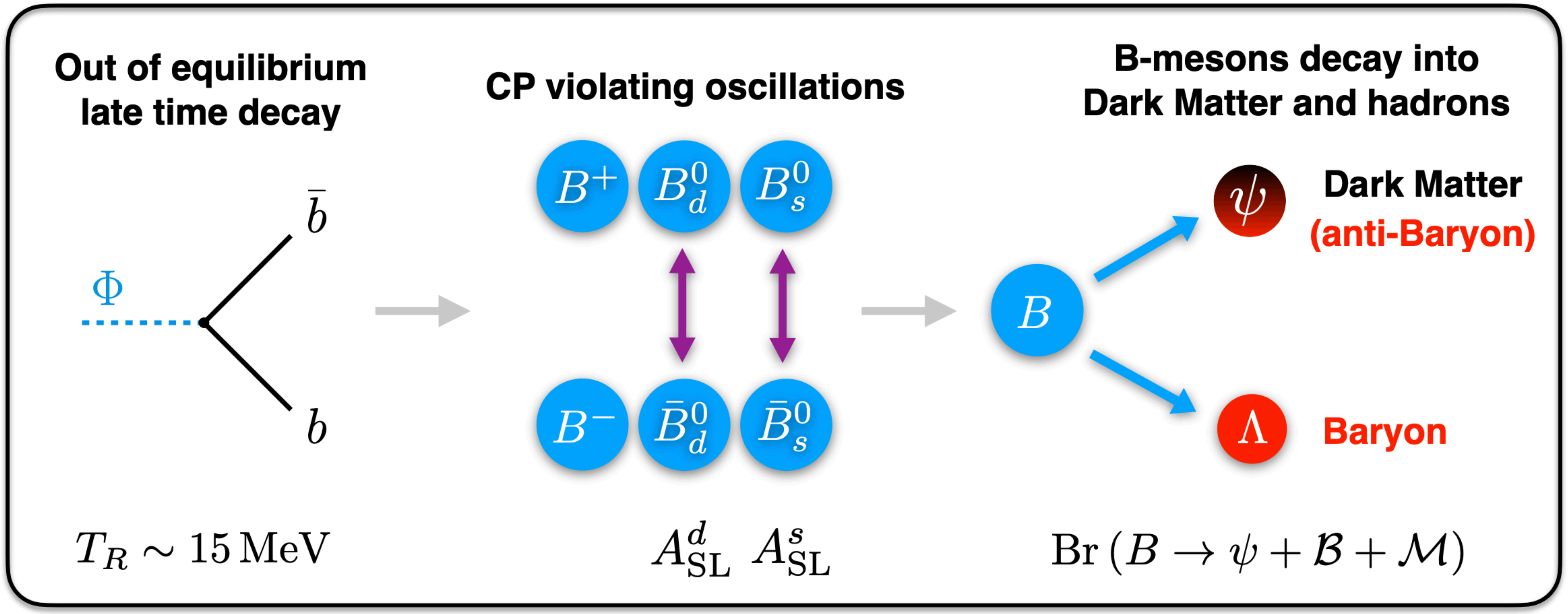
B-Mesogenesis



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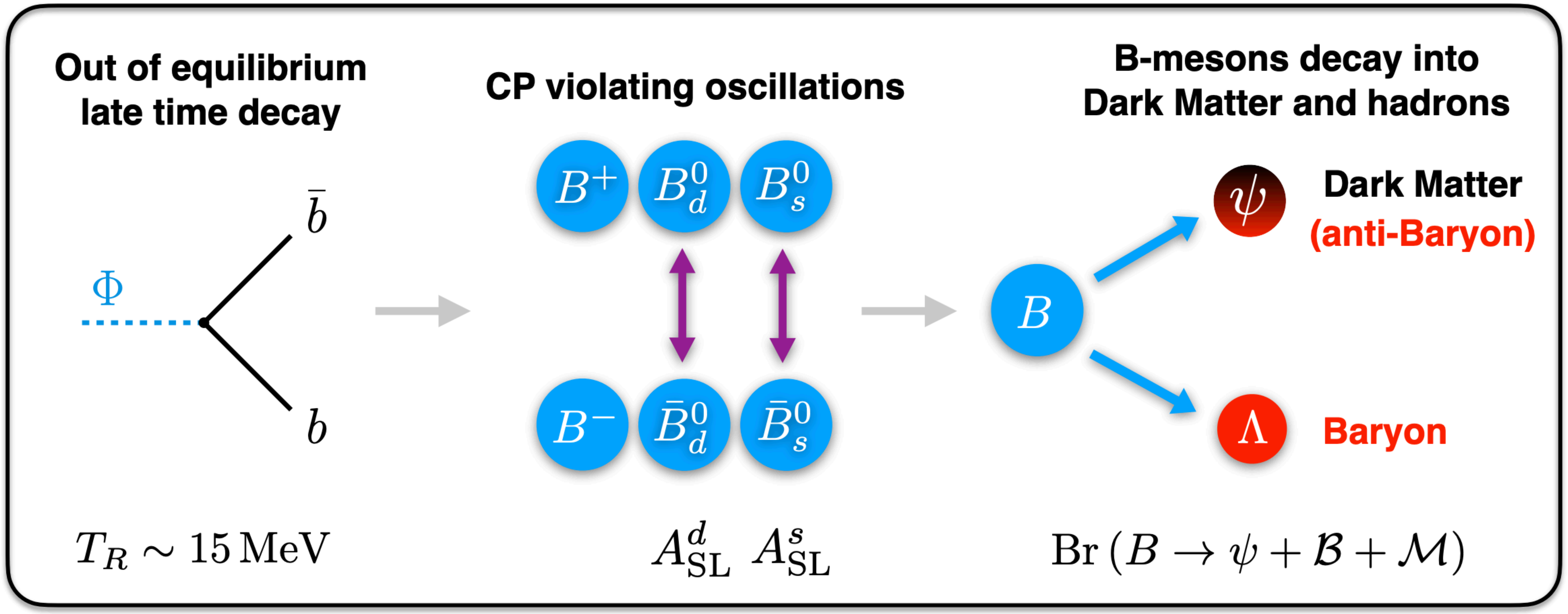
B-Mesogenesis



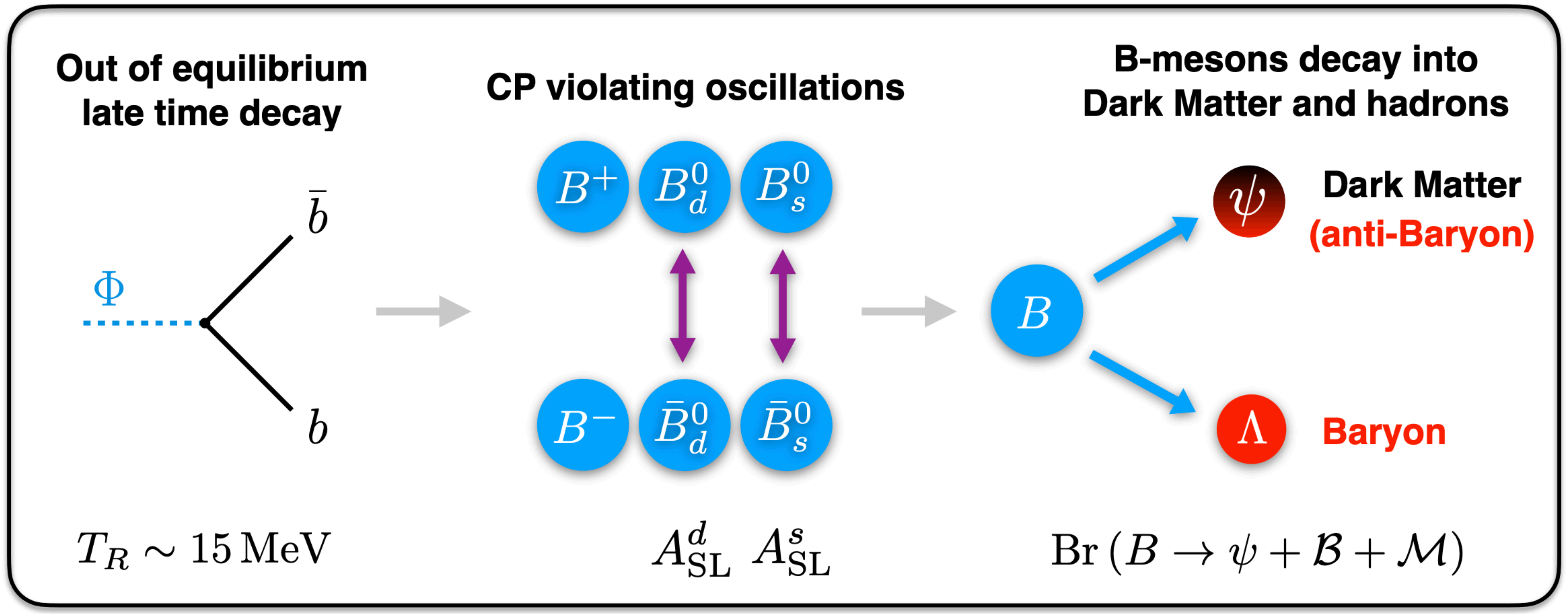
[arXiv:1810.00880]

Any Baryogenesis mechanism needs:

- ☑ Out-of-equilibrium interactions
- ☑ C and CP violation
- ☑ Apparent baryon number violation

– Sakharov

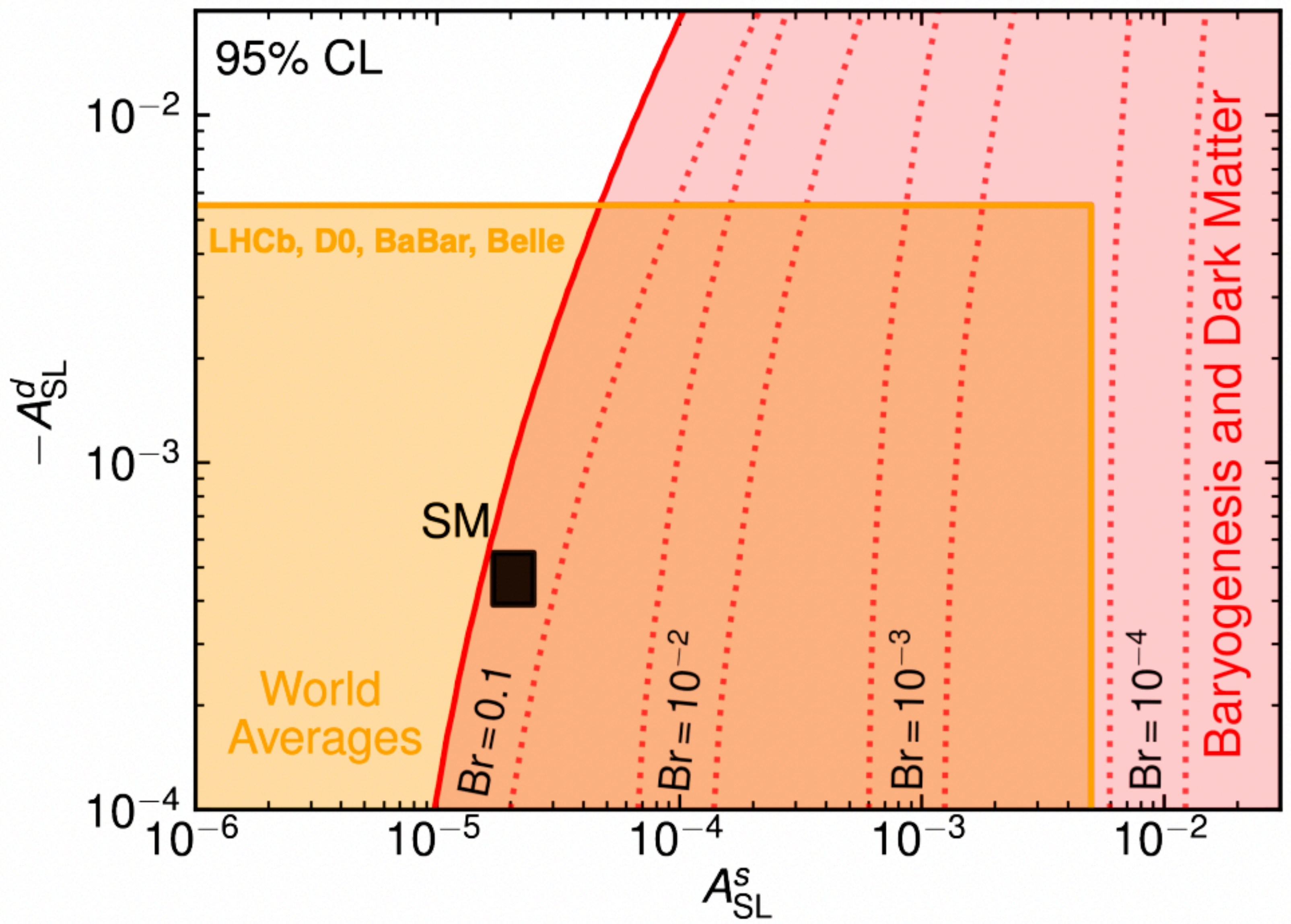
B-Mesogenesis



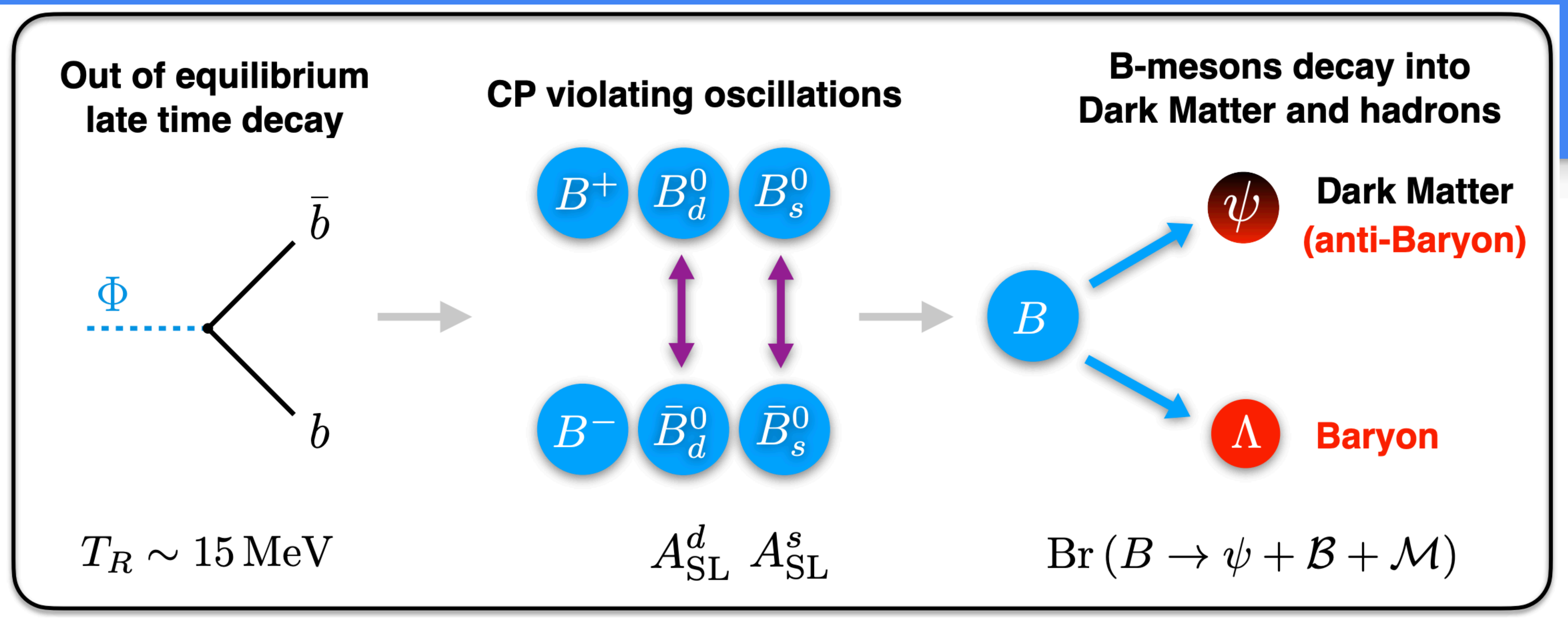
[arXiv:1810.00880]

- Baryon number conserving ($\Delta B = 0$).
- Operates at very low temperatures ($5\ \mathrm{MeV} \lesssim T \lesssim 30\ \mathrm{MeV}$).
- Predicts decays $B \to \psi\, \mathcal{B}\, \mathcal{M}$ where ψ is a dark anti-baryon, and any number of light mesons can be in the final state.
- Inclusive $\mathrm{Br}(B \to \psi\, \mathcal{B}\, \mathcal{M})$ is directly related to the baryon asymmetry of the Universe, and can be related to exclusive $\mathrm{Br}\,(B \to \psi\, \mathcal{B})$ by phase-space analysis.
- <u>Measurable signature at colliders!</u>

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



B-Mesogenesis



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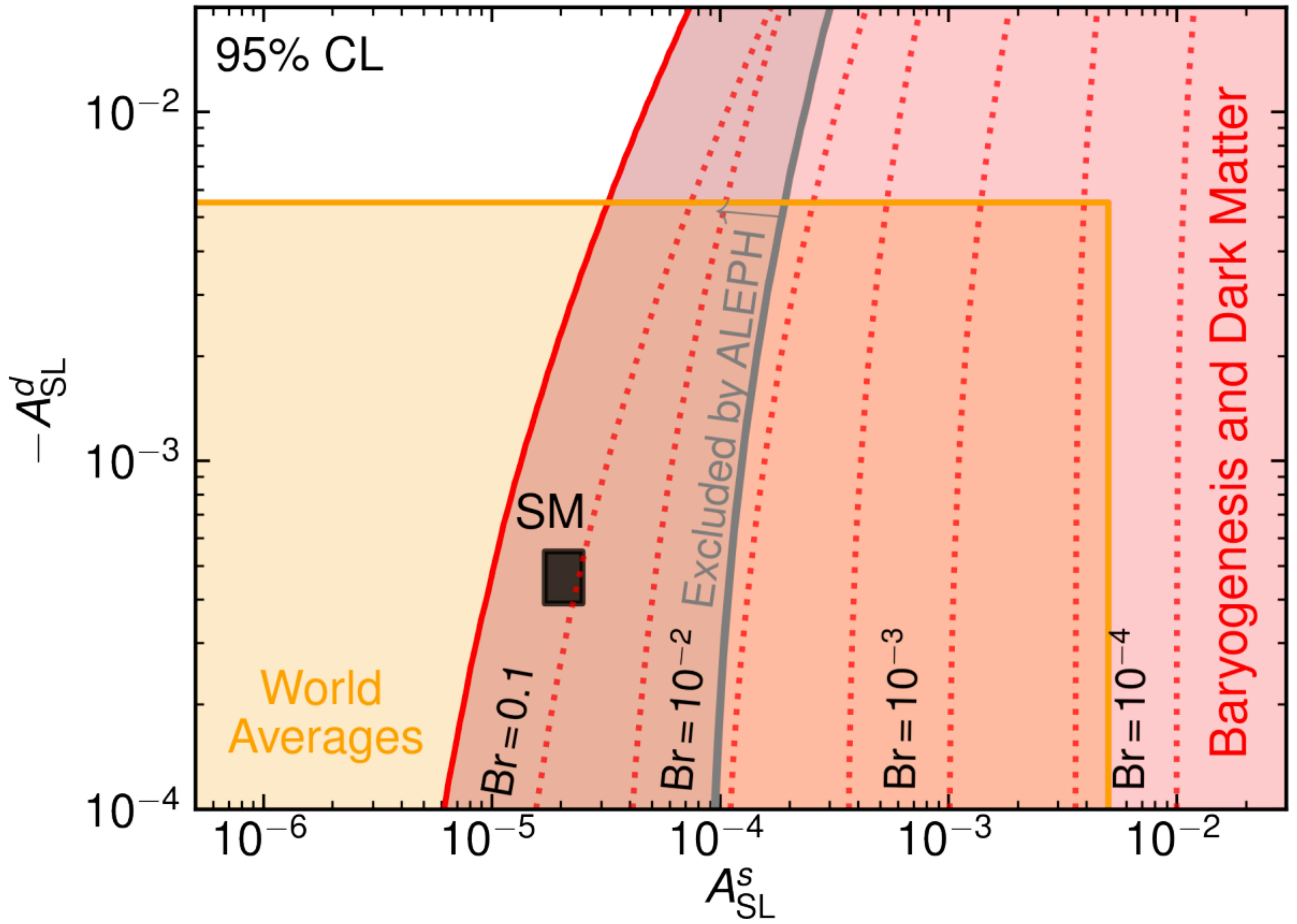
[arXiv:2101.02706]

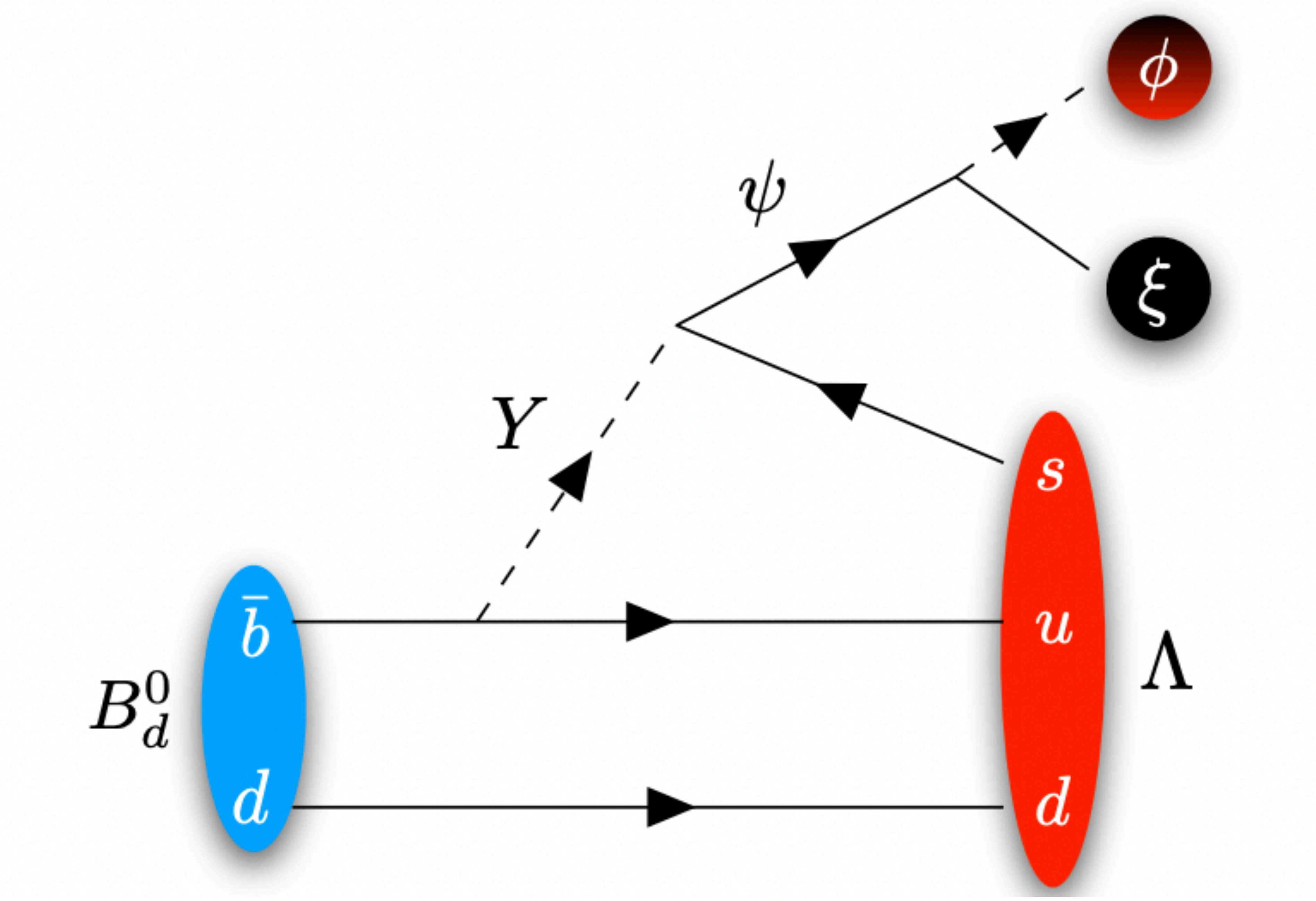


A small problem...

Operator which couples three quarks to ψ allows for decays of ψ to light anti-baryons (would erase the baryon asymmetry as baryon number is conserved in this mechanism)

To avoid this, introduce dark-sector particles ϕ, ξ, where we require $\psi \to \phi\xi$ rapidly in the early Universe

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



[arXiv:1810.00880]

Kinematic limits on m_ψ

$B \to \psi \mathcal{B}$ requires:

$$m_\psi < m_B - m_p \simeq 4.34\,\mathrm{GeV}\,.$$

Proton stability requires:

$$m_\psi > m_p - m_e \simeq 937.8\,\mathrm{MeV}$$

$$0.94\,\mathrm{GeV} < m_\psi < 4.34\,\mathrm{GeV}$$

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Bounds from neutron stars suggest also

$$m_\psi > m_\phi > 1.2\ \text{GeV}$$

[arXiv:1802.08244]

Previous searches at colliders

$$\mathcal{L}_{\text{eff}} = \sum_{i,j} \mathcal{O}_{u_i d_j} \frac{y_{ij}^2}{M_Y^2}$$

BABAR
[arXiv:2306.08490]
[arXiv:2302.00208]

Belle
[arXiv:2110.14086]

- Four flavour combination effective operators $\mathcal{O}_{ud}$, $\mathcal{O}_{us}$, $\mathcal{O}_{cd}$ and $\mathcal{O}_{cs}$.
- Constraints from direct collider searches only for $\mathcal{O}_{ud}$ and $\mathcal{O}_{us}$.
- Only one operator expected to produce sizeable branching fractions → we need to explore the full set!

Operator and Decay	Initial State	Final State	ΔM (MeV)
$\mathcal{O}_{ud} = \psi\, b\, u\, d$ $\bar{b} \to \psi\, u\, d$	B_d	$\psi + n\,(udd)$	4340.1
	B_s	$\psi + \Lambda\,(uds)$	4251.2
	B^+	$\psi + p\,(duu)$	4341.0
	Λ_b	$\psi + \pi^0$	5484.5
$\mathcal{O}_{us} = \psi\, b\, u\, s$ $\bar{b} \to \psi\, u\, s$	B_d	$\psi + \Lambda\,(usd)$	4164.0
	B_s	$\psi + \Xi^0\,(uss)$	4025.0
	B^+	$\psi + \Sigma^+\,(uus)$	4090.0
	Λ_b	$\bar{\psi} + K^0$	5121.9
$\mathcal{O}_{cd} = \psi\, b\, c\, d$ $\bar{b} \to \psi\, c\, d$	B_d	$\psi + \Lambda_c + \pi^-\,(cdd)$	2853.6
	B_s	$\psi + \Xi_c^0\,(cds)$	2895.0
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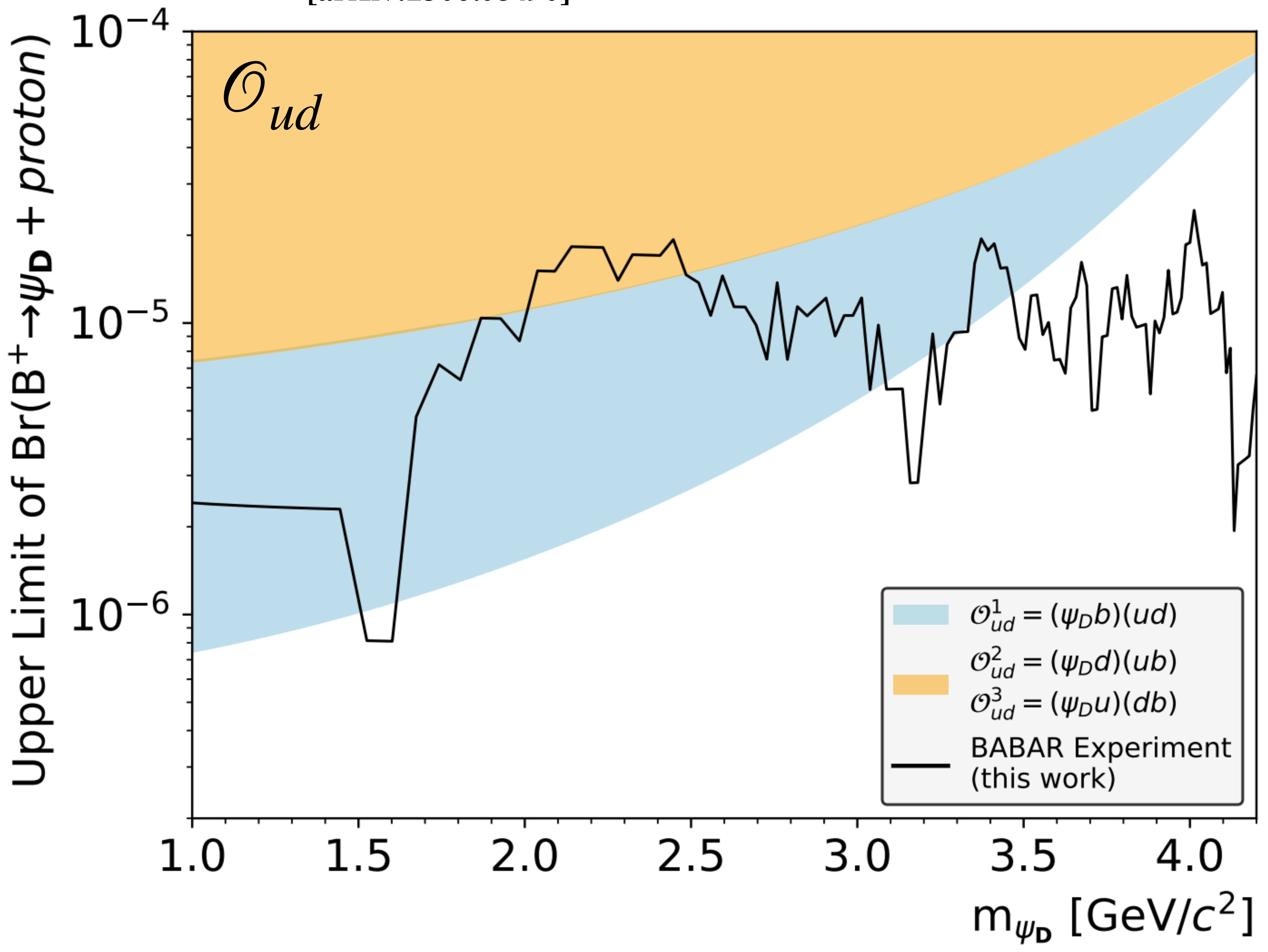
$\mathcal{O}_{cs} = \psi\, b\, c\, s$ $\bar{b} \to \psi\, c\, s$	B_d	$\psi + \Xi_c^0\,(csd)$	2807.8
	B_s	$\psi + \Omega_c\,(css)$	2671.7
	B^+	$\psi + \Xi_c^+\,(csu)$	2810.4
	Λ_b	$\bar{\psi} + D^- + K^+$	3256.2

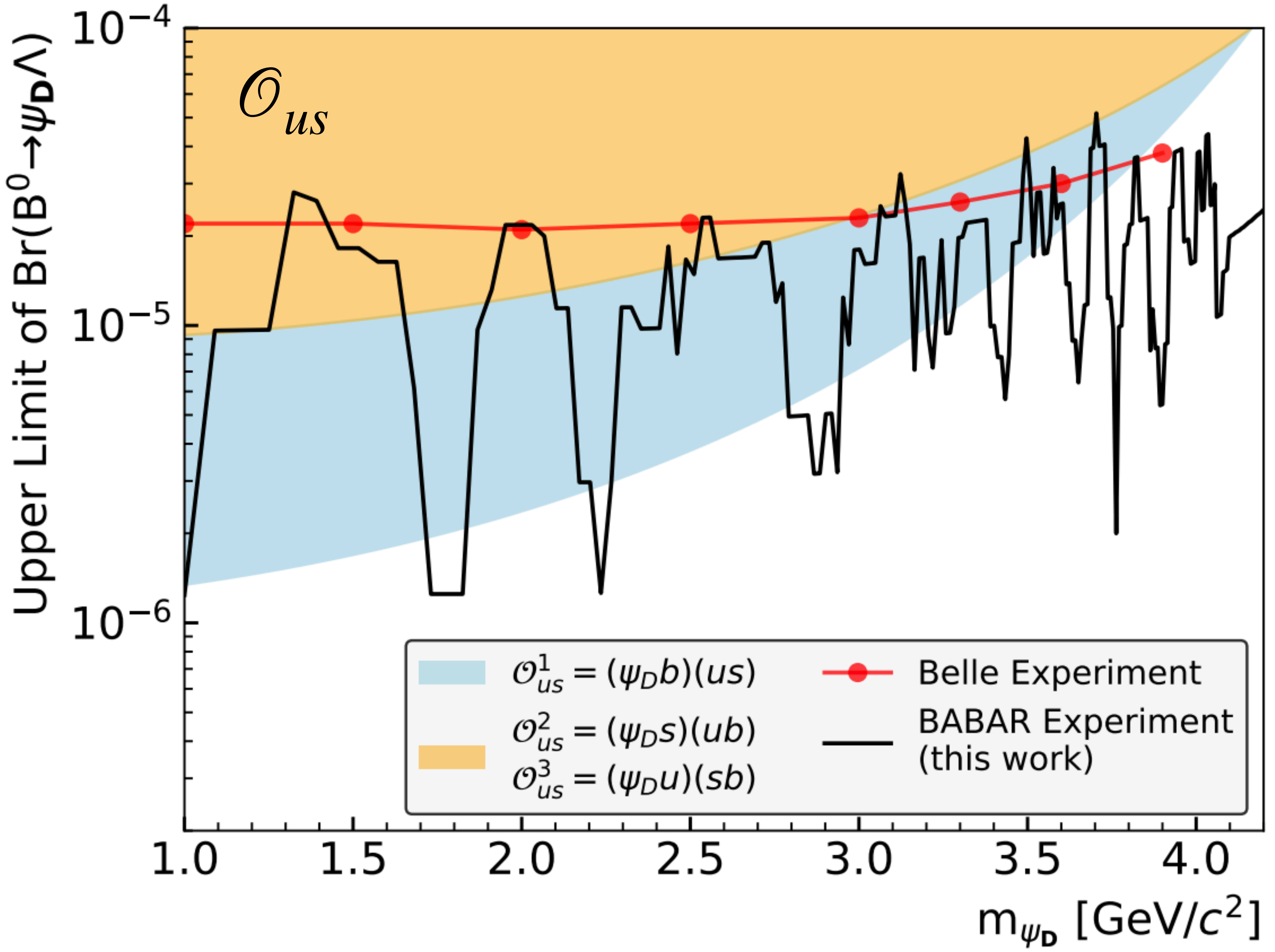
[arXiv:2101.02706]

Previous searches at colliders

Measurement of $B^+ \to \psi_D p$ by BABAR
[arXiv:2306.08490]

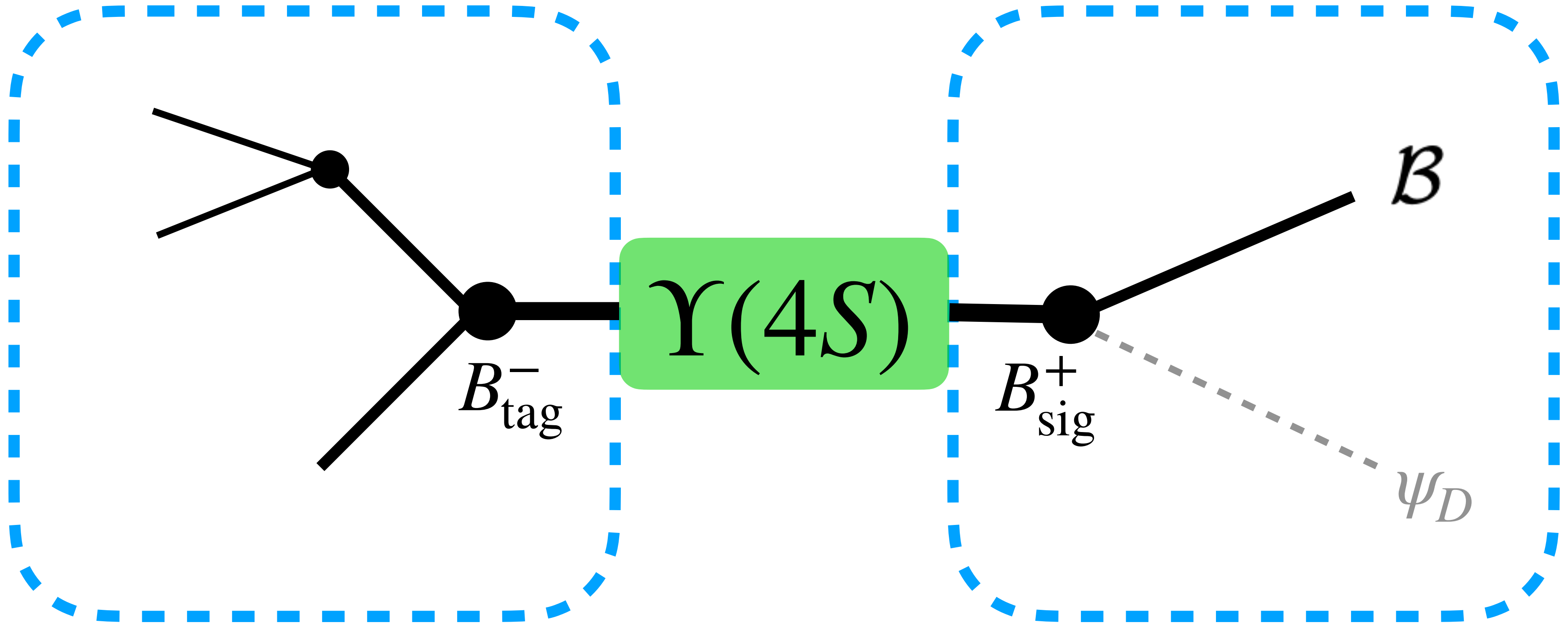


Measurements of $B^0 \to \psi_D \Lambda^0$ by BABAR and Belle
[arXiv:2302.00208] [arXiv:2110.14086]



Full event reconstruction at Belle II

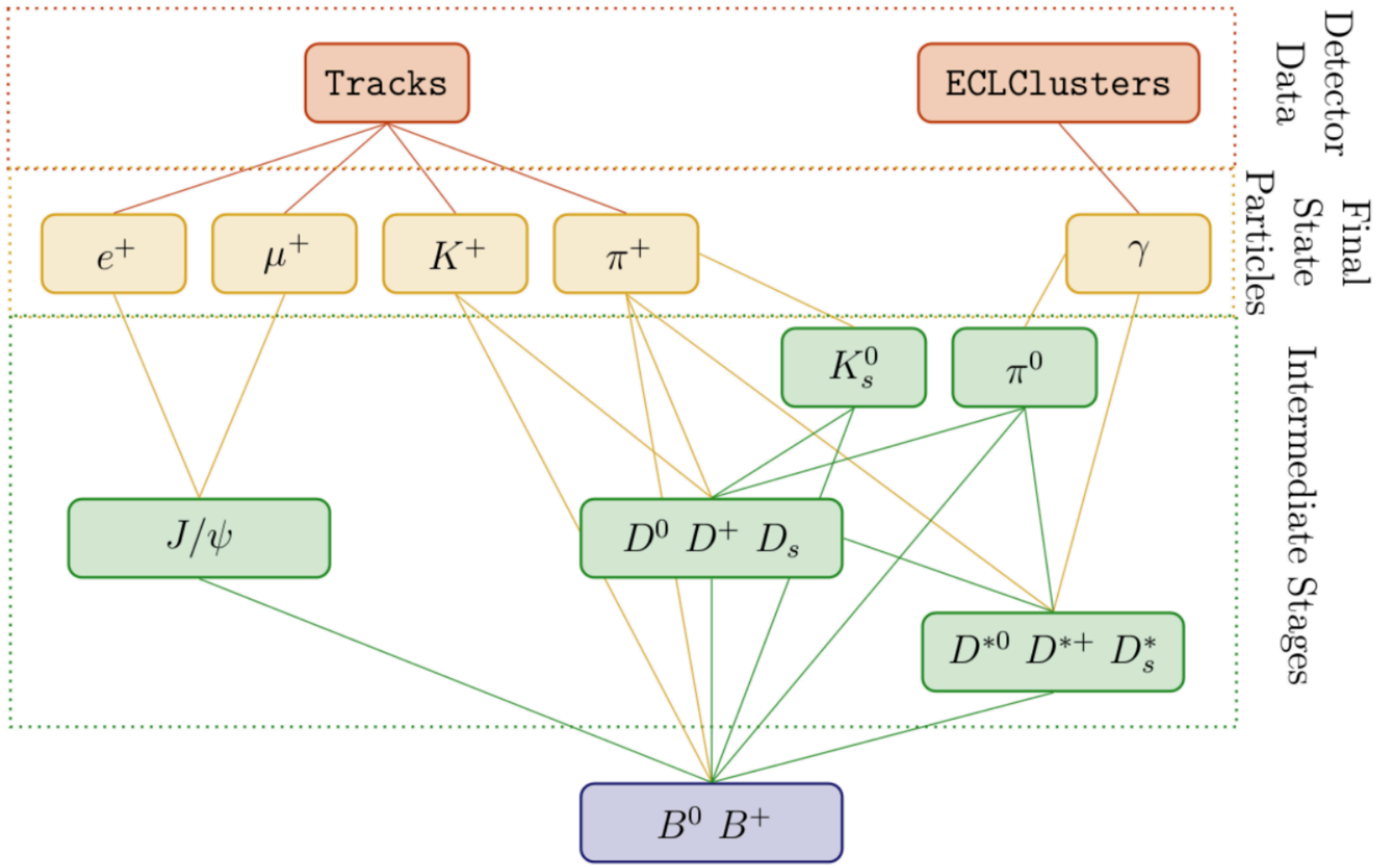
- Events produced at fixed energy allows for the full reconstruction of events
- Can infer properties of "signal side" given that the "tag side" (generic decay process) has been reconstructed correctly
- *Full Event Interpretation (FEI)* algorithm performs hierarchical event reconstruction



Dark baryon leaves missing energy signature

Reconstructed in any hadronic decay mode → "*hadronic tagging method*"

Reconstructed in signal decay mode

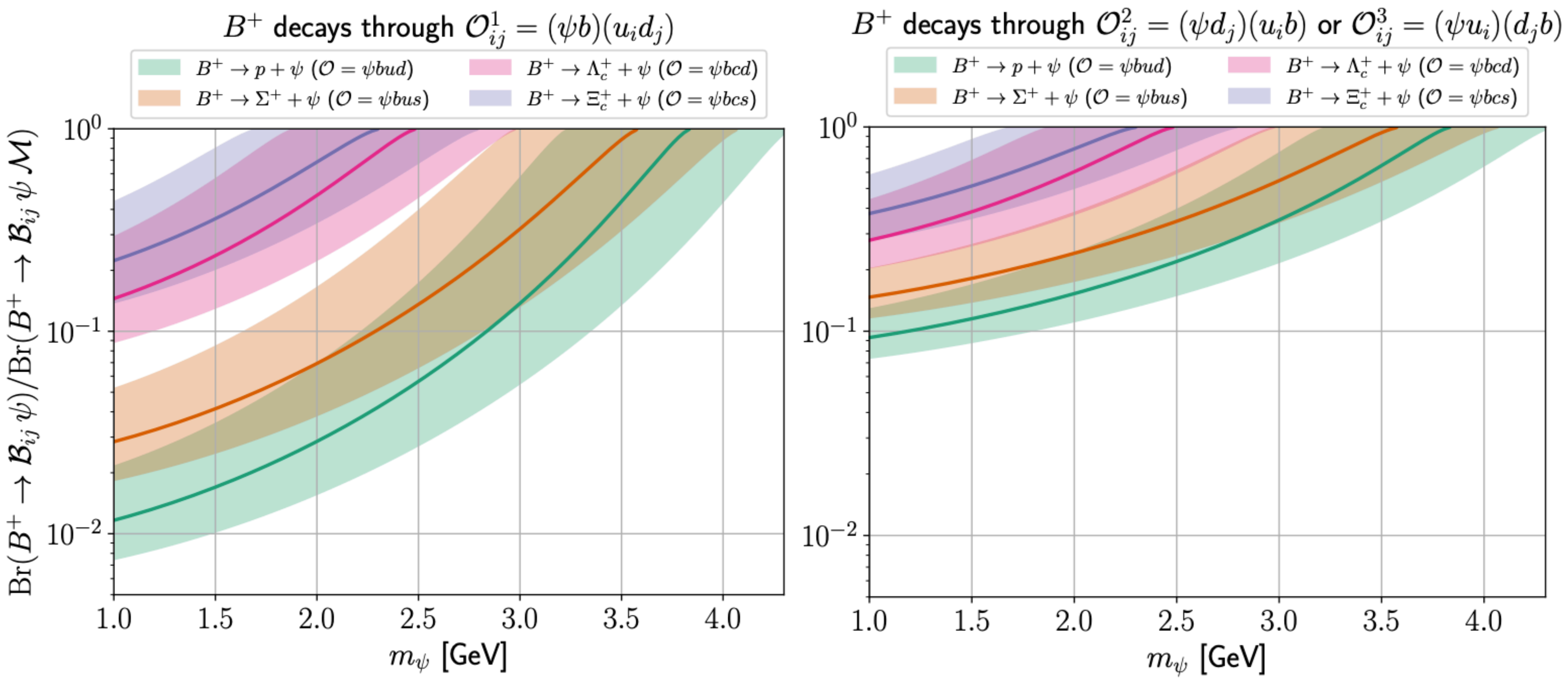


B-Mesogenesis at Belle II

B-Mesogenesis requires $\mathrm{Br}(B \to \psi \mathcal{B} \mathcal{M}) \gtrsim 10^{-4}$

Based on Belle II $B^+ \to K^+ \nu \bar{\nu}$ [arXiv:2311.14647]
Belle $B \to ha', a' \to \mathrm{inv}$ analyses, estimate sensitivity of Belle II exclusive measurement as

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



[arXiv:2101.02706]

Ratio between exclusive and inclusive BFs $\gtrsim (1 - 10\%)$

This suggests that the B-Mesogenesis parameter space should be explorable via exclusive searches at Belle II

Analysis plan

- Provide constraints across the full set of B-*Mesogenesis* operators by measuring six decays.
- Signal extraction by fitting momentum of the signal-side SM baryon in the $B_{\rm sig}$ frame (exploit two-body kinematics).
- Interpretation:
  - Neutral B-*Mesogenesis* (covered in previous slides) **[arXiv:1810.00880]**
  - B_c^+-*Mesogenesis* **[arXiv:2109.09751]**
  - R-parity violating B-meson decays to a baryon and light neutralino **[arXiv:2208.06421]**

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[arXiv:2101.02706]

Signal simulation

- Produce 1 million signal events for 30 m_{ψ_D} from 1MeV/c^2 up to just below the kinematic limit. Linear spacing in the momentum of the signal-side SM baryon in the B_{sig} frame (what we will later fit)

Operator	Decay	ΔM(MeV/c^2)
$\mathcal{O}_{ud}$	$B^+ \to \psi_D p$	4341.0
$\mathcal{O}_{us}$	$B^+ \to \psi_D \Sigma^+$	4090.0
	$B^0 \to \psi_D \Lambda$	4164.0
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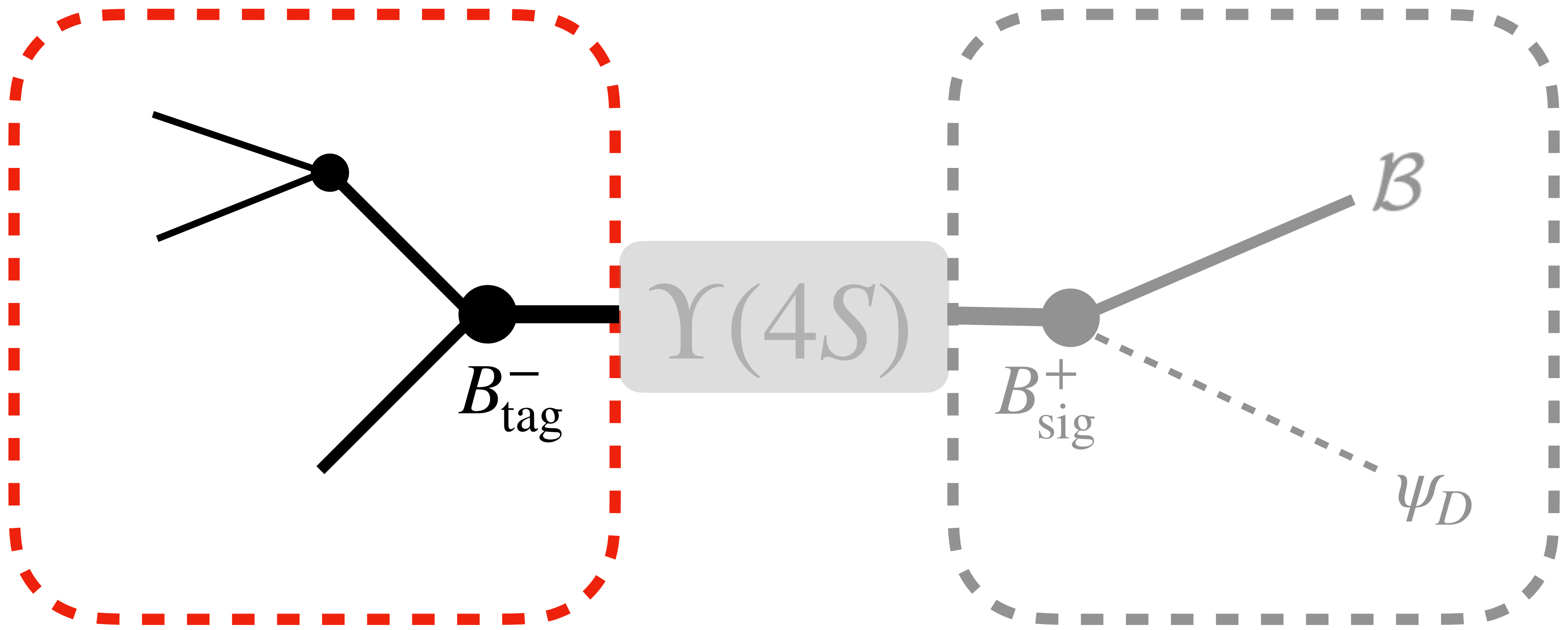
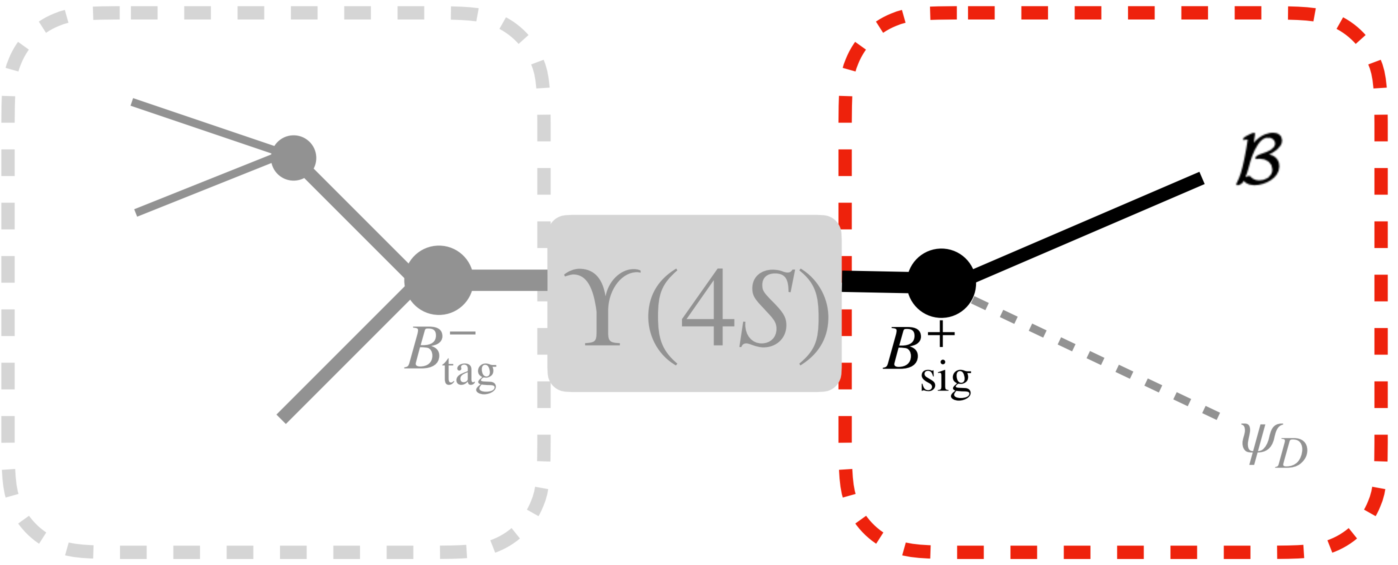
Tag-side reconstruction



- Reconstruct using hadronic FEI (skim)
- Tag side main selections:
  - $|\Delta E| = |E^*_{\rm beam} - E^*_B| < 0.1$ GeV
  - $M_{bc} = \sqrt{E^{*2}_{\rm beam}/c^4 - \vec{p}^{*2}_B/c^2} > 5.24$ GeV/c^2
  - FEI signal probability > 0.001 (from skim)
  - Keep 3 best candidates ranked by FEI signal probability

Signal-side reconstruction

- Reconstruct signal-side SM baryon and require reconstructed mass within 100 MeV of nominal (PDG) mass
- If baryon is not final-state-particle, perform vertex fit, require fit succeeds and update daughters
- Reconstruct B_{sig}



$B^+ \to \psi_D \Lambda_c^+$

Decay mode	$\mathcal{B}$
$\Lambda_c^+ \to \Lambda\pi^+\pi^0$	7.02%
$\Lambda_c^+ \to pK^-\pi^+$	6.26%
$\Lambda_c^+ \to \Lambda\pi^-\pi^+\pi^+$	3.62%
	16.90%

$B^0 \to \psi_D \Lambda^0$

Use Belle II `stdLambdas`:
$\Lambda \to p^+\pi^-$ ~ 64%
with vertex fit and selections on reconstructed mass

$B^+ \to \psi_D \Xi_c^+$

Decay mode	$\mathcal{B}$
$\Xi_c^+ \to \Xi^0\pi^+\pi^0$	6.70%
$\Xi_c^+ \to \Xi^0\pi^-\pi^+\pi^+$	5.00%
$\Xi_c^+ \to \Xi^0\pi^+$	1.60%
	13.30%

$B^+ \to \psi_D \Sigma^+$ $\Sigma^+ \to p^+\pi^0$ ~ 50%

$B^+ \to \psi_D p^+$ p^+ *already final-state particle*

$B^0 \to \psi_D \Xi_c^0$

Decay mode	$\mathcal{B}$
$\Xi_c^0 \to \Xi^-\pi^+\pi^-\pi^+$	4.80%
$\Xi_c^0 \to \Lambda K^-\pi^+$	1.45%
$\Xi_c^0 \to \Xi^-\pi^+$	1.43%
	7.68%

Ξ^- From `stdHyperons`
$\Xi^- \to \Lambda\pi^-$ ~ 100%

Ξ^0 From `stdHyperons`
$\Xi^0 \to \Lambda\pi^0$ ~ 100%

π^0 From `stdPi0s` with efficiency 50%
$\pi^0 \to \gamma\gamma$

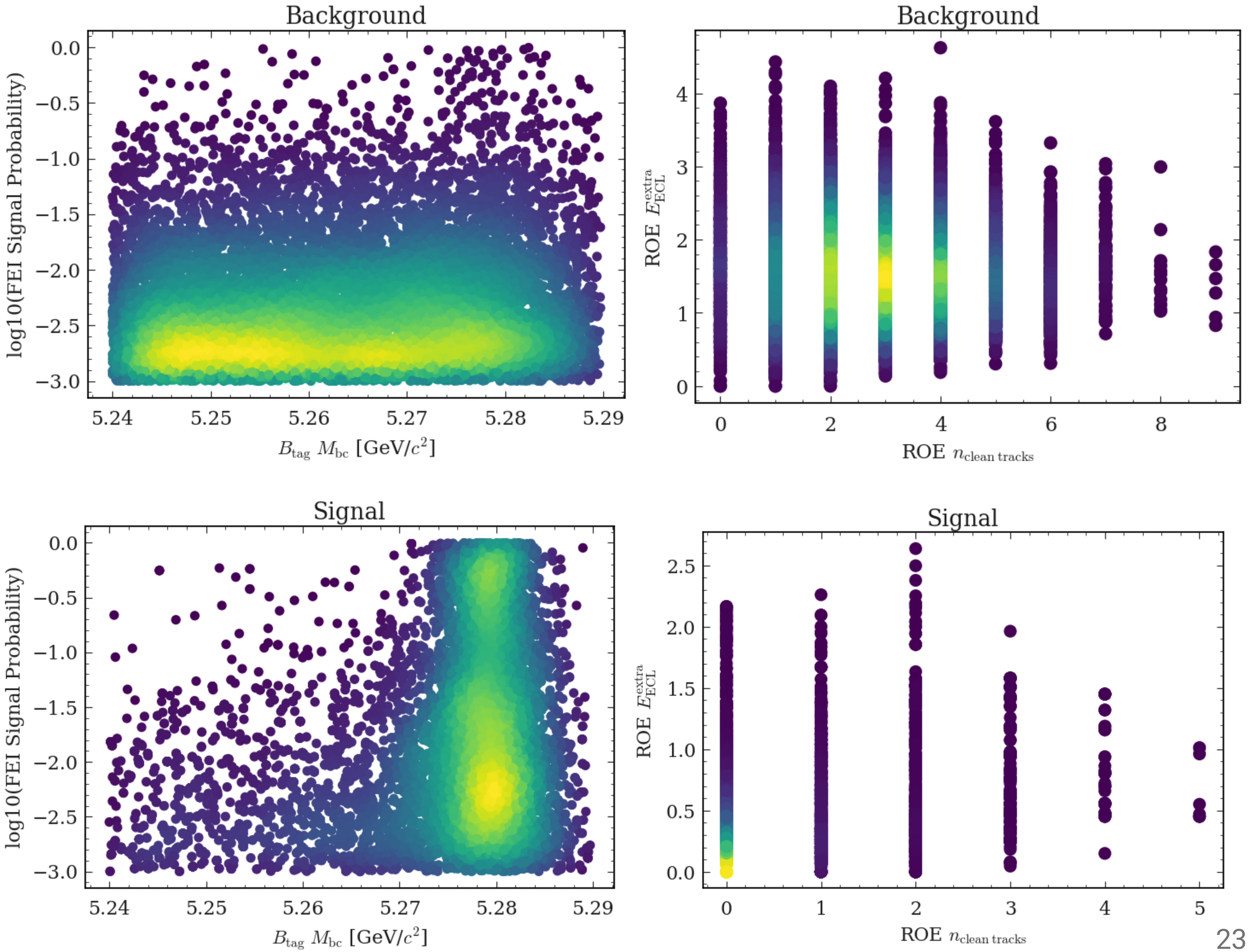
π^+, p^+, K^+
Particle ID > 0.6 and and $|dr| < 0.5$ cm and $|dz| < 2$ cm and nCDCHits ≥ 20 and inCDCAcceptance

Event selection

- Apply rectangular preselection at reconstruction stage to reduce size of dataset but preserve some events for side band studies.

The *rest-of-event* (ROE):

clean tracks and clusters not taken into account by the tag side or signal-side baryon



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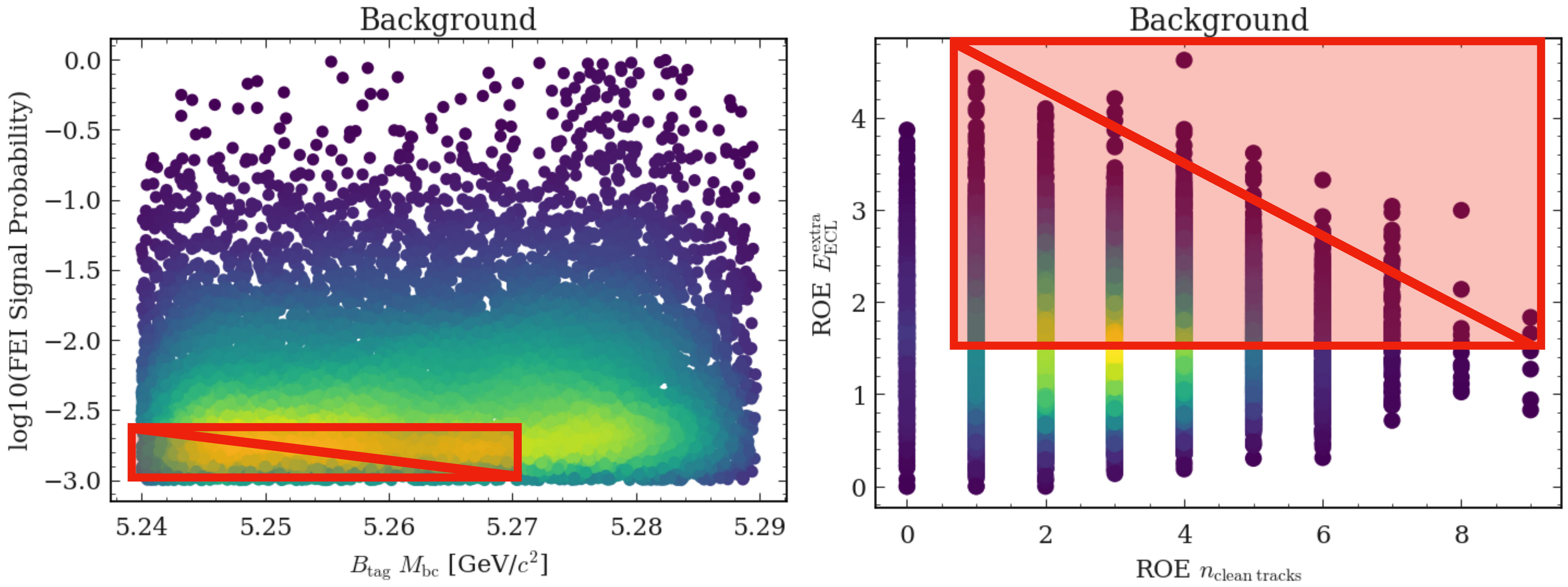

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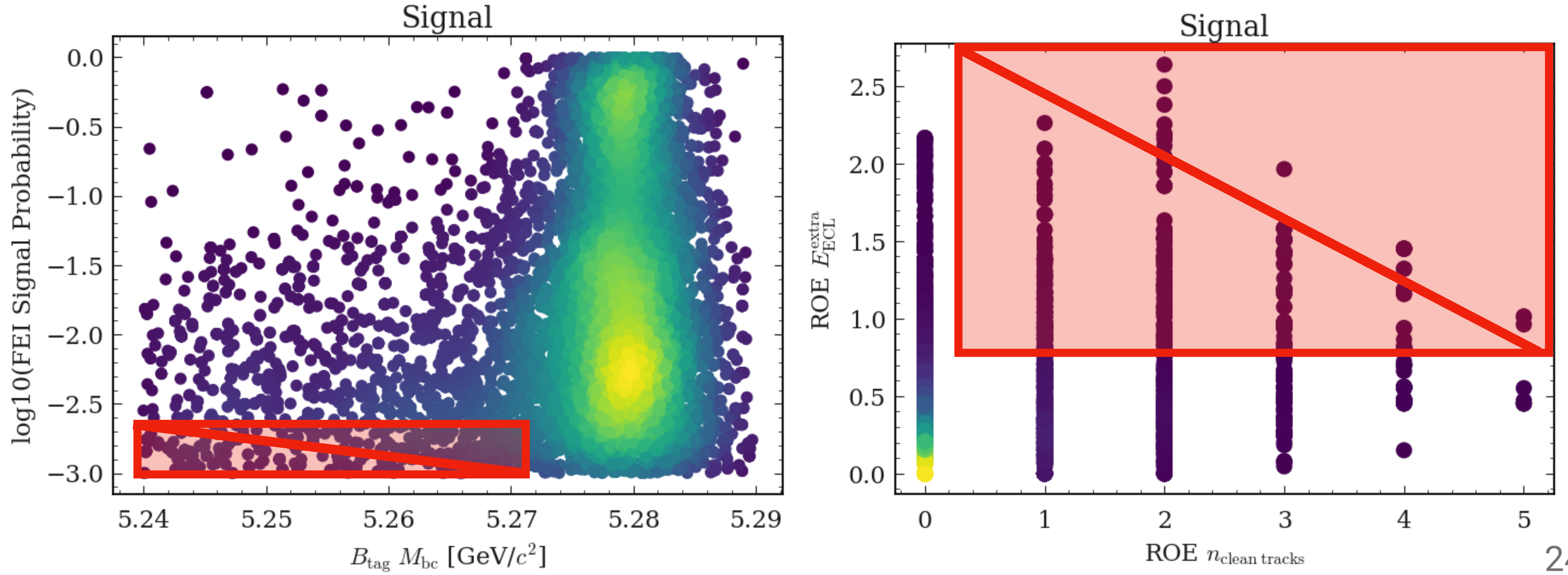

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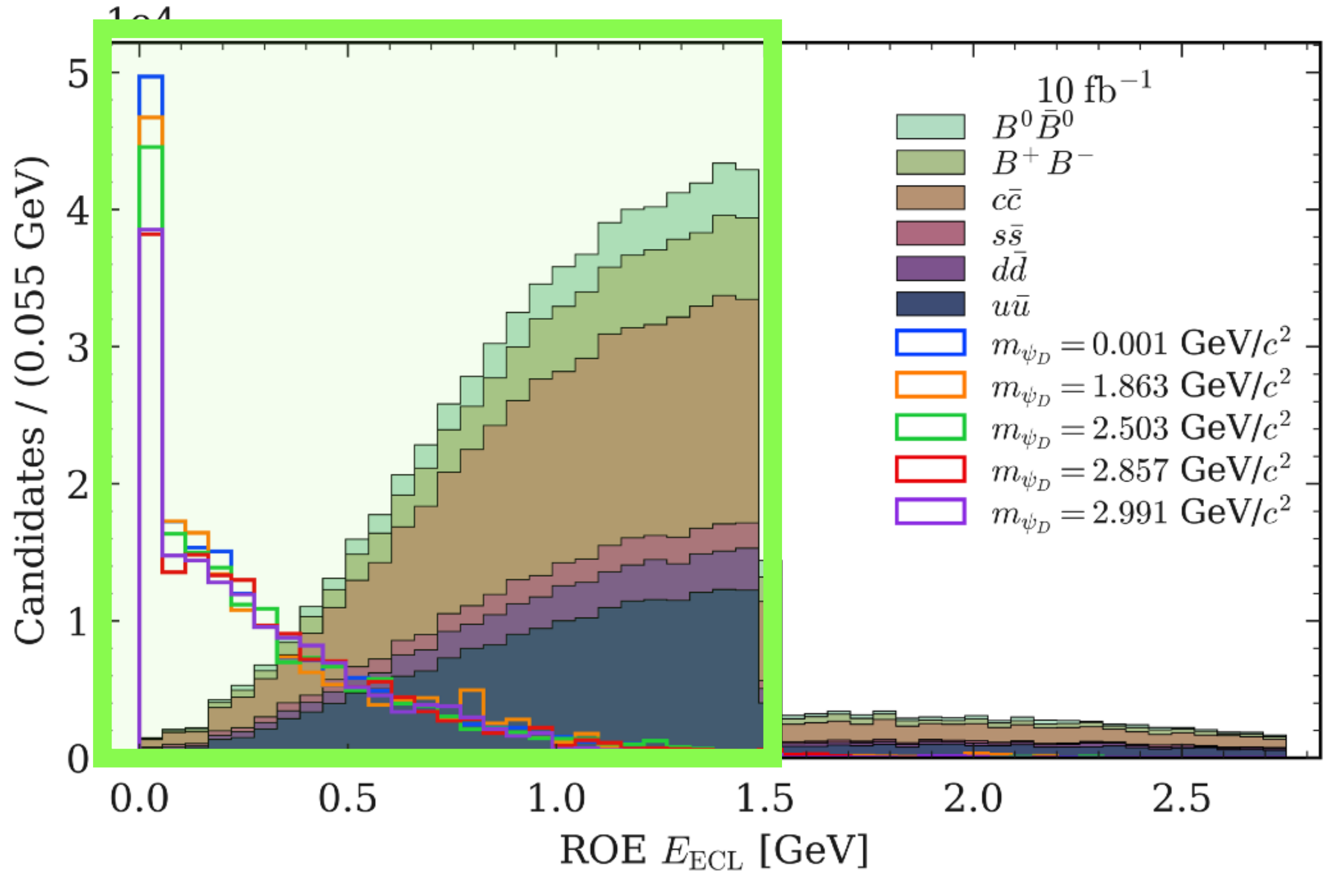
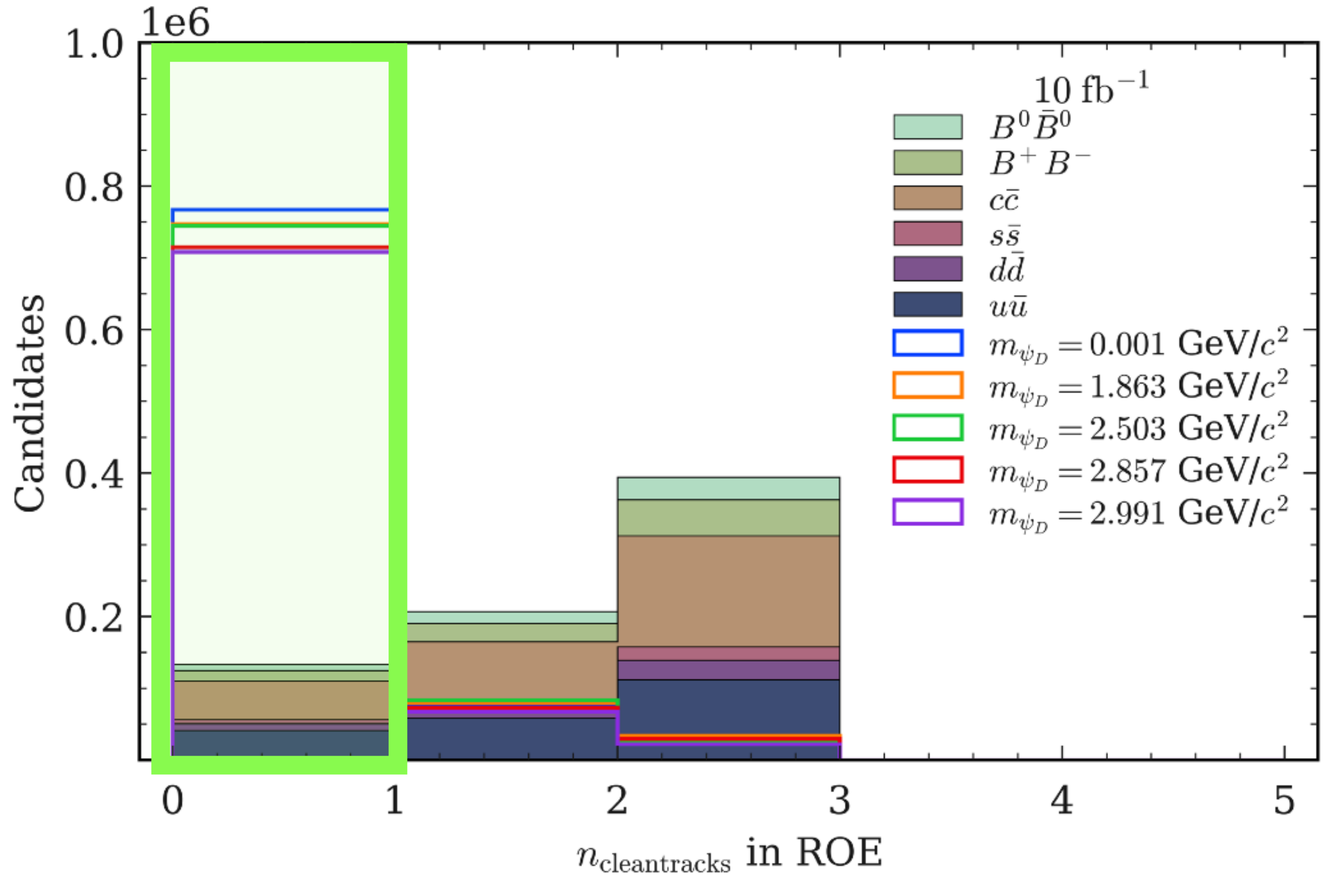
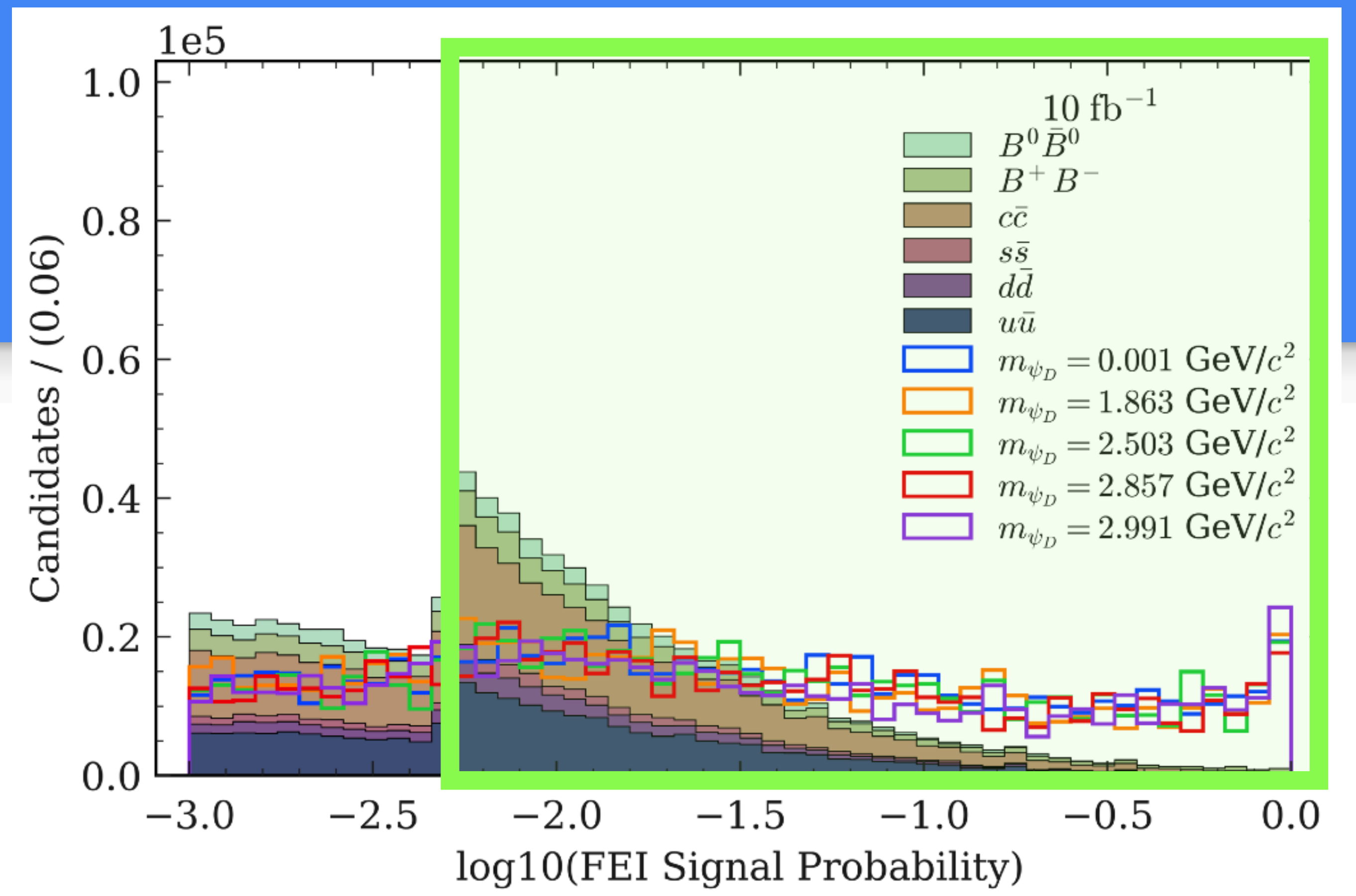
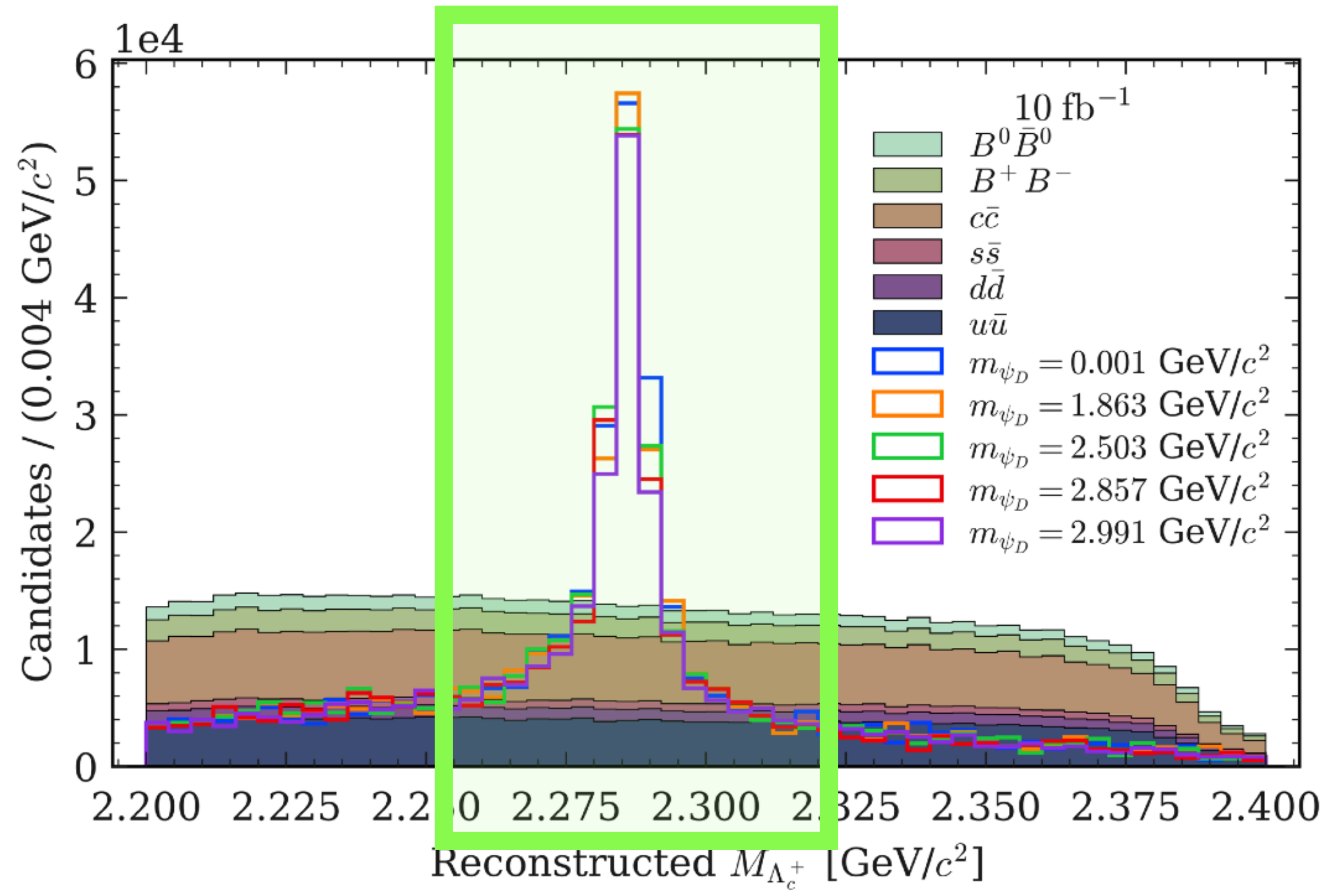


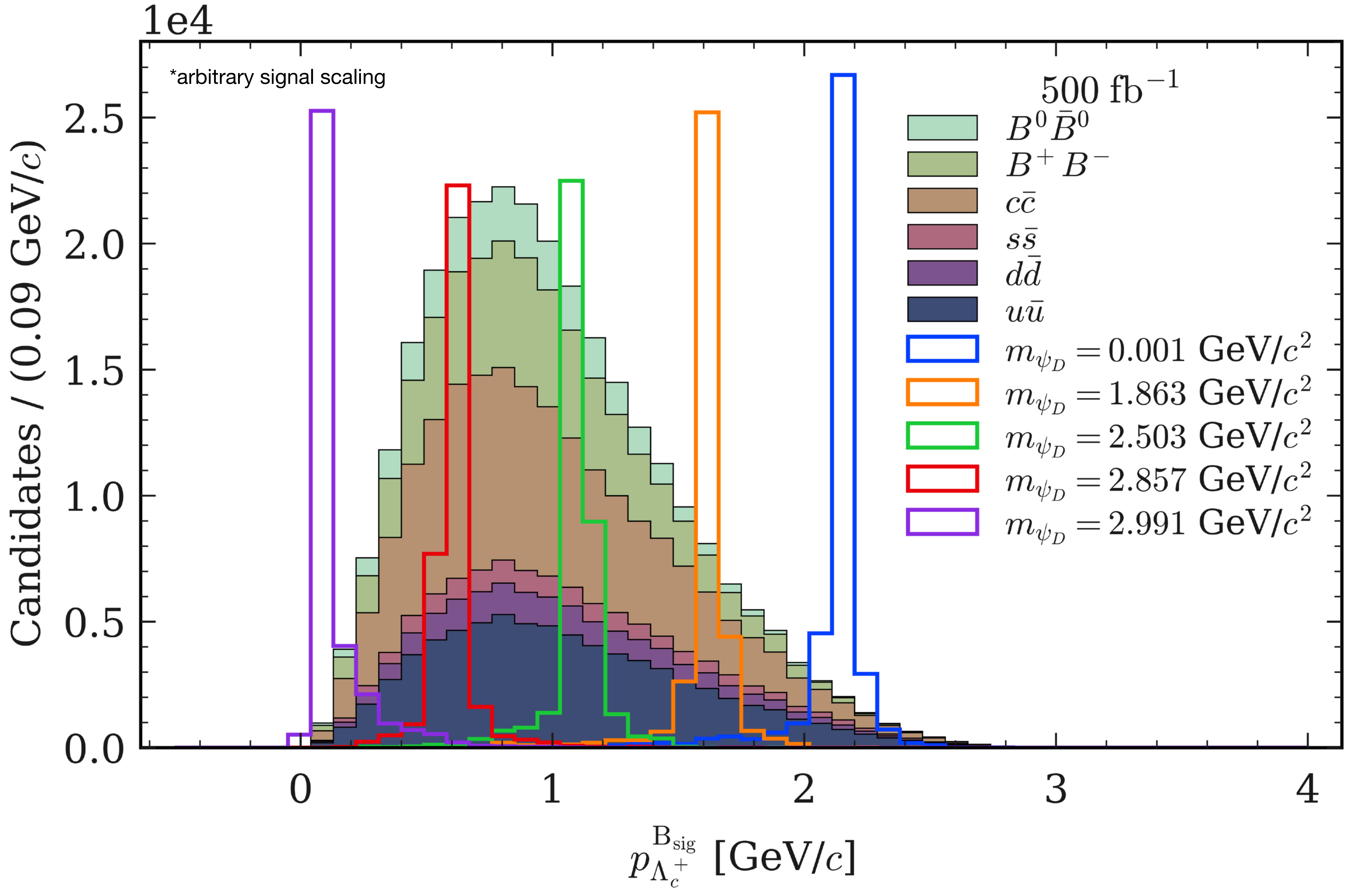






	0.001 <= m < 2.085	**2.085 <= m < 2.734**	**2.734 <= m < 2.984**	**charged**	**mixed**	**uubar**	**ddbar**	**ssbar**	**ccbar**
Preselection	8.6e+04	8.2e+04	7.3e+04	3.3e+06	2e+06	7.6e+06	1.8e+06	1.3e+06	1.1e+07
ROE $n_{\rm cleantracks} = 0$	7.5e+04	7.2e+04	6.3e+04	5.3e+05	3.1e+05	1.5e+06	3.4e+05	2.1e+05	2e+06
$B_{\rm tag}\ M_{\rm bc} > 5.27$	6.9e+04	6.6e+04	5.8e+04	3.7e+05	2.1e+05	8.3e+05	2e+05	1.2e+05	1.1e+06
$\log 10$**(FEI Signal Probability)**> -2.3	5.2e+04	4.9e+04	4.4e+04	1.9e+05	7.6e+04	3.6e+05	7.6e+04	4.8e+04	4.7e+05
ROE $E_{\rm ECL}^{\rm extra}$ **< 1.5**	5.1e+04	4.9e+04	4.4e+04	8.4e+04	3.2e+04	1.4e+05	3.1e+04	2.2e+04	1.8e+05
$2.248 <=$ **reconstructed** $M_{\Lambda_c^+} <= 2.324$	3.7e+04	3.5e+04	3.1e+04	3e+04	1.1e+04	5e+04	1e+04	7.5e+03	6.2e+04

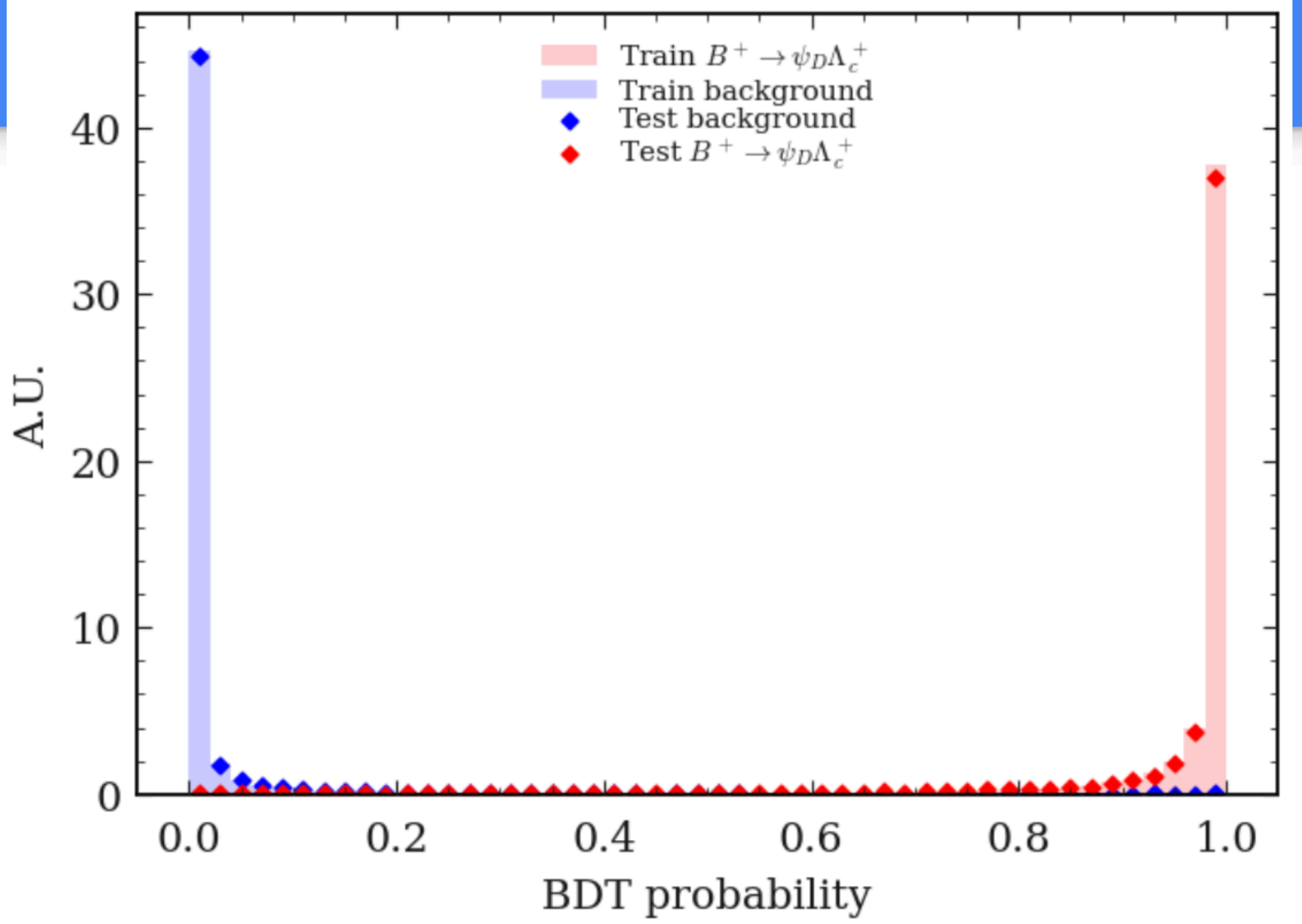
Event selection (examples: $B^+ \to \psi_D \Lambda_c^+$)



Background suppression

Boosted decision tree classifier using `xgboost` with hyperparameters tuned via `hyperopt` cross-validated procedure.

Train model to classify a signal process vs all background processes ($B^+B^-, B^0\bar{B}^0, q\bar{q}$). One BDT for each signal channel.



<u>Typical set of continuum suppression features:</u>

KSFW moments, Cleo Cones, thrust variables…

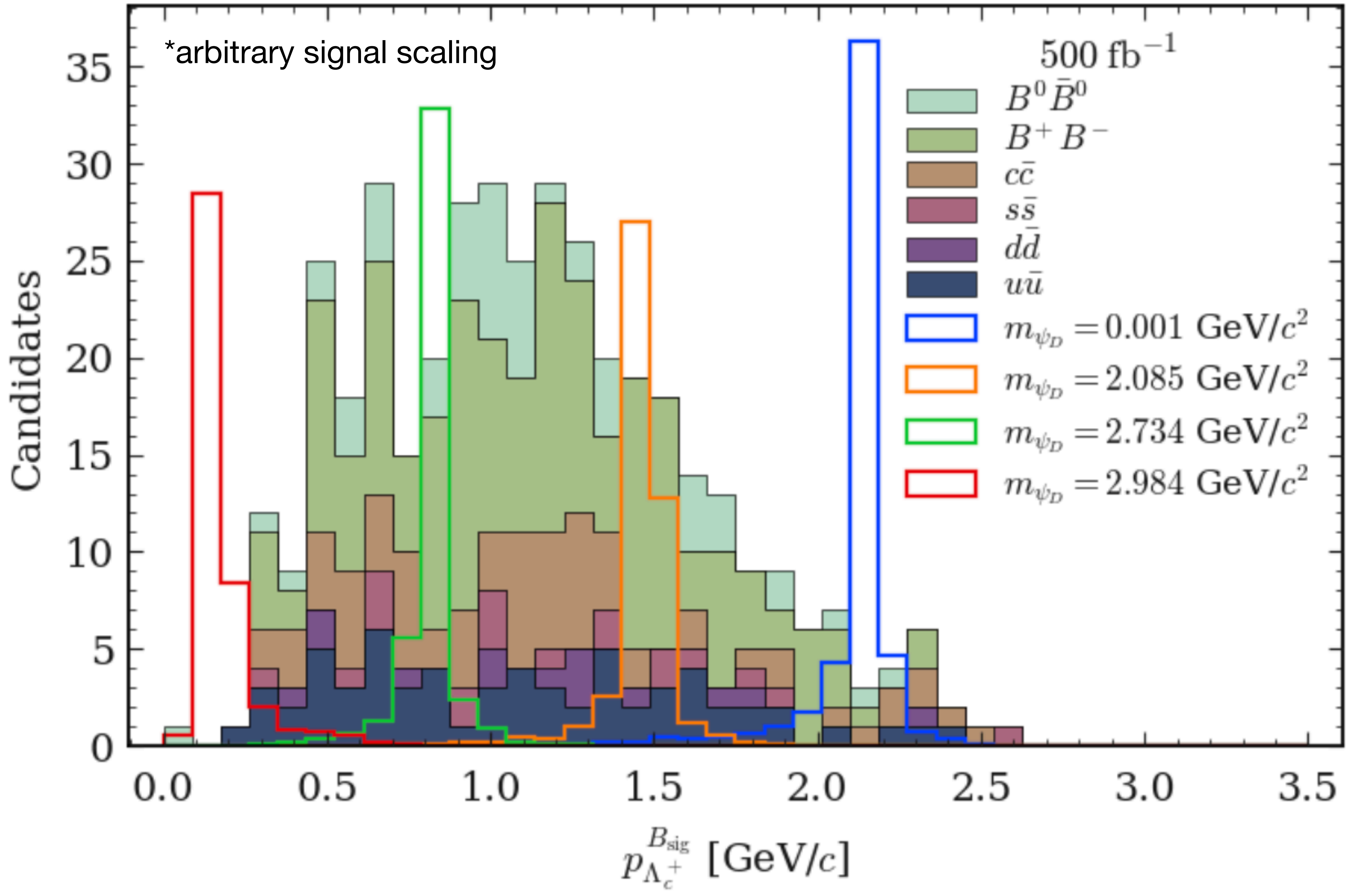
<u>Notable signal vs B background features (take inspiration from $B^+ \to K^+\nu\bar{\nu}$ analysis):</u>

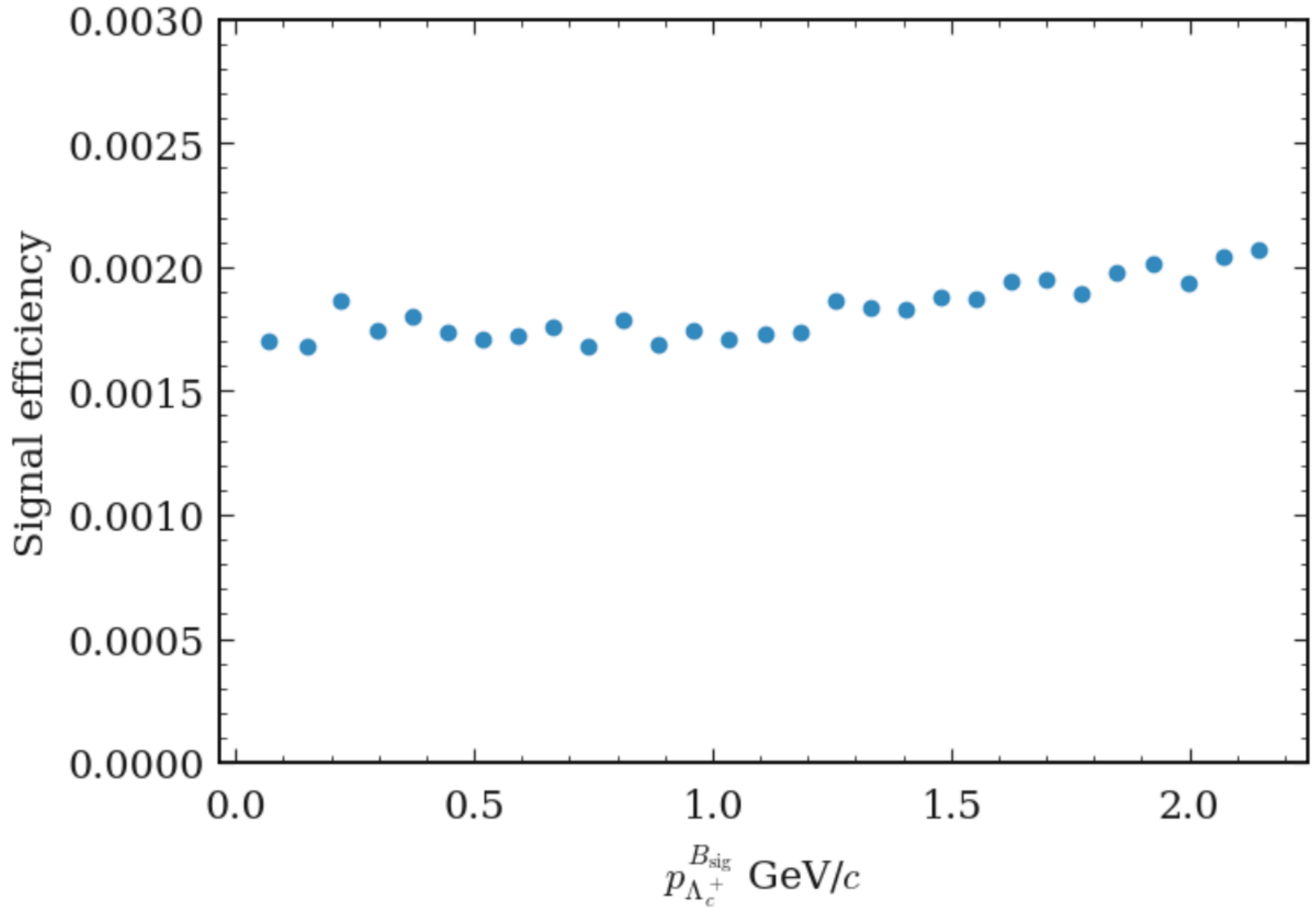
$E_{\mathrm{ECL}}^{\mathrm{ROE}}$, quality of signal-side SM baryon vertex fit, number of clean tracks in the event, FEI signal probability, invariant mass of signal-side SM baryon, sum of missing energy and momentum in CMS frame

Optimise selection on BDT score by maximising Punzi figure-of-merit $\varepsilon/(\sigma/2 + \sqrt{N_{\mathrm{bg}}})$ for each signal process.

Best candidate selection and signal efficiency

Best candidates based on max FEI signal probability



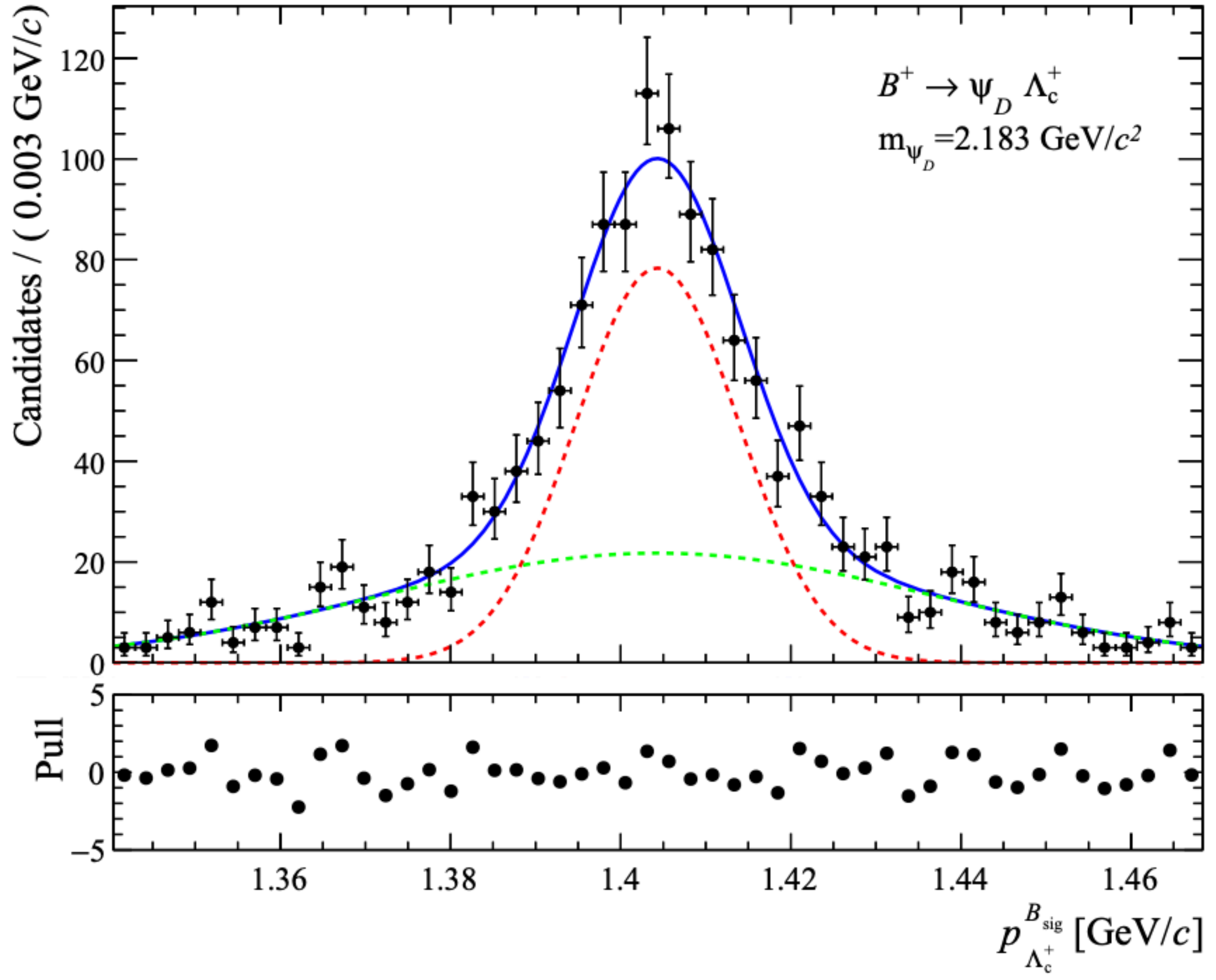


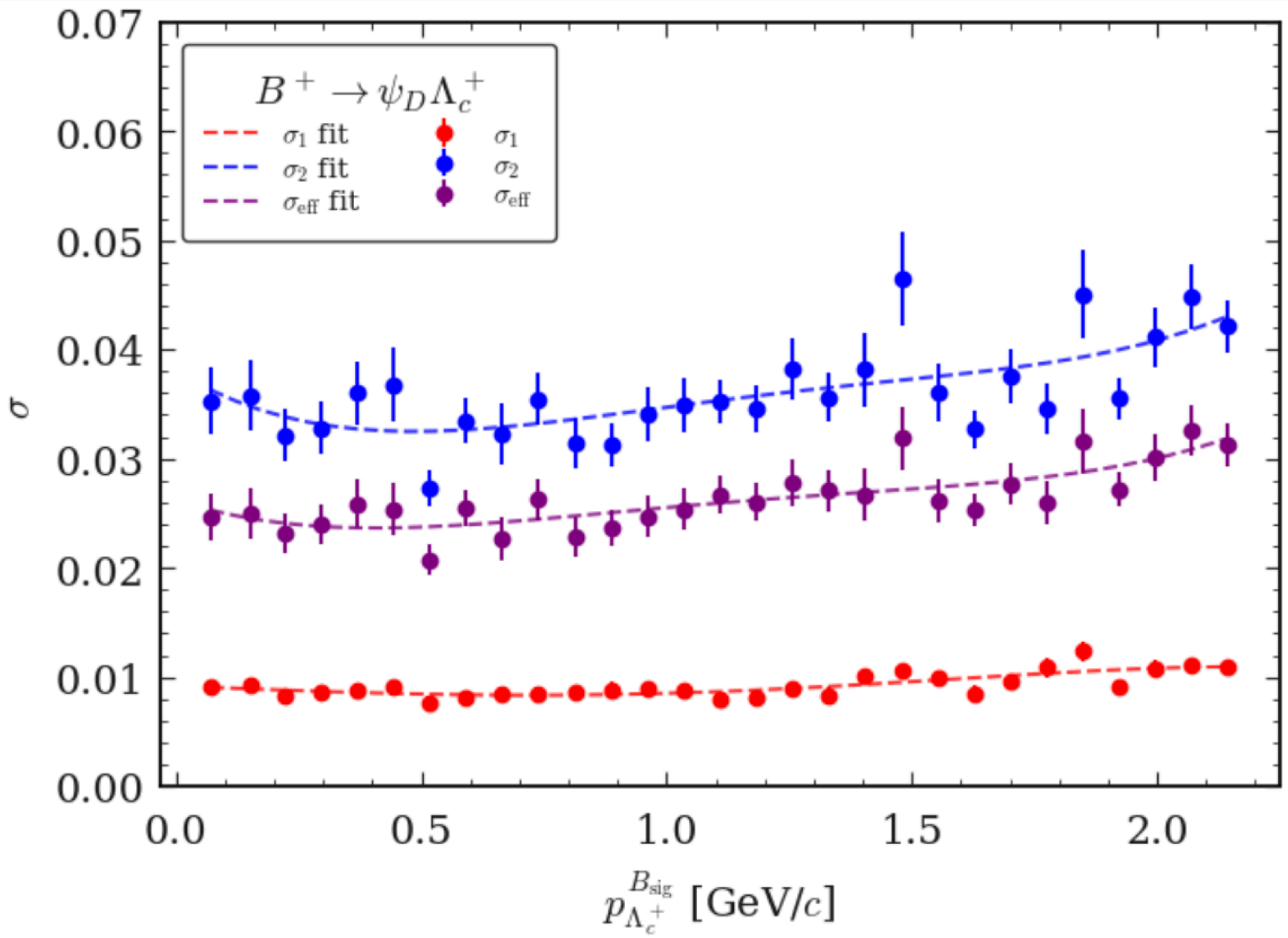
Signal fit

Signal unbinned fit to double Gaussian with shared mean μ, relative contribution of each Gaussian f

$$\mathrm{PDF_{sig}}(x) = \frac{f}{\sigma_1\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_1}\right)^2} + \frac{(1-f)}{\sigma_2\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_2}\right)^2}$$

$$\sigma_{\mathrm{eff}} = \sqrt{f\sigma_1^2 + (1-f)\sigma_2^2}.$$





Parameterise fit parameters using Chebyshev polynomials to allow for scan across full mass range.

Will need to account data/MC difference in resolution by looking at control channel eg. $B^+ \to K^+ J/\psi$

Background fit and peaking backgrounds

- Background will be modelled with KDE

Relevant two-body decays from PDG

Decay	Branching fraction (PDG)
$B^+ \to \Lambda_c^+ \bar{\Xi}_c(2645)^0$	$< 7.9 \times 10^{-4}$
$B^+ \to \Lambda_c^+ \bar{\Xi}_c(2790)^0$	$(1.1 \pm 0.4) \times 10^{-3}$
$B^+ \to \Lambda_c^+ \bar{\Xi}_c^0$	$(9.5 \pm 2.3) \times 10^{-4}$
$B^+ \to \Lambda_c^+ \bar{\Xi}_c'^0$	$< 6.5 \times 10^{-4}$
$B^+ \to \Lambda_c^+ \bar{\Xi}_c(2930)^0$	$(1.7 \pm 0.5) \times 10^{-4}$
$B^+ \to p^+ \bar{\Sigma}_c(2455)^0$	$(3.0 \pm 0.7) \times 10^{-5}$
$B^+ \to p^+ \Delta^{++}$	$< 1.4 \times 10^{-7}$
$B^+ \to p^+ \bar{\Delta}^0$	$< 1.38 \times 10^{-6}$
$B^+ \to p^+ \bar{\Sigma}_c(2800)^0$	$(2.7 \pm 0.9) \times 10^{-5}$
$B^+ \to p^+ \bar{\Sigma}_c(2520)^0$	$< 3 \times 10^{-6}$
$B^+ \to p^+ \bar{\Lambda}$	$(2.4^{+1.0}_{-0.9}) \times 10^{-7}$
$B^+ \to p^+ \bar{\Lambda}(1520)$	$(3.1 \pm 0.6) \times 10^{-7}$
$B^0 \to \Lambda \bar{\Delta}^0$	$< 9.3 \times 10^{-7}$
$B^0 \to \Lambda \bar{\Lambda}$	$< 3.2 \times 10^{-7}$

- Will veto windows corresponding to peaking backgrounds where the number of expected events is considered significant.
- Need to consider if there are additional processes systematically to form a complete set.

Summary

- B-*Mesogenesis* is a mechanism proposed to explain dark matter abundance + baryon asymmetry

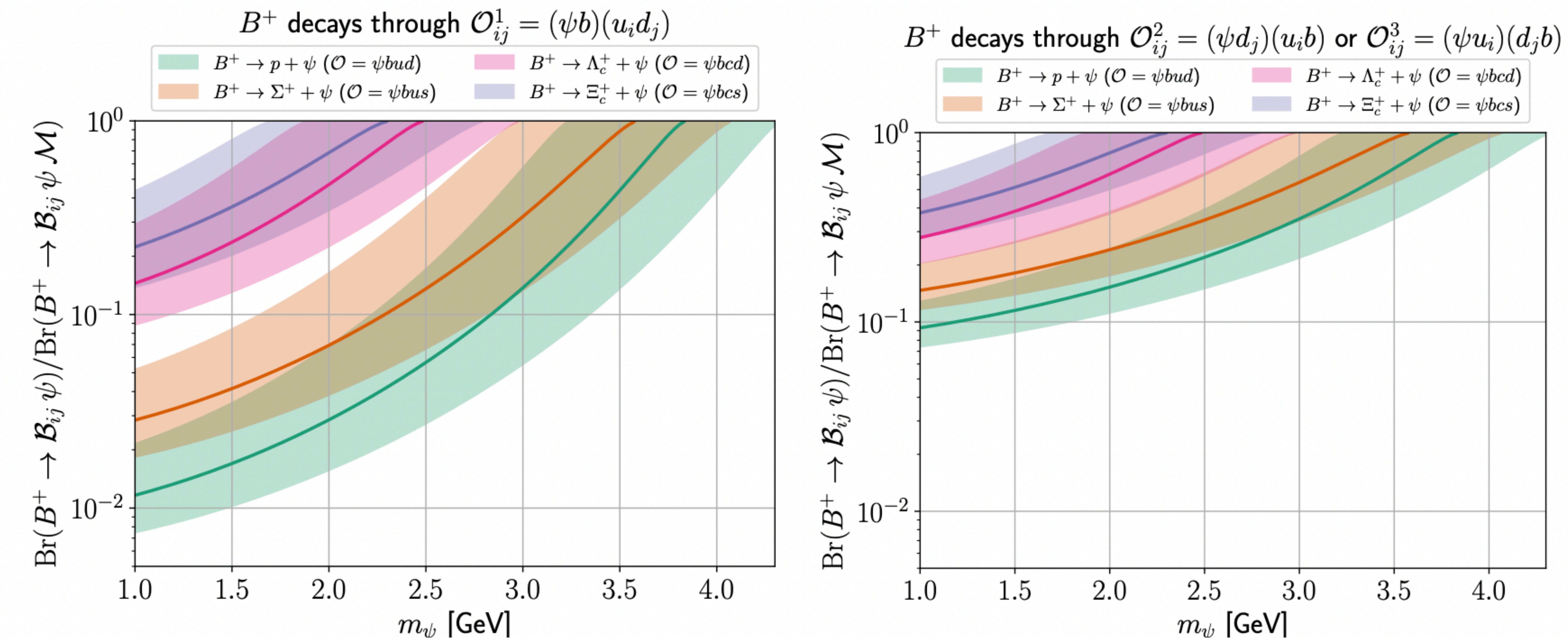
- Belle II should be able to fully explore the parameter space of (neutral) B-*Mesogenesis*

- This analysis will cover six decays across all four flavour-combination operators: $B^+ \to \psi_D p$, $B^+ \to \psi_D \Lambda_c^+$, $B^+ \to \psi_D \Xi_c^+$, $B^+ \to \psi_D \Sigma^+$, $B^0 \to \psi_D \Lambda$ and $B^0 \to \psi_D \Xi_c^0$

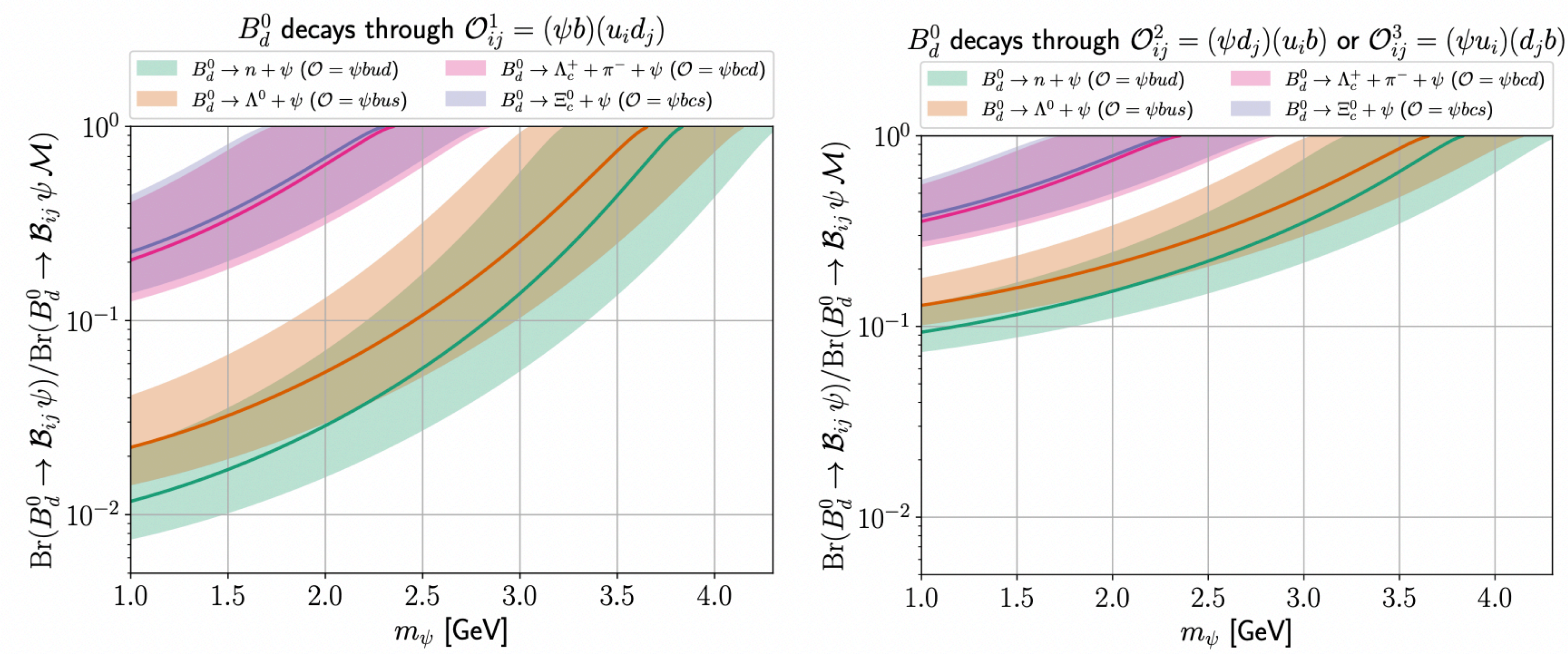
- Can additionally provide constraints on RPV-SUSY decays of B to SM baryon and light neutrino, and B_c^+-*Mesogenesis*

Back-up

[arXiv:2101.02706]

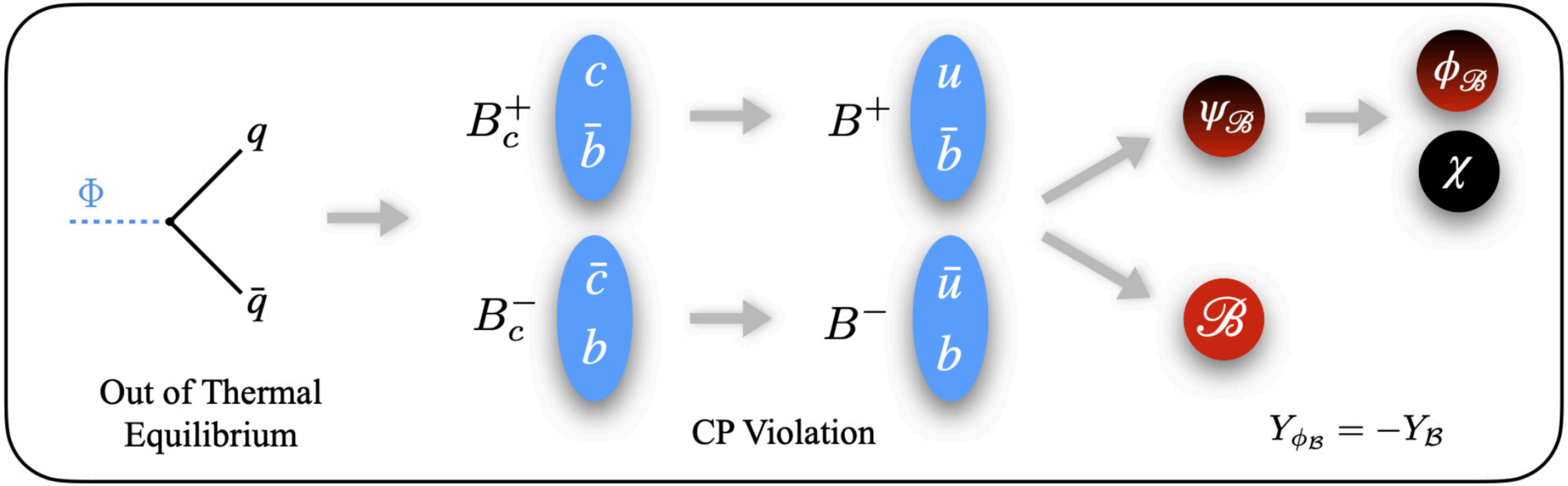


[arXiv:2101.02706]



[arXiv:2208.06421]

B_c^+ Mesogenesis



$$Y_\mathcal{B} \equiv \frac{n_\mathcal{B} - n_{\bar{\mathcal{B}}}}{s} \propto \sum_f a_{\rm CP}^f {\rm Br}_{B_c^+}^f \times \sum_{\mathcal{B}^+} {\rm Br}_{B^+}^{\mathcal{B}^+},$$

$$a_{\rm CP}^f \equiv A_{\rm CP}^f / \left(1 + A_{\rm CP}^f\right),$$

$${\rm Br}_{B_c^+}^f \equiv {\rm Br}\left(B_c^+ \to B^+ + f\right),$$

$${\rm Br}_{B^+}^{\mathcal{B}^+} \equiv {\rm Br}\left(B^+ \to \bar{\psi}_\mathcal{B} + \mathcal{B}^+\right).$$

[arXiv:2208.06421]

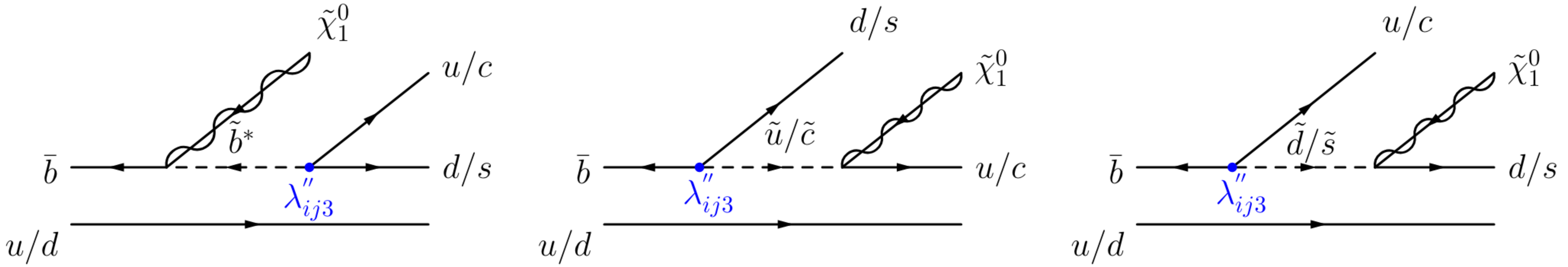


Figure 1. Parton-level diagrams for the decays $B \to \mathcal{B}\tilde{\chi}_1^0$, where $\mathcal{B}$ stands for one of the baryons and λ''_{ij3} the corresponding RPV coupling: p, n (for λ''_{113}); Λ, Σ^+, Σ^0 (for λ''_{123}); Λ_c^+, Σ_c^+, Σ_c^0 (for λ''_{213}); and Ξ_c^+, Ξ_c^0 (for λ''_{223}).