Universität Siegen
TP1 Theoretical Particle Physics
CPPS Center for Particle Physics Siegen

Constraining B-Mesogenesis with $B^+ \to p^+ \psi$

Based on JHEP 08 (2025) 141 in collaboration with Prof. Dr. Alexander Lenz and Ali Mohamed

Zachary Wüthrich - 9. September

Belle II Germany Meeting 2025

OUTLINE

- **Theoretical Foundations** - ingredients for B-mesogenesis
- **Calculational Toolkit** - inclusive lifetime calculations
- **Models of B-Mesogenesis** - minimal set up
- **Phenomenology** - exclusion plots for Br$(B^+ \to p^+\psi)$

Theoretical Foundations

BARYOGENESIS

- **Why is there more matter than anti-matter?**
- **From BBN particle abundance and CMB anisotropies we know:**

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.1 \pm 0.3) \times 10^{-10}$$

- **In inflation models, initial condition solutions require extreme fine tuning:**

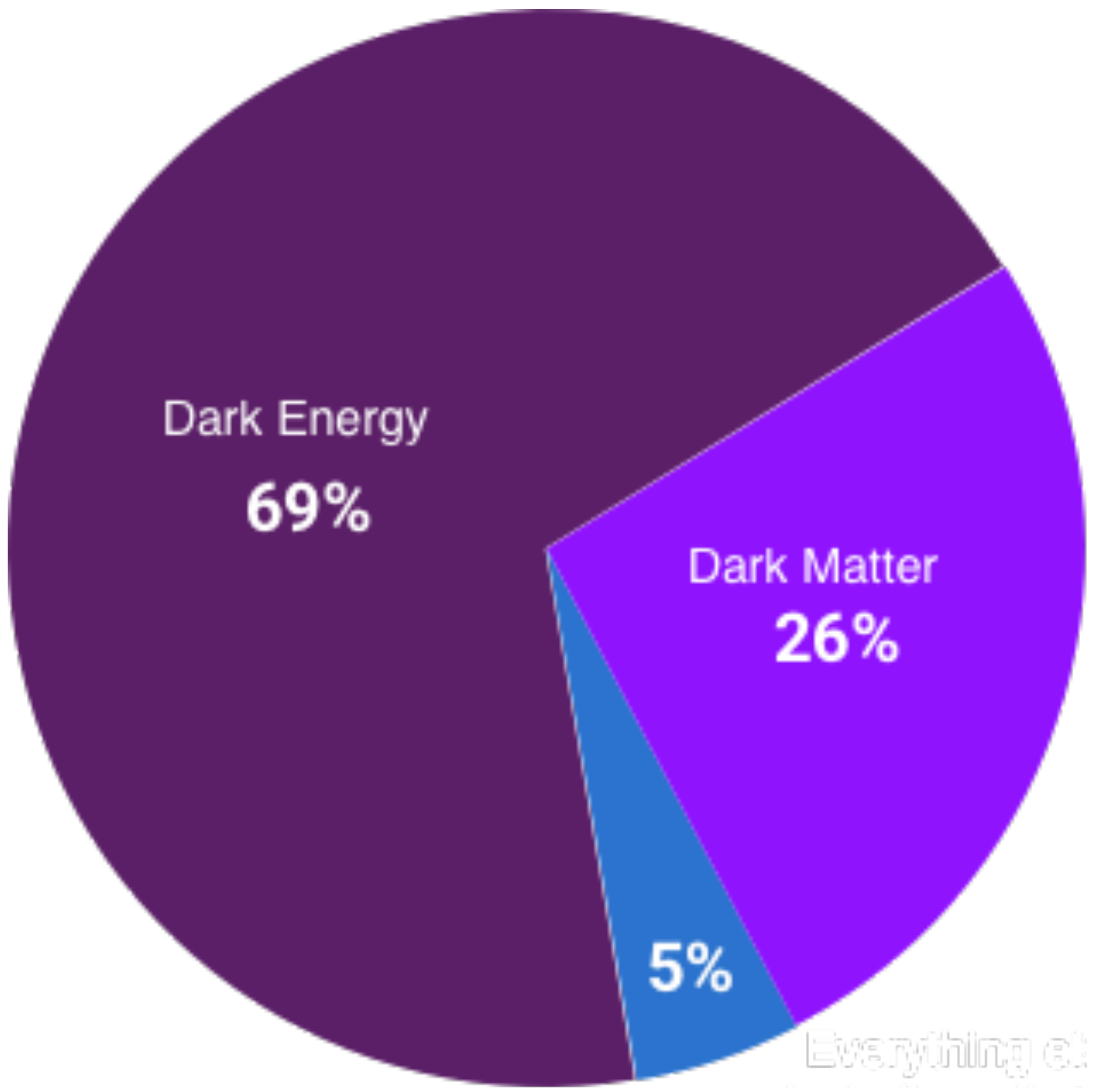
$$n_B - n_{\bar{B}} \approx 1{,}000{,}000{,}001 - 1{,}000{,}000{,}000$$

SAKHAROV CONDITIONS

- **Condition 1:** Baryon number violation
- **Condition 2:** C & CP Violation
- **Condition 3:** Departure from Thermal Equilibrium

DARK MATTER

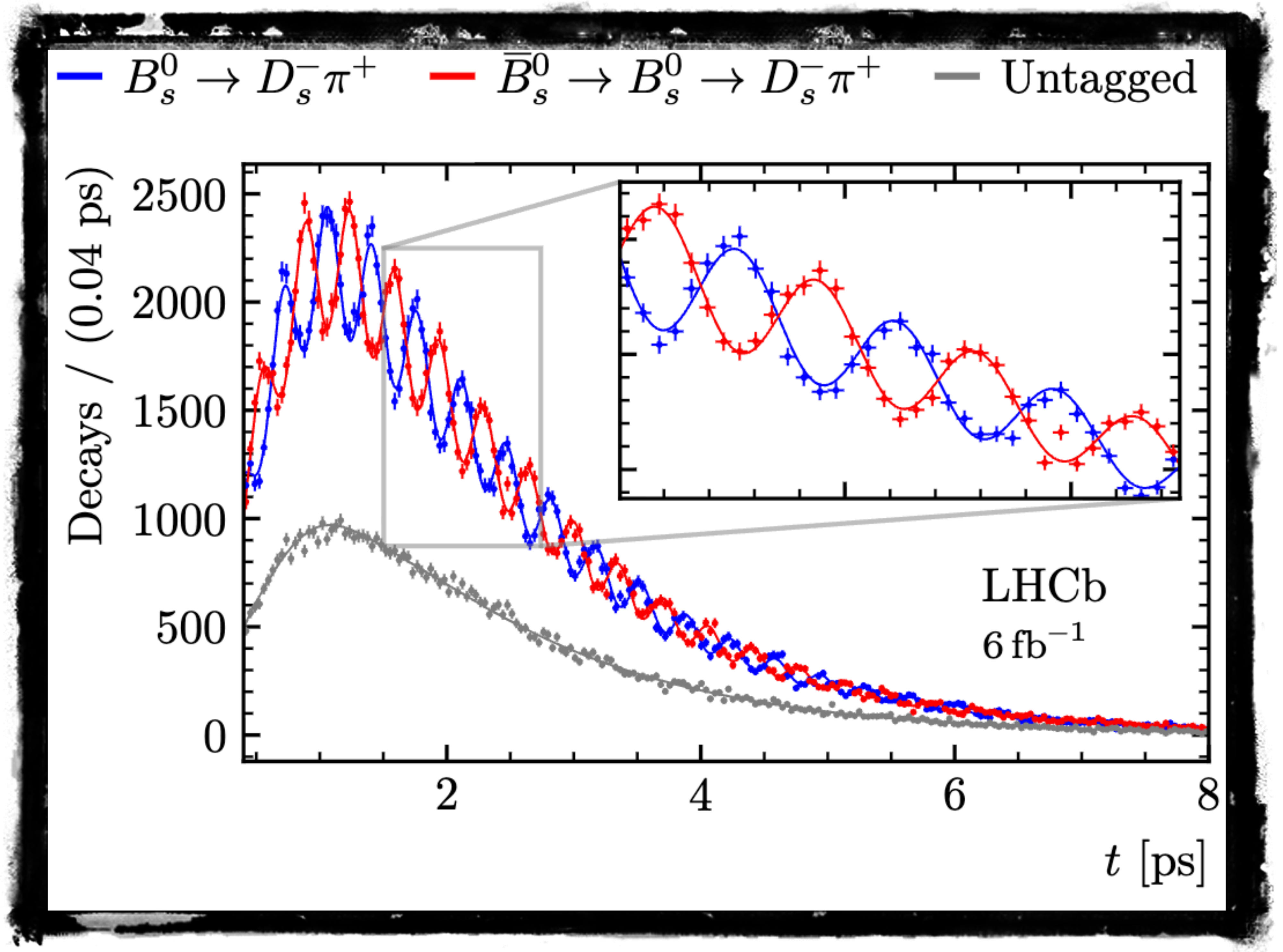
- **Wide range of possible masses (eV to TeV)**
  - **Our model:** $1 \lesssim m_\psi \lesssim 5$ **GeV**
- **Should be Cold Dark Matter (CDM)**
- **Very weakly interacting**



https://chandra.harvard.edu/darkuniverse/

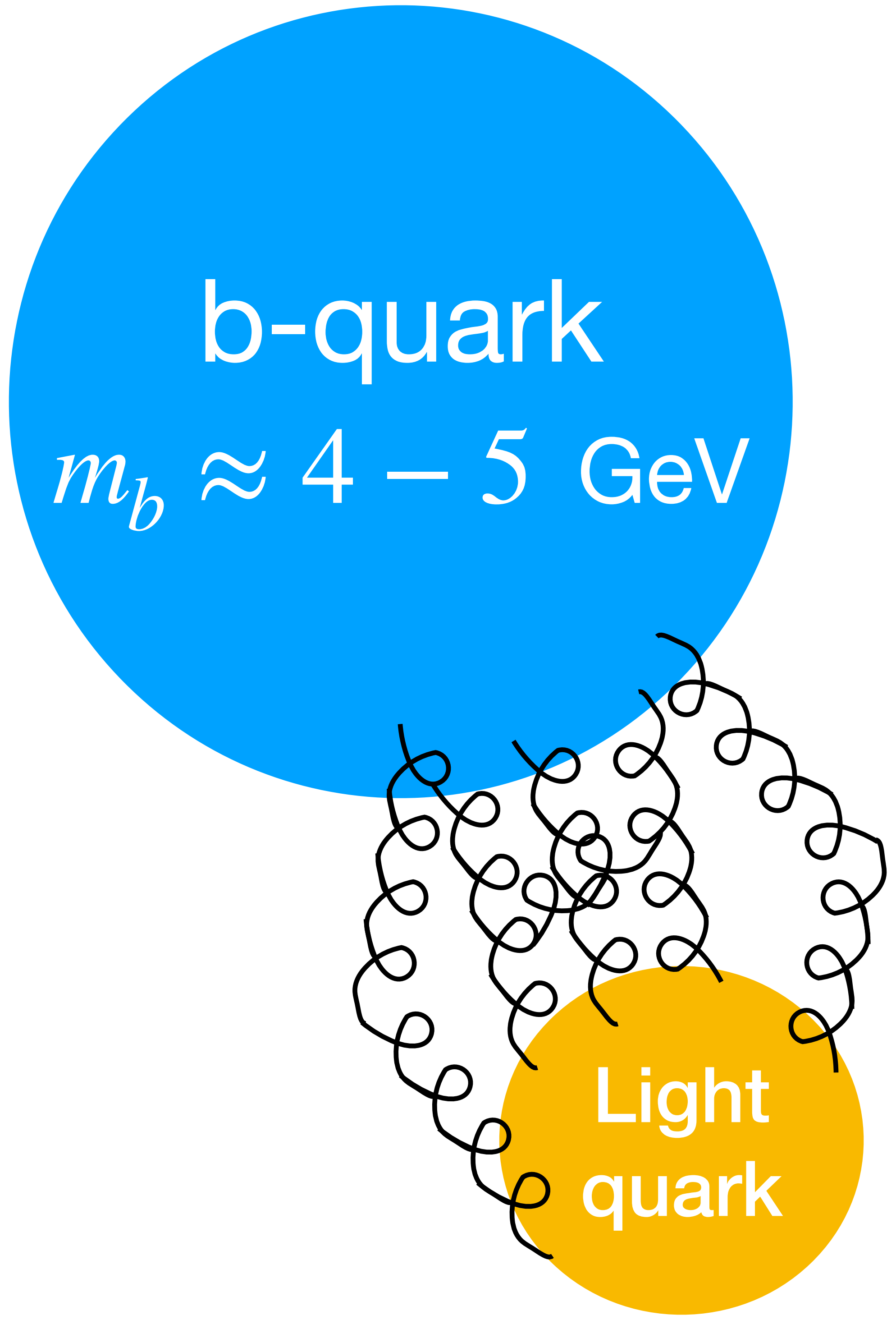
B-MESONS

- $5.2 < m_B < 5.4$ GeV
- Mean lifetime: $\sim 10^{-12}$ s
- Room for significant CP violation



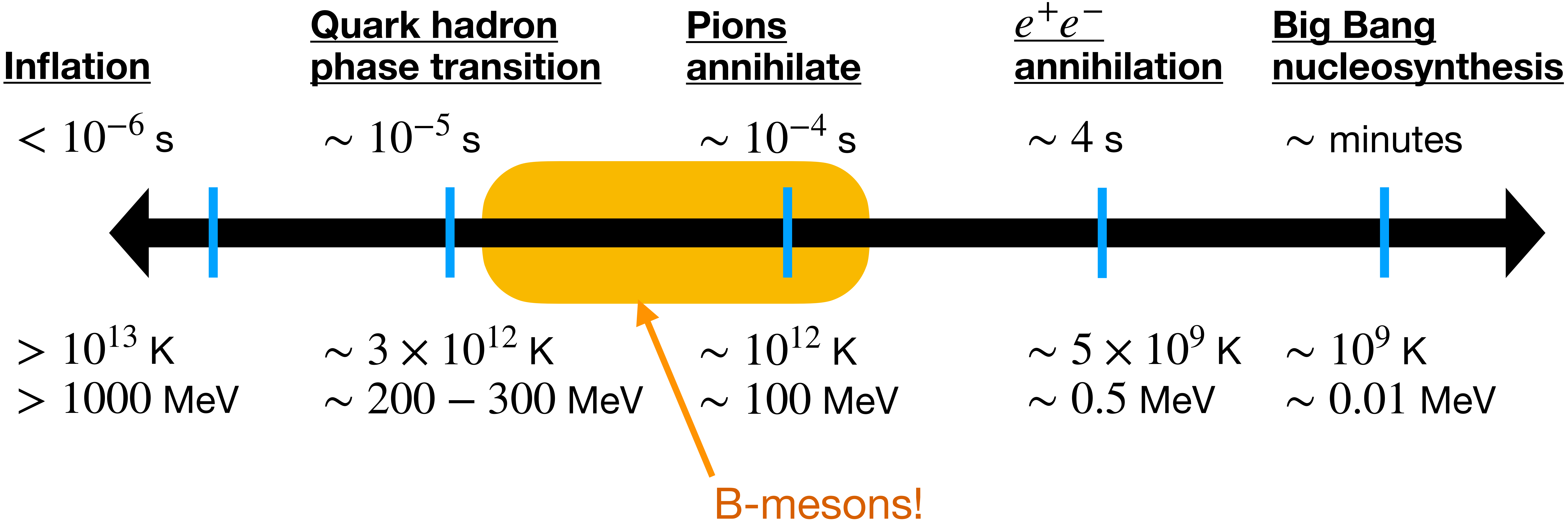
Run 2 LHCb data

http://lhcb-public.web.cern.ch



$m_q \lesssim 100$ MeV

TIMELINE OF THE UNIVERSE



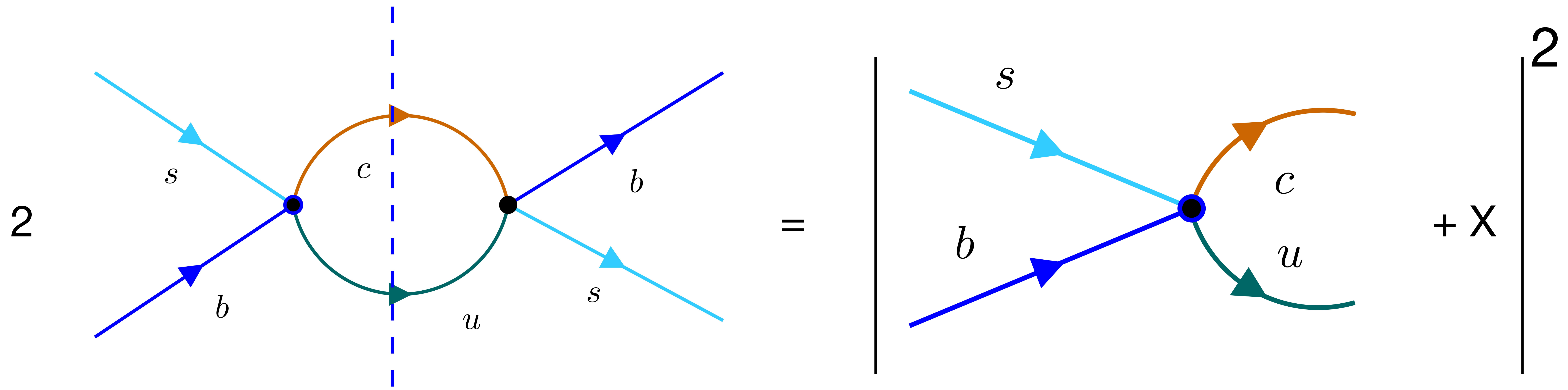
Calculational Toolkit

OPTICAL THEOREM

$$S_{fi} \equiv \langle f|S|i\rangle = \delta_{fi} + iT_{fi}$$

$$T_{fi} = (2\pi)^4 \delta^{(4)}(p_f - p_i)\mathcal{M}_{fi}$$

$$2\,\mathrm{Im}\,\mathcal{M}_{ii} = \sum_n \int_n (2\pi)^4 \delta^{(4)}\left(\sum_{j=1}^{n} p_j - p_i\right) |\mathcal{M}_{ni}|^2$$



HEAVY QUARK EXPANSION

- Method to calculate the **total decay rate:** $\Gamma(B)$
- Consequence of the optical theorem:

$$\Gamma(B) = \frac{1}{2M_B}\langle B|\mathcal{T}|B\rangle$$

$$\mathcal{T} \equiv \mathrm{Im}\, i \int d^4x\, \mathrm{T}\{\mathcal{H}_{eff}(x)\mathcal{H}_{eff}(0)\}$$

- Separate the short and long distance dynamics with an **OPE**:

$$\Gamma(B) = \Gamma_3\langle\mathcal{O}_3\rangle + \Gamma_5\frac{\langle\mathcal{O}_5\rangle}{m_b^2} + \Gamma_6\frac{\langle\mathcal{O}_6\rangle}{m_b^3} + \ldots + 16\pi^2\left[\tilde{\Gamma}_6\frac{\left\langle\tilde{\mathcal{O}}_6\right\rangle}{m_b^3} + \tilde{\Gamma}_7\frac{\left\langle\tilde{\mathcal{O}}_7\right\rangle}{m_b^4} + \ldots\right]$$

LIFETIME RATIOS

$$\left(\frac{\tau(B^+)}{\tau(B_d)}\right)^{\text{Exp.}} = 1.076 \pm 0.004\,. \qquad \left(\frac{\tau(B^+)}{\tau(B_d)}\right)^{\text{HQE}} = 1.081^{+0.014}_{-0.016}\,,$$

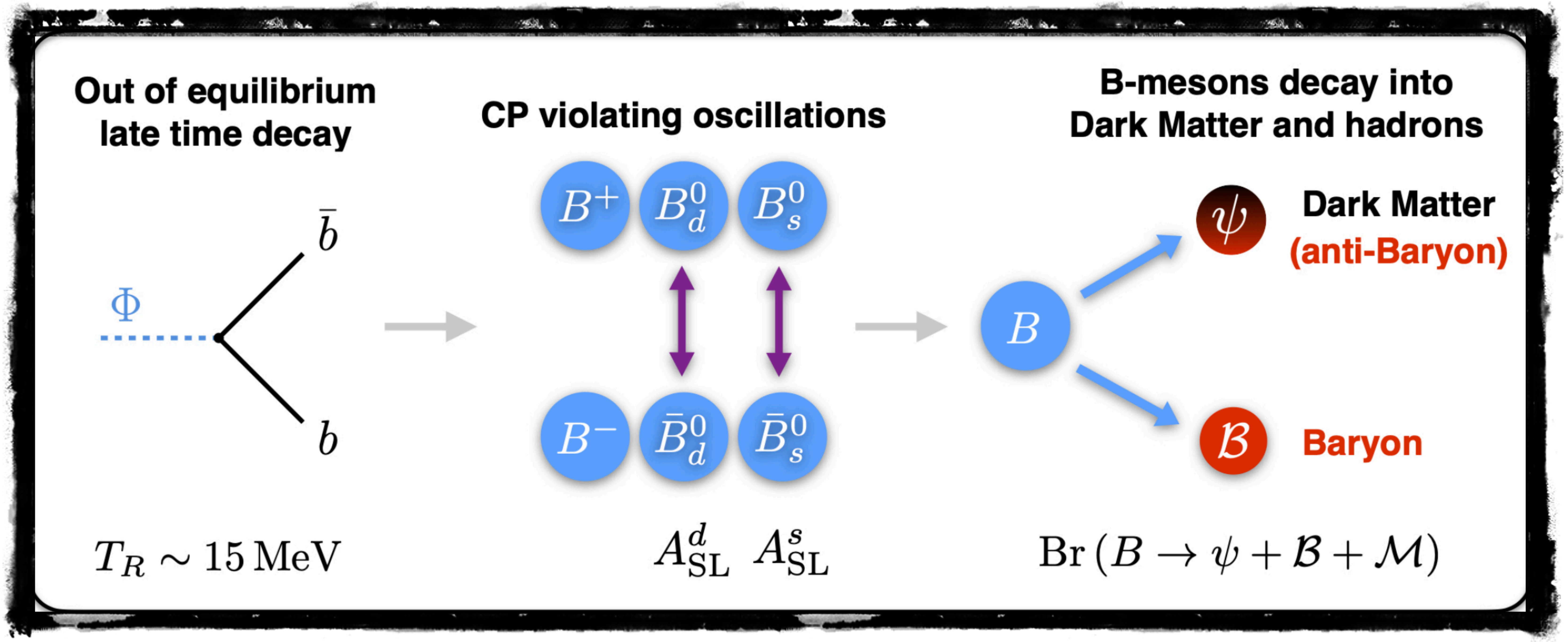
$$\frac{\tau(B^+)}{\tau(B_d)}^{\text{HQE}} = 1 + \left[\Gamma^{\text{SM}}(B_d) - \Gamma^{\text{SM}}(B^+)\right]\tau^{\text{Exp.}}(B^+) + \left[\Gamma^{\text{BSM}}(B_d) - \Gamma^{\text{BSM}}(B^+)\right]\tau^{\text{Exp.}}(B^+),$$

$$\Gamma(B_d) - \Gamma(B^+) = \left[\tilde{\Gamma}_6^{B_d}\frac{\langle\tilde{O}_6\rangle_{B_d}}{m_b^3} - \tilde{\Gamma}_6^{B^+}\frac{\langle\tilde{O}_6\rangle_{B^+}}{m_b^3}\right] + \mathcal{O}\left(\frac{1}{m_b^4}\right)$$

Models of B-Mesogenesis

B-MESOGENESIS

Baryogenesis and dark matter from B-mesons



G. Elor, M. Escudero and A. Nelson,
Phys. Rev. D **99**, 035031

G. Alonso-Álvarez, G. Elor and M. Escudero
Phys. Rev. D **104**, 035028

A.E. Nelson and H. Xiao
Phys. Rev. D 100 (2019) 075002

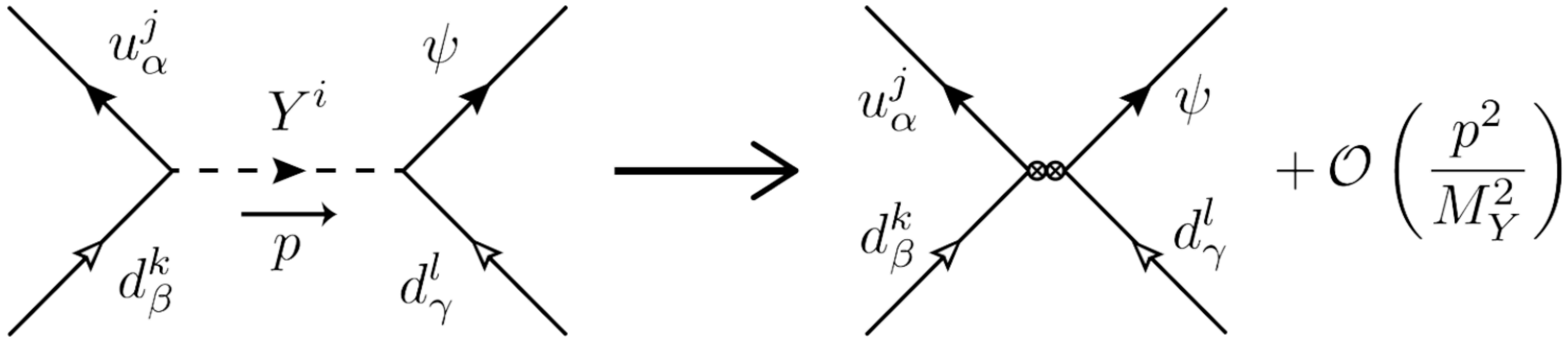
THE EFFECTIVE HAMILTONIAN

- Start with **UV complete** theory

$$\mathcal{L}_{-1/3} = -\sum_{\alpha,\beta} y_{u_\alpha d_\beta} \epsilon_{ijk} Y^{*i} \bar{u}^j_{\alpha R} d^{c,k}_{\beta R} - \sum_{\gamma} y_{\psi d_\gamma} Y_i \bar{\psi} d^{c,i}_{\gamma R} + \text{h.c.}\,,$$

$$\mathcal{L}_{+2/3} = -\sum_{\alpha,\beta} y_{d_\alpha d_\beta} \epsilon_{ijk} Y^{*i} \bar{d}^j_{\alpha R} d^{c,k}_{\beta R} - \sum_{\gamma} y_{\psi u_\gamma} Y_i \bar{\psi} u^{c,i}_{\gamma R} + \text{h.c.}\,,$$

- **Integrate out** heavy scalar



- Perform **matching** to determine the effective Hamiltonian

$$\mathcal{H}_{-1/3} = -G_{(d)} \bar{\mathcal{O}}_{(d)} \psi^c - G^*_{(d)} \bar{\psi}^c \mathcal{O}_{(d)} + \{b \leftrightarrow d\},$$

EFFECTIVE OPERATORS

- **Many new physics operators**
  - Both for $\mathscr{L}_{+2/3}$ and $\mathscr{L}_{-1/3}$
- **Red - poorly constrained**
- **Yellow - unconstrained**

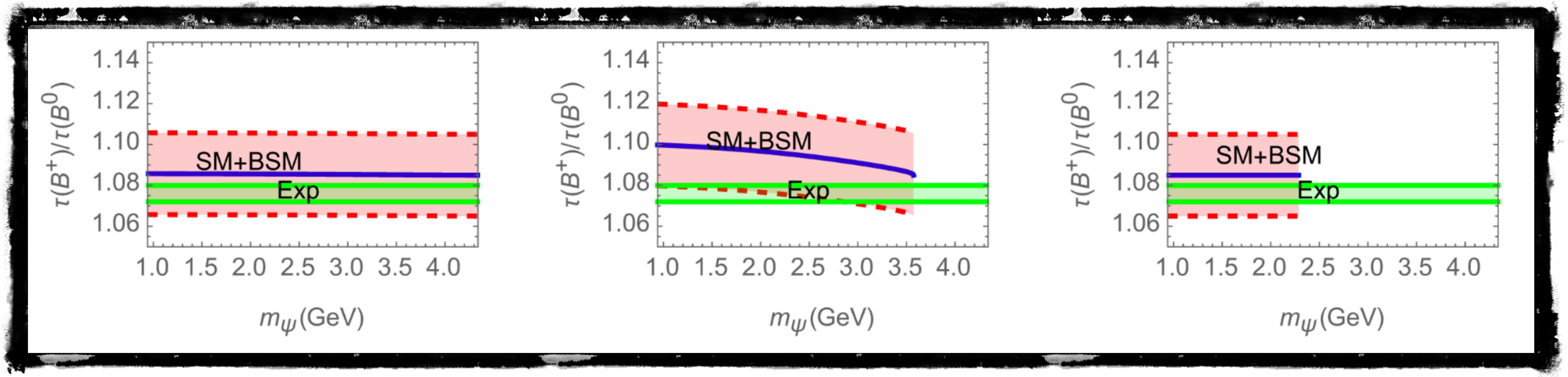
Operator	Affects B^+?	Affects B_d?
$(\bar{b}d^c)(\bar{\psi}u^c)$	Yes	Yes
$(\bar{b}d^c)(\bar{\psi}c^c)$	No	Yes
$(\bar{b}d^c)(\bar{d}s^c)$	No	Yes
$(\bar{b}s^c)(\bar{d}s^c)$	No	Yes
$(\bar{b}s^c)(\bar{\psi}u^c)$	Yes	No

Operator	Affects B^+?	Affects B_d?
$(\bar{b}u^c)(\bar{\psi}d^c)$	Yes	Yes
$(\bar{b}c^c)(\bar{\psi}d^c)$	No	Yes
$(\bar{d}u^c)(\bar{\psi}b^c)$	Yes	Yes
$(\bar{d}c^c)(\bar{\psi}b^c)$	No	Yes
$(\bar{\psi}d^c)(\bar{\psi}b^c)$	No	Yes
$(\bar{b}u^c)(\bar{u}d^c)$	Yes	Yes
$(\bar{b}c^c)(\bar{c}d^c)$	No	Yes
$(\bar{b}c^c)(\bar{u}d^c)$	Yes	Yes
$(\bar{b}u^c)(\bar{c}d^c)$	Yes	Yes
$(\bar{b}u^c)(\bar{\psi}s^c)$	Yes	No
$(\bar{\psi}b^c)(\bar{u}s^c)$	Yes	No
$(\bar{b}u^c)(\bar{u}s^c)$	Yes	No
$(\bar{b}u^c)(\bar{c}s^c)$	Yes	No
$(\bar{b}c^c)(\bar{u}s^c)$	Yes	No

Phenomenology

LIFETIME RATIOS

Can lifetime ratios constrain these models?



EXCLUSIVE DECAY RATES

- **Light Cone Sum Rules (LCSR)** calculations done by Boushmelev and Wald
  Phys. Rev. D 109 (2024) 055049

$$\Gamma_{(d)}(B^+ \to p\psi) = \boxed{|G_{(d)}|^2}\Bigg\{\Bigg[\Big(F^{(d)}_{B\to p_R}(m_\psi^2)\Big)^2 + \frac{m_\psi^2}{m_p^2}\Big(\widetilde{F}^{(d)}_{B\to p_L}(m_\psi^2)\Big)^2\Bigg] \times (m_B^2 - m_p^2 - m_\psi^2) + 2m_\psi^2 F^{(d)}_{B\to p_R}(m_\psi^2)\widetilde{F}^{(d)}_{B\to p_L}(m_\psi^2)\Bigg\}\frac{\lambda^{1/2}(m_B^2, m_p^2, m_\psi^2)}{16\pi m_B^3},$$

- **Inclusive rate** has the same prefactor dependence

$$\Gamma_3^{(d)}(b \to du\psi) = \frac{\boxed{|G_{(d)}|^2}}{16}\frac{m_b^5}{192\,\pi^3}\left[1 - 8\,\rho + 8\rho^3 - \rho^4 - 12\,\rho^2\log(\rho)\right],$$

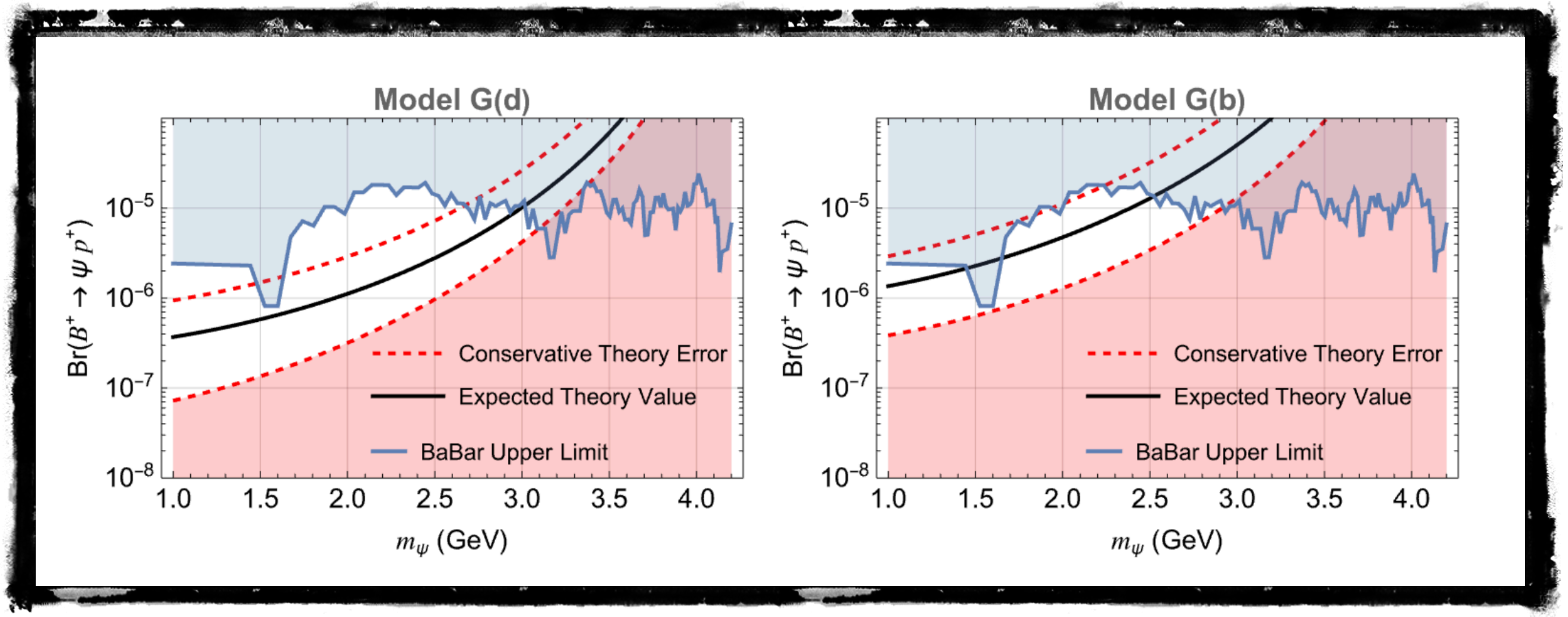
$$\Gamma_3^{(b)}(b \to du\psi) = \Gamma_3^{(d)}(b \to du\psi)\Big|_{G_{(d)}\to G_{(b)}},$$

EXCLUSIVE/INCLUSIVE RATIO

- **Enforcing a lower bound**
- **Inclusive rate from Γ_3**

$$Br(B^+ \to \psi \mathcal{B}\mathcal{M}) > 10^{-4}\,,$$

$$Br(B^+ \to p^+\psi) > 10^{-4}\frac{\Gamma(B^+ \to p^+\psi)}{\Gamma(B^+ \to \psi\mathcal{B}\mathcal{M})} \equiv 10^{-4}\frac{\Gamma(B^+ \to p^+\psi)}{\Gamma(b \to du\psi)}$$



OUTLOOK

- Need better precision in the SM lifetime ratios **(theory)**
- Need more calculations of the exclusive decay rate in various models **(theory)**
- Need a larger source of CP violation **(theory)**
- Need to push the exclusion plots for Br$(B^+ \to p\psi)$ as a function of m_ψ down an order of magnitude **(experiment)**
  - This could fully exclude multiple models within B-Mesogenesis

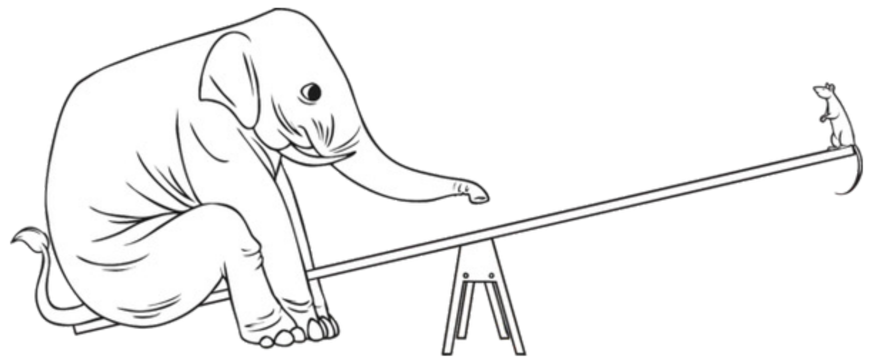
Backup Slides

CONDITION 1: BARYON NUMBER VIOLATION

- In the SM, baryon number is conserved at tree level, but violated at loop level due to triangular anomalies
  - The currents $\partial_\mu J_L^\mu = \partial_\mu J_B^\mu$ so in the SM $B - L$ is conserved but $B + L$ can be violated.

- $B + L$ processes are governed by “Sphalerons”
  - Sphaleron: Unstable solution to the EOM of EW theory at finite temperature

- Sphaleron processes are suppressed unless $T \gg T_{EW}$

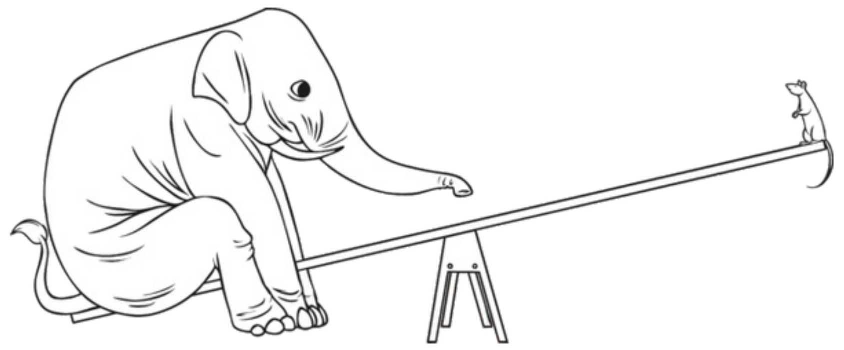


CONDITION 2: C & CP VIOLATION

- A short "proof" as to why we need C & CP violation through a toy model:
- Suppose there is a super heavy boson X with the following decays:

Decay	Decay Rate	ΔB
$\mathrm{X} \rightarrow qq$	α	2/3
$\mathrm{X} \rightarrow \bar{q}\bar{l}$	$1-\alpha$	-1/3
$\bar{\mathrm{X}} \rightarrow \bar{q}\bar{q}$	$\bar{\alpha}$	-2/3
$\bar{\mathrm{X}} \rightarrow ql$	$1-\bar{\alpha}$	1/3

- Then the asymmetry is $\varepsilon = \Delta B_X + \Delta B_{\bar{X}} = \alpha - \bar{\alpha}$

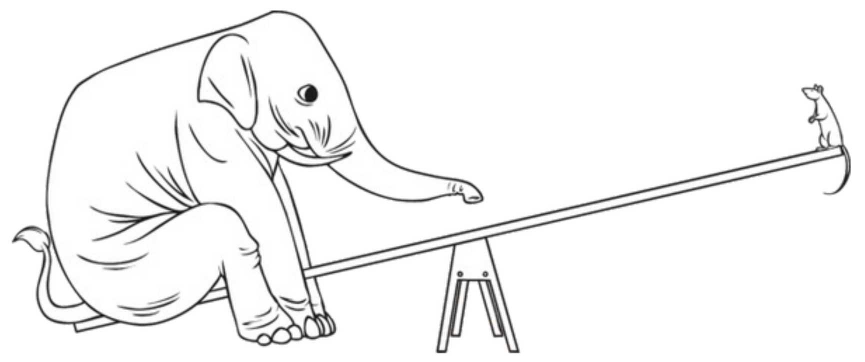


CONDITION 3: DEPARTURE FROM THERMAL EQUILIBRIUM

- A proof that baryon number is conserved in thermal equilibrium:
  - Recall B is odd under C & CP, and CPT commutes with the Hamiltonian H

$$\langle B\rangle_T = \mathrm{Tr}\left[e^{-\beta H}B\right] = \mathrm{Tr}\left[\mathrm{CPT}(\mathrm{CPT})^{-1}e^{-\beta H}B\right]$$
$$= \mathrm{Tr}\left[e^{-\beta H}(\mathrm{CPT})^{-1}B\ \mathrm{CPT}\right]$$
$$= -\mathrm{Tr}\left[e^{-\beta H}B\right]$$

- The mechanism for departure from thermal equilibrium is model dependent
  - **Out of equilibrium decays (GUT baryogenesis and standard leptogenesis)**
  - EW phase transition
  - Dynamics of topological defects



B-Meson Mixing and Lifetimes

Standard Formalism

- Hamiltonian describing meson/anti-meson system:

$$\hat{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} \equiv \begin{pmatrix} \langle B_q | H | B_q \rangle & \langle B_q | H | \overline{B_q} \rangle \\ \langle \overline{B_q} | H | B_q \rangle & \langle \overline{B_q} | H | \overline{B_q} \rangle \end{pmatrix} \equiv \hat{M} - \frac{i}{2}\hat{\Gamma}$$

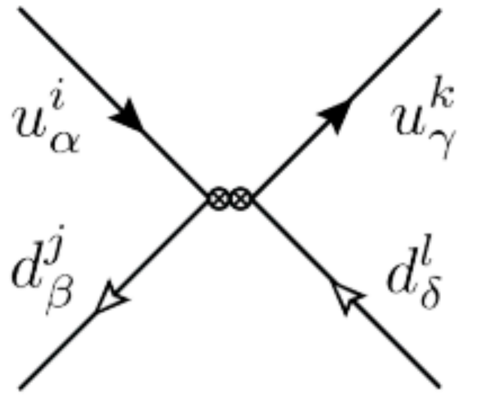
- Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B_q}(t)\rangle \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2}\hat{\Gamma}^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\overline{B_q}(t)\rangle \end{pmatrix}$$

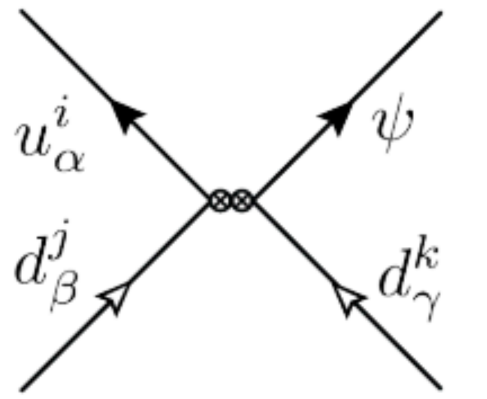
- Calculate observables:

$$\Delta M_q \equiv M_H^q - M_L^q,\ \Delta\Gamma_q \equiv \Gamma_H^q - \Gamma_L^q$$

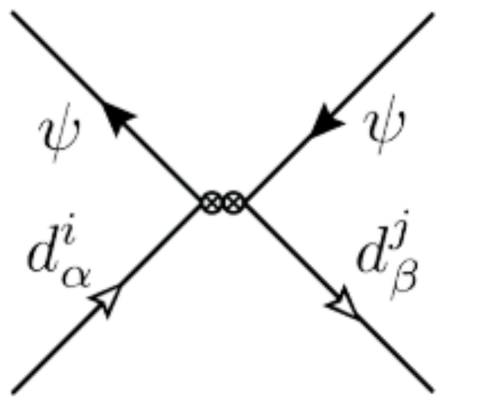
EFFECTIVE VERTICES



$$= \mathrm{i}\frac{y^*_{u_\alpha d_\beta} y_{u_\gamma d_\delta}}{M_Y^2} \left(\delta_{ik}\delta_{jl} - \delta_{il}\delta_{jk}\right) \left(C P_R \otimes P_L C^{-1}\right)$$

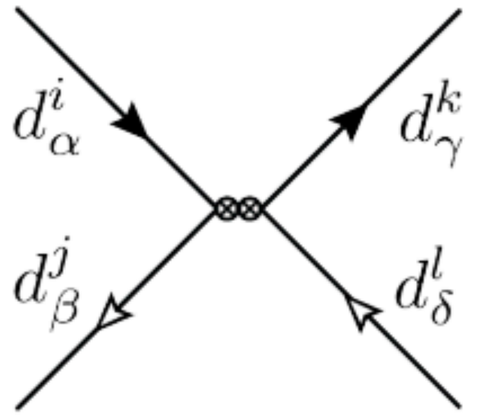


$$= \mathrm{i}\frac{y_{u_\alpha d_\beta} y_{\psi d_\gamma}}{M_Y^2} \epsilon_{ijk} \left(P_L C^{-1} \otimes P_L C^{-1}\right)$$

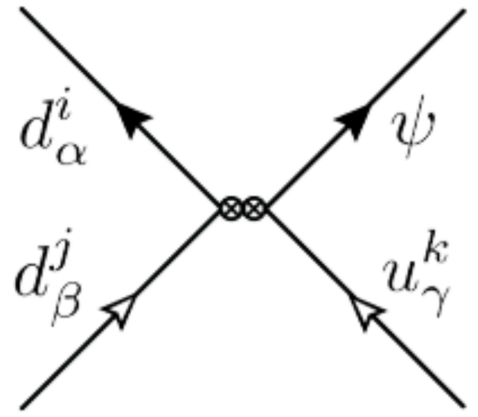


$$= \mathrm{i}\frac{y_{\psi d_\alpha} y^*_{\psi d_\beta}}{M_Y^2} N_c \delta_{ij} \left(C P_R \otimes P_L C^{-1}\right)$$

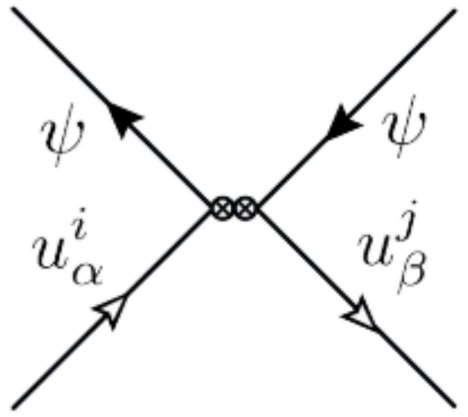
(a) Effective vertices for $\mathcal{L}_{-1/3}$.



$$= \mathrm{i}\frac{y^*_{d_\alpha d_\beta} y_{d_\gamma d_\delta}}{M_Y^2} \left(\delta_{ik}\delta_{jl} - \delta_{il}\delta_{jk}\right) \left(C P_R \otimes P_L C^{-}\right.$$



$$= \mathrm{i}\frac{y_{d_\alpha d_\beta} y_{\psi u_\gamma}}{M_Y^2} \epsilon_{ijk} \left(P_L C^{-1} \otimes P_L C^{-1}\right)$$

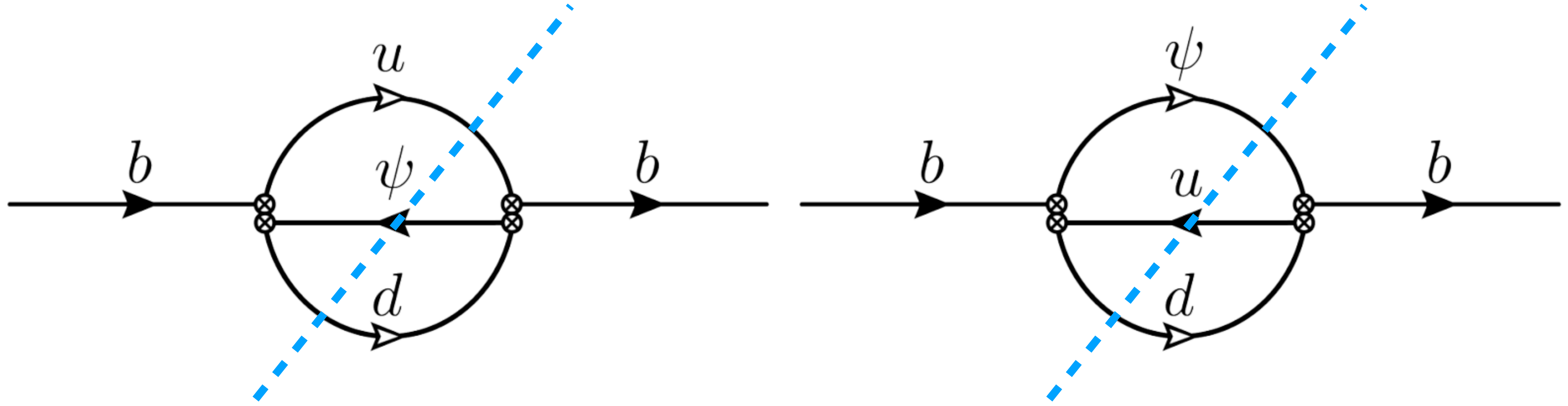


$$= \mathrm{i}\frac{y_{\psi u_\alpha} y^*_{\psi u_\beta}}{M_Y^2} N_c \delta_{ij} \left(C P_R \otimes P_L C^{-1}\right)$$

(b) Effective vertices for $\mathcal{L}_{+2/3}$.

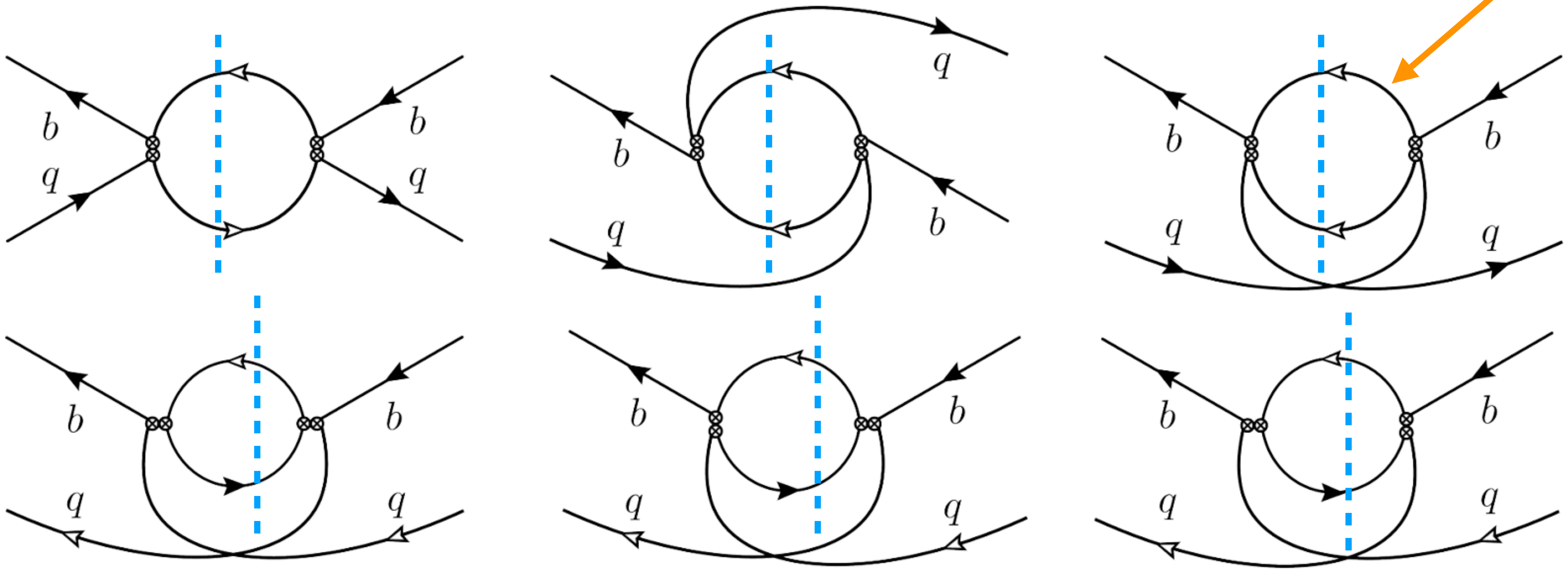
NEW DECAY CHANNELS

Γ_3

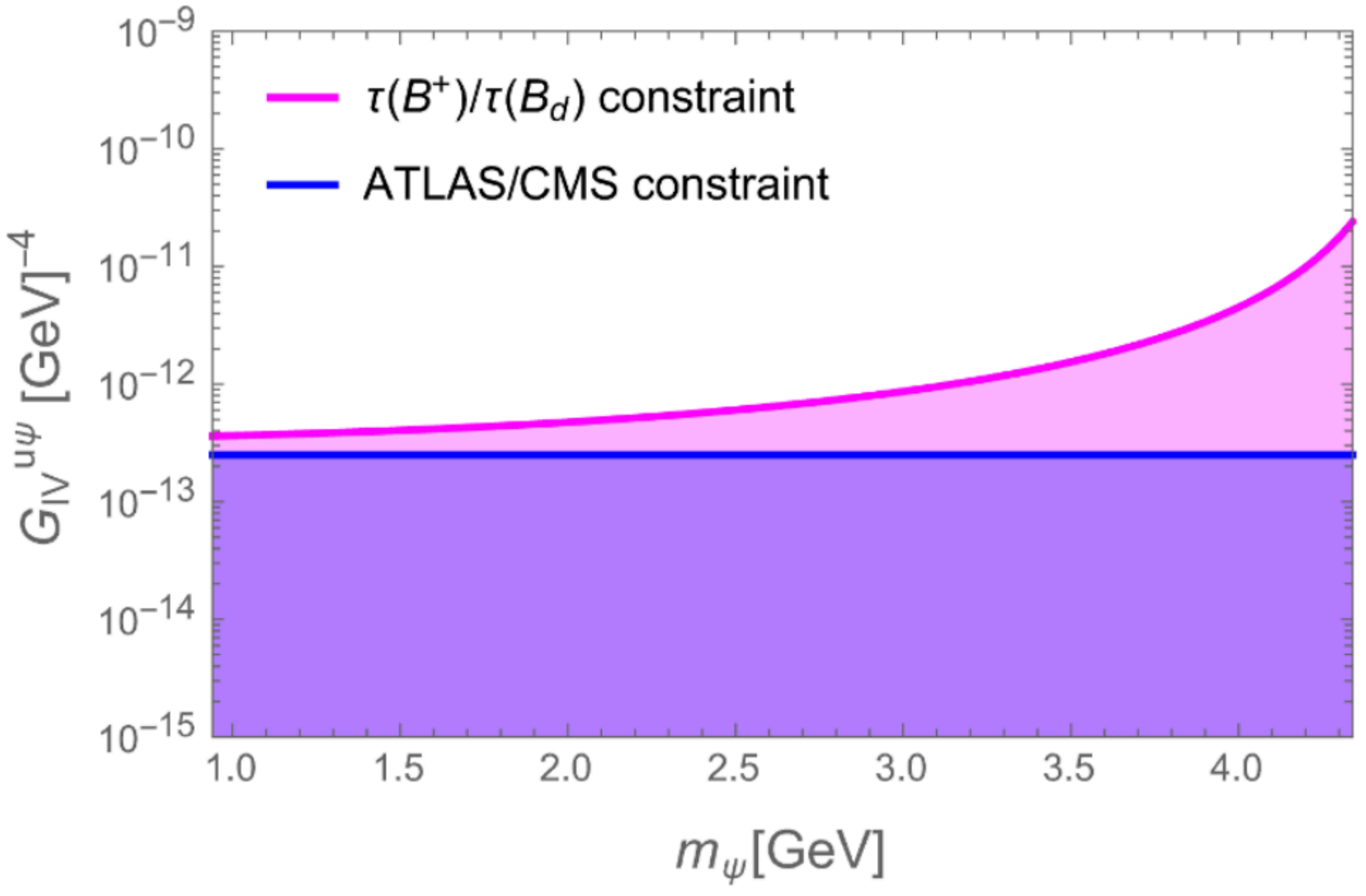


Internal particles could be light quarks or ψ

$\tilde{\Gamma}_6$



LIFETIME RATIO CONSTRAINT



EXCLUSIVE PARAMETERS

Dominant uncertainty

Along with m_b on the inclusive side

Parameter	interval	Ref.
b-quark $\overline{\text{MS}}$ mass	$\overline{m}_b(3\text{ GeV}) = 4.47^{+0.04}_{-0.03}\,\text{GeV}$	[46]
Form Factors	$F^{(d)}_{B\to p_R}(0) = 0.022^{+0.013}_{-0.013}\,\text{GeV}^2$ $\widetilde{F}^{(d)}_{B\to p_L}(0) = 0.005^{+0.002}_{-0.001}\,\text{GeV}^2$ $F^{(b)}_{B\to p_R}(0) = -0.041^{+0.019}_{-0.018}\,\text{GeV}^2$ $\widetilde{F}^{(b)}_{B\to p_L}(0) = -0.007^{+0.003}_{-0.002}\,\text{GeV}^2$	[7]
Slope parameters	$b^{(d)}_{B\to p_R} = 4.46^{+0.97}_{-1.72}\,\text{GeV}^2$ $b^{(d)}_{B\to p_L} = -2.27^{+0.10}_{-0.08}\,\text{GeV}^2$ $b^{(b)}_{B\to p_R} = -2.00^{+1.58}_{-3.62}\,\text{GeV}^2$ $b^{(b)}_{B\to p_L} = -2.85^{+0.17}_{-0.15}\,\text{GeV}^2$	[7]

Slide from FPCP2023 Alex Lenz

CP VIOLATION

1. **CP violation in Mixing**: Consider a **flavour specific (** $\mathcal{A}_{\bar{f}} = 0 = \bar{\mathcal{A}}_f$**) decay** $B \to f$

$$A^q_{\rm fs} = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to \bar{f}\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to \bar{f}\right)}$$

$\boxed{\bar{\mathcal{A}}_{\bar{f}} = \mathcal{A}_f}$ = No direct CP violation

$$a^q_{\rm fs} \approx \frac{|\Gamma^q_{12}|}{|M^q_{12}|} \sin \phi^q_{12}$$

e.g. $B \to X l \nu$
or $\bar{B}_s \to D_s^+ \pi^-$
or $\bar{B}_d \to D^+ K^-$

2. **CP violation in interference of mixing and decay**

$$A^q_{\rm ind} = \frac{\Gamma\left(\bar{B}_q(t) \to f\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar{B}_q(t) \to f\right) + \Gamma\left(B_q(t) \to f\right)}$$

e.g. $B_s \to J/\Psi \phi$
or $B_d \to J/\Psi K_s$

See also 1511.09466, hep-ph/0201071

3. **CP violation in decay**

$$A^q_{\rm dir} = \frac{\Gamma\left(\bar{B}_q(t) \to \bar{f}\right) - \Gamma\left(B_q(t) \to f\right)}{\Gamma\left(\bar{B}_q(t) \to \bar{f}\right) + \Gamma\left(B_q(t) \to f\right)} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}$$

e.g. ΔA_{CP}
or $D^0 \to \pi^- \pi^+, K^- K^+$