

How large can CP violation in Neutral B-Meson mixing be? *Implications for Baryogenesis and Future Searches*

Miguel Escudero Abenza
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based on: 2410.13936 [PRD] with Carlos Miró and Miguel Nebot

but
also
see:

with Alonso-Álvarez & Elor [2101.02706]
with Elor & Nelson [1810.00880]

Moriond EW 2025
24-03-2025

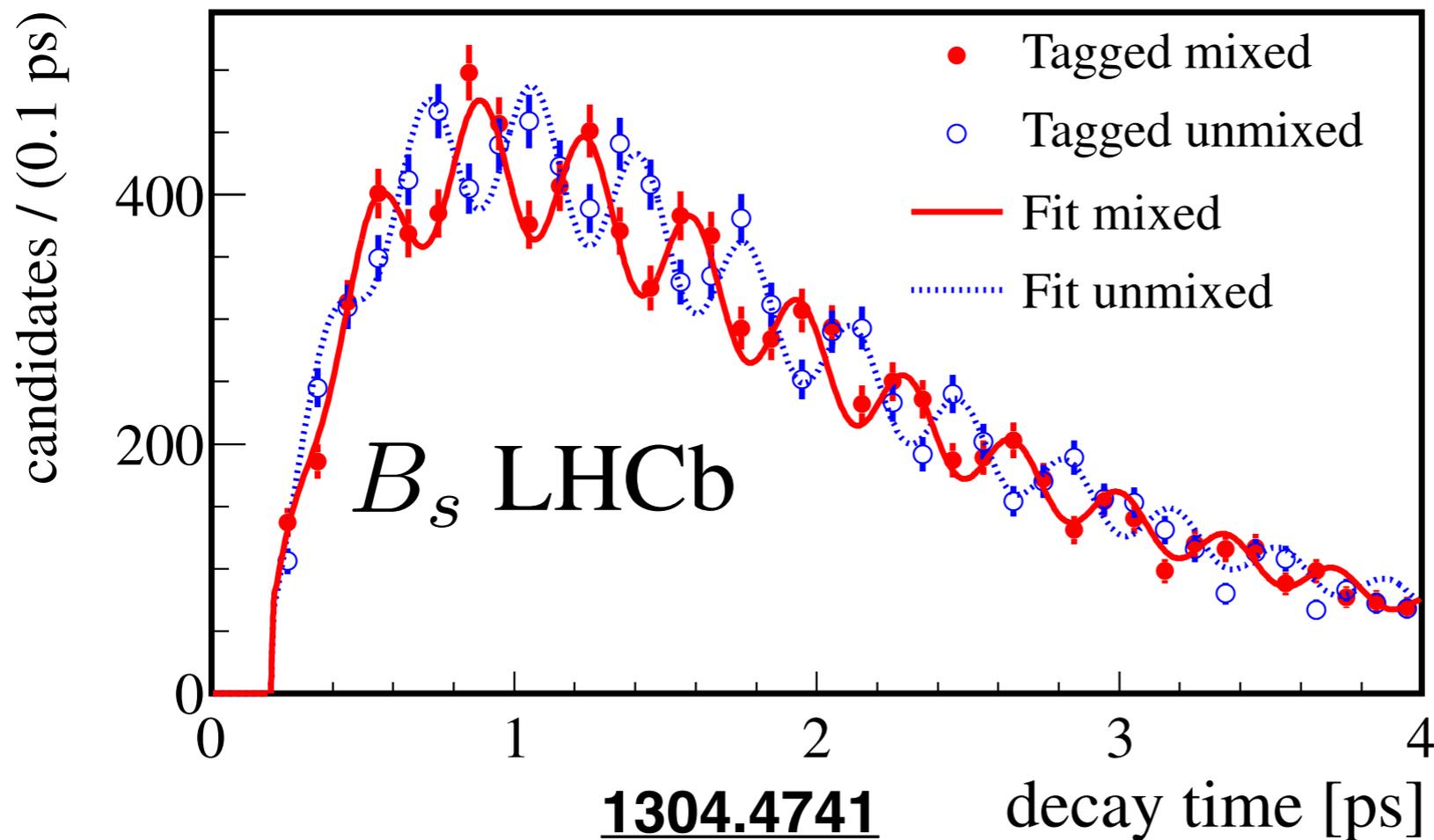


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Neutral B-mesons are flavor eigenstates but not mass eigenstates and they oscillate.

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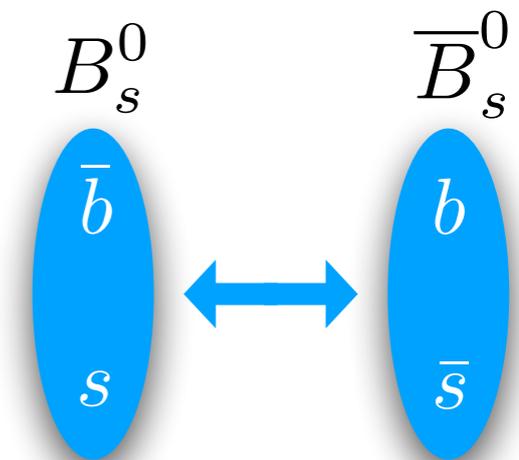
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$$\tau_B = 1.52 \text{ ps}$$

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

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



CP Violation in B-Meson Mixing

Key question: are these mass eigenstates also eigenstates of CP?

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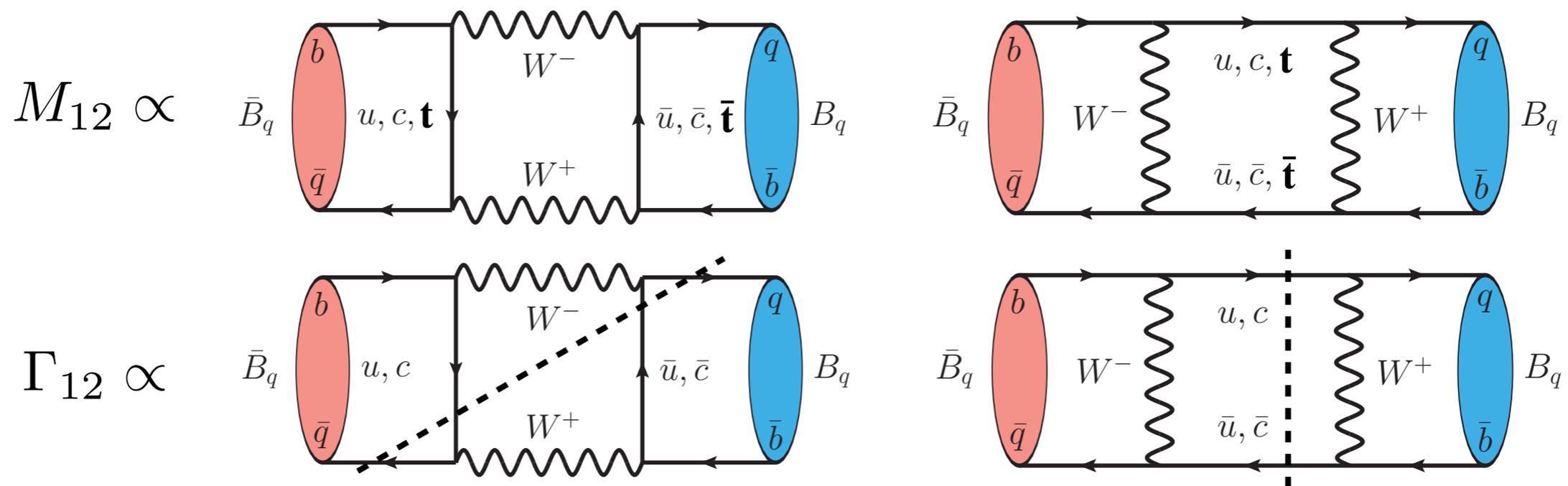
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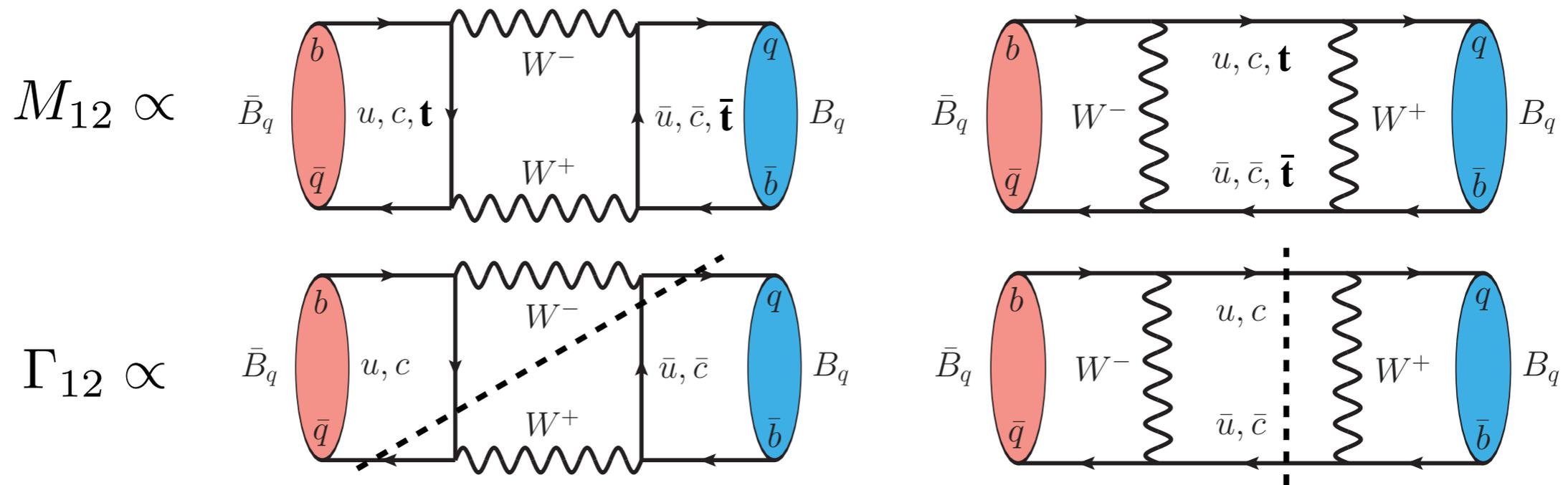
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BSM?

Z's, W's, Scalars, Leptoquarks etc ...

see e.g. Nir 9911321

CP Violation in B-Meson Mixing

The key quantity that measures CP violation in mixing are the semileptonic CP asymmetries:

$$A_{\text{SL}}^q = \text{Im} \left(\frac{\Gamma_{12}^q}{M_{12}^q} \right) = \frac{\Gamma(\bar{B}_q^0 \rightarrow B_q^0 \rightarrow f) - \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \bar{f})}{\Gamma(\bar{B}_q^0 \rightarrow B_q^0 \rightarrow f) + \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \bar{f})}$$

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Standard Model

Lenz & Tetlalmatzi-Xolocotzi
1912.07621

$$A_{\text{SL}}^d |_{\text{SM}} = (-4.7 \pm 0.4) \times 10^{-4}$$

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World averages
[HFLAV]
LHCb, Belle,
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- 1) Measurements are consistent with no CP violation in Mixing
- 2) There is *a priori* room for new physics [factors of 4 Bd, 20 Bs]

Motivations to study these Asymmetries

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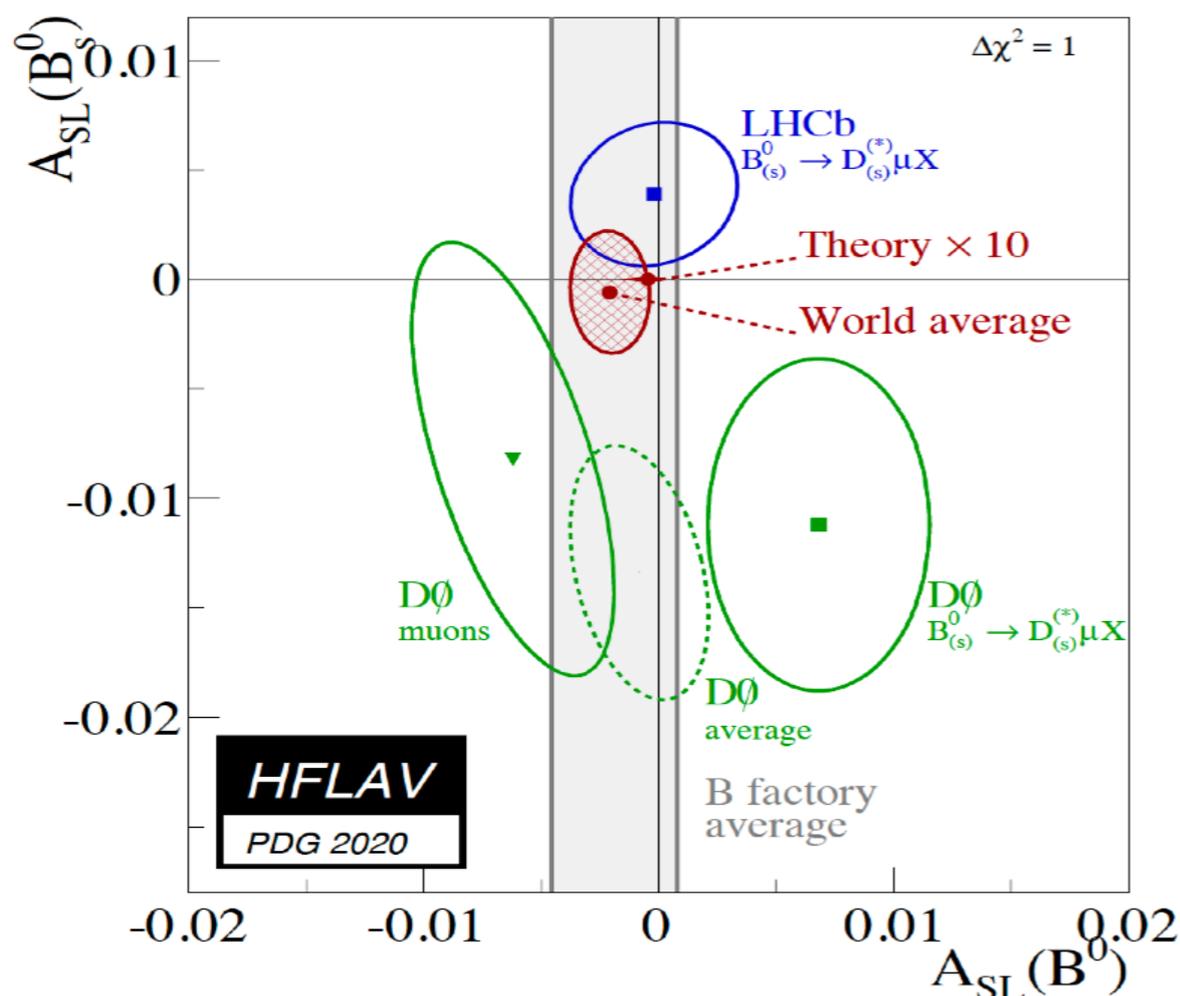
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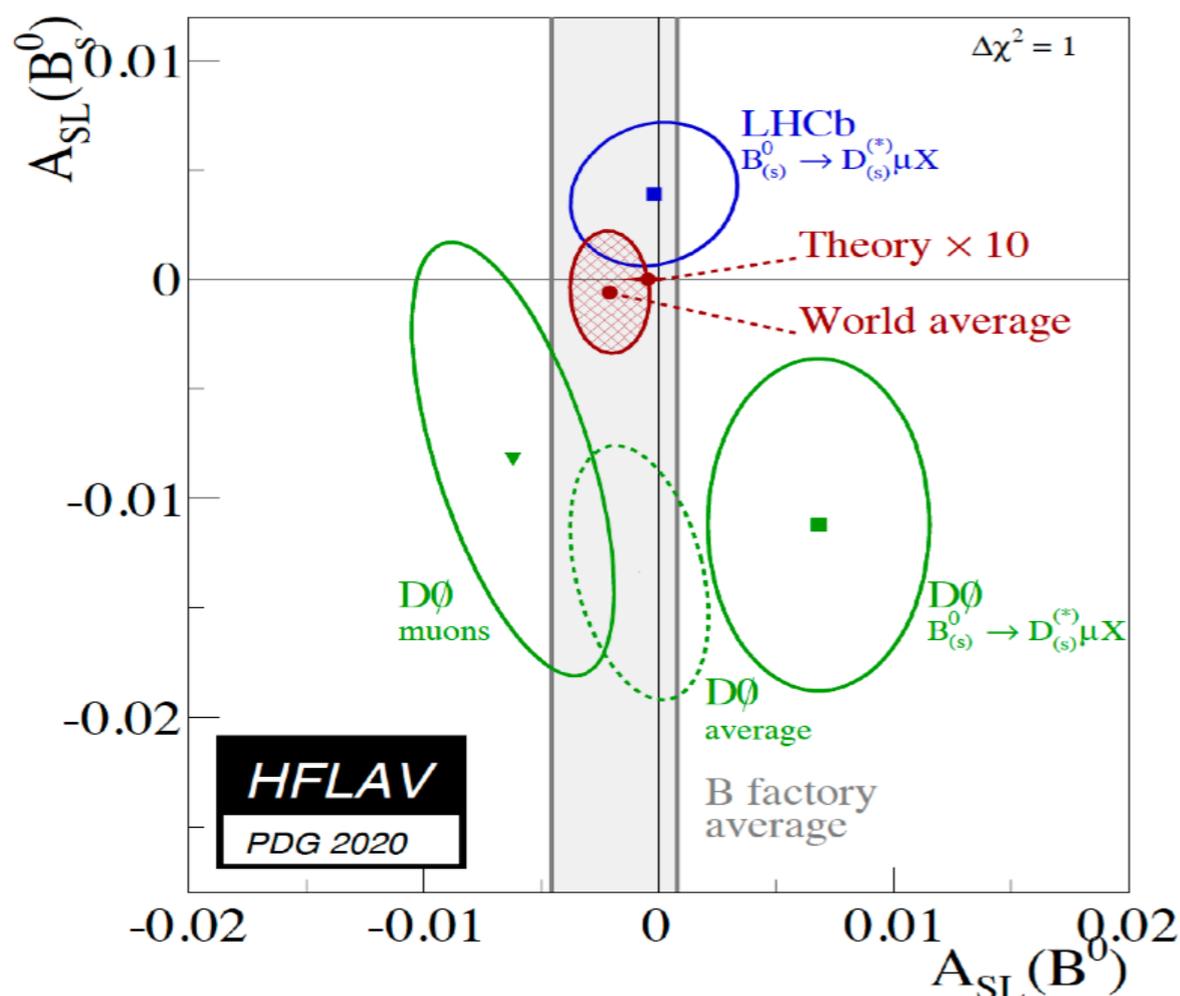
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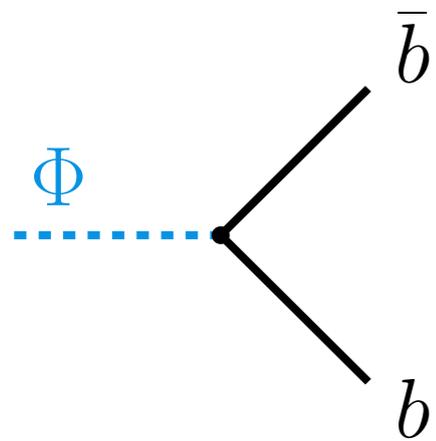
4) Time dependent CPV measurements of ϕ_s reaching $\simeq 1^\circ$!

5) B-Mesogenesis

Elor, Escudero & Nelson [1810.00880]

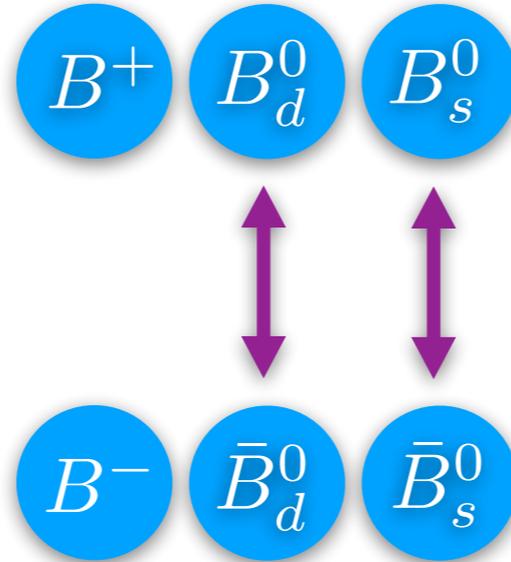
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Out of equilibrium
late time decay



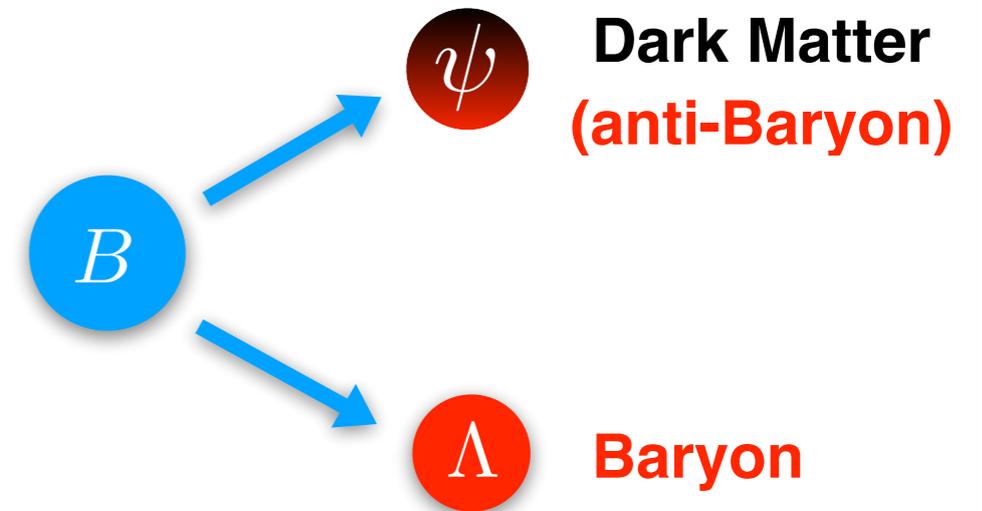
$$T_R \sim 15 \text{ MeV}$$

CP violating oscillations



$$A_{\text{SL}}^d \quad A_{\text{SL}}^s$$

B-mesons decay into
Dark Matter and hadrons



$$\text{Br}(B \rightarrow \psi + \mathcal{B} + \mathcal{M})$$

Baryogenesis

$$n_B/n_\gamma|_{\text{today}} = 6 \times 10^{-10}$$

and

Dark Matter

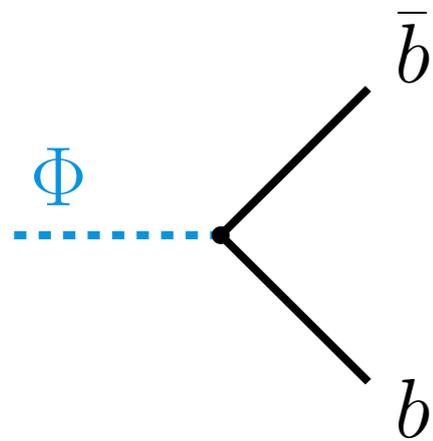
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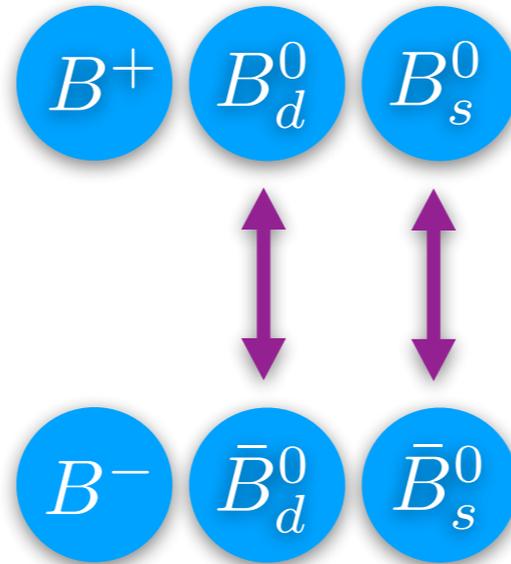
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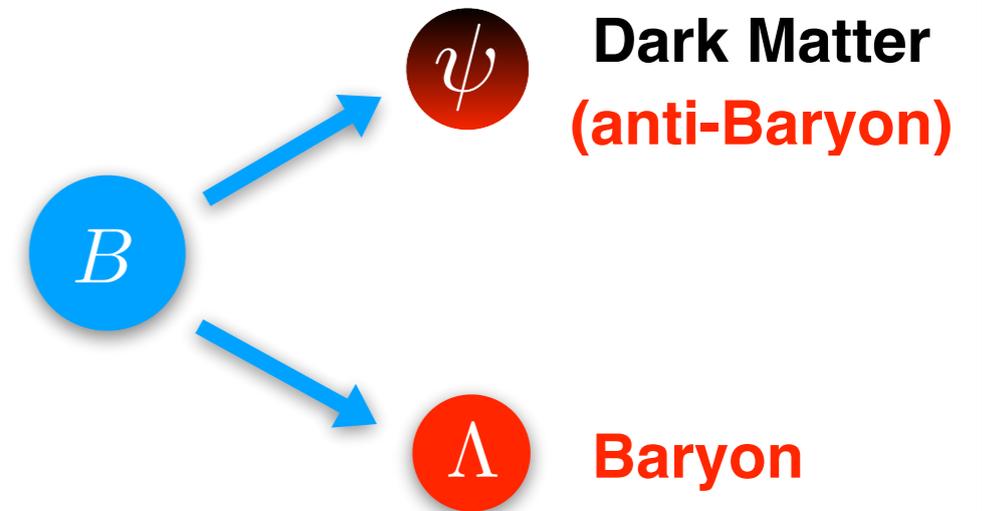
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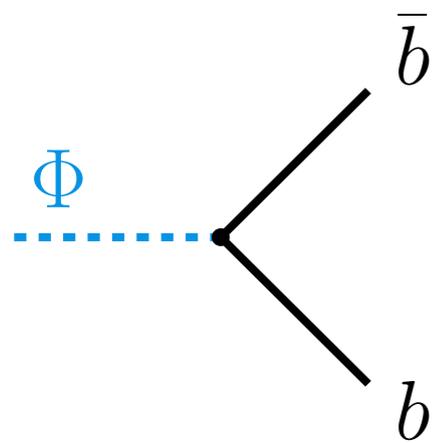
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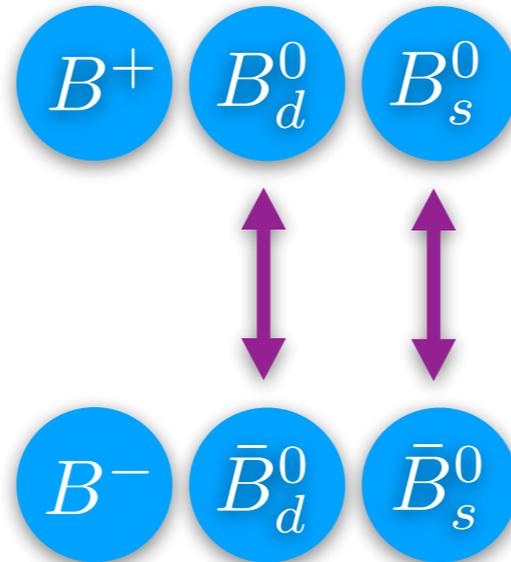
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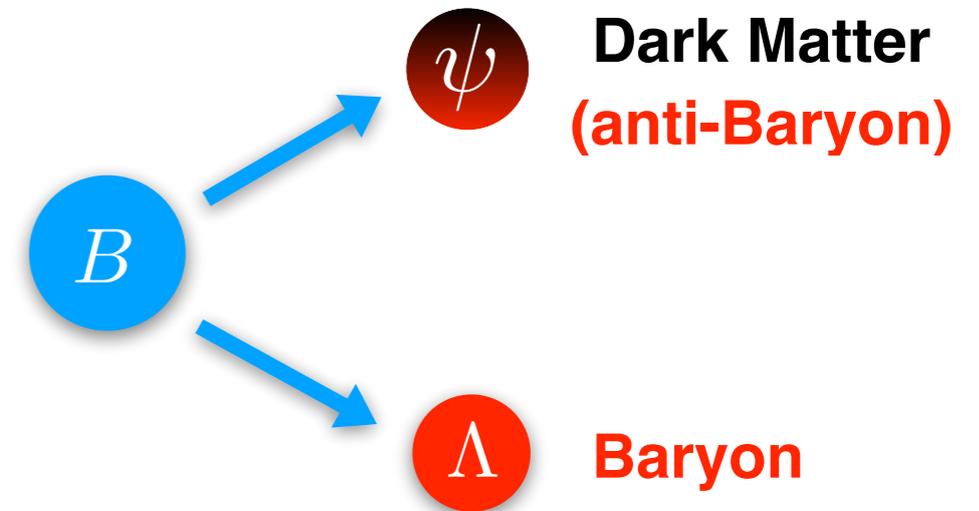
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Key:

$$A_{\text{SL}}^q \geq + 10^{-4}$$

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Understand how large could these asymmetries be Beyond the Standard Model (given all known experimental data as of today).

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Procedure:

- 1) Explore generic modifications to B-meson mass mixing: M_{12}^q**
- 2) Explore implications of CKM non-unitarity (additional singlet vector-like down- and up-type quarks)**
- 3) Consider modifications to Γ_{12}^q**

Modifications to Mass Mixing

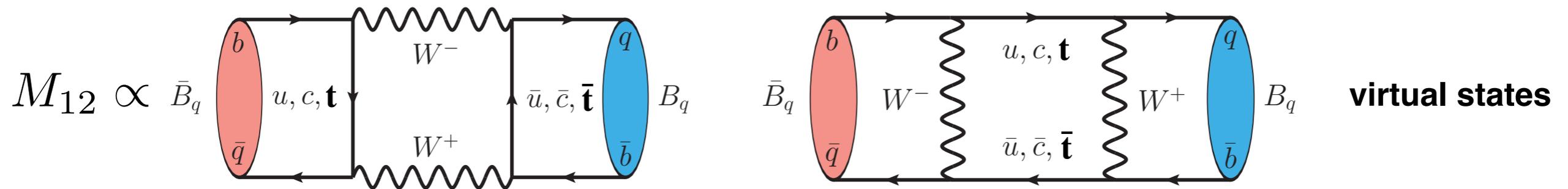
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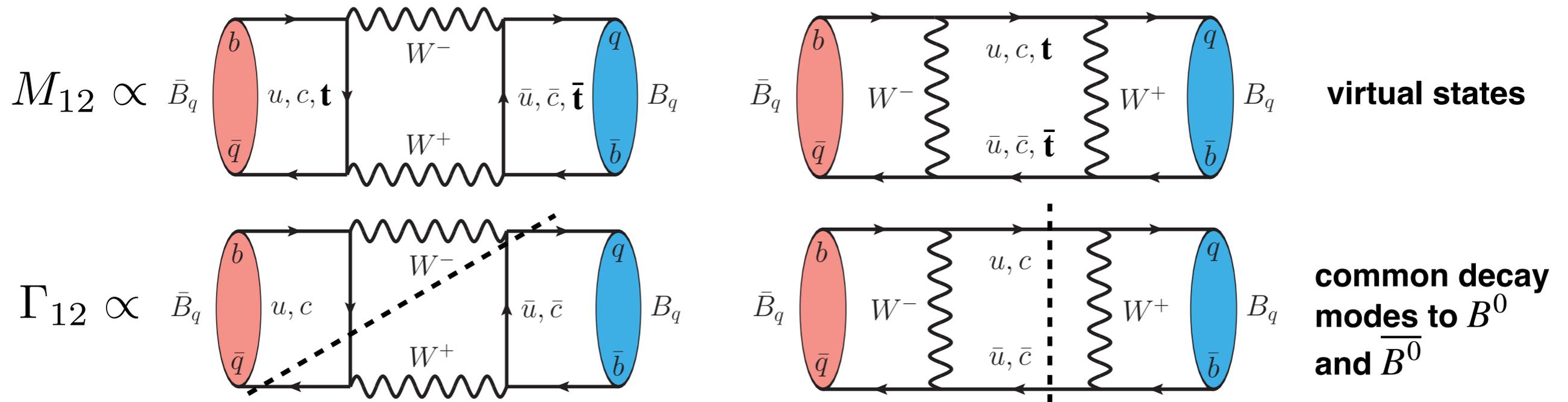
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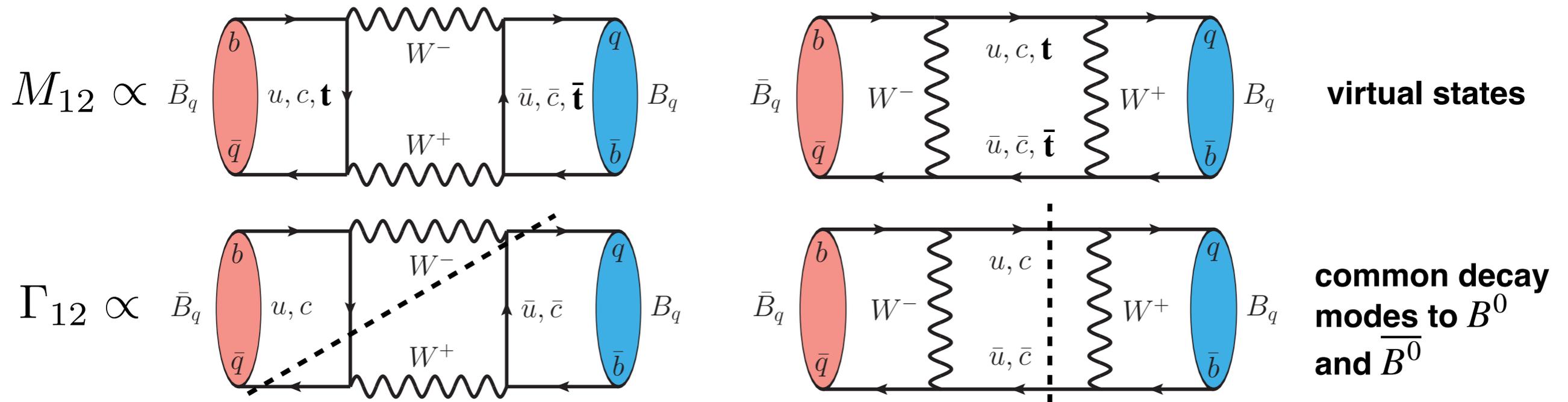
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In the presence of heavy new physics consider only modifications to M_{12}^q and assume $\Gamma_{12}^q = \Gamma_{12}^q|_{\text{SM}}$ and check how large can $A_{\text{SL}}^q = \text{Im}(\Gamma_{12}^q/M_{12}^q)$ be.

$$M_{12}^q = M_{12}^{q,\text{SM}} |\Delta_q| e^{i\phi_q^\Delta}$$

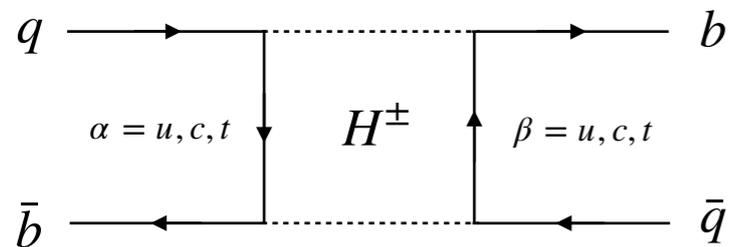
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- **Apply for an array of BSM models:** *Slide courtesy of Carlos Miró*

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Two-Higgs-doublet models

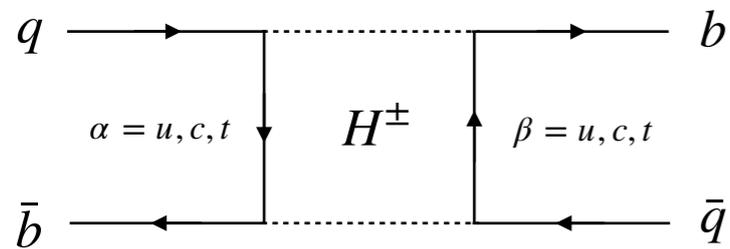


e.g. S. Iguro & Y. Omura, 1802.01732

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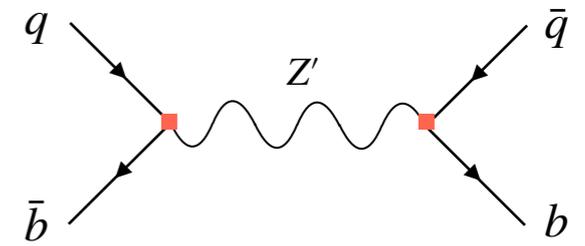
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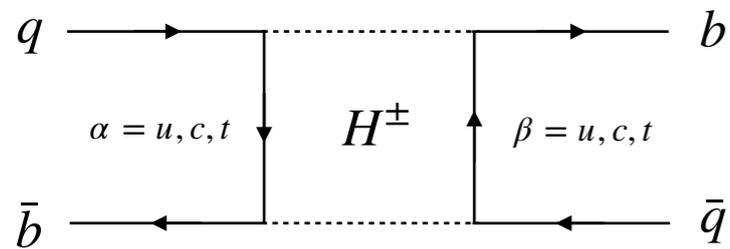


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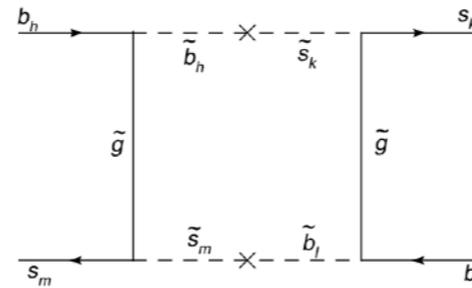
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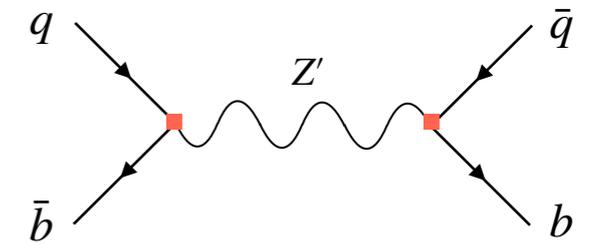
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Supersymmetric models



e.g. R-M. Wang et al., 1102.2031

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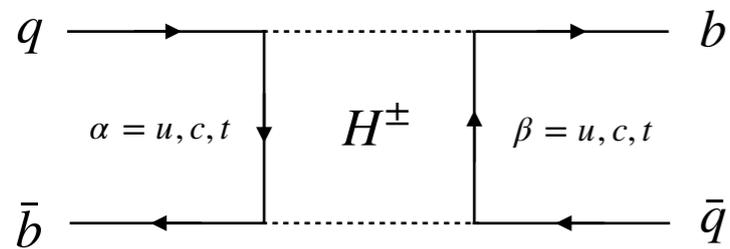


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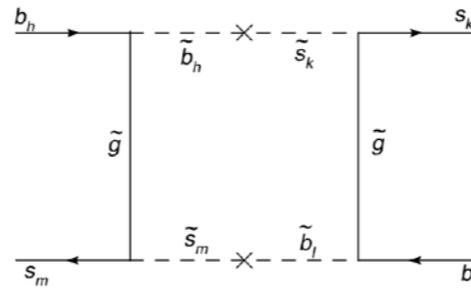
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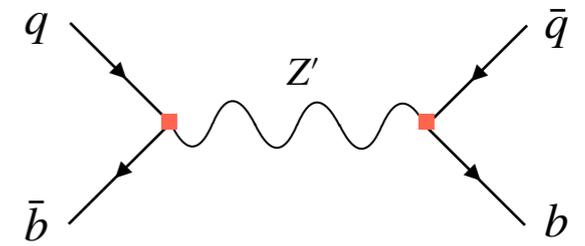
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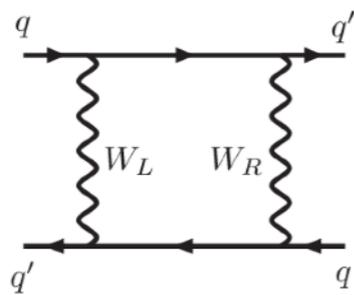
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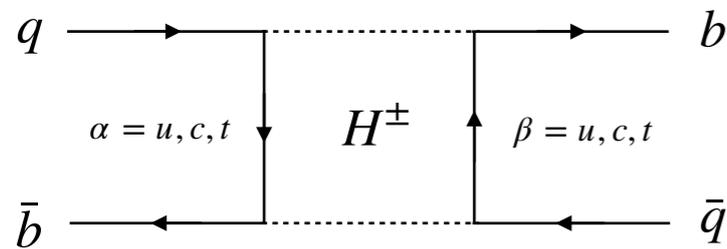


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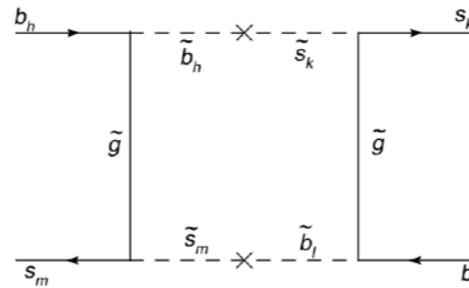
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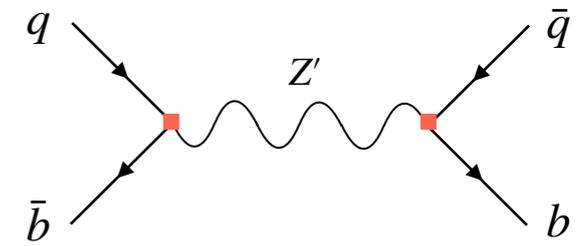
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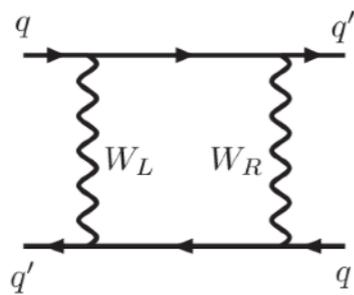
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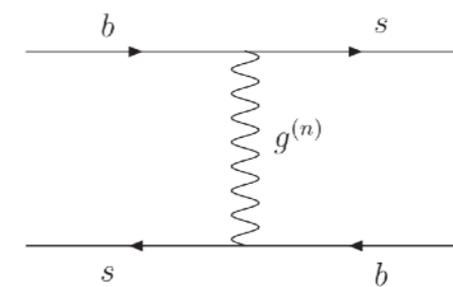
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Extra dimensions



e.g. A. Datta et al., 1011.5979

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- **Main observables/inputs:**
 - **Tree-level CKM elements:** $|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cb}|, |V_{tb}|, \gamma$ [PDG 24']
 - **B-Meson mass differences** $|\Delta M_d|, |\Delta M_s|$ [PDG 24']
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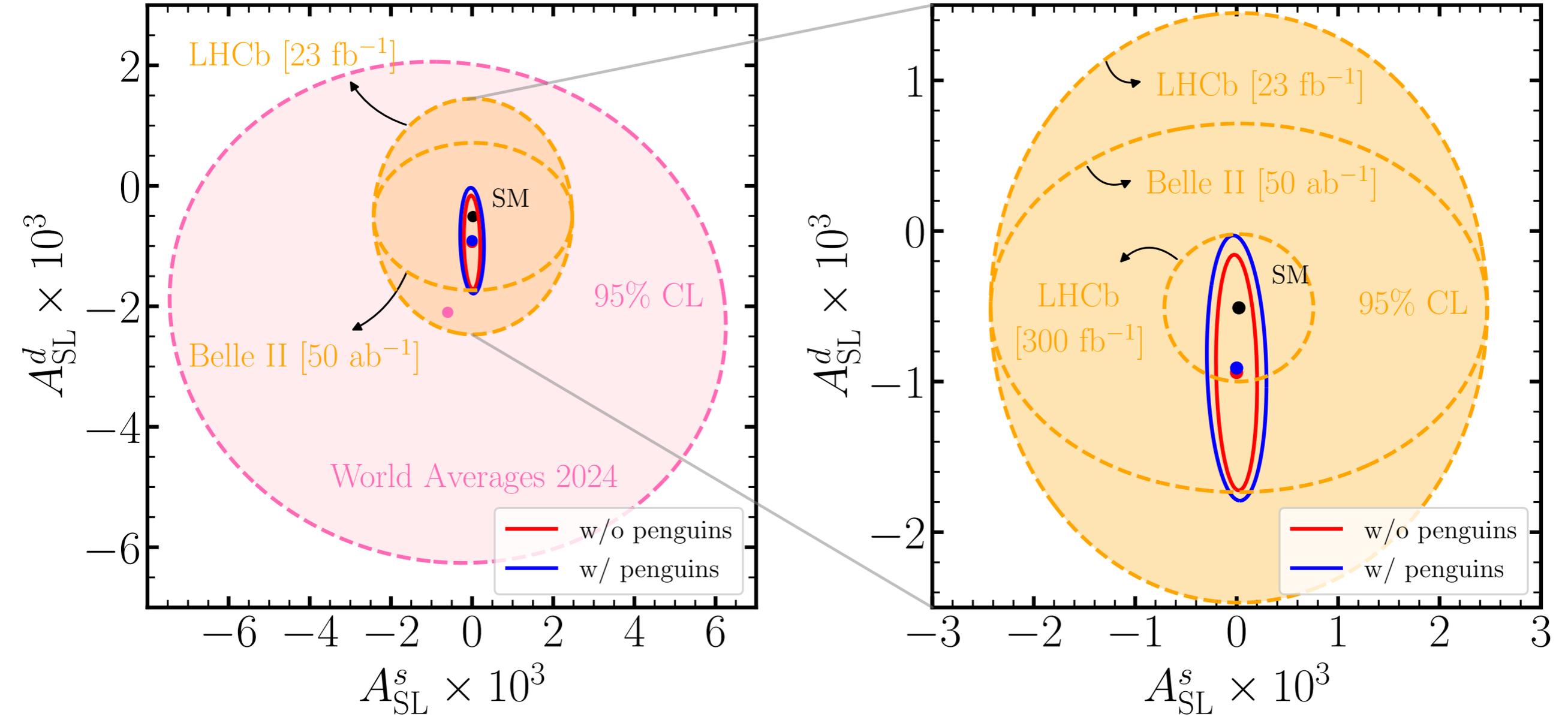
Modifications to Mass Mixing

- **Global Fit to the CKM matrix and the amplitude and phase of M_{12}^d and M_{12}^s fixing $\Gamma_{12}^q = \Gamma_{12}^q |_{\text{SM}}$**
- **Main observables/inputs:**
 - **Tree-level CKM elements:** $|V_{ud}|, |V_{us}|, |V_{ub}|, |V_{cb}|, |V_{tb}|, \gamma$ [PDG 24']
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- **Parameters:** $\{ |\Delta_d|, |\Delta_s|, \phi_d^\Delta, \phi_s^\Delta, f_{B_d}^2 B_{B_d}, f_{B_s}^2 B_{B_s}, \theta_{12}, \theta_{13}, \theta_{23}, \delta \}$

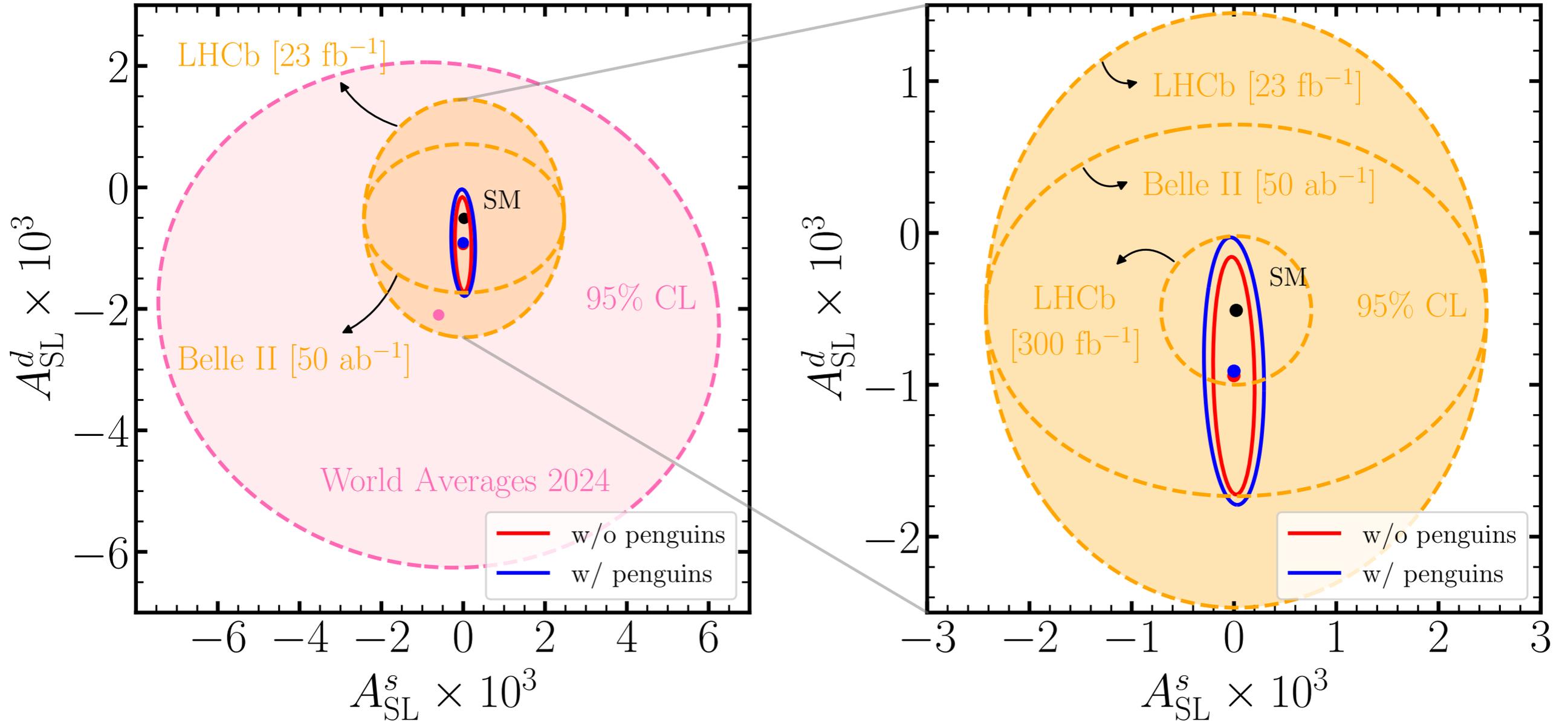
$$M_{12}^d = M_{12}^{d,\text{SM}} |\Delta_d| e^{i\phi_d^\Delta} \quad M_{12}^s = M_{12}^{s,\text{SM}} |\Delta_s| e^{i\phi_s^\Delta}$$

Obtain allowed ranges for A_{SL}^d and A_{SL}^s

Modifications to Mass Mixing

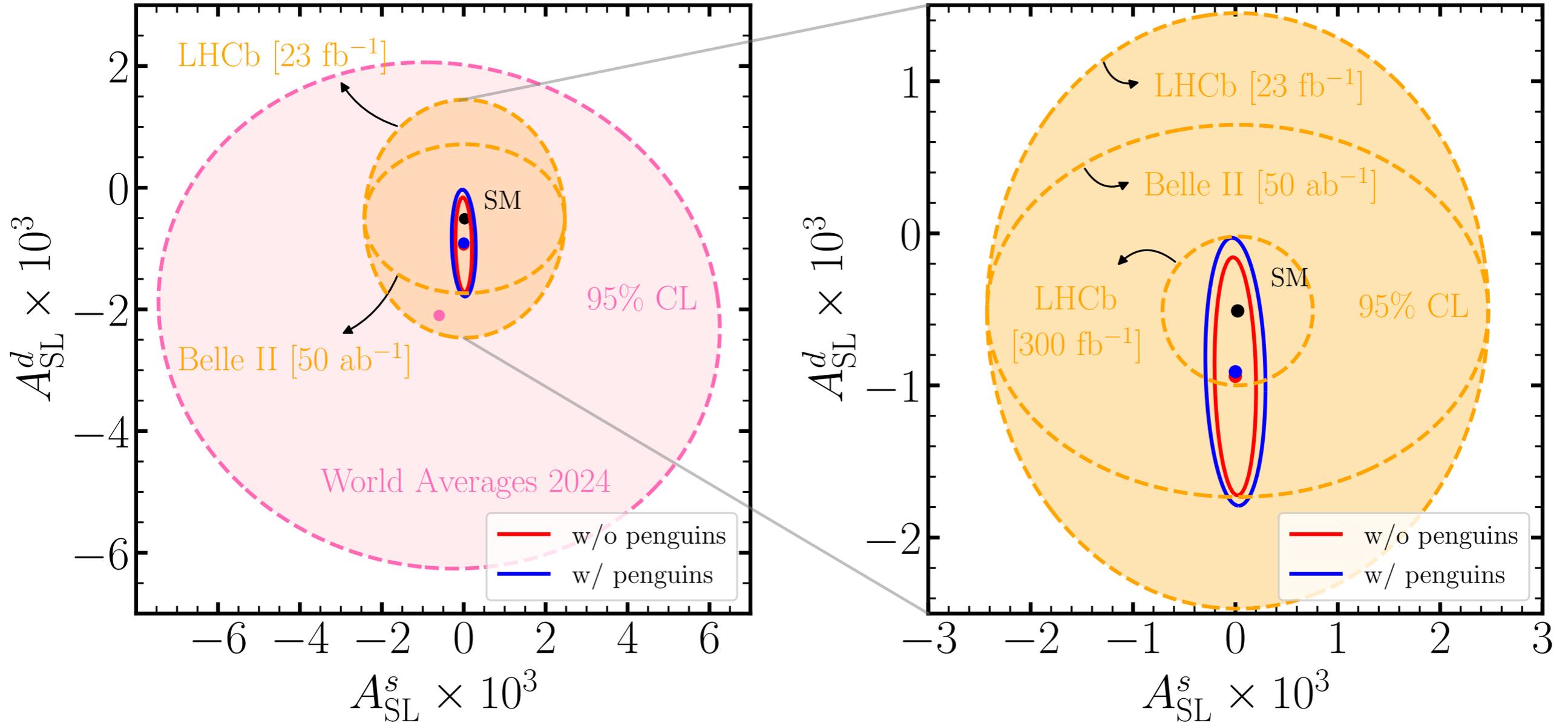


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- Ranges for A_{SL}^d and A_{SL}^s arise primarily from the freedom from the CKM parameters and from time dependent CP violation measurements (and their potential penguin pollution specially relevant for A_{SL}^s)

Allowing for CKM non-Unitarity

- One of the main reasons $A_{SL}^q |_{SM}$ are small is the unitarity of the CKM matrix. What happens if we relax this assumption?

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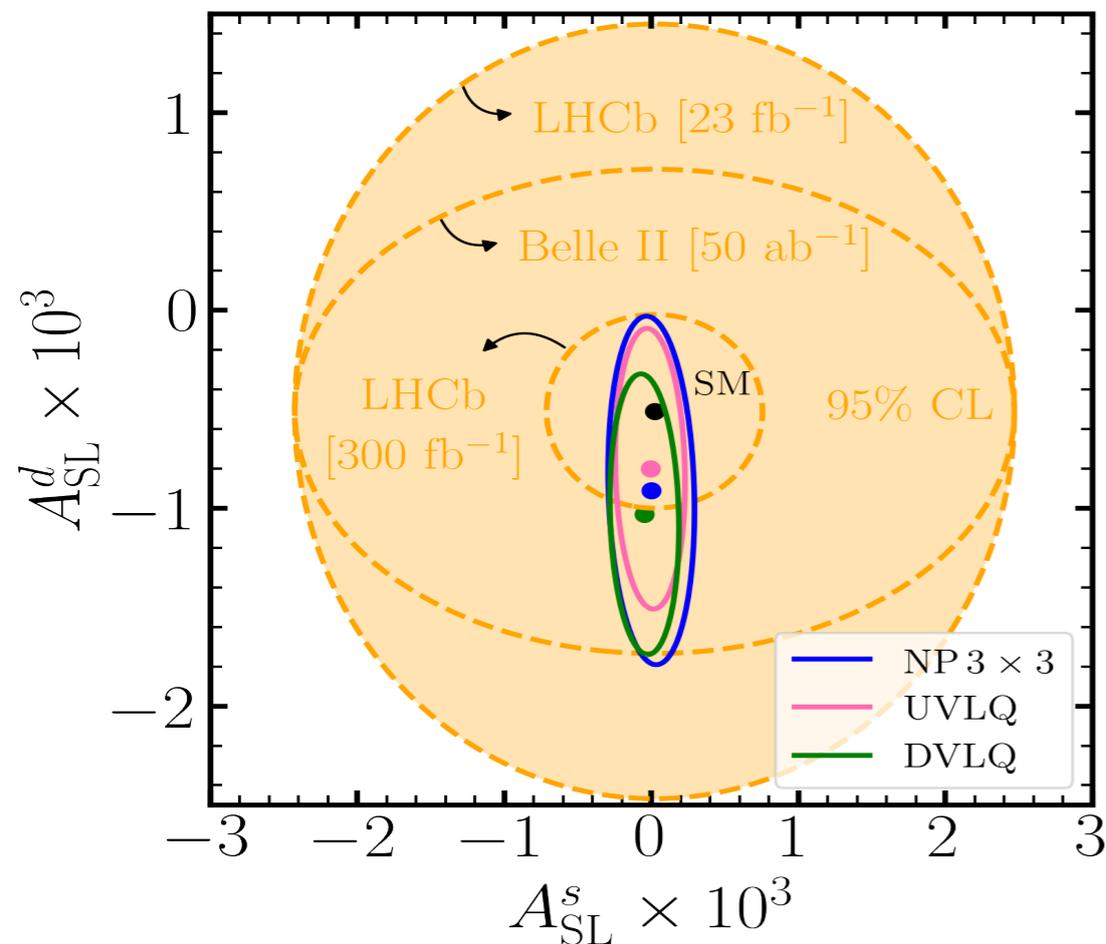
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Result:

Not enough freedom is allowed and the results are similar to the general case of new physics in M_{12}^q

Modifying decay mixing Γ_{12}^q

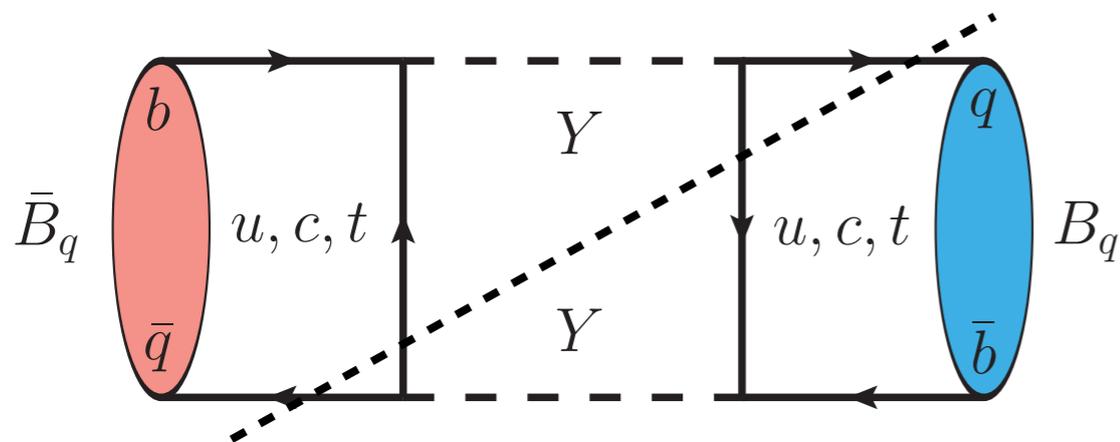
- **There is no generic way to modify Γ_{12}^q . Two approaches:**
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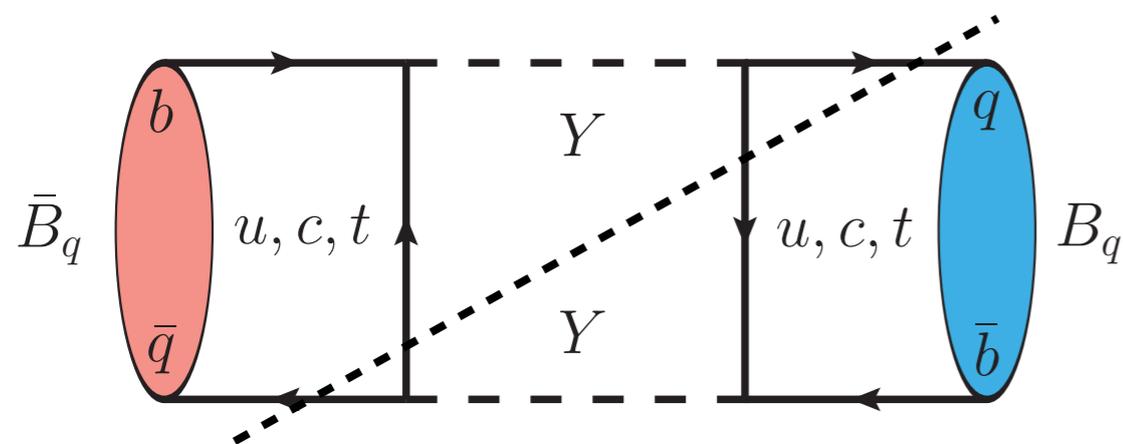
$$\mathcal{L} = - \sum_k y_{\psi d_k} Y d_{kR}^c \bar{\psi} - \sum_{i,j} y_{u_i d_j} Y^* \bar{u}_{iR} d_{jR}^c + \text{h.c.}$$

$Y \sim (3,1)_{-1/3}$ scalar boson

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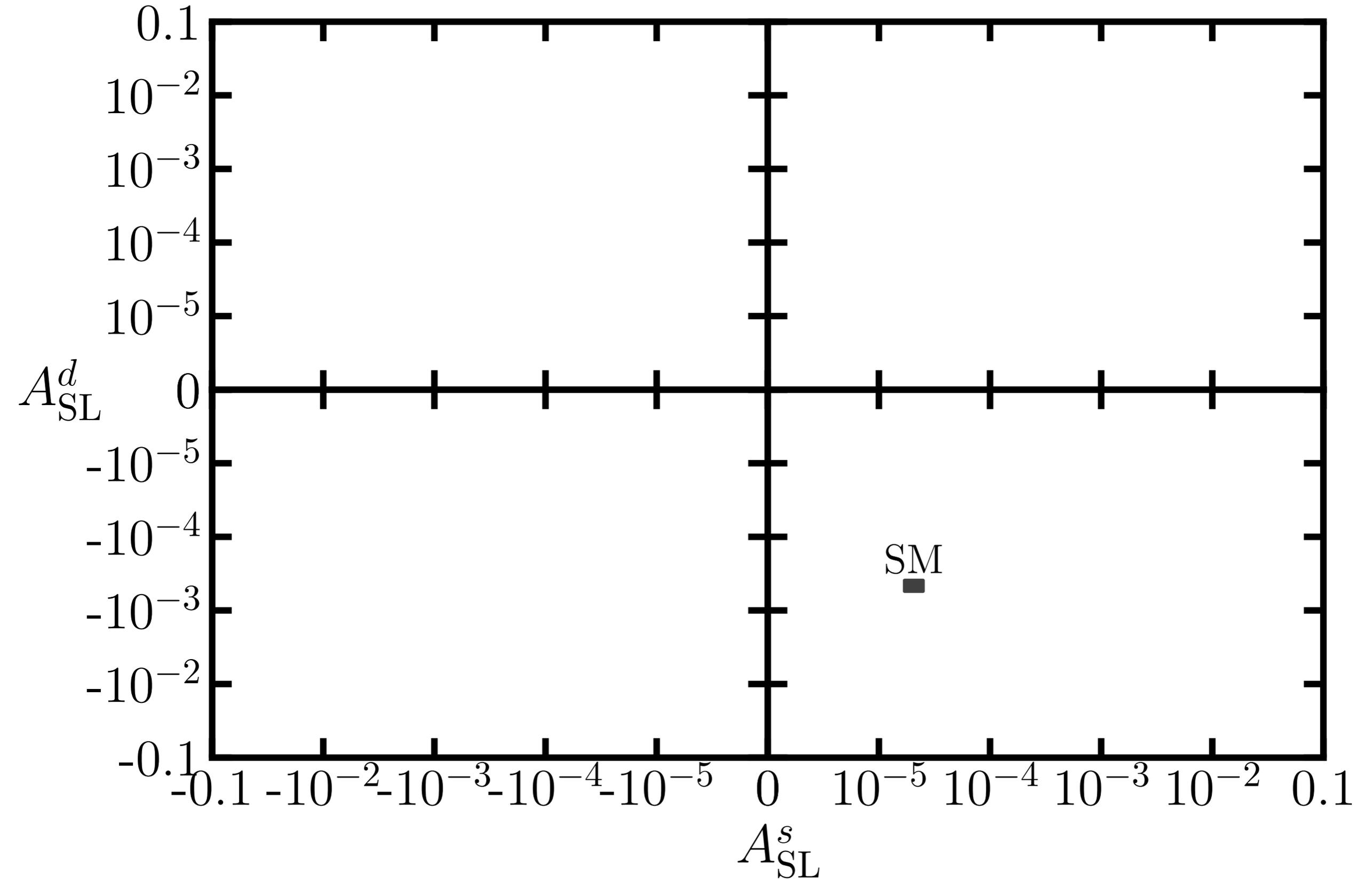
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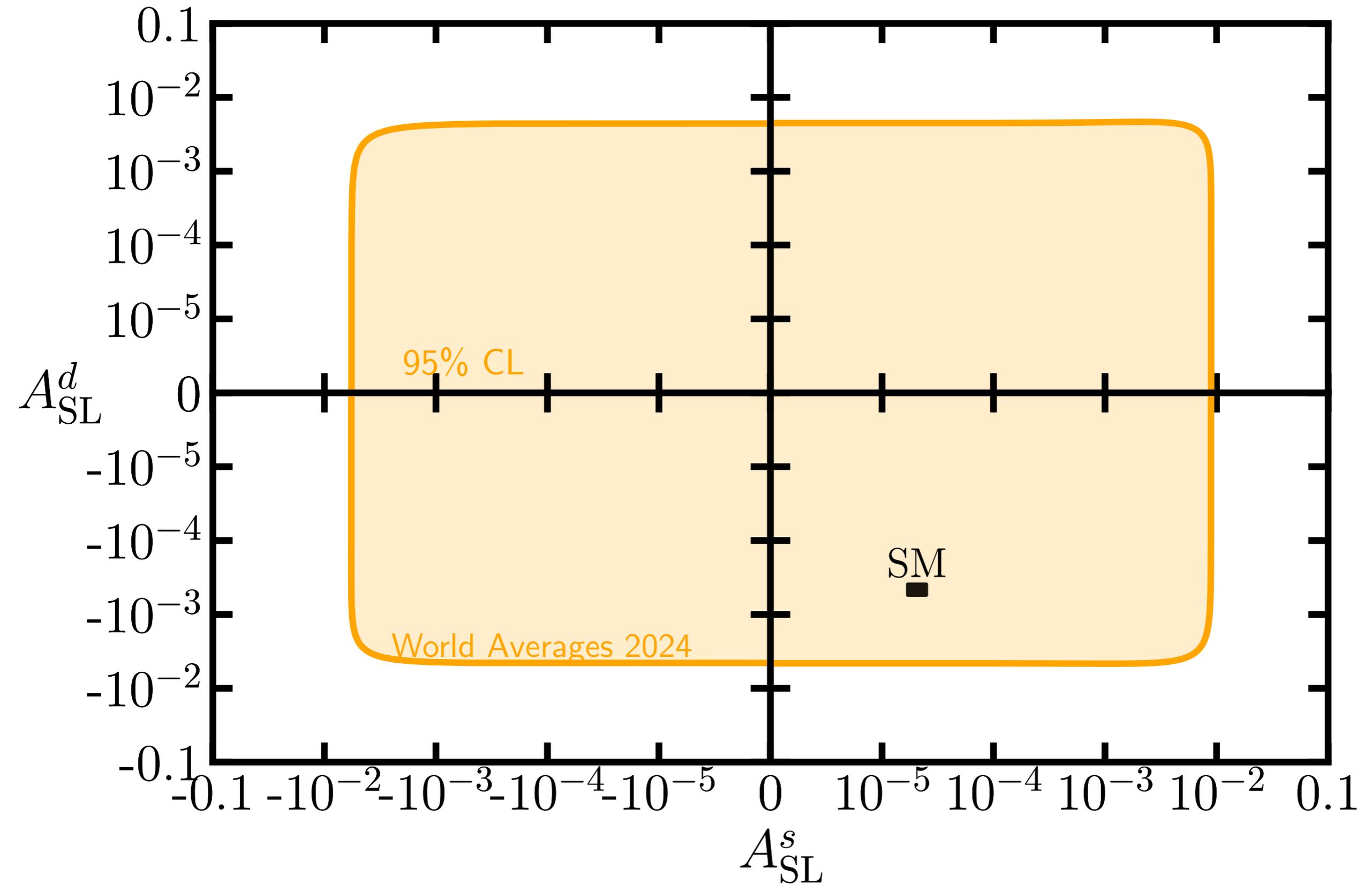
- Found that it cannot substantially modify Γ_{12}^q because the mass of Y should be at least 500 GeV.
- Also, the contributions to M_{12}^q from the top quark should be somehow suppressed.

(These features seem to be generic)

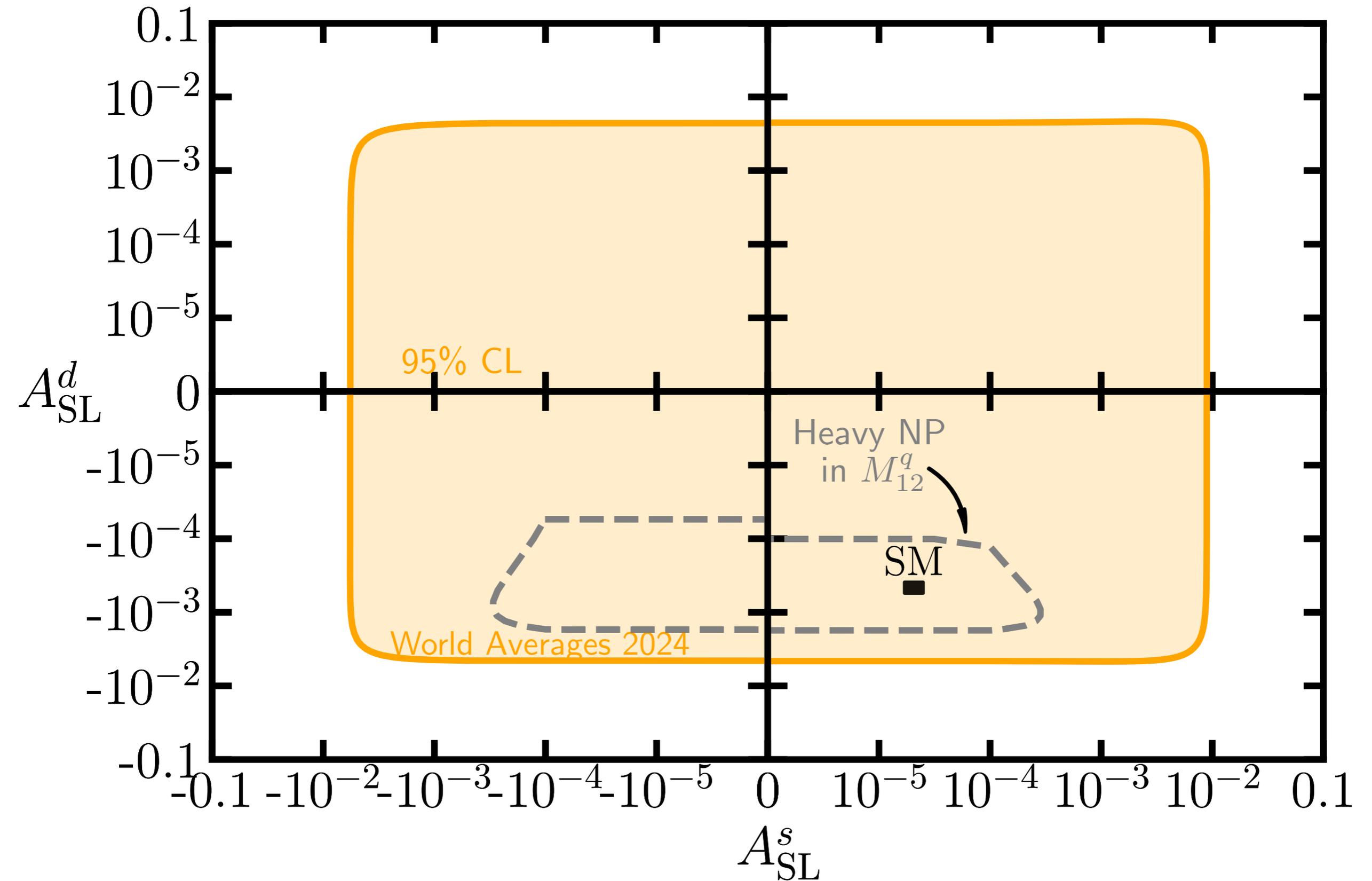
Global Picture: Implications



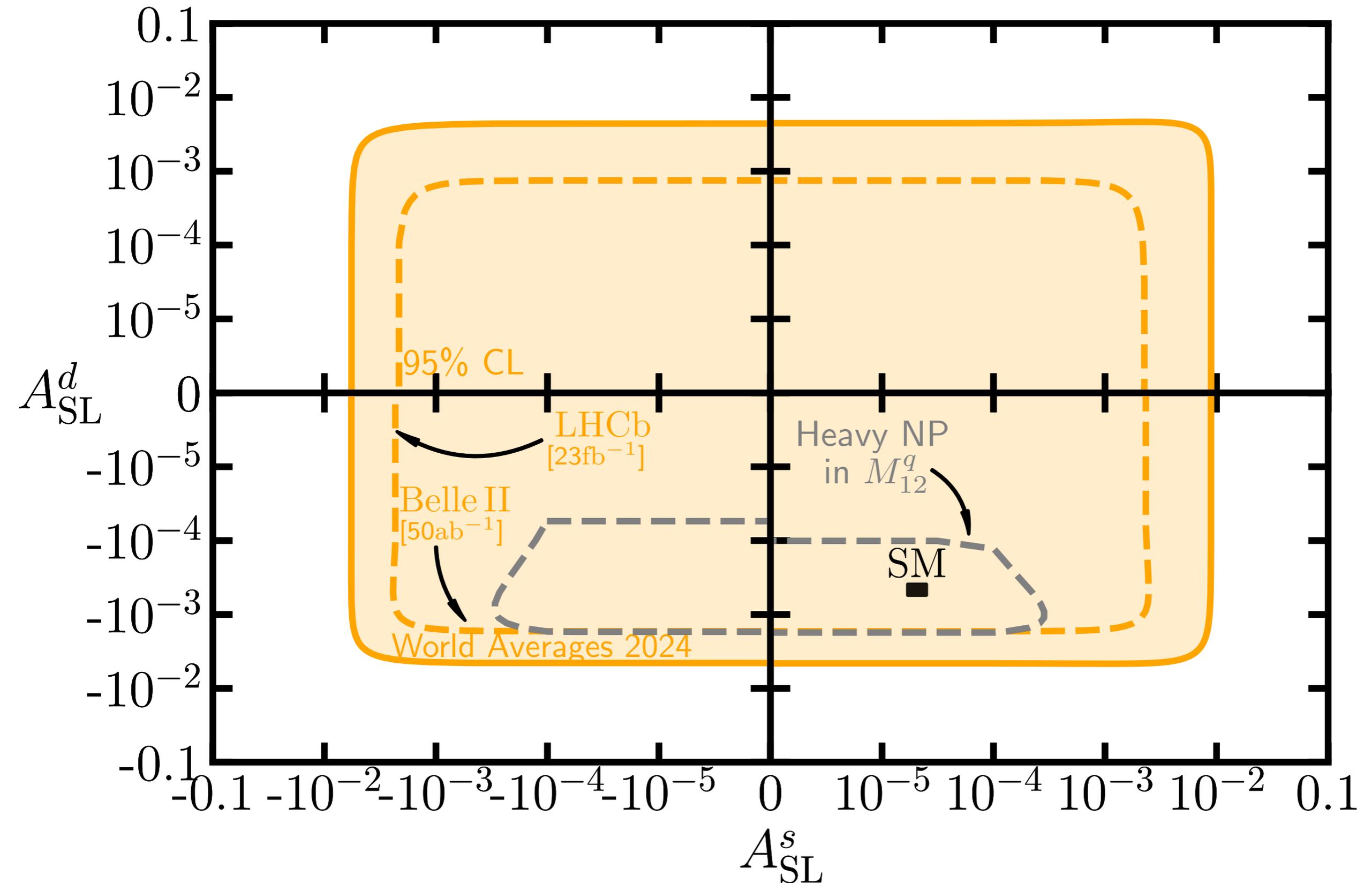
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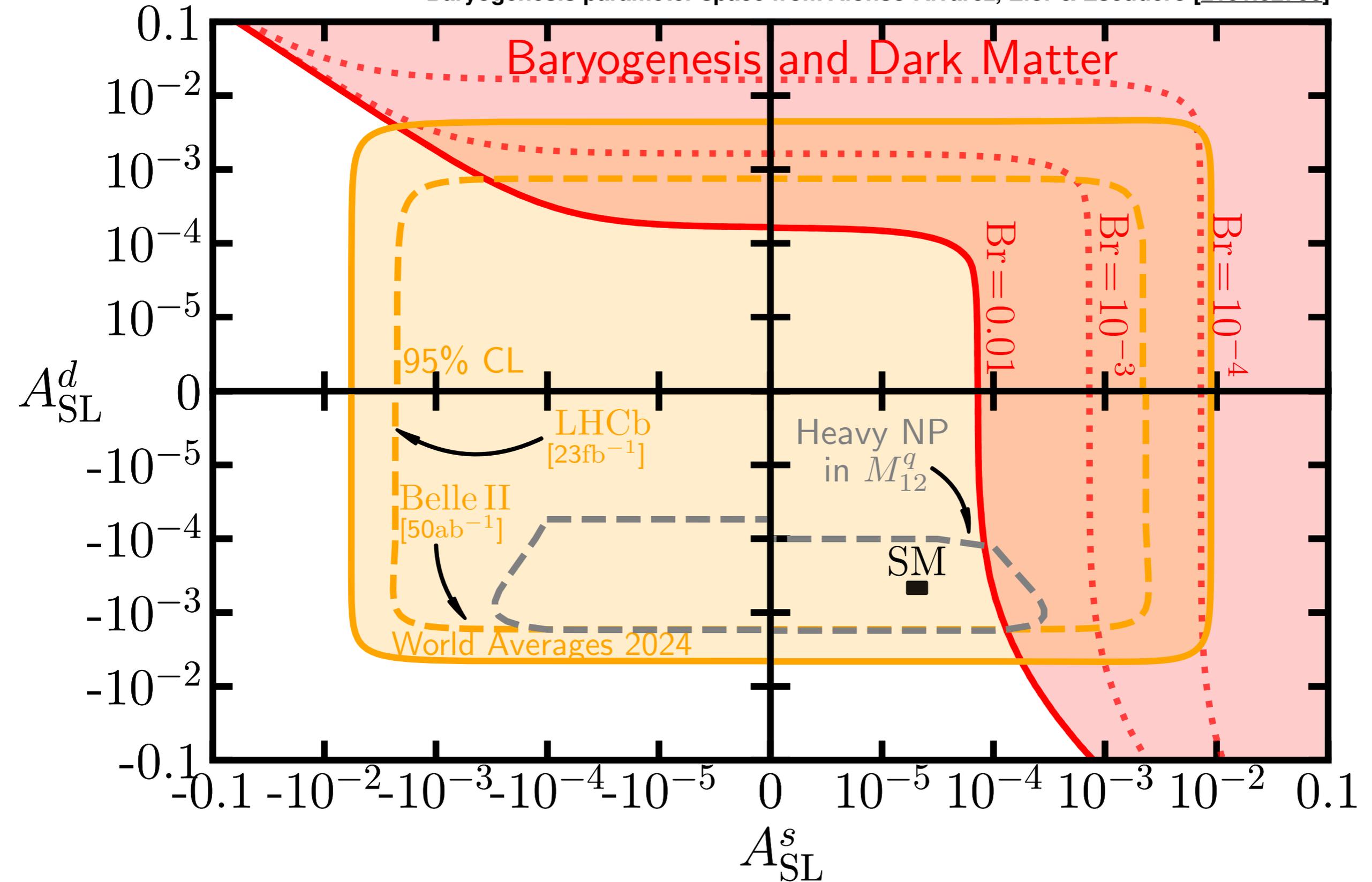


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Baryogenesis parameter space from Alonso-Álvarez, Elor & Escudero [2101.02706]



Conclusions

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Implications:

- 1) These numbers are below current projected sensitivity for LHC and Belle-II (but maybe HL-LHC or FCCee could get them)
- 2) The small asymmetries found put in tension the B-Mesogenesis mechanism

Outlook

Experiment:

No measurements of the semileptonic asymmetries since 2014. Totally worth doing them. Null test of the SM and/or a signal of non-trivial BSM physics.

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Theory:

Can one build a model that features large asymmetries?

Penguins: they are comparable to current error bars, how can this error be reduced?

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Great thanks to my outstanding collaborators on this project:

Carlos Miró



Valencia → Turin

Miguel Nebot



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Thank You!