Two recent exotic results from Fermilab

& New light particles

(HyperCP events & D0 anomaly)

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Outline

- The HyperCP events
  - Experiments: HyperCP (Fermilab) , KTeV (Fermilab) , Belle (KEK) data
  - Theoretical interpretations: a new light particle
  - Implications to B decay processes

- The D0 anomalous like-sign dimuon charge asymmetry
  - Experimental data from D0 (Fermilab)
  - Theory: a model-independent approach with a light spin-1 particle

The HyperCP events

Introduction

- The detection of a new particle having a sub-GeV mass would likely hint at the presence of physics beyond the SM.

- This possibility has been raised recently by the observation of three events for the rare decay mode $\Sigma^+ \rightarrow p\, \mu^+ \mu^-$ with dimuon invariant masses narrowly clustered around 214.3 MeV by the HyperCP Collaboration a few years ago.

HyperCP data (Fermilab) (1/4)

PRL **94,** 021801 (2005) PHYSICAL REVIEW LETTERS week ending 21 JANUARY 2005

Evidence for the Decay $\Sigma^+ \rightarrow p\mu^+\mu^-$

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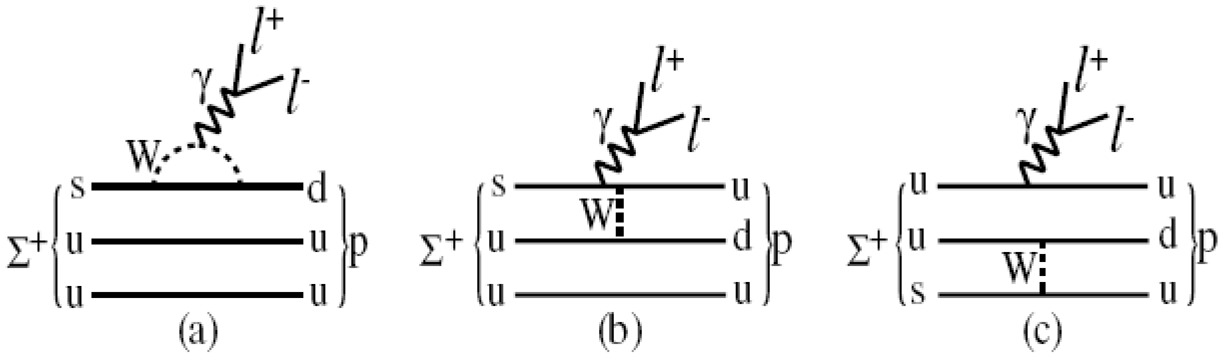
HyperCP data (Fermilab) (2/4)

$$\Sigma^+ \to p\mu^+\mu^-$$



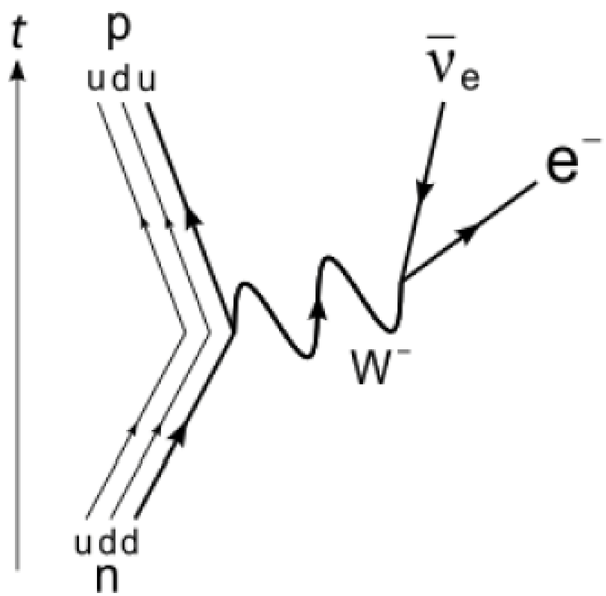
FCNC

internal conversion

SM

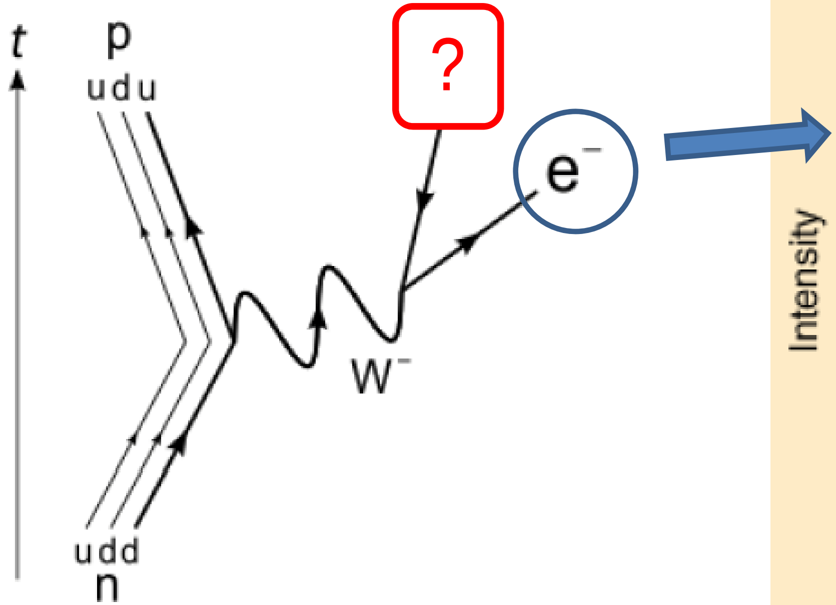
Digression: History of β decay (1/3)

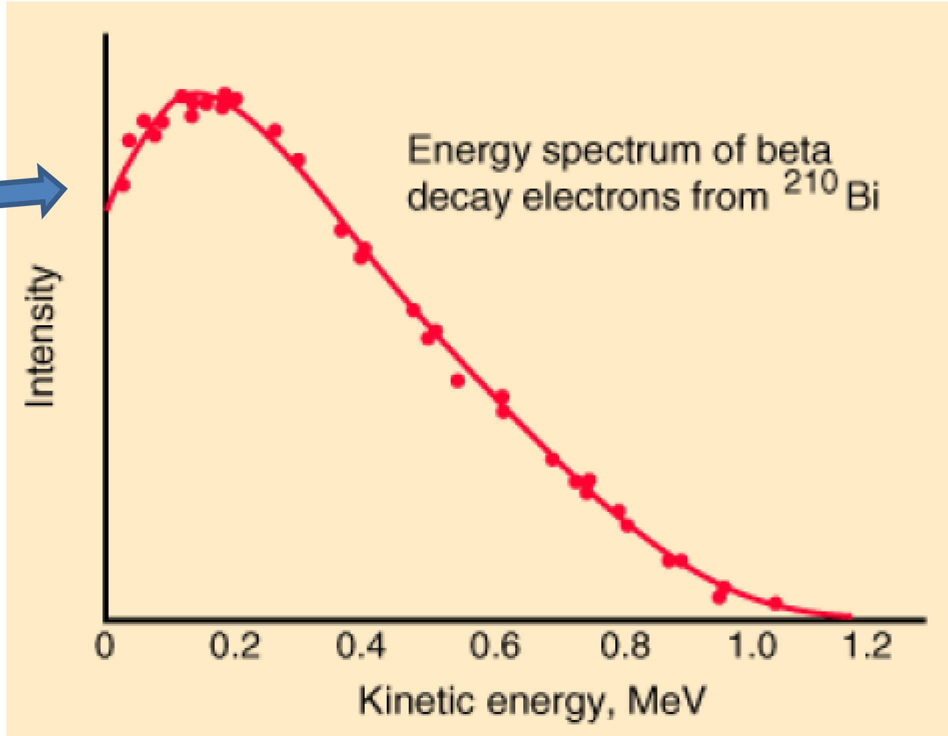
$n \rightarrow p\ e^-\ \bar{\nu}_e$



Digression: History of β decay (2/3)

$n \rightarrow p\ e^-$? ➔ 2 body decay ?

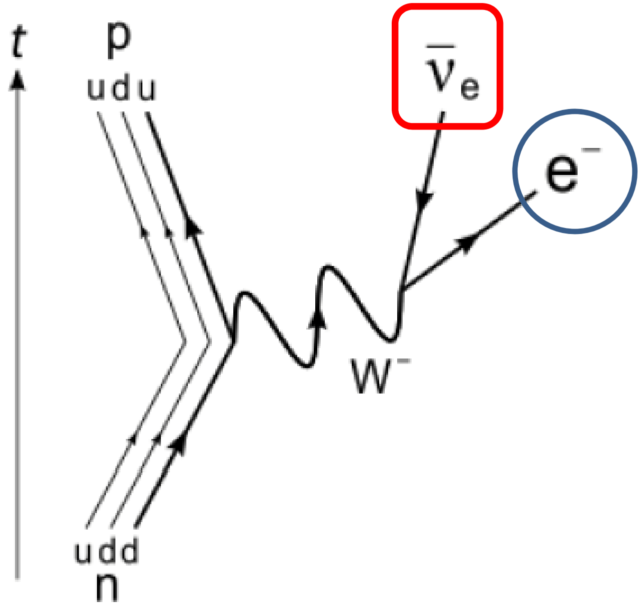


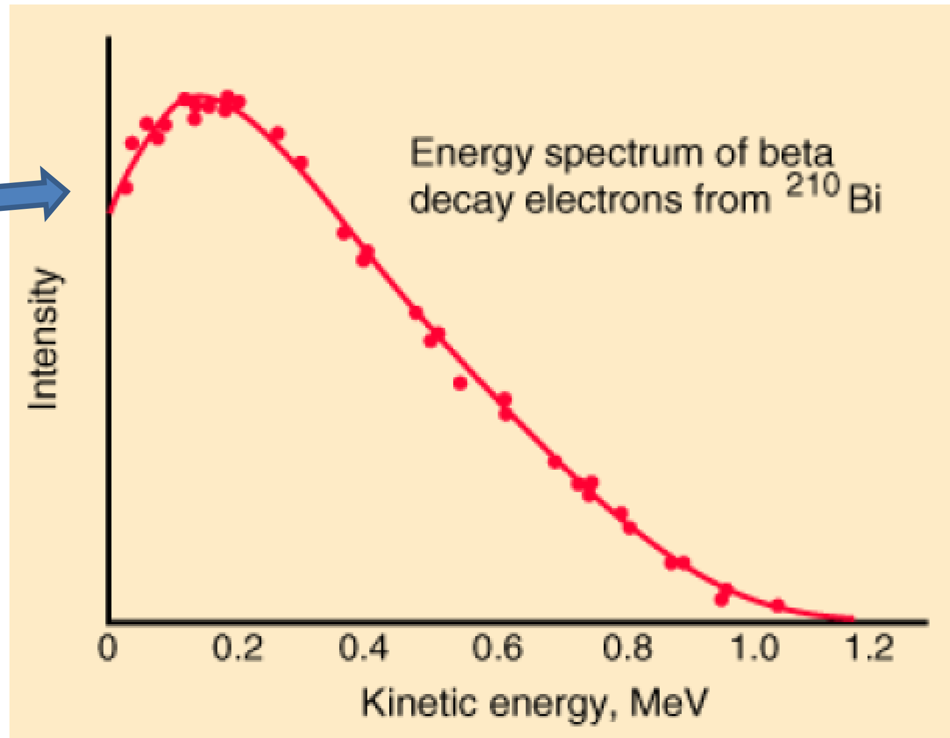


Continuous energy spectrum

Digression: History of β decay (3/3)

$n \rightarrow p\ e^-\ \bar{\nu}_e$ ➔ 3 body decay !





Continuous energy spectrum

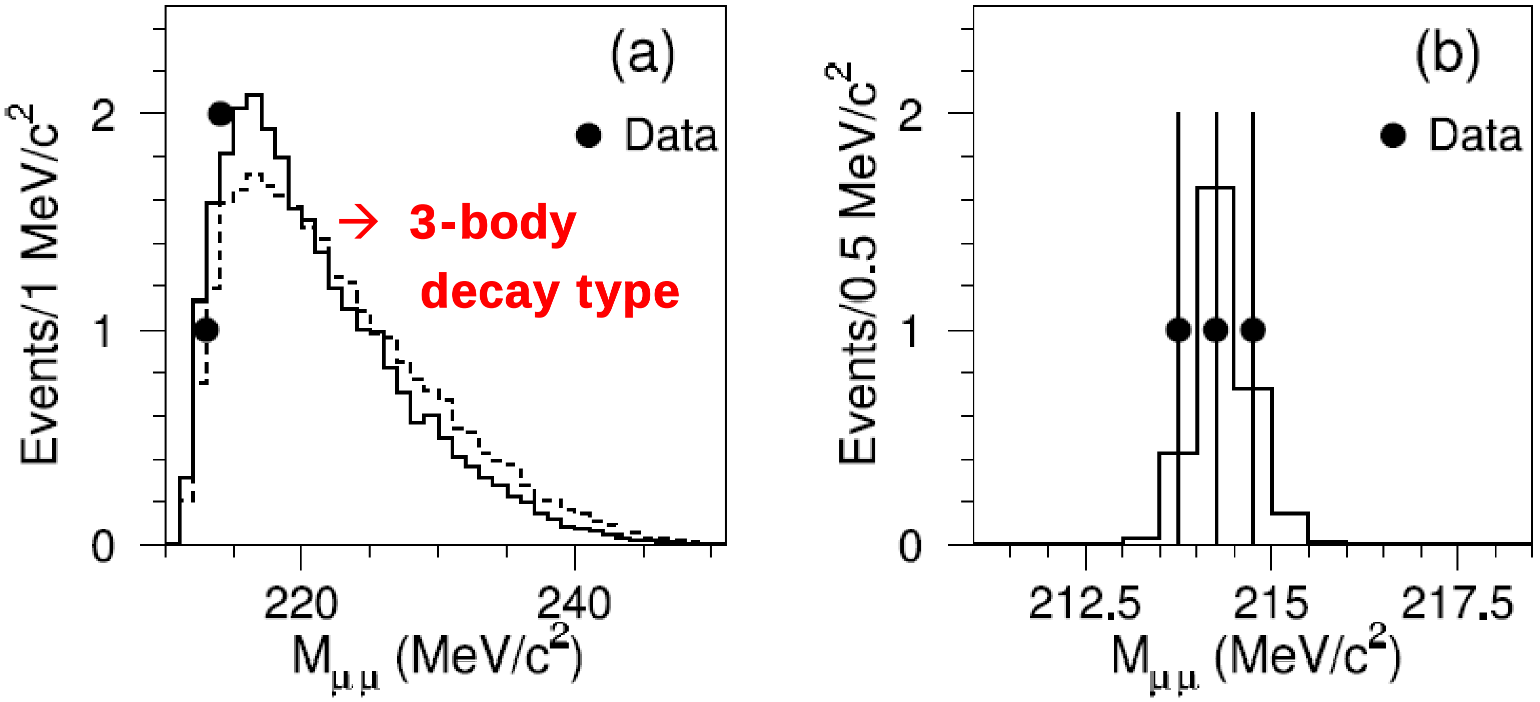
➔ 3 body decay

What if an opposite situation happens?

(i.e., 3 body decay ?? → No, 2 body decay !!)

HyperCP data (Fermilab) (3/4)

$$\Sigma^+ \rightarrow p\mu^+\mu^-$$



→ 3-body decay type

213.7, 214.3, 214.7 MeV/c²

→ within 1 MeV/c² !!

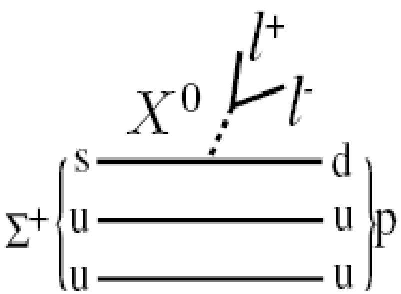
FIG. 4. Real (points) and MC (histogram) dimuon mass distributions for (a) $\Sigma^+_{p\mu\mu}$ MC events (arbitrary normalization) with a form-factor decay (solid histogram) and uniform phase-space decay (dashed histogram) model, and (b) $\Sigma^+_{pP\mu\mu}$ MC events normalized to match the data.

HyperCP data (Fermilab) (4/4)

- The dimuon mass distribution for $\Sigma^+ \rightarrow p\,\mu^+\mu^-$ decay is expected to be broad (← 3-body decays).

- Assuming a "3-body decay," the probability that the three events have the same dimuon mass (within 1 MeV/c^2) is less than 1% !!

  ➔ The unexpectedly narrow dimuon mass distribution may suggest a two-body decay:



$$\Sigma^+ \to pX^0, \;\; X^0 \to \mu^+\mu^-$$

with a X^0 mass of 214.3 ± 0.5 MeV/c^2

Possible new particle (X^0) interpretations (1/2)

- In the spinless case, X^0 could be
  - Sgoldstino in SUSY models

    D.S. Gorbunov and V.A. Rubakov (2006)
  - CP-odd Higgs boson in the next-to-minimal SUSY SM (NMSSM)

    X.G. He, J. Tandean and G. Valencia (2007)

- In the spin-1 case, one possible candidate for X^0 is
  - Gauge (U) boson of an extra U(1) gauge group in some extensions of the SM

    C.H. Chen, C.Q. Geng, and C.W. Kao (2008);

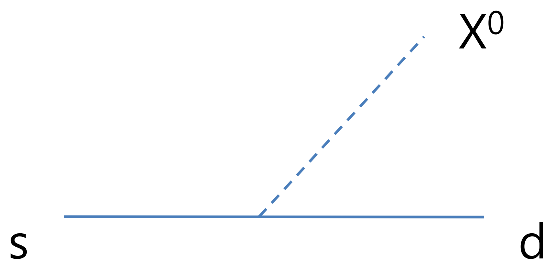
    M. Pospelov (2008); M. Reece and L.T. Wang (2009)

Possible new particle (X^0) interpretations (2/2)

- The presence of X^0 in $\Sigma^+ \rightarrow p\,\mu^+\,\mu^-$ implies that it also contributes to other $|\Delta S| = 1$ transitions: e.g., $K \rightarrow \pi\,\mu^+\,\mu^-$.

$$\mathcal{L}_{qq'X} = i\bar{q}'(g_S + g_P\gamma_5)q\,X + \mathrm{H.c.}$$

(Spin 0 case)



- The "scalar part" of the s-d-X coupling is already constrained by $K \rightarrow \pi\,\mu\,\mu$ data to be negligibly small.

The "pseudoscalar part" of the s-d-X coupling can be probed by $K \rightarrow \pi\,\pi\,\mu\,\mu$ measurements.

➔ KTeV experiment

KTeV data (Fermilab)

$Br(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 9.44 \times 10^{-11}$

arXiv:0911.4516

$$\mathcal{B}(K_L \to \pi^0\pi^0 X_P \to \pi^0\pi^0\mu^+\mu^-) = (8.3^{+7.5}_{-6.6}) \times 10^{-9}$$
$$\mathcal{B}(K_L \to \pi^0\pi^0 X_A \to \pi^0\pi^0\mu^+\mu^-) = (1.0^{+0.9}_{-0.8}) \times 10^{-10}$$

He, Tandean, Valencia

- The scenario in which X has spin 0 and its s-d-X pseudoscalar coupling is “real” is disfavored.

➔ But, the case where the s-d-X psedoscalar coupling is almost “purely imaginary” is still allowed.

- The scenario in which X has spin 1 is not yet strongly challenged by the KTeV data.

Belle data (KEK)

$$\mathcal{B}(B^0 \to K^{*0}X^0,\ K^{*0} \to K^+\pi^-,\ X^0 \to \mu^+\mu^-) < 2.01 \times 10^{-8}$$

$$\mathcal{B}(B^0 \to \rho^0 X^0,\ \rho^0 \to \pi^+\pi^-,\ X^0 \to \mu^+\mu^-) < 1.51 \times 10^{-8}$$

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- This results rule out some of “sgoldstino” scenario.

➔ The Belle result also restricts the spinless X^0 scenario.

Focus on B decays

- Various B meson decay processes can be used to search
  for the hypothetical new particle X^0.

➔ B decays become important to probe the X^0 .

- Consider the contributions of X with “spin 1.” C.H. Chen & C.Q. Geng (2007)
- Adopt a model-independent approach.
- Our assumptions are
  - Assume that X has both “vector” and “axial-vector” couplings to b-d & b-s.
  - X does not interact strongly and decays inside the detector with $\mathcal{B}(X \to \mu^+\mu^-) = 1.$

Effective Lagrangian with a Light X^0

- Assuming that X has spin 1 & does not carry electric or color charge, the Lagrangian describing the effective b-q-X couplings (q = d, s) is

$$\begin{aligned} \mathcal{L}_{bqX} &= -\bar{q}\gamma_\mu\left(g_{Vq} - g_{Aq}\gamma_5\right)b\,X^\mu + \text{H.c.} \\ &= -\bar{q}\gamma_\mu\left(g_{\text{L}q}P_\text{L} + g_{\text{R}q}P_\text{R}\right)b\,X^\mu + \text{H.c.} \end{aligned}$$

$$g_{\text{L}q,\text{R}q} = g_{Vq} \pm g_{Aq}, \qquad P_{\text{L,R}} = \tfrac{1}{2}(1 \mp \gamma_5).$$

Generally, the constants $g_{Vq,Aq}$ can be complex.

B^0 - bar B^0 mixing (1/3)

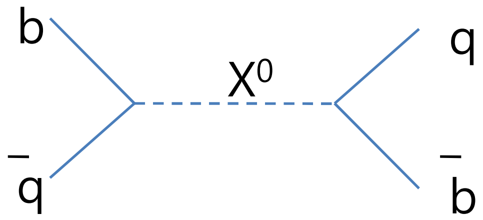
- It is characterized by the physical mass difference ΔM_q (q = d, s) between the heavy and light mass-eigenstates in the B_q^0-$\bar{B}_q^0$ system.

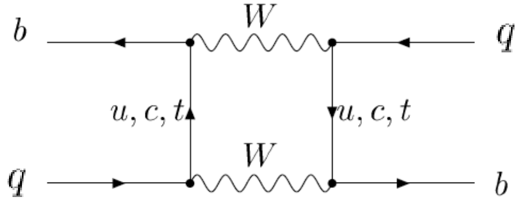
$$\Delta M_q = 2\,|M_{12}^q|, \qquad \text{where } M_{12}^q = M_{12}^{q,\mathrm{SM}} + M_{12}^{q,X}$$

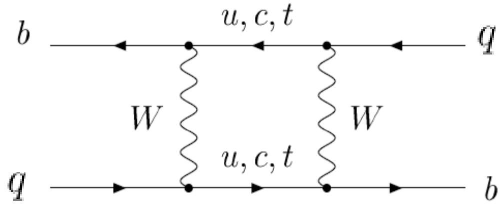
$$2m_{B_q} M_{12}^q = \langle B_q^0 | \mathcal{H}_{b\bar{q}\to\bar{b}q} | \bar{B}_q^0 \rangle$$

$$\Delta M_q^{\mathrm{exp}} = \Delta M_q^{\mathrm{SM}} \left|1 + \delta_q\right| , \qquad \delta_q = \frac{M_{12}^{q,X}}{M_{12}^{q,\mathrm{SM}}}$$

$$\delta_q = \frac{M_{12}^{q,X}}{M_{12}^{q,\mathrm{SM}}} =$$







B^0 - bar B^0 mixing (2/3)

$$\mathrm{Re}\,\delta_d = \Big\{-4.4\left[(\mathrm{Re}\,g_{Vd})^2 - (\mathrm{Im}\,g_{Vd})^2\right] - 8.2\,(\mathrm{Re}\,g_{Vd})(\mathrm{Im}\,g_{Vd}) + 17\left[(\mathrm{Re}\,g_{Ad})^2 - (\mathrm{Im}\,g_{Ad})^2\right] + 33\,(\mathrm{Re}\,g_{Ad})(\mathrm{Im}\,g_{Ad})\Big\} \times 10^{12}$$

$$\mathrm{Re}\,\delta_s = \Big\{-2.5\left[(\mathrm{Re}\,g_{Vs})^2 - (\mathrm{Im}\,g_{Vs})^2\right] + 0.2\,(\mathrm{Re}\,g_{Vs})(\mathrm{Im}\,g_{Vs}) + 9.9\left[(\mathrm{Re}\,g_{As})^2 - (\mathrm{Im}\,g_{As})^2\right] - 0.7\,(\mathrm{Re}\,g_{As})(\mathrm{Im}\,g_{As})\Big\} \times 10^{11}$$

(1) q = d

$$\Delta M_d^{\mathrm{exp}} = (0.507 \pm 0.005)\,\mathrm{ps}^{-1} \qquad \Delta M_d^{\mathrm{SM}} = \left(0.563^{+0.068}_{-0.076}\right)\mathrm{ps}^{-1}$$

using the approximation $|1+\delta_d| \simeq 1 + \mathrm{Re}\,\delta_d$,

$$\Rightarrow \quad -0.22 \le \mathrm{Re}\,\delta_d \le +0.02$$

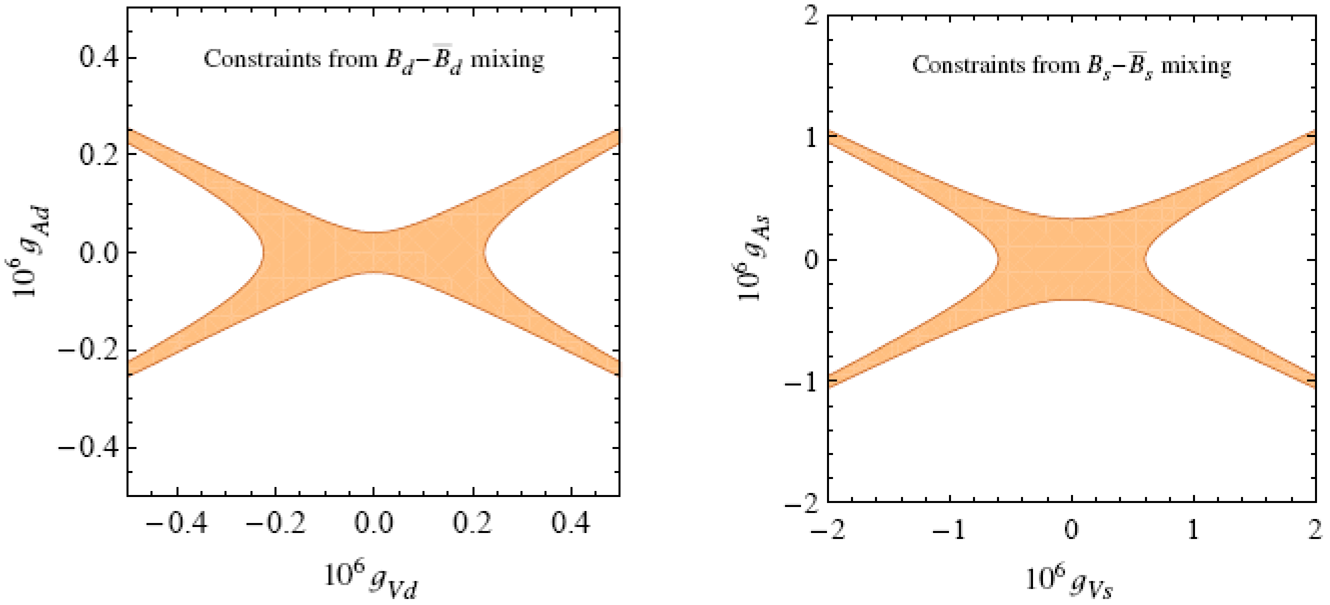
(2) q = s

$$\Delta M_s^{\mathrm{exp}} = (17.77 \pm 0.12)\,\mathrm{ps}^{-1} \qquad \Delta M_s^{\mathrm{SM}} = \left(17.6^{+1.7}_{-1.8}\right)\mathrm{ps}^{-1}$$

$$\Rightarrow \quad -0.09 \le \mathrm{Re}\,\delta_s \le 0.11$$

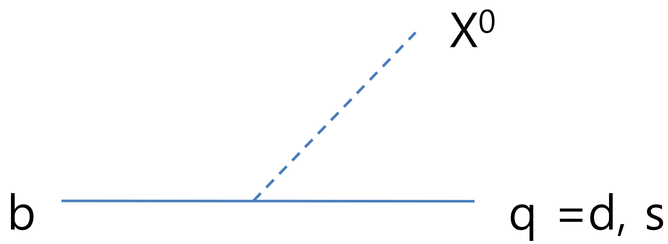
B^0 - bar B^0 mixing (3/3)

$$-0.7\times10^{-14} < (\mathrm{Re}\,g_{Vd})^2-(\mathrm{Im}\,g_{Vd})^2+1.9\,(\mathrm{Re}\,g_{Vd})(\mathrm{Im}\,g_{Vd}) < 5.0\times10^{-14}$$
$$-1.3\times10^{-14} < (\mathrm{Re}\,g_{Ad})^2-(\mathrm{Im}\,g_{Ad})^2+1.9\,(\mathrm{Re}\,g_{Ad})(\mathrm{Im}\,g_{Ad}) < 0.2\times10^{-14}$$
$$-4.4\times10^{-13} < (\mathrm{Re}\,g_{Vs})^2-(\mathrm{Im}\,g_{Vs})^2-0.1\,(\mathrm{Re}\,g_{Vs})(\mathrm{Im}\,g_{Vs}) < 3.6\times10^{-13}$$
$$-0.9\times10^{-13} < (\mathrm{Re}\,g_{As})^2-(\mathrm{Im}\,g_{As})^2-0.1\,(\mathrm{Re}\,g_{As})(\mathrm{Im}\,g_{As}) < 1.1\times10^{-13}$$



if $g_{Vq,Aq}$ are taken to be real.

Inclusive decay b → q X



- Decay rate:

$$\Gamma(b \to qX) = \frac{|\boldsymbol{p}_X|}{8\pi\, m_b^2 m_X^2}\Big\{|g_{Vq}|^2\Big[(m_b+m_q)^2+2m_X^2\Big]\Big[(m_b-m_q)^2-m_X^2\Big] + |g_{Aq}|^2\Big[(m_b-m_q)^2+2m_X^2\Big]\Big[(m_b+m_q)^2-m_X^2\Big]\Big\}$$

- Branching ratio:

$$\mathcal{B}(b \to sX) \simeq \frac{\Gamma(b \to sX)}{\Gamma_{B_d^0}} = 8.55 \times 10^{13}\,(|g_{Vs}|^2 + |g_{As}|^2)$$

$$|g_{Vs}|^2 + |g_{As}|^2 < 8.0 \times 10^{-21}$$

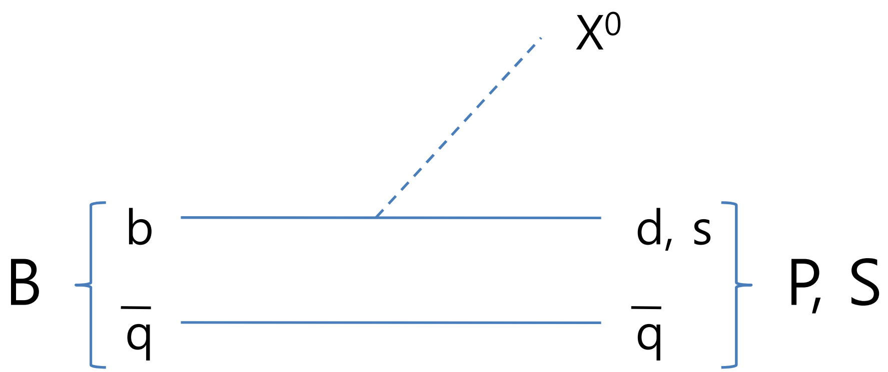
- BaBar data:

$$\mathcal{B}(b \to s\ell^+\ell^-)_{m_{\ell\ell}\in[0.2\,\mathrm{GeV},1.0\,\mathrm{GeV}]} = (0.08 \pm 0.36^{+0.07}_{-0.04}) \times 10^{-6}$$

the average over $\ell = e$ and μ.

$$\mathcal{B}(b \to sX) < 6.8 \times 10^{-7} \quad 90\%\text{-C.L.}$$

B → P X decays (1/2)



- Decay amplitude & rate:

$$\mathcal{M}(\bar{B} \to PX) = \frac{2 g_{Vq}}{\kappa_P} F_1^{BP} \, \varepsilon_X^* \cdot p_P$$

the vector coupling only!

$$\mathcal{M}(\bar{B} \to SX) = \frac{2i g_{Aq}}{\kappa_S} F_1^{BS} \, \varepsilon_X^* \cdot p_S$$

the axial-vector coupling only!

$$\Gamma(B \to P(S)X) = \frac{|\mathbf{p}_X|^3}{2\pi \, \kappa_{P(S)}^2 \, m_X^2} \left| g_{V(A)q} F_1^{BP(S)} \right|^2$$

B → P X decays (2/2)

$$\mathcal{B}(B^+ \to \pi^+ X) = 1.06 \times 10^{13} |g_{Vd}|^2$$
$$\mathcal{B}(B_d \to \pi^0 X) = 4.96 \times 10^{12} |g_{Vd}|^2$$
$$\mathcal{B}(B^+ \to K^+ X) \simeq \mathcal{B}(B_d \to K^0 X) = 1.85 \times 10^{13} |g_{Vs}|^2$$

Exp. data:

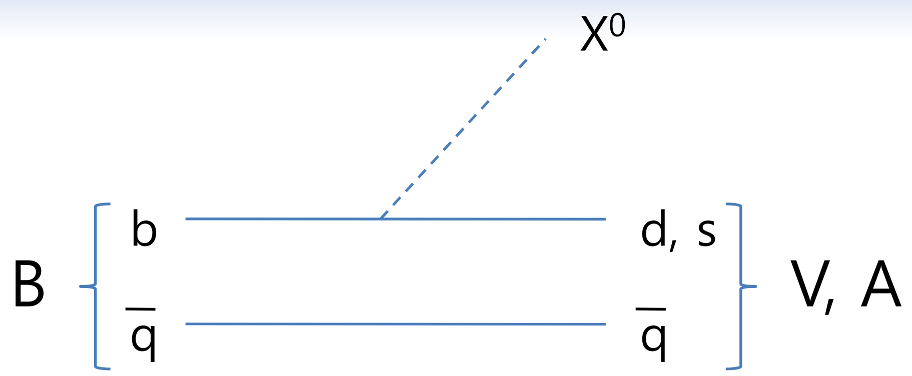
$$\mathcal{B}(B^+ \to \pi^+ \mu^+ \mu^-) < 6.9 \times 10^{-8}$$
$$\mathcal{B}(B_d \to \pi^0 \mu^+ \mu^-) < 1.84 \times 10^{-7} \qquad \text{at } 90\% \text{ C.L.}$$
$$\mathcal{B}(B \to K \mu^+ \mu^-)_{m_{\mu\mu} \leq 2\,\mathrm{GeV}} = (0.81^{+0.18}_{-0.16} \pm 0.05) \times 10^{-7}$$
$$\mathcal{B}(B \to K X) < 3.2 \times 10^{-8}$$

⇒

$$|g_{Vd}|^2 < 6.5 \times 10^{-21}$$
$$|g_{Vs}|^2 < 1.7 \times 10^{-21}$$

most stringent constraints !

B → V X decays



$$\mathcal{B}(B_d^0 \to \rho^0 X) = 1.77 \times 10^{10} |g_{Vd}|^2 + \underline{6.18 \times 10^{12} |g_{Ad}|^2}$$
$$\mathcal{B}(B_d^0 \to K^{*0} X) = 5.45 \times 10^{10} |g_{Vs}|^2 + \underline{1.79 \times 10^{13} |g_{As}|^2}$$

Belle data:

$$\mathcal{B}(B_d \to \rho^0 X) < 0.81 \times 10^{-8}$$
$$\mathcal{B}(B_d \to K^{*0} X) < 2.3 \times 10^{-8} \quad \text{at 90\% C.L.}$$

⇒

$$0.00286 \, |g_{Vd}|^2 + |g_{Ad}|^2 < 1.3 \times 10^{-21}$$
$$0.00304 \, |g_{Vs}|^2 + |g_{As}|^2 < 1.3 \times 10^{-21}$$

Combining B → PX & V X decays

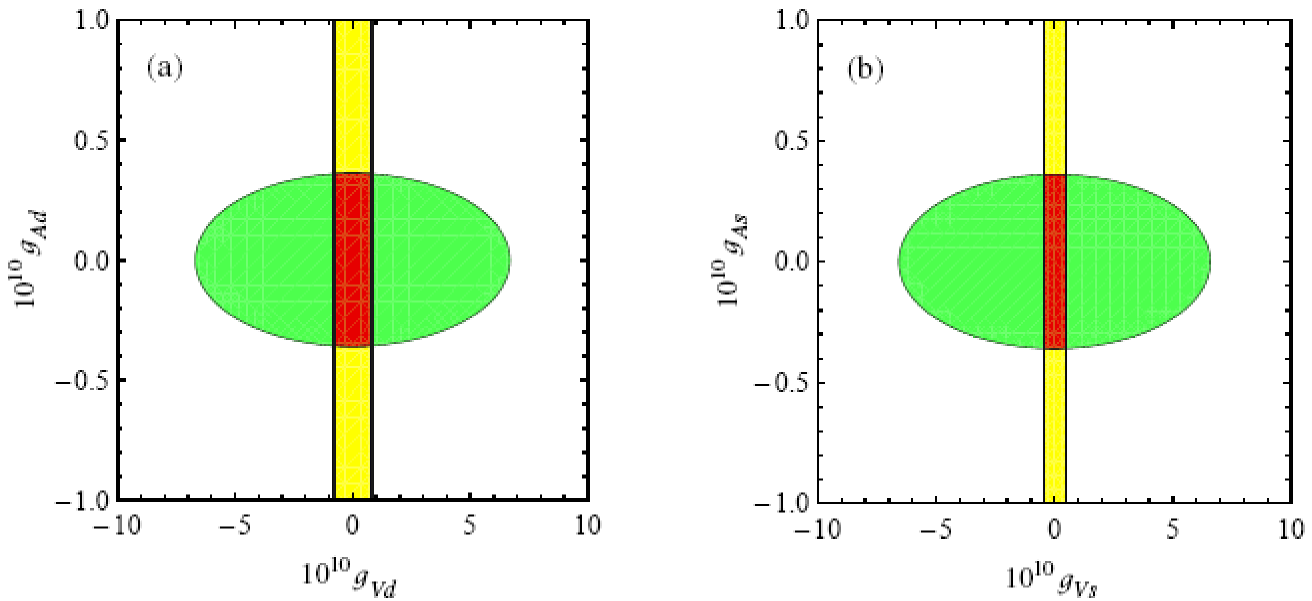


FIG. 3: Parameter space of g_{Vq} and g_{Aq}, taken to be real, subject to constraints on (a) $B \to \pi X$ (lightly shaded, yellow region), $B \to \rho X$ (medium shaded, green region), and both of them (heavily shaded, red region) and (b) $B \to KX$ (lightly shaded, yellow region), $B \to K^* X$ (medium shaded, green region), and both of them (heavily shaded, red region).

$$|g_{Vd}|^2 < 6.5 \times 10^{-21}, \qquad |g_{Ad}|^2 < 1.3 \times 10^{-21}$$
$$|g_{Vs}|^2 < 1.7 \times 10^{-21}, \qquad |g_{As}|^2 < 1.3 \times 10^{-21}$$

Our predictions: B → P X decays

- Using g_{Vd} bounds:

$$\mathcal{B}(B_d^0 \to \pi^0 X) < 3.2 \times 10^{-8}$$

$$\mathcal{B}(B_d^0 \to \eta X) < 2.4 \times 10^{-8} , \qquad \mathcal{B}(B_d^0 \to \eta' X) < 1.6 \times 10^{-8} ,$$

$$\underline{\mathcal{B}(B_s^0 \to K^0 X) < 8.2 \times 10^{-8}} , \qquad \mathcal{B}(B_c \to D_d^+ X) < 1.7 \times 10^{-8}$$

- Using g_{Vs} bounds:

$$\mathcal{B}(B_s^0 \to \eta X) < 1.2 \times 10^{-8} , \qquad \mathcal{B}(B_s^0 \to \eta' X) < 1.7 \times 10^{-8}$$

$$\mathcal{B}(B_c \to D_s^+ X) < 2.3 \times 10^{-9} ,$$

Our predictions: B → V X decays

- Using g_{Vd} & g_{Ad} bounds:

$$\mathcal{B}(B^+ \to \rho^+ X) < 1.7 \times 10^{-8} , \qquad \mathcal{B}(B_d^0 \to \omega X) < 7.0 \times 10^{-9} ,$$
$$\mathcal{B}(B_s^0 \to K^{*0} X) < 2.2 \times 10^{-8} , \qquad \mathcal{B}(B_c \to D_d^{*+} X) < 5.0 \times 10^{-9}$$

- Using g_{Vs} & g_{As} bounds:

$$\mathcal{B}(B_s^0 \to \phi X) < 3.9 \times 10^{-8} , \qquad \mathcal{B}(B_c \to D_s^{*+} X) < 3.9 \times 10^{-9}$$

Our predictions: B → S X & A X

- B → S X

In contrast to the B → P X case, g_{Aq} is the only relevant coupling !

$$\mathcal{B}(B^+ \to a_0^+(1450)X) \; < \; 1.1 \times 10^{-8} \, , \qquad \mathcal{B}(B_d^0 \to a_0^0(1450)X) \; < \; 5.1 \times 10^{-9}$$
$$\mathcal{B}(B^+ \to K_0^{*+}(1430)X) \; \simeq \; \mathcal{B}(B_d^0 \to K_0^{*0}(1430)X) \; < \; 1.0 \times 10^{-8} \, .$$

- B → A X

In contrast to the B → V X case, the g_{Vq} term in the longitudinal component H_0 is dominant.

$$\mathcal{B}(B^+ \to a_1^+(1260)X) \; \simeq \; 2\mathcal{B}(B_d^0 \to a_1^0(1260)X) \; < \; 1.6 \times 10^{-8}$$
$$\mathcal{B}(B^+ \to b_1^+(1235)X) \; \simeq \; 2\mathcal{B}(B_d^0 \to b_1^0(1235)X) \; < \; 1.2 \times 10^{-7}$$
$$\mathcal{B}(B^+ \to K_1^{*+}(1270)X) \; \simeq \; \mathcal{B}(B_d^0 \to K_1^{*0}(1270)X) \; < \; 2.6 \times 10^{-8}$$
$$\mathcal{B}(B^+ \to K_1^{*+}(1400)X) \; \simeq \; \mathcal{B}(B_d^0 \to K_1^{*0}(1400)X) \; < \; 1.3 \times 10^{-8}$$

Summary

- The possibility that X has spin 1 is not well challenged by experiment yet.

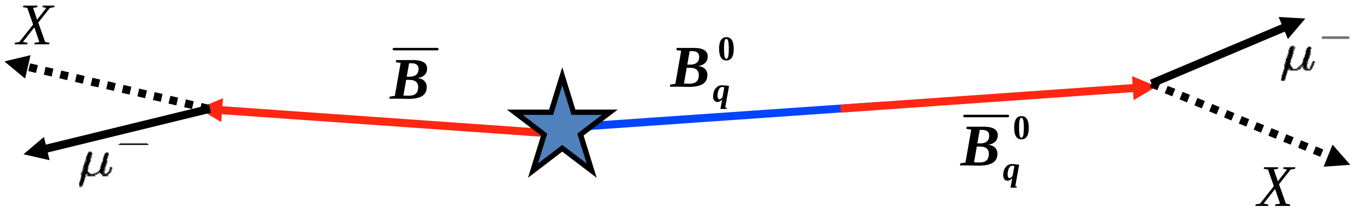
- Various B meson decay processes can be used to search for the hypothetical new particle X^0.

  → The $B \to M X$ branching ratios are predicted to reach the 10^{-7} level, which is comparable to the upper limits ($\sim 10^{-8}$) for the branching ratios of $B \to \rho^0 X$, $K^{*0} X$ recently measured by Belle.

- We would like to encourage our experimental colleagues to make more efforts to search for the X^0, e.g., at Belle II and LHCb experiments.

The D0 anomaly

D0 Anomaly (1/2)



- The D0 Collaboration, with 6.1 fb^{-1} of data
  anomalously large CP violation in the like-sign dimuon charge asymmetry

$$A_{\mathrm{sl}}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

where N_b^{++} and N_b^{--} represent the number of events containing two b hadrons decaying semileptonically and producing two positive or two negative muons, respectively.

The D0 result $$A_{\mathrm{sl}}^b = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$

3.2σ away from the standard model (SM) prediction of -0.2×10^{-3}

D0 Anomaly (2/2)

- $A^b_{\rm sl}$ is related to the asymmetries $a^{d,s}_{\rm sl}$ in B_d and B_s decays by

$$A^b_{\rm sl} = (0.506 \pm 0.043) a^d_{\rm sl} + (0.494 \pm 0.043) a^s_{\rm sl}$$

$a^q_{\rm sl}$ is the "wrong-charge" asymmetry,

$$a^q_{\rm sl} \equiv \frac{\Gamma(\bar{B}_q \to \mu^+ X) - \Gamma(B_q \to \mu^- X)}{\Gamma(\bar{B}_q \to \mu^+ X) + \Gamma(B_q \to \mu^- X)}$$

- Using the current experimental value $a^d_{\rm sl} = -0.0047 \pm 0.0046$

which is consistent with zero

to obtain the D0 value of $A^b_{\rm sl}$

$$a^s_{\rm sl} = -0.0146 \pm 0.0075$$

much larger than the SM prediction $(2.1 \pm 0.6) \times 10^{-5}$

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~ 70 papers so far

Theory (1/2)

- mass and width differences ΔM_s and $\Delta\Gamma_s$, respectively,

  between the heavy and light mass-eigenstates in the B_s-$\bar{B}_s$ system

off-diagonal elements M_s^{12} and Γ_s^{12} of the mass and decay matrices, respectively,

  which characterize B_s-$\bar{B}_s$ mixing.

$$(\Delta M_s)^2 - \frac{1}{4}(\Delta\Gamma_s)^2 = 4\left|M_s^{12}\right|^2 - \left|\Gamma_s^{12}\right|^2$$

$$\Delta M_s \, \Delta\Gamma_s = 4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right| \cos\phi_s$$

$$\phi_s = \arg\left(-M_s^{12}/\Gamma_s^{12}\right)$$

$$a_{\rm sl}^s = \frac{4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right| \sin\phi_s}{4\left|M_s^{12}\right|^2 + \left|\Gamma_s^{12}\right|^2}$$

Theory (2/2)

- Since $\Delta\Gamma_s \ll \Delta M_s$ and $|\Gamma_s^{12}| \ll |M_s^{12}|$,

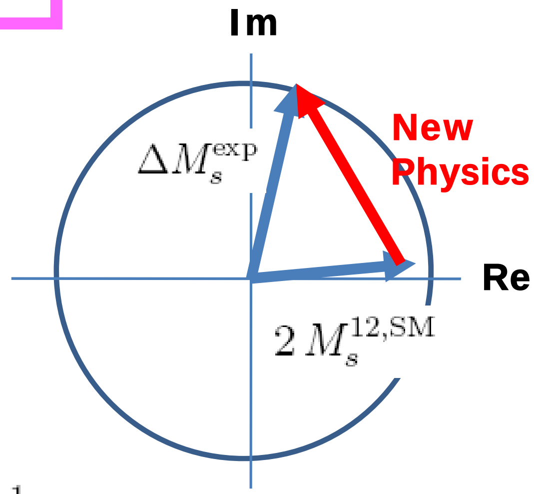
$$\Delta M_s \simeq 2\,|M_s^{12}|\,, \qquad \Delta\Gamma_s \simeq 2\,|\Gamma_s^{12}|\cos\phi_s$$

$$a_{\rm sl}^s \simeq \frac{|\Gamma_s^{12}|\sin\phi_s}{|M_s^{12}|} \simeq \frac{2\,|\Gamma_s^{12}|\sin\phi_s}{\Delta M_s}$$

- Experimental values

$$\Delta M_s^{\rm exp} = 17.77 \pm 0.12 \ {\rm ps}^{-1}$$

$$\Delta\Gamma_s^{\rm exp} = 0.062^{+0.034}_{-0.037} \ {\rm ps}^{-1}$$



- SM predictions

$$2\,M_s^{12,{\rm SM}} = 20.1(1 \pm 0.40)\,e^{-0.035i} \ {\rm ps}^{-1}$$

$$2\,|\Gamma_s^{12,{\rm SM}}| = 0.096 \pm 0.039 \ {\rm ps}^{-1}$$

$$\phi_s^{\rm SM} = (4.2 \pm 1.4) \times 10^{-3} = 0.24^\circ \pm 0.08^\circ$$

Lenz, Nieste;
Kubo, Lenz

Effective Lagrangian with a Light X^0

- Assuming that X has spin 1 & does not carry electric or color charge, the Lagrangian describing the effective b-q-X couplings (q = d, s) is

$$
\begin{aligned}
\mathcal{L}_{bqX} &= -\bar{q}\gamma_\mu\left(g_{Vq} - g_{Aq}\gamma_5\right)b\,X^\mu \;+\; \mathrm{H.c.} \\
&= -\bar{q}\gamma_\mu\left(g_{\mathrm{L}q}P_{\mathrm{L}} + g_{\mathrm{R}q}P_{\mathrm{R}}\right)b\,X^\mu \;+\; \mathrm{H.c.}
\end{aligned}
$$

$$
g_{\mathrm{L}q,\mathrm{R}q} = g_{Vq} \pm g_{Aq}, \qquad P_{\mathrm{L,R}} = \tfrac{1}{2}(1 \mp \gamma_5).
$$

Generally, the constants $g_{Vq,Aq}$ can be complex.

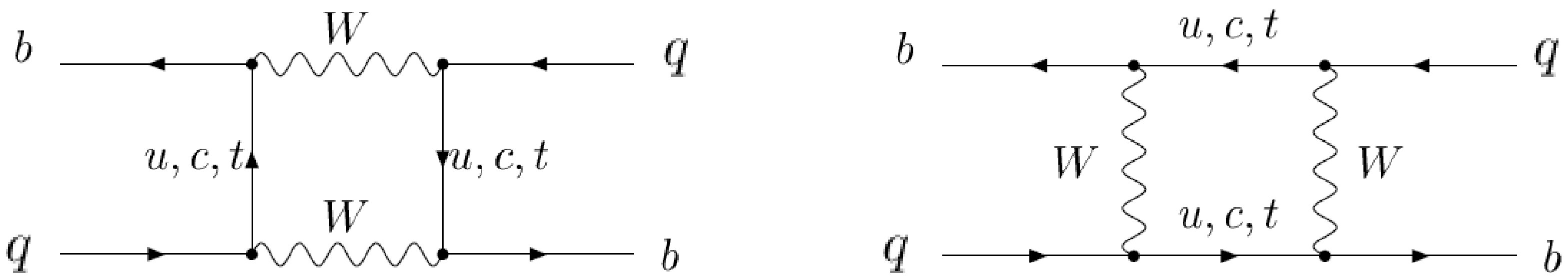
B^0 - bar B^0 mixing: M_s^{12} (1/3)

- It is characterized by the physical mass difference ΔM_q (q = d, s) between the heavy and light mass-eigenstates in the B_q^0-$\bar{B}_q^0$ system.

$$\Delta M_q = 2\,|M_{12}^q|, \qquad \text{where } M_{12}^q = M_{12}^{q,\mathrm{SM}} + M_{12}^{q,X}$$

$$2m_{B_q} M_{12}^q = \langle B_q^0 | \mathcal{H}_{b\bar{q}\to\bar{b}q} | \bar{B}_q^0 \rangle$$

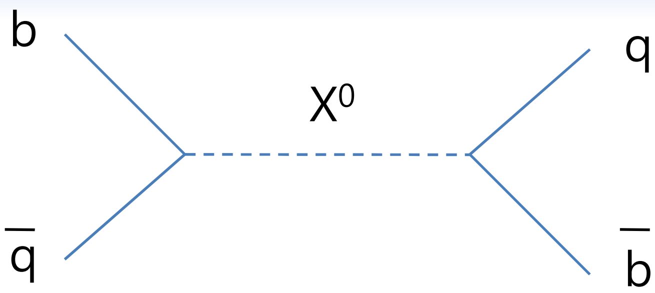
SM:



$$M_{12}^{q,\mathrm{SM}} \simeq \frac{G_F^2 m_W^2}{12\pi^2} f_{B_q}^2 m_{B_q} \eta_B B_{B_q} \left(V_{tb}V_{tq}^*\right)^2 S_0\left(\bar{m}_t^2/m_W^2\right)$$

B^0 - bar B^0 mixing: M_s^{12} (2/3)

X contribution:



for the tree-level transition $b\bar{q} \to X^* \to \bar{b}q$ $\quad 2m_{B_q} M_{12}^q = \langle B_q^0 | \mathcal{H}_{b\bar{q}\to\bar{b}q} | \bar{B}_q^0 \rangle$

$$\mathcal{H}^X_{\bar{b}d\to\bar{d}b} = \frac{1}{2} [\, \bar{b}\gamma_\mu (g_L P_L + g_R P_R) d \,] \frac{-i\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{m_X^2}\right)}{p^2 - m_X^2} [\, \bar{b}\gamma_\nu (g_L P_L + g_R P_R) d \,]$$

dominant if $m_X << m_b$

$$M_{12}^{q,X} = \frac{f_{B_q}^2 m_{B_q}}{3(m_X^2 - m_{B_q}^2)} \Bigg[(g_{Vq}^2 + g_{Aq}^2) P_1^{\rm VLL} + \frac{g_{Vq}^2 (m_b - m_q)^2 + g_{Aq}^2 (m_b + m_q)^2}{m_X^2} P_1^{\rm SLL} + (g_{Vq}^2 - g_{Aq}^2) P_1^{\rm LR} + \frac{g_{Vq}^2 (m_b - m_q)^2 - g_{Aq}^2 (m_b + m_q)^2}{m_X^2} P_2^{\rm LR} \Bigg]$$

B^0 - bar B^0 mixing: M_s^{12} (3/3)

$$\Delta M_s^{\rm exp} = 2\left|M_s^{12}\right|$$

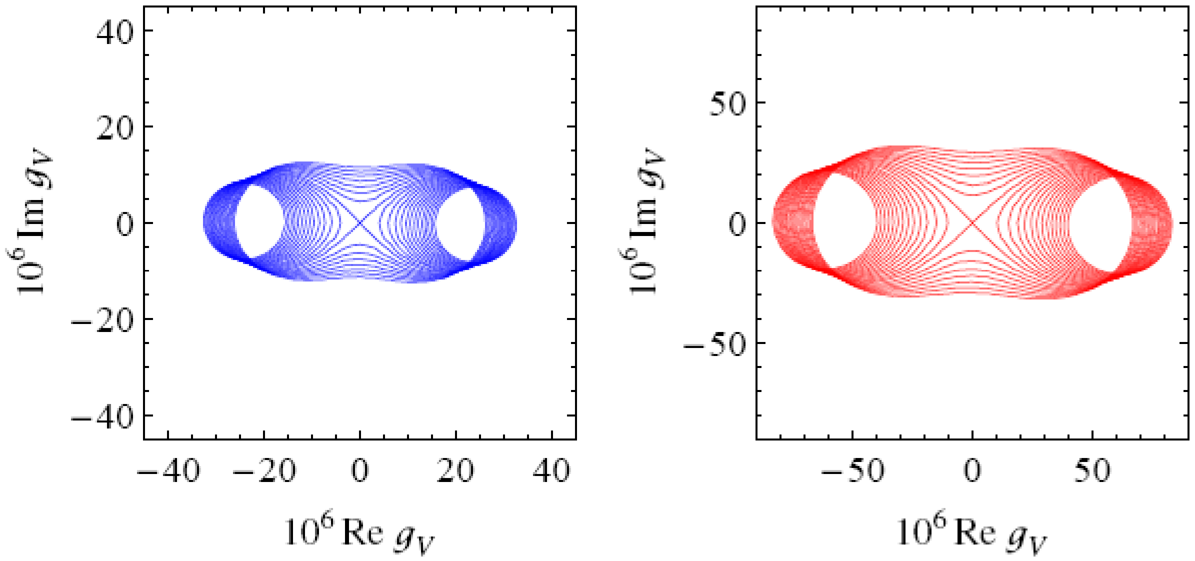


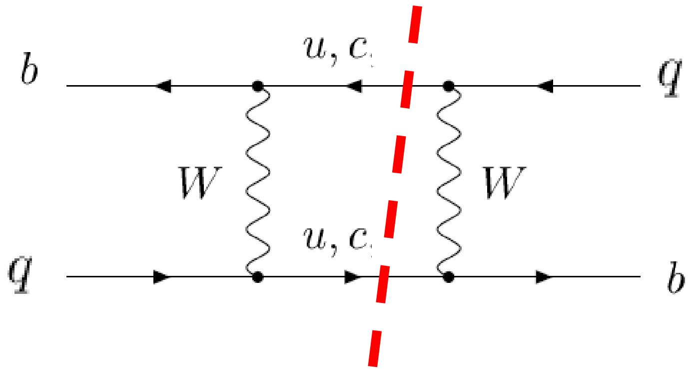
FIG. 1: Regions of Re g_V and Im g_V allowed by $\Delta M_s^{\rm exp} = 2\left|M_s^{12}\right|$ constraint for $m_X = 2\,{\rm GeV}$ (left plot) and $m_X = 4\,{\rm GeV}$ (right plot) under the assumption $g_A = 0$.

B^0 - bar B^0 mixing: Γ_s^{12} (1/3)

- As for Γ_s^{12}, it is in general affected by any physical state f into which both B_s and $\bar{B}_s$ can decay.

$$\Gamma_s^{12} = \sum_f' (\mathcal{M}(B_s \to f))^* \mathcal{M}(\bar{B}_s \to f)$$

In the SM, this is dominated by the CKM-favored $b \to c\bar{c}s$ tree-level processes



$$\left| \frac{\Gamma_s^{12}}{M_s^{12}} \right| \sim 10^{-3}$$

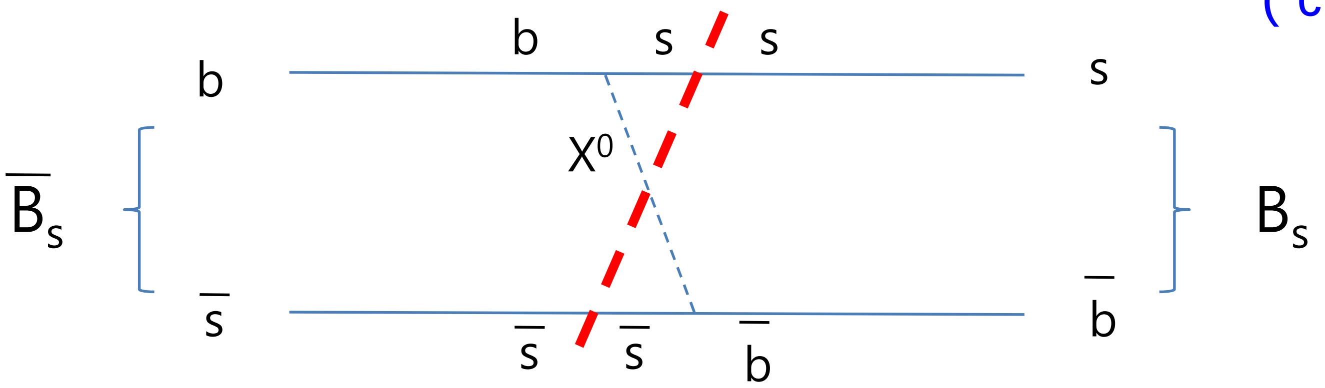
B^0 - bar B^0 mixing: Γ_s^{12} (2/3)

- In contrast, with the X mass $m_X < m_b$, the dominant processes contributing to $\Gamma_s^{12,X}$ arise from decays induced by $b\,(\bar{b}) \to s\,(\bar{s})\,X$, such as $\bar{B}_s\,(B_s) \to \eta X$, $\bar{B}_s\,(B_s) \to \eta' X$, and $\bar{B}_s\,(B_s) \to \phi X$.

$$\Gamma_s^{12,X} = \sum\nolimits'_{f_X} \left(\mathcal{M}(B_s \to f_X)\right)^* \mathcal{M}(\bar{B}_s \to f_X)$$

If $m_X < m_b$, m_X can be produced as a "physical particle" !

(cf. heavy Z')



B^0 - bar B^0 mixing: Γ_s^{12} (3/3)

$$\Gamma(b \to sX)$$

$$\Gamma_s^{12,X} \simeq \frac{|\vec{p}_X|}{8\pi\, m_b^2 m_X^2}\Big\{g_V^2\Big[(m_b+m_s)^2+2m_X^2\Big]\Big[(m_b-m_s)^2-m_X^2\Big] + g_A^2\Big[(m_b-m_s)^2+2m_X^2\Big]\Big[(m_b+m_s)^2-m_X^2\Big]\Big\}$$

$$\Gamma_s^{12,X} \simeq \Gamma_s^{12,X}(\eta X)+\Gamma_s^{12,X}(\eta' X)+\Gamma_s^{12,X}(\phi X)$$

$$\Gamma_s^{12,X}(PX) = \frac{g_V^2\, |\vec{p}_P|^3}{2\pi\, m_X^2}\left(F_1^{B_s P}\right)^2$$

$$\Gamma_s^{12,X}(\phi X) = \frac{|\vec{p}_\phi|}{8\pi\, m_{B_s}^2}\left(H_0^2+H_+^2+H_-^2\right)$$

Theory (1/2)

- mass and width differences ΔM_s and $\Delta\Gamma_s$, respectively,

  between the heavy and light mass-eigenstates in the B_s-$\bar{B}_s$ system

  off-diagonal elements M_s^{12} and Γ_s^{12} of the mass and decay matrices, respectively,

  which characterize B_s-$\bar{B}_s$ mixing.

$$(\Delta M_s)^2 - \frac{1}{4}(\Delta\Gamma_s)^2 = 4\left|M_s^{12}\right|^2 - \left|\Gamma_s^{12}\right|^2$$

$$\Delta M_s \, \Delta\Gamma_s = 4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right| \cos\phi_s$$

$$\phi_s = \arg\left(-M_s^{12}/\Gamma_s^{12}\right)$$

$$a_{\rm sl}^s = \frac{4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right| \sin\phi_s}{4\left|M_s^{12}\right|^2 + \left|\Gamma_s^{12}\right|^2}$$

$a_{sl}^{s,\,exp}$, ($\Delta M_s^{exp}\,\Delta\Gamma_s^{exp}$), $\Gamma(b\to sX)$

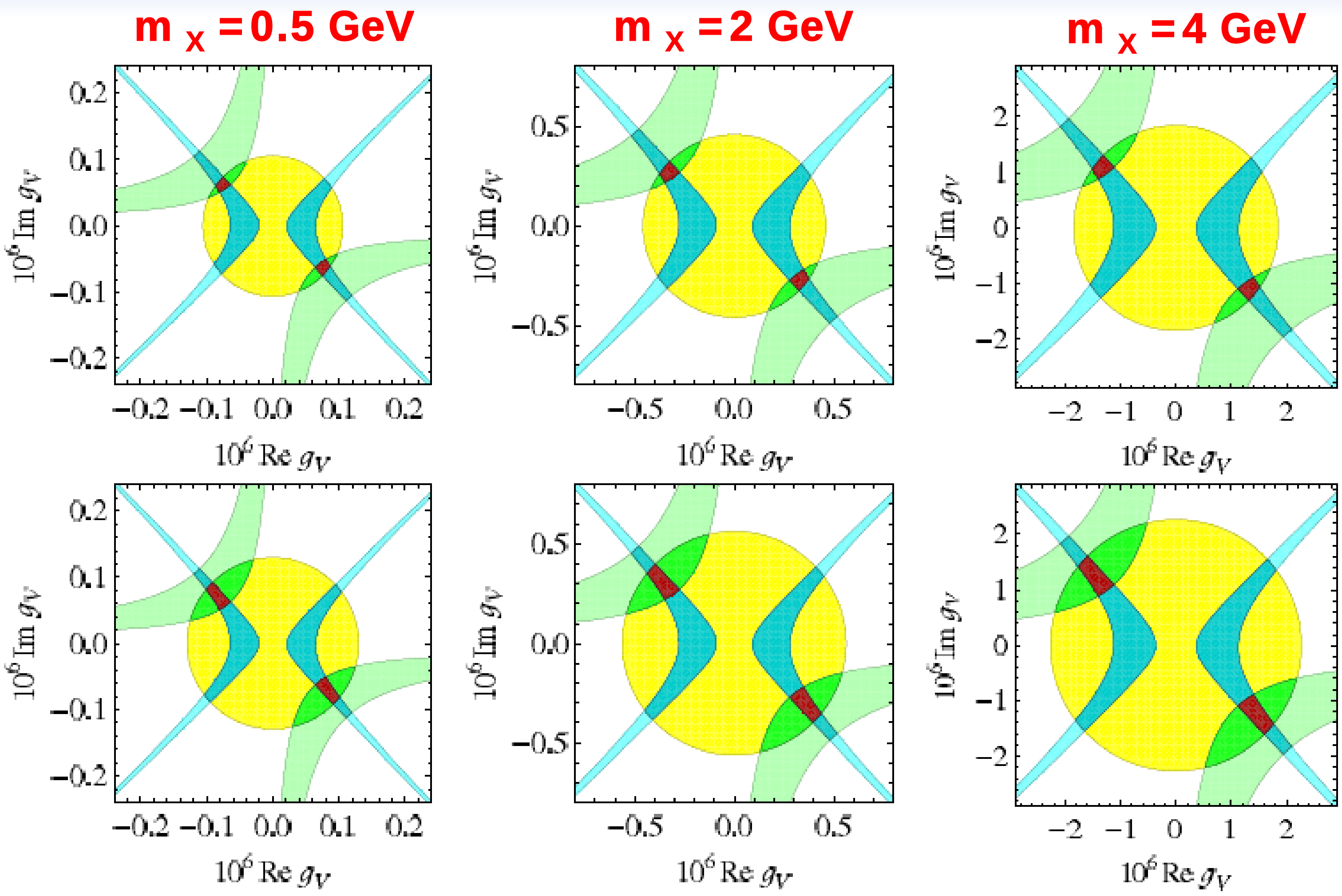


FIG. 2: Regions of $\mathrm{Re}\, g_V$ and $\mathrm{Im}\, g_V$ allowed by $a_{\rm sl}^{s,\rm exp}$ constraint (green), $\Delta M_s^{\rm exp}\Delta\Gamma_s^{\rm exp}$ constraint (blue), $\Gamma(b\to sX) < 0.1\,\mathrm{ps}^{-1}$ (yellow), and all of them (dark red) for $m_X = 0.5\,\mathrm{GeV}$ (upper left plot), 2 GeV (upper middle plot), and 4 GeV (upper right plot), under the assumption $g_A = 0$. The lower plots are the same as the upper ones, except that $\Gamma(b\to sX) < 0.15\,\mathrm{ps}^{-1}$.

$|\Gamma_s^{12} / \Gamma_s^{12,SM}|$, $\sin \phi_s$

$m_X = 4$ GeV

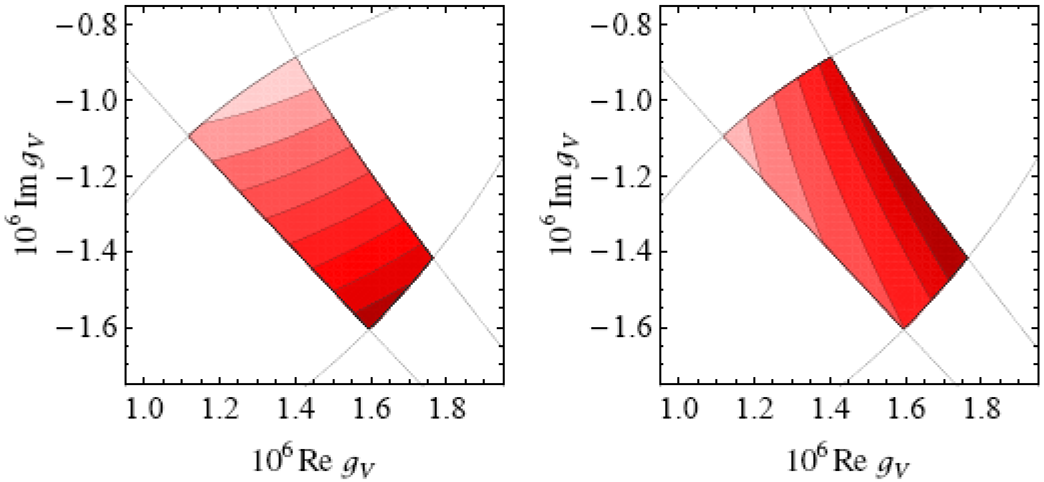


FIG. 3: Values of $|\Gamma_s^{12}|$ (left plot) and $\sin\phi_s$ (right plot) for $m_X = 4\,\mathrm{GeV}$ and the $(\mathrm{Re}\, g_V, \mathrm{Im}\, g_V)$ overlap region in the fourth quadrant of the lower-right plot in Fig. 2 allowed by all the constraints, with $\Gamma(b \to sX) < 0.15\,\mathrm{ps}^{-1}$. In the left plot, from darkest to lightest, the differently shaded (red colored) areas correspond to $\left|\Gamma_s^{12}/\Gamma_s^{12,\mathrm{SM}}\right| > 3.1, 2.9, 2.7, \ldots, 1.5$, respectively, with each region including the area of the next darker region and $\left|\Gamma_s^{12,\mathrm{SM}}\right|$ being its central value. Similarly, in the right plot, from darkest to lightest $\sin\phi_s < -0.99, -0.98, -0.96, -0.93, -0.89, -0.85$.

$a_{sl}^{s,\,exp}$, $(\Delta M_s^{exp}\,\Delta\Gamma_s^{exp})$, $\Gamma(b\text{->}sX)$

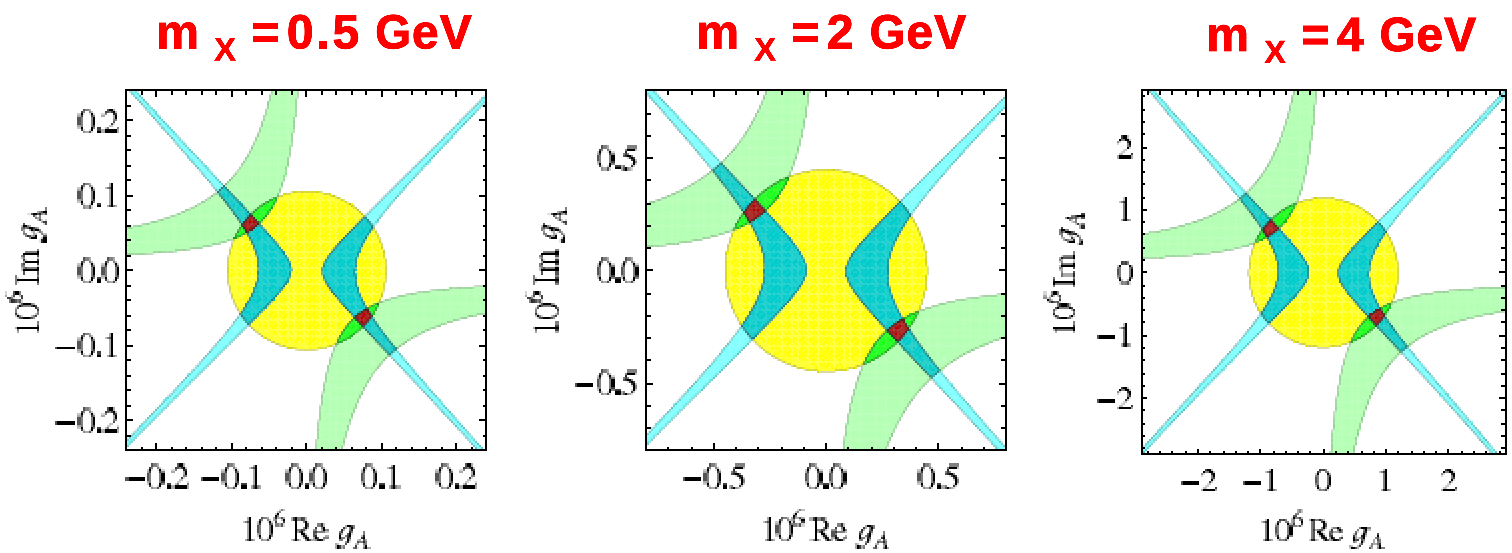


FIG. 4: Regions $\mathrm{Re}\, g_A$ and $\mathrm{Im}\, g_A$ allowed by $a_{\rm sl}^{s,\rm exp}$ constraint (green), $\Delta M_s^{\rm exp}\Delta\Gamma_s^{\rm exp}$ constraint (blue), $\Gamma(b\to sX) < 0.1\,\mathrm{ps}^{-1}$ (yellow), and all of them (dark red) for $m_X = 0.5\,\mathrm{GeV}$ (left plot), $2\,\mathrm{GeV}$ (middle plot), and $4\,\mathrm{GeV}$ (right plot), under the assumption $g_V = 0$.

Summary

- We have investigated the possibility that the D0 anomaly arises from the contribution of a light spin-1 particle to the B_s mixing.

- In contrast to a heavy Z' particle, X can be produced as a physical particle in B_s decay, and so it affects not only M_s^{12} , but also Γ_s^{12}.

- Under constraints from available experimental data, the effect of X can increase $|\Gamma_s^{12}|$ to become a few times larger than its SM value, and enlarge the size of $\sin\phi_s$ by a factor of a few hundred.
  ➔ Can explain the D0 anomaly.
  ➔ But, $m_X \sim 0.2$ GeV is unlikely allowed.

Thank you!