Exploring a New Light Spin-1 Particle in $b \to s$ Transitions

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Outline

- Introduction
- Anomalous *CP*-violation in B_s-$\bar{B}_s$ mixing due to a new light spin-1 boson
- Effects of a new light spin-1 boson on rare $b \to s$ decays
- Conclusions

Preliminary

- The standard model (SM) predicts very small *CP*-violation in mixing in the B_d and B_s systems.

- Hence any sizable measurement of mixing CPV in $B_{d,s}$ systems would likely be evidence for new physics

- Most experimental data on $B_{d,s}$ processes were consistent with SM expectations, until recently . . .

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- Most experimental data on $B_{d,s}$ processes were consistent with SM expectations, until recently . . .

- Last May the D0 Collaboration at Fermilab announced their measurement of anomalously large CPV in B_s mixing

D0 measurement

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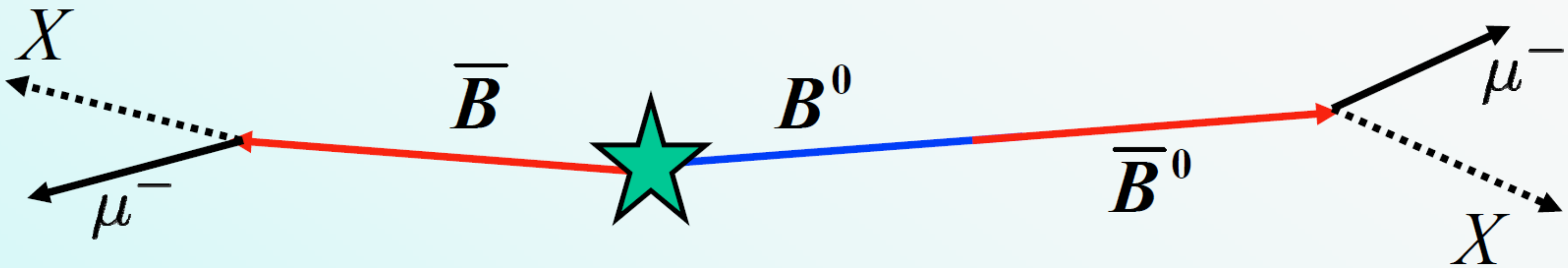
Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

We measure the charge asymmetry $A \equiv (N^{++} - N^{--})/(N^{++} + N^{--})$ of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. From A we extract the like-sign dimuon charge asymmetry in semileptonic b-hadron decays: $A^b_{\text{sl}} = -0.009\,57 \pm 0.002\,51(\text{stat}) \pm 0.001\,46(\text{sys})$. It differs by 3.2 standard deviations from the standard model prediction $A^b_{\text{sl}}(\text{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$, and provides first evidence of anomalous CP violation in the mixing of neutral B mesons.

$$A^b_{\text{sl}} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

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

Dimuon charge asymmetry



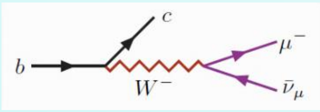
- We measure *CP* violation in mixing using **the dimuon charge asymmetry of semileptonic *B* decays**:

Here X = anything

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

$B^0 = B_d$ or B_s

- N_b^{++}, N_b^{--} – number of events with two b hadrons decaying semileptonically and producing two muons of the same charge
- One muon comes from direct semileptonic decay $b \to \mu^- X$
- Second muon comes from direct semileptonic decay after neutral B meson mixing: $B^0 \to \overline{B}^0 \to \mu^- X$



More on D0 result

- Both B_d & B_s were produced in $p\bar{p} \to b\bar{b}$ at Tevatron

- Consequently both "wrong sign" semileptonic decays $B_d \to \bar{B}_d \to \mu^- X$ and $B_s \to \bar{B}_s \to \mu^- X$ (& their *CP* conjugates) contribute to $A_{\rm sl}^b$
  - Example of "right sign" decay $B_d \to \mu^- X$

- Thus $A_{\rm sl}^b = (0.506 \pm 0.043) a_{\rm sl}^d + (0.494 \pm 0.043) a_{\rm sl}^s$ D0

  - charge asymmetry for "wrong sign" semileptonic decay ($q = d$ or s) induced by oscillations

$$a_{\rm sl}^q = \frac{\Gamma(\bar{B}_q^0(t) \to \mu^+ X) - \Gamma(B_q^0(t) \to \mu^- X)}{\Gamma(\bar{B}_q^0(t) \to \mu^+ X) + \Gamma(B_q^0(t) \to \mu^- X)}$$

  - coefficients of $a_{\rm sl}^{d,s}$ calculated from other measurements

Dimuon charge asymmetries

- From *B* factories $a_{\rm sl}^{d} = -0.0047 \pm 0.0046$
  - consistent with no CPV in B_d-$\bar{B}_d$ mixing
- The new D0 result $A_{\rm sl}^{b} = -0.00957 \pm 0.00251\ ({\rm stat}) \pm 0.00146\ ({\rm syst})$

  then translates into $a_{\rm sl}^{s,\rm exp} = -(14.6 \pm 7.5) \times 10^{-3}$

- This is about 2-sigmas larger than the SM prediction

$$a_{\rm sl}^{s,\rm SM} = (2.1 \pm 0.6) \times 10^{-5}$$

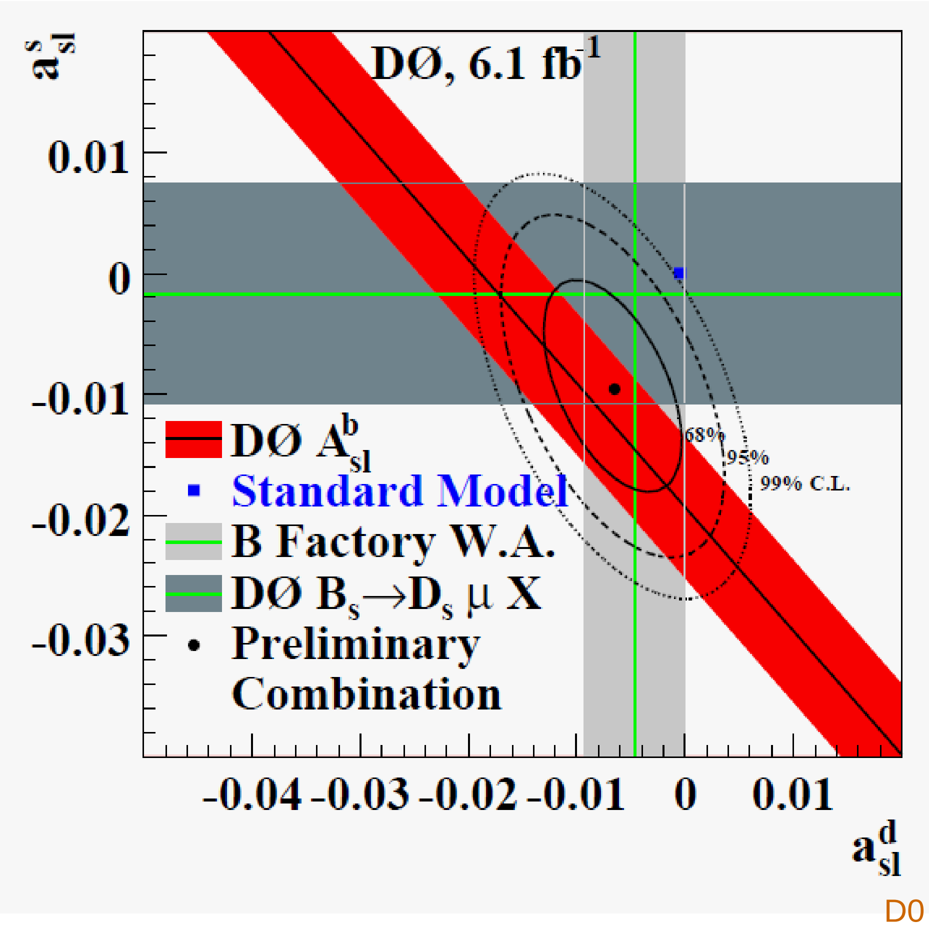
Lenz & Nierste

  - indicating anomalously large CPV in B_s-$\bar{B}_s$ mixing
- Previously D0 also measured $a_{\rm sl}^{s}$ directly, but with large error:

$$a_{\rm sl}^{s} = -0.0017 \pm 0.0091$$

Dimuon charge asymmetries

- Comparison of $a_{\rm sl}^{d,s}$ & $A_{\rm sl}^{b}$ measurements and SM prediction for $a_{\rm sl}^{d,s}$



$$A_{\rm sl}^b = (0.506 \pm 0.043) a_{\rm sl}^d + (0.494 \pm 0.043) a_{\rm sl}^s$$

- Although the new D0 data still needs to be confirmed by other experiments, it may hint at *CP*-violating new physics

Observables of interest

- Besides $a_{\rm sl}^s$, the relevant observables are the mass & width differences ΔM_s & $\Delta\Gamma_s$, respectively, between the mass eigenstates in the $B_s - \bar{B}_s$ system.

- Experimental values

$$\Delta M_s^{\rm exp} = 17.77 \pm 0.12 \text{ ps}^{-1} , \qquad \Delta\Gamma_s^{\rm exp} = 0.062^{+0.034}_{-0.037} \text{ ps}^{-1}$$

- Theoretically they are related to the off-diagonal matrix elements M_s^{12} and Γ_s^{12} of the mass and decay matrices, respectively, which characterize $B_s - \bar{B}_s$ mixing

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

$$\Delta M_s \, \Delta\Gamma_s = 4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right| \cos\phi_s , \qquad \phi_s = \arg\left(-M_s^{12}/\Gamma_s^{12}\right)$$

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

Commonly used approximations

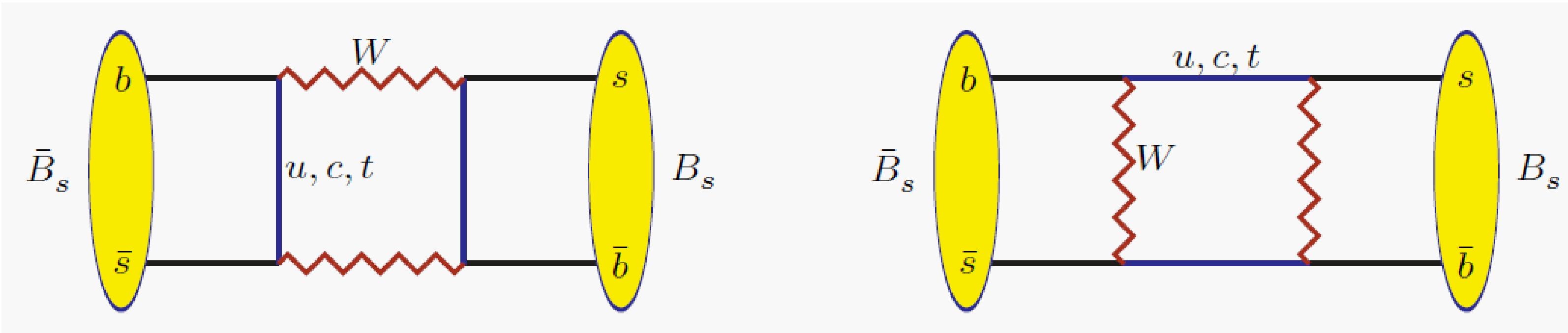
- Since $\Delta\Gamma_s << \Delta M_s$ and $|\Gamma_s^{12}| << |M_s^{12}|$

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

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

SM contribution to B_q–$\bar{B}_q$ mixing

- It comes from 4-quark operators induced by box diagrams



- The t-quark contribution dominates M_s^{12}.

$$M_s^{12,\mathrm{SM}} \simeq \frac{G_F^2 m_W^2}{12\pi^2} f_{B_s}^2 m_{B_s} \eta_B B_{B_s} \left(V_{tb}V_{ts}^*\right)^2 S_0\left(m_t^2/m_W^2\right)$$

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

Lenz & Nierste
Kubo & Lenz

- This is compatible with measurement of $\Delta M_s \simeq 2\left|M_s^{12}\right|$

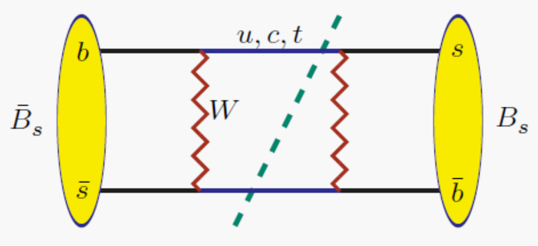
$$\Delta M_s^{\mathrm{exp}} = 17.77 \pm 0.12\ \mathrm{ps}^{-1}$$

SM contribution to $B_q - \bar{B}_q$ mixing

- In general Γ_s^{12} arises from any physical state *f* into which both B_s and $\bar{B}_s$ can decay

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

- The SM contribution to Γ_s^{12} is dominated by the CKM-favored $b \to c\bar{c}s$ tree-level processes



- Recent prediction: $2\left|\Gamma_s^{12,\mathrm{SM}}\right| = 0.096 \pm 0.039\ \mathrm{ps}^{-1}$

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

Lenz & Nierste
Kubo & Lenz

- This is compatible with measurement of $\Delta\Gamma_s \simeq 2\left|\Gamma_s^{12}\right| \cos\phi_s$

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

Contribution of a new light spin-1 particle

- We consider the contribution to $B_s - \bar{B}_s$ mixing from a new light spin-1 boson, referred to as X.
- Adopting a model-independent approach, we assume X
  - is lighter than the b quark
  - carries no color or electric charge
  - has a simple form of flavor-changing couplings to b & s quarks
- The effective Lagrangian for b-s-X interactions

$$\mathcal{L}_{bsX} = -\bar{s}\gamma_\mu \big(g_V - g_A\gamma_5\big) b\, X^\mu + \text{H.c.} = -\bar{s}\gamma_\mu \big(g_\text{L} P_\text{L} + g_\text{R} P_\text{R}\big) b\, X^\mu + \text{H.c.}$$

g_V and g_A parametrize the vector and axial-vector couplings, respectively

$g_{\text{L,R}} = g_V \pm g_A, \qquad P_{\text{L,R}} = \frac{1}{2}(1 \mp \gamma_5)$

Generally, the constants $g_{V,A}$ can be complex

New light spin-1 bosons in other contexts

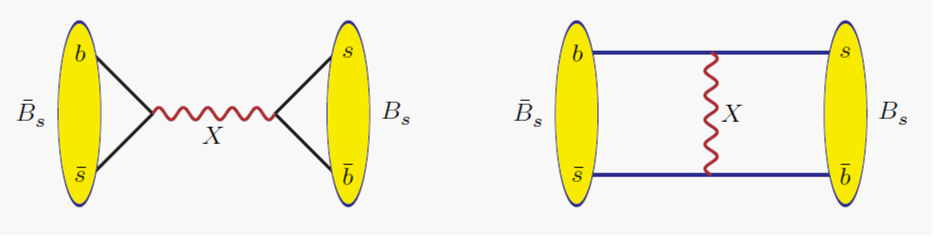
- New-physics scenarios involving nonstandard spin-1 bosons with masses of a few GeV or less have been discussed in various other contexts in the literature.

- Their existence is generally still compatible with currently available data and also desirable, as they may offer possible explanations for some of the recent experimental anomalies and unexpected observations.

- Examples
  - NuTeV anomaly
  - muon g-2
  - cosmic ray excesses due to dark matter
  - HyperCP anomaly

Contribution of X to M_s^{12}

- It is mediated by X at tree level



$$M_s^{12,X} = \frac{f_{B_s}^2\, m_{B_s}}{3\left(m_X^2 - m_{B_s}^2\right)} \Bigg[\left(g_V^2 + g_A^2\right) P_1^{\rm VLL} + \frac{g_V^2\, (m_b - m_s)^2 + g_A^2\, (m_b + m_s)^2}{m_X^2}\, P_1^{\rm SLL} + \left(g_V^2 - g_A^2\right) P_1^{\rm LR} + \frac{g_V^2\, (m_b - m_s)^2 - g_A^2\, (m_b + m_s)^2}{m_X^2}\, P_2^{\rm LR} \Bigg]$$

- The 2nd and 4th terms would be negligible if $m_X >> m_b$.

- The P_i's contain bag parameters & QCD-correction factors.

- Combined SM & X-mediated contribution

$$M_s^{12} = M_s^{12,\rm SM} + M_s^{12,X}$$

Contribution of X to Γ_s^{12}

- Since $m_X < m_b$, the dominant contribution comes 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 $\bar{B}_s\,(B_s) \to \phi X$.

- It follows that

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

$$f_X = \eta X,\; \eta' X,\; \phi X, \ldots \;\; \text{for kinematically allowed} \;\; B_s \to f_X$$

- Combined SM & X-mediated contribution

$$\Gamma_s^{12} = \Gamma_s^{12,\mathrm{SM}} + \Gamma_s^{12,X}$$

X contributions to Γ_s^{12}

- Inclusive

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

- Exclusive

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

$$\Gamma_s^{12,X}(PX) = \frac{g_V^2 \, |\vec{p}_P|^3}{2\pi\, m_X^2} \big(F_1^{B_s P}\big)^2 \ , \qquad \Gamma_s^{12,X}(\phi X) = \frac{|\vec{p}_\phi|}{8\pi\, m_{B_s}^2} \big(H_0^2 + H_+^2 + H_-^2\big)$$

Constraint from ΔM_s

- Use $\Delta M_s^{\rm exp} = 17.77 \pm 0.12\ {\rm ps}^{-1}$, $\Delta M_s \simeq 2\left|M_s^{12}\right|$, $M_s^{12} = M_s^{12,\rm SM} + M_s^{12,X}$

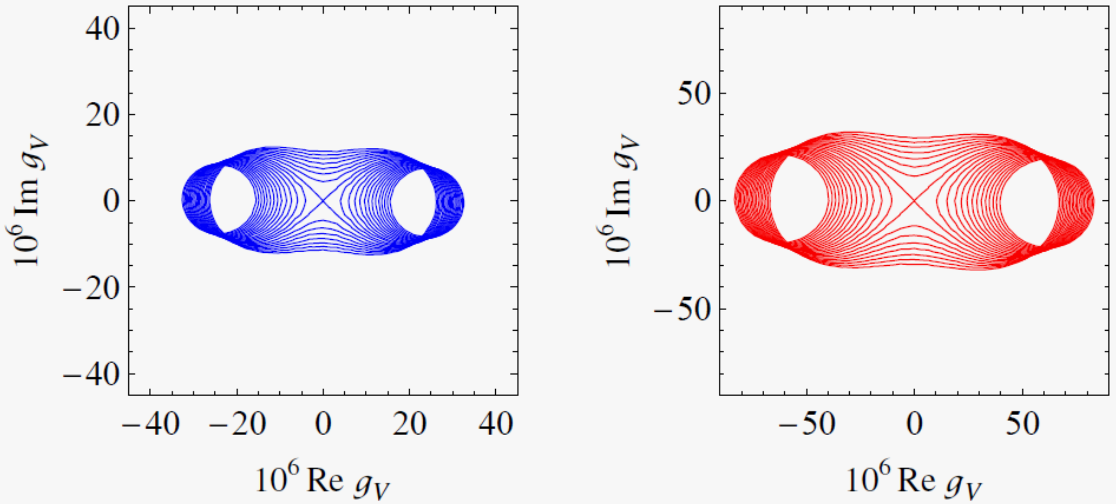


FIG. 1: Regions of ${\rm Re}\,g_V$ and ${\rm Im}\,g_V$ allowed by $\Delta M_s^{\rm exp} = 2\left|M_s^{12}\right|$ constraint for $m_X = 2\,{\rm GeV}$ (left plot) and $m_X = 4\,{\rm GeV}$ (right plot) under the assumption $g_A = 0$.

- If $g_A = 0$, Re g_V & Im g_V can be as large as a several times 10^{-5}
- If $g_V = 0$, the limits on g_A are a few times stronger
- The other observables provide stricter limits

Stricter constraints

- Use

$$\Delta M_s \, \Delta\Gamma_s \;=\; 4\left|M_s^{12}\right|\left|\Gamma_s^{12}\right| \cos\phi_s \;, \qquad \phi_s \;=\; \arg\!\left(-M_s^{12}/\Gamma_s^{12}\right)$$

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

- For the left-hand sides

$$\Delta M_s^{\rm exp} \;=\; 17.77 \pm 0.12 \ {\rm ps}^{-1} \;, \qquad \Delta\Gamma_s^{\rm exp} \;=\; 0.062^{+0.034}_{-0.037} \ {\rm ps}^{-1}$$

$$a_{\rm sl}^{s,\rm exp} = -(14.6 \pm 7.5) \times 10^{-3}$$

- For the right-hand sides

$$M_s^{12} = M_s^{12,\rm SM} + M_s^{12,X}, \qquad \Gamma_s^{12} = \Gamma_s^{12,\rm SM} + \Gamma_s^{12,X}$$

- Need to include an additional constraint from $b \to sX$.

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

- An extra constraint on g_V and g_A comes from the inclusive decay $b \to sX$, as its rate $\Gamma(b \to sX)$ contributes to the total width of B_s.
- Also relevant are the measured values of the total widths of B_d and B_u because they get contributions from the same $\Gamma(b \to sX)$.
- Theoretically the predictions for total widths $\Gamma_{Bd,Bs,Bu}$ involve large errors due to $\Gamma_B \propto m_b^5$ leading to errors of at least 20%.
- We can then require $\Gamma(b \to sX) < 0.15\,\Gamma_{Bs} = 0.1\ \mathrm{ps}^{-1}$, but will also consider the somewhat larger bound $\Gamma(b \to sX) < 0.15\ \mathrm{ps}^{-1}$
- Since the SM predicts $\Gamma_{Bd}/\Gamma_{Bs} \sim \Gamma_{Bd}/\Gamma_{bu} \sim 1$, the $\Gamma(b \to sX)$ contributions to $\Gamma_{Bd,Bs,Bu}$ respect the experimental ratios

$$\Gamma_{B_d}/\Gamma_{B_s} = 1.05 \pm 0.06 \ \text{ and } \ \Gamma_{B_d}/\Gamma_{B_u} = 1.071 \pm 0.009$$

Allowed values of g_V if $g_A = 0$

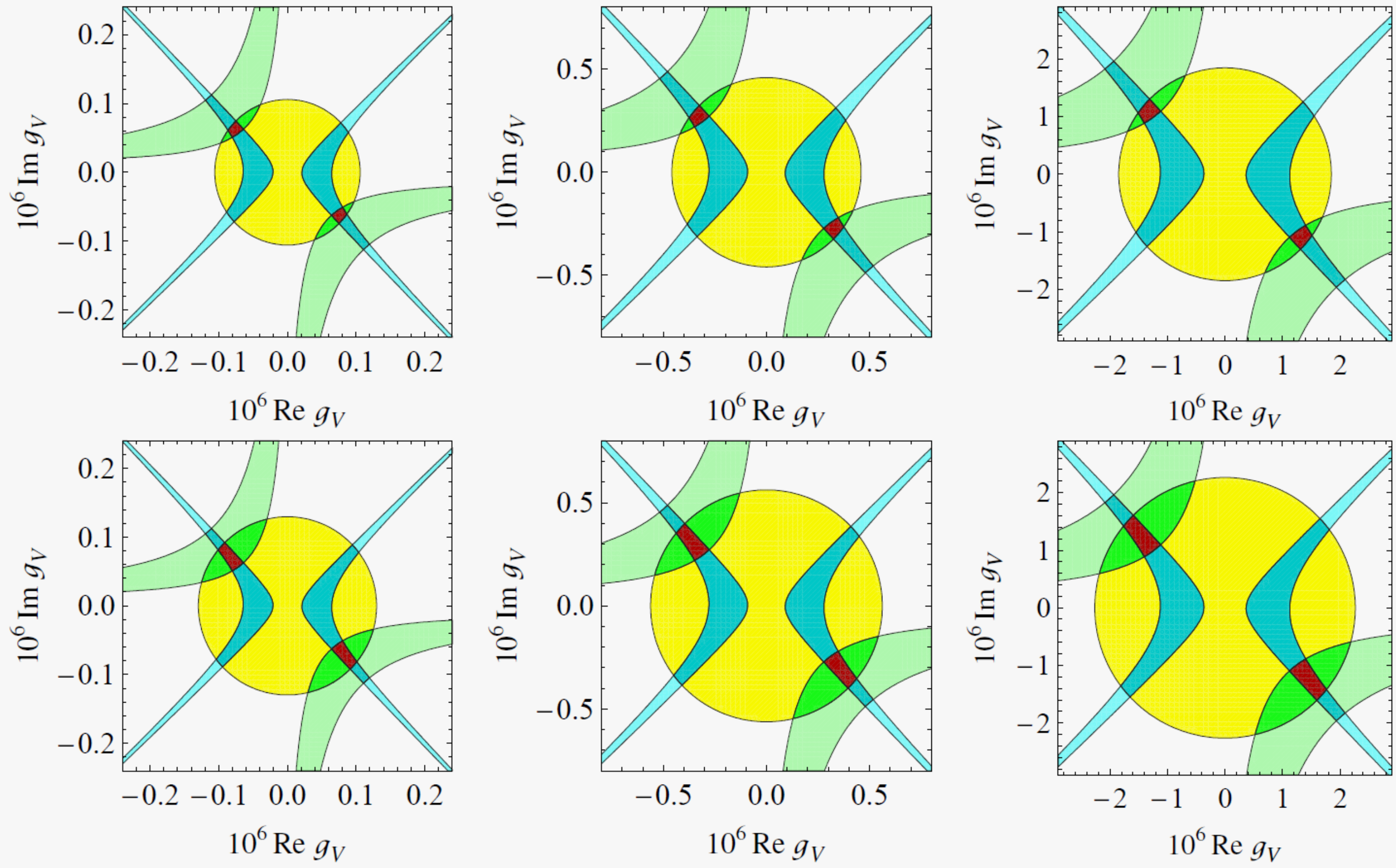


FIG. 2: Regions of Re g_V and Im g_V allowed by $a_{\rm sl}^{s,\rm exp}$ constraint (green), $\Delta M_s^{\rm exp} \Delta\Gamma_s^{\rm exp}$ constraint (blue), $\Gamma(b \to sX) < 0.1\,{\rm ps}^{-1}$ (yellow), and all of them (dark red) for $m_X = 0.5$ GeV (upper left plot), 2 GeV (upper middle plot),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

Allowed values of g_A if $g_V = 0$

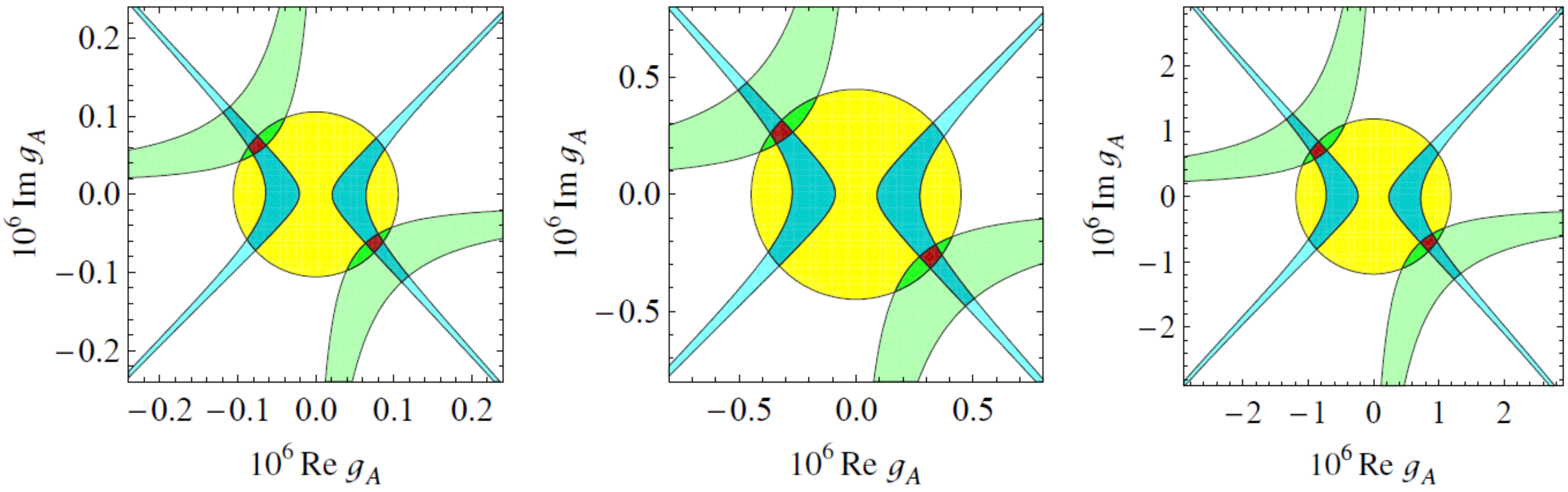


FIG. 4: Regions Re g_A and Im g_A allowed by $a_{\rm sl}^{s,\rm exp}$ constraint (green), $\Delta M_s^{\rm exp}\Delta\Gamma_s^{\rm exp}$ constraint (blue), $\Gamma(b \to sX) < 0.1\,{\rm ps}^{-1}$ (yellow), and all of them (dark red) for $m_X = 0.5$ GeV (left plot), 2 GeV (middle plot), and 4 GeV (right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

- Thus for m_X values in the 1-to-4 GeV range, $g_{V,A}$ are of order 10^{-7} to 10^{-6} with comparable real & imaginary parts.

Effects of X in more detail

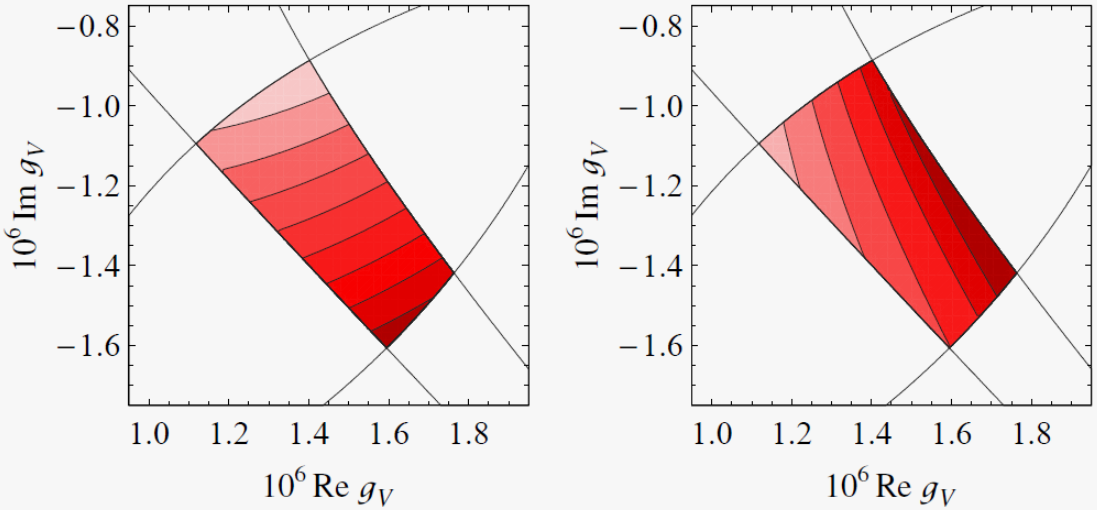


FIG. 3: Values of $|\Gamma_s^{12}|$ (left plot) and $\sin\phi_s$ (right plot) for $m_X = 4\,\mathrm{GeV}$ and the $(\mathrm{Re}\,g_V, \mathrm{Im}\,g_V)$ overlap region in the fourth quadrant of the lower-right plot in Fig. 2 allowed by all the constraints, with $\Gamma(b \to sX) < 0.15\,\mathrm{ps}^{-1}$.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

$|\Gamma_s^{12}|$ can be enhanced to 3.1 times the central value of $|\Gamma_s^{12,\mathrm{SM}}|$

the magnitude of $\sin\phi_s$ can be increased to almost 1, which is roughly a few hundred times larger than its SM value

Combining them leads to $-0.016 \lesssim a_{\mathrm{sl}}^s \lesssim -0.007$

$$a_{\mathrm{sl}}^{s,\mathrm{exp}} = -(14.6 \pm 7.5) \times 10^{-3}$$

Effects of X on rare $b \to s$ decays

- It is of interest to see if X can contribute to some other b-meson processes, perhaps with detectable effects.
- One way this can happen is if it has additional couplings to other fermions.

- Thus we assume that X has flavor-conserving couplings to the electron and muon, besides its flavor-changing ones to b & s.

- Accordingly, it can contribute to a number of rare $b \to s$ decays involving the leptons via $b \to s \ell^+ \ell^-$, where $\ell = e, \mu$.

- We consider the effects of X on
  - inclusive $\bar{B}_d \to \bar{X}_s \ell^+ \ell^-$
  - exclusive $\bar{B}_d \to \bar{K}^{(*)} \ell^+ \ell^-$ & $\bar{B}_s \to \phi \ell^+ \ell^-$
  - $\bar{B}_s \to \ell^+ \ell^-$

Interactions of X

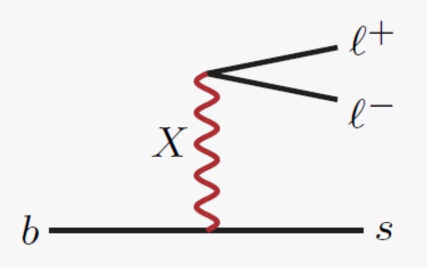
- Effective Lagrangians

$$\mathcal{L}_{bsX} \;=\; -\bar{s}\gamma^\nu\left(g_{Vs} - g_{As}\gamma_5\right)b\,X_\nu \;+\; \text{H.c.}$$

$$\mathcal{L}_{\ell X} \;=\; -\bar{\ell}\gamma^\nu\left(g_{V\ell} - g_{A\ell}\,\gamma_5\right)\ell\,X_\nu$$

$g_{V\ell}$ and $g_{A\ell}$ are real parameters because of the hermiticity of $\mathcal{L}_{\ell X}$

Inclusive $\bar{B}_d \to \bar{X}_s \ell^+ \ell^-$



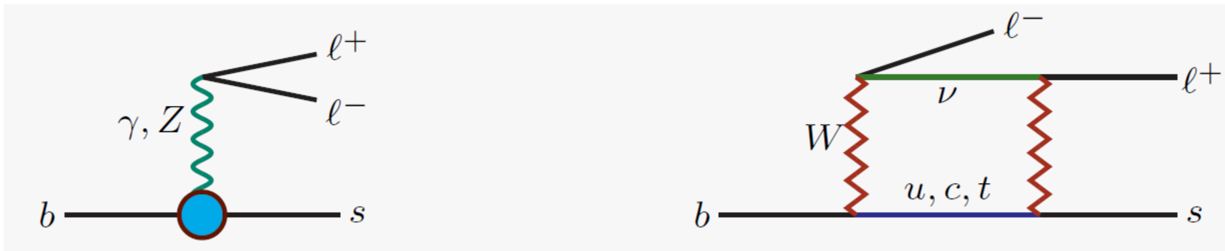
- X-induced amplitude

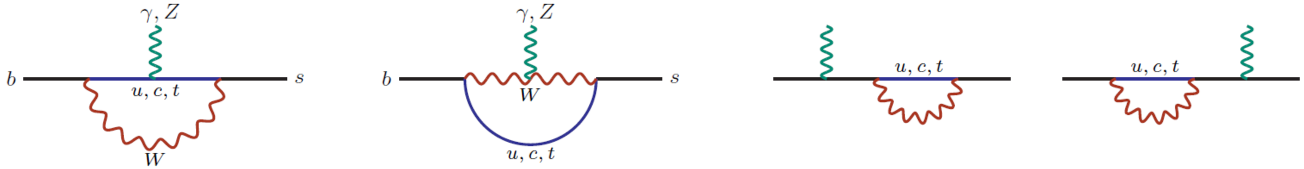
$$\mathcal{M}^X_{b\to s\bar{\ell}\ell} = -\frac{\bar{s}\gamma^\nu(g_{Vs} - g_{As}\gamma_5)b\,\bar{\ell}\gamma_\nu(g_{V\ell} - g_{A\ell}\gamma_5)\ell}{q^2 - m_X^2 + i\Gamma_X m_X} - \frac{2g_{A\ell}\,m_\ell\,\bar{s}\left[(m_b - m_s)g_{Vs} + (m_b + m_s)g_{As}\gamma_5\right]b\,\bar{\ell}\gamma_5\ell}{m_X^2\left(q^2 - m_X^2 + i\Gamma_X m_X\right)}$$

$q = p_{\ell^+} + p_{\ell^-}$ is the combined momentum of the dilepton and Γ_X the total width of X

- The q^2 dependence in the denominators distinguishes this scenario from those involving heavy new particles.

SM contribution to $\bar{B}_d \to \bar{X}_s \ell^+ \ell^-$





- SM amplitude

$$\mathcal{M}^{\rm SM}_{b\to s\bar\ell\ell} = \frac{-\alpha_{\rm e} G_{\rm F} V_{ts}^* V_{tb}}{\sqrt{2}\,\pi} \Big[C_9^{\rm eff}\, \bar s\gamma^\nu P_{\rm L} b\, \bar\ell\gamma_\nu \ell + C_{10}^{\rm eff}\, \bar s\gamma^\nu P_{\rm L} b\, \bar\ell\gamma_\nu\gamma_5 \ell - \frac{2iC_7^{\rm eff}}{q^2}\, q_\nu\, \bar s\sigma^{\beta\nu}\big(m_b P_{\rm R} + m_s P_{\rm L}\big) b\, \bar\ell\gamma_\beta \ell \Big]$$

$C^{\rm eff}_{7,9,10}$ are Wilson coefficients

$\bar{B}_d \to \bar{K}\ell^+\ell^-$

- Sum of SM & *X*-induced amplitudes

$$\mathcal{M}(\bar{B} \to \bar{K}\ell^+\ell^-) \;=\; \frac{-\alpha_e G_F \lambda_t}{2\sqrt{2}\,\pi}\Big\{A\,(p_B+p_K)^\nu\,\bar{\ell}\gamma_\nu\ell \;+\; \big[C\,(p_B+p_K)^\nu + D\,q^\nu\big]\bar{\ell}\gamma_\nu\gamma_5\ell\Big\}$$

$$q = p_{\ell+} + p_{\ell-} = p_B - p_K,$$

$$A \;=\; \left(C_9^{\rm eff} + \frac{\kappa\,g_{Vs}\,g_{V\ell}}{\Delta_X}\right)F_1 \;+\; \frac{2m_b\,C_7^{\rm eff}\,F_T}{m_B+m_K}\,, \qquad C \;=\; \left(C_{10}^{\rm eff} - \frac{\kappa\,g_{Vs}\,g_{A\ell}}{\Delta_X}\right)F_1\,,$$

$$D \;=\; C_{10}^{\rm eff}\,\frac{m_B^2-m_K^2}{q^2}\big(F_0-F_1\big) \;+\; \frac{m_B^2-m_K^2}{m_X^2\,q^2}\,\frac{\kappa\,g_{Vs}\,g_{A\ell}\,\big[F_1\,m_X^2 + F_0\big(q^2-m_X^2\big)\big]}{\Delta_X}$$

$$\lambda_t \;=\; V_{ts}^*V_{tb}\,, \qquad \kappa \;=\; \frac{2\sqrt{2}\,\pi}{\alpha_e\,G_F\,\lambda_t}\,, \qquad \Delta_X \;=\; q^2 - m_X^2 + i\Gamma_X m_X$$

$F_{0,1,T}$ are $\bar{B} \to \bar{K}$ form factors of $b \to s$ quark operators

- It's independent of g_{As}

$\bar{B}_d \to \bar{K}^{(*)}\ell^+\ell^-$

- Sum of SM & *X*-induced amplitudes

$$\mathcal{M}(\bar{B}\to\bar{K}^*\ell^+\ell^-) = \frac{-\alpha_e G_F \lambda_t}{2\sqrt{2}\,\pi}\Big\{\Big[\mathcal{A}\,\epsilon_{\beta\nu\sigma\tau}\,\varepsilon^{*\nu}p_B^\sigma p_{K^*}^\tau - i\mathcal{C}\,\varepsilon_\beta^* + i\mathcal{D}\,\varepsilon^*\!\cdot q\,(p_B+p_{K^*})_\beta\Big]\bar{\ell}\gamma^\beta\ell$$
$$+\Big[\mathcal{E}\,\epsilon_{\beta\nu\sigma\tau}\,\varepsilon^{*\nu}p_B^\sigma p_{K^*}^\tau - i\mathcal{F}\,\varepsilon_\beta^* + i\mathcal{G}\,\varepsilon^*\!\cdot q\,(p_B+p_{K^*})_\beta + i\mathcal{H}\,\varepsilon^*\!\cdot q\,q_\beta\Big]\bar{\ell}\gamma^\beta\gamma_5\ell\Big\}$$

$$\mathcal{A} = \left(C_9^{\rm eff} + \frac{\kappa\, g_{Vs}\, g_{V\ell}}{\Delta_X}\right)\frac{2\,V}{m_B+m_{K^*}} + \frac{4m_b\, C_7^{\rm eff}\, T_1}{q^2}\,,$$

$$\mathcal{C} = \left(C_9^{\rm eff} + \frac{\kappa\, g_{As}\, g_{V\ell}}{\Delta_X}\right)A_1(m_B+m_{K^*}) + 2m_b\, C_7^{\rm eff}\, T_2\,\frac{m_B^2-m_{K^*}^2}{q^2}\,,$$

$$\mathcal{D} = \left(C_9^{\rm eff} + \frac{\kappa\, g_{As}\, g_{V\ell}}{\Delta_X}\right)\frac{A_2}{m_B+m_{K^*}} + 2m_b\, C_7^{\rm eff}\left(\frac{T_2}{q^2} + \frac{T_3}{m_B^2-m_{K^*}^2}\right),$$

$$\mathcal{E} = \left(C_{10}^{\rm eff} - \frac{\kappa\, g_{Vs}\, g_{A\ell}}{\Delta_X}\right)\frac{2\,V}{m_B+m_{K^*}}\,, \qquad \mathcal{F} = \left(C_{10}^{\rm eff} - \frac{\kappa\, g_{As}\, g_{A\ell}}{\Delta_X}\right)A_1(m_B+m_{K^*})\,,$$

$$\mathcal{G} = \left(C_{10}^{\rm eff} - \frac{\kappa\, g_{As}\, g_{A\ell}}{\Delta_X}\right)\frac{A_2}{m_B+m_{K^*}}\,,$$

$$\mathcal{H} = \left(C_{10}^{\rm eff} - \frac{\kappa\, g_{As}\, g_{A\ell}}{\Delta_X}\right)\frac{(A_1-A_2)m_B + (A_1-2A_0+A_2)m_{K^*}}{q^2} - \frac{2\kappa\, g_{As}\, g_{A\ell}\, A_0 m_{K^*}}{\Delta_X\, m_X^2}$$

V, $A_{0,1,2}$, and $T_{1,2,3}$ are $\bar{B}\to\bar{K}^*$ form factors of $b\to s$ operators

Observables in $\bar{B}_d \to \bar{K}^{(*)} \ell^+ \ell^-$

- Branching ratios of $\bar{B}_d \to \bar{K}^{(*)} \ell^+ \ell^-$

- $\bar{K}^*$ longitudinal polarization fraction F_L and lepton forward-backward asymmetry $A_{\rm FB}$ in $\bar{B}_d \to \bar{K}^* \ell^+ \ell^-$

$$\frac{1}{d\Gamma\big(\bar{B} \to \bar{K}^* \ell^+ \ell^-\big)/dq^2} \frac{d^2\Gamma\big(\bar{B} \to \bar{K}^* \ell^+ \ell^-\big)}{dq^2\, d(\cos\theta)} = \frac{3}{4}\big(1 - \cos^2\theta\big) F_L + \frac{3}{8}\big(1 + \cos^2\theta\big)\big(1 - F_L\big) + A_{\rm FB} \cos\theta \ ,$$

- They have been measured by BaBar, Belle, and CDF
  - will be measured at LHCb and future *B* factories

Allowed parameter space subject to constraints

- Constraints used are from data on
  - $\mathcal{B}(B \to X_s \ell^+\ell^-)$
  - $\mathcal{B}(B \to K^{(*)} \ell^+\ell^-)$
  - $\mathcal{B}\big(B \to (J/\psi, \psi')K^{(*)},\ (J/\psi, \psi') \to \ell^+\ell^-\big)$
  - anomalous magnetic moments of electron and muon.

- We find that there is available parameter space of X that is consistent with the data
  - regardless of whether or not the anomalous result from D0 will be corroborated by future measurements.

- The allowed ranges of the couplings (g_{Vs}, g_{As}) & $(g_{V\ell}, g_{A\ell})$ vary widely and depend on m_X & Γ_X.

Constraints from $\mathcal{B}(B \to X_s \ell^+ \ell^-)$

$$\mathcal{B}^{\rm low}_{\rm exp}(\bar B \to X_s \ell^+ \ell^-) = (1.6 \pm 0.5) \times 10^{-6} , \qquad \mathcal{B}^{\rm high}_{\rm exp}(\bar B \to X_s \ell^+ \ell^-) = (4.4 \pm 1.2) \times 10^{-7}$$

low- and high-q^2 ranges $1\,{\rm GeV}^2 \le q^2 \le 6\,{\rm GeV}^2$ and $q^2 \ge 14.4\,{\rm GeV}^2$, respectively

$$\mathcal{B}^{\rm low}_{\rm SM}(\bar B \to X_s e^+ e^-) = (1.64 \pm 0.11) \times 10^{-6}$$
$$\mathcal{B}^{\rm high}_{\rm SM}(\bar B \to X_s e^+ e^-) = 2.09 \times 10^{-7} \left(1^{+0.32}_{-0.30}\right)$$

$$\mathcal{B}^{\rm low}_{\rm SM}(\bar B \to X_s \mu^+ \mu^-) = (1.59 \pm 0.11) \times 10^{-6}$$
$$\mathcal{B}^{\rm high}_{\rm SM}(\bar B \to X_s \mu^+ \mu^-) = 2.40 \times 10^{-7} \left(1^{+0.29}_{-0.26}\right)$$

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$$-5 \times 10^{-7} \le \mathcal{B}^{\rm low}_X(\bar B \to X_s \ell^+ \ell^-) \le 4 \times 10^{-7} , \qquad 0 \le \mathcal{B}^{\rm high}_X(\bar B \to X_s \ell^+ \ell^-) \le 3.5 \times 10^{-7}$$

$$\mathcal{B}_X\left(\bar B \to X_s \ell^+ \ell^-\right) = \tau_B \Gamma^X_{b \to s \bar\ell \ell}$$

$$\tau_B = \tfrac{1}{2}\left(\tau_{B^+} + \tau_{B^0}\right) = 1.582\,{\rm ps}$$

Constraints from $\mathcal{B}(B \to K^{(*)} \ell^+\ell^-)$

TABLE I: Experimental branching-ratios of $B \to K^{(*)}\ell^+\ell^-$ from Belle [12] and $B^{+(0)} \to K^{+(*0)}\mu^+\mu^-$ from CDF [13], in units of 10^{-7}, used to constrain the X contributions, for different q^2 ranges. The statistical and systematic errors have been combined in quadrature.

q^2 (GeV^2)	$\mathcal{B}(B \to K\ell^+\ell^-)$	$\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	$\mathcal{B}(B \to K^*\ell^+\ell^-)$	$\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)$
$[1, 6]$	$1.36^{+0.24}_{-0.22}$	1.01 ± 0.27	$1.49^{+0.47}_{-0.42}$	1.60 ± 0.56
$[14.18, 16]$	-	-	$1.05^{+0.30}_{-0.27}$	1.51 ± 0.38
> 16	-	-	$2.04^{+0.31}_{-0.29}$	1.35 ± 0.39

TABLE II: Standard-model predictions for branching-ratios of $B \to K^{(*)}\ell^+\ell^-$, in units of 10^{-7}, for different q^2 ranges, from Refs. [26].

q^2 (GeV^2)	$\mathcal{B}(B \to K\ell^+\ell^-)$	$\mathcal{B}(B \to K^*\ell^+\ell^-)$
$[1, 6]$	$1.53^{+0.49}_{-0.45}$	$2.60^{+1.82}_{-1.34}$
$[14.18, 16]$	-	$1.32^{+0.43}_{-0.36}$
> 16	-	$1.54^{+0.48}_{-0.42}$

$$-0.7 \times 10^{-7} \le \mathcal{B}_X\left(\bar{B} \to \bar{K}\ell^+\ell^-\right)_{q^2\in[1,6]\,\mathrm{GeV}^2} \le 0.4 \times 10^{-7},$$

$$-3 \times 10^{-7} \le \mathcal{B}_X\left(\bar{B} \to \bar{K}^*\ell^+\ell^-\right)_{q^2\in[1,6]\,\mathrm{GeV}^2} \le 0.5 \times 10^{-7},$$

$$-0.5 \times 10^{-7} \le \mathcal{B}_X\left(\bar{B} \to \bar{K}^*\ell^+\ell^-\right)_{q^2\in[14.18,16]\,\mathrm{GeV}^2} \le 0.7 \times 10^{-7},$$

$$-0.1 \times 10^{-7} \le \mathcal{B}_X\left(\bar{B} \to \bar{K}^*\ell^+\ell^-\right)_{q^2>16\,\mathrm{GeV}^2} \le 1.1 \times 10^{-7},$$

$$\mathcal{B}_X\left(\bar{B} \to \bar{K}^{(*)}\ell^+\ell^-\right) = \tau_B \Gamma_X\left(\bar{B} \to \bar{K}^{(*)}\ell^+\ell^-\right)$$

Constraints from $\mathcal{B}(B\to(J/\psi,\psi')K^{(*)}, (J/\psi,\psi')\to\ell^+\ell^-)$

- SM predictions for $\mathcal{B}(B\to(J/\psi,\psi')K^{(*)})$ have large errors

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$$\mathcal{B}(J/\psi \to \ell^+\ell^-) \simeq 5.9\%$$

$$\mathcal{B}(\psi' \to \ell^+\ell^-) \simeq 0.77\%$$

$$-3\times10^{-5} \;\le\; \mathcal{B}_X\big(\bar B\to\bar K\ell^+\ell^-\big)_{q^2\in[8.6,10.2]\,\mathrm{GeV}^2} \;\le\; 5\times10^{-5}\,,$$

$$-1\times10^{-5} \;\le\; \mathcal{B}_X\big(\bar B\to\bar K^*\ell^+\ell^-\big)_{q^2\in[8.6,10.2]\,\mathrm{GeV}^2} \;\le\; 7\times10^{-5}\,,$$

$$-1\times10^{-6} \;\le\; \mathcal{B}_X\big(\bar B\to\bar K^{(*)}\ell^+\ell^-\big)_{q^2\in[12.8,14.2]\,\mathrm{GeV}^2} \;\le\; 4\times10^{-6}$$

Examples of allowed $(g_{V\ell}, g_{A\ell})g_{Vs}$ ranges

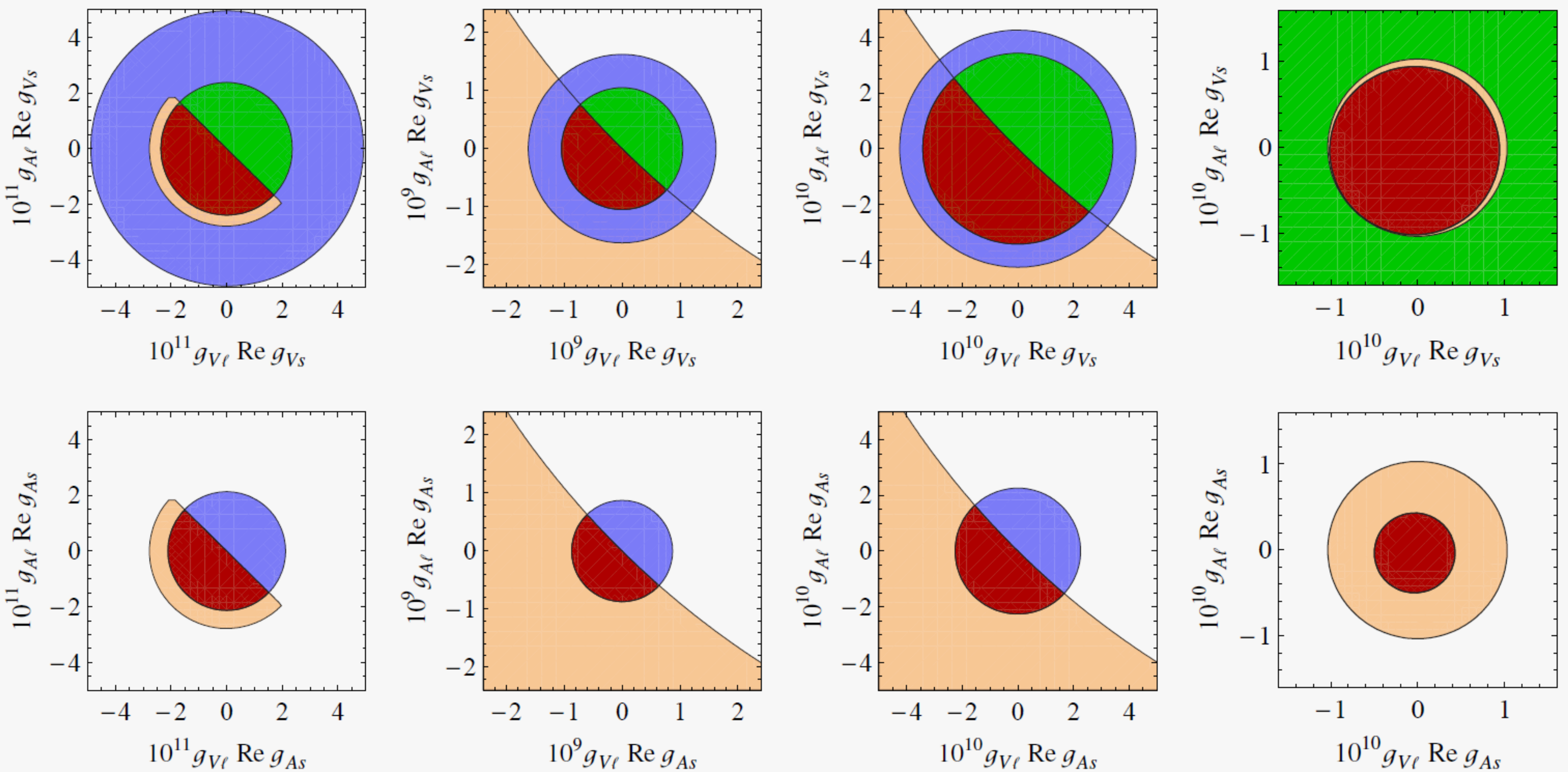


FIG. 1: Regions of $(g_{V\ell}, g_{A\ell})\,\mathrm{Re}\,g_{Vs}$ for $\mathrm{Im}\,g_{Vs} = g_{As} = 0$ (top plots) and of $(g_{V\ell}, g_{A\ell})\,\mathrm{Re}\,g_{As}$ for $\mathrm{Im}\,g_{As} = g_{Vs} = 0$ (bottom plots) satisfying constraints from $\bar{B} \to X_s \ell^+\ell^-$ (orange, lightly shaded), $\bar{B} \to \bar{K}\ell^+\ell^-$ (green, medium shaded), $\bar{B} \to \bar{K}^*\ell^+\ell^-$ (blue, heavily shaded), and all of them (dark red). From left to right, the plots correspond to $m_X = 2$, 3, 3.7, and 4 GeV, all obtained with $\Gamma_X = 0.1\,\mathrm{MeV}$.

Examples of allowed $(g_{V\ell}, g_{A\ell})g_{Vs}$ ranges

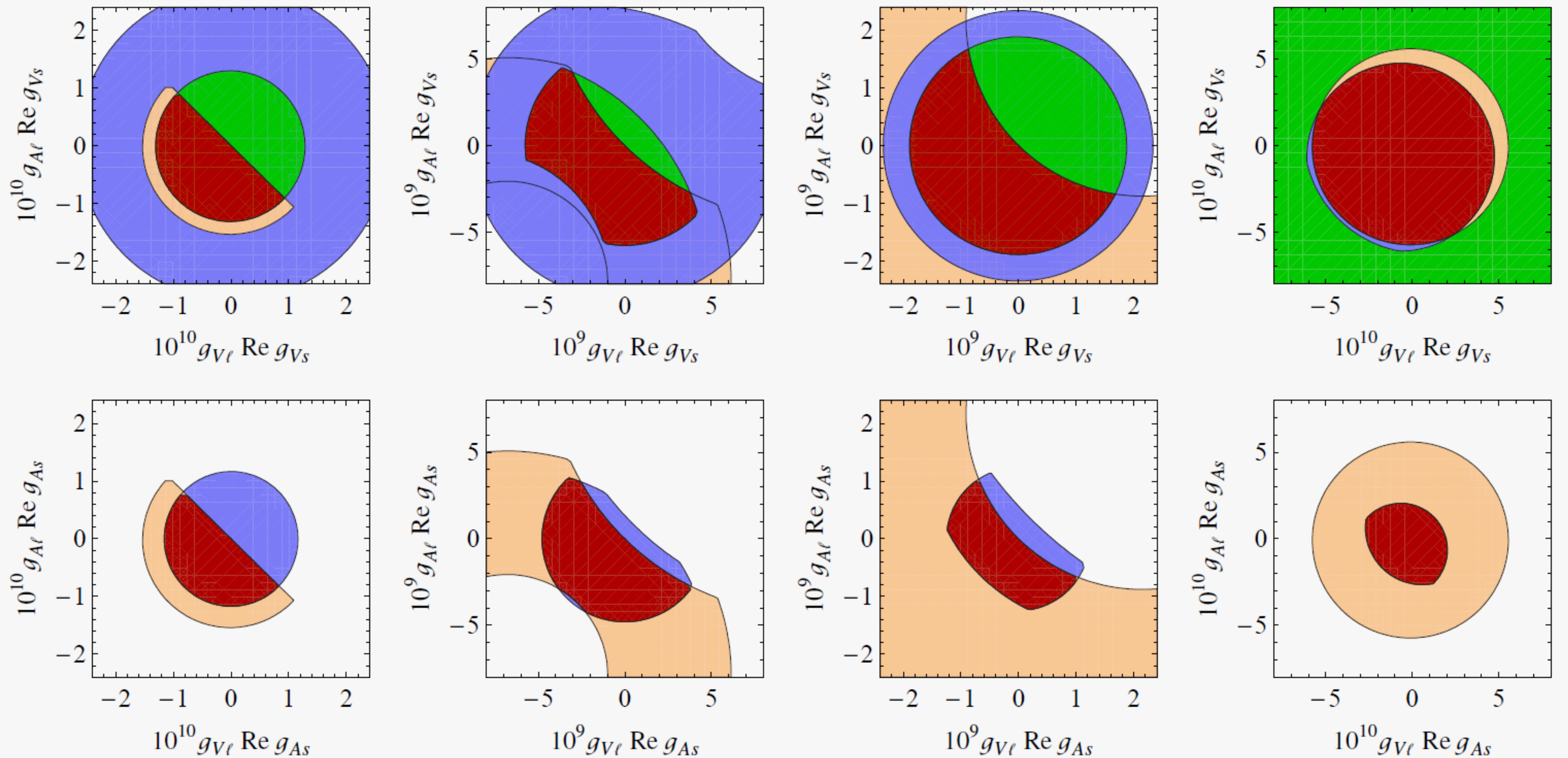


FIG. 2: The same as Fig. 1, but with $\Gamma_X = 3\,\mathrm{MeV}$.

Anomalous magnetic moments of leptons

- X contribution

$$a_\ell^X(m_X) \;=\; \frac{m_\ell^2}{4\pi^2 m_X^2}\left(g_{V\ell}^2\, f_V(r) + g_{A\ell}^2\, f_A(r)\right)$$

$$r = m_\ell^2/m_X^2,$$

$$f_V(r) \;=\; \int_0^1 dx\, \frac{x^2 - x^3}{1 - x + r x^2}\,, \qquad f_A(r) \;=\; \int_0^1 dx\, \frac{-4x + 5x^2 - (1+2r)x^3}{1 - x + r x^2}$$

$$a_e^X(2\,\mathrm{GeV}) \;=\; \left(5.5\, g_{Ve}^2 - 27.6\, g_{Ae}^2\right) \times 10^{-10}\,, \qquad a_\mu^X(2\,\mathrm{GeV}) \;=\; \left(22.8\, g_{V\mu}^2 - 117\, g_{A\mu}^2\right) \times 10^{-6}\,,$$

$$a_e^X(3\,\mathrm{GeV}) \;=\; \left(2.4\, g_{Ve}^2 - 12.2\, g_{Ae}^2\right) \times 10^{-10}\,, \qquad a_\mu^X(3\,\mathrm{GeV}) \;=\; \left(10.3\, g_{V\mu}^2 - 52.2\, g_{A\mu}^2\right) \times 10^{-6}\,,$$

$$a_e^X(3.7\,\mathrm{GeV}) \;=\; \left(1.6\, g_{Ve}^2 - 8.1\, g_{Ae}^2\right) \times 10^{-10}\,, \qquad a_\mu^X(3.7\,\mathrm{GeV}) \;=\; \left(6.8\, g_{V\mu}^2 - 34.3\, g_{A\mu}^2\right) \times 10^{-6}\,,$$

$$a_e^X(4\,\mathrm{GeV}) \;=\; \left(1.4\, g_{Ve}^2 - 6.9\, g_{Ae}^2\right) \times 10^{-10}\,, \qquad a_\mu^X(4\,\mathrm{GeV}) \;=\; \left(5.8\, g_{V\mu}^2 - 29.4\, g_{A\mu}^2\right) \times 10^{-6}\,.$$

Constraints from lepton g-2

$$a_e^{\rm exp} = (115965218073 \pm 28) \times 10^{-14}$$

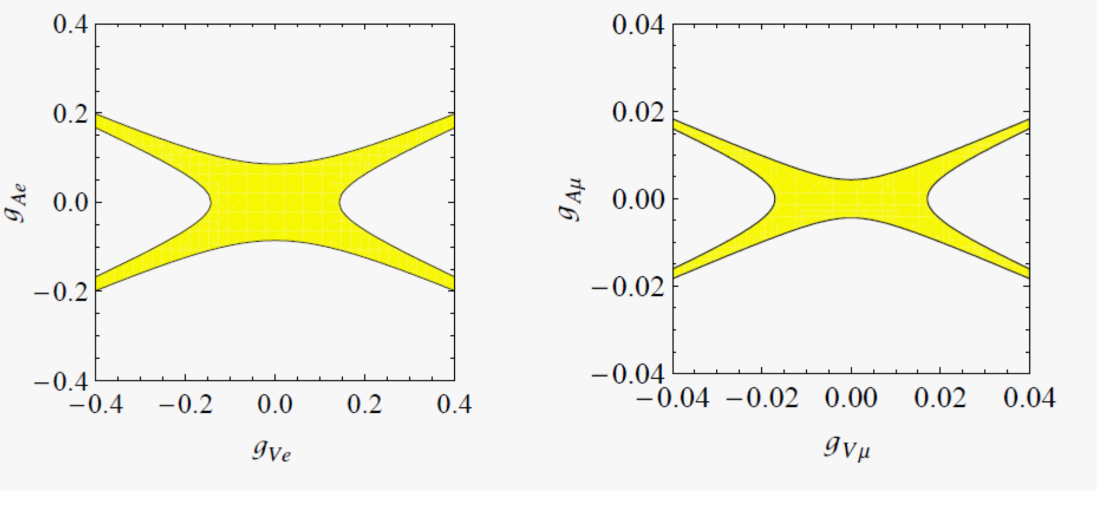
$$a_e^{\rm exp} - a_e^{\rm SM} = (-206 \pm 770) \times 10^{-14}$$

$$a_\mu^{\rm exp} = (11659209 \pm 6) \times 10^{-10}$$

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (29 \pm 9) \times 10^{-10}$$

$$-9 \times 10^{-12} \le a_e^X \le 5 \times 10^{-12}\,, \qquad -1 \times 10^{-9} \le a_\mu^X \le 3 \times 10^{-9}$$

- For m_X = 3 GeV



Couplings compatible with D0 dimuon anomaly

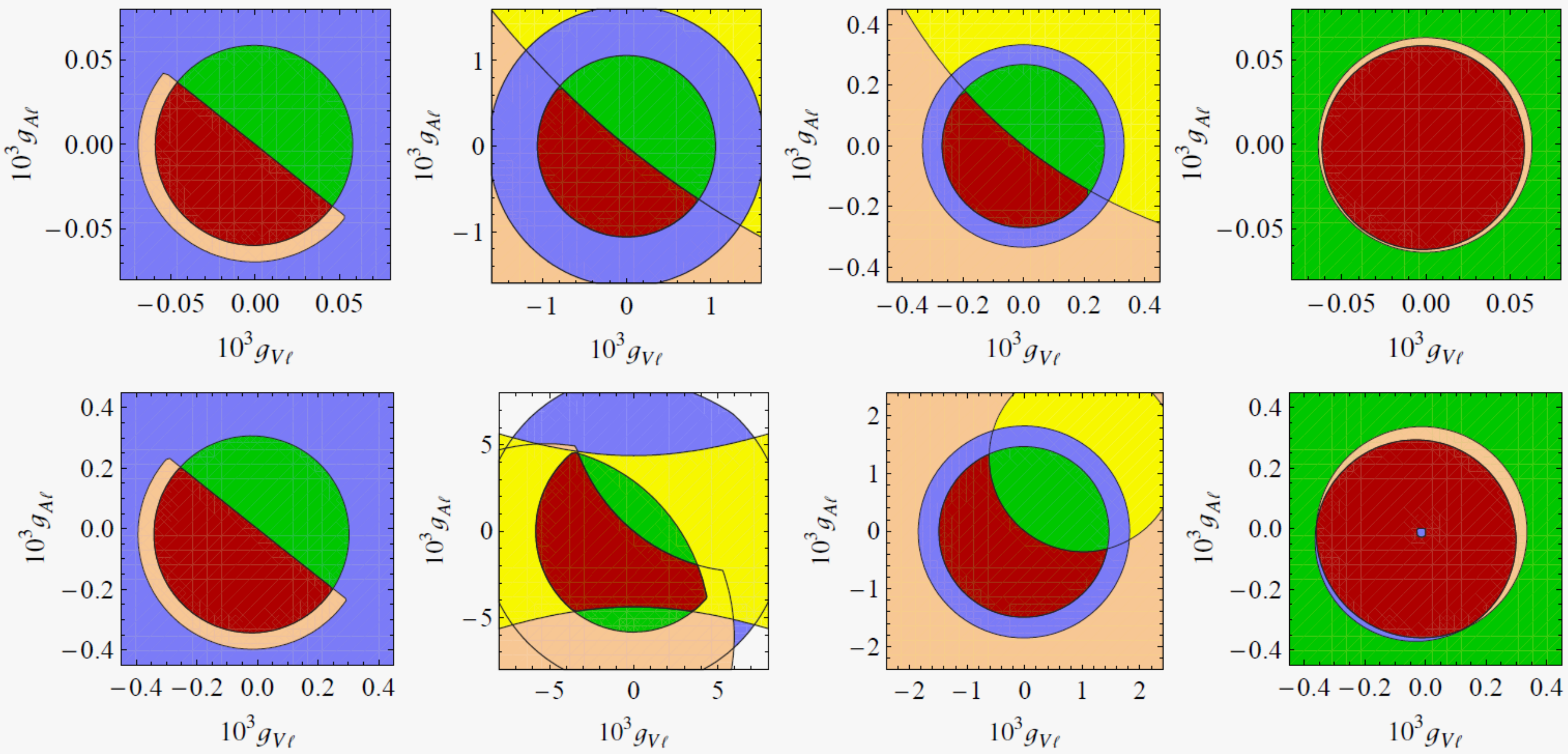


FIG. 4: Allowed ranges of $g_{V\ell}$ and $g_{A\ell}$ for $g_{As} = 0$ and g_{Vs} values given in the text, subject to constraints from $B \to X_s \ell^+ \ell^-$ (orange, lightly shaded), $B \to K \ell^+ \ell^-$ (green, medium shaded), $B \to K^* \ell^+ \ell^-$ (blue, heavily shaded), a_μ (yellow, very lightly shaded), and all of them (dark red). The plots from left to right correspond to $m_X = 2$, 3, 3.7, and 4 GeV, and all the top (bottom) ones to $\Gamma_X = 0.1\,\mathrm{MeV}$ ($3\,\mathrm{MeV}$).

Predictions

- Since X couplings to other particles are not specified, its total width Γ_X is unknown.

- Illustrative choices of couplings

for $\Gamma_X = 0.1\,\mathrm{MeV}$

$$(g_{V\ell},\, g_{A\ell})g_{Vs} \;=\; \begin{cases} (1,\, -2) \times 10^{-11} & \text{for} \quad m_X = 2 \text{ GeV} \\ (-1,\, 0.2) \times 10^{-9} & \text{for} \quad m_X = 3 \text{ GeV} \\ (1,\, -3) \times 10^{-10} & \text{for} \quad m_X = 3.7 \text{ GeV} \\ (-0.9,\, 0.3) \times 10^{-10} & \text{for} \quad m_X = 4 \text{ GeV} \end{cases}$$

and for $\Gamma_X = 3\,\mathrm{MeV}$

$$(g_{V\ell},\, g_{A\ell})g_{Vs} \;=\; \begin{cases} (5,\, -11) \times 10^{-11} & \text{for} \quad m_X = 2 \text{ GeV} \\ (-5,\, 2) \times 10^{-9} & \text{for} \quad m_X = 3 \text{ GeV} \\ (9,\, -16) \times 10^{-10} & \text{for} \quad m_X = 3.7 \text{ GeV} \\ (-5,\, 2) \times 10^{-10} & \text{for} \quad m_X = 4 \text{ GeV} \end{cases}$$

Effects of X on $\mathcal{B}(B \to K^{(*)} \ell^+ \ell^-)$

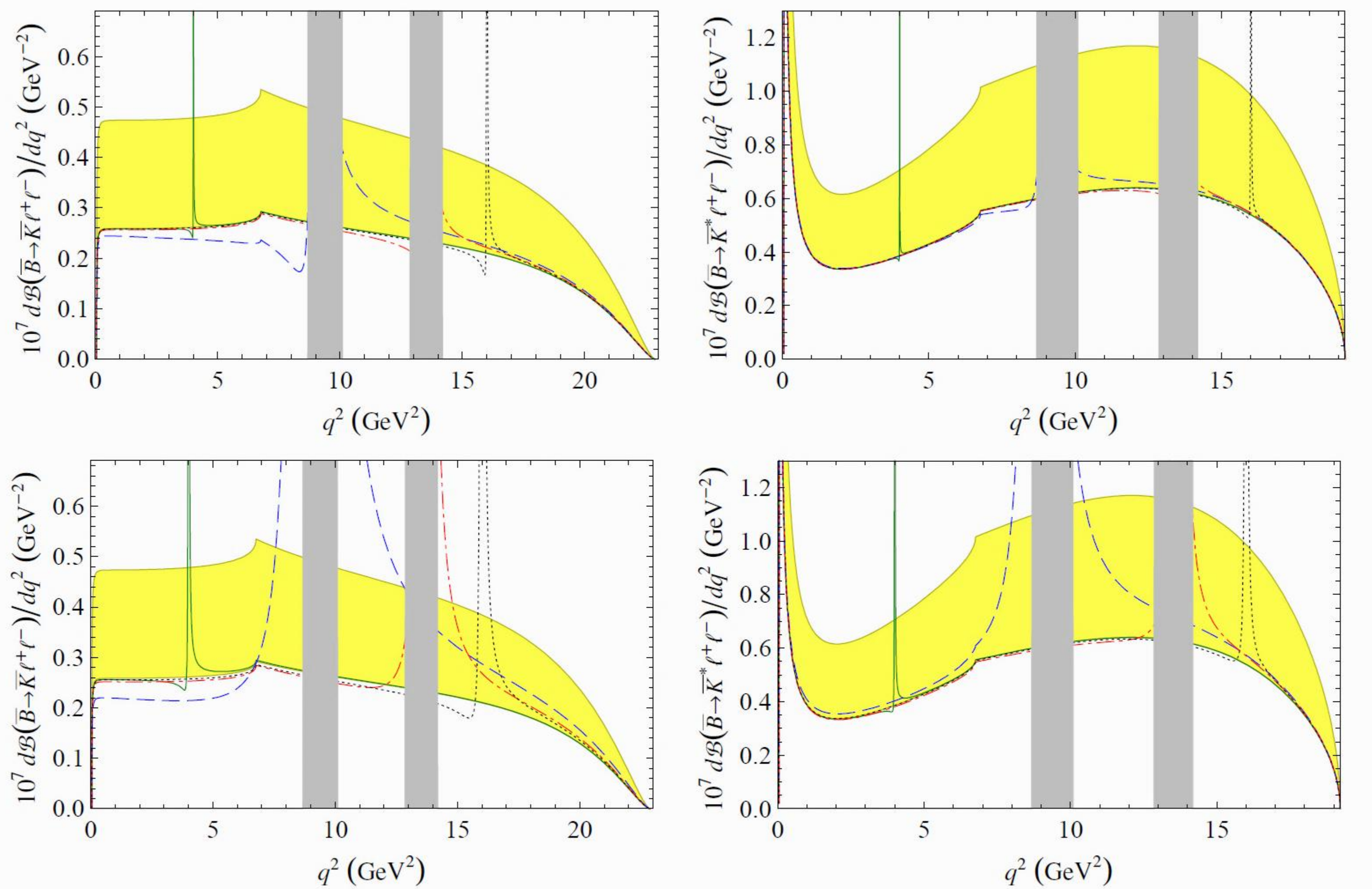


FIG. 5: Differential branching ratios of $\bar{B} \to \bar{K}\ell^+\ell^-$ (left plots) and $\bar{B} \to \bar{K}^*\ell^+\ell^-$ (right plots) as functions of the squared dilepton-mass in the SM (yellow curved bands) and its combination with the X contribution for $m_X = 2\,\mathrm{GeV}$ (green solid curves), $3\,\mathrm{GeV}$ (blue dashed curves), $3.7\,\mathrm{GeV}$ (red dot-dashed curves), and $4\,\mathrm{GeV}$ (black dotted curves), with the $g_{V\ell,A\ell}\, g_{Vs}$ numbers in Eq. (29) (Eq. (30)) and $\Gamma_X = 0.1\,\mathrm{MeV}$ ($3\,\mathrm{MeV}$) used in the top (bottom) plots.

Effects of X on F_L and A_{FB} in $B \to K^{(*)} \ell^+ \ell$

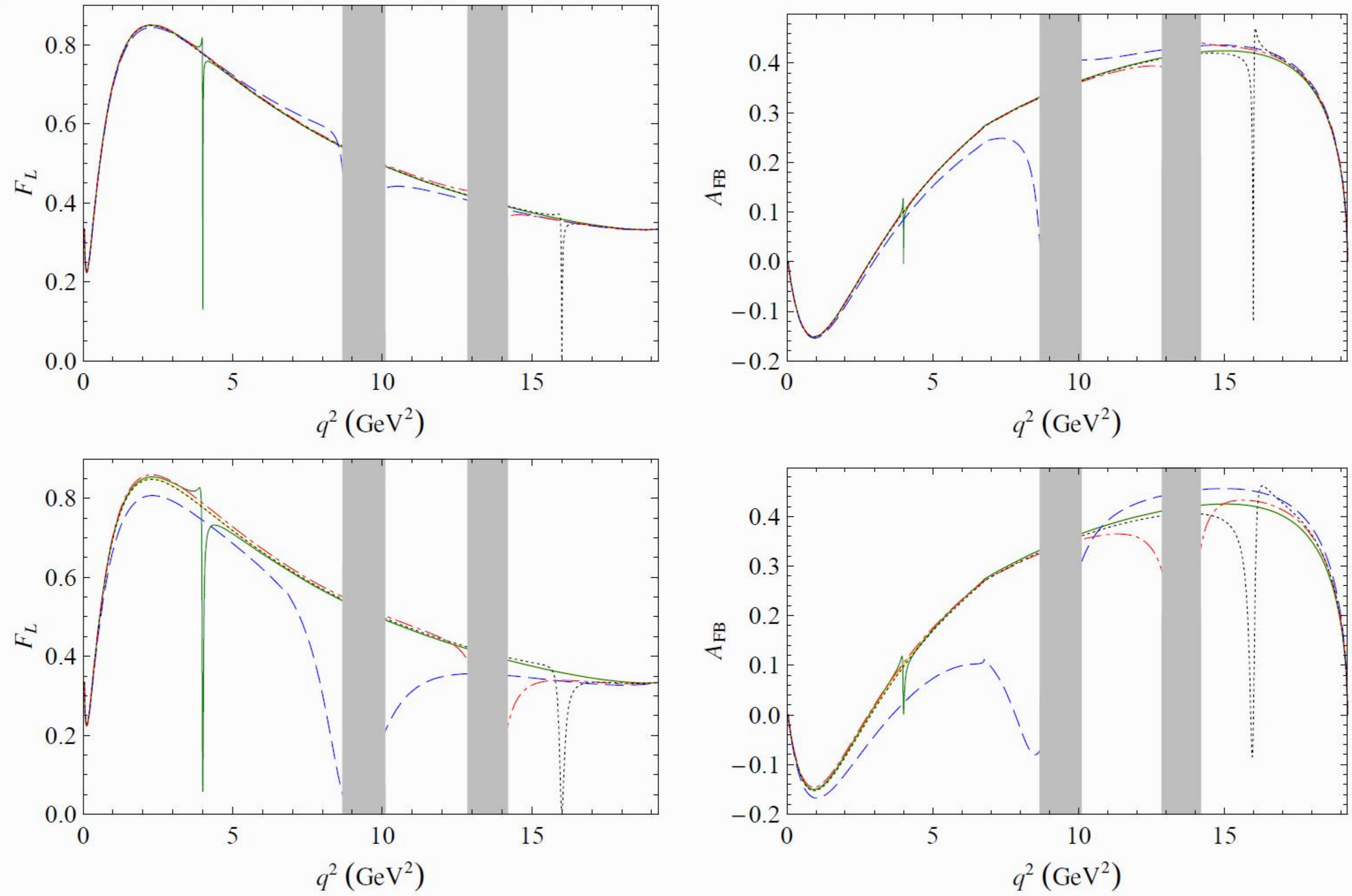


FIG. 6: Plots of $\bar{K}^*$ longitudinal polarization fraction (left) and lepton forward-backward asymmetry (right) for $\bar{B} \to \bar{K}^* \ell^+ \ell^-$ in the SM (solid curves) and its combination with the X contribution for $m_X = 2\,\mathrm{GeV}$ (green solid curves), $3\,\mathrm{GeV}$ (blue dashed curves), $3.7\,\mathrm{GeV}$ (red dot-dashed curves), and $4\,\mathrm{GeV}$ (black dotted curves), with the $g_{V\ell,A\ell}\, g_{Vs}$ numbers in Eq. (29) (Eq. (30)) and $\Gamma_X = 0.1\,\mathrm{MeV}$ ($3\,\mathrm{MeV}$) used in the top (bottom) plots.

$\bar{B}_s \to \ell^+\ell^-$

- Amplitudes

$$\mathcal{M}^X_{\bar{B}_s\to\ell^+\ell^-} = \frac{-2i f_{B_s} g_{As} g_{A\ell} m_\ell}{m_X^2} \bar{\ell}\gamma_5\ell$$

$$\mathcal{M}^{\rm SM}_{\bar{B}_s\to\ell^+\ell^-} = \frac{-i\alpha_{\rm e} G_{\rm F}\lambda_t f_{B_s} m_\ell}{\sqrt{2}\,\pi} C_{10}^{\rm eff} \bar{\ell}\gamma_5\ell$$

- Rate

$$\Gamma\left(\bar{B}_s \to \ell^+\ell^-\right) = \frac{\alpha_{\rm e}^2 G_{\rm F}^2 |\lambda_t|^2 f_{B_s}^2 m_\ell^2}{16\pi^3} \left| C_{10}^{\rm eff} + \frac{\kappa\, g_{As} g_{A\ell}}{m_X^2} \right|^2 \sqrt{m_{B_s}^2 - 4m_\ell^2}$$

- It's independent of g_{Vs}

$\bar{B}_s \to \ell^+\ell^-$

- Experimental limits

$$\mathcal{B}_{\rm exp}(B_s \to e^+e^-) < 2.8 \times 10^{-7}\,, \qquad \mathcal{B}_{\rm exp}(B_s \to \mu^+\mu^-) < 3.2 \times 10^{-8}$$

- SM expectations

$$\mathcal{B}_{\rm SM}(B_s \to e^+e^-) \simeq 7.5 \times 10^{-14}\,, \qquad \mathcal{B}_{\rm SM}(B_s \to \mu^+\mu^-) \simeq 3.2 \times 10^{-9}$$

- Examples of effect of *X*

$$-4.8 \times 10^{-9} \lesssim g_{As}\, g_{A\ell} \lesssim 3.5 \times 10^{-9}$$

$$3.4 \times 10^{-14} \lesssim \mathcal{B}(B_s \to e^+e^-) \lesssim 11 \times 10^{-14}$$
$$1.5 \times 10^{-9} \lesssim \mathcal{B}(B_s \to \mu^+\mu^-) \lesssim 4.9 \times 10^{-9}$$

- The *X* contributions are easily accommodated by present experimental limits and can produce significant modifications to the SM predictions.

Conclusions

- We have explored the possibility that the D0 dimuon anomaly arises from the contribution of a new light spin-1 boson, *X*, to $B_s - \bar{B}_s$ mixing.
- The *X* contribution can lead to a prediction consistent with the D0 measurement within its 1-sigma range and possibly even reaches its central value.
- We have subsequently explored the possibility that *X* also has flavor-conserving couplings to charged leptons, besides its flavor-changing ones to *b* & *s*.
- Then it can contribute to some of the rare $b \to s$ decays to be measured at LHCb and future B factories.
- With greater precision, they will probe the existence of *X*, or its couplings, stringently.