TESTING A SPIN-2 MEDIATOR IN $b \to s\mu^+\mu^-$ DECAYS

BLAZENKA MELIC

Theoretical Physics Division

Rudjer Boskovic Institute, Zagreb

arXiv 1801.07115 in collaboration with Svjetlana Fajfer & Monalisa Patra (IJS, Ljubljana)

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SPIN-2 PARTICLE

- ❑ SPIN-2 PARTICLE – as a low-energy signature independent on the UV completition
  - possible existance in lattice QCD as spin-2 long-lived glueballs
  - in modified gravity – in theories with large dimensions, wrapped or extra dimensions

- ❑ we will consider non-universal couplings with the matter (e.g. RS-type models with the SM field localized differently in the bulk)

- ❑ study of implications of such a massive (complex) spin-2 boson on anomalies in $b \to s\mu^+\mu^-$ decays assuming that in the lepton sector spin-2 particle couples only to muons

FRAMEWORK (I)

Lagrangian of a spin-2 field (Fierz-Pauli linearized term):

$$\boxed{\mathcal{L}_{PF}=-\frac{1}{2}G^{\dagger}_{\mu\nu}(\Box+M^2)G^{\mu\nu}+\frac{1}{2}G^{\mu\dagger}_{\mu}(\Box+M^2)G^{\nu}_{\nu}-G^{\dagger}_{\mu\nu}\partial^{\mu}\partial^{\nu}G^{\rho}_{\rho}+G^{\dagger}_{\mu\nu}\partial^{\mu}\partial^{\rho}G^{\nu}_{\rho}+h.c.}$$

Lagrangian of a spin-2 field interacting with the matter:

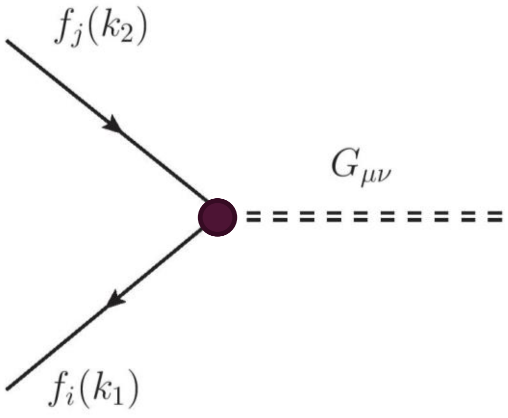
$$\boxed{\mathcal{L}_5=-\frac{i}{4\Lambda}\left\{a^L_{ij}\left[\bar{\psi}_i\left(\gamma_\mu\partial_\nu+\gamma_\nu\partial_\mu\right)P_L\psi_j\right]+b^L_{ij}\left[\left(\partial_\nu\bar{\psi}_i\gamma_\mu+\partial_\mu\bar{\psi}_i\gamma_\nu\right)P_L\psi_j\right]\right\}G^{\mu\nu}+(L\to R)}$$

$$a^{L,R}_{ij}=-b^{L,R}_{ij}$$

$$\left.\begin{aligned}&\mathcal{L}_4\subset-G^{\mu}_{\mu}\lambda_{ij}\bar{\psi}_i\psi_j+h.c.\\ &\mathcal{L}'_5=-\frac{1}{2\Lambda}\eta_{\mu\nu}\left\{c^L_{ij}\bar{\Psi}_i i\gamma_\rho\partial^\rho\Psi_j\right\}G^{\mu\nu}+(L\to R)\end{aligned}\right\}$$

produce scalar/pseudoscalar operators which contributions are highly suppressed in $b\to s\mu^+\mu^-$ decays

FRAMEWORK (II)



Feynman rule – spin-2 boson interaction with fermions:

$$\frac{-1}{4\Lambda}(X_{\mu\nu}+X_{\nu\mu}) \qquad X_{\mu\nu} = a^L_{ij}\gamma_\mu(k_{1\nu}+k_{2\nu})P_L + a^R_{ij}\gamma_\mu(k_{1\nu}+k_{2\nu})P_R$$

Feynman rule – spin-2 boson propagator:

$$P_{\mu\nu,\rho\sigma}(q^2) = \frac{i}{q^2-m_G^2}\left[\left(\eta_{\mu\rho}-\frac{q_\mu q_\rho}{m_G^2}\right)\left(\eta_{\nu\sigma}-\frac{q_\nu q_\sigma}{m_G^2}\right)+\left(\eta_{\nu\rho}-\frac{q_\nu q_\rho}{m_G^2}\right)\left(\eta_{\mu\sigma}-\frac{q_\mu q_\sigma}{m_G^2}\right)-\frac{2}{3}\left(\eta_{\mu\nu}-\frac{q_\mu q_\nu}{m_G^2}\right)\left(\eta_{\rho\sigma}-\frac{q_\rho q_\sigma}{m_G^2}\right)\right]$$

for $q^2 << m_G^2$:

$$\frac{1}{q^2-m_G^2} = -\frac{1}{m_G^2}\left[\frac{1}{1-q^2/m_G^2}\right] = -\frac{1}{m_G^2}\left[1+\frac{q^2}{m_G^2}+\frac{q^4}{m_G^4}+\cdots\right]$$

Choi, Shim, Song, hep-th/9411092
Guidice, Rattazzi, Wells, hep-ph/9811291
Han, Lykken, Zhang, hep-ph/9811350
G instein et al, hep-ph/1203 2183

EFFECTIVE LAGRANGIAN FOR $b \to s\mu^+\mu^-$ TRANSITIONS

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big(\sum_i C_i(\mu)\mathcal{O}_i(\mu) + C_i'(\mu)\mathcal{O}_i'(\mu) + \sum_{j;h.d.} C_j^{h.d.}\mathcal{O}_j^{h.d.}\Big) + \text{h.c}$$

dim=6 SM operators

$$\mathcal{O}_7 = \frac{e^2}{g^2} m_b (\bar{s}\sigma_\mu P_R b)F^{\mu\nu}$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_7' = \frac{e^2}{g^2} m_b (\bar{s}\sigma_\mu P_L b)F^{\mu\nu}$$

$$\mathcal{O}_9' = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10}' = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

dim=6 BSM operators

$$\mathcal{O}_P = \frac{e^2}{16\pi^2}(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell) \qquad \mathcal{O}_P' = \frac{e^2}{16\pi^2}(\bar{s}P_L b)(\bar{\ell}\gamma_5 \ell)$$

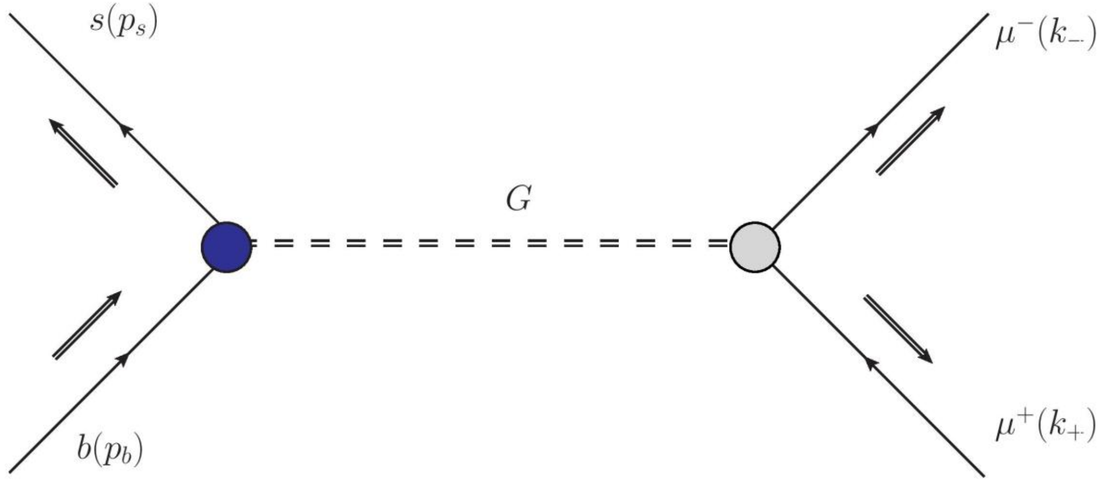
$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}P_R b)(\bar{\ell}\ell) \qquad \mathcal{O}_S' = \frac{e^2}{16\pi^2}(\bar{s}P_L b)(\bar{\ell}\ell)$$

$$\mathcal{O}_T = \frac{e^2}{16\pi^2}(\bar{s}\sigma_{\mu\nu} P_L b)(\bar{\ell}\sigma^{\mu\nu} \ell) \qquad \mathcal{O}_{T5} = \frac{e^2}{16\pi^2}(\bar{s}\sigma_{\mu\nu} P_L b)(\bar{\ell}\sigma^{\mu\nu} \gamma_5 \ell)$$

spin-2 mediator will generate new dim=8 operators

SPIN-2 MEDIATOR IN $b \to s\mu^+\mu^-$ TRANSITIONS (I)

Building effective lagrangian from the following transition amplitude:



new L & R operators of dim = 8 !

reducing the number of operators:
i) equations of motion
ii) Fierz rearrangements
iii) global fit analysis indicates that B-physics anomalies are explained by NP physics for $C_9 \simeq -C_{10}$, i.e. the new interactions should be of V-A type:

$$a_{sb}^R, a_{\mu\mu}^R = 0 \quad \to \quad C_i^{(8)} = -C_{i5}^{(8)}$$

we are left only with the L-operators:

SPIN-2 MEDIATOR IN $b \to s\mu^+\mu^-$ TRANSITIONS (II)

'reduceable' dim=8 operators :

$$\mathcal{O}_S^{(q,8)} = \boxed{m_\ell m_q} \frac{e^2}{16\pi^2} (\bar{s} P_R b)(\bar{\mu}\mu) \qquad (q=b) \qquad C_S^{(8)} = \frac{4}{3} C_G \boxed{a_{sb}^L a_{\mu\mu}^L} \qquad \left(C_S^{(8)} = \frac{4}{3} C_G\, a_{sb}^L \left[a_{\mu\mu}^L + a_{\mu\mu}^R \right] \right)$$

$$\mathcal{O}_{S'}^{(q,8)} = \boxed{m_\ell m_q} \frac{e^2}{16\pi^2} (\bar{s} P_L b)(\bar{\mu}\mu) \qquad C_{S'}^{(8)} = 0 \qquad \left(C_{S'}^{(8)} = \frac{4}{3} C_G\, a_{sb}^R \left[a_{\mu\mu}^L + a_{\mu\mu}^R \right] \right)$$

$$\boxed{C_G = \frac{16\pi^2 v^2}{e^2} \frac{1}{V_{tb} V_{ts}^*} \frac{1}{16\Lambda^2 m_G^2}}$$

'real' dim=8 operators :

$$\mathcal{O}_L^{(8)} = (\bar{s}\gamma^\mu i \overset{\leftrightarrow}{\partial^\nu} P_L b)(\bar{\ell}\gamma_\mu i \overset{\leftrightarrow}{\partial_\nu} \ell) \qquad C_L^{(8)} = -C_G \boxed{a_{sb}^L a_{\mu\mu}^L}$$

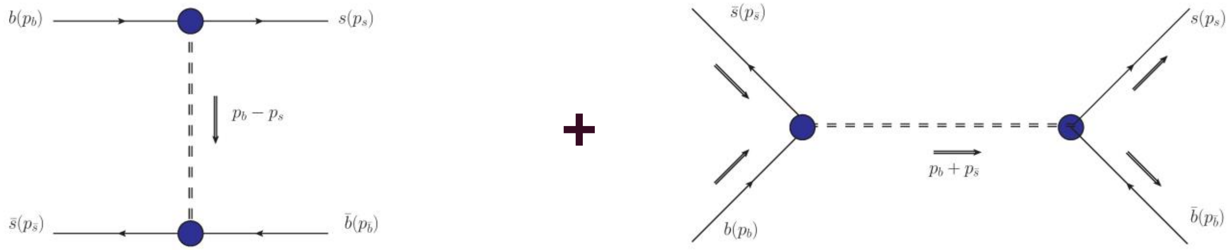
$$\mathcal{O}_{L5}^{(8)} = (\bar{s}\gamma^\mu i \overset{\leftrightarrow}{\partial^\nu} P_L b)(\bar{\ell}\gamma_\mu i \overset{\leftrightarrow}{\partial_\nu} \gamma_5 \ell) \qquad C_{L5}^{(8)} = C_G \boxed{a_{sb}^L a_{\mu\mu}^L}$$

$$\mathcal{O}_{LL}^{(8)} = (\bar{s}\gamma^\nu i \overset{\leftrightarrow}{\partial^\mu} P_L b)(\bar{\ell}\gamma^\mu i \overset{\leftrightarrow}{\partial^\nu} P_L \ell) \qquad C_{LL}^{(8)} = -2C_G \boxed{a_{sb}^L a_{\mu\mu}^L}$$

CONSTRAINTS ON SPIN-2 COUPLING WITH QUARKS

a^L_{sb}

a) $B_s - \overline{B}_s$ MIXING



$$\Delta M_s = (\Delta M_s)_{SM} + \underbrace{(\Delta M_s)_{m_b^2 \mathcal{Q}_1} + (\Delta M_s)_{m_b^2 \mathcal{Q}_2} + (\Delta M_s)_{m_b^2 \mathcal{Q}_3}}_{\text{dim=8 contrib.}}$$

$$\mathcal{Q}_6^{(8)} = (\bar{s}^\alpha \gamma^\mu i \overleftrightarrow{\partial}_\nu P_L b^\alpha)(\bar{s}^\beta \gamma^\mu i \overleftrightarrow{\partial}_\nu P_L b^\beta) \rightarrow m_b^2 \mathcal{Q}_1 = m_b^2 (\bar{s}_L^\alpha \gamma^\mu b_L^\alpha)(\bar{s}_L^\beta \gamma^\mu b_L^\beta)$$

$$\mathcal{Q}_2^{(8)} = m_b^2 (\bar{s}_L^\alpha b_R^\alpha)(\bar{s}_L^\beta b_R^\beta)$$

(operators ~ m_b^2 and $m_b m_s$ are neglected)

$$\mathcal{Q}_3^{(8)} = m_b^2 (\bar{s}_L^\alpha b_R^\beta)(\bar{s}_L^\beta b_R^\alpha) \longrightarrow \boxed{\left(\frac{a^L_{sb}}{\Lambda m_G}\right)^2 < 1.4 \times 10^{-12} \text{ GeV}^{-4}}$$

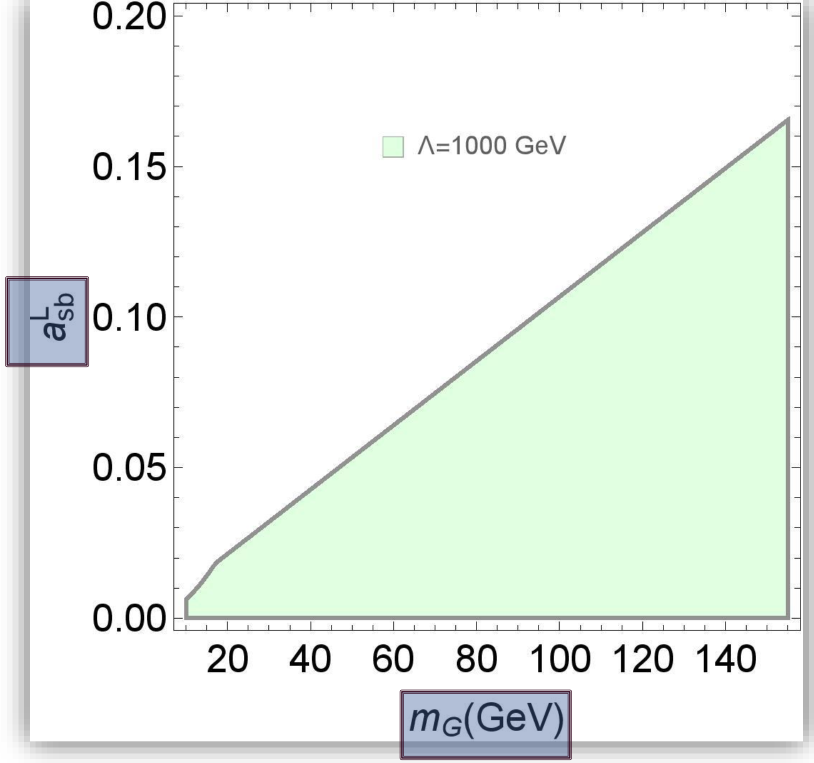
b) TOP DECAY WIDTH

$$SU(2)_L \rightarrow a^L_{sb} \simeq a^L_{tc}$$

$$t \rightarrow c\, G_{\mu\nu}$$

$$\Gamma_t^{NP} = \frac{|a^L_{sb}|^2 m_t^7}{192\pi \Lambda^2 m_G^4}\left(1 - \frac{m_G^2}{m_t^2}\right)^4 \left(2 + 3\frac{m_G^2}{m_t^2}\right)$$

Combined bound from $B_s - \overline{B}_s$ and the top decay width:

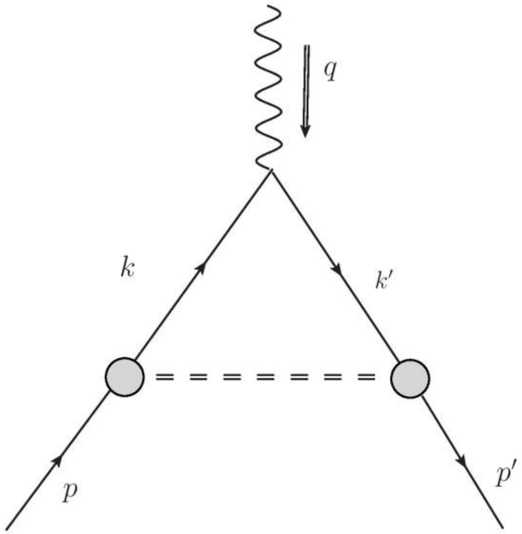


for mG > 150 GeV – strong constraints from LHC

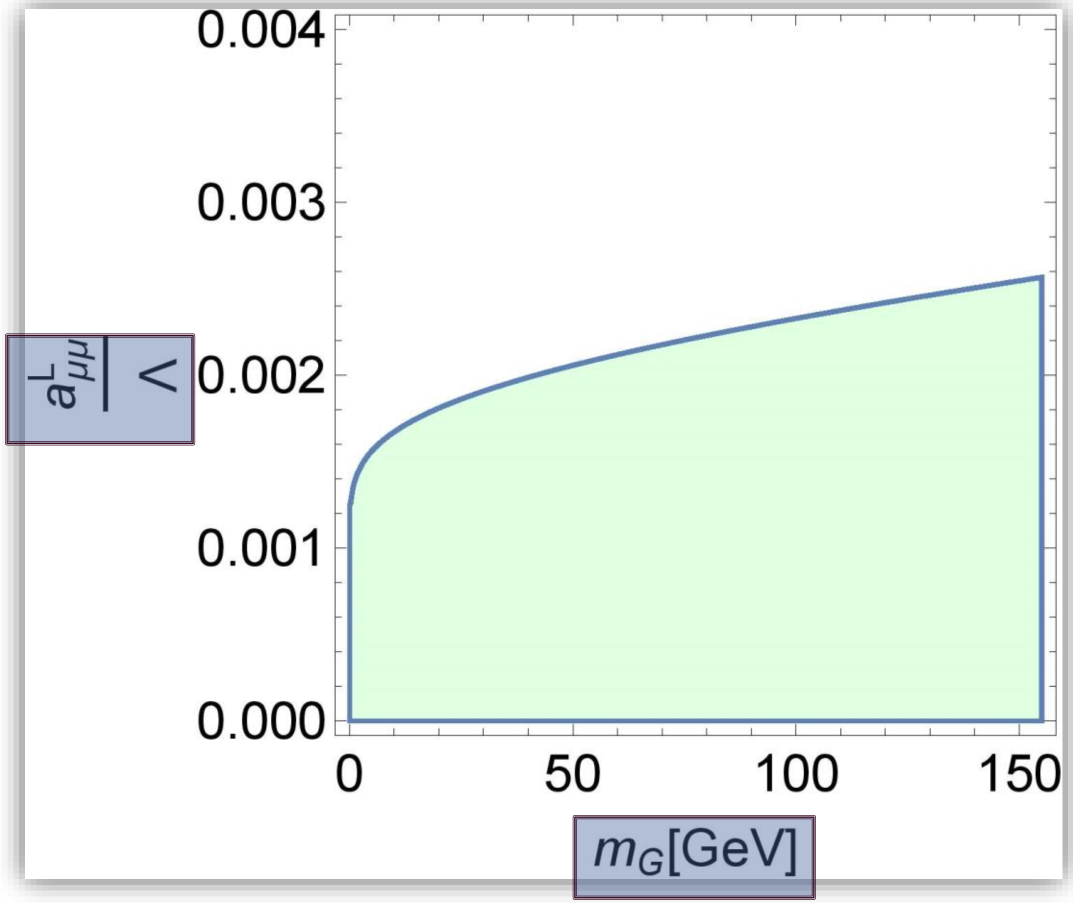
CONSTRAINT ON SPIN=2 COPLING WITH MUONS

$a^L_{\mu\mu}$

MUON ANOMALOUS MAGNETIC MOMENT



Bound of $a^L_{\mu\mu}$ from $(g-2)_\mu$:



much weaker or no constraints from:

$Z \to 4\mu$

$pp \to \mu^+\mu^-$ at $13TeV$ with $36.1fb^{-1}$

EFFECTS OF SPIN-2 PARTICLE IN $B \to K\mu^+\mu^-$ (I)

$$\frac{d^2\Gamma_\ell}{dq^2 d\cos\theta} = \underbrace{a_\ell(q^2)}_{\text{SM + NP}} + \underbrace{\boxed{\tilde{b}_\ell(q^2)\cos\theta}}_{\text{NP effects}} + \underbrace{c_\ell(q^2)\cos^2\theta}_{\text{SM + NP}} + \underbrace{\boxed{\tilde{d}_\ell(q^2)\cos^3\theta + \tilde{e}_\ell(q^2)\cos^4\theta}}_{\text{NP effects}}$$

⬇

$$a_\ell(q^2) \sim |F_V|^2, |F_A|^2, |F_P|^2, F_A F_P, \boxed{|F_S^{NP}|^2}$$

$$c_\ell(q^2) \sim |F_V|^2, |F_A|^2, \boxed{|F_V^{NP}|, |\mathrm{F}_A^{NP}|, |\mathrm{F}_P^{NP}| \ldots. C_{LL}^{(8)} \cdot (f_+^2, f_+ F_s^{NP})}$$

$$\boxed{\tilde{b}_\ell(q^2)} \sim F_V F_V^{NP}, F_A F_A^{NP} \ldots. C_{LL}^{(8)} \cdot (f_+{}^2, f_+ F_V, f_+ F_A)$$

$$\boxed{\tilde{d}_\ell(q^2)} \sim F_V F_V^{NP}, F_A F_A^{NP} \ldots. C_{LL}^{(8)} (f_+ F_V, f_+ F_A)$$

$$\boxed{\tilde{e}_\ell(q^2)} \sim |F_V^{NP}|^2, |F_A^{NP}|^2, (C_{LL}^{(8)} \mathrm{f}_+)^2$$

$$F_V(q^2) = C_9 f_+(q^2) + \frac{2m_b}{m_B + m_K} C_7 f_T(q^2)$$

$$F_A(q^2) = C_{10} f_+(q^2)$$

$$F_P(q^2) = -m_\ell C_{10}\left[f_+(q^2) - \frac{m_B^2 - m_K^2}{q^2}\left(f_0(q^2) - f_+(q^2) \right) \right]$$

$$F_V^{NP}(q^2) = -\beta_\ell \sqrt{\lambda(q^2)} C_L^{(8)} f_+(q^2)$$

$$F_A^{NP}(q^2) = -\beta_\ell \sqrt{\lambda(q^2)} C_{L5}^{(8)} f_+(q^2)$$

$$F_S^{NP}(q^2) = m_\ell \frac{m_B^2 - m_K^2}{2}\left(C_S^{(8)} + C_{S'}^{(8)} \right) f_0(q^2)$$

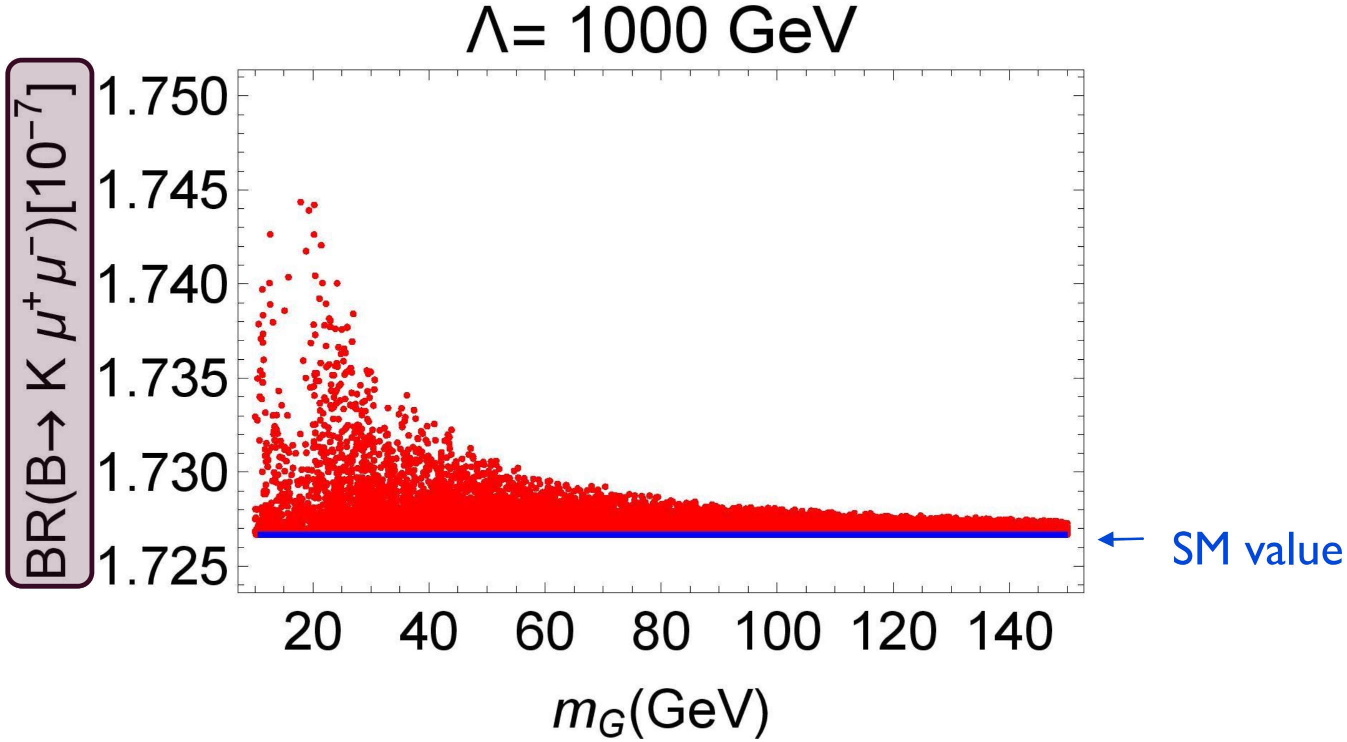
$$F_P^{NP}(q^2) = m_\ell \beta_\ell \sqrt{\lambda(q^2)} C_{L5}^{(8)} \left[f_+(q^2) - \frac{m_B^2 - m_K^2}{q^2}\left(f_0(q^2) - f_+(q^2) \right) \right]$$

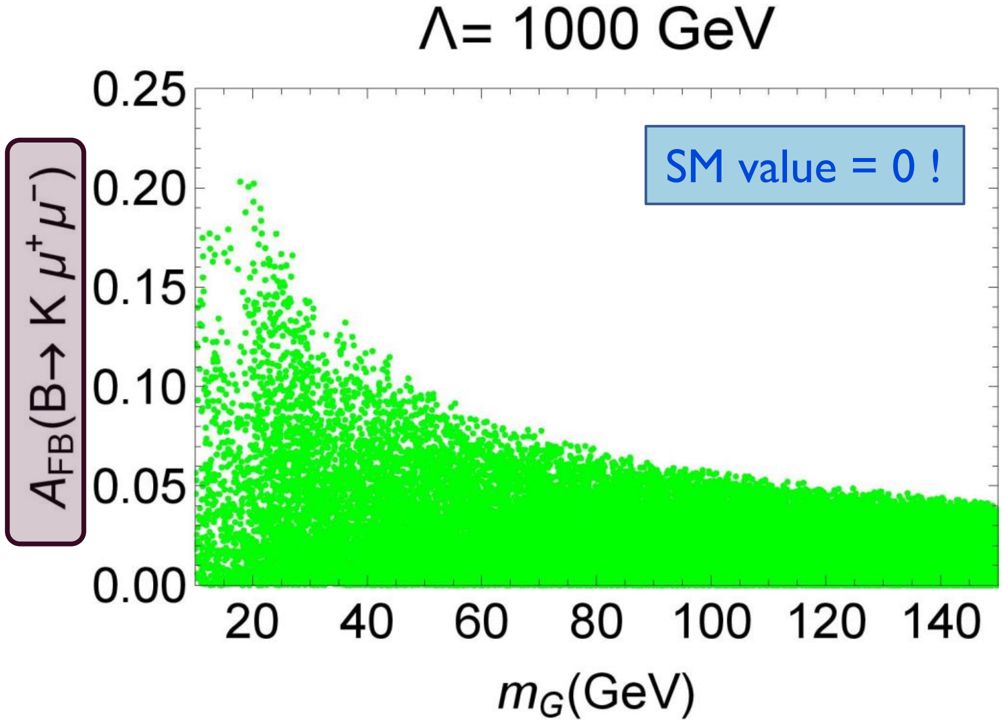
EFFECTS OF SPIN-2 PARTICLE IN $B \to K\mu^+\mu^-$ (II)

$$\frac{d^2\Gamma_\ell}{dq^2 d\cos\theta} = \underbrace{a_\ell(q^2)}_{\text{SM + NP}} + \underbrace{\boxed{\tilde{b}_\ell(q^2)\cos\theta}}_{\text{NP effects}} + \underbrace{c_\ell(q^2)\cos^2\theta}_{\text{SM + NP}} + \underbrace{\boxed{\tilde{d}_\ell(q^2)\cos^3\theta + \tilde{e}_\ell(q^2)\cos^4\theta}}_{\text{NP effects}}$$

$$\Gamma_\ell = 2\int dq^2 \left(a_\ell(q^2) + \frac{c_\ell(q^2)}{3} + \frac{\tilde{e}_\ell(q^2)}{5} \right)$$

$$A_{FB} = \frac{1}{\Gamma_\ell}\int dq^2 \left(\int_0^1 - \int_{-1}^0\right) d\cos\theta \left(\frac{d^2\Gamma_\ell}{dq^2 d\cos\theta}\right) = \frac{1}{\Gamma_\ell}\int dq^2 \left(\tilde{b}_\ell(q^2) + \frac{\tilde{d}_\ell(q^2)}{2}\right)$$





SM value = 0 !

EFFECTS OF SPIN-2 PARTICLE IN $B \to K^*(\to K\pi)\mu^+\mu^-$ (I)

$$\boxed{\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi} = \frac{9}{32\pi} I(q^2,\theta_\ell,\theta_{K^*},\phi)}$$

$$\begin{aligned} I(q^2,\theta_\ell,\theta_{K^*},\phi) = {} & I_1^s \sin^2\theta_{K^*} + I_1^c \cos^2\theta_{K^*} + (I_2^s \sin^2\theta_{K^*} + I_2^c \cos^2\theta_{K^*})\cos 2\theta_\ell + I_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi \\ & + I_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi \\ & + (I_6^s \sin^2\theta_{K^*} + I_6^c \cos^2\theta_{K^*})\cos\theta_\ell + I_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi \end{aligned}$$

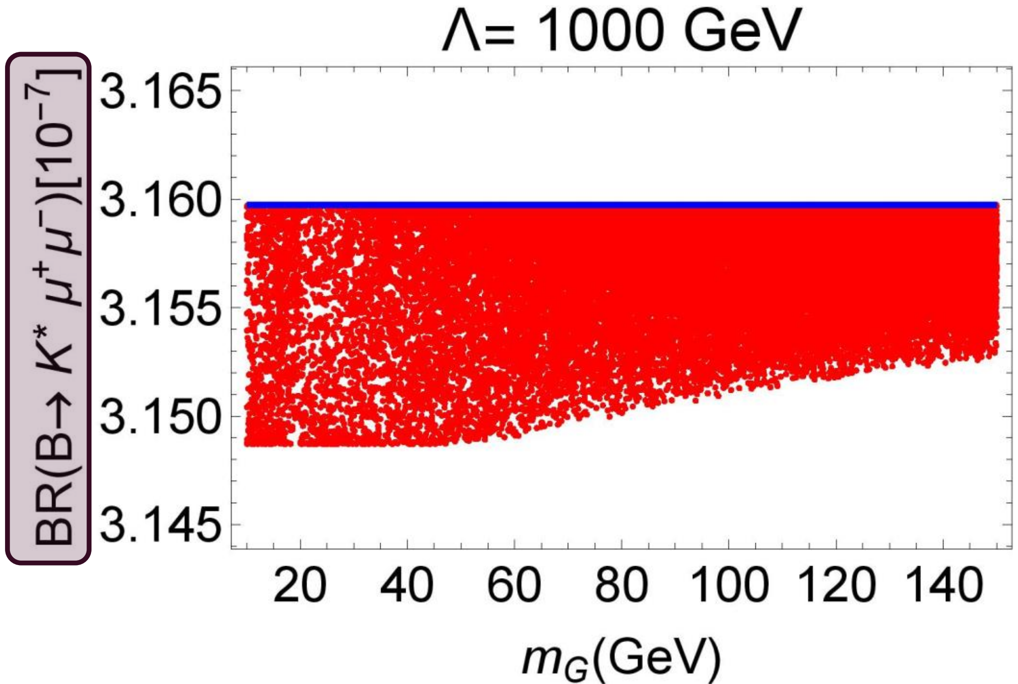
$$I_i \equiv I_i^{SM} + C_{7,9,10}(C_{L,L5}^{(8)}, C_{LL}^{(8)})\cos\theta_\ell \approx I_i^{SM} + I_i^{int}\cos\theta_\ell$$

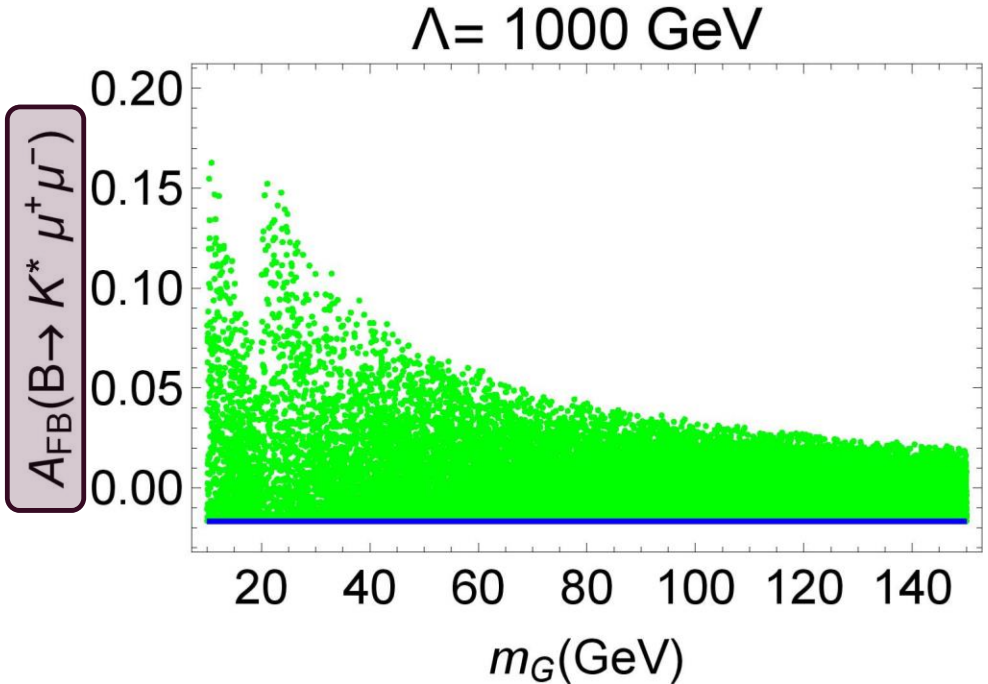
NEW ASYMMETRIES APPEAR !

EFFECTS OF SPIN-2 PARTICLE IN $B \to K^*(\to K\pi)\mu^+\mu^-$ (II)

$$A_{FB}^{K^*} = \frac{1}{\Gamma}\int dq^2 \int_0^{2\pi} d\phi \int_{-1}^{1} d\cos\theta_{K^*} \left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_\ell \left(\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_{K^*}\, d\phi}\right) = \frac{3}{8}\left(2I_6^{s(SM)} + I_6^{c(int)} + I_1^{c(int)} + 2I_1^{s(int)}\right)$$

$$A_{FB,SM}^{K^*} = -0.035^{+0.036}_{-0.033}$$





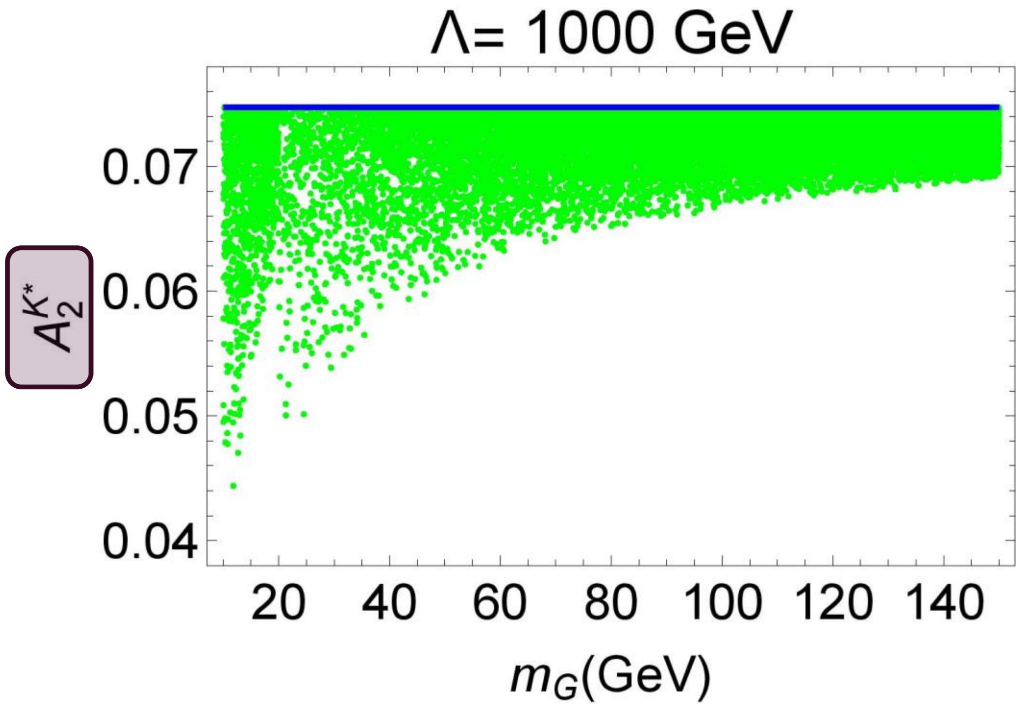
EFFECTS OF SPIN-2 PARTICLE IN $B \to K^*(\to K\pi)\mu^+\mu^-$ (III)

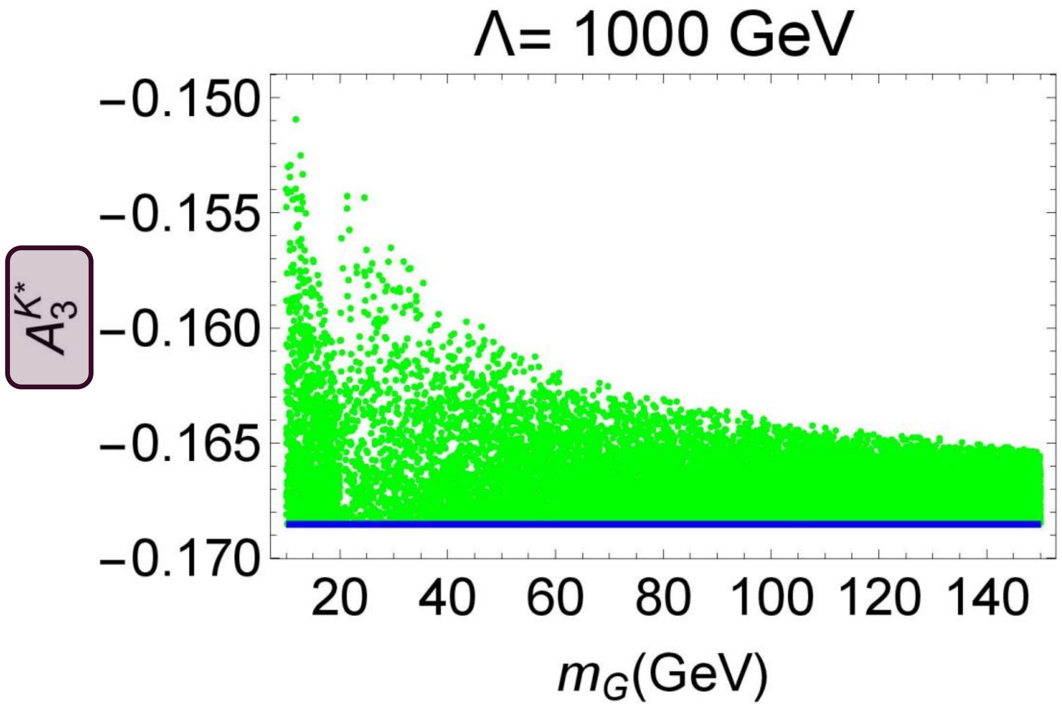
$$A_2^{K^*} = \frac{1}{\Gamma}\int dq^2 \left(\int_{-\pi/2}^{\pi/2} - \int_{\pi/2}^{3\pi/2}\right) d\phi \left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_{K^*} \left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_\ell \, \Gamma_{tot}$$

$$= \frac{1}{\pi}\left(2I_4^{(SM)} + I_5^{(int)}\right)$$

$$A_3^{K^*} = \frac{1}{\Gamma}\int dq^2 \left(\int_{-\pi/2}^{\pi/2} - \int_{\pi/2}^{3\pi/2}\right) d\phi \left(\int_0^1 - \int_{-1}^0\right) d\cos\theta_{K^*} \int_{-1}^1 d\cos\theta_\ell \, \Gamma_{tot}$$

$$= \frac{3}{8}\left(2I_5^{(SM)} + I_4^{(int)}\right)$$





CONCLUSIONS

- ☐ we considered spin-2 mediator in $b \to s\mu^+\mu^-$ transitions

- ☐ we considered flavor non-universal couplings to left-handed b and s quarks, and spin-2 particle couplings to muons only

- ☐ B-B mixing, top-quark decay and $(g-2)_\mu$ form factor provide constraints to the couplings

- ☐ spin-2 mediation increases insignificantly BR($B \to K\mu^+\mu^-$) and BR($B \to K^*(\to K\pi)\mu^+\mu^-$)

  → this simple model cannot explain observed R_K and R_{K*} anomalies

- ☐ spin-2 mediator can create forward-backward asymmetries ~10-20% for rather small m_G = 20 – 40 GeV

  - this is specially interesting for $B \to K\mu^+\mu^-$ decay where $A_{FB}(B \to K\mu^+\mu^-)_{SM} = 0$

THANK YOU !

Windows on The Universe, Qui Nhon 2018