

2022年理论物理前沿讲习班：暗物质与新物理暑期学校，2022/07/06-07/07

B ANOMALIES AND POSSIBLE EXPLANATIONS

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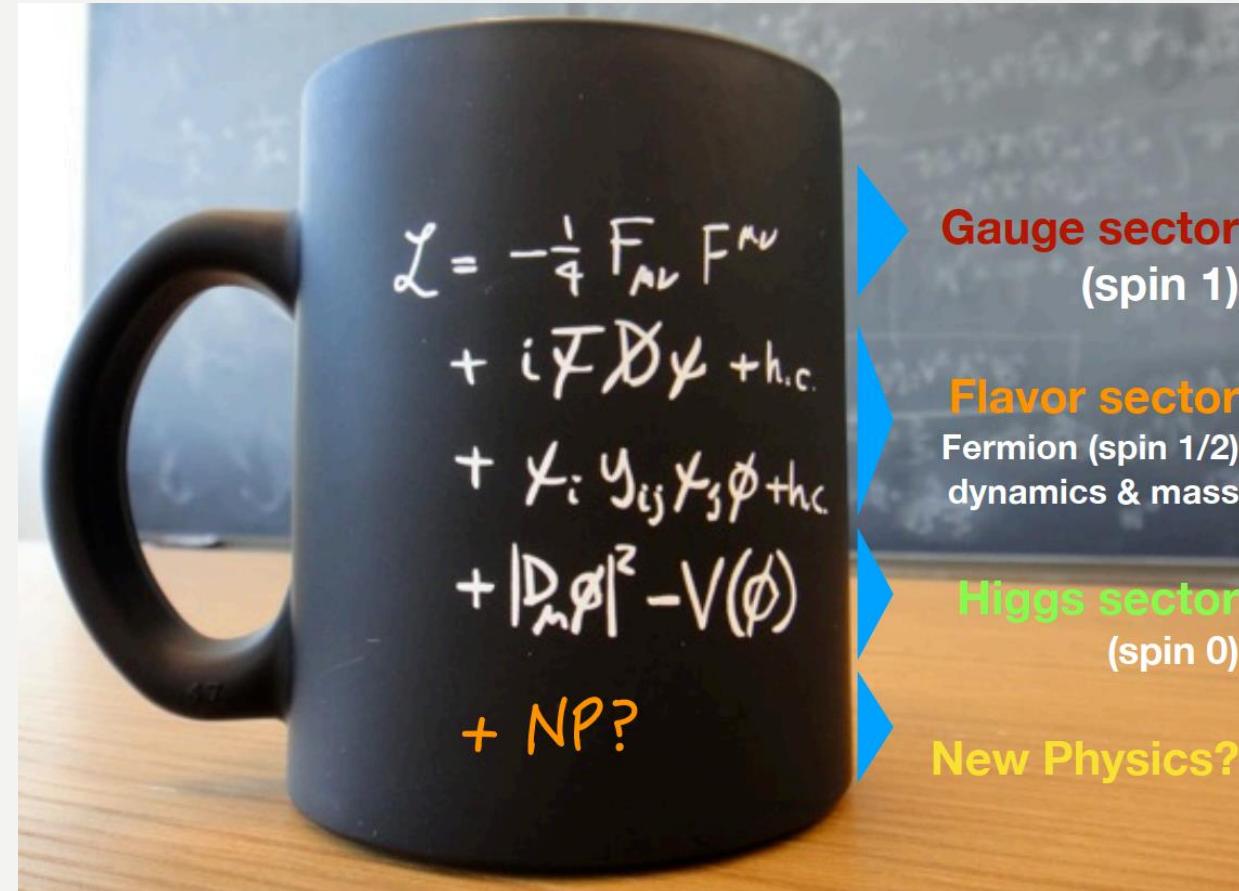
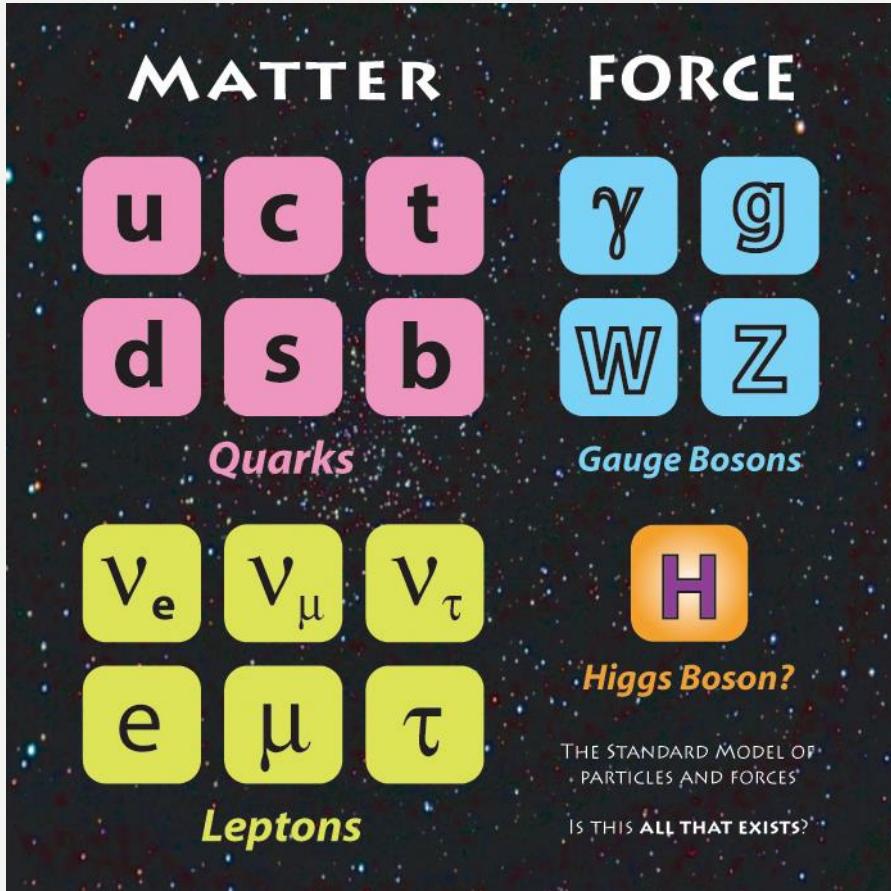
OUTLINE

- **Introduction**
- **LFUV in $b \rightarrow c\tau\nu$ decays**
- **Anomalies in $b \rightarrow s\ell^+\ell^-$ decays**
- **Summary**

Introduction

SM OF PARTICLE PHYSICS

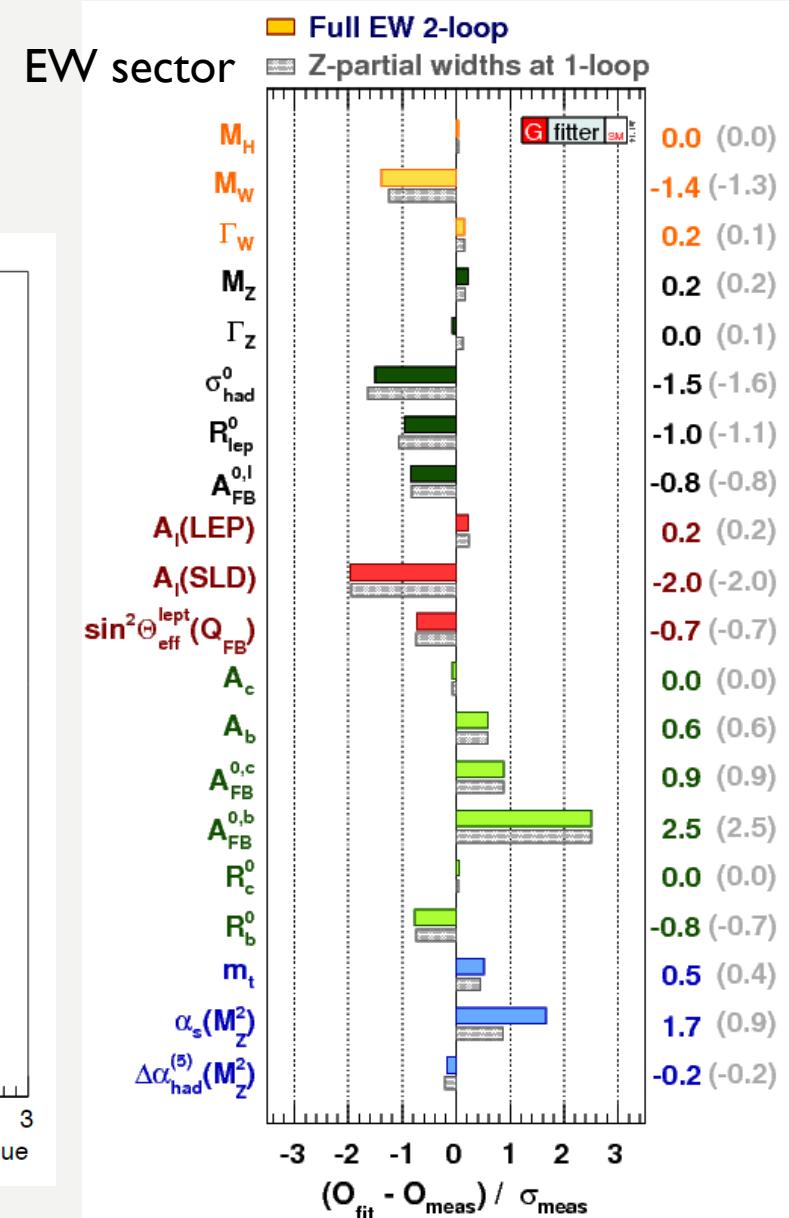
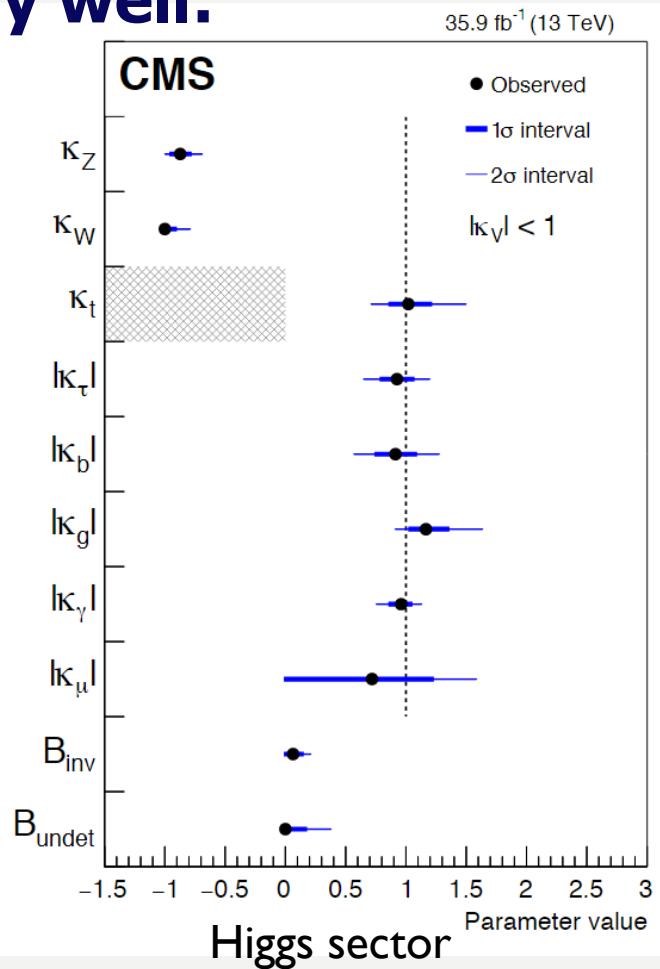
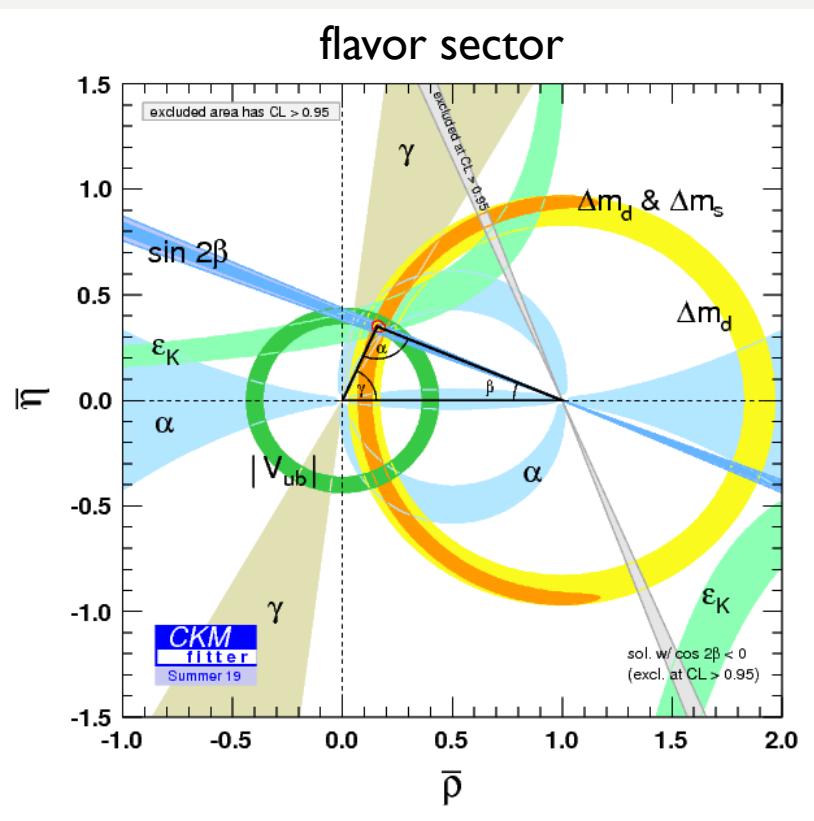
□ Matter fundamental constituents and their interactions:



□ SM: a great triumph of the 20th century science.

SM OF PARTICLE PHYSICS

- Up to now, SM works very well:



- However, the SM only an EF of a more fundamental theory!

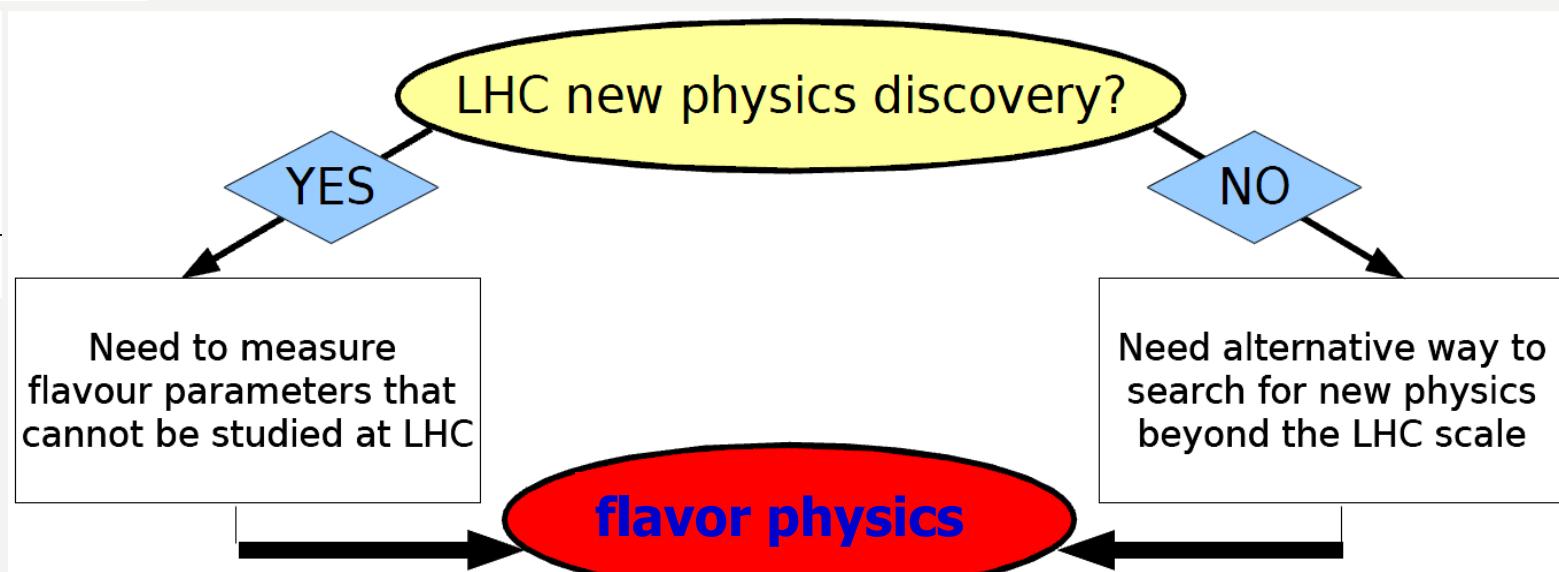
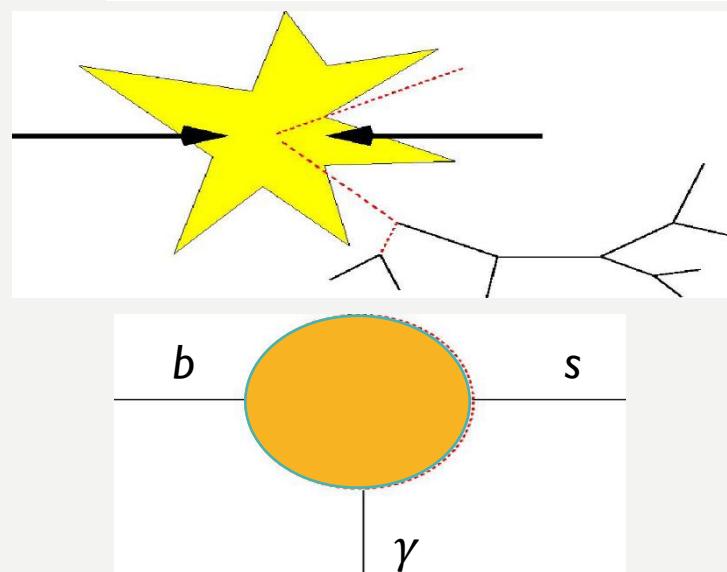
OPEN QUESTIONS OF SM

- **What is dark matter made of?**
- **Why is there more matter than anti-matter in the Universe?**
- **Why are the forces of Nature of such different strengths?**
- **Why are neutrino masses non-zero and so small?**
- **Why are there three generations of matter particles?**
- **How can we stabilize the electro-weak scale?**
-

**we need to go
beyond the SM!**

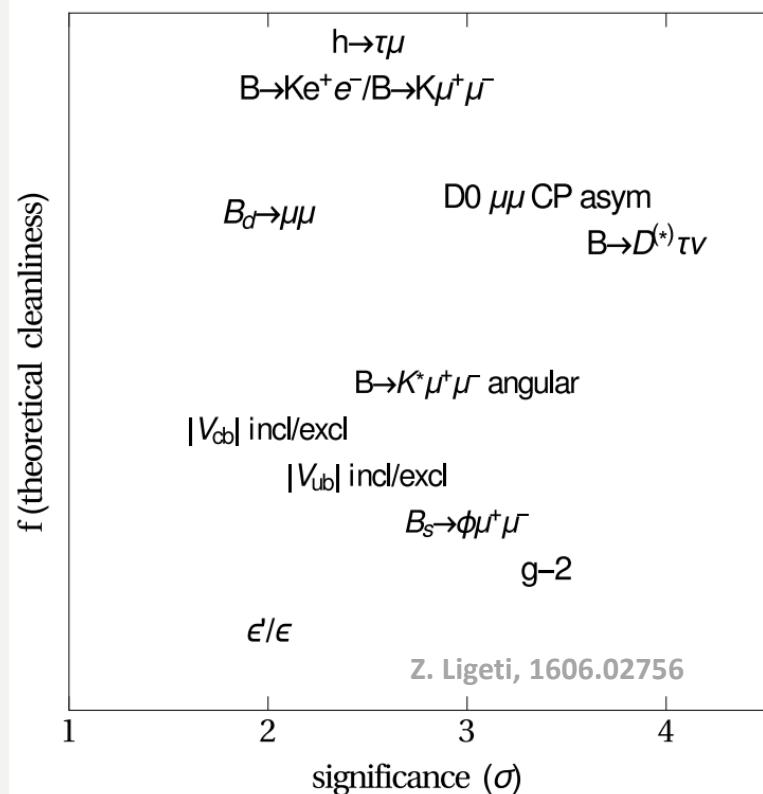
TWO WAYS FOR NEW PHYSICS

- Direct detection @ energy frontier:
- Indirect search @ intensity frontier:



CURRENT EXP. STATUS

- No direct signals of new particles/interactions observed @ LHC.
- Many interesting flavor anomalies observed @ low-energy processes.
 $\tau^\pm \rightarrow \pi^\pm K_S \nu_\tau$, $b \rightarrow c \tau \bar{\nu}$, $b \rightarrow s \mu^+ \mu^-$, $(g-2)_{\mu,e}$, V_{ub} , V_{cb} , V_{us} , $\Delta A_{CP}(\pi K)$, ...



✓ Evidence for New Physics

✓ Statistical fluctuation in exp.

✓ Under-estimated systematics

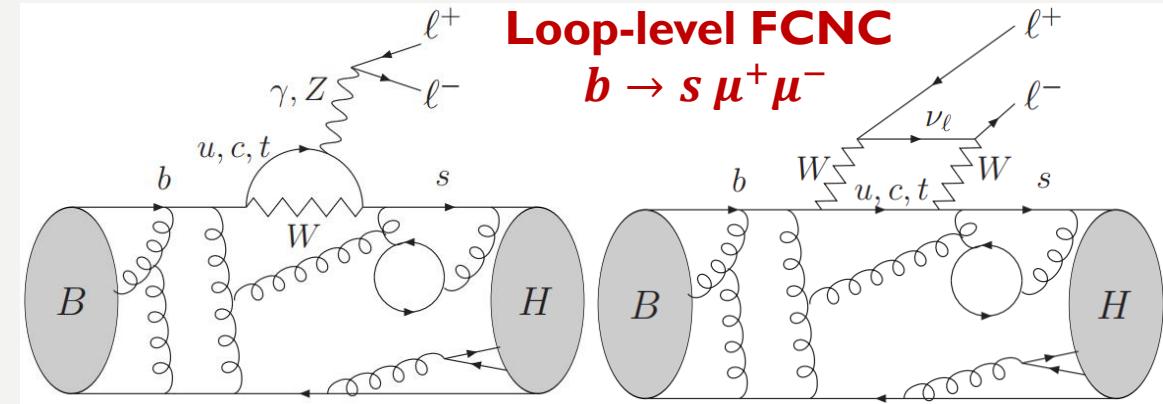
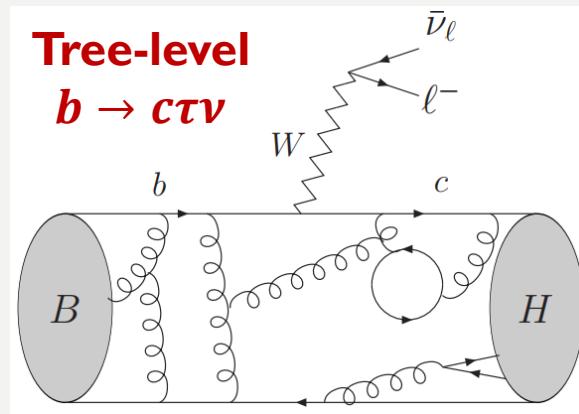
✓ Incorrect SM prediction or measurement

➤ **But very interesting and mandatory to investigate hints of these deviations!**



$b \rightarrow c\tau\nu$ AND $b \rightarrow s \mu^+ \mu^-$ ANOMALIES

- Observed in both charged- and neutral-current B-meson processes.



- Quarks always confined in hadrons; ➔ complex strong interactions!

➔ *optimized
observables*

$$R_{H_c} = \frac{\mathcal{B}(H_b \rightarrow H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \rightarrow H_c \ell'^- \bar{\nu}_{\ell'})}$$

$$R_{H_s} = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma(H_b \rightarrow H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma(H_b \rightarrow H_s e^+ e^-)}{dq^2} dq^2}$$

- They are (largely) free from CKM & hadronic parameters ("clean");

LFU IN THE SM

□ Lepton-gauge interactions: Lepton flavor universality

$$\begin{aligned}\mathcal{L}_{cc}^{\ell} &\equiv g_W \bar{\nu}_L \gamma_{\mu} V_{\text{PMNS}} \hat{e}_L W^{+\mu} + \text{h.c.} \\ &= g_W \sum_{i=1,2,3} \bar{\nu}_L^i \gamma_{\mu} \left(V_{\text{PMNS}}^{ie} \hat{e}_L + V_{\text{PMNS}}^{i\mu} \hat{\mu}_L + V_{\text{PMNS}}^{i\tau} \hat{\tau}_L \right) W^{+\mu} + \text{h.c.}\end{aligned}$$

The W-boson couples
with different strengths to different lepton families



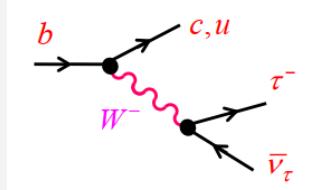
Universality!

However: if the neutrino flavor is not observed $|\mathcal{M}_j|^2 \propto \sum_{i=1,2,3} |V_{\text{PMNS}}^{ij}|^2 = 1 \quad \forall j$

$$\mathcal{L}_{nc}^{\ell} \equiv (\bar{e} \gamma_{\mu} \hat{e} + \bar{\mu} \gamma_{\mu} \hat{\mu} + \bar{\tau} \gamma_{\mu} \hat{\tau}) (g_{\gamma} A^{\mu} + g_Z Z^{\mu})$$

The photon and Z-boson couple
with the same strength to the three lepton families

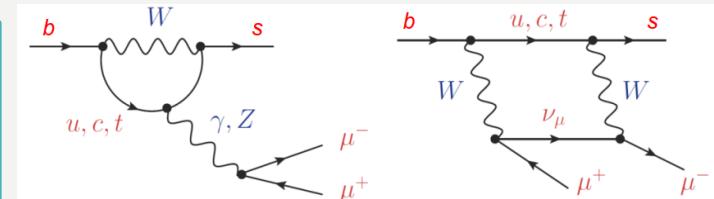
$$R_{H_c} = \frac{\mathcal{B}(H_b \rightarrow H_c \tau^- \bar{\nu}_{\tau})}{\mathcal{B}(H_b \rightarrow H_c \ell'^- \bar{\nu}_{\ell'})}$$



□ Key observation: different leptons involved; difference due to phase space & helicity suppression;

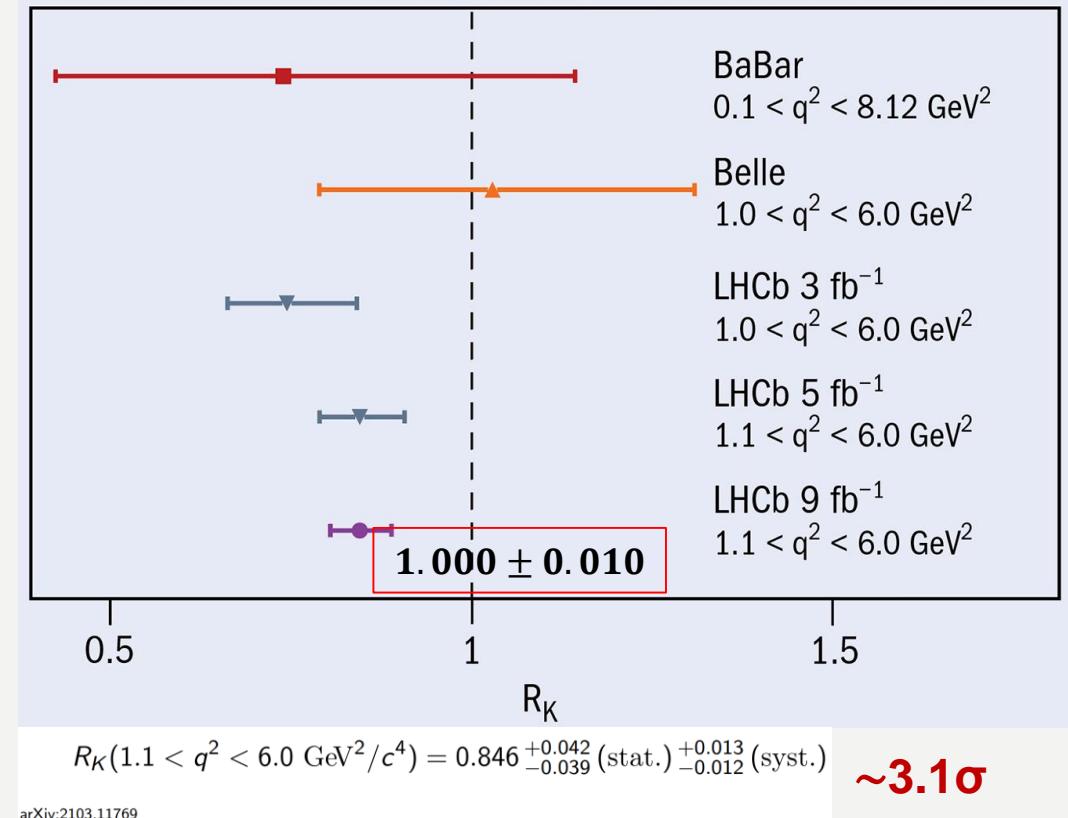
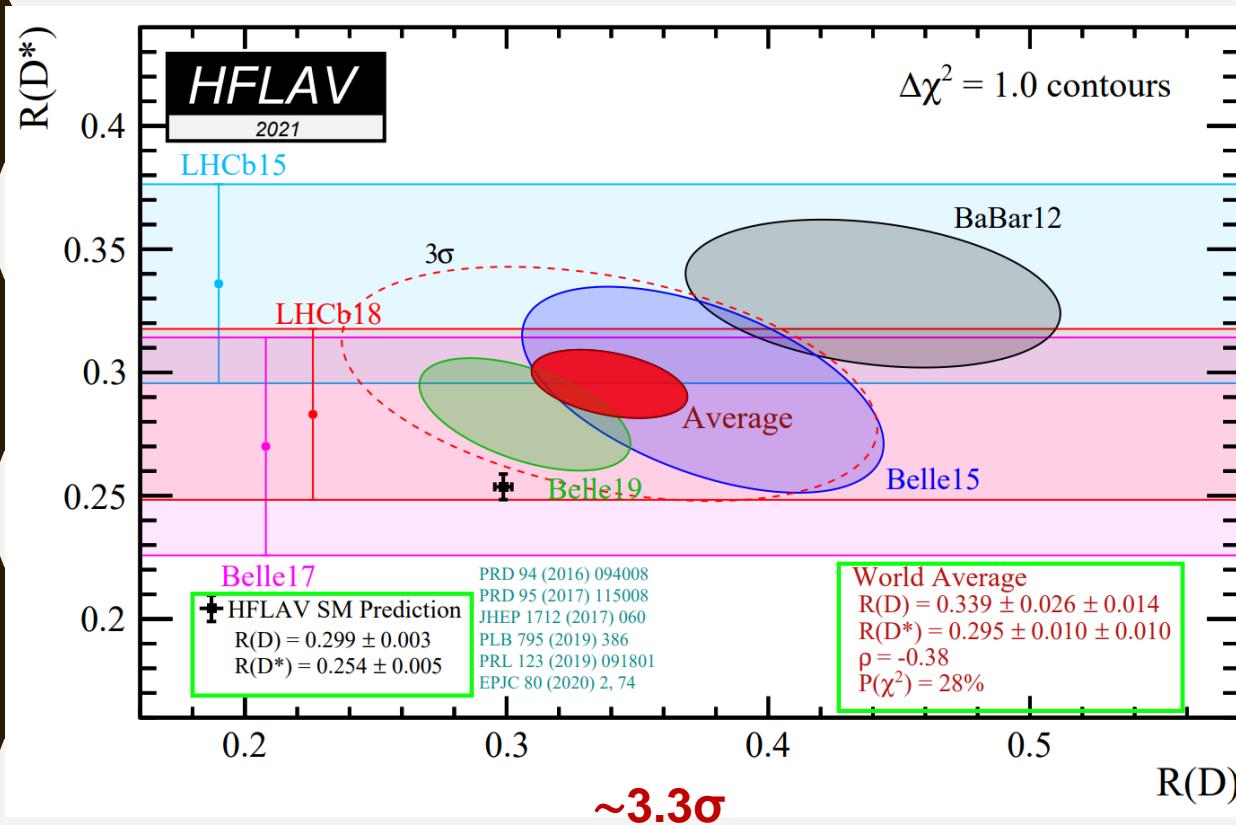
→ **LFU test?**

$$R_{H_s} = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma(H_b \rightarrow H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma(H_b \rightarrow H_s e^+ e^-)}{dq^2} dq^2}$$



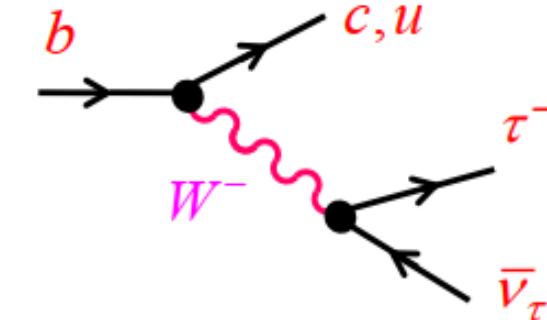
$b \rightarrow c\tau\nu$ AND $b \rightarrow s \mu^+ \mu^-$ ANOMALIES

□ Several exps. for $R(D^{(*)})$ and $R(K^{(*)})$ point to the same direction;



really hints of deviations from lepton universality?

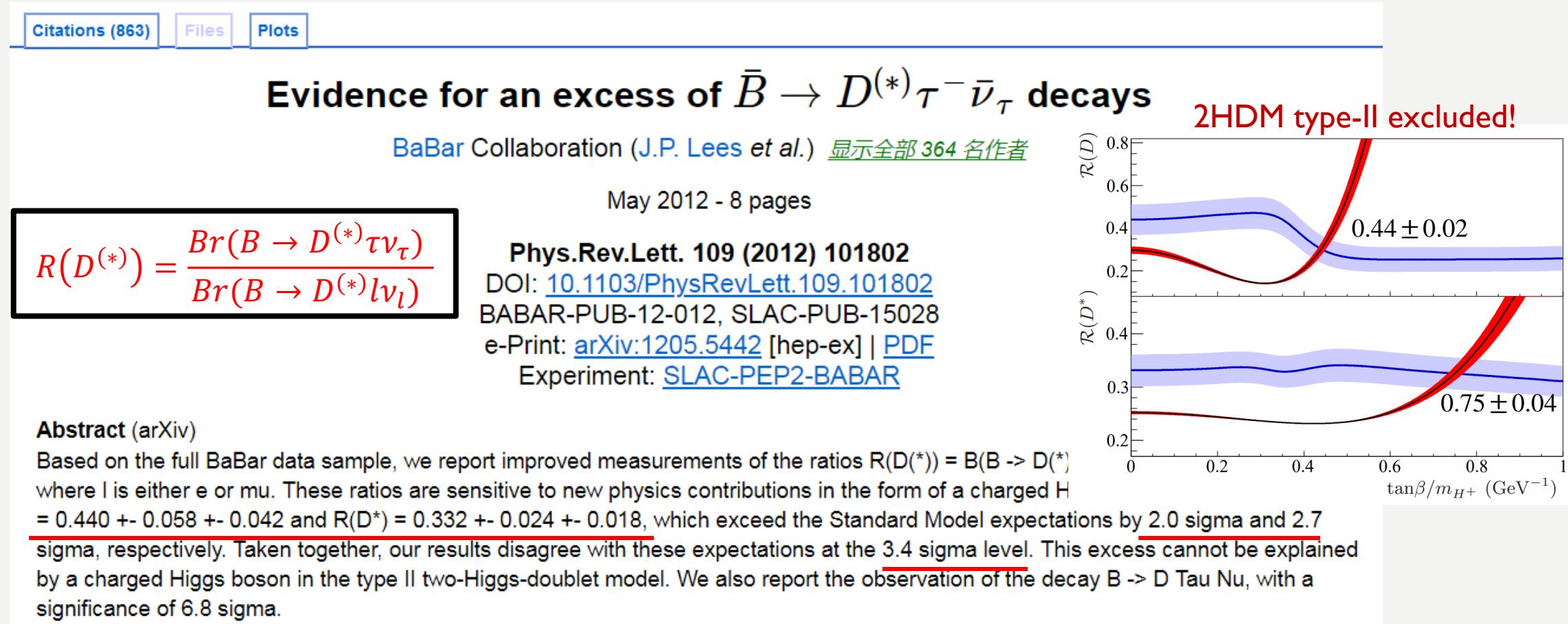
$$R_{H_c} = \frac{\mathcal{B}(H_b \rightarrow H_c \tau^- \bar{\nu}_\tau)}{\mathcal{B}(H_b \rightarrow H_c \ell'^- \bar{\nu}_{\ell'})}$$



b → *cτν* anomalies

R(D) AND R(D*) ANOMALIES

- First observed @ BaBar in 2012



- Later Belle & LHCb also performed/confirmed same measurements.

EXP. STATUS @2019 SPRING

□ WA as of 2021:

$R(D)$: 1.4σ

$R(D^*)$: 2.8σ

combined: $\sim 3.3\sigma$

□ Other observables:

$$R(J/\psi) = \frac{Br(B_c \rightarrow J/\psi \tau \nu_\tau)}{Br(B_c \rightarrow J/\psi l \nu_l)} \quad \text{LHCb 1711.05623}$$

$$= 0.71 \pm 0.17 \pm 0.18 \text{ (Exp.)}$$

$$= 0.258 \pm 0.004 \text{ (SM)}$$

□ Sum rules based on HQS:

$$\frac{R(\Lambda_c)}{R(\Lambda_c)^{\text{SM}}} = 0.28 \frac{R(D)}{R(D)^{\text{SM}}} + 0.72 \frac{R(D^*)}{R(D^*)^{\text{SM}}} + \delta$$

$\delta=0$ holds under any NP existence as long as $|C_T| \ll 1$

$$R(\Lambda_c) = \frac{Br(\Lambda_b \rightarrow \Lambda_c \tau \nu_\tau)}{Br(\Lambda_b \rightarrow \Lambda_c l \nu_l)} \quad \text{LHCb 2201.03497}$$

$$= 0.242 \pm 0.026 \pm 0.04 \pm 0.059 \text{ (Exp.)}$$

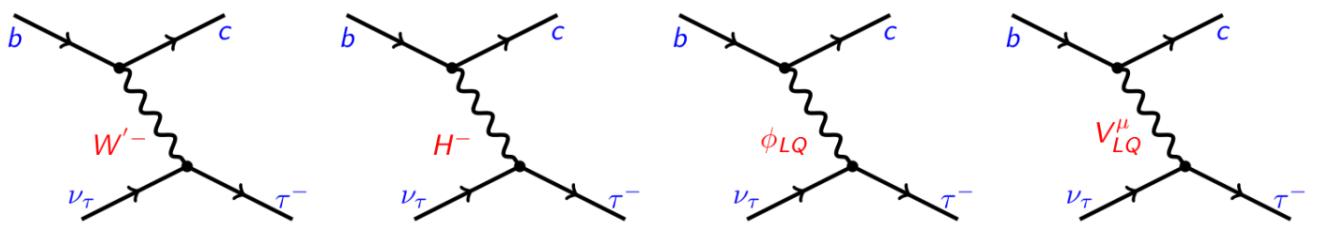
$$= 0.324 \pm 0.004 \text{ (SM)}$$

□ The measured $R(\Lambda_c)$ is not consistent with the $R(D^{(*)})$ anomaly.

WHAT SHOULD WE DO

- **$b \rightarrow c\tau\nu_\tau$ decay: W^\pm -mediated tree-level process; massive τ makes it sensitive to mediators:**

$W'^\pm, H^\pm, \text{LQs}, \dots$



- **Check SM predictions: BGL vs CLN parametrizations of $B \rightarrow D^{(*)}$ FFs;**

$$\langle D | \bar{c} \Gamma_{\mu_1 \mu_2} b | \overline{B} \rangle = \sum_i S_{\mu_1 \mu_2}^i F_i(q^2)$$

$$\langle D^*(\lambda) | \bar{c} \Gamma_\mu b | \overline{B} \rangle = \sum_\lambda \sum_i \epsilon^\alpha(\lambda) S_{\alpha \mu}^i F_i(q^2)$$

Exp. data+Lattice/LCSR+unitarity bounds+HQE to higher orders	R(D)	R(D*)
D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ph]]	0.299 ± 0.003	
F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]	0.299 ± 0.003	0.257 ± 0.003
D.Bigi, P.Gambino, S.Schacht, JHEP 1711 (2017) 061 [arXiv:1707.09509 [hep-ph]]		0.260 ± 0.008
S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ph]]	0.299 ± 0.004	0.257 ± 0.005

- **Latest SM predictions: $R(D) = 0.288 \pm 0.004$, $R(D^*) = 0.249 \pm 0.001$**

[F. Bernlochner et al., 2206.11281](https://arxiv.org/abs/2206.11281)

WHAT SHOULD WE DO

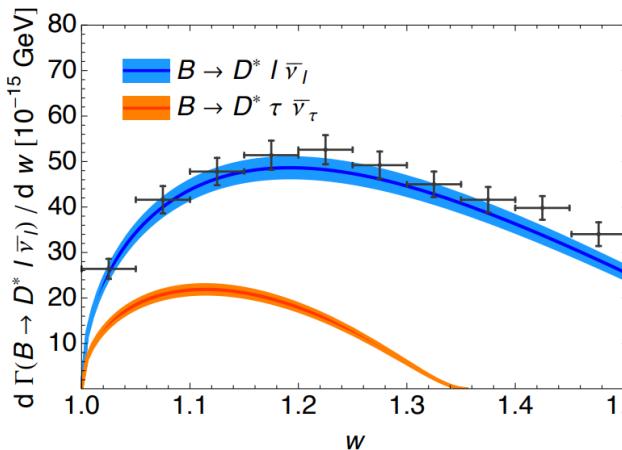
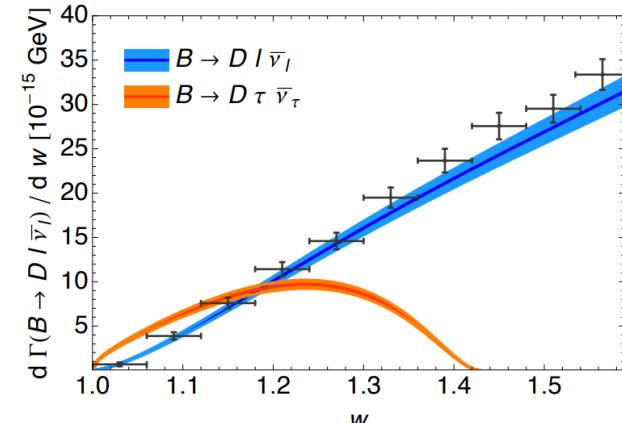
□ State-of-the-art results for $B \rightarrow D^{(*)}$ FFs;

Interesting if heavy quark symmetry inspired Form Factors are used:

$$\hat{h}(w) = h(w)/\xi(w) \quad \leftarrow \text{Leading Isgur-Wise function}$$

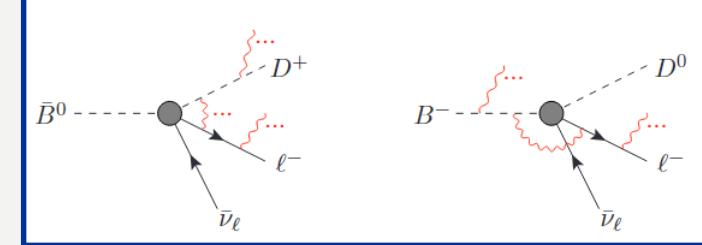
$B \rightarrow D^* \ell \bar{\nu}_\ell$

$$\begin{aligned} \hat{h}_+ &= 1 + \hat{\alpha}_s \left[C_{V_1} + \frac{w+1}{2} (C_{V_2} + C_{V_3}) \right] + (\varepsilon_c + \varepsilon_b) \hat{L}_1, \\ \hat{h}_- &= \hat{\alpha}_s \frac{w+1}{2} (C_{V_2} - C_{V_3}) + (\varepsilon_c - \varepsilon_b) \hat{L}_4, \\ \hat{h}_V &= 1 + \hat{\alpha}_s C_{V_1} + \varepsilon_c (\hat{L}_2 - \hat{L}_5) + \varepsilon_b (\hat{L}_1 - \hat{L}_4), \\ \hat{h}_{A_1} &= 1 + \hat{\alpha}_s C_{A_1} + \varepsilon_c \left(\hat{L}_2 - \hat{L}_5 \frac{w-1}{w+1} \right) + \varepsilon_b \left(\hat{L}_1 - \hat{L}_4 \frac{w-1}{w+1} \right), \\ \hat{h}_{A_2} &= \hat{\alpha}_s C_{A_2} + \varepsilon_c (\hat{L}_3 + \hat{L}_6), \\ \hat{h}_{A_3} &= 1 + \hat{\alpha}_s (C_{A_1} + C_{A_3}) + \varepsilon_c (\hat{L}_2 - \hat{L}_3 + \hat{L}_6 - \hat{L}_5) + \varepsilon_b (\hat{L}_1 - \hat{L}_4), \end{aligned}$$



□ EM corrections to $R(D^+)$ & $R(D^0)$ by 5% & 3%,

for soft-photon energy cut at 20-40MeV;



Boer/Kitahara/Nisandzic, 1803.05881

WHAT SHOULD WE DO

□ Difficult to explain the $R(D^{(*)})$ anomalies in SM;  possible NP?

$R(D)$: 1.4σ

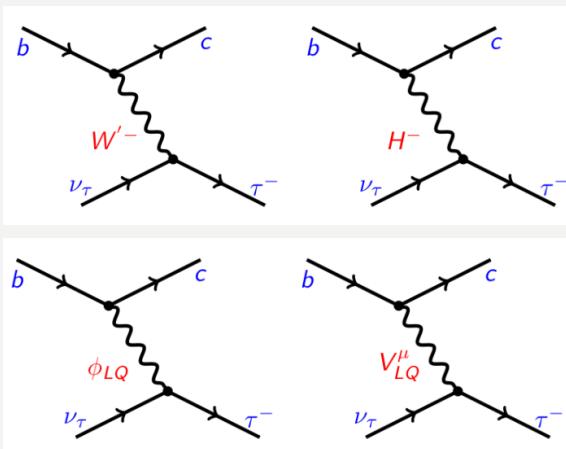
$R(D^*)$: 2.8σ

combined: $\sim 3.3\sigma$

 NP $\sim 10 - 15\%$ of a SM tree decay \Rightarrow huge effect

- If NP interfere with SM we need it to be 10%
- If NP doesn't interfere with SM, we need it to be a 40% effect

□ Many NP explanations!



Evidence for an excess of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ decays #1

BaBar Collaboration • J.P. Lees (Annecy, LAPP) et al. (May, 2012)

Published in: *Phys.Rev.Lett.* 109 (2012) 101802 • e-Print: 1205.5442 [hep-ex]

 pdf  links  DOI  cite

1,041 citations

Measurement of the branching ratio of $\bar{B} \rightarrow D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \rightarrow D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle #6

Belle Collaboration • M. Huschle (Karlsruhe U., EKP) et al. (Jul 12, 2015)

Published in: *Phys.Rev.D* 92 (2015) 7, 072014 • e-Print: 1507.03233 [hep-ex]

 pdf  links  DOI  cite

817 citations

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu)$ #7

LHCb Collaboration • Roel Aaij (CERN) et al. (Jun 29, 2015)

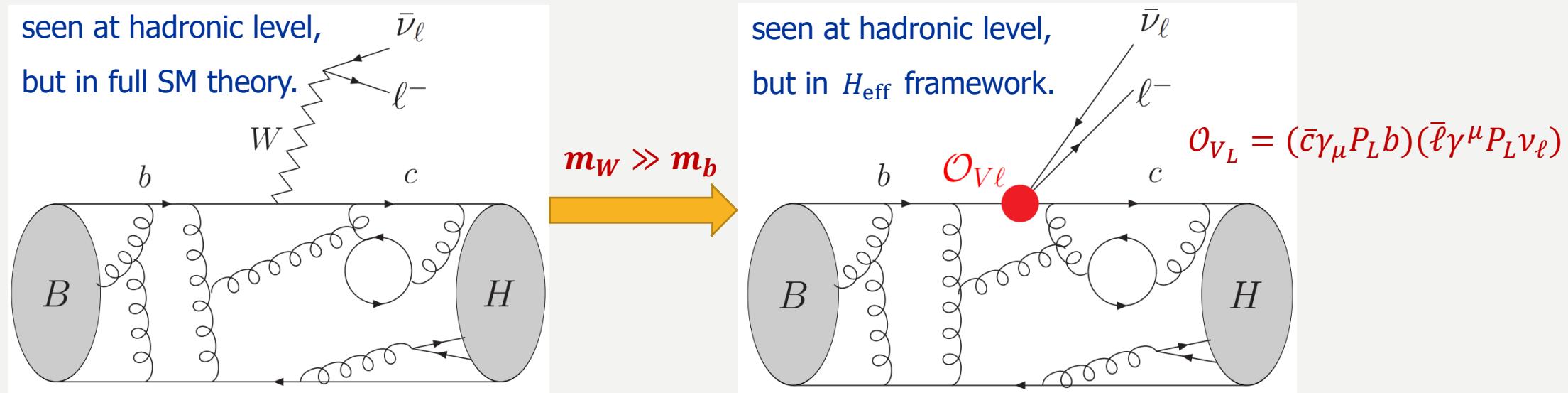
Published in: *Phys.Rev.Lett.* 115 (2015) 11, 111803, *Phys.Rev.Lett.* 115 (2015) 15, 159901 (erratum) • e-Print: 1506.08614 [hep-ex]

 pdf  links  DOI  cite

1,031 citations

THEORETICAL BASICS

- **$b \rightarrow c\tau\nu_\tau$ decay: W^\pm -mediated tree-level process in the SM;**



- **Most general low-energy effective Lagrangian for $b \rightarrow c\tau\nu_\tau$:**

$$\mathcal{L}_{\text{SM}}^{(6)} = -\frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{O}_{V_L} + \text{H.c.},$$

$$\mathcal{L}_{\text{NP}}^{(6)} = -\frac{4G_F}{\sqrt{2}} V_{cb} (C_{V_L} \mathcal{O}_{V_L} + C_{V_R} \mathcal{O}_{V_R} + C_{S_L} \mathcal{O}_{S_L} + C_{S_R} \mathcal{O}_{S_R} + C_T \mathcal{O}_T) + \text{H.c.}$$

$$\mathcal{O}_{V_{L(R)}} = (\bar{c}\gamma^\mu P_{L(R)} b)(\bar{\tau}\gamma_\mu P_L \nu_\tau),$$

$$\mathcal{O}_{S_{L(R)}} = (\bar{c}P_{L(R)} b)(\bar{\tau}P_L \nu_\tau),$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau).$$

THEORETICAL BASICS

leptonic sector

- Decay amplitude for $B \rightarrow D^{(*)}\tau\nu$ decay:

$$\mathcal{A}(B \rightarrow D\ell^-\bar{\nu}_\ell) = \frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{C}_{V\ell} \langle D|\bar{c}\gamma_\mu P_L b|B\rangle L^\mu, \quad L^\mu = \bar{u}_\ell \gamma^\mu P_L v_\nu,$$

- Hadronic sector $\langle H|\bar{c}\Gamma b|B\rangle$: Lorentz invariance & parity conservation

$J^P(H)$	Γ	$\langle P(p_P) V^\mu(x) M(p_M)\rangle$	$= \left[(p_M + p_P)^\mu - \frac{m_M^2 - m_P^2}{q^2} q^\mu \right] F_1(q^2) + q^\mu \frac{m_M^2 - m_P^2}{q^2} F_0(q^2),$
0^-	γ_μ	$\langle P(p_P) S(x) M(p_M)\rangle$	$= \frac{m_M^2 - m_P^2}{m_{q_d} - m_{q_u}} F_0(q^2),$
0^-	$\sigma_{\mu\nu}$	$\langle P(p_P) A^\mu(x) M(p_M)\rangle$	$= \langle P(p_P) P M(p_M)\rangle = 0,$
1^-	γ_μ	$\langle P(p_P) T^{\mu\nu}(x) M(p_M)\rangle$	$= -i(p_M^\mu p_P^\nu - p_P^\mu p_M^\nu) \frac{2F_T(q^2)}{m_M + m_P},$
1^-	$\gamma_\mu \gamma_5$	$\langle P(p_P) T_5^{\mu\nu}(x) M(p_M)\rangle$	$= -\epsilon^{\mu\nu\alpha\beta} p_{M\alpha} p_{P\beta} \frac{2F_T(q^2)}{m_M + m_P},$
1^-	$\sigma_{\mu\nu}$		
1^-	$\sigma_{\mu\nu} \gamma_5$		

For $B \rightarrow P$ transition, 3 FFs.

THEORETICAL BASICS

□ Hadronic sector $\langle H | \bar{c} \Gamma b | B \rangle$: Lorentz invariance & parity conservation

$J^P(H)$	Γ	
0^-	γ_μ	$\langle V(p_V, \lambda_V) V^\mu(x) M(p_M) \rangle = -i \epsilon^{\mu\nu\rho\sigma} \epsilon_{\nu*}(\lambda_V) p_{M\rho} p_{V\sigma} \frac{2V(q^2)}{m_M + m_V},$
0^-	$\sigma_{\mu\nu}$	$\langle V(p_V, \lambda_V) A^\mu(x) M(p_M) \rangle = (m_M + m_V) A_1(q^2) \left(\epsilon^{*\mu}(\lambda_M) - q^\mu \frac{(\epsilon^*(\lambda_M) \cdot q)}{q^2} \right)$
1^-	γ_μ	$+ q^\mu (\epsilon^*(\lambda_M) \cdot q) \frac{2m_V}{q^2} A_0(q^2)$
1^-	$\gamma_\mu \gamma_5$	$- \frac{\epsilon^*(\lambda_M) \cdot q}{m_M + m_V} A_2(q^2) \left((p_M + p_V)_\mu - q^\mu \frac{m_M^2 - m_V^2}{q^2} \right),$
1^-	$\sigma_{\mu\nu}$	$\langle V(p_V, \lambda_V) S(x) M(p_M) \rangle = 0,$
1^-	$\sigma_{\mu\nu} \gamma_5$	$\text{For } B \rightarrow V \text{ transition, 7 FFs.}$
		$\langle V(p_V, \lambda_V) P(x) M(p_M) \rangle = -(\epsilon^*(\lambda_M) \cdot q) \frac{2m_V}{m_{q_d} + m_{q_u}} A_0(q^2),$
		$\langle V(p_V, \lambda_V) T^{\mu\nu}(x) M(p_M) \rangle = \epsilon^{\mu\nu\rho\sigma} \left\{ -\epsilon_{\rho*}(\lambda_M) (p_M + p_V)_\sigma T_1(q^2) \right.$
		$+ 2 \frac{(\epsilon^*(\lambda_M) \cdot q)}{q^2} p_{M\rho} p_{D^*\sigma} \left(T_1(q^2) - T_2(q^2) - \frac{q^2}{m_M^2 - m_V^2} T_3(q^2) \right)$
		$\left. + \epsilon^{*\rho}(\lambda_M) q^\sigma \frac{m_B^2 - m_V^2}{q^2} (T_1(q^2) - T_2(q^2)) \right\}.$

□ These FFs are now precisely predicted
with the help of LQCD & LCSR.

THEORETICAL BASICS

□ Differential decay rates for $B \rightarrow D\tau\nu$:

$$\frac{d\Gamma(B \rightarrow D\tau\bar{\nu})}{dq^2 d\cos\theta_\tau} = \frac{G_F^2 V_{cb}^2}{256 m_B^3 \pi^3} q^2 \lambda_D^{1/2}(q^2) \left(1 - \frac{m_\tau^2}{q^2}\right)^2 \left\{ J_0(q^2) + J_1(q^2) \cos\theta_\tau + J_2(q^2) \cos^2\theta_\tau \right\}$$

□ Differential decay rates for $B \rightarrow D^*\tau\nu$:

$$\begin{aligned} \frac{d^4\Gamma(B \rightarrow D^*\tau\bar{\nu})}{dq^2 d\cos\theta_\tau d\cos\theta_D d\phi} &\equiv I(q^2, \theta_\tau, \theta_D, \phi) \\ &= \frac{9}{32\pi} \left\{ I_1^s \sin^2\theta_D + I_1^c \cos^2\theta_D + (I_2^s \sin^2\theta_D + I_2^c \cos^2\theta_D) \cos 2\theta_\tau \right. \\ &\quad + (I_3 \cos 2\phi + I_9 \sin 2\phi) \sin^2\theta_D \sin^2\theta_\tau + (I_4 \cos\phi + I_8 \sin\phi) \sin 2\theta_D \sin 2\theta_\tau \\ &\quad \left. + (I_5 \cos\phi + I_7 \sin\phi) \sin 2\theta_D \sin\theta_\tau + (I_6^s \sin^2\theta_D + I_6^c \cos^2\theta_D) \cos\theta_\tau \right\}. \end{aligned}$$

□ Observables:

$$R(D^{(*)}) = \frac{\mathcal{B}(B \rightarrow D^{(*)}\tau\nu)}{\mathcal{B}(B \rightarrow D^{(*)}\ell\nu)}$$

$$P_L^{D^*}(q^2) = \frac{d\Gamma^{\lambda_{D^*}=0}(B \rightarrow D^*\tau\nu)/dq^2}{d\Gamma(B \rightarrow D^*\tau\nu)/dq^2}$$

$$P_\tau^{D^{(*)}}(q^2) = \frac{d\Gamma^{\lambda_\tau=1/2}(B \rightarrow D^{(*)}\tau\nu)/dq^2 - d\Gamma^{\lambda_\tau=-1/2}(B \rightarrow D^{(*)}\tau\nu)/dq^2}{d\Gamma(B \rightarrow D^{(*)}\tau\nu)/dq^2}$$

.....

CORRELATION WITH OTHER OBSERVABLE

- Many $b \rightarrow c\tau\nu$ -mediated processes: how about their correlations?

➤ Inclusive decay $B \rightarrow X_c \tau\nu$:

- $R(D^{(*)}) \quad \rightarrow \quad Br(B \rightarrow D\tau\nu) + Br(B \rightarrow D^*\tau\nu) = (2.39 \pm 0.13)\% \quad Br(B \rightarrow D^{**}\tau\nu) > 0.5\%$ Freytsis et al, 1506.08896

- $\left. \frac{Br(B \rightarrow X_c \tau\nu)}{Br(B \rightarrow X_c \ell\nu)} \right|_{OPE} = 0.222 \pm 0.007 \quad \left. Br(B \rightarrow X_c e\nu) = (10.8 \pm 0.4)\% \right\} \rightarrow Br(B \rightarrow X_c \tau\nu) = (2.40 \pm 0.12)\%$
It is not a problem of form factors

- LEP: $Br(b \rightarrow X\tau\nu) = (2.41 \pm 0.23)\%$

already saturate the
inclusive decay width!

➤ Purely leptonic decay $B_c \rightarrow \tau\nu$: $\langle 0 | \bar{c} \gamma_\mu \gamma_5 b | B_c^- \rangle = -if_{B_c} p_\mu$

$b \rightarrow c\tau\nu \leftrightarrow b\bar{c} \rightarrow \tau\nu$: $Br(B_c \rightarrow \tau\nu) < 10\%$ (30%, 40%) Akeroyd-Chen, 1708.04072
Alonso et al, Celis et al

$$\begin{aligned} \mathcal{B}(P^- \rightarrow \ell\bar{\nu}_\ell) &= \frac{G_F^2 |V_{qu} V_{qd}|^2 m_P m_\ell^2}{8\pi} f_P^2 \tau_P \left(1 - \frac{m_\ell^2}{m_P^2}\right)^2 \\ &\quad \left|1 + C_{LL}^V - C_{RL}^V + \frac{m_P^2}{m_\ell(m_{qu} + m_{qd})} (C_{RL}^S - C_{LL}^S)\right|^2 \end{aligned}$$

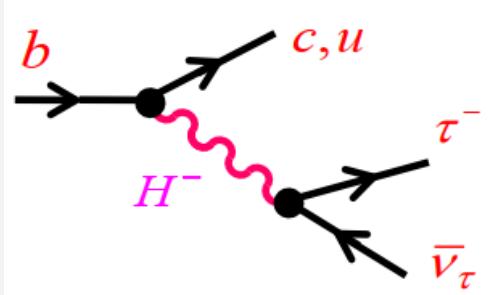
➤ Exclusive & inclusive baryonic decay:

$\Lambda_b \rightarrow \Lambda_c \tau\nu$ and $\Lambda_b \rightarrow X_c \tau\nu, \dots$

SCALAR NP: CELIS/JUNG/LI/PICH, 1612.07757

□ Low-energy effective Lagrangian with H^\pm mediators:

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{q_u q_d} [\bar{q}_u (g_L^{q_u q_d \ell} \mathcal{P}_L + g_R^{q_u q_d \ell} \mathcal{P}_R) q_d] [\bar{\ell} \mathcal{P}_L \nu_\ell]$$

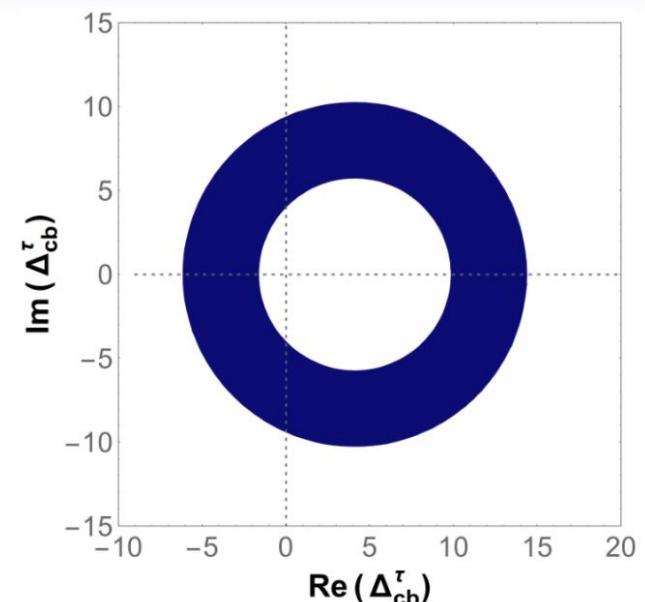
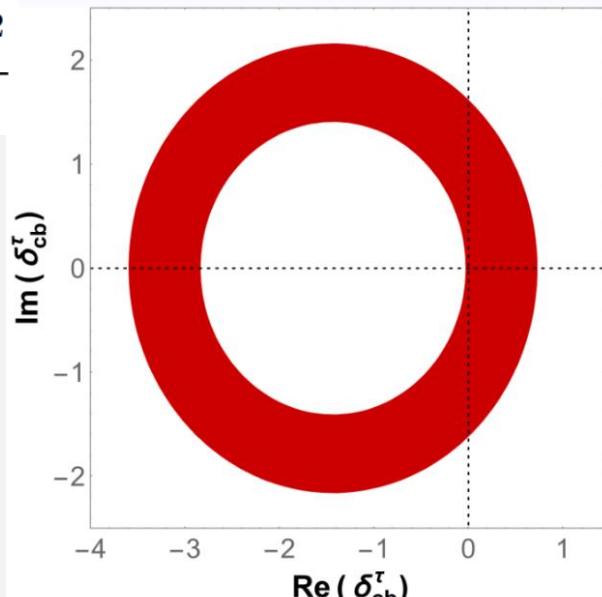


□ Scalar NP contributions to $b \rightarrow c\tau\nu$ processes:

$$R(D): \quad \delta_{cb}^\ell \equiv \frac{(g_L^{cb\ell} + g_R^{cb\ell})(m_B - m_D)^2}{m_\ell (\bar{m}_b - \bar{m}_c)}$$

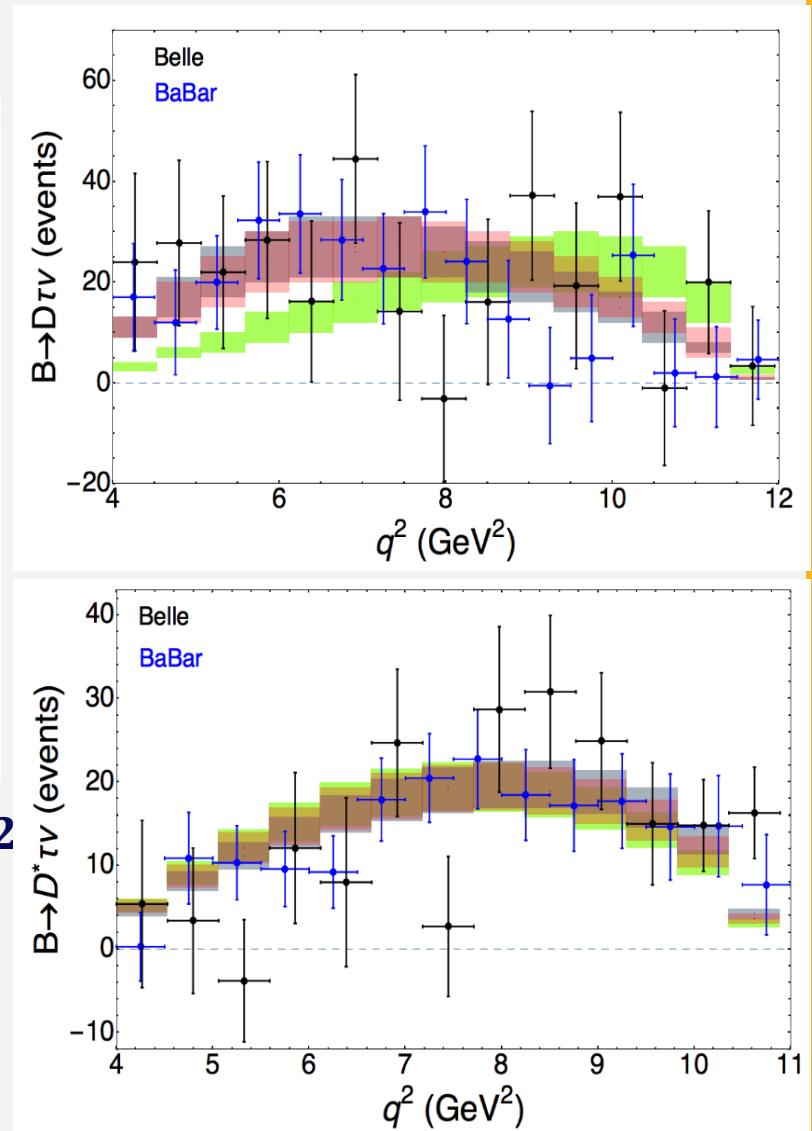
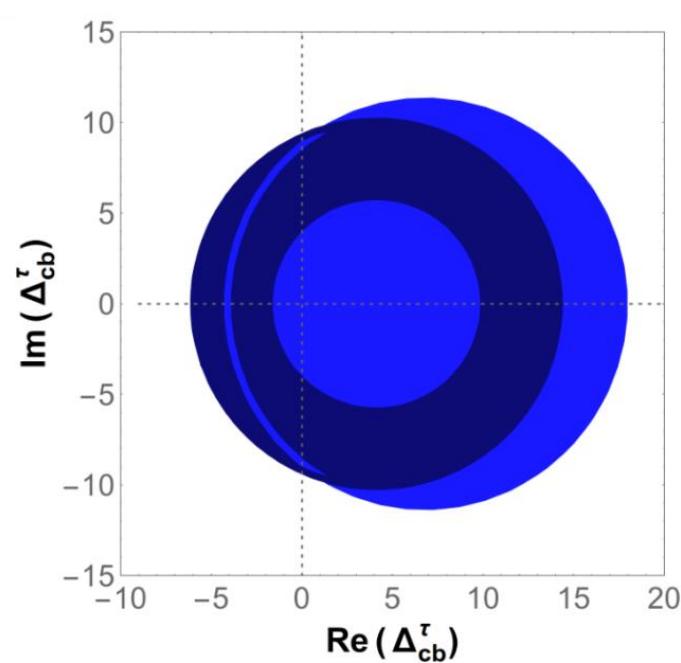
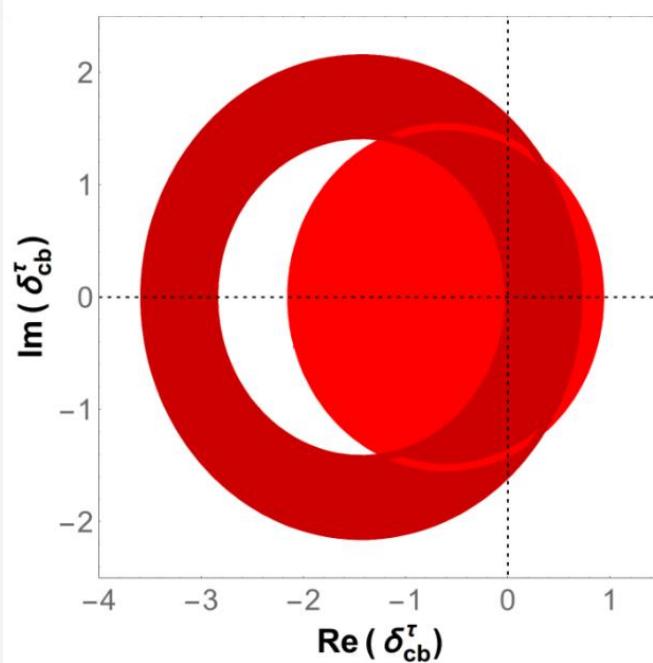
$$R(D^*): \quad \Delta_{cb}^\ell \equiv \frac{(g_L^{cb\ell} - g_R^{cb\ell})m_B^2}{m_\ell (\bar{m}_b + \bar{m}_c)}$$

- *any values of $R(D)$ & $R(D^*)$ can be trivially explained.*
- *preferred scalar couplings from $R(D^*)$ quite huge.*



SCALAR NP: CELIS/JUNG/LI/PICH, 1612.07757

□ Constraints from other $b \rightarrow c\tau\nu$ observables:



□ Differential decay widths $d\Gamma(B \rightarrow D^{(*)}\tau\nu)/dq^2$

➤ *although the exp. data very uncertain, already constraining, especially for $B \rightarrow D\tau\nu$!*

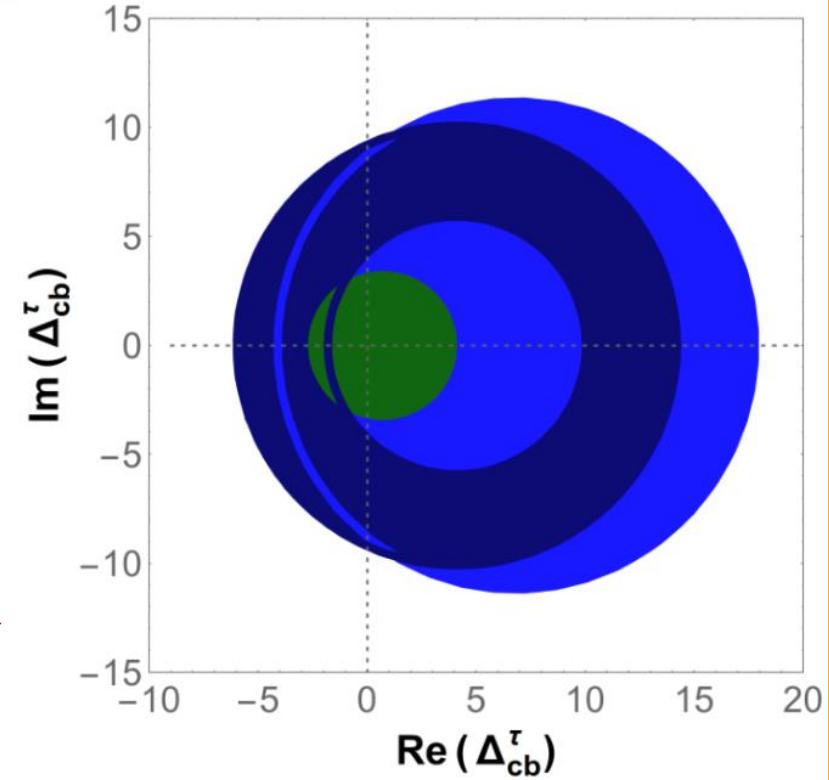
SCALAR NP: CELIS/JUNG/LI/PICH, 1612.07757

□ Decay width of $B_c^- \rightarrow \tau \bar{\nu}_\tau$: [Li+ '16; Alonso+'16; Akeroyd+'17]

$$\Gamma(B_c^- \rightarrow \tau^- \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c}^3 \frac{m_\tau^2}{m_{B_c}^2} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left| C_V - C_S \frac{m_{B_c}^2}{m_\tau [m_b(\mu_b) + m_c(\mu_b)]} \right|^2$$

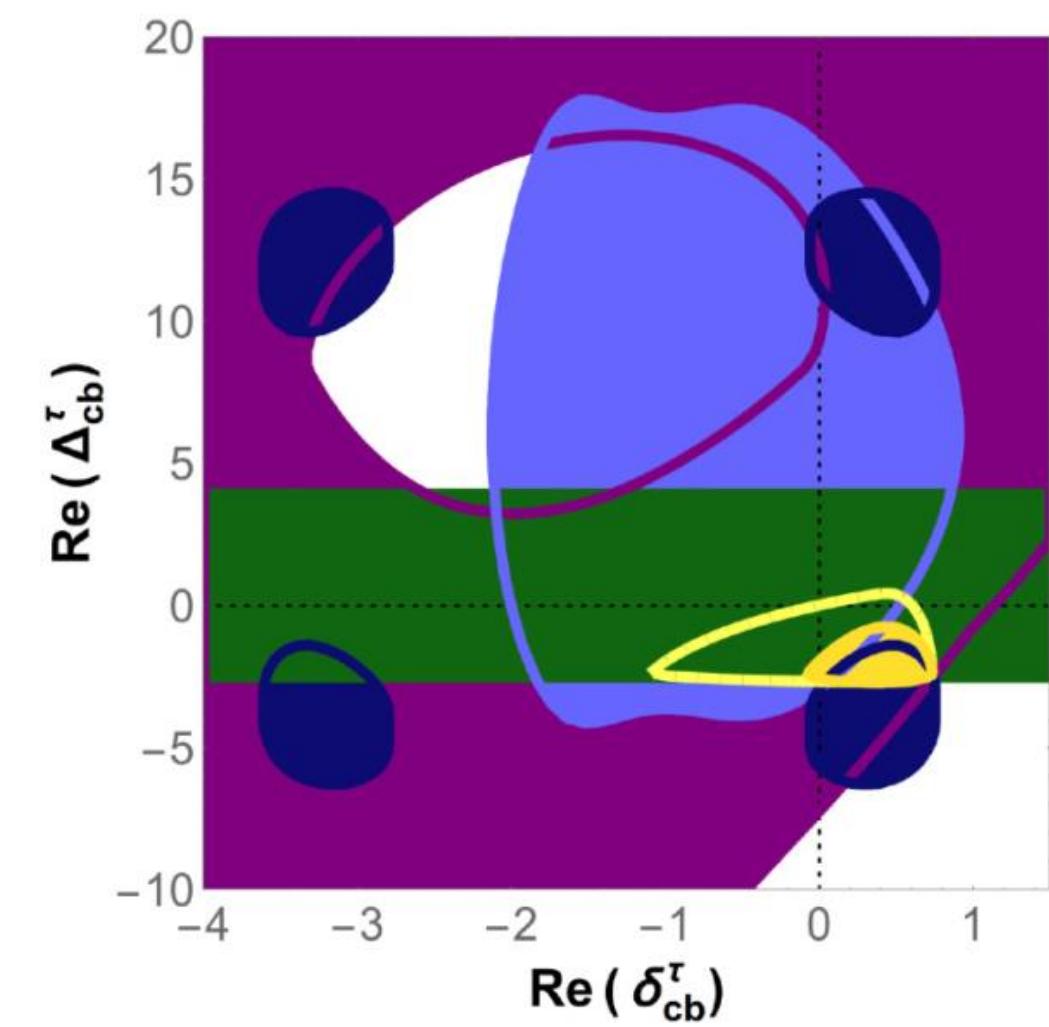
$$C_S \langle 0 | \bar{c} \gamma_5 b | B_c \rangle \bar{\tau} (1 - \gamma_5) \nu_\tau$$

- $B_c^- \rightarrow \tau \bar{\nu}_\tau$ is an obvious $b \rightarrow c \tau \bar{\nu}_\tau$ transition;
- with large scalar couplings, its width even oversaturate the B_c total width;
- *excludes second real solution in Δ_{cb}^τ plane, or even scalar NP for $R(D^*)$.*



SCALAR NP: CELIS/JUNG/LI/PICH, 1612.07757

□ Global fit with scalar NP: real couplings



- $R(D)$ and $R(D^*)$
- $d\Gamma(B \rightarrow D^{(*)}\tau\nu)/dq^2$
- $R(X_c) = \frac{Br(B \rightarrow X_c\tau\nu_\tau)}{Br(B \rightarrow X_c l\nu_l)}$
- $Br(B_c \rightarrow \tau\nu) < 40\%$
- global fit @ 95% CL
- when complex couplings are allowed.

SCALAR LQ: LI/YANG/ZHANG, 1605.09308

- One single scalar LQ with $M_\phi \sim 1\text{TeV}$ and $(3, 1, -1/3)$ added to SM;

$$\begin{aligned}\mathcal{L}_\phi = & (D_\mu \phi)^\dagger D_\mu \phi - M_\phi^2 |\phi|^2 - g_{h\phi} |\Phi|^2 |\phi|^2 \\ & + \bar{Q}^c \lambda^L i\tau_2 L \phi^* + \bar{u}_R^c \lambda^R e_R \phi^* + \text{h.c.},\end{aligned}$$

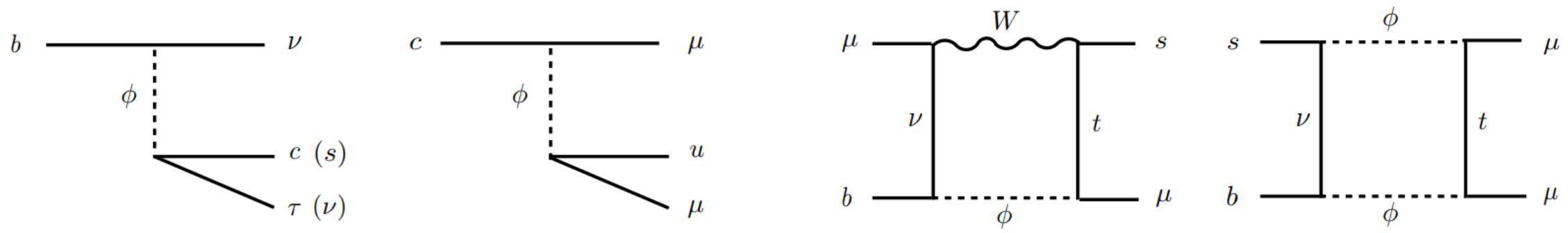
[Bauer and Neubert, 1511.01900]

- ϕ interacts with fermions via:

$$\mathcal{L}_{\text{int}}^\phi = \bar{u}_L^c \lambda_{ul}^L l_L \phi^* - \bar{d}_L^c \lambda_{d\nu}^L \nu_L \phi^* + \bar{u}_R^c \lambda_{ul}^R l_R \phi^* + \text{h.c.}$$

- Both tree- and loop-level

four-fermion operators generated: $(\bar{u}_i d_j)(\bar{\nu} \ell)$, $(\bar{u}_i u_j)(\bar{\ell} \ell)$, $(\bar{d}_i d_j)(\bar{\nu} \nu)$



$B \rightarrow D^{(*)} \tau \nu$, $B_c \rightarrow \tau \nu$, $B \rightarrow X_c \tau \nu$, $B \rightarrow X_s \bar{\nu} \nu$, $B \rightarrow K^{(*)} \bar{\nu} \nu$, $K \rightarrow \pi \bar{\nu} \nu$,

SCALAR LQ: LI/YANG/ZHANG, 1605.09308

- Total H_{eff} for $b \rightarrow c\tau\nu$ transitions: integrating out ϕ ;

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[C_V(M_\phi) \bar{c} \gamma_\mu P_L b \bar{\tau} \gamma^\mu P_L \nu_\tau + C_S(M_\phi) \bar{c} P_L b \bar{\tau} P_L \nu_\tau \right. \\ \left. - \frac{1}{4} C_T(M_\phi) \bar{c} \sigma_{\mu\nu} P_L b \bar{\tau} \sigma^{\mu\nu} P_L \nu_\tau \right]$$

- C_V, C_S, C_T : WCs at matching scale M_ϕ ; featured by tensor operator;

$$C_V(M_\phi) = 1 + \frac{\lambda_{b\nu_\tau}^L \lambda_{c\tau}^{L*}}{4\sqrt{2} G_F V_{cb} M_\phi^2}, \\ C_S(M_\phi) = C_T(M_\phi) = -\frac{\lambda_{b\nu_\tau}^L \lambda_{c\tau}^{R*}}{4\sqrt{2} G_F V_{cb} M_\phi^2}.$$

$$C_S(\mu_b) = \left[\frac{\alpha_s(m_t)}{\alpha_s(\mu_b)} \right]^{\frac{\gamma_S}{2\beta_0^{(5)}}} \left[\frac{\alpha_s(M_\phi)}{\alpha_s(m_t)} \right]^{\frac{\gamma_S}{2\beta_0^{(6)}}} C_S(M_\phi) \\ C_T(\mu_b) = \left[\frac{\alpha_s(m_t)}{\alpha_s(\mu_b)} \right]^{\frac{\gamma_T}{2\beta_0^{(5)}}} \left[\frac{\alpha_s(M_\phi)}{\alpha_s(m_t)} \right]^{\frac{\gamma_T}{2\beta_0^{(6)}}} C_T(M_\phi)$$

- C_S, C_T : scale dependent; needs to be run down to μ_b ;

SCALAR LQ: LI/YANG/ZHANG, 1605.09308

- Four best-fit solutions for $R(D^{(*)})$ along with acceptable q^2 spectra;

$$(\lambda_{b\nu_\tau}^L \lambda_{c\tau}^{L*}, \lambda_{b\nu_\tau}^L \lambda_{c\tau}^{R*}) = (C''_{SR}, C''_{SL}) = \begin{cases} (-0.35, -0.03), & P_A \\ (0.96, 2.41), & P_B \\ (-5.74, 0.03), & P_C \\ (-6.34, -2.39), & P_D \end{cases}$$

[Freytsis, Ligeti, Ruderman,
1506.08896]

- **P_A solution: explains naturally $R(D^{(*)})$, $R(K)$ and $(g-2)_\mu$, while satisfying other constraints without fine-tuning;** [Bauer & Neubert, 1511.01900]

One Leptoquark to Rule Them All: A Minimal Explanation for $R_{D^{(*)}}$, R_K and $(g-2)_\mu$

Martin Bauer (U. Heidelberg), Matthias Neubert (JGU Mainz & MITP)

Phys. Rev. Lett. 116, 141802 (2016)

We show that by adding a single new scalar particle to the Standard Model, a TeV-scale leptoquark with the quantum numbers of a right-handed down quark, one can explain in a natural way three of the most striking anomalies of particle physics: the violation of lepton universality in $\bar{B} \rightarrow \bar{K}\ell^+\ell^-$ decays, the enhanced $\bar{B} \rightarrow D^{(*)}\tau\bar{\nu}$ decay rates, and the anomalous magnetic moment of the muon. Constraints from other precision measurements in the flavor sector can be satisfied without fine-tuning. Our model predicts enhanced $\bar{B} \rightarrow \bar{K}^{(*)}\nu\bar{\nu}$ decay rates and a new-physics contribution to $B_s - \bar{B}_s$ mixing close to the current central fit value.

SCALAR LQ: LI/YANG/ZHANG, 1605.09308

- **Question:** the four best-fit solutions could be discriminated from each other by other $b \rightarrow c\tau\nu$ processes, especially by $B_c \rightarrow \tau\nu$?
- $\Gamma(B_c \rightarrow \tau\nu)$ with LQ-exchanged contribution:

$$\Gamma(B_c^- \rightarrow \tau^- \bar{\nu}_\tau) = \frac{G_F^2}{8\pi} |V_{cb}|^2 f_{B_c}^2 m_{B_c}^3 \frac{m_\tau^2}{m_{B_c}^2} \left(1 - \frac{m_\tau^2}{m_{B_c}^2}\right)^2 \left|C_V - C_S \frac{m_{B_c}^2}{m_\tau [m_b(\mu_b) + m_c(\mu_b)]}\right|^2$$



$$\Gamma(B_c^- \rightarrow \tau^- \bar{\nu}_\tau) = \begin{cases} 2.22 \times 10^{-2} \Gamma_{B_c}, & \text{SM} \\ 2.45 \times 10^{-2} \Gamma_{B_c}, & P_A \\ 1.33 \Gamma_{B_c}, & P_B \\ 2.39 \times 10^{-2} \Gamma_{B_c}, & P_C \\ 1.31 \Gamma_{B_c}, & P_D \end{cases}$$

- P_B & P_D already excluded by $\Gamma(B_c \rightarrow \tau\nu)$, as the predicted decay widths have already overshot the total width; need only P_A & P_C !

SCALAR LQ: LI/YANG/ZHANG, 1605.09308

- P_A & P_C solutions: can be discriminated from each other?

$$\mathcal{H}_{\text{fit}} = \frac{4G_F}{\sqrt{2}} V_{cb} \left\{ \left[1 + \begin{pmatrix} 0.129 & \text{for } P_A \\ -2.117 & \text{for } P_C \end{pmatrix} \right] \bar{c} \gamma_\mu P_L b \bar{\tau} \gamma^\mu P_L \nu_\tau + \begin{pmatrix} 0.018 & \text{for } P_A \\ -0.018 & \text{for } P_C \end{pmatrix} \bar{c} P_L b \bar{\tau} P_L \nu_\tau \right. \\ \left. + \begin{pmatrix} -0.002 & \text{for } P_A \\ 0.002 & \text{for } P_C \end{pmatrix} \bar{c} \sigma_{\mu\nu} P_L b \bar{\tau} \sigma^{\mu\nu} P_L \nu_\tau \right\} @ \mu_b = m_b = 4.18 \text{ GeV}$$

- P_A & P_C contribute mainly to the SM-like operator $\bar{c} \gamma_\mu P_L b \bar{\tau} \gamma^\mu P_L \nu_\tau$:

$$C_V^{\text{fit}} = \begin{cases} 1.129, & \text{for } P_A \\ -1.117, & \text{for } P_C \end{cases}$$

nearly same absolute values, both enhancing the SM result by $\sim 12\%$, but the sign of solution P_C is flipped relative to the SM.

- P_A & P_C : tiny values but opposite signs for scalar/tensor operators.

EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Most general $SU(3)_C \otimes U(1)_Q$ -invariant \mathcal{L}_{eff} @ $\mu_b = m_b$ scale:

$$\mathcal{L}_{SM}^{(6)} = -\frac{4G_F}{\sqrt{2}} V_{cb} \mathcal{O}_{V_L} + \text{H.c.},$$

$$\mathcal{L}_{NP}^{(6)} = -\frac{4G_F}{\sqrt{2}} V_{cb} (C_{V_L} \mathcal{O}_{V_L} + C_{V_R} \mathcal{O}_{V_R} + C_{S_L} \mathcal{O}_{S_L} + C_{S_R} \mathcal{O}_{S_R} + C_T \mathcal{O}_T) + \text{H.c.}$$

$$\mathcal{O}_{V_{L(R)}} = (\bar{c}\gamma^\mu P_{L(R)} b)(\bar{\tau}\gamma_\mu P_L \nu_\tau),$$

$$\mathcal{O}_{S_{L(R)}} = (\bar{c}P_{L(R)} b)(\bar{\tau}P_L \nu_\tau),$$

$$\mathcal{O}_T = (\bar{c}\sigma^{\mu\nu} P_L b)(\bar{\tau}\sigma_{\mu\nu} P_L \nu_\tau).$$

□ Observables considered:

- Ratios $R(D)$ and $R(D^*)$;
- Differential distributions $d\Gamma(B \rightarrow D^{(*)}\tau\nu)/dq^2$;
- Leptonic decay rate $Br(B_c \rightarrow \tau \nu_\tau) \leq 10(30)\%$;
- Longitudinal polarization fraction $P_L^{D^*}$;
- Polarization fraction of the τ lepton $P_\tau^{D^*}$;

$$P_L^{D^*}(q^2) = \frac{d\Gamma^{\lambda_{D^*}=0}(B \rightarrow D^*\tau\nu)/dq^2}{d\Gamma(B \rightarrow D^*\tau\nu)/dq^2}.$$

$$P_L^{D^*} = 0.60 \pm 0.08 \pm 0.04 \text{ vs } \text{Belle, 1901.06380}$$

$$P_L^{D^*} = 0.455 \pm 0.003 \quad \sim 1.5\sigma$$

$$P_\tau^{D^{(*)}}(q^2) = \frac{d\Gamma^{\lambda_\tau=1/2}(B \rightarrow D^{(*)}\tau\nu)/dq^2 - d\Gamma^{\lambda_\tau=-1/2}(B \rightarrow D^{(*)}\tau\nu)/dq^2}{d\Gamma(B \rightarrow D^{(*)}\tau\nu)/dq^2}$$

$$P_\tau(D^*)^{\text{exp}} = -0.38^{+0.51+0.21}_{-0.51-0.16} \text{ vs } \text{Belle, 1612.00529}$$

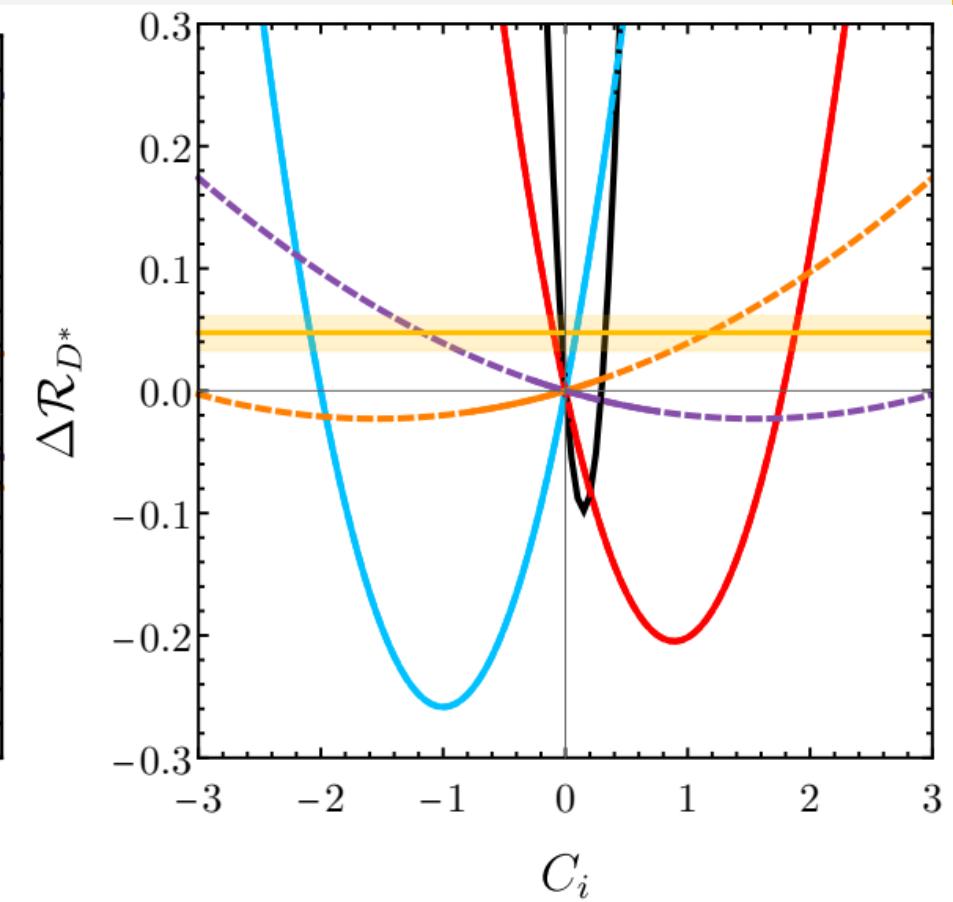
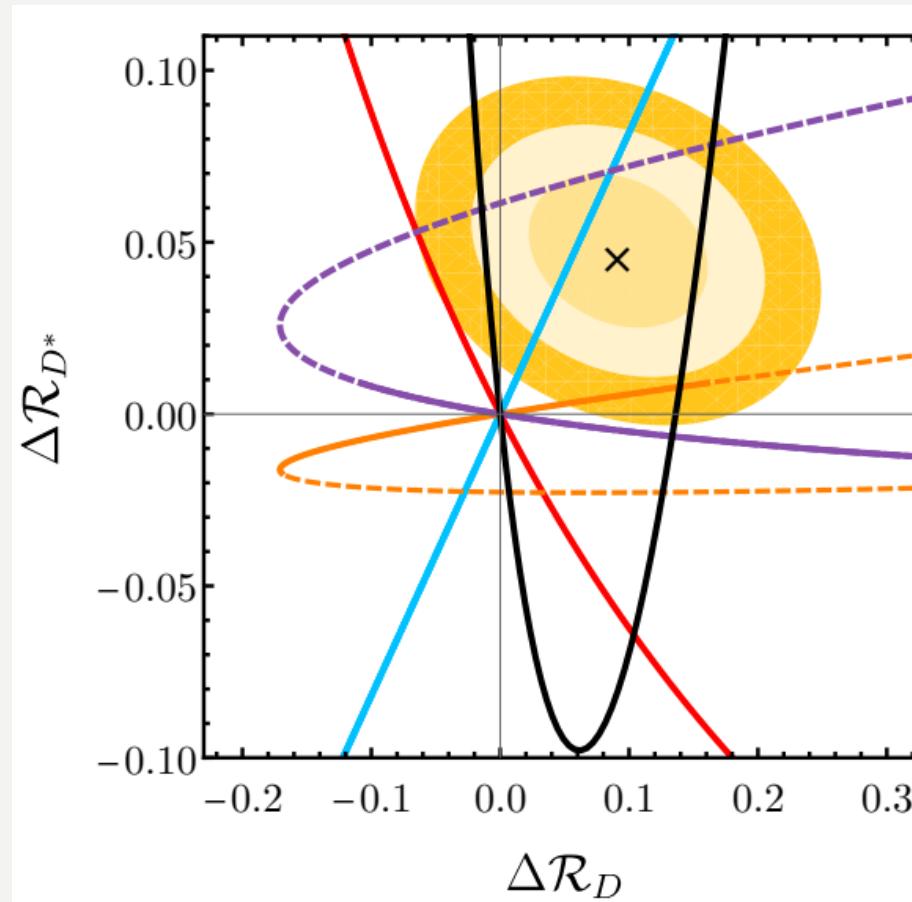
EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Global fit:

[see also Murgui
etal, 1904.09311]

$$\Delta X = X - X_{SM}$$

- C_{LL}^V
- C_{RL}^V
- C_{RL}^S
- C_{LL}^S
- C_{LL}^T



□ dashed: $Br(B_c \rightarrow \tau \nu_\tau) \leq 10\%$; \rightarrow

C_{LL}^S already excluded!
 C_{RL}^S can but only at 3σ !

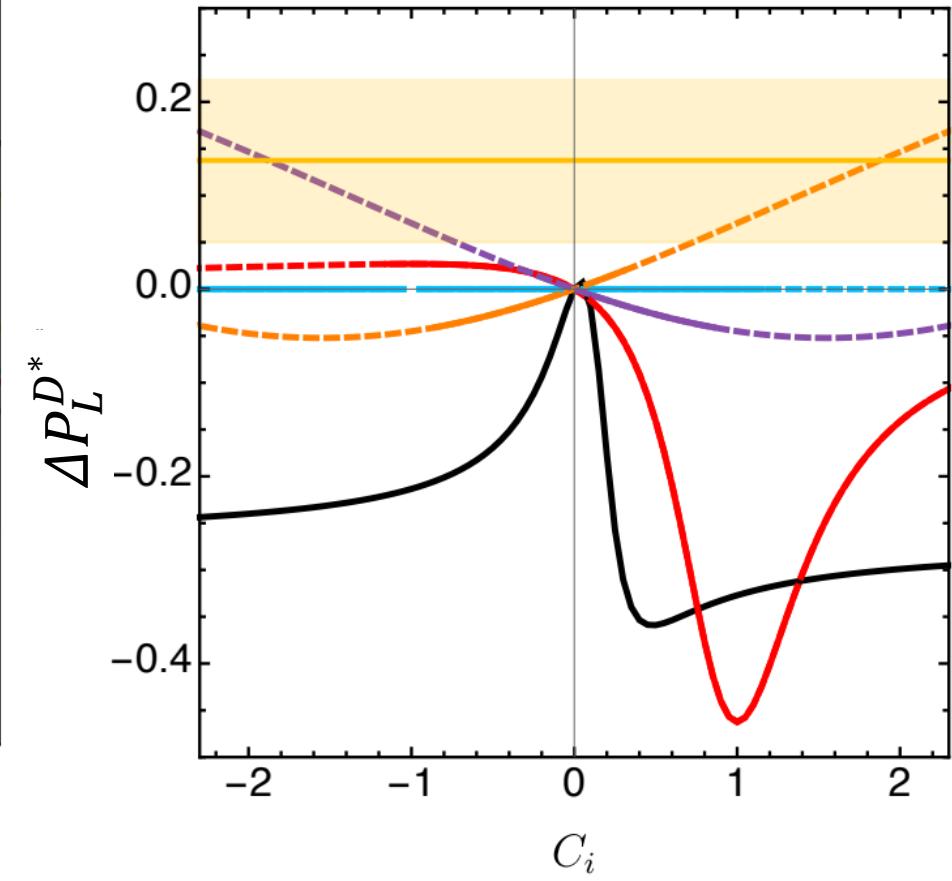
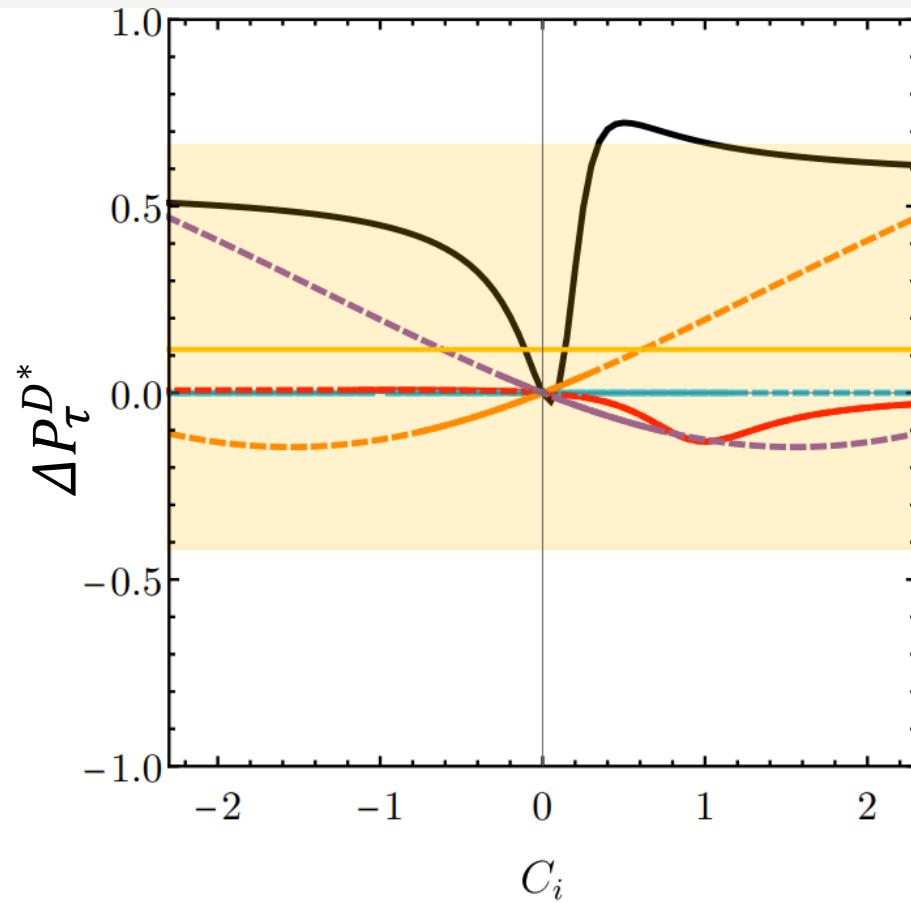
EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Global fit:

[see also Murgui
etal, 1904.09311]

$$\Delta X = X - X_{SM}$$

- C_{LL}^V
- C_{RL}^V
- C_{RL}^S
- C_{LL}^S
- C_{LL}^T

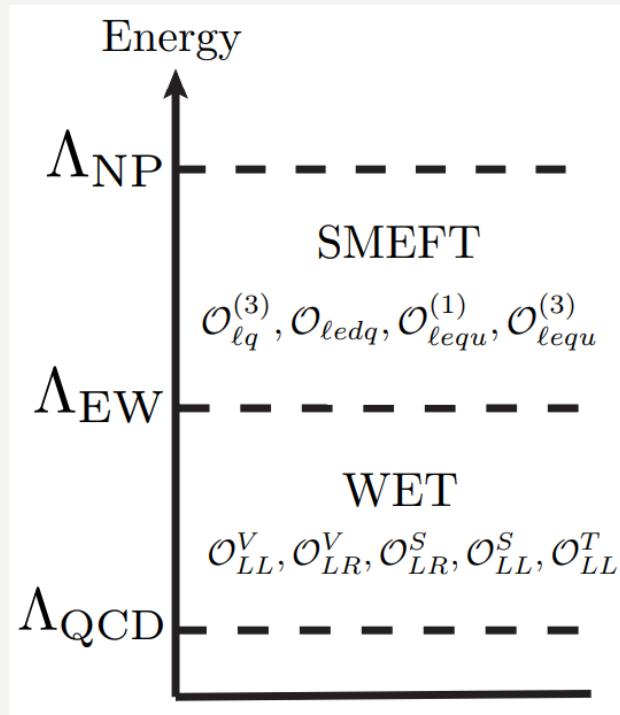


- $P_L^{D^*}$ & $P_\tau^{D^*}$ very potential to distinguish different contributions;
- difficult to accommodate 1σ $P_L^{D^*}$ for any C_i ; even excluded C_{LL}^T !

EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Global fit within the SMEFT:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda^2} \sum_i C_i(\Lambda) Q_i$$



[Buchmuller, Wyler '86; Grzadkowski et al, 1008.4884]

□ Operators contributing to $b \rightarrow c\tau\nu$:

$$Q_{lq}^{(3)} = (\bar{l}\gamma_\mu\tau^I l)(\bar{q}\gamma^\mu\tau^I q), \quad Q_{ledq} = (\bar{l}^j e)(\bar{d}q^j),$$
$$Q_{lequ}^{(1)} = (\bar{l}^j e)\varepsilon_{jk}(\bar{q}^k u), \quad Q_{lequ}^{(3)} = (\bar{l}^j \sigma_{\mu\nu} e)\varepsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u),$$

□ Basic procedure:

➤ Evolution from Λ_{NP} to Λ_{EW} ; [<http://einstein.ucsd.edu/smeft/>]

➤ Matching SMEFT onto WET at Λ_{EW} ;

$$\mathcal{L}_{\text{WET}} = \mathcal{L}_{\text{QCD+QED}}^{(u,d,c,s,b,e,\mu,\tau,\nu_e,\nu_\mu,\nu_\tau)} + \mathcal{L}_{\text{SM}}^{(6)} + \mathcal{L}_{\text{NP}}^{(6)},$$

➤ Evolution from Λ_{EW} down to μ_b ;

EFT ANALYSIS: HU/LI/YANG, 1810.04939

- Matching result without C_{V_R} , because it is explicitly LFU in SMEFT;

$$C_{V_L} = -\frac{\sqrt{2}}{2G_F \Lambda^2} \sum_n \left[C_{lq}^{(3)} \right]_{332n} \frac{V_{nb}}{V_{cb}},$$

$$C_{S_R} = -\frac{\sqrt{2}}{4G_F \Lambda^2} \frac{1}{V_{cb}} [C_{ledq}]_{3332}^*,$$

$$C_{S_L} = -\frac{\sqrt{2}}{4G_F \Lambda^2} \sum_n \left[C_{lequ}^{(1)} \right]_{33n2}^* \frac{V_{nb}}{V_{cb}},$$

$$C_T = -\frac{\sqrt{2}}{4G_F \Lambda^2} \sum_n \left[C_{lequ}^{(3)} \right]_{33n2}^* \frac{V_{nb}}{V_{cb}}.$$

- Here $\mu_b = 4.18 \text{ GeV}$ and $\Lambda = 1 \text{ TeV}$;

- Terms $\propto V_{u(c)b}$ neglected, need keep only $n = 3$;
- With 3-loop QCD & 1-loop EW/QED evolutions;

Evolution & matching

$$C_{V_L}(\mu_b) = -1.503 \left[C_{lq}^{(3)} \right]_{3323}(\Lambda),$$

$$C_{V_R}(\mu_b) = 0,$$

$$C_{S_L}(\mu_b) = -1.257 \left[C_{lequ}^{(1)} \right]_{3332}(\Lambda)$$

$$+ 0.2076 \left[C_{lequ}^{(3)} \right]_{3332}(\Lambda),$$

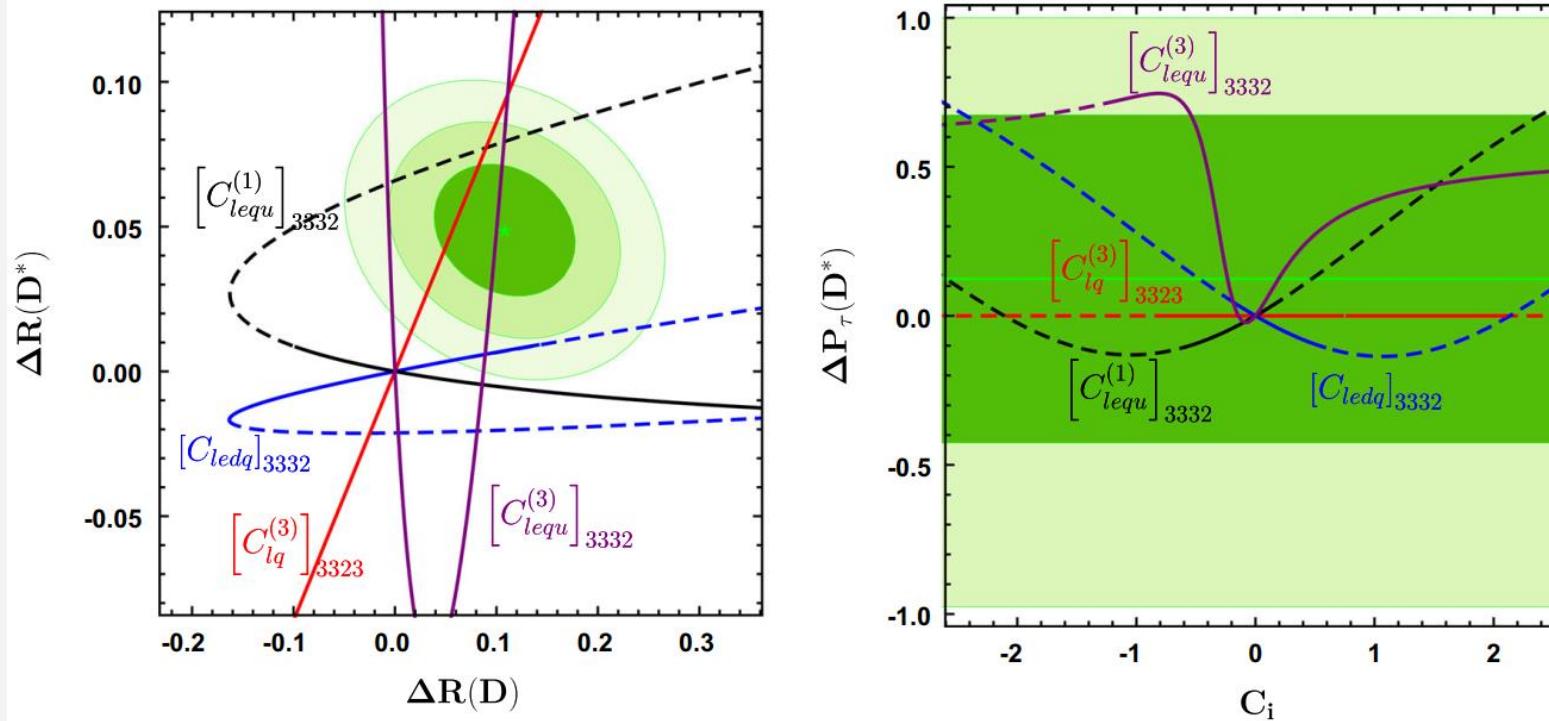
$$C_{S_R}(\mu_b) = -1.254 \left[C_{ledq} \right]_{3332}(\Lambda),$$

$$C_T(\mu_b) = 0.002725 \left[C_{lequ}^{(1)} \right]_{3332}(\Lambda)$$

$$- 0.6059 \left[C_{lequ}^{(3)} \right]_{3332}(\Lambda),$$

EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Fit result with only a single WC at each time;



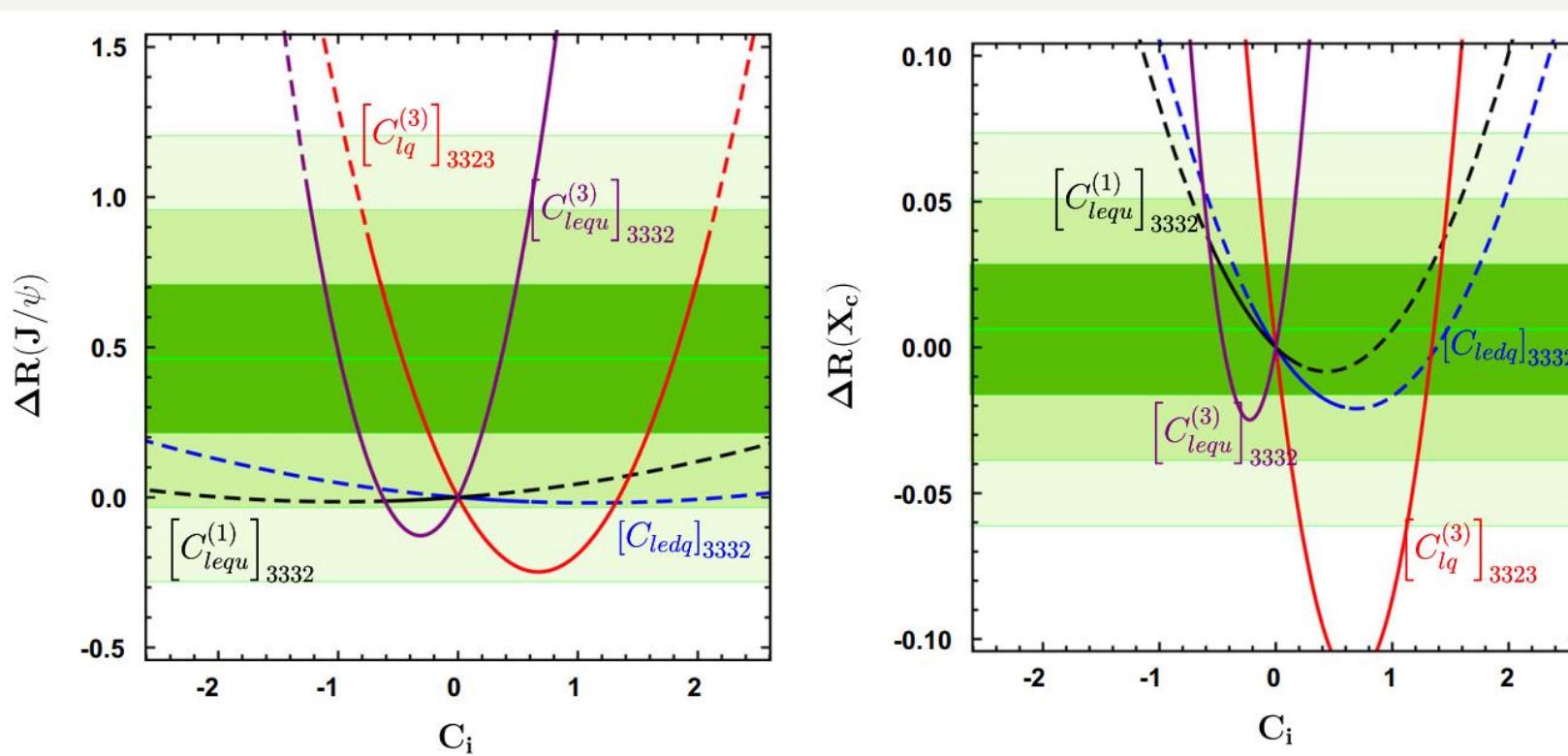
$$\begin{aligned} C_{V_L}(\mu_b) &= -1.503 \left[C_{lq}^{(3)} \right]_{3323} (\Lambda), \\ C_{V_R}(\mu_b) &= 0, \\ C_{S_L}(\mu_b) &= -1.257 \left[C_{lequ}^{(1)} \right]_{3332} (\Lambda) \\ &\quad + 0.2076 \left[C_{lequ}^{(3)} \right]_{3332} (\Lambda), \\ C_{S_R}(\mu_b) &= -1.254 \left[C_{ledq} \right]_{3332} (\Lambda), \\ C_T(\mu_b) &= 0.002725 \left[C_{lequ}^{(1)} \right]_{3332} (\Lambda) \\ &\quad - 0.6059 \left[C_{lequ}^{(3)} \right]_{3332} (\Lambda), \end{aligned}$$

Dashed: $Br(B_c \rightarrow \tau \bar{\nu}_\tau) \leq 10\%$

- $\left[C_{lequ}^{(1)} \right]_{3332}$ already excluded by $R(D^{(*)})$ at 3σ ;
- $\left[C_{ledq} \right]_{3332}$ can explain $R(D^{(*)})$ only marginally at $\sim 2\sigma$;
- $\left[C_{lq}^{(3)} \right]_{3323}$ or $\left[C_{lequ}^{(3)} \right]_{3323}$ can explain $R(D^{(*)})$ at $\sim 1\sigma$;
- $\Delta P_\tau(D^*)$ helpful to discriminate between $\left[C_{lq}^{(3)} \right]_{3323}$ and $\left[C_{lequ}^{(3)} \right]_{3323}$;

EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Fit result with only a single WC at each time;



$$C_{V_L}(\mu_b) = -1.503 [C_{lq}^{(3)}]_{3323}(\Lambda),$$

$$C_{V_R}(\mu_b) = 0,$$

$$C_{S_L}(\mu_b) = -1.257 [C_{lequ}^{(1)}]_{3332}(\Lambda) + 0.2076 [C_{lequ}^{(3)}]_{3332}(\Lambda),$$

$$C_{S_R}(\mu_b) = -1.254 [C_{ledq}]_{3332}(\Lambda),$$

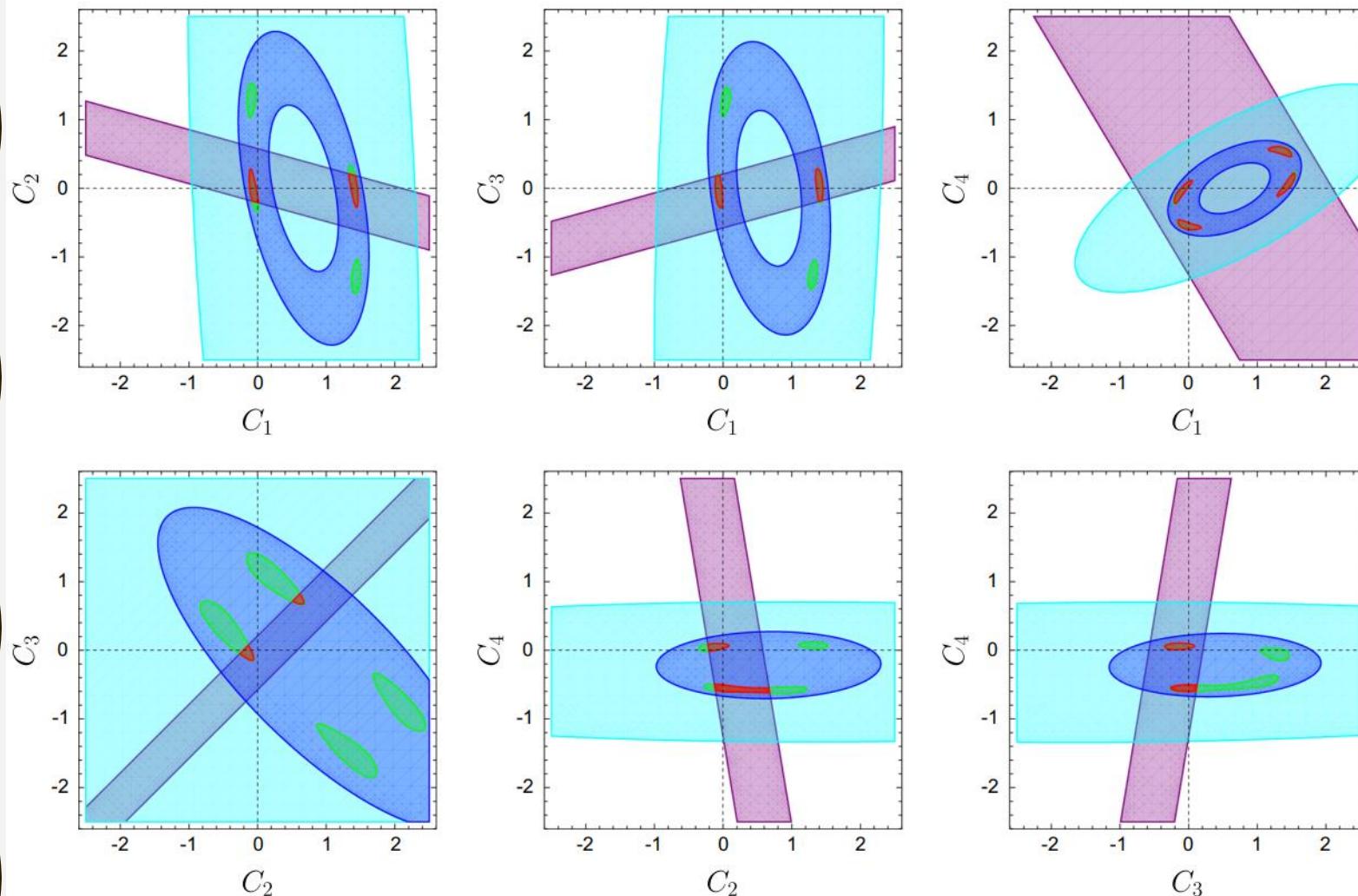
$$C_T(\mu_b) = 0.002725 [C_{lequ}^{(1)}]_{3332}(\Lambda) - 0.6059 [C_{lequ}^{(3)}]_{3332}(\Lambda),$$

Dashed: $Br(B_c \rightarrow \tau \nu_\tau) \leq 10\%$

- $\Delta R(J/\psi)$ and $\Delta R(X_c)$ further exclude some allowed intervals of $[C_{lq}^{(3)}]_{3323}$ and $[C_{lequ}^{(3)}]_{3323}$!
- Tensor solution not favored by $P_L(D^*)$: $P_L(D^*) = 0.142 \pm 0.001$ vs $0.60 \pm 0.08 \pm 0.04$.

EFT ANALYSIS: HU/LI/YANG, 1810.04939

□ Fit result with simultaneous two WCs at a time;

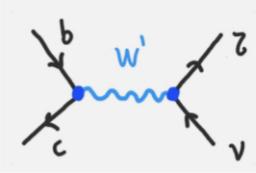
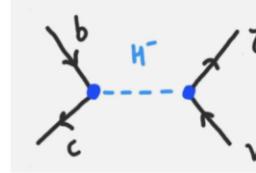
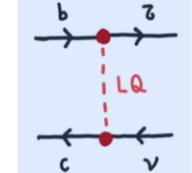


$$C_1 \equiv \left[C_{lq}^{(3)} \right]_{3323}(\Lambda), \quad C_2 \equiv \left[C_{ledq} \right]_{3332}(\Lambda),$$
$$C_3 \equiv \left[C_{lequ}^{(1)} \right]_{3332}(\Lambda), \quad C_4 \equiv \left[C_{lequ}^{(3)} \right]_{3332}(\Lambda),$$

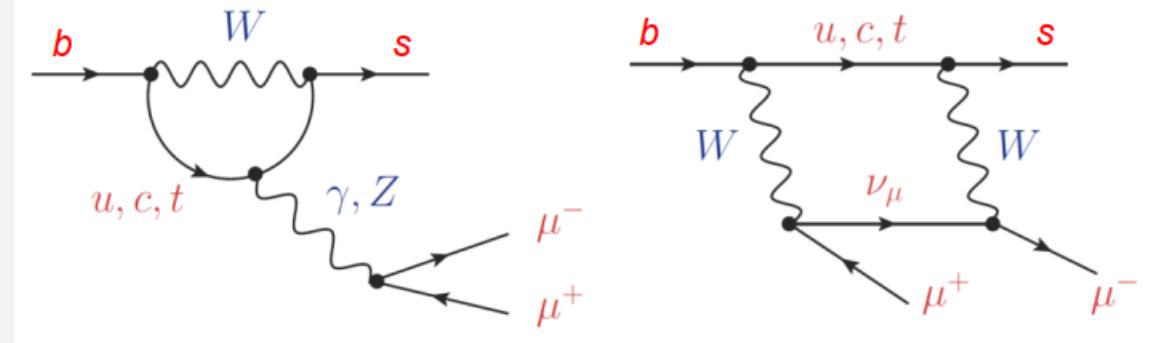
- ✓ Green: $R(D)$ & $R(D^*)$
- ✓ Cyan: $R(J/\psi)$
- ✓ Blue: $R(X_c)$
- ✓ Red: $Br(B_c \rightarrow \tau \nu_\tau) \leq 10\%$

- **strongest from $R(D^{(*)})$;**
- **$Br(B_c \rightarrow \tau \nu_\tau) \leq 10\%$ very complementary, making parts of the allowed regions already excluded;**

SUMMARY OF $b \rightarrow c$ ANOMALIES

- Since 2012, $R(D^{(*)})$ anomalies triggered a lot of attention; If confirmed with more precise data from LHCb & Belle II, first indication of LFUV.
 - Most preferred solution: a global modification of C_{LL}^V associated with $(\bar{c}\gamma_\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu)$;
 - Various specific UV models with few TeV mediators;
 - Interplay with anomalies in neutral-current B decays;
 - Many UV-complete NP models;
- Possible tree-level mediators:
 -  $(1, 3, 0)$
 -  $(1, 2, 1/2)$
 -  $(3, X, Y)$
 - Challenges for New Physics explanations:
 - ⇒ Flavor observables: $B \rightarrow K\nu\bar{\nu}$, Δm_{B_s} , ... [Many papers...]
 - ⇒ Electroweak constraints (one-loop): $\tau \rightarrow \mu\nu\bar{\nu}$, $Z \rightarrow \ell\ell$ [Feruglio et al. '16]
 - ⇒ LHC direct and indirect bounds. [Eboli. '88, Greljo et al. '15, Faroughy et al. '16]
- Scalar and vector leptoquarks are the **only viable candidates**

$$R_{H_s} = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma(H_b \rightarrow H_s \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma(H_b \rightarrow H_s e^+ e^-)}{dq^2} dq^2}$$

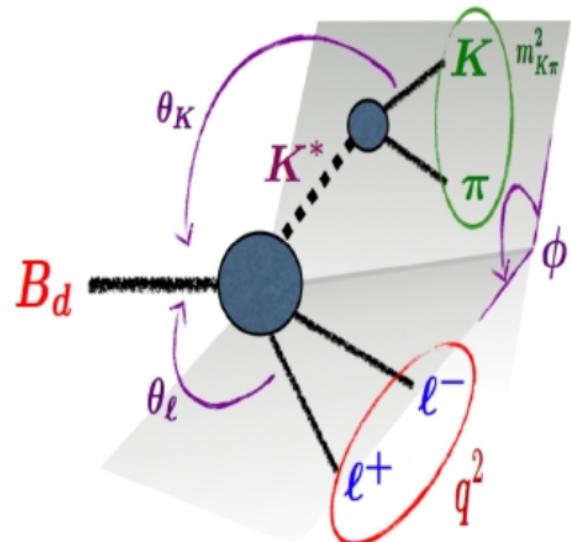


$b \rightarrow s$ anomalies

$b \rightarrow s$ ANOMALIES

□ Differential angular distributions of $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_K d\cos\theta_l d\phi} = \frac{9}{32\pi} \left[J_{1s} \sin^2\theta_K + J_{1c} \cos^2\theta_K + (J_{2s} \sin^2\theta_K + J_{2c} \cos^2\theta_K) \cos 2\theta_l \right. \\ + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi \\ + (J_{6s} \sin^2\theta_K + J_{6c} \cos^2\theta_K) \cos\theta_l + J_7 \sin 2\theta_K \sin\theta_l \sin\phi \\ \left. + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi \right]$$



[Figure borrowed from Javier Virto]

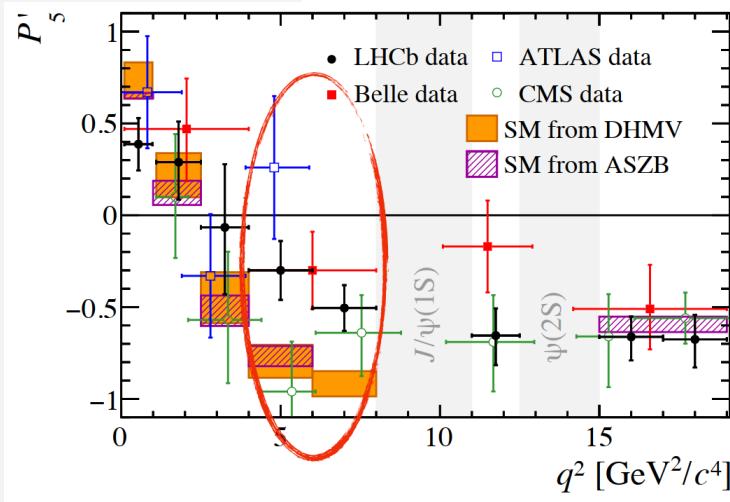
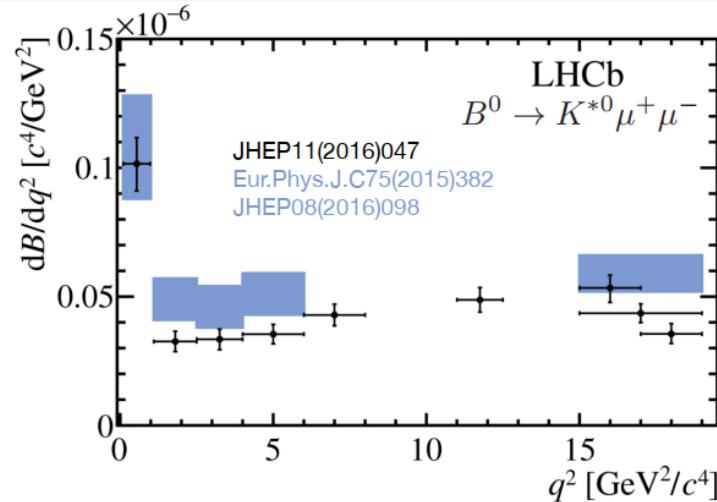
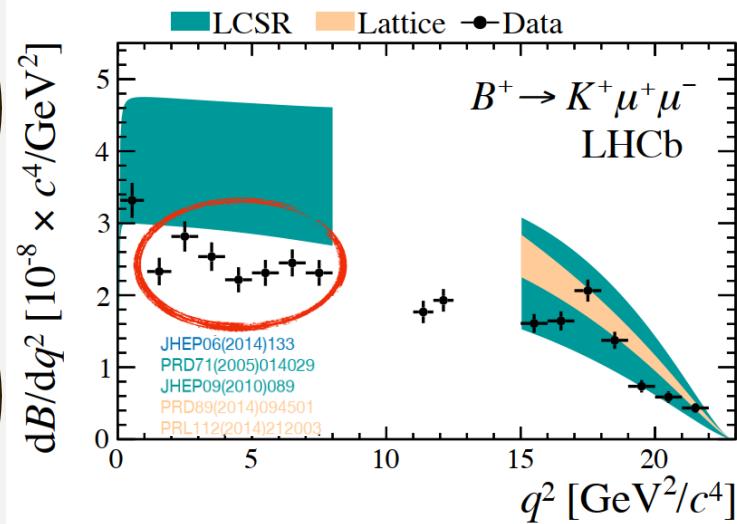
Optimized observables
[Descotes-Genon et al, 2012, 2013]

$$P'_5 = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

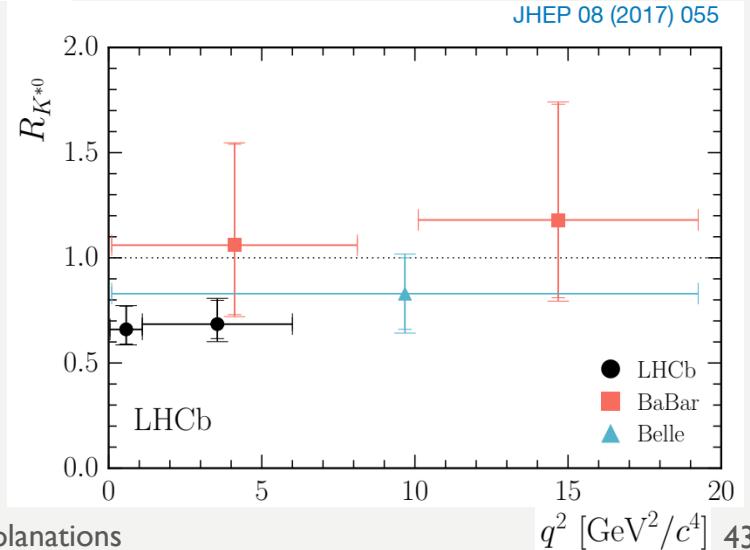
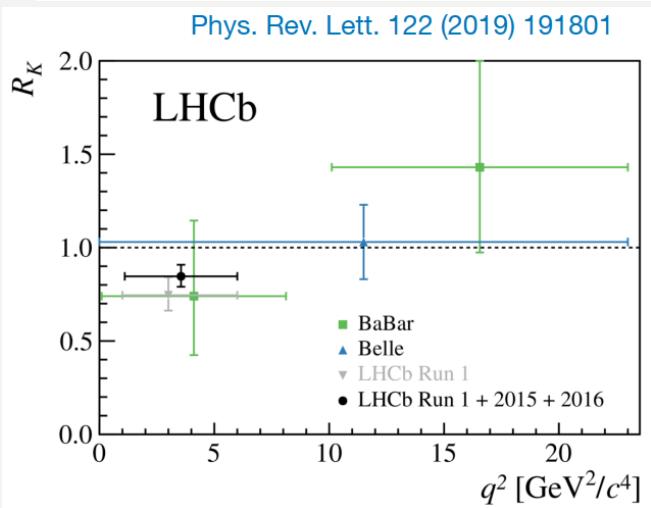
$b \rightarrow s$ ANOMALIES

□ Since P'_5 anomaly @ 2013, several anomalies observed;

LHCb, JHEP 02 (2016) 104,
 Belle, PRL 118 (2017) 111801,
 CMS-PAS-BPH-15-008,
 ATLAS-CONF-2017-023
 Eur.Phys.J.C75(2015)382
 JHEP08(2016)098
 PRD89(2014) 094501

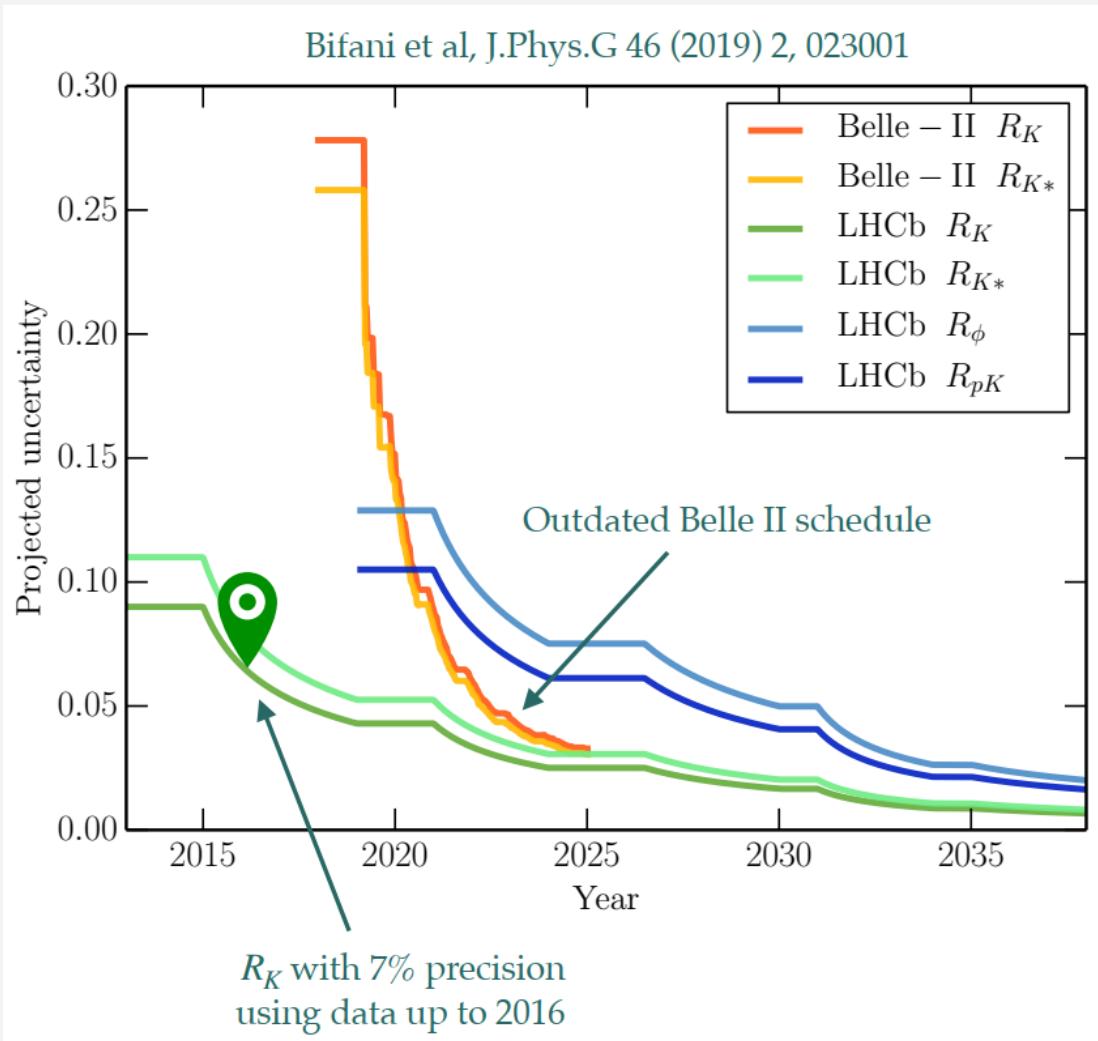


$$R_H = \frac{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B \rightarrow H \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q_{\min}^2}^{q_{\max}^2} \frac{d\Gamma[B \rightarrow H e^+ e^-]}{dq^2} dq^2}$$



PROSPECTS FOR $R(H_s)$ MEASUREMENTS

□ Projected uncertainty for various $R(H_s)$ ratios from Belle-II and LHCb:



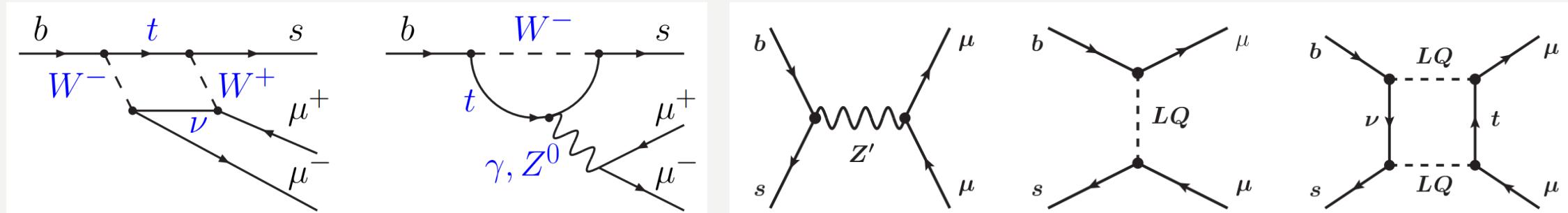
Yield	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^+ \rightarrow K^+ e^+ e^-$	254 ± 29 [5]	1 120	3 300	7 500	46 000
$B^0 \rightarrow K^{*0} e^+ e^-$	111 ± 14 [6]	490	1 400	3 300	20 000
$B_s^0 \rightarrow \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda_b^0 \rightarrow p K e^+ e^-$	–	120	360	820	5 000
$B^+ \rightarrow \pi^+ e^+ e^-$	–	20	70	150	900
R_X precision	Run 1 result	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
R_K	$0.745 \pm 0.090 \pm 0.036$ [5]	0.043	0.025	0.017	0.007
$R_{K^{*0}}$	$0.69 \pm 0.11 \pm 0.05$ [6]	0.052	0.031	0.020	0.008
R_ϕ	–	0.130	0.076	0.050	0.020
R_{pK}	–	0.105	0.061	0.041	0.016
R_π	–	0.302	0.176	0.117	0.047

$1.1 < q^2 < 6.0 \text{ GeV}^2$ extrapolated from Run 1 data

➤ **We will obtain definite answers for LFUV test in $b \rightarrow s \ell^+ \ell^-$ decays.**

OPTIMAL PROBES OF NP

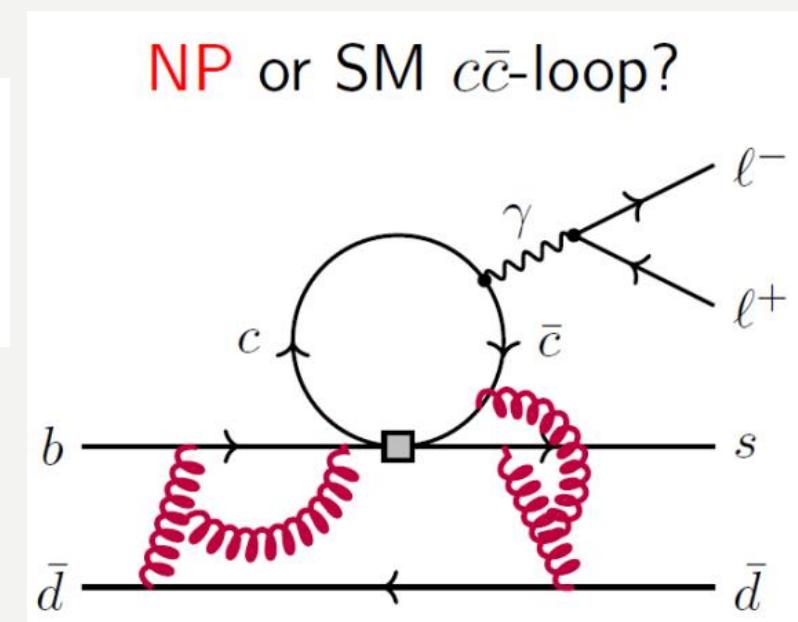
- **$b \rightarrow s\ell^+\ell^-$ decays: loop-induced FCNC processes; sensitive to NP;**



- **NP scale probed:**

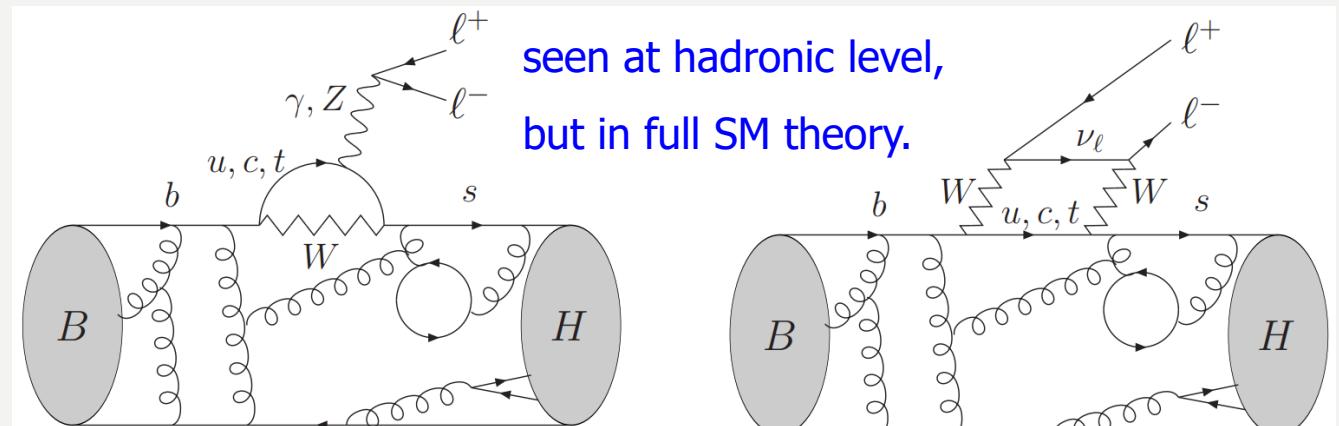
$$\Lambda_{\text{NP}} \times \sqrt{|\mathcal{C}_{9,10}^{\text{NP}}|} \sim \begin{cases} \frac{4\pi\sqrt{2}M_W}{ge\sqrt{|V_{tb}V_{ts}^*|}} = 36 \text{ TeV} & (\text{generic tree level}), \\ \frac{\sqrt{2}M_W}{e\sqrt{|V_{tb}V_{ts}^*|}} = 2 \text{ TeV} & (\text{weak loop}), \\ \sqrt{2}M_W/e = 400 \text{ GeV} & (\text{MFV, weak loop}). \end{cases}$$

- **Caution: NP could be easily mimicked by hadronic effects;**

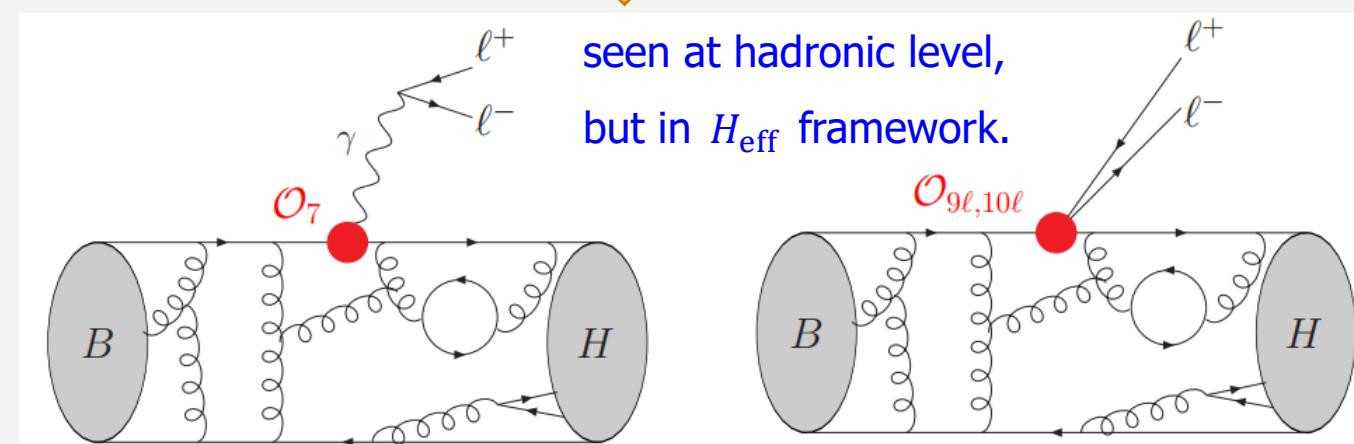


THEORETICAL BASICS

□ Separate the different scales involved;



$m_W \gg m_b$



□ H_{eff} for $b \rightarrow sll$ transitions:

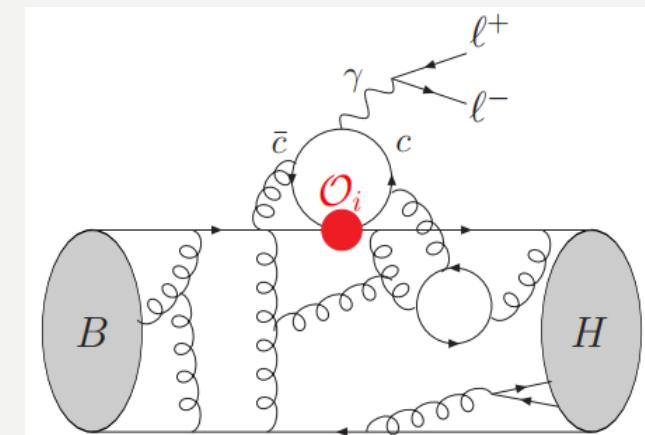
$$\mathcal{H}_{\text{eff}}(b \rightarrow s \ell^+ \ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i,$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s} \sigma_{\mu\nu} P_R b) F^{\mu\nu},$$

$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} (\bar{s} \gamma_\mu P_L b) (\bar{\ell} \gamma^\mu \ell),$$

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

$$O_{1,2} = \bar{c} \gamma_\mu (1 - \gamma_5) b \bar{s} \gamma^\mu (1 - \gamma_5) c$$



THEORETICAL BASICS

□ Matrix elements of $B \rightarrow K^{(*)}\ell^+\ell^-$ decays:

Matrix elements of quark currents from $Q_{7,9,10,S,P}$ naively factorize:

$$\mathcal{A} \sim \langle \ell^+ \ell^- | J_{\text{lep}} | 0 \rangle \langle V(P) | J_{\text{had}} | \bar{B} \rangle$$

Not possible for the hadronic Hamiltonian!

$$\tilde{h}_\lambda(q^2) \sim \epsilon_{\lambda,\mu} \int d^4x e^{iqx} \langle V(P) | T\{ J_{had}^{\mu,e.m.}(x) \mathcal{H}_{had}^{eff}(0) \} | B \rangle$$

□ Helicity amplitudes of $B \rightarrow K^{(*)}\ell^+\ell^-$ decays:

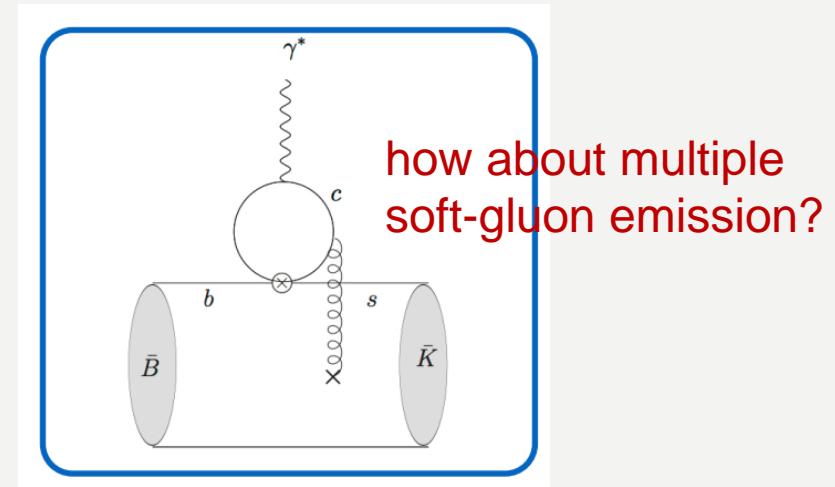
$$H_\lambda^V(q^2) \quad \propto \quad (C_9 - C'_9) \tilde{V}_\lambda(q^2) + \frac{2m_b m_B}{q^2} (C_7 - C'_7) \tilde{T}_\lambda(q^2) - 16\pi^2 \frac{m_B^2}{q^2} \tilde{h}_\lambda(q^2)$$

$$H_\lambda^A(q^2) \propto (C_{10} - C'_{10}) \tilde{V}_\lambda(q^2)$$

$$H^S(q^2) \propto \frac{m_b}{m_W} (C_S - C'_S) \tilde{S}(q^2)$$

$$H^P(q^2) \quad \propto \quad \frac{m_b}{m_W} (C_P - C'_P) \tilde{S}(q^2) + \frac{2m_\ell m_B}{q^2} (C_{10} - C'_{10}) \left(1 + \frac{m_s}{m_b}\right) \tilde{S}(q^2)$$

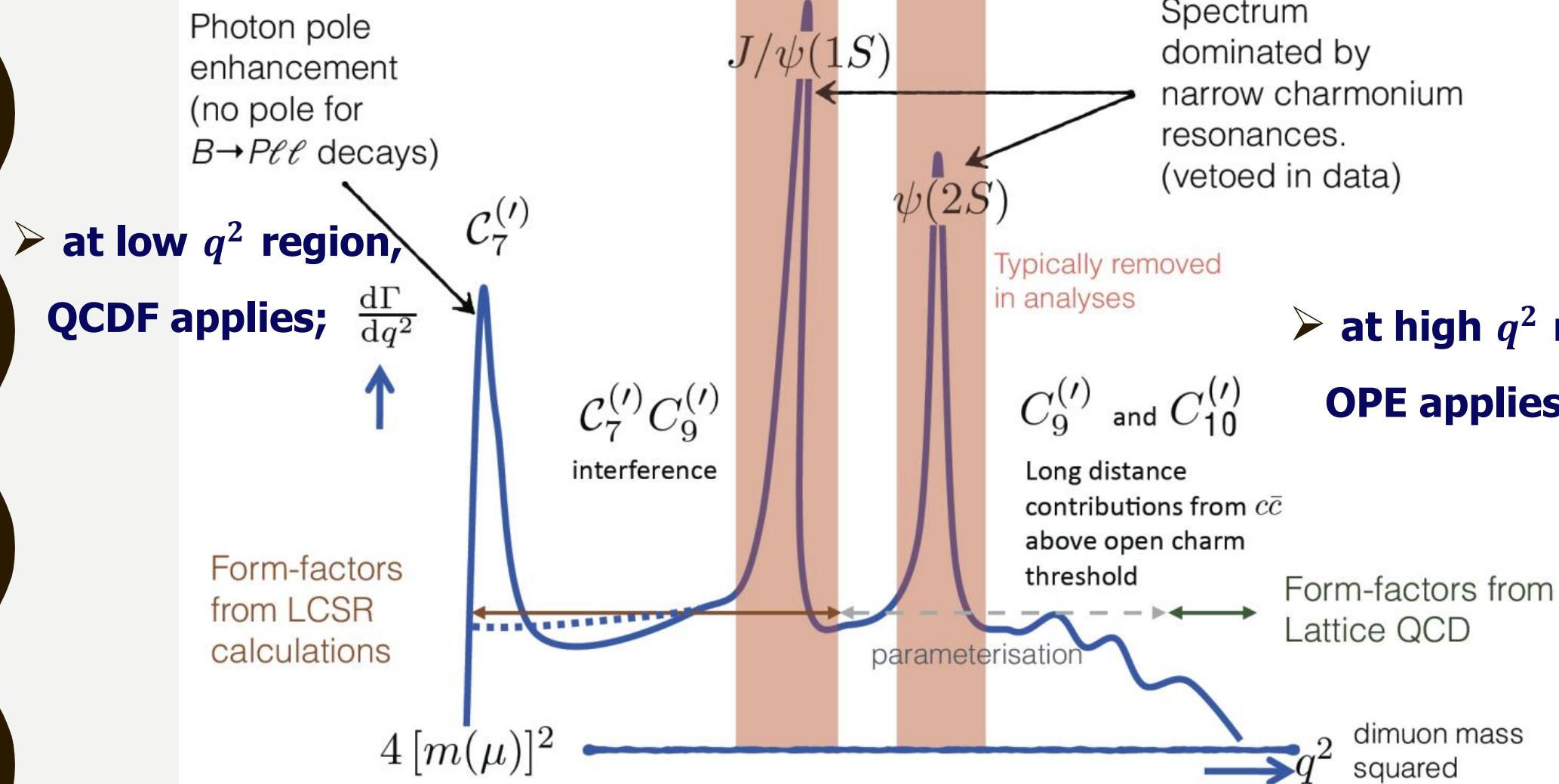
- *Main sources of uncertainties come from the FFs and from the hadronic parameters.*



- A. Khodjamirian et al., JHEP 09 (2010) 089;
 - B. T. Blake et al., EPJC 78 (2018) 6, 453;
 - C. C. Bobeth et al., EPJC 78 (2018) 6, 451;

THEORETICAL BASICS

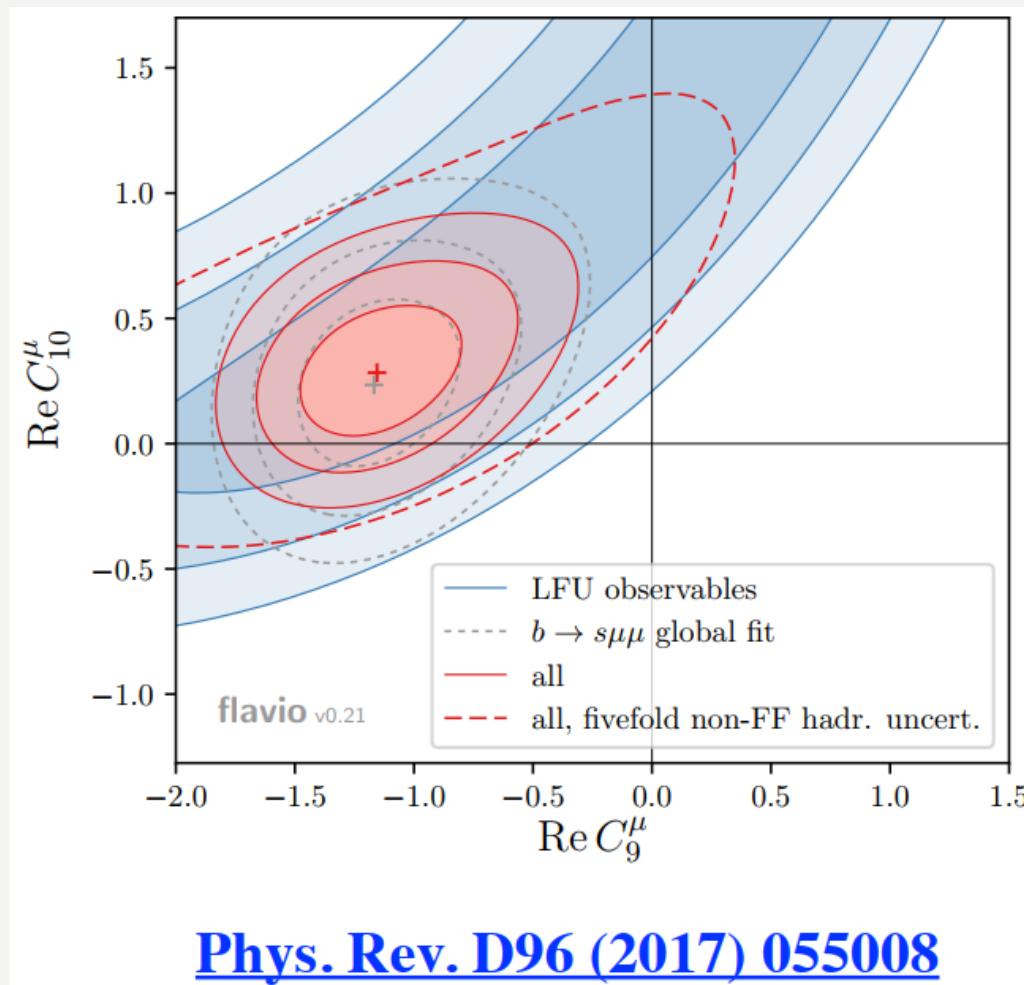
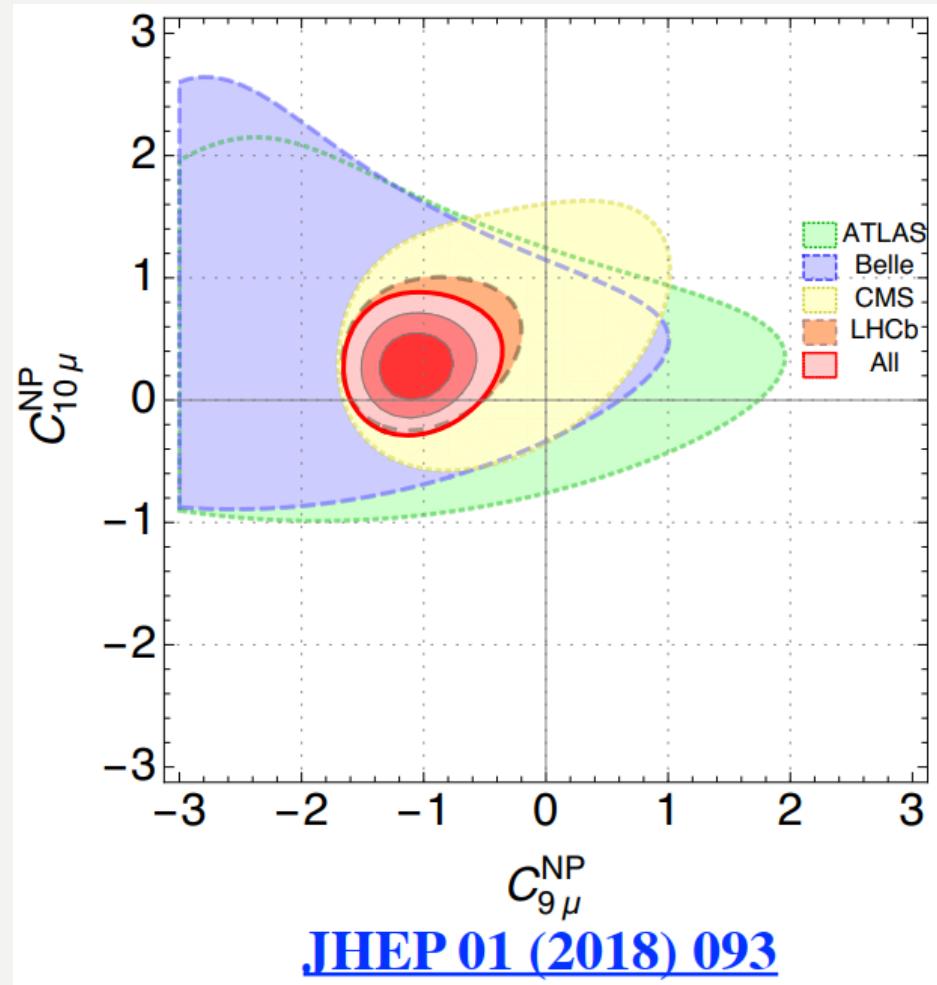
□ Expected q^2 spectrum
of $B \rightarrow K^{(*)}\ell^+\ell^-$ decays:



GLOBAL FIT

◆ Remind: $C_7 = -0.29$, $C_8 = -0.16$, $C_9 = 4.20$, $C_{10} = -4.01$

□ Possible to explain everything simply requiring NP effect in C_9^μ :



GLOBAL FIT

◆ Remind: $C_7 = -0.29$, $C_8 = -0.16$, $C_9 = 4.20$, $C_{10} = -4.01$

□ Latest fit for δC_9 and δC_7 : T. Hurtha, F. Mahmoudib, S. Neshatpour, 2006.04213

$B \rightarrow K^* \bar{\mu}\mu/\gamma$ observables ($\chi^2_{\text{SM}} = 85.1$)			
	best-fit value	χ^2_{min}	Pull _{SM}
δC_9	-1.11 ± 0.15	49.7	6.0σ
δC_7 & δC_9	0.01 ± 0.03 -1.22 ± 0.25	49.4	5.6σ

$$h_{\pm}(q^2) = h_{\pm}^{(0)} + \frac{q^2}{1 \text{ GeV}^2} h_{\pm}^{(1)} + \frac{q^4}{1 \text{ GeV}^4} h_{\pm}^{(2)},$$

$$h_0(q^2) = \sqrt{q^2} \times \left(h_0^{(0)} + \frac{q^2}{1 \text{ GeV}^2} h_0^{(1)} + \frac{q^4}{1 \text{ GeV}^4} h_0^{(2)} \right)$$

- while the central values are all non-zero, within the 1σ range they are compatible with zero when taken individually.

□ Un-known power corrections

parametrized as: 18 free parameters

$B \rightarrow K^* \bar{\mu}\mu/\gamma$ observables ($\chi^2_{\text{SM}} = 85.15$, $\chi^2_{\text{min}} = 25.96$; Pull _{SM} = 4.7σ)		
	Real	Imaginary
$h_{+}^{(0)}$	$(-2.37 \pm 13.50) \times 10^{-5}$	$(7.86 \pm 13.79) \times 10^{-5}$
$h_{+}^{(1)}$	$(1.09 \pm 1.81) \times 10^{-4}$	$(1.58 \pm 1.69) \times 10^{-4}$
$h_{+}^{(2)}$	$(-1.10 \pm 2.66) \times 10^{-5}$	$(-2.45 \pm 2.51) \times 10^{-5}$
$h_{-}^{(0)}$	$(1.43 \pm 12.85) \times 10^{-5}$	$(-2.34 \pm 3.09) \times 10^{-4}$
$h_{-}^{(1)}$	$(-3.99 \pm 8.11) \times 10^{-5}$	$(1.44 \pm 2.82) \times 10^{-4}$
$h_{-}^{(2)}$	$(2.04 \pm 1.16) \times 10^{-5}$	$(-3.25 \pm 3.98) \times 10^{-5}$
$h_0^{(0)}$	$(2.38 \pm 2.43) \times 10^{-4}$	$(5.10 \pm 3.18) \times 10^{-4}$
$h_0^{(1)}$	$(1.40 \pm 1.98) \times 10^{-4}$	$(-1.66 \pm 2.41) \times 10^{-4}$
$h_0^{(2)}$	$(-1.57 \pm 2.43) \times 10^{-5}$	$(3.04 \pm 29.87) \times 10^{-6}$

GLOBAL FIT

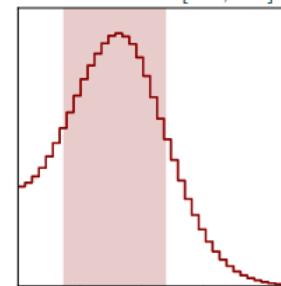
◆ Remind: $C_7 = -0.29$, $C_8 = -0.16$, $C_9 = 4.20$, $C_{10} = -4.01$

□ Prospect of the fit to δC_9 : T. Hurtha, F. Mahmoudib, S. Neshatpour, 2006.04213

First LHCb upgrade		
	best-fit value	Pull _{SM}
δC_9	-1.11 ± 0.06	15.1σ

HL-upgrade		
	best-fit value	Pull _{SM}
δC_9	-1.11 ± 0.04	21.4σ

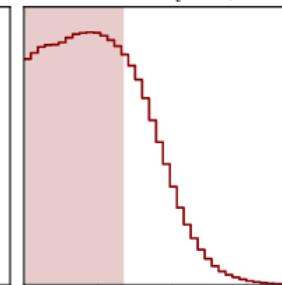
68% HPDI: [1.5, 4.8]



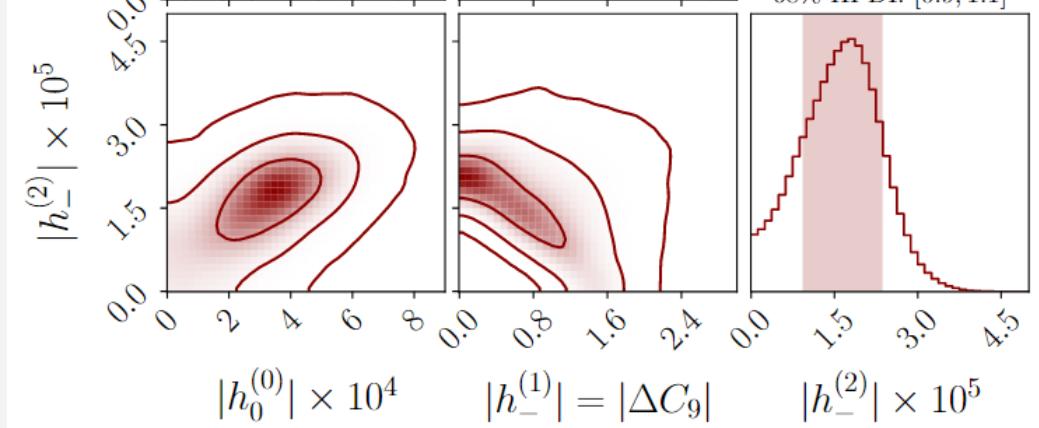
new LHCb data

strengthen evidence
of non-vanishing h's.

68% HPDI: [0.01, 1.07]



68% HPDI: [0.9, 1.1]



$$\begin{aligned}
 H_V^- &\propto \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L-} - 16\pi^2 h_-^{(2)} q^4 \right] \\
 &\quad + \left(C_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L-}, \\
 H_V^+ &\propto \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L+} - 16\pi^2 \left(h_+^{(0)} \right. \right. \\
 &\quad \left. \left. + h_+^{(1)} q^2 + h_+^{(2)} q^4 \right) \right] + \left(C_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L+}, \\
 H_V^0 &\propto \frac{m_B^2}{q^2} \left[\frac{2m_b}{m_B} \left(C_7^{\text{SM}} + h_-^{(0)} \right) \tilde{T}_{L0} - 16\pi^2 \sqrt{q^2} \left(h_0^{(0)} \right. \right. \\
 &\quad \left. \left. + h_0^{(1)} q^2 \right) \right] + \left(C_9^{\text{SM}} + h_-^{(1)} \right) \tilde{V}_{L0}.
 \end{aligned}$$

data-driven method for non-fact. PCS

GLOBAL FIT

◆ Remind: $C_7 = -0.29$, $C_8 = -0.16$, $C_9 = 4.20$, $C_{10} = -4.01$

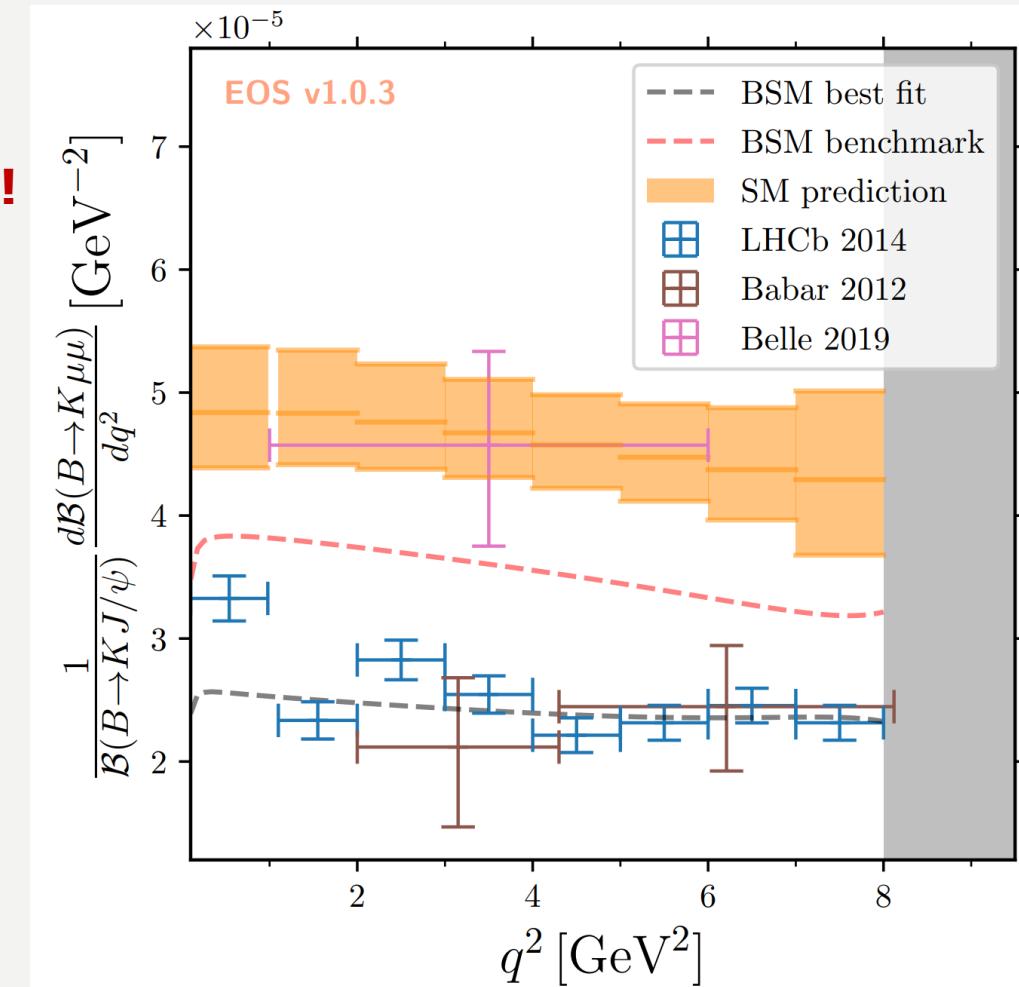
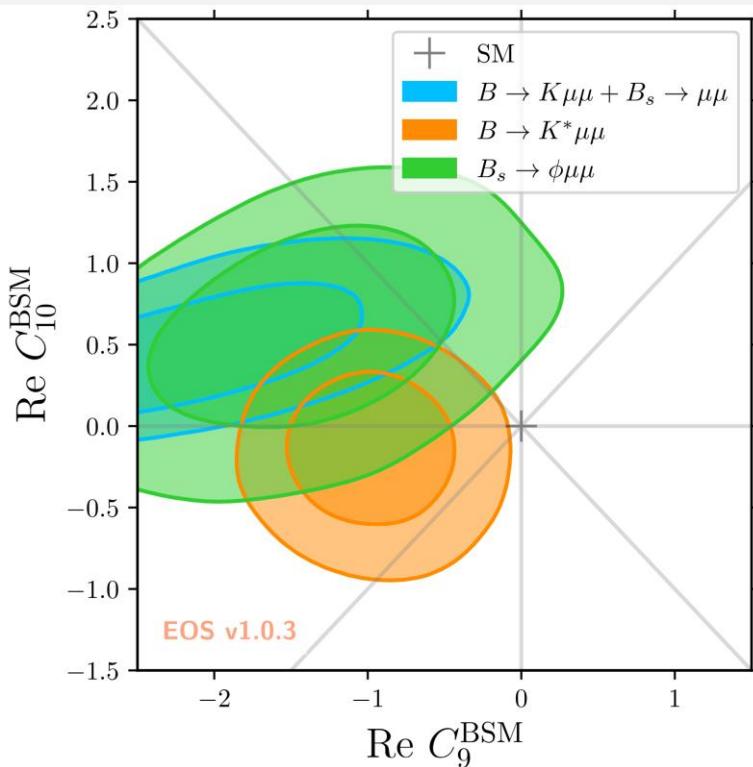
□ Prospect of the fit to δC_9 & δC_{10} :

Nico Gubernari *et al.*, 2206.03797

$$\mathcal{H}_{c,\lambda}^{B \rightarrow M}(q^2) = \frac{1}{\phi_\lambda^{B \rightarrow M}(\hat{z}) \mathcal{P}(\hat{z})} \sum_{n=0}^{\infty} \beta_{\lambda,n}^{B \rightarrow M} p_n(\hat{z})$$

A novel parametrization of non-local form factors!

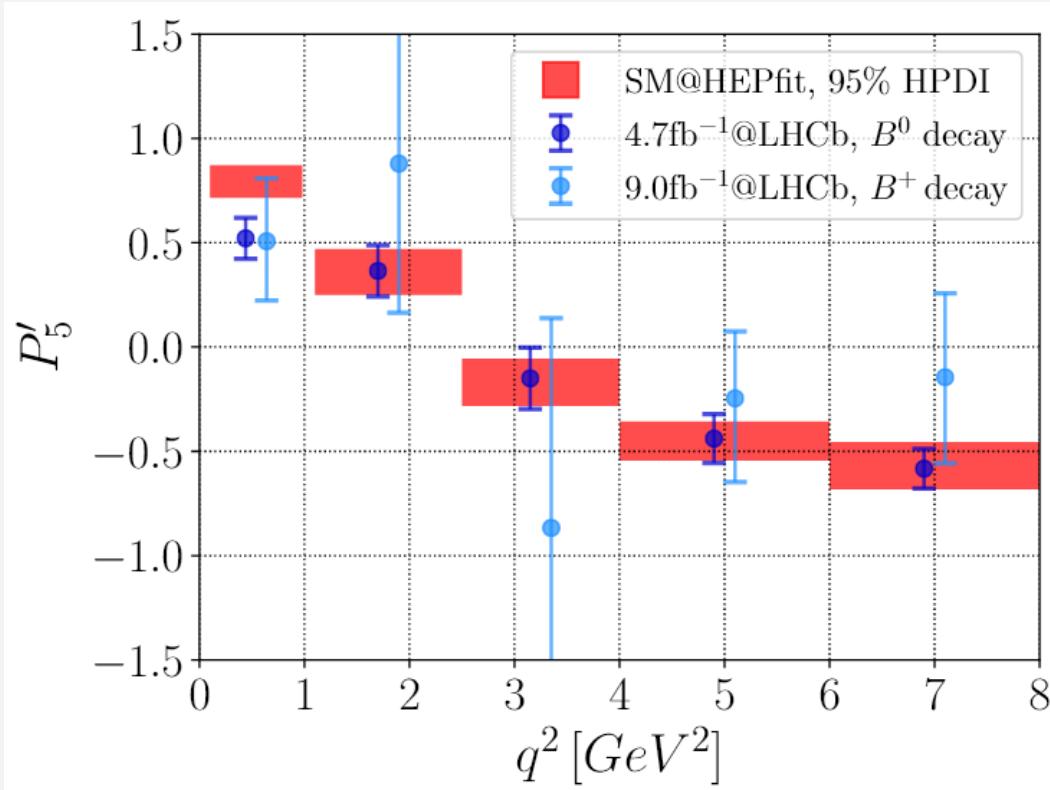
□ A large tension
is observed in
 $B \rightarrow K\mu^+\mu^-$!



GLOBAL FIT

◆ Remind: $C_7 = -0.29$, $C_8 = -0.16$, $C_9 = 4.20$, $C_{10} = -4.01$

□ Another global fit: M. Ciuchini et al, 2011.01212



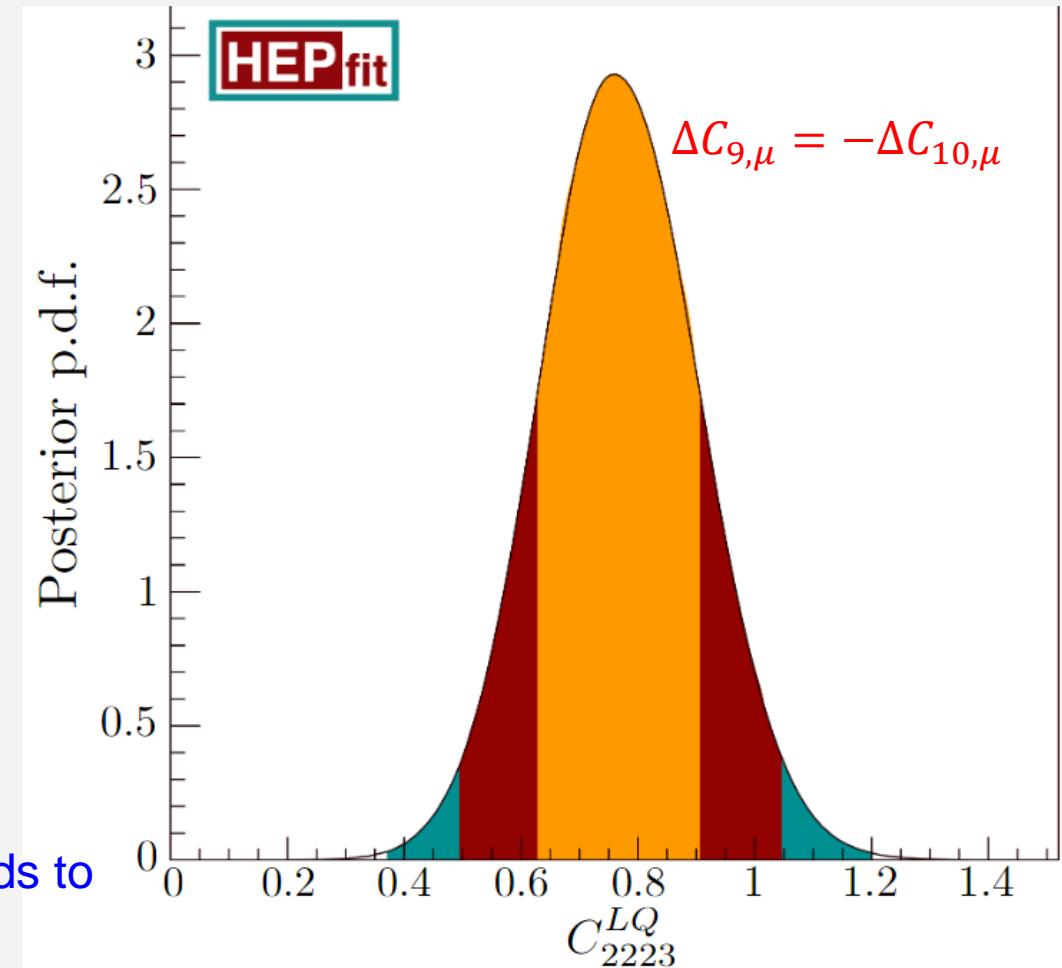
P'_5 accommodated with sizable hadronic effects.

Preferred scenario with $C_{2223}^{LQ} = 0.77 \pm 0.13$, corresponds to $\Delta C_{9,\mu} = -\Delta C_{10,\mu} = -0.54 \pm 0.09$ for $\Lambda = 30\text{TeV}$.

SMEFT

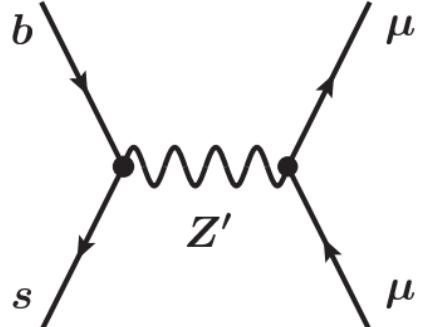
$$O_{2223}^{LQ(1)} = (\bar{L}_2 \gamma_\mu L_2)(\bar{Q}_2 \gamma^\mu Q_3),$$

$$O_{2223}^{LQ(3)} = (\bar{L}_2 \gamma_\mu \tau^A L_2)(\bar{Q}_2 \gamma^\mu \tau^A Q_3),$$



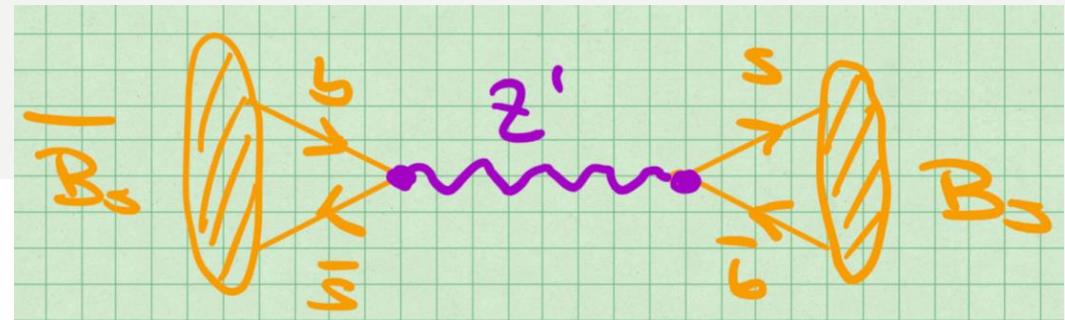
SPECIFIC NP MODELS

□ How to reproduce the needed extra contributions to $\Delta C_{9,\mu} = -\Delta C_{10,\mu}$:



Z' model building

Easiest (but not unique) solution



List of “ingredients”:

- A Z' boson that contributes to \mathcal{O}_9 (and optionally to \mathcal{O}_{10})
- The Z' must have flavor violating couplings to quarks
- The Z' must have non-universal couplings to leptons
- Optional (but highly desirable!): interplay with some other physics

- How about the constraints from other processes such as the mass difference of neutral mesons?
- Further possible implications for other processes like $b \rightarrow s \bar{v} \bar{v}$, or collider physics?

SUMMARY OF $b \rightarrow s$ ANOMALIES

- Contrast to $R(K^{(*)})$, angular observables suffer from unknown LD contributions.
- Although efforts to estimate PCs are ongoing, a real estimate not established yet.
- Significance of tensions depends on theoretical assumptions on the size of PCs.
- Whether tensions in the angular observables are signs of NP or just due to under-estimated hadronic corrections? Need more effects!

Thank You for your attention!