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Lepton universality violations (LUV) in B decays

JHEP12(2019)065 and PRD96(2017)093006

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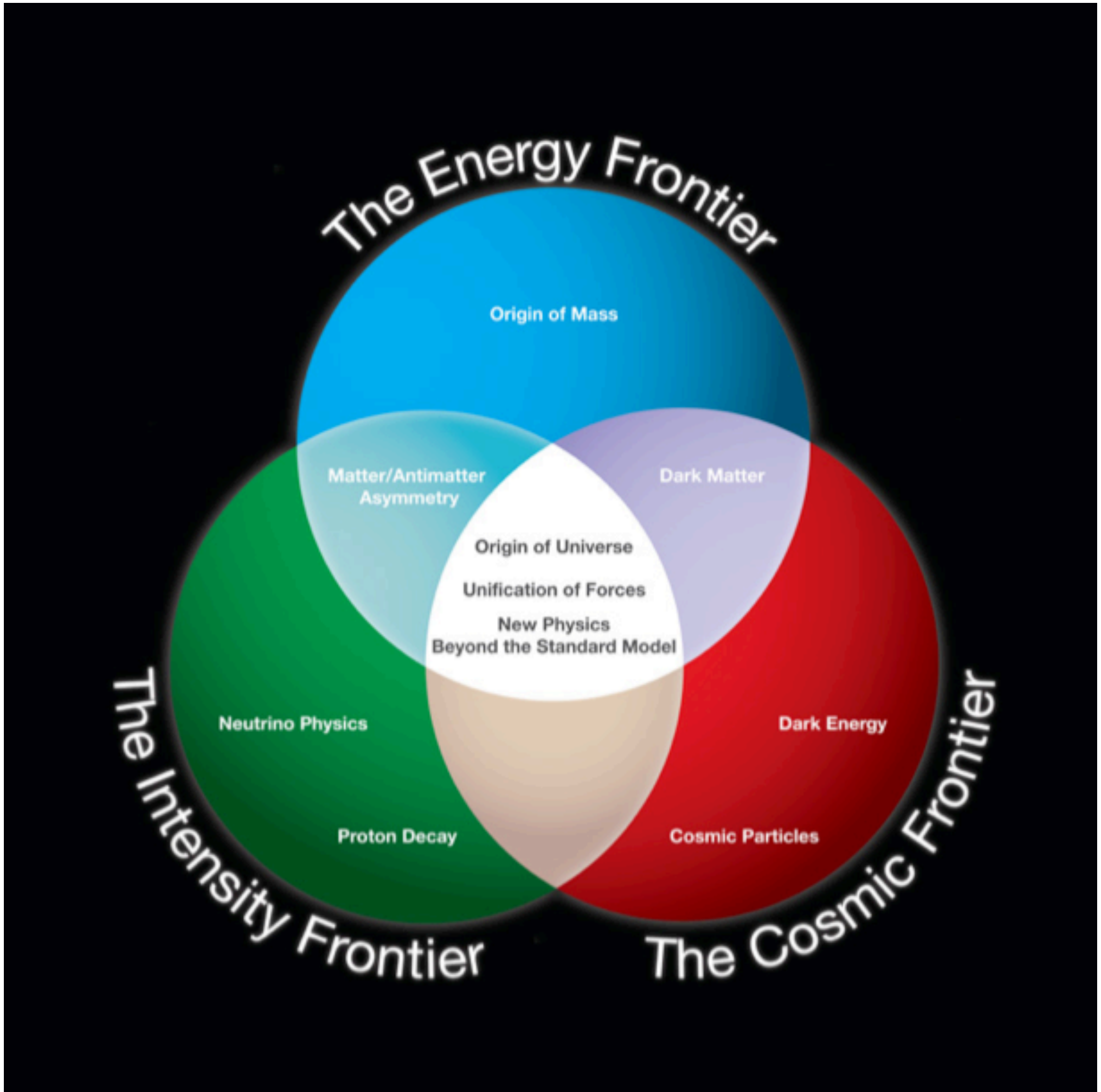
Frontiers in high energy physics



US Particle Physics Scientific Opportunities: A Strategic Plan for the Next 10 Years

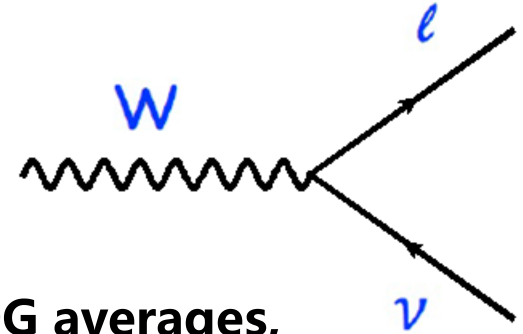
CMS&ATLAS:
Higgs;
Supersymmetric Particles;
New interactions;
…

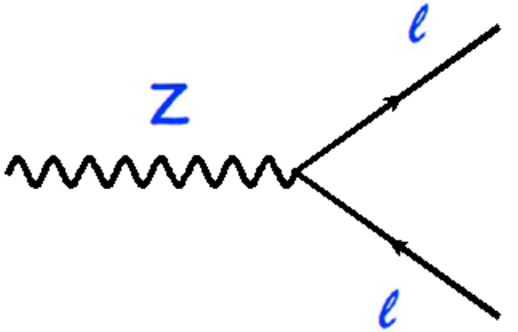
LCHb&BelleII&BESIII:
New hadronic States;
Heavy flavor physics (B physics);
…

Indirect detection of NP via the test of the lepton universality (LU) is one of the hot topics.

Lepton universality in the SM/EW

The interactions between leptons and gauge bosons are the same for all leptons.





From PDG averages,

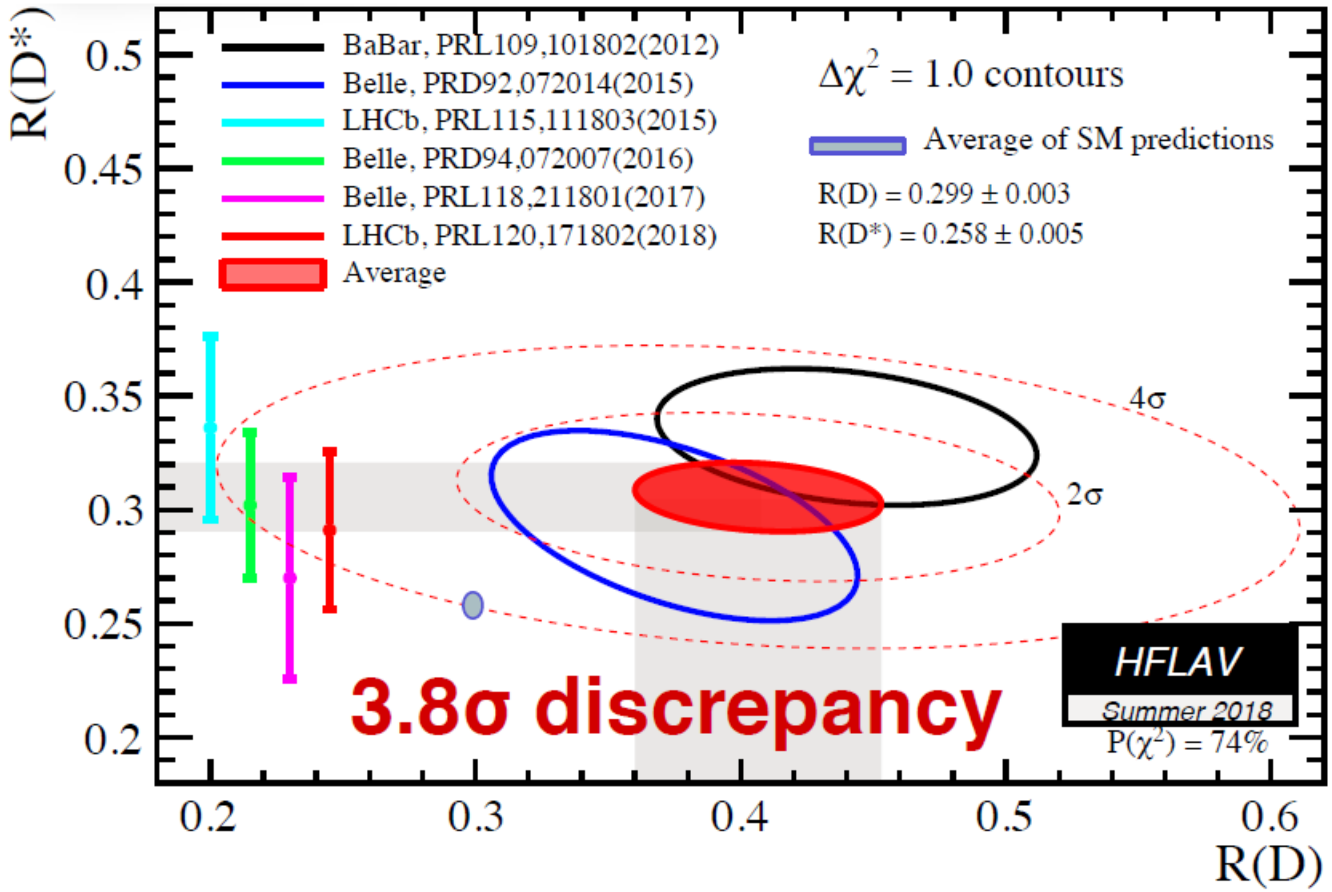
$$\frac{B(W^+ \to \mu^+\nu)}{B(W^+ \to e^+\nu)} = 0.991 \pm 0.018$$
$$\frac{B(W^+ \to \tau^+\nu)}{B(W^+ \to e^+\nu)} = 1.043 \pm 0.024$$
$$\frac{B(W^+ \to \tau^+\nu)}{B(W^+ \to \mu^+\nu)} = 1.070 \pm 0.026$$

$$\frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$
$$\frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

SM predictions : ~1

LU in SM is thoroughly tested. However, some LUV signals (R_D , R_{D^*} , R_{K^*} , R_K, etc.) in B semi-leptonic decays have attracted lots of attentions.

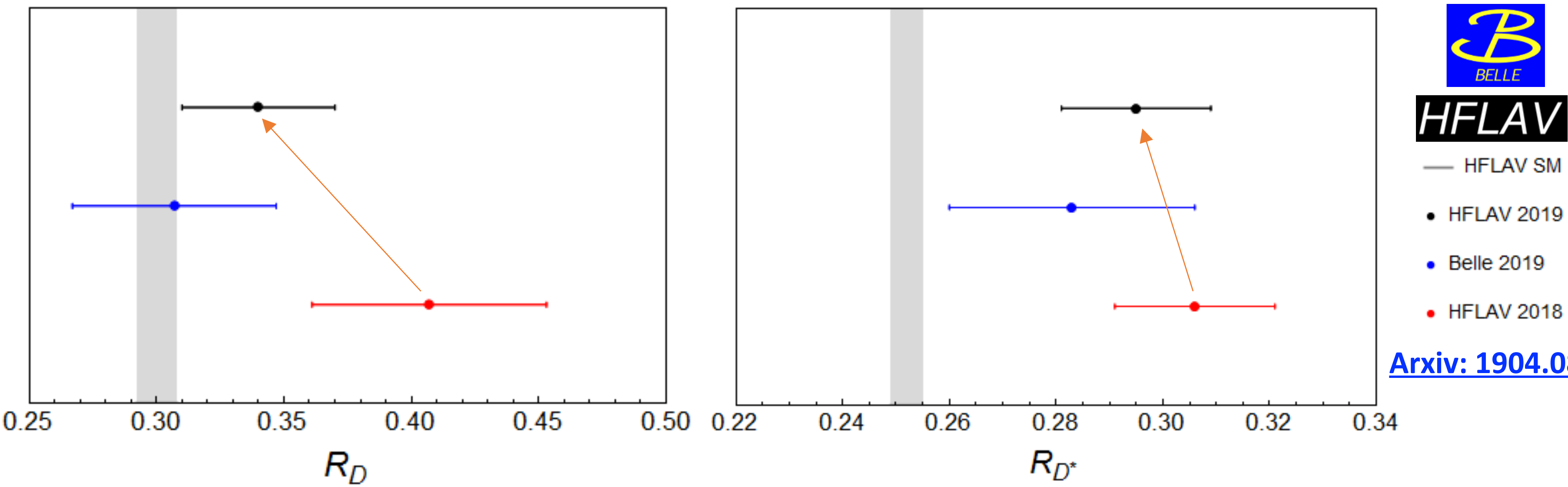
LUV signal in the b → c l ν decay



τ≠ℓ type

$$R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu})}{\Gamma(B \to D^{(*)}\ell\bar{\nu})}, \qquad (\ell = \mu, e)$$

LUV signal in the b → c l ν decay



Arxiv: 1904.08794

- ☐ **Belle 2019 measurements compatible with SM within 1.2σ.**
- ☐ **HFLAV 2019 results closer to SM predictions.**

PRL120(2018)121801

$$R_{J/\psi} = \frac{\Gamma(B_c \to J/\psi \tau \bar{\nu})}{\Gamma(B_c \to J/\psi \mu \bar{\nu})} = 0.71 \pm 0.17 \pm 0.18$$

- **Tension with SM (0.248) ~2σ, but the significance of $R_{J/\psi}$ is less than 4σ.**

These new data call for a reassessment of the significance of the tension of the signal with the SM and of the possible NP scenarios aiming at explaining it.

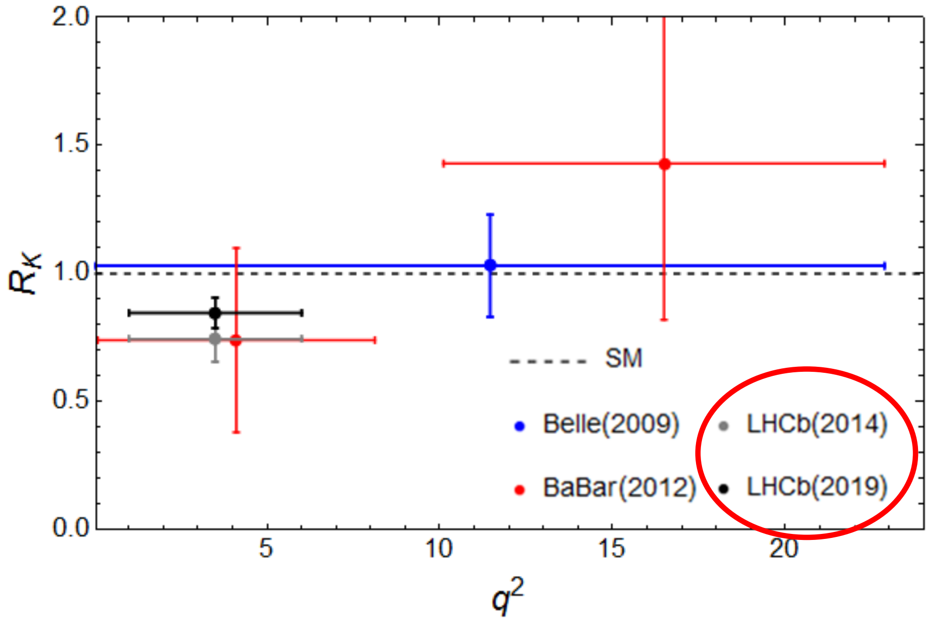
LUV signal in the b → s l l decay

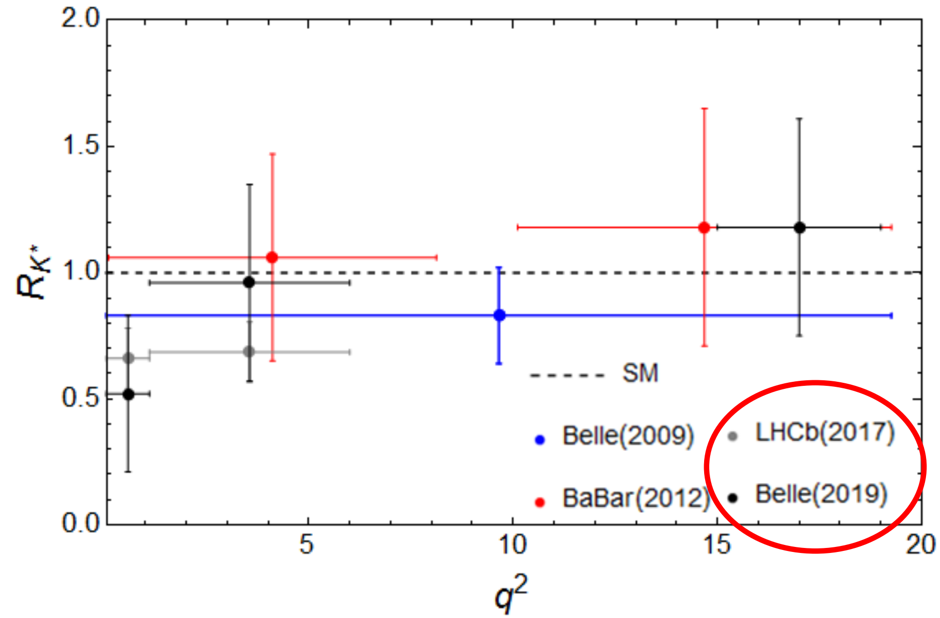
Testing LUV in b → s l l decays, i.e., R_K and R_{K*} :

$$R^{\rm SM}_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)} \simeq 1$$

Very clean !

Belle: PRL103(2009)171801
BaBar: PRD86(2012)032012
LHCb: PRL113(2014)151601
LHCb: JHEP08(2017)055
LHCb: PRL122(2019)191801
Belle: ArXiv:1904.02440 (2019)





- ☐ **Due to large experimental uncertainties from Belle 2009 and BaBar 2012 measurements , there is no significant deviation from the SM prediction.**
- ☐ **Adding 2015 and 2016 data, the 2019 LHCb R_K becomes ~2.5σ from SM.**
- ☐ **For R_{K*}, the Belle 2019 result becomes closer to SM.**

Our purpose

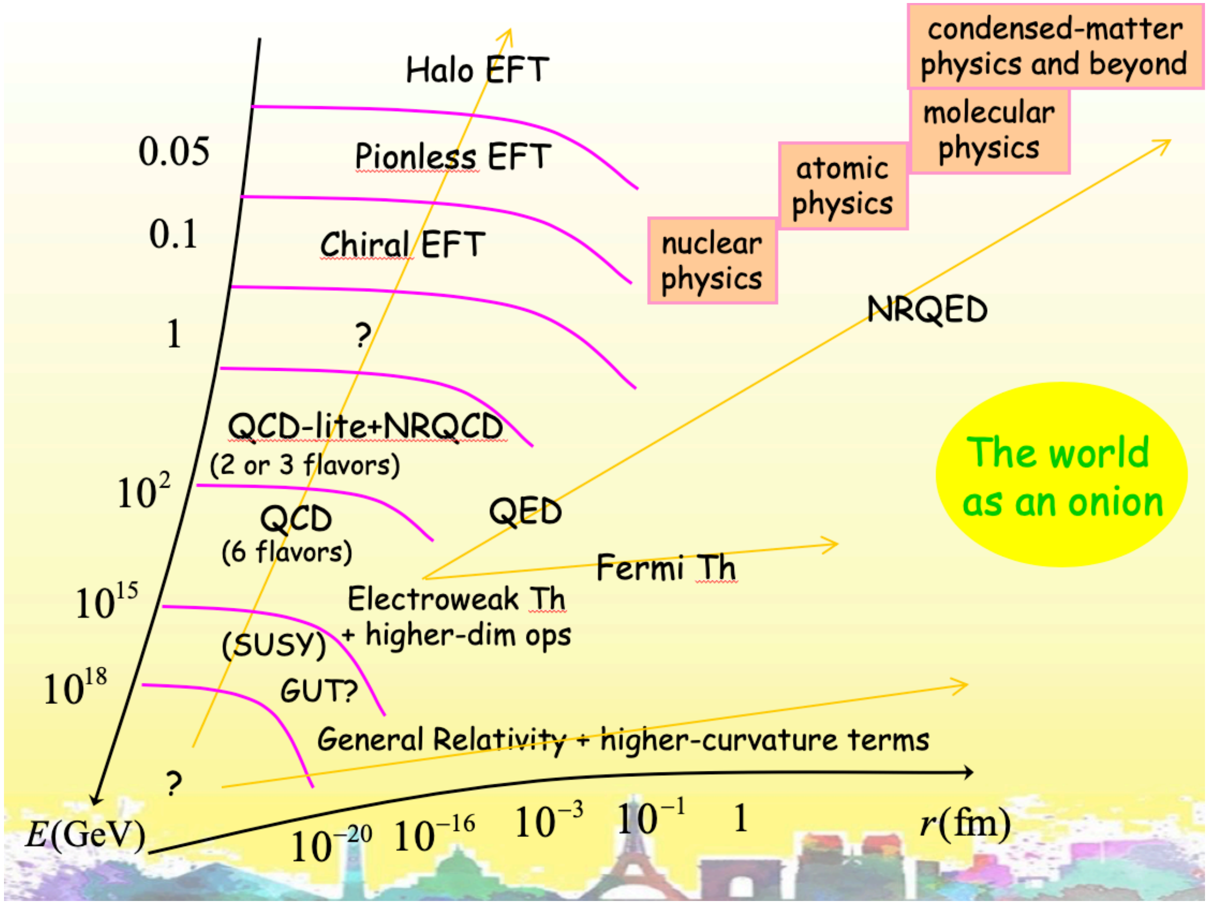
① Using low energy effective field theories to calculate relevant observables

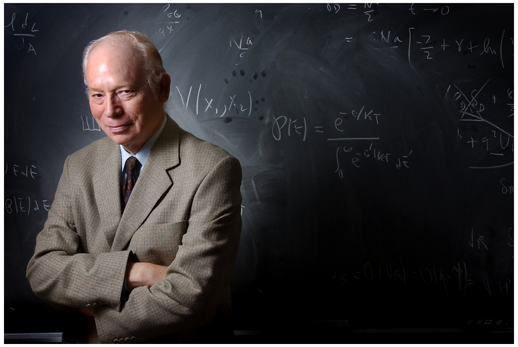
② Performing χ^2 fits and constraining the NP couplings. Then, using frequentist statistics to assess the significance

③ Testing NP models, identifying or constructing observables which are sensitive to new physics

Contents

We are entering the era of EFTs



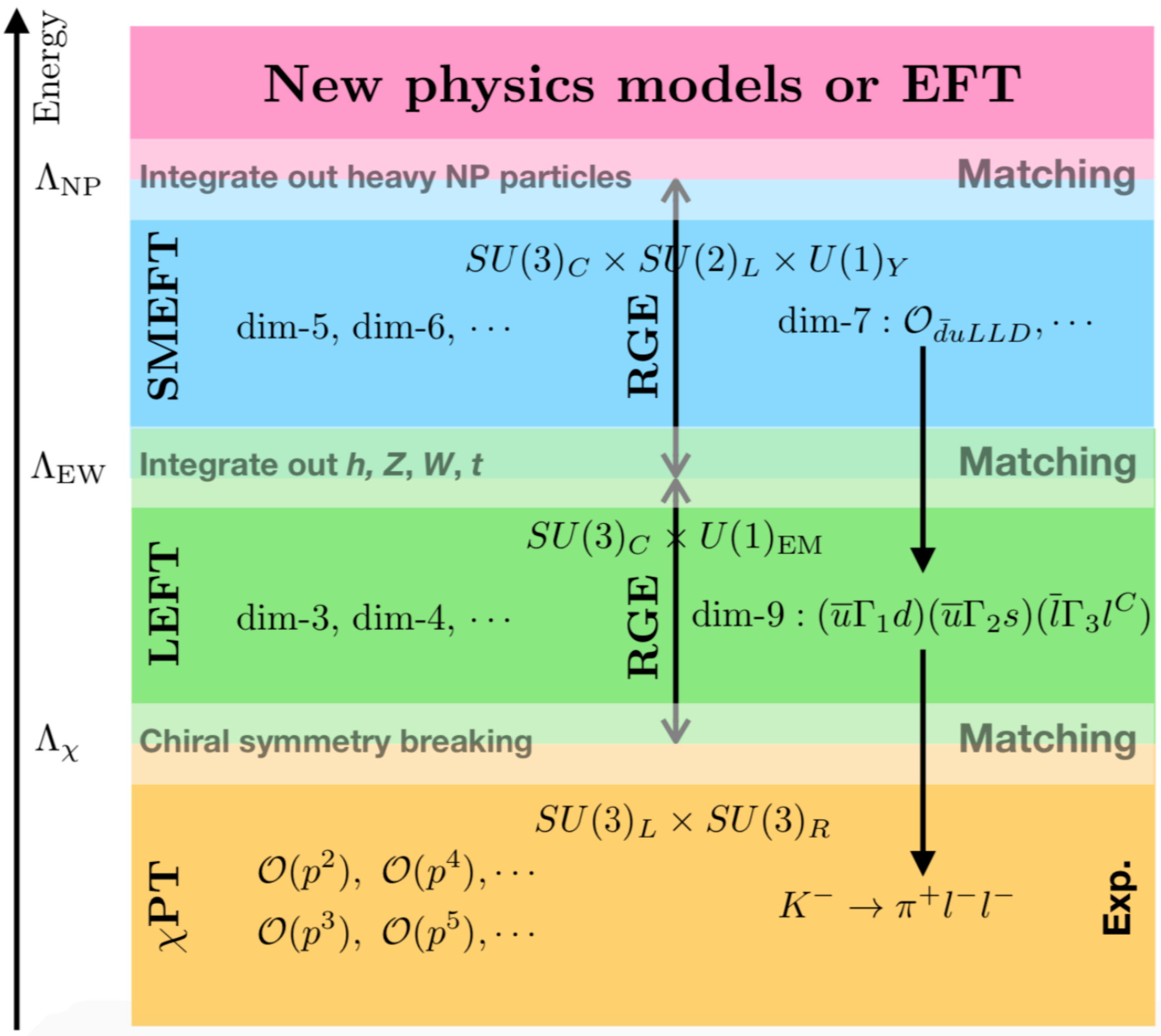


Phenomenological Lagrangians

Steven Weinberg

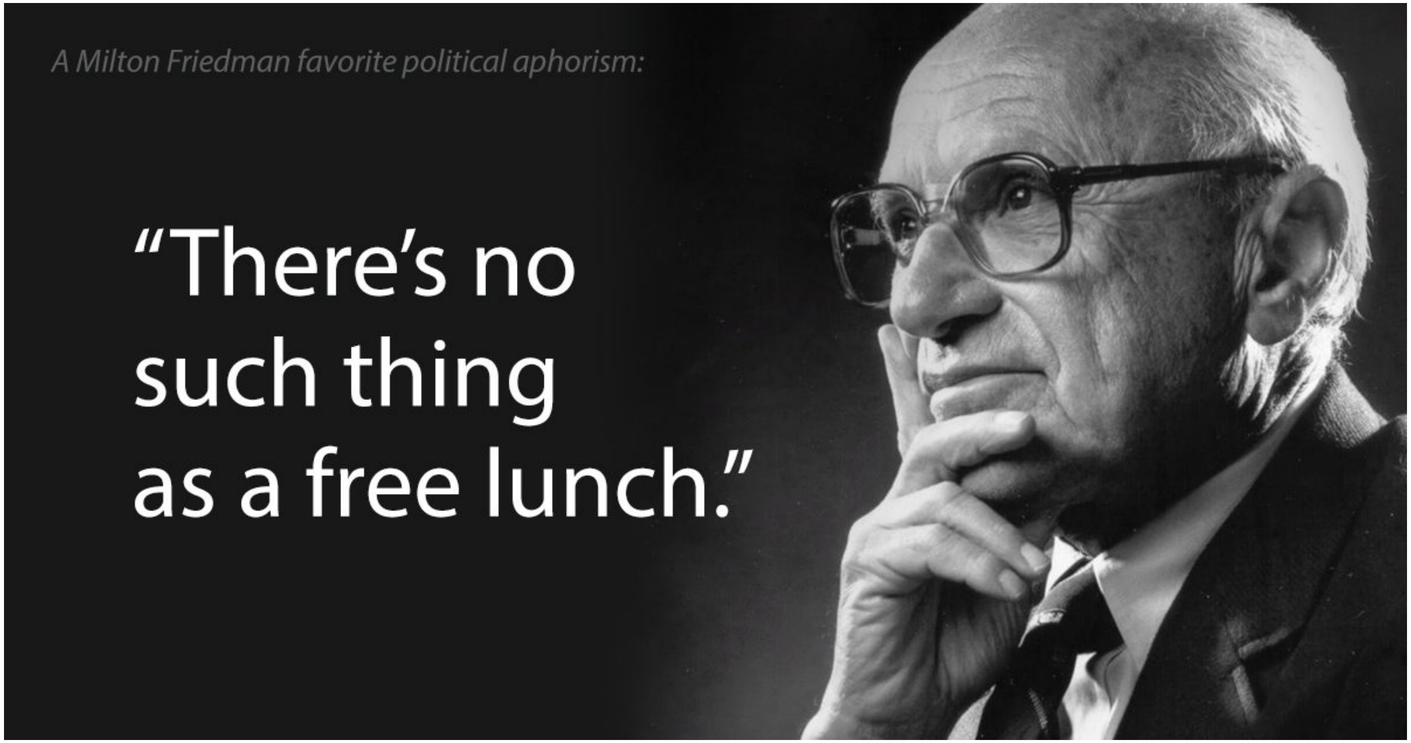
Physica A96 (1979) 327-340

LEFTs: bottom-up approach to new physics



Courtesy of H. L. Wang, Chiral2019

EFTs sacrifices predictability for the sake of systematicity

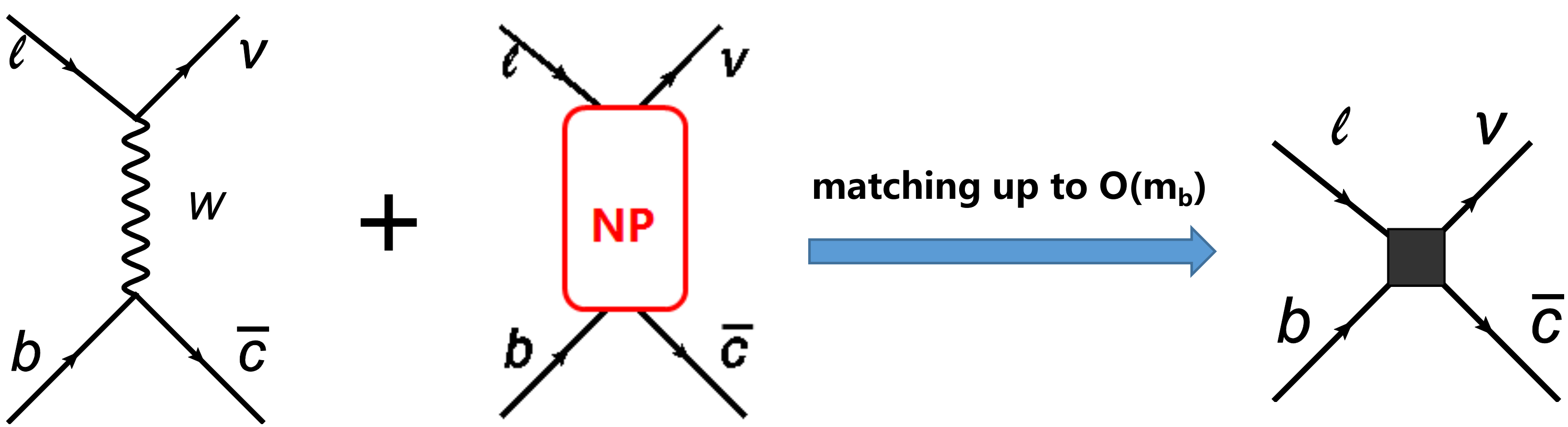


LEFTs: bottom-up approach to new physics

CC : b→ c l ν

J. Martin Camalich et al, PRD 94 (2016) 094021

$$
\begin{aligned}
\mathcal{L}_{\rm eff} \; = \; & -\frac{4G_F V_{cb}}{\sqrt{2}}[(1+\epsilon_L)\bar{\ell}\gamma_\mu P_L \nu_\tau \bar{c}\gamma^\mu P_L b \\
& +\epsilon_R \bar{\ell}\gamma_\mu P_L \nu_\tau \bar{c}\gamma^\mu P_R b + \epsilon_T \bar{\ell}\sigma_{\mu\nu} P_L \nu_\tau \bar{c}\sigma^{\mu\nu} P_L b \\
& +\epsilon_{S_L} \bar{\ell} P_L \nu_\tau \bar{c} P_L b + \epsilon_{S_R} \bar{\ell} P_L \nu_\tau \bar{c} P_R b + \text{H.C.}].
\end{aligned}
$$



- Wilson coefficients in red stand for NP contributions.

LEFTs: bottom-up approach to new physics

FCNC : b → s l l

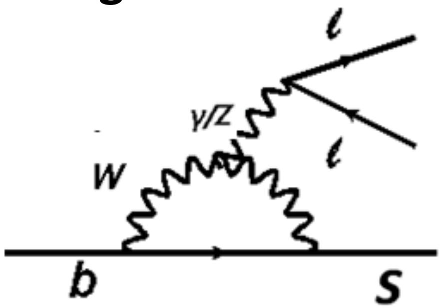
J. Martin Camalich et al, JHEP05(2013)043

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$$

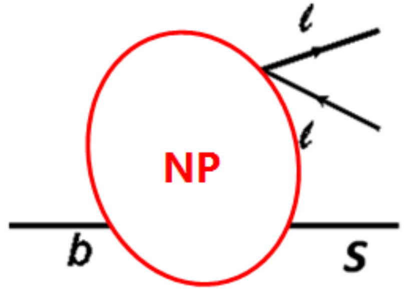
$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p [C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3,\cdots,6} C_i P_i + C_{8g} Q_{8g}]$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = - \frac{4G_F}{\sqrt{2}} \lambda_t [C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}' + C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T']$$

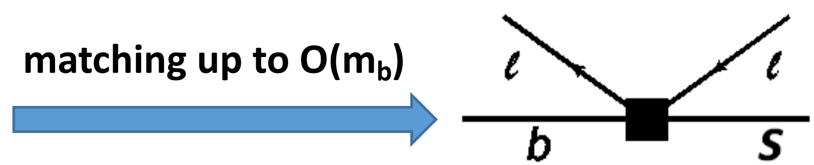
e.g.



+



matching up to O(m_b)

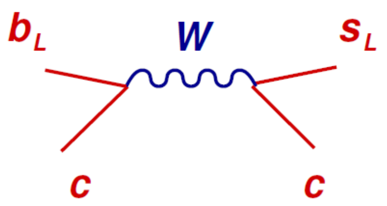


$$\propto \quad C_{9(10)}^{\rm SM} O_{9(10)}({\rm SM}) + \delta C_{9(10)} O_{9(10)}({\rm NP}) + C_{9(10)}' O_{9(10)}'({\rm NP})$$

- ☐ **Different values of Wilson coefficients** $C_i^{\rm expt.} = C_i^{\rm SM} + \delta C_i$
- ☐ **Wilson coefficients can be complex and introduce new sources of CP violation.**

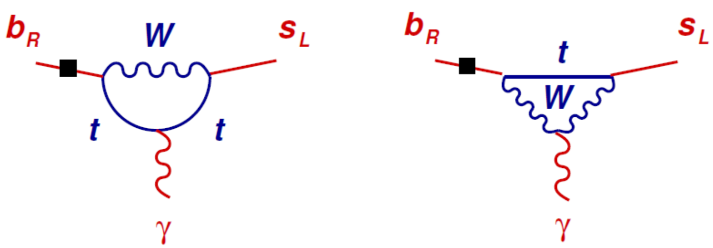
SM operators and Feynman diagrams for b → s l l decays

Charm contributions:

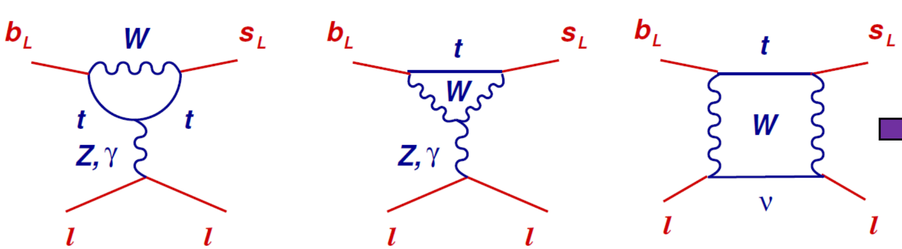


$$G_F\, V_{cb}\, V_{cs}^*\, C_2\, \bar{c}_L \gamma^\mu b_L\, \bar{s}_L \gamma_\mu c_L$$

Flavor Changing Neutral Currents(FCNC):



$$\frac{e}{4\pi^2}\, G_F\, V_{tb}\, V_{ts}^*\, m_b\, C_7\, \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$



$$G_F\, V_{tb}\, V_{ts}^*\, \frac{\alpha}{4\pi}\, C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

- Wilson coefficient $C_i(\mu)$ are calculated in perturbative theory at $\mu=m_W$ and rescaled to $\mu=m_b$.
- O_S , O_p and O_T cannot explain R_K and R_{K^*} J. Martin Camalich et al, PRL.113.241802.

Nonperturbative inputs

- **For the $b \to c\, l\, \nu$ decay:**
  - **Form factors :**

    $B \to D^{(*)} \tau \nu$: HQET & fitting to B factories data & LQCD

    $B \to J/\psi\, \tau \nu$: covariant LFQM

- **For the $b \to s\, l\, l$ decay (*only low bins are considered*):**
  - **In the low bin ($q^2 \leq 6$ GeV^2):**

    Form factors $F(q^2)$:

    Power corrections (LCSR)

    HQEFT $$F(q^2) = F^\infty(q^2) + a_F + b_F q^2/m_B^2 + \mathcal{O}([q^2/m_B^2]^2)$$

    Soft form factors (LCSR & Dyson-Schwinger)

    Charm loops ~ $\frac{m_B^2}{q^2} h_\lambda(q^2)$:

    HQEFT $$h_\lambda(q^2) = h_\lambda^\infty(q^2) + r_\lambda(q^2) \qquad r_\lambda(q^2) = A_\lambda + B_\lambda \frac{q^2}{4m_c^2}$$

    QCDF LCSR

  - **In the high bin ($q^2 \geq 15$ GeV^2):**

    Form factors $F(q^2)$: Lattice QCD

    PRL112(2014)212003

    Charm loops contributions can be neglected !!!

Statistics : χ^2 fit & Frequentist analysis

$\vec{y}$ *27 hadronic parameters (b→sll)*
20 hadronic parameters (b→clv)
$\vec{\epsilon}$ *Wilson coefficients*

□ χ^2 fit

$$\tilde{\chi}^2(\vec{\epsilon},\ \vec{y}) = \chi^2_{\rm exp}(\vec{\epsilon},\ \vec{y}) + \chi^2_{\rm th}(\vec{y})$$

$$\chi^2_{\rm exp}(\vec{\epsilon},\ \vec{y}) = [\vec{O}^{\rm th}(\vec{\epsilon},\ \vec{y}) - \vec{O}^{\rm exp}]^T \cdot (V^{\rm exp})^{-1} \cdot [\vec{O}^{\rm th}(\vec{\epsilon},\ \vec{y}) - \vec{O}^{\rm exp}],$$

$$\chi^2_{\rm th}(\vec{y}) = (\vec{y} - \vec{y}_0)^T \cdot (V^{\rm th})^{-1} \cdot (\vec{y} - \vec{y}_0),$$

□ Frequentist analysis

- **P-value: it is a statement how well the SM or BSM describes the data**

$$\text{P-value}_{\rm SM} = 1 - \text{CDF}[\chi^2\text{-distribution}[n_{\rm exp}], \chi^2_{\rm min,SM}]$$
$$\text{P-value}_{\rm NP} = 1 - \text{CDF}[\chi^2\text{-distribution}[n_{\rm exp} - n_\epsilon], \chi^2_{\rm min,NP}]$$

- **$\text{Pull}_{\rm SM}$: the significance of deviation from SM**

$$\Delta\chi^2_{\rm SM} = \text{Quantile}[\chi^2\text{-distribution}[1], \text{CDF}[\chi^2\text{-distribution}[n_\epsilon], \chi^2_{\rm min,SM} - \chi^2_{\rm min,NP}]]$$
$$\text{Pull}_{\rm SM} = \sqrt{\Delta\chi^2_{\rm SM}}$$

The larger the $\text{p-value}_{\rm NP}$, the higher the significance of deviation from SM (the larger the $\text{Pull}_{\rm SM}$) but the smaller $\text{p-value}_{\rm SM}$ tells us that the SM hypothesis under consideration may not be adequate to explain the data.

Contents

Interesting observables for b→c l ν decays

The most reliable

Observables	Data (averages)				SM
	HFLAV 2018		HFLAV 2019		
R_D	0.407(39)(24)	corr = −0.20	0.340(27)(13)	corr = −0.38	0.312(19)
R_{D^*}	0.306(13)(7)		0.295(11)(8)		0.253(4)
$R_{J/\psi}$	0.71(17)(18)				0.248(3)
$P_\tau^{D^*}$	−0.38(51)(19)				−0.505(23)
$F_L^{D^*}$	0.60(8)(4)				0.455(9)

τ polarization asymmetry $P_\tau^{D^*}$ and the longitudinal polarization of D ($F_L^{D^*}$) in the B->D* τ ν decay:

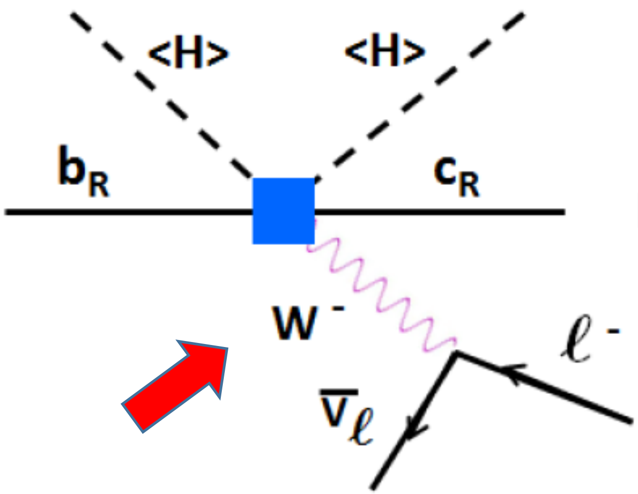
$$P_\tau^{D^*} = \frac{\Gamma(\lambda_\tau = \frac{1}{2}) - \Gamma(\lambda_\tau = -\frac{1}{2})}{\Gamma(\lambda_\tau = \frac{1}{2}) + \Gamma(\lambda_\tau = -\frac{1}{2})},$$

$$F_L^{D^*} = \frac{\Gamma(\lambda_{D^*} = 0)}{\Gamma(\lambda_{D^*} = 1) + \Gamma(\lambda_{D^*} = 0) + \Gamma(\lambda_{D^*} = -1)},$$

Right-handed vector operator cannot explain LUV

SMEFT

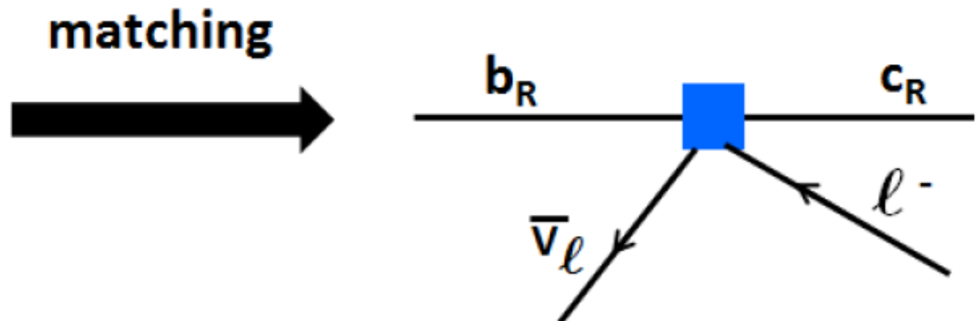
$$\frac{v^2}{\Lambda^2} C_{H\bar{\nu}_\ell \ell}(i\tilde{H}^\dagger D_\mu H)(\bar{c}_R \gamma^\mu b_R)$$



LEEFT

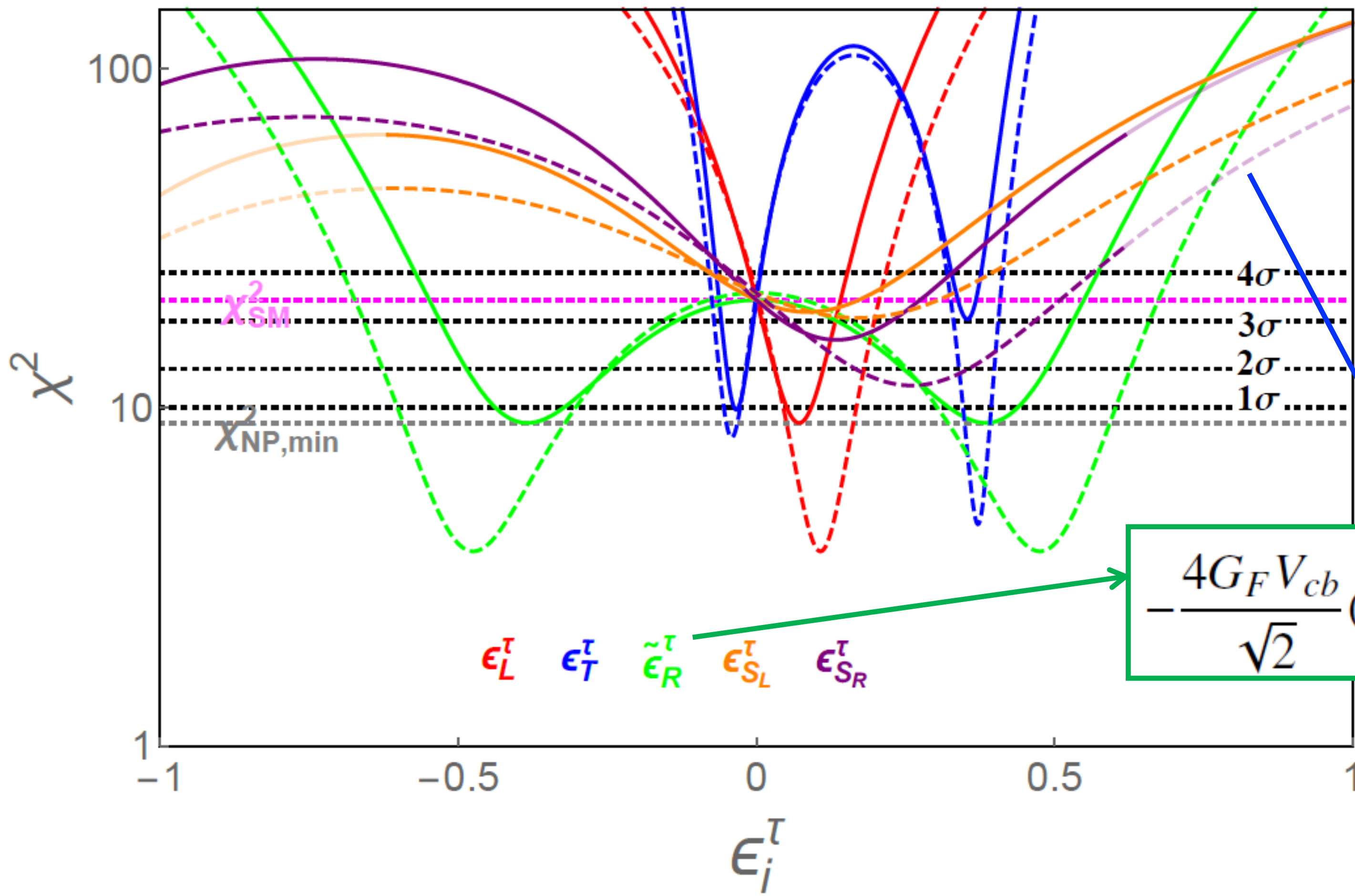
$$\epsilon_R^\ell \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \bar{c}_R \gamma^\mu b_R$$

$$\epsilon_R^\ell = \frac{v^2}{\Lambda^2} a \cdot C_{H\bar{\nu}_\ell \ell} + \mathcal{O}(\frac{v^4}{\Lambda^4}) = \epsilon_R^{\ell'} + \mathcal{O}(\frac{v^4}{\Lambda^4})$$



NP particles do not directly couple to two leptons in the two-Higgs model. Therefore, the right-handed vector operator cannot contribute to and explain lepton universality violation.

Fits to R_D and R_{D^*} only



Solid lines: 2019 HFLAV

Dashed lines: 2018 HFLAV

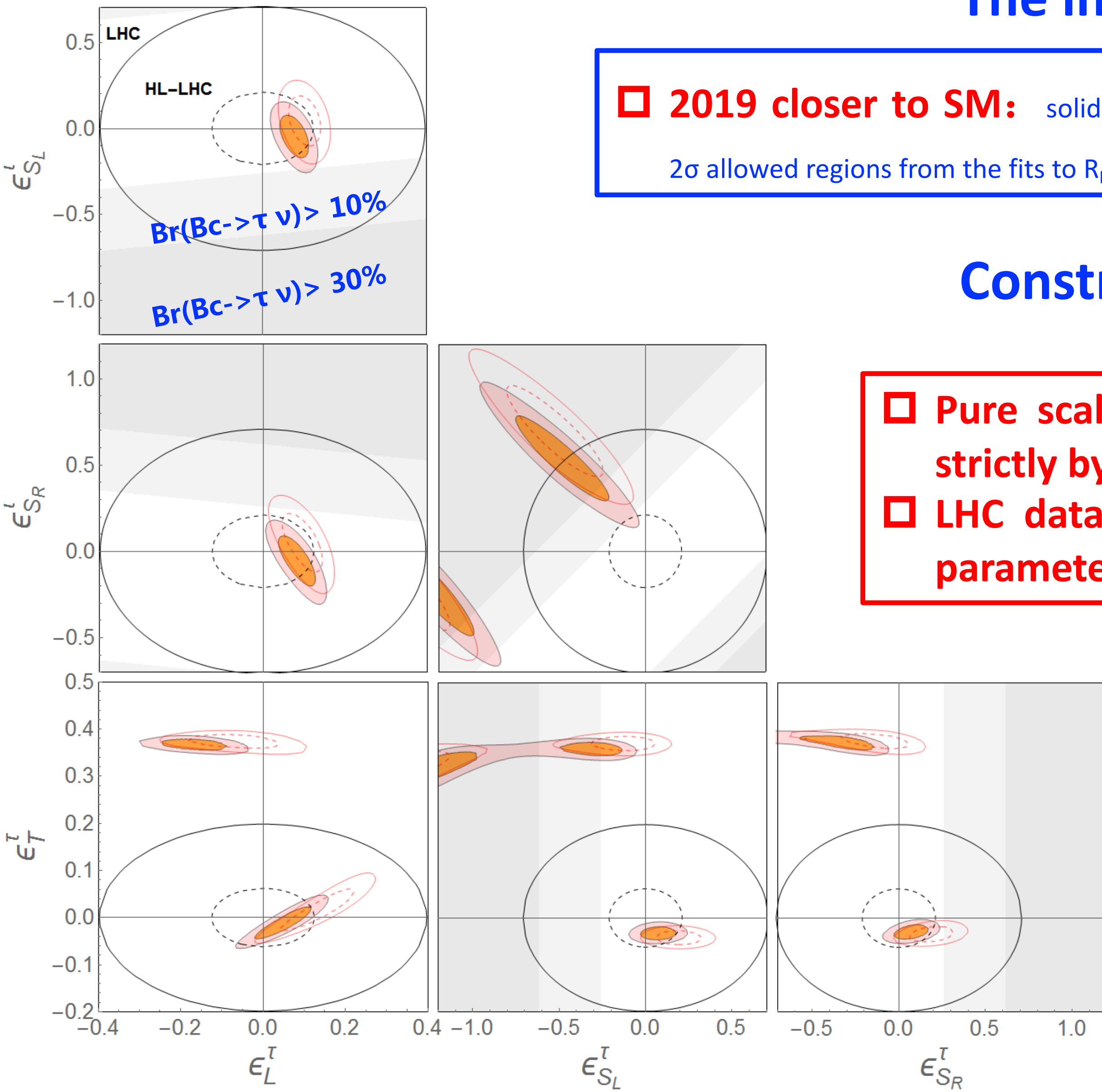
Faded lines : Br(Bc → τ ν) > 30%

$$-\frac{4G_F V_{cb}}{\sqrt{2}}(\tilde{\epsilon}_R^\tau \bar{\tau}\gamma_\mu N_R)(\bar{c}\gamma^\mu P_R b)$$

right-handed neutrino

- **Dotted lines show that the significance of deviating from SM is more than 3σ.**
- **The (left)vector and tensor operators give a better fit to the data (than the other two).**
- ***The χ^2 difference shows that the 2018 HFLAV data are in conflict with the 2019 HFLAV data.***

Fits to R_D and R_{D^*} only: 6 2D plots



The impact of the 2019 data

- **2019 closer to SM:** solid ellipses (empty red ellipses) represent 1σ and 2σ allowed regions from the fits to R_D and R_{D^*} data (2018 HFLAV average)

Constraints from other data

- **Pure scalar operators are constrained strictly by the Br(Bc → τ ν)—(2,2).**
- **LHC data exclude large region of the parameter space—(3,123)**

- Empty black solid (dashed) ellipses indicate the 2σ upper bounds from the LHC data (HL-LHC projections) on pp → τhX+MET-- **PRL.122.131803**
- Note that 30% and 10% are from the constraints of Bc lifetime and LEP1 data, respectively--**PRD 96, 075011; PRL. 118, 081802**

Fits to R_D and R_{D^*} only

$\chi^2_{\rm SM} = 20.75$ **p-value in SM : 1.38×10^{-2}**

	Best fit	$\chi^2_{\rm min}$	p-value	Pull$_{\rm SM}$	1σ range
ϵ^τ_L	0.07	9.00	0.34	3.43	$(0.05, 0.09)$
ϵ^τ_T	-0.03	9.85	0.28	3.30	$(-0.04, -0.02)$
$\epsilon^\tau_{S_L}$	0.09	19.14	1.41×10^{-2}	1.27	$(0.02, 0.15)$
$\epsilon^\tau_{S_R}$	0.13	15.84	4.47×10^{-2}	2.22	$(0.07, 0.20)$
~~ϵ^τ_R~~	~~0.38~~	~~9.00~~	~~0.34~~	~~3.43~~	~~$(0.32, 0.44)$~~
$\epsilon^\tau_{S_L} = -4\epsilon^\tau_T$	0.09	12.25	0.14	2.92	$(0.06, 0.12)$
$(\epsilon^\tau_{S_L}, \epsilon^\tau_T)$	$(0.07, -0.03)$	8.7	0.27	3.03	$\epsilon^\tau_{S_L} \in (0.00, 0.14)$ $\epsilon^\tau_T \in (-0.04, -0.02)$
$(\epsilon^\tau_{S_L}, \epsilon^\tau_{S_R})$	$(-0.47, 0.53)$	8.7	0.27	3.03	$\epsilon^\tau_{S_L} \in (-0.66, -0.30)$ $\epsilon^\tau_{S_R} \in (0.37, 0.69)$
$(\epsilon^\tau_{S_R}, \epsilon^\tau_T)$	$(0.07, -0.03)$	8.7	0.27	3.03	$\epsilon^\tau_{S_R} \in (0.00, 0.14)$ $\epsilon^\tau_T \in (-0.04, -0.02)$
$(\epsilon^\tau_L, \epsilon^\tau_T)$	$(0.05, -0.01)$	8.7	0.27	3.03	$\epsilon^\tau_L \in (0.00, 0.09)$ $\epsilon^\tau_T \in (-0.03, 0.01)$
$(\epsilon^\tau_L, \epsilon^\tau_{S_L})$	$(0.08, -0.04)$	8.7	0.27	3.03	$\epsilon^\tau_L \in (0.05, 0.10)$ $\epsilon^\tau_{S_L} \in (-0.13, 0.04)$
$(\epsilon^\tau_L, \epsilon^\tau_{S_R})$	$(0.08, -0.05)$	8.7	0.27	3.03	$\epsilon^\tau_L \in (0.05, 0.11)$ $\epsilon^\tau_{S_R} \in (-0.15, 0.04)$

- The significance of deviation from SM is more than 3σ.

Testing 3 N P models

Mediator	Spin	$SU(3)$	$SU(2)$	$U(1)$	ϵ_L^τ	$\tilde{\epsilon}_R^\tau$	$\epsilon_{S_R}^\tau$	$\epsilon_{S_L}^\tau$	ϵ_T^τ
H	0	$\mathbf{1}$	$\mathbf{2}$	$+1/2$	✗	✗	✓	✓	✗
W'_L	1	$\mathbf{1}$	$\mathbf{3}$	0	✓	✗	✗	✗	✗
W'_R	1	$\mathbf{1}$	$\mathbf{1}$	$+1$	✗	✓	✗	✗	✗
S_1	0	$\bar{\mathbf{3}}$	$\mathbf{1}$	$+1/3$	✓	✓	✗	✓	✓
S_3	0	$\bar{\mathbf{3}}$	$\mathbf{3}$	$+1/3$	✓	✓	✗	✗	✗
R_2	0	$\mathbf{3}$	$\mathbf{2}$	$+7/6$	✓	✓	✗	✓	✓
U_1	1	$\mathbf{3}$	$\mathbf{1}$	$+2/3$	✓	✓	✓	✗	✗
U_3	1	$\mathbf{3}$	$\mathbf{3}$	$+2/3$	✓	✓	✗	✗	✗
V_2	1	$\bar{\mathbf{3}}$	$\mathbf{2}$	$+5/6$	✗	✗	✓	✗	✗

H → In conflict with Br(Bc → τ ν) data

W'_L → In conflict with LHC data (PLB.2016.11.011)

W'_R → Right-handed neutrinos not considered in this work

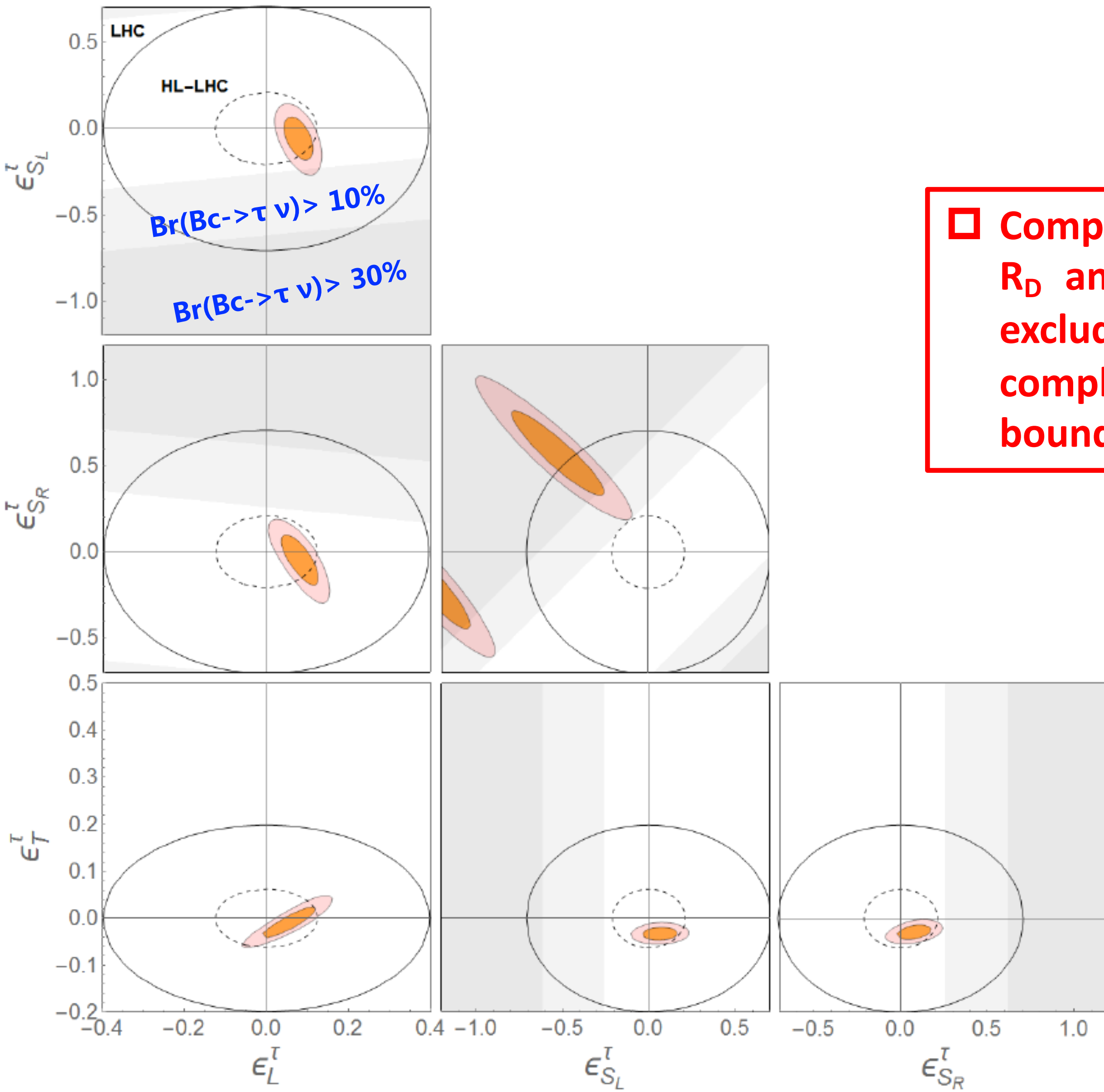
S_1, S_3, R_2, U_1, U_3 → The leptoquark models in the red box are favored by current data. Note that these models cannot induce a right-handed neutrino operator at low energy.

V_2 → In conflict with Br(Bc → τ ν) data

For example, assuming NP couplings are O(1) order:

$$m_{S_1} \simeq 2.3 \text{ TeV}, \; m_{U_1} \simeq 3.3 \text{ TeV} \qquad m_{S_1} \simeq m_{R_2} \simeq 2.3 \text{ TeV}$$

Fits to all the 2019 HFLAV data



- Compared with 2D plots fitting to R_D and R_{D*} only, the extra data exclude the parameter space in complementarity with the LHC bounds.

Fits to all the 2019 HFLAV data

$\chi^2_{\mathrm{min,SM}} = 26.53$

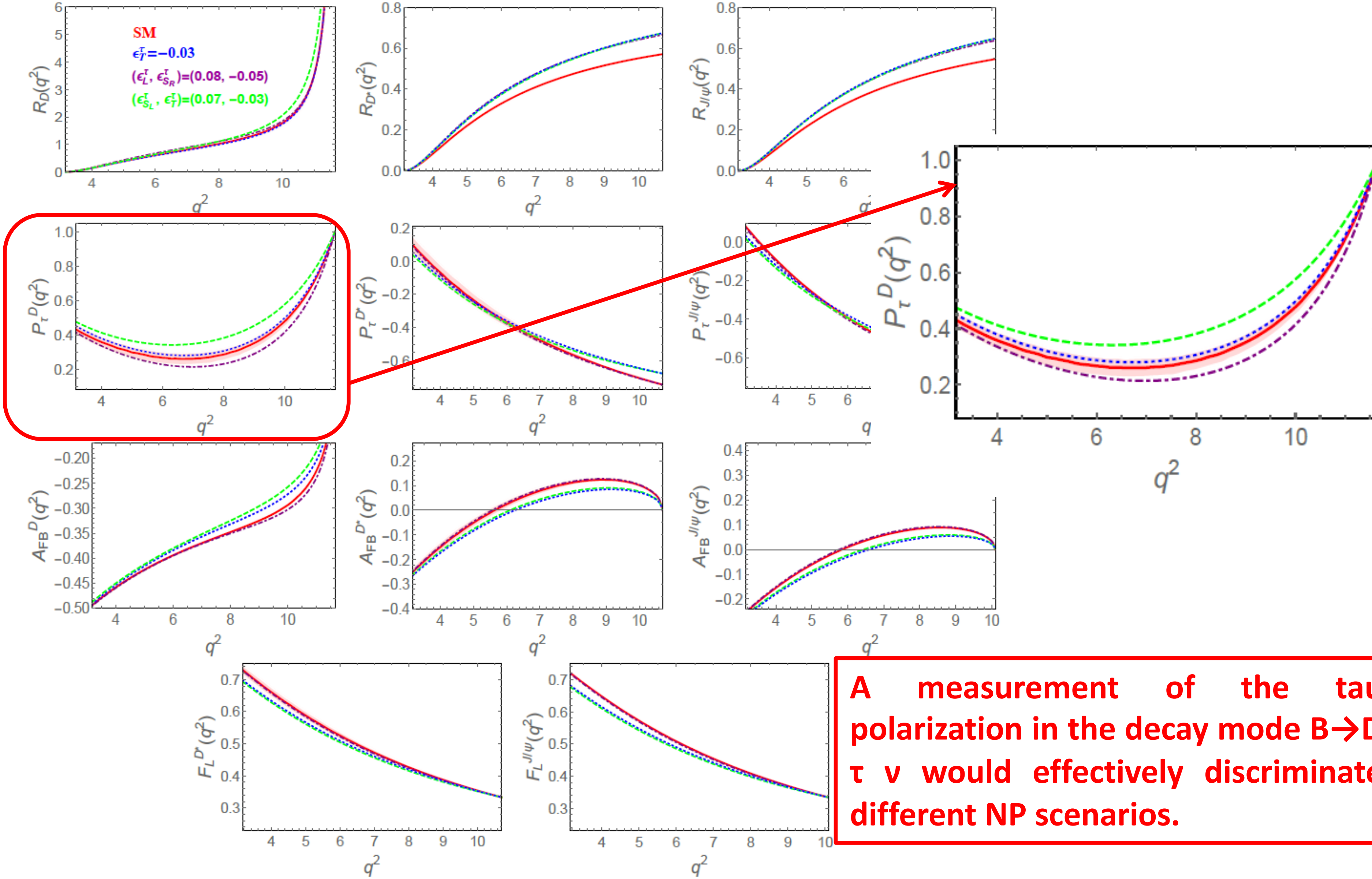
p-value in SM : 9.02×10^{-3}

	Best fit	χ^2_{min}	p-value	$\mathrm{Pull_{SM}}$	1σ range
ϵ_L^τ	0.07	14.56	0.20	3.46	(0.05, 0.09)
ϵ_T^τ	−0.03	15.70	0.15	3.29	(−0.04, −0.02)
$\epsilon_{S_L}^\tau$	0.08	25.23	8.44×10^{-3}	1.14	(0.01, 0.14)
$\epsilon_{S_R}^\tau$	0.14	21.24	3.10×10^{-2}	2.30	(0.08, 0.20)
$(\epsilon_{S_L}^\tau, \epsilon_T^\tau)$	(0.07, −0.03)	14.75	0.14	3.00	$\epsilon_{S_L}^\tau \in (0.00, 0.13)$ $\epsilon_T^\tau \in (-0.04, -0.02)$
$(\epsilon_{S_L}^\tau, \epsilon_{S_R}^\tau)$	(−0.51, 0.56)	12.14	0.28	3.37	$\epsilon_{S_L}^\tau \in (-0.69, -0.34)$ $\epsilon_{S_R}^\tau \in (0.41, 0.73)$
$(\epsilon_{S_R}^\tau, \epsilon_T^\tau)$	(0.08, −0.03)	14.38	0.16	3.05	$\epsilon_{S_R}^\tau \in (0.01, 0.14)$ $\epsilon_T^\tau \in (-0.04, -0.02)$
$(\epsilon_L^\tau, \epsilon_T^\tau)$	(0.05, −0.01)	14.32	0.16	3.06	$\epsilon_L^\tau \in (0.01, 0.10)$ $\epsilon_T^\tau \in (-0.03, 0.01)$
$(\epsilon_L^\tau, \epsilon_{S_L}^\tau)$	(0.08, −0.06)	14.09	0.17	3.09	$\epsilon_L^\tau \in (0.06, 0.10)$ $\epsilon_{S_L}^\tau \in (-0.14, 0.03)$
$(\epsilon_L^\tau, \epsilon_{S_R}^\tau)$	(0.08, −0.05)	14.33	0.16	3.06	$\epsilon_L^\tau \in (0.05, 0.11)$ $\epsilon_{S_R}^\tau \in (-0.14, 0.05)$

- **The significance of deviation from SM is more than 3σ.**

Possibility of discriminating different NP structure

Only fitted to R_D/R_{D^*}



A measurement of the tau polarization in the decay mode B→D τ ν would effectively discriminate different NP scenarios.

Possibility of discriminating different NP structure

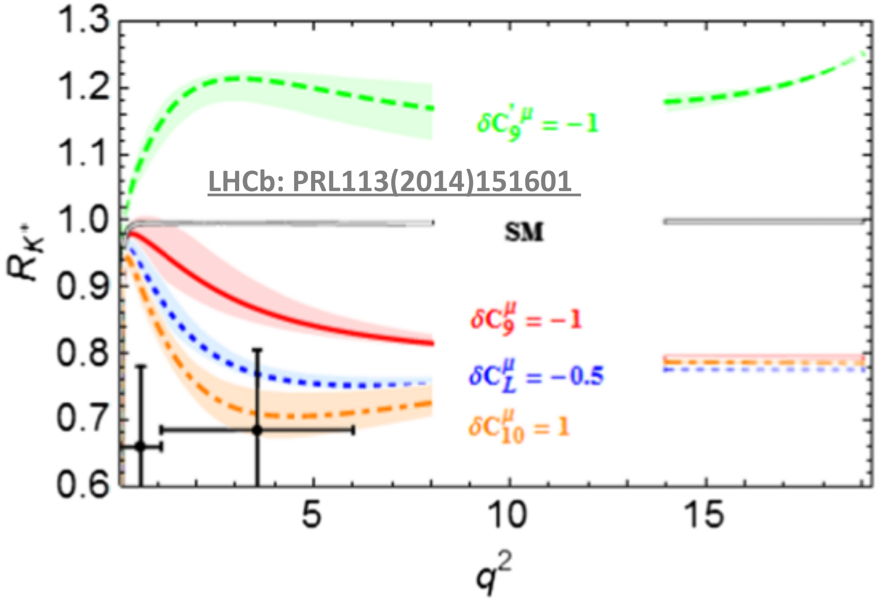
No corresponding NP

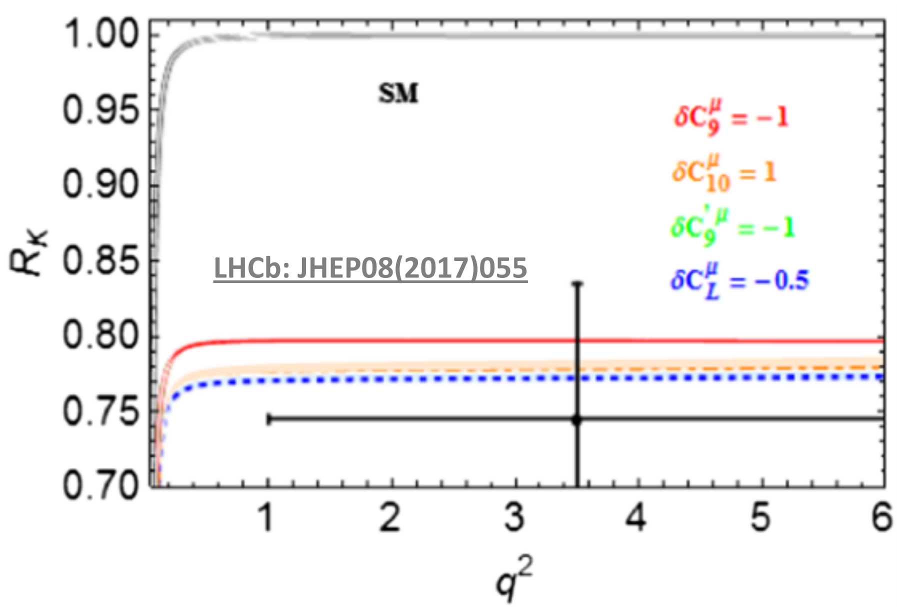
Observables	SM	$\epsilon_T^\tau = -0.03$	$(\epsilon_{S_L}^\tau,\ \epsilon_T^\tau) = (0.07, -0.03)$	$(\epsilon_L^\tau,\ \epsilon_{S_R}^\tau) = (0.08, -0.05)$	$(\epsilon_L^\tau, \epsilon_T^\tau, \epsilon_{S_L}^\tau, \epsilon_{S_R}^\tau) = (0.16, 0.05, -0.33, 0.14)$
R_D	$0.312^{+0.019}_{-0.018}$	$0.303^{+0.019}_{-0.018}$	$0.340^{+0.023}_{-0.021}$	$0.339^{+0.020}_{-0.018}$	$0.343^{+0.017}_{-0.016}$
P_τ^D	$0.338^{+0.033}_{-0.034}$	$0.358^{+0.033}_{-0.034}$	$0.427^{+0.032}_{-0.032}$	$0.288^{+0.034}_{-0.034}$	$0.117^{+0.033}_{-0.033}$
A_{FB}^D	$-0.358^{+0.003}_{-0.003}$	$-0.344^{+0.004}_{-0.003}$	$-0.334^{+0.005}_{-0.004}$	$-0.363^{+0.002}_{-0.002}$	$-0.383^{+0.002}_{-0.001}$
R_{D^*}	$0.253^{+0.004}_{-0.004}$	$0.293^{+0.004}_{-0.004}$	$0.291^{+0.004}_{-0.003}$	$0.293^{+0.004}_{-0.004}$	$0.297^{+0.009}_{-0.008}$
$P_\tau^{D^*}$	$-0.505^{+0.024}_{-0.022}$	$-0.477^{+0.020}_{-0.019}$	$-0.487^{+0.019}_{-0.017}$	$-0.513^{+0.023}_{-0.021}$	$-0.430^{+0.042}_{-0.041}$
$A_{FB}^{D^*}$	$0.068^{+0.013}_{-0.013}$	$0.030^{+0.012}_{-0.012}$	$0.038^{+0.012}_{-0.012}$	$0.073^{+0.013}_{-0.013}$	$0.083^{+0.017}_{-0.016}$
$F_L^{D^*}$	$0.455^{+0.009}_{-0.008}$	$0.444^{+0.008}_{-0.007}$	$0.440^{+0.007}_{-0.007}$	$0.452^{+0.008}_{-0.008}$	$0.497^{+0.015}_{-0.014}$
$R_{J/\psi}$	$0.248^{+0.003}_{-0.003}$	$0.291^{+0.004}_{-0.004}$	$0.289^{+0.004}_{-0.004}$	$0.288^{+0.004}_{-0.004}$	$0.284^{+0.003}_{-0.003}$
$P_\tau^{J/\psi}$	$-0.512^{+0.011}_{-0.010}$	$-0.481^{+0.009}_{-0.008}$	$-0.490^{+0.008}_{-0.008}$	$-0.519^{+0.010}_{-0.010}$	$-0.453^{+0.020}_{-0.019}$
$A_{FB}^{J/\psi}$	$0.042^{+0.006}_{-0.006}$	$0.007^{+0.006}_{-0.006}$	$0.013^{+0.006}_{-0.006}$	$0.046^{+0.006}_{-0.006}$	$0.061^{+0.007}_{-0.007}$
$F_L^{J/\psi}$	$0.446^{+0.003}_{-0.003}$	$0.434^{+0.003}_{-0.003}$	$0.430^{+0.002}_{-0.002}$	$0.443^{+0.003}_{-0.003}$	$0.490^{+0.005}_{-0.005}$

Indeed, P_τ^D is an excellent observable which can be measured in Belle II and upgraded LHCb.

Contents

Predictions in the SM and in selected NP scenarios



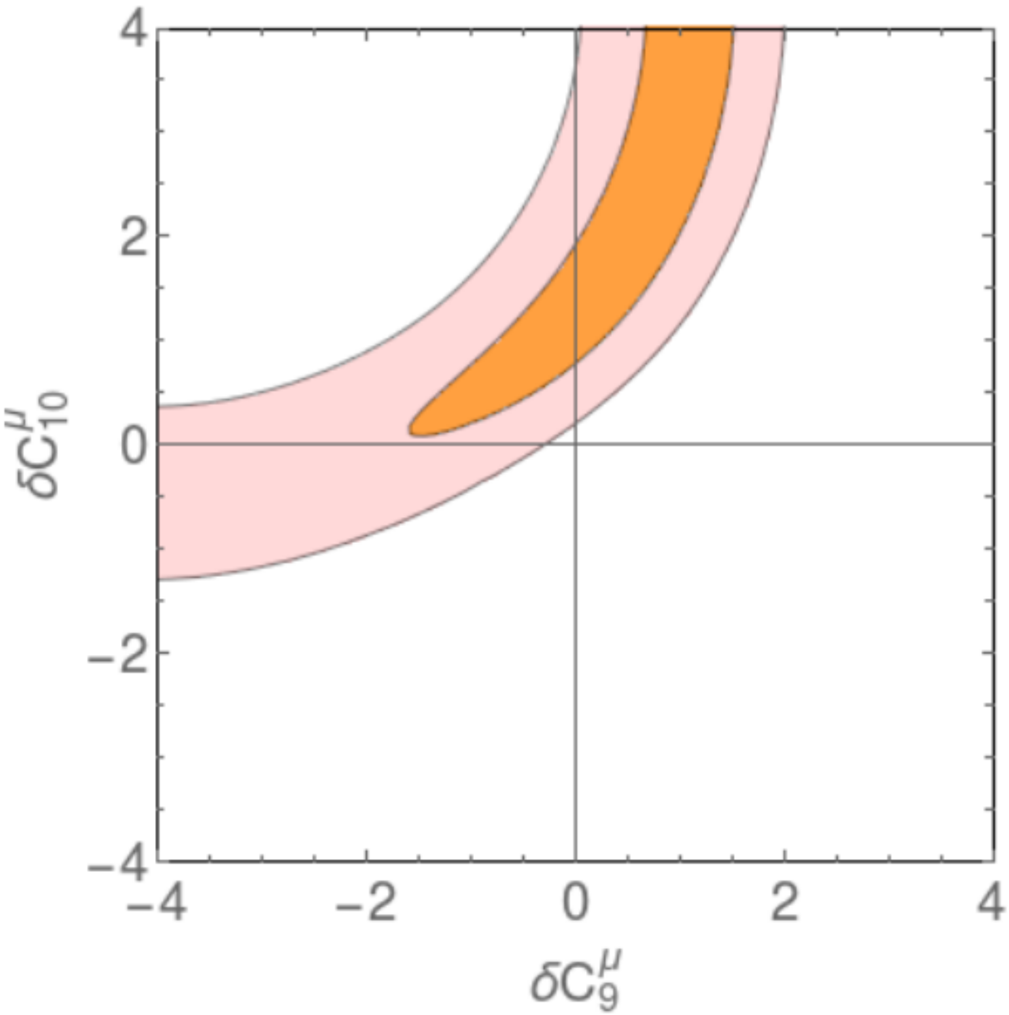


$$\delta C_L = \delta C_9 = -\delta C_{10}$$

The relation connected to the new models, such as leptoquark models.

- Kinematics range for B→K* l l decay is $q^2 \in [4m_l^2, (m_B - m_{K^*})^2]$ GeV^2.
- Only the operators O_9, O_{10} can explain the experimental data.
- The blank kinematic range for B→K* l l decay represents charmonium region which is dominated by long-distance (hadronic) effects.

Fits to R_K and R_{K*} before the 2019 data



Data(3):

LHCb: PRL113(2014)151601
LHCb: JHEP08(2017)055

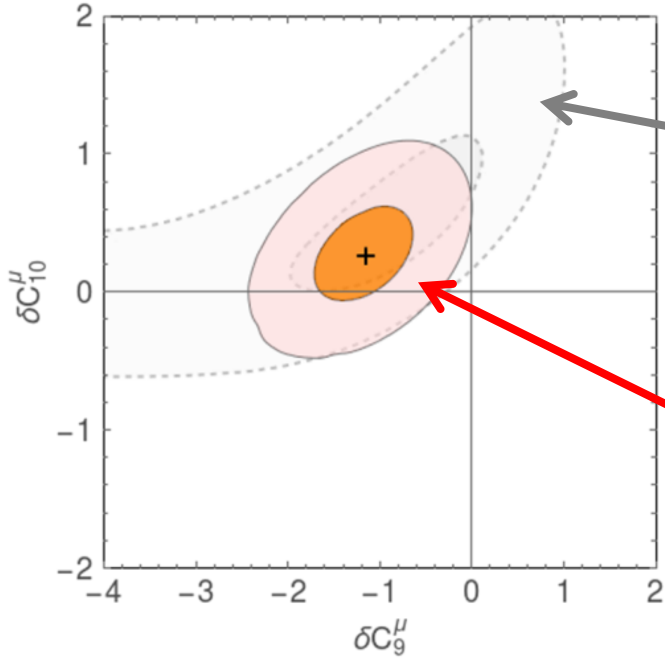
R_K bin[1,6] GeV^2

R_{K*} bin[0.045,1.1] GeV^2

bin[1.1,6] GeV^2

- **Both δC_9 and δC_{10} have no boundary.**

Fits to all the data before 2019



Data(65):

R_K bin[1,6] GeV^2

R_{K^*} bin[0.045,1.1] GeV^2

bin[1.1,6] GeV^2

R(Bs → μ+ μ-)

BR(B → K*γ)

All angular observables from LHCb, LTLAS,CMS, Belle: F_L, P_1, P_2, P_3, P_4', P_5', P_6', P_8'.

Coefficient	Best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^{μ}	−1.37	61.98 [64 dof]	0.548	4.37	[−1.70, −1.03]	[−2.41, −0.41]
δC_{10}^{μ}	0.60	71.72 [64 dof]	0.237	3.06	[0.40, 0.82]	[−0.01, 1.28]
δC_L^{μ}	−0.59	63.62 [64 dof]	0.490	4.18	[−0.74, −0.44]	[−1.05, −0.16]
Coefficient	Best fit	$\chi^2_{\rm min}$	p-value	SM exclusion [σ]	Parameter ranges	
$(\delta C_9^{\mu}, \delta C_{10}^{\mu})$	(−1.15, 0.28)	60.33 [63 dof]	0.572	4.17	$C_9^{\mu} \in [-1.54, -0.81]$	$C_{10}^{\mu} \in [0.06, 0.50]$

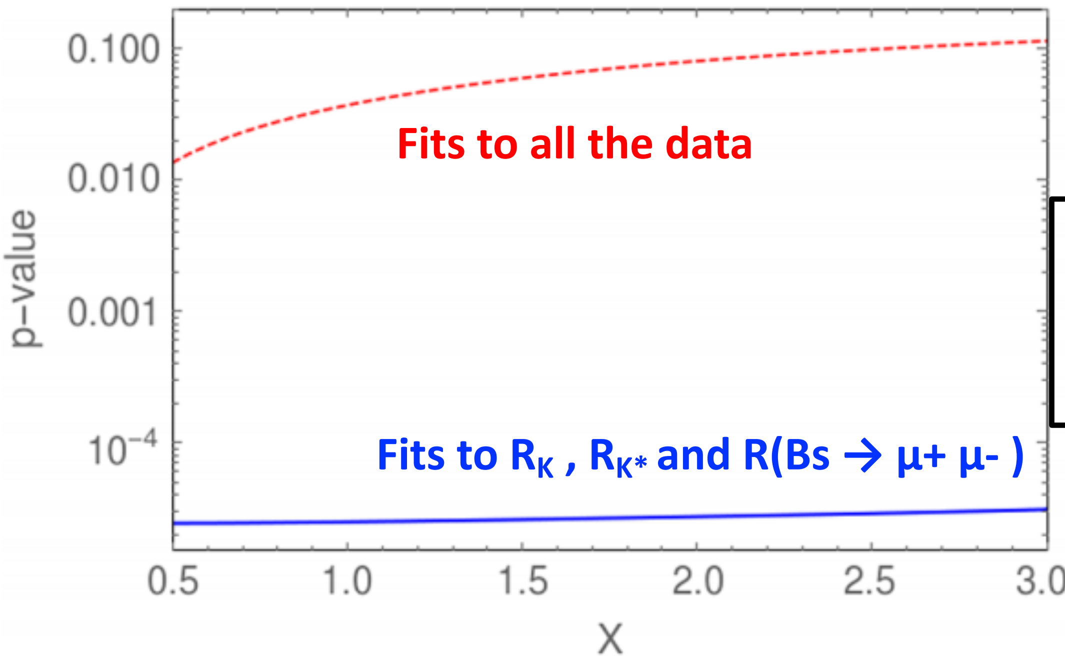
- **The significance of the SM exclusion in the fits is about 4σ.**
- **δC_9 is negative. However, the value of δC_{10} is poorly determined by the global fit.**

Robustness of fits with respect to hadronic uncertainties

PRD93(1):014028,2016, JHEP, 05:043, 2013

27 hadronic parameters in low q^2

QCDf(11)	$\mu, \xi_\perp(0), \xi_\parallel(0), f_{K^*}, a1_\perp, a2_\perp(0), a1_\parallel(0), a2_\parallel(0), \omega_0, r_\perp, r_\parallel$
Power Corrections(8)	$V_-(\lvert a\rvert_{\max}), V_-(\lvert b\rvert_{\max}), V_+(\lvert a\rvert_{\max}), V_+(\lvert b\rvert_{\max}), T_+(\lvert b\rvert_{\max}), V_0(\lvert b\rvert_{\max}), T_0(\lvert a\rvert_{\max}), T_0(\lvert b\rvert_{\max})$
Charm contributions(8)	$h_-\rvert_{c\bar{c}}(\lvert a\rvert_{\max}), h_-\rvert_{c\bar{c}}(\lvert b\rvert_{\max}), \phi_-\rvert_{c\bar{c}}, h_+\rvert_{c\bar{c}}(\lvert a\rvert_{\max}), h_+\rvert_{c\bar{c}}(\lvert b\rvert_{\max}), \phi_+\rvert_{c\bar{c}}, h_0\rvert_{c\bar{c}}, \phi_0\rvert_{c\bar{c}}$

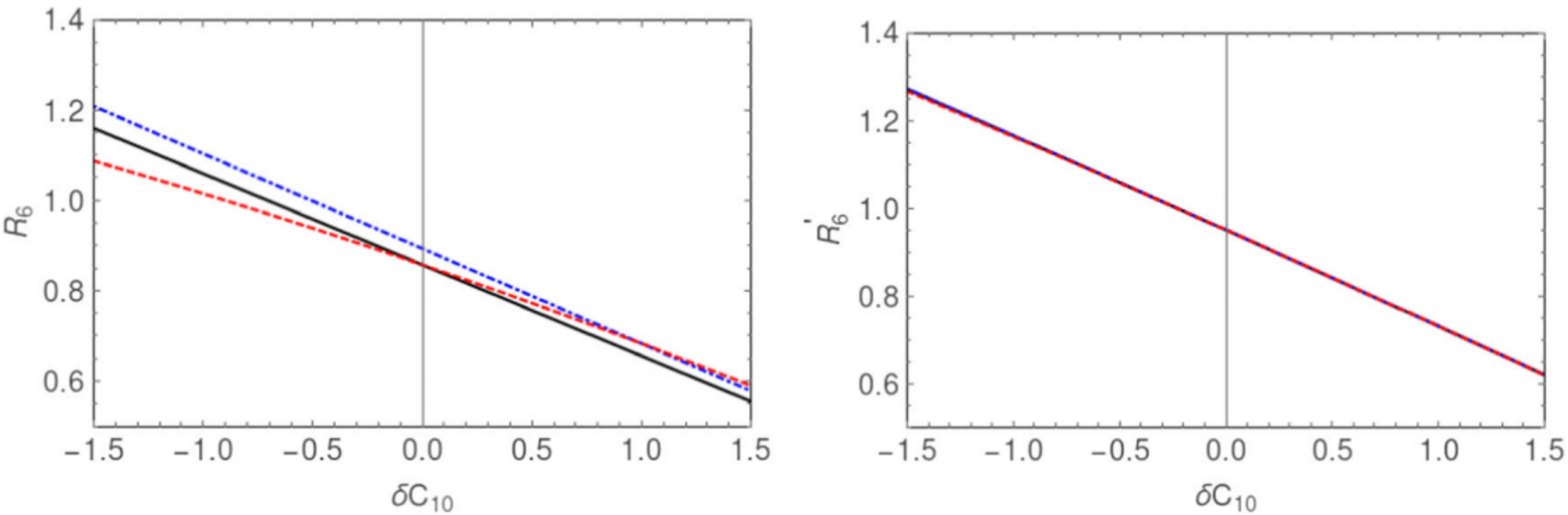


X-dependence study

Plot of the p-values as a function of x. The variable x is a factor by which we multiply all the uncertainty ranges of the 27 hadronic parameters.

The results fitting to R_K , R_{K^*} and R(Bs → μ+ μ-) are available but only three observable cannot constrain δC_9.

Constructing an observable only sensitive to C_{10}



$\delta C_9 = 0$

$\delta C_9 = -\delta C_{10}$

$\delta C_9 = -1$

R_6', R_6

Bin [0.045,1.1] GeV^2

$$R_6' = \langle P_2^{(\mu)} \rangle / \langle P_2^{(e)} \rangle$$

$$P_2 = \frac{\Sigma_6}{8\Sigma_{2s}}$$

$$R_6[a,b] = \frac{\int_a^b \Sigma_6^\mu dq^2}{\int_a^b \Sigma_6^e dq^2} \approx \frac{C_{10}^\mu}{C_{10}^e} \times \frac{\int_a^b |\vec{k}| q^2 \beta_\mu^2 \mathrm{Re}[H_{V-}^{(\mu)}(q^2)] V_-(q^2)}{\int_a^b |\vec{k}| q^2 \mathrm{Re}[H_{V-}^{(e)}(q^2)] V_-(q^2)}$$

$$H_V(\lambda) = -iN \left[\tilde{V}_\lambda(q^2) C_9 + \frac{2 m_b m_B}{q^2} \tilde{T}_\lambda(q^2) C_7 - \frac{16\pi^2 m_B^2}{q^2} h_\lambda(q^2) \right]$$

large in the very low bin.

- **These constructed observables are almost exclusively sensitive to C_{10} .**
- **Experimentally, these observables can be measured by LHCb and Belle.**

Updating the global fit of b→s l l decay including 2019 data

The predictions in SM:

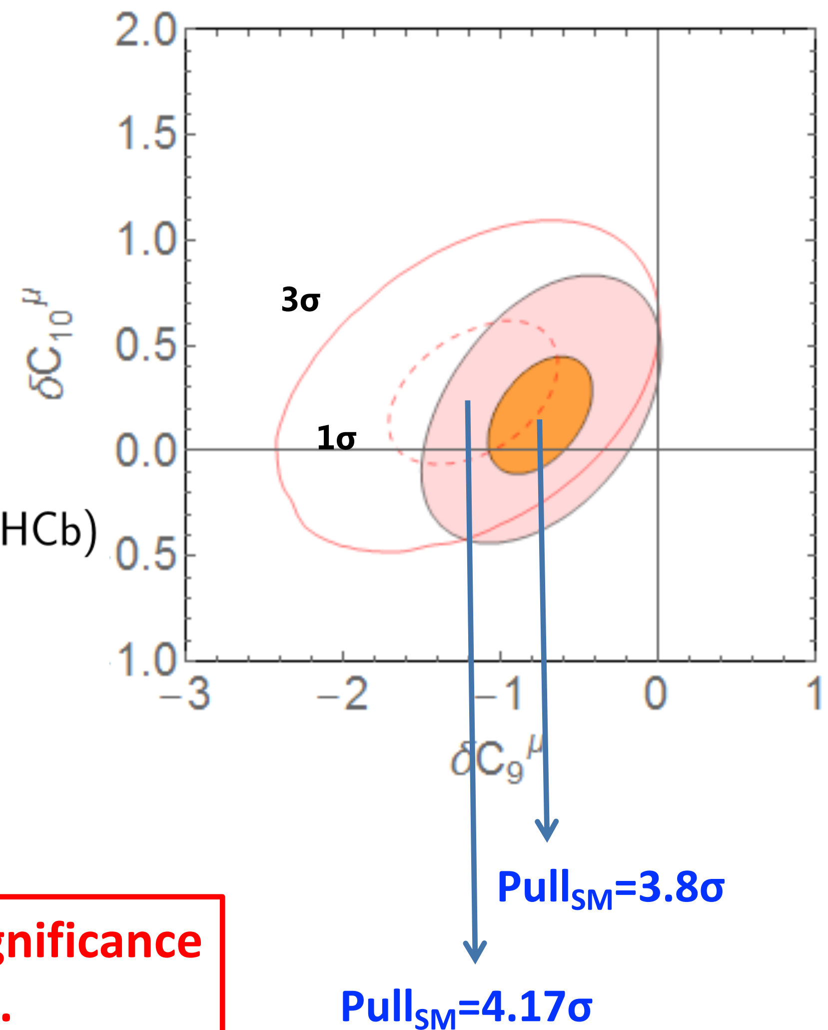
$$R_{K^{(*)}}^{\mathrm{SM}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)} \simeq 1$$

Considering the new data in 2019

$$R_{K[1,6]\ \mathrm{GeV}^2} = 0.846^{+0.060}_{-0.054}(\mathrm{stat.})^{+0.016}_{-0.014}(\mathrm{syst.}) \quad \text{(LHCb)}$$

$$R_{K^*[0.045,1.1]\ \mathrm{GeV}^2} = 0.52^{+0.36}_{-0.26} \pm 0.05 \quad \text{(Belle)}$$

$$R_{K^*[1.1,6]\ \mathrm{GeV}^2} = 0.96^{+0.45}_{-0.29} \pm 0.11 \quad \text{(Belle)}$$



μ≠e type

For a global fit including new data, the significance of deviation from SM is still more than 3σ.

Contents

Summary $b \to c\, l\, \nu$

① Significance of the SM exclusion in our fits is **more than 3σ**.

② In addition to the known **$B_c \to \tau\nu$** constraint, it is shown that **the LHC monotau constraint** excludes large regions of the parameter space.mFurthermore, it is shown that **$F_L^{D^*}$** excludes the parameter space complementary with the LHC bounds.

③ We tested some new physics models using our parameter space.

④ We also found that the **τ polarization in the $B \to D\tau\nu$ decay** is sensitive to the various new-physics scenarios which are favored by the current data.

Summary $b \to s\,l\,l$

① Only the operators **O_9, O_{10} can explain** the experimental data.

② **δC_{10} is poorly determined** by global fit but we also discuss some observables which are almost only sensitive to C_{10}. And it is feasible to measure these observations in future.

③ For a updated global fit including the 2019 data, the significance of **the SM exclusion is still more than 3σ**.

Outlook

- In the next few years, with the collection of more data at the B factories and improvement of experimental precision, we will **continually update our analysis**.

- In addition, new theoretical works on the theoretical side will be needed, **to better access uncertainties**.

- Meantime, it is also important to continue to find or construct **new observables** which are more sensitive to new physics.

- **Moving to baryon/hyperon decays**

$$\Sigma^+ \to p\ell\ell \qquad \Sigma^+ \to p\gamma$$

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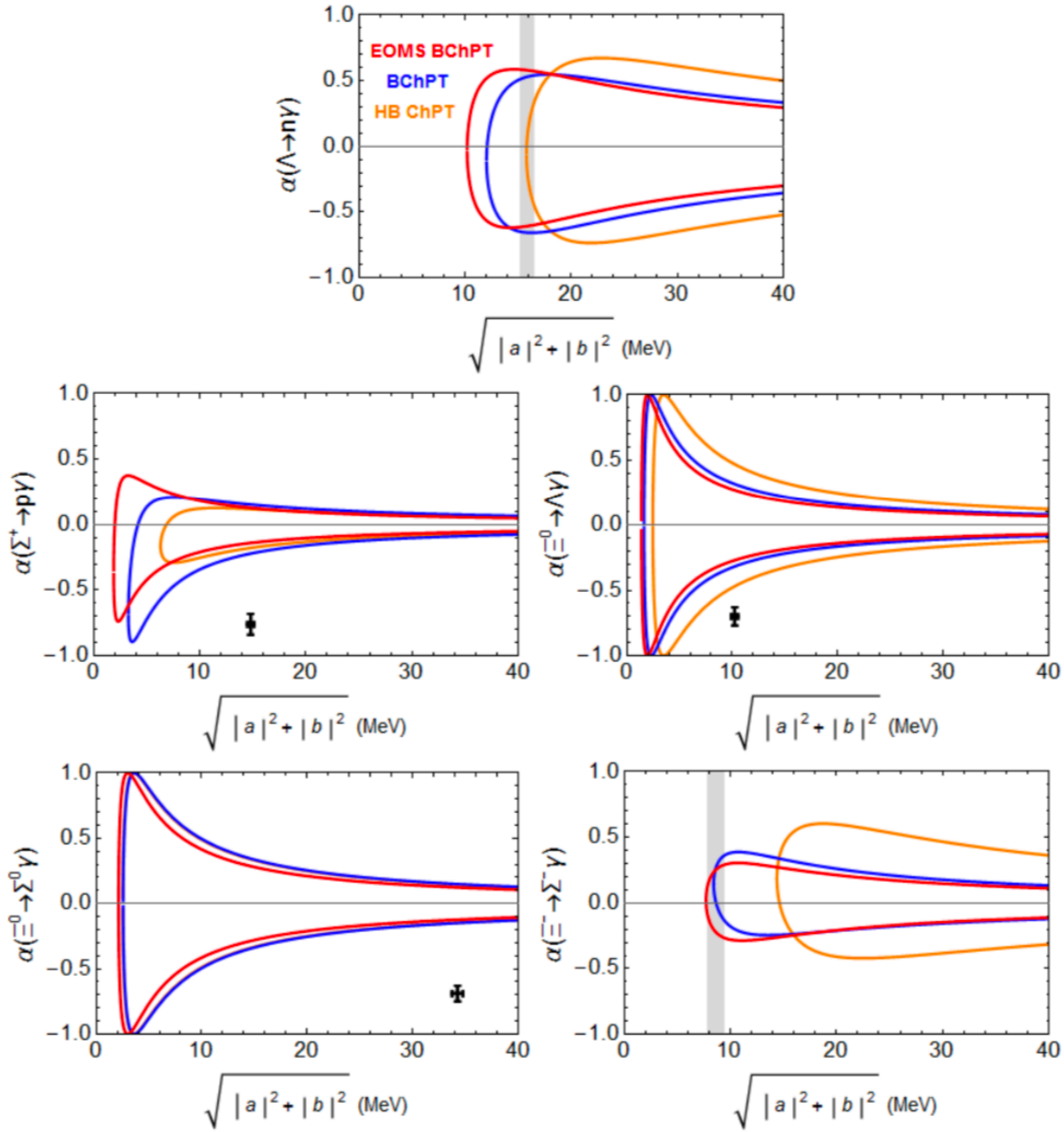
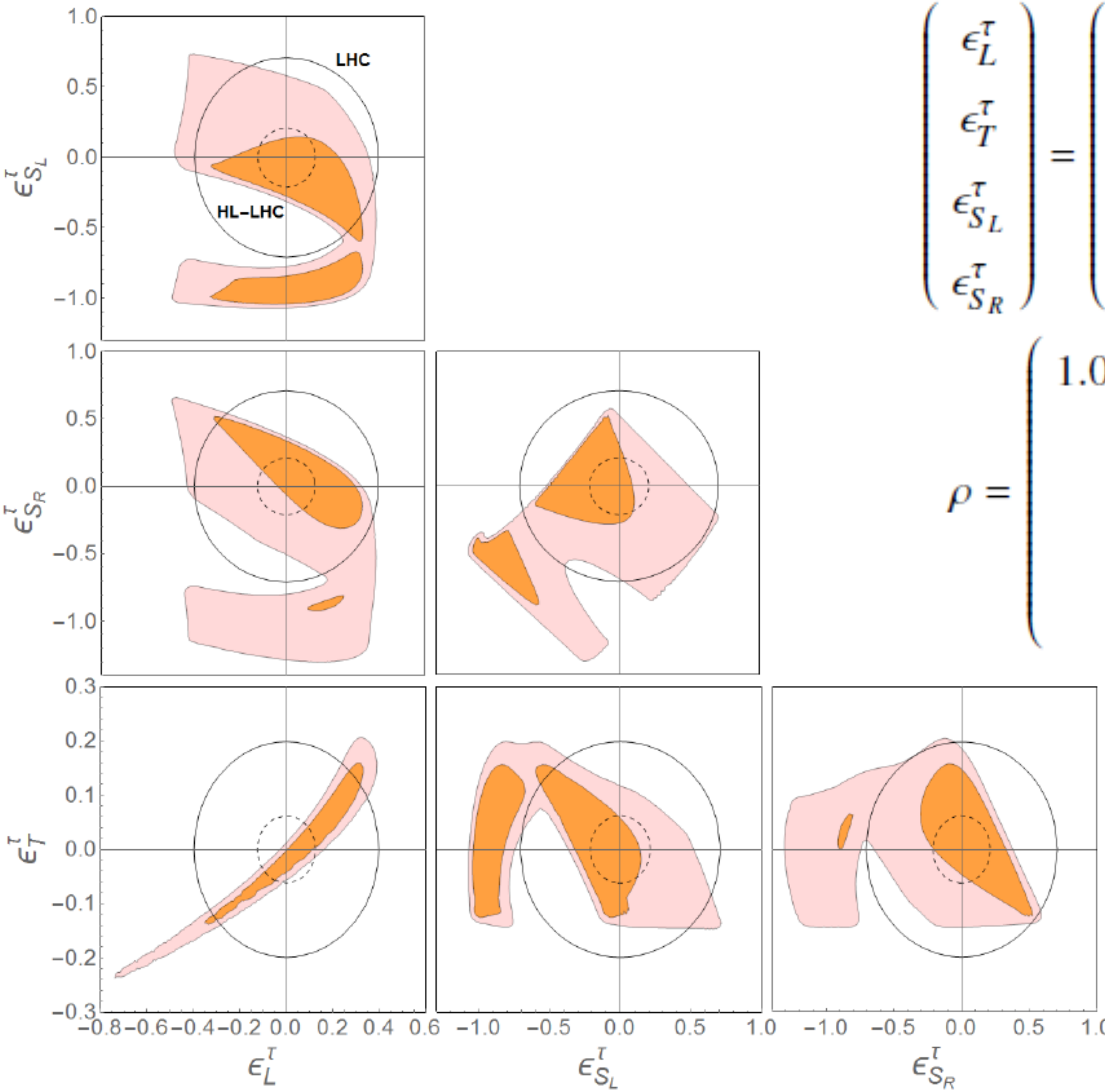
Thanks for your attention！

December 15, 2019

Backup slides


EOMS BChPT
BChPT
HB ChPT
α(Λ→nγ)
α(Σ⁺→pγ)
α(Ξ⁰→Λγ)
α(Ξ⁰→Σ⁰γ)
α(Ξ⁻→Σ⁻γ)
√(|a|² + |b|²) (MeV)
1.0
0.5
0.0
−0.5
−1.0
0
10
20
30
40

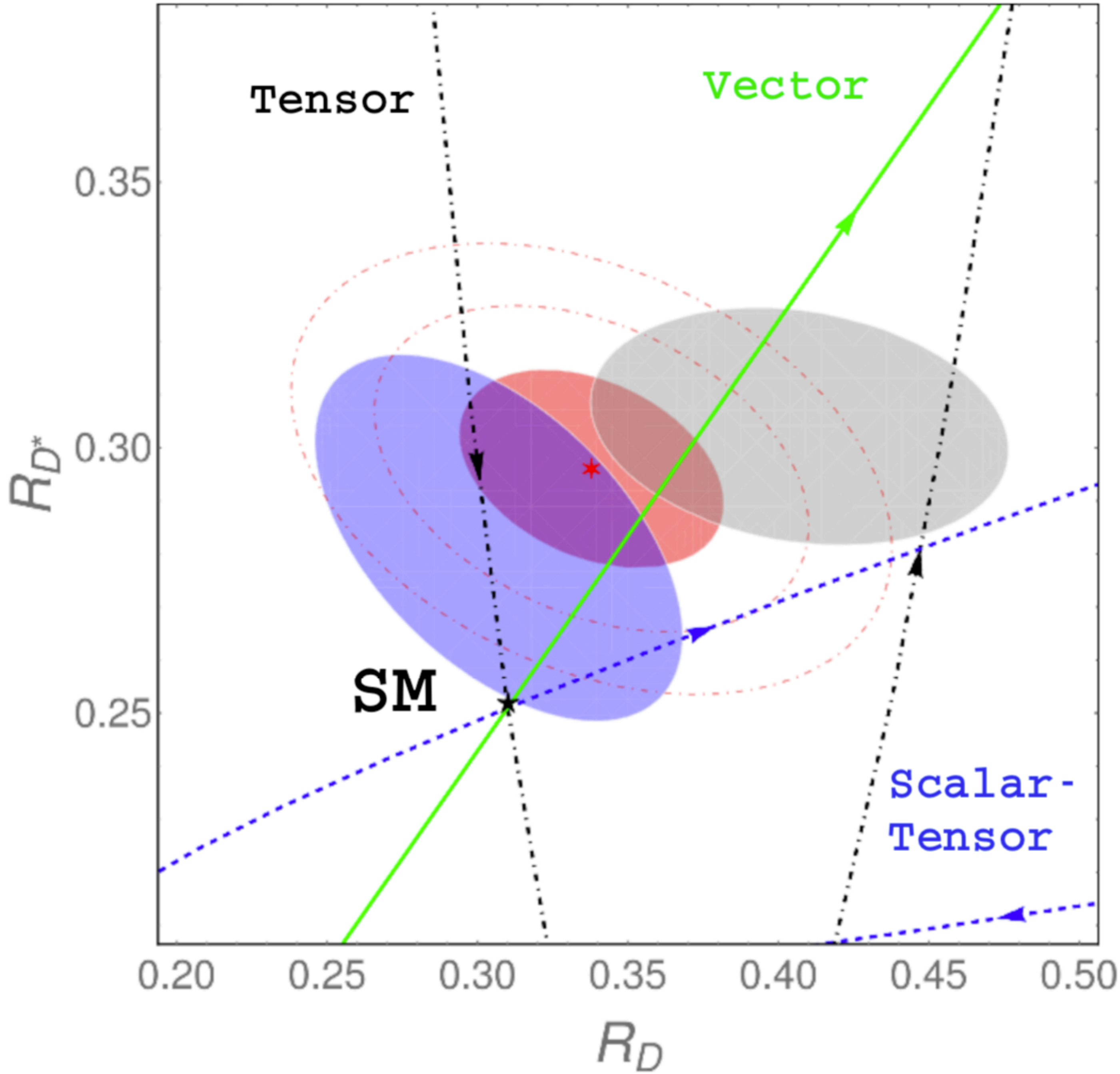
4D global fit for b → c l ν decay



$$\begin{pmatrix} \epsilon^\tau_L \\ \epsilon^\tau_T \\ \epsilon^\tau_{S_L} \\ \epsilon^\tau_{S_R} \end{pmatrix} = \begin{pmatrix} 0.16 \pm 0.20 \\ 0.05 \pm 0.09 \\ -0.33 \pm 0.21 \\ 0.14 \pm 0.22 \end{pmatrix},$$

$$\rho = \begin{pmatrix} 1.000 & 0.816 & 0.913 & -0.915 \\ & 1.000 & 0.951 & -0.920 \\ & & 1.000 & -0.986 \\ & & & 1.000 \end{pmatrix},$$

p-value = 0.12
$\mathrm{Pull_{SM}}$ = 2.64



Tensor
Vector
0.35
0.30
0.25
R_{D^*}
SM
Scalar-
Tensor
0.20
0.25
0.30
0.35
0.40
0.45
0.50
R_D