Pre-SUSY 2021: The Summer School on Supersymmetry and Unification of Fundamental Interactions

北京航空航天大學
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Hints of new physics in semi-leptonic B decays

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OUTLINE

- Background
- Theoretical framework
- Results and discussions
  - Flavor-changing-neutral-current(FCNC) $b \to s\, l\, l$ decays
  - Charged-current(CC) $b \to c\, \tau\, \nu$ *decays*
- Summary and outlook

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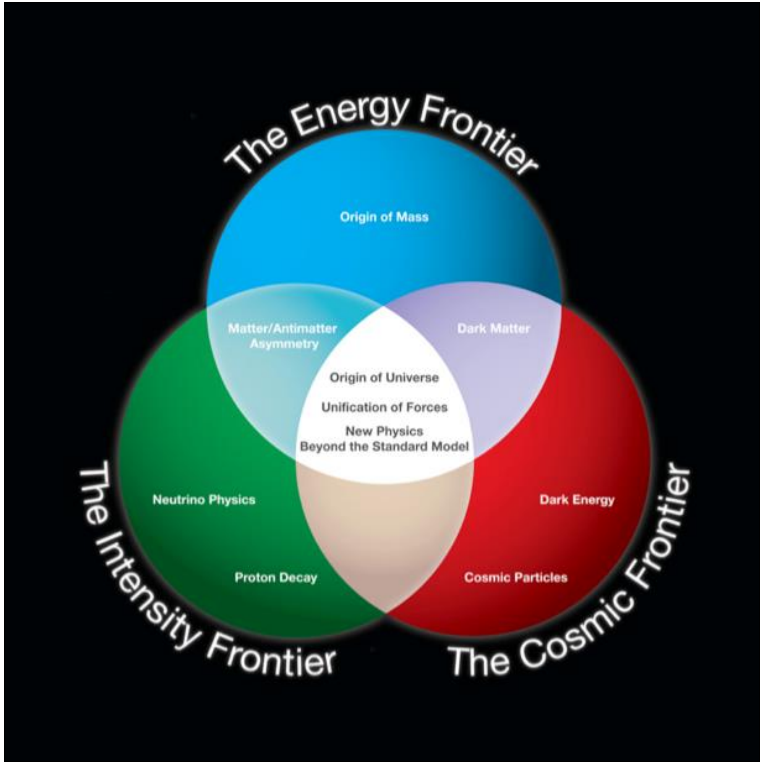
Frontiers in high energy physics

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: the same interactions between leptons and gauge bosons

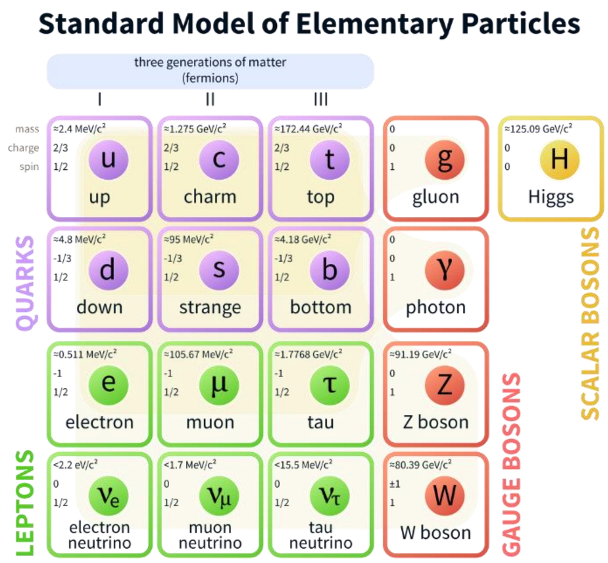
SM Lagrangian

$$\mathcal{L}_{SM} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^i_{\mu\nu}W^{i\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{\theta}{16\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

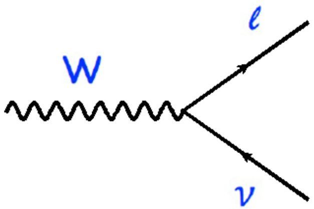
$$+ \sum_{\psi=\{l,e,u,d,q\}} \bar{\psi} i \not{D} \psi - \left[\bar{l}HY_l e + \bar{q}HY_d d + \bar{q}\tilde{H}Y_u u + \text{hc.}\right]$$

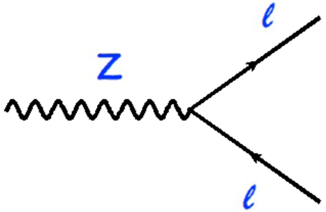
$$+ D_\mu H^\dagger D^\mu H + \frac{m_h^2}{2}(H^\dagger H) - \lambda(H^\dagger H)^2$$

$$D_\mu \sim \partial_\mu + ig_s G^a_\mu T^a + ig\, W^i_\mu t^i + ig' B_\mu$$



Lepton universality (LU) in the Standard Model (SM)





From the 2020 PDG averages

$$\frac{B(W^+ \to \mu^+\nu)}{B(W^+ \to e^+\nu)} = 0.991 \pm 0.018$$

$$\frac{B(W^+ \to \tau^+\nu)}{B(W^+ \to e^+\nu)} = 1.043 \pm 0.024$$

$$\boxed{\frac{B(W^+ \to \tau^+\nu)}{B(W^+ \to \mu^+\nu)} = 1.070 \pm 0.026}$$

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

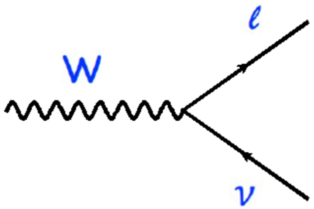
$$\frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

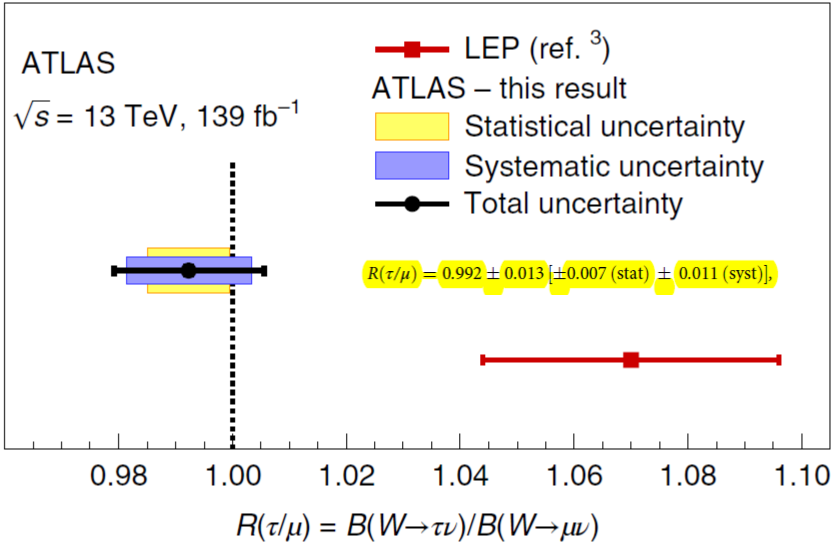
Predictions in the SM: ~1; the largest deviation about 2.7 sigma

Lepton universality (LU) in the Standard Model (SM)

ATLAS: 139 fb pp collision data at 13 TeV

Nature Physics 17 (2021)813





Lepton universality (LU) in the Standard Model (SM)

However, some LU violation signals (R_D , R_{D^*} , R_K , R_{K^*} , etc.) in B semi-leptonic decays have shown persistent deviation from the SM

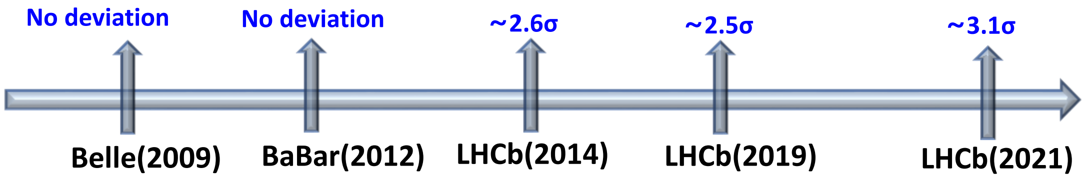
$$\mathbf{R}^{\mathrm{SM}}_{\mathbf{K}^{(*)}} = \frac{\mathbf{\Gamma}(\mathbf{B} \to \mathbf{K}^{(*)}\mu^+\mu^-)}{\mathbf{\Gamma}(\mathbf{B} \to \mathbf{K}^{(*)}\mathbf{e}^+\mathbf{e}^-)} \cong \mathbf{1}$$

$$\mathbf{R}^{\mathrm{SM}}_{\mathbf{D}^{(*)}} = \frac{\mathbf{\Gamma}(\mathbf{B} \to \mathbf{D}^{(*)}\tau\bar{\nu})}{\mathbf{\Gamma}(\mathbf{B} \to \mathbf{D}^{(*)}\ell\bar{\nu})}, \qquad (\ell = \mu, \mathbf{e})$$

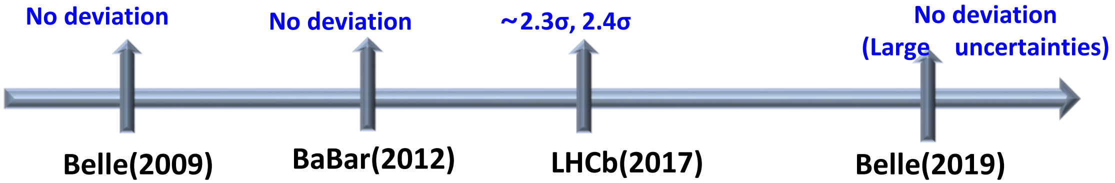
Progress in experimental measurements

- ☐ μ≠e type

R_K

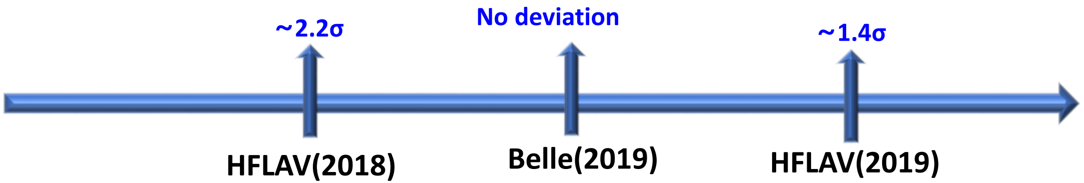


R_{K^*}

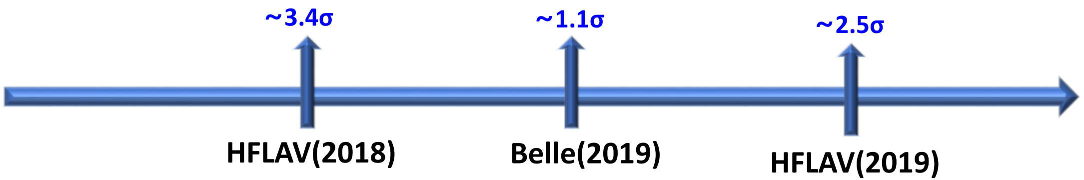


- ☐ τ≠μ/e type

R_D



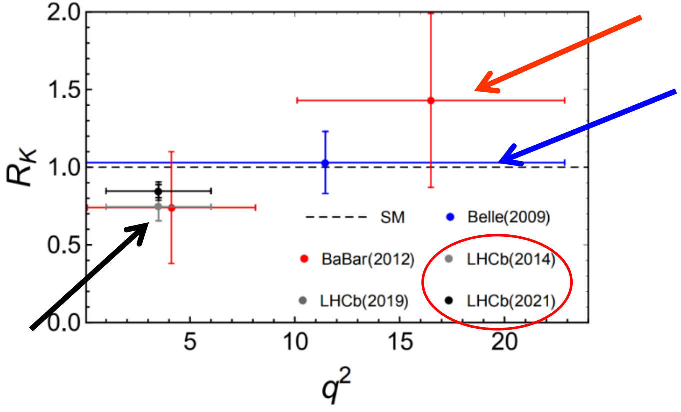
R_{D^*}

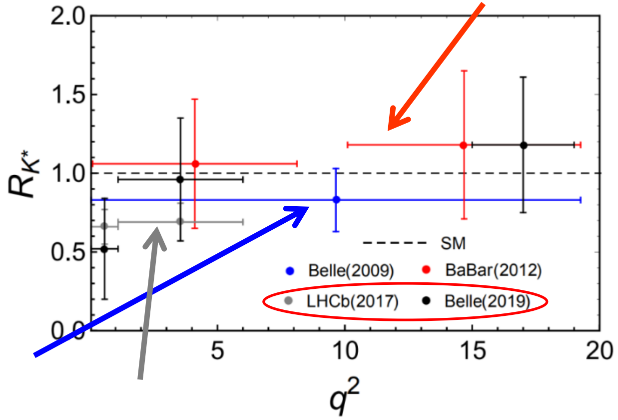


Testing LUV (μ≠e) in FCNC $b \to s\, l\, l$ decays, i.e., R_K and R_{K^*}

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

Belle: PRL103(2009)171801
BaBar: PRD86(2012)032012
LHCb: PRL113(2014)151601
LHCb: arXiv: 2103.11769
LHCb: JHEP08(2017)055
LHCb: PRL122(2019)191801
Belle: PRL126 (2019)161801

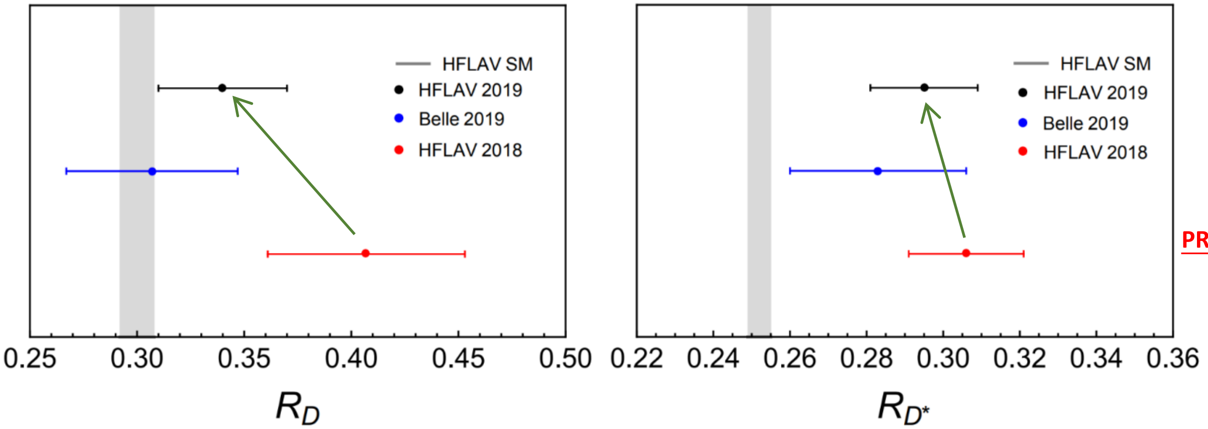




- Belle 2009 and BaBar 2012 measurements , no anomalies.
- LHCb 2014 - 2021, the significance of tension with the SM increases 2.6σ - 3.1σ for R_K.
- For R_{K^*}, the LHCb 2017 measurements deviate from the SM with a significance of ~2.3σ, 2.4σ.

Testing LUV ($\tau \neq \mu/e$) in $b \to c\, \tau\, \nu$ decays, i.e., R_D and R_{D^*}

$$\mathbf{R}^{\mathrm{SM}}_{\mathbf{D}^{(*)}} = \frac{\Gamma(\mathbf{B} \to \mathbf{D}^{(*)} \tau \bar{\nu})}{\Gamma(\mathbf{B} \to \mathbf{D}^{(*)} \ell \bar{\nu})}, \qquad (\ell = \mu, \mathbf{e})$$



HFLAV

PRL124(2019)161803

- ☐ **Belle 2019 measurement of R_D and R_{D^*} with a semi-leptonic tagging method;**
- ☐ **Belle 2019 measurements are compatible with the SM within 1.2σ;**
- ☐ **HFLAV 2019 results are closer to the SM predictions.**

Theoretical approaches to study anomalies in B physics

□ "Top-down" approaches:

- Leptoquark model

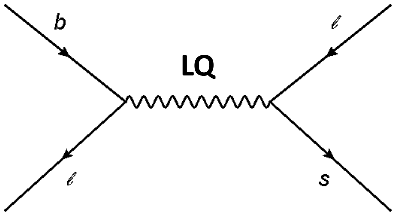
  Oleg Popov et al, PRD100.035028
  Claudia Cornella et al, JHEP07(2019)168
  Leandro Da Rold et al, JHEP12(2019)112

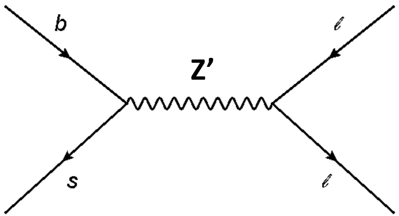
- Z' boson model

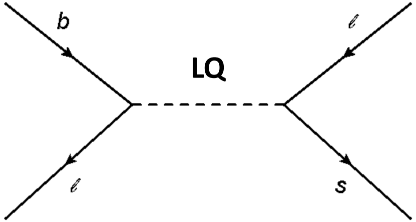
  Ashutosh Kumar Alok et el, EPJC80 (2020)7,682
  Wolfgang Altmannshofer et al, PRD101.015004
  Siddharth Dwivedi et al, EPJC80 (2020) 3, 263

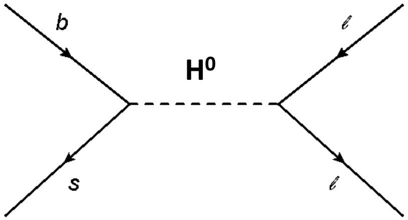
- Two-Higgs-doublet model

  Astrid Ordell et al, PRD100.115038
  Ya-Dong Yang et al, JHEP09(2018)149
  Luigi Delle Rose et al, PRD101.115009









□ "Bottom-up" approach:

- low-energy effective Hamiltonian approach.

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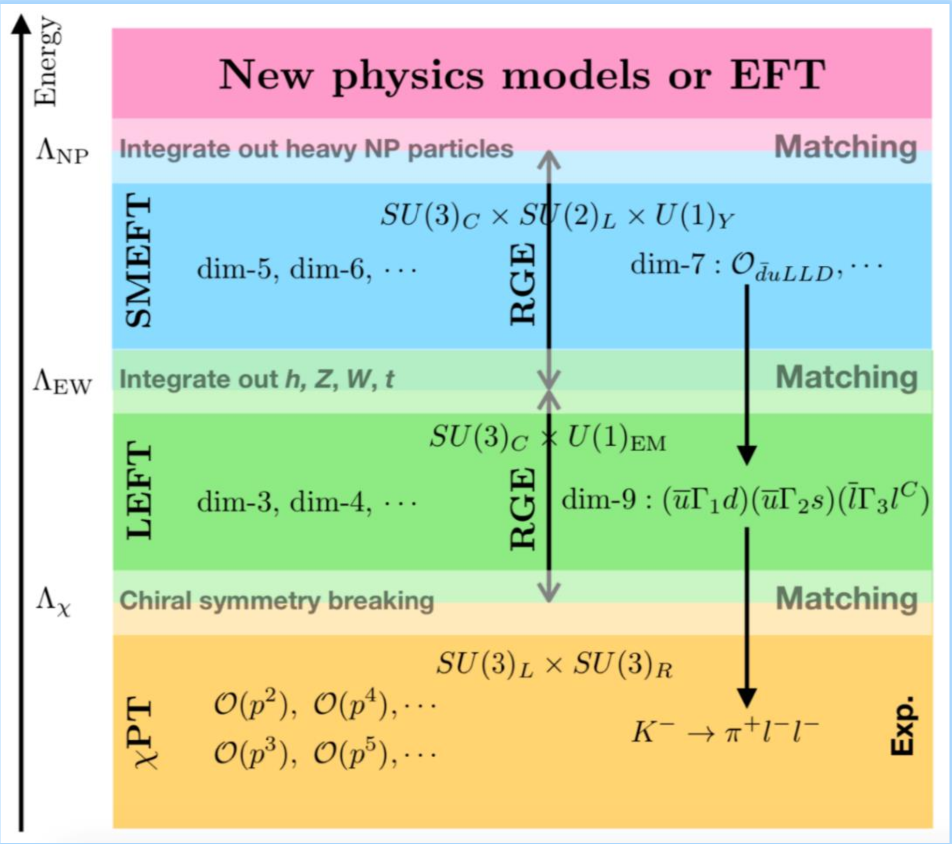
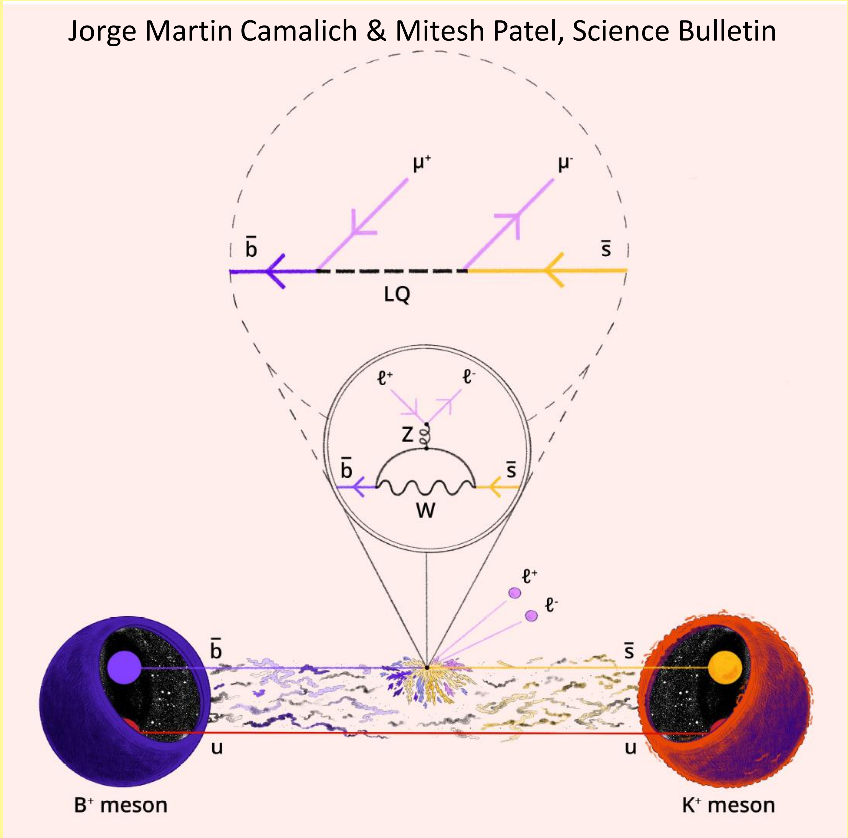
Low-energy effective Hamiltonian approach





Low-energy effective Hamiltonian approach

□FCNC： $b \to s\, l\, l$ transition

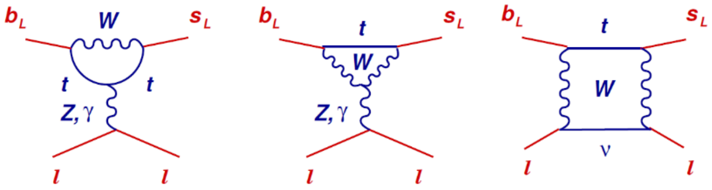
The low energy effective Hamiltonian at O(m_b) scale:

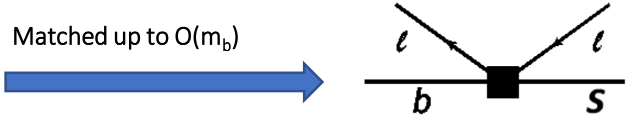
$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$$

$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 O_1^p + C_2 O_2^p + \sum_{i=3,\cdots,6} C_i O_i + C_{8g} O_{8g} \right]$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} \lambda_t \left[C_7 O_7 + C_9 O_9 + C_{10} O_{10} \right]$$

e.g





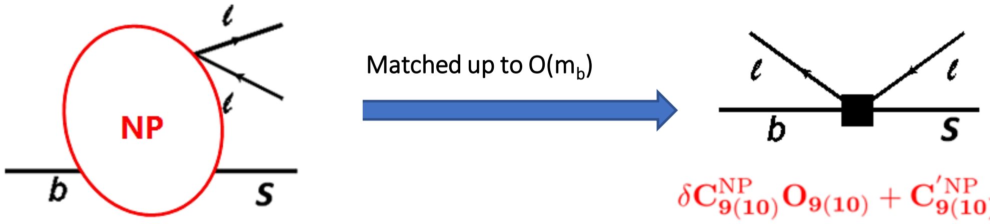
$$G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)}\, \bar{s}_L \gamma^\mu b_L\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

- **Wilson coefficients Ci(μ) calculated in perturbation theory at μ=m_W and rescaled to μ=m_b.**
- For a specific decay mode, another important work is to calculate hadronic matrix elements produced by **operators involving non-perturbative effects.**

Low-energy effective Hamiltonian approach

☐FCNC： $b \to s\, l\, l$ transition

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



$$\delta\mathrm{C}^{\mathrm{NP}}_{9(10)}\mathrm{O}_{9(10)} + \mathrm{C}'^{\mathrm{NP}}_{9(10)}\mathrm{O}'_{9(10)}$$

☐New chirally-flipped operators:

$$\mathcal{O}'_{9(10)} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi}\, \bar{s}\gamma^\mu P_R b\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

- Different values of Wilson coefficients $\boxed{\mathrm{C}_i^{\mathrm{expt.}} = \mathrm{C}_i^{\mathrm{SM}} + \delta\mathrm{C}_i + \mathrm{C}'_i}$
- Wilson coefficients can be complex and introduce new sources of CP violation;
- Note that O_S , O_p and O_T cannot explain R_K and R_{K*} from J. Martin Camalich et al, PRL113.241802.

Key steps in studies of the $b \to s\, l\, l$ decays

Using the low energy effective Hamiltonian to calculate amplitude and observables

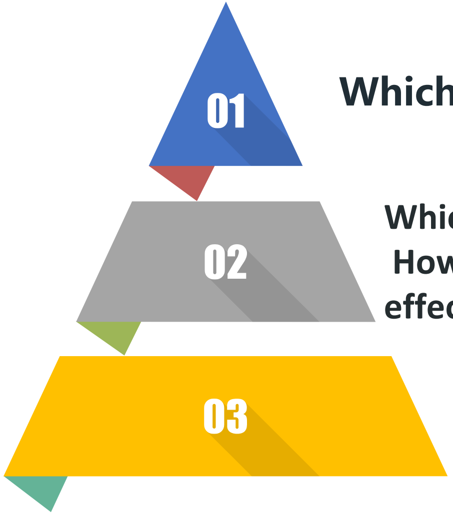
↓

Fitting to experimental data and constraining δCi

↓

Using the frequentist statistic approach to analyze fit results

Key questions



Which Wilson coefficients ?

Which decay channels and observables?
How to estimate non-perturbative effects?

What fitting strategy?
And which statistical quantities?

Key steps in studies of the $b \to s\, l\, l$ decays

Using the low energy effective Hamiltonian to calculate amplitude and observables

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Fitting to experimental data and constraining δCi

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Key questions

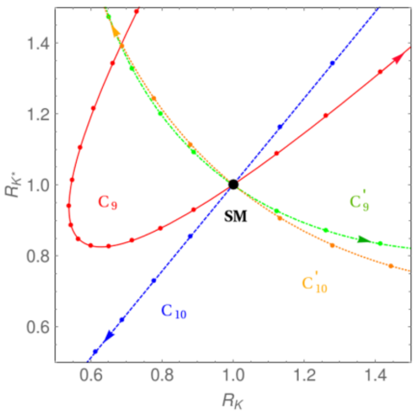
01 **Which Wilson coefficients ?**

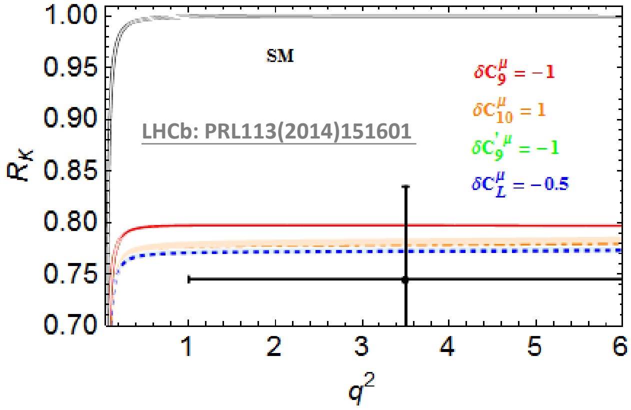
02 Which decay channels and observables? How to estimate non-perturbative effects?

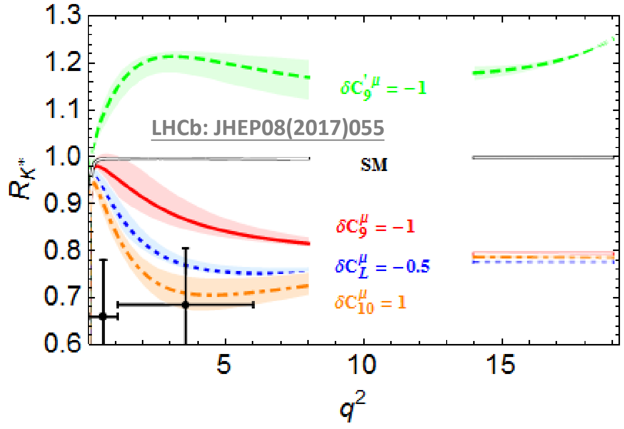
03 What fitting strategy? And which statistical quantities?

Predictions in the SM and in selected NP scenarios

- Assuming that the NP only appears in the muon channels and all Wilson coefficients are real.







- Only the operators O_9, O_{10} instead of O_9', O_{10}' are favored by the data.

Key steps in studies of the $b \to s\, l\, l$ decays

Using the low energy effective Hamiltonian to calculate amplitude and observables

↓

Fitting to experimental data and constraining δCi

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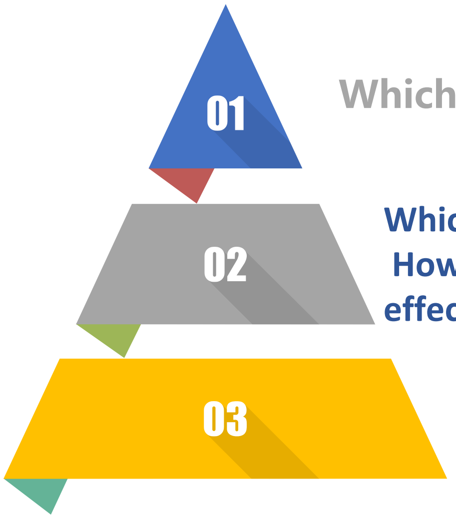
Key questions



Which Wilson coefficients ?

Which decay channels and observables?
How to estimate non-perturbative effects?

What fitting strategy?
And which statistical quantities?

Interesting decay channels of $b \to s\, l\, l$ decays

processes	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to K^* \gamma$	$\surd$		
$B_s \to \mu^+ \mu^-$			$\surd$
$B \to K^{(*)} \mu^+ \mu^-$	$\surd$	$\surd$	$\surd$

- Note that $\mathrm{BR}(\mathrm{B} \to K^* \gamma)$ can fix better soft form factors.

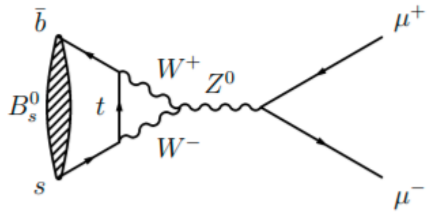
E.g: Form factors $F(q^2)$: **HQEFT**

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

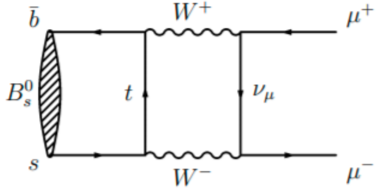
Soft form factors

$B_s \to \mu^+\mu^-$ decay

Penguin



Box



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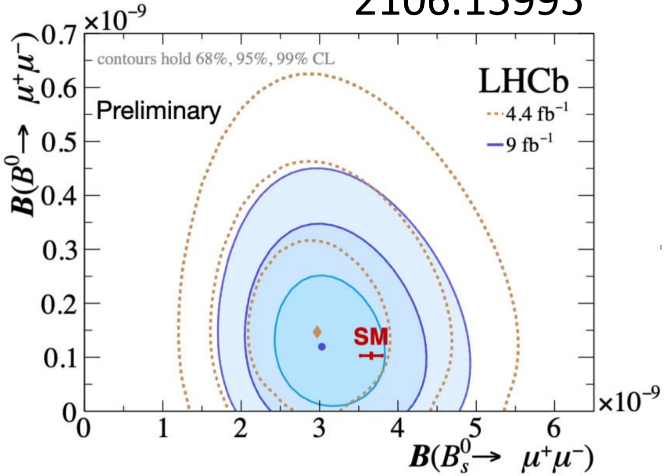


Branching ratio:

$$\mathrm{BR}(\mathbf{B_s} \to \mu^+\mu^-)^{\mathrm{SM}} = \tau_{\mathbf{B_s}} \frac{\mathbf{G_F^2}\alpha^2}{\mathbf{16\pi^3}} |\mathbf{V_{tb}V_{ts}^*}|^2 \mathbf{m_{B_s}} \mathbf{m_\mu^2} \beta_\mu(\mathbf{m_{B_s}^2}) |\mathbf{C_{10}}|^2 \mathbf{f_{B_s}}$$

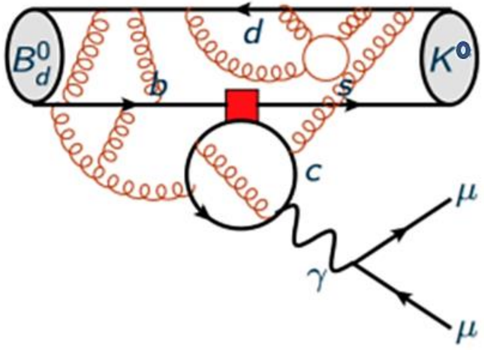
Define R:

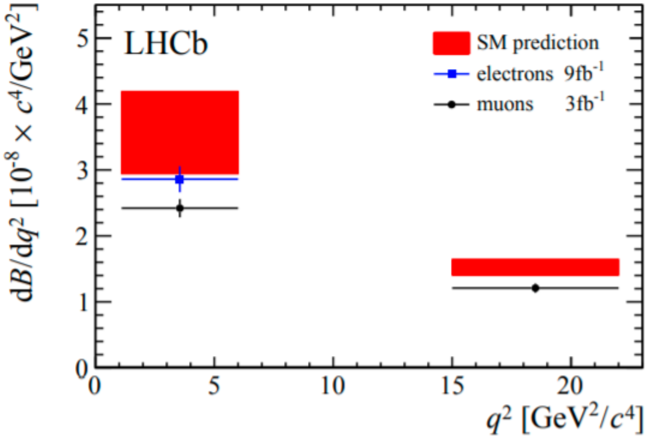
$$\mathbf{R} = \frac{\mathrm{BR}(\mathbf{B_s} \to \mu^+\mu^-)_{\mathrm{exp}}}{\mathrm{BR}(\mathbf{B_s} \to \mu^+\mu^-)_{\mathrm{SM}}}$$

- **Very clean** (f_{Bs} has been calculated accurately by the LQCD) FLAG 2019, *EPJC*80(2020)2,113
- **Very rare** (GIM and helicity suppression)

$B\to K\mu^+\mu^-$ decay

2103.11769





The differential decay rate:

$$\frac{d\Gamma_K}{dq^2} = \mathcal{N}_K|\vec{k}|^3 f_+(q^2)^2\left(\left|C_{10}^\ell + C_{10}'^\ell\right|^2 + \left|C_9^\ell + C_9'^\ell + 2\frac{m_b}{m_B+m_K}C_7\frac{f_T(q^2)}{f_+(q^2)} - 8\pi^2 h_K\right|^2\right)$$
$$+\mathcal{O}\left(\frac{m_\ell^4}{q^4}\right) + \frac{m_\ell^2}{m_B^2}\times O\left(\alpha_s, \frac{q^2}{m_B^2}\times\frac{\Lambda}{m_b}\right),$$

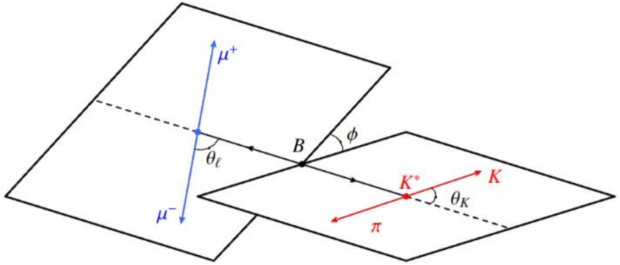
$$\boxed{R_K = \frac{\Gamma(B\to K\mu^+\mu^-)}{\Gamma(B\to Ke^+e^-)}}$$

- Kinematics range for the 3-body decay is $q^2 \in [4m_l^2,(m_B-m_K)^2]$
- There are very complicated non-perturbative effects
- Charmonium region cannot be calculated by perturbation theory

$B \to K^*(\to K\pi)\mu^+\mu^-$ decay

Kinematics of 4-body decay:

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



$$\begin{aligned} I^{(\ell)}(q^2, \theta_\ell, \theta_K, \phi) =& \Big(I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + (I_2^s \sin^2\theta_K + I_2^c \cos^2\theta_K)\cos 2\theta_\ell \\ &+ I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi \\ &+ I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi \\ &+ (I_6^s \sin^2\theta_K + I_6^c \cos^2\theta_K)\cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi \\ &+ I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big), \end{aligned}$$

☐ Focusing on low bins ($q^2 \leq 6$ GeV^2):

- Form factors $F(q^2)$: **HQEFT**

Power corrections

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

Soft form factors

- Charm loops $h_\lambda(q^2)$: **HQEFT**

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

Calculated in LCSR + QCDF

$$F_L = S_{1c}, \qquad P_1 = \frac{2S_3}{1-F_L},$$

$$P_2 = \frac{2}{3}\frac{A_{FB}}{1-F_L}, \qquad P_3 = \frac{-S_9}{(1-F_L)},$$

$$P_4' = \frac{S_4}{\sqrt{F_L(1-F_L)}}, \qquad P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}},$$

$$P_6' = \frac{S_7}{\sqrt{F_L(1-F_L)}}, \qquad P_8' = \frac{S_8}{\sqrt{F_L(1-F_L)}},$$

$$S_i = \frac{I_i + \bar{I}_i}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}}$$

In total, 27 hadronic parameters !!!

Research procedures: $b \to s\, l\, l$ decays

Using the low energy effective Hamiltonian to calculate amplitude and observables

↓

Fitting to experimental data and constraining δC_i

↓

Using the frequentist statistic approach to analyze fit results

Key questions

01 Which Wilson coefficients ?

02 Which decay channels and observables?
How to estimate non-perturbative effects?

03 **What fitting strategy?**
And which statistical quantities?

Statistics: χ^2 fit & Frequentist analysis

☐ χ^2 fit

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

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

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

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

- The theory term is also parameterized in a Gaussian form

$$\chi^2_{\rm th}(\vec{y}) = \sum_i \left(\frac{y_i - \bar{y}_i}{\delta y_i}\right)^2,$$

- In order to obtain best-fit values in a particular scenario, we can construct a profile χ^2 depending only on certain Wilson coefficients

$$\chi^2(\vec{\epsilon}) = \min_{\vec{y}} \tilde{\chi}^2(\vec{\epsilon},\vec{y})$$

☐ Frequentist analysis

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

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

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

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

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

OUTLINE

- ❑ Background
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- ❑ **Results and discussions**
  - ➢ **Flavor-changing-neutral-current(FCNC) $b \to s\, l\, l$ decays**
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Latest experimental data

Observable	Value	Source	
$BR(B_s \to \mu^+\mu^-)$	$(2.8^{+0.8}_{-0.7}) \times 10^{-9}$	ATLAS	ATLAS: JHEP04(2019)098
	$(2.9 \pm 0.7 \pm 0.2) \times 10^{-9}$	CMS	CMS: JHEP04(2020)188
	$(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$	LHCb update	Moriond 2021 seminar
	$(2.842 \pm 0.333) \times 10^{-9}$	our average	
	$(3.63 \pm 0.13) \times 10^{-9}$	SM prediction	
$R_K[1.1, 6]$	0.846 ± 0.044	LHCb	Moriond 2021 seminar
$R_K[1, 6]$	1.03 ± 0.28	Belle	Belle: JHEP03(2021)105
$R_{K^*}[0.045, 1.1]$	$\boxed{0.660 \pm 0.113}$	LHCb	LHCb: JHEP08(2017)055
$R_{K^*}[1.1, 6]$	0.685 ± 0.122	LHCb	
$R_{K^*}[0.045, 1.1]$	0.52 ± 0.365	Belle	Belle: PRL126(2019)161801
$R_{K^*}[1.1, 6]$	0.96 ± 0.463	Belle	

- **Conservative** experimental uncertainties.

$$0.66^{+0.11}_{-0.07} \pm 0.03 \to 0.66 \pm \sqrt{0.11^2 + 0.03^2} = 0.66 \pm 0.113$$

Clean Fit (2021 update)

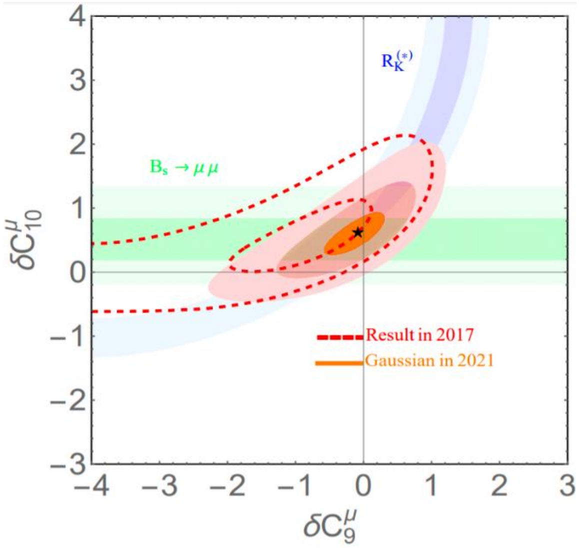
Data (7): LHCb (4) + Belle(3)

R_K bin[1,6] GeV^2 bin[1.1,6] GeV^2

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

bin[1.1,6] GeV^2

$R(B_s \to \mu^+\mu^-)$



$\chi^2_{\rm min,SM} = 31.32$ **p-value in SM : 5.4×10^{-5}**

Coeff.	best fit	$\chi^2_{\rm min}$	p-value	Pull$_{\rm SM}$	1σ range	3σ range	ρ
δC_9^{μ}	-0.82	14.70 [6 dof]	0.02	4.08	$[-1.06, -0.60]$	$[-1.60, -0.20]$	–
δC_{10}^{μ}	0.65	6.52 [6 dof]	0.37	4.98	$[0.52, 0.80]$	$[0.25, 1.11]$	–
δC_L^{μ}	-0.40	7.36 [6 dof]	0.29	4.89	$[-0.48, -0.31]$	$[-0.66, -0.15]$	–
$(\delta C_9^{\mu}, \delta C_{10}^{\mu})$	$(-0.11, 0.59)$	6.38 [5 dof]	0.27	4.62	$\delta C_9^{\mu} \in [-0.41, 0.17]$	$\delta C_{10}^{\mu} \in [0.38, 0.81]$	0.762

- **Compared to the 2017 results, the significance of deviation from the SM has increased up to ~ 5σ .**
- **Scenarios with pure axial currents provide the best description of the data.**

Global Fit (2021 update)

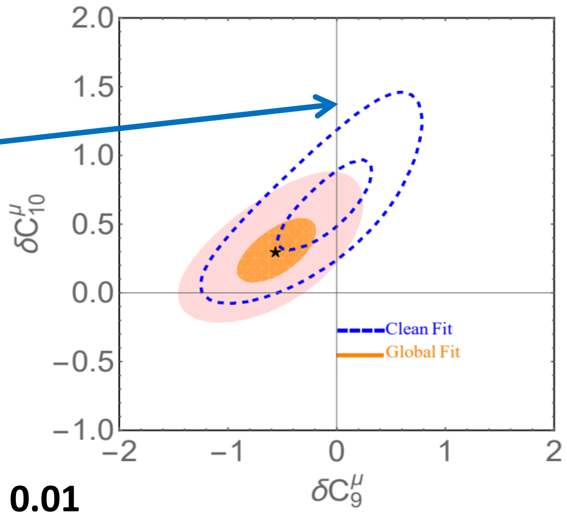
Data (94)

R_K bin[1,6] GeV^2

R_{K*} bin[0.045,1.1] GeV^2
bin[1.1,6] GeV^2

$R(B_s \to \mu^+\mu^-)$ $BR(B \to K^*\gamma)$

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



$\chi^2_{\text{min,SM}} = 126.88$ **p-value in SM : 0.01**

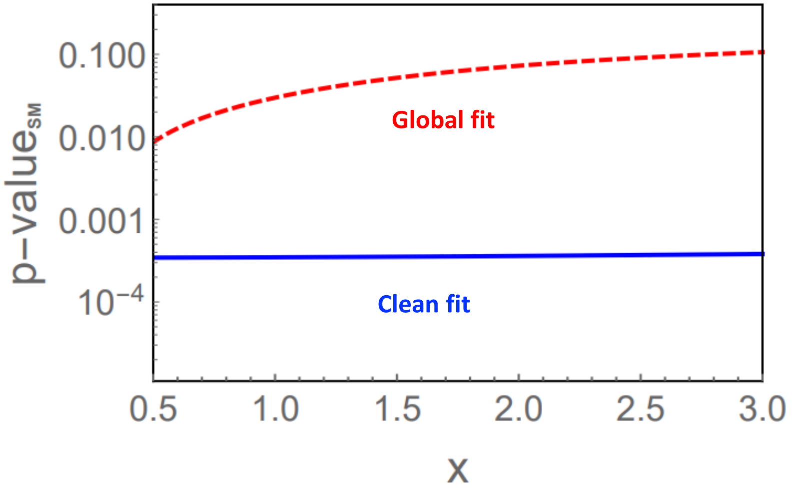
Coeff.	best fit	χ^2_{min}	p-value	Pull_{SM}	1σ range	3σ range	ρ
δC_9^{μ}	-0.85	106.32 [93 dof]	0.16	4.53	$[-1.06, -0.64]$	$[-1.50, -0.27]$	–
δC_{10}^{μ}	0.54	107.82 [93 dof]	0.14	4.37	$[0.41, 0.67]$	$[0.16, 0.94]$	–
δC_L^{μ}	-0.39	102.81 [93 dof]	0.23	4.91	$[-0.48, -0.31]$	$[-0.65, -0.15]$	–
$(\delta C_9^{\mu}, \delta C_{10}^{\mu})$	$(-0.56, 0.30)$	102.36 [92 dof]	0.22	4.58	$\delta C_9^{\mu} \in [-0.79, -0.31]$	$\delta C_{10}^{\mu} \in [0.15, 0.49]$	0.317

- **Compared to the clean fit, δC_9 (δC_{10}) is far away from (close to) the SM.**
- **Compared to the 2017 results, the value of δC_9 and δC_{10} are better constrained.**

Robustness of fits with respect to hadronic uncertainties

- 27 hadronic parameters in low q^2: PRD93(1):014028,2016, JHEP, 05:043, 2013

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)	$h_-\lvert_{c\bar{c}}(\lvert a\rvert_{\max}), h_-\lvert_{c\bar{c}}(\lvert b\rvert_{\max}), \phi_-\lvert_{c\bar{c}}, h_+\lvert_{c\bar{c}}(\lvert a\rvert_{\max}), h_+\lvert_{c\bar{c}}(\lvert b\rvert_{\max}), \phi_+\lvert_{c\bar{c}}, h_0\lvert_{c\bar{c}}, \phi_0\lvert_{c\bar{c}}$



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.

- **Global fit result is sensitive to hadronic uncertainties. Therefore, hadronic uncertainties should be further studied in the future**

Summary 1

- Only operators O_9, O_{10} can explain the experiment data
- We obtain conservative parameter space of new physics
- Significance of the SM exclusion is ~5σ
- Global fit result is sensitive to hadronic uncertainties which should be future studied in the future

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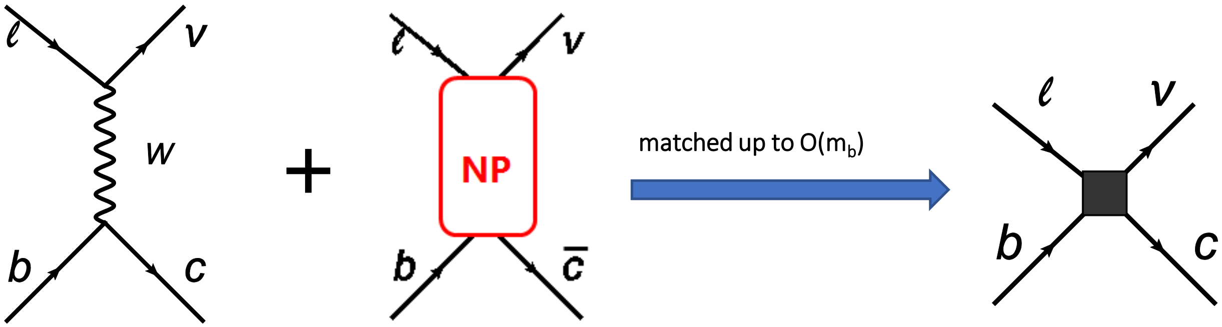
Charged-current (CC) $b \to c\,\tau\,\nu$ decays

□ Low energy effective Lagrangian

Jorge Martin Camalich et al, PRD94.094021

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

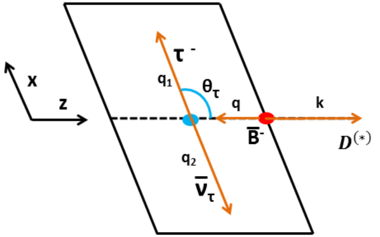


- ➢ **Wilson coefficients ϵ stand for NP contributions.**
- ➢ **Right-handed vector cannot explain LUV** 1505.05164**. Consider**

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

Hadronic matrix elements in the *b→c τ ν amplitudes*

$$
\begin{aligned}
\langle D(k)|\bar c\gamma^\mu b|\bar B(p)\rangle &= (p+k)^\mu f_+(q^2) + (p-k)^\mu \frac{m_B^2-m_D^2}{q^2}(f_0(q^2)-f_+(q^2)),\\
\langle D(k)|\bar c b|\bar B(p)\rangle &= \frac{m_B^2-m_D^2}{m_b-m_c} f_0(q^2),\\
\langle D(k)|\bar c\sigma^{\mu\nu} b|\bar B(p)\rangle &= \frac{2if_T(q^2)}{m_B+m_D}(k^\mu p^\nu - p^\mu k^\nu),\\
\langle D(k)|\bar c\sigma^{\mu\nu}\gamma_5 b|\bar B(p)\rangle &= \frac{2f_T(q^2)}{m_B+m_D}\epsilon^{\mu\nu\alpha\beta}k_\alpha p_\beta,\\
\langle V(k,\epsilon)|\bar c\gamma^\mu b|P(p)\rangle &= \frac{2iV(q^2)}{m_P+m_V}\epsilon^{\mu\nu\alpha\beta}\epsilon^*_\nu k_\alpha p_\beta,\\
\langle V(k,\epsilon)|\bar c\gamma_5 b|P(p)\rangle &= -\frac{2m_V}{m_b+m_c}A_0(q^2)\epsilon^*\cdot q,\\
\langle V(k,\epsilon)|\bar c\gamma^\mu\gamma_5 b|P(p)\rangle &= 2m_V A_0(q^2)\frac{\epsilon^*\cdot q}{q^2}q^\mu + (m_P+m_V)A_1(q^2)\left(\epsilon^{*\mu} - \frac{\epsilon^*\cdot q}{q^2}q^\mu\right)\\
&\quad -A_2(q^2)\frac{\epsilon^*\cdot q}{m_P+m_V}\left((p+k)^\mu - \frac{m_P^2-m_V^2}{q^2}q^\mu\right)\\
\langle V(k,\epsilon)|\bar c\sigma^{\mu\nu} b|P(p)\rangle &= \frac{\epsilon^*\cdot q}{(m_P+m_V)^2}T_0(q^2)\epsilon^{\mu\nu\alpha\beta}p_\alpha k_\beta\\
&\quad +T_1(q^2)\epsilon^{\mu\nu\alpha\beta}p_\alpha\epsilon^*_\beta + T_2(q^2)\epsilon^{\mu\nu\alpha\beta}k_\alpha\epsilon^*_\beta,\\
\langle V(k,\epsilon)|\bar c\sigma^{\mu\nu}\gamma_5 b|P(p)\rangle &= \frac{i\epsilon^*\cdot q}{(m_P+m_V)^2}T_0(q^2)(p^\mu k^\nu - k^\mu p^\nu)\\
&\quad +iT_1(q^2)(p^\mu\epsilon^{*\nu} - \epsilon^{*\mu}p^\nu) + iT_2(q^2)(k^\mu\epsilon^{*\nu} - \epsilon^{*\mu}k^\nu), \qquad (2
\end{aligned}
$$



- **Decay constant:**
  - $B_c \to \tau\,\nu$: LQCD HPQCD: PRD91.114509

- **Form factors :**
  - $B \to D^{(*)}\tau\,\nu$: HQET(LO) & fitting to data & LQCD Jorge Martin Camalich et al, PRD94.094021
  - $B_c \to J/\psi\,\tau\,\nu$: covariant light-front quark model (LFQM) Cai-Dian Lv et al, PRD79.054012

Interesting observables for $b \to c\, \tau\, \nu$ 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)

□ Further observables

τ polarization asymmetry $P_\tau^{D^*}$ and the longitudinal polarization of D ($F_L^{D^*}$) in the $\mathbf{B}\to D^*\, \tau\, \nu$ decay:

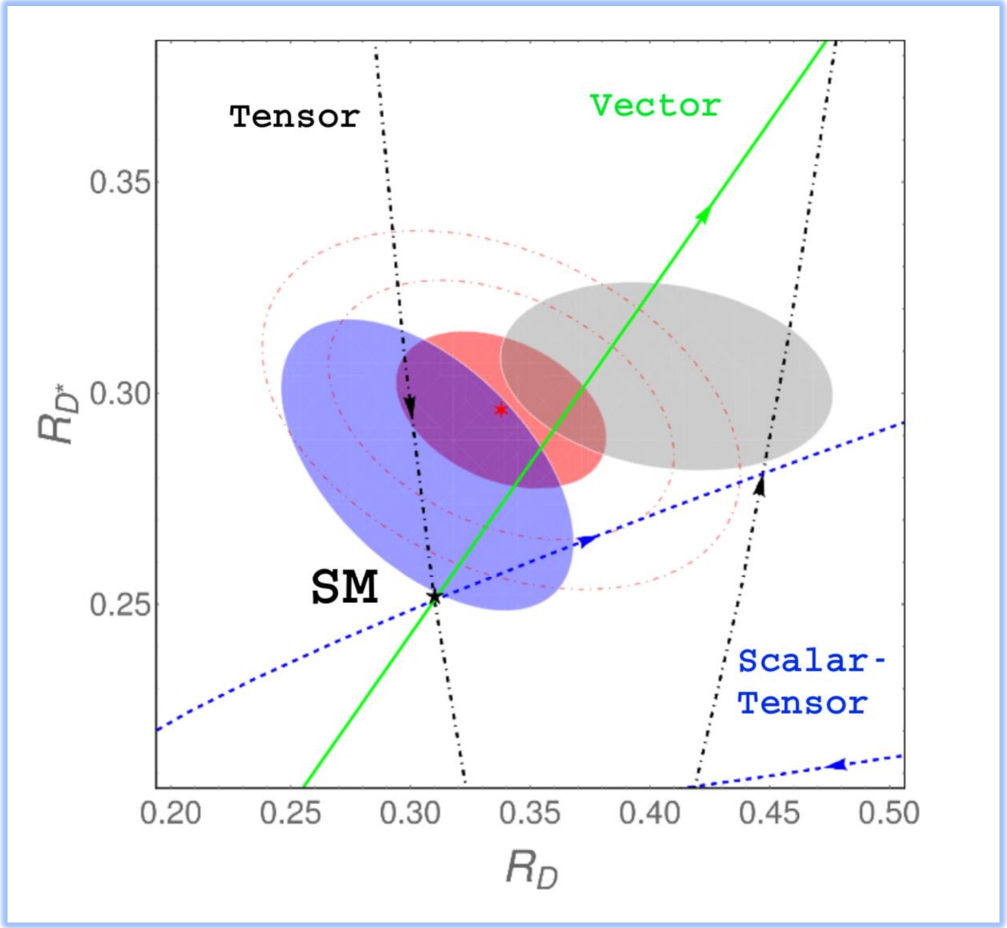
$$P_\tau^{D^*} = \frac{\Gamma(\lambda_\tau = \frac{1}{2}) - \Gamma(\lambda_\tau = -\frac{1}{2})}{\Gamma(\lambda_\tau = \frac{1}{2}) + \Gamma(\lambda_\tau = -\frac{1}{2})},$$

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

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

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

Fits to R_D and R_{D^*} only

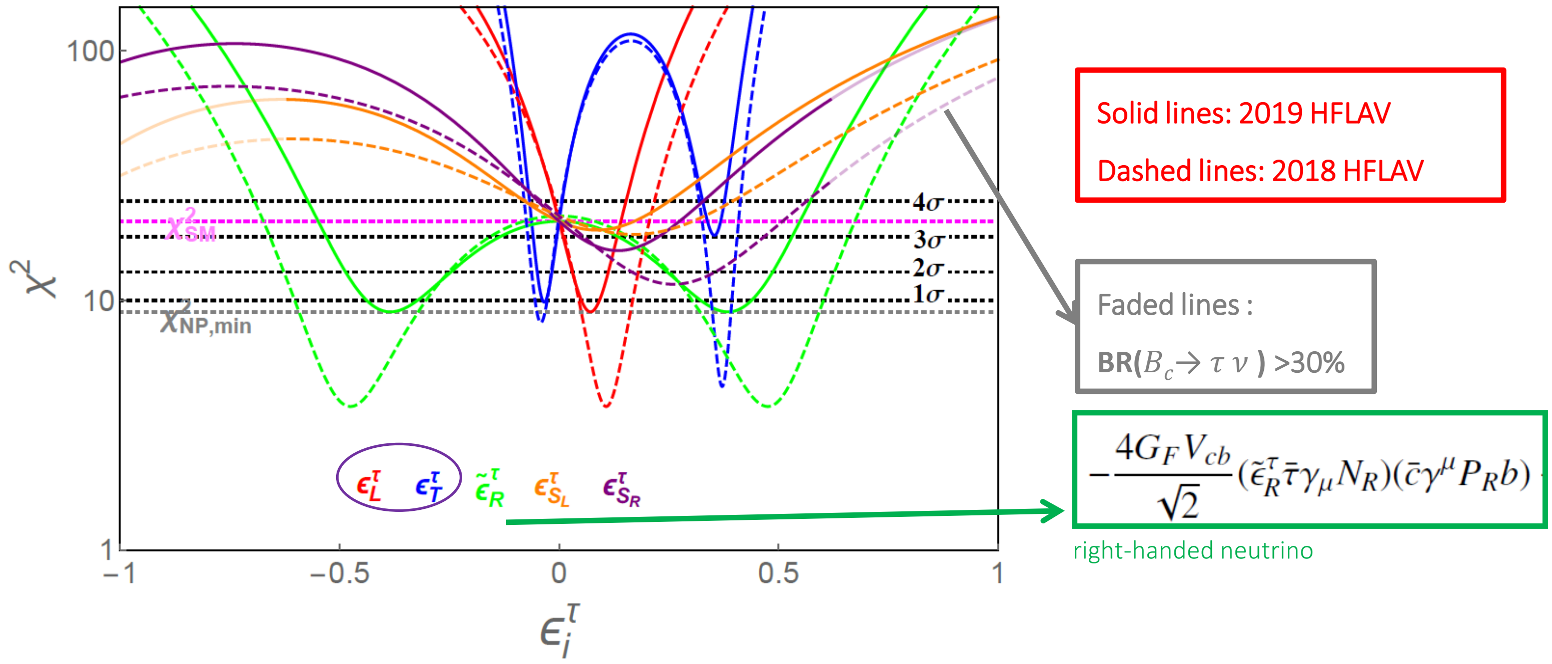


- New Belle measurement with semileptonic tag
- 2018HFLAV
- The combination of the above two

- Vector: ϵ_L^τ or $\tilde{\epsilon}_R^\tau$
- Scalar-Tensor $\epsilon_{SL}^\tau = -4\epsilon_T^\tau$
- Tensor ϵ_T^τ

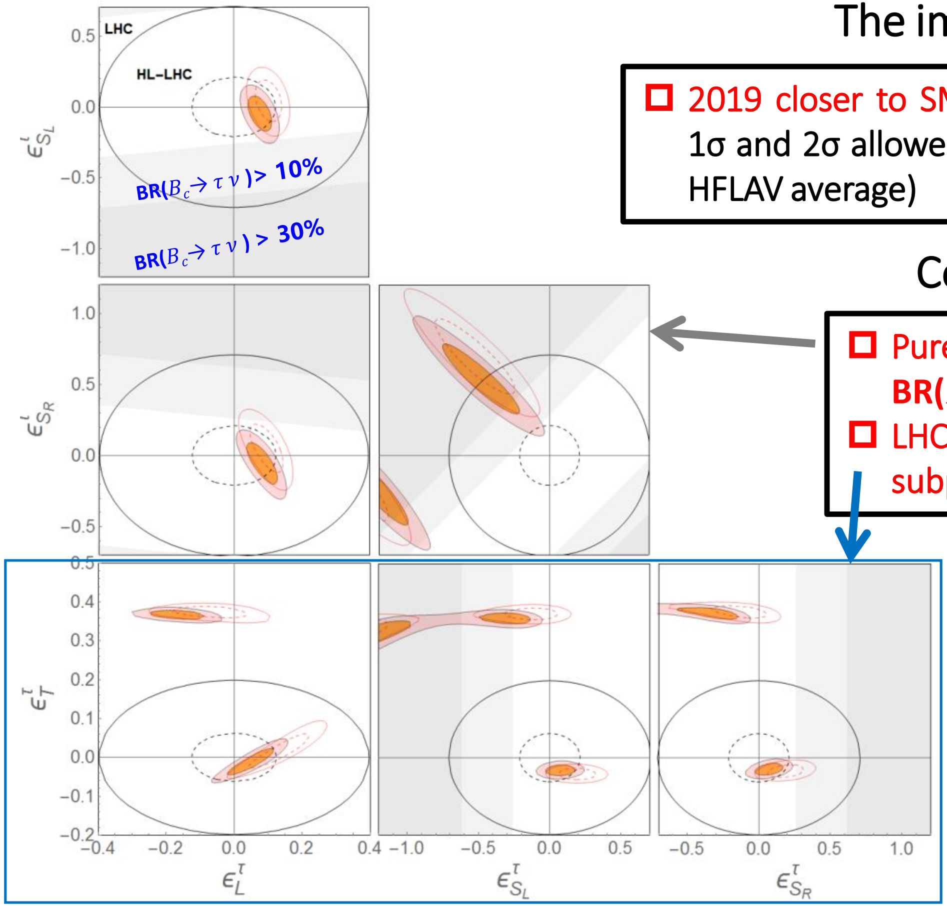
- 2018 HFLAV, only vector and scalar-tensor works
- After Belle, tensor also works

Fits to R_D and R_{D^*} only



- **Dotted lines show that the significance of deviation from SM is more than 3σ.**
- **The (left)vector and tensor operators give better fits 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 : six 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($B_c \to \tau\,\nu$)** —subplot(2,2).
- LHC data exclude large region of the parameter space—subplots (3,123)

- Empty black solid (dashed) ellipses indicate the 2σ upper bounds from the LHC data (HL-LHC projections) on pp → τ_hX+MET-- **PRL122.131803**
- Note that 30% and 10% exlusions are from the constraints of Bc lifetime and LEP1 data, respective--**PRD96.075011; PRL118.081802**

Fits to R_D and R_{D^*} only

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

	Best fit	χ^2_{min}	p-value	Pull_{SM}	1σ range
ϵ_L^τ	0.07	9.00	0.34	3.43	(0.05, 0.09)
ϵ_T^τ	−0.03	9.85	0.28	3.30	(−0.04, −0.02)
$\epsilon_{S_L}^\tau$	0.09	19.14	1.41×10^{-2}	1.27	(0.02, 0.15)
$\epsilon_{S_R}^\tau$	0.13	15.84	4.47×10^{-2}	2.22	(0.07, 0.20)
$\tilde{\epsilon}_R^\tau$	0.38	9.00	0.34	3.43	(0.32, 0.44)
$\epsilon_{S_L}^\tau = -4\epsilon_T^\tau$	0.09	12.25	0.14	2.92	(0.06, 0.12)
$(\epsilon_{S_L}^\tau, \epsilon_T^\tau)$	(0.07, −0.03)	8.7	0.27	3.03	$\epsilon_{S_L}^\tau \in (0.00, 0.14)$ $\epsilon_T^\tau \in (-0.04, -0.02)$
$(\epsilon_{S_L}^\tau, \epsilon_{S_R}^\tau)$	(−0.47, 0.53)	8.7	0.27	3.03	$\epsilon_{S_L}^\tau \in (-0.66, -0.30)$ $\epsilon_{S_R}^\tau \in (0.37, 0.69)$
$(\epsilon_{S_R}^\tau, \epsilon_T^\tau)$	(0.07, −0.03)	8.7	0.27	3.03	$\epsilon_{S_R}^\tau \in (0.00, 0.14)$ $\epsilon_T^\tau \in (-0.04, -0.02)$
$(\epsilon_L^\tau, \epsilon_T^\tau)$	(0.05, −0.01)	8.7	0.27	3.03	$\epsilon_L^\tau \in (0.00, 0.09)$ $\epsilon_T^\tau \in (-0.03, 0.01)$
$(\epsilon_L^\tau, \epsilon_{S_L}^\tau)$	(0.08, −0.04)	8.7	0.27	3.03	$\epsilon_L^\tau \in (0.05, 0.10)$ $\epsilon_{S_L}^\tau \in (-0.13, 0.04)$
$(\epsilon_L^\tau, \epsilon_{S_R}^\tau)$	(0.08, −0.05)	8.7	0.27	3.03	$\epsilon_L^\tau \in (0.05, 0.11)$ $\epsilon_{S_R}^\tau \in (-0.15, 0.04)$

- **Vectors are the best. Scalars are ruled out**
- **The significance of deviation from SM is more than 3σ**

Testing 3 NP models： colorless scalar, vector, or leptoquarks

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	**1**	**2**	+1/2	✗	✗	✓	✓	✗
W_L'	1	**1**	**3**	0	✓	✗	✗	✗	✗
W_R'	1	**1**	**1**	+1	✗	✓	✗	✗	✗
S_1	0	$\bar{\mathbf{3}}$	**1**	+1/3	✓	✓	✗	✓	✓
S_3	0	$\bar{\mathbf{3}}$	**3**	+1/3	✓	✓	✗	✗	✗
R_2	0	**3**	**2**	+7/6	✓	✓	✗	✓	✓
U_1	1	**3**	**1**	+2/3	✓	✓	✓	✗	✗
U_3	1	**3**	**3**	+2/3	✓	✓	✗	✗	✗
V_2	1	$\bar{\mathbf{3}}$	**2**	+5/6	✗	✗	✓	✗	✗

H → In conflict with BR($B_c \to \tau\nu$) 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($B_c \to \tau\nu$) data

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

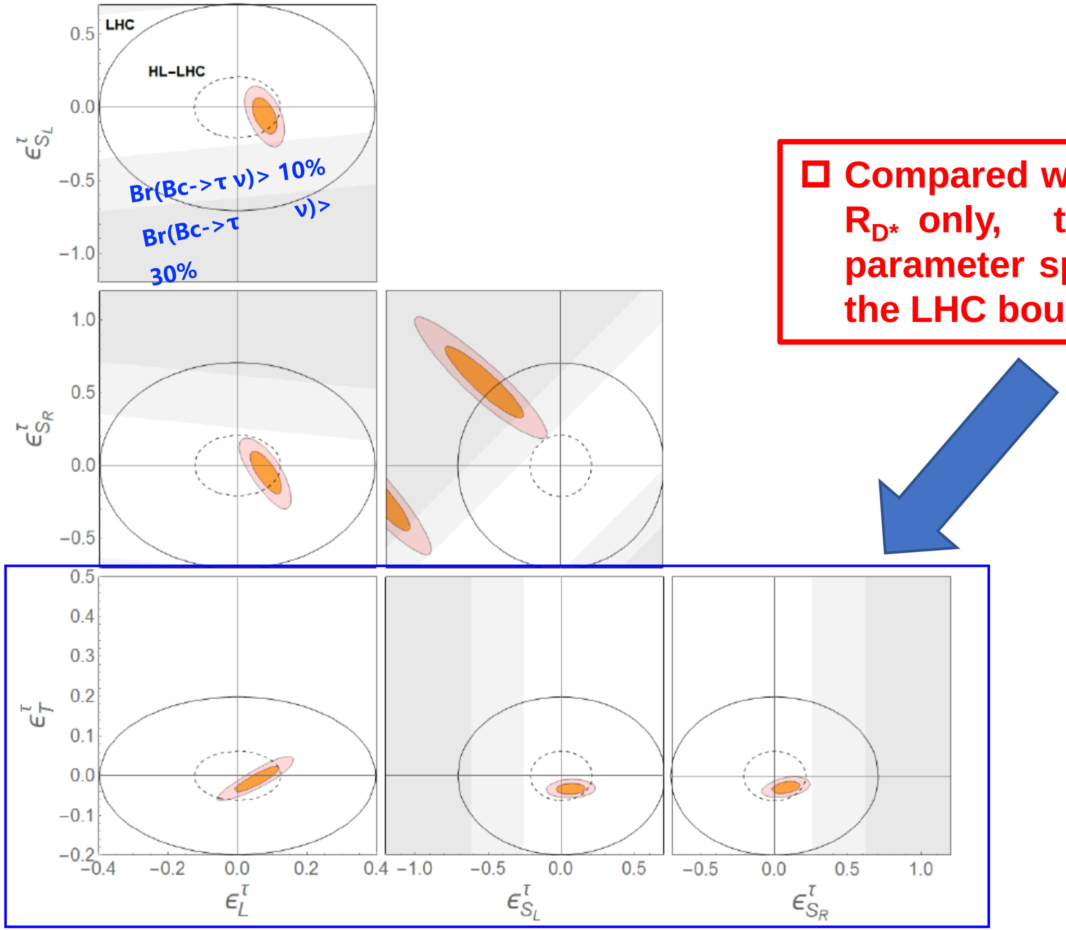
➢ **Scalar LQ**

$$m_{S_1} \approx m_{S_3} \approx m_{R_2} \approx 2.3\ \mathrm{TeV}$$

➢ **Vector LQ**

$$m_{U_1} \approx m_{U_3} \approx 3.3\ \mathrm{TeV}$$

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

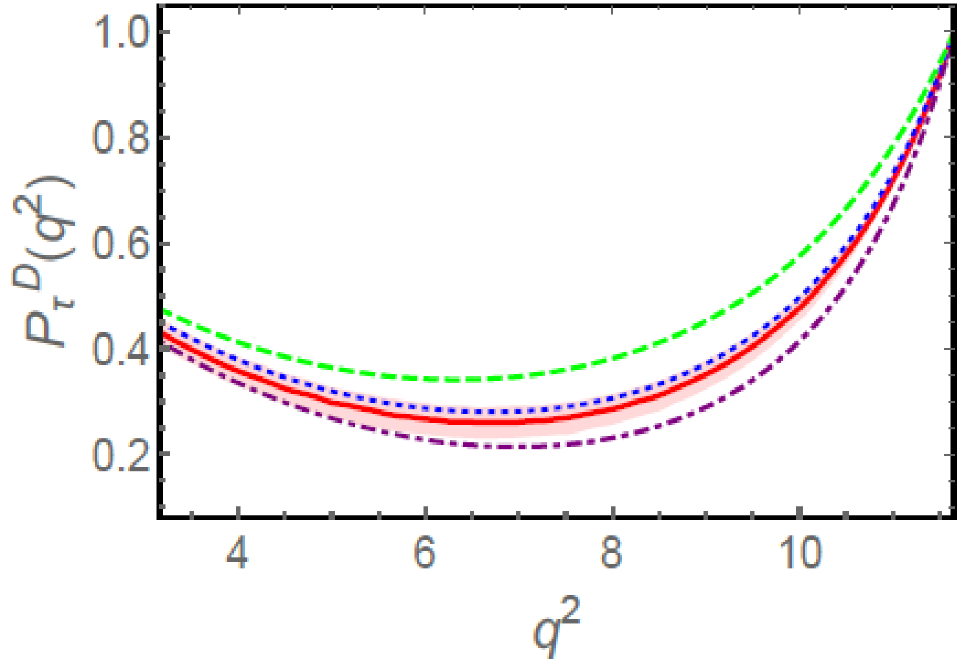
$\chi^2_{min,SM} = 26.53$

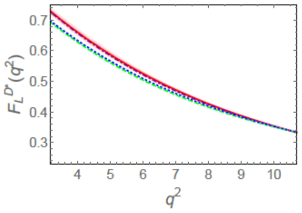
p-value in SM : 9.02×10^{-3}

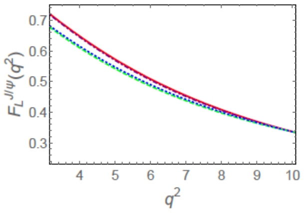
	Best fit	$\chi^2_{\rm min}$	p-value	Pull$_{\rm SM}$	1σ range
ϵ_L^τ	0.07	14.56	0.20	3.46	$(0.05, 0.09)$
ϵ_T^τ	-0.03	15.70	0.15	3.29	$(-0.04, -0.02)$
$\epsilon_{S_L}^\tau$	0.08	25.23	8.44×10^{-3}	1.14	$(0.01, 0.14)$
$\epsilon_{S_R}^\tau$	0.14	21.24	3.10×10^{-2}	2.30	$(0.08, 0.20)$
$(\epsilon_{S_L}^\tau, \epsilon_T^\tau)$	$(0.07, -0.03)$	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	$\epsilon_L^\tau \in (0.05, 0.11)$ $\epsilon_{S_R}^\tau \in (-0.14, 0.05)$

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

Possibility of discriminating different NP structures: Only fitting to R_D and R_{D^*}







A measurement of the tau polarization in the decay mode $B \rightarrow D\, \tau\, \nu$ 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.

Summary 2

- Significance of the SM exclusion is more than 3σ.

- BR($B_c \to \tau\nu$), the LHC monotau and $F_L^{D^*}$ can exclude large regions of the parameter space.

- We tested some NP models in which LQs can explain the data.

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

OUTLINE

- ❑ Background
- ❑ Theoretical framework
- ❑ Results and discussions
  - ➢ Flavor-changing-neutral-current(FCNC) $b \to s\, l\, l$ decays
  - ➢ Charged-current(CC) $b \to c\, \tau\, \nu$ *decays*
- ❑ **Summary and outlook**

Summary and Outlook

- Significance of the SM exclusion for $b \to s\, l\, l$ transition is ~5σ

- Significance of the SM exclusion for $b \to c\, \tau\, \nu$ transition is more than 3σ

- We also test some NP models, only some LQs can explain the current data

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

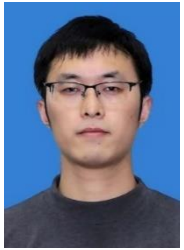
Summary and Outlook

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 assess uncertainties.**
  - **Form factors and charm contributions for $b \to s\, l\, l$ transition**
  - **Form factors for $b \to c\, \tau\, \nu$ transition**
- **Meantime, it is also important to continue to find or construct new observables which are very sensitive to new physics.**

北京航空航天大學
BEIHANG UNIVERSITY

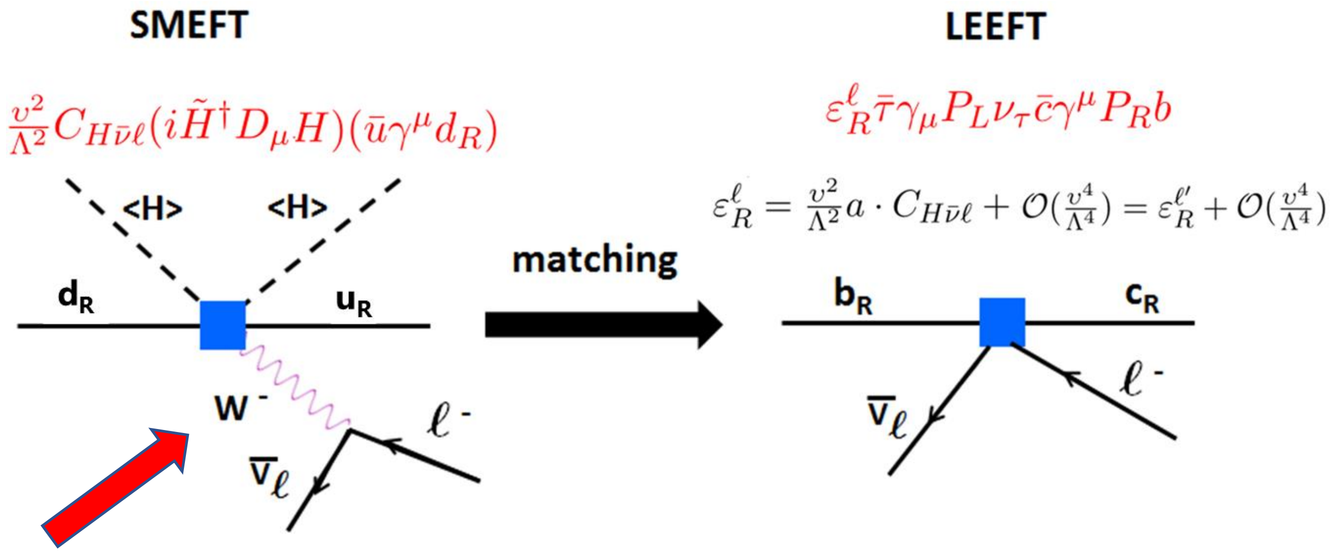
Thanks for your attention!



Rui-Xiang Shi Beihang U.	Jorge Martin Camalich La Laguna U.	Sebastian Jäger Sussex U.	Benjamín Grinstein UCSD	Shuang-Yi Li Beihang U.

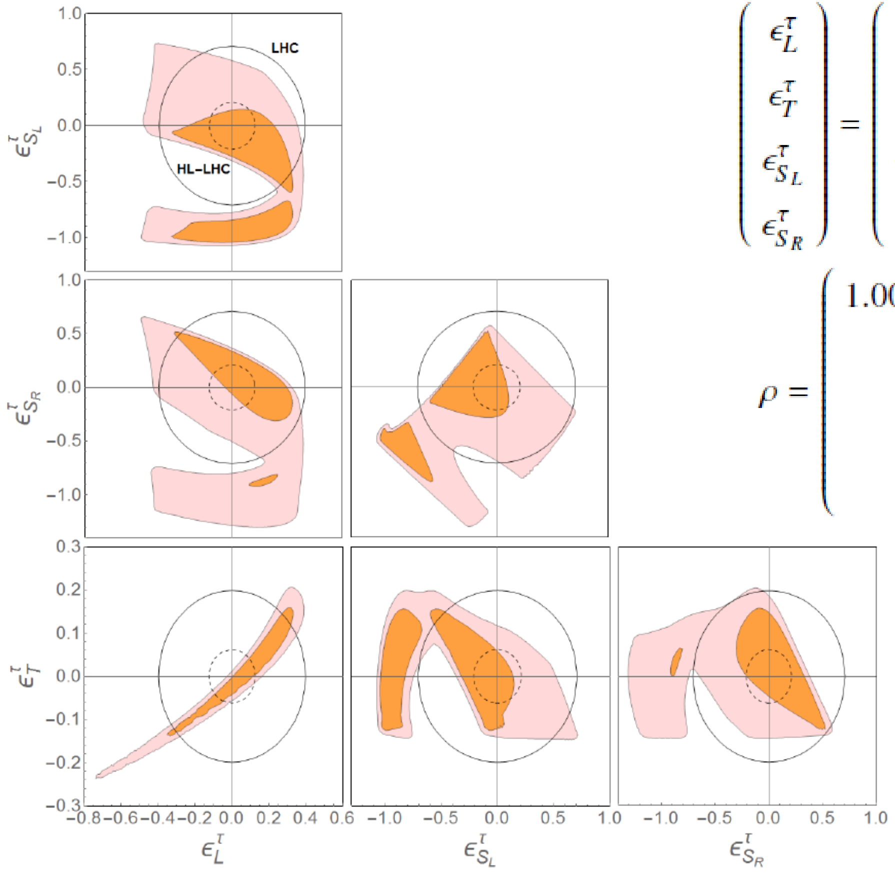
Backup slides

Right-handed vector operator cannot explain LUV



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.

4D global fit for $b \to c\,\tau\,\nu$ decays



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

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

p-value = 0.12
Pull_{SM} = 2.64