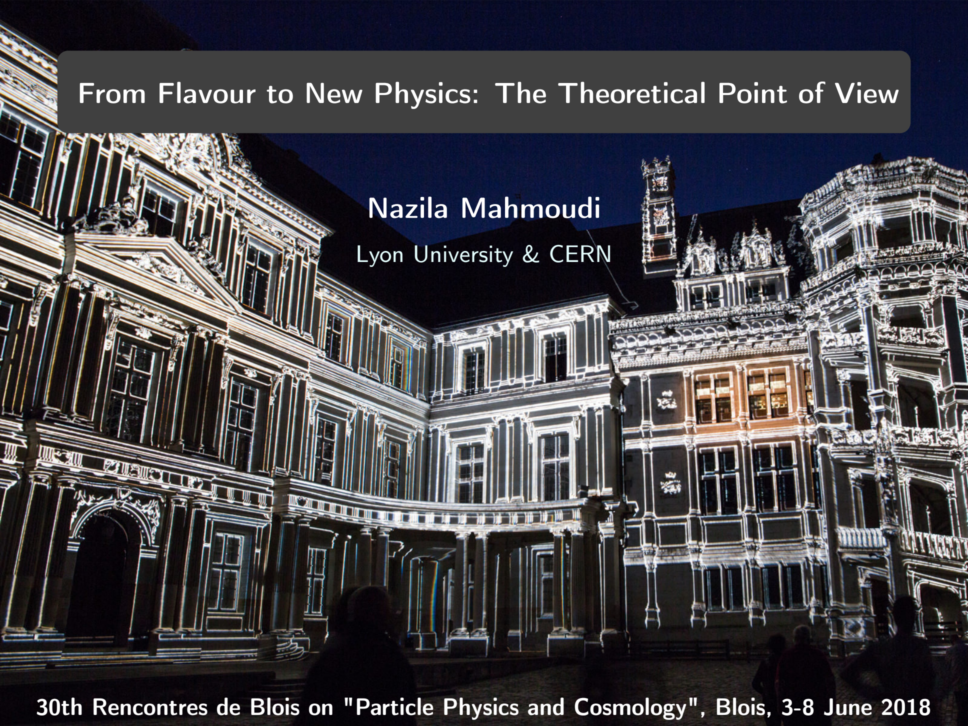
From Flavour to New Physics: The Theoretical Point of View

Nazila Mahmoudi

Lyon University & CERN



30th Rencontres de Blois on "Particle Physics and Cosmology", Blois, 3-8 June 2018

- Tests of the Standard Model paradigms and parameters
- Probing New Physics at the intensity frontier

Two main paths to New Physics

- Test **CP violation**
- Study **Rare decays**

Focus of this talk: recent anomalies in rare decays

How to make theoretical sense of the data?

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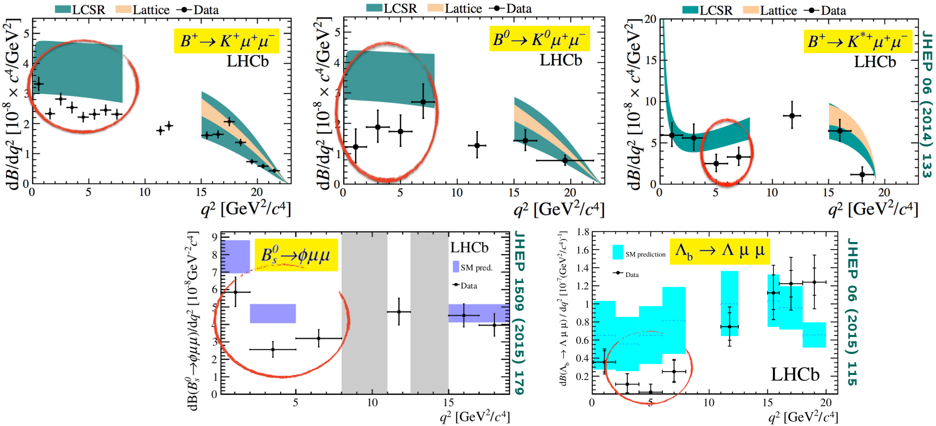
Exclusive $b \to s$ measurements with muons in the final state seem to show a consistent deviation pattern with the SM predictions



- deviations with the SM predictions between 1 and 3.5 σ
- general trend: EXP < SM in low q^2
- ... but the branching ratios have very large theory uncertainties!

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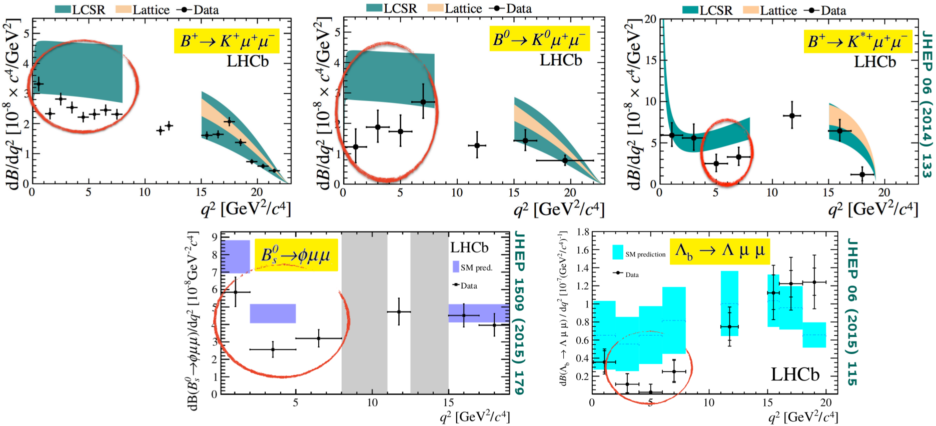

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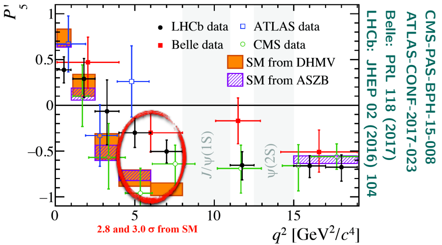
Let's look at cleaner observables:

Prime example: P_5' long standing anomaly

- 2013 ($1\ \mathrm{fb}^{-1}$): disagreement with the SM for P_2 and P_5' (PRL 111, 191801 (2013))
- March 2015 ($3\ \mathrm{fb}^{-1}$): confirmation of the deviations (LHCb-CONF-2015-002)
- Dec. 2015: 2 analysis methods, both show the deviations (JHEP 1602, 104 (2016))



Also measured by ATLAS, CMS and Belle

- tension with the SM at 2-3σ
- deviations are again in muons and at low q^2
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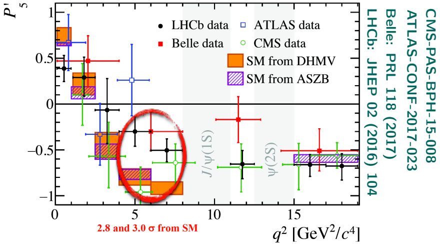

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Let's look at extremely clean observables!

$R_K = BR(B^+ \to K^+ \mu^+ \mu^-)/BR(B^+ \to K^+ e^+ e^-)$

$R_{K^*} = BR(B^0 \to K^{*0} \mu^+ \mu^-)/BR(B^0 \to K^{*0} e^+ e^-)$

$$R_K^{\rm exp} = 0.745^{+0.090}_{-0.074}({\rm stat}) \pm 0.036({\rm syst})$$

$$R_K^{\rm SM} = 1.0006 \pm 0.0004$$

$$R_{K^*}^{\rm exp,bin1} = 0.660^{+0.110}_{-0.070}({\rm stat}) \pm 0.024({\rm syst})$$

$$R_{K^*}^{\rm exp,bin2} = 0.685^{+0.113}_{-0.069}({\rm stat}) \pm 0.047({\rm syst})$$

$$R_{K^*}^{\rm SM,bin1} = 0.906 \pm 0.028$$

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Bordone, Isidori, Pattori, EPJC 76 (2016) 8, 440

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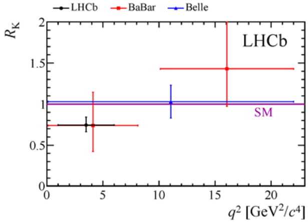

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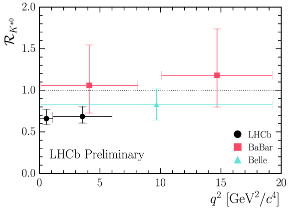

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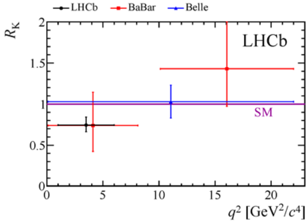

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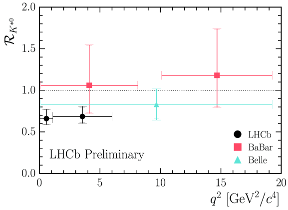

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Can we easily make theoretical sense of these data?

Yes!

Theoretical framework: Effective Hamiltonian

separation between low and high energies using Operator Product Expansion

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) \mathcal{O}_i(\mu)$$

$$\mathcal{O}_7 \propto (\bar{s}\sigma^{\mu\nu} P_R) F^a_{\mu\nu}$$
$$\mathcal{O}_9 \propto (\bar{s}\gamma^{\mu} b_L)(\bar{\ell}\gamma_{\mu}\ell)$$
$$\mathcal{O}_{10} \propto (\bar{s}\gamma^{\mu} b_L)(\bar{\ell}\gamma_{\mu}\gamma_5\ell)$$

courtesy of J. Matias

In the SM:

$$C_7 = -0.29 \qquad C_9 = 4.20 \qquad C_{10} = -4.01$$

New physics:

- Corrections to the Wilson coefficients: $C_i \to C_i^{\rm SM} + \delta C_i^{\rm NP}$
- Additional operators: Chirally flipped ($\mathcal{O}'_i$), (pseudo)scalar ($\mathcal{O}_S$ and $\mathcal{O}_P$)

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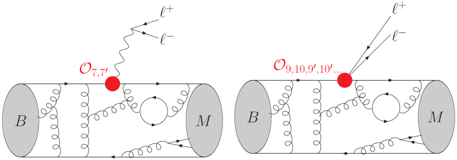

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Different observables have different sensitivities to the Wilson coefficients!

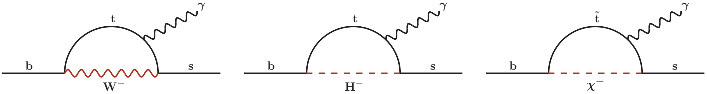
decay	obs	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$
$B \to X_s \gamma$	BR	X		
$B \to K^* \gamma$	BR, $\mathrm{A_I}$	X		
$B \to K \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$	X	X	X
$B \to K^* \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$, angular obs.	X	X	X
$B_s \to \phi \ell^+ \ell^-$	$\mathrm{dBR}/\mathrm{d}q^2$, angular obs.	X	X	X
$B_s \to \mu^+ \mu^-$	BR			X

The only reason C_9 is the main player to explain the anomalies is that C_7 and C_{10} are severely constrained!

$$\delta \langle P_5' \rangle_{[4.3,8.68]} \simeq -0.52\,\delta C_7 \quad -0.03\,\delta C_8 \quad -0.08\,\delta C_9 \quad -0.03\,\delta C_{10}$$

Inclusive branching ratio of $B \to X_s\gamma$

Contributing loops:



Main operator: $\mathcal{O}_7$
but higher order contributions from $\mathcal{O}_1$, ..., $\mathcal{O}_8$

- Standard OPE for inclusive decays
- Very precise theory prediction (at NNLO)

Experimental value (HFAG 2017): $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.32 \pm 0.15) \times 10^{-4}$

SM prediction: $\mathrm{BR}(\bar{B} \to X_s\gamma) = (3.34 \pm 0.22) \times 10^{-4}$

SuperIso v4.0
M. Misiak et al., Phys. Rev. Lett. 98 (2007) 022002
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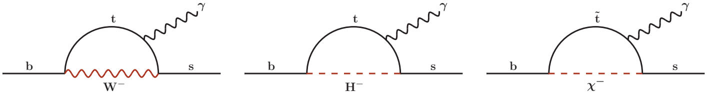

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Relevant operators:

$$\mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5\ell)$$
$$\mathcal{O}_S = \frac{e^2}{16\pi^2}(\bar{s}_L^\alpha b_R^\alpha)(\bar{\ell}\,\ell)$$
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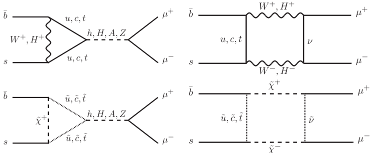

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2\alpha^2}{64\pi^3} f_{B_s}^2 \tau_{B_s} m_{B_s}^3 |V_{tb}V_{ts}^*|^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}}$$
$$\times \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left|C_S - C_S'\right|^2 + \left|(C_P - C_P') + 2\,(C_{10} - C_{10}')\,\frac{m_\mu}{m_{B_s}}\right|^2 \right\}$$

Largest contributions in SM from a Z penguin top loop (75%) and a W box diagram (24%)

Experimental measurement:

HFAG 2017 combination: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.1 \pm 0.7) \times 10^{-9}$

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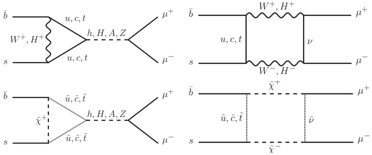

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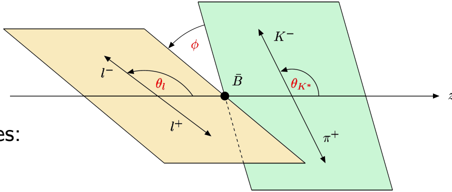

Angular distributions

The full angular distribution of the decay $\bar{B}^0 \to \bar{K}^{*0} \ell^+ \ell^-$ ($\bar{K}^{*0} \to K^- \pi^+$) is completely described by four independent kinematic variables: q^2 (dilepton invariant mass squared), θ_ℓ, θ_{K^*}, ϕ

Differential decay distribution:

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

$J(q^2, \theta_\ell, \theta_{K^*}, \phi) = \sum_i J_i(q^2)\, f_i(\theta_\ell, \theta_{K^*}, \phi)$

↘ angular coefficients J_{1-9}

↘ functions of the spin amplitudes A_0, $A_\parallel$, $A_\perp$, A_t, and A_S

Spin amplitudes: functions of Wilson coefficients and form factors

Main operators:

$$\mathcal{O}_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu\gamma_5 \ell)$$
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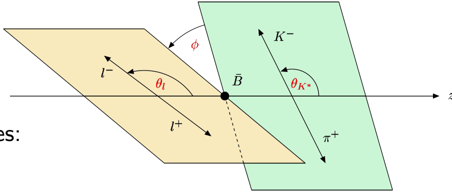

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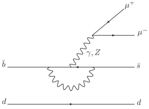

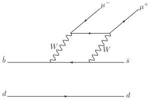

Optimised observables: form factor uncertainties cancel at leading order

$$\langle P_1 \rangle_{\rm bin} = \frac{1}{2} \frac{\int_{\rm bin} dq^2 [J_3 + \bar{J}_3]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\rm bin} = \frac{1}{8} \frac{\int_{\rm bin} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}]}$$

$$\langle P_4' \rangle_{\rm bin} = \frac{1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_4 + \bar{J}_4] \qquad \langle P_5' \rangle_{\rm bin} = \frac{1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_5 + \bar{J}_5]$$

$$\langle P_6' \rangle_{\rm bin} = \frac{-1}{2\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_7 + \bar{J}_7] \qquad \langle P_8' \rangle_{\rm bin} = \frac{-1}{\mathcal{N}'_{\rm bin}} \int_{\rm bin} dq^2 [J_8 + \bar{J}_8]$$

with

$$\mathcal{N}'_{\rm bin} = \sqrt{-\int_{\rm bin} dq^2 [J_{2s} + \bar{J}_{2s}] \int_{\rm bin} dq^2 [J_{2c} + \bar{J}_{2c}]}$$

+ CP violating clean observables and other combinations

U. Egede et al., JHEP 0811 (2008) 032, JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

Or alternatively:

$$S_i = \frac{J_{i(s,c)} + \bar{J}_{i(s,c)}}{\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}} \,, \qquad P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1-F_L)}}$$

Issue of the hadronic power corrections

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=7,9,10} C_i^{(\prime)} O_i^{(\prime)} \Big]$$

$\langle \bar{K}^* | \mathcal{H}_{\rm eff}^{\rm sl} | \bar{B} \rangle$: $B \to K^*$ form factors V, $A_{0,1,2}$, $T_{1,2,3}$

Transversity amplitudes:

$$A_\perp^{L,R} \simeq N_\perp \left\{ (C_9^+ \mp C_{10}^+) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7^+ T_1(q^2) \right\}$$

$$A_\parallel^{L,R} \simeq N_\parallel \left\{ (C_9^- \mp C_{10}^-) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7^- T_2(q^2) \right\}$$

$$A_0^{L,R} \simeq N_0 \Big\{ (C_9^- \mp C_{10}^-) \left[(\ldots) A_1(q^2) + (\ldots) A_2(q^2) \right] + 2m_b C_7^- \left[(\ldots) T_2(q^2) + (\ldots) T_3(q^2) \right] \Big\}$$

$$A_S = N_S (C_S - C_S') A_0(q^2)$$

$$\left(C_i^\pm \equiv C_i \pm C_i' \right)$$

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1\ldots6} C_i O_i + C_8 O_8 \right]$$

$$\mathcal{A}_\lambda^{\rm (had)} = -i \frac{e^2}{q^2} \int d^4x\, e^{-iq\cdot x} \langle \ell^+ \ell^- | j_\mu^{\rm em,lept}(x) | 0 \rangle \times \int d^4y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{ j^{{\rm em,had},\mu}(y) \mathcal{H}_{\rm eff}^{\rm had}(0) \} | \bar{B} \rangle$$

$$\equiv \frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}\Big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\Big)}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]$$

Issue of the hadronic power corrections

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=7,9,10} C_i^{(\prime)} O_i^{(\prime)} \Big]$$

$\langle \bar{K}^* | \mathcal{H}_{\rm eff}^{\rm sl} | \bar{B} \rangle$: $B \to K^*$ **form factors** $V, A_{0,1,2}, T_{1,2,3}$

Transversity amplitudes:

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only guesstimates possible at present
but estimates possible with some work on the theory side

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$\rightarrow$ **unknown**

only guesstimates possible at present
but estimates possible with some work on the theory side

The significance of the anomalies depends on the assumptions made for the unknown power corrections!

This does not affect R_K and R_K^*

Many observables $\rightarrow$ **Global fits**

NP manifests itself in shifts of individual coefficients with respect to SM values:

$$C_i(\mu) = C_i^{\rm SM}(\mu) + \delta C_i$$

$\rightarrow$ Scans over the values of δC_i
$\rightarrow$ Calculation of flavour observables

Theoretical uncertainties and correlations

- Monte Carlo analysis
- variation of the "standard" input parameters: masses, scales, CKM, ...
- decay constants taken from the latest lattice results
- $B \to K^{(*)}$ and $B_s \to \phi$ form factors are obtained from the lattice+LCSR combinations (1411.3161, 1503.05534), including all the correlations
- Parameterisation of uncertainties from power corrections:

$$A_k \to A_k \left(1 + a_k \exp(i\phi_k) + \frac{q^2}{6\ {\rm GeV}^2} b_k \exp(i\theta_k)\right)$$

$|a_k|$ between 10 to 60%, $b_k \sim 2.5 a_k$
Low recoil: $b_k = 0$

$\Rightarrow$ Computation of a (theory + exp) correlation matrix

Global fits of the observables obtained by minimisation of

$$\chi^2 = \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right) \cdot \left(\Sigma_{\rm th} + \Sigma_{\rm exp}\right)^{-1} \cdot \left(\vec{O}^{\rm th} - \vec{O}^{\rm exp}\right)$$

$\left(\Sigma_{\rm th} + \Sigma_{\rm exp}\right)^{-1}$ is the inverse covariance matrix.

More than 100 observables relevant for leptonic and semileptonic decays:

- $\mathrm{BR}(B \to X_s\gamma)$
- $\mathrm{BR}(B \to X_d\gamma)$
- $\mathrm{BR}(B \to K^*\gamma)$
- $\Delta_0(B \to K^*\gamma)$
- $\mathrm{BR}^{\rm low}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm high}(B \to X_s\mu^+\mu^-)$
- $\mathrm{BR}^{\rm low}(B \to X_s e^+e^-)$
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- $\mathrm{BR}(B \to K^0\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^{*+}\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^+\mu^+\mu^-)$
- $\mathrm{BR}(B \to K^* e^+e^-)$
- R_K
- R_{K^*}
- $B \to K^{*0}\mu^+\mu^-$: BR, F_L, A_{FB}, S_3, S_4, S_5, S_7, S_8, S_9
  in 8 low q^2 and 4 high q^2bins
- $B_s \to \phi\mu^+\mu^-$: BR, F_L, , S_3, S_4, S_7
  in 3 low q^2 and 2 high q^2bins

Computations performed using SuperIso public program

NP Fit results: single operators

Best fit values considering all observables besides R_K and R_{K^*}
(under the assumption of 10% non-factorisable power corrections)

All $b \to s$ data except $R_{K^{(*)}}$		$(\chi^2_{\rm SM} = 98.1)$	
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-1.02 ± 0.20	79.7	4.3σ
δC_{10}	0.18 ± 0.25	97.6	0.8σ
δC_9^μ	-1.05 ± 0.19	77.5	4.5σ
δC_9^e	0.72 ± 0.58	96.9	1.1σ
δC_{10}^μ	0.27 ± 0.25	96.8	1.1σ
δC_{10}^e	-0.56 ± 0.50	97.1	1.0σ

$\rightarrow$ C_9 and C_9^μ solutions are favoured with SM pulls of 4.3 and 4.5σ

$\rightarrow$ C_{10}-like solutions do not play a role

T. Hurth, FM, D. Martinez Santos, S. Neshatpour, Phys.Rev. D96 (2017) no.9, 095034

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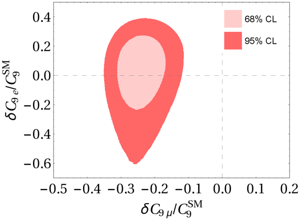
Best fit values in the one operator fit considering *only* R_K and R_{K^*}

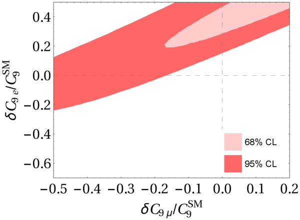
Only R_K and R_{K^*} $(\chi^2_{\rm SM} = 18.7)$			
	b.f. value	$\chi^2_{\rm min}$	${\rm Pull}_{\rm SM}$
δC_9	-1.99 ± 5.81	18.6	0.3σ
δC_{10}	4.09 ± 12.23	18.5	0.5σ
δC_9^μ	-1.47 ± 0.52	5.3	3.7σ
δC_9^e	1.58 ± 0.49	3.6	3.9σ
δC_{10}^μ	1.38 ± 0.44	2.8	4.0σ
δC_{10}^e	-1.44 ± 0.44	2.3	4.1σ

$\to$ NP in C_9^e, C_9^μ, C_{10}^e, or C_{10}^μ are favoured by the $R_{K^{(*)}}$ ratios (significance: $3.7 - 4.1\sigma$)

T. Hurth, FM, D. Martinez Santos, S. Neshatpour,Phys.Rev. D96 (2017) no.9, 095034 using all but R_K and R_{K^*} | using only R_K and R_{K^*}

$(C_9^\mu - C_9^e)$





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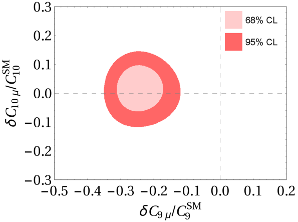

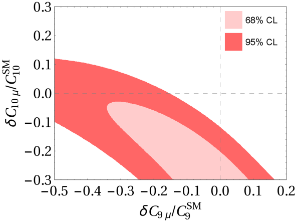

The two sets are compatible at least at the 2σ level.

Consistent possible explanation to the anomalies with about 25% reduction in C_9

The hadronic contributions (in terms of helicity amplitudes) appear in:

$$H_V(\lambda) = -i\,N'\left\{C_9^{\rm eff}\,\tilde{V}_\lambda(q^2) + \frac{m_B^2}{q^2}\left[\frac{2\,\hat{m}_b}{m_B}\,C_7^{\rm eff}\,\tilde{T}_\lambda(q^2) - 16\pi^2\mathcal{N}_\lambda(q^2)\right]\right\}$$

$\left(N' = -\frac{4G_F m_B}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\right)$

$\mathcal{N}_\lambda(q^2)$ = **leading nonfact.** $+ h_\lambda$

Helicity FFs $\tilde{V}_{L/R}$, $\tilde{T}_{L/R}$ are combinations of the standard FFs $V, A_{0,1,2}, T_{1,2,3}$

The most general parametrisation up to higher order terms in q^2 of the non-factorisable power corrections $h_{\lambda(=+,-,0)}(q^2)$ which is compatible with the analyticity structure is:

$$\delta H_V^{\rm p.c.}(\lambda=\pm) = iN'm_B^2\frac{16\pi^2}{q^2}h_\lambda(q^2) = iN'm_B^2 16\pi^2\left(\frac{h_\lambda^{(0)}}{q^2} + h_\lambda^{(1)} + q^2 h_\lambda^{(2)}\right)$$

$$\delta H_V^{\rm PC}(\lambda=0) = i\,N'm_B^2\frac{16\pi^2}{\sqrt{q^2}}\left(h_0^{(0)} + q^2\,h_0^{(1)} + q^4\,h_0^{(2)}\right)$$

New Physics effect:

$$\delta H_V^{C_9^{\rm NP}}(\lambda=\pm) = -iN'\,\tilde{V}_L(q^2)\,C_9^{\rm NP} = -iN'\left(a_\lambda\,C_9^{\rm NP} + q^2 b_\lambda\,C_9^{\rm NP}\right)$$

and similarly for $\lambda = 0$ and for C_7
$\Rightarrow$ NP effects can be embedded in the hadronic effects.

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$\left(N' = -\frac{4G_F m_B}{\sqrt{2}}\frac{e^2}{16\pi^2}V_{tb}V_{ts}^*\right)$ $\qquad$ $\mathcal{N}_\lambda(q^2)$ = **leading nonfact.** $+\,h_\lambda$

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$\Rightarrow$ NP effects can be embedded in the hadronic effects.

We can do a fit for both (hadronic quantities $h^{(0,1,2)}_{+,-,0}$ (18 parameters) and Wilson coefficients C_i^{NP}(2 or 4 parameters))

Due to this embedding the two fits can be compared with the Wilk's test

For low q^2 (up to 8 GeV^2):

	2 (δC_9)	4 ($\delta C_7, \delta C_9$)	18 ($h^{(0,1,2)}_{+,-,0}$)
0 (plain SM)	4.2σ	4.1σ	3.1σ
2 (δC_9)	—	1.4σ	1.1σ
4 ($\delta C_7, \delta C_9$)	—	—	0.95σ

V.G. Chobanova, T. Hurth, FM, D. Martinez Santos, S. Neshatpour, JHEP 1707 (2017) 025

$\rightarrow$ Adding δC_9 improves over the SM hypothesis by 4.2σ
$\rightarrow$ Including in addition δC_7 or hadronic parameters improves the situation only mildly
$\rightarrow$ One cannot rule out the hadronic option

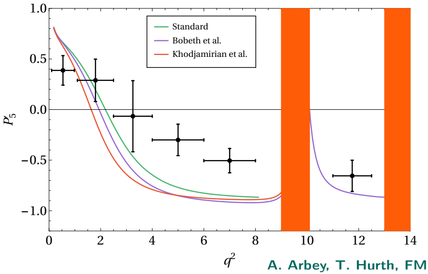
Adding 16 more parameters does not improve the fits significantly

The situation is still inconclusive

Various methods for hadronic effects

$$\frac{e^2}{q^2}\epsilon_\mu L_V^\mu\left[Y(q^2)\tilde{V}_\lambda + \mathrm{LO\ in}\ \mathcal{O}(\frac{\Lambda}{m_b},\frac{\Lambda}{E_{K^*}}) + h_\lambda(q^2)\right]$$

	factorisable	non-factorisable	power corrections (soft gluon)	region of calculation	physical region of interest
Standard	✓	✓	✗	$q^2 \lesssim 7$ GeV^2	directly
Khodjamirian et al. [1006.4945]	✓	✗	✓	$q^2 < 1$ GeV^2	extrapolation by dispersion relation
Bobeth et al. [1707.07305]	✓	✓	✓	$q^2 < 0$ GeV^2	extrapolation by analyticity



A. Arbey, T. Hurth, FM, S. Neshatpour, to appear

Addition of the missing pieces seem to increase the tension!

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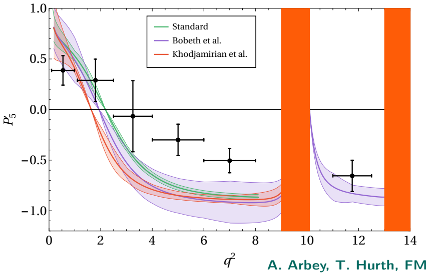

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Addition of the missing pieces seem to increase the tension!

1) Unknown power corrections

- Global significance of the anomalies depends on the assumptions on the power corrections
- Towards a calculation...
- Problem: they are not calculable in QCD factorisation
- Alternative approaches exist, e.g. based on light cone sum rule techniques, analyticity or empirical approaches $\rightarrow$ the available partial calculation seems to increase the tension in P_5'

2) Cross-check with other $R_{\mu/e}$ ratios

- R_K and R_{K^*} ratios are theoretically very clean
- The tensions cannot be explained by hadronic uncertainties

Cross-checks needed with other ratios:

	Predictions assuming 12 fb^{-1} luminosity			
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.785, 0.913]$	$[0.909, 0.933]$	$[1.005, 1.042]$	$[1.001, 1.018]$
$R_{S_5}^{[1.1,6.0]}$	$[-0.787, 0.394]$	$[0.603, 0.697]$	$[0.881, 1.002]$	$[1.053, 1.146]$
$R_{K^*}^{[15,19]}$	$[0.621, 0.803]$	$[0.577, 0.771]$	$[0.589, 0.778]$	$[0.586, 0.770]$
$R_K^{[15,19]}$	$[0.597, 0.802]$	$[0.590, 0.778]$	$[0.659, 0.818]$	$[0.632, 0.805]$
$R_\phi^{[1.1,6.0]}$	$[0.748, 0.852]$	$[0.620, 0.805]$	$[0.578, 0.770]$	$[0.578, 0.764]$
...				

A confirmation of the deviations in the ratios would indirectly confirm the NP interpretation of the anomalies in the angular observables!

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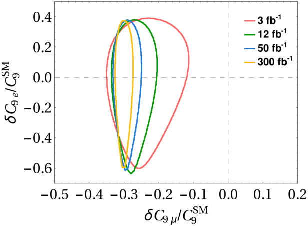
3) Future LHCb prospects

Global fits using the angular observables only (NO theoretically clean R ratios)

Considering several luminosities, assuming the current central values



LHCb will be able to establish new physics within the angular observables even in the pessimistic case that there will be no theoretical progress on non-factorisable power corrections!

Pull$_{\rm SM}$ for the fit to ΔC_9^μ based on the ratios R_K and R_{K^*} for the LHCb upgrade

ΔC_9^μ	Syst. Pull$_{\rm SM}$	Syst./2 Pull$_{\rm SM}$	Syst./3 Pull$_{\rm SM}$
12 fb^{-1}	6.1σ (4.3σ)	7.2σ (5.2σ)	7.4σ (5.5σ)
50 fb^{-1}	8.2σ (5.7σ)	11.6σ (8.7σ)	12.9σ (9.9σ)
300 fb^{-1}	9.4σ (6.5σ)	15.6σ (12.3σ)	19.5σ (16.1σ)

(): assuming 50% correlation between each of the R_K and R_{K^*} measurements

Only a small part of the 50 fb^{-1} is needed to establish NP in the $R_{K^{(*)}}$ ratios even in the pessimistic case that the systematic errors are not reduced by then at all.

This is independent of the hadronic uncertainties!

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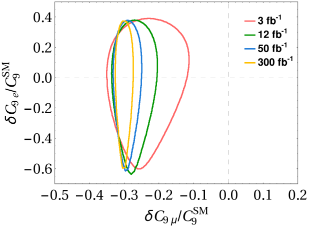
Global fits using the angular observables only (NO theoretically clean R ratios)

Considering several luminosities, assuming the current central values



LHCb will be able to establish new physics within the angular observables even in the pessimistic case that there will be no theoretical progress on non-factorisable power corrections!

$\text{Pull}_{\rm SM}$ for the fit to ΔC_9^μ based on the ratios R_K and R_{K^*} for the LHCb upgrade

ΔC_9^μ	Syst. $\text{Pull}_{\rm SM}$	Syst./2 $\text{Pull}_{\rm SM}$	Syst./3 $\text{Pull}_{\rm SM}$
12 fb^{-1}	6.1σ (4.3σ)	7.2σ (5.2σ)	7.4σ (5.5σ)
50 fb^{-1}	8.2σ (5.7σ)	11.6σ (8.7σ)	12.9σ (9.9σ)
300 fb^{-1}	9.4σ (6.5σ)	15.6σ (12.3σ)	19.5σ (16.1σ)

(): assuming 50% correlation between each of the R_K and R_{K^*} measurements

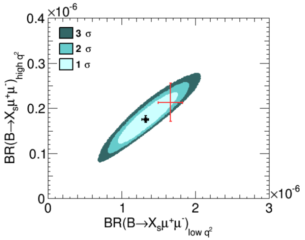
Only a small part of the 50 fb^{-1} is needed to establish NP in the $R_{K^{(*)}}$ ratios even in the pessimistic case that the systematic errors are not reduced by then at all.

This is independent of the hadronic uncertainties!

4) Cross-check with inclusive modes

Inclusive decays are theoretically cleaner (see e.g. T. Huber, T. Hurth, E. Lunghi, JHEP 1506 (2015) 176)

At Belle-II, for inclusive $b \to s\ell\ell$:



T. Hurth, FM, JHEP 1404 (2014) 097

T. Hurth, FM, S. Neshatpour, JHEP 1412 (2014) 053

Predictions based on our model-independent analysis

black cross: future measurements at Belle-II assuming the best fit solution

red cross: SM predictions

$\to$ Belle-II will check the NP interpretation with theoretically clean modes

New physics scenarios

Global fits: New physics is likely to appear in C_9:

$$O_9 = \frac{e^2}{(4\pi)^2}(\bar{s}\gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$

It can also affect C_9' and C_{10} in a much lesser extent.

However, difficult to generate $\delta C_9 \sim -1$ at loop level...

$\rightarrow$ Need for tree level diagrams...

Mainstream scenarios:

- Z' bosons
- leptoquarks
- composite models

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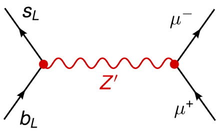

Z' obvious candidate to generate the O_9 operator:

- Flavour-changing couplings to left-handed quarks
- Vector-like couplings to leptons
- Flavour violation or non-universality in the lepton sector

Leptoquarks:

- t-channel diagrams
- Different possible representations, can be scalar (spin 0) or vector (spin 1)
- Cannot alter only C_9, but both C_9 and C_{10} $(= -C_9)$
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Composite models:

- Neutral resonance ρ_μ coupling to the muons via composite elementary mixing
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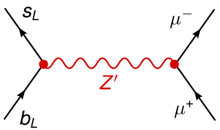

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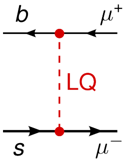

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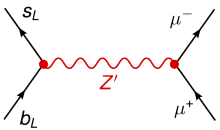

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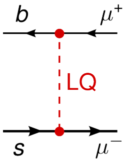

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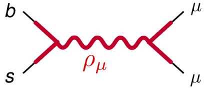

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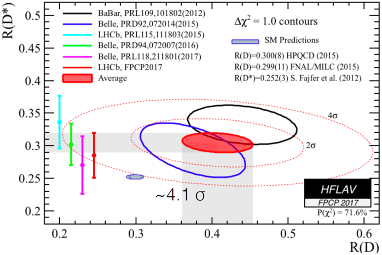
"Shalt the next round of LHCb data giveth us the v'rdict!"
His Royal Highness King Henri III

Backup



Experiment	R_{D^*}	R_D	Re-scaled Correlation
BaBar (2012) [3]	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$	-0.27
Belle (2015) [4]	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$	-0.49
LHCb (2015) [5]	$0.336 \pm 0.027 \pm 0.030$	–	–
Belle (2016) [6]	$0.302 \pm 0.030 \pm 0.011$	–	–
Belle (2017) [17]	$0.270 \pm 0.035^{+0.028}_{-0.025}$	–	–
LHCb (2017) [8]	$0.285 \pm 0.019 \pm 0.025$ (syst) ± 0.013 (BF)	–	–
Average	$0.304 \pm 0.013 \pm 0.007$	$0.407 \pm 0.039 \pm 0.024$	-0.20
SM [2, 18]	0.252 ± 0.003	0.299 ± 0.003	

LHCb 1708.08856: $R(D^*) = 0.285 \pm 0.019 \pm 0.025 \pm 0.013$

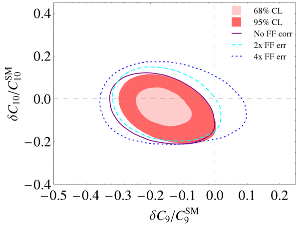
Belle 1709.00129: $R(D^*) = 0.270 \pm 0.035(stat)^{+0.028}_{-0.025}(syst)$

[17]: arXiv:1608.06391 ICHEP16

[8]: LHCb internal note

Fits with different assumptions for the form factor uncertainties:

- correlations ignored (solid line)
- normal form factor errors (filled areas)
- 2 $\times$ form factor errors (dashed line)
- 4 $\times$ form factor errors (dotted line)



The size of the form factor errors has a crucial role in constraining the allowed region!

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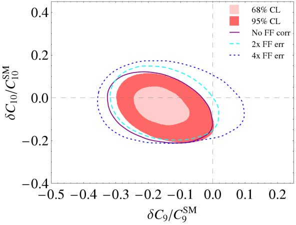

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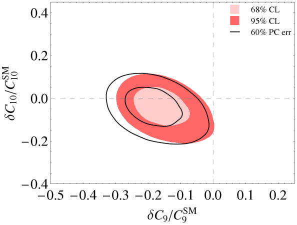
Fits assuming different power correction uncertainties:

- 10% uncertainty (filled areas)
- 60% uncertainty (solid line)



60% power correction uncertainty leads to only 17-20% error at the observable level. Significance of the tension depends on the assumption on the size of the power corrections

Wilson coefficients sensitive to NP:

Preliminary!

$$C_7,\, C_8,\, C_9^\ell,\, C_{10}^\ell,\, C_S^\ell,\, C_P^\ell$$

$\to$ 10 independent WC (considering $\ell = e, \mu$)

+ 10 primed Wilson coefficients

108 observables

Set of WC	Nb parameters	χ^2_{min}	Pull$_{SM}$	Improv.
SM	0	118.2	-	-
$C_9^{(e,\mu)}$ real	2	83.3	5.56σ	5.56σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$ real	6	80.7	4.82σ	0.48σ
All non-primed WC real	10	79.7	4.17σ	0.11σ
All WC real (incl. primed)	20	74.6	3.14σ	0.15σ

- No real improvement in the fits when going beyond the $C_9^{(e,\mu)}$ case
- Pull with the SM decreases when all WC are varied
- Many parameters are not constrained

Fit results with more than two operators: All observables

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All observables $(\chi^2_{\rm SM} = 118.2,\ \chi^2_{\rm min} = 74.6)$	
δC_7 0.00 ± 0.01	δC_8 0.85 ± 0.21
$\delta C_7'$ 0.02 ± 0.02	$\delta C_8'$ -1.78 ± 0.25

δC_9^μ -1.47 ± 0.16	δC_9^e -1.70 ± 0.65	δC_{10}^μ 0.04 ± 0.18	δC_{10}^e -1.03 ± 0.26
$\delta C_9'^\mu$ 0.01 ± 0.30	$\delta C_9'^e$ 0.00 ± 1.41	$\delta C_{10}'^\mu$ -0.15 ± 0.16	$\delta C_{10}'^e$ 0.00 ± 1.41
δC_S^μ 0.00 ± 2.20	δC_S^e 0.17 ± 3.61	δC_P^μ 0.45 ± 0.26	δC_P^e 0.07 ± 7.10
$\delta C_S'^\mu$ 0.00 ± 1.41	$\delta C_S'^e$ 0.00 ± 1.41	$\delta C_P'^\mu$ 0.00 ± 1.41	$\delta C_P'^e$ 0.00 ± 1.41

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