Status report on b to s anomalies

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Based on

Egede,Hurth,Matias,Ramon,Reece:
New observables in the decay mode $\bar{B}_d \to \bar{K}^{*0}\ell^+\ell^-$
arXiv:0807.2589, JHEP 0811 (2008) 032

Egede,Hurth,Matias,Ramon,Reece:
New physics reach of the decay mode $\bar{B} \to \bar{K}^{*0}\ell^+\ell^-$
arXiv:1005.0571, JHEP 1010 (2010) 056

Descotes-Genon,Hurth,Matias,Virto:
Optimizing the basis of $B \to K^*\ell\ell$ observables in the full kinematic range
arXiv:1303.5794, JHEP 1305 (2013) 137

Hurth, Mahmoudi:
On the LHCb anomaly in $B \to K^*\ell^+\ell^-$
arXiv:1312.526, JHEP 1404 (2014) 097

Hurth, Mahmoudi, Neshatpour:
Global fits Global fits to $b \to s\ell\ell$ data and signs for lepton non-universality
arXiv:1410.4545, JHEP 1412 (2014) 053

On the anomalies in the latest LHCb data
arXiv:1603.00865, Nucl.Phys. B909 (2016) 737

Chobanova, Hurth, Mahmoudi, Neshatpour, Martinez Santos:
Large hadronic power corrections or NP in the rare decay $B \to K^*\mu^+\mu^-$
arXiv:1702.02234, JHEP 1707 (2017) 025

Hurth, Mahmoudi, Neshatpour, Martinez Santos:
On lepton non-universality in exclusive $b \to s\ell^+\ell^-$ decays
arXiv:1705.06274, Phys.Rev.D96 (2017) 095034

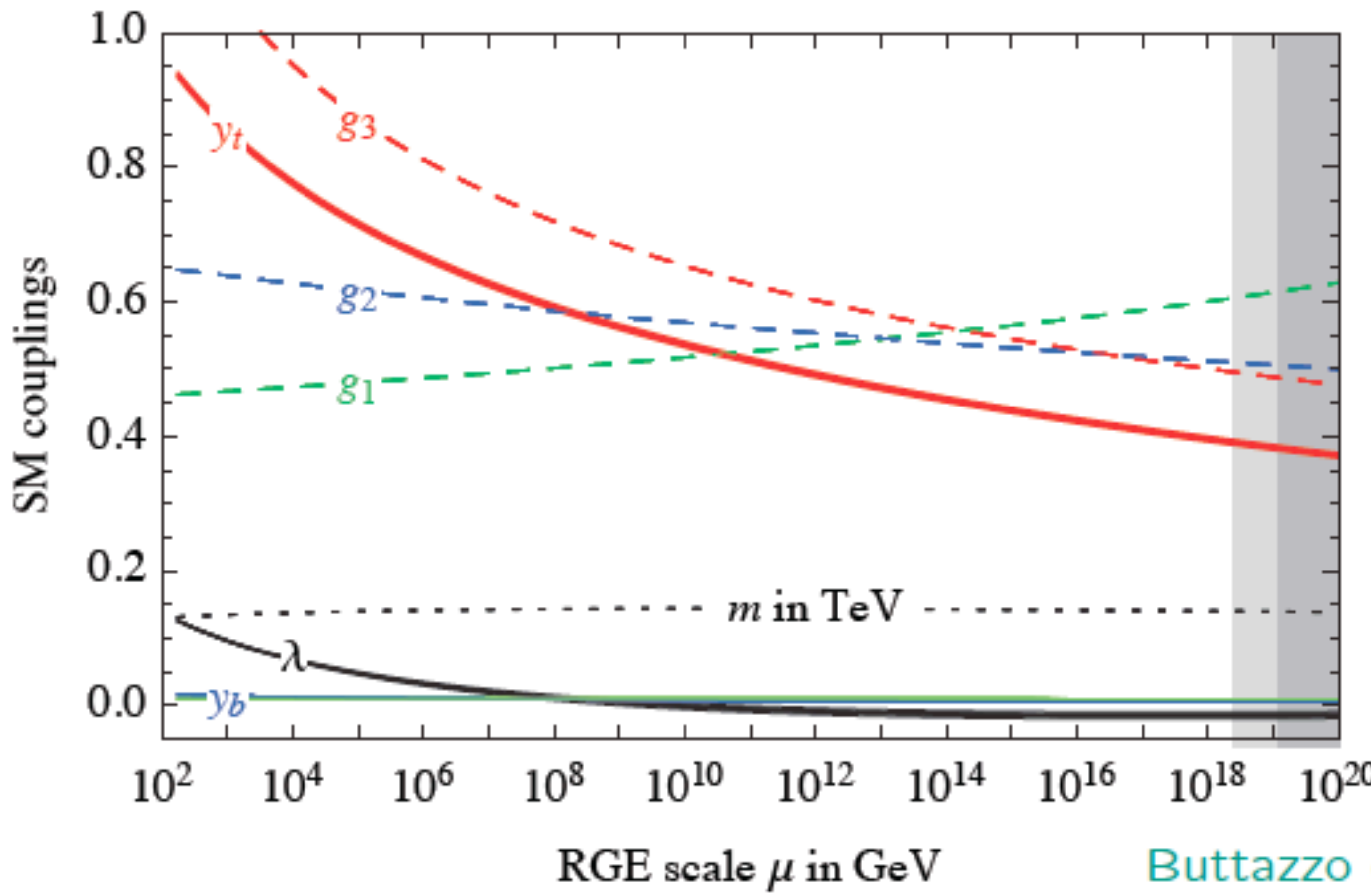
Arby, Hurth, Mahmoudi, Neshatpour:
Hadronic and NP contributions in $B \to K^*\ell^+\ell^-$
arXiv:1806.02791

Prologue from my 2016 talk on inclusive semileptonic B decays

Self-consistency of the SM

Do we need new physics beyond the SM ?

- It is possible to extend the validity of the SM up to the M_P as weakly coupled theory.



Buttazzo et al. arXiv:1307.3536

High-energy extrapolation shows that the Yukawa couplings, weak gauge couplings and the Higgs self coupling remain perturbative in the entire energy domain between the electroweak and Planck scale (no Landau poles !).

- Renormalizability implies no constraints on the free parameters of the SM Lagrangian.

Experimental evidence beyond SM

- Dark matter (visible matter accounts for only 4% of the Universe)
- Neutrino masses (Dirac or Majorana masses ?)
- Baryon asymmetry of the Universe (new sources of CP violation needed)

Caveat:

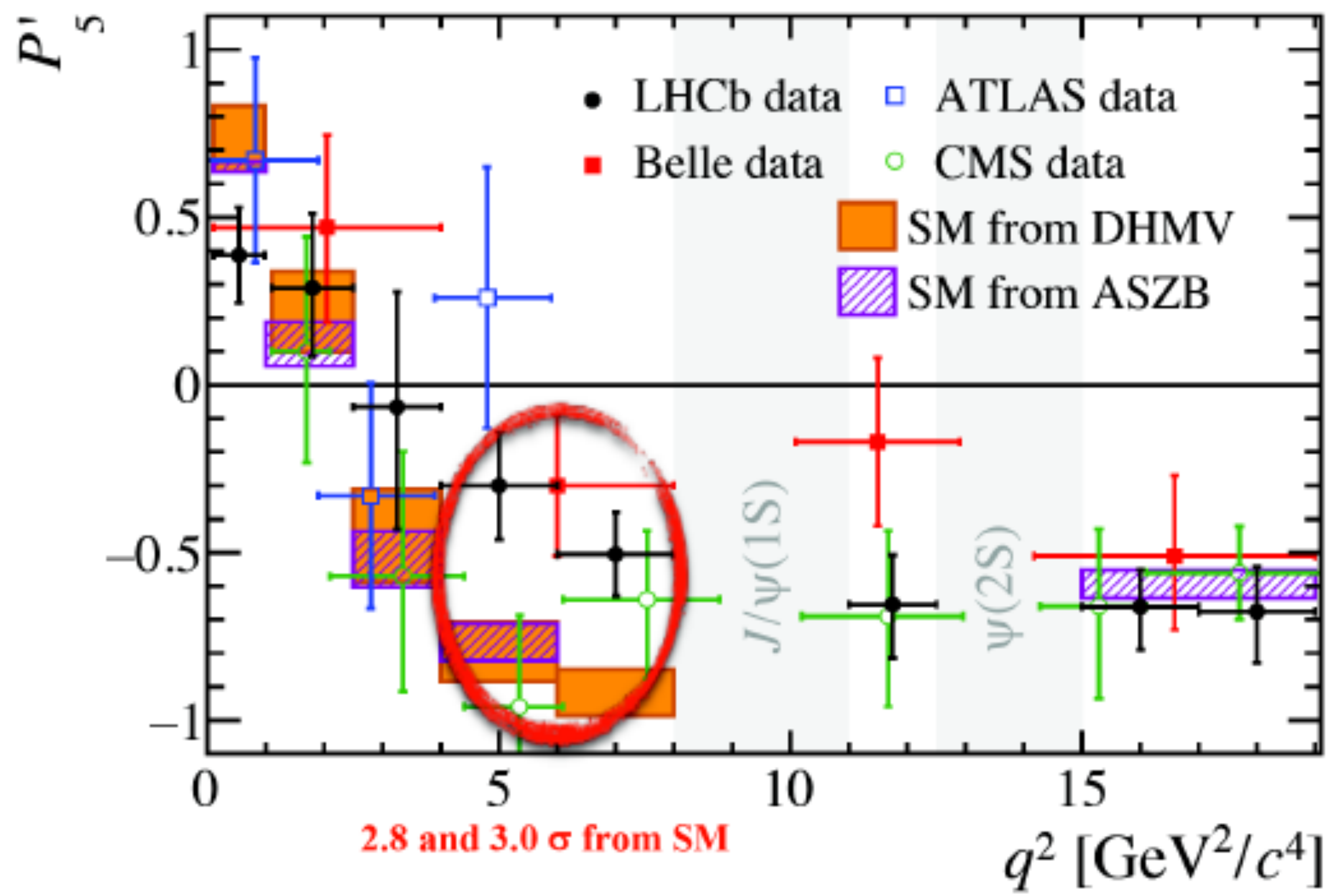
Answers perhaps wait at energy scales which we do not reach with present experiments.

The LHCb Anomalies

Anomalies in $B \to K^*\mu^+\mu^-$ angular observables, in particular P_5' ; S_5

Long standing anomaly **2-3σ**:

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



LHCb, JHEP 02 (2016) 104; Belle, PRL 118 (2017); ATLAS, ATLAS-CONF-2017-023; CMS, CMS-PAS-BPH-15-008

- Also measured by ATLAS, CMS and Belle

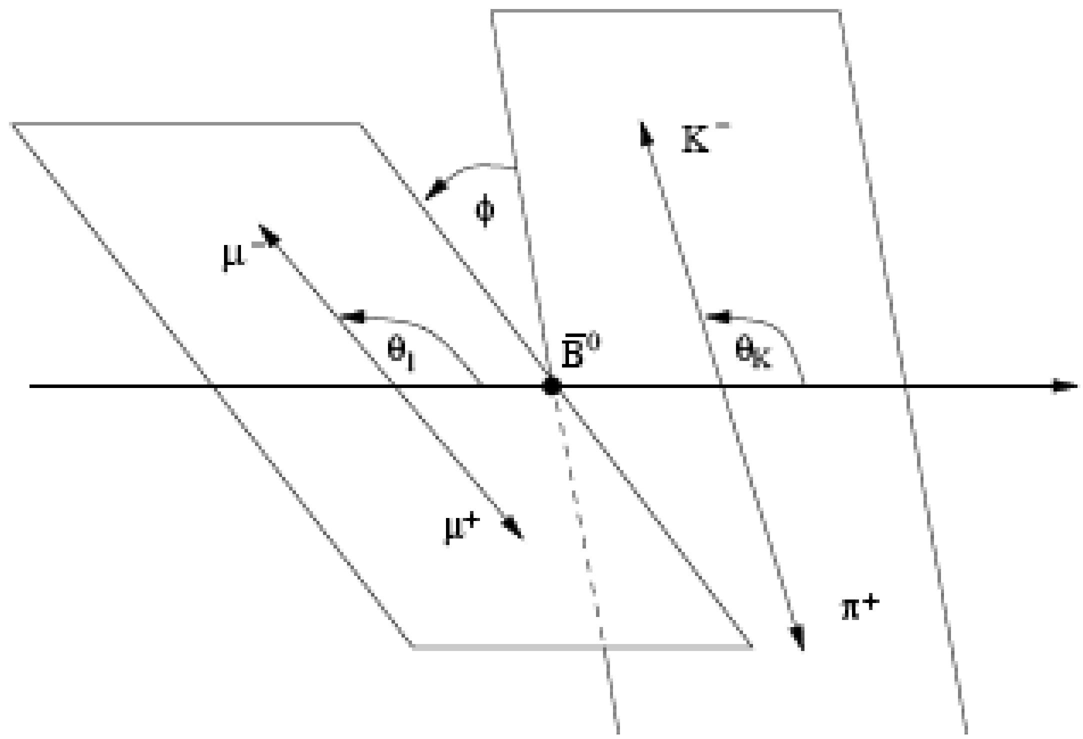
New Physics or underestimated hadronic uncertainties

(form factors, power corrections) ?

More details:

Differential decay rate of $B \to K^* \ell\ell$

Assuming the $\bar{K}^*$ to be on the mass shell, the decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^- \pi^+)\ell^+\ell^-$ described by the lepton-pair invariant mass, s, and the three angles θ_l, θ_{K^*}, ϕ.



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

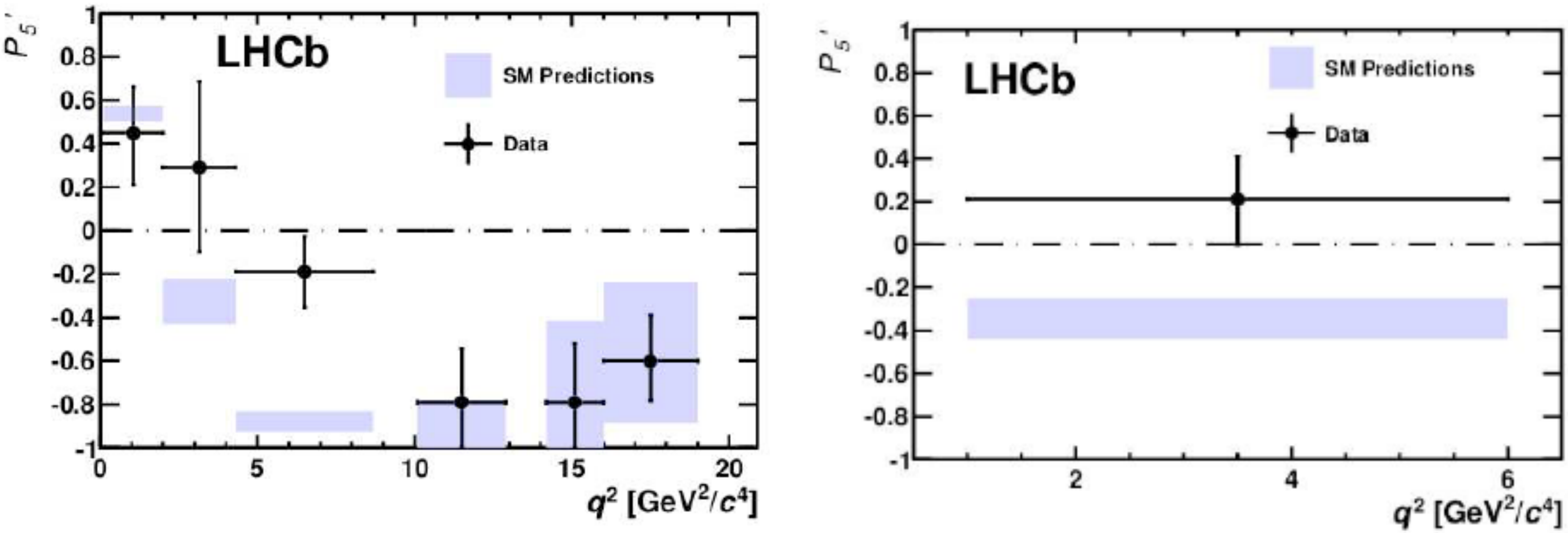
$$J(q^2, \theta_l, \theta_K, \phi) =$$

$$\begin{aligned}
&= J_{1s} \sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3 \sin^2\theta_K \sin^2\theta_l \cos 2\phi \\
&\quad + J_4 \sin 2\theta_K \sin 2\theta_l \cos\phi + J_5 \sin 2\theta_K \sin\theta_l \cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l \\
&\quad + J_7 \sin 2\theta_K \sin\theta_l \sin\phi + J_8 \sin 2\theta_K \sin 2\theta_l \sin\phi + J_9 \sin^2\theta_K \sin^2\theta_l \sin 2\phi
\end{aligned}$$

Large number of independent angular observables

First measurements of new angular observables LHCb arXiv:1308.1707

SM predictions Descotes-Genon, Hurth, Matias, Virto arXiv:1303.5794



LHCb Anomaly

a statistical fluctuation, an underestimation

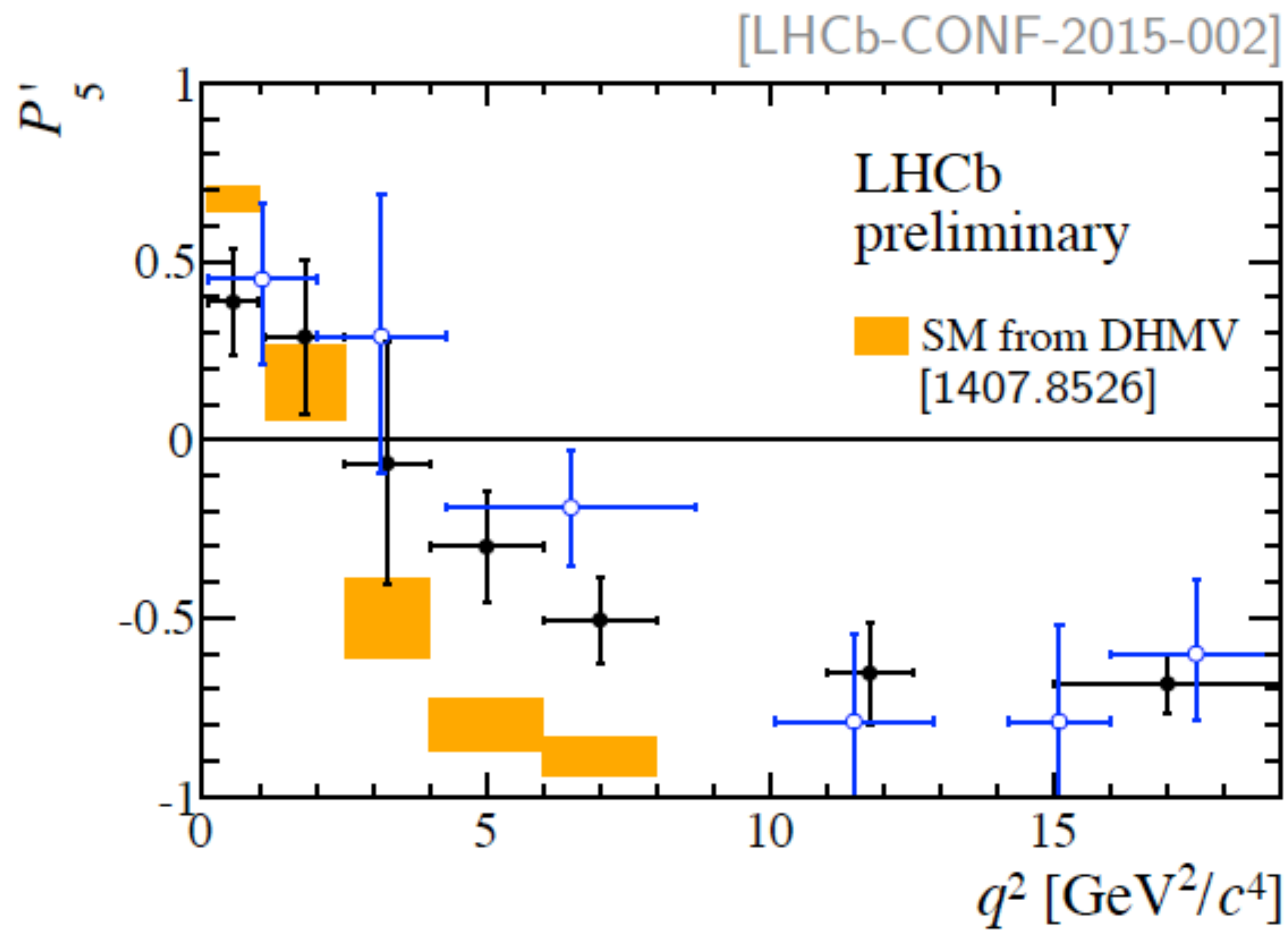
of Λ/m_b corrections or new physics in C_9 ?

C_7 $(B \to X_s\gamma)$ C_{10} $(B \to \mu^+\mu^-)$

$$O_7^{(\prime)} \propto m_b\, \bar{s}\sigma_{\mu\nu}P_{R(L)}b\, F^{\mu\nu} \quad O_9^{(\prime)} \propto \bar{s}\,\gamma^{\mu}P_{L(R)}\,\bar{\ell}\gamma_{\mu}\ell \quad O_{10}^{(\prime)} \propto \bar{s}\,\gamma^{\mu}P_{L(R)}\,\bar{\ell}\gamma_{\mu}\gamma_5\ell$$

Update of LHCb at Moriond 2015

LHCb arXiv:1512.04442

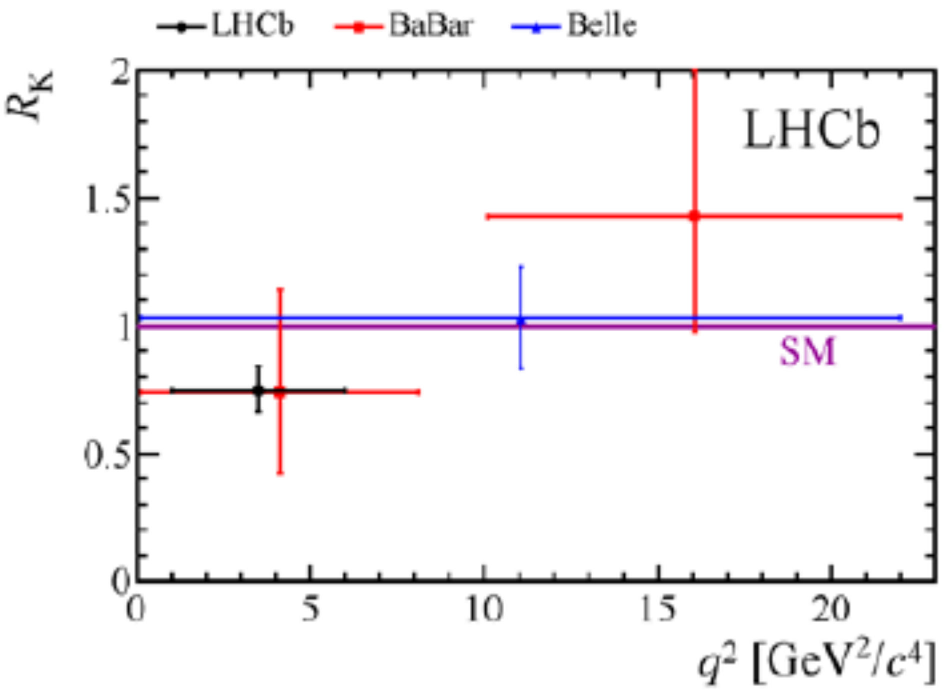


$3\,fb^{-1}$

- Tension seen in P'_5 in [PRL 111, 191801 (2013)] confirmed
- $[4.0, 6.0]$ and $[6.0, 8.0]\,\mathrm{GeV}^2/c^4$ show deviations of 2.9σ each
- Naive combination results in a significance of 3.7σ
- Compatible with $1\,fb^{-1}$ measurement

Lepton flavour universality in $B^+ \to K^+\ell^+\ell^-$

- June 2014 (3 fb^{-1}): measurement of R_K in the [1-6] GeV^2 bin (PRL 113, 151601 (2014)): **2.6σ** tension in [1-6] GeV^2 bin
- SM prediction very accurate (leading corrections from QED, giving rise to large logarithms involving the ratio $m_B/m_{\mu,e}$)



BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801

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

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

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

Bordone, Isidori, Pattori, arXiv:1605.07633

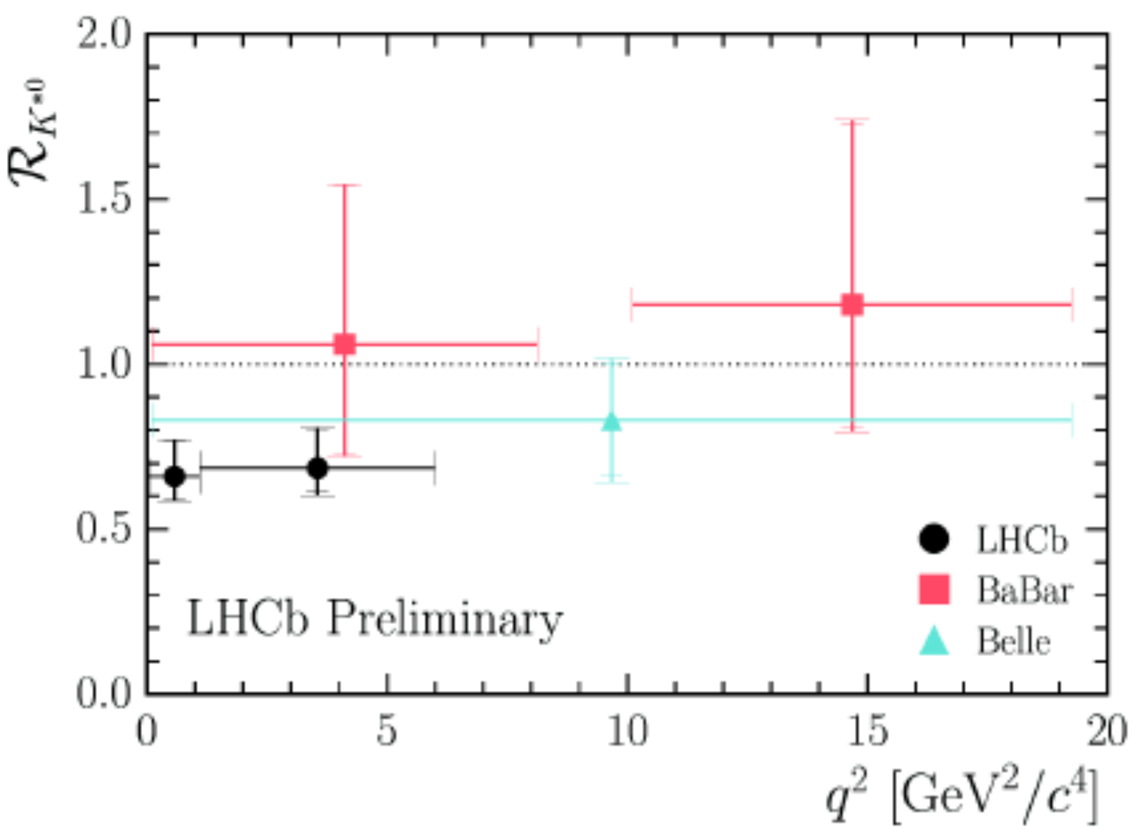
Would be a spectacular fall of the SM !

Lepton flavour universality in $B^0 \to K^{*0}\ell^+\ell^-$

- LHCb measurement (April 2017): JHEP 08 (2017) 055

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

- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2



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

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

$$R_{K^*}^{\mathrm{SM,bin1}} = 0.906 \pm 0.020_{\mathrm{QED}} \pm 0.020_{\mathrm{FF}}$$

$$R_{K^*}^{\mathrm{SM,bin2}} = 1.000 \pm 0.010_{\mathrm{QED}}$$

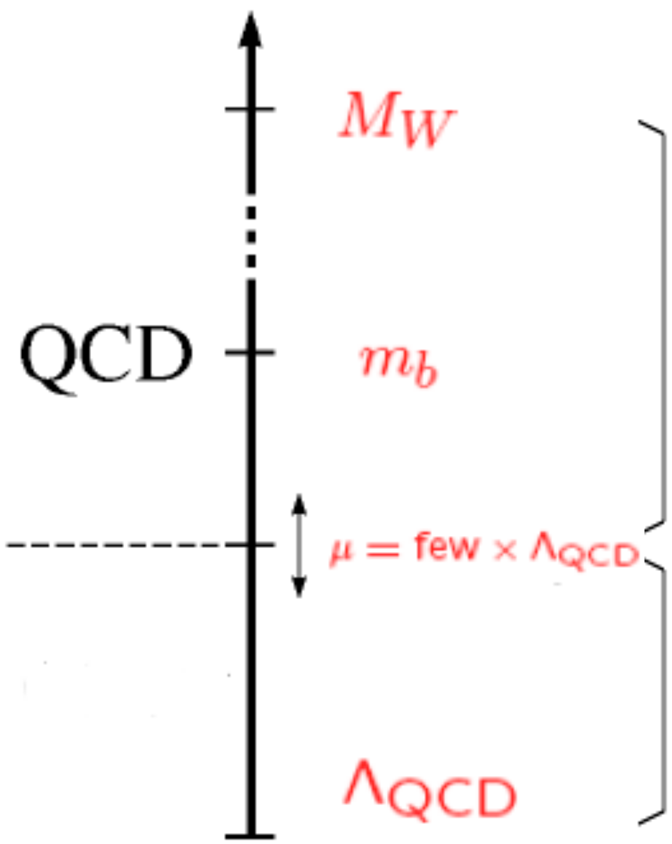
Bordone, Isidori, Pattori, arXiv:1605.07633

BaBar, PRD 86 (2012) 032012; Belle, PRL 103 (2009) 171801

2.2-2.5σ tension with the SM predictions in each bin

Theoretical Tools

Theoretical tools for flavour precision observables



short-distance physics
perturbative

long-distance physics
nonperturbative

Factorization theorems: separating long- and short-distance physics

- Electroweak effective Hamiltonian: $H_{eff} = -\frac{4G_F}{\sqrt{2}} \sum C_i(\mu, M_{heavy}) \; \mathcal{O}_i(\mu)$

- $\mu^2 \approx M_{New}^2 >> M_W^2$: 'new physics' effects: $C_i^{SM}(M_W) + C_i^{New}(M_W)$

How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Inclusive modes $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$

How to compute the hadronic matrix elements $\mathcal{O}_i(\mu = m_b)$?

Heavy mass expansion for inclusive modes:

$$\Gamma(\bar{B} \to X_s\gamma) \stackrel{m_b\to\infty}{\longrightarrow} \Gamma(b \to X_s^{parton}\gamma)\,, \quad \Delta^{nonpert.} \sim \Lambda^2_{QCD}/m_b^2$$

No linear term Λ_{QCD}/m_b (perturbative contributions dominant)

An old story:

– If one goes beyond the leading operator ($\mathcal{O}_7$, $\mathcal{O}_9$):
  breakdown of local expansion

A new dedicated analysis:

naive estimate of non-local matrix elements leads to 5% uncertainty.

SCET analysis in $B \to X_s\gamma$: Benzke,Lee,Neubert,Paz, arXiv:1003.5012

in $B \to X_s\ell\ell$: Benzke,Hurth,Turczyk, arXiv:1705.10366

In semileptonic case $\mathcal{O}(1/m_b^2)$ contributions numerically relevant

(work in progress)

Exclusive modes $B \to K^{(*)}\ell\ell$

QCD-improved factorization: BBNS 1999

$$\mathcal{T}_a^{(i)} = C_a^{(i)}\xi_a + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(\Lambda/m_b)$$

(Soft-collinear effective theory)

– Separation of perturbative hard kernels from process-independent nonperturbative functions like form factors

– Relations between formfactors in large-energy limit

– Limitation: insufficient information on power-suppressed Λ/m_b terms (breakdown of factorization: 'endpoint divergences')

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More details:

"Full formfactor approach" Altmannshofer et al., arXiv:0811.1214

- we have factorizable and nonfactorizable power corrections
- using full QCD formfactors in the factorization formula takes factorizable power corrections into account automatically
- nonfactorizable contributions generated by four-quark and $\mathcal{O}_8$ operators

Exclusive modes $B \to K^{(*)}\ell\ell$

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

(This does not affect R_K and R_K^* of course, but does affect combined fits!)

Effective Hamiltonian for $b \to s\ell\ell$ transitions

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

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

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

Transversity amplitudes:

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

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

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

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

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

Effective Hamiltonian for $b \to s\ell\ell$ transitions

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

$$\mathcal{H}_{\text{eff}}^{\text{had}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1\dots6} C_i O_i + C_8 O_8 \right]$$

$$\begin{aligned}
\mathcal{A}_\lambda^{(\text{had})} =& -i \frac{e^2}{q^2} \int d^4x e^{-iq\cdot x} \langle \ell^+ \ell^- | j_\mu^{\text{em,lept}}(x) | 0 \rangle \\
& \times \int d^4y\, e^{iq\cdot y} \langle \bar{K}_\lambda^* | T\{ j^{\text{em,had},\mu}(y) \mathcal{H}_{\text{eff}}^{\text{had}}(0) \} | \bar{B} \rangle \\
\equiv & \frac{e^2}{q^2} \epsilon_\mu L_V^\mu \Big[\underbrace{\text{LO in } \mathcal{O}(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}})}_{\text{Non-Fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections}} \Big]
\end{aligned}$$

Beneke et al.:
106067; 0412400

Model independent Analysis

Model-independent global fits to $b \to s$ data

Relevant operators: $\mathcal{O}_7, \mathcal{O}_8, \mathcal{O}'_{9\mu,e}, \mathcal{O}'_{10\mu.e}$

Scan over the values of δC_i: $C_i(\mu) = C_i^{\mathrm{SM}} + \delta C_i$

More than 100 observables included

Experimental and theoretical correlations considered

Several groups doing global fits.

Global fits to $\leq$ 2016 data

Hurth et al. arXiv:1603.00865
Descotes-Genon et al. arXiv:1510.04239
Ciuchini et al. arXiv:1512.07157
Beaujean et al. arXiv:1508.01526
Altmannshofer et al. arXiv:1503.06199
Alonso et al. arXiv:1407.7044

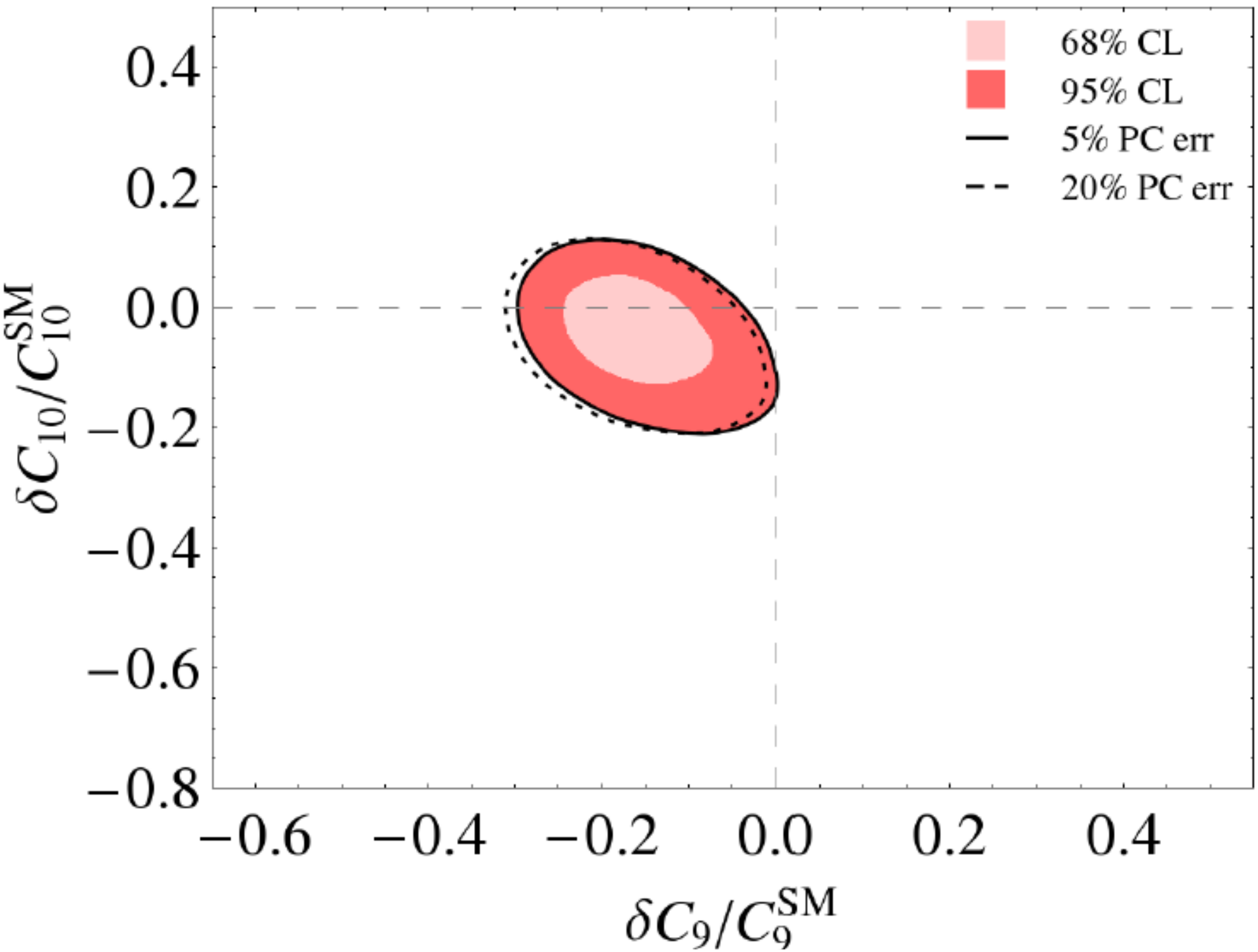
Fits to the data including R_{K^*} of 2017

Capdevilla et al. arXix:1704.05340
Geng et al. arXiv:1704.05446
Altmannshofer et al. arXiv:1704.05435
D'Amico et al. arXiv:1704.05438
Ciuchini et al. arXiv:1704.05447
Hurth et al. arXiv:1705.06274

Fit results for two operators

$\{C_9, C_{10}\}$

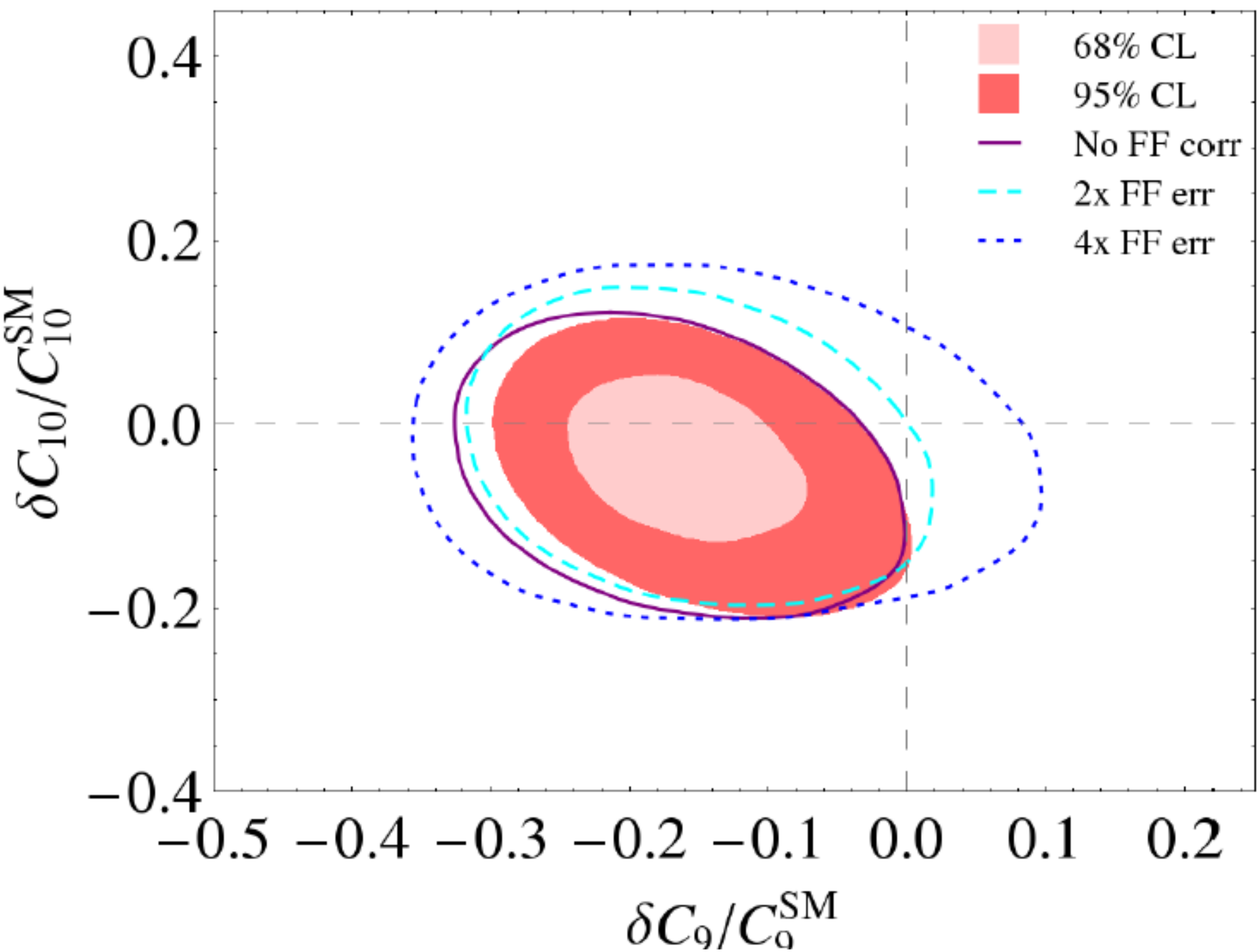
data of 2015/2016



The assumption on the power correction errors have a rather mild impact on the constraints of the allowed region

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

Fits assuming different form factor uncertainties

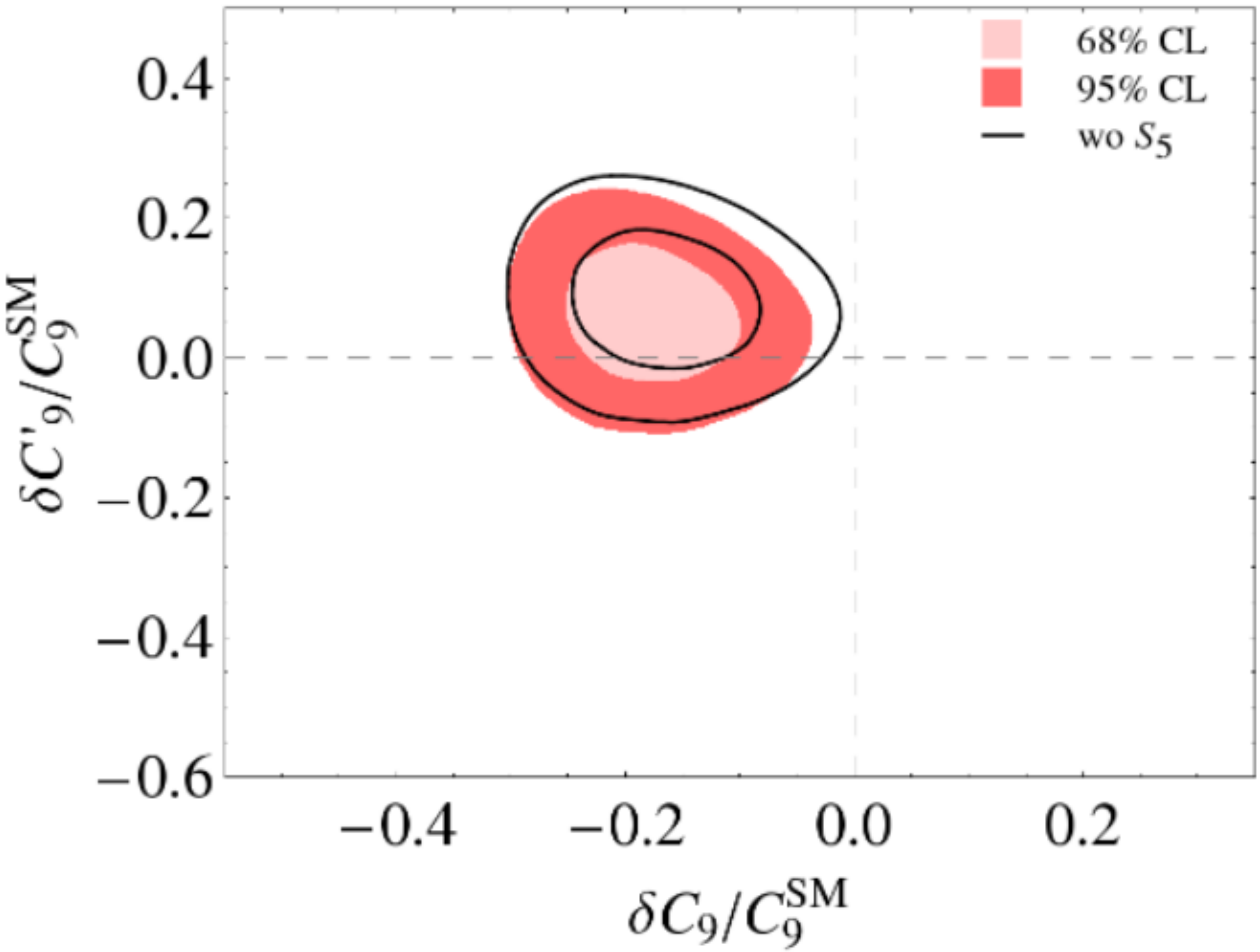


The size of the form factor errors has a crucial role in constraining the allowed region (LCSR-calculation Zwicky et al. arXiv:1503.0553)

Hurth,Mahmoudi,Neshatpour arXiv:1603.00865

Omitting S_5 from the fit

data of 2015/2016



S_5 is not the only observable which drives $\delta C_9/C_9^{SM}$ to negative values

New physics or hadronic effects

Hurth, Mahmoudi, Neshatpour, Chobanova, Martinez Santos arXiv:1702.02234

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791

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

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

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

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

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

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

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:

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

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

New physics or hadronic effects

Hurth, Mahmoudi, Neshatpour, Chobanova, Martinez Santos arXiv:1702.02234

Arby, Hurth, Mahmoudi, Neshatpour arXiv: 1806.02791

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

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.

Wilk's test

Hurth, Mahmoudi, Neshatpour, Chobanova, Martinez Santos arXiv:1702.02234

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791

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

→ Adding δC_9 improves over the SM hypothesis by 4.2σ

→ Including in addition δC_7 or hadronic parameters improves the situation only mildly

→ One cannot rule out the hadronic option

Adding 16 more parameters does not really improve the fit

The situation is still inconclusive

(LHCb upgrade prospects: NP versus hadronic effects 34 σ)

Separate NP fits with a single operator

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

data of 2017 (with R_{K^*} !)

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

	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull_{SM}}$
ΔC_9	-0.48	18.3	0.3σ
$\Delta C_9'$	$+0.78$	18.1	0.6σ
ΔC_{10}	-1.02	18.2	0.5σ
$\Delta C_{10}'$	$+1.18$	17.9	0.7σ
ΔC_9^μ	-0.35	5.1	3.6σ
ΔC_9^e	$+0.37$	3.5	3.9σ
ΔC_{10}^μ	-1.66 -0.34	2.7	4.0σ
ΔC_{10}^e	-2.36 $+0.35$	2.2	4.0σ

$\rightarrow$ NP in C_9^e, C_9^μ, C_{10}^e, or C_{10}^μ are favoured by the $R_{K^{(*)}}$ ratios (significance: $3.6-4.0\sigma$)

$\rightarrow$ NP contributions in primed operators do not play a role.

Best fit values considering all observables besides R_K and R_{K^*}

(under the assumption of 10% non-factorisable power corrections)

	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull_{SM}}$
ΔC_9	-0.24	70.5	4.1σ
$\Delta C_9'$	-0.02	87.4	0.3σ
ΔC_{10}	-0.02	87.3	0.4σ
$\Delta C_{10}'$	$+0.03$	87.0	0.7σ
ΔC_9^μ	-0.25	68.2	4.4σ
ΔC_9^e	$+0.18$	86.2	1.2σ
ΔC_{10}^μ	-0.05	86.8	0.8σ
ΔC_{10}^e	-2.14 $+0.14$	86.3	1.1σ

$\rightarrow$ C_9 and C_9^μ solutions are favoured with SM pulls of 4.1 and 4.4σ

$\rightarrow$ Primed operators have a very small SM pull

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

Separate NP fits with a single operator

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

data of 2017 (with R_{K^*} !)

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

	b.f. value	$\chi^2_{\rm min}$	${\rm Pull_{SM}}$
ΔC_9	-0.48	18.3	0.3σ
$\Delta C_9'$	$+0.78$	18.1	0.6σ
ΔC_{10}	-1.02	18.2	0.5σ
$\Delta C_{10}'$	$+1.18$	17.9	0.7σ
ΔC_9^μ	-0.35	5.1	3.6σ
ΔC_9^e	$+0.37$	3.5	3.9σ
ΔC_{10}^μ	-1.66 -0.34	2.7	4.0σ
ΔC_{10}^e	-2.36 $+0.35$	2.2	4.0σ

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

	b.f. value	$\chi^2_{\rm min}$	${\rm Pull_{SM}}$
ΔC_9	-0.24	70.5	4.1σ
$\Delta C_9'$	-0.02	87.4	0.3σ
ΔC_{10}	-0.02	87.3	0.4σ
$\Delta C_{10}'$	$+0.03$	87.0	0.7σ
ΔC_9^μ	-0.25	68.2	4.4σ
ΔC_9^e	$+0.18$	86.2	1.2σ
ΔC_{10}^μ	-0.05	86.8	0.8σ
ΔC_{10}^e	-2.14 $+0.14$	86.3	1.1σ

Slight decoherence between the two subsets

Separate NP fits with a single operator

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

data of 2017 (with R_{K^*} !)

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

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

Within chiral basis: Slight decoherence between the two subsets again

	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
$\Delta C_9^\mu = -\Delta C_{10}^\mu$ ($\Delta C_{\rm LL}^\mu$)	-0.16	3.4	3.9σ
$\Delta C_9^e = -\Delta C_{10}^e$ ($\Delta C_{\rm LL}^e$)	$+0.19$	2.8	4.0σ
$\Delta C_9^{\mu\prime} = -\Delta C_{10}^{\mu\prime}$ ($\Delta C_{\rm RL}^\mu$)	-0.01	18.3	0.4σ
$\Delta C_9^{e\prime} = -\Delta C_{10}^{e\prime}$ ($\Delta C_{\rm RL}^e$)	$+0.01$	18.3	0.4σ
$\Delta C_9^\mu = +\Delta C_{10}^\mu$ ($\Delta C_{\rm LR}^\mu$)	$+0.09$	17.5	1.0σ
$\Delta C_9^e = +\Delta C_{10}^e$ ($\Delta C_{\rm LR}^e$)	-0.55	1.4	4.1σ
$\Delta C_9^{\mu\prime} = +\Delta C_{10}^{\mu\prime}$ ($\Delta C_{\rm RR}^\mu$)	-0.01	18.4	0.2σ
$\Delta C_9^{e\prime} = +\Delta C_{10}^{e\prime}$ ($\Delta C_{\rm RR}^e$)	$+0.61$	2.0	4.1σ

	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
$\Delta C_9^\mu = -\Delta C_{10}^\mu$ ($\Delta C_{\rm LL}^\mu$)	-0.10	79.4	2.8σ
$\Delta C_9^e = -\Delta C_{10}^e$ ($\Delta C_{\rm LL}^e$)	$+0.08$	86.3	1.1σ
$\Delta C_9^{\mu\prime} = -\Delta C_{10}^{\mu\prime}$ ($\Delta C_{\rm RL}^\mu$)	-0.01	87.3	0.4σ
$\Delta C_9^{e\prime} = -\Delta C_{10}^{e\prime}$ ($\Delta C_{\rm RL}^e$)	-0.01	87.0	0.7σ
$\Delta C_9^\mu = +\Delta C_{10}^\mu$ ($\Delta C_{\rm LR}^\mu$)	-0.12	79.5	2.8σ
$\Delta C_9^e = +\Delta C_{10}^e$ ($\Delta C_{\rm LR}^e$)	$+0.50$ -1.12	85.8 86.7	1.3σ 0.9σ
$\Delta C_9^{\mu\prime} = +\Delta C_{10}^{\mu\prime}$ ($\Delta C_{\rm RR}^\mu$)	$+0.03$	87.1	0.6σ
$\Delta C_9^{e\prime} = +\Delta C_{10}^{e\prime}$ ($\Delta C_{\rm RR}^e$)	-0.54	86.3	1.1σ

Adding the observable $B_s \to \mu\mu$ as C_{10}-discriminator to ratios has only a very mild effect.

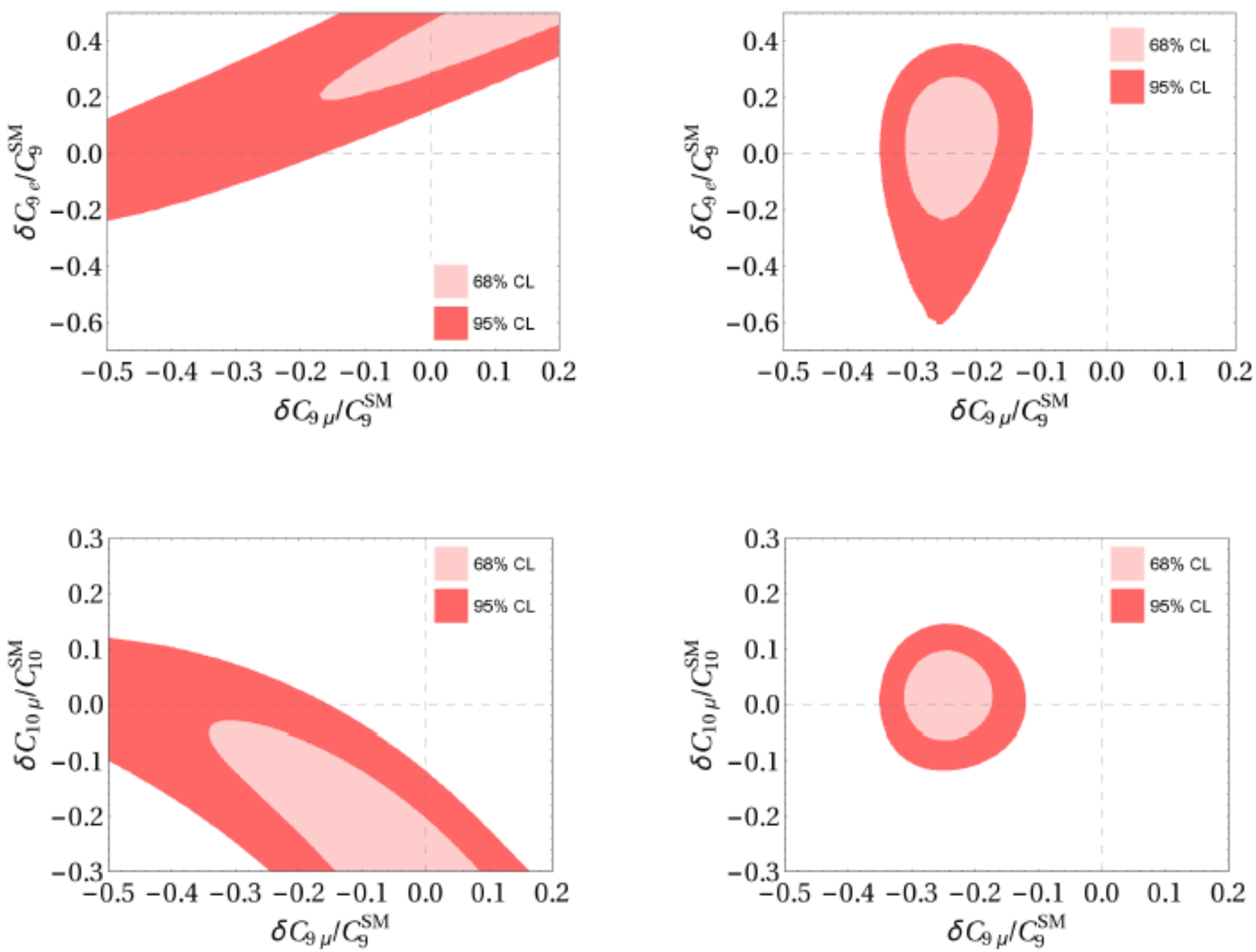
Separate NP fits with two operators

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

using only R_K and R_{K^*} — using all but R_K and R_{K^*}

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

$(C_9^\mu - C_{10}^\mu)$



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

Global fit to 108 $b \to s$ observable with 20 operators

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791

20 Wilson coefficients sensitive to NP: $C_7, C_8, C_9^\ell, C_{10}^\ell, C_{Q_1}^\ell, C_{Q_2}^\ell$

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

Set of WC	Nr. parameters	$\chi^2_{\rm min}$	Pull$_{\rm SM}$	Improvement
SM	0	118.2	-	-
C_9^μ	1	84.6	5.8σ	5.8σ
$C_9^{(e,\mu)}$	2	83.3	5.6σ	1.1σ
$C_7, C_8, C_9^{(e,\mu)}, C_{10}^{(e,\mu)}$	6	80.1	4.9σ	0.6σ
All non-primed WC	10	78.2	4.3σ	0.3σ
All WC (incl. primed)	20	70.2	3.5σ	0.5σ

- No real improvement in the fits when going beyond the C_9^μ case
- Pull with the SM decreases when all WC are varied
- Many parameters are not constrained

NP significance of 5.8σ in C_9^μ is based on the assumption of 10% error for power corrections

Future prospects

Future LHCb prospects for ratios R_K and R_{K^*}

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Pull_{SM} for the fit to ΔC_9^μ based on the ratios R_K and R_{K^*} for the LHCb upgrade

Assuming current central values remain.

ΔC_9^μ	Syst. Pull_{SM}	Syst./2 Pull_{SM}	Syst./3 Pull_{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

There is the possibility to establish NP already with 12 fb^{-1}

Future LHCb prospects for ratios R_K and R_{K^*}

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

Pull_{SM} for the fit to ΔC_9^μ based on the ratios R_K and R_{K^*} for the LHCb upgrade

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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

However, with R_K and R_{K^*} only, significance for all 6 favored NP scenarios, $\Delta C_9^{e,\mu}$,$\Delta C_{10}^{e,\mu}$, $\Delta C_{LL}^{e,\mu}$ very similar.

$B_s \to \mu\mu$ will not help in the future to decide which NP option is realized!

$B_s \to \mu\mu$ will not help in the future to decide which NP option is realized!

	Pull$_{\mathrm{SM}}$ with R_K and R_K^* [$+$ BR($B_s \to \mu^+\mu^-$)] prospects		
LHCb lum.	12 fb^{-1}	50 fb^{-1}	300 fb^{-1}
C_9^μ	7.4σ [7.4σ]	12.9σ [12.9σ]	19.5σ [19.5σ]
C_{10}^μ	8.1σ [7.6σ]	13.9σ [13.5σ]	20.8σ [20.6σ]

For R_K and R_{K^*} in each of the upgraded luminosities we have assumed the optimistic scenario with systematic errors reduced by a factor 3 with no correlation among the errors.

For BR($B_s \to \mu^+\mu^-$) we have considered the absolute experimental error to be 3.8×10^{-10}, 3.2×10^{-10}, 2.6×10^{-10} from the prospected LHCb results with 12, 50 and 300 fb^{-1} luminosity as well as the prospected ATLAS and CMS results.

Side remark: Restricting power of $B \to \mu\mu$ is related to C_{10}, but also to C_{Q_1}, C_{Q_2}

Other ratios allow to discriminate between the NP options

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

	Predictions assuming 12 fb^{-1} luminosity			
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.785, 0.913]$	$[0.909, 0.933]$	$[1.005, 1.042]$	$[1.001, 1.018]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[6.048, 14.819]$	$[-0.288, -0.153]$	$[0.816, 0.928]$	$[0.974, 1.061]$
$R_{S_5}^{[1.1,6.0]}$	$[-0.787, 0.394]$	$[0.603, 0.697]$	$[0.881, 1.002]$	$[1.053, 1.146]$
$R_{F_L}^{[15,19]}$	$[0.999, 0.999]$	$[0.998, 0.998]$	$[0.997, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.616, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{S_5}^{[15,19]}$	$[0.615, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{K^*}^{[15,19]}$	$[0.621, 0.803]$	$[0.577, 0.771]$	$[0.589, 0.778]$	$[0.586, 0.770]$
$R_{K}^{[15,19]}$	$[0.597, 0.802]$	$[0.590, 0.778]$	$[0.659, 0.818]$	$[0.632, 0.805]$
$R_{\phi}^{[1.1,6.0]}$	$[0.748, 0.852]$	$[0.620, 0.805]$	$[0.578, 0.770]$	$[0.578, 0.764]$
$R_{\phi}^{[15,19]}$	$[0.623, 0.803]$	$[0.577, 0.771]$	$[0.586, 0.776]$	$[0.583, 0.769]$

see also Capdevila et al., arXiv:1605.03156; Serra et al., arXiv:1610.08761

Back to the problem of nonfactorizable power corrections in angular observables

Crosscheck with $R_{\mu,e}$ ratios

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

NP in the ratios would indirectly confirm the NP interpretation

of the anomalies in the angular observables

(if there is a coherent picture)

Calculations beyond guessing numbers

Any unreasonable calculation is better than a fit (M.B.).

Methods offered in the analysis of $B \to K\ell^+\ell^-$ to calculate power corrections Kjodjamirian et al. arXIv: 1211.0234, also 1006.4945

Most recently: Estimate of power corrections based on analyticity structure Bobeth et al. arXiv:1707.07305

Towards complete SM predictions for the angular observables

LCOPE in the euclidean and then analytical continuation to the physical region (disperson relation or z-expansion).

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

	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

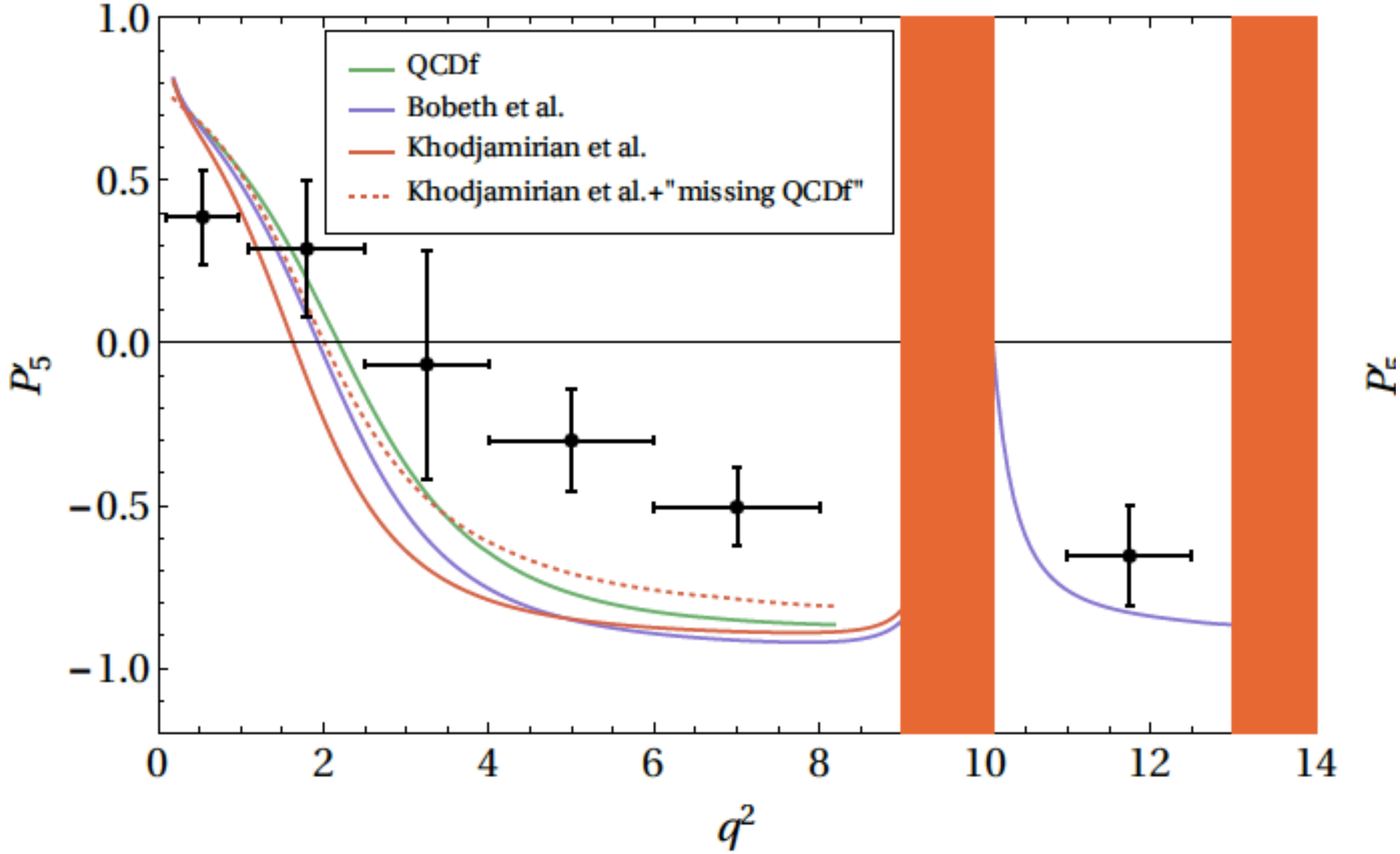
- Extrapolation by dispersion relation misses leading nonfact. QCDf contribution (not recommended in Khodjamirian et al. arXiv:1006.4945)

- Adding the QCDf piece in physical region after extrapolation is problematic (see i.e. PMD method in Ciuchini et al. arXiv:1704.05447)

- Bobeth et al. method is most complete and promising approach (see recent paper on convergence of z-expansion arXiv:1805.06378)

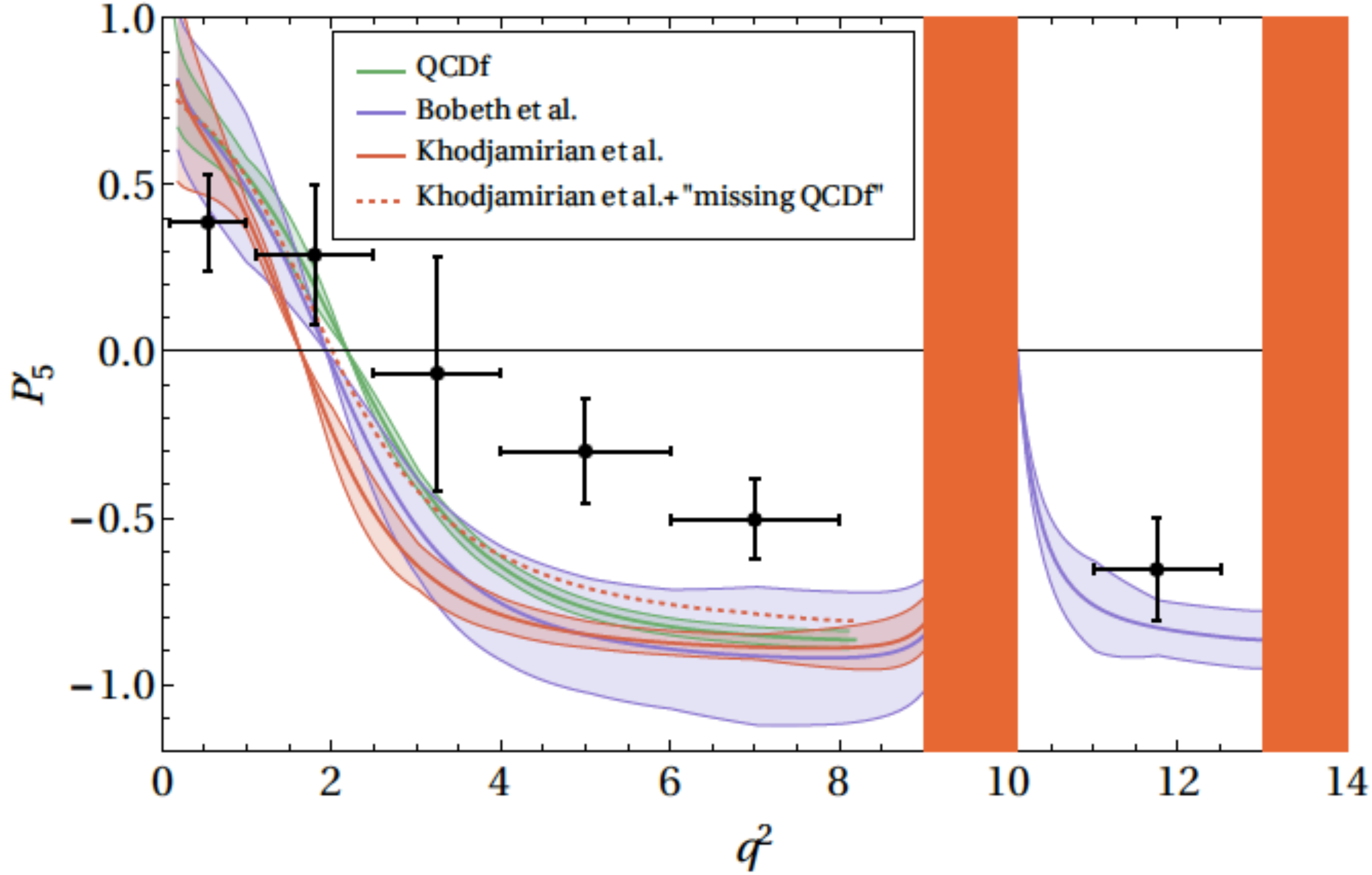
Comparison of various approaches

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791



Comparison of various approaches

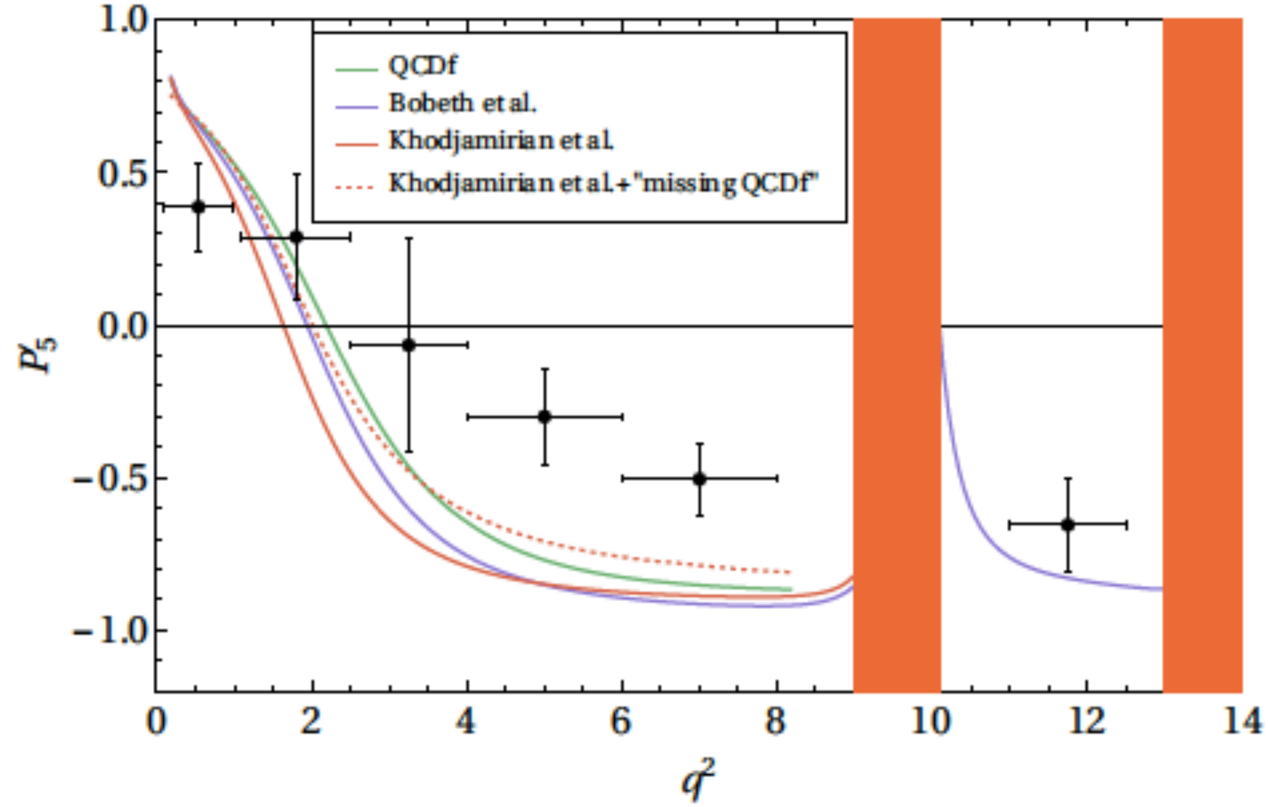
Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791

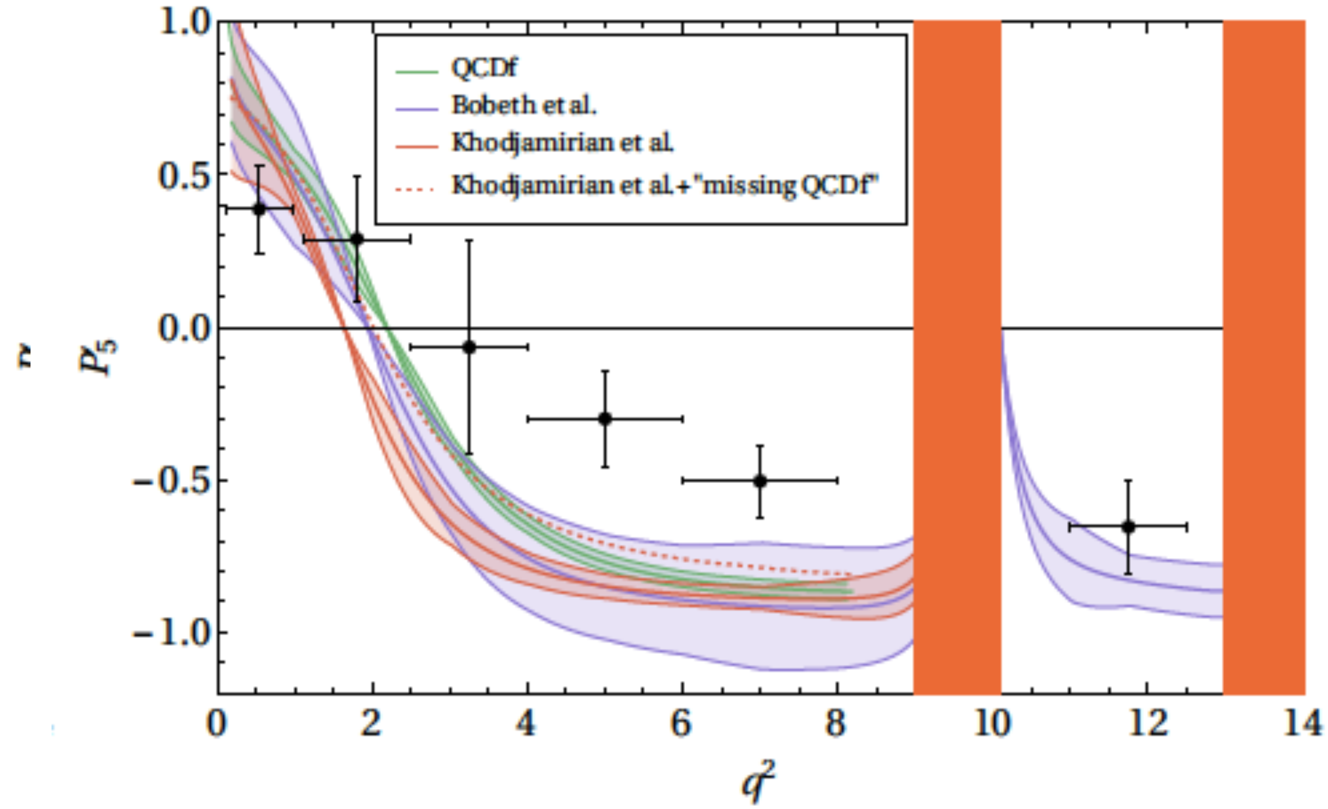


Correlations of theory errors are not given in Bobeth et al.

Comparison of various approaches

Arby,Hurth,Mahmoudi,Neshatpour arXiv: 1806.02791





Correlations of theory errors are not given in Bobeth et al.

NP significance

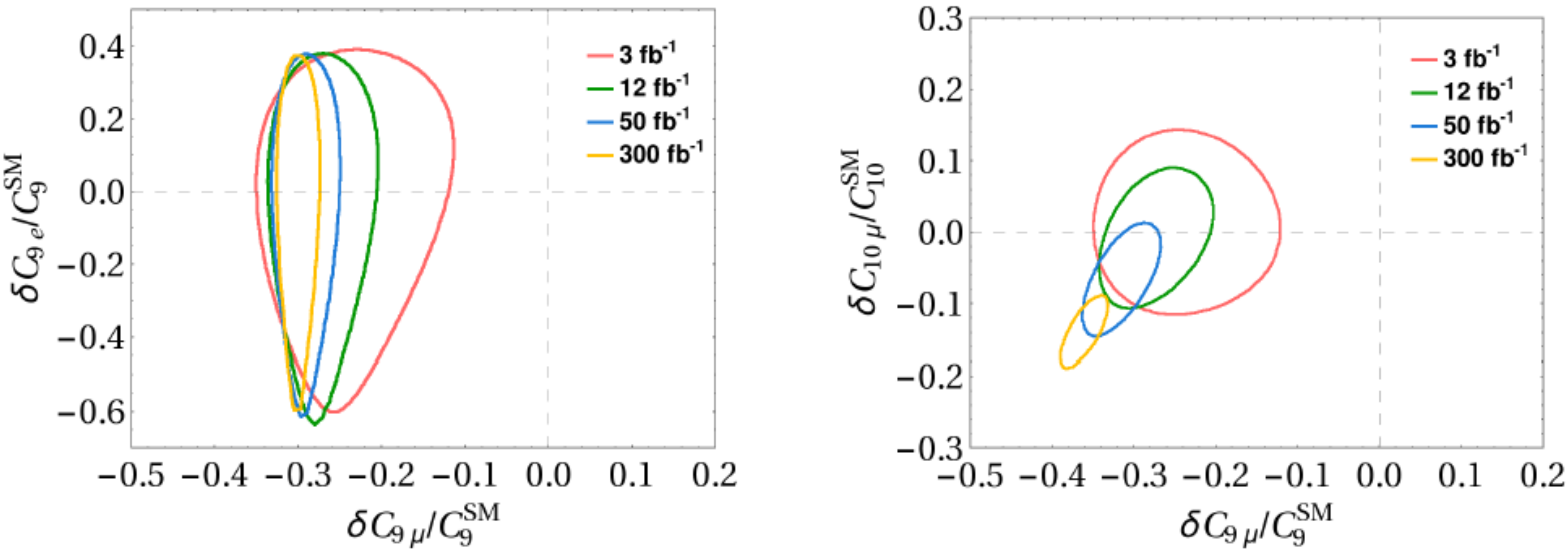
	SM	δC_7		δC_9		δC_{10}	
	b.f. value	b.f. value	$\chi^2_{\rm min}$	b.f. value	$\chi^2_{\rm min}$	b.f. value	$\chi^2_{\rm min}$
QCDf +"10%"	60.9	-0.03 ± 0.02	$58.9(1.4\sigma)$	-1.05 ± 0.21	$45.4(3.9\sigma)$	-0.17 ± 0.35	$60.7(0.5\sigma)$
Bobeth et al.	54.8	-0.03 ± 0.03	$53.5(1.1\sigma)$	-1.26 ± 0.28	$43.9(3.3\sigma)$	0.48 ± 0.63	$54.1(0.8\sigma)$

Future LHCb prospects for the angular observables

Hurth, Mahmoudi, Martinez Santos, Neshatpour arXiv: 1705.06274

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

Considering several luminosities, assuming the current central values

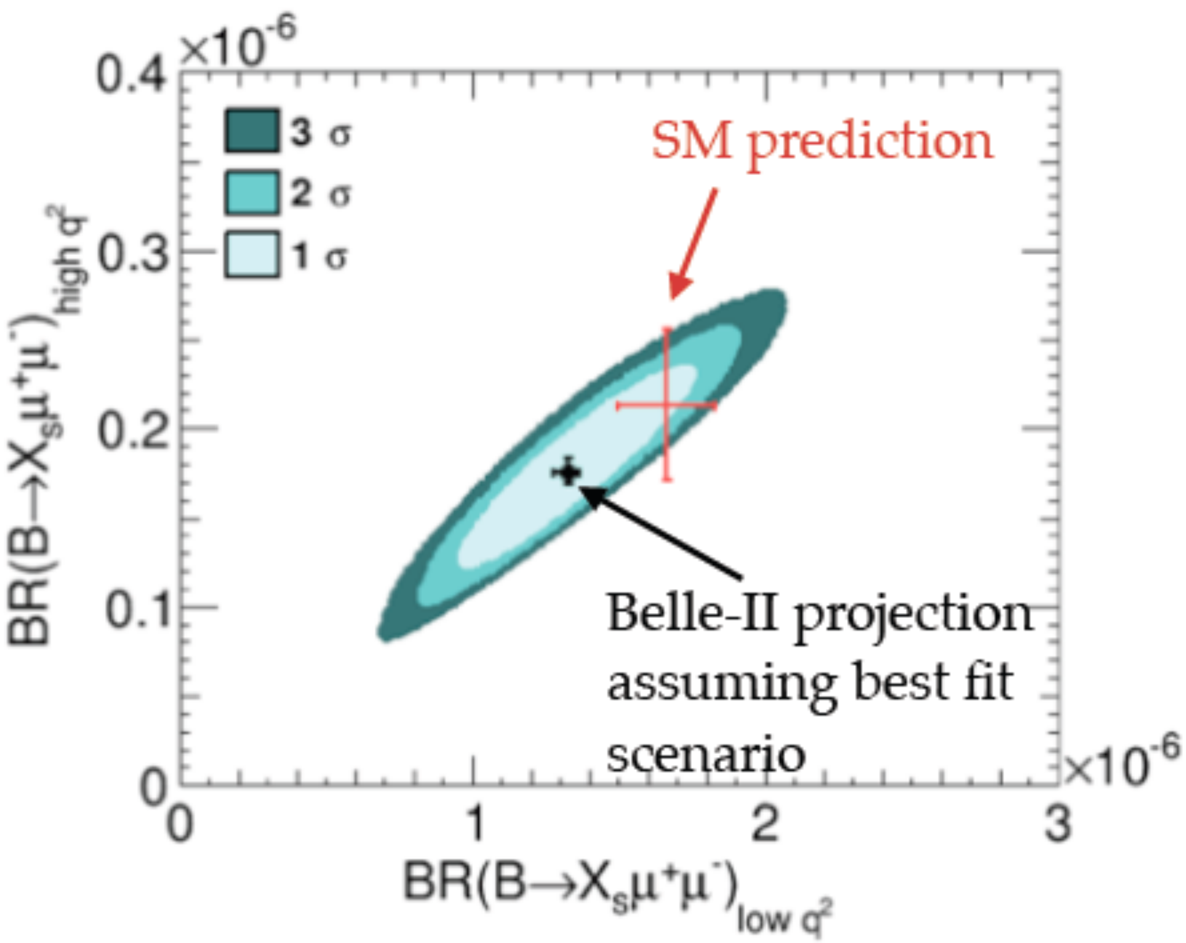


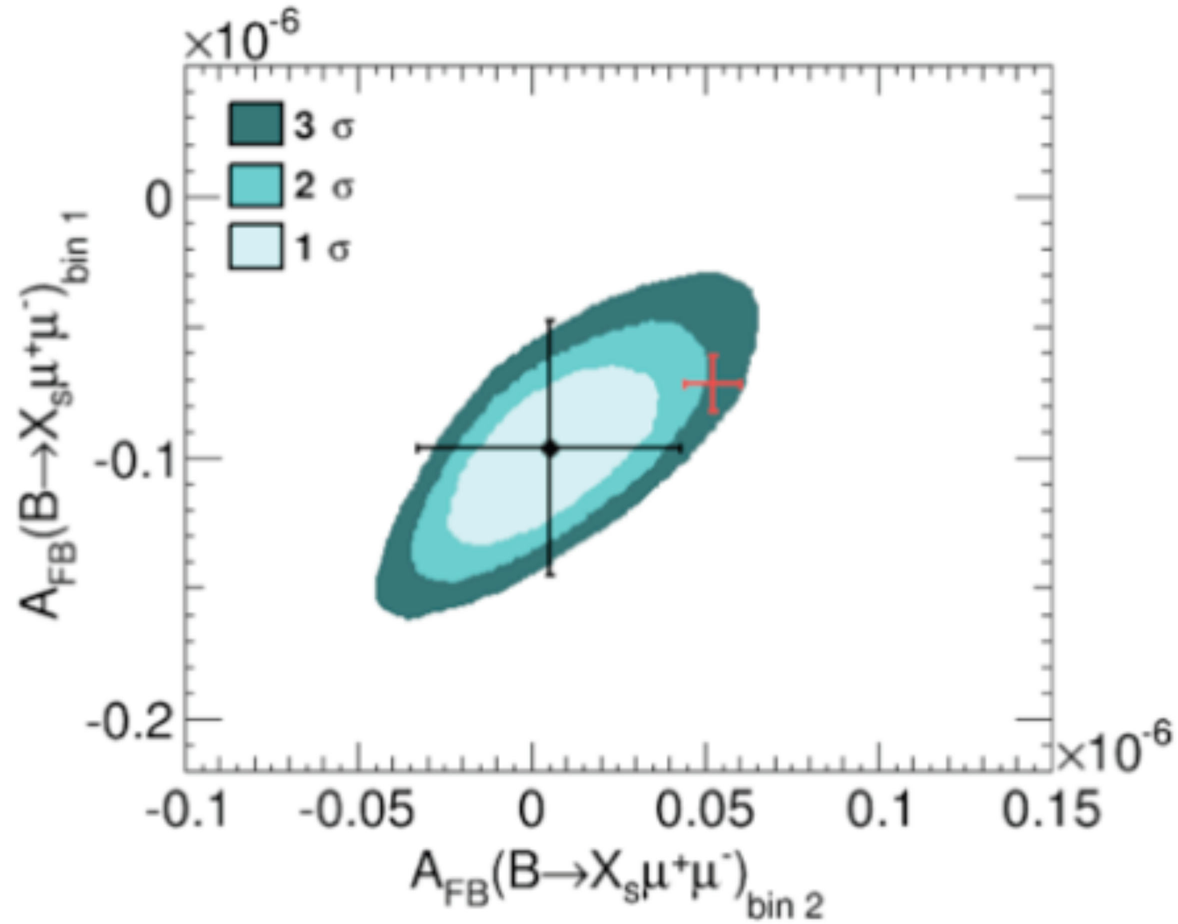
LHCb upgrade will be able to distinguish between NP and hadronic effects within the angular observables – even without any theoretical progress

Crosscheck of LHCb anomalies with inclusive modes

Hurth, Mahmoudi, Neshatpour, arXiv:1410.4545

if SM deviations in R_K and P_5' persist until Belle-II





If NP then the effect of C_9 and C_9' are large enough to be checked at Belle-II with theoretically clean modes.

Hurth, Mahmoudi, arXiv:1312.5267 Experimental extrapolation by Kevin Flood

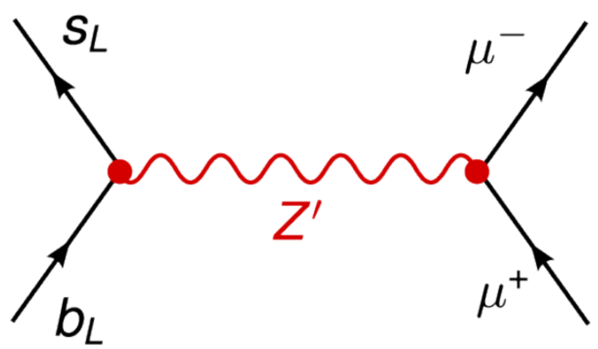
Extra

New physics explanations (1σ solutions)

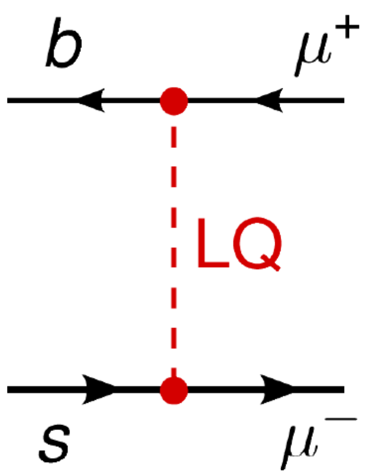
Difficult to generate $\delta C_9 = -1$ at loop level (MSSM with MFV)

Various models under discussion (tree level contributions):

Z' bosons



Leptoquarks



Altmannshofer, Straub arXiv:1308.1501
Gauld, Goertz, Haisch arXiv:1308.1959;1310.1082
Buras,De Fazio,Girrbach arXiv:1311.6729
Altmannshofer,Gori,Pospelov,Yavin arXiv:1403.1269
...

Hiller, Schmaltz arXiv:1408.1627
Sahoo, Mohanta arXiv:1501.05193
Becirevic, Fajfer, Kosnik arXiv:1503.09024
Bauer, Neubert arXiv:1511.01900 (loop)
...

Model explaining all anomalies by one leptoquark

Bauer, Neubert arXiv:1511.01900

- $$R_{D^{(*)}}^{\tau/l} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})/\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{SM}}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})/\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\nu})_{SM}}$$

  3.9σ deviation from $\tau - \mu/e$ universality

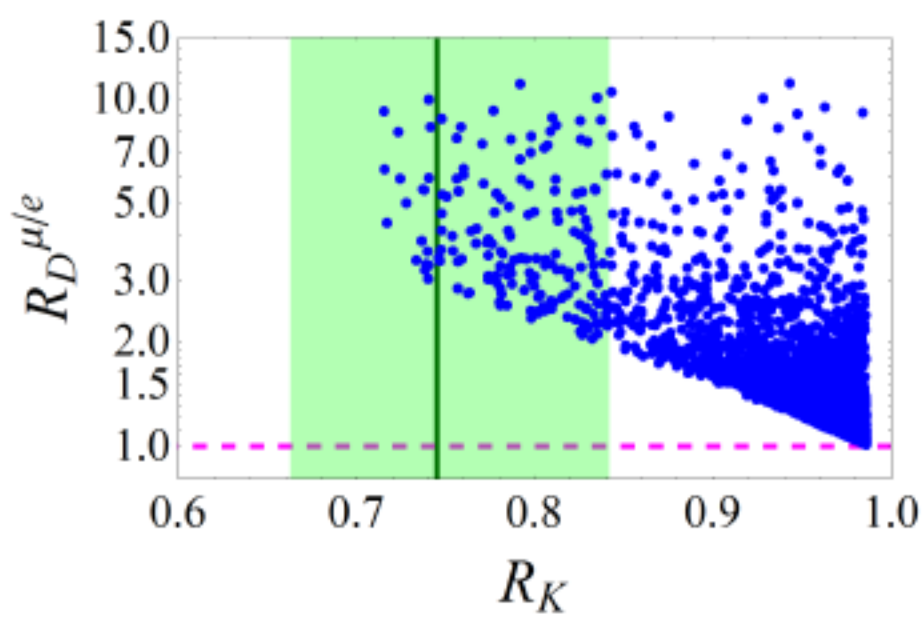
- $$R_K^{\mu/e} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

  2.6σ deviation from $\mu - e$ universality

- $(g-2)_\mu$

Problem with $R_D^{\mu/e}$?

Becirevic et al. arXiv:1608.07583



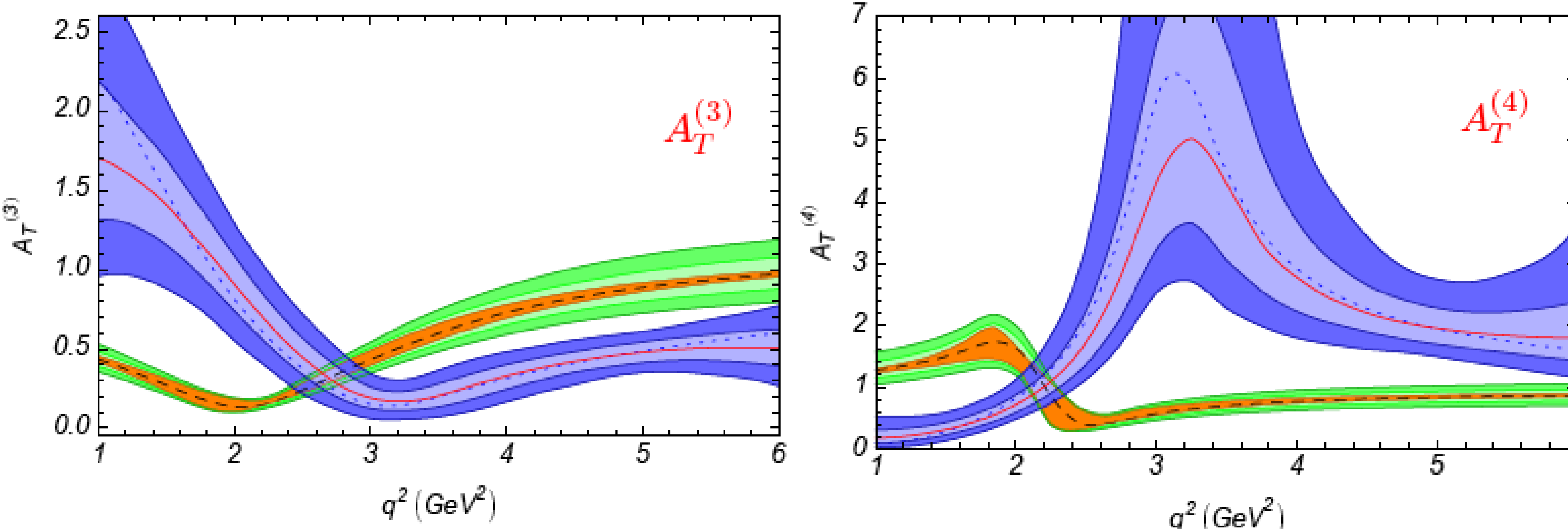
Previous predictions versus LHCb Monte Carlo (10 fb^1)

Egede,Hurth,Matias,Ramon,Reece,arXiv:0807.2589,arXiv:1005.0571

– unknown Λ/m_b power corrections

$A_{\perp,\|,0} = A^0_{\perp,\|,0}\,(1 + c_{\perp,\|,0})$ vary c_i in a range of $\pm 10\%$ and also of $\pm 5\%$

Guesstimate



The experimental errors assuming SUSY scenario (b) with large-gluino mass and positive mass insertion, is compared to the theoretical errors assuming the SM.

This was the dream in 2008

see also Altmannshofer et al.,arXiv:0811.1214; Bobeth et al.,arXiv:0805.2525

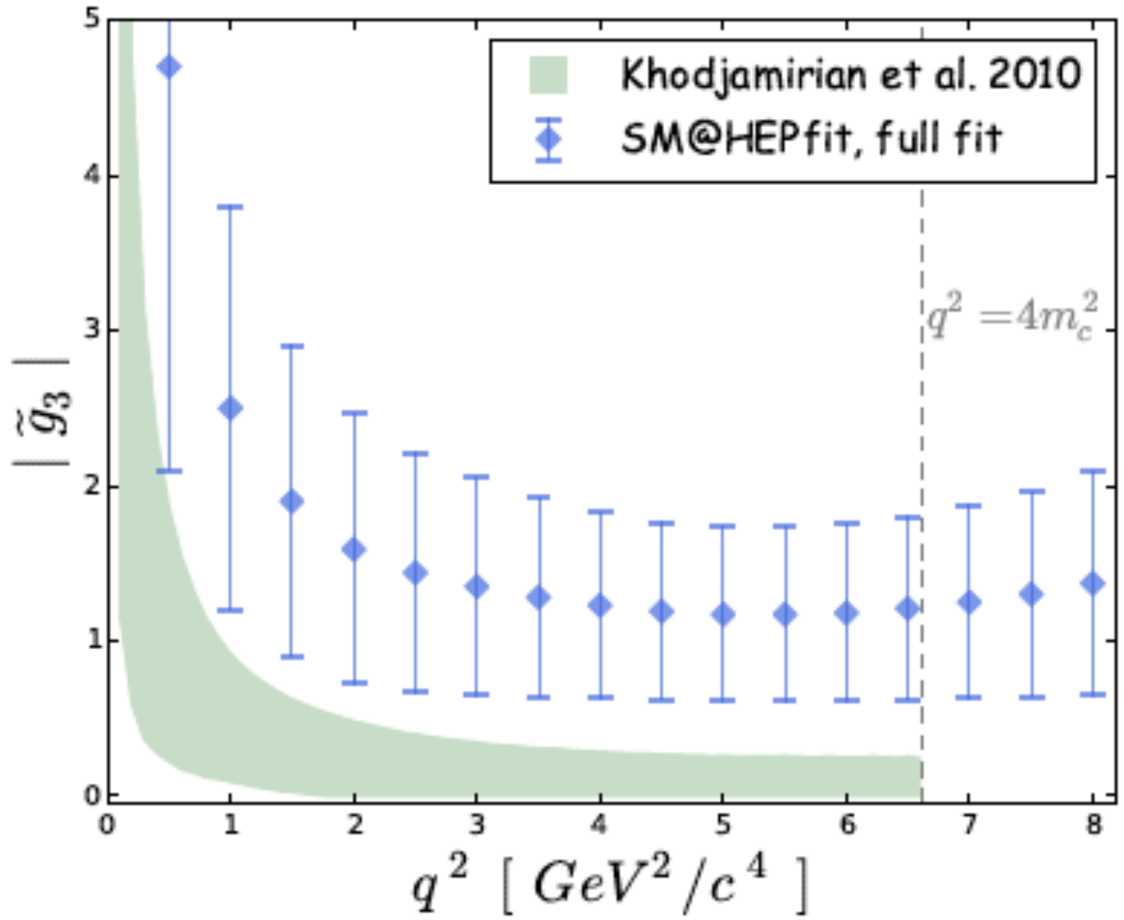
Fit the unknown power corrections to the data

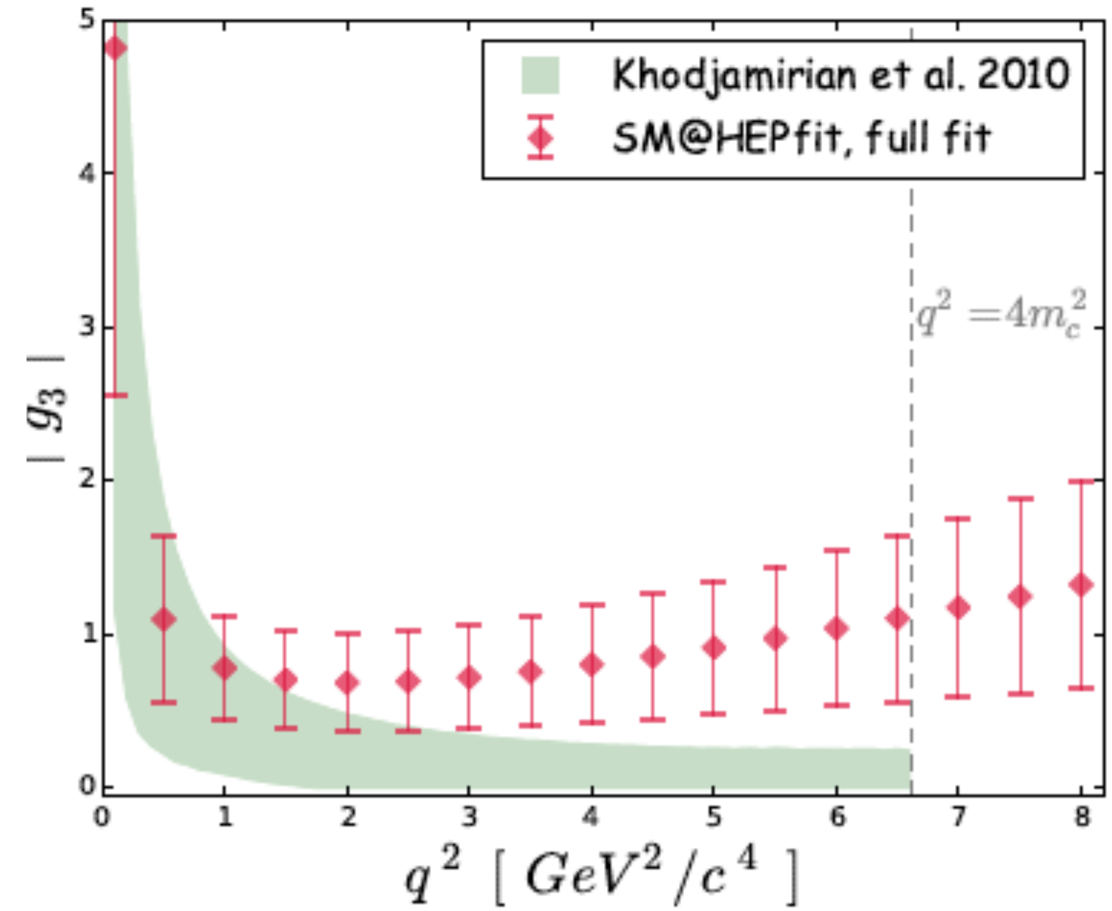
Ciuchini et al. arXiv:1512.07157

data of 2015/2016

Leading SCET amplitude with general ansatz with 18 parameters for power corrections Camalich,Jäger arXiv:1212.2263

Fit needs 20 – 50% power corrections (on the observable level)





No sign for q^2 dependence in the theory-independent fit

Significant q^2 dependence if power corrections are fixed at 1GeV via result of LCSR calculation Kjodjamirian et al. arXiv:1211.0234

Power corrections in QCD improved factorization

$$\mathcal{T}_a^{(i)} = \xi_a C_a^{(i)} + \phi_B \otimes T_a^{(i)} \otimes \phi_{a,K^*} + O(1/m_b)$$ BBNS 1999

Power corrections cannot be calculated within QCDf in general.

$\rightarrow$ Significance of the tensions in the angular observables depend on the assumptions on the power corrections.

Fit of the power corrections to the data:
Ciuchini et al. (arXiv:1512.07157): Fit produces 20-50% nonfact. power corrections on the observable level in the critical bins.

Variation of power corrections $(1 + C_i)$ or more sophisticated ansatz:
Hurth et al. (arXiv:1603.00865): Assumption of 60% (10%) nonfact. power corrections on the amplitude level lead to 17-20% (3%) on the observable level (S_3, S_4, S_5) only.

Do large power corrections at $\mathcal{O}(50\%)$ - on the observable level - question the validity of the QCDf ansatz?