Rare B-decay anomalies: finding NP with $B \to K^* \mu^+ \mu^-$

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In collaboration with T. Hurth, N. Mahmoudi

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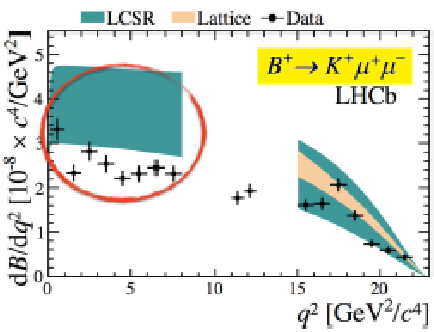
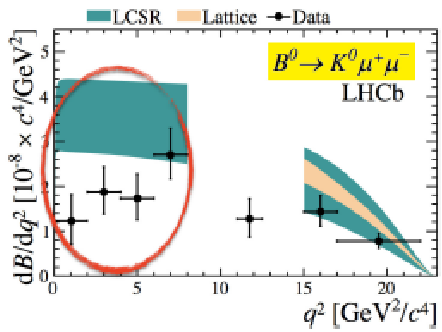
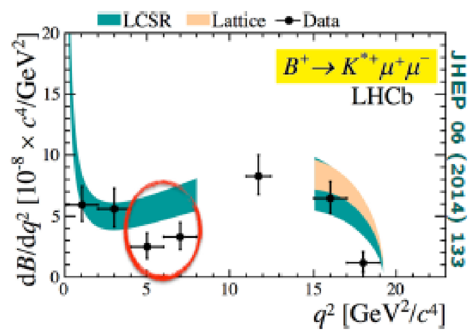
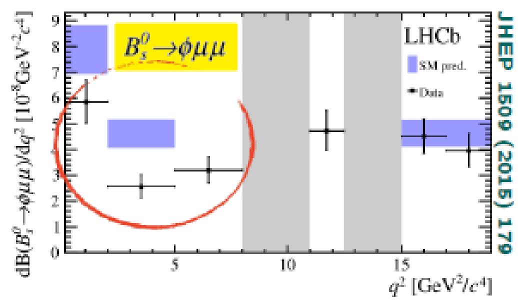
Several deviations ("anomalies") with respect to the SM predictions in $b \to s\ell\ell$ measurements

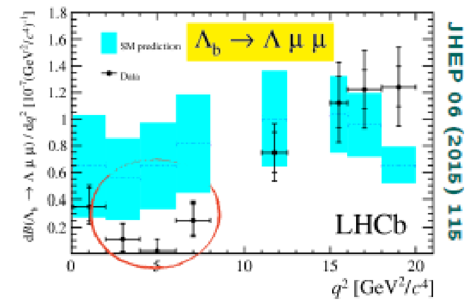
- Branching fractions:
  - $B \to K\mu^+\mu^-$
  - $B \to K^*\mu^+\mu^-$
  - $B_s \to \phi\mu^+\mu^-$
  - $\Lambda_b \to \Lambda\mu^+\mu^-$



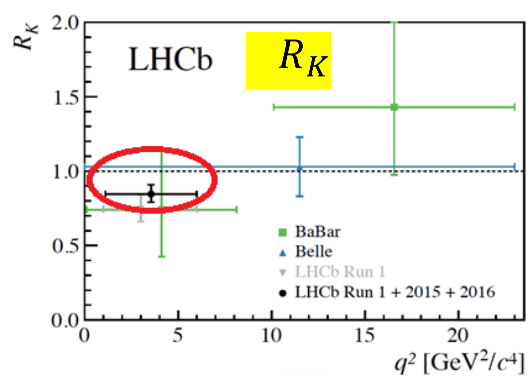


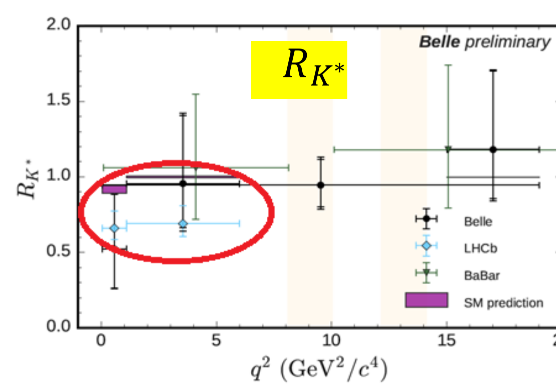






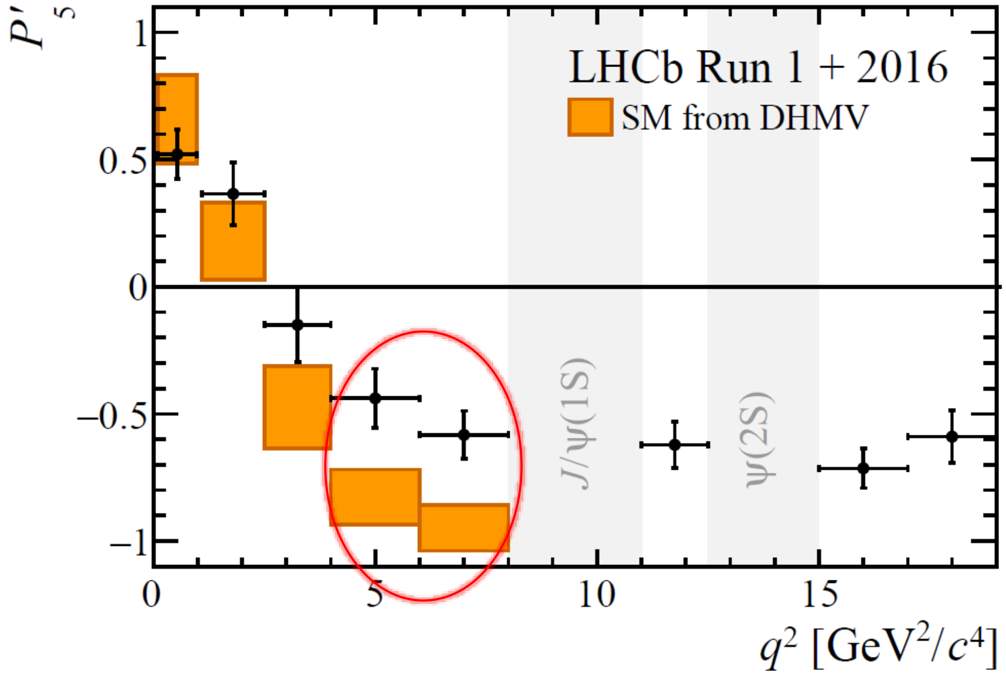
- Lepton flavour violating ratios:
  - R_K
  - R_{K^*}





Several deviations ("anomalies") with respect to the SM predictions in $b \to s\ell\ell$ measurements

- Long standing anomaly in the $B \to K^* \mu^+ \mu^-$ angular observable P'_5 / S_5 $\left(= P'_5 \times \sqrt{F_L(1-F_L)}\right)$
  - 2013 LHCb (1 fb^{-1})
  - 2016 LHCb (3 fb^{-1})
  - 2020 LHCb (4.7 fb^{-1})



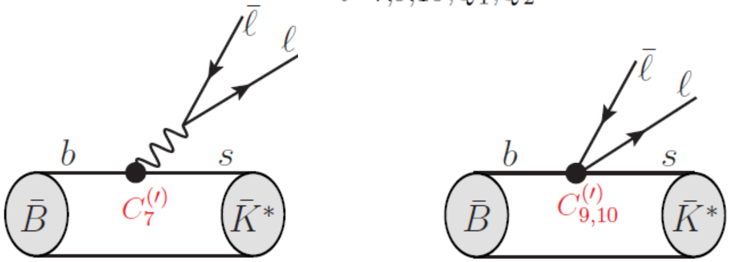
[E. Smith CERN Seminar '20
LHCb 2003.04831]

- 2.5σ & 2.9σ local tension in P'_5 with the respect SM predictions (DHMV)
- deviations in other angular observables/bins

Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\text{eff}} = \mathcal{H}_{\text{eff}}^{\text{had}} + \mathcal{H}_{\text{eff}}^{\text{sl}}$

$$\mathcal{H}_{\text{eff}}^{\text{had}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=1...6} C_i(\mu) O_i(\mu) + C_8(\mu) O_8(\mu) \Big]$$

$$\mathcal{H}_{\text{eff}}^{\text{sl}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=7,9,10,Q_1,Q_2} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) \Big]$$



factorisable contributions:
7 independent form factors $\tilde{V}_{\pm,0}, \tilde{T}_{\pm,0}, \tilde{S}$

[Khodjamirian et al. '10, Bharucha et al. '15, Gubernari et al. '18]

Helicity amplitudes:

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

$$H_A(\lambda) = -i\, N' (C_{10} - C_{10}') \tilde{V}_\lambda(q^2)$$

$$H_P = i\, N' \Big\{ \frac{2\, m_\ell \hat{m}_b}{q^2} (C_{10} - C_{10}') \Big(1 + \frac{m_s}{m_b} \Big) \tilde{S}(q^2) \Big\}$$

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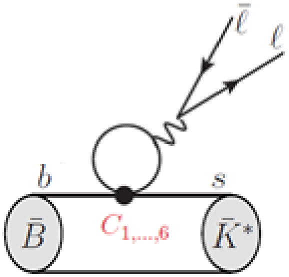

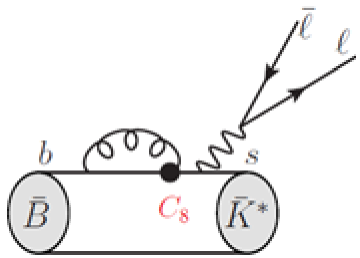

non-local effects: in general "naïve" factorization not applicable

$$\frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\underbrace{Y(q^2)\tilde V_\lambda}_{\text{fact., perturbative}} + \underbrace{\text{LO in } \mathcal{O}\big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\big)}_{\text{non-fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections,}} \Big]$$

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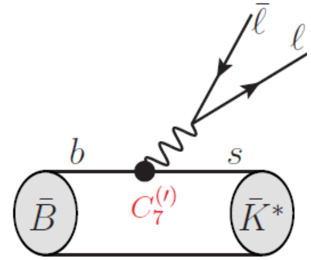

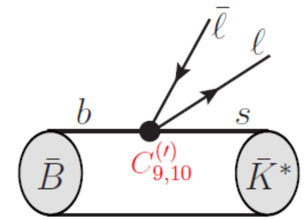

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- To distinguish hadronic effects from NP in $C_{7,9}$ good control over hadronic contributions needed

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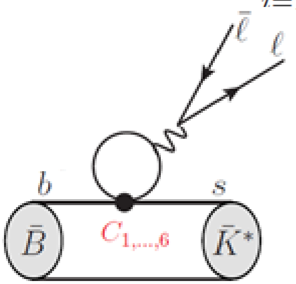

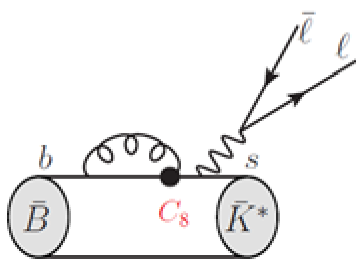

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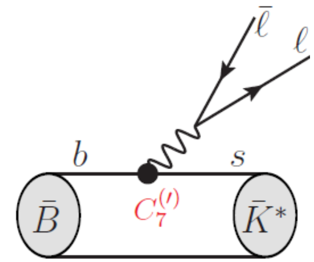

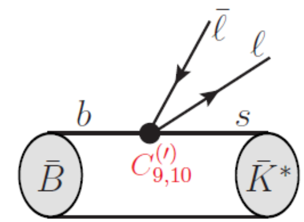

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Calculated at LO in QCD factorisation [Beneke et al. '01 & '04], but higher powers are unknown

- partial calculation with LCSR and dispersion relations [Khodjamirian et al. 1006.4945]
- recent progress exploiting analyticity of amplitudes [Bobeth et al. 1707.07305] & ongoing work or van Dyk et al.

Power corrections often "guesstimated"

➢ Significance of tensions in $B \to K^* \mu^+ \mu^-$ angular observables depends on the choice of "guesstimate" made for the size of the power corrections (h_λ)

NP effect vs. hadronic contributions

Instead of making assumptions on the size of the power corrections h_λ, they can be parameterised by a general ansatz (compatible with the analyticity structure): [Jäger, Camalich, 1412.3183], [Ciuchini et al. 1512.07157]

$$h_{\pm,[0]} = \left[\sqrt{q^2}\times\right] \left(h^{(0)}_{\pm,[0]} + q^2\, h^{(1)}_{\pm,[0]} + q^4\, h^{(2)}_{\pm,[0]}\right)$$

$\Longrightarrow$ NP effects in C_9 are embedded in the hadronic contributions [A. Arbey, T. Hurth, F. Mahmoudi, SN, 1806.02791]

Due to the embedding, fits to NP and hadronic contributions can be compared with the Wilks' test

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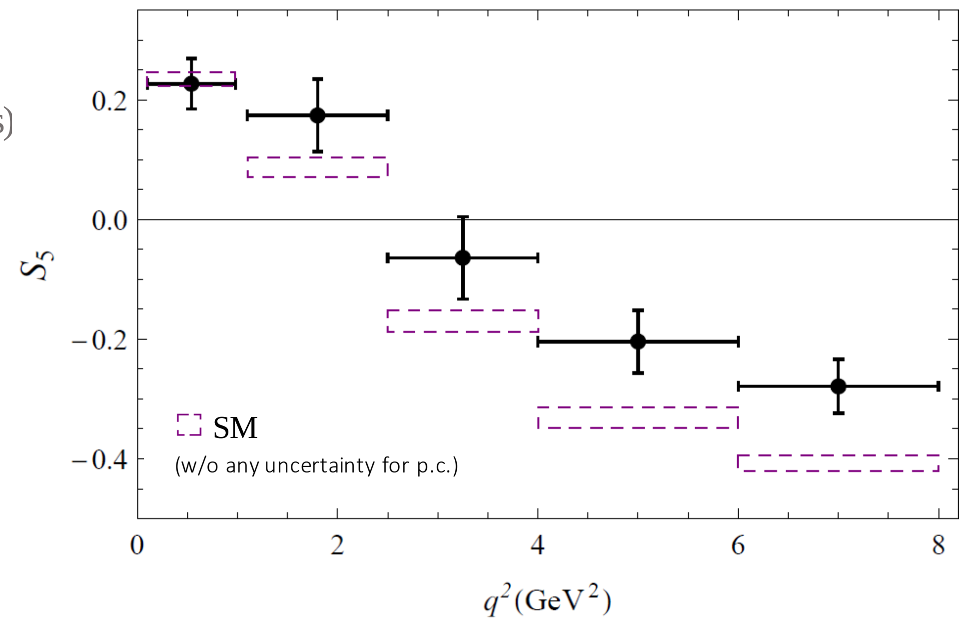
Fit to

- Wilson coefficient $\delta C_9^{\rm NP}$
- Hadronic quantities $h^{(0,1,2)}_{+,-,0}$ (18 parameters)

$B \to K^*\mu^+\mu^-$ observables (low q^2) and BR($B \to K^*\gamma$)



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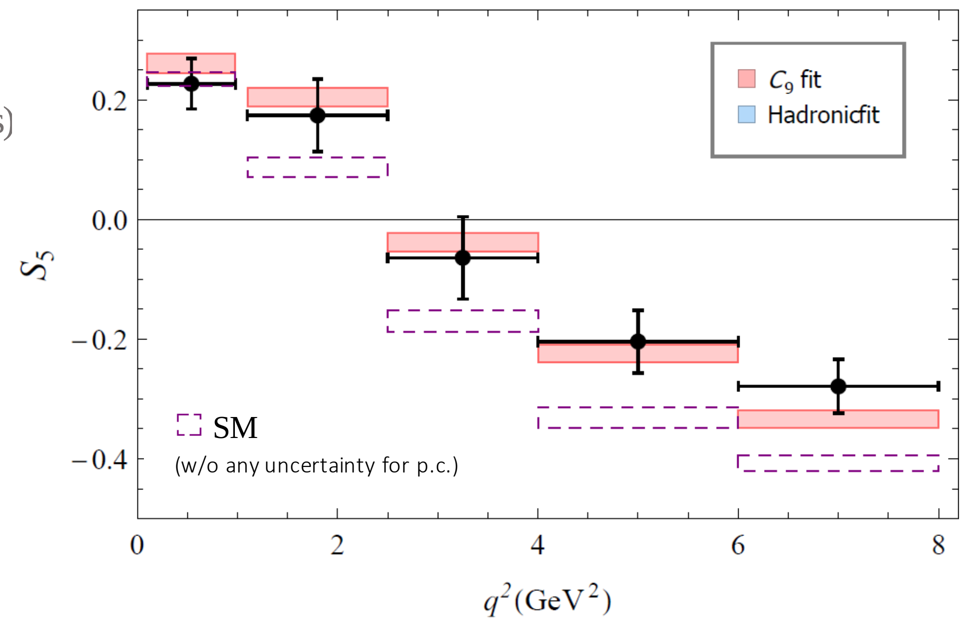
	Real δC_9 (1)	Hadronic fit (18)
Plain SM	(6.0σ)	(4.7σ)
Real δC_9	--	(1.5σ)



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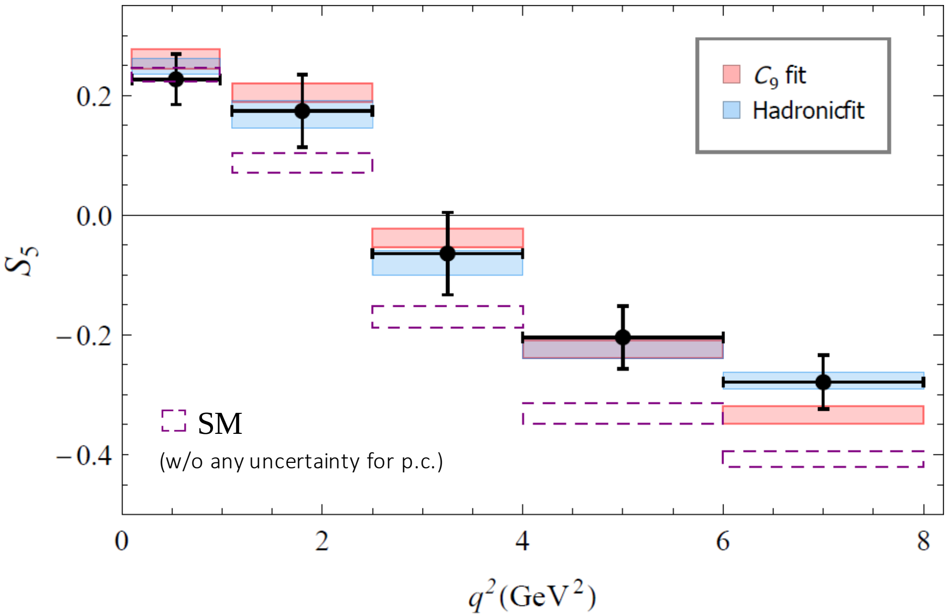

- Fit to δC_9 improves description of the data with 6σ compared to the SM (w/o any uncertainty for p.c.)
- Hadronic fit also describes the data well, however adding 17 more parameters compared to the NP in C_9 doesn't significantly improve the fit ($\sim 1.5\sigma$)

The hadronic fit includes 18 free parameters

$B \to K^* \bar{\mu}\mu/\gamma$ observables ($\chi^2_{SM} = 85.15$, $\chi^2_{min} = 25.96$; $\mathrm{Pull}_{SM} = 4.7\sigma$)		
	Real	Imaginary
$h_+^{(0)}$	$(-2.37 \pm 13.50) \times 10^{-5}$	$(7.86 \pm 13.79) \times 10^{-5}$
$h_+^{(1)}$	$(1.09 \pm 1.81) \times 10^{-4}$	$(1.58 \pm 1.69) \times 10^{-4}$
$h_+^{(2)}$	$(-1.10 \pm 2.66) \times 10^{-5}$	$(-2.45 \pm 2.51) \times 10^{-5}$
$h_-^{(0)}$	$(1.43 \pm 12.85) \times 10^{-5}$	$(-2.34 \pm 3.09) \times 10^{-4}$
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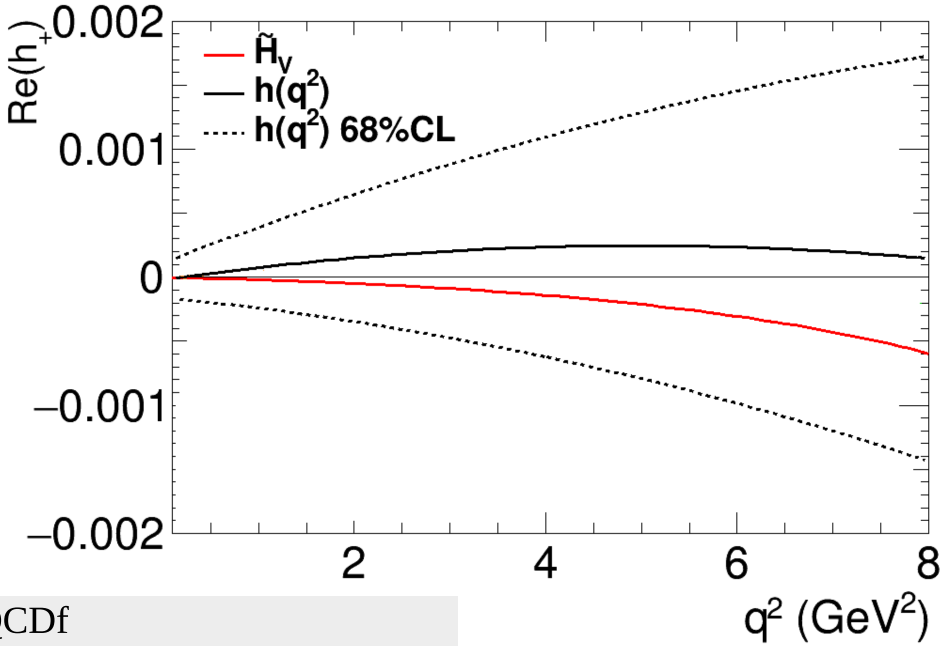

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Solid black line: h_λ
Dashed black line: 68% C.L. region of h_λ fit

- h_λ compatible with zero at 1σ level

$\longrightarrow$ too many free parameters to get strongly constrained with current data

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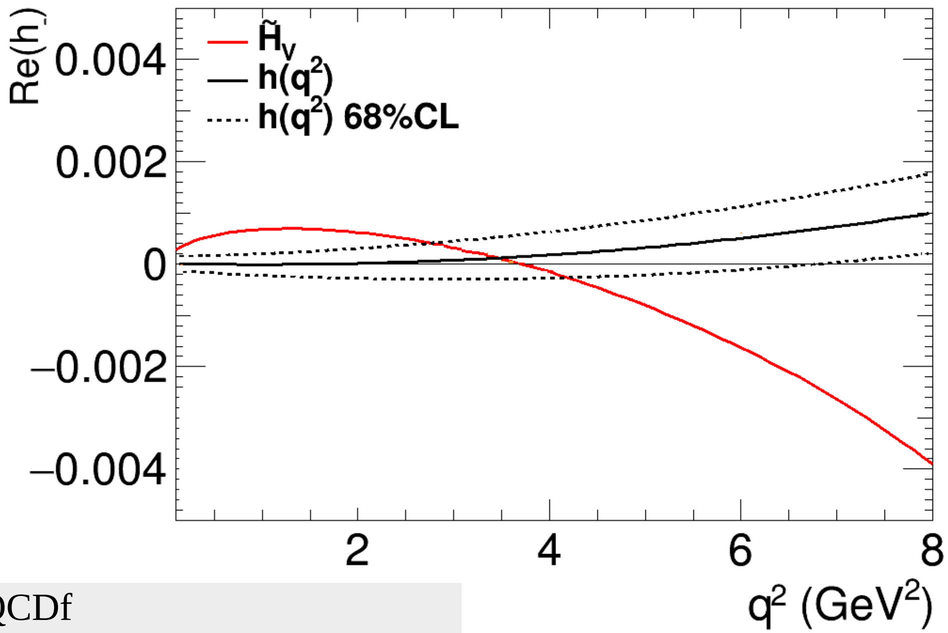

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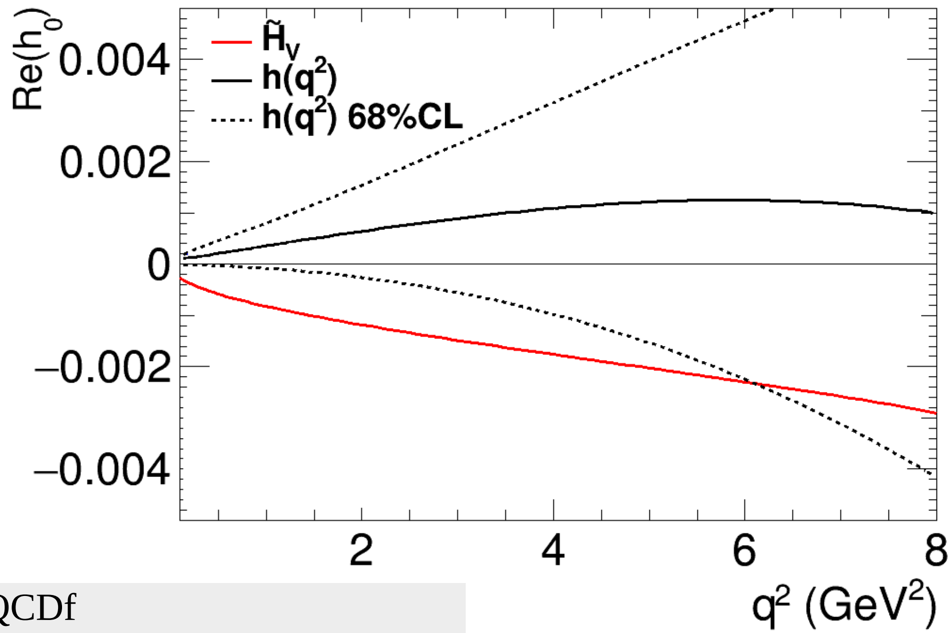

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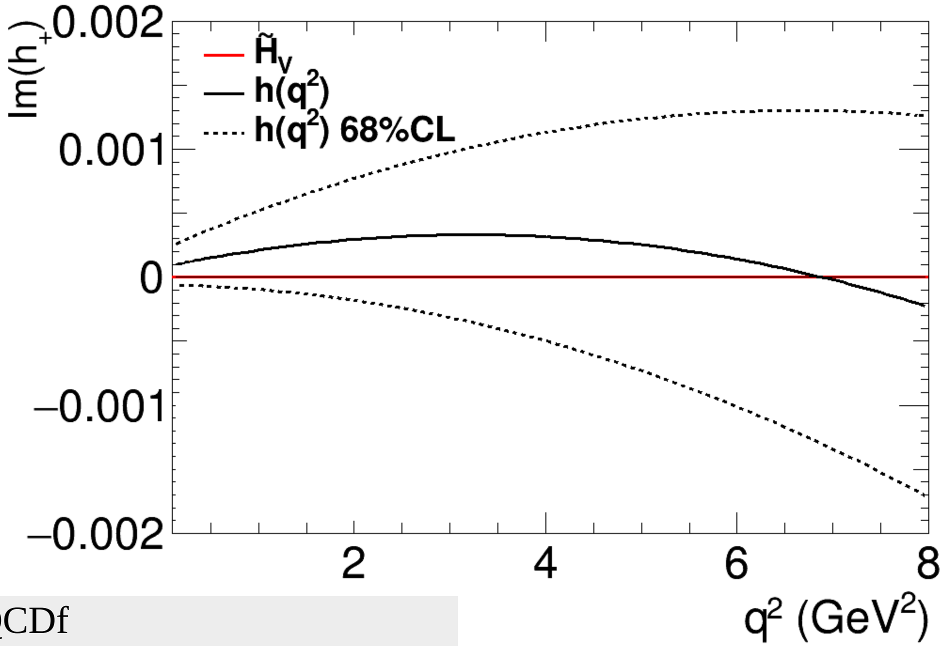

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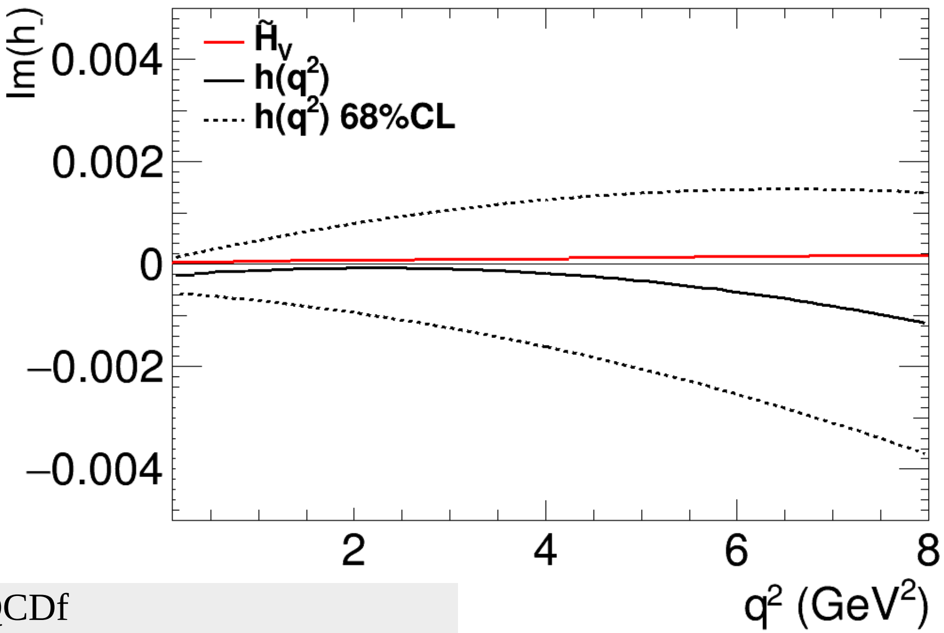
$h_-^{(2)}$	$(2.04 \pm 1.16) \times 10^{-5}$	$(-3.25 \pm 3.98) \times 10^{-5}$
$h_0^{(0)}$	$(2.38 \pm 2.43) \times 10^{-4}$	$(5.10 \pm 3.18) \times 10^{-4}$
$h_0^{(1)}$	$(1.40 \pm 1.98) \times 10^{-4}$	$(-1.66 \pm 2.41) \times 10^{-4}$
$h_0^{(2)}$	$(-1.57 \pm 2.43) \times 10^{-5}$	$(3.04 \pm 29.87) \times 10^{-6}$



Red line: LO QCDf
Solid black line: h_λ
Dashed black line: 68% C.L. region of h_λ fit

- h_λ compatible with zero at 1σ level

$\longrightarrow$ too many free parameters to get strongly constrained with current data

The hadronic fit includes 18 free parameters

	$B \to K^* \bar{\mu}\mu/\gamma$ observables ($\chi^2_{\rm SM} = 85.15,\ \chi^2_{\rm min} = 25.96;\ {\rm Pull}_{\rm SM} = 4.7\sigma$)	
	Real	Imaginary
$h_+^{(0)}$	$(-2.37 \pm 13.50) \times 10^{-5}$	$(7.86 \pm 13.79) \times 10^{-5}$
$h_+^{(1)}$	$(1.09 \pm 1.81) \times 10^{-4}$	$(1.58 \pm 1.69) \times 10^{-4}$
$h_+^{(2)}$	$(-1.10 \pm 2.66) \times 10^{-5}$	$(-2.45 \pm 2.51) \times 10^{-5}$
$h_-^{(0)}$	$(1.43 \pm 12.85) \times 10^{-5}$	$(-2.34 \pm 3.09) \times 10^{-4}$
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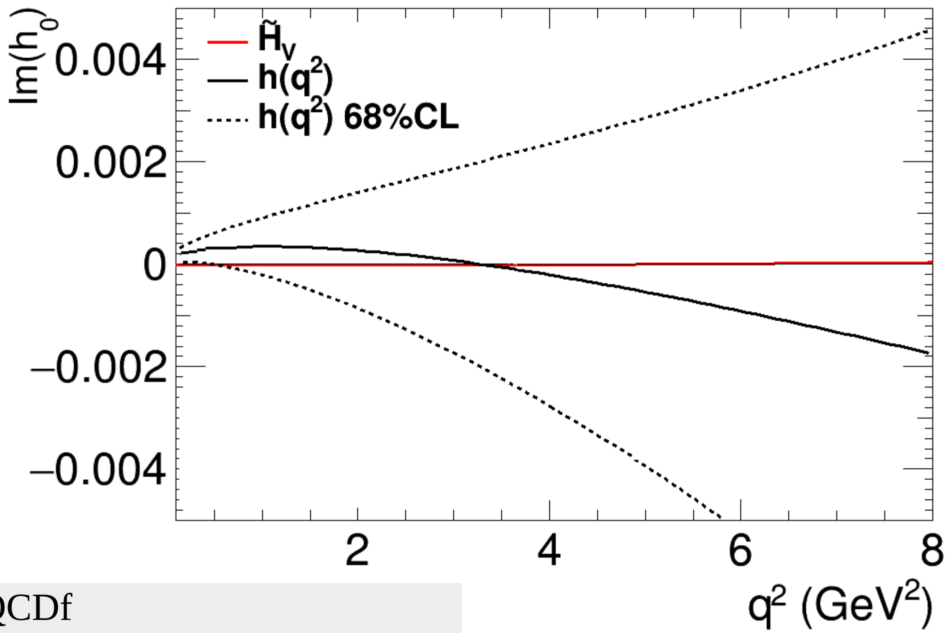

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Solid black line: h_λ
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- h_λ compatible with zero at 1σ level

$\longrightarrow$ too many free parameters to get strongly constrained with current data

NP fit vs. hadronic fit

A (minimal) description of hadronic contributions with fewer free parameters

$$h_\lambda(q^2) = -\frac{\tilde{V}_\lambda(q^2)}{16\pi^2}\frac{q^2}{m_B^2}\Delta C_9^{\lambda,\mathrm{PC}}$$

for each helicity ($\lambda = +, -, 0$) a different ΔC_9^{PC}
→ three real (six complex) parameters

- If NP in C_9 is the favoured scenario, the three different fitted helicities should give the same value
  ⇒ Can work as a null test for NP

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$B \to K^* \bar{\mu}\mu/\gamma$ observables ($\chi^2_{\rm SM} = 85.15,\ \chi^2_{\rm min} = 39.40;\ {\rm Pull}_{\rm SM} = 5.5\sigma$)	
	best fit value
$\Delta C_9^{+,\mathrm{PC}}$	$(3.39 \pm 6.44) + i(-14.98 \pm 8.40)$
$\Delta C_9^{-,\mathrm{PC}}$	$(-1.02 \pm 0.22) + i(-0.68 \pm 0.79)$
$\Delta C_9^{0,\mathrm{PC}}$	$(-0.83 \pm 0.53) + i(-0.89 \pm 0.69)$

Fitted parameters not the same for different helicities but in agreement with each other within 1σ

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Fitted parameters not the same for different helicities but in agreement with each other within 1σ

Fit to only BR($B \to K^*\gamma$) and $B \to K^*\mu^+\mu^-$ observables (low q^2)		
	Real δC_9 (1)	Hadronic fit; complex $\Delta C_9^{\lambda,\mathrm{PC}}$ (6)
Plain SM (0)	(6.0σ)	(5.5σ)
Real δC_9 (1)	--	(1.8σ)

- Adding the hadronic parameters improve the fit with less than 2σ significance

Strong indication that the NP interpretation is a valid option, although the situation remains inconclusive

Future prospects

Future prospect

LHCb projections for $B \to K^* \mu^+ \mu^-$ with 14, 50 and 300 fb^{-1} luminosity

Keeping present central values, the three benchmark points don't give acceptable fits (p-value $\approx$ 0)

We assume two extreme scenarios, adjusting the experimental data such that

- ❑ Central value of C_9 remains the same
- ❑ Central values of the hadronic fit remains the same

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Central value of C_9 is always the same			
	14 fb^{-1} (Syst.)	**50 fb^{-1} (Syst./4)**	**300 fb^{-1} (Syst./4)**
	Real δC_9	Real δC_9	Real δC_9
Plain SM	8.1σ	15.1σ	21.4σ

- ➢ Very good fits for C_9 by construction
- ➢ Good hadronic fits for all three benchmark points of this scenario, but no improvement compared to C_9
- ↪ Uncertainties of most hadronic parameters become very large for higher luminosities indicating most of the 18 parameters are not needed to describe the data

LHCb projections for $B \to K^* \mu^+ \mu^-$ with 14, 50 and 300 fb^{-1} luminosity

Keeping present central values, the three benchmark points don't give acceptable fits (p-value $\approx$ 0)

We assume two extreme scenarios, adjusting the experimental data such that

- ❑ Central value of C_9 remains the same
- ❑ Central values of the hadronic fit remains the same

Central values of the hadronic fit remain the same						
	14 fb^{-1} (Syst.)		50 fb^{-1} (Syst./4)		300 fb^{-1} (Syst./4)	
	Real δC_9	Hadronic fit h_λ	Real δC_9	Hadronic fit h_λ	Real δC_9	Hadronic fit h_λ
Plain SM	7.9σ	7.9σ	14.6σ	22.5σ	18.9σ	41.8σ
Real δC_9	--	4.0σ	--	17.5σ	--	37.4σ

- ➢ Hadronic fit, gives an improvement with 4σ significance compared to fit to C_9 after Run 2 (14 fb^{-1}) but situation still remains inconclusive
- ➢ After first LHCb upgrade (50 fb^{-1}) conclusive judgment can be made that NP cannot be established

Global analysis of $b \to s\ell^+\ell^-$ observables

Considering all the relevant data on $b \to s$ transitions

(117 observables)

- R_K, R_{K^*}
- $\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)$
- $\mathrm{BR}(B_s \to e^+e^-)$
- $\mathrm{BR}(B \to X_s\, \mu^+\mu^-)$
- $\mathrm{BR}(B \to X_s\, e^+e^-)$
- $\mathrm{BR}(B \to K^* e^+e^-)$
- $\mathrm{BR}(B \to K^{*+}\mu^+\mu^-)$
- $B_s \to \phi\, \mu^+\mu^-$: BR, ang. obs.
- $B^{0(+)} \to K^{0(+)}\mu^+\mu^-$: BR, ang. obs.
- $B \to K^{*0}\mu^+\mu^-$: BR, ang. obs.
- $\Lambda_b \to \Lambda\, \mu^+\mu^-$: BR, ang. obs.

All observables ($\chi^2_{\rm SM} = 157.3$)			
	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
δC_9	-0.94 ± 0.14	126.8	5.5σ
δC_9^μ	-0.93 ± 0.13	115.2	6.5σ
δC_9^e	0.84 ± 0.26	145.5	3.4σ
δC_{10}	0.20 ± 0.22	156.4	0.9σ
δC_{10}^μ	0.51 ± 0.17	146.4	3.3σ
δC_{10}^e	-0.78 ± 0.23	144.3	3.6σ
$\delta C_{\rm LL}^\mu$	-0.53 ± 0.10	125.4	5.6σ
$\delta C_{\rm LL}^e$	0.43 ± 0.13	144.8	3.5σ

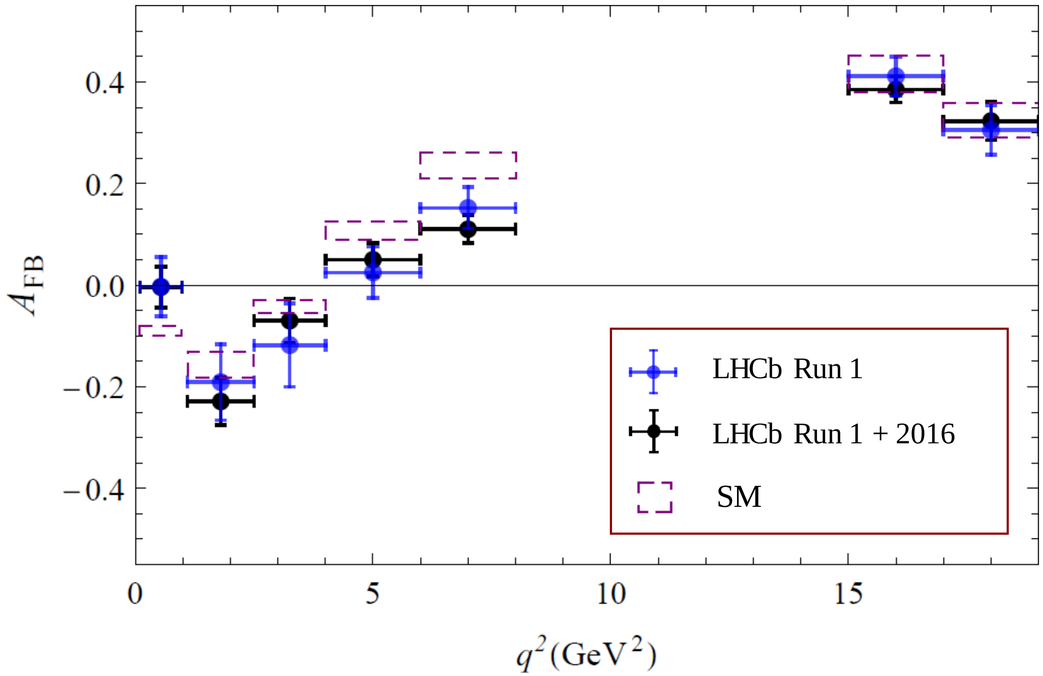
Computations performed using SuperIso public program

(assuming 10% error for p.c.)

- Most favoured scenario is δC_9^μ followed by $\delta C_{\rm LL}^\mu$ $(\delta C_9^\mu = -\delta C_{10}^\mu)$, same hierarchy as pre 2020 LHCb
- Significance have increased by $\sim 1\sigma$ for the most prominent scenarios compared to 2019
- Change in significance mainly due to the recent LHCb analysis of the $B \to K^*\mu^+\mu^-$ angular obervables with 4.7 fb^{-1} ($\to$ larger $\chi^2_{\rm SM}$)

Global analysis of $b \to s$ transitions: one-operator fit

Using all the relevant data on $b \to s$ transitions



- Most favoured scenario is δC_9^μ followed by δC_{LL}^μ $\left(\delta C_9^\mu = -\delta C_{10}^\mu\right)$, same hierarchy as pre 2020 LHCb
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  - ↪ smaller experimental uncertainties

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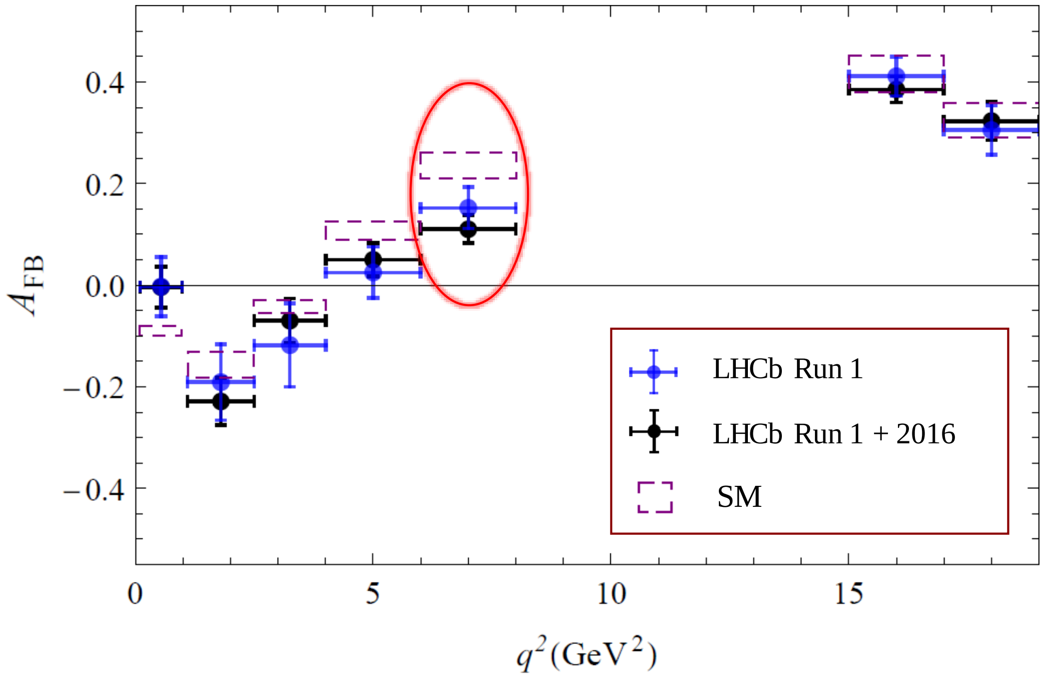

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- Change in significance mainly due to the recent LHCb analysis of the $B \to K^* \mu^+ \mu^-$ angular observables with 4.7 fb^{-1} ($\to$ larger $\chi^2_{\rm SM}$)
  - ↪ smaller experimental uncertainties
  - ↪ further tensions

Using all the relevant data on $b \to s$ transitions

Multi-dimensional fit: $C_7, C_8, C_9^\ell, C_{10}^\ell, C_S^\ell, C_P^\ell$ + primed coefficients (20 d.o.f. freedom)

All observables with $\chi^2_{\rm SM} = 157.28$ ($\chi^2_{\rm min} = 100.34$; Pull$_{\rm SM} = 4.3\sigma$)			
δC_7		δC_8	
0.05 ± 0.03		-0.71 ± 0.43	
$\delta C_7'$		$\delta C_8'$	
-0.01 ± 0.02		-0.09 ± 0.86	
δC_9^μ	δC_9^e	δC_{10}^μ	δC_{10}^e
-1.11 ± 0.19	-6.69 ± 1.37	0.08 ± 0.25	3.97 ± 4.99
$\delta C_9'^\mu$	$\delta C_9'^e$	$\delta C_{10}'^\mu$	$\delta C_{10}'^e$
0.18 ± 0.35	1.84 ± 1.75	-0.13 ± 0.21	0.05 ± 5.01
$C_{Q_1}^\mu$	$C_{Q_1}^e$	$C_{Q_2}^\mu$	$C_{Q_2}^e$
-0.07 ± 0.12	-1.52 ± 0.98	-0.10 ± 0.14	-4.36 ± 1.46
$C_{Q_1}'^\mu$	$C_{Q_1}'^e$	$C_{Q_2}'^\mu$	$C_{Q_2}'^e$
0.05 ± 0.12	-1.40 ± 1.56	-0.17 ± 0.15	-4.33 ± 2.33

- Several Wilson coefficients in the electron sector were previously undetermined in the 20-dimension fit now all WC are constrained (some still weakly) $\leftarrow$ updated upper bound on $B_s \to e^+e^-$ [LHCb 2003.03999]

- Significance of the fit has increased by $\sim 1\sigma$ compared to our 2019 fit

Summary

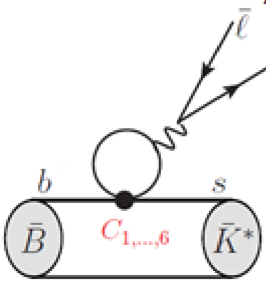
- Significance of tensions depend on assumptions for power corrections
- Statistical comparison favours NP, however situation remains inconclusive
- Future data (after the first LHC upgrade) can give strong indications whether NP better describe the anomalies or hadronic contributions
- Most favoured NP scenario still C_9^μ followed by C_{LL}^μ – no change compared to pre-2020
- Increase of $\sim 1\sigma$ for the favoured NP scenarios

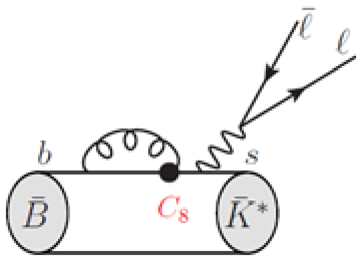
Thank you!

Backup

Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$

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

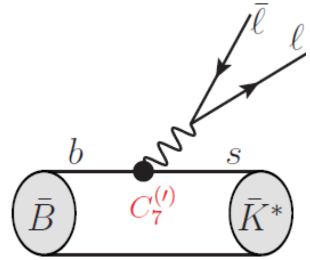


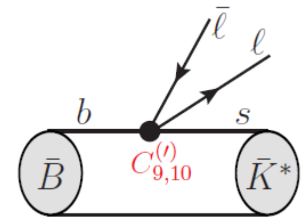


non-local effects: in general "naïve" factorization not applicable

$$\frac{e^2}{q^2}\epsilon_\mu L_V^\mu \Big[\underbrace{Y(q^2)\tilde{V}_\lambda}_{\text{fact., perturbative}} + \underbrace{\text{LO in } \mathcal{O}\big(\frac{\Lambda}{m_b}, \frac{\Lambda}{E_{K^*}}\big)}_{\text{non-fact., QCDf}} + \underbrace{h_\lambda(q^2)}_{\text{power corrections,}} \Big]$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \Big[\sum_{i=7,9,10,Q_1,Q_2} C_i^{(\prime)}(\mu) O_i^{(\prime)}(\mu) \Big]$$





factorisable contributions:
7 independent form factors $\tilde{V}_{\pm,0}, \tilde{T}_{\pm,0}, \tilde{S}$

[Khodjamirian et al. '10, Bharucha et al. '15, Gubernari et al. '18]

Helicity amplitudes:

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

$$h_{\pm,[0]} = \Big[\sqrt{q^2}\times\Big] \Big(h_{\pm,[0]}^{(0)} + q^2\, h_{\pm,[0]}^{(1)} + q^4\, h_{\pm,[0]}^{(2)} \Big)$$

$$\delta H_V^{\rm PC}(\lambda = \pm) = i\,N' \frac{m_B^2}{q^2}\, 16\pi^2 h_\pm(q^2) = i\,N' \frac{m_B^2}{q^2}\, 16\pi^2 \Big[h_\pm^{(0)} + q^2\, h_\pm^{(1)} + q^4\, h_\pm^{(2)} \Big]$$

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

Comparison of fit to $B \to K^*\mu^+\mu^-$ angular observables with Run 1 data (3 fb^{-1}) compared to Run + 2016 data (4.7 fb^{-1})

Only $B \to K^*\mu^+\mu^-$ angular observables			
	χ^2_{SM}	$\chi^2_{\min}(\delta C_9)$	$\text{Pull}_{\text{SM}}(\delta C_9)$
Run 1	57.25	43.08	4.0σ
Run 1 + 2016	81.07	52.27	5.4σ

Wilks' test

$B \to K^* \bar{\mu}\mu/\gamma$ observables; low q^2 bins up to 8 GeV^2									
nr. of free parameters	1 (Real δC_9)	2 (Real $\delta C_7, \delta C_9$)	2 (Comp. δC_9)	4 (Comp. $\delta C_7, \delta C_9$)	3 (Real $\Delta C_9^{\lambda,\mathrm{PC}}$)	6 (Comp. $\Delta C_9^{\lambda,\mathrm{PC}}$)	9 (Real $h_{+,-,0}^{(0,1,2)}$)	18 (Comp. $h_{+,-,0}^{(0,1,2)}$)
0 (plain SM)	6.0σ	5.6σ	5.8σ	5.4σ	5.4σ	5.5σ	5.0σ	4.7σ
1 (Real δC_9)	—	0.5σ	1.5σ	1.2σ	0.6σ	1.8σ	1.1σ	1.5σ
2 (Real $\delta C_7, \delta C_9$)	—	—	—	1.4σ	—	—	1.3σ	1.6σ
2 (Comp. δC_9)	—	—	—	0.8σ	—	1.7σ	—	1.4σ
4 (Comp. $\delta C_7, \delta C_9$)	—	—	—	—	—	—	—	1.5σ
3 (Real $\Delta C_9^{\lambda,\mathrm{PC}}$)	—	—	—	—	—	2.2σ	1.4σ	1.7σ
6 (Comp. $\Delta C_9^{\lambda,\mathrm{PC}}$)	—	—	—	—	—	—	—	0.1σ
9 (Real $h_{+,-,0}^{(0,1,2)}$)	—	—	—	—	—	—	—	1.5σ

LHCb projections for $B \to K^*\mu^+\mu^-$ with 14, 50 and 300 fb^{-1} luminosity

Keeping present central values, the three benchmark points don't give acceptable fits (p-value $\approx$ 0)

We assume two extreme scenarios, adjusting the experimental data such that

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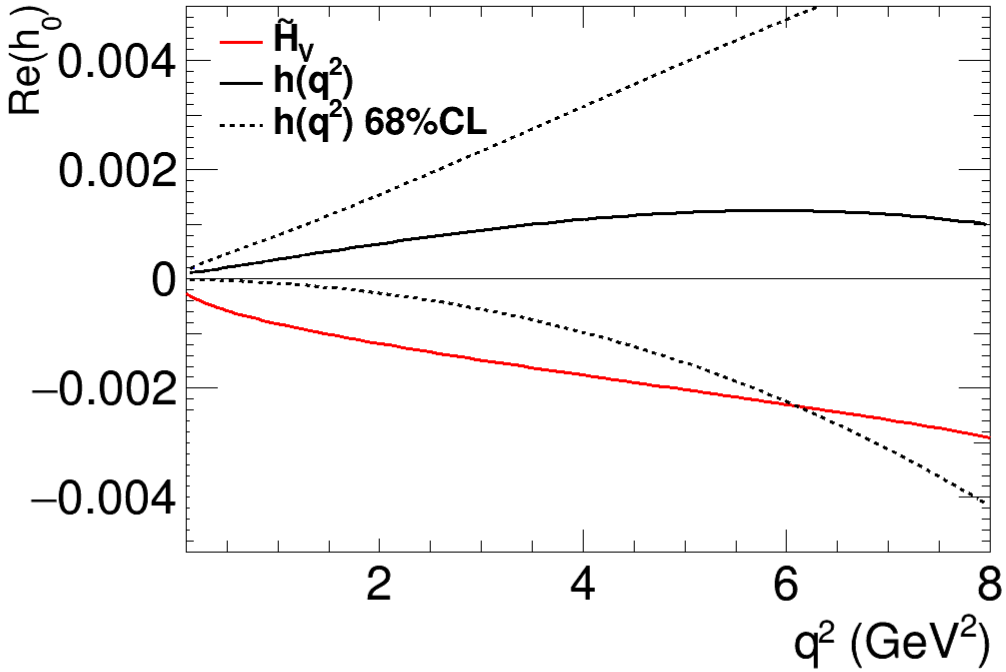

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- After first LHCb upgrade (50 fb^{-1}) conclusive judgment is possible

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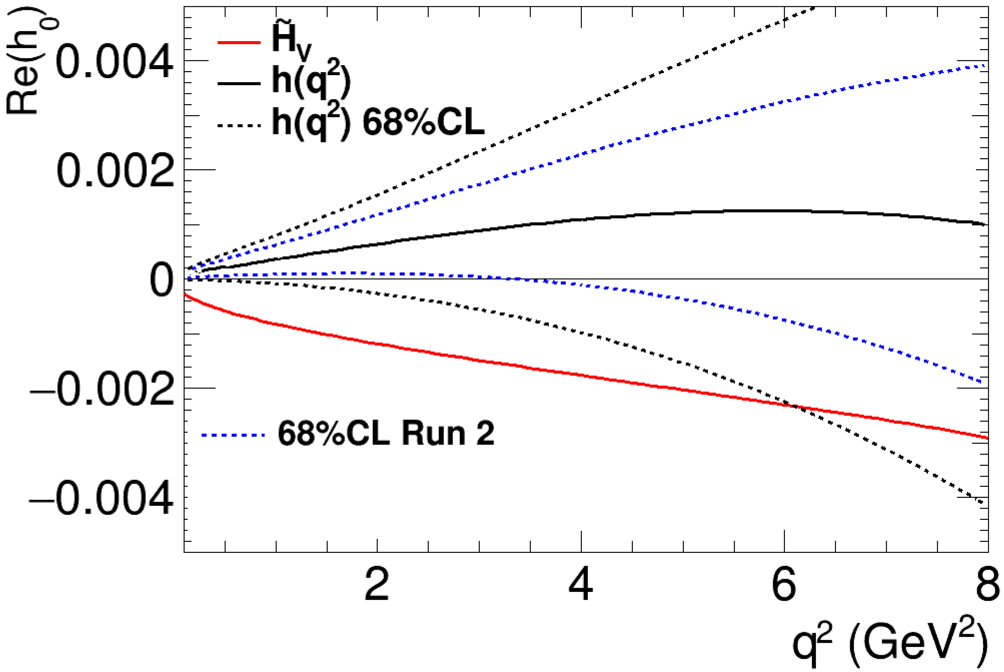

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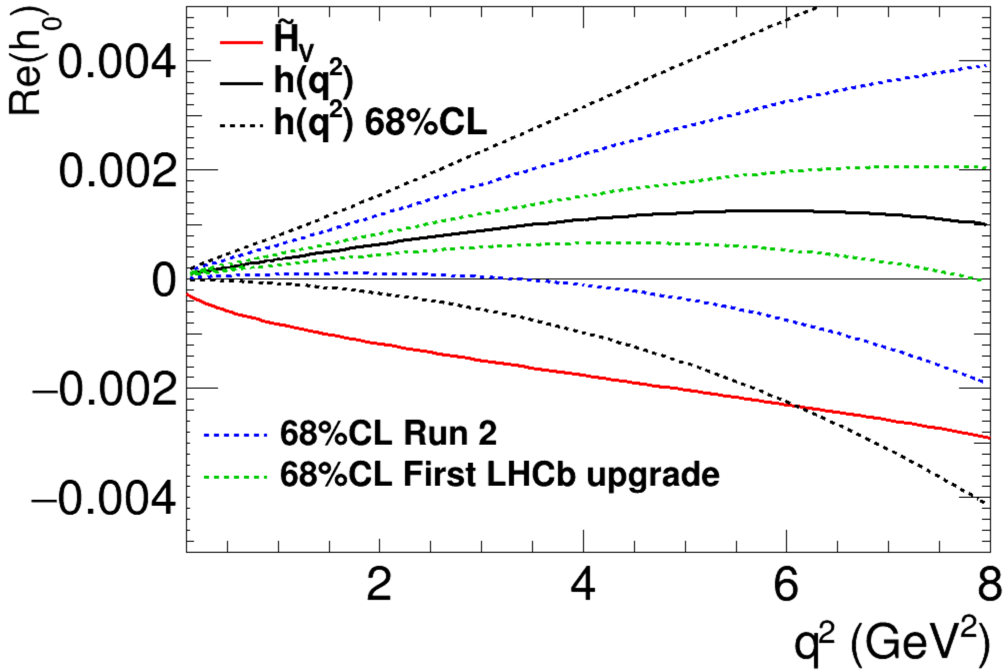

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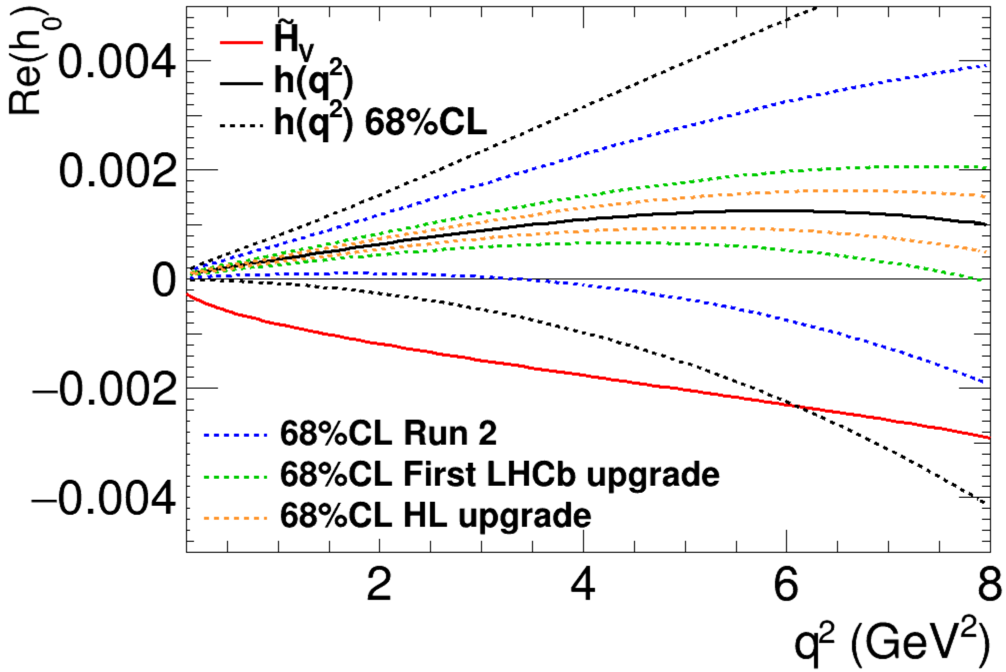

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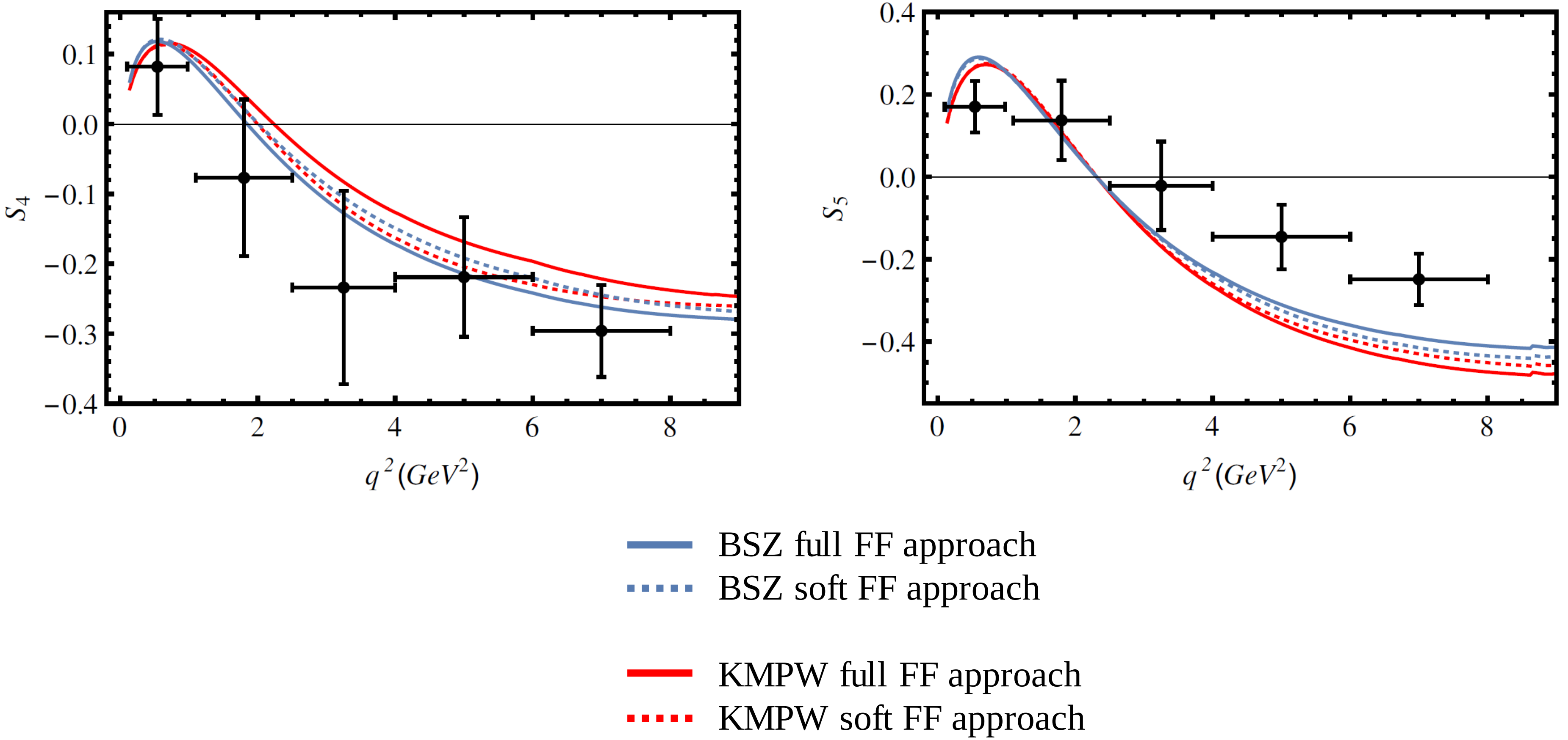
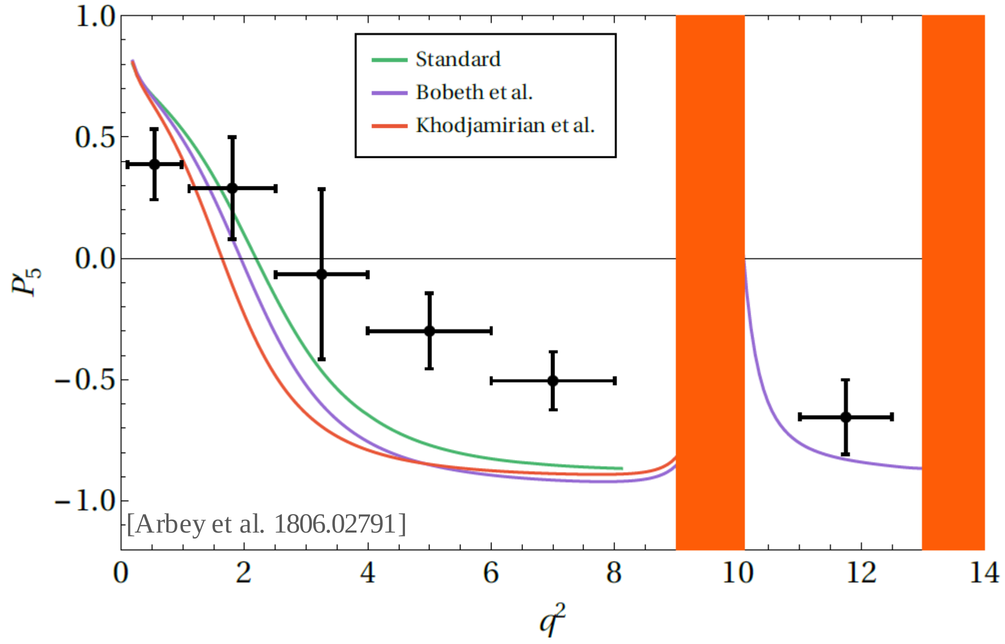
Impact of choice of form factors (BSZ vs KMPW) and approach (full FF , soft FF)



Impact of power corrections



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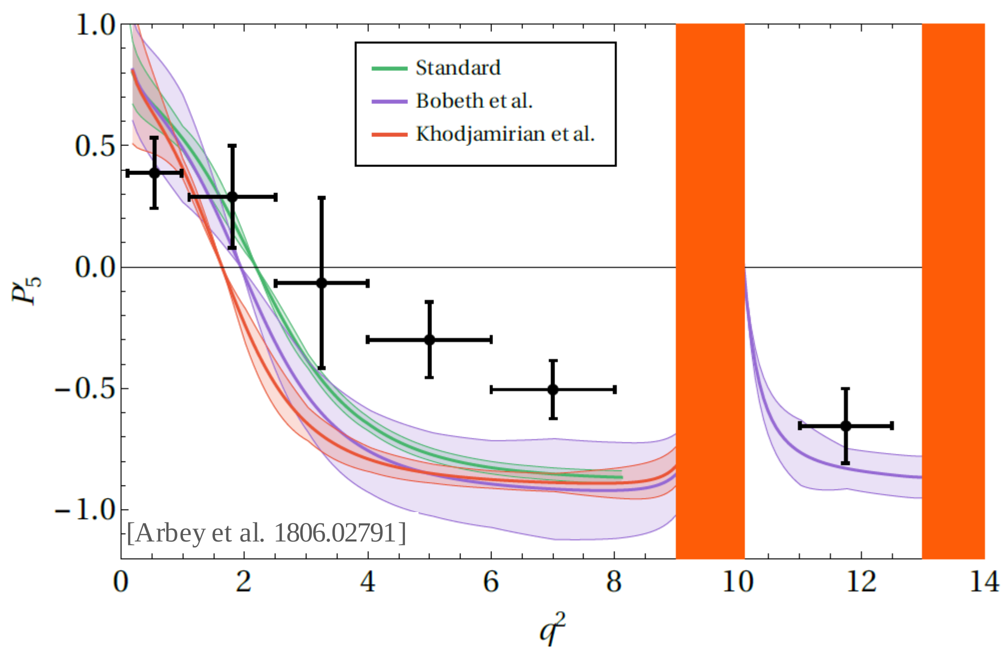

Impact of power corrections