Institute for Research in Fundamental Sciences

School of Particles and Accelerators

Flavour anomalies in $b \to s$ transitions and their implications for New Physics

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arXiv:1705.06274, arXiv:1702.02234 & arXiv:1603.00865

Thanks to T. Hurth, F. Mahmoudi, D. Martinez Santos and V. Chobanova

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October 23-26, 2017

Indirect Searches for New Physics

Indirect hints for New Physics from flavour sector

- Only few hints of Beyond the Standard Model effects and "flavour anomalies" among the best

Flavour anomalies (not all)

$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly	
$\sim 3.5\sigma$	nonSM-like same-sign dimuon charge asymmetry	
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates	
$\sim 3.2\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$	$BR(B_s \to \phi\mu^+\mu^-)$
$\sim 3\sigma$	anomaly in one of the angular observables of $B \to K^*\mu^+\mu^-$	P_5'
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$	
$\sim 2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result	
$\sim 2.6\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-/Ke^+e^-$	R_K
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K^*\mu^+\mu^-/K^*e^+e^-$	R_{K^*}

W. Altmannshofer; Aspen Winter Conference 2016

- Flavour Changing Neutral Current (FCNC) processes are especially interesting

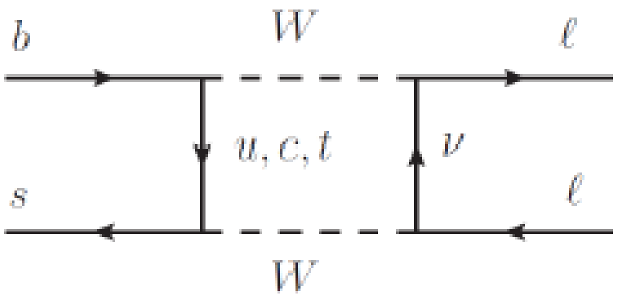
  $\to$ potential to discover New Physics before directly observed in experiments

FCNC: $b \to s$

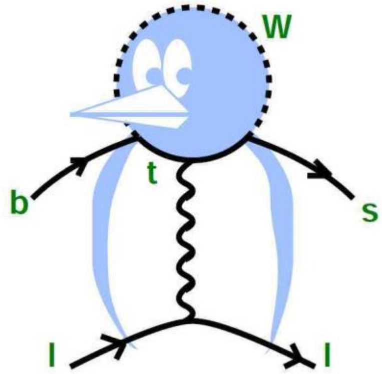
$b \to s$ are in particular very interesting as:

- Like other FCNCs only occur in loops (via $W^{\pm}$ exchange)

Box diagram:



Penguin diagram:



Loop suppressed in the SM ⇒ Even small New Physics effects can be comparable to SM contributions

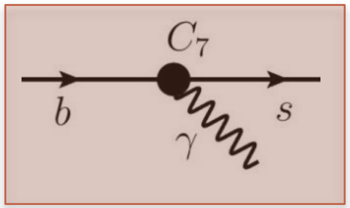
- Good control over long-distance strong interactions (m_b much larger than Λ_{QCD})

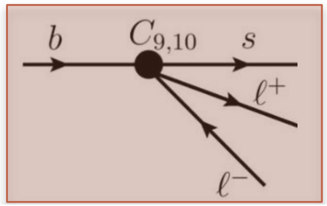
  ⟶ QCD contributions are rather well-known

- The experimental situation is very promising
  ⟶ Data already available (BaBar, CDF, Belle, LHCb) & more to come (Belle II, LHCb upgrade, …)

- Effective Hamiltonian for $b \to s\ell^+\ell^-$ transitions: $\mathcal{H}_{\rm eff} = \frac{-4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (C_i O_i)$

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





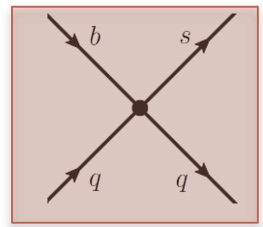
$$O_7 = \frac{e}{(4\pi)^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu} \quad O_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \ell)$$

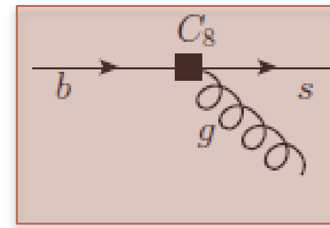
$$O_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

chirality flipped operators (O_i')

Most relevant for (semi-) leptonic decays

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





$$O_{1,2} \propto (\bar{s}\, \Gamma_m\, c)(\bar{c}\, \Gamma_n\, b) \qquad O_8 \propto (\bar{s}\, \sigma^{\mu\nu} T^a P_R\, b)\, G^a_{\mu\nu}$$

$$O_{3-6} \propto (\bar{s}\, \Gamma_m\, b)\, \Sigma_q\, (\bar{q}\, \Gamma_n\, q)$$

Short-distance effects: Wilson coefficients $C_i(\mu)$ ($\mu = m_b$)

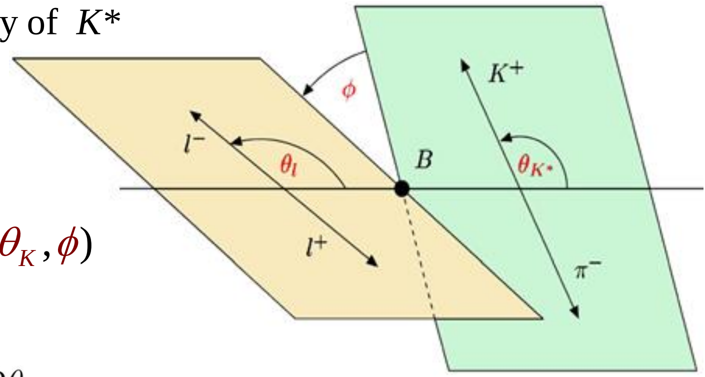
- Calculated *perturbatively*
- Contain all the contributions from scales higher than μ

Long-distance effects: matrix elements of operators $\langle O_i \rangle$

- Require *non-perturbative* methods
- Introduce the main theoretical uncertainties

Observed in experiment: $B \to K^*(\to K^+ \pi^-)\mu^+\mu^-$

Angular behaviour of K^+ and π^- $\longrightarrow$ additional information on the helicity of K^*



Angular distribution described by four independent kinematic variables q^2 and three angles $\theta_\ell, \theta_{K^*}, \phi$

$$\sum_{\text{final state spins}} |\mathcal{M}|^2 \longrightarrow \frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$

$$\begin{aligned} J(q^2,\theta_\ell,\theta_{K^*},\phi) = {} & J_1^s \sin^2\theta_{K^*} + J_1^c \cos^2\theta_{K^*} + (J_2^s \sin^2\theta_{K^*} + J_2^c \cos^2\theta_{K^*}) \cos 2\theta_\ell \\ & + J_3 \sin^2\theta_{K^*} \sin^2\theta_\ell \cos 2\phi + J_4 \sin 2\theta_{K^*} \sin 2\theta_\ell \cos\phi + J_5 \sin 2\theta_{K^*} \sin\theta_\ell \cos\phi \\ & + (J_6^s \sin^2\theta_{K^*} + J_6^c \cos^2\theta_{K^*}) \cos\theta_\ell + J_7 \sin 2\theta_{K^*} \sin\theta_\ell \sin\phi \\ & + J_8 \sin 2\theta_{K^*} \sin 2\theta_\ell \sin\phi + J_9 \sin^2\theta_{K^*} \sin^2\theta_\ell \sin 2\phi \end{aligned}$$

J_i: functions of helicity amplitudes $H_V(\lambda), H_A(\lambda), H_P$, in the SM, described by: $(\lambda = -1, 0, +1)$

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

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

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

- Wilson coefficients: $C_{1-6,\,8}^{(\prime)}, C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}, C_P^{(\prime)}$
- 7 independent form factors: $\tilde{V}_-, \tilde{V}_0, \tilde{V}_+, \tilde{T}_-, \tilde{T}_0, \tilde{T}_+, \tilde{S}$

$B \to K^* \mu^+ \mu^-$ observables

Differential decay rate: $\frac{d\Gamma}{dq^2} = \frac{3}{4}(J_1 - J_2/3)$

Forward Backward Asymmetry: $A_{FB}(q^2) = [\int_{-1}^{0} - \int_{0}^{1}]\, d\cos\theta_l \frac{d^2\Gamma}{dq^2\, d\cos\theta_l} / \frac{d\Gamma}{dq^2} = -\frac{3}{8} J_6 / \frac{d\Gamma}{dq^2}$

Forward-Backward Asymmetry zero-crossing: $q_0^2 = 2m_b \frac{C_7^{\text{eff}}}{C_9^{\text{eff}}} + O(\alpha_s, \Lambda/m_b)$

Longitudinal Polarization Fraction: $F_L = -2J_2^c / \frac{d\Gamma}{dq^2}$

Many other angular observables…

- minimize form factor uncertainties
- sensitive to specific Wilson coefficients

Optimized obesrvables:

$$\langle P_1 \rangle_{\text{bin}} = \frac{1}{2} \frac{\int_{\text{bin}} dq^2 [J_3 + \bar{J}_3]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_2 \rangle_{\text{bin}} = \frac{1}{8} \frac{\int_{\text{bin}} dq^2 [J_{6s} + \bar{J}_{6s}]}{\int_{\text{bin}} dq^2 [J_{2s} + \bar{J}_{2s}]} \qquad \langle P_4' \rangle_{\text{bin}} = \frac{1}{\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_4 + \bar{J}_4]$$

$$\langle P_5' \rangle_{\text{bin}} = \frac{1}{2\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_5 + \bar{J}_5] \qquad \langle P_6' \rangle_{\text{bin}} = \frac{-1}{2\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_7 + \bar{J}_7] \qquad \langle P_8' \rangle_{\text{bin}} = \frac{-1}{\mathcal{N}'_{\text{bin}}} \int_{\text{bin}} dq^2 [J_8 + \bar{J}_8]$$

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

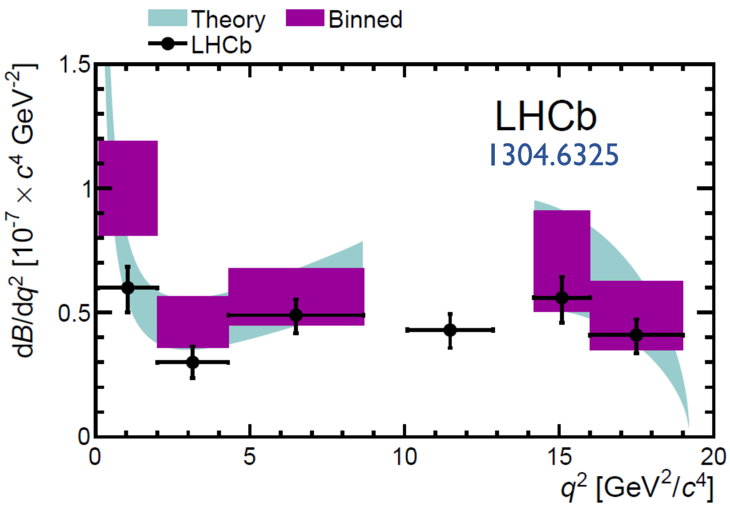
U. Egede et al., JHEP 0811 (2008) 032
U. Egede et al.,JHEP 1010 (2010) 056
J. Matias et al., JHEP 1204 (2012) 104
S. Descotes-Genon et al., JHEP 1305 (2013) 137

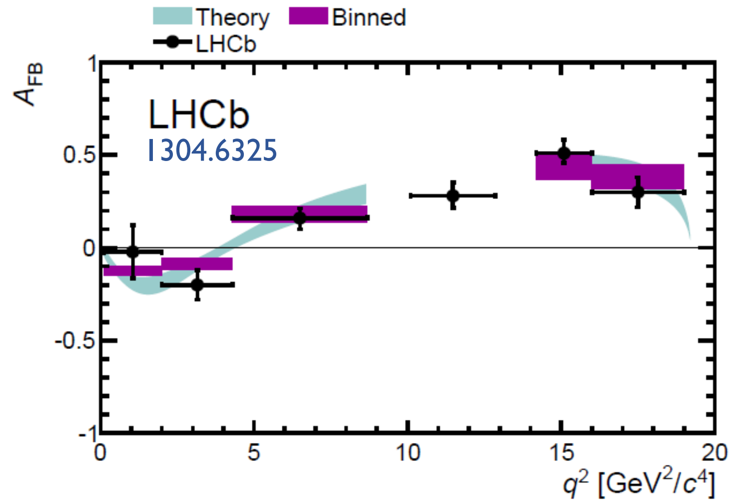
Or alternatively : $S_i = (J_i^{(s,c)} + \bar{J}_i^{(s,c)}) / (\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2})$

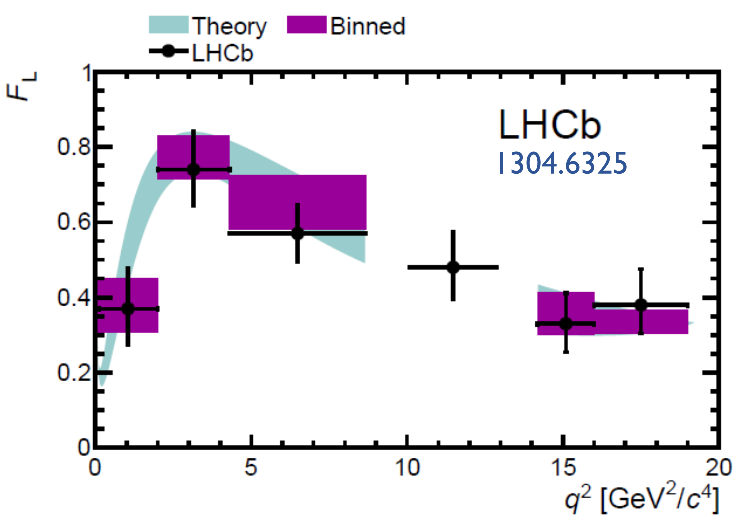
W. Altmannshofer et al., JHEP 0901 (2009) 019

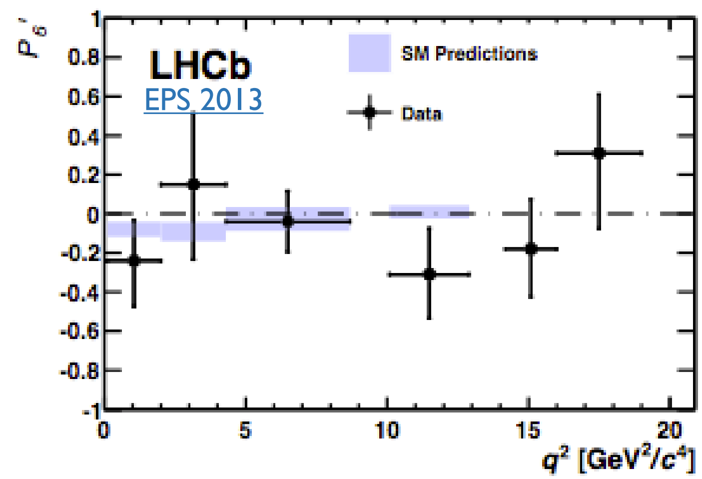
2013 LHCb results with 1fb^{-1} data

Good agreement between SM prediction and measurement for most observables









Anomaly among penguins

Anomaly in P_5'

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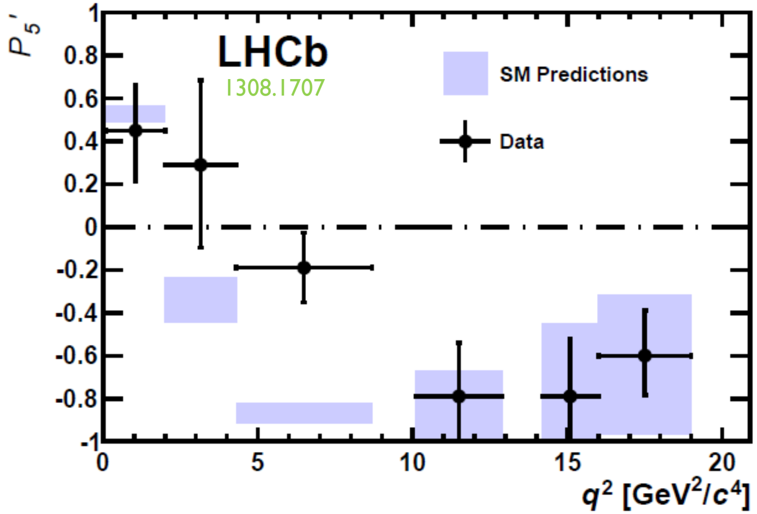
Good agreement between SM prediction and measurement for most observables

However, …



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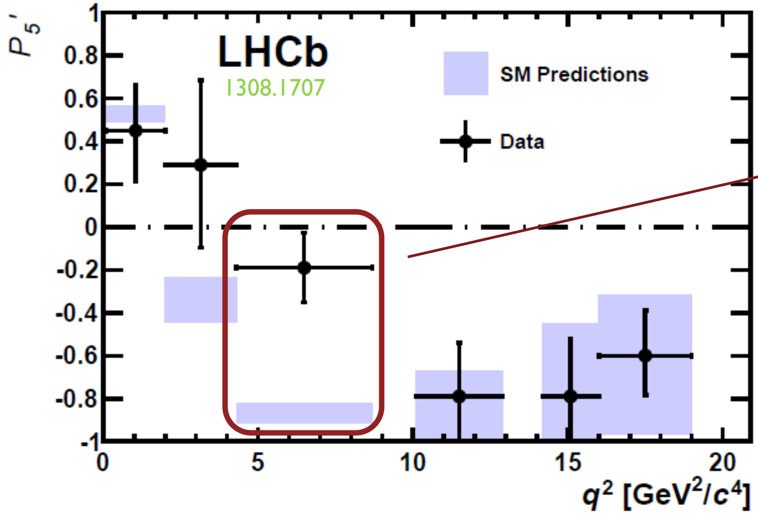

A 3.7σ deviation in the [4.30,8.68] GeV^2 bin of P_5'

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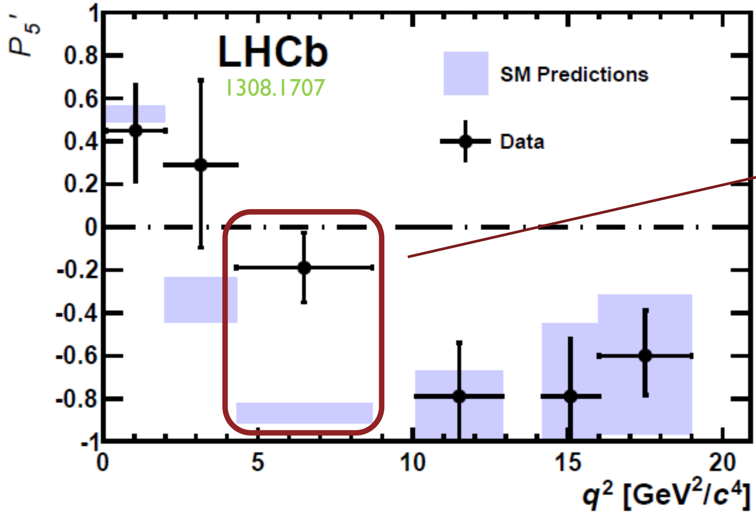


A 3.7σ deviation in the [4.30,8.68] GeV^2 bin of P_5'

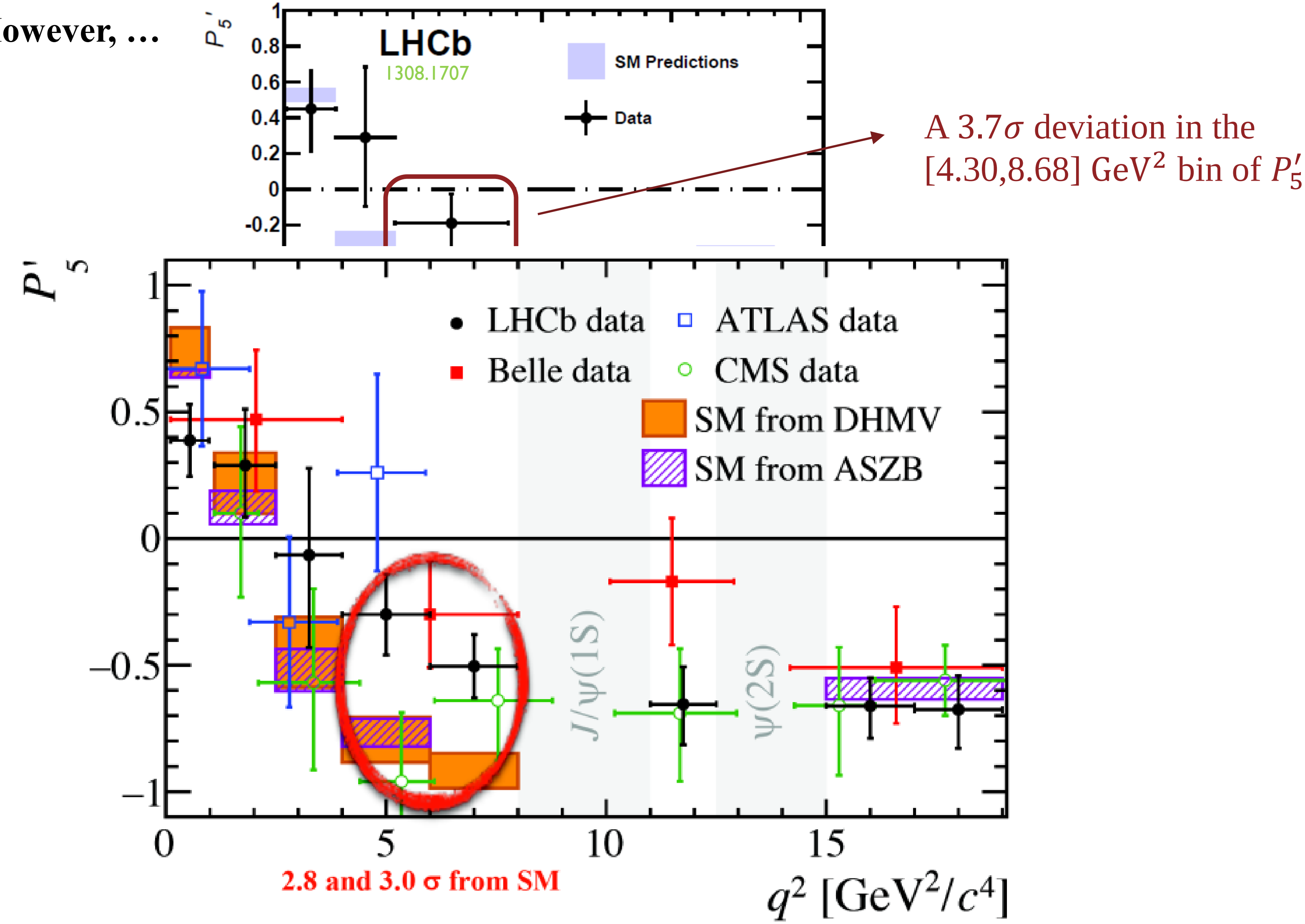
Possible explanations for the tension in P_5'

- Statistical fluctuations
- New Physics
- Theoretical issues $\longrightarrow$ underestimated hadronic contributions

2013 LHCb results with 1fb^{-1} data

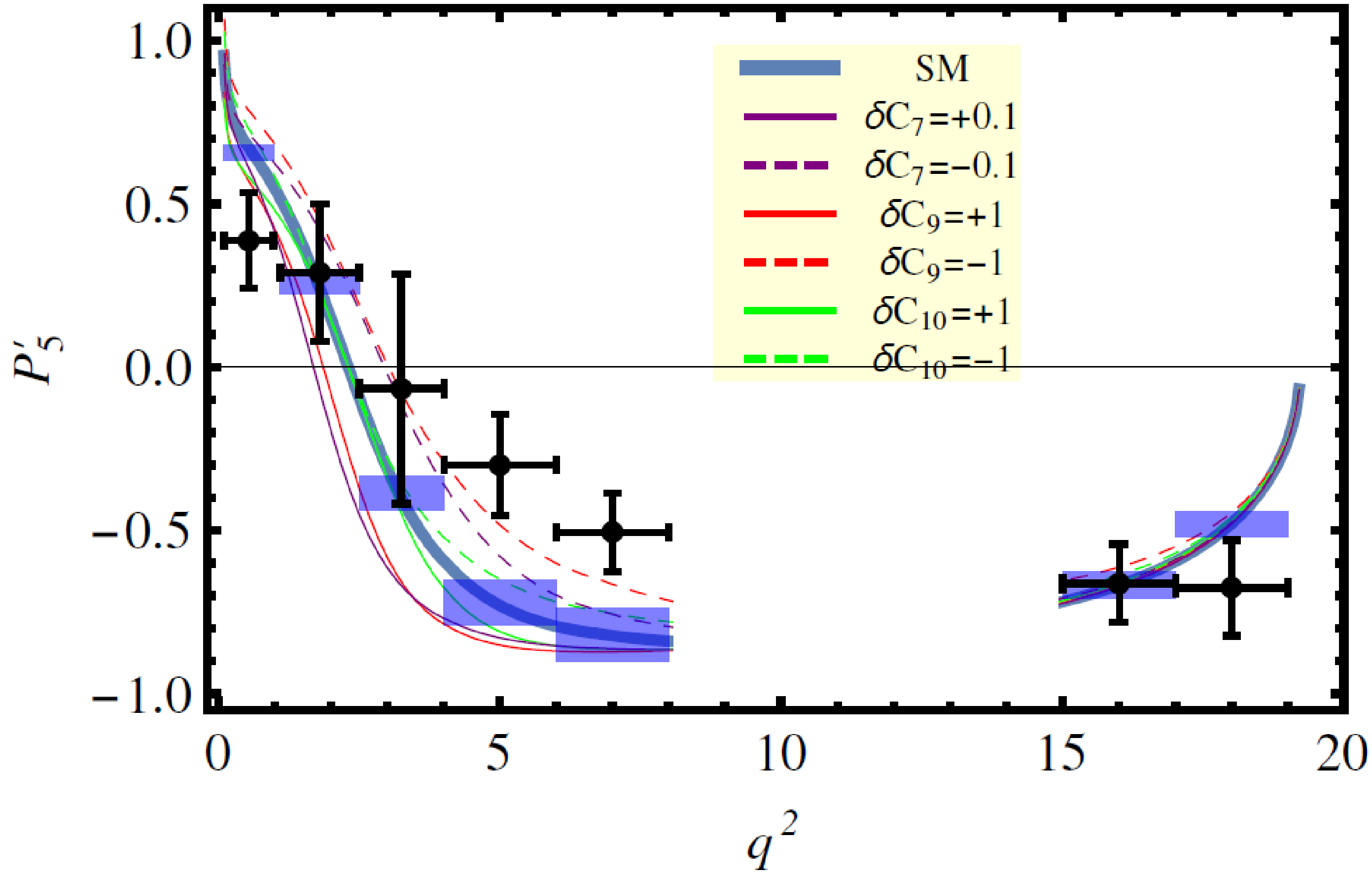
Good agreement between SM prediction and measurement for most observables

However, …



If tension in P_5' due to NP ⟶ modified Wilson coefficients: $C_i = C_i^{SM} + \delta C_i$

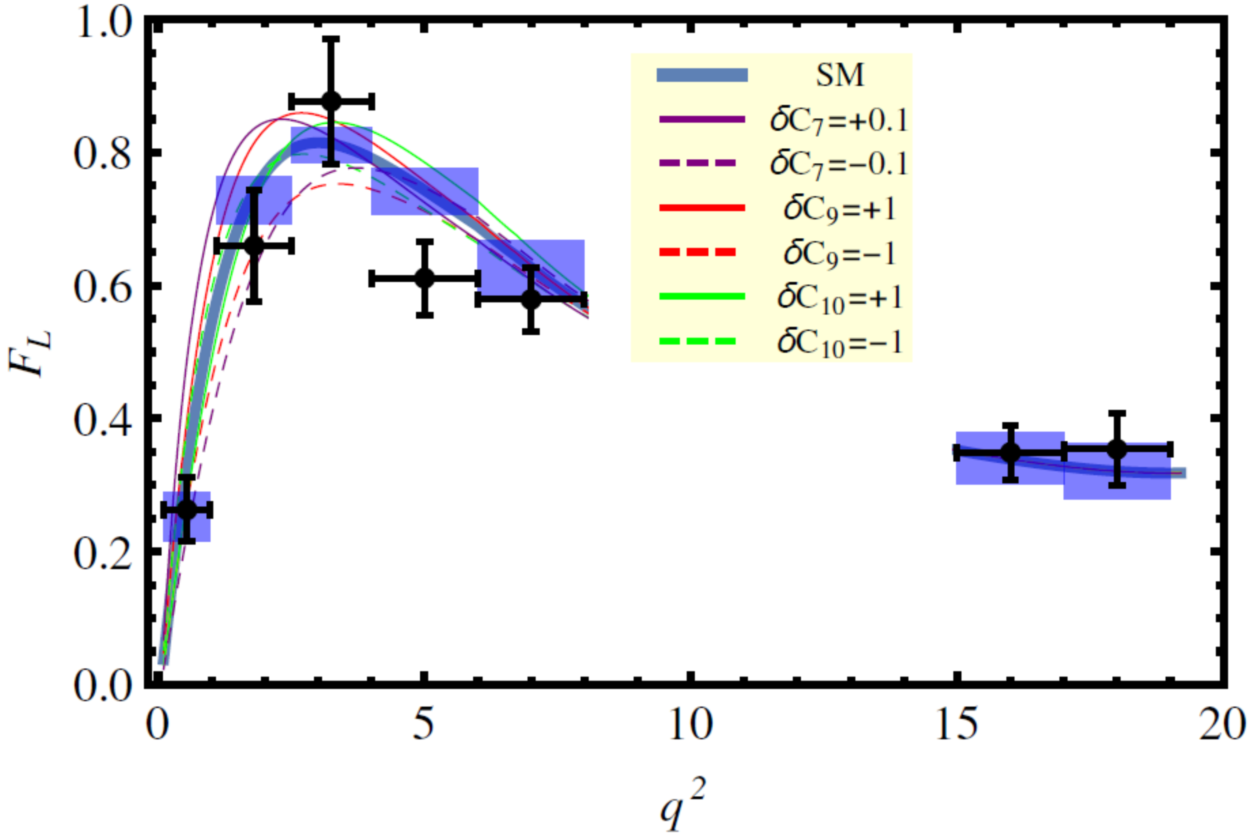
Effect of benchmark contributions to Wilson coefficients (25%-35%) on P_5' prediction



$\delta C_9 \sim -1$ and to a lesser degree $\delta C_7 \sim -0.1$ can decrease the tension

Effect of modified Wilson coefficients

Effect of benchmark contributions to (primed) Wilson coefficients (25%-35%) on other observables



- sensitivity to C_i not the same for different observables and bins
- a specific δC_i while reducing tension for one observable can increase tension in other observables

⟹ *global analysis required*

Global fit of Wilson coefficients $C_7^{(\prime)}, C_9^{(\prime)}, C_{10}^{(\prime)}$

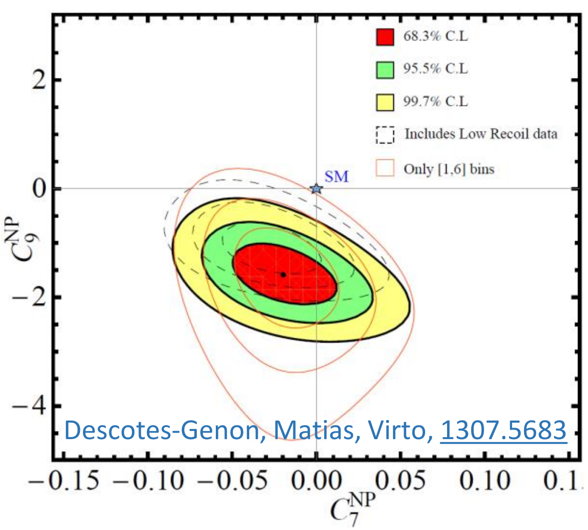
considering all relevant $b \to s$ leptonic and semileptonic decays (more than 100 observables)

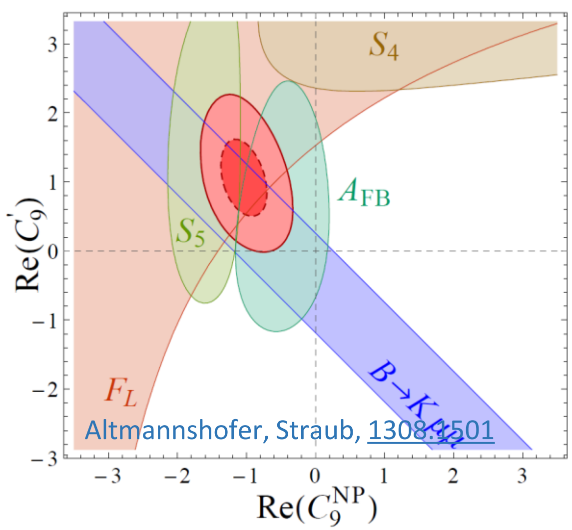
	b.f. value	$\chi^2_{\rm min}$	$\text{Pull}_{\rm SM}$	68% C.L.	95% C.L.
$\delta C_9/C_9^{\rm SM}$	-0.18	123.8	3.0σ	$[-0.25, -0.09]$	$[-0.30, -0.03]$
$\delta C_9'/C_9^{\rm SM}$	$+0.03$	131.9	1.0σ	$[-0.05, +0.12]$	$[-0.11, +0.18]$
$\delta C_{10}/C_{10}^{\rm SM}$	-0.12	129.2	1.9σ	$[-0.23, -0.02]$	$[-0.31, +0.04]$

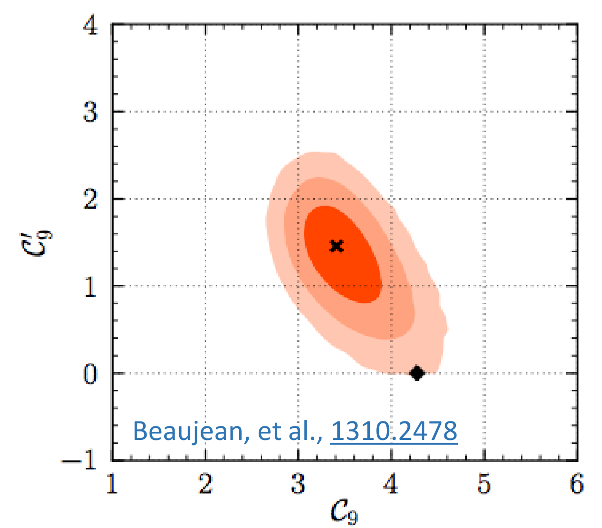
Best fit when assuming NP in $\delta C_9 \sim -1$ with $\text{Pull}_{\rm SM} = 3\sigma$

Several groups doing global fits (with similar results):

Descotes-Genon et al.: 1307.5683; Altmannshofer et al.: 1308.1501; Beaujean et al.: 1310.2478;
Horgan et al.: 1310.3887; Hurth et al.:1312.5267; Hurth et al.: 1410.4545; Altmannshofer et al.: 1411.3161;



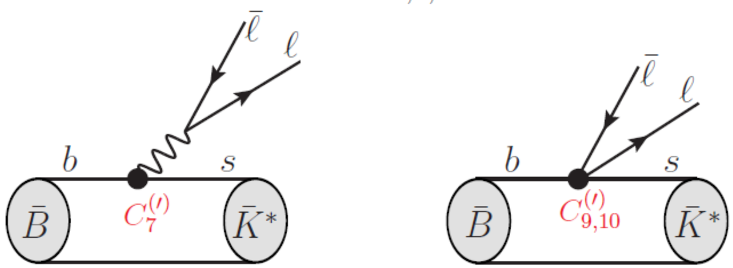




Underestimated hadronic corrections: a closer look at the calculations for $B \to K^*\ell^+\ell^-$

$$\mathcal{A}(B \to K^*\ell^+\ell^-) = \langle K^*\ell^+\ell^-|(\mathcal{H}_{\rm eff}^{\rm sl} + \mathcal{H}_{\rm eff}^{\rm had})|B\rangle$$

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



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

$\mathcal{H}_{\rm eff}^{\rm had}$ contributes to $b \to s\bar\ell\ell$ through virtual photon exchange ⇒ affect only the $H_V(\lambda)$

Factorisation of leptonic and hadronic parts

- $\langle K_\lambda^*|O_7|B\rangle \longrightarrow \tilde{T}_\lambda$
- $\langle K_\lambda^*|O_{9,10}|B\rangle \longrightarrow \tilde{V}_\lambda$ ⟹ 7 independent FFs $(\lambda = -1, 0, +1)$
- $\langle K_\lambda^*|O_{S,P}|B\rangle \longrightarrow \tilde{S}$

Helicity amplitudes:

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

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

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

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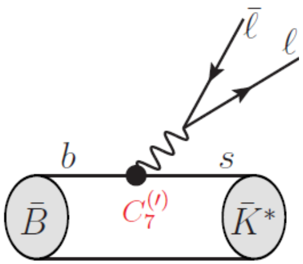

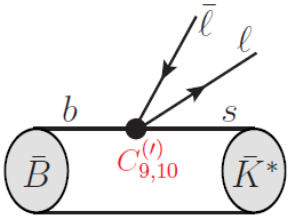

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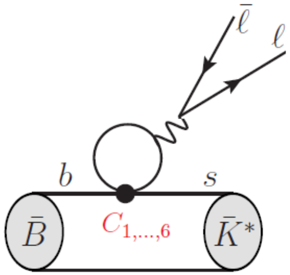
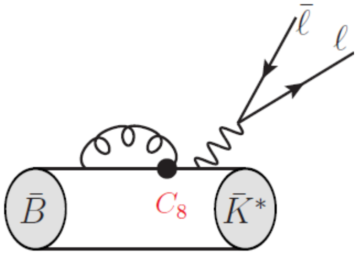
- $\langle K_\lambda^* | O_{9,10} | B \rangle \longrightarrow \tilde{V}_\lambda$ ⟹ 7 independent FFs
- $\langle K_\lambda^* | O_{S,P} | B \rangle \longrightarrow \tilde{S}$

$(\lambda = -1, 0, +1)$

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





In general "naïve" factorization not applicable

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

Usually guesstimated to 10% of LO non-fact

$$\left(C_9^{\rm eff} \equiv C_9 + Y(q^2) \right)$$

Helicity amplitudes:

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

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

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

Hadronic effects vs. New Physics

Hadronic effects can "in principle" mimic $C_9^{\rm NP}$ since they both contribute to helicity amplitude H_V

A possible parametrisation of the non-factorisable power corrections

$$h_\lambda(q^2) = h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4} h_\lambda^{(2)} \qquad (\lambda = +,-,0)$$

M. Ciuchini et al., 1512.07157
S. Jäger and J. Camalich: 1412.3183

Hadronic power correction: $\delta H_V^{\rm p.c.}(\lambda) = iN' m_B^2 \frac{16\pi^2}{q^2} h_\lambda(q^2) = iN' m_B^2 \frac{16\pi^2}{q^2}\left(h_\lambda^{(0)} + q^2 h_\lambda^{(1)} + q^4 h_\lambda^{(2)}\right)$

New Physics effect: $\delta H_V^{C_9^{\rm NP}}(\lambda) = -iN' \tilde{V}_\lambda(q^2) C_9^{\rm NP} = iN' m_B^2 \frac{16\pi^2}{q^2}\left(a_\lambda^{\tilde V} C_9^{\rm NP} + q^2 b_\lambda^{\tilde V} C_9^{\rm NP} + q^4 c_\lambda^{\tilde V} C_9^{\rm NP}\right)$

Comparing fit for hadronic quantities $h_{+,-,0}^{(0,1,2)}$ (18 parameters) and Wilson coefficients $C_9^{\rm NP}$ (2 parameters)

Fit for all $B \to K^* \mu^+ \mu^-$ observables		
	δC_9	Hadronic fit
Plain SM	4.1σ	2.7σ
δC_9	--	0.76σ

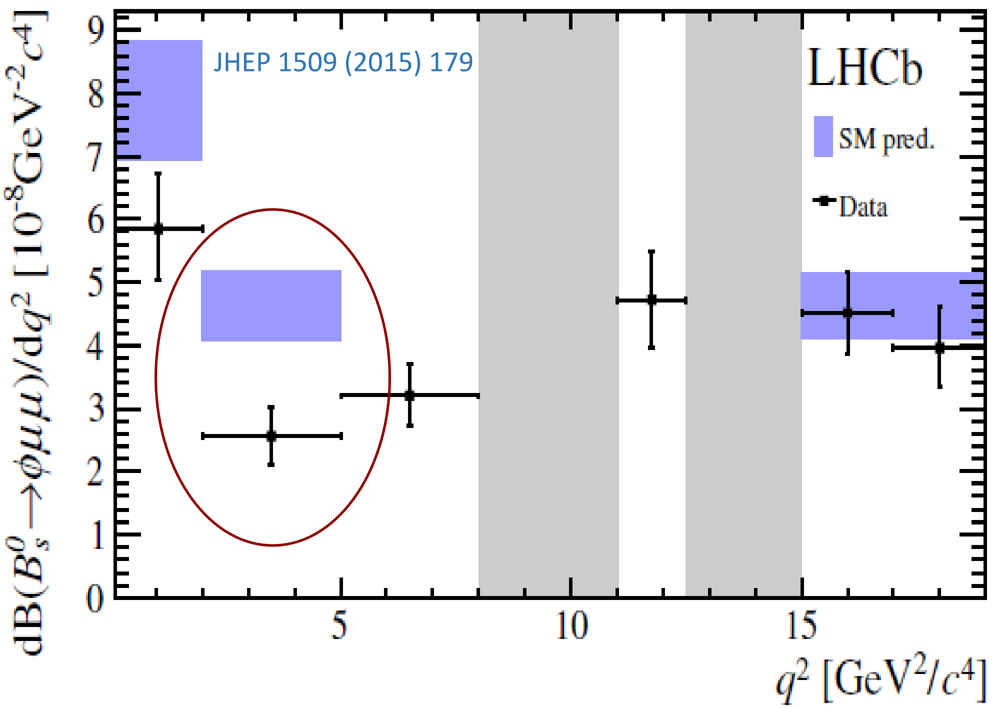
V. Chobanova, D. Martinez Santos, F. Mahmoudi, T. Hurth, SN, 1702.02234

- Adding the hadronic parameters (16 more parameters) does not really improve the fits
- Strong indication that the NP interpretation is a valid option, but the situation remains inconclusive

Anomaly in $BR(B_s \to \phi\, \mu^+ \mu^-)$

2015: another anomaly in $BR(B_s \to \phi\, \mu^+ \mu^-)$

- Same theoretical description as $B \to K^* \mu^+ \mu^-$
  - Replacement of $B \to K^*$ form factors with the $B_s \to \phi$ form factors
  - Also consider $B_s - \bar{B}_s$ oscillations
- 3.2σ tension in the [1-6] GeV^2 bin
- Branching ratio is dependent on all form factors $\Longrightarrow$ ***Large theoretical uncertainty***



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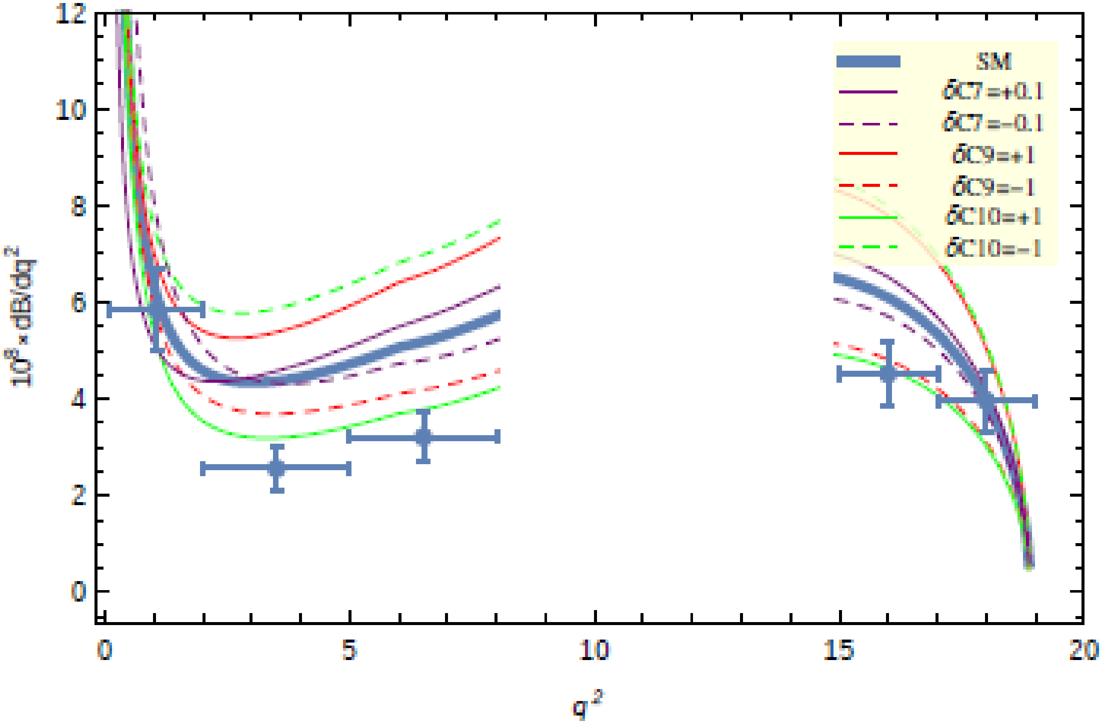
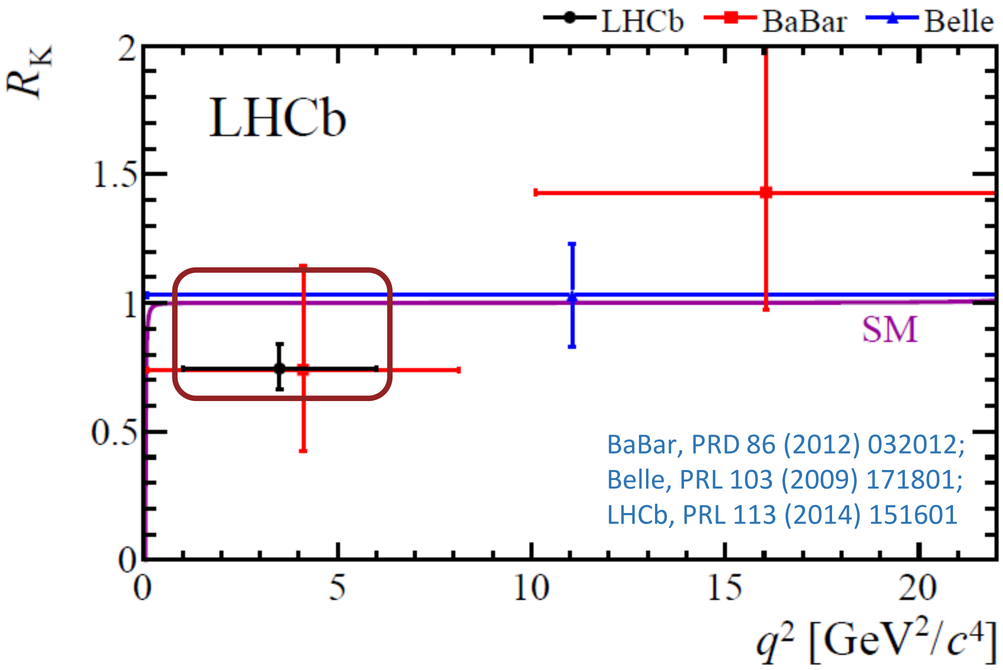


$\delta C_9 \sim -1$ can reduce the tension in agreement with the P_5' explanation

2014: another anomaly from LHCb in $R_K = \frac{BR(B^+ \to K^+ \mu^+ \mu^-)}{BR(B^+ \to K^+ e^+ e^-)}$

- Theoretical description similar to $B \to K^* \mu^+ \mu^-$, but different since K-meson is scalar
- hadronic uncertainties cancel out $\Longrightarrow$ ***theoretically very clean***



R_K^{SM} in [1-6] GeV^2 =1.0006 ± 0.0004

R_K^{exp} in [1-6] GeV^2 =0.745 ± 0.097

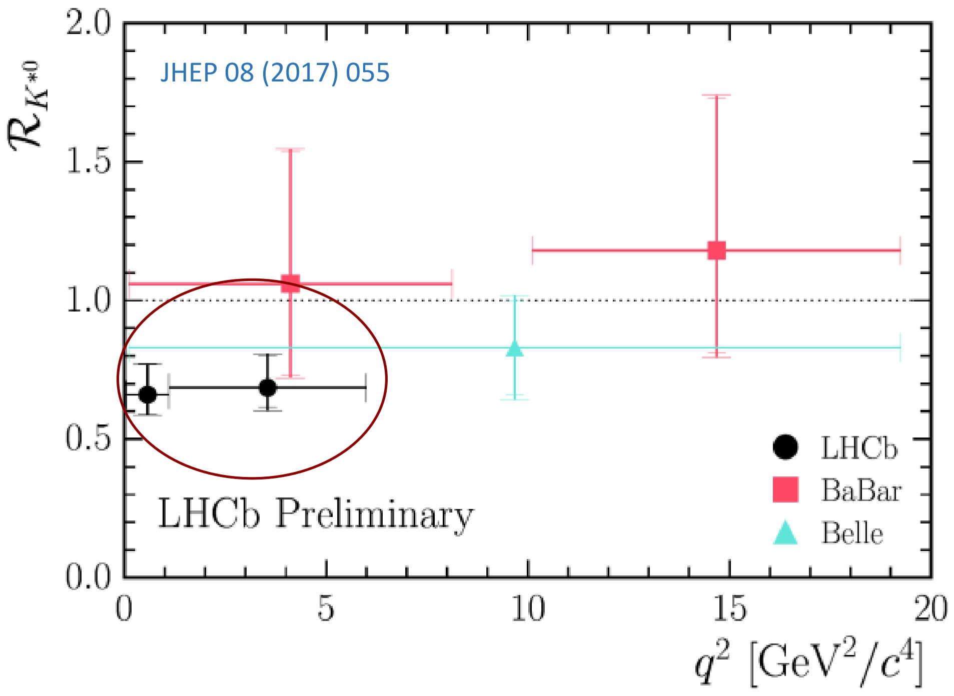
2.6σ tension with SM prediction

⇨ *lepton non-universality* ($C_i^\mu \neq C_i^e$)

If confirmed this would be a groundbreaking discovery
and a very spectacular fall of the SM

2017: another anomaly from LHCb in $R_{K^*} = \frac{BR(B\to K^*\mu^+\mu^-)}{BR(B\to K^* e^+ e^-)}$

- hadronic uncertainties cancel out $\Longrightarrow$ ***theoretically (very) clean***
- Two q^2 regions: [0.045-1.1] and [1.1-6.0] GeV^2



$R_{K^*}^{\text{SM,bin 1}} = 0.906 \pm 0.020_{\text{QED}} \pm 0.020_{\text{FF}}$

$R_{K^*}^{\text{SM,bin 2}} = 1.000 \pm 0.010_{\text{QED}}$

Bordone, Isidori, Pattori, arXiv:1605.07633

$R_{K^*}^{\text{exp,bin 1}} = 0.660^{+0.110}_{-0.070}$ (stat) ± 0.024 (syst)

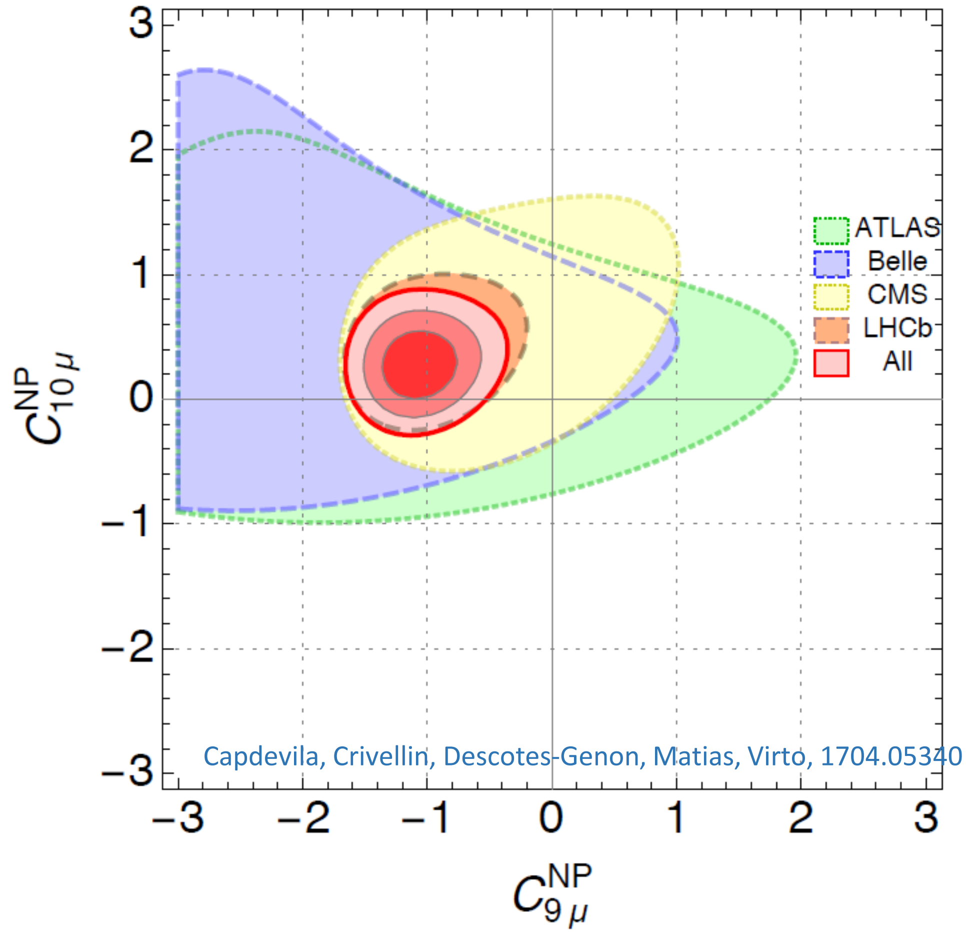
$R_{K^*}^{\text{exp,bin 2}} = 0.685^{+0.113}_{-0.069}$ (stat) ± 0.047 (syst)

2.3σ and 2.5σ tension for bin 1 and bin2 with SM prediction

lepton non-universality $(C_i^{\mu} \neq C_i^{e})$

Consistency of NP fit for different anomalies

Global analysis



See also fits by:
Geng, Grinstein, Jager, Camalich, Ren, Shi, 1704.05446;
Altmannshofer, Stangl, Straub, 1704.05435;
D. Martinez Santos, F. Mahmoudi, T. Hurth, SN, 1705.06274
…

Fit for $\delta C_9^{NP} \sim -1 \Longrightarrow 4-5\sigma$ deviations from the SM

ONLY IF guesstimates of power corrections correct

Comparison of NP fit results: clean vs not so clean

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

	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
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

$$\Delta C_i^{(\prime)} \equiv \delta C_i^{(\prime)} / C_i^{\rm SM}$$

D. Martinez Santos, F. Mahmoudi, T. Hurth, SN, 1705.06274

Best fit values considering
only R_K and R_{K^*} ratios

	b.f. value	$\chi^2_{\rm min}$	$\mathrm{Pull}_{\rm SM}$
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

- NP in C_9 and C_9^μ favoured with SM pulls of 4.1 and 4.4σ
- C_{10}-like solutions do not play a role

- NP in C_9^e, C_9^μ, C_{10}^e or C_{10}^μ, favoured by the $R_{K^{(*)}}$ ratios (significance: 3.6-4.0σ)
- Primed operators have very small SM pull

Considering only the clean observables R_K and R_{K^*} it is not possible to differentiate between best NP fits $C_9^{e/\mu}$ or $C_{10}^{e/\mu}$

Are tensions due to hadronic effects or NP (which NP scenario)?

How to resolve the issue:

1. Unknown power corrections

   - Crucial for significance of the anomalies
   - Not calculable in QCD factorisation
   - Alternative approaches exist based on light-cone sum rules and more recently using the analyticity approach

   Khodjamirian et al. JHEP 1009 (2010) 089
   Dimou, Lyon, Zwicky PRD 87, 074008 (2012), PRD 88, 094004 (2013)
   Bobeth et al. arXiv:1707.07305

2. Crosscheck with inclusive modes

   - Inclusive decays are theoretically better known than the exclusive decays
     (e.g. T. Huber, T. Hurth, E. Lunghi, JHEP 1506 (2015) 176)

   - Experimental results to come from Belle-II can clarify the source of the tension
     T. Hurth, F. Mahmoudi, JHEP 1404 (2014) 097
     T. Hurth, F. Mahmoudi, SN, JHEP 1412 (2014) 053

Are tensions due to hadronic effects or NP (which NP scenario)?

3. Crosscheck with other $R_{\mu/e}$ ratios within future LHCb results

- Hadronic uncertainties cancel out $\Longrightarrow$ theoretically clean
- Considering the $R_{K^{(*)}}$ tensions are reconfirmed with 12 fb^{-1} data, the best fit NP scenarios could be differentiated

	Predictions assuming 12 fb^{-1} luminosity			
Obs.	C_9^μ	C_9^e	C_{10}^μ	C_{10}^e
$R_{F_L}^{[1.1,6.0]}$	$[0.785, 0.913]$	$[0.909, 0.933]$	$[1.005, 1.042]$	$[1.001, 1.018]$
$R_{A_{FB}}^{[1.1,6.0]}$	$[6.048, 14.819]$	$[-0.288, -0.153]$	$[0.816, 0.928]$	$[0.974, 1.061]$
$R_{S_3}^{[1.1,6.0]}$	$[0.890, 0.932]$	$[0.768, 0.919]$	$[0.230, 0.838]$	$[0.714, 0.873]$
$R_{S_4}^{[1.1,6.0]}$	$[0.971, 1.152]$	$[0.822, 0.950]$	$[0.161, 0.822]$	$[0.695, 0.862]$
$R_{S_5}^{[1.1,6.0]}$	$[-0.787, 0.394]$	$[0.603, 0.697]$	$[0.881, 1.002]$	$[1.053, 1.146]$
$R_{F_L}^{[15,19]}$	$[0.999, 0.999]$	$[0.998, 0.998]$	$[0.997, 0.998]$	$[0.998, 0.998]$
$R_{A_{FB}}^{[15,19]}$	$[0.616, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{S_5}^{[15,19]}$	$[0.615, 0.927]$	$[1.002, 1.061]$	$[0.860, 0.994]$	$[1.046, 1.131]$
$R_{\phi}^{[1.1,6.0]}$	$[0.748, 0.852]$	$[0.620, 0.805]$	$[0.578, 0.770]$	$[0.578, 0.764]$
$R_{\phi}^{[15,19]}$	$[0.623, 0.803]$	$[0.577, 0.771]$	$[0.586, 0.776]$	$[0.583, 0.769]$

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- In the SM all these observables are predicted to be 1
- These tensions, if observed cannot be explained by hadronic uncertainties
  $\Longrightarrow$ would indirectly confirm the NP interpretation of the anomalies in the angular observables!

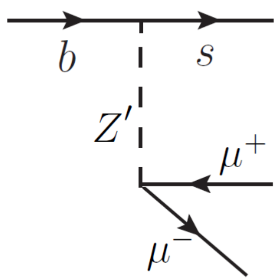
Observed pattern (δC_9~-1 & δC_7~0, δC_{10}~0)

Very hard to accommodate in many NP model (MSSM, extra dimension, …)

Prime candidates:

Models with Z' gauge boson:

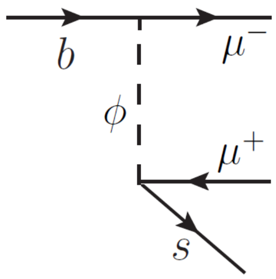
- non-universal flavour coupling to leptons
- flavour-changing couplings to LH quarks



Altmannshofer et al. '13/'14; Haisch et al. '13;
Buras et al. '13/'14; Crivellin et al. '14/'15;
Falkowski et al '15; …

lepto-quark models:

- scalar particles carrying colour & EW charge



Hiller et al. '14; Biswas et al. '14;
Nardechia et al. '14; Becirevic et al. '15;
Grinstein et al. '15; …

other models …

Should respect constrains from other decays (in these models constraints from $B_s - \bar{B}_s$ mixing can be accomodated)

Conclusions:

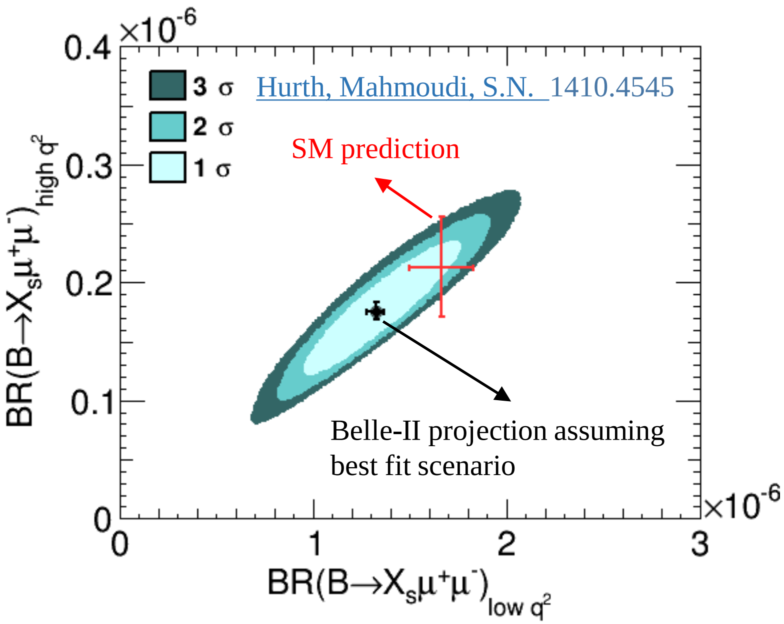
- Rare $b \to s$ transitions are powerful probes of New Physics
- Global analysis of $b \to s$ data favours a 25% reduction in C_9 with respect to the SM
- Significance of the anomalies depends on the assumptions on the hadronic uncertainties
- At the moment, from a statistical point of view, the New Physics explanation describes the anomalies better than underestimated hadronic
- The recent measurement of R_{K^*} supports the NP hypothesis, but the experimental errors are still large and the update of R_K and other ratios is eagerly awaited!
- If the tensions remain, even in the pessimistic case that there will be no theoretical progress in non-factorisable power corrections, Belle II and/or LHCb upgrade can resolve it

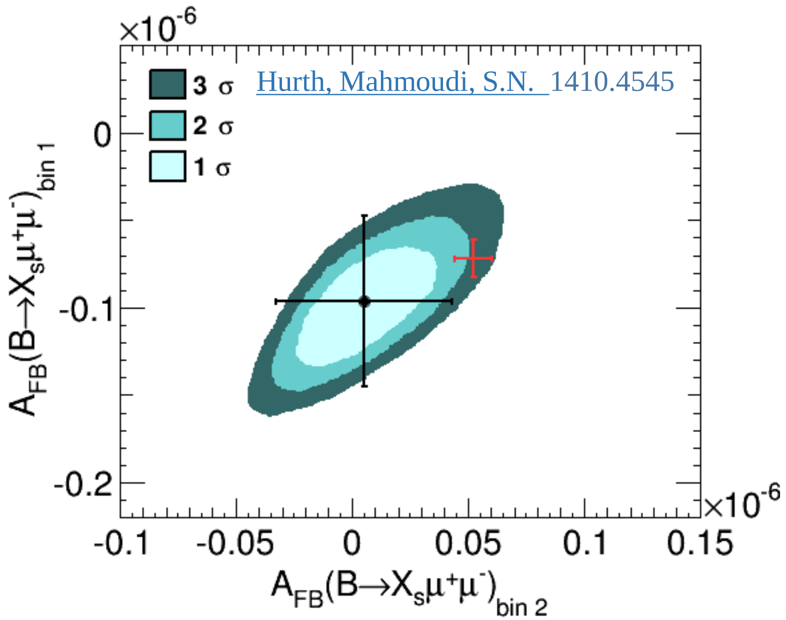
Backup

Are tensions due to hadronic effects or NP (which NP scenario)?

Crosschecking with the inclusive mode $B \to X_s \mu^+\mu^-$

- Using the best fit point of C_7, C_9, C_{10} we predict the branching ratio at low- and high-q^2 at 1,2 and 3σ ranges also for A_{FB}
- The black cross corresponds to the future Belle-II measurement assuming the best fit scenario
- Expected uncertainty of 2.9% (4.1%) for the branching fraction in the low- (high-)q^2 region, absolute uncertainty of 0.050 in the low-q^2 bin 1 ($1 < q2 < 3.5$ GeV^2), 0.054 in the low-q^2 bin 2 ($3.5 < q2 < 6$ GeV^2) for the normalised A_{FB}





NP effect of C_9 is large enough to be checked by the theoretically cleaner inclusive modes at Belle-II

Are tensions due to hadronic effects or NP (which NP scenario)?

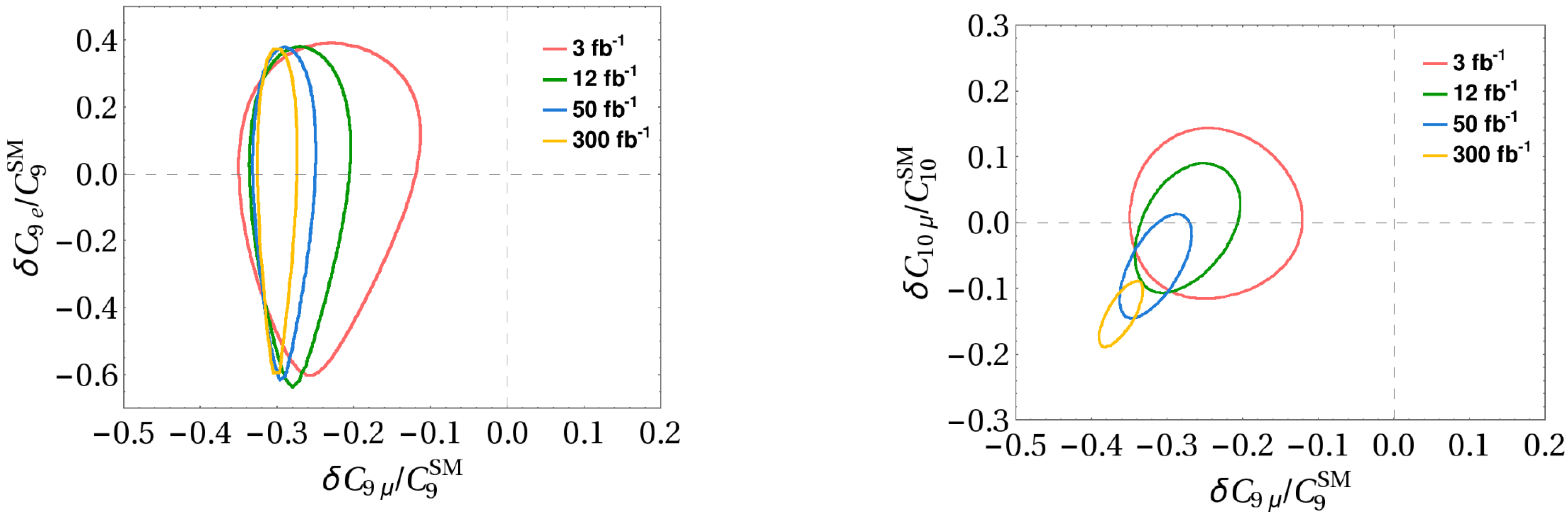
LHCb prospects

D. Martinez Santos, F. Mahmoudi, T. Hurth, SN, 1705.06274

- Global fits using only R_K and R_{K^*}
- Considering several luminosities, assuming the current central values

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)

- Global fits using the angular observables only (excluding the clean ratios)
- Considering several luminosities, assuming the current central values



Hadronic effects vs. New Physics

Non-factorisable contributions appear in:

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

$$\mathcal{N}_\lambda(q^2) = \text{Leading Order QCDf of non-factorisable piece} + h_\lambda(q^2)$$

A possible parametrisation of the non-factorisable power corrections

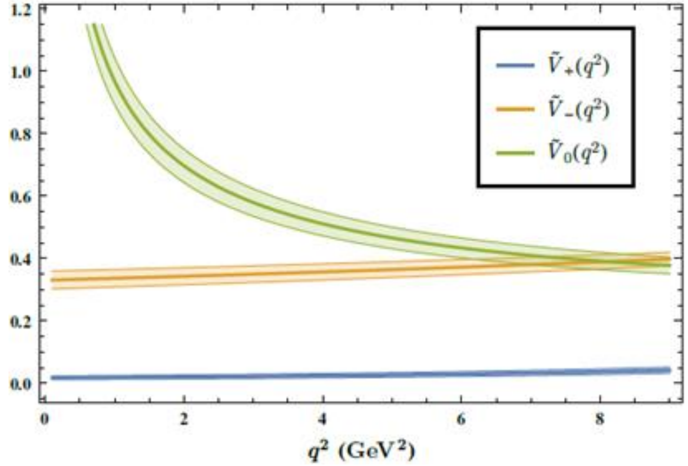
$$h_\lambda(q^2) = h_\lambda^{(0)} + \frac{q^2}{1\text{GeV}^2}h_\lambda^{(1)} + \frac{q^4}{1\text{GeV}^4}h_\lambda^{(2)} \qquad (\lambda = +,-,0)$$

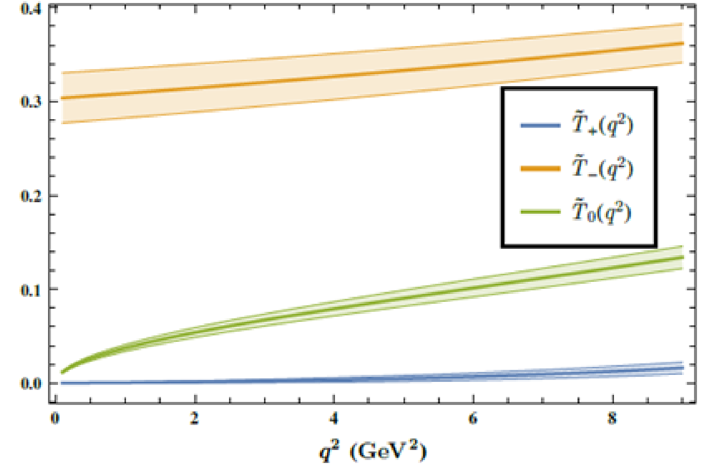
M. Ciuchini et al., 1512.07157
S. Jäger and J. Camalich: 1412.3183

It seems: $h_\lambda^{(0)} \longrightarrow C_7^{\rm NP}$, $h_\lambda^{(1)} \longrightarrow C_9^{\rm NP}$ and $h_\lambda^{(2)}$ term cannot be mimicked by $C_{7,9}$ M. Ciuchini et al., 1512.07157

However, $\lambda = +,-,0$

and $\tilde{V}_\lambda$ and $\tilde{T}_\lambda$ both have a q^2 dependence





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However, $\lambda = +,-,0$

and $\tilde{V}_\lambda$ and $\tilde{T}_\lambda$ both have a q^2 dependence

- Mild q^4-terms can rise due to form factor terms
- C_7^{NP} and C_9^{NP} can cause effects similar to $h_\lambda^{(0,1,2)}$

Wilks' test

Fit to NP and power corrections using only $B \to K^* \mu^+ \mu^-$ observables at low-q^2 to keep the embedding

Comparison of the hadronic fit with the NP fit through likelihood ratio tests

p-values can be obtained (via Wilks' theorem)

$\Longrightarrow$ p-value indicates the significance of the new parameters added

up to 6 GeV^2 observables			
	δC_9	$\delta C_7, \delta C_9$	Hadronic fit
Plain SM	4.5×10^{-3} (2.8σ)	9.4×10^{-3} (2.6σ)	6.2×10^{-2} (1.9σ)
δC_9	--	0.27 (1.1σ)	0.37 (0.89σ)
δC_7 & δC_9	--	--	0.41 (0.86σ)

up to 8 GeV^2 observables			
	δC_9	$\delta C_7, \delta C_9$	Hadronic fit
Plain SM	3.7×10^{-5} (4.1σ)	6.3×10^{-5} (4.0σ)	6.1×10^{-3} (2.7σ)
δC_9	--	0.13 (1.5σ)	0.45 (0.76σ)
δC_7 & δC_9	--	--	0.61 (0.52σ)

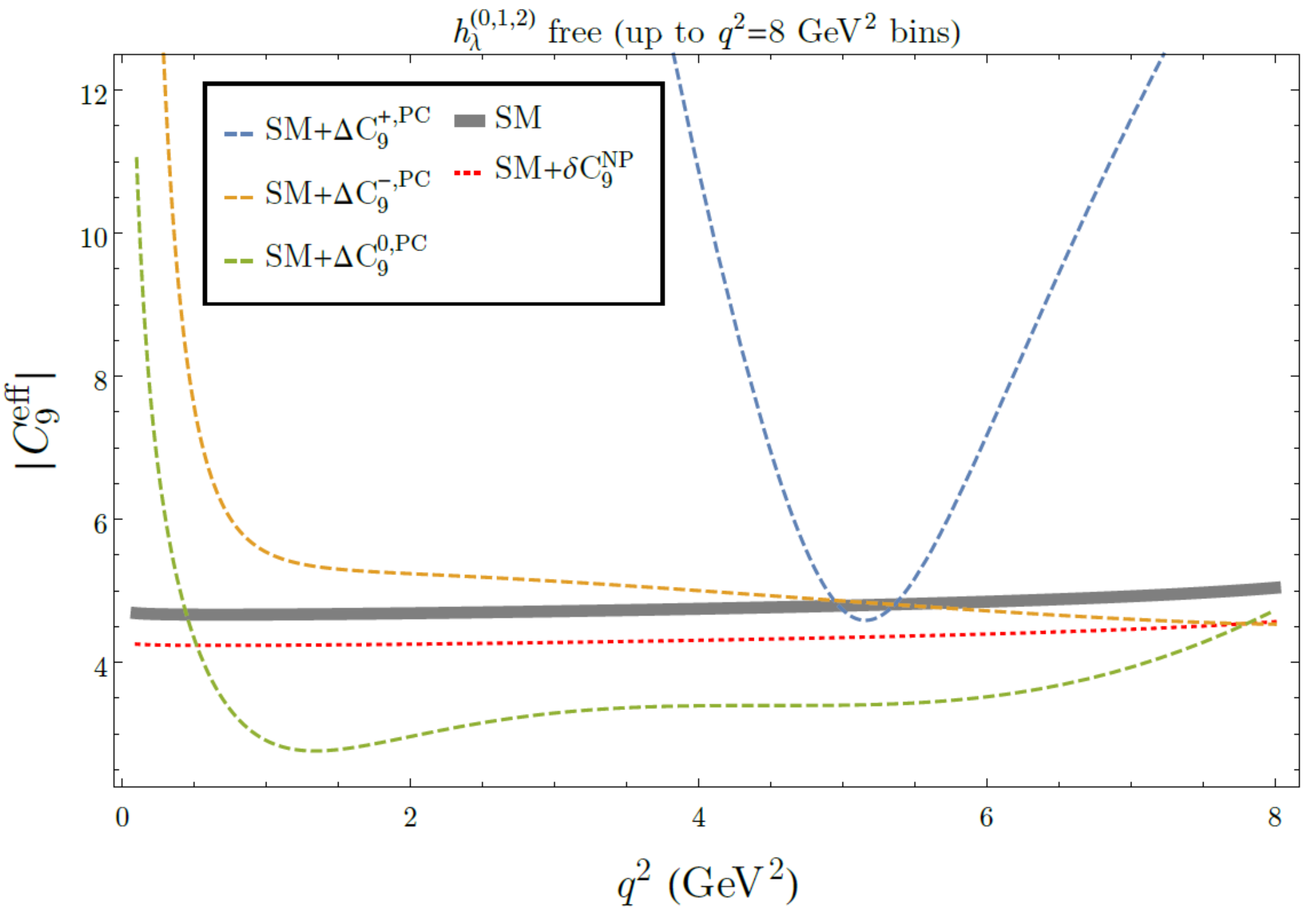
- Adding the hadronic parameters (16 more parameters) does not really improve the fits
- Strong indication that the NP interpretation is a valid option, even if the situation remains inconclusive

Hadronic corrections as shift to C_9

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

The effect of the power corrections could also be described through a q^2-dependent shift in C_9 via

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



Hadronic corrections as shift to C_9 assuming $h_+^{(0)}$ to be constrained

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

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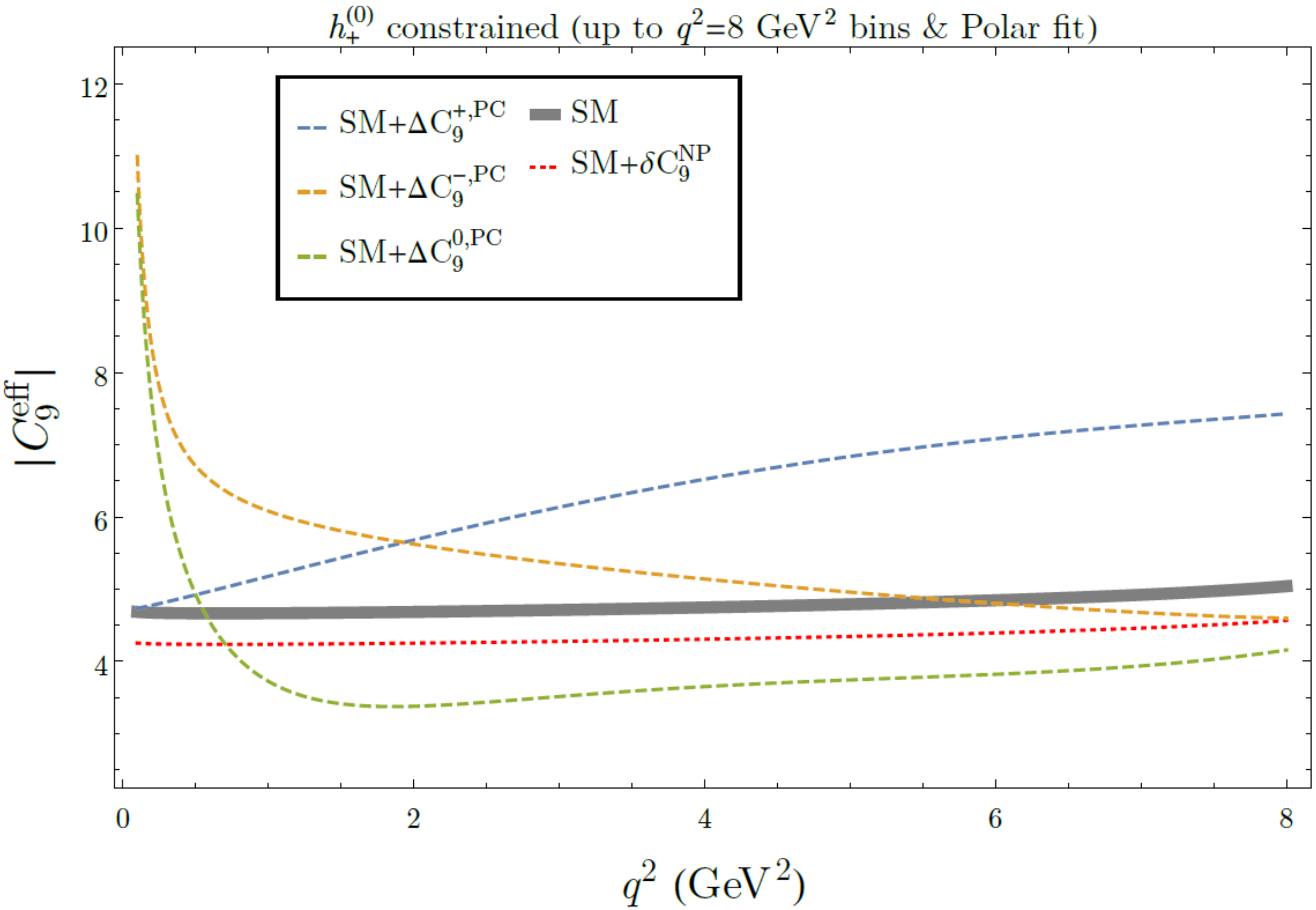
$$\Delta C_9^{\lambda,{\rm PC}} = -16\pi^2\frac{m_B^2}{q^2}\frac{h_\lambda(q^2)}{\tilde{V}_\lambda(q^2)}$$

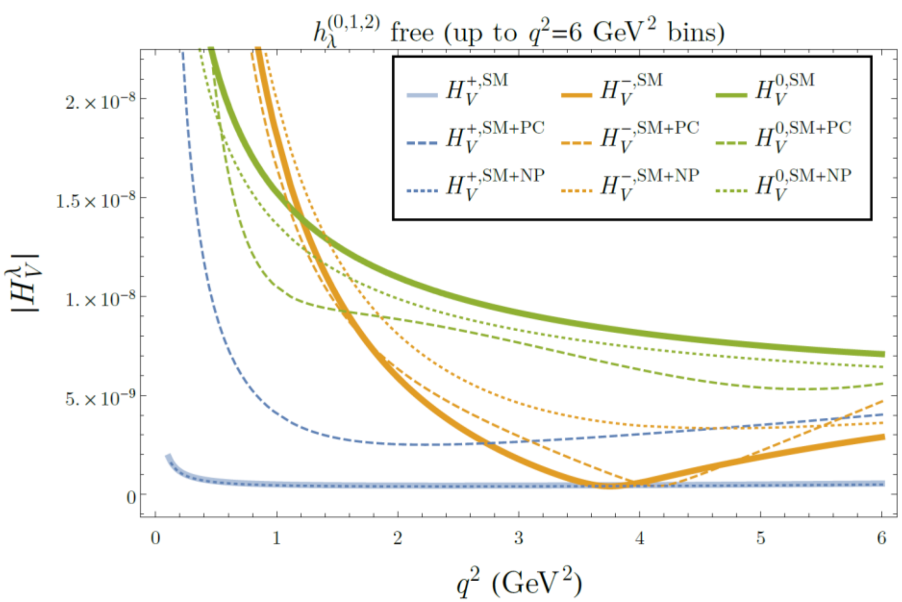
$(|h_+^{(0)}/h_-^{(0)}| < 0.2)$

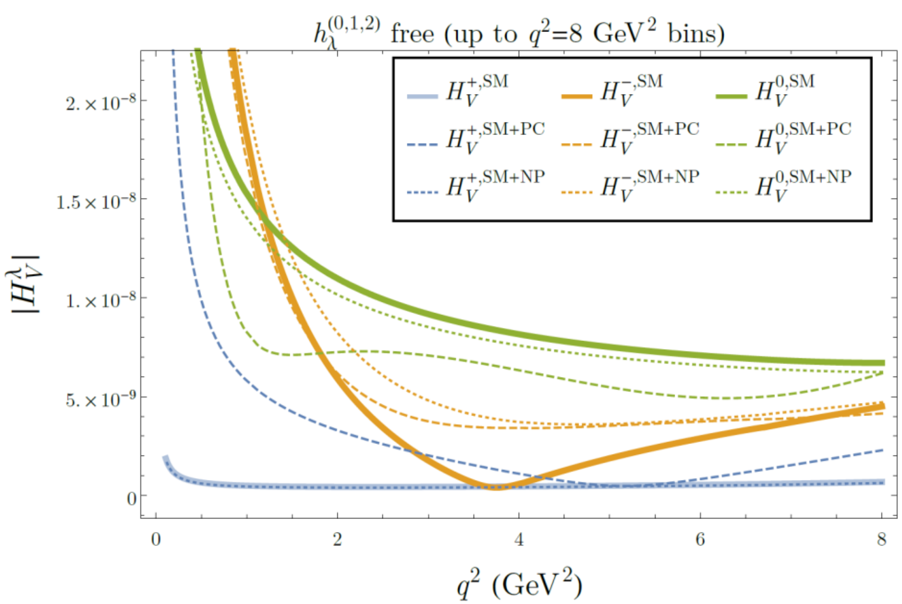


Fit parameters of power corrections and shapes of the different corrections

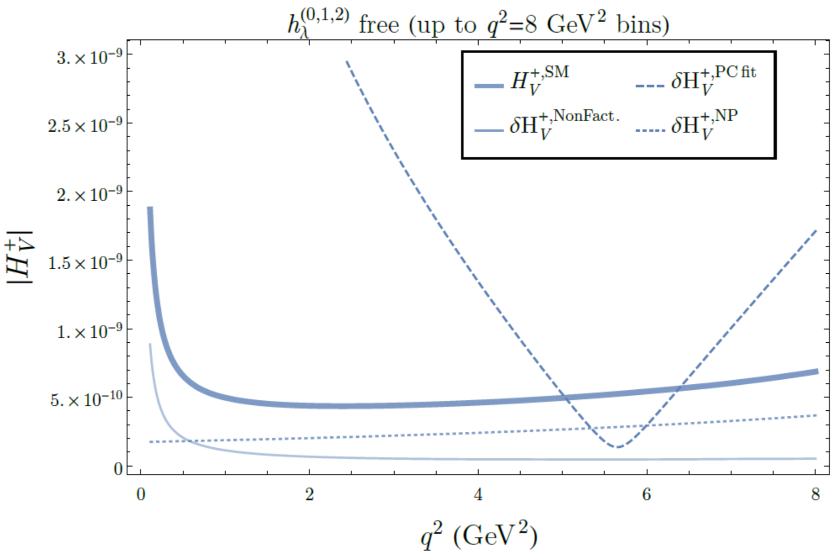
up to $q^2 = 6$ GeV^2 obs.		
	Real	Imaginary
$h_+^{(0)}$	$(2.3 \pm 2.3) \times 10^{-4}$	$(-2.0 \pm 2.3) \times 10^{-4}$
$h_+^{(1)}$	$(-1.2 \pm 3.5) \times 10^{-4}$	$(3.3 \pm 38.6) \times 10^{-5}$
$h_+^{(2)}$	$(1.2 \pm 6.8) \times 10^{-5}$	$(-3.5 \pm 8.1) \times 10^{-5}$
$h_-^{(0)}$	$(-7.7 \pm 19.8) \times 10^{-5}$	$(4.5 \pm 3.6) \times 10^{-4}$
$h_-^{(1)}$	$(-3.7 \pm 20.8) \times 10^{-5}$	$(-7.4 \pm 4.2) \times 10^{-4}$
$h_-^{(2)}$	$(2.7 \pm 3.9) \times 10^{-5}$	$(1.5 \pm 0.8) \times 10^{-4}$
$h_0^{(0)}$	$(-6.1 \pm 38.4) \times 10^{-5}$	$(7.8 \pm 4.0) \times 10^{-4}$
$h_0^{(1)}$	$(3.8 \pm 5.2) \times 10^{-4}$	$(-1.0 \pm 0.6) \times 10^{-3}$
$h_0^{(2)}$	$(-4.7 \pm 8.7) \times 10^{-5}$	$(1.6 \pm 1.3) \times 10^{-4}$

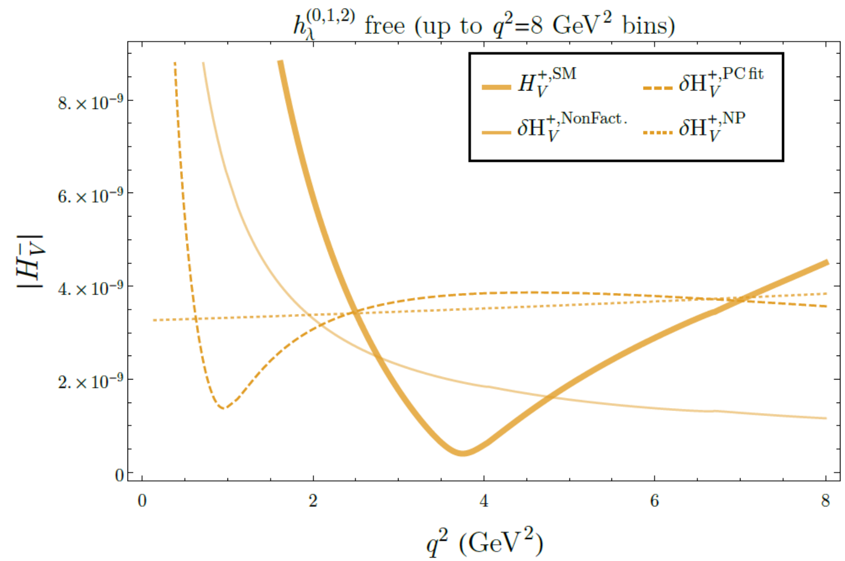
up to $q^2 = 8$ GeV^2 obs.		
	Real	Imaginary
$h_+^{(0)}$	$(1.2 \pm 2.0) \times 10^{-4}$	$(-1.6 \pm 2.1) \times 10^{-4}$
$h_+^{(1)}$	$(1.2 \pm 2.3) \times 10^{-4}$	$(-1.1 \pm 3.0) \times 10^{-4}$
$h_+^{(2)}$	$(-2.6 \pm 3.4) \times 10^{-5}$	$(2.3 \pm 4.4) \times 10^{-5}$
$h_-^{(0)}$	$(-1.0 \pm 1.8) \times 10^{-4}$	$(2.9 \pm 3.2) \times 10^{-4}$
$h_-^{(1)}$	$(2.5 \pm 13.3) \times 10^{-5}$	$(-3.4 \pm 3.2) \times 10^{-4}$
$h_-^{(2)}$	$(9.2 \pm 18.7) \times 10^{-6}$	$(1.7 \pm 4.8) \times 10^{-5}$
$h_0^{(0)}$	$(-2.6 \pm 3.3) \times 10^{-4}$	$(6.5 \pm 3.9) \times 10^{-4}$
$h_0^{(1)}$	$(7.5 \pm 4.4) \times 10^{-4}$	$(-8.7 \pm 3.6) \times 10^{-4}$
$h_0^{(2)}$	$(-8.6 \pm 5.8) \times 10^{-5}$	$(9.6 \pm 6.2) \times 10^{-5}$

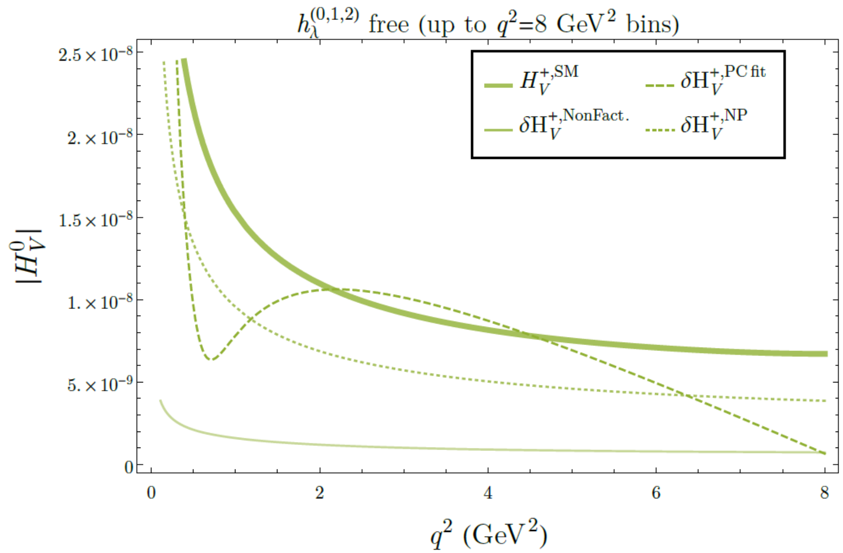




Size of different contributions to the helicity amplitudes

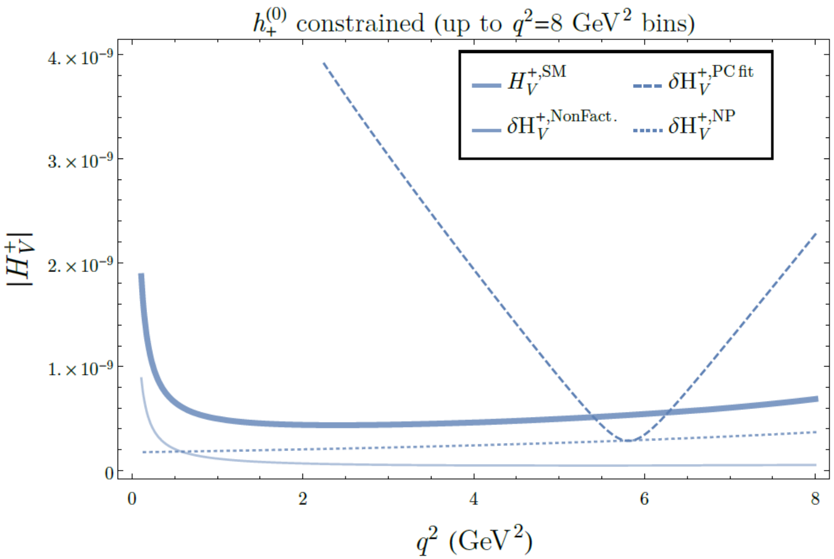


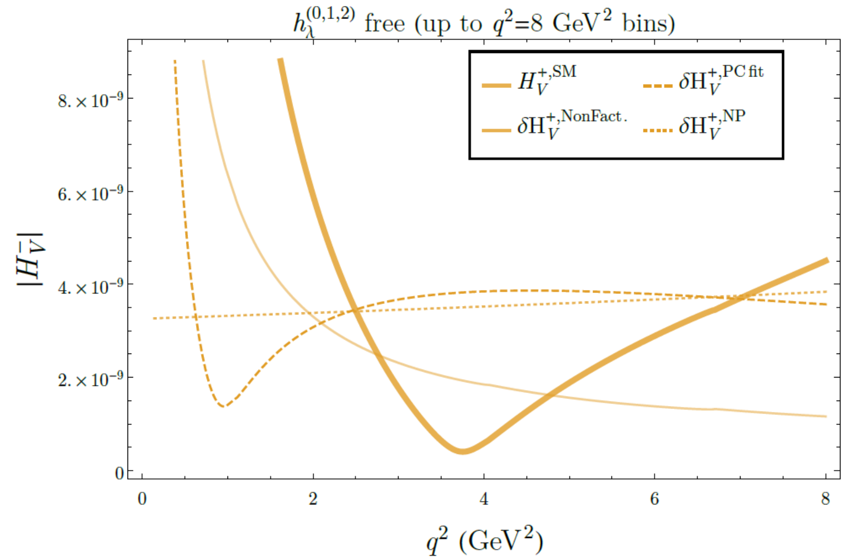


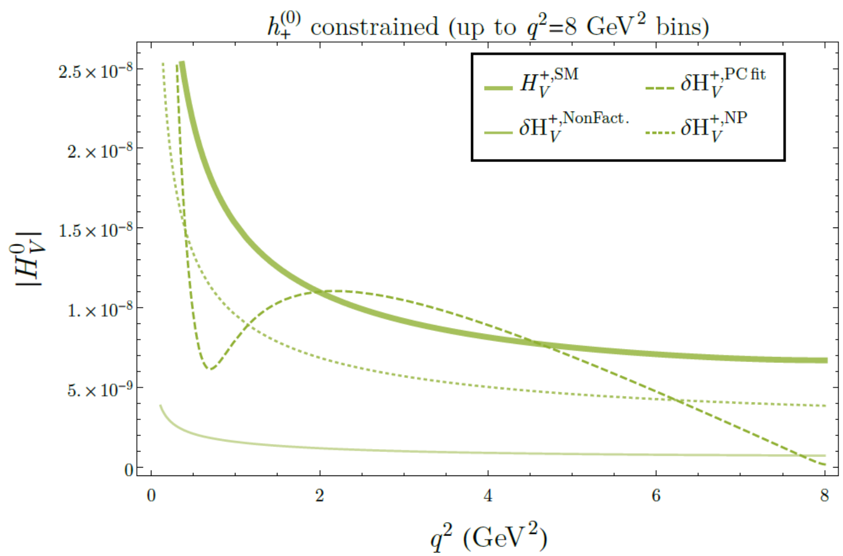


Size of different contributions to the helicity amplitudes

Assuming $h_+^{(0)}$ to be constrained $\quad (|h_+^{(0)}/h_-^{(0)}| < 0.2)$







Angular coefficients

$$
\begin{aligned}
I_1^c &= F\left\{\frac{1}{2}\left(|H_V^0|^2+|H_A^0|^2\right)+|H_P|^2+\frac{2m_\ell^2}{q^2}\left(|H_V^0|^2-|H_A^0|^2\right)+\beta^2|H_S|^2\right\}\\
I_1^s &= F\left\{\frac{\beta^2+2}{8}\left(|H_V^+|^2+|H_V^-|^2+(V\to A)\right)+\frac{m_\ell^2}{q^2}\left(|H_V^+|^2+|H_V^-|^2-(V\to A)\right)\right\}\\
I_2^c &= -F\,\frac{\beta^2}{2}\left(|H_V^0|^2+|H_A^0|^2\right)\\
I_2^s &= F\,\frac{\beta^2}{8}\left(|H_V^+|^2+|H_V^-|^2\right)+(V\to A)\\
I_3 &= -\frac{F}{2}\mathrm{Re}\left[H_V^+(H_V^-)^*\right]+(V\to A)\\
I_4 &= F\,\frac{\beta^2}{4}\mathrm{Re}\left[\left(H_V^-+H_V^+\right)\left(H_V^0\right)^*\right]+(V\to A)\\
I_5 &= F\left\{\frac{\beta}{2}\mathrm{Re}\left[\left(H_V^--H_V^+\right)\left(H_A^0\right)^*\right]+(V\leftrightarrow A)-\frac{\beta\,m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[H_S^*(H_V^++H_V^-)\right]\right\}\\
I_6^s &= F\beta\,\mathrm{Re}\left[H_V^-(H_A^-)^*-H_V^+(H_A^+)^*\right]\\
I_6^c &= 2F\frac{\beta\,m_\ell}{\sqrt{q^2}}\mathrm{Re}\left[H_S^*H_V^0\right]\\
I_7 &= F\left\{\frac{\beta}{2}\,\mathrm{Im}\left[\left(H_A^++H_A^-\right)\left(H_V^0\right)^*+(V\leftrightarrow A)\right]-\frac{\beta\,m_\ell}{\sqrt{q^2}}\,\mathrm{Im}\left[H_S^*(H_V^--H_V^+)\right]\right\}\\
I_8 &= F\,\frac{\beta^2}{4}\mathrm{Im}\left[(H_V^--H_V^+)(H_V^0)^*\right]+(V\to A)\\
I_9 &= F\,\frac{\beta^2}{2}\mathrm{Im}\left[H_V^+(H_V^-)^*\right]+(V\to A)
\end{aligned}
$$