$B \to K^{(*)}\mu^+\mu^-$: SM versus New Physics

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Based on: SDG, JM, J. Virto, **Phys. Rev. D88 (2013) 074002**
SDG, L. Hofer, JM, J. Virto, **JHEP 1412 (2014) 125** , L. Hofer and J.M. to appear'15

January 10, 2015

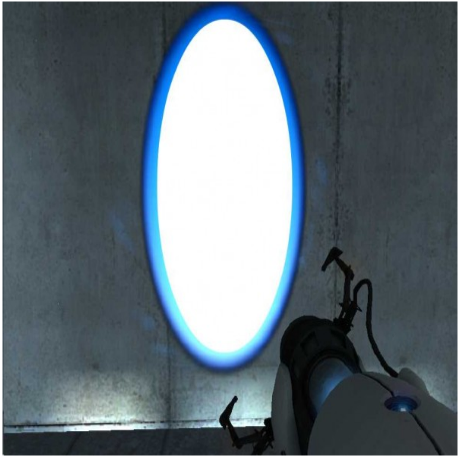
PLAN of the TALK

- Motivation and theoretical description of $B \to K^*(\to K\pi)l^+l^-$ at large recoil.
- Analysis of LHCb data on $P_i^{(\prime)}$ and model independent understanding of the anomaly.
- Possible explanations of the pattern of deviations and most updated SM predictions.
- New symmetry results and S-wave.
- Conclusions

Motivation

Many of us thought that the "scalar particle" found at CERN was going to be ALSO

$\Rightarrow$ the PORTAL for NEW PHYSICS.



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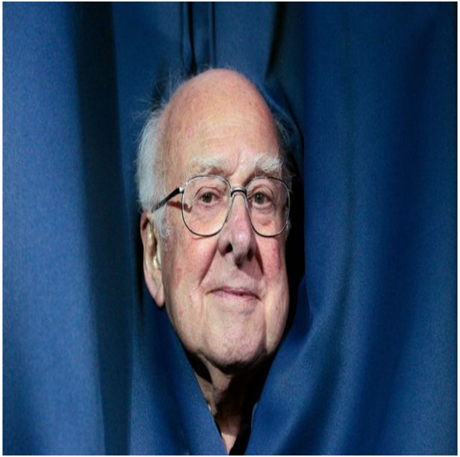

BUT the "scalar particle" found resembles very much the SM Higgs particle, with SM-like couplings up to the present precision $\Rightarrow$ it will be a long term task...

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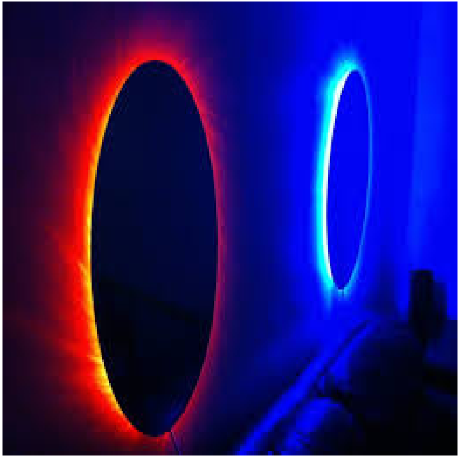


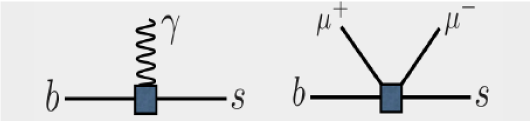
HOWEVER, there are OTHER PORTALS:
RARE B DECAYS (FCNC)

- New Physics same footing as SM
- They allow you to explore higher scales Λ
- A promising golden handle: $B \to K^* \mu^+ \mu^-$

⇒ In this portal the best paradigm to unveil **New Physics** in Flavour Physics will be an accurate determination of Wilson coefficients. In particular those associated to operators:

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu}, \quad \mathcal{O}_9 = \frac{\mathbf{e^2}}{\mathbf{16\pi^2}}(\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L b})(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell),$$

and chiral counterparts $\mathcal{O}'_{7,9,10}$ (L $\leftrightarrow$ R)



- Wilson Coefficients are tested $C_i = C_i^{SM} + \mathbf{C_i^{NP}}$ $\left\{ \begin{array}{l} \text{different levels of accuracy} \\ \text{allow different ranges of NP} \end{array} \right.$

Wilson coefficients [$\mu_b = \mathcal{O}(m_b)$]	Observables	SM values
$\mathbf{C_7^{eff}}(\mu_b)$	$\mathcal{B}(\bar{\mathbf{B}} \to \mathbf{X_s}\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, A_{FB}, F_L,$	-0.292
$\mathbf{C_9}(\mu_b)$	$\mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L,$	4.075
$\mathbf{C_{10}}(\mu_b)$	$\mathcal{B}(\mathbf{B_s} \to \mu^+\mu^-), \mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L,$	-4.308
$\mathbf{C'_7}(\mu_b)$	$\mathcal{B}(\bar{B} \to X_s\gamma), A_I(B \to K^*\gamma), S_{K^*\gamma}, A_{FB}, F_L$	-0.006
$\mathbf{C'_9}(\mu_b)$	$\mathcal{B}(B \to X_s\ell\ell), A_{FB}, F_L$	0
$\mathbf{C'_{10}}(\mu_b)$	$\mathcal{B}(B_s \to \mu^+\mu^-), A_{FB}, F_L,$	0

More Precision Observables are necessary to overconstrain the deviations $\mathbf{C_i^{NP}}$

$\Rightarrow$ In this portal the best paradigm to unveil **New Physics** in Flavour Physics will be an accurate determination of Wilson coefficients. In particular those associated to operators:

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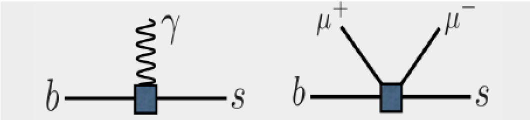

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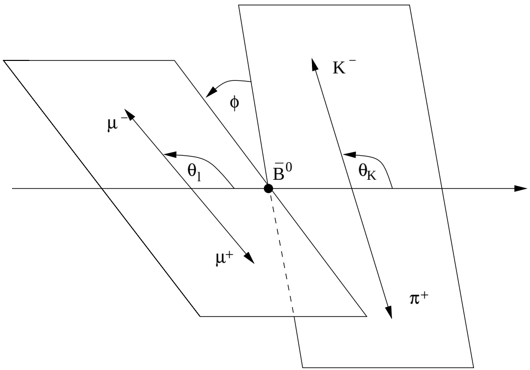
$\Rightarrow$ $B \to K^*(\to K\pi)\mu^+\mu^-$ can fulfill this requirement providing a large set of clean observables that can test in an unprecedented way C_9 and $C'_{7,9,10}$.

All those new observables $P_i^{(\prime)}$ come from the angular distribution $\mathbf{\bar{B}_d} \to \mathbf{\bar{K}^{*0}}(\to \mathbf{K}^-\pi^+)\mathbf{l}^+\mathbf{l}^-$ with the K^{*0} on the mass shell. It is described by $\mathbf{s} = \mathbf{q^2}$ and three angles θ_ℓ, $\theta_{\mathbf{K}}$ and ϕ

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



θ_ℓ: Angle of emission between $\bar{K}^{*0}$ and μ^- in di-lepton rest frame.
$\theta_{\mathbf{K}}$: Angle of emission between $\bar{K}^{*0}$ and K^- in di-meson rest frame.
ϕ: Angle between the two planes.

$\mathbf{q^2}$: dilepton invariant mass square.

Notice LHCb uses $\theta_\ell^{LHCb} = \pi - \theta_\ell^{us}$

Three regions in q^2:

- **large recoil for** K^*: $E_{K^*} \gg \Lambda_{QCD}$ or $4m_\ell^2 \leq q^2 < 9$ GeV^2
- resonance region ($q^2 = m^2_{J/\Psi}, \ldots$) betwen $9 < q^2 < 14$ GeV^2.
- **low-recoil for** K^*: $E_{K^*} \sim \Lambda_{QCD}$ or $14 < q^2 \leq (m_B - m_{K^*})^2$.

Relation between J_i and P_j, P'_k observables

The differential distribution splits in J_i coefficients:

$$J(q^2,\theta_l,\theta_K,\phi) =$$
$$J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l$$
$$+J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\,.$$

The coefficients $\mathbf{J_i}$ of the distribution can be reexpressed now in terms of this basis of clean observables:

Correspondence $\mathbf{J_i} \leftrightarrow \mathbf{P_i^{(\prime)}}$:

BROWN: LO FF-dependent observables (F_L Longitudinal Polarization Fraction of K^*)

RED: LO FF-independent observables at large-recoil (defined from these eqs.)

Here for simplicity ($m_\ell = 0$). See [J.M'12] for $m_\ell \neq 0$.

$$(\mathbf{J_{2s}} + \bar{\mathbf{J}}_{\mathbf{2s}}) = \frac{1}{4}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad (\mathbf{J_{2c}} + \bar{\mathbf{J}}_{\mathbf{2c}}) = -\mathbf{F_L}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

$$\mathbf{J_3} + \bar{\mathbf{J}}_{\mathbf{3}} = \frac{1}{2}\mathbf{P_1}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad \mathbf{J_3} - \bar{\mathbf{J}}_{\mathbf{3}} = \frac{1}{2}\mathbf{P_1^{CP}}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

$$\mathbf{J_{6s}} + \bar{\mathbf{J}}_{\mathbf{6s}} = 2\mathbf{P_2}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad \mathbf{J_{6s}} - \bar{\mathbf{J}}_{\mathbf{6s}} = 2\mathbf{P_2^{CP}}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

$$\mathbf{J_9} + \bar{\mathbf{J}}_{\mathbf{9}} = -\mathbf{P_3}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad \mathbf{J_9} - \bar{\mathbf{J}}_{\mathbf{9}} = -\mathbf{P_3^{CP}}\mathbf{F_T}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

$$\mathbf{J_4} + \bar{\mathbf{J}}_{\mathbf{4}} = \frac{1}{2}\mathbf{P'_4}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad \mathbf{J_4} - \bar{\mathbf{J}}_{\mathbf{4}} = \frac{1}{2}\mathbf{P_4^{\prime CP}}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

$$\mathbf{J_5} + \bar{\mathbf{J}}_{\mathbf{5}} = \mathbf{P'_5}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad \mathbf{J_5} - \bar{\mathbf{J}}_{\mathbf{5}} = \mathbf{P_5^{\prime CP}}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

$$\mathbf{J_7} + \bar{\mathbf{J}}_{\mathbf{7}} = -\mathbf{P'_6}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}} \qquad \mathbf{J_7} - \bar{\mathbf{J}}_{\mathbf{7}} = -\mathbf{P_6^{\prime CP}}\sqrt{\mathbf{F_T F_L}}\frac{\mathbf{d\Gamma + d\bar\Gamma}}{\mathbf{dq^2}}$$

The Optimized basis of CP conserving and CP violating Observables

P_i, P_i' defines an **Optimal Basis** of observables, a compromise between:

- *Excellent experimental accessibility and simplicity of the fit.*
- *Reduced FF dependence (in the large-recoil region:* $0.1 \leq q^2 \leq 8\ \mathrm{GeV}^2$).

$$\mathbf{P_5'} = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R)}{\sqrt{|A_0|^2(|A_\parallel|^2 + |A_\perp|^2)}} = c_1 + \mathcal{O}(\alpha_s\, \xi_{\perp,\parallel}) \qquad \mathbf{S_5} = \sqrt{2}\frac{\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^{R*} A_\perp^R)}{|A_\parallel|^2 + |A_\perp|^2 + |A_0|^2} = \frac{c_1 \xi_\perp \xi_\parallel}{c_2 \xi_\perp^2 + c_3 \xi_\parallel^2}$$

Our proposal for **CP-conserving basis**:

$$\left\{ \frac{\mathbf{d\Gamma}}{\mathbf{dq^2}}, \mathbf{A_{FB}}, \mathbf{P_1}, \mathbf{P_2}, \mathbf{P_3}, \mathbf{P_4'}, \mathbf{P_5'}, \mathbf{P_6'} \right\} \text{ or } \mathbf{P_3} \leftrightarrow \mathbf{P_8'} \text{ and } \mathbf{A_{FB}} \leftrightarrow \mathbf{F_L}$$

where $P_1 = A_T^2$ [Kruger, J.M'05],
$P_2 = \frac{1}{2}A_T^{\mathrm{re}}, P_3 = -\frac{1}{2}A_T^{\mathrm{im}}$ [Becirevic, Schneider'12]
$P'_{4,5,6}$ [Descotes, JM, Ramon, Virto'13]).

The corresponding **CP-violating basis** ($J_i + \bar{J}_i \to J_i - \bar{J}_i$ in numerators):

$$\left\{ \mathbf{A_{CP}}, \mathbf{A_{FB}^{CP}}, \mathbf{P_1^{CP}}, \mathbf{P_2^{CP}}, \mathbf{P_3^{CP}}, \mathbf{P_4'^{CP}}, \mathbf{P_5'^{CP}}, \mathbf{P_6'^{CP}} \right\} \text{ or } \mathbf{P_3^{CP}} \leftrightarrow \mathbf{P_8'^{CP}} \text{ and } \mathbf{A_{FB}^{CP}} \leftrightarrow \mathbf{F_L^{CP}}$$

Theoretical Framework at low-q^2: How to compute the P_i observables.

"Barcelona/Aachen" approach: QCDF+exploit the symmetry relations at large-recoil among FF:

$$\frac{m_B}{m_B+m_{K^*}} V(q^2) = \frac{m_B+m_{K^*}}{2E} A_1(q^2) = T_1(q^2) = \frac{m_B}{2E} T_2(q^2) = \xi_\perp(E)$$

$$\frac{m_{K^*}}{E} A_0(q^2) = \frac{m_B+m_{K^*}}{2E} A_1(q^2) - \frac{m_B-m_{K^*}}{m_B} A_2(q^2) = \frac{m_B}{2E} T_2(q^2) - T_3(q^2) = \xi_\parallel(E)$$

$\Rightarrow$ Transparent, valid for **ANY** FF parametrization (BZ, KMPW,...) and easy to reproduce.

$\Rightarrow$ Dominant correlations automatically implemented in a transparent way.

$\Rightarrow$ This allows you to construct **clean** observables from the observation that at LO in $1/m_b$, α_s and large-recoil limit (E_K^* large):

$$\begin{aligned} A_\perp^{L,R} &= \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\text{eff}} + \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^\prime) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\text{eff}} + \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_\perp(E_{K^*}), \quad A_\parallel^{L,R} \propto \xi_\perp(E_{K^*}) \\ A_0^{L,R} &= -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\text{eff}} - \mathcal{C}_9^{\text{eff}\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^\prime) + 2\hat{m}_b (\mathcal{C}_7^{\text{eff}} - \mathcal{C}_7^{\text{eff}\prime}) \right] \xi_\parallel(E_{K^*}). \end{aligned}$$

$\Rightarrow$ Symmetry Breaking corrections (α_s and P.C.) are added in our computation:

- known α_s factorizable and non-factorizable corrections from QCDF.
- factorizable power corrections (using a systematic procedure for each FFp, see later)
- non-factorizable power corrections including charm-quark loops.

Analysis of LHCb data on

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

Present bins: [0.1,2], [2,4.3], [4.3,8.68], [1,6], [14.18,16], [16,19] GeV^2.

Observable	Experiment	SM prediction	Pull
$\langle P_1\rangle_{[0.1,2]}$	$-0.19^{+0.40}_{-0.35}$	$0.007^{+0.043}_{-0.044}$	-0.5
$\langle P_1\rangle_{[2,4.3]}$	$-0.29^{+0.65}_{-0.46}$	$-0.051^{+0.046}_{-0.046}$	-0.4
$\langle P_1\rangle_{[4.3,8.68]}$	$0.36^{+0.30}_{-0.31}$	$-0.117^{+0.056}_{-0.052}$	$+1.5$
$\langle P_1\rangle_{[1,6]}$	$0.15^{+0.39}_{-0.41}$	$-0.055^{+0.041}_{-0.043}$	$+0.5$
$\langle P_2\rangle_{[0.1,2]}$	$0.03^{+0.14}_{-0.15}$	$0.172^{+0.020}_{-0.021}$	-1.0
$\langle P_2\rangle_{[2,4.3]}$	$0.50^{+0.00}_{-0.07}$	$0.234^{+0.060}_{-0.086}$	**$+2.9$**
$\langle P_2\rangle_{[4.3,8.68]}$	$-0.25^{+0.07}_{-0.08}$	$-0.407^{+0.049}_{-0.037}$	**$+1.7$**
$\langle P_2\rangle_{[1,6]}$	$0.33^{+0.11}_{-0.12}$	$0.084^{+0.060}_{-0.078}$	$+1.8$
$\langle A_{\rm FB}\rangle_{[0.1,2]}$	$-0.02^{+0.13}_{-0.13}$	$-0.136^{+0.051}_{-0.048}$	$+0.8$
$\langle A_{\rm FB}\rangle_{[2,4.3]}$	$-0.20^{+0.08}_{-0.08}$	$-0.081^{+0.055}_{-0.069}$	-1.1
$\langle A_{\rm FB}\rangle_{[4.3,8.68]}$	$0.16^{+0.06}_{-0.05}$	$0.220^{+0.138}_{-0.113}$	-0.5
$\langle A_{\rm FB}\rangle_{[1,6]}$	$-0.17^{+0.06}_{-0.06}$	$-0.035^{+0.037}_{-0.034}$	-2.0

- $\mathbf{P_1}$: No substantial deviation (large error bars).
- $\mathbf{A_{\rm FB}}$-$\mathbf{P_2}$: A slight tendency for a lower value of the second and third bins of $A_{\rm FB}$ is consistent with a $2.9\,\sigma$ ($1.7\,\sigma$) deviation in the second (third) bin of P_2.
- **Zero**: Preference for a slightly higher q^2-value for the zero of $A_{\rm FB}$ (same as the zero of P_2).

Both effects can be accommodated with $\mathcal{C}_7^{\rm NP} < 0$ and/or $\mathcal{C}_9^{\rm NP} < 0$.

Connection via $\mathcal{H}_{eff}$

Observable	Experiment	SM prediction	Pull
$\langle P_4' \rangle_{[0.1,2]}$	$0.00^{+0.52}_{-0.52}$	$-0.342^{+0.031}_{-0.026}$	$+0.7$
$\langle P_4' \rangle_{[2,4.3]}$	$0.74^{+0.54}_{-0.60}$	$0.569^{+0.073}_{-0.063}$	$+0.3$
$\langle P_4' \rangle_{[4.3,8.68]}$	$1.18^{+0.26}_{-0.32}$	$1.003^{+0.028}_{-0.032}$	$+0.6$
$\langle P_4' \rangle_{[1,6]}$	$0.58^{+0.32}_{-0.36}$	$0.555^{+0.067}_{-0.058}$	$+0.1$
$\langle P_5' \rangle_{[0.1,2]}$	$0.45^{+0.21}_{-0.24}$	$0.533^{+0.033}_{-0.041}$	-0.4
$\langle P_5' \rangle_{[2,4.3]}$	$0.29^{+0.40}_{-0.39}$	$-0.334^{+0.097}_{-0.113}$	$\mathbf{+1.6}$
$\langle P_5' \rangle_{[4.3,8.68]}$	$-0.19^{+0.16}_{-0.16}$	$-0.872^{+0.053}_{-0.041}$	$\mathbf{+4.0}$
$\langle P_5' \rangle_{[1,6]}$	$0.21^{+0.20}_{-0.21}$	$-0.349^{+0.088}_{-0.100}$	$+2.5$
$\langle P_4' \rangle_{[14.18,16]}$	$-0.18^{+0.54}_{-0.70}$	$1.161^{+0.190}_{-0.332}$	-2.1
$\langle P_4' \rangle_{[16,19]}$	$0.70^{+0.44}_{-0.52}$	$1.263^{+0.119}_{-0.248}$	-1.1
$\langle P_5' \rangle_{[14.18,16]}$	$\mathbf{-0.79^{+0.27}_{-0.22}}$	$\mathbf{-0.779^{+0.328}_{-0.363}}$	$+0.0$
$\langle P_5' \rangle_{[16,19]}$	$\mathbf{-0.60^{+0.21}_{-0.18}}$	$\mathbf{-0.601^{+0.282}_{-0.367}}$	$+0.0$

Definition of the anomaly:

- $\mathbf{P_5'}$: There is a striking $4.0\,\sigma$ ($1.6\,\sigma$) deviation in the third (second) bin of P_5'.

  Consistent with large negative contributions in $\mathcal{C}_7^{\rm NP}$ and/or $\mathcal{C}_9^{\rm NP}$.

- $\mathbf{P_4'}$: in agreement with the SM, but within large uncertainties, and it has future potential to determine the sign of $\mathcal{C}_{10}^{\rm NP}$.

- $\mathbf{P_6'}$ and $\mathbf{P_8'}$: show small deviations with respect to the SM, but such effect would require complex phases in $\mathcal{C}_9^{\rm NP}$ and/or $\mathcal{C}_{10}^{\rm NP}$.

Us: $(-0.19-(-0.872))/\sqrt{0.16^2+0.053^2}=4.05$ and **Exp**: $(-0.19-(-0.872+0.053))/\sqrt{0.16^2+0.053^2}=3.73$

Our SM predictions+LHCb data

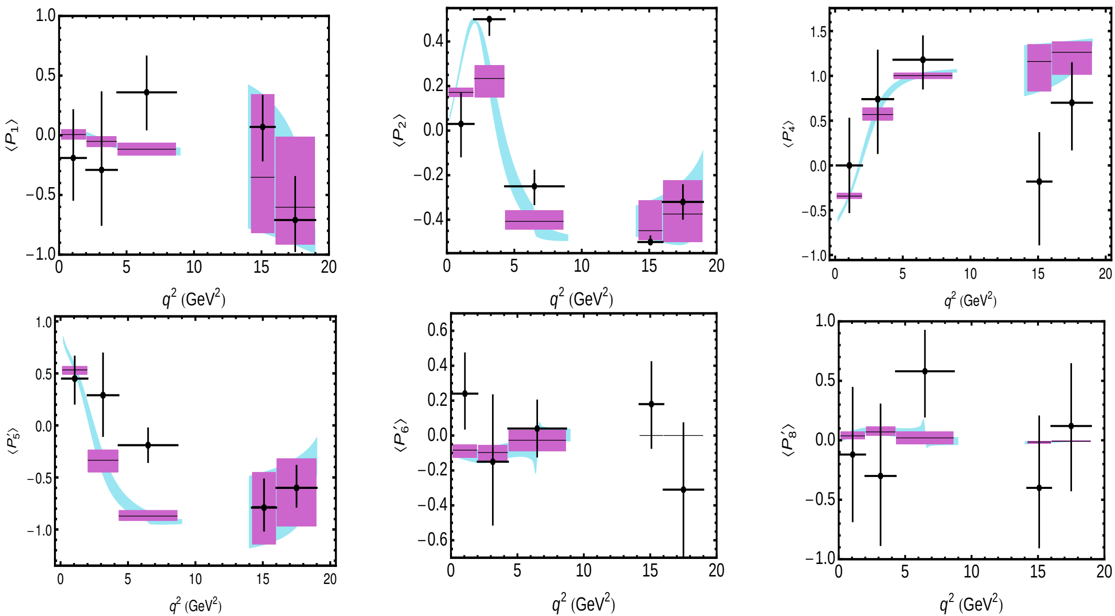


Figure : Experimental measurements and SM predictions for some $B \to K^* \mu^+ \mu^-$ observables. The black crosses are the experimental LHCb data. The blue band corresponds to the SM predictions for the differential quantities, whereas the purple boxes indicate the corresponding binned observables.

Model Independent Analysis

Goal: Determine the Wilson coefficients $\mathcal{C}_{7,9,10}$, $\mathcal{C}'_{7,9,10}$: $\mathcal{C}_i = \mathcal{C}_i^{SM} + \mathcal{C}_i^{NP}$

Standard χ^2 frequentist approach: Asymmetric errors included, estimate theory uncertainties for each set of $\mathcal{C}_i^{NP}$ and all uncertainties are combined in quadrature.

IMPORTANT: *Experimental correlations are included in the updated plot*

We do three analysis: a) large-recoil data b) large+low-recoil data c) [1-6] bin

Observables:

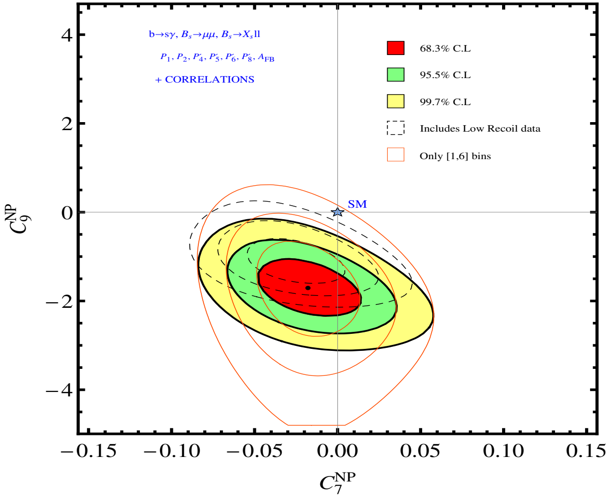
- $B \to K^*\mu^+\mu^-$: We take observables P_1, P_2, P_4', P_5', P_6' and P_8' in the following binning:
  -**large-recoil**: $[0.1, 2], [2, 4.3], [4.3, 8.68]$ GeV^2.
  -**low recoil**: [14.18,16], [16,19] GeV^2
  -**wide large-recoil bin**: $[1, 6]$ GeV^2.

- Radiative and dileptonic B decays: $\mathcal{B}(B \to X_s\gamma)_{E_\gamma > 1.6\mathrm{GeV}}$, $\mathcal{B}(B \to X_s\mu^+\mu^-)_{[1,6]}$ and $\mathcal{B}(B_s \to \mu^+\mu^-)$, $A_I(B \to K^*\gamma)$ and the $B \to K^*\gamma$ time-dependent CP asymmetry $S_{K^*\gamma}$

Updated result with experimental correlations

Updated result using $\mathbf{P_i}, \mathbf{P'_i}, \mathbf{A}_{\rm FB}$ and **experimental correlations**.

2013 Data favours clearly contributions inside C_7 and C_9.



From the analysis of the set $\mathbf{P_i}, \mathbf{P'_i}, \mathbf{A}_{\rm FB}+$ **BR** $+$ exp. correlations we get:

4.3σ (large-recoil)
3.6σ (large + low recoil)
2.8σ for [1-6] bin.

Colored: large-recoil and dashed: large+low recoil orange: [1-6] bin

- We checked (for completeness) that we find **same significance** using $\mathbf{P_i}, \mathbf{P'_i}, \mathbf{F_L}$ instead of $\mathbf{A}_{\rm FB}$. **Positive:** **Our SM $\mathbf{F_L}$** fully compatible with all data (not only LHCb) and less correlated. **Negative:** Result using F_L is less solid than using A_{FB} since it depends on choice of FF.

Result of our analysis (large+low recoil data+rad) if we allow **all Wilson coefficients** to vary freely:

Coefficient	$1\,\sigma$	$2\,\sigma$	$3\,\sigma$
$\mathcal{C}_7^{\rm NP}$	$[-0.05,-0.01]$	$[-\mathbf{0.06},\mathbf{0.01}]$	$[-0.08,0.03]$
$\mathcal{C}_9^{\rm NP}$	$[-1.6,-0.9]$	$[-1.8,-0.6]$	$[-\mathbf{2.1},-\mathbf{0.2}]$
$\mathcal{C}_{10}^{\rm NP}$	$[-\mathbf{0.4},\mathbf{1.0}]$	$[-1.2,2.0]$	$[-2.0,3.0]$
$\mathcal{C}_{7'}^{\rm NP}$	$[-\mathbf{0.04},\mathbf{0.02}]$	$[-0.09,0.06]$	$[-0.14,0.10]$
$\mathcal{C}_{9'}^{\rm NP}$	$[-\mathbf{0.2},\mathbf{0.8}]$	$[-0.8,1.4]$	$[-1.2,1.8]$
$\mathcal{C}_{10'}^{\rm NP}$	$[-\mathbf{0.4},\mathbf{0.4}]$	$[-1.0,0.8]$	$[-1.4,1.2]$

Table : 68.3% ($1\,\sigma$), 95.5% ($2\,\sigma$) and 99.7% ($3\,\sigma$) confidence intervals for the NP contributions to WC.

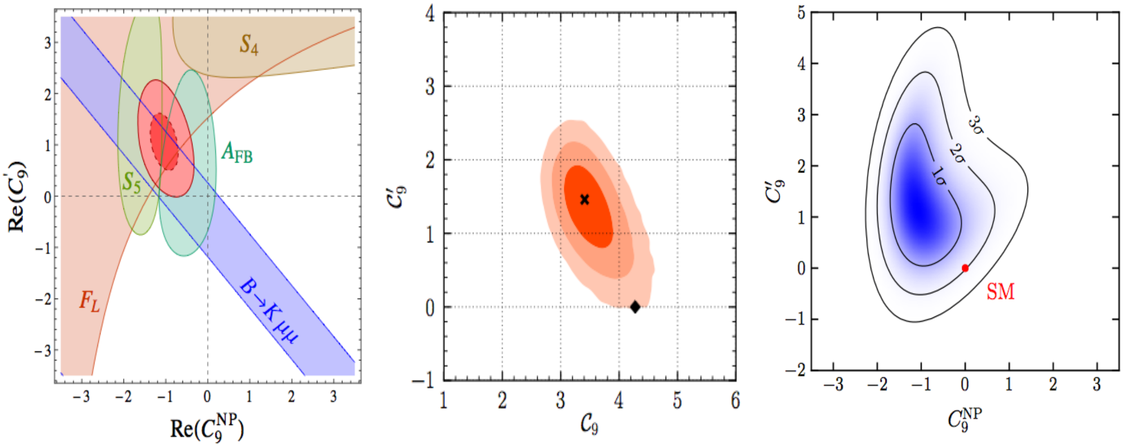
In conclusion our pattern of [PRD88 (2013) 074002] obtained from an $\mathcal{H}_{eff}$ approach is

$$\mathbf{C_9^{NP}} \sim [-\mathbf{1.6},-\mathbf{0.9}],\quad \mathbf{C_7^{NP}} \sim [-\mathbf{0.05},-\mathbf{0.01}],\quad \mathbf{C_9'} \sim \pm\delta \quad \mathbf{C_{10}},\mathbf{C'_{7,10}} \sim \pm\epsilon$$

where δ is small and ϵ is smaller.

Other groups later on confirmed independently the same finding of $C_9^{NP} < 0$:

- different observables S_i ([1,6] bins and low recoil from $B^+ \to K^+\mu^+\mu^-$), other techniques (lattice) and statistical approaches (bayesian)



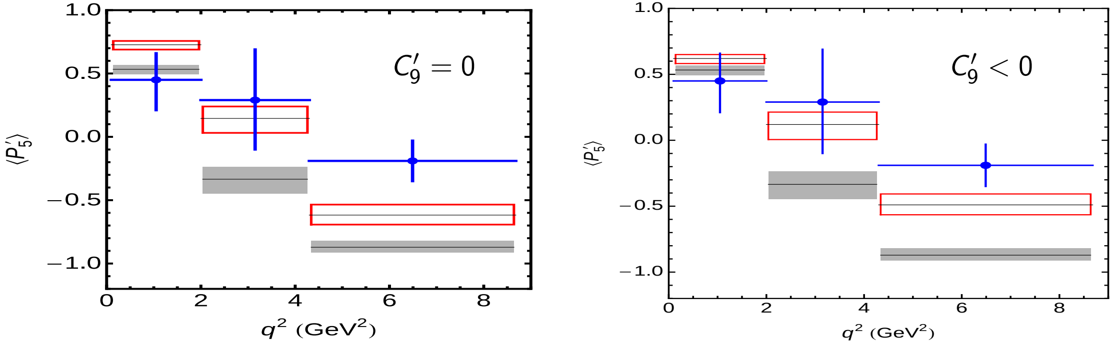
(1) Altmannshofer, Straub 1308.1501, (2) Beaujean, Bobeth, van Dyk 1310.2478, (3) Horgan et al. 1310.3887
(1) Hambrock, Hiller, Schacht, Zwicky 1308.4379.

However, all those groups also claimed $C_9^{NP} + C_9' \simeq 0 \Rightarrow C_9' = -C_9^{NP}$, i.e., POSITIVE
$\Rightarrow$ based mainly on 1 fb^{-1} data at on $B^- \to K^-\mu^+\mu^-$

BUT

We showed in [1307.5683] that:

- 3rd bin of P_5' prefers clearly a C_9' NEGATIVE, i.e., $C_9^{NP} + C_9' < 0$.



There was TENSION between $B \to K^*\mu^+\mu^-$ data and $B^- \to K^-\mu\mu$ (not with $B^0 \to K^0\mu^+\mu^-$)

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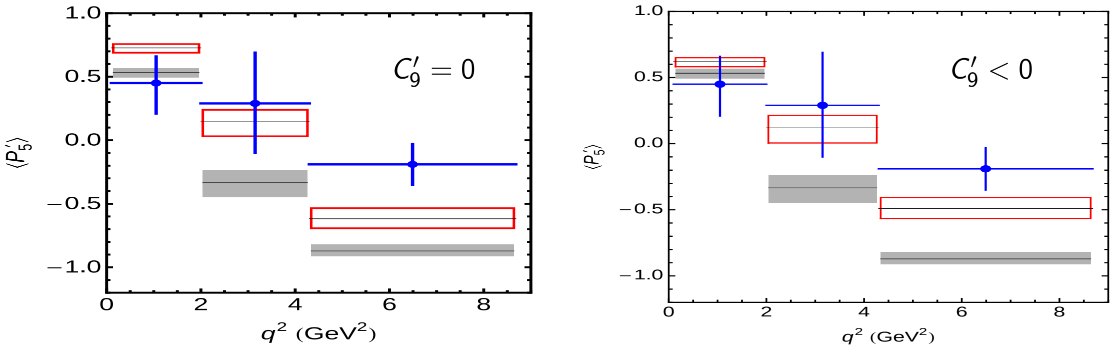
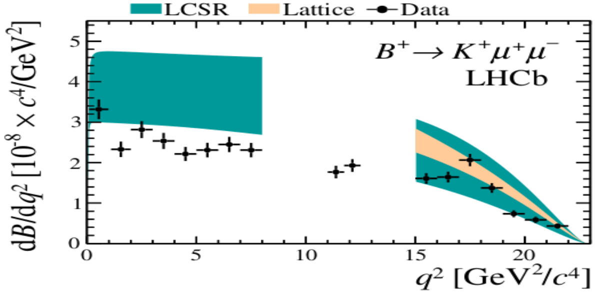
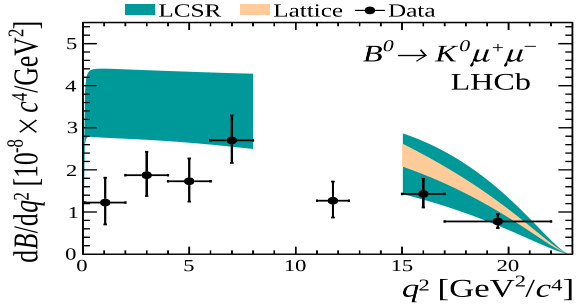


There was TENSION between $B \to K^*\mu^+\mu^-$ data and $B^- \to K^-\mu\mu$ (not with $B^0 \to K^0\mu^+\mu^-$)

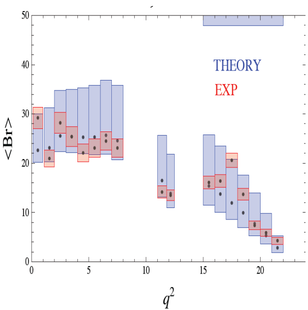
... till the new 3 fb^{-1} data from LHCB on $B^+ \to K^+\mu^+\mu^-$ CAME OUT

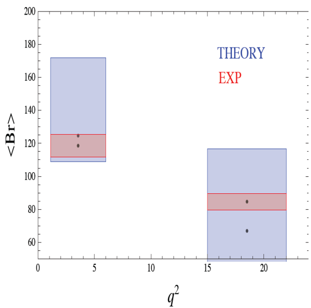
New **3 fb^{-1} data** shows excellent consistency between anomaly in P_5' ($B \to K^*$) and $B \to K$ modes:

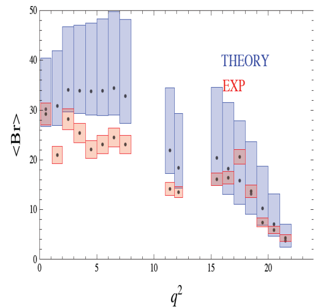


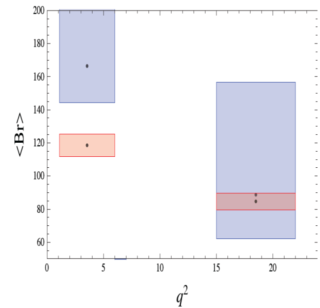


CONFIRMS a deficit in the 3 fb^{-1} $B^+ \to K^+\mu^+\mu^-$ and $B^0 \to K^0\mu^+\mu^-$ data









Confirms $C_9^{NP} + C_9' < 0$ from D.M.V. 1307.5683 $\qquad$ $C_9^{NP} + C_9' \simeq 0$

Independent cross-check (Wingate) from lattice low-recoil.

Possible Explanations of the Anomaly

and

Updated SM predictions

Different explanations raised to explain the anomaly and tensions

- Factorizable or non-factorizable power corrections?
  $\rightarrow$ under control

- Effect from charm resonances? [Lyon,Zwicky] versus [Khodjamirian, Mannel, Pivovarov, Wang]
  KMPW says positive contribution to C_9^{eff}
  Controversial LZ says negative (easy to test by checking other observables, i.e, P_1)

- Statistical fluctuation of data?
  $\rightarrow$ perform consistency checks [Matias,Serra]

$\Rightarrow$ New physics explanation within a 'model"

- Possible model: Z' respecting ΔM constrain. [Descotes,JM,Virto'13]
- R_K deficit: Consistent with $C_9^{NP\mu} = -1.5$ but with Universal LFV.

Including power corrections factorizable and non-factorizable

General idea: (Jäger,Camalich): Parametrize power corrections to form factors:

$$F(q^2) = F^{\rm soft}(\xi_{\perp,\|}(q^2)) + \Delta F^{\alpha_s}(q^2) + a_F + b_F \frac{q^2}{m_B^2} + \ldots$$

$\Rightarrow$ fit $a_F, b_F, \ldots$ to the full form factor F (taken e.g. from LCSR)

BUT two CRUCIAL POINTS not to miss:

I. Power corrections are constrained from

- exact kinematic FF relations at $q^2 = 0$. Example $a_{T1} = a_{T2}$ from $T_1(0) = T_2(0)$
- definition of input scheme to fix $\xi_{\perp,\|}$. Example $a_{A2} = \frac{m_B + m_{K*}}{m_B - m_{K*}} a_{A1}$ from $\xi_\| \equiv c_1 A_1(q^2) + c_2 A_2(q^2)$

$\Rightarrow$ Correlations among $a_{F_i}, b_{F_i}, \ldots$ that cannot be VIOLATED.

II. Freedom to choose the most appropriate scheme to reduce the impact of power corrections:

- input: $\{T_1, A_0\}$ to define $\{\xi_\perp, \xi_\|\}\Rightarrow$ power corrections eliminated in T_1 and A_0
- our input: $\{V, c_1 A_1 + c_2 A_2\}\Rightarrow$ power corrections eliminated in V and minimized in A_1, A_2

Philosophy of [Jäger& Camalich'12 and '14]: *No Form Factor computation (LCSR, DSE,...) is trustable* $\Rightarrow$ For this reason they need to focus on observables less sensitive to FF like the P_i and they do not give predictions for the S_i (in any paper), because with their approach the errors on the S_i would be huge.

We disagree with this point of view: good to reduce dependence on FF but up to a compromise.

Jaeger-Camalich 2012

- a_F, b_F and Δa_F, Δb_F estimated from average of central values of different FF parametrizations:
  $\Rightarrow$ Lost fundamental correlations
  $\Rightarrow$ Central values of P_i from SFF
- Definition of $\xi_{\perp,\|}$ from T_1, A_0: Non-optimal scheme chosen x2 errors size. (P_i indep. of A_0)
- q^2-dependence for $\xi_{\perp,\|}$: old HQET limit prediction, $\Rightarrow$ Transfer known info artificially inflated unknown power corrections.
- Identification $\xi_\perp(0) = T_1^{exp}(0)$ from $B \to K^*\gamma$ assumes SM, and inconsistently includes non-factorizable PC inside T_1.
- ALL Form Factors in helicity basis.
- only P_i considered.

Our paper JHEP12(2014)125

- Work consistently **within one FF parametrisation** at a time (KMPW, BZ) compute a_F, b_F.
  $\Rightarrow$ **Respect correlations**:
  (central values and errors)
  $\Rightarrow$ Central values of P_i from SFF+PC **reproduce exactly FF.**
- $\Delta a_F, \Delta b_F = \mathcal{O}(\Lambda/m_B) \times F$
- Definition of $\xi_{\perp,\|}$ from $V, A_1 + A_2$ like Beneke et al.: **choose the most appropriate scheme**.
- q^2-dependence of $\xi_{\perp,\|}$: $\frac{\xi_i(0) m_F^2}{m_F^2 - s}(1 + b_F[z(s,\tau_0) - z(0,\tau_0)] + \ldots$
- We do a flat scan of power correction parameters and provide each error separately.
- We include non-factorizable PC.
- ALL Form Factors always consistently in Transversity Basis.

Jaeger-Camalich 2014

- Soft FF are **undervalutated**: $\xi_\perp(0) = 0.31 \pm 0.04$ meaning of this error unclear!: Average of LCSR **ONLY c.v.**!!! $\xi_\perp(0) = 0.31^{+0.20}_{-0.10}$ (our KMPW)
  $\Rightarrow$ F_L error smaller than us!
  $\Rightarrow$ Central values of P_i from SFF
- $\Delta a_F, \Delta b_F = 10\% \, x \, \xi_{\perp,\|}(0)$ (our same approach) BUT some Helicity FF : T_+, $V_+ \simeq 0$
- Definition of $\xi_{\perp,\|}$:
  - Still **BAD scheme** used x2
  - **Wrong**: our scheme is $\xi_\perp(q^2) \propto V(q^2)$ not $V_-(q^2)$!!
    $\Rightarrow$ P_5' **IS** scheme dependent
- They do also flat scan but do not provide errors that are added linearly.
- ALL Form Factors in helicity basis.
- only P_i considered.

Further Comment on scheme dependence

It is a well known fact in QFT the problem of scheme dependence and

→ the convenience to choose the most appropriate scheme.

- one should choose the renormalisation scheme in such a way that effects of unknown power corrections get absorbed as much as possible into the soft form factors (input parameters taken from LCSR calculations or from experiment.)

  → complete analogy to the case of perturbative loop calculations.

- one can always construct a scheme that artificially blows up uncertainties from power corrections: Consider an observable depending on only one single form factor.
  - **good scheme**: Take this FF directly as input and power corrections would not appear at all.
  - **bad scheme**: Instead one could choose a scheme where this FF is related to a different input parameter up to unknown power corrections, but obviously this increases the uncertainty of the result artificially.

In summary: **In the P_5' case the combination of a bad scheme choice to define $\xi_{\perp,\|}$ together with a change of FF basis from transversity (where they are computed) to helicity (J.&C choice) blow up factorizable power correction errors (x 3-5)**

EXAMPLE of overvalued power corrections:

Jaeger&Camalich'14: $\mathbf{S_5^{[1,6]}} = \mathbf{-0.13^{+0.22}_{-0.19}}$ (only error from P_5'): *They added errors linearly.*
(but $\xi_\perp(0)$ is clearly undervalutated so the error is possibly larger)

On the contrary, two very different methods gets very good agreement:

Our computation'14: Model-independent (applicable to different LCSR), dimens. arguments for p.c.
$\mathbf{S_5^{[1,6]}} = \mathbf{-0.18^{+0.05+0.05}_{-0.06-0.05}}$ CASE BZ par. (cv. use of m_c^{MS} or m_c^{pole})

Errors: Param+Hadronic+ Factorizable p.c.+non-factorizable p.c.+charm-loop effects: Flat scan p.c.

Altmannshofer&Straub'13: Full form factors with correlations using BZ (factorizable p.c. included)
$\mathbf{S_5^{[1,6]}} = \mathbf{-0.14 \pm 0.02}$ (non-factorizable p.c. + charm not included)
Error gaussian to flat scan x2 approx. $\rightarrow +0.04$ (good agreement with our $+0.05$)

$\rightarrow$ The error in J&C $+0.22$ based on an estimated of p.c. is $> 200\%$ larger when compared to us. Bad scheme used in J&C induced a factor of 2 in some bins.

Besides some FF errors in J&C like V_+ has duplicate error size from 2012 to 2014?
and no complete set of FF are presented in 2014 to compare with 2012.

Non-factorizable contributions and charm-loop effects

We add to this:

- non-factorizable power corrections: power corrections that are not part of form factors

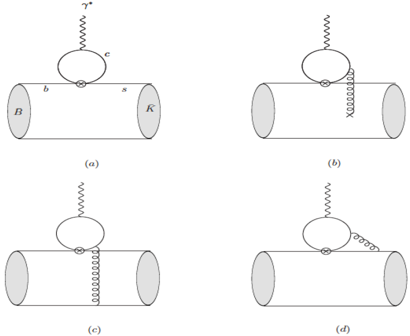
  $\Rightarrow$ We single out the pieces not associated to FF $\mathcal{T}_i^{\rm had} = \mathcal{T}_i|_{C_7^{(\prime)}\to 0}$ entering $\langle K^*\gamma^*|H_{eff}|B\rangle$ and multiply each of them with a complex q^2-dependent factor:

$$\mathcal{T}_i^{\rm had} \to \left(1 + r_i(q^2)\right)\mathcal{T}_i^{\rm had},$$

with

$$r_i(s) = r_i^a e^{i\phi_i^a} + r_i^b e^{i\phi_i^b}(s/m_B^2) + r_i^c e^{i\phi_i^c}(s/m_B^2)^2.$$

$r_i^{a,b,c} \in [0, 0.1]$ and $\phi_i^{a,b,c} \in [-\pi, \pi]$: random scan and take the maximum deviation from the central values $r_i(q^2) \equiv 0$ to each side, to obtain asymmetric error bars.



Charm loop: Insertion of 4-quark operators ($\mathcal{O}_{1,2}^c$) or penguin operators ($\mathcal{O}_{3-6}$) induces a positive contribution in $C_9^{\rm eff}$.

- **We followed LCSR computation and prescription** from KMPW to recast the effect inside $C_9^{\rm eff}$.

$$\mathcal{C}_9 \to \mathcal{C}_9 + s_i \delta C_9^{KMPW}(q^2)$$

even if KMPW says $s_i = 1$, we allow s_i in a range $[-1, 1]$.

Figure 1: *Charm-loop effect in $B \to K^{(*)}\ell^+\ell^-$: (a)-the leading-order factorizable contribution; (b)*

Non-factorizable contributions and charm-loop effects

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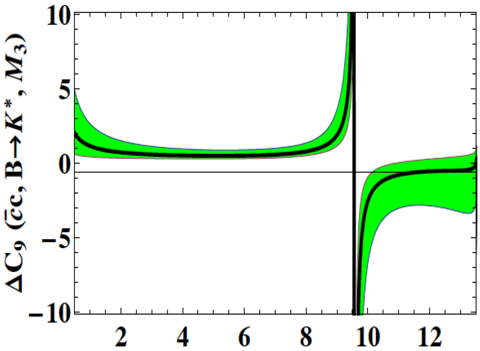

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even if KMPW says $s_i = 1$, we allow s_i in a range $[-1, 1]$.

In [Lyon,Zwicky'14] a 350% "correction" to the FA to explain the anomaly in P_5' instead of NP.

• Many model-dependent assumptions: resonance model extrapolated far from resonances, constant fudge factors η_c, η_c' are valid everywhere?

$$C_9^{eff} = C_9 + \eta_c h_c(q^2) + h_{rest}(q^2) \quad C_9^{\prime eff} = C_9' + \eta_c' h_c(q^2)$$

same for $B \to K\mu\mu$ than for $B \to K^*\mu\mu$? can a 350% correction be accommodated within QCD? constraints on new $\bar{b}sc\bar{c}$ structures??

We propose different tests to disprove it:

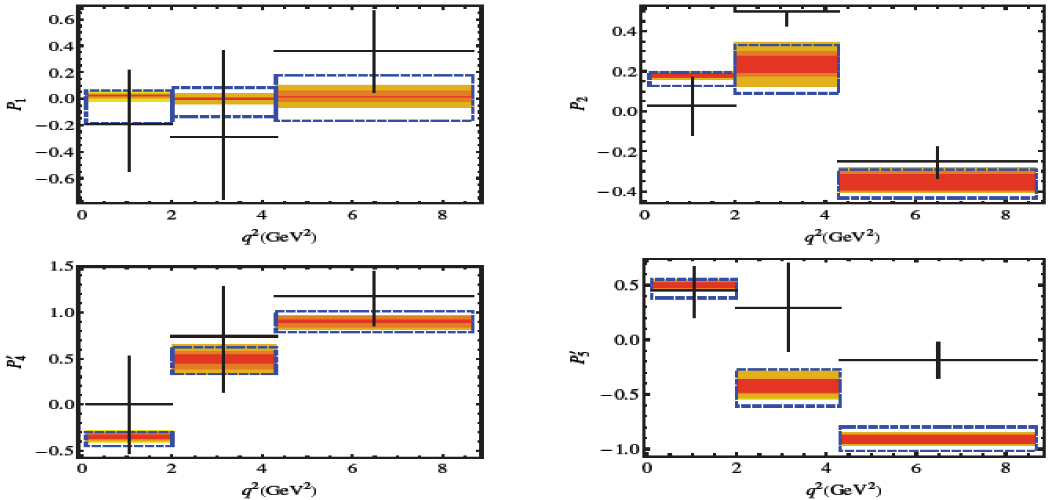
- The proposal should survive a **global analysis** of all P_i. Indeed **NONE** of the illustrative examples selected works for all observables in all bins, **either fail for some bin of P_2 and/or P_5'**.
- $B^+ \to \pi^+\mu^+\mu^-$: $b \to d$ transition assume no NP. Similar charm contribution with few changes $(1 - \frac{R_b}{R_t} e^{i\alpha})$ prefactor infront of charm loop and presence of annihilation contributions.

$$\mathrm{At}\, 8\, \mathrm{GeV}^2 \quad |C_9^+|^2 \sim 32.1\, \mathrm{with}\, \eta_c + \eta_c' = 1(FA) \quad |C_9^+|^2 \sim 2.5\, \mathrm{with}\, \eta_c + \eta_c' = -2.5(LZ)$$

  where $C_9^+ = C_9^{\rm eff} + C_9^{\prime\rm eff}$.

  $\Rightarrow$ *Test:* If no suppression is seen in the measured BR w.r.t. SM the L&Z proposal is in trouble. However one can play with the phase to pass the test, assuming a huge SU(3) breaking.
- **Finally if R_K deviation is confirmed increasing its significance the proposed charm pollution cannot explain it while on the contrary our pattern [see D. Ghosh et al.'14] can make it. This is probably one of the clearest discriminating method.**

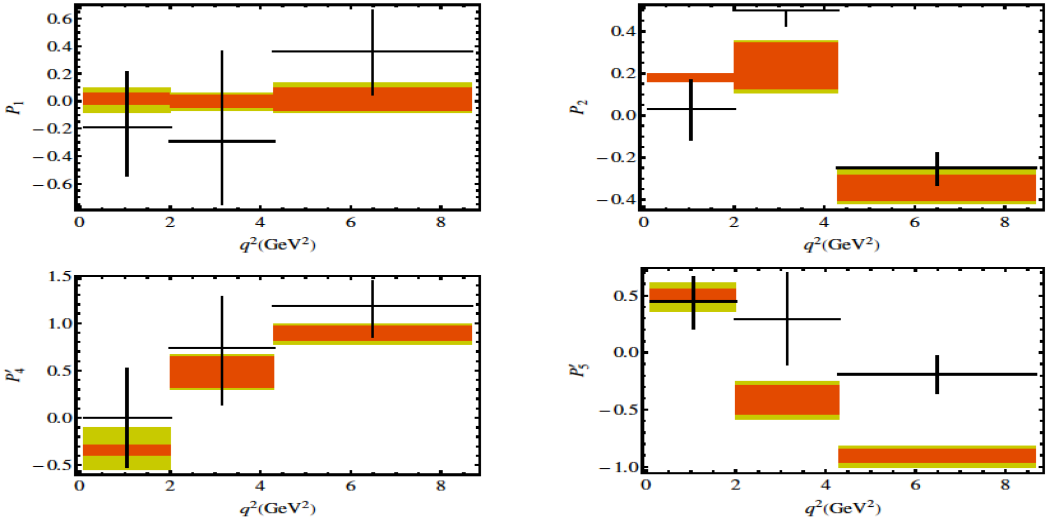
The most complete prediction including all errors in KMPW parametrization for the relevant observables.
Errors included: parametric, FF, factorizable and non-factorizable p.c. **NOT** charm loops.



Blue prediction in scheme 2 (T_1, A_0). (see 1407.8526 for BZ and more observables).
Summary: Power corrections cannot be the explanation of anomaly

Our final Predictions in SM [1407.8526]

<u>The most complete prediction including all errors in KMPW parametrization for the relevant observables.</u>
<u>Errors</u> added in quadrature: parametric, FF, factorizable and non-factorizable p.c. **including** charm loops.



Orange band is all errors except charm. Green band is charm loop.

Symmetries and S-wave

- Number of symmetries of S-wave and P-wave part is 4 (same as P-wave).
- Number of free parameters (observables)

$$2n_{Amplitudes} - n_{symmetries} = 2(6+2) - 4 = 12\, observables$$

8 P-wave observables and 4 S-wave observables . BUT S-wave part has 6 parameters:

$$\frac{\mathbf{W_S}}{\Gamma'_{full}} = \frac{3}{16\pi}\left[\mathbf{F_S}\sin^2\theta_\ell + \mathbf{A_S}\sin^2\theta_\ell\cos\theta_K + \mathbf{A_S^4}\sin\theta_K\sin 2\theta_\ell\cos\phi\right.$$
$$\left.+\mathbf{A_S^5}\sin\theta_K\sin\theta_\ell\cos\phi + \mathbf{A_S^7}\sin\theta_K\sin\theta_\ell\sin\phi + \mathbf{A_S^8}\sin\theta_K\sin 2\theta_\ell\sin\phi\right]$$

Only 4 parameters out of $F_S, A_S, A_S^{4,5,7,8}$ are independent!!! Two new constraints [L. Hofer, J.M'15]:

$$\begin{aligned}
\bar{k}_S F_T\left[\bar{k}_2^2 - \bar{P}_1^2 - 4\bar{P}_2^2 - 4\bar{P}_3^2\right] &= -\frac{8}{3}\bar{P}_2\left[\bar{A}_S^4\bar{A}_S^5 + \bar{A}_S^7\bar{A}_S^8\right] + \frac{4}{3}\bar{P}_3\left[\bar{A}_S^5\bar{A}_S^7 - 4\bar{A}_S^4\bar{A}_S^8\right]\\
&+\frac{1}{3}(\bar{k}_2+\bar{P}_1)\left[4(\bar{A}_S^4)^2 + (\bar{A}_S^7)^2\right] + \frac{1}{3}(\bar{k}_2-\bar{P}_1)\left[(\bar{A}_S^5)^2 + 4(\bar{A}_S^8)^2\right],\\
\bar{A}_S\sqrt{\frac{F_T}{1-F_T}}\left[\bar{k}_2^2 - \bar{P}_1^2 - 4\bar{P}_2^2 - 4\bar{P}_3^2\right] &= -4\bar{P}_2\left[\bar{P}_4'\bar{A}_S^5 + 2\bar{P}_5'\bar{A}_S^4 - 2\bar{P}_6'\bar{A}_S^8 - \bar{P}_8'\bar{A}_S^7\right]\\
&+4\bar{P}_3\left[\bar{P}_5'\bar{A}_S^7 - \bar{P}_6'\bar{A}_S^5 - 2\bar{P}_4'\bar{A}_S^8 + 2\bar{P}_8'\bar{A}_S^4\right]\\
&+2(\bar{k}_2+\bar{P}_1)\left[2\bar{P}_4'\bar{A}_S^4 - \bar{P}_6'\bar{A}_S^7\right] + 2(\bar{k}_2-\bar{P}_1)\left[\bar{P}_5'\bar{A}_S^5 - 2\bar{P}_8'\bar{A}_S^8\right].
\end{aligned}$$

where $\bar{k}_2 = 1 + F_T^{CP}/F_T$, $\bar{k}_S = 1 + F_S^{CP}/F_S$ and $\bar{P}_i = P_i + P_i^{CP}$, $\bar{A}_S^i = (A_S^i + A_S^{iCP})/\sqrt{F_S(1-F_S)}$

Consequences:

- 1st quadratic equation $\bar{A}_S^5 = f(\bar{A}_S^4, \bar{A}_S^7, \bar{A}_S^8, \bar{P}_{1,2,3}, F_T)$
- 2on linear equation $\bar{A}_S = g(\bar{A}_S^4, \bar{A}_S^5, \bar{A}_S^7, \bar{A}_S^8, \bar{P}_{1,2,3}, \bar{P}'_{4,5,6,8}, F_T)$

One obtains immediately **the constraints**:

$$|\bar{A}_S^4| \leq \frac{1}{2}\sqrt{3\bar{k}_S F_T(\bar{k}_2 - \bar{P}_1)}, \qquad |\bar{A}_S^5| \leq \sqrt{3\bar{k}_S F_T(\bar{k}_2 + \bar{P}_1)},$$
$$|\bar{A}_S^7| \leq \sqrt{3\bar{k}_S F_T(\bar{k}_2 - \bar{P}_1)}, \qquad |\bar{A}_S^8| \leq \frac{1}{2}\sqrt{3\bar{k}_S F_T(\bar{k}_2 + \bar{P}_1)}.$$

More interestingly **at the maximum of P_2** namely $\mathbf{q_1^2}$ (taken no NP phases $O^{CP} \sim 0$ and $P_3 \sim 0$):

$$A_S^4(\mathbf{q_1^2}) = \frac{1}{2}A_S^5(\mathbf{q_1^2}) \quad \text{and} \quad A_S^7(\mathbf{q_1^2}) = 2A_S^8(\mathbf{q_1^2})$$

And **at the zero of P_2** namely $\mathbf{q_0^2}$ two relations are fulfilled (under same hypothesis and $P_{6,8} \sim 0$):

$$[(4A_S^{4\,2} + A_S^{7\,2})(1+P_1) + (A_S^{5\,2} + 4A_S^{8\,2})(1-P_1)]_{\mathbf{q_0^2}} = 3[(1-F_S)F_S F_T(1-P_1^2)]_{\mathbf{q_0^2}}$$

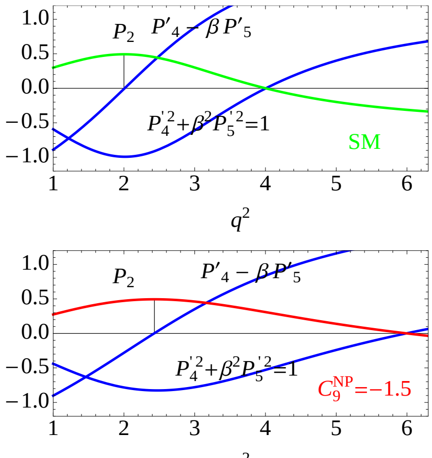
$$A_S(\mathbf{q_0^2}) = \left[\frac{2F_L(2A_S^4(1+P_1)P'_4 + A_S^5(1-P_1)P'_5)}{\sqrt{F_L F_T}(1-P_1^2)}\right]_{\mathbf{q_0^2}}$$

From the symmetries of the distribution in absence of scalars [JM, N. Serra'14]

$$\bar{P}_2 = +\frac{1}{2\bar{k}_1}\left[(\bar{P}'_4\bar{P}'_5+\delta_1)+\frac{1}{\beta}\sqrt{(-1+\bar{P}_1+\bar{P}'^2_4)(-1-\bar{P}_1+\beta^2\bar{P}'^2_5)+\delta_2+\delta_3\bar{P}_1+\delta_4\bar{P}^2_1}\right]$$

$$\text{where } \bar{P}_i = P_i + P_i^{CP} \qquad \beta=\sqrt{1-4m_\ell^2/s}$$

Assuming NP is real in WC it is an excellent approximation $\delta_i \sim (\mathrm{Im}A_i)^2 \to 0$, $P_i^{CP} \to 0$.



- **At the zero of P_2 called q_0^2**

$$P'^2_4(q_0^2)+\beta^2 P'^2_5(q_0^2) = 1+\eta(q_0^2)$$

where $\eta(q_0^2) \to 0$ if $P_1 \to 0$

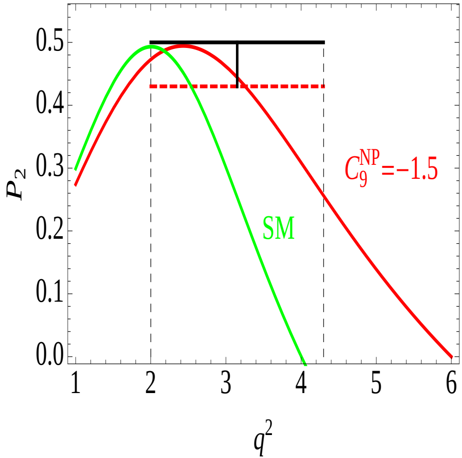
  - with $\eta = 0$ if not fulfilled this equation is a test of presence of RHC.
  - with η included this equation establishes a relation between the zero of A_{FB} and the anomaly in P'_5

- **At the maximum of P_2 called q_1^2**

$$P'_4(q_1^2) = \beta P'_5(q_1^2)$$

A closer look at the 2nd bin of P_2

[L.Hofer, JM'15]



$$P_2^{exp}{}_{[2,4.3]} = 0.5 \pm 0.07$$
$$P_2^{SM**}{}_{[2,4.3]} = 0.24^{+0.11}_{-0.14}$$
$$P_2^{C_9^{NP}=-1.5}{}_{[2,4.3]} = 0.43$$

** KMPW in BZ: 0.16 ± 0.12.

This bin is as interesting/important as the third bin of P_5'.
It contains three important infos:

- If 3fb^{-1} data confirms saturation
  $\Rightarrow$ shift of maximum of P_2 from $q_1^{2SM} = 2$ GeV^2.
- At LO the position of the maximum (free from SFF) is:

$$q_1^2 = \frac{2 m_b M_B C_7^{eff}}{C_{10} - C_9^{eff}(q_1^2)}$$

with $C_7^{eff\prime} = C_9' = C_{10}' = 0$ and $P_2^{max}(q_1^2) = 1/2$

- **We have established a new link between:**

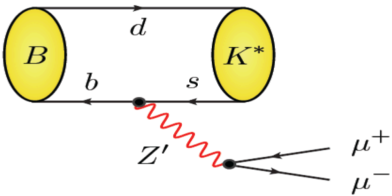
Maximum of P_2 and presence of RH currents:

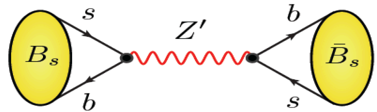
$$P_2^{max} = 1/2 \Rightarrow \text{NO RH currents}$$

Intuitively,
At the maximum of $P_2 \Rightarrow |n_\perp| \simeq |n_\parallel| \Rightarrow P_1 \simeq 0$

A Z' particle?

- We proposed in [**PRD88(2013)074002**] a simple "model" a $\mathbf{Z'}$ **gauge boson** contributing to $\mathcal{O}_9 = e^2/(16\pi^2)\,(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$ with couplings:





$$\mathcal{L}^q = \left(\bar{s}\gamma_\nu P_L b \Delta_L^{sb} + \bar{s}\gamma_\nu P_R b \Delta_R^{sb} + h.c.\right) Z'^\nu \quad \mathcal{L}^{lep} = \left(\bar{\mu}\gamma_\nu P_L \mu \Delta_L^{\mu\bar{\mu}} + \bar{\mu}\gamma_\nu P_R \mu \Delta_R^{\mu\bar{\mu}} + \ldots\right) Z'^\nu$$

- $\Delta_R^{sb} \sim 0$ and Δ_L^{sb} with same phase as $V_{tb}V_{ts}^*$ (to avoid ϕ_s), $\Delta_L^{\mu\mu} = \Delta_R^{\mu\mu}$ (to keep $C_{10}^{NP} \sim 0$).
- The model would contribute to Δm_S ($\Delta_R^{sb} \sim 0$ kills the largest contribution) bound on Δ_L^{sb}.
- Considering the constraints from [Buras, de Fazio, Girrbach] our Z' with $M_Z' = 1$ TeV (compatible with Δm_S) and couplings to muons of at least order 0.1-0.2 would yield $C_9^{NP} \sim \mathcal{O}(-1)$.
- Recent analysis on R_K from [D. Ghosh, M. Nardecchia, S.A. Renner'14] points that our NP solution also works for R_K with NP in muons and not electrons. Also our second scenario with NP in $C_9^{NP\mu}$ and $C_9'^{\mu}$ NEGATIVE is preferred.

Particular embeddings of a Z' inside models discussed by [R. Gauld et al'13, W. Altmannshofer et al.'14].

Conclusions

- Our analysis of the LHCb data on $B \to K^* \mu^+ \mu^-$ based on the clean observables $P_i^{(\prime)}$ together with a set of radiative data shows the following **pattern**:

$$\mathbf{C_9^{NP}} \sim [-\mathbf{1.6}, -\mathbf{0.9}], \quad \mathbf{C_7^{NP}} \sim [-\mathbf{0.05}, -\mathbf{0.01}], \quad \mathbf{C_9'} \sim \pm\delta \quad \mathbf{C_{10}}, \mathbf{C'_{7,10}} \sim \pm\epsilon$$

  with δ and ϵ small.

- New 3fb^{-1} data on $B^- \to K^- \mu^+ \mu^-$ and $B^0 \to K^0 \mu^+ \mu^-$ **confirms this pattern.**

- Possible alternative explanations to NP to explain the anomaly: **power corrections** are indeed under control and **huge charm loop effects** can be easily tested.

- Using the **symmetries** of the distribution on the P and S-wave we found: a) the S-wave parameters are not independent, b) a connection between the zero of A_{FB} and the anomaly in P_5', c) we have established a new link between the value of the maximum of P_2 and the presence of RH currents.

- A simple **model with a Z'** can possibly explain the deviations observed. But we should wait for 3fb^{-1} data on $B \to K^* \mu^+ \mu^-$ to come soon.

Back-up slides:

The folding technique.

S-wave pollution

Full fit of the angular distribution with a small dataset

Under the assumption of ABSENCE of NP: no new scalars and real Wilson coefficients one has

- Free parameters F_L, P_1, $P'_{4,5}$.
- P_2 is a function of the other observables and $P'_{6,8}$ are set to zero.

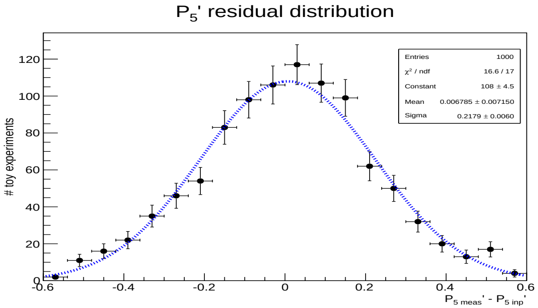


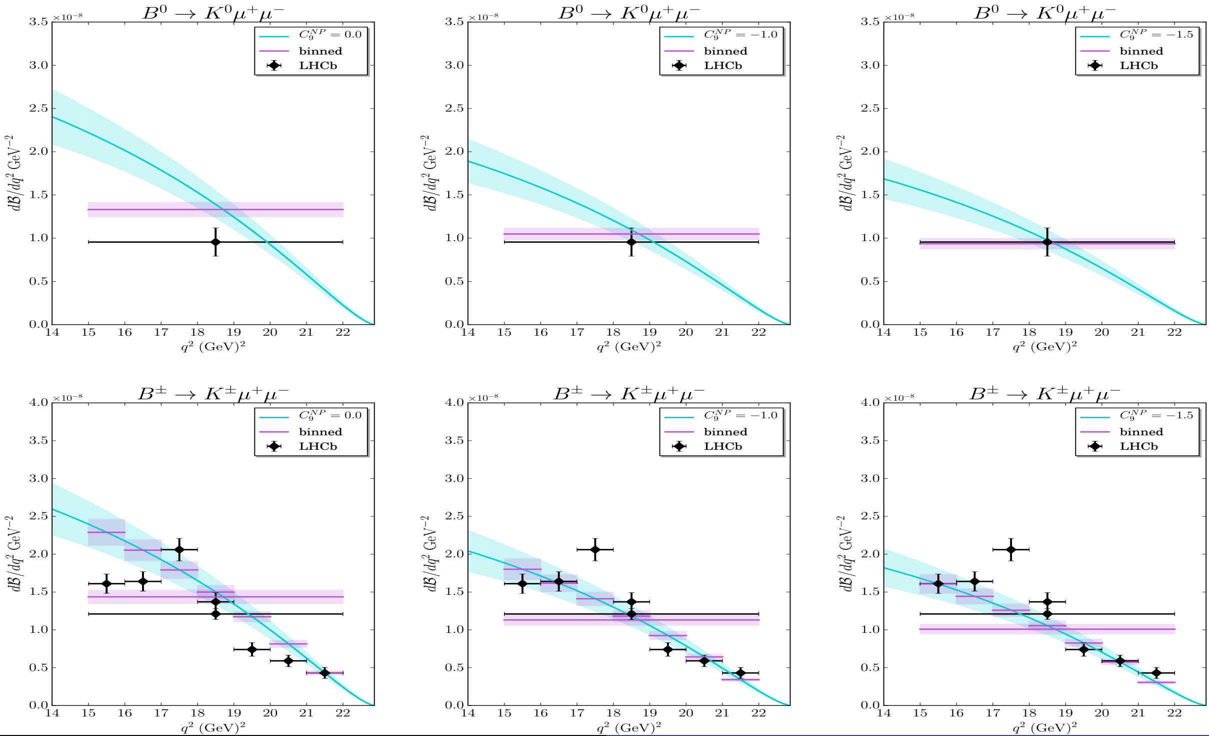
Figure : Residual distribution of P'_5 when fitting with 100 events. The fit of a gaussian distribution is superimosed.

We find testing this fit for values around the measured values: **convergence and unbiased pulls** with as little as 50 events per bin. Gaussian pulls are obtained with only 100 events.

This opens the possibility to perform a full angular fit analysis with small bins in q^2

The main hypothesis (real WC) can be tested measuring P_i^{CP}.

Independent cross check from "Lattice": M. Wingate (private communication and preliminary result)
$\Rightarrow$ confirming our result with $C_9^{NP} + C_9' \sim -1$



The Folding Technique

HOW to approach experimental data?

- Full angular distribution: Difficult it requires more data. Possible way using symmetries N.Serra, JM'14.
- Uniangular distributions: • Integrates out the interesting observables • S-wave polluted in a bad way. JM'12.
- **Breakthrough at LHCb:** Substitute *uniangular distributions* → *folded distributions*.

A prototypical example: The **identification** of $\phi \leftrightarrow \phi + \pi$ (for $\phi < 0$) produces a "**folded**" angle $\hat{\phi} \in [0, \pi]$ with $\theta_K, \theta_\ell \in [0, \pi]$ in terms of which a (folded) differential rate $d\hat{\Gamma}(\hat{\phi}) = d\Gamma(\hat{\phi}) + d\Gamma(\hat{\phi} - \pi)$ is:

$$\frac{1}{\Gamma_{full}} \frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\hat{\phi}} = \frac{9}{16\pi}\Big[2\mathbf{F_L}\cos^2\theta_K \sin^2\theta_\ell + \frac{1}{4}\mathbf{F_T}\sin^2\theta_K(3+\cos 2\theta_\ell)$$

$$+\frac{1}{2}\mathbf{P_1}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_\ell\cos 2\hat{\phi} + 2\mathbf{P_2}\mathbf{F_T}\sin^2\theta_K\cos\theta_\ell - \mathbf{P_3}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_\ell\sin 2\hat{\phi}\Big](\mathbf{1} - \mathbf{F_S}) + \frac{\mathbf{W_1}}{\mathbf{\Gamma_{full}}}$$

where the S-wave piece is

$$\delta^{(1)}_{\mathbf{sw}} = \frac{\mathbf{W_1}}{\mathbf{\Gamma_{full}}} = \frac{3}{8\pi}(\mathbf{F_S} + \mathbf{A_S}\cos\hat{\theta}_K)\sin^2\theta_\ell$$

This folded distribution is used to determine $\mathbf{P}_{1,2,3}$. Generalization with lepton masses in [JM'12].

Advantages of folding:

- It reduces the # of coefficients (observables) to a manageable experimentally subset. In this case: 11 J + 8 $\tilde{J}$ → 7 J + 4 $\tilde{J}$
- It helps to disentangle the unwanted S-wave pollution due to its distinct angular dependence.

Proposal for new foldings

- **An important remark is that at LHCb P_1 is obtained in a folding in association with $P_{2,3}$.** But P_1 ($=A_T^2$) who is called to play a relevant role in determining the presence of RH currents in Nature ($C'_{7,9,10}$) has large error bars.

We propose 3 foldings (second, third and fourth in the list) that can disentangle P_1 from $P_{2,3}$.

Obs.	S-wave	Folding	$\hat{\phi}$ range
$P_{1,2,3}$	A_s	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi}-\pi,\hat{\theta}_l,\hat{\theta}_K)$	$[0,\pi]$
P_1	A_{s5}, A_{s8}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\hat{\theta}_l,\pi-\hat{\theta}_K) + d\Gamma(-\hat{\phi},\pi-\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(-\hat{\phi},\pi-\hat{\theta}_l,\pi-\hat{\theta}_K)$	$[0,\pi]$
P_1 and P_2	A_{s4}, A_{s5}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\hat{\theta}_l,\pi-\hat{\theta}_K) + d\Gamma(-\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(-\hat{\phi},\hat{\theta}_l,\pi-\hat{\theta}_K)$	$[0,\pi]$
P_1 and P_3	A_{s5}, A_{s7}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\hat{\theta}_l,\pi-\hat{\theta}_K) + d\Gamma(\hat{\phi},\pi-\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\pi-\hat{\theta}_l,\pi-\hat{\theta}_K)$	$[0,\pi]$
P_1 and P'_4	A_{s5}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(-\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\pi-\hat{\theta}_l,\pi-\hat{\theta}_K) + d\Gamma(-\hat{\phi},\pi-\hat{\theta}_l,\pi-\hat{\theta}_K)$	$[0,\pi]$
P_1 and P'_5	A_s, A_{s5}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(-\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\pi-\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(-\hat{\phi},\pi-\hat{\theta}_l,\hat{\theta}_K)$	$[0,\pi]$
P_1 and P'_6	A_s, A_{s7}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\pi-\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\pi-\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\pi-\hat{\phi},\pi-\hat{\theta}_l,\hat{\theta}_K)$	$[-\pi/2,\pi/2]$
P_1 and P'_8	A_{s7}	$d\Gamma(\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\pi-\hat{\phi},\hat{\theta}_l,\hat{\theta}_K) + d\Gamma(\hat{\phi},\pi-\hat{\theta}_l,\pi-\hat{\theta}_K) + d\Gamma(\pi-\hat{\phi},\pi-\hat{\theta}_l,\pi-\hat{\theta}_K)$	$[-\pi/2,\pi/2]$

Table : Foldings needed to single out the interesting observables, with the corresponding remaining S-wave pollution. For all foldings, $\hat{\theta}_\ell$ and $\hat{\theta}_K$ lie within $[0,\pi/2]$, whereas $\hat{\phi}$ has different ranges depending on the observables considered.

S-wave pollution

[S. Descotes, T. Hurth, JM, J. Virto'13], [J.M'12]

- Another possible source of uncertainty is the **S-wave contribution** coming from $B \to K_0^* l^+ l^-$.
  [Becirevic, Tayduganov '13], [Blake et al.'13]
- We will assume that both P and S waves are described by q^2-dependent FF times a Breit-Wigner function.
- The **distinct** angular dependence of the S-wave terms in **folded** distributions allow to disentangle the signal of the P-wave from the S-wave: $P_i^{(\prime)}$ *can be* **disentangled** *from S-wave pollution* [JM'12].

Problem: Changing the normalization used for the distribution from

$$\frac{d\Gamma_K^*}{dq^2} \equiv \Gamma'_{K^*} \to \Gamma'_{full}$$

introduces a $(1 - \mathbf{F_S})$ in front of the P-wave.

$$\Gamma'_{full} = \Gamma'_{K^*} + \Gamma'_S$$

and the longitudinal polarization fraction associated to Γ'_S is

$$\mathbf{F_S} = \frac{\Gamma'_S}{\Gamma'_{full}} \qquad \text{and} \qquad 1 - \mathbf{F_S} = \frac{\Gamma'_{K^*}}{\Gamma'_{full}}$$

The modified distribution including the **S-wave** and new normalization Γ'_{full}:

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\left[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K\right.$$
$$+(\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - F_L\cos^2\theta_K)\cos 2\theta_l + \frac{1}{2}\mathbf{P_1}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\frac{1}{2}\mathbf{P'_4}\sin 2\theta_K\sin 2\theta_l\cos\phi + \mathbf{P'_5}\sin 2\theta_K\sin\theta_l\cos\phi\right)$$
$$-\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\mathbf{P'_6}\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\mathbf{P'_8}\sin 2\theta_K\sin 2\theta_l\sin\phi\right)$$
$$\left.+2\mathbf{P_2}\mathbf{F_T}\sin^2\theta_K\cos\theta_l - \mathbf{P_3}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\right](1-\mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

in the massless case and where the polluting terms are

$$\frac{\mathbf{W_S}}{\Gamma'_{full}} = \frac{3}{16\pi}\left[\mathbf{F_S}\sin^2\theta_\ell + \mathbf{A_S}\sin^2\theta_\ell\cos\theta_K + \mathbf{A_S^4}\sin\theta_K\sin 2\theta_\ell\cos\phi\right.$$
$$\left.+\mathbf{A_S^5}\sin\theta_K\sin\theta_\ell\cos\phi + \mathbf{A_S^7}\sin\theta_K\sin\theta_\ell\sin\phi + \mathbf{A_S^8}\sin\theta_K\sin 2\theta_\ell\sin\phi\right]$$

We can get **bounds** on the size of the S-wave polluting terms.Let's take for instance A_S

$$\mathbf{A_S} = 2\sqrt{3}\frac{1}{\Gamma'_{full}}\int \mathrm{Re}\left[({A'_0}^L A_0^{L*} + {A'_0}^R A_0^{R*}) BW_{K_0^*}(m^2_{K\pi}) BW^\dagger_{K^*}(m^2_{K\pi})\right] dm^2_{K\pi}$$

where

$$\mathbf{F_S} = \frac{8}{3}\frac{\tilde{J}^c_{1a}}{\Gamma'_{full}} = \frac{|{A'_0}^L|^2 + |{A'_0}^R|^2}{\Gamma'_{full}}\mathbf{Y} \qquad \mathbf{Y} = \int dm^2_{K\pi} |BW_{K_0^*}(m^2_{K\pi})|^2$$

Y factor included to take into account the width of scalar resonance K_0^*

A bound is obtained once we define the $S-P$ interference integral

$$\mathbf{Z} = \int \left| BW_{K_0^*}(m^2_{K\pi}) BW^\dagger_{K^*}(m^2_{K\pi})\right| dm^2_{K\pi}$$

and use the bound from the Cauchy-Schwartz inequality

$$\left|\int (\mathrm{Re},\mathrm{Im})\left[({A'_0}^L A_j^{L*} \pm {A'_0}^R A_j^{R*}) BW_{K_0^*}(m^2_{K\pi}) BW^\dagger_{K^*}(m^2_{K\pi})\right] dm^2_{K\pi}\right|$$
$$\leq \mathbf{Z} \times \sqrt{[|{A'_0}^L|^2 + |{A'_0}^R|^2][|A_j^L|^2 + |A_j^R|^2]}$$

From the definitions of $\mathbf{F_S}$ and $\mathbf{F_L}$ and $\mathbf{P_1}$ one gets the following bound:

$$|\mathbf{A_S}| \leq 2\sqrt{3}\sqrt{\mathbf{F_S(1-F_S)F_L}}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}}$$

the factor $(1-F_S)$ in the bound arises due to the fact that $\mathbf{F_L}$ is defined with respect to Γ'_{K^*} rather than Γ'_{full}.

$$\begin{aligned}
|\mathbf{A_S^4}| &\leq \sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1-\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \sim [0.05-0.11, 0.10-0.19] \\
|\mathbf{A_S^5}| &\leq 2\sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1+\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \sim [0.11-0.22, 0.11-0.23] \\
|\mathbf{A_S^7}| &\leq 2\sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1-\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \sim [0.11-0.22, 0.19-0.38] \\
|\mathbf{A_S^8}| &\leq \sqrt{\frac{3}{2}}\sqrt{\mathbf{F_S(1-F_S)}(1-\mathbf{F_L})\left(\frac{1+\mathbf{P_1}}{2}\right)}\,\frac{\mathbf{Z}}{\sqrt{\mathbf{XY}}} \sim [0.05-0.11, 0.06-0.11]
\end{aligned}$$

Large recoil and low recoil ranges with $F_S \sim 7\%$.
Symmetries will add non-trivial correlations [L.Hofer, JM, N.Serra'14]