Knowns & Unknowns in LFUV fits

based on arXiv: 1704.05447

in collaboration with

M. Valli

also supported by
Talking about $B \rightarrow K^{*}\mu\mu$ channel & the $P'_{5}$ anomaly:

“Unless any other statistically significant anomaly shows up, from this single decay mode we cannot learn much about New Physics!”

In our analysis of this exclusive decay, anomalies disappear when one conservatively (gu)estimates non-factorizable QCD power corrections.

Ciuchini et al., *JHEP* **1606** (2016) 116
**UPDATE**: CURRENT SITUATION MAY LOOK LIKE THIS

Is evidence for New Physics (NP) in $Q_{9V}$ operator indisputable? What is its significance @ present?

i.e., my collaborators & I harmlessly lying on the ground … OR MAYBE NOT?

... **INDEED:**

$$R_{K(*)}^{LHCb}, [1(1),6] < 1$$

$$Q_{5}, [4,8] > 0$$

*Is evidence for New Physics (NP) in $Q_{9V}$ operator indisputable?*

*What is its significance @ present?*
Main content of this ~10 min contribution

“Flavourful Easter eggs”
Helicity ($\lambda$) amplitudes relevant in this study:

$$H_V(\lambda) \propto C_9 \bar{V}_\lambda + \frac{2m_b m_B}{q^2} C_7 \bar{T}_\lambda - \frac{16\pi^2 m_B^2}{q^2} h_\lambda,$$

$$H_A(\lambda) \propto C_{10} \bar{V}_\lambda, \quad H_P \propto \frac{2m_\ell m_B}{q^2} C_{10} \left(1 + \frac{m_s}{m_B}\right) \bar{S}.$$  

**The known knowns:**
(form factors)

QCD sum rules on light-cone (LCSR) at large recoil in agreement with extrapolated Lattice results at low recoil.

**The known unknowns:**
(long-distance effects)

non-factorizable power corrections to the amplitude of exclusive decay modes; estimates from LCSR may suggest small effects in B to K amplitude, but not in B to K* one!

$\longrightarrow$ possible degeneracy in $H_V$ with NP in $Q_7^{\gamma} \& Q_9^{\gamma}$

**The unknowns (not so) unknown ...**

See Jäger & Virto's talks for further details ...
Our global analysis is carried out by means of Bayesian inference.

We use the Information Criterion for Predictive Bayesian Model Selection:

\[ IC = -2 \log L + 4 \sigma_{\log L}^2 \]

1st term \(\rightarrow\) how well model fits data

2nd term \(\rightarrow\) penalty on model complexity

\( \Delta IC \simeq \ln \frac{P(\text{data}|M_1)}{P(\text{data}|M_2)} \)

<table>
<thead>
<tr>
<th>Evidence against higher ( IC (M_1) )</th>
</tr>
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<tbody>
<tr>
<td>0 to 2</td>
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<tr>
<td>2 to 6</td>
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<tr>
<td>6 to 10</td>
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<tr>
<td>&gt; 10</td>
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</tbody>
</table>

MCMC with total of 93 SM parameters with Gaussian or flat prior distribution.

DATA INCLUDED: MEASUREMENTS RELATED TO K(*) & PHI IN LARGE RECOIL REGION ONLY + Bs TO MU MU & B TO Xs GAMMA (LHCb, BELLE, ATLAS, CMS, SEE BACKUP!).

**About known knowns** …

Form factors from LCSR &/or Lattice, with correlations.

… and known unknowns

Non-factorizable part of B to K*ll amplitude parametrized as follows:

Ciuchini et al., *JHEP 1606 (2016) 116*

\[
h_\lambda (q^2) = h_\lambda^{(0)} + \frac{q^2}{1 \text{ GeV}^2} h_\lambda^{(1)} + \frac{q^4}{1 \text{ GeV}^4} h_\lambda^{(2)}
\]

also used as a proxy also for Bs —> \(\phi\) \(\mu\) \(\mu\) mode. i.e. flat priors with large ranges

<table>
<thead>
<tr>
<th>(h_{0,\pm}^{(0,1,2)})</th>
<th>(\in [0, 2 \cdot 10^{-3}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Arg} \left( h_{0,\pm}^{(0,1,2)} \right) )</td>
<td>(\in [0, 2\pi))</td>
</tr>
</tbody>
</table>

**Unknown unknowns in \(\Delta B=1\) EFT**

2 different approaches implemented

PMD approach, LCSR on cc-loop + dispersion relation in whole large recoil region

**PHENOMENOLOGICAL MODEL DRIVEN**

PDD approach, LCSR result enforced only nearby the light-cone, i.e. \(q^2 \leq 1 \text{ GeV}^2\)

**PHENOMENOLOGICAL DATA DRIVEN**

Khodjamirian et al., *JHEP 1009 (2010) 089*
“Chasing well-known Easter eggs!”

Q: What is the significance of $C_{9, \mu}^{\text{NP}} \neq 0$?
dashed lines in 1D histograms
16th, 50th, 84th percentiles
2D joint probability density
1,2,3 σ contours (darker to lighter)
blue lines and blue square
SM limit of NP Wilson coeffs
flat prior ranges for NP
\[ C_7^{NP} \in [-0.3, 0.3] \]
\[ C_{9,\mu}^{NP} \in [-4, 4] \]
\[ C_{9,e}^{NP} \in [-4, 4] \]

\[ C_{9,\mu}^{NP} = -1.64^{+0.23}_{-0.23} \]
\[ C_{9,e}^{NP} = -1.27^{+0.63}_{-0.56} \]

\[ C_7^{NP} = 0.01^{+0.01}_{-0.01} \]

\[ C_{9,\mu}^{NP} = 1.27^{+0.63}_{-0.56} \]
\[ C_{9,e}^{NP} = 0.68^{+0.78}_{-0.73} \]

PMD: IC = 174
PDD: IC = 170

Significance of NP clearly affected by known unknowns!
NP results — Part II —

“Digging in ~ no man’s land …”

Q: Is NP in $Q_{9V,\mu}$ the « only way to go »?
Flat prior ranges for NP:

- $C_7^{NP} \in [-0.3, 0.3]$
- $C_{10,\mu}^{NP} \in [-0.7, 0.7]$
- $C_{10,e}^{NP} \in [-4, 4]$

Other parameters:

- $C_{10,\mu} = 0.02^{+0.09}_{-0.09}$
- $C_{10,e} = 1.79^{+0.53}_{-0.59}$
- $C_{10,e} = -1.63^{+0.51}_{-0.58}$

Dashed lines in 1D histograms:
- 16th, 50th, 84th percentiles
- 2D joint probability density
- 1, 2, 3 $\sigma$ contours (darker to lighter)
- Blue lines and blue square

SM limit of NP Wilson coeffs

PMD: $|C| = 221$

PDD: $|C| = 172$

“Disfavoured” NP scenarios allowed by a more careful treatment of non-factorizable QCD power corrections.
NP results — Part III —

*** The Bayesian State Of Mind ***
dashed lines in 1D histograms
16th, 50th, 84th percentiles
2D joint probability density
1,2,3 $\sigma$ contours (darker to lighter)
blue lines and blue square
SM limit of NP Wilson coeffs

flat prior ranges for NP
$C_7^{NP} \in [-0.3, 0.3]$
$C_9^{NP} \in [-4, 4]$
$C_{10,\mu}^{NP} \in [-0.7, 0.7]$
$C_{10,e}^{NP} \in [-5, 5]$

PMD: $|C| = 178$
PDD: $|C| = 174$

NP significance boils down by the interplay among $C_9^\mu, C_9^e$ & $C_{10}^e$ when we leave room for more generous hadronic contributions.
Summary & Conclusions

Size of arrows proportional to money I may bet on …

Size of arrows proportional to amount of money some of my collaborators might put on …

NOVEL NP SCENARIOS ARISE WHEN WE TAKE A MORE CONSERVATIVE APPROACH FOR POORLY ESTIMATED HADRONIC UNCERTAINTIES. E.g.: Electronic Axial NP models

SIGNIFICANCE (~2\sigma TO ~7\sigma) OF NP IN THE MUONIC VECTOR CURRENT DEPENDS ON ESTIMATED HADRONIC UNCERTAINTIES. On general grounds it is the NP scenario preferred by current data.

WE MAY BE SITTING IN FRONT OF ~2\sigma-3\sigma NP EVIDENCE … I.E., AS OF NOW, THE SM PREDICTION IS COMPATIBLE AT ~2.5\sigma LEVEL WITH \( R_K \) & \( R_{K^*} \).
Backups
In this NP case we are constraining one coeff precisely, i.e. independently on the approach adopted for $h_1$!

$$C_{9,\pm}^{NP} = \frac{1}{2} (C_{9,\mu}^{NP} \pm C_{9,e}^{NP})$$
The document contains a table of results for flat prior ranges for NP Wilson coefficients, along with 1D histograms showing the 16th, 50th, and 84th percentiles. The histograms for 1D and 2D joint probability densities are depicted, with 1, 2, and 3σ contours (darker to lighter). Yellow stars mark the SM limit of NP Wilson coefficients. The Wilson coefficients are indicated as follows:

- $C_7^{NP} = 0.01^{+0.01}_{-0.01}$
- $C_9^{NP} = -1.11^{+0.55}_{-0.43}$
- $C_9,\mu = -0.66^{+0.76}_{-0.71}$
- $C_9,\pm = -0.51^{+0.39}_{-0.51}$
- $C_9,\pm = -0.47^{+0.51}_{-0.40}$
- $C_{10,\pm} = 0.54^{+0.39}_{-0.49}$
- $C_{10,\pm} = 1.11^{+0.55}_{-0.43}$

The formulas for the Wilson coefficients are:

- $C_9,\mu = \frac{1}{2} (C_9^{NP} + C_9^{NP})$
- $C_{10,\mu} = \frac{1}{2} (C_{10,\mu} + C_{10,\mu})$
Fitting w/o any of the Angular Observables.

Dashed lines in 1D histograms
16th, 50th, 84th percentiles
2D joint probability density
1,2,3 \( \sigma \) contours (darker to lighter)
Blue lines and blue square
SM limit of NP Wilson coeffs

PMD WITH ALL MEASUREMENTS
PDD WITH ALL MEASUREMENTS
PMD W/O ANGULAR OBS DATA
Exploring NP effects only in the muon channel.

\[ C_{9,\mu}^{NP} = -1.61^{+0.20}_{-0.20} \]
\[ C_{9,\mu}^{NP} = -1.22^{+0.62}_{-0.59} \]

PMD: $IC = 173$
PDD: $IC = 171$

\[ C_{10,\mu}^{NP} = 0.06^{+0.09}_{-0.08} \]
\[ C_{10,\mu}^{NP} = 0.09^{+0.1}_{-0.09} \]

Dashed lines in 1D histograms
16th, 50th, 84th percentiles
2D joint probability density
1, 2, 3 $\sigma$ contours (darker to lighter)
Blue lines and blue square
SM limit of NP Wilson coeffs
Exploring NP effects only in the electron channel.

\[ C_{9,e}^{NP} = 0.76^{+1.38}_{-0.87} \]
\[ C_{9,e}^{NP} = 0.93^{+0.97}_{-0.76} \]

PMD: \( IC = 217 \)
PDD: \( IC = 169 \)

\[ C_{10,e}^{NP} = -1.23^{+1.43}_{-0.87} \]
\[ C_{10,e}^{NP} = -1.11^{+0.91}_{-0.76} \]
$C_9 = -C_{10}$ case

Dashed lines in 1D histograms
- 16th, 50th, 84th percentiles
- 2D joint probability density
- $1,2,3 \sigma$ contours (darker to lighter)
- Blue lines and blue square
- SM limit of NP Wilson coeffs

PMD: $|C| = 216$

PDD: $|C| = 171$
dashed lines in 1D histograms
16th, 50th, 84th percentiles
2D joint probability density
1,2,3 \( \sigma \) contours (darker to lighter)
blue lines and blue square
SM limit of NP Wilson coeffs

\[ C_9 = -C_{10} \text{ case} \]

PMD: \( IC = 216 \)
PDD: \( IC = 171 \)
Vector-like + C\textsubscript{7} NP case

\begin{align*}
\text{PMD approach} & \quad \log L = -70.9, \sigma_{\log L}^2 = 8.1, \ IC \simeq 174 \\
\text{PDD approach} & \quad \log L = -68.4, \sigma_{\log L}^2 = 8.3, \ IC \simeq 170 \quad \text{(IC less than } \sim 2 \text{ units w/o C\textsubscript{7}})
\end{align*}

Axial-like + C\textsubscript{7} NP case

\begin{align*}
\text{PMD approach} & \quad \log L = -87.0, \sigma_{\log L}^2 = 11.8, \ IC \simeq 221 \\
\text{PDD approach} & \quad \log L = -69.1, \sigma_{\log L}^2 = 8.6, \ IC \simeq 172 \quad \text{(IC less than } \sim 2 \text{ units w/o C\textsubscript{7}})
\end{align*}

Bayesian NP case

\begin{align*}
\text{PMD approach} & \quad \log L = -70.8, \sigma_{\log L}^2 = 9.0, \ IC \simeq 178 \\
\text{PDD approach} & \quad \log L = -68.4, \sigma_{\log L}^2 = 9.2, \ IC \simeq 174
\end{align*}

Purely Muonic NP case

\begin{align*}
\text{PMD approach} & \quad \log L = -70.7, \sigma_{\log L}^2 = 7.9, \ IC \simeq 173 \\
\text{PDD approach} & \quad \log L = -68.6, \sigma_{\log L}^2 = 8.5, \ IC \simeq 171
\end{align*}

Purely Electronic NP case

\begin{align*}
\text{PMD approach} & \quad \log L = -86.7, \sigma_{\log L}^2 = 10.8, \ IC \simeq 217 \\
\text{PDD approach} & \quad \log L = -68.2, \sigma_{\log L}^2 = 8.2, \ IC \simeq 169
\end{align*}

\begin{align*}
\sim\text{SU(2)}_L \text{ NP case} \\
\text{PMD approach} & \quad \log L = -85.8, \sigma_{\log L}^2 = 11.1, \ IC \simeq 216 \\
\text{PDD approach} & \quad \log L = -68.3, \sigma_{\log L}^2 = 8.7, \ IC \simeq 171
\end{align*}
Set of measurements included in the present analysis

<table>
<thead>
<tr>
<th>LHCb</th>
<th>ATLAS</th>
<th>CMS</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_L, A_{FB}, S_{3,4,5,7,8,9}$</td>
<td>$F_L, A_{FB}, S_{3,4,5,7,8}$</td>
<td>$P_1, P_5', F_L, A_{FB}, B(B \to K^* \mu \mu)$</td>
<td>$P_5' (\mu, e)$</td>
</tr>
<tr>
<td>i.e. available angular info for $K^{(*)}\phi$ modes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(B \to K^{(*)} l l, \gamma)$</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>$\mathcal{B}(B_s \to \phi \mu \mu, \gamma)$</td>
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<td></td>
</tr>
<tr>
<td>$R_K,[1,6], R_{K^*},[0.045,1.1],[1.1,6]$</td>
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</tbody>
</table>

We use data in the large recoil region only, i.e. where anomalies show up. **We take into account correlation matrices when experimentally provided.**

<table>
<thead>
<tr>
<th>LHCb, HFAG</th>
<th>ATLAS</th>
<th>CMS-PAS-BPH-15-008</th>
<th>PRL 118 (2017) 111801</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B_s \to \mu \mu), \mathcal{B}(B \to X_s \gamma)$</td>
<td></td>
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</table>

JHEP 1611 (2016) 047
JHEP 1602 (2016) 104
JHEP 1509 (2015) 179
JHEP 1504 (2015) 064
PRL 113 (2014) 151601
indico.cern.ch/event/580620/

ATLAS-CONF-2017-023

PRL 118 (2017) 111801

twiki.cern/…/CMSPublic/…
Effective Field Theory of Weak Interactions for $b \rightarrow s \ell \ell$ transitions

$Q_{1}^{q=u,c} = (\bar{s}_{L} \gamma_{\mu} T^{a} q_{L})(\bar{q}_{L} \gamma^{\mu} T^{a} b_{L})$  

$Q_{2}^{q=u,c} = (\bar{s}_{L} \gamma_{\mu} q_{L})(\bar{q}_{L} \gamma^{\mu} b_{L})$

$P_{3} = (\bar{s}_{L} \gamma_{\mu} b_{L}) \sum_{q}(\bar{q} \gamma^{\mu} q)$

$P_{4} = (\bar{s}_{L} \gamma_{\mu} T^{a} b_{L}) \sum_{q}(\bar{q} \gamma^{\mu} T^{a} q)$

$P_{5} = (\bar{s}_{L} \gamma_{\mu_{1}} \gamma_{\mu_{2}} \gamma_{\mu_{3}} b_{L}) \sum_{q}(\bar{q} \gamma^{\mu_{1}} \gamma^{\mu_{2}} \gamma^{\mu_{3}} q)$

$P_{6} = (\bar{s}_{L} \gamma_{\mu_{1}} \gamma_{\mu_{2}} \gamma_{\mu_{3}} T^{a} b_{L}) \sum_{q}(\bar{q} \gamma^{\mu_{1}} \gamma^{\mu_{2}} \gamma^{\mu_{3}} T^{a} q)$

$Q_{8g} = \frac{g_{s}}{16\pi^{2}} m_{b} \bar{s} \sigma_{\mu \nu} P_{R} G^{\mu \nu} b$

$H_{\Delta B=1} \sim H_{\text{had}}^{\text{eff}} + H_{\gamma}^{\text{sl+}}$

Within Standard Model (SM), quantum running from $M_{W}$ down to low scale $\sim 5$ GeV

$C_{1} \sim -0.25, C_{2} \sim 1.0, C_{8} \sim -0.2$

$C_{7} \sim -0.3, C_{9} \sim 4.2, C_{10} \sim -4.1$

**FOCUS OF PRESENT ANALYSIS**

CP-conserving New Physics (NP) effects, phenomenologically seen as shifts of SM Wilson coefficients at the low scale:

$C_{7}^{NP}, C_{9,e}^{NP}, C_{9,\mu}^{NP}, C_{10, e}^{NP}, C_{10, \mu}^{NP}$
\[ A^{(\text{had})}(\bar{B} \to \bar{K}^* \ell \ell) \sim \frac{e^2}{q^2} \langle \ell^- \ell^+ | \bar{\ell} \gamma_\mu \ell | 0 \rangle \int d^4 x \, e^{i q x} \langle \bar{K}^* | T\{ \bar{q}(x) \gamma^\mu q(x) \mathcal{H}_{\text{eff}}^{\text{had}}(0) \} | \bar{B} \rangle \]

i.e. @ first order in \( \alpha_{\text{em}} \) the hadronic piece can contribute!

The above correlator is the weakest part of the theoretical prediction.

**OBS.**

Single soft gluon emission from charm-loop estimated with LCSRs.


arXiv:1006.4945

**DRAWBACKS ON PHENO APPLICATIONS!**

- Correlator expanded on the light-cone: maybe a right estimate, but for small \( q^2 \).
- Multiple soft gluon emission is likely relevant: negligible when \( q^2 \ll 4m^2_c \).
\[ h_{\lambda} \equiv \frac{\epsilon_{\mu}(\lambda)}{m_B^2} \int d^4 x \ e^{i q x} \langle \bar{K}^* | T \{ j_{\text{em}}^{\mu}(x) \mathcal{H}_{\text{eff}}^{\text{had}}(0) \} | B \rangle \]

non-factorizable hadronic part of B to K*ll amplitude

In the K* helicity basis, \( \langle \bar{K}^* \ell^- \ell^+ | \mathcal{H}_{\text{eff}}^{\Delta B=1} | B \rangle \) can be decomposed as:

\[
H_V(\lambda) \propto C_9 \tilde{V}_\lambda + \frac{2m_b m_B}{q^2} C_7 \tilde{T}_\lambda - \frac{16\pi^2 m_B^2}{q^2} h_\lambda, \quad (\lambda = 0, \pm) \\
H_A(\lambda) \propto C_{10} \tilde{V}_\lambda, \quad H_P \propto \frac{2m_{\ell} m_B}{q^2} C_{10} \left( 1 + \frac{m_s}{m_B} \right) \tilde{S},
\]

1) All the observables introduced so far are functions of \( H_{V,A,P} \).

In the approximation of \( \sim \) const form factors in \( q^2 \):

2) The 0th order and 1st order power correction in \( q^2 \) is degenerate with NP effects in \( Q_7 \) and \( Q_9 \) respectively.

3) Higher order power-corrections in \( q^2 \) instead likely associated to genuinely Standard hadronic physics.
short distance (SD) physics  long distance (LD) cc-loop from JHEP 1009 (2010) 089

1) Light-blue band identifiable with LD cc-loop read from the fit

IMPORTANT DEPARTURE FROM THEORETICAL ESTIMATES BASED ON LCSR + SINGLE SOFT GLUON APPROX VALID FOR $q^2 << 4 m_c^2$

2) NP contributing to $Q_{9V}$ should be independent of dilepton mass

$q^2$ DEPENDENCE SHOWN IN LIGHT-BLUE BAND DISFAVORS NEW SD EFFECTS, BUT POINTS TO UNDERESTIMATED HADRONIC PHYSICS!
Ciuchini et al. ‘16

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Absolute value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_0^{(0)}$</td>
<td>$(5.7 \pm 2.0) \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$h_0^{(1)}$</td>
<td>$(2.3 \pm 1.6) \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$h_0^{(2)}$</td>
<td>$(2.8 \pm 2.1) \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$h_+^{(0)}$</td>
<td>$(7.9 \pm 6.9) \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$h_+^{(1)}$</td>
<td>$(3.8 \pm 2.8) \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$h_+^{(2)}$</td>
<td>$(1.4 \pm 1.0) \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$h_-^{(0)}$</td>
<td>$(5.4 \pm 2.2) \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$h_-^{(1)}$</td>
<td>$(5.2 \pm 3.8) \cdot 10^{-5}$</td>
</tr>
<tr>
<td>$h_-^{(2)}$</td>
<td>$(2.5 \pm 1.0) \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

Columns identify NP cases (I) - (VI) in 1704.05447.