Quo Vadis flavor anomalies?

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The Future of Particle Physics: A Quest for Guiding Principles
October 2, 2018

Outline

1. The flavour anomalies:
    - $R(D^{*})$
    - R_K and R_{K^*}
    - P_5'
2. Global fits results.
3. Conclusions.

Modern Flavour Physics

Study the CKM matrix

Arises from Higgs Yukawa interactions

Unitary in the SM, with one CP violating phase.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Test unitarity with many measurements.

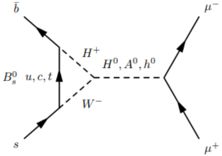
Find new sources of CPV

wru anti-matter!?

Measure decays of ground state b-hadrons

Properties influenced by virtual particles in NP models

Compare results to SM predictions (need QCD input).



Particularly sensitive to NP models preferring third generation.

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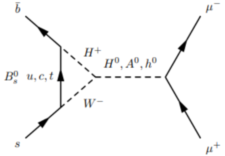
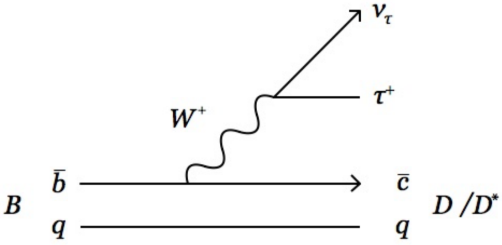


Particularly sensitive to NP models preferring third generation.

Why semi-leptonic decays?

⇛ A decay is semi-leptonic if its products are part leptons and part hadrons.



$$\frac{d\Gamma}{dq^2}(B \to D\ell\nu) \propto$$

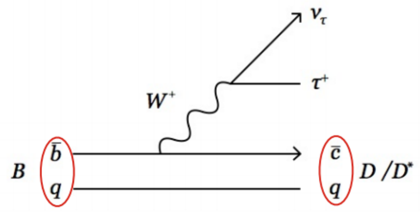
$$\underset{\text{EW}}{\underset{\uparrow}{G_F^2|V_{cb}|^2}}\,\underset{\text{QCD}}{\underset{\uparrow}{f(q^2)^2}}$$

⇛ These decays can be factorised into the weak and strong parts, greatly simplifying theoretical calculations.

Types of semi-leptonic decays

Two types of semi-leptonic b-decay

Charged current

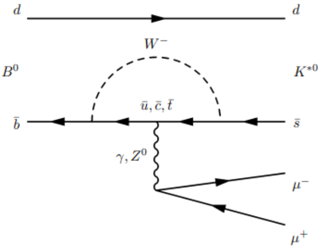


Can proceed via tree level -large O(%) branching fractions.

Factorised up to (small) QED corrections.

When you factorise, QCD part broken down into form-factors.

Neutral current



Forbidden at tree level - low $O(10^{-6})$ branching fractions.

Factorised up to corrections from $B \to h(\to \mu^+\mu^-)h$ decays.

Anomalies

⇛ Today I will talk about three anomalies in B decays:

- $R(D^*)$
- R_{K/K^*}
- P_5'

Anomaly 1

$$R(D^*) = \frac{\mathcal{B}(B \to D^* \tau \nu)}{\mathcal{B}(B \to D^* \mu \nu)}$$

$R(D^{*})$

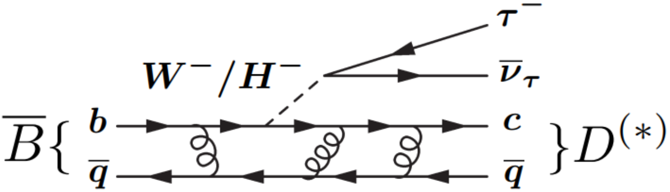
⇛ Large rate of charged current decays allow for measurement in semi-tauonic decays

$$R(D^{*}) = \frac{\mathcal{B}(B \to D^{*}\tau\nu)}{\mathcal{B}(B \to D^{*}\mu\nu)}$$

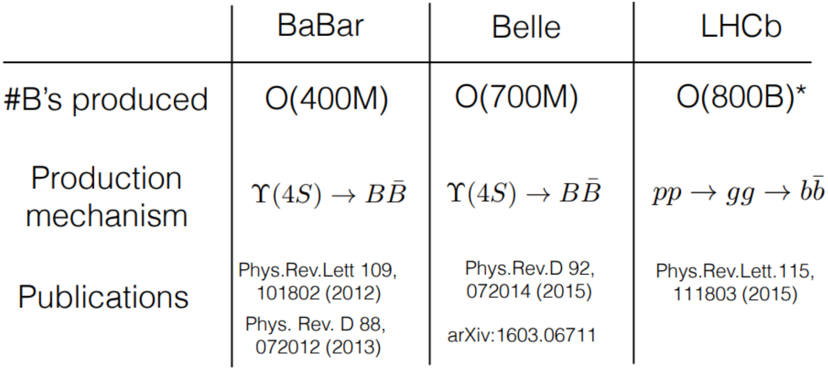
⇛ Form ratio of decays with different lepton generations.

⇛ Cancel QCD uncertainties.

⇛ $R(D^{*})$ is sensitive to the NP with strong 3rd generation couplings.



The Rule of three

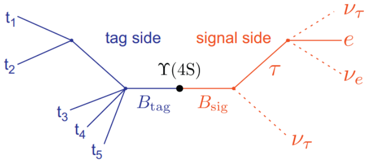


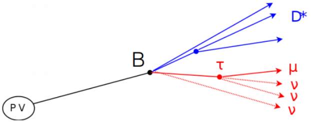
	BaBar	Belle	LHCb
#B's produced	O(400M)	O(700M)	O(800B)*
Production mechanism	$\Upsilon(4S) \to B\bar{B}$	$\Upsilon(4S) \to B\bar{B}$	$pp \to gg \to b\bar{b}$
Publications	Phys.Rev.Lett 109, 101802 (2012) Phys. Rev. D 88, 072012 (2013)	Phys.Rev.D 92, 072014 (2015) arXiv:1603.06711	Phys.Rev.Lett.115, 111803 (2015)

Experimental challenges

⇛ With the $\tau \to \mu\nu\nu$ decay we are missing 3 neutrinos!
⇛ No sharp peak in any distributions.

⇛ At B-factories, can control this using tagging technique.

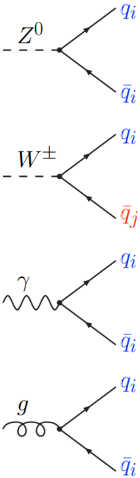


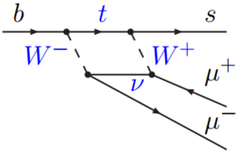


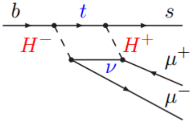
⇛ More difficult at LHCb, compensate using large boost (flight information) and huge B production

Introduction to anomaly 2 & 3

- The SM allows only the charged interactions to change flavour.
    - Other interactions are flavour conserving.
- One can escape this constraint and produce $b \longrightarrow s$ and $b \longrightarrow d$ at loop level.
    - These kind of processes are suppressed in SM → Rare decays.
    - New Physics can enter in the loops.



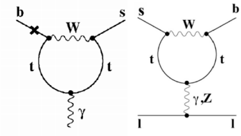




Analysis of Rare decays

Analysis of FCNC in a model-independent approach, effective Hamiltonian:

$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\Delta F=1} \propto \sum_{i=1}^{10} V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \dots$$



- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \, (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu}$
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b) \; (\bar{\ell}\gamma_\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b) \; (\bar{\ell}\gamma_\mu\gamma_5 \ell)$, ...

• **SM** Wilson coefficients up to NNLO + e.m. corrections at $\mu_{ref} = 4.8$ GeV [Misiak et al.]:

$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3$$

• **NP** changes short distance $\mathcal{C}_i - \mathcal{C}_i^{\rm SM} = \mathcal{C}_i^{\rm NP}$ and induce new operators, like

$\mathcal{O}'_{7,9,10} = \mathcal{O}_{7,9,10} \; (P_L \leftrightarrow P_R)$ ... also scalars, pseudoescalar, tensor operators...

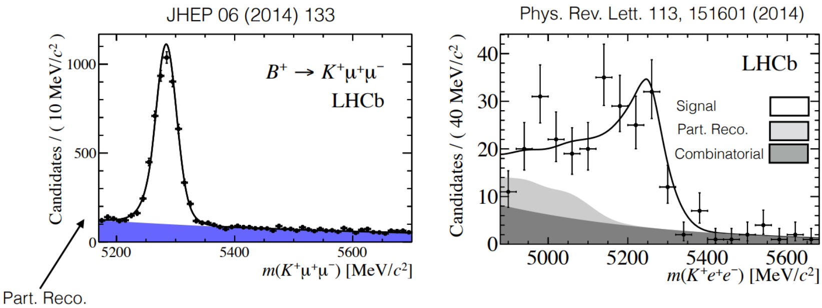
Anomaly 2

$$R_{K/K^*} = \frac{\mathcal{B}(B \to K/K^* \mu\mu)}{\mathcal{B}(B \to K/K^* ee)}$$

Measurement at LHCb

⇛ Most precise measurements performed at LHCb.

⇛ Main challenge is due to electron Bremsstrahlung.

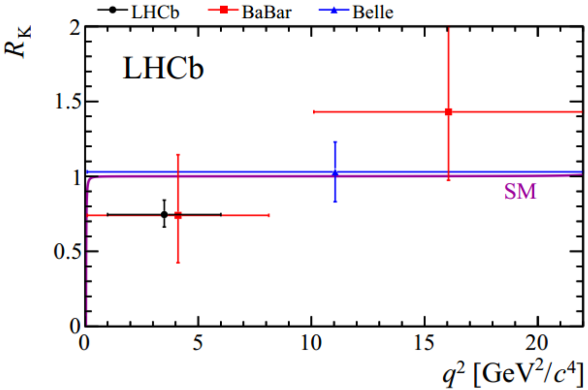


⇛ To protect ourself from electron reconstruction issue we use double ratio:

$$R_K = \frac{\mathcal{B}(B \to K\mu\mu) \times \mathcal{B}(B \to KJ/\psi(\to ee))}{\mathcal{B}(B \to Kee) \times \mathcal{B}(B \to KJ/\psi(\to \mu\mu))}$$

Result

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



⇛ 2.6 σ away from SM prediction.

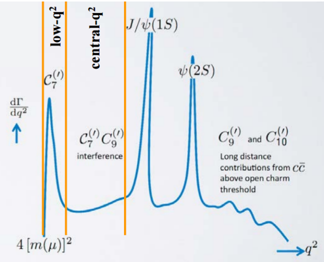
The continuation - R_{K^*}

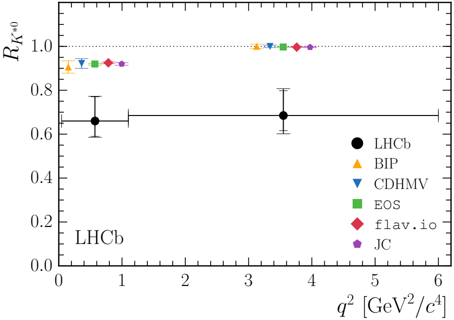
⇛ The neutral continuation of the R_K measurement is to measure its partner:

$$R_{K^*} = \frac{\mathcal{B}(B \to K^* \mu\mu)}{\mathcal{B}(B \to K^* ee)}$$

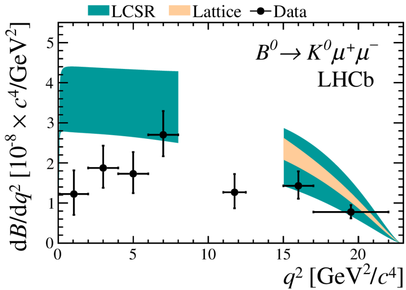
⇛ Measurement performed in two q^2 bins.

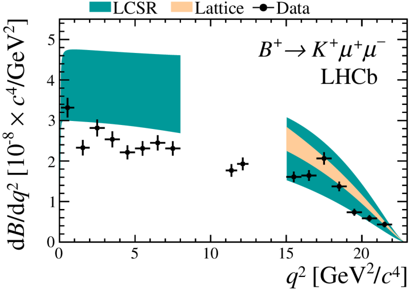
⇛ Normalized in double ratio to $B \to K^* J/\psi$.



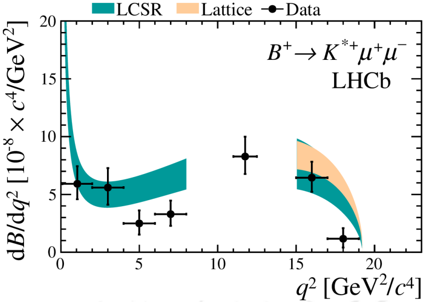


Branching fraction measurements of $B \to K^{*\pm}\mu\mu$





- Despite large theoretical errors the results are consistently smaller than SM prediction.



Anomaly 3

$$P_5' = \sqrt{2}\frac{\Re(A_\perp^L A_\parallel^{L^*} - A_\perp^R A_\parallel^{R^*})}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_0|^2)}}$$

$B^0 \to K^{*}\mu^{-}\mu^{+}$ kinematics

$\Rightarrow$ The kinematics of $B^0 \to K^{*}\mu^{-}\mu^{+}$ decay is described by three angles θ_l, θ_k, ϕ and invariant mass of the dimuon system (q^2):

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$

$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$

$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi$$

$$+J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big],$$

Transversity amplitudes

⇛ One can link the angular observables to transversity amplitudes

$$J_{1s} = \frac{(2+\beta_\ell^2)}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] + \frac{4m_\ell^2}{q^2}\mathrm{Re}\left(A_\perp^L A_\perp^{R*} + A_\parallel^L A_\parallel^{R*}\right) ,$$

$$J_{1c} = |A_0^L|^2 + |A_0^R|^2 + \frac{4m_\ell^2}{q^2}\left[|A_t|^2 + 2\mathrm{Re}(A_0^L A_0^{R*})\right] + \beta_\ell^2 |A_S|^2 ,$$

$$J_{2s} = \frac{\beta_\ell^2}{4}\left[|A_\perp^L|^2 + |A_\parallel^L|^2 + |A_\perp^R|^2 + |A_\parallel^R|^2\right] , \qquad J_{2c} = -\beta_\ell^2\left[|A_0^L|^2 + |A_0^R|^2\right] ,$$

$$J_3 = \frac{1}{2}\beta_\ell^2\left[|A_\perp^L|^2 - |A_\parallel^L|^2 + |A_\perp^R|^2 - |A_\parallel^R|^2\right] , \qquad J_4 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Re}(A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*})\right] ,$$

$$J_5 = \sqrt{2}\beta_\ell\left[\mathrm{Re}(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}) - \frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_\parallel^L A_S^* + A_\parallel^{R*} A_S)\right] ,$$

$$J_{6s} = 2\beta_\ell\left[\mathrm{Re}(A_\parallel^L A_\perp^{L*} - A_\parallel^R A_\perp^{R*})\right] , \qquad J_{6c} = 4\beta_\ell\frac{m_\ell}{\sqrt{q^2}}\mathrm{Re}(A_0^L A_S^* + A_0^{R*} A_S) ,$$

$$J_7 = \sqrt{2}\beta_\ell\left[\mathrm{Im}(\mathrm{A}_0^{\mathrm{L}}\mathrm{A}_\parallel^{\mathrm{L}*} - \mathrm{A}_0^{\mathrm{R}}\mathrm{A}_\parallel^{\mathrm{R}*}) + \frac{\mathrm{m}_\ell}{\sqrt{\mathrm{q}^2}}\mathrm{Im}(\mathrm{A}_\perp^{\mathrm{L}}\mathrm{A}_{\mathrm{S}}^* - \mathrm{A}_\perp^{\mathrm{R}*}\mathrm{A}_{\mathrm{S}}))\right] ,$$

$$J_8 = \frac{1}{\sqrt{2}}\beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_0^{\mathrm{L}}\mathrm{A}_\perp^{\mathrm{L}*} + \mathrm{A}_0^{\mathrm{R}}\mathrm{A}_\perp^{\mathrm{R}*})\right] , \qquad J_9 = \beta_\ell^2\left[\mathrm{Im}(\mathrm{A}_\parallel^{\mathrm{L}*}\mathrm{A}_\perp^{\mathrm{L}} + \mathrm{A}_\parallel^{\mathrm{R}*}\mathrm{A}_\perp^{\mathrm{R}})\right] ,$$

Link to effective operators

⇛ So here is where the magic happens. At leading order the amplitudes can be written as:

$$A_{\perp}^{L,R} = \sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\rm eff}+\mathcal{C}_9^{\rm eff\prime})\mp(\mathcal{C}_{10}+\mathcal{C}_{10}^{\prime})+\frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\rm eff}+\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\perp}(E_{K^*})$$

$$A_{\parallel}^{L,R} = -\sqrt{2}Nm_B(1-\hat{s})\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9^{\rm eff\prime})\mp(\mathcal{C}_{10}-\mathcal{C}_{10}^{\prime})+\frac{2\hat{m}_b}{\hat{s}}(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\perp}(E_{K^*})$$

$$A_{0}^{L,R} = -\frac{Nm_B(1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}}\left[(\mathcal{C}_9^{\rm eff}-\mathcal{C}_9^{\rm eff\prime})\mp(\mathcal{C}_{10}-\mathcal{C}_{10}^{\prime})+2\hat{m}_b(\mathcal{C}_7^{\rm eff}-\mathcal{C}_7^{\rm eff\prime})\right]\xi_{\parallel}(E_{K^*}),$$

where $\hat{s}=q^2/m_B^2$, $\hat{m}_i=m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

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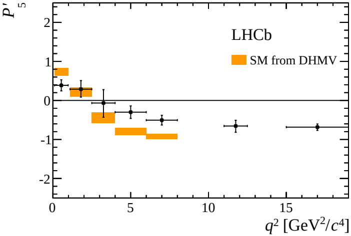
where $\hat{s}=q^2/m_B^2$, $\hat{m}_i=m_i/m_B$. The $\xi_{\parallel,\perp}$ are the form factors.

$\Rrightarrow$ Now we can construct observables that cancel the ξ form factors at leading order:

$$P_5^{\prime}=\frac{J_5+\bar{J}_5}{2\sqrt{-(J_2^c+\bar{J}_2^c)(J_2^s+\bar{J}_2^s)}}$$

Compatibility with SM



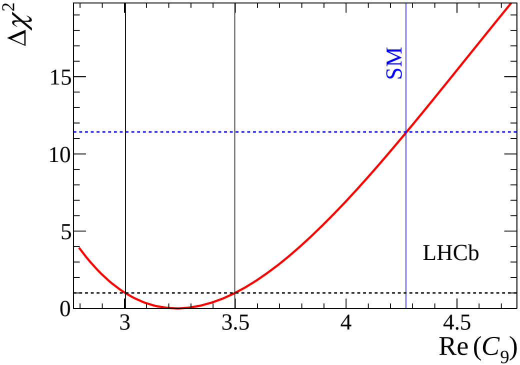
⇛ Use EOS software package to test compatibility with SM.

⇛ Perform the χ^2 fit to the measured:

$$F_L, A_{FB}, S_{3,...,9}.$$

⇛ Float a vector coupling: $\Re(C_9)$.

$$\Delta\Re(C_9) \equiv \Re(C_9)^{\text{fit}} - \Re(C_9)^{\text{SM}} = -1.03$$



⇛ Best fit is found to be $3.4\ \sigma$ away from the SM.

Global picture of P_5'

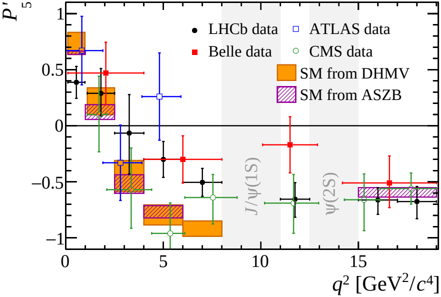
⇛ 2013 LHCb: arXiv::1308.1707

⇛ 2015 LHCb: arXiv::1512.0444

⇛ 2016 Belle: arXiv::1604.04042

⇛ 2017: ATLAS-CONF-2017-023 $(20.5\ \mathrm{fb}^{-1})$ and CMS-PAS-BPH-15-008 $(20.8\ \mathrm{fb}^{-1})$

⇛ Theory: DHMV: arXiv::1407.8526 ASZB: arXiv::1411.3161



Global fit to $b \to s\ell\ell$ measurements

Link the observables

⇛ Fits prepare by `S. Descotes-Genon, L. Hofer, J. Matias, J. Virto`, arXiv::1510.04239

- Inclusive
  - $B \to X_s \gamma$ (BR) .... $\mathcal{C}_7^{(\prime)}$
  - $B \to X_s \ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
- Exclusive leptonic
  - $B_s \to \ell^+\ell^-$ (BR) .... $\mathcal{C}_{10}^{(\prime)}$
- Exclusive radiative/semileptonic
  - $B \to K^* \gamma$ (BR, S, A_I) .... $\mathcal{C}_7^{(\prime)}$
  - $B \to K \ell^+\ell^-$ (dBR/dq^2) .... $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
  - $\mathbf{B \to K^*}\ell^+\ell^-$ (dBR/dq^2, **Optimized Angular Obs.**) .. $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
  - $B_s \to \phi \ell^+\ell^-$ (dBR/dq^2, Angular Observables) .... $\mathcal{C}_7^{(\prime)}, \mathcal{C}_9^{(\prime)}, \mathcal{C}_{10}^{(\prime)}$
  - $\Lambda_b \to \Lambda \ell^+\ell^-$ (None so far)
  - etc.

Statistic details

⇛ Frequentist approach:

$$\chi^2(C_i) = [O_{\text{exp}} - O_{\text{th}}(C_i)]_j \, [Cov^{-1}]_{jk} \, [O_{\text{exp}} - O_{\text{th}}(C_i)]_k$$

- $\mathbf{Cov} = \mathbf{Cov}^{\text{exp}} + \mathbf{Cov}^{\text{th}}$. We have Cov^{exp} for the first time
- Calculate Cov^{th}: correlated multigaussian scan over all nuisance parameters
- Cov^{th} depends on C_i: Must check this dependence

For the Fit:

- Minimise $\chi^2 \to \chi^2_{\text{min}} = \chi^2(C_i^0)$ (Best Fit Point = C_i^0)
- Confidence level regions: $\chi^2(C_i) - \chi^2_{\text{min}} < \Delta\chi_{\sigma,n}$

⇛ The results from 1D scans:

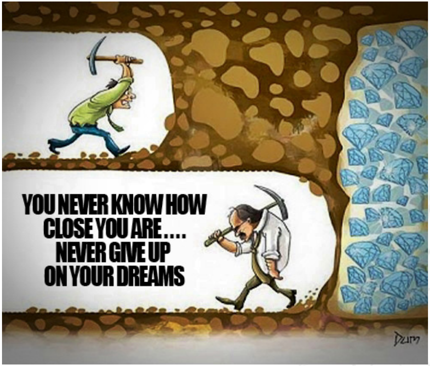
Coefficient $\mathcal{C}_i^{NP} = \mathcal{C}_i - \mathcal{C}_i^{SM}$	Best fit	1σ	3σ	Pull_{SM}
$\boldsymbol{\mathcal{C}_9^{\text{NP}}}$	-1.09	$[-1.29, -0.87]$	$[-1.67, -0.39]$	**4.5** ⇐
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{10}^{\text{NP}}$	-0.68	$[-0.85, -0.50]$	$[-1.22, -0.18]$	**4.2** ⇐
$\mathcal{C}_9^{\text{NP}} = -\mathcal{C}_{9'}^{\text{NP}}$	-1.06	$[-1.25, -0.86]$	$[-1.60, -0.40]$	4.8 ⇐ (no R_K)

Where to look for more?

- ⇛ There are couple of models that can accommodate these (see next talk).
- ⇛ Usual models need high mass particle outside the reach of LHC.

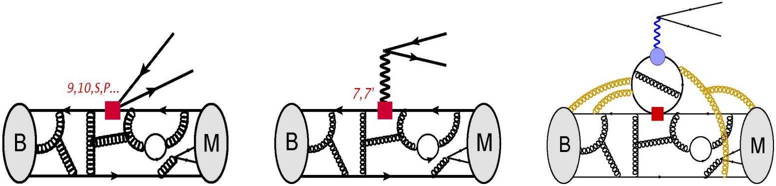
My opinion

Before moving to high energy frontier to look for something we should explore more precisely the electroweak sector.
We can get more clues about the underlying physics



Backup

$B \to K^* \ell\ell$ Amplitudes



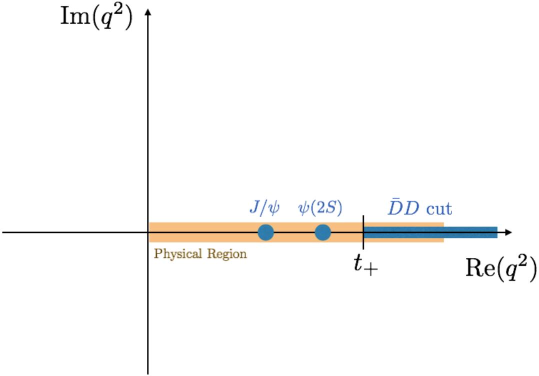
$$A_\lambda^{L,R} = N_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- Local (Form Factors) : $\mathcal{F}_\lambda^{(T)}(q^2) = \langle \bar{M}_\lambda(k) |\, \bar{s}\, \Gamma_\lambda^{(T)}\, b \,| \bar{B}(k+q) \rangle$
- Non-Local : $\mathcal{H}_\lambda(q^2) = i\, \mathcal{P}_\mu^\lambda \int d^4x\, e^{iq\cdot x} \langle \bar{M}_\lambda(k) | T\{ \mathcal{J}^\mu_{\text{em}}(x), \mathcal{C}_i\, \mathcal{O}(0) \} | \bar{B}(q+k) \rangle$
- CKM structure : $\mathcal{H}_\lambda = -\frac{\lambda_u}{\lambda_t} \mathcal{H}_\lambda^{(u)} - \frac{\lambda_c}{\lambda_t} \mathcal{H}_\lambda^{(c)} \quad \Rightarrow \quad \mathcal{O} \sim (\bar{c}b)(\bar{s}c)$

Analytic structure of $\mathcal{H}_\lambda(q^2)$

[Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305]

Neglecting OZI- and CKM-suppressed contributions :

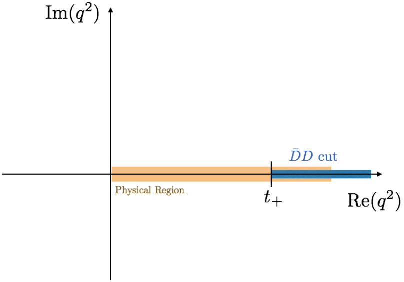


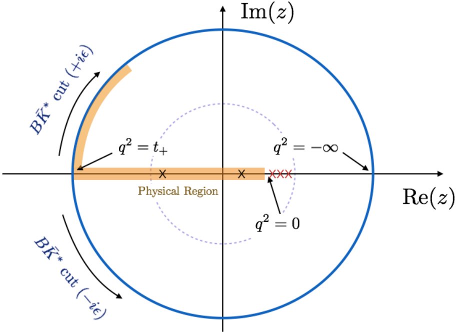
$\hat{\mathcal{H}}_\lambda(q^2) = (q^2 - M^2_{J/\psi})(q^2 - M^2_{\psi(2S)})\,\mathcal{H}_\lambda(q^2)$ has no poles.

Accessing $q^2 > 0$: z expansion

[Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305]

- Conformal mapping : $$q^2 \mapsto z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$





- $\hat{\mathcal{H}}_\lambda(q^2(z))$ is **analytic in $|z| < 1$**
- Taylor expand $\hat{\mathcal{H}}_\lambda(z)$ around $z = 0$.
- Expansion needed for $|z| < 0.52$ ($-7\,\mathrm{GeV}^2 \leqslant \mathrm{q}^2 \leqslant 14\mathrm{GeV}^2$)

Accessing $q^2 > 0$: z expansion

[**Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305**]

Some details for actual parametrisation :

- Try to capture most features of the expansion (better convergence)
- Parametrize the ratios $\mathcal{H}_\lambda(q^2)/\mathcal{F}_\lambda(q^2)$ instead
- The poles should not modify the asymptotic behaviour at $|q^2| \to \infty$

$$\mathcal{H}_\lambda(z) = \frac{1 - z\, z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z\, z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z)$$

$$\hat{\mathcal{H}}_\lambda(z) = \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)} z^k\right] \mathcal{F}_\lambda(z)$$

where $\alpha_k^{(\lambda)}$ are complex coefficients, and the expansion is truncated after the term z^K. We will take $K = 2$ (16 real parameters).

Experimental constraints on z parametrisation

[**Bobeth, Chrzaszcz, van Dyk, Virto 1707.07305**]

Experimental constraints :

- The residues of the poles are given by $B \to K^{*}\psi_n$:

$$\mathcal{H}_\lambda(q^2 \to M_{\psi_n}^2) \sim \frac{M_{\psi_n} f_{\psi_n}^* \mathcal{A}_\lambda^{\psi_n}}{M_B^2(q^2 - M_{\psi_n}^2)} + \cdots$$

- Angular analyses [**Belle**, **Babar**, **LHCb**] determine :

$$|r_\perp^{\psi_n}|,\ |r_\|^{\psi_n}|,\ |r_0^{\psi_n}|,\ \arg\{r_\perp^{\psi_n} r_0^{\psi_n *}\},\ \arg\{r_\|^{\psi_n} r_0^{\psi_n *}\},$$

where $$r_\lambda^{\psi_n} \equiv \underset{q^2 \to M_{\psi_n}^2}{\mathrm{Res}} \frac{\mathcal{H}_\lambda(q^2)}{\mathcal{F}_\lambda(q^2)} \sim \frac{M_{\psi_n} f_{\psi_n}^* \mathcal{A}_\lambda^{\psi_n}}{M_B^2\, \mathcal{F}_\lambda(M_{\psi_n}^2)}$$

- We produce correlated pseudo-observables from a fit (5+5).

Prior Fit to z parametrisation

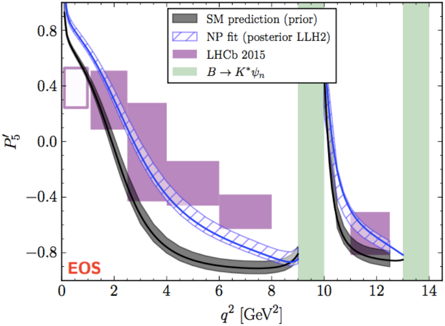
(Prior) Fit to Experimental and theoretical pseudo-observables :

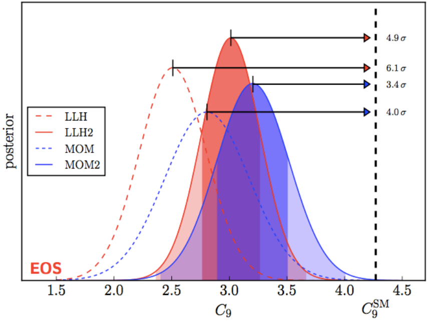
k	0	1	2
$\mathrm{Re}[\alpha_k^{(\perp)}]$	-0.06 ± 0.21	-6.77 ± 0.27	18.96 ± 0.59
$\mathrm{Re}[\alpha_k^{(\parallel)}]$	-0.35 ± 0.62	-3.13 ± 0.41	12.20 ± 1.34
$\mathrm{Re}[\alpha_k^{(0)}]$	0.05 ± 1.52	17.26 ± 1.64	–
$\mathrm{Im}[\alpha_k^{(\perp)}]$	-0.21 ± 2.25	1.17 ± 3.58	-0.08 ± 2.24
$\mathrm{Im}[\alpha_k^{(\parallel)}]$	-0.04 ± 3.67	-2.14 ± 2.46	6.03 ± 2.50
$\mathrm{Im}[\alpha_k^{(0)}]$	-0.05 ± 4.99	4.29 ± 3.14	–

Table: Mean values and standard deviations (in units of 10^{-4}) of the prior PDF for the parameters $\alpha_k^{(\lambda)}$.

New Physics Analysis

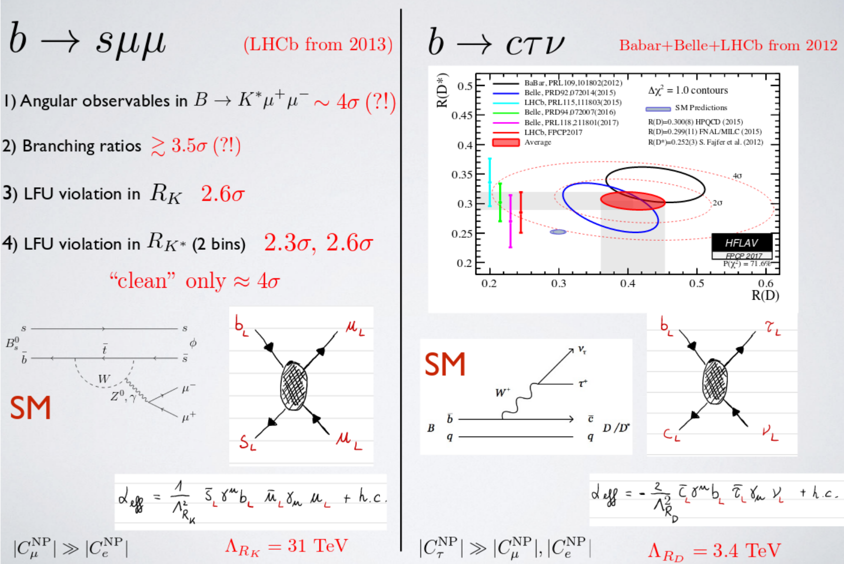
SM predictions and Fit including $B \longrightarrow K^{*}\mu^{+}\mu^{-}$ data and $\mathcal{C}_9^{\mathbf{NP}}$:





The NP hypothesis with $\mathcal{C}_9^{\mathbf{NP}} \sim -1$ is favored strongly in the global fit

Scale of NP?



$b \to s\mu\mu$ (LHCb from 2013)

1) Angular observables in $B \to K^*\mu^+\mu^- \sim 4\sigma$ (?!)

2) Branching ratios $\gtrsim 3.5\sigma$ (?!)

3) LFU violation in R_K 2.6σ

4) LFU violation in R_{K^*} (2 bins) $2.3\sigma,\ 2.6\sigma$

"clean" only $\approx 4\sigma$

SM

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2_{R_K}} \bar{s}_L \gamma^\mu b_L\, \bar{\mu}_L \gamma_\mu \mu_L + h.c.$$

$|C_\mu^{\rm NP}| \gg |C_e^{\rm NP}|$ $\Lambda_{R_K} = 31$ TeV

$b \to c\tau\nu$ Babar+Belle+LHCb from 2012

SM

$$\mathcal{L}_{eff} = -\frac{2}{\Lambda^2_{R_D}} \bar{c}_L \gamma^\mu b_L\, \bar{\tau}_L \gamma_\mu \nu_L + h.c.$$

$|C_\tau^{\rm NP}| \gg |C_\mu^{\rm NP}|, |C_e^{\rm NP}|$ $\Lambda_{R_D} = 3.4$ TeV

⇛ Stolen from M. Nardecchia

Conclusions

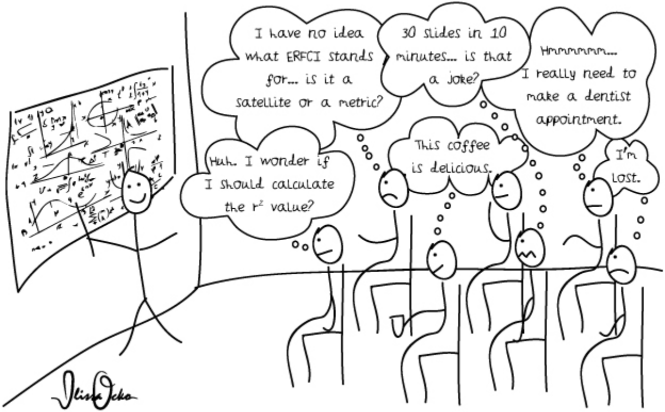
- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

Conclusions

- Clear tensions wrt. SM predictions!
- Measurements cluster in the same direction.
- We are not opening the champagne yet!
- Still need improvement both on theory and experimental side.
- Time will tell if this is QCD+fluctuations or new Physics:

”... when you have eliminated all the
Standard Model explanations, whatever remains,
however improbable, must be New Physics.”
prof. Joaquim Matias

Thank you for the attention!



Amplitudes method

⇛ Fit for amplitudes as (continuous) functions of q^2 in the region: $q^2 \in [1.1.6.0]\ \mathrm{GeV}^2/\mathrm{c}^4$.

⇛ Needs some Ansatz:

$$A(q^2) = \alpha + \beta q^2 + \frac{\gamma}{q^2}$$

⇛ The assumption is tested extensively with toys.

⇛ Set of 3 complex parameters α, β, γ per vector amplitude:

- $L,\ R,\ 0,\ \|,\ \perp,\ \Re,\ \Im \rightarrowtail\ \ 3 \times 2 \times 3 \times 2 = 36$ DoF.
- Scalar amplitudes: $+4$ DoF.
- Symmetries of the amplitudes reduces the total budget to: 28.

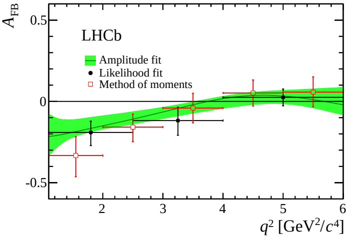
⇛ The technique is described in JHEP06(2015)084.

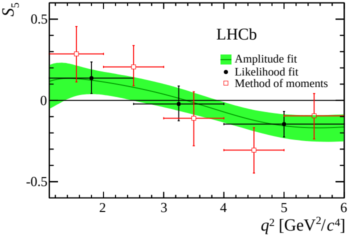
⇛ Allows to build the observables as continuous functions of q^2:

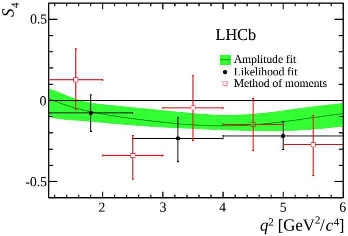
- At current point the method is limited by statistics.
- In the future the power of this method will increase.

⇛ Allows to measure the zero-crossing points for free and with smaller errors than previous methods.

Amplitudes - results







Zero crossing points:

$$
\begin{aligned}
q_0(S_4) &< 2.65 && \text{at } 95\% \; CL \\
q_0(S_5) &\in [2.49, 3.95] && \text{at } 68\% \; CL \\
q_0(A_{FB}) &\in [3.40, 4.87] && \text{at } 68\% \; CL
\end{aligned}
$$