Lecture 3
Hot Topics: Hints to new Physics"?

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Contents

Introduction

Flavour has attracted renewed attention:

- Various measurements showing “anomalies”
- ... unlike at the high energy frontier
- A large set of these anomalies allow for a consistent interpretation (Leptoquarks, Z')
- However, be cautious!!

Where do we stand?

Landscape of Anomalies

Seven "sets" of anomalies:

- Branching ratios of $b \to s\,\mu\mu$ processes
- Angular distributions in $b \to s\,\mu\mu$ processes
- Ratios of $b \to s\,ee$ versus $b \to s\,\mu\mu$ (LUV)
- Ratios of exclusive $b \to c\tau\bar{\nu}$ versus $b \to c\ell\bar{\nu}$ (LUV)

- CP Violation: Δa_{CP} in Charm and Kaon ϵ'/ϵ
- Exclusive versus inclusive V_{xb}
- Anomalous magnetic moment of the muon

Leptoquark Anomalies

Non-Leptoquark Anomalies

A closer look at $b \to s\ell\ell$

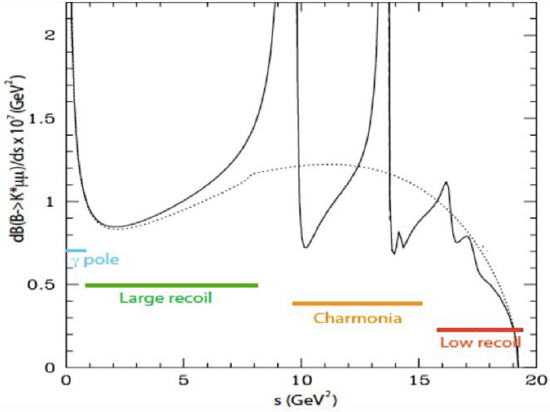
Compute the matrix element of H_{eff}

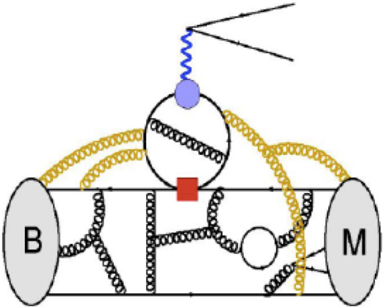
$$\langle B|H_{\text{eff}}|K^{(*)}\ell\ell\rangle = \frac{4G_F}{\sqrt{2}}\lambda_{\text{CKM}} \sum_k C_k(\Lambda/\mu)\ \langle B|\mathcal{O}_k(\mu)|K^{(*)}\ell\ell\rangle$$

Relevant matrix elements

- $\langle B|\mathcal{O}_{7,8}(\mu)|K^{(*)}\ell\ell\rangle$: Tensor Form Factor
- $\langle B|\mathcal{O}_{9,10}(\mu)|K^{(*)}\ell\ell\rangle$: Vector/Axial Vector Form Factor
- $\langle B|\mathcal{O}_{1,2}(\mu)|K^{(*)}\ell\ell\rangle$: Non-local matrix elements

$$T_\mu(q) = \int d^4x\, e^{iqx}\, T[J_\mu^{\rm em}(x)(C_1 O_1(0) + C_2 O_2(0))]$$





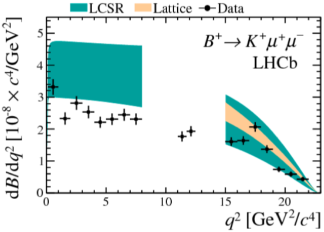
The hadronic Caveat:

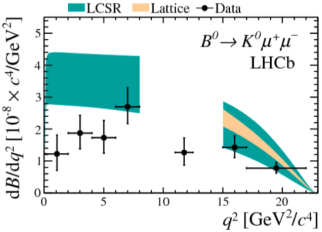
- Farm factor matrix elements: Lattice QCD
- Non-local matrix elements: QCD sum rule estimates hard to make a statement about the precision

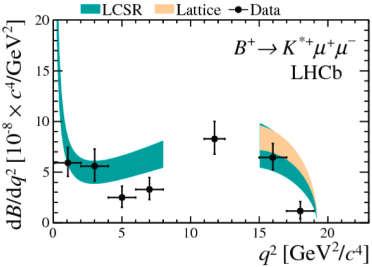
Remarks

- Cut out the resonance regions, remainig effects from the tails?
- Below charm threshold: Reliable QCD calculations based on OPE
- Above the J/ψ and below the $D\bar{D}$ threshold: QCD sum rules
- Above the $D\bar{D}$ threshold: very difficult

Branching ratios of $b \to s\mu\mu$ processes

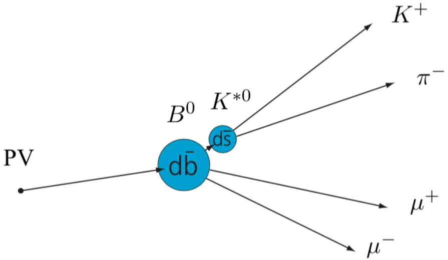




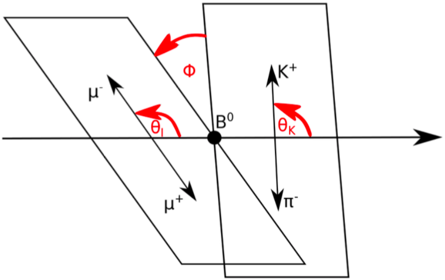


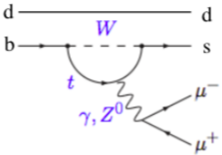
Angular Distributions in $b \to s\mu\mu$ processes

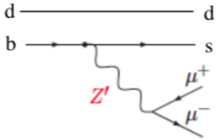
Decay Topology



Decay Angles







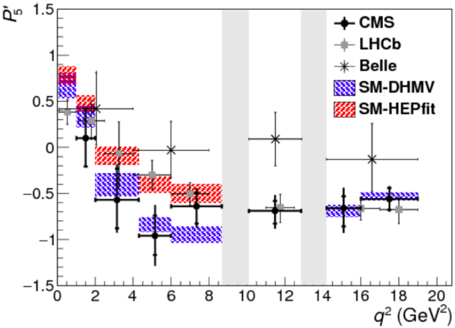
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Bigg|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K +$$
$$+\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l$$
$$-F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

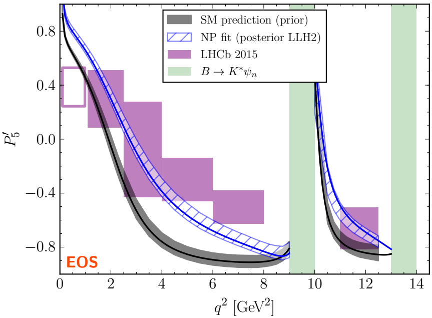
fraction of longitudinal polarisation of the K*

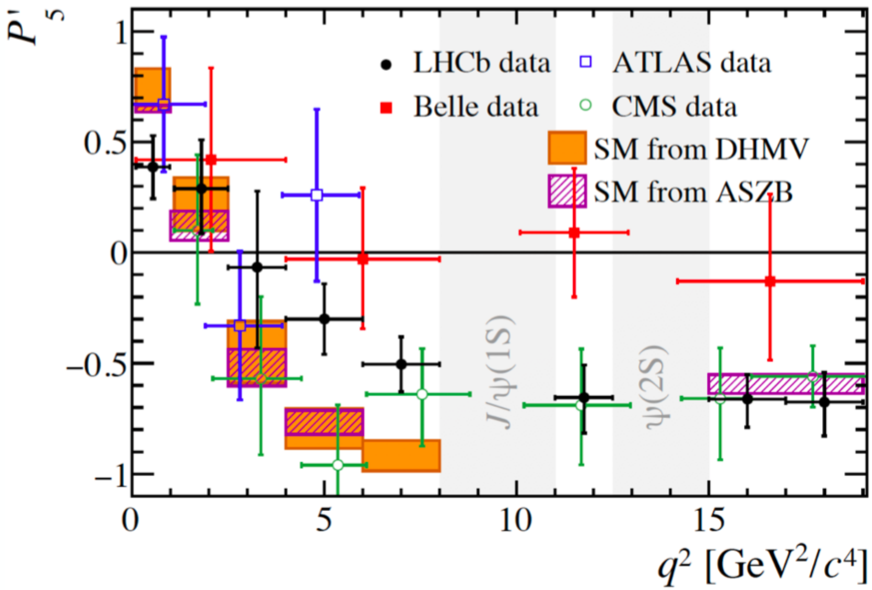
forward-backward asymmetry of the dilepton system

Angular Distributions in $b \to s\mu\mu$ processes

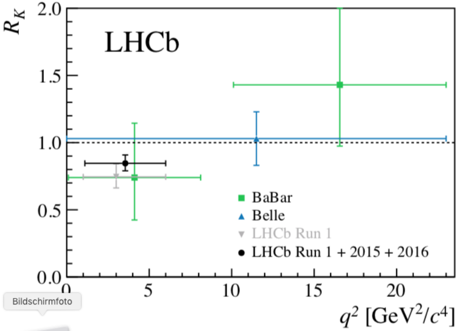
$$P_5' = S_5/\sqrt{F_L(1-F_L)}$$

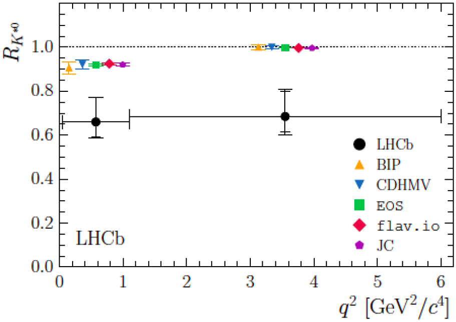





P'5
LHCb data
ATLAS data
Belle data
CMS data
SM from DHMV
SM from ASZB
J/ψ(1S)
ψ(2S)
1
0.5
0
−0.5
−1
0
5
10
15
q² [GeV²/c⁴]

Ratios of $b \to s\, e^+ e^-$ and $b \to s\, \mu^+ \mu^+$ rates





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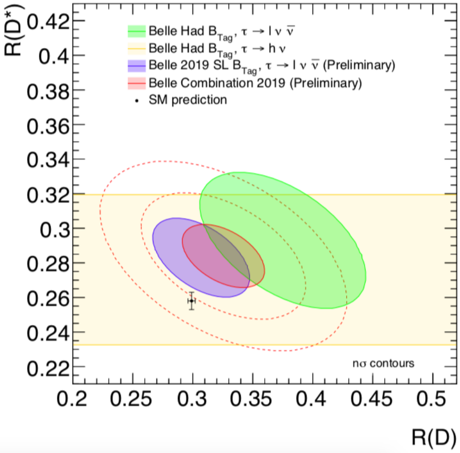
Anomalies in charged currents

- Precise prediction for exclusive decays
- Use the measurements for the light leptons
- Use HQE to predict the form factor f_0 which appears only in $B \to D^{(*)}\tau\bar{\nu}$
- Comparison to inclusive rates calculated in HQE

$$R(D) = \frac{\Gamma(B \to D\tau\bar{\nu})}{\Gamma(B \to D\ell\bar{\nu})} \qquad R(D^*) = \frac{\Gamma(B \to D^*\tau\bar{\nu})}{\Gamma(B \to D^*\ell\bar{\nu})}$$

Ratios of $b \to c\tau\bar{\nu}$ and $b \to c\ell\bar{\nu}$ rates



Effective Field Theory Analysis

Effective Hamiltonian at the bottom scale:

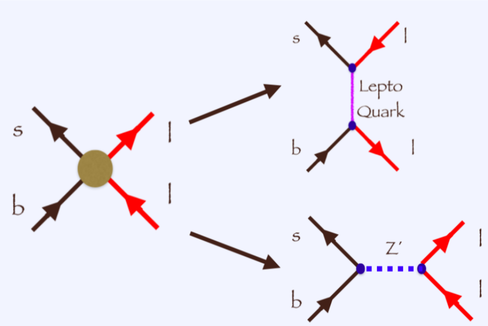
$$H_{\rm eff} = \frac{G_F}{\sqrt{2}} \lambda_{\rm CKM} \sum_i C_i O_i + \frac{1}{\Lambda_{\rm NP}^2} \sum_i C_i^{\rm NP} O_i^{\rm NP}$$

All the current anomalies can be incorporated by a shift in the coefficients $C_{9^{(\prime)}}$ and $C_{10^{(\prime)}}$ for the Muon channel

$$\mathcal{O}_{9\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10\ell} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_{9\ell'} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \quad \mathcal{O}_{10\ell'} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

Interpretation in simplified models



- Introduce a Z'
- Introduce a Leptoquark

$\rightarrow$ Leptoquark seems to be more promising!

Conclusions

- *Semi-leptonic B-decay data still displays a clear preference for new effects in 4-f semi-leptonic operators w/ LH quarks*
- *The solution with muonic $C_9 = -C_{10}$ now favoured over pure C_9*
  Welcome news from the standpoint of UV completions
- *Even better description of data obtained by allowing for additional $C_9^{univ.}$*
- *Interestingly, such effect is RG-generated from 4-f operators above the EW scale, in particular semi-tauonic ones, able to explain $b \to c$ discrepancies*
- *Also interestingly, this whole picture finds a natural realization in the U_1-LQ model*

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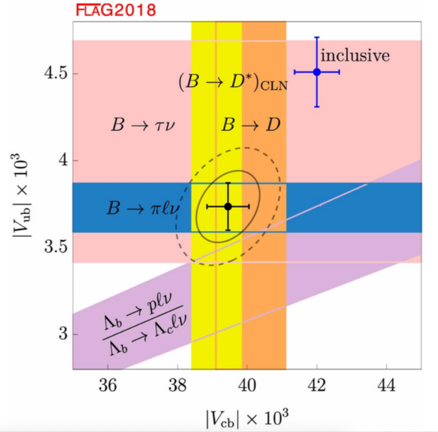
D. Guadagnoli, B discrepancies after Moriond 2019

Inclusive versus Exclusive V_{xb}

Charged Current Semileptonics are under scrutiny:

- Tensions between inclusive and exclusive determinations of V_{cb}
- Tensions between inclusive and exclusive determinations of V_{ub}



Exclusive V_{cb} has been discussed recently

- CLN form factor parametrization is too simple
- More sophisticated BGL parametriztion

$\lvert V_{cb}\rvert = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$	Exclusive $\lvert V_{cb}\rvert$ (BGL)
$\lvert V_{cb}\rvert = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$	Exclusive $\lvert V_{cb}\rvert$ (CLN)

(2018!!)

some people (including me) have already declared the V_{cb} problem to be solved, but ...

- There were problems with the above BELLE analysis
- Recent Babar paper based on BGL (arXiv:1903.10002 [hep-ex])

$$|V_{cb}| = (38.36 \pm 0.90) \times 10^{-3}$$

- New BELLE re-analysis, also based on BGL (arXiv: 1809.03290v3 [hep-ex])

$$|V_{cb}| = (38.3 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$$

- Uses $\mathcal{F}(1) = 0.906 \pm 0.013$

The V_{cb} problem still exists!

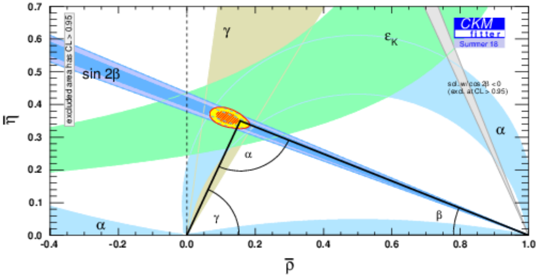
but it may be a problem in $\mathcal{F}(1)$.

A comment on V_{ub}

- Inclusive V_{ub} is more difficult that Inclusive V_{cb}
- Shape function-dependent methods GGOU and BLNP
- Update for BLNP urgently needed
- Most precise V_{ub} from $B \to \pi\ell\bar{\nu}$
- Method is Lattice QCD $\otimes$ Light Cone sum rules
- Need for V_{ub} extraction from other exclusive channels

CP Violation

- ... in Bottom decays



- ... in Charm decays: New $\Delta a_{\rm CP}$ from LHCb
- ... in Kaon Decays: ϵ'/ϵ

CP Violation in Charm Decays

- Experimental results
  - note that while the new result does constitute an observation of CP-violation in the difference...

$$\Delta a_{CP}^{dir} = a_{CP}(K^-K^+) - a_{CP}(\pi^-\pi^+) = (-0.156 \pm 0.029)\%$$ LHCb 2019

  - ... it is not yet so for the individual decay asymmetries

$$a_{CP}(K^-K^+) = (0.04 \pm 0.12\ (\text{stat}) \pm 0.10\ (\text{syst}))\%\,,$$
$$a_{CP}(\pi^-\pi^+) = (0.07 \pm 0.14\ (\text{stat}) \pm 0.11\ (\text{syst}))\%\,.$$

LHCb 2017

- Need confirmation from other experiments (Belle II)
- What does this result mean? New Physics? Standard Model?

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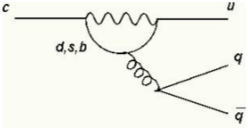
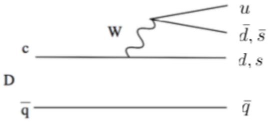
Generic Expectation

★ Generic expectation is that CP-violating observables in the SM are small

$\Delta c = 1$ amplitudes allow to reach third -generation quarks!



"Penguin" amplitude



"Tree" amplitude

★ The Unitarity Triangle relation for charm:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

With b-quark contribution neglected: only 2 generations contribute
⇒ **real 2x2 Cabibbo matrix**

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$

Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

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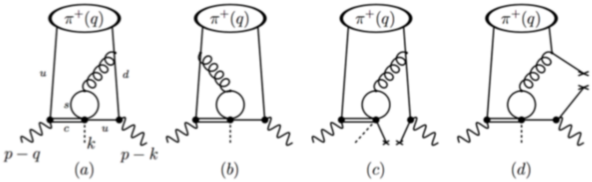
QCD Sum Rule Calculation Khodjamirian, Petrov (2017)

- Evaluate (leading) diagrams contributing to the correlation function
  - calculate OPE in terms of known LC DAs Khodjamirian, AAP: PLB774 (2017) 235



  - analytically continue from the space-like region of $P^2=(p-k-q)^2$ (with auxiliary 4-momentum $k\neq0$) to $P^2 = m_D^2$, relying on the local quark-hadron duality
  - extract absolute value and the phase of matrix element $\mathcal{P}^s_{\pi\pi}$
  - vary parameters of the calculation to estimate uncertainties

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To take home ...

- The magnitude of hadronic MEs defining CPV are computed

$$r_\pi = \frac{|\mathcal{P}^s_{\pi\pi}|}{|\mathcal{A}_{\pi\pi}|} = 0.093 \pm 0.011\,, \qquad r_K = \frac{|\mathcal{P}^d_{KK}|}{|\mathcal{A}_{KK}|} = 0.075 \pm 0.015$$

- The magnitude of direct CPV asymmetry in $D \to \pi^+\pi^-$ and $D \to K^+K^-$ can be predicted from the calculation of the relevant hadronic matrix elements from LCSRs

$$\Delta a^{dir}_{CP} = 0.020 \pm 0.003\%$$

- No topological amplitude decomposition was used (note that OPE hierarchy sorts out the leading penguin-type diagrams)
- The strong phase difference is not yet reliably accessible: duality violations are not easily identifiable (e.g. broad scalar resonances influencing hadronic matrix elements)

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ϵ' / ϵ

(NLO) **Present Status of ε′/ε in the SM** April 2019

RBC-UKQCD (1505.07863)	$(\varepsilon'/\varepsilon)_{SM} = (1.4 \pm 6.9) \cdot 10^{-4}$	No isospin breaking correction (IB)
AJB, Gorbahn, Jäger Jamin (1507.06345)	$(\varepsilon'/\varepsilon)_{SM} = (1.9 \pm 4.5) \cdot 10^{-4}$	Lattice results + IB
AJB + Gérard (1507.06326)	$(\varepsilon'/\varepsilon)_{SM} < (6.0 \pm 2.4) \cdot 10^{-4}$	Dual QCD bound
Kitahara, Nierste, Tremper (1607.06727)	$(\varepsilon'/\varepsilon)_{SM} = (1.1 \pm 5.1) \cdot 10^{-4}$	Lattice results + IB
Gisbert, Pich (1712.06147)	$(\varepsilon'/\varepsilon)_{SM} = (15 \pm 7) \cdot 10^{-4}$	Chiral Pert. Th. (No meson evolution!!) but FSI
Experiment (NA48, KTeV)	$(\varepsilon'/\varepsilon)^{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$	

(borrowed from A. Buras)

Summary on ε'/ε in the SM (DQCD)

ε'/ε anomaly could turn out to be the largest anomaly in flavour physics !

$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$ ★

$(\varepsilon'/\varepsilon)_{SM} < (6.0 \pm 2.4) \cdot 10^{-4}$ Dual QCD

$(\varepsilon'/\varepsilon)_{SM} < 11 \cdot 10^{-4}$ (DQCD + GP pion loops) (supported by Bijnens + Ecker

AJB Expectation (May 2018) 1805.11096 $(\varepsilon'/\varepsilon)_{SM} = (5 \pm 2) \cdot 10^{-4}$

Possible NP has to enhance ε'/ε (important message for model builders)

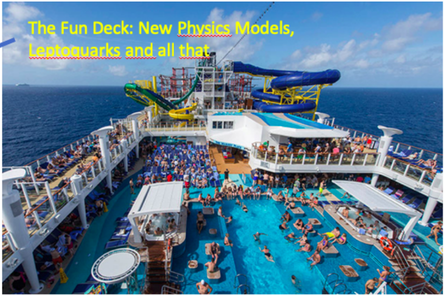
Will new RBC-UKQCD results support this claim?

(borrowed from A. Buras)

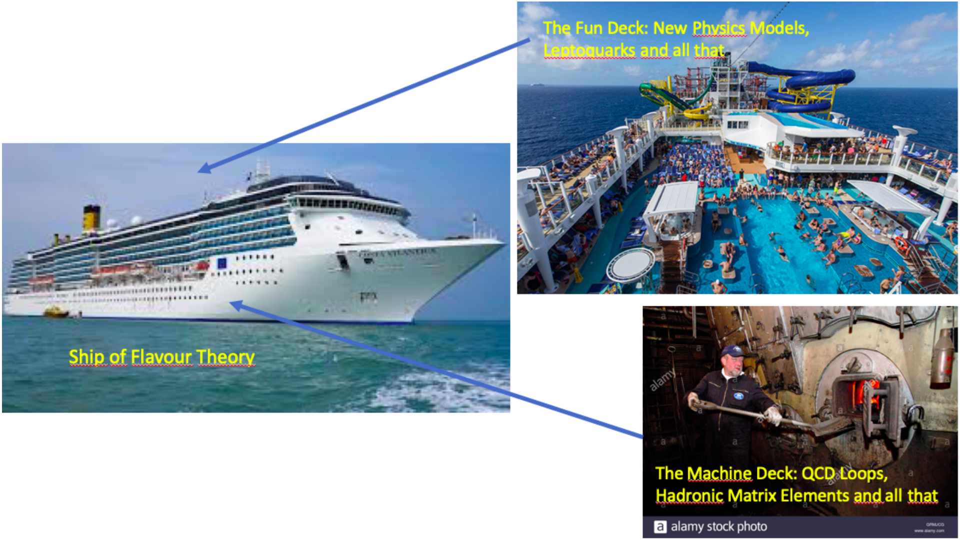
Conclusions / Questions

- What is the impact of the recent data on the “leptoquark-like anomalies?
- What is the status of exclusive V_{cb}?
- Scrutinize the methods for inclusive V_{ub}
- Is there “new physics” in CP violating observables?
  - Δa_{CP} in Charm
  - ϵ' / ϵ
- Do we understand the hadronic matrix elements well enough?


Ship of Flavour Theory


The Fun Deck: New Physics Models,
Leptoquarks and all that


Ship of Flavour Theory


The Fun Deck: New Physics Models,
Leptoquarks and all that
Ship of Flavour Theory
The Machine Deck: QCD Loops,
Hadronic Matrix Elements and all that
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