Recent Topics in Flavour Phenomenology

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Outline

- Inclusive and Exclusive measurements of $|V_{cb}|$, $|V_{ub}|$
- Review of SM predictions of $R(D^{(*)})$!
- Few anomalous results :
  - ✓ **NP effects in b->s decays ?**
  - ✓ **NP effects in b->c decays ?**
- Summary and outlook !

B-Physics: Goal

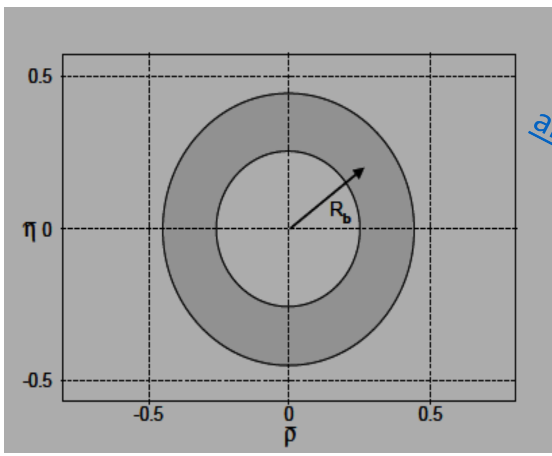
Quark Mixing matrix

Wolfenstein Parametrization

Unitarity Triangle

$$V \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix},$$

$$R_b^2 = \bar{\rho}^2 + \bar{\eta}^2 \propto \left|\frac{V_{ub}}{V_{cb}}\right|^2$$



arXiv:hep-ph/0304132v2

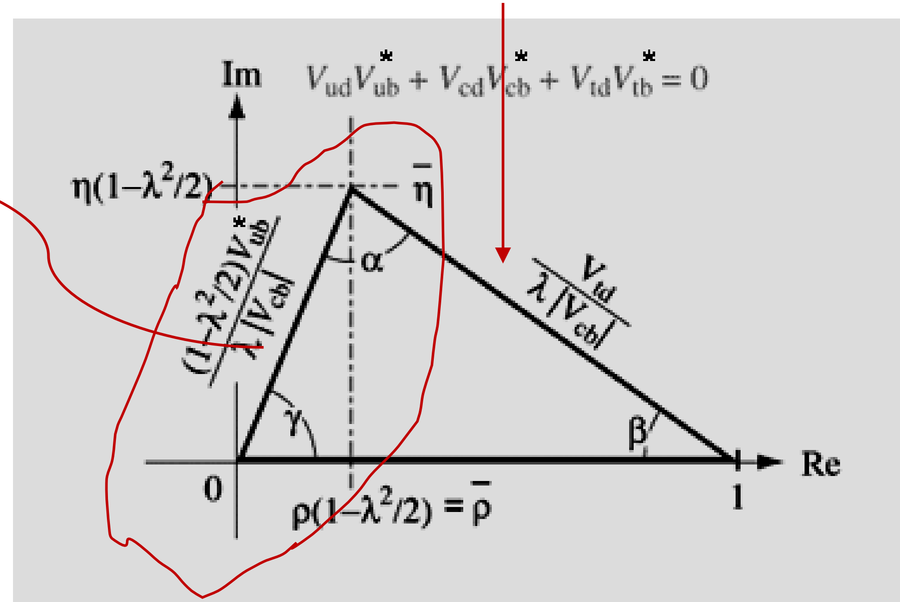


Figure 1. The unitarity relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ drawn in the complex $[\bar{\rho}, \bar{\eta}]$ plane.

- Consistency check in the SM !!
- Searches for NP evidences !!

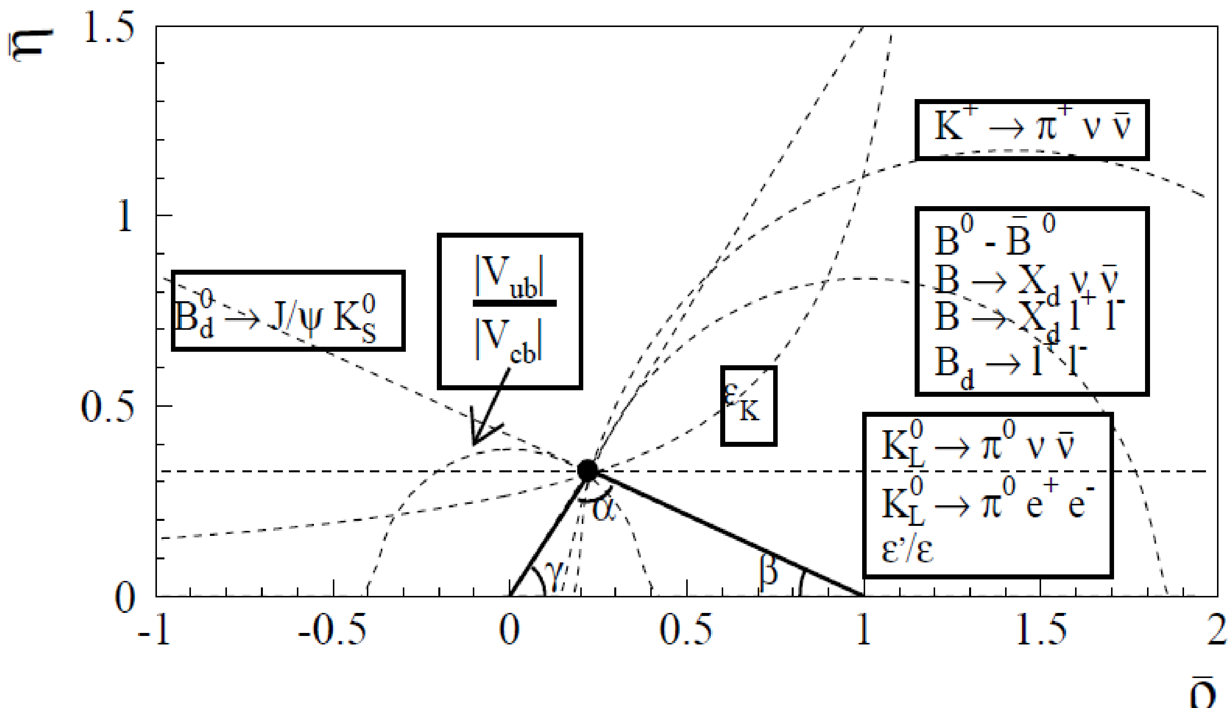
To find where the apex lies on the UT we have to look at other decays !!

- Loop induced decays and CP violating B-decays are useful !!

✓**Precise determination of $|V_{ub}|$, $|V_{cb}|$ is of utmost importance !**

Ideal UT

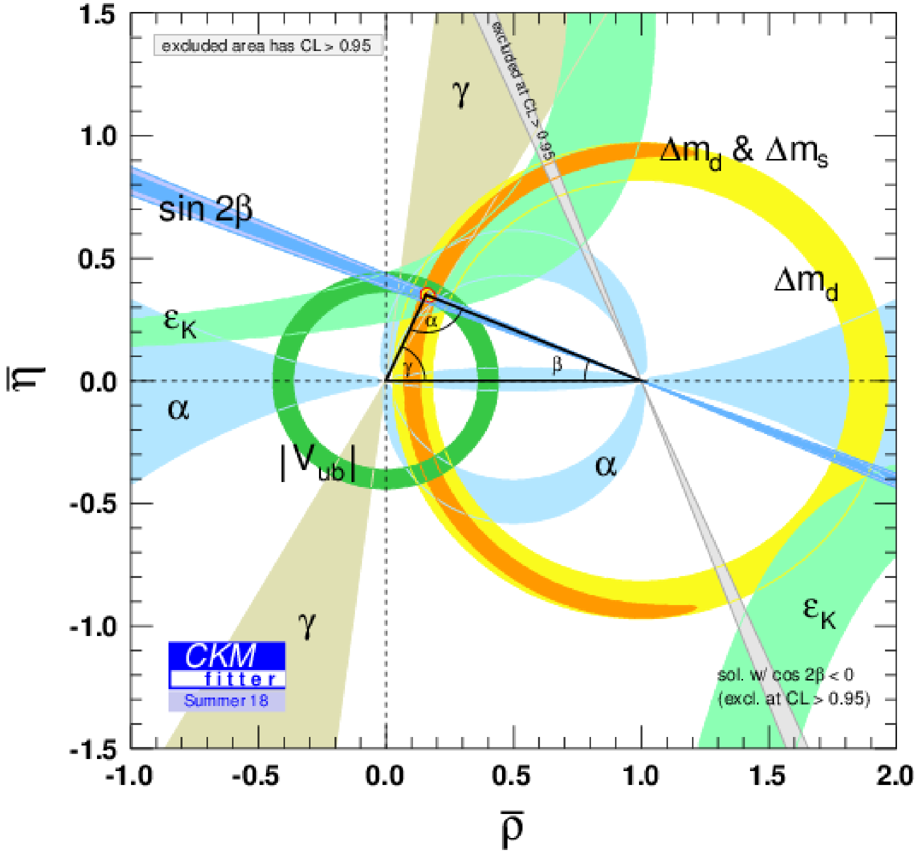
✓Various curves in the (ρ,η) plane extracted from different decays and transitions using the SM formulae cross each other at a single point



M. Battaglia et al.
arXiv:hep-ph/0304132v2

✓Any inconsistencies in the (ρ, η) plane will then give us some hints about the physics beyond the SM !!

UT Fit Results



Exist a unique preferred region defined by the entire set of obsevables under consideration.

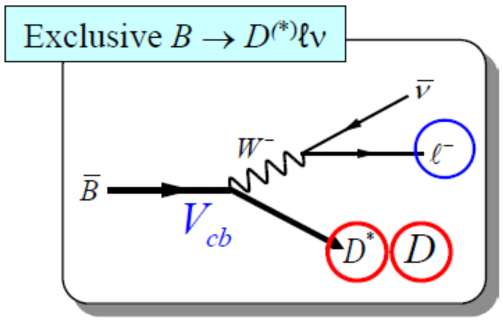
CKM elements: Semileptonic decays

Measurement of $|V_{ub}|$ and $|V_{cb}|$

Semileptonic B-decays provide a clean environment !!

Exclusive Measurement

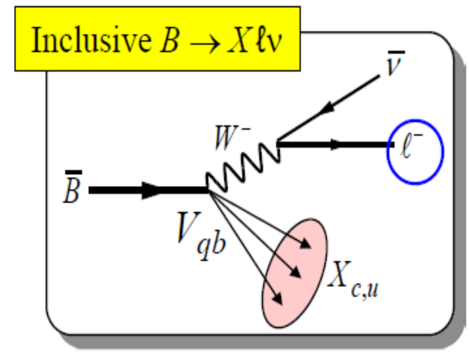
- B-> D ℓ ν and B-> D^* ℓ ν
- B-> π ℓ ν



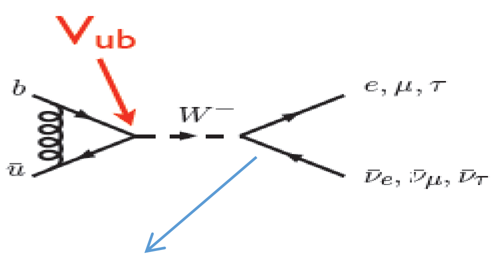
Inclusive Measurement

B-> X_c ℓ ν

B-> X_u ℓ ν

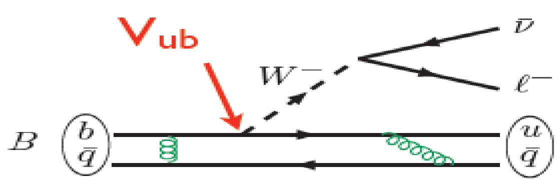


Leptonic



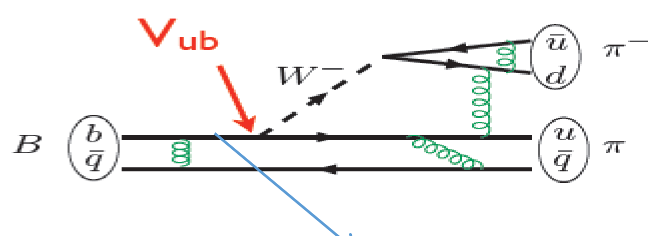
Helicity suppressed

Semileptonic



Leptonic and hadronic currents factorize

Hadronic



Complex QCD interactions

Inclusive vs Exclusive

- Inclusive $b \to c(u) l\nu$ decay rates have a solid description via OPE/HQE
- Exclusive s.l. decays (b->c) have a similarly solid description in terms of heavy-quark effective theory (HQET), B-> π formfactors are calculated using LCSR and lattice !

- Inclusive decays: Non perturbative unknowns can be extracted experimentally!
  ⇨ Experimentally Challenging !!
- Exclusive decays: Non perturbative unknowns have to be calculated !
  ⇨ Major theoretical challenges !!

❖ A more precise evaluation of the $b \to s\gamma$ photon spectrum will lead to a more precise effective shape function ⇨ Useful for $|V_{ub}|$ measurement !!

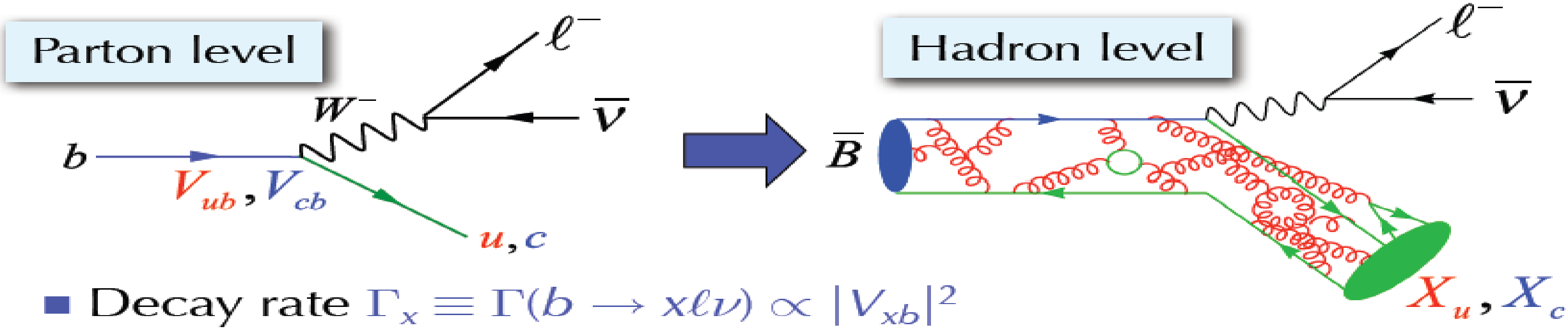
Inclusive Semileptonic

- **Theoretical framework is OPE/HQE !**
- **Analysis of the final state lepton and hadron energy distribution yields:**
  - ✓ **b-quark mass !**
  - ✓ **Non-perturbative QCD parameters !**
  - ✓ **Consistency check of the OPE/HQE and other effective theory approaches !**
- **As per the measurement is concern : small statistical and systematic errors !**
  - ✓ **High sensitivity to the theoretical uncertainties !**

Precise predictions in the SM including reliable uncertainties is possible !!

Decay Width

OPE relates parton to meson decay rate: $1/m_b$ and $\alpha_s(m_b)$



$$\Gamma_{SL} = |V_{cb}|^2 \frac{G_F^2 m_b^5}{192\pi^3}(1 + A_{EW})A_{pert} \times [c_0(r) + \frac{0}{m_b} + c_2(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}) + c_3(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}) + \ldots]$$

free quark decay — perturbative corrections — Non-perturbative power corrections — $r = m_c/m_b$

Main sources of uncertainties : (1) Mass of the b-quark and the mass ratio ‘r’
(3) Higher order QED and QCD radiative corr.
(4) Higher order of the $1/m_b$ corrections !
(5) Extractions of OPE parameters !
(6) Parton Hadron Duality !!

- ✓ OPE parameters can be extracted from the moments of the differential distributions
- ✓ Global fit to decay rate and moments extracts: μ_π^2, μ_G^2, ρ_D^3, ρ_{LS}^3, $|V_{cb}|$, m_b, m_c

V_{cb} : Inclusive decays

Alberti, Gambino , Healy and Nandi, PRL 2015; Gambino, Healy , Turczyk, PLB 2016

$$\Gamma_{sl} = \Gamma_0 \left[1 + a^{(1)} \frac{\alpha_s(m_b)}{\pi} + a^{(2,\beta_0)} \beta_0 \left(\frac{\alpha_s}{\pi}\right)^2 + a^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \left(-\frac{1}{2} + p^{(1)} \frac{\alpha_s}{\pi}\right) \frac{\mu_\pi^2}{m_b^2} + \left(g^{(0)} + g^{(1)} \frac{\alpha_s}{\pi}\right) \frac{\mu_G^2(m_b)}{m_b^2} + d^{(0)} \frac{\rho_D^3}{m_b^3} - g^{(0)} \frac{\rho_{LS}^3}{m_b^3} + \text{higher orders} \right]$$

$\overline{m}_c(3\text{ GeV}) = 0.986(13)\text{ GeV}$

After fitting the parameters with the available data on width and moments :

$$\frac{\Gamma}{z(r)\Gamma_0} = 1 - 0.116_{\alpha_s} - 0.030_{\alpha_s^2} - 0.042_{1/m^2} - 0.002_{\alpha_s/m^2} - 0.030_{1/m^3} + 0.005_{1/m^4} + 0.005_{1/m^5}$$

$1 - 8r + 8r^3 - r^4 - 12r^2 \ln r$

$A_{ew}|V_{cb}^2|G_F^2 m_b^5/192\pi^3$

1.014

$|V_{cb}| = (42.42 \pm 0.86) \times 10^{-3}$ ⇨ Fit without (α_s/m_b^2) and ($1/m_b^{4,5}$) and h.o. contributions ,
Gambino and Schwanda, PRD 2014

$|V_{cb}| = (42.21 \pm 0.78) \times 10^{-3}$ ⇨ Fit without ($1/m_b^{4,5}$) and h.o. contributions ,
Alberti, Gambino , Healy and Nandi, PRL 2015

$|V_{cb}| = (42.11 \pm 0.74) \times 10^{-3}$ ⇨ Fit includes all the known h.o. corrections,
Gambino, Healy , Turczyk, PLB 2016

V_{cb} :Exclusive decays

$$\frac{d\Gamma(\bar{B} \to D\,\ell\,\bar{\nu})}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} (m_B + m_D)^2\, m_D^3 (w^2 - 1)^{3/2} |V_1(w)|^2\, \eta_{EW}{}^2$$

$w \to v_B \cdot v_D$

$\eta_{EW}{}^2 \to 1.0066 \pm 0.0016$

Zero recoil expansion, HQET

$$\frac{V_1(w)}{V_1(1)} \approx 1 - 8\rho_1^2 z + (51.\rho_1^2 - 10.)z^2 - (252.\rho_1^2 - 84.)z^3$$

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

Fermilab Lattice and MILC , 2015: 1.0541 ± 0.0083

$\eta_{EW}\, V(1)\, |V_{cb}| = 41.57 \pm 0.45 \pm 0.89$, HFAG 16

$$|V_{cb}| = (39.18 \pm 0.94_{\text{exp}} \pm 0.31_{\text{th}}) \times 10^{-3}$$

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* \ell \bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3} |V_{cb}|^2 (w^2 - 1)^{1/2} P(w) (\eta_{ew} \mathcal{F}(w))^2$$

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

Fermilab Lattice and MILC , 2014

$$|V_{cb}| = (38.71 \pm 0.47_{\text{exp}} \pm 0.59_{\text{th}}) \times 10^{-3}$$

$$\mathcal{F}^2(w) = h_{A_1}^2(w) \left(1 + 4\frac{w}{w+1}\frac{1 - 2wr + r^2}{(1-r)^2}\right)^{-1} \times \left[2\frac{1 - 2wr + r^2}{(1-r)^2}\left(1 + R_1^2(w)\frac{w-1}{w+1}\right) + \left(1 + (1 - R_2(w))\frac{w-1}{1-r}\right)^2\right].$$

Recent updates

Bigi, Gambino and Schacht, Grinstein, Kobach , Jaiswal, SN, Patra

- The CLN parameterization, which has played a useful role in the past, may no longer be adequate to cope with the present accuracy of lattice calculations.

Known functions of z

✓ BGL/BCL are valid alternatives

$$F_i = \tilde{f}_i \sum_n b_{in} z^n$$

$$z(w,\mathcal{N}) = \frac{\sqrt{1+w}-\sqrt{2\mathcal{N}}}{\sqrt{1+w}+\sqrt{2\mathcal{N}}},$$

Weak Unitarity constraints

$0 \leq z \leq 0.0646$

$$\mathcal{N} = \frac{t_+ - t_0}{t_+ - t_-}.$$

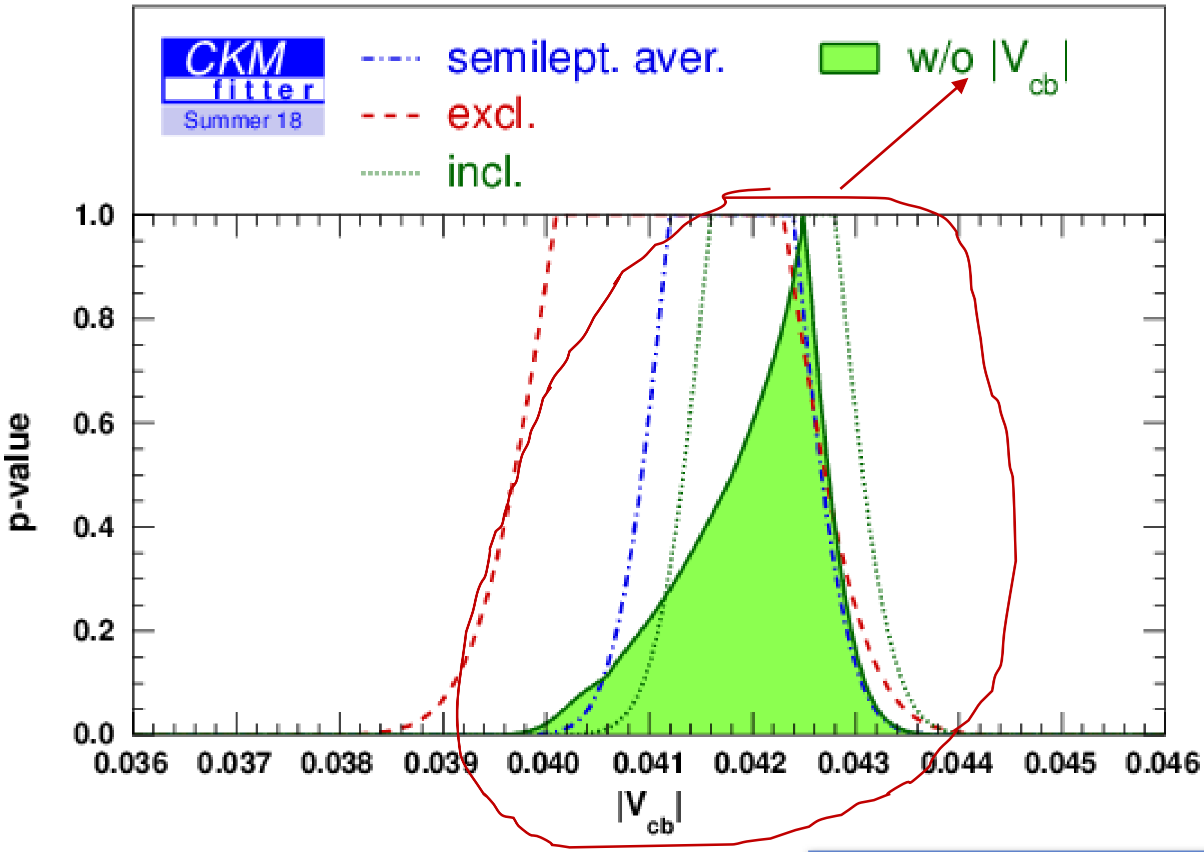
$$\sum_{i=1}^{H} \sum_{n=0}^{\infty} b_{in}^2 \leq 1.$$

$$t = q^2 = (p-p')^2, \quad t_+ = (m_B + m_D)^2, \quad t_- = (m_B - m_D)^2$$

Here all helicity amplitudes $i = 1 \ldots H$ for processes involving $\bar{B}^{(*)}\bar{D}^{(*)}$ with the right quantum numbers must be included.

Strong Unitarity condition

$|V_{cb}|$: Summary



Indirect extraction prefers the **inclusive** determination of $|V_{cb}|$

Recent Updates

$|V_{cb}| = (40.49 \pm 0.97) \times 10^{-3}$

From a fit to rates of B-> D $\ell \nu_\ell$, BGL+ LQCD
Bigi and Gambino PRD 2016

$|V_{cb}| = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$

$|V_{cb}| = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$

From a fit to rates of B-> D* $\ell \nu_\ell$, BGL+ LQCD !
Grinstein and Kobach , PLB 2017 ,
Bigi, Gambino and Schacht PLB 2017

Parameters	Data+Lattice Best Fit Values	Data+Lattice Err. from $\Delta\chi^2 = 1$
$\lvert V_{cb}\rvert \times 10^3$	41.7	$\left(^{+2.0}_{-2.1}\right)$
$\lvert V_{cb}\rvert \times 10^3$	41.2	(1.0)

B-> D* $\ell \nu_\ell$

$|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$ CLN + LQCD
$|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$ BGL + LQCD

From B-> D* $\ell \nu_\ell$ Belle 2018

Jaiswal, SN, Patra JHEP 2017

Combined analysis of B-> D $\ell \nu_\ell$ and B-> D* $\ell \nu_\ell$

V_{ub} :Exclusive decays

The decay rate for B->$\pi\ell\nu$ (ℓ = e, μ):

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3} \mathbf{p}_\pi^3 |f_+^{B\pi}(q^2)|^2$$

Precision limited by the uncertainties in the form factor !

Complementary approaches: lattice QCD and light-cone sum rule (LCSR)

Best at high q^2 (> 14 GeV^2)

Applicable at low q^2 (< 12 GeV^2)

Fermilab/MILC, HPQCD, RBC/UKQCD

$|V_{ub}| = (3.72 \pm 0.16) \times 10^{-3}$ PRD, 2015

$|V_{ub}| = 3.61(32) \times 10^{-3}$ PRD, 2015

Non perturbative function: pion distribution amplitudes !

A significant progress has been made !

At large recoil, direct LCSR calculations for the form factors are available !

Extracted values

FLAG 2016 => 3.73 ± 0.14 ,
HFLAG (FLAG + LCSR, BCL) 2016 => 3.67 $\pm 0.09 \pm 0.12$

Comments on inclusive determinations of $|V_{ub}|$

- The charmless s.l. decay channel $b \to u\ell^{-}\bar{\nu}$ can in principle provide a clean determination of $|V_{ub}|$ along the lines of that of $|V_{cb}|$!!
- The main problem is the large background from $b \to c\ell^{-}\bar{\nu}$ decay !!
- Experimental cuts necessary to distinguish the $b \to u$ from the $b \to c$ transitions

  ⇒ Enhance the sensitivity to the non-perturbative aspects of the decay!

  ⇓

  Complicate the theoretical interpretation of the measurement !!

- The inclusive decay rate $B \to X_u l \nu$ is calculated using the OPE !!
- There are several methods to suppress this background

  ⇒ Restrict the phase space region where the decay rate is measured!

  ⇒ Great care must be taken to ensure that the OPE is valid in the relevant phase space region.

V_{ub} : inclusive measurements

- ✓ Several theoretical schemes are available to analyze the data in the threshold region !
  - ➢ All of them differ in their treatment of perturbative corrections and the parametrization of non-perturbative effects.

Framework	$\|V_{ub}\|[10^{-3}]$
BLNP	$4.44 \pm 0.15^{+0.21}_{-0.22}$
DGE	$4.52 \pm 0.16^{+0.15}_{-0.16}$
GGOU	$4.52 \pm 0.15^{+0.11}_{-0.14}$
ADFR	$4.08 \pm 0.13^{+0.18}_{-0.12}$
BLL (m_X/q^2 only)	$4.62 \pm 0.20 \pm 0.29$

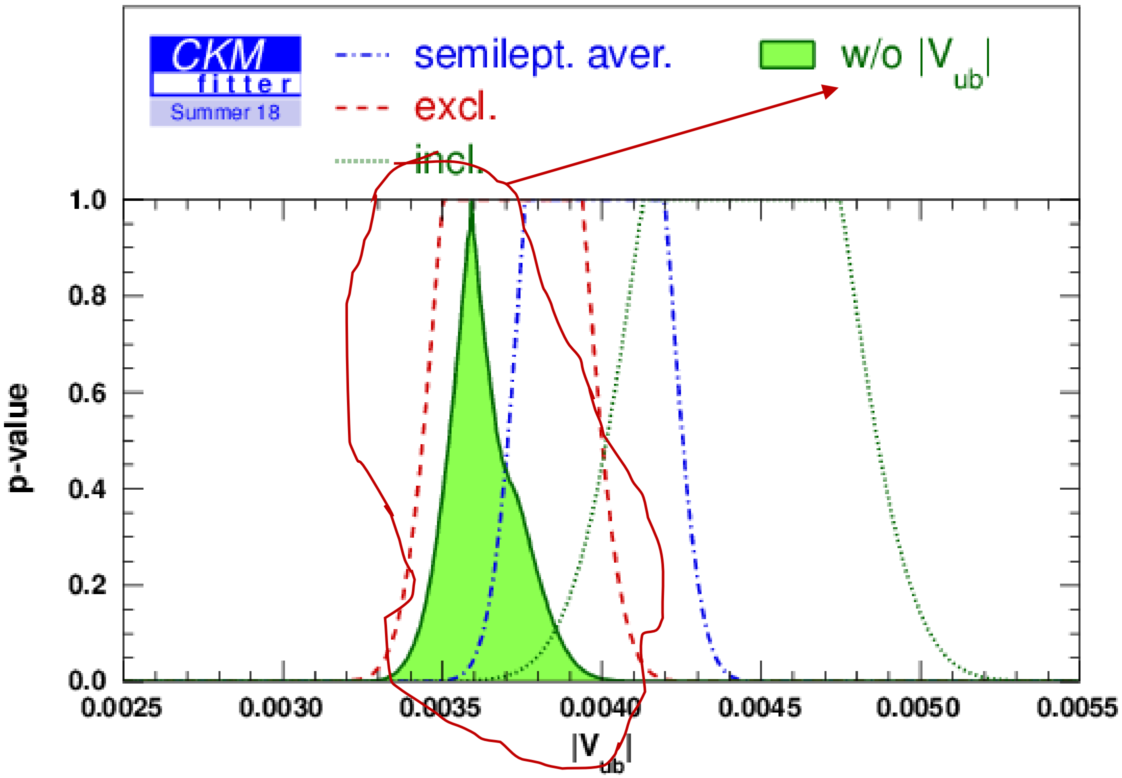
From HFLAV 2016, arxiv: 1612.07233

Inclusive and exclusive measurements do not agree with each others -> 2-3 σ discrepancy !

Could it be due NP effects in b-> u ?

Sources of errors: Statistical , experimental, B-> $X_c \ell \nu_\ell$ and B-> $X_u \ell \nu_\ell$ modelling, HQE parameters, missing higher order corrections, q^2 modelling , weak annihilation, SF parameterization

$|V_{ub}|$: Summary !



Indirect extraction prefers the **exclusive** determination of $|V_{ub}|$

$B \to D^{(*)} \tau \nu_\tau$ ($b \to c\, \tau \nu_\tau$)

Observables : $R(D^{(*)})$

$$\mathcal{R}(D) = \frac{\mathcal{B}\left(\overline{B} \to D\tau^-\overline{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B} \to Dl^-\overline{\nu}_l\right)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}\left(\overline{B} \to D^*\tau^-\overline{\nu}_\tau\right)}{\mathcal{B}\left(\overline{B} \to D^*l^-\overline{\nu}_l\right)}.$$

- ✓ Form factors, fitted from the decays **$B \to D^{(*)} \ell \nu_\ell$**, play a crucial role in the Standard Model (SM) predictions of **$R(D^{(*)})$**

- ✓ In the decays **$B \to D^{(*)} \tau\nu_\tau$**, there are additional form factors that can not be extracted directly from the fit !

Predictions rely on various theory inputs such as lattice and the HQET relations between the form factors.

$R(D) = 0.300(8)$, $R(D^*) = 0.252(3)$ → Old predictions => heavily relied on HQET relations !

Precise lattice calculations of the zero recoil form factors shows discrepancies with the respective HQET predictions (higher order corrections are missing) !

✓ **Revisit the predictions of R(D) and R(D*) using the lattice inputs !**

R(D) and R(D*) : SM

- Prediction of R(D) without any inputs from HQET is possible !
  - Lattice results for the relevant form factors are available at zero and non-zero recoil (HPQCD and MILC)
- For R(D*): At the moment, HQET relations between the form factors need to be used => The known corrections are represented in terms of the sub-leading Isgur-Wise functions !

✓ Can be extracted from the lattice inputs and the fit results of **B-> D$^{(*)}$** $\ell \nu_\ell$

The unknown corrections in the ratios of the HQET form factor are parametrized by additional parameters $(\Delta \leq 20\%)$ which are then constrained along with the other HQET parameters !

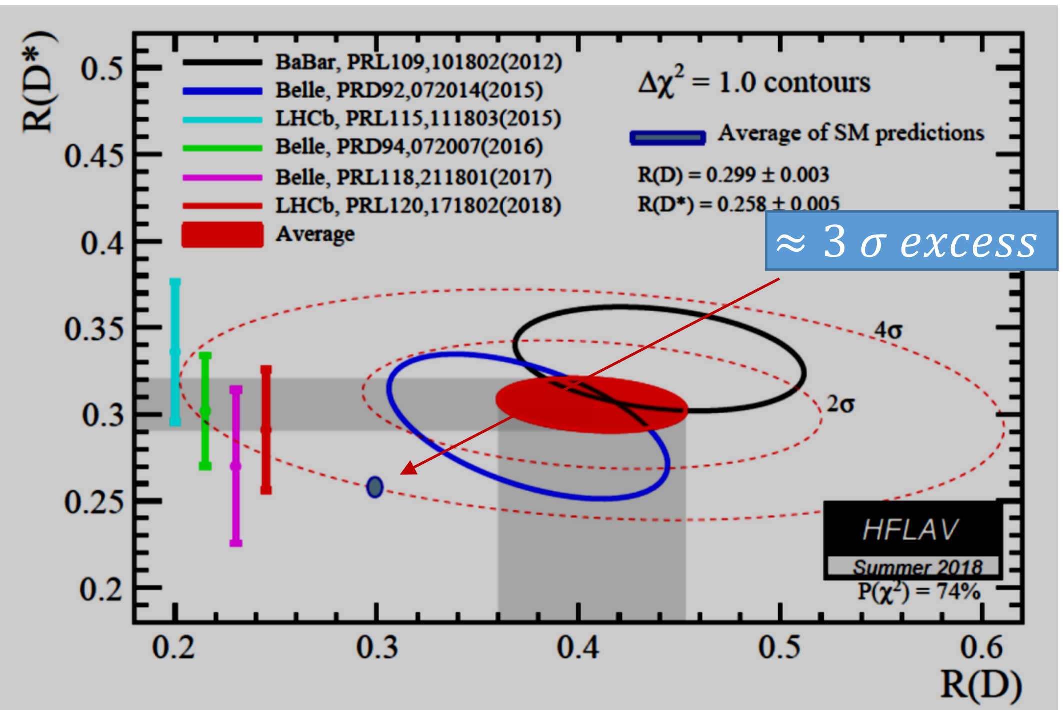
✓ With the Δs fit improves considerably !

✓ **Including all these inputs the additional form factor and hence R(D*) are predicted !**

Present status

	R(D)	R(D*)
D.Bigi, P.Gambino, Phys.Rev. D94 (2016) no.9, 094008 [arXiv:1606.08030 [hep-ph]]	0.299 +- 0.003	
F.Bernlochner, Z.Ligeti, M.Papucci, D.Robinson, Phys.Rev. D95 (2017) no.11, 115008 [arXiv:1703.05330 [hep-ph]]	0.299 +- 0.003	0.257 +- 0.003
D.Bigi, P.Gambino, S.Schacht, JHEP 1711 (2017) 061 [arXiv:1707.09509 [hep-ph]]		0.260 +- 0.008
S.Jaiswal, S.Nandi, S.K.Patra, JHEP 1712 (2017) 060 [arXiv:1707.09977 [hep-ph]]	0.299 +- 0.004	0.257 +- 0.005
Arithmetic average	**0.299 +- 0.003**	**0.258 +- 0.005**

The arithmetic average is used only for illustration and doesn't imply consent from the authors of the calculations. The SM uncertainty is currently subject to debate that HFLAV is following without taking a stance in this.



HFLAV 2018

Other Measurements:

$P_\tau(D^*) = -0.38 \pm 51^{+0.21}_{-0.16}$

$F_L(D^*) = 0.60 \pm 0.08 \pm 0.035$

SM predictions of other related Obs:

Bhattacharya, SN, Patra, arxiv:1805.08222

Jaiswal, SN, Patra, work in progress….

Observables	SM prediction with	
	CLN parameterization	BGL parameterization
$R(D^*)$	$0.260(6)$	$0.257(5)$
$R(D)$	$0.305(3)$	$0.302(3)$
$P_\tau^{(D^*)}$	$-0.491(25)$	$-0.492(17)$
$P_\tau^{(D)}$	$0.3355(4)$	$0.324(3)$
$F_L^{D^*}$	$0.457(10)$	$0.454(15)$
$A_{FB}^{(D^*)}$	$-0.058(14)$	$-0.058(30)$
$A_{FB}^{(D)}$	$0.3586(3)$	$0.3598(3)$

Large off-shell effects in the $\bar{D}^*$ contribution to $B \to \bar{D}\pi\pi$ and $B \to \bar{D}\pi\bar{\ell}\nu_\ell$ decays.

Alain Le Yaouanc[a], Jean-Pierre Leroy[a] and Patrick Roudeau[b]

June 27, 2018

Abstract

We stress that, although the D^* is very narrow (one hundred of keV), the difference between the full D^* contribution to $B \to D\pi\pi$ and its zero width limit, which stems from the resonance tail, is surprisingly large : several percents. This phenomenon is a general effect which appears when considering the production of particles that are coupled to an intermediate virtual state, stable or not, and it persists whether the width is large or not. The effects of various cuts and of the inclusion of damping factors at the strong and weak vertices are discussed. It is shown how the zero width limit, needed to compare with theoretical expectations, can be extracted. One also evaluates the virtual D_V^* contribution, which comes out roughly as expected from theory, but which is however much more dependent on cuts and uncontrollable "off-shell" effects. We suggest a way to estimate the impact of the damping factors.

Closing the Gap on R_{D^*} by including longitudinal effects

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(Dated: June 20, 2018)

Measurements of the $R_{D^*} \equiv \text{Br}(B \to \tau\nu D^*)/\text{Br}(B \to e\nu D^*)$ parameter remain in tension with the standard model prediction, despite recent results helping to close the gap. The standard model prediction it is compared with considers the D^* as an external particle, even though what is detected in experiments is a $D\pi$ pair it decays into, from which it is reconstructed. We argue that the experimental result must be compared with the theoretical prediction considering the full 4-body decay ($B \to l\nu D^* \to l\nu D\pi$). We show that the longitudinal degree of freedom of the off-shell D^* helps to further close the disagreement gap with experimental data. We find values for the ratio $R^l_{D\pi} \equiv \text{Br}(B \to \tau\nu_\tau D\pi)/\text{Br}(B \to l\nu_l D\pi)$ of $R^e_{D\pi} = 0.271 \pm 0.003$ and $R^\mu_{D\pi} = 0.273 \pm 0.003$, where the uncertainty comes from the uncertainty of the form factors parameters. Comparing against $R_{D\pi}$ reduces the gap with the latest LHCb result from 0.94σ to 0.37σ, while the gap with the latest Belle result is reduced from 0.40σ to just 0.04σ and with the world average results from 3.4σ to 2.2σ.

NP sensitivities in B->D$^{(*)}\tau\nu_\tau$

✓Many NP model can explain the excess !!

Model independent approach

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[(1 + C_{V_1}) \mathcal{O}_{V_1} + C_{V_2} \mathcal{O}_{V_2} + C_{S_1} \mathcal{O}_{S_1} + C_{S_2} \mathcal{O}_{S_2} + C_T \mathcal{O}_T \Big],$$

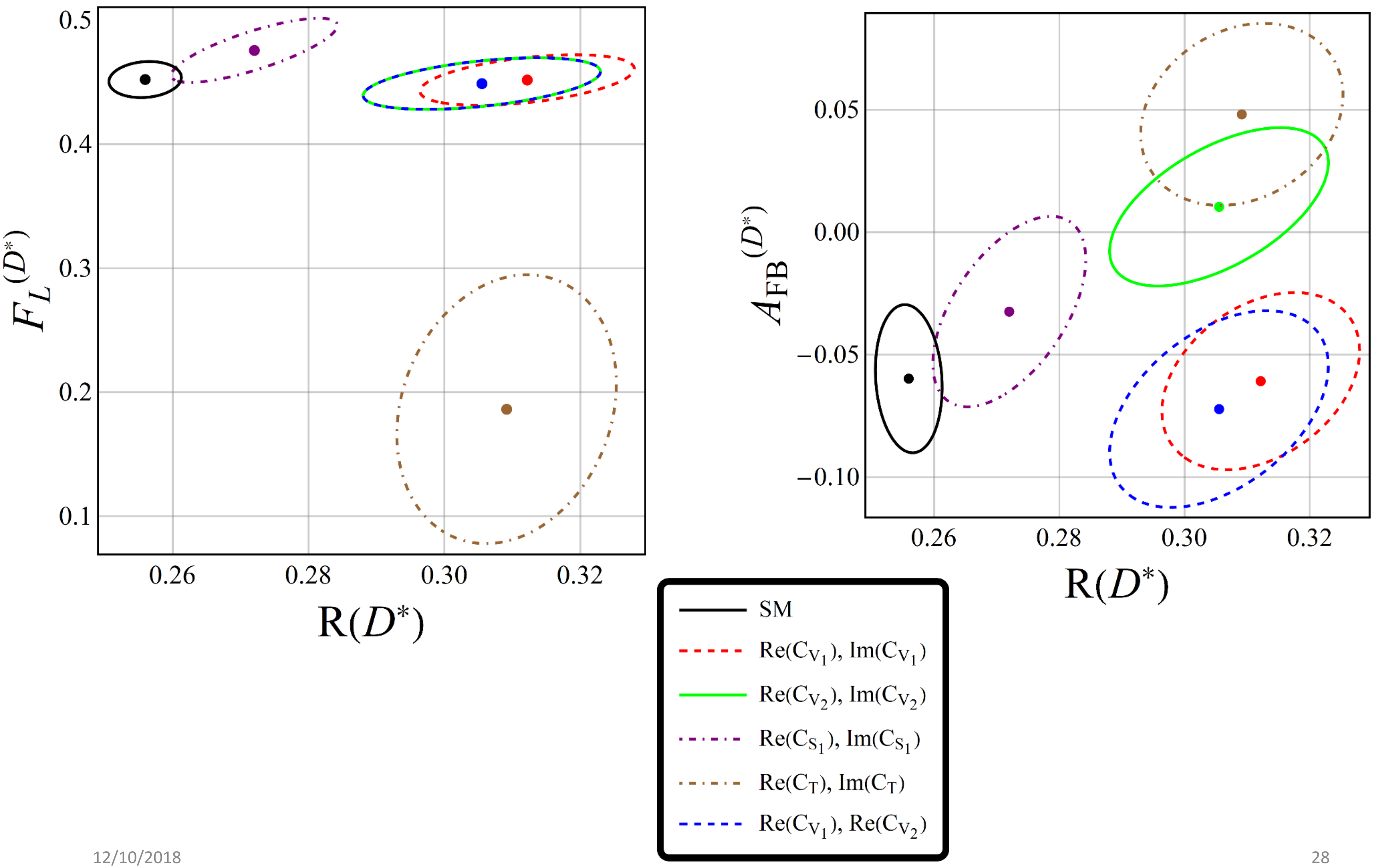
$$\mathcal{O}_{V_1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}), \; \mathcal{O}_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_{\tau L}),$$
$$\mathcal{O}_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_{\tau L}), \quad \mathcal{O}_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_{\tau L}), \; \mathcal{O}_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_{\tau L}),$$

Results

Case	NP parameter(s)	p-value (%)	$\mathcal{B}(B_c \to \tau\nu)(\%)$
1	$\mathcal{R}e(C_{V_1}), \mathcal{R}e(C_{V_2})$	80.84	2.59
2	$\mathcal{R}e(C_{S_1}), \mathcal{R}e(C_{S_2})$	83.71	68.29
3	$\mathcal{R}e(C_{V_1}), \mathcal{I}m(C_{V_1})$	72.73	2.67
4	$\mathcal{R}e(C_{V_2}), \mathcal{I}m(C_{V_2})$	80.84	2.59
5	$\mathcal{R}e(C_{S_1}), \mathcal{I}m(C_{S_1})$	19.59	9.98
6	$\mathcal{R}e(C_{S_2}), \mathcal{I}m(C_{S_2})$	83.71	82.68
7	$\mathcal{R}e(C_T), \mathcal{I}m(C_T)$	79.03	2.19

Jaiswal, SN, Patra, work in progress

Correlations among obs..

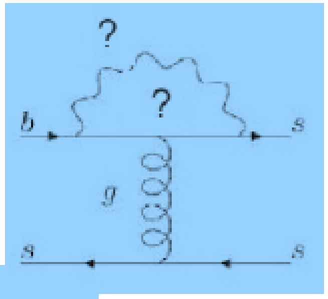


Fit results with $F_L(D^*)$

Case	NP parameter(s)	p-value (%)	$\mathcal{B}(B_c \to \tau\nu)(\%)$
1	$\mathcal{R}e(C_{V_1}), \mathcal{R}e(C_{V_2})$	58.74	2.59
2	$\mathcal{R}e(C_{S_1}), \mathcal{R}e(C_{S_2})$	86.74	72.75
3	$\mathcal{R}e(C_{V_1}), \mathcal{I}m(C_{V_1})$	52.21	2.67
4	$\mathcal{R}e(C_{V_2}), \mathcal{I}m(C_{V_2})$	58.74	2.59
5	$\mathcal{R}e(C_{S_1}), \mathcal{I}m(C_{S_1})$	16.3	10.17
6	$\mathcal{R}e(C_{S_2}), \mathcal{I}m(C_{S_2})$	86.74	86.31
7	$\mathcal{R}e(C_T), \mathcal{I}m(C_T)$	11.87	2.19

b-> s decays : NP ?

Study of b->s decays



- **b-> s** transition is a loop level process in the SM !

✓ Could be sensitive to new effects beyond the SM !

The effective Hamiltonian for $b \to s$ transitions can be written as

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C'_i O'_i) + \text{h.c.}$$

In the SM, the relevant operators at LO

$$O_7 = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_R b)F^{\mu\nu},$$
$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)\,,$$
$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)\,,$$

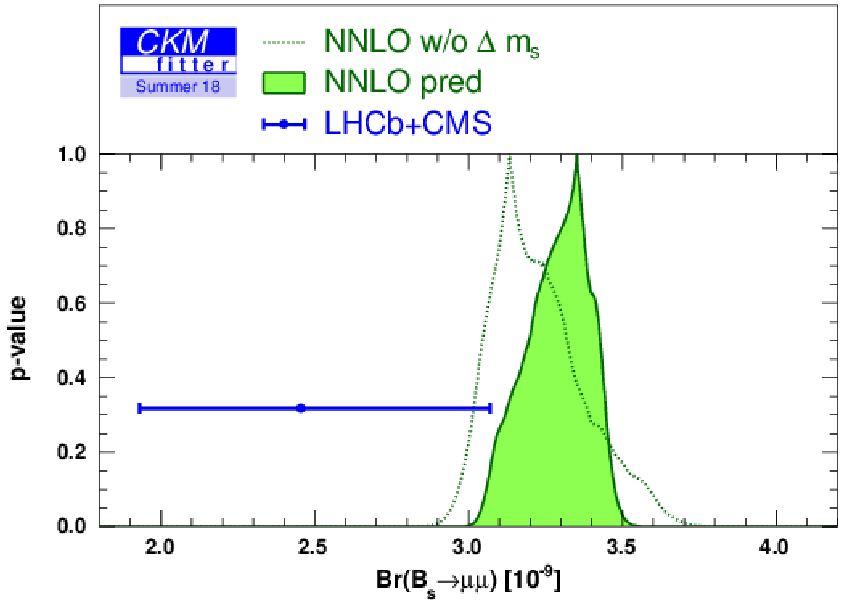
In many concrete model, the operators those are most sensitive to NP !

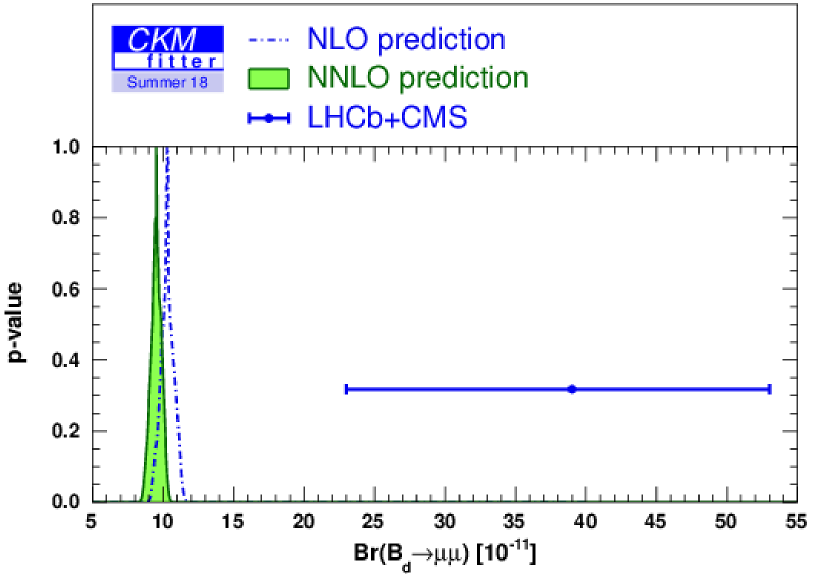
$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}, \qquad O_8^{(\prime)} = \frac{g m_b}{e^2}(\bar{s}\sigma_{\mu\nu}T^a P_{R(L)}b)G^{\mu\nu\,a},$$
$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu \ell)\,, \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5 \ell)\,,$$
$$O_S^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\ell)\,, \qquad O_P^{(\prime)} = \frac{m_b}{m_{B_s}}(\bar{s}P_{R(L)}b)(\bar{\ell}\gamma_5\ell)\,,$$

Rare decays: $B_q \to \mu\mu$

In the SM the branching fraction of the leptonic FCNC decay $B_q \to \ell\ell$

$$\frac{m_{B_q} m_\ell^2}{8\pi}\sqrt{1-\frac{4m_\ell^2}{m_{B_q}^2}}\left(\frac{G_F m_W}{\pi}\right)^4 |V_{tb}V_{tq}^*|^2 \, |C_{10}(\mu, x_t)|^2 \, \frac{f_{B_q}^2}{\Gamma_H^q}$$





Angular observables in B-> K*μμ

The differential decay rates of $\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-$ and $B^0 \to K^{*0}\mu^+\mu^-$ decays, in terms of q^2 and the three angles, are given by

$$\frac{d^4\Gamma[\overline{B}^0 \to \overline{K}^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i I_i(q^2) f_i(\vec{\Omega}) \quad \text{and}$$

$$\frac{d^4\bar{\Gamma}[B^0 \to K^{*0}\mu^+\mu^-]}{dq^2\, d\vec{\Omega}} = \frac{9}{32\pi}\sum_i \bar{I}_i(q^2) f_i(\vec{\Omega}),$$

Formed from combinations of spherical harmonics !

q^2 dependent angular observables !

Bilinear combinations of the six amplitudes ➡ $\mathcal{A}^{L,R}_{0,\|,\perp}$

$$S_i = (I_i + \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

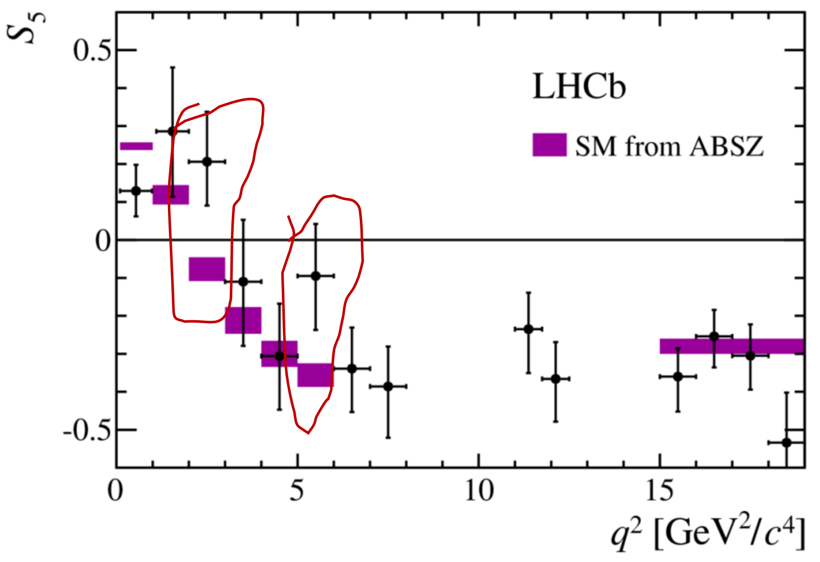
$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{d\Gamma}{dq^2} + \frac{d\bar{\Gamma}}{dq^2}\right)$$

q^2 dependent CP averages and asymmetries !

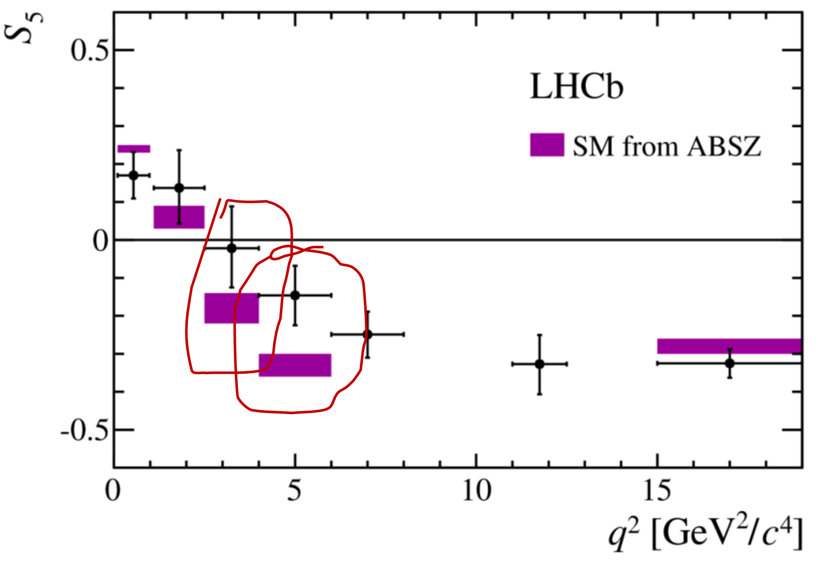
For detail, LHCb collaboration, JHEP 2016

Anomalous Results

✓**Recent experimental results have shown interesting deviations from the SM.**



Determined from moment analysis !



Maximum likelihood fit !

✓ **3.4σ deviations in S_5 or P_5' !**

NP or SM ??

- ➢These differences could be explained by contributions from physics beyond the Standard Model !

- ➢ Could it be due to the non factorizable corrections those are not accounted for in the Standard Model predictions ?

- ✓ Disentangling New Physics effects from the Standard Model requires a good understanding of all the uncertainties that might plague the theoretical estimations within the Standard Model.

Ciuchini et.al. JHEP 2016

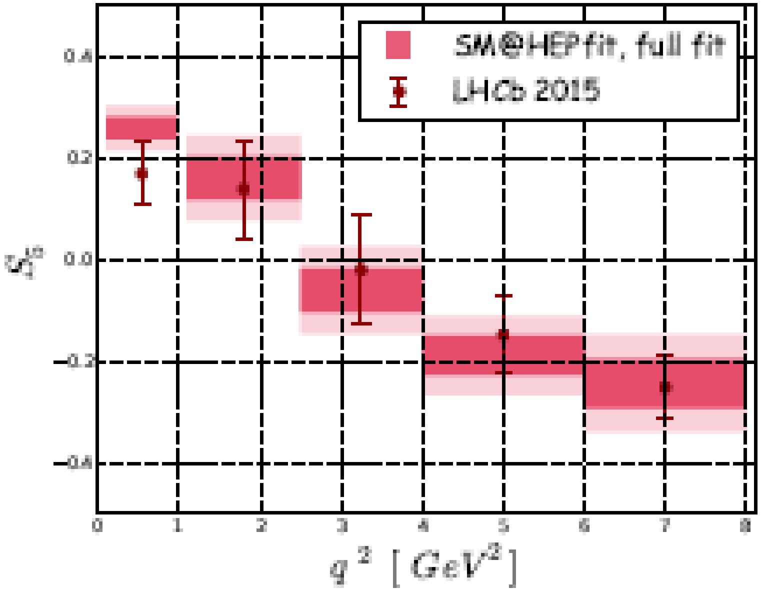
Instead of estimating the hadronic uncertainties from first principles or by some approximate methods, one can try to extract these from data and compare their size to other factorizable and SD contributions to estimate the legitimacy of their magnitude.

Parametric fit !

Ciuchini et.al. JHEP 2016

✓ The non-factorizable contributions are parameterized which might have been underestimated as one gets close to the charm resonances !

➢ The non-factorizable contributions are significantly smaller than the SD contribution, even as one gets close to the charm resonance !



✓ **Requires the presence of a sizable, perfectly acceptable, non-factorizable power corrections !**

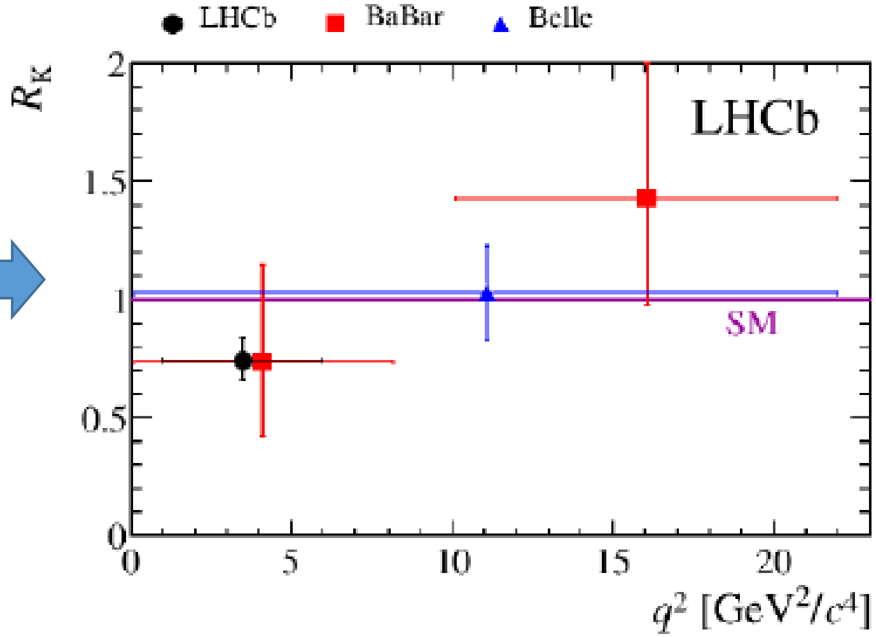
R_K in B -> Kℓℓ

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right) \times \left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right),$$

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

In SM, $R_K \cong 1$

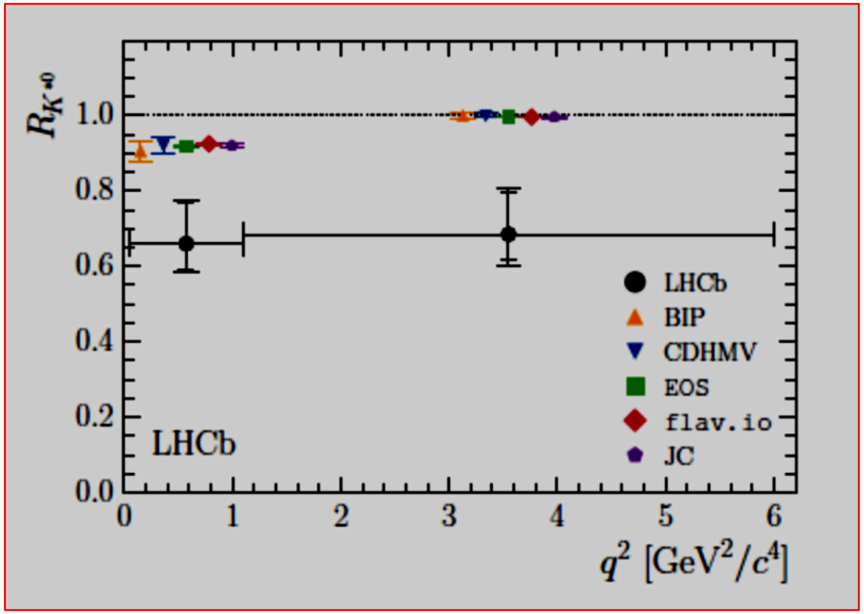
R_K measured in low q^2 regions is 3σ away from the SM !



R_{K^*} in B -> $K^*\ell\ell$

LHCb 2017

$$R_{K^{*0}} = \frac{\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to \mu^+\mu^-))} \Bigg/ \frac{\mathcal{B}(B^0 \to K^{*0}e^+e^-)}{\mathcal{B}(B^0 \to K^{*0}J/\psi(\to e^+e^-))}$$



q^2 range [GeV$^2/c^4$]	$R^{SM}_{K^{*0}}$
[0.045, 1.1]	0.906 ± 0.028
	0.922 ± 0.022
	$0.919 ^{+0.004}_{-0.003}$
	0.925 ± 0.004
	$0.920 ^{+0.007}_{-0.006}$
[1.1, 6.0]	1.000 ± 0.010
	1.000 ± 0.006
	$0.9968 ^{+0.0005}_{-0.0004}$
	0.9964 ± 0.005
	0.996 ± 0.002

Compatible with the SM at 2.1σ

$$R_{K^{*0}} = \begin{cases} 0.66 ^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1 \ \text{GeV}^2/c^4\,, \\ 0.69 ^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 \ \ < q^2 < 6.0 \ \text{GeV}^2/c^4\,. \end{cases}$$

Compatible with the SM at 2.5σ

Violation of lepton Universality ?

- Ratios of decay rates such as B-> $K^{(*)}\ell\ell$ for different leptons ℓ = e or μ are protected from hadronic uncertainties and can be very accurately predicted in the Standard Model (SM) !

Therefore, significant discrepancies with experiment in these observables would have to be interpreted as unambiguous signals of new physics (NP) that, in addition, must be related to new lepton non-universal interactions.

Among all the possible operators present in effective Hamiltonian , only the semileptonic ones can explain the observed discrepancies !!

$$\mathcal{O}_9^{(\prime)\ell} = \frac{\alpha_{em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)}b)\,(\bar{\ell}\gamma^\mu\ell), \qquad \mathcal{O}_{10}^{(\prime)\ell} = \frac{\alpha_{em}}{4\pi}(\bar{s}\gamma^\mu P_{L(R)}b)\,(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

✓ Scalar operators are highly constrained from the Br(B_s -> μμ)

Alonso, Grinstein and Camalich , PRL 2014

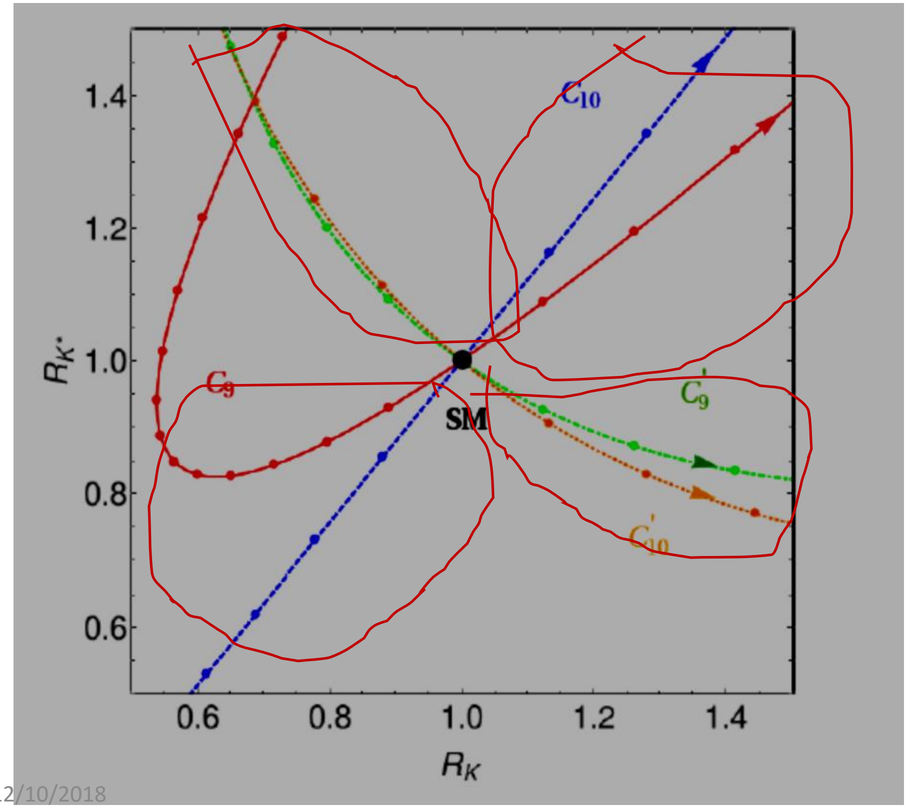
Data analysis

R_K and R_{K^*} in the bins $[1,\ 6]$ GeV^2 and $[1.1,\ 6]$ GeV^2, respectively

arXiv:1704.05446

$$\frac{\Gamma_K}{\Gamma_K^{\rm SM}} = \left(2.9438\ \left(|C_9 + C_9'|^2 + |C_{10} + C_{10}'|^2\right) - 2{\rm Re}\left[(C_9 + C_9')(0.8152 + i\,0.0892)\right] + 0.2298\right)\ 10^{-2},$$

$$\frac{\Gamma_{K^*}}{\Gamma_{K^*}^{\rm SM}} = \left(2.420\ \left(|C_9 - C_9'|^2 + |C_{10} - C_{10}'|^2\right) - 2{\rm Re}\left[(C_9 - C_9')(2.021 + i\,0.188)\right] + 1.710\right.$$
$$\left. + 1.166\ \left(|C_9|^2 + |C_{10}|^2 + |C_9'|^2 + |C_{10}'|^2\right) - 2{\rm Re}\left[C_9(5.255 + i\,0.239)\right] + 29.948\right)\ 10^{-2},$$



✓ The possibilities are new physics in C_{10} and/or C_9

OUT LOOK

- ✓ Improvements in the SM extractions of V_{cb} and V_{ub} are possible ….efforts are going on..

- The deficits with respect to expectations reported by the LHCb experiment in muon-to-electron ratios of the $B \to K^{(*)} \ell\ell$ decay rates point to genuine manifestations of lepton non-universal new physics.

b -> c transitions : Some hint for NP ⟶ LUV ?

- All the effects observed so far are well compatible with NP only involving left-handed currents.

The onset of SUPER-B (BELLE-II) factory will bring us to a high precision era

•A more precise extractions of the CKM elements are necessary in order to understand SM, QCD, and for an implicit search of NP !

✓ Considerable progress has been made !!

✓ Much more to do in order to improve precision !!

THANK YOU

Continue: Fit results

The SM disagrees with these measurements at 3.7σ significance. arXiv:1704.05446

Only R_K and R_{K*}

Coeff.	best fit	χ^2_{min}	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^μ	-1.64	4.52	0.104	3.87	[-2.31,-1.13]	[<-4, -0.31]
δC_{10}^μ	1.27	2.24	0.326	4.15	[0.91,1.70]	[0.31,3.04]
δC_L^μ	-0.66	2.93	0.231	4.07	[-0.85,-0.49]	[-1.26,-0.16]
Coeff.	best fit	χ^2_{min}	p-value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(0.85, 2.69)	1.99	0.158	3.78	$C_9^\mu \in$ [-0.71, 1.38]	$C_{10}^\mu \in$ [0.61, >4]

R_K and R_{K*} and the other angular observables !

Coeff.	best fit	χ^2_{min}	p-value	SM exclusion [σ]	1σ range	3σ range
δC_9^μ	-1.37	61.98 [64 dof]	0.548	4.37	[-1.70, -1.03]	[-2.41, -0.41]
δC_{10}^μ	0.60	71.72 [64 dof]	0.237	3.06	[0.40, 0.82]	[-0.01, 1.28]
δC_L^μ	-0.59	63.62 [64 dof]	0.490	4.18	[-0.74, -0.44]	[-1.05, -0.16]
Coeff.	best fit	χ^2_{min}	p-value	SM exclusion [σ]	parameter ranges	
$(\delta C_9^\mu, \delta C_{10}^\mu)$	(-1.15, 0.28)	60.33 [63 dof]	0.572	4.17	$C_9^\mu \in$ [-1.54, -0.81]	$C_{10}^\mu \in$ [0.06, 0.50]

NP models !

Other models that can explain $R(D^{(*)})$ and $R(K^{(*)})$!!

✓The model consists of an extended gauge group $SU(2)_1 \times SU(2)_2 \times U(1)_Y$ which breaks spontaneously around the TeV scale to the electroweak gauge group. Fermion mixing effects with vector-like fermions give rise to potentially large new physics contributions in flavour transitions mediated by W' and Z' boson !!

arXiv : 1608.01349

✓ Vector or scalar (R_2-model) type leptoquark and RPV SUSY are amongst the model that can explain both the anomalies independently !!

Damir, svjetlana, Anjan, Rukmani, Namit…..many more !!

✓ The (V – A) structure of the quark current in the b -> s transition may come from a Z' penguin, where Z' will couple to muons and top quarks, and the flavor changing transition is predominantly due to a top-W penguin loop.

arXiv:1704.06005v2

✓ A model with an extra vector boson associated with the gauging (and spontaneous breaking) of muon-number minus tau-number, $L_\mu - L_\tau$, can explain the observed discrepancies in $R(K^{(*)})$ arXiv:1508.07009v1

Approaches

1) BNLP (Bosch, Lange, Neubert and Paz) => Shape function based !

- ✓Includes corrections upto α_s at leading order in $1/m_b$ expansion, power corrections upto $1/m_b^2$ has taken into account . Corrections at order α_s^2 are not added in the evaluation of V_{ub} !

2) GGOU (Gambino, Giordano, Ossola and Uraltsev) => OPE hard cutoff based !

- ✓Includes all known perturbative and non-perturbative effects through ($\alpha_s^2\ \beta_0^2$) and $1/m_b^3$!

3) Dressed gluon approximation (Andersen and Gardi) => Resummation based !

- ✓This approach try to compute the shape function, different from the above two approaches ! Unknown NNLO corrections are the missing pieces !

4) Other approaches : a) SIMBA (Tackmann, Lacker, Ligeti, Stewart…..)

b) Analytic coupling (Aglietti et.al.)

c) Method to avoid shape function (Bauer, Ligeti, Luke…)