New physics searches with heavy flavour observables

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Outline

- Puzzles in B Physics !!
  - ✓ Inclusive and exclusive measurements of $|V_{cb}|$, $|V_{ub}|$
- Few anomalous results :
  - ✓ **NP effects in b->s decays ?**
  - ✓ **NP effects in b->c decays ?**
- Status of NP searches in B_q mixing : CP observables !
  - ✓ Mostly consistent with the SM
- OUT LOOK

B-Physics: Goal

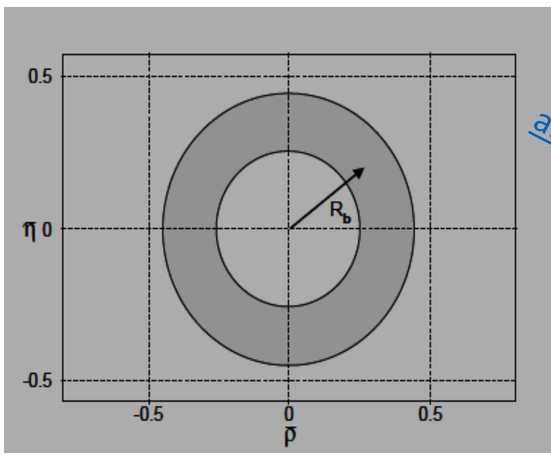
Quark Mixing matrix

Wolfenstein Parametrization

Unitarity Triangle

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

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



arXiv:hep-ph/0304132v2

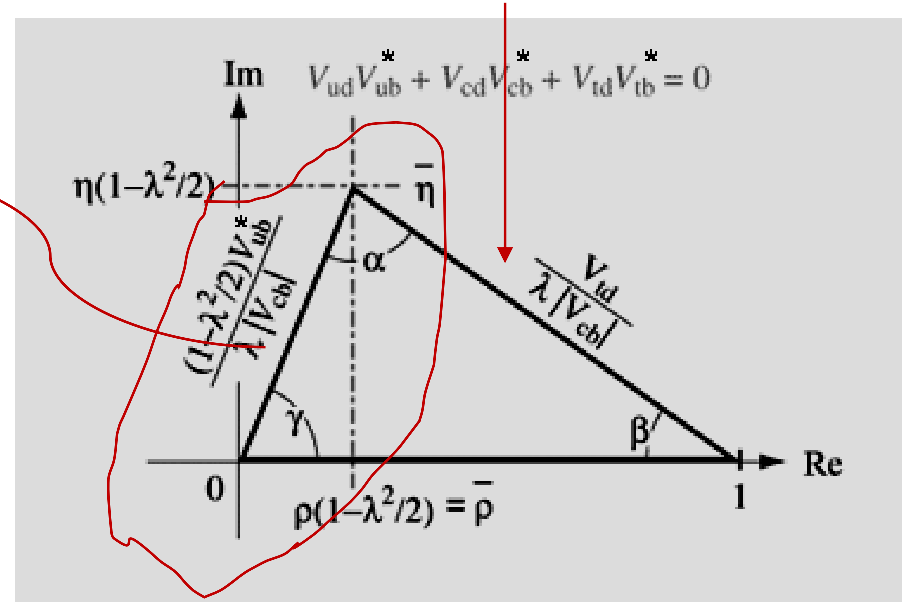


Figure 1. The unitarity relation $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ drawn in the complex $[\bar{\rho}, \bar{\eta}]$ plane.

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

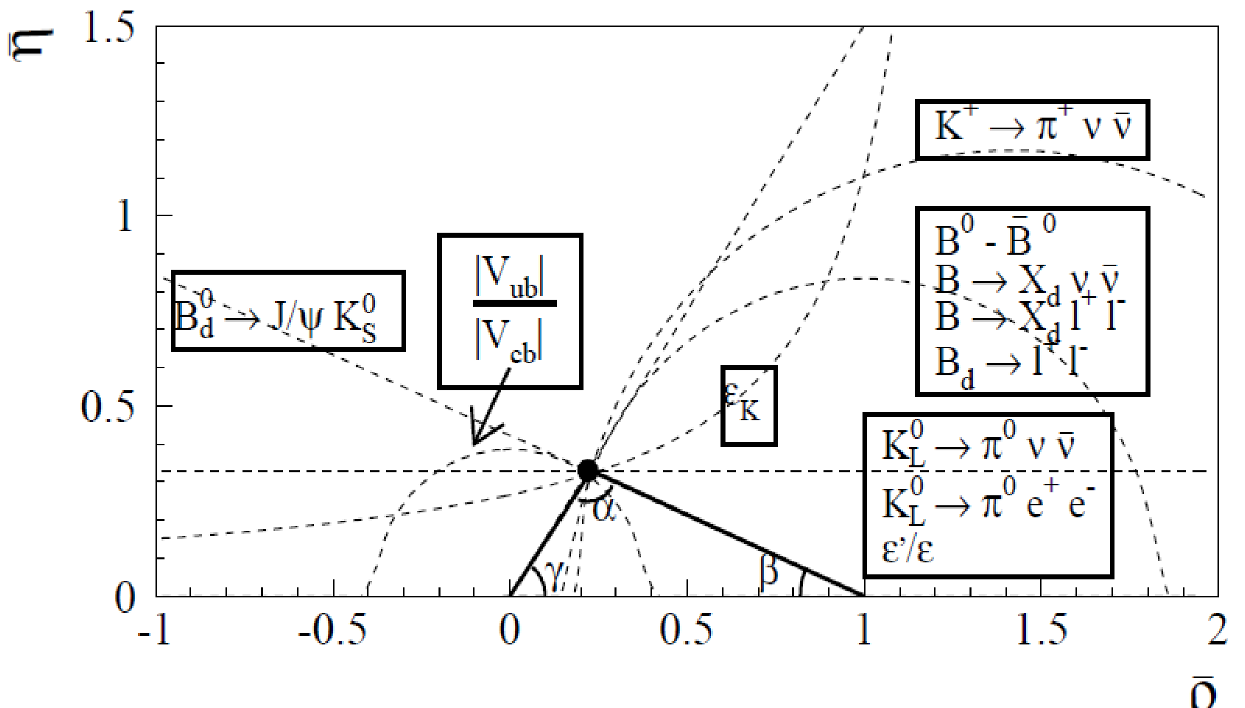
To find where the apex lies on the UT we have to look at other decays !!

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

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

Ideal UT

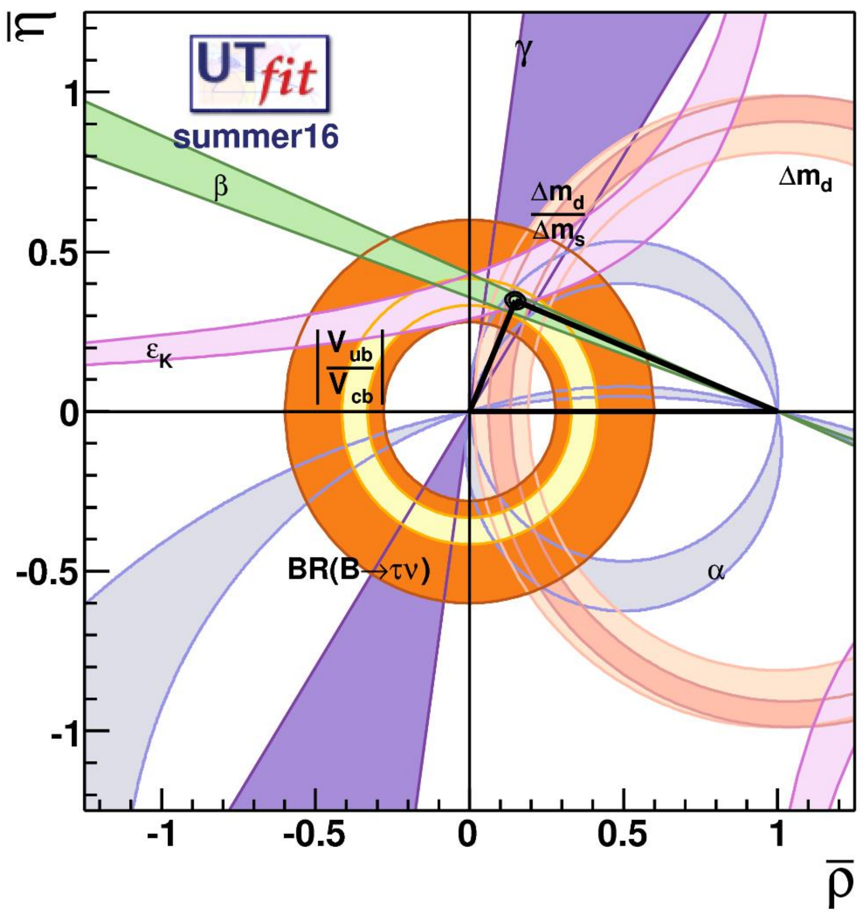
✓Various curves in the (ρ,η) plane extracted from different decays and transitions using the SM formulae cross each other at a single point



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.

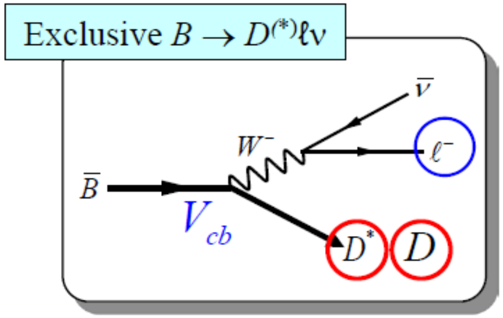
CKM elements: Semileptonic decays

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

Semileptonic B-decays provide a clean environment !!

Exclusive Measurement

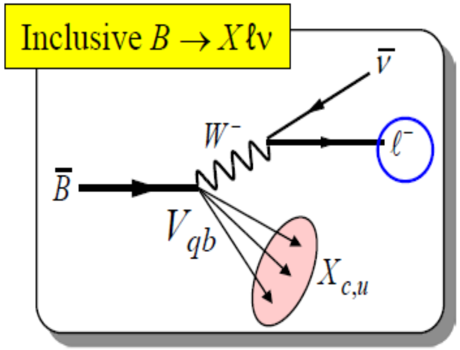
- **B-> D ℓ ν and** B-> $D^* \ell$ ν
- **B-> π ℓ ν**



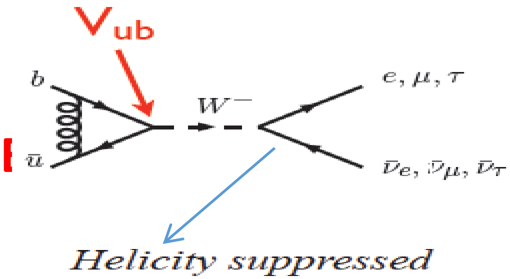
Inclusive Measurement

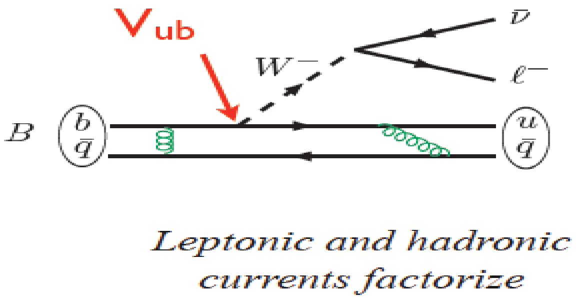
B-> $X_c \ell$ ν

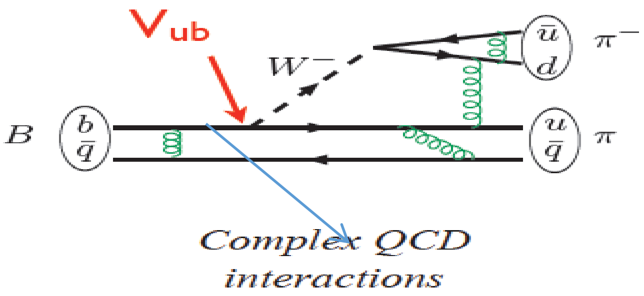
B-> $X_u \ell$ ν



Leptonic **Semileptonic** **Hadronic**







Inclusive vs Exclusive

- Tree level semileptonic (s.l.) decays of B mesons are crucial for determining the $|V_{ub}|$ and $|V_{cb}|$ elements of the CKM matrix !
- Inclusive $b \rightarrow c(u) l \nu$ 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 $b \rightarrow s\gamma$ photon spectrum will lead to a more precise effective shape function ⟹ Useful for $|V_{ub}|$ measurement !!

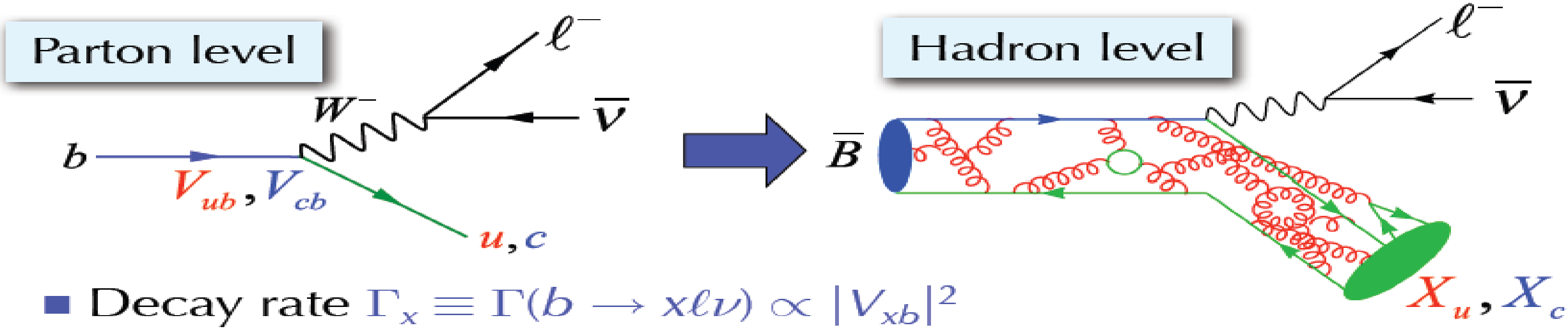
Inclusive Semileptonic

- **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 $\alpha_s(m_b)$



■ Decay rate $\Gamma_x \equiv \Gamma(b \to x\ell\nu) \propto |V_{xb}|^2$

$$\Gamma_{SL} = \underbrace{|V_{cb}|^2 \frac{G_F^2 m_b^5}{192\pi^3}}_{\text{free quark decay}} \underbrace{(1 + A_{EW}) A_{pert}}_{\text{perturbative corrections}} \times \underbrace{[c_0(r) + \frac{0}{m_b} + c_2(r, \frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}) + c_3(r, \frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}) + \ldots]}_{\text{Non-perturbative power corrections}}$$

$r = m_c/m_b$

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

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

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

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

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

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

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

$$1.014$$

$|V_{cb}| = (42.42 \pm 0.86) \times 10^{-3}$ ⇒ 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

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

$w \to v_B \cdot v_D$

1.0066 ± 0.0016

Zero recoil expansion, HQET

Fermilab Lattice and MILC , 2015 1.0541 ± 0.0083

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

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

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

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

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

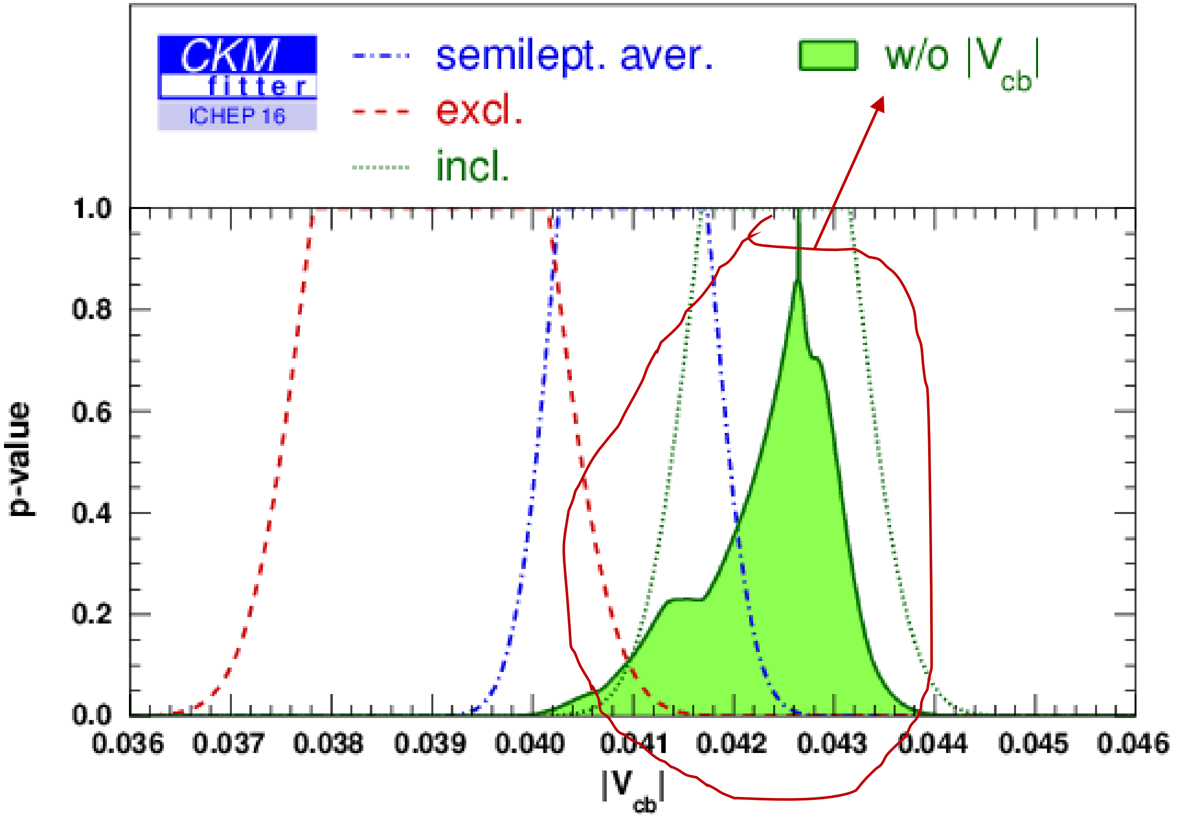
$$\frac{d\Gamma}{dw}(\bar{B}\to D^*\ell\bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2(w^2-1)^{1/2}P(w)(\eta_{\rm ew}\mathcal{F}(w))^2$$

Fermilab Lattice and MILC , 2014

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

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

$|V_{cb}|$: Summary



CKM
fitter
ICHEP 16
semilept. aver.
excl.
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w/o |V_cb|
p-value
1.0
0.8
0.6
0.4
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0.036
0.037
0.038
0.039
0.040
0.041
0.042
0.043
0.044
0.045
0.046
|V_cb|

Recent updates

Bigi, Gambino and Schacht, PRD 2016, PLB 2017

- 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.

✓ BGL/BCL are valid alternatives

Known functions of z

$$F_i = f_i \sum_n b_{in} z^n$$

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

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

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

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

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

$$0 \leq z \leq 0.0646$$

Strong Unitarity condition

$$|V_{cb}| = 40.49(97) \times 10^{-3}$$

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

BGL Fit:	Data + lattice	Data + lattice + LCSR
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$

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

V_{ub} :Exclusive decays

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

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

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 !

LO: Twist 2 ,3, 4 quark-antiquark and quark-antiquark-gluon !

NLO: Twist – 2 and 3 two particle contribution are known at order α_s

NNLO: Twist-2 contribution at order α_s^2 !

$$|V_{ub}| = (3.50^{+0.38}_{-0.33}|_{th.} \pm 0.11|_{exp.}) \times 10^{-3}$$ → Khodjamirian, PRD 2011

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

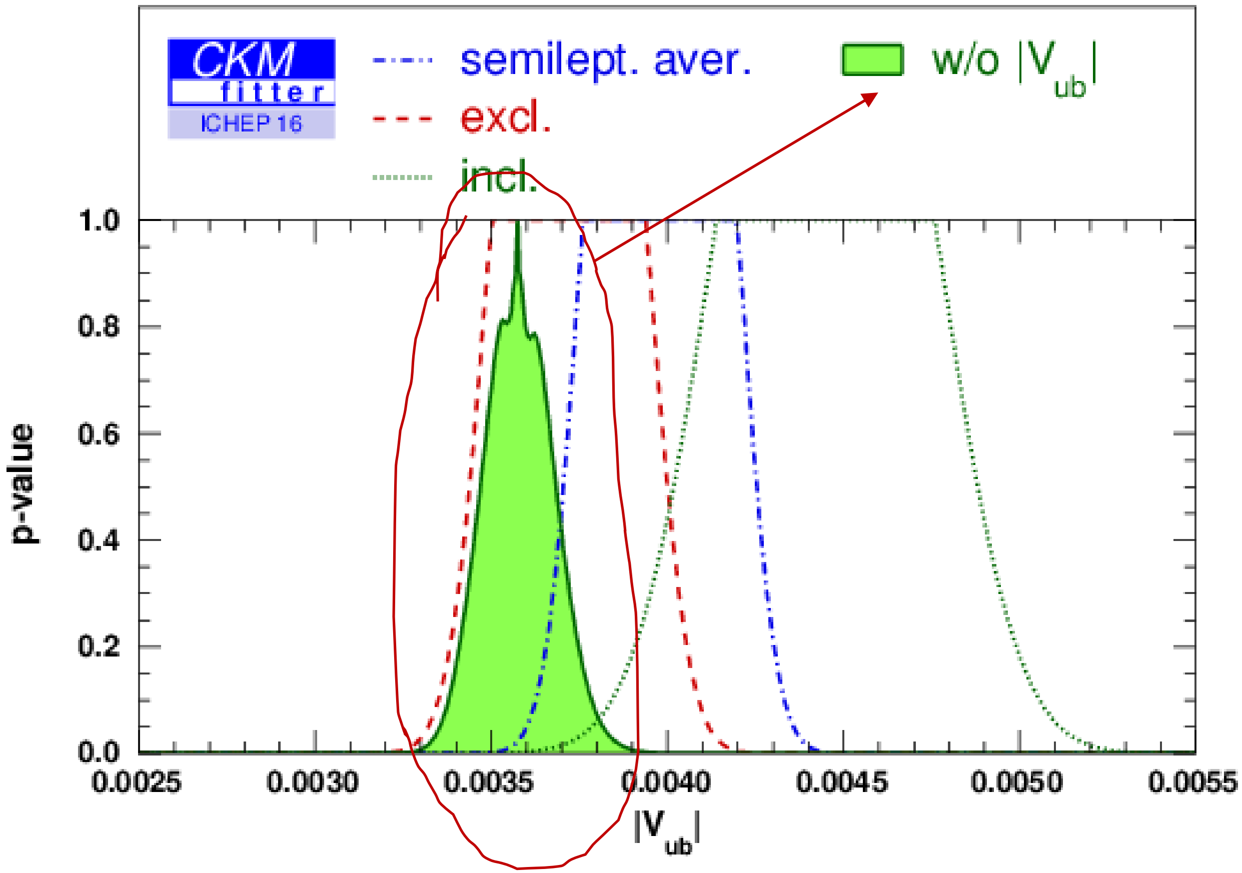
In GeV m_b=4.569±0.029 m_b=4.541±0.023 m_b=4.177±0.043

cut (GeV)	BLNP	GGOU	DGE
$E_e > 2.1$	$428 \pm 50 \,^{+31}_{-36}$	$421 \pm 49 \,^{+23}_{-33}$	$390 \pm 45 \,^{+26}_{-28}$
$E_e - q^2$	$453 \pm 22 \,^{+33}_{-38}$	not available	$417 \pm 20 \,^{+28}_{-29}$
$E_e > 2.0$	$454 \pm 26 \,^{+27}_{-33}$	$450 \pm 26 \,^{+18}_{-25}$	$434 \pm 25 \,^{+23}_{-25}$
$E_e > 1.9$	$493 \pm 46 \,^{+27}_{-29}$	$493 \pm 46 \,^{+17}_{-22}$	$485 \pm 45 \,^{+21}_{-25}$
$q^2>8$, $m_X<1.7$	$430 \pm 23 \,^{+26}_{-28}$	$432 \pm 23 \,^{+27}_{-30}$	$427 \pm 22 \,^{+20}_{-20}$
$P_+ < 0.66$	$415 \pm 25 \,^{+28}_{-27}$	$424 \pm 26 \,^{+32}_{-32}$	$424 \pm 26 \,^{+37}_{-32}$
$m_X < 1.55$	$430 \pm 20 \,^{+28}_{-27}$	$429 \pm 20 \,^{+21}_{-22}$	$453 \pm 21 \,^{+24}_{-22}$
$E_\ell > 1$	$432 \pm 24 \,^{+19}_{-21}$	$442 \pm 24 \,^{+9}_{-11}$	$446 \pm 24 \,^{+13}_{-13}$
$E_\ell > 1$	$449 \pm 27 \,^{+20}_{-22}$	$460 \pm 27 \,^{+10}_{-11}$	$463 \pm 28 \,^{+13}_{-13}$
HFAG average	$445 \pm 16 \,^{+21}_{-22}$	$451 \pm 16 \,^{+12}_{-15}$	$452 \pm 16 \,^{+15}_{-16}$

Inclusive and exclusive measurements do not agree with each others. 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 !



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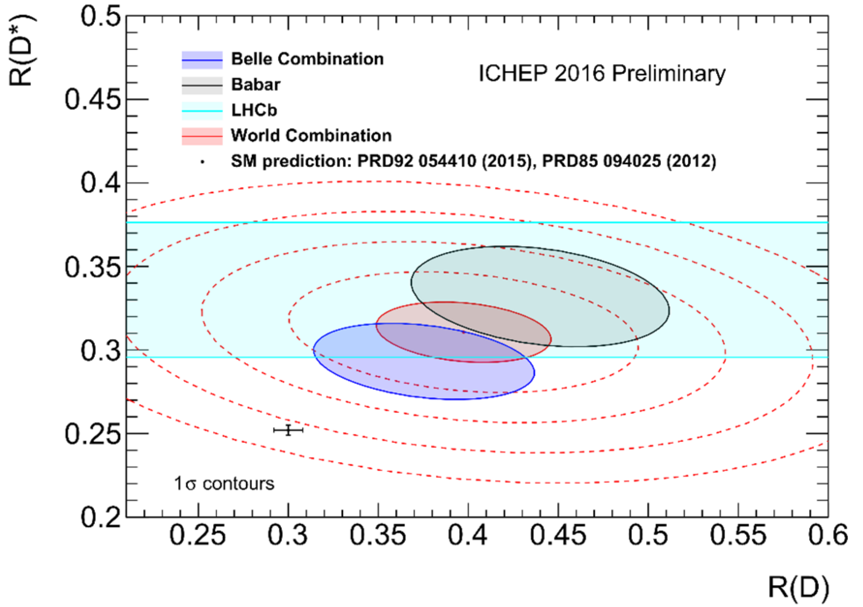
0.6
0.4
0.2
0.0
0.0025
0.0030
0.0035
0.0040
0.0045
0.0050
0.0055
|Vub|

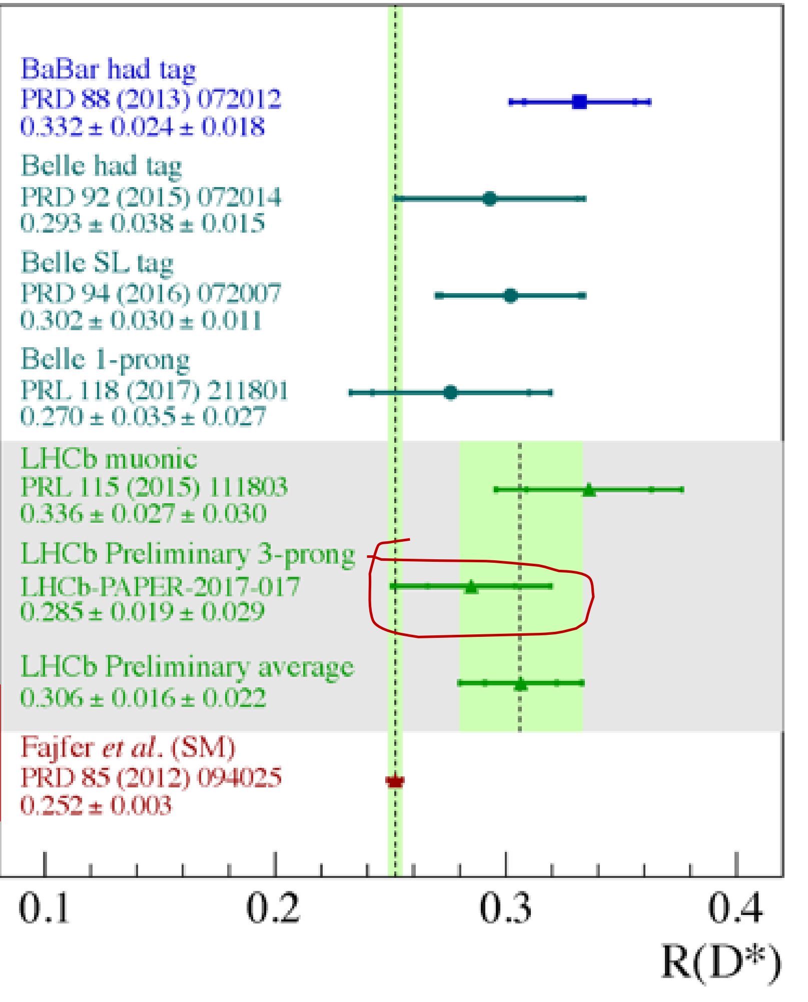
$B \rightarrow D^{(*)}\tau\nu_\tau$ ($b \rightarrow c\, \tau\nu_\tau$)

Observables and the data

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

LHCb paper 2017-017





New WA : 0.305 ±0.015
3.4σ above the SM !

Formfactors

$$\langle D(K)|\bar{c}\gamma_\mu b|\bar{B}(p)\rangle = \left[(p+k)_\mu - \frac{m_B^2 - m_D^2}{q^2} q_\mu\right] F_1(q^2) + q_\mu \frac{m_B^2 - m_D^2}{q^2} F_0(q^2)$$

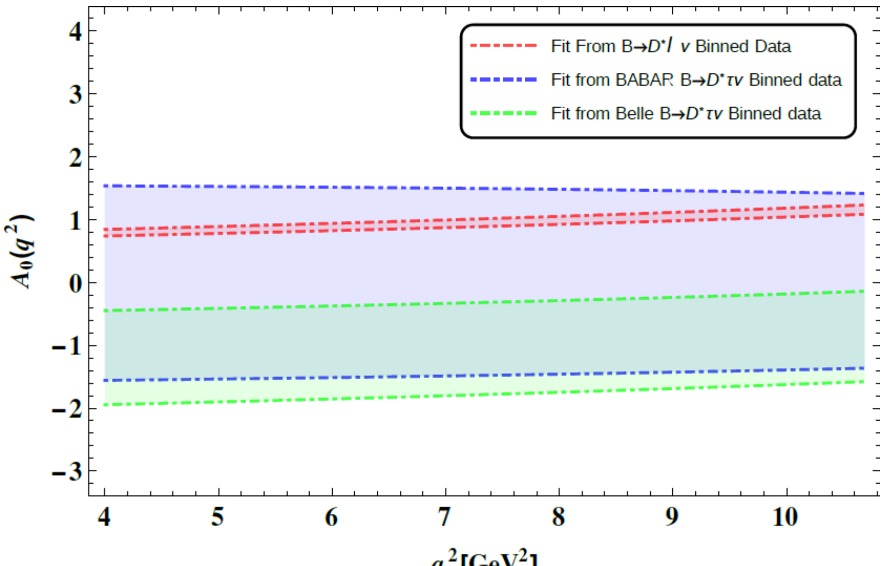
$$\langle D^*(k,\varepsilon)|\bar{c}\gamma_\mu b|\bar{B}(p)\rangle = i\epsilon_{\mu\nu\rho\sigma}\varepsilon^{\nu *} p^\rho k^\sigma \frac{2V(q^2)}{m_B + m_{D^*}}$$

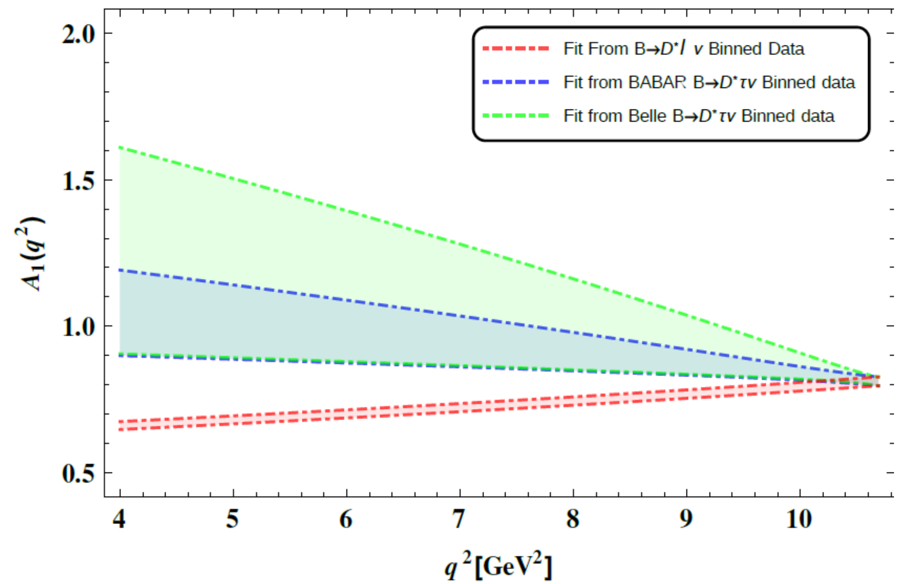
$$\begin{aligned}\langle D^*(k,\varepsilon)|\bar{c}\gamma_\mu\gamma_5 b|\bar{B}(p)\rangle = {} & \varepsilon_\mu^*(m_B + m_{D^*})A_1(q^2) \\ & - (p+k)_\mu(\varepsilon^* q)\frac{A_2(q^2)}{m_B + m_{D^*}} \\ & - q_\mu(\varepsilon^* q)\frac{2m_{D^*}}{q^2}\left[A_3(q^2) - A_0(q^2)\right],\end{aligned}$$

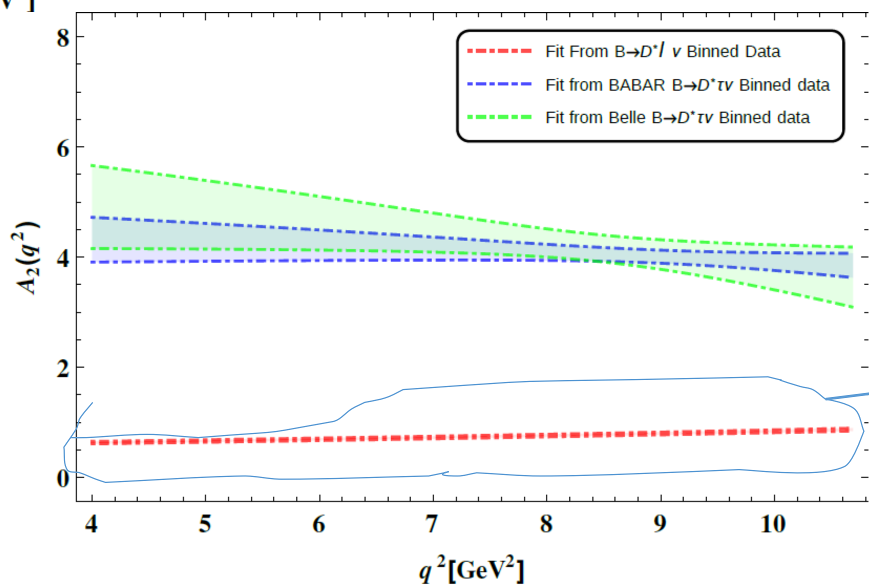
where

$$A_3(q^2) = \frac{m_B + m_{D^*}}{2m_{D^*}} A_1(q^2) - \frac{m_B - m_{D^*}}{2m_{D^*}} A_2(q^2).$$

Form factors from B-> $D^{(*)}\tau\nu_\tau$



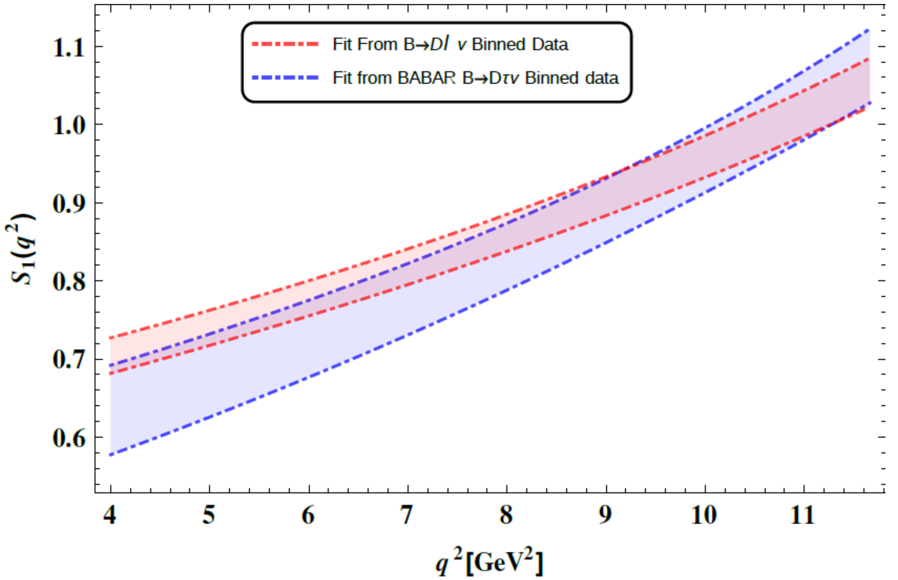


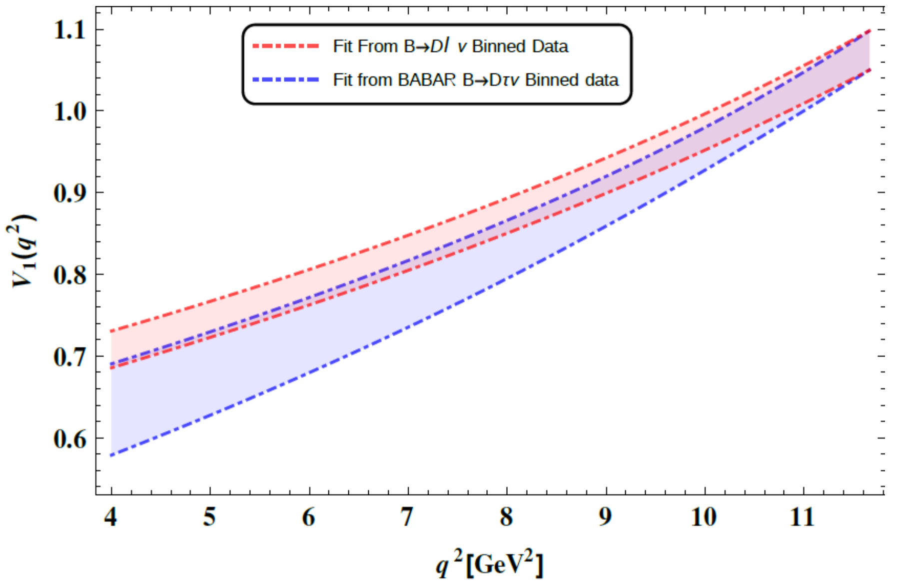


Bhattacharya, Nandi, Patra, PRD 2017

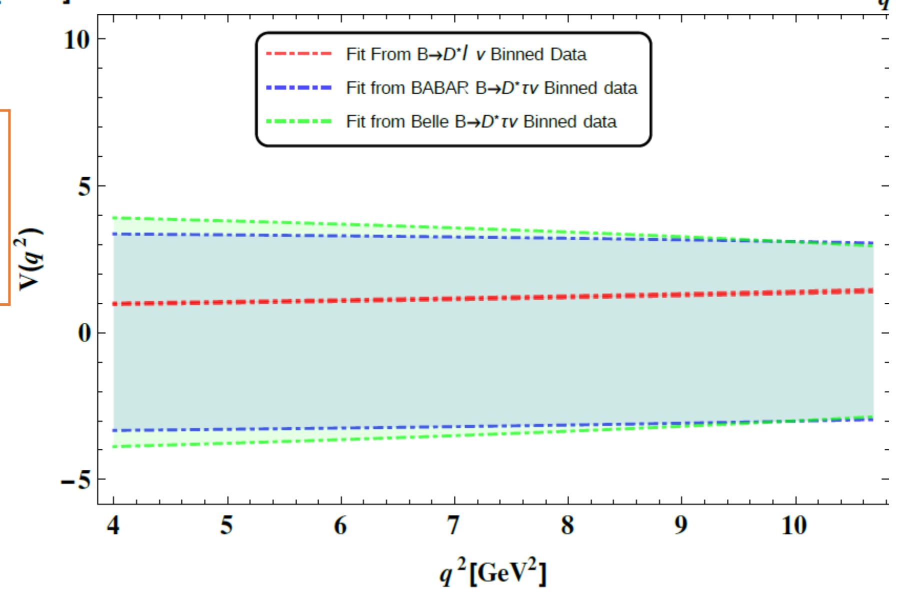
Large deviations !

Formfactors





Bhattacharya, Nandi, Patra, PRD 2017



NP sensitivities in B->D$^{(*)}$τν$_τ$

✓Many NP model can explain the excess !!

Model independent approach

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

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

PHYSICAL REVIEW D 95, 075012 (2017)

Looking for possible new physics in $B \to D^{(*)}\tau\nu_\tau$ in light of recent data

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(Received 20 November 2016; published 11 April 2017)

We study the decays $B \to D^{(*)}\tau\nu_\tau$ in light of the available data from *BABAR*, Belle, and LHCb. We divide our analysis into two parts: in one part we fit the form factors in these decays directly from the data without adding any additional new physics contributions and compare our fit results with those available from the decays $B \to D^{(*)}\ell\nu_\ell$. We find that the q^2 distributions of the form factors associated with the pseudovector current, obtained from $B \to D^{(*)}\tau\nu_\tau$ and $B \to D^{(*)}\ell\nu_\ell$ respectively, do not agree with each other, whereas the other form factors are consistent with each other. In the next part of our analysis, we look for possible new effective operators of dimension 6 amongst new vector, scalar, and tensor types that can best explain the current data in the decays $B \to D^{(*)}\tau\nu_\tau$. We use the information-theoretic approaches, especially of the "second-order Akaike information criterion" in the analysis of empirical data. Normality tests for the distribution of residuals are done after selecting the best possible scenarios, for cross validation. We find that it is the contribution from the operator involving left- or right-handed vector current that passes all the selection criteria defined for the best-fit scenario and that can successfully accommodate all the available data sets.

Results

Experiment	Data set index	Observables	Cases	χ^2_{min}	D.o.f.	Parameters	Akaike Wgts (w_i)	Normality (S-W)
BABAR	1	$R(D)_{bin}$	5	7.41	12	C_T	0.26	0.38
			1	7.79	12	C_{V_1}	0.22	0.29
			2	7.79	12	C_{V_2}	0.22	0.29
			3	9.17	12	C_{S_1}	0.11	0.18
			4	9.17	12	C_{S_2}	0.11	0.18
	2	$R(D^*)_{bin}$	1	6.3	10	C_{V_1}	0.56	0.11
			2	7.18	10	C_{V_2}	0.36	0.12
	3	Combined	8	13.01	22	C_{V_2}, C_{S_2}	0.32	0.86
			2	19.12	24	C_{V_2}	0.22	0.59
			7	14.23	22	C_{V_2}, C_{S_1}	0.17	0.79
			6	14.61	22	C_{V_1}, C_{V_2}	0.14	0.19
Belle(2016)	4	$R(D^*)_{bin}$	2	9.07	15	C_{V_2}	0.47	0.95
			1	9.43	15	C_{V_1}	0.39	1.00
BABAR + Belle(2016)	5	Combined	8	22.59	39	C_{V_2}, C_{S_2}	0.31	0.95
			2	28.33	41	C_{V_2}	0.19	0.94
			7	23.69	39	C_{V_2}, C_{S_1}	0.18	0.89
			6	24.16	39	C_{V_1}, C_{V_2}	0.14	0.69
BABAR + Belle(2015)+ LHCb + Belle(Latest)	6	Combined	2	48.54	28	C_{V_2}	0.52	0.02
			8	45.71	26	C_{V_2}, C_{S_2}	0.16	0.01
			7	46.87	26	C_{V_2}, C_{S_1}	0.09	0.02
			6	47.24	26	C_{V_1}, C_{V_2}	0.08	0.04
Belle(2016) + Belle(2015)+ LHCb + Belle New	7	Combined	2	28.81	19	C_{V_2}	0.34	0.64
			1	30.81	19	C_{V_1}	0.13	0.77
			4	31.29	19	C_{S_2}	0.1	0.83
			3	31.48	19	C_{S_1}	0.09	0.91
			5	31.52	19	C_T	0.09	0.82

Lifetime of B_c^- Mesons Constrains Explanations for Anomalies in $B \to D^{(*)}\tau\nu$

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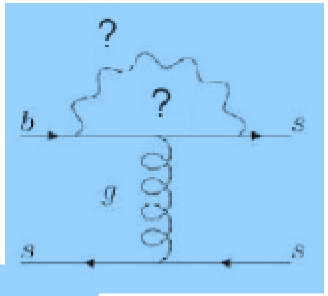
We investigate a new constraint on new-physics interpretations of the anomalies observed in $B \to D^{(*)}\tau\nu$ decays making use of the lifetime of the B_c^- meson. A constraint is obtained by demanding that the rate for $B_c^- \to \tau^-\bar{\nu}$ does not exceed the fraction of the total width that is allowed by the calculation of the lifetime in the standard model. This leads to a very strong bound on new-physics scenarios involving scalar operators since they lift the slight, but not negligible, chiral suppression of the $B_c^- \to \tau^-\bar{\nu}$ amplitude in the standard model. The new constraint renders a scalar interpretation of the enhancement measured in R_{D^*} implausible, including explanations implementing extra Higgs doublets or certain classes of leptoquarks. We also discuss the complementarity of $R_{D^{(*)}}$ and a measurement of the longitudinal polarization of the τ in the $B \to D^*\tau\nu$ decay in light of our findings.

DOI: 10.1103/PhysRevLett.118.081802

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

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

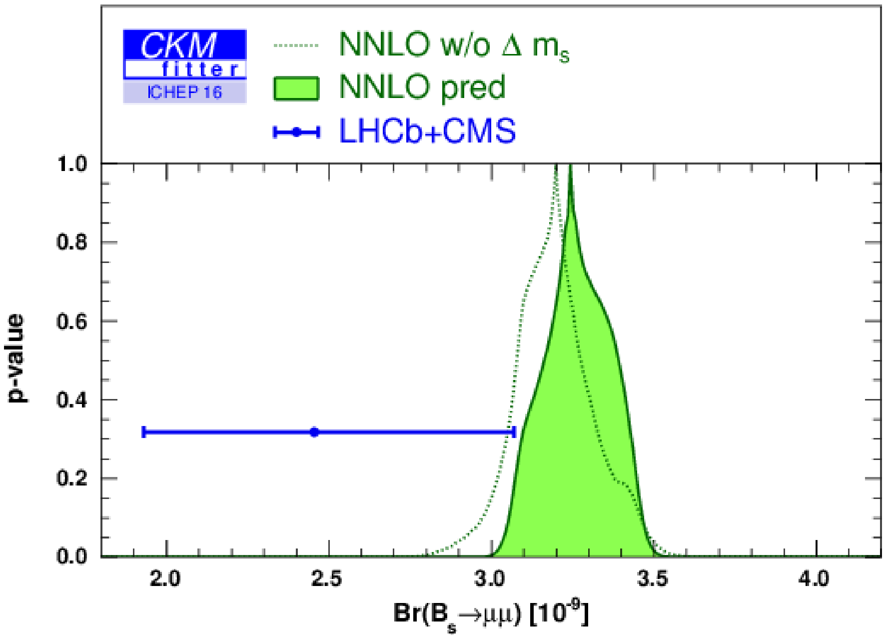
In many concrete model, the operators those are most sensitive to NP !

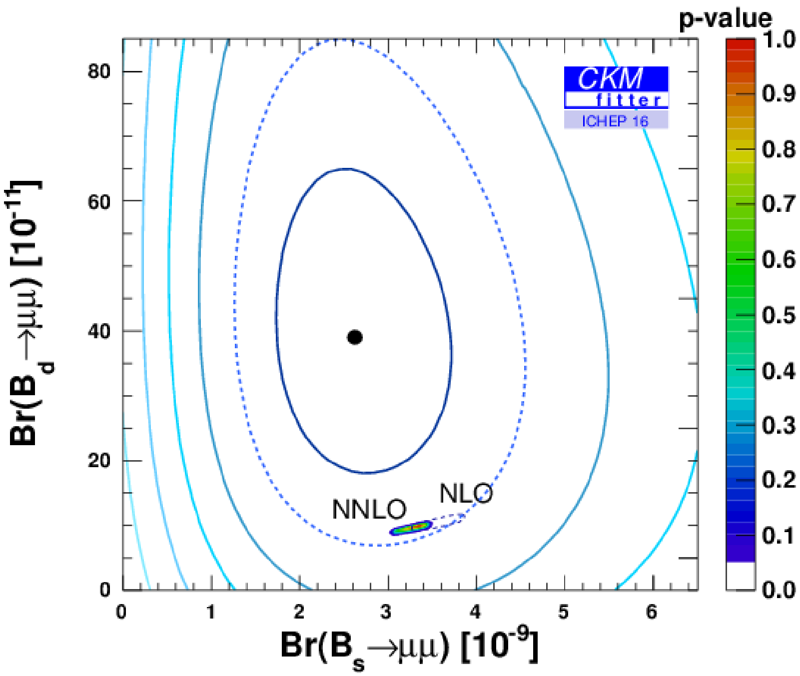
$$O_7^{(\prime)} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}, \qquad O_8^{(\prime)} = \frac{g m_b}{e^2} (\bar{s}\sigma_{\mu\nu} T^a P_{R(L)} b) G^{\mu\nu\, a},$$
$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell), \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu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

Rare decays: B_q-> μμ

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

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





Allowed by the data

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

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

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

Formed from combinations of spherical harmonics !

q^2 dependent angular observables !

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

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

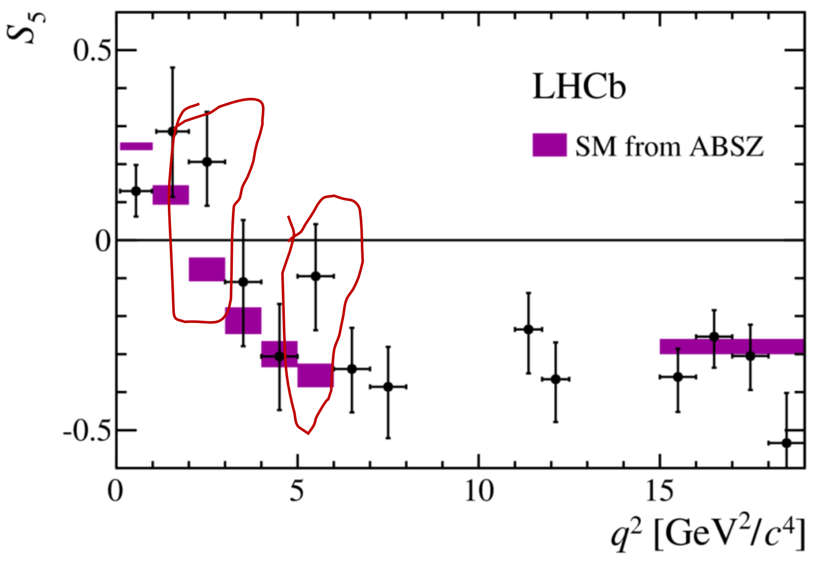
$$A_i = (I_i - \bar{I}_i) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}q^2}\right)$$

q^2 dependent CP averages and asymmetries !

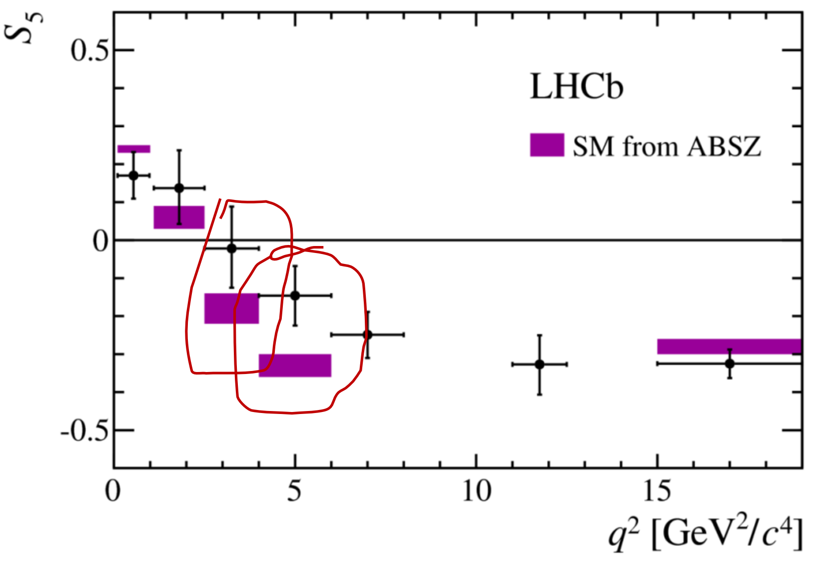
For detail, LHCb collaboration, JHEP 2016

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

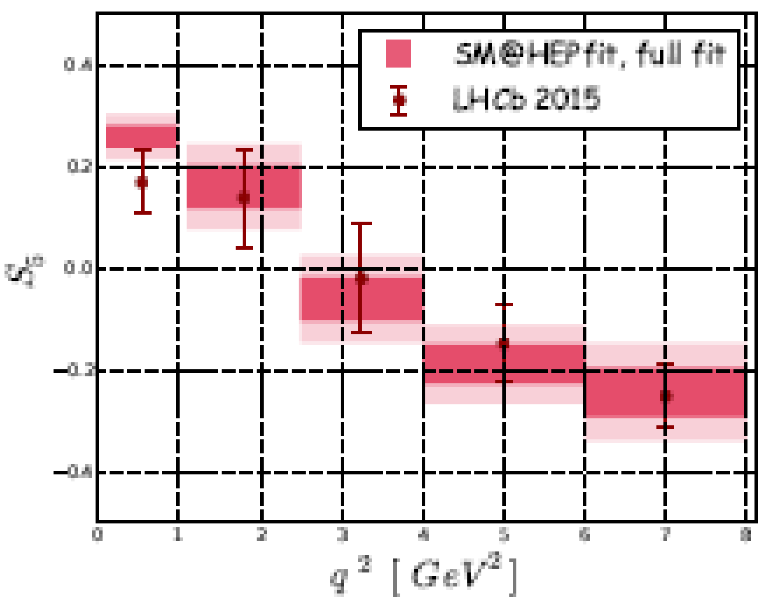
Instead of estimating the hadronic uncertainties from first principles or by some approximate methods, one can try to extract these from data and compare their size to other factorizable and SD contributions to estimate the legitimacy of their magnitude.

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 !**

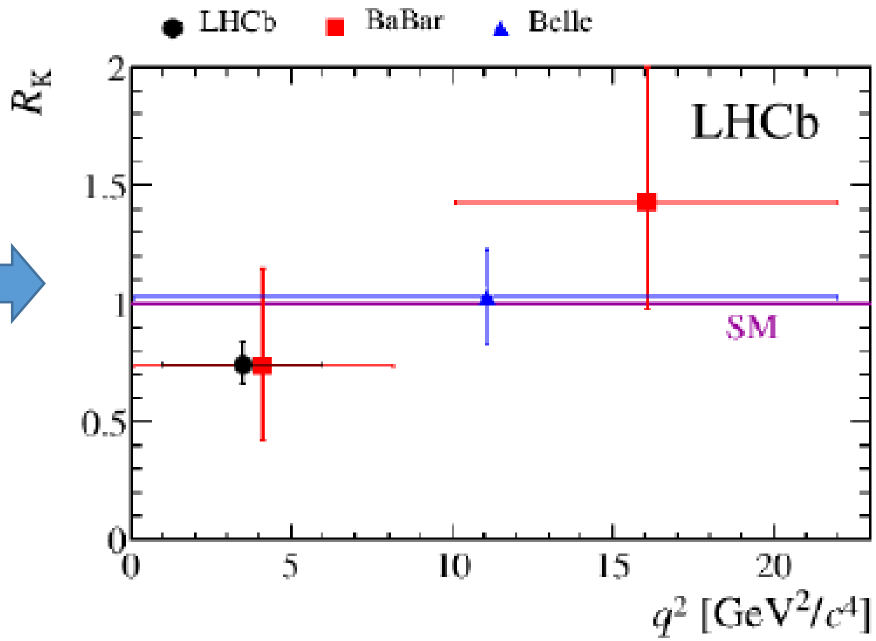
R_K in B -> K$\ell\ell$

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

In SM, $R_K \cong 1$

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

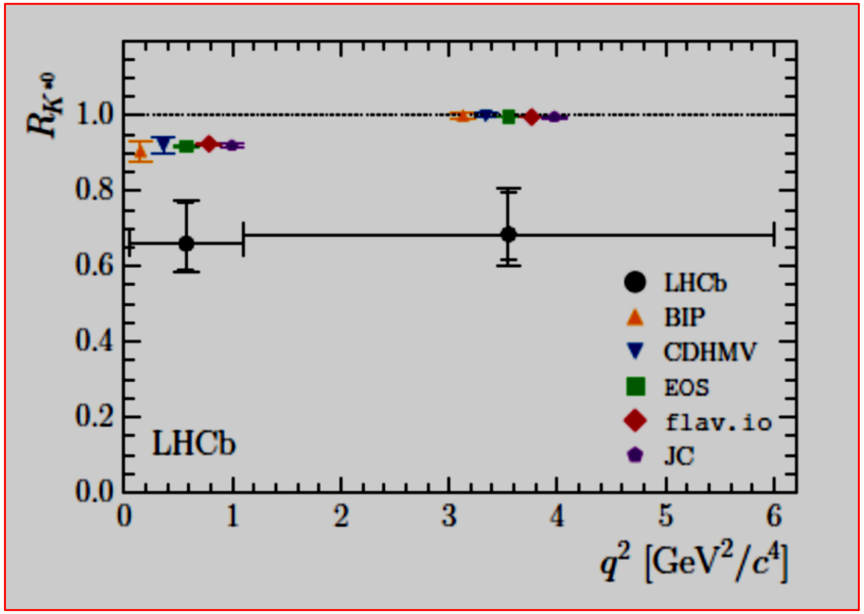
R_K measured in low q^2 regions is 3σ away from the SM !



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

LHCb 2017

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



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

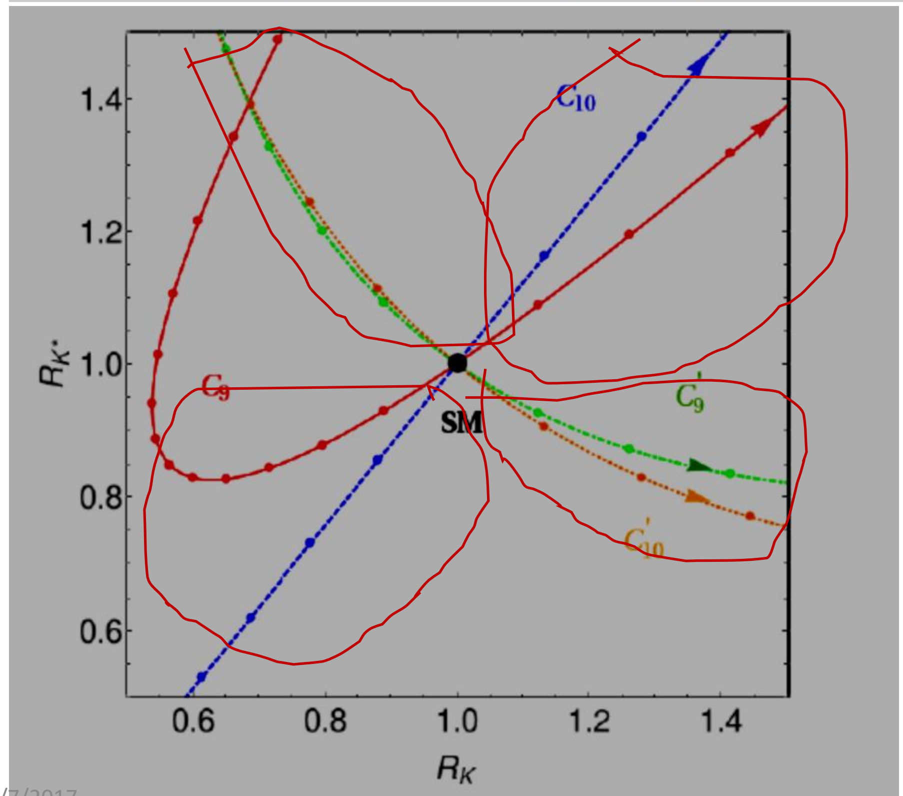
Data analysis

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

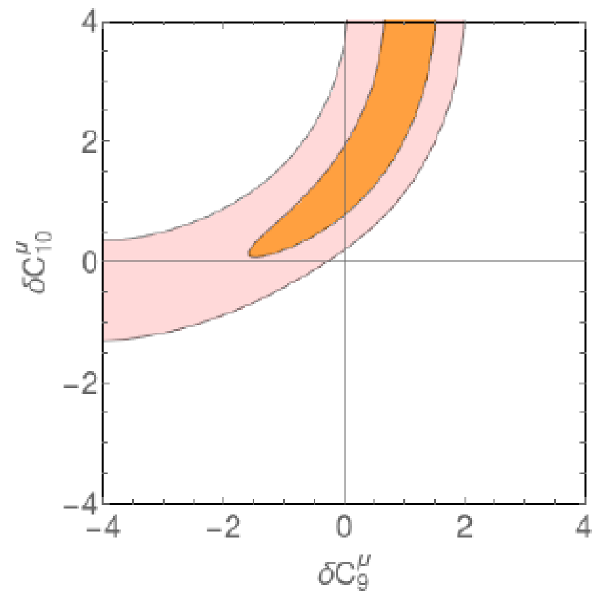
arXiv:1704.05446

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

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



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



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

➢ A simple dynamical model based on a $SU(2)_L$ triplet of massive vector bosons, coupled predominantly to third generation fermions (both quarks and leptons), can significantly improve the description of present data.

✓ It can explain R(D), R(D*), R(K), R(K*) and the tension between exclusive and inclusive determination of V_{ub} and V_{cb} !

The flavour structure of the new currents is consistent with an approximate $U(2)_q \times U(2)_L$ flavour symmetry acting on the first two generations of quarks and leptons, all the other fermions are singlet !

✓ Leading breaking terms to this symmetry are the two spurion doublets, which give rise to the mixing between 3rd and the first two generations !

arXiv:1506.01705v2, arXiv:1705.10729v1

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 !!

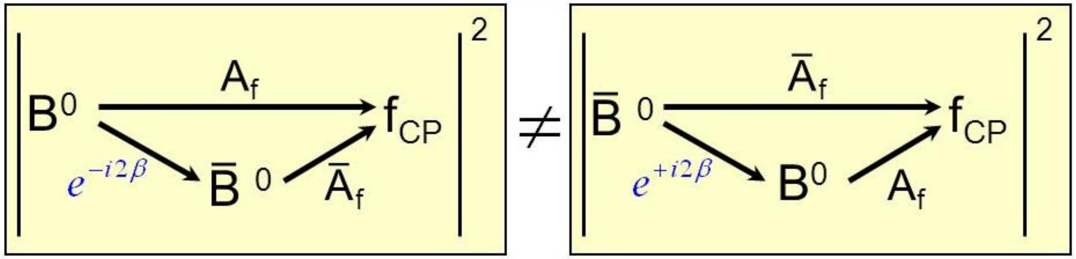
✓ The (V – A) structure of the quark current in the b -> s transition may come from a Z' penguin, where Z' will couple to muons and top quarks, and the flavor changing transition is predominantly due to a top-W penguin loop.

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

B_q–$\overline{B_q}$ mixing

CP Observables : B_d & B_s



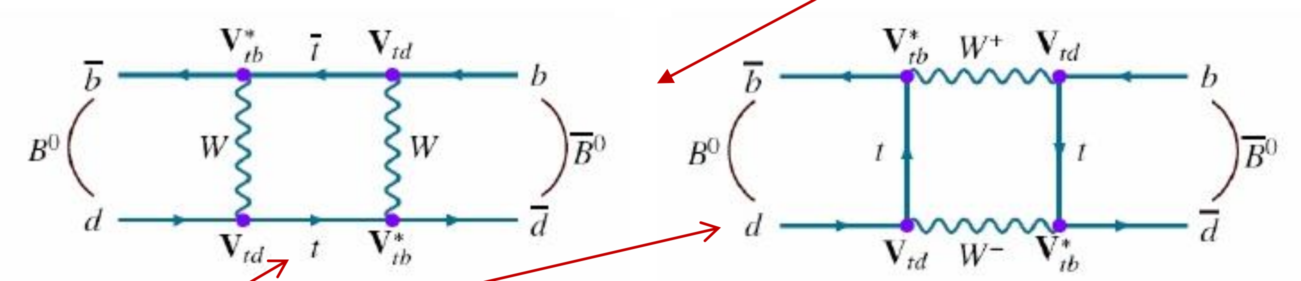
Mixing Induced CP asymmetry

$$\lambda_{f_{CP}} = -\eta_{CP} e^{-i2\beta} \frac{A(\bar{B}^0 \to f_{CP})}{A(B^0 \to f_{CP})}$$

$$\mathcal{A}_f(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0 \to f}(\Delta t) - \Gamma_{B^0 \to f}(\Delta t)}{\Gamma_{\bar{B}^0 \to f}(\Delta t) + \Gamma_{B^0 \to f}(\Delta t)} = \frac{2\,\mathrm{Im}(\lambda_f)}{1 + |\lambda_f|^2} \sin(\Delta m \Delta t) - \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \cos(\Delta m \Delta t)$$

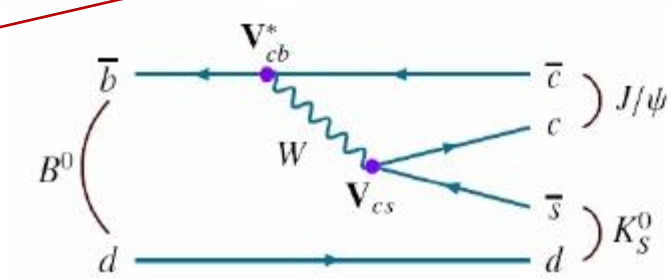
S_f

C_f



B_s system : similar diagrams with d->s

Relevant Diagrams



$\Delta m_d\, e^{-2i\beta}$

Other CP Obs.

Time dependent CP asymmetries in B_s -> f

Large

$$A_{CP,f}(t) = -\frac{A_{\rm CP}^{\rm dir}\cos(\Delta M_s t) + A_{\rm CP}^{\rm mix}\sin(\Delta M_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) + A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_s t}{2})}.$$

$$A_{\Delta\Gamma} = -\frac{2|\lambda_f|}{1+|\lambda_f|^2}\cos\left[\arg(\lambda_f)\right] = -\frac{2|\lambda_f|}{1+|\lambda_f|^2}\cos\left[\phi_s\right]$$

Hard to measure in B_d decays since $\Delta\Gamma_d$ is expected to be small !

Semileptonic CP asymmetries in B_d & B_s

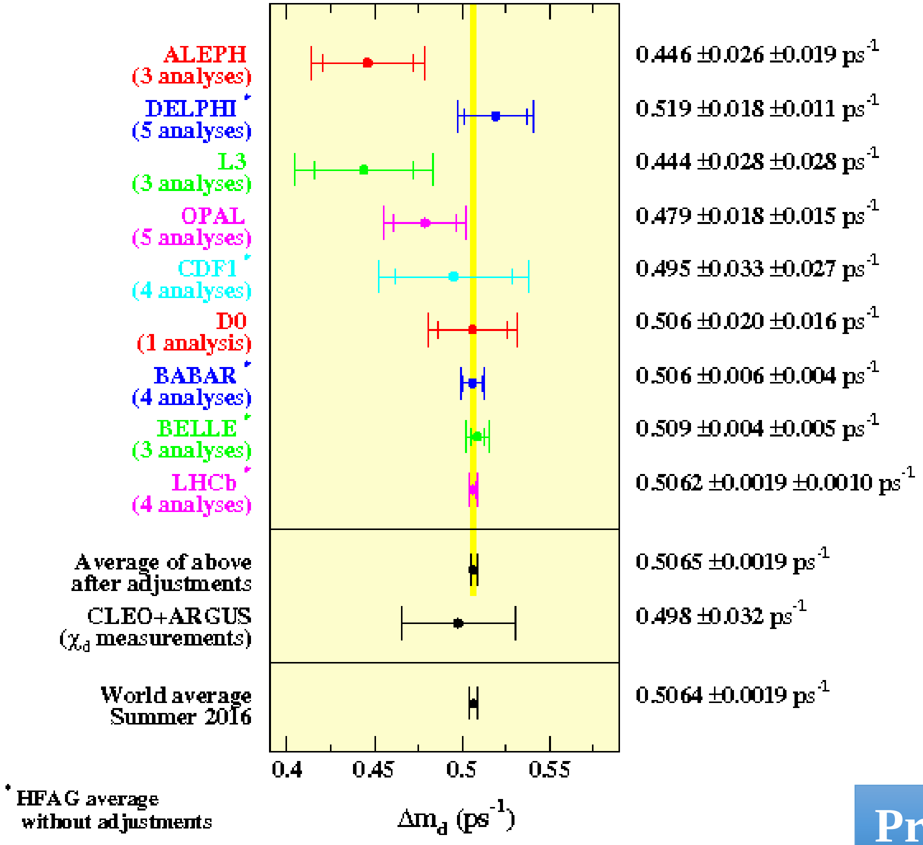
$$a_{sl}^q \equiv a_{fs}^q = \frac{\Gamma\left(\overline{B}_q(t)\to f\right) - \Gamma\left(B_q(t)\to \overline{f}\right)}{\Gamma\left(\overline{B}_q(t)\to f\right) + \Gamma\left(B_q(t)\to \overline{f}\right)} = \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right|\sin\phi_q$$

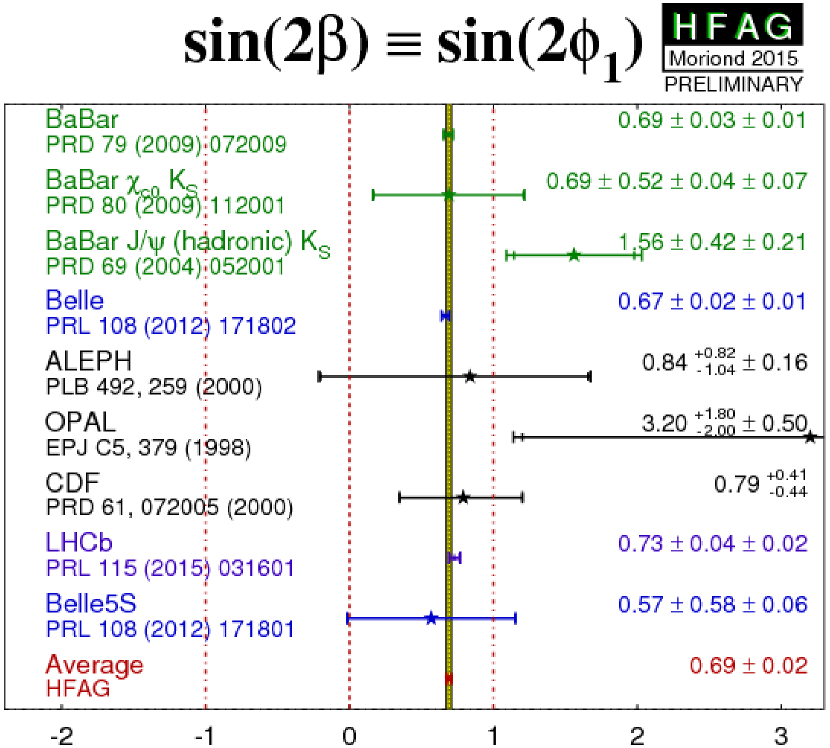
Di-muon asymmetry

C_d and C_s are roughly equal !

$$A_{CP} = C_d a_{\rm sl}^d + C_s a_{\rm sl}^s + \frac{1}{2}C_{\Delta\Gamma_d}\frac{\Delta\Gamma_d}{\Gamma_d}$$

Δm_d & Sin(2β) (Exp.)



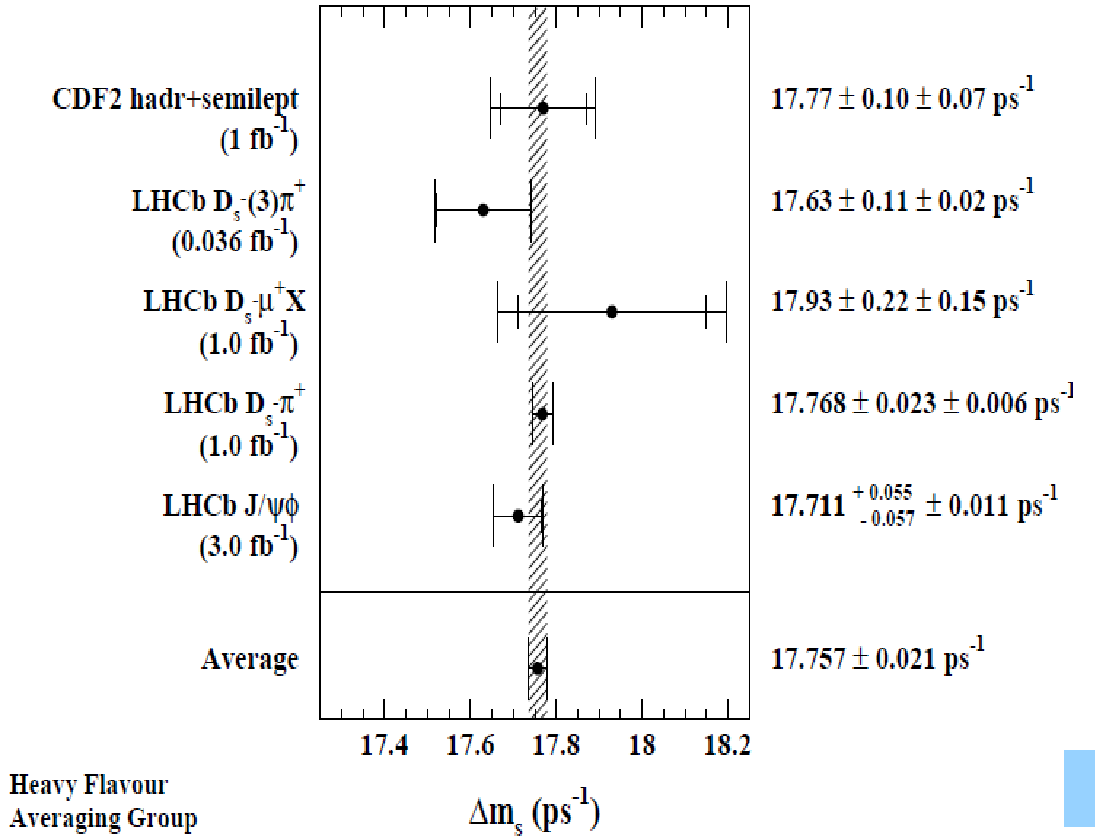


Prediction → $\mathrm{Sin}2\beta = 0.724 \pm 0.028$

$$\Delta M_d^{\rm SM} = 0.543 \pm 0.091\ \mathrm{ps}^{-1}$$

Measured values

B_s - mixing

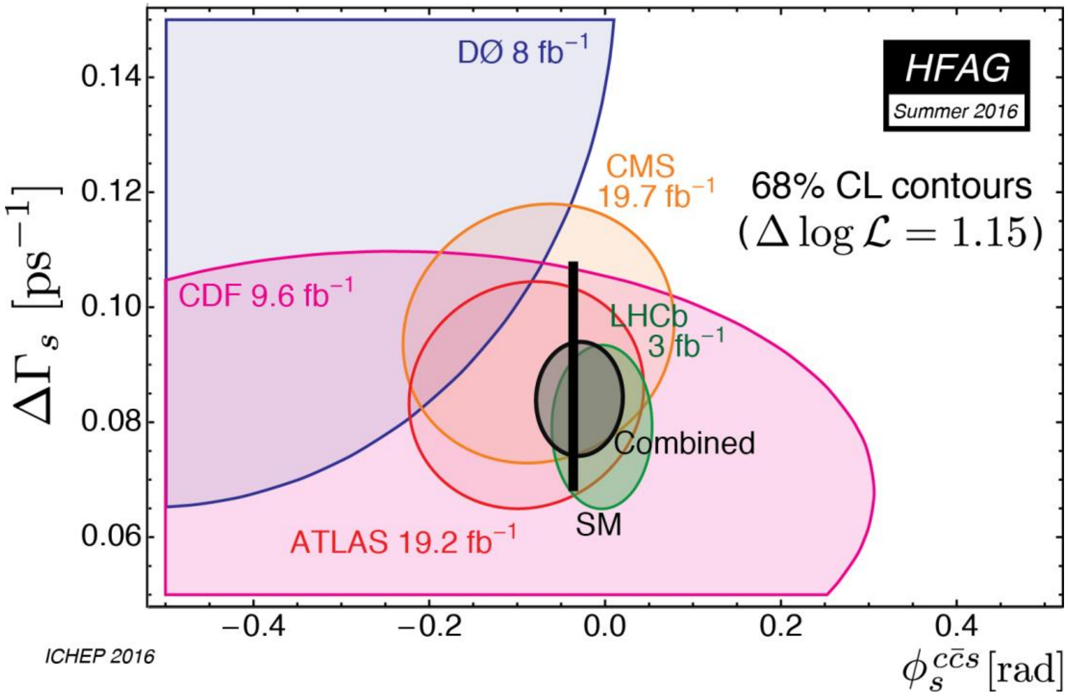


$$\Delta M_s^{\mathrm{SM},2015} = (18.3 \pm 2.7)\ \mathrm{ps}^{-1}$$

Measured value is consistent with the SM predictions

Measured CP phase

CP phase and it's correlation with $\Delta\Gamma_s$



$$\Delta\Gamma_s^{\mathrm{SM},2015} = (0.088 \pm 0.020)\ \mathrm{ps}^{-1}$$

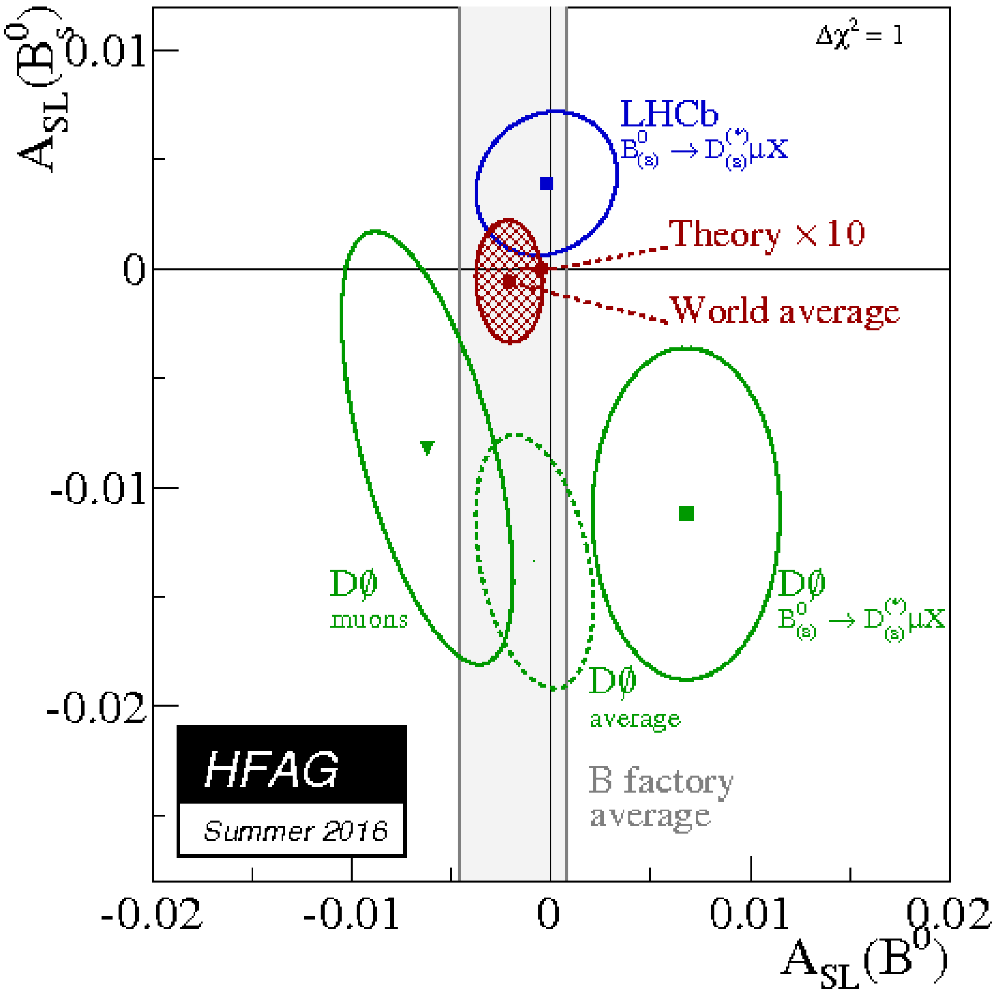
$$\phi_s^{\mathrm{SM}} = (2.1 \pm 0.1)^\circ$$

World average:
$\Delta\Gamma_s$ = (0.086 ± 0.006) ps^{-1}

$\emptyset_s$ = −0.030 ± 0.033

- ✓ The combined fit along with correlations between $\Delta\Gamma_s$ and $\emptyset_s$ are consistent with the SM predictions

Correlations between the asymmetries in B_d and B_s



Experiment	measured a^d_{sl} (%)
LHCb $D^{(*)}\mu\nu X$	$-0.02 \pm 0.19 \pm 0.30$
D0 $D^{(*)}\mu\nu X$	$+0.68 \pm 0.45 \pm 0.14$
BaBar $D^*\ell\nu X$	$+0.29 \pm 0.84^{+1.88}_{-1.61}$
BaBar $\ell\ell$	$-0.39 \pm 0.35 \pm 0.19$

World averages

$$a^s_{sl} = -0.0006 \pm 0.0028$$

$$a^d_{sl} = -0.0021 \pm 0.0017$$

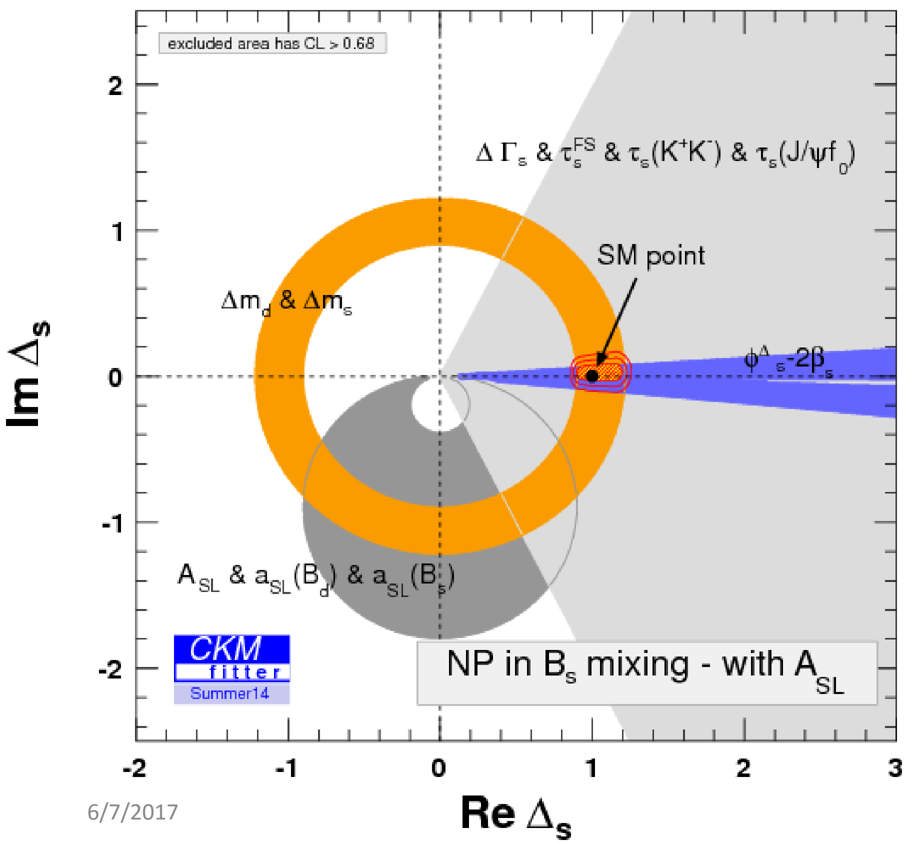
Although the measured values are consistent with the SM within the uncertainties, a deviation from the SM predictions by 0.5σ is obtained because of the correlation.

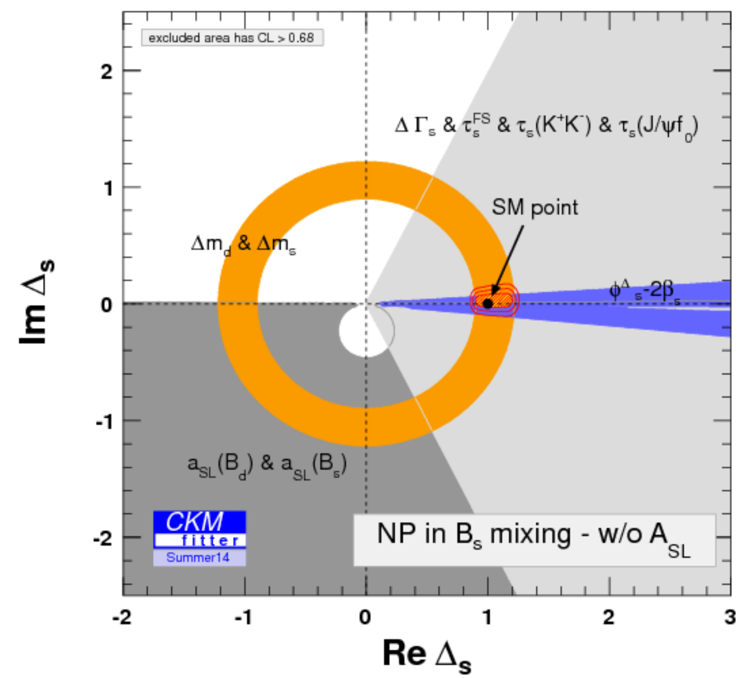
Constraints on NP in B_s

Model independent approach

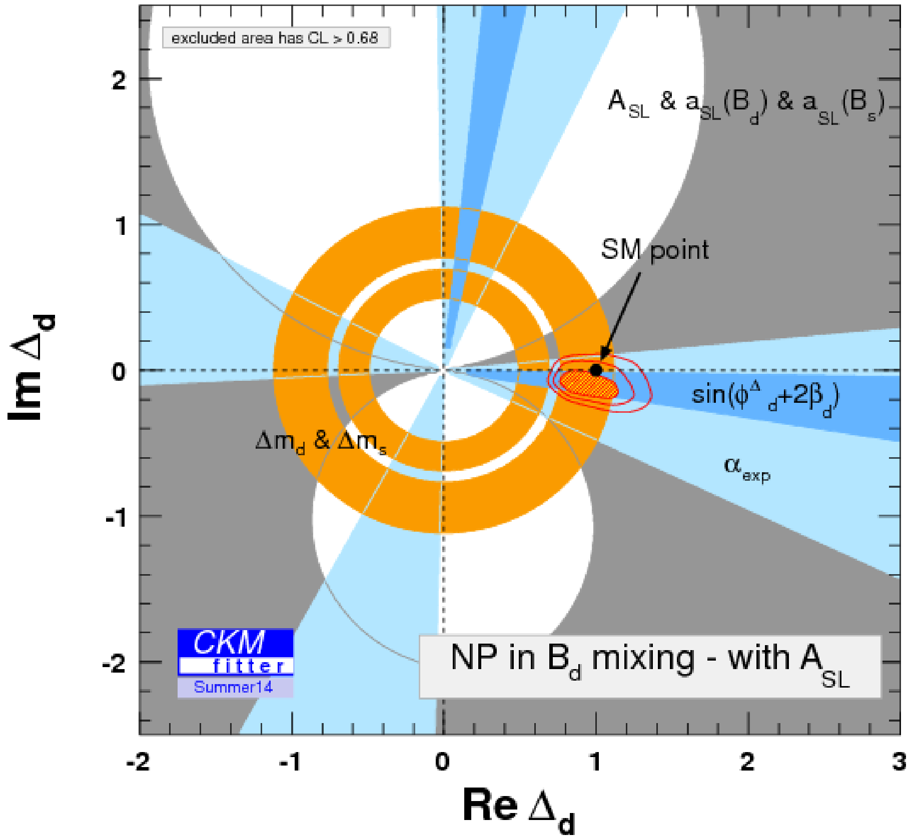
$$M_{12}^s = M_{12}^{s,\mathrm{SM}} |\Delta_s| e^{i\phi_s^\Delta} ,$$
$$\Gamma_{12}^s = \Gamma_{12}^{s,\mathrm{SM}} .$$

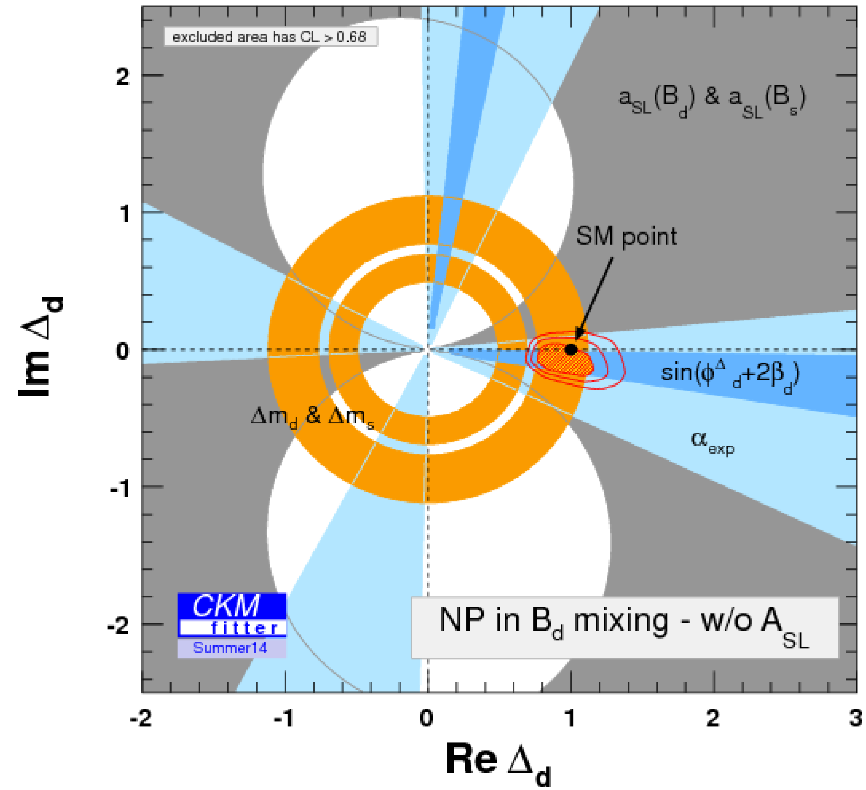
$$\Delta M_s^{\mathrm{Exp}} = 2 \left| M_{12}^{s,\mathrm{SM}} \right| \cdot |\Delta_s| ,$$
$$\Delta \Gamma_s^{\mathrm{Exp}} = 2 \left| \Gamma_{12}^{s,\mathrm{SM}} \right| \cos\left(\phi_{12}^{s,\mathrm{SM}} + \phi_s^\Delta\right) ,$$
$$a_{sl}^{s,\mathrm{Exp}} = \frac{\left|\Gamma_{12}^{s,\mathrm{SM}}\right|}{\left|M_{12}^{s,\mathrm{SM}}\right|} \cdot \frac{\sin\left(\phi_{12}^{s,\mathrm{SM}} + \phi_s^\Delta\right)}{|\Delta_s|} .$$





NP in B_d





No significant deviations from the SM are visible , however, **30% to 40% NP** contributions in B_d and B_s sector are still allowed at 3σ

OUT LOOK

- The deficits with respect to expectations reported by the LHCb experiment in muon-to-electron ratios of the B-> $K^{(*)}$ $\ell\ell$ 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.

- Left-handed four-fermion operators are also the most natural candidates to build a connection between anomalies in charged and neutral current semileptonic processes.

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

Back up slides

Kinematical cuts!

- There are three main kinematical cuts which separate the $b \to u\ell^{-}\nu$ signal from the $b \to c\ell^{-}\nu$ background:

1. A cut on the lepton energy $E_\ell > (M_B^2 - M_D^2)/2M_B$, 10% of the signal selected !
2. A cut on the hadronic invariant mass $q^2 > M_B^2 - M_D^2$, 80% ……………………!
3. A cut on the leptonic invariant mass $M_X < M_D$, 20%……………………!

✓Forces us into the corner of the phase space …required to introduce shape functions!

$$\frac{d^3\Gamma}{dp_X^+\,dp_X^-\,dE_\ell} = \frac{G_F^2|V_{ub}|^2}{192\pi^3}\int dk\, C(E_\ell, p_X^-, p_X^+, k)\, F(k) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$$

$$p_X^+ = E_X - |\mathbf{p}_X|, \qquad p_X^- = E_X + |\mathbf{p}_X|,$$

Perturbatively calculable functions

Non-perturbative Shape function

Uncertainties due to unknown higher order corrections !

1. From comparison with B-> $X_s\gamma$ (L.O.)
2. From the knowledge of the moments !
3. Modelling !

Recent updates and comments on R(D*)

SM predictions for R(D) based on recent Lattice calculations:

- R(D) = 0.299 $\pm$ 0.011, J.A.Bailey et al. [FNAL/MILC Collaboration], PRD 2015
- R(D) = 0.300 $\pm$ 0.008, H. Na et al., PRD(2015)

✓ Combining the two calculation above (FLAG Working Groups) : **R(D) = 0.300 $\pm$ 0.008**

P. Gambino and D. Bigi in arXiv:1606.08030 [hep-ph] (PRD 2016) combined the two lattice calculations, wih the experimental Form Factor of the B→ D l ν from BaBar (2010) and Belle (2016), and they have obtained **R(D)=0.299+-0.003.**

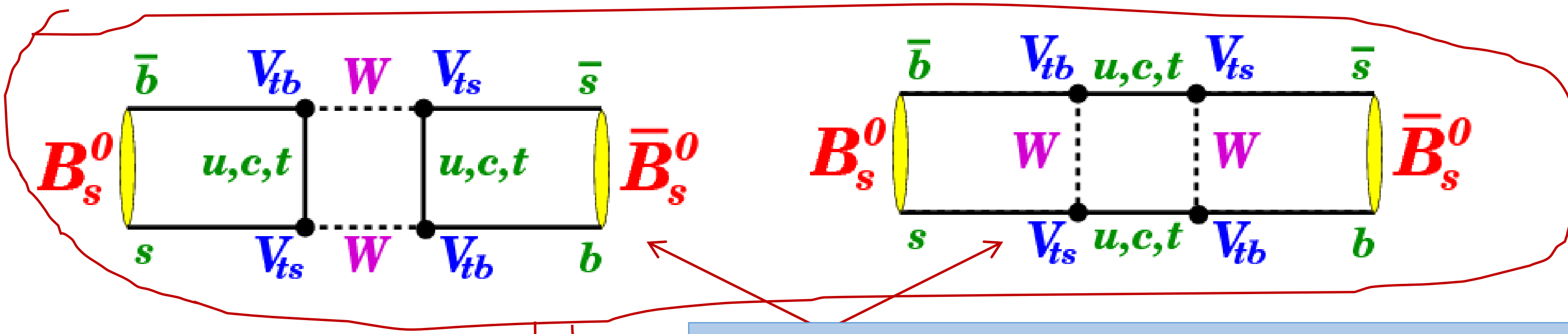
✓ The result is compatible with the results above, but more accurate.

- The SM prediction for **R(D*) =0.252 $\pm$ 0.003**, S.Fajfer, J.F.Kamenik, and I.Nisandzic, PRD(2012)

✓ The prediction depends on the formfactor parameter $R_0(1)$, the estimate of which rely on exact HQET relations !

❖ The error could be larger than what has been estimated !

CP asymmetry in B_s



Due to weak interaction B_s can transform to anti-B_s and vice versa .

$$\Delta M_s := M_H^s - M_L^s$$
$$= 2\,|M_{12}^s| \left(1 - \frac{|\Gamma_{12}^s|^2 \sin^2 \phi_{12}^s}{8\,|M_{12}^s|^2} + \ldots\right)$$

$$\Delta\Gamma_s := \Gamma_L^s - \Gamma_H^s$$
$$= 2\,|\Gamma_{12}^s| \cos\phi_{12}^s \left(1 + \frac{|\Gamma_{12}^s|^2 \sin^2 \phi_{12}^s}{8\,|M_{12}^s|^2} + \ldots\right)$$

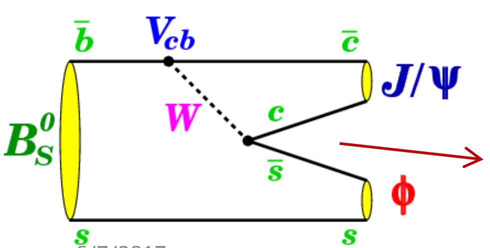
Dispersive part → $M_{12}^s = |M_{12}^s| e^{i\phi_M}$, → $e^{i\phi_M} = \frac{V_{ts}^* V_{tb}}{V_{ts} V_{tb}^*}$

Absorptive part → $\Gamma_{12}^s = |\Gamma_{12}^s| e^{i\phi_\Gamma}$.

$$\phi_{12}^s := \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right) = \pi + \phi_M - \phi_\Gamma$$

There can also be new physics contributions to Γ_{12}^s, e.g. by modified tree-level operators or by new $bs\tau\tau$-operators, as discussed below.

Dighe, Kundu, SN, Bauer, Haisch, Bobeth …



$$\phi_s = -\arg(\lambda_f) = -\arg\left(\frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right)$$
$$= -\pi + \phi_M - \arg\left(\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right) .$$

SM predictions

Mass and Life time differences between heavy light mass eigenstates

$$\Delta M_s^{\mathrm{SM},2015} = (18.3 \pm 2.7)\ \mathrm{ps}^{-1}$$

$$\Delta M_d^{\mathrm{SM},2015} = (0.528 \pm 0.078)\ \mathrm{ps}^{-1}$$

$$\Delta \Gamma_s^{\mathrm{SM},2015} = (0.088 \pm 0.020)\ \mathrm{ps}^{-1}$$

$$\Delta \Gamma_d^{\mathrm{SM},2015} = (2.61 \pm 0.59) \cdot 10^{-3}\ \mathrm{ps}^{-1}$$

Semileptonic CP asymmetris

$$a_{\mathrm{fs}}^{d,\mathrm{SM},2015} = (-4.7 \pm 0.6) \cdot 10^{-4}\ ,$$
$$\phi_{12}^{d,\mathrm{SM},2015} = (-0.096 \pm 0.025)\ \mathrm{rad} = -5.5^\circ \pm 1.4^\circ\ .$$

$$a_{\mathrm{fs}}^{s,\mathrm{SM},2015} = (2.22 \pm 0.27) \cdot 10^{-5}$$

$$\phi_{12}^{s,\mathrm{SM},2015} = (4.6 \pm 1.2) \cdot 10^{-3}\ \mathrm{rad} = 0.26^\circ \pm 0.07^\circ\ .$$

Moments

OPE parameters can be extracted from the moments of the differential distributions

Leptonic Energy Moments: $M_1^\ell = \frac{1}{\Gamma}\int dE_\ell\, E_\ell \frac{d\Gamma}{dE_\ell}; \qquad M_n^\ell = \frac{1}{\Gamma}\int dE_\ell\, \left(E_\ell - M_1^\ell\right)^n \frac{d\Gamma}{dE_\ell} \quad (n>1),$

Moments of Invariant Hadronic Mass:

$$M_1^X = \frac{1}{\Gamma}\int dM_X^2\,(M_X^2 - \bar{M}_D^2)\frac{d\Gamma}{dM_X^2}; \qquad M_n^X = \frac{1}{\Gamma}\int dM_X^2\,(M_X^2 - \langle M_X^2\rangle)^n \frac{d\Gamma}{dM_X^2} \quad (n>1),$$

$$M_n^\ell = \left(\frac{m_b}{2}\right)^n \left[\varphi_n(r) + \bar{a}_n(r)\frac{\alpha_s}{\pi} + \bar{b}_n(r)\,\frac{\mu_\pi^2}{m_b^2} + \bar{c}_n(r)\,\frac{\mu_G^2}{m_b^2} + \bar{d}_n(r)\,\frac{\rho_D^3}{m_b^3} + \bar{s}_n(r)\,\frac{\rho_{LS}^3}{m_b^3} + \ldots\right]$$

$$M_n^X = m_b^{2n}\sum_{l=0}\left[\frac{M_B - m_b}{m_b}\right]^l \left(E_{nl}(r) + a_{nl}(r)\frac{\alpha_s}{\pi} + b_{nl}(r)\frac{\mu_\pi^2}{m_b^2} + c_{nl}(r)\frac{\mu_G^2}{m_b^2} + d_{nl}(r)\frac{\rho_D^3}{m_b^3} + s_{nl}(r)\frac{\rho_{LS}^3}{m_b^3} + \ldots\right).$$

arXiv:hep-ph/0304132v2

$\mathbf{M}_n^l$ and $\mathbf{M}_n^x$ are highly sensitive to the quark masses and OPE parameters !

- Global fit to decay rate and moments extracts: $|V_{cb}|$, m_b, m_c, μ_π^2, μ_G^2, ρ_D^3, ρ_{LS}^3

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…)