Quark Flavour Physics

selected topics

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- Why?
- Where are we?
- Where would we like to go?

DESY THEORY WORKSHOP
29 September - 02 October 2015

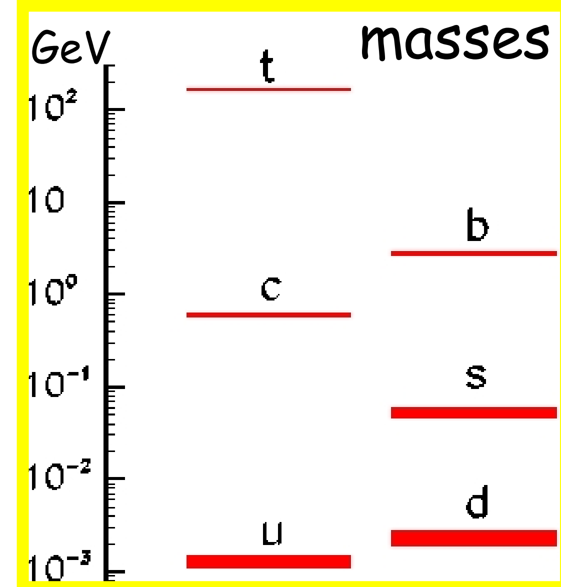
HELMHOLTZ ASSOCIATION

Physics at the LHC
and beyond

DESY

DESY Hamburg, Germany

Flavour physics in the SM: rich phenomenology (FCNC suppression, mixing, CP violation, …) but little understanding of the "why" and the "how"

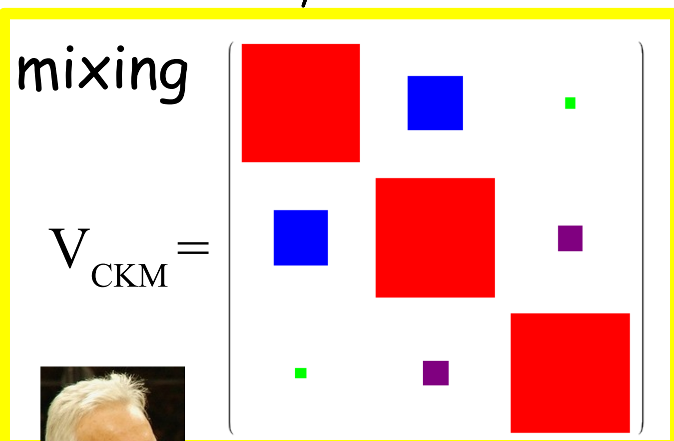


$$\mathcal{L}_{\mathrm{SM}} = \mathcal{L}_{\mathrm{EWSB}} + \mathcal{L}_{\mathrm{kin}} + \mathcal{L}_{\mathrm{gauge}} + \mathcal{L}_{\mathrm{Y}}$$

The Yukawa Lagrangian describes quark flavour physics in terms of 10 physical parameters:

6 masses, 3 mixing angles + 1 CPV phase

the Cabibbo-Kobayashi-Maskawa matrix



Beyond the SM: a powerful indirect probe of the New Physics scale Λ

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{\mathcal{L}_5}{\Lambda} + \frac{\mathcal{L}_6}{\Lambda^2} + \ldots$$

has accidental (approximate) symmetries

may violate accidental symmetries

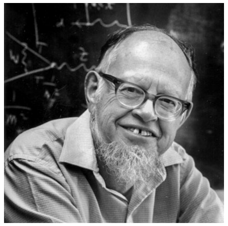
The CKM matrix in the SM

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{pmatrix} d & s & b \\ 0.9743(2) & 0.2250(6) & 3.6(1)\cdot 10^{-3} e^{-i68(3)^\circ} \\ -0.2250(6) e^{i0.035(1)^\circ} & 0.9734(2) e^{-i0.0019(1)^\circ} & 4.24(6)\cdot 10^{-2} \\ 8.8(2)\cdot 10^{-3} e^{-i22(1)^\circ} & -4.13(5)\cdot 10^{-2} e^{i1.06(4)^\circ} & 0.99911(2) \end{pmatrix}$$

Standard parametrization (PDG): s_{12}, s_{13}, s_{23}, δ

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

Wolfenstein parametrization: λ, A, ρ, η



$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

The CKM matrix in the SM

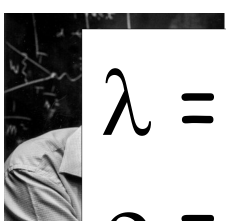
$$
\begin{array}{c} \\ u \\ c \\ t \end{array}
\begin{array}{c}
\begin{array}{ccc} \quad d \quad & \quad s \quad & \quad b \quad \end{array} \\
\begin{pmatrix}
0.9743(2) & 0.2250(6) & 3.6(1)\cdot 10^{-3}\, e^{-i\,68(3)^\circ} \\
-0.2250(6)\, e^{i\,0.035(1)^\circ} & 0.9734(2)\, e^{-i\,0.0019(1)^\circ} & 4.24(6)\cdot 10^{-2} \\
8.8(2)\cdot 10^{-3}\, e^{-i\,22(1)^\circ} & -4.13(5)\cdot 10^{-2}\, e^{i\,1.06(4)^\circ} & 0.99911(2)
\end{pmatrix}
\end{array}
$$

Standard parametrization (PDG): s_{12}, s_{13}, s_{23}, δ

$s_{12} = 0.2250 \pm 0.0006$ $\qquad$ $s_{23} = (4.205 \pm 0.053)\times 10^{-2}$

$s_{13} = (3.65 \pm 0.11)\times 10^{-3}$ $\qquad$ $\delta = (67.8 \pm 2.8)^\circ$

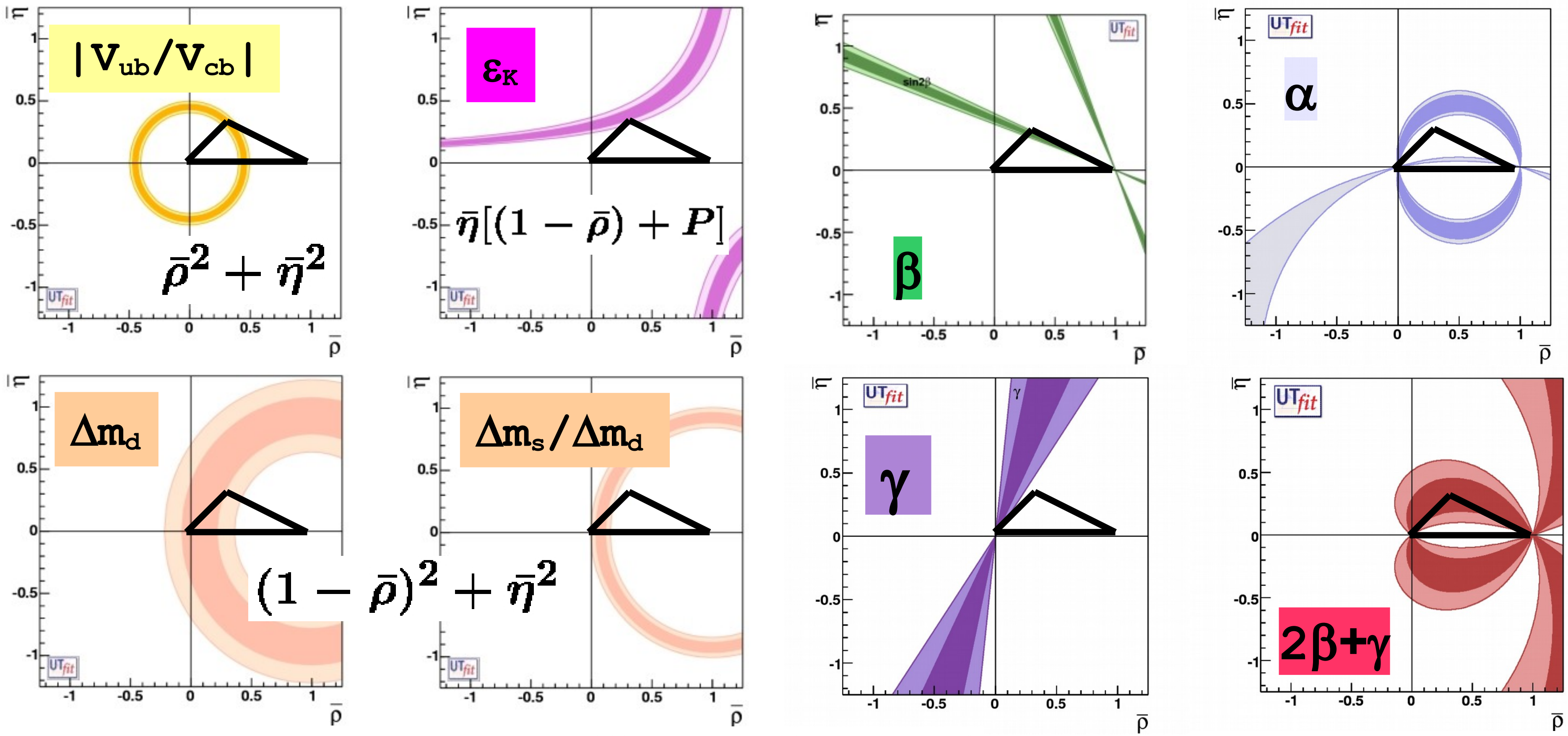
Wolfenstein parametrization: λ, A, ρ, η



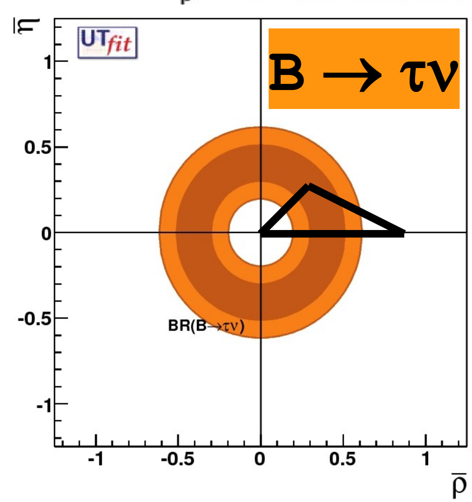
$\lambda = 0.2250 \pm 0.0006$ $\qquad$ $A = 0.829 \pm 0.012$

$\rho = 0.145 \pm 0.019$ $\qquad$ $\eta = 0.357 \pm 0.013$

Unitarity Triangle analysis: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$



Original goal:
- determine the UT apex and the CKM matrix parameters



Overconstrained fit:
- predict observables, hadronic parameters and constrain NP

SM results

Summer 2015

SM determination of the Unitarity Triangle

$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$

$R_u\, e^{i\gamma} + R_t\, e^{-i\beta} = 1$

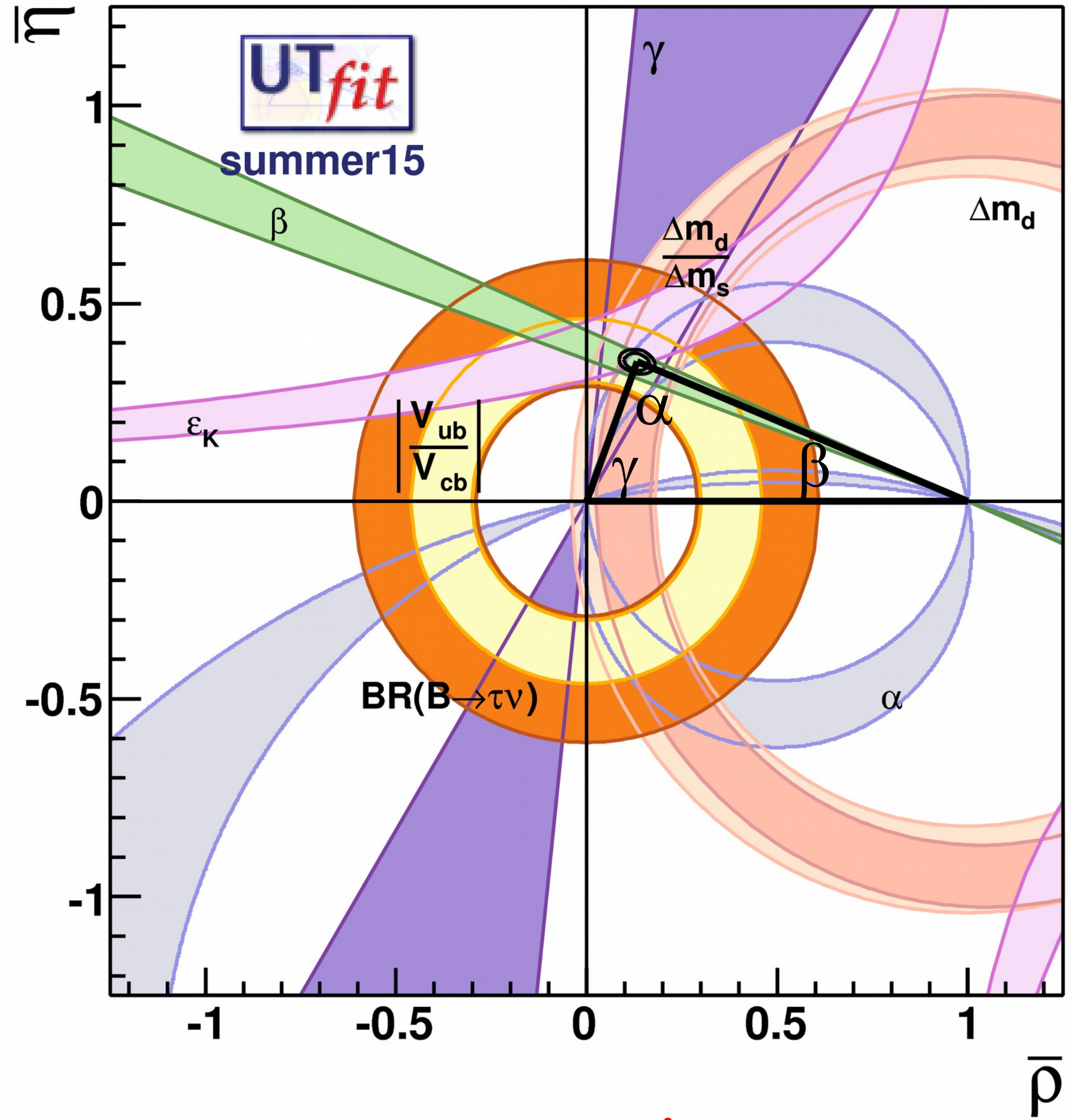
$R_u = 0.372 \pm 0.013$

$R_t = 0.917 \pm 0.022$

$\gamma = (67.7 \pm 2.8)^\circ$

$\beta = (22.04 \pm 0.85)^\circ$

$\alpha = (90.0 \pm 2.7)^\circ$



apex coordinates

$\bar{\rho} = 0.142 \pm 0.018$

$\bar{\eta} = 0.348 \pm 0.012$

SM predictions: B_d & K

	Measurement	%	Prediction	Pull(σ)
$\sin 2\beta$	0.679±0.023	3.5	0.746±0.039	+1.5
γ [°]	71.4±6.5	9	66.9±3.0	< 1
α [°]	92.5±5.5	6	88.1±3.4	< 1
$\lvert V_{cb}\rvert \cdot 10^3$	40.8±1.1	3	42.4±0.6	+1.1
$\lvert V_{ub}\rvert \cdot 10^3$	3.8±0.4	11	3.64±0.12	< 1
$\varepsilon_K \cdot 10^3$	2.228±0.011	0.5	2.03±0.18	-1.1
$BR(B\rightarrow \tau\nu)\cdot 10^{-4}$	1.06±0.20	20	0.81±0.07	-1.3

V_{cb} and V_{ub}

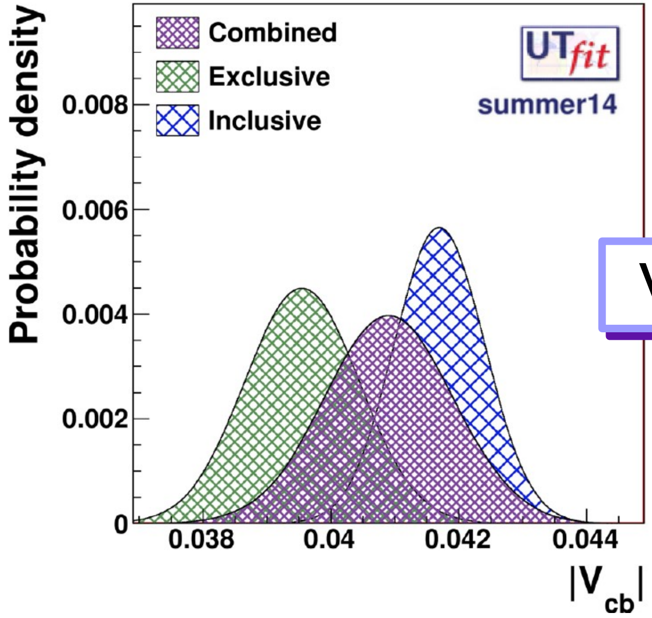
UTfit average

V_{cb} *(excl)* = (39.2 ± 0.7) 10^{-3}

PDG 2014

V_{cb} *(incl)* = (42.2 ± 0.7) 10^{-3}

~3σ discrepancy



UTfit input value: average à la PDG

V_{cb} = (40.8 ± 1.1) 10^{-3}

uncertainty ~ 2.7%

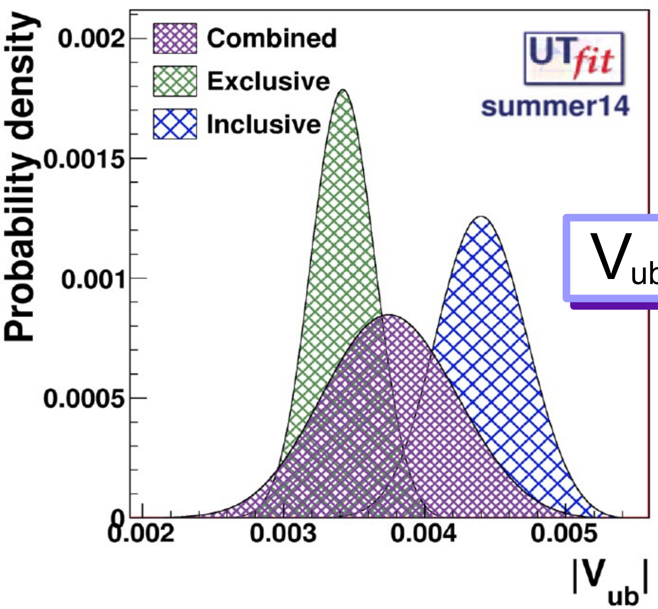
UTfit average

V_{ub} *(excl)* = (3.69 ± 0.15) 10^{-3}

PDG 2014

V_{ub} *(incl)* = (4.40 ± 0.22) 10^{-3}

~2.7σ discrepancy



UTfit input value: average à la PDG

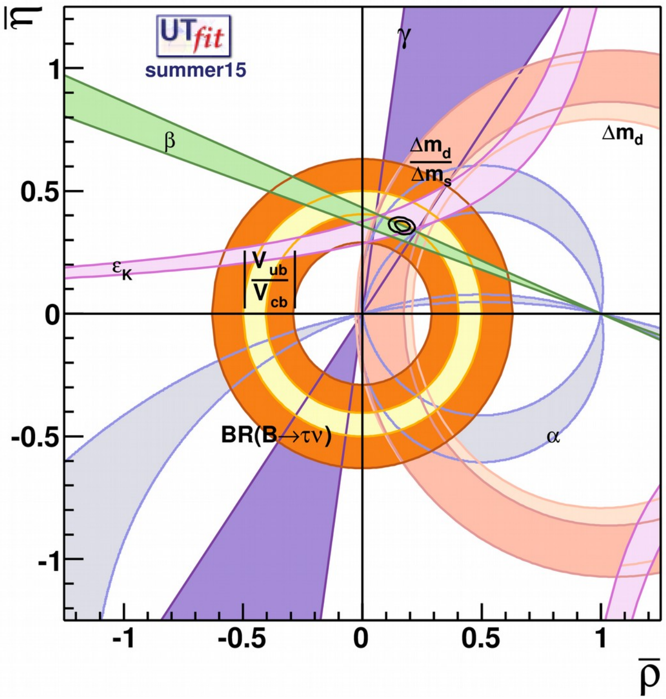
V_{ub} = (3.80 ± 0.40) 10^{-3}

uncertainty ~ 11%

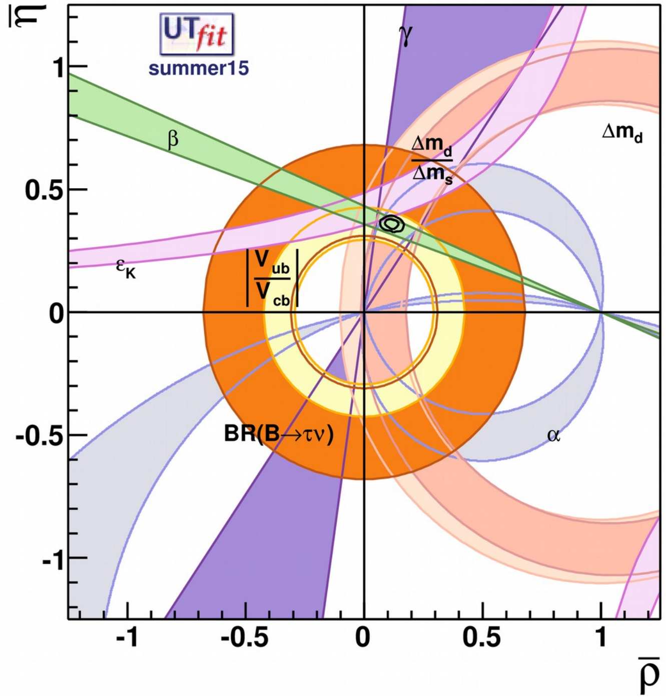
+ $\Lambda_b \to p\mu\nu$ exclusive semileptonic decay @LHCb

$|V_{ub}/V_{cb}| = 0.083 \pm 0.006$

arXiv: 1504.01568



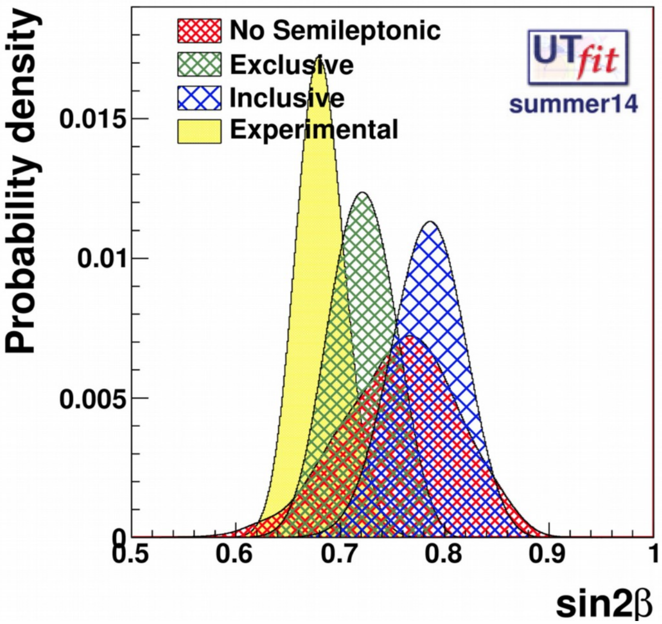
inclusive
vs
exclusive



only
inclusive
values

$\sin 2\beta_{fit}$ =
0.782 ± 0.028

~2.8σ



only
exclusive
values

$\sin 2\beta_{fit}$ =
0.725 ± 0.019

~1.6σ

$\sin 2\beta_{fit}$ = 0.76 ± 0.10* ← *no semileptonic*

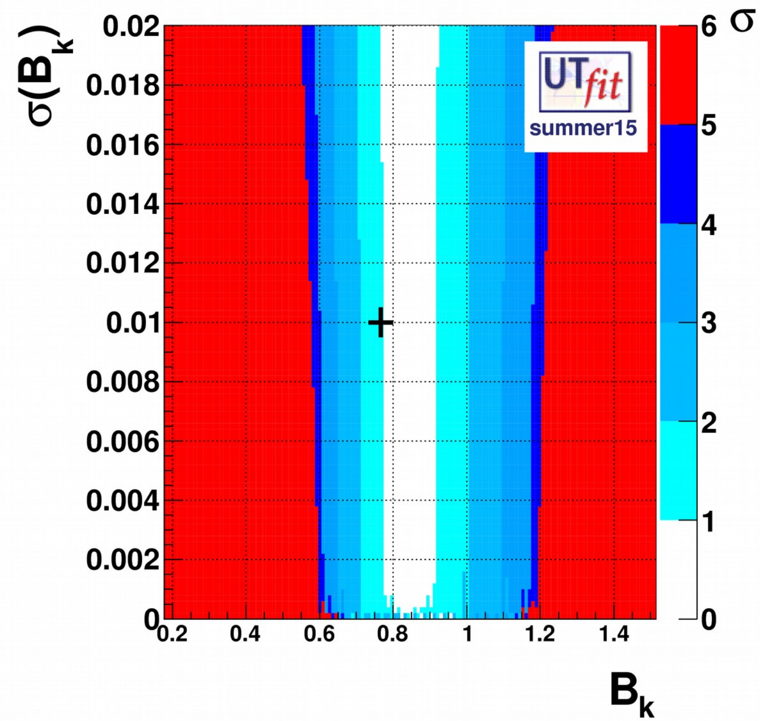
~0.8σ

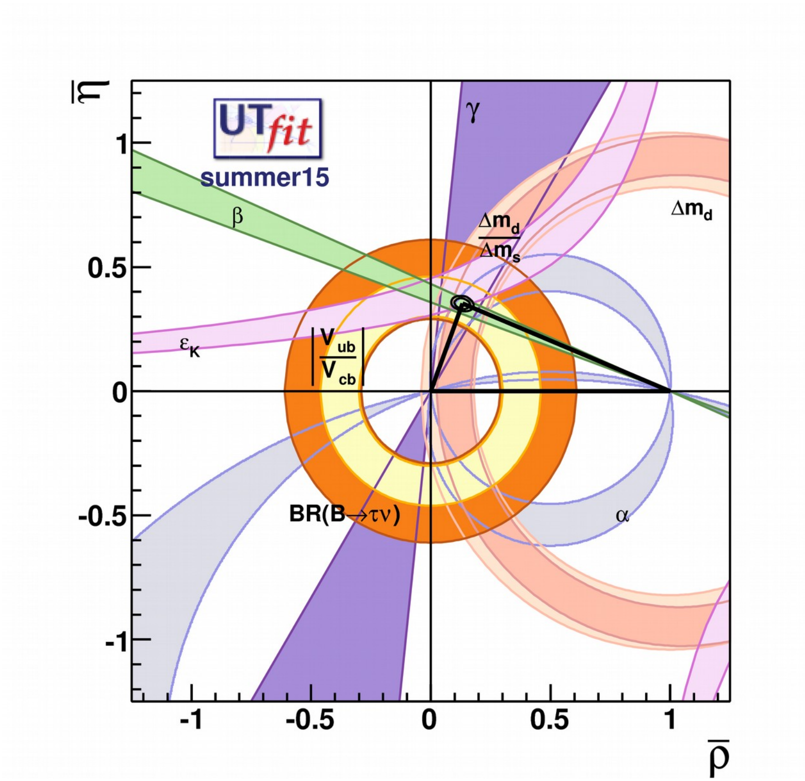
ε_K & B_K

$B_K^{lattice} = 0.766 \pm 0.010$

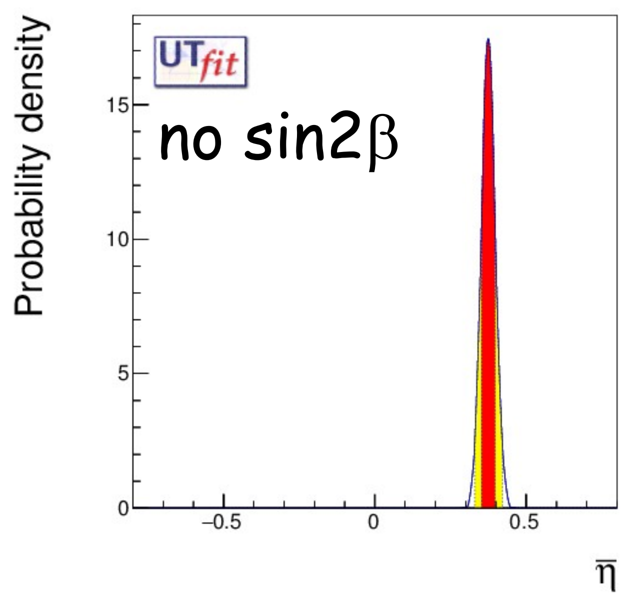
$B_k^{prediction} = 0.845 \pm 0.074$

~1σ

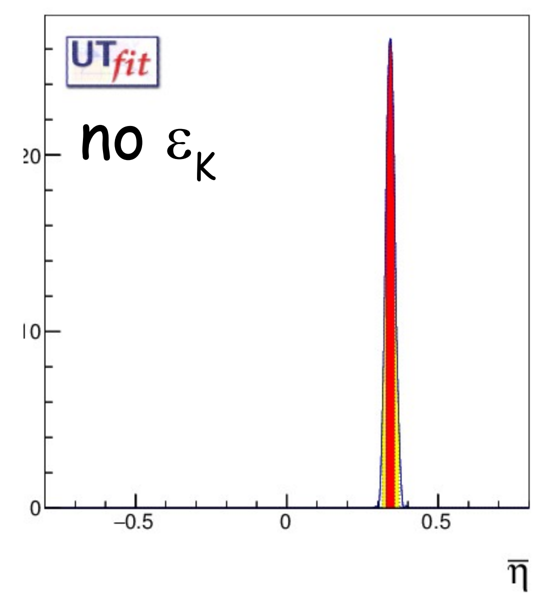




$\bar{\eta} = 0.375 \pm 0.023$



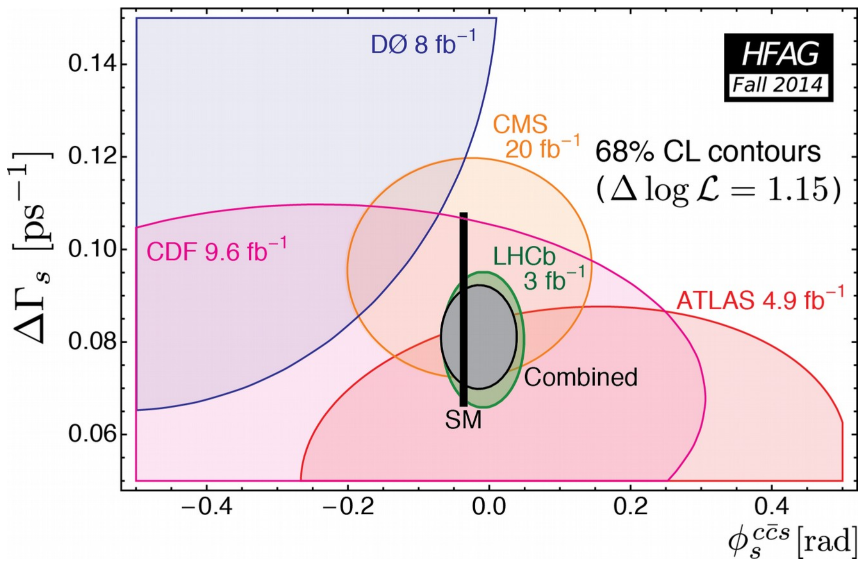
$\bar{\eta} = 0.343 \pm 0.015$

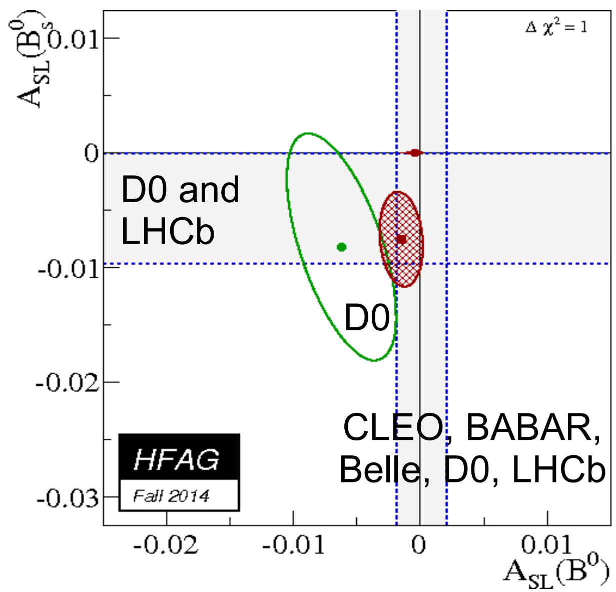


given $B_K^{lattice}$, ε_K calls for large A or η

SM predictions: B_s

	Measurement	%	Prediction	Pull (σ)
Δm_s [ps^{-1}]	17.761±0.022	0.1	17.3±1.0	< 1
β_s[°]	0.97±0.94	97	1.057±0.038	< 1
$\Delta\Gamma_s/\Gamma_s$	0.124±0.09	73	0.169±0.011	< 1
$A_{SL}^s \cdot 10^4$	-75±41	55	-0.13±0.01	+1.8





UT analysis beyond the SM

generic NP contributions to mixing amplitudes

		ρ,η	C_d	φ_d	C_s	φ_s	$C_{\varepsilon K}$
Tree processes	γ (DK)	X					
Tree processes	V_{ub}/V_{cb}	X					
1↔3 family	Δm_d	X	X				
1↔3 family	ACP (J/Ψ K)	X		X			
1↔3 family	ACP (Dπ(ρ),DKπ)	X		X			
1↔3 family	A_{SL}		X	X			
1↔3 family	α (ρρ,ρπ,ππ)	X		X			
1↔3 family	A_{CH}		X	X	X	X	
2↔3 family	τ(Bs), $\Delta\Gamma_s/\Gamma_s$				X	X	
2↔3 family	Δm_s				X		
2↔3 family	ASL(Bs)				X	X	
2↔3 family	ACP (J/Ψ φ)	~X				X	
1↔2 familiy	ε_K	X					X

K mixing amplitude (1 real param): $\mathrm{Im}\,A_K = C_\varepsilon \,\mathrm{Im}\,A_K^{SM}$

B_d and B_s mixing amplitudes (2+2 real parameters):

- two parametrizations -

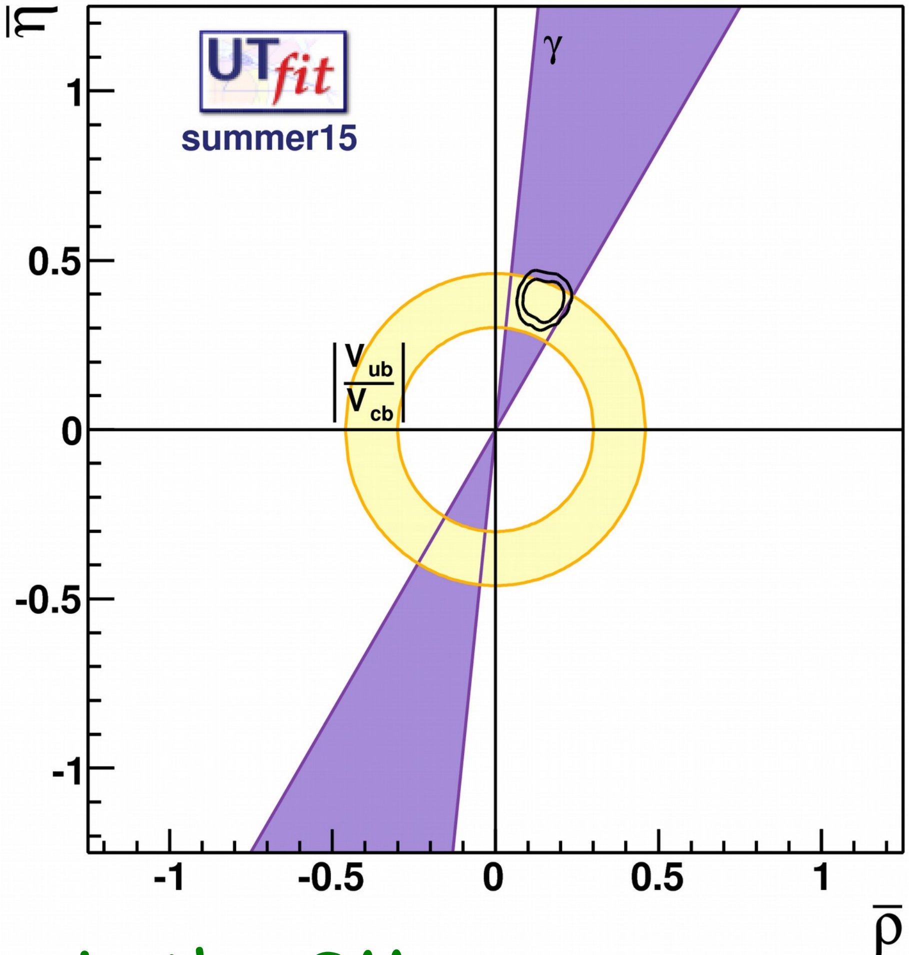
$q=d,s,\quad \varphi_d^{SM}=\beta,\quad \varphi_s^{SM}=-\beta_s$

$$A_q e^{2i\varphi_q} = C_{B_q} e^{2i\varphi_{B_q}} A_q^{SM} e^{2i\varphi_q^{SM}} = \left(1+\frac{A_q^{NP}}{A_q^{SM}} e^{2i(\varphi_q^{NP}-\varphi_q^{SM})}\right) A_q^{SM} e^{2i\varphi_q^{SM}}$$

UT parameters in the presence of NP

model-independent determination of the CKM parameters

assumptions:
* three generations
* negligible NP in tree decays



$\bar{\rho} = 0.147 \pm 0.043$

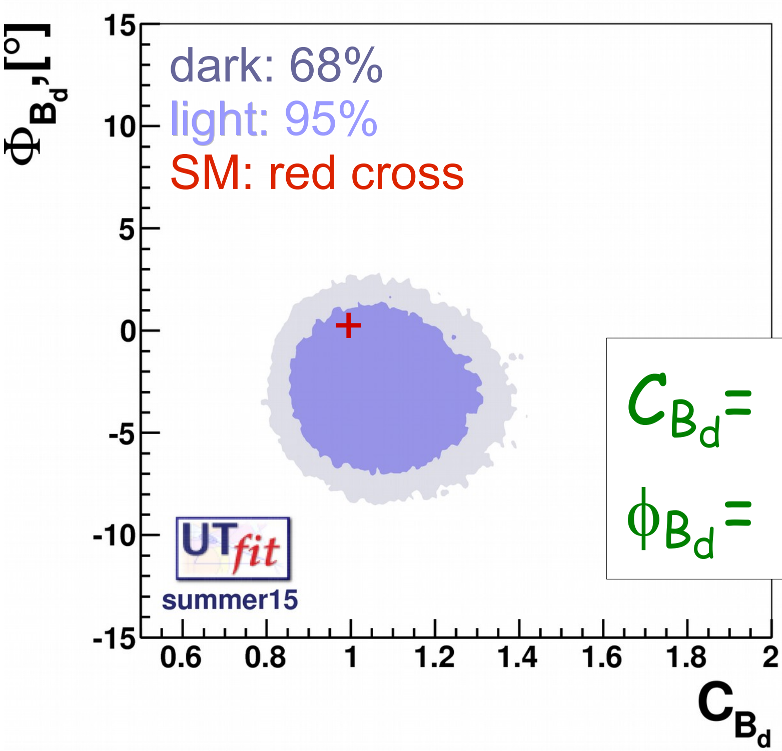
$\bar{\eta} = 0.384 \pm 0.044$

in the SM was:

$\bar{\rho} = 0.142 \pm 0.018$

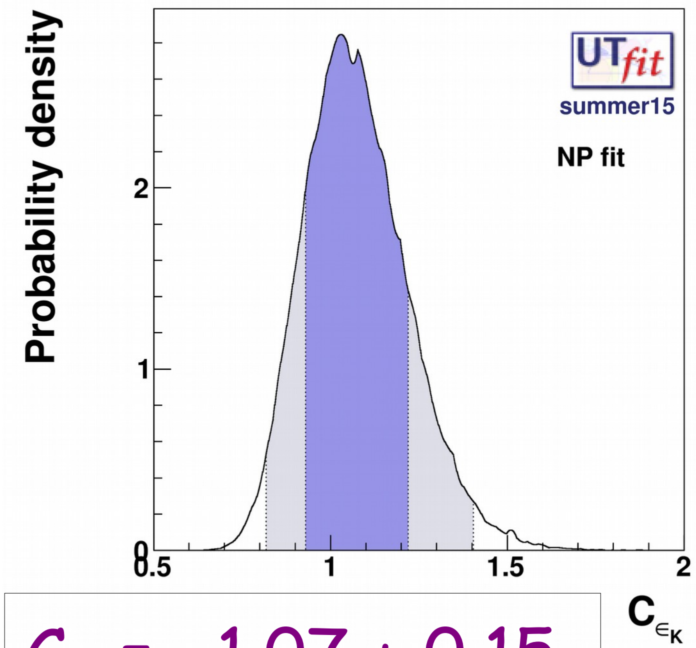
$\bar{\eta} = 0.357 \pm 0.013$

New Physics parameters



C_{B_d} = 1.09 ± 0.15

ϕ_{B_d} = (-2.9 ± 2.8)°



C_{ε_K} = 1.07 ± 0.15

$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

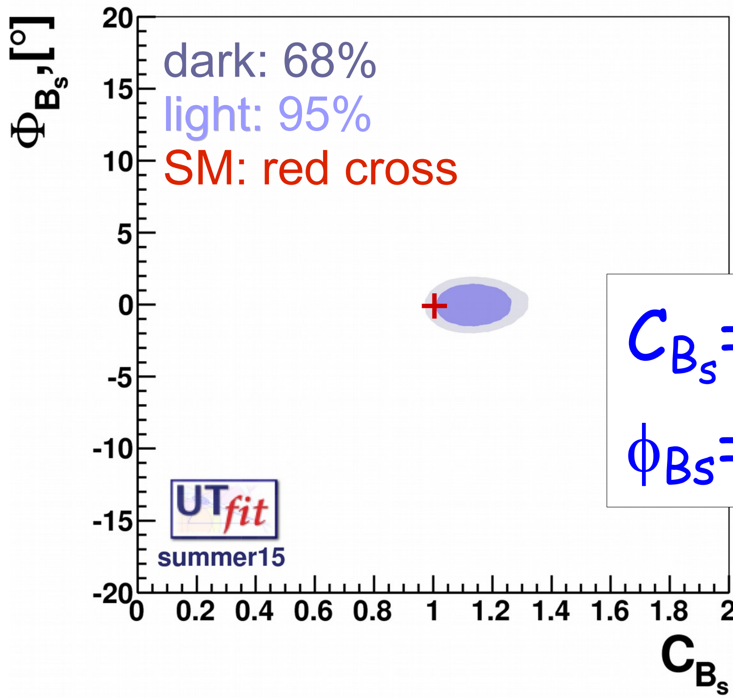
$$\Delta m_q = C_{B_q} (\Delta m_q)^{SM}$$

$$a_{CP}^{B_d \to J/\psi K_s} \to \sin 2(\beta + \varphi_{B_d})$$

$$a_{CP}^{B_s \to J/\psi \varphi} \to -\beta_s + \varphi_{B_s}$$

$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$

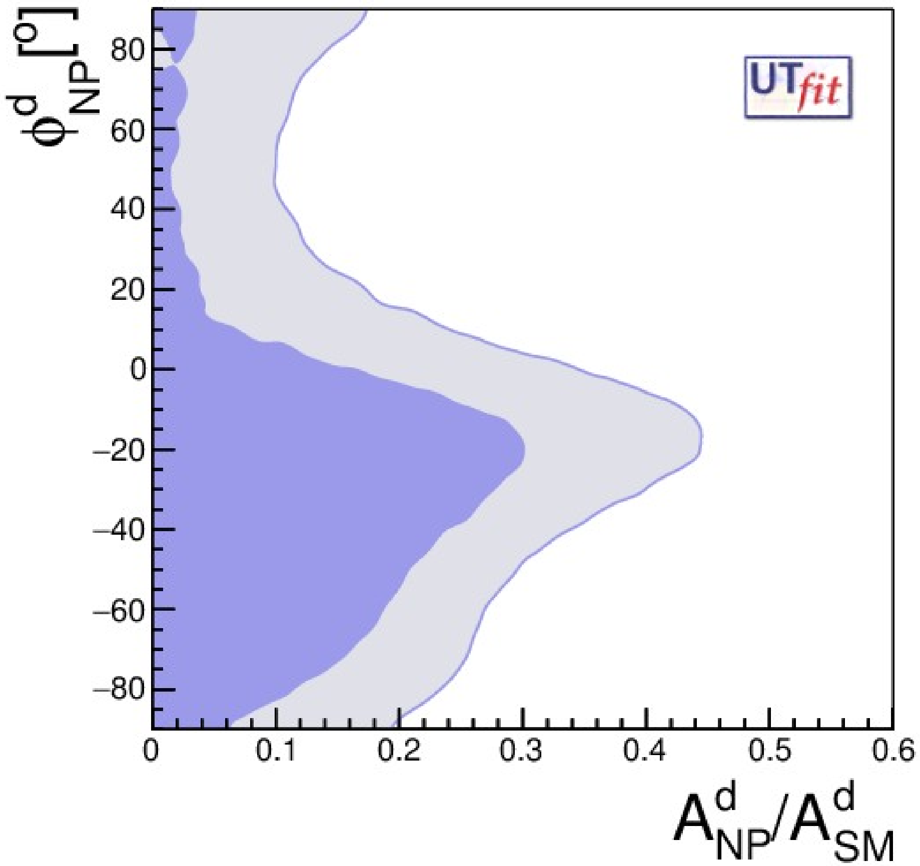
$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

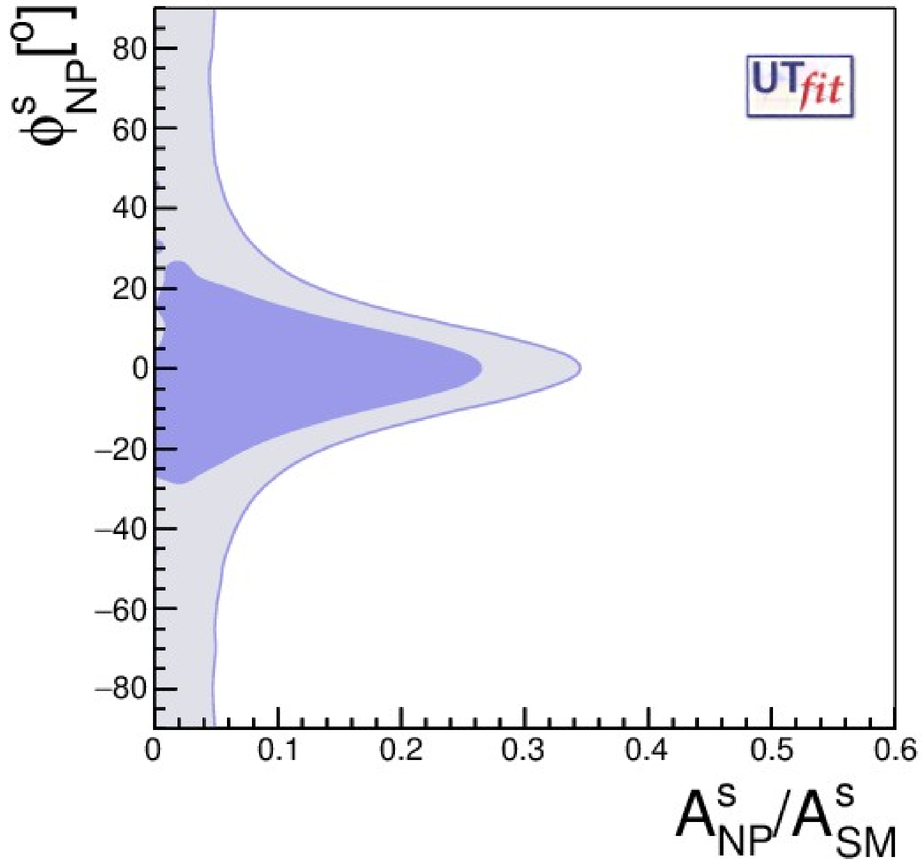


C_{B_s} = 1.14 ± 0.09

ϕ_{B_s} = (-0.03 ± 0.96)°

Implications for the NP amplitudes





The ratio of NP/SM amplitudes is:

< ~10% @68% prob. (20% @95%) in B_d mixing

< ~5% @95% prob. (10% @95%) in B_s mixing

EFT analysis of ΔF=2 transitions: the NP scale Λ

The mixing amplitudes $A_q e^{2i\phi_q} = \langle \bar{M}_q | H_{\rm eff}^{\Delta F=2} | M_q \rangle$

$$H_{eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i(\mu) Q_i(\mu) + \sum_{i=1}^{3} \tilde{C}_i(\mu) \tilde{Q}_i(\mu)$$

$$Q_1 = \bar{q}_L^\alpha \gamma_\mu b_L^\alpha \, \bar{q}_L^\beta \gamma^\mu b_L^\beta \quad \text{(SM/MFV)}$$

$$Q_2 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_R^\beta b_L^\beta \qquad Q_3 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_R^\beta b_L^\alpha$$

$$Q_4 = \bar{q}_R^\alpha b_L^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad Q_5 = \bar{q}_R^\alpha b_L^\beta \, \bar{q}_L^\beta b_R^\alpha$$

$$\tilde{Q}_1 = \bar{q}_R^\alpha \gamma_\mu b_R^\alpha \, \bar{q}_R^\beta \gamma^\mu b_R^\beta$$

$$\tilde{Q}_2 = \bar{q}_L^\alpha b_R^\alpha \, \bar{q}_L^\beta b_R^\beta \qquad \tilde{Q}_3 = \bar{q}_L^\alpha b_R^\beta \, \bar{q}_L^\beta b_R^\alpha$$

$C_i(\Lambda)$ can be extracted from the data (one by one)

Loop factor L:

- tree/strong interact. NP, L ~ 1
- perturbative NP, L ~ α_s^2, α_W^2

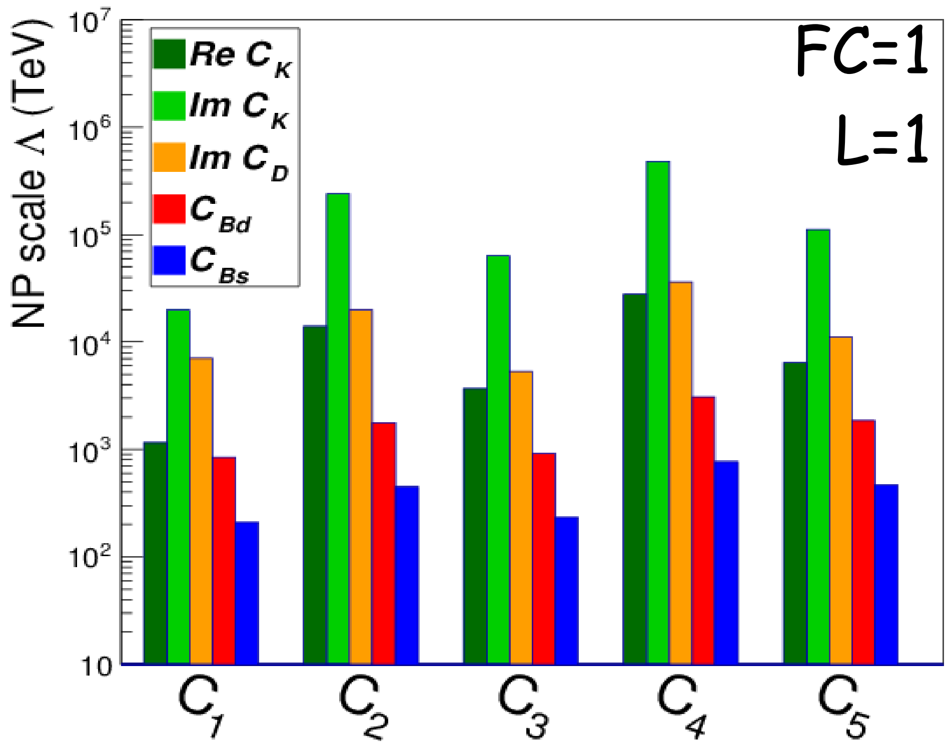
$$\Lambda = \sqrt{\frac{L \cdot FC}{C_i(\Lambda)}}$$

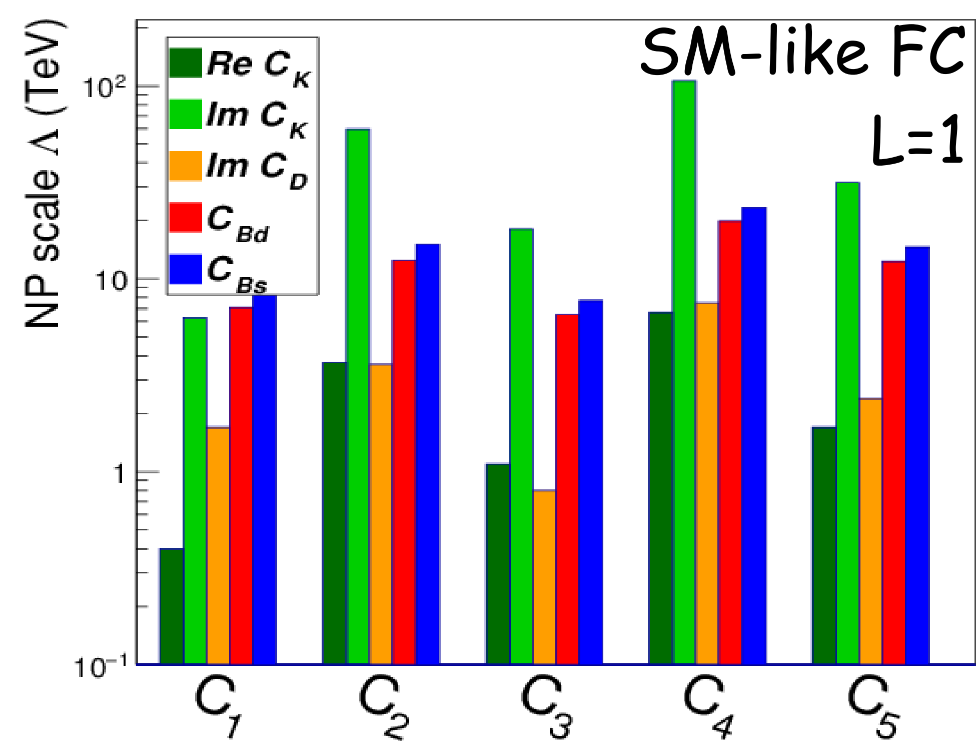
Flavor couplings FC: (i) generic $|FC| \sim 1$ | (ii) SM-like $|FC| \sim F_{SM}$

arbitrary phases

Lower bound on the NP scale Λ from ΔF=2 transitions (TeV @95% prob.)

	K	D	B_d	B_s
FC~1	4.8×10^5	3.6×10^4	3.1×10^3	764
FC~SM	106	7.5	20	23





In case of loop mediation, bounds are reduced by α_s, α_w, …

Deviations from the SM to keep an eye on

- ε'/ε
- $BR(B_s \to \mu\mu)$, $BR(B \to \mu\mu)$
- $R(B \to D\tau\nu)$, $R(B \to D^*\tau\nu)$
- $\Gamma(B^+ \to K^+\mu\mu)/\Gamma(B^+ \to K^+ee)$
- q^2 spectrum of $B \to K^*\mu\mu$

Deviations from the SM to keep an eye on

- ε'/ε
- BR(
- R(B
- Γ(B
- q^2 s

Direct CP violation in $K \to \pi\pi$

Long-established experimental result:

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

<u>Theory breaking news</u>: all the hadronic matrix elements entering the SM prediction have finally been computed on the lattice

(RBC-UKQCD coll.'s, arXiv:1505.07863)

$$(\varepsilon'/\varepsilon)_{SM} = (1.4 \pm 6.8) \times 10^{-4} \qquad -2.1\sigma$$

(Buras et al., arXiv:1507.06345)

$$= (1.9 \pm 4.5) \times 10^{-4} \qquad -2.9\sigma$$

- a "new" constraint on $\bar{\eta}$ in the UT analysis
- one of the most powerful NP probes in flavour physics finally fully at work!!

Deviations from the SM to keep an eye on

- ε'/ε
- **BR($B_s \to \mu\mu$), BR($B \to \mu\mu$)**

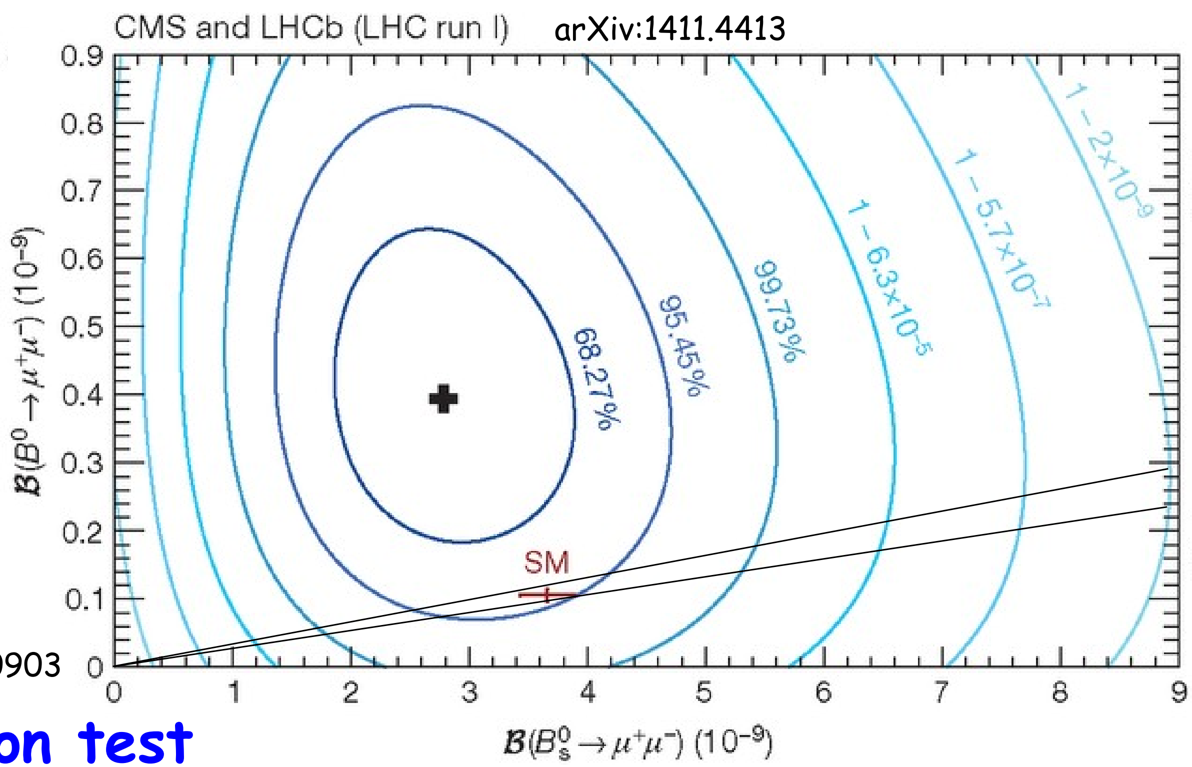
$$\mathrm{BR}(\mathrm{B}_s \to \mu^+\mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}$$

$$\mathrm{BR}(\mathrm{B}_s \to \mu^+\mu^-)_{SM} = (3.65 \pm 0.23) \times 10^{-9} \quad +1.2\sigma$$

$$\mathrm{BR}(\mathrm{B} \to \mu^+\mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$$

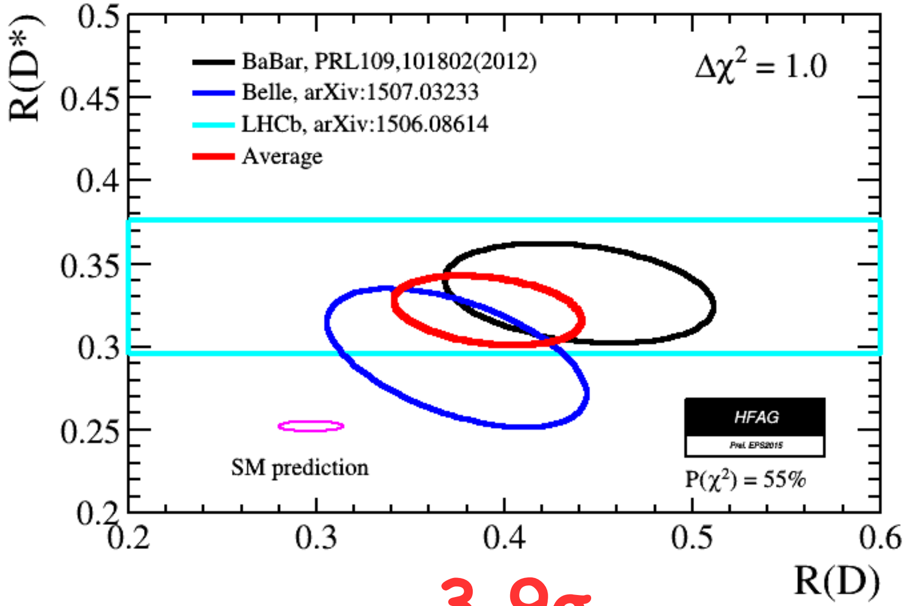
$$\mathrm{BR}(\mathrm{B} \to \mu^+\mu^-)_{SM} = (1.06 \pm 0.09) \times 10^{-10} \quad -2.2\sigma$$

SM predictions from
Bobeth et al., arXiv:1311.0903



Minimal Flavour Violation test

an eye on



3.9σ

$$R(X) = \frac{\Gamma(B \to X\tau\nu)}{\Gamma(B \to X\ell\nu)}$$

$R(D) =$ -1.7σ

$0.391 \pm 0.041 \pm 0.028$

$R(D)_{\rm SM} = 0.297 \pm 0.017$

Kamenik&Mescia, arXiv:0802.3790

$R(D^*) =$ -3σ

$0.322 \pm 0.018 \pm 0.012$

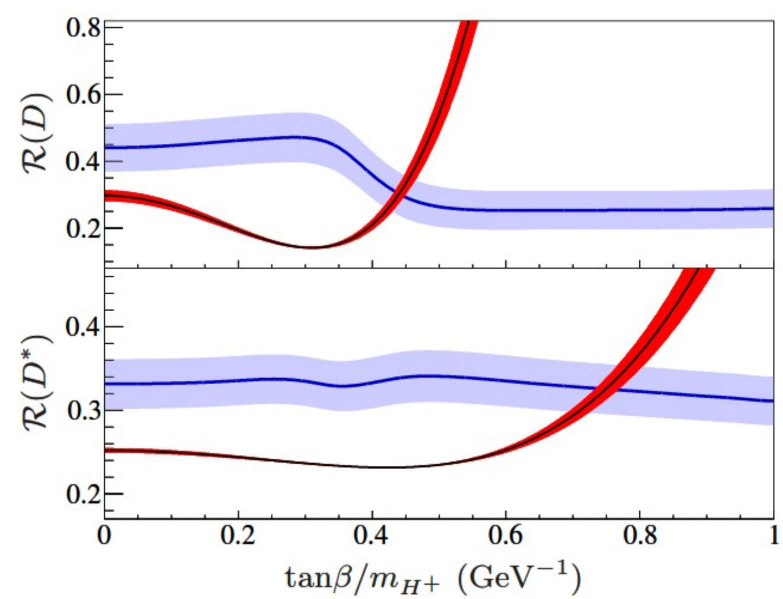
$R(D^*)_{\rm SM} = 0.252 \pm 0.003$

Fajfer et al., arXiv:1203.2654

- $R(B \to D\tau\nu)$, $R(B \to D^*\tau\nu)$
- Γ(B
- q^2 s

simplest realizations of 2HDM cannot explain the excess in the two channels simultaneously

more exotic NP required, e.g. 2HDM-type III, leptoquarks, compositeness, …

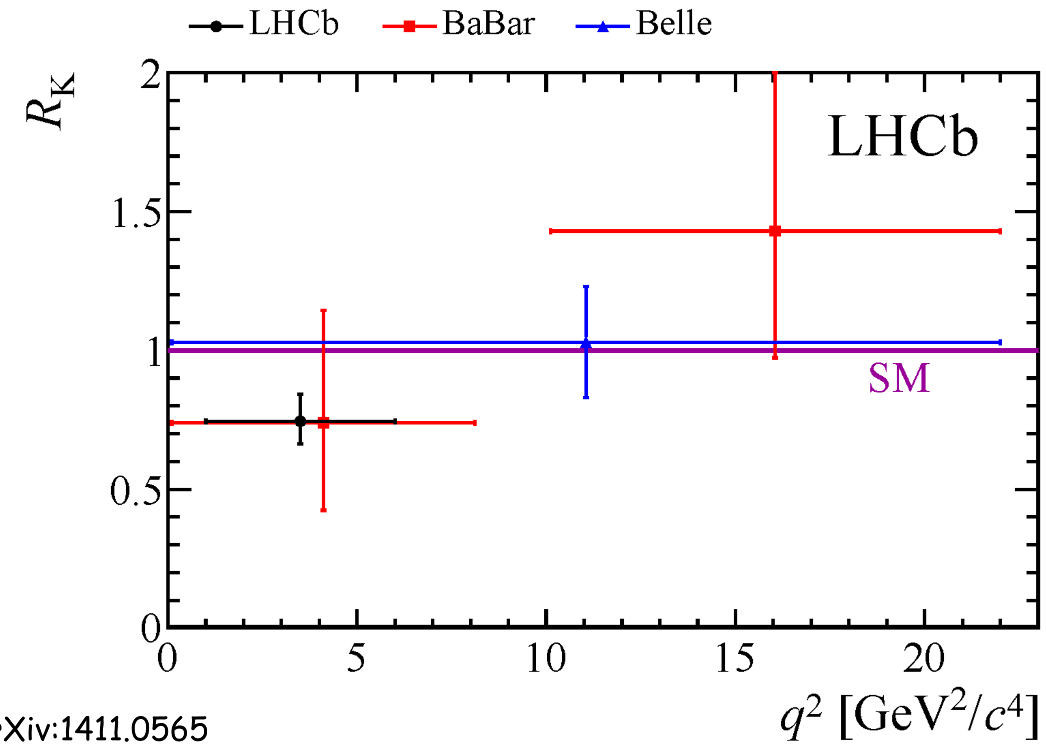


Deviati

Also beyond the SM, such a large violation of lepton universality is not easily obtained

it may be correlated to large LFV in B decays

$b \to s\, \ell_i^+ \ell_j^-$



Glashow et al., arXiv:1411.0565

- $\Gamma(B^+ \to K^+\mu\mu)/\Gamma(B^+ \to K^+ee)$

LHCb Collaboration, arXiv:1406.6482

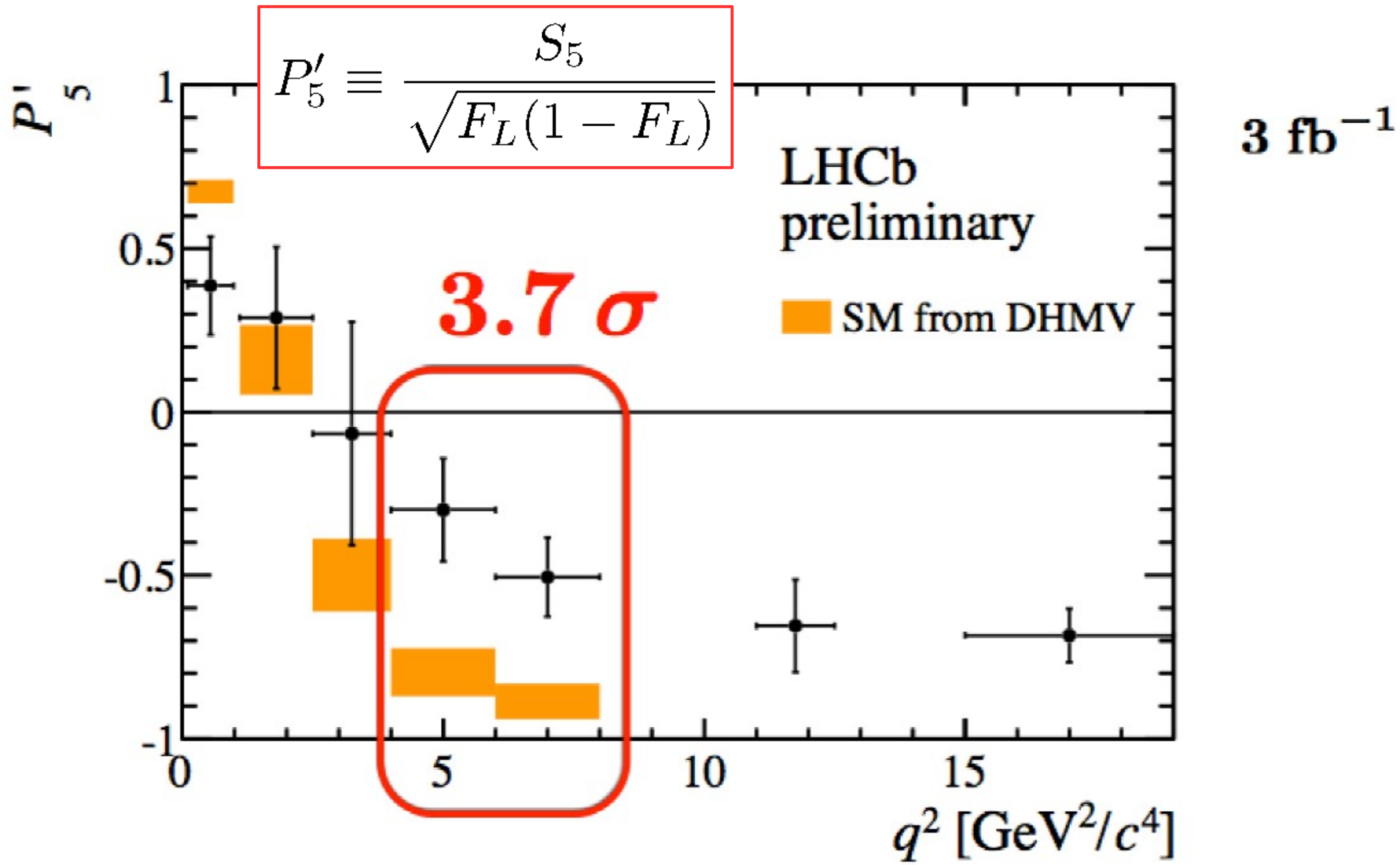
$$R_K = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+\mu^+\mu^-]}{dq^2} dq^2}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} \frac{d\Gamma[B^+ \to K^+e^+e^-]}{dq^2} dq^2} = 0.745^{+0.090}_{-0.074}\,({\rm stat}) \pm 0.036\,({\rm syst})$$

+2.6σ

$$R_K^{\rm SM} = 1.0003 \pm 0.0001$$

Bobeth et al., arXiv:0709.4174

...n eye on



SM prediction from Descotes-Genon et al., arXiv:1407.8526

- q^2 spectrum of $B \to K^*\mu\mu$

$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\,\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi$$
$$+ I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$

angular analysis

$$S_i = \left(I_i^{(s,c)} + \bar{I}_i^{(s,c)}\right) / \Gamma'$$
$$(2\,\Gamma' \equiv d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)$$

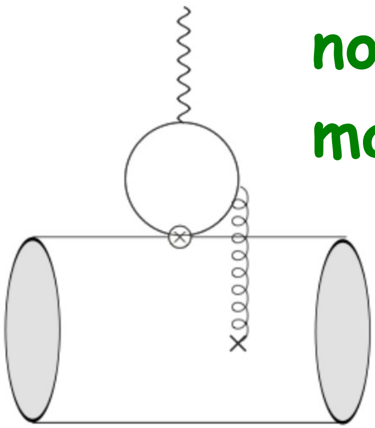
8 CP-AVERAGED OBSERVABLES

$F_L, A_{FB}, S_{3,4,5,7,8,9}$

$B \to K^*\ell^+\ell^-$

estimated by Kodjamirian et al., arXiv:1006.4945 in the single soft-gluon approximation

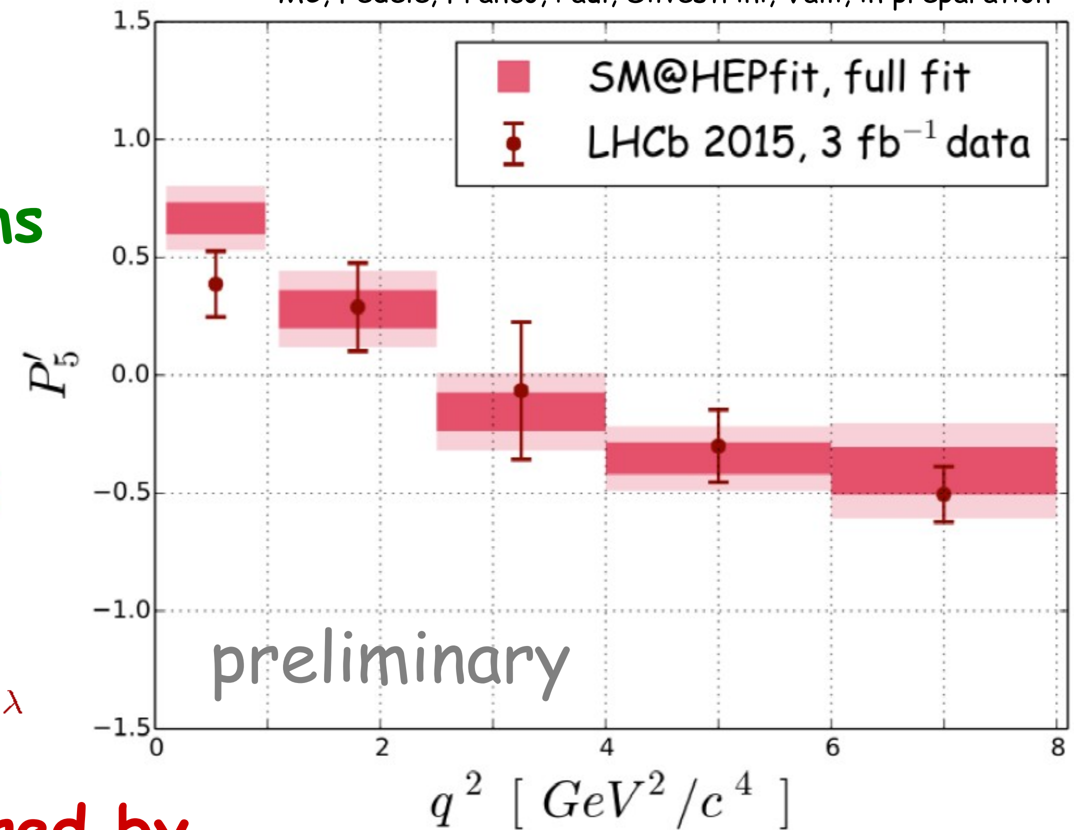
MC, Fedele, Franco, Paul, Silvestrini, Valli, in preparation



non-factorizable terms may be important:

$$h_\lambda = h_\lambda^{(0)} + h_\lambda^{(1)} q^2 + h_\lambda^{(2)} q^4$$

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

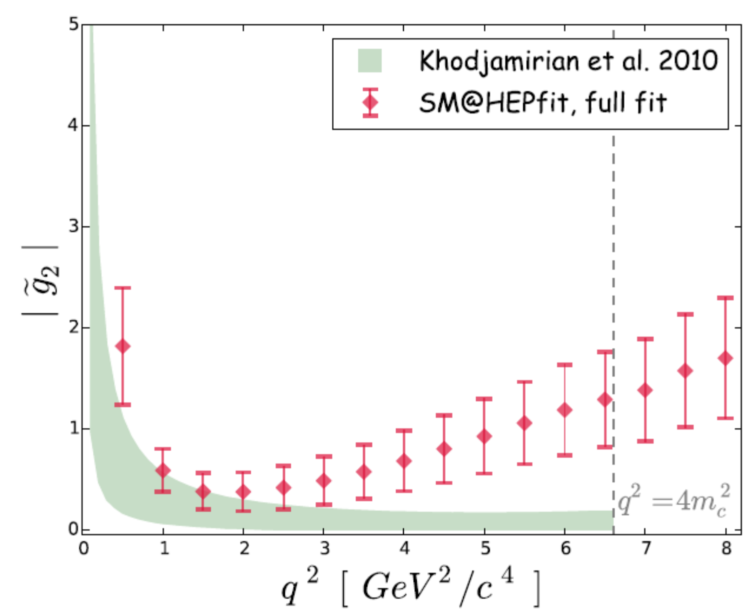


BSM sensitivity could be hindered by hadronic uncertainties

Pulls (σ)

For details see talks: A. Paul @EPS15
M. Valli @SUSY15

Bin q^2 $[GeV^2/c^4]$	A_{FB}	F_L	S_3	S_4	S_5	S_7	S_8	S_9
$[0.1, 0.98]$	1.9	−0.9	0.0	0.7	−1.2	0.1	0.9	−1.2
$[1.1, 2.5]$	−0.6	−0.9	−0.8	−0.3	0.7	−2.0	−0.8	−1.3
$[2.5, 4]$	−1.3	1.8	0.6	−1.0	0.7	0.5	0.2	−0.8
$[4, 6]$	−0.6	0.5	1.1	−1.1	−0.4	−0.1	1.7	−0.5
$[6, 8]$	0.7	1.4	0.3	−2.5	−1.5	−0.3	−1.2	0.4
$[1.1, 6]$	−1.3	0.6	0.9	−1.0	0.4	−0.8	0.5	−0.7



Summary

Flavour physics remains a tool of choice for indirect New Physics search

The SM picture looks very consistent but O(10%) NP corrections are still possible

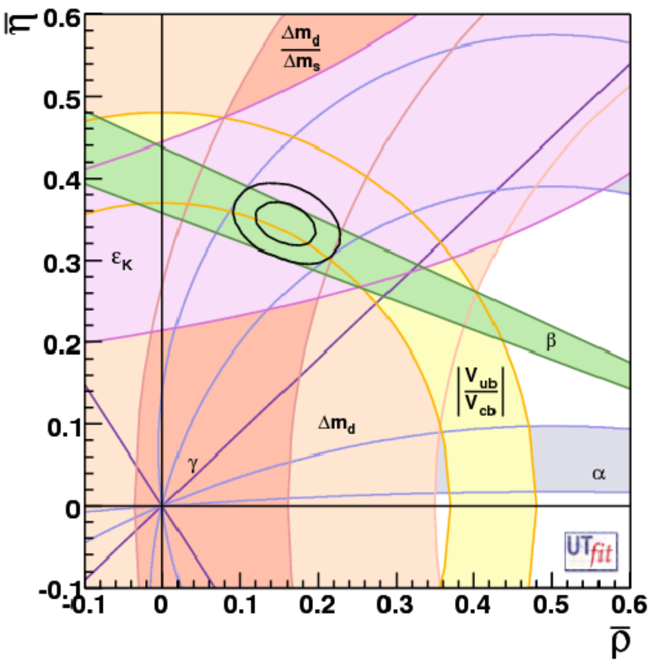
The usual bunch of "tensions" are found in the data: some are new, some long-standing, some odd-looking, some likely not there. No reason to get excited yet, nor to get bored either. Let's wait and see.

In the next decade an intense experimental program will bring flavour physics in the "percent era"

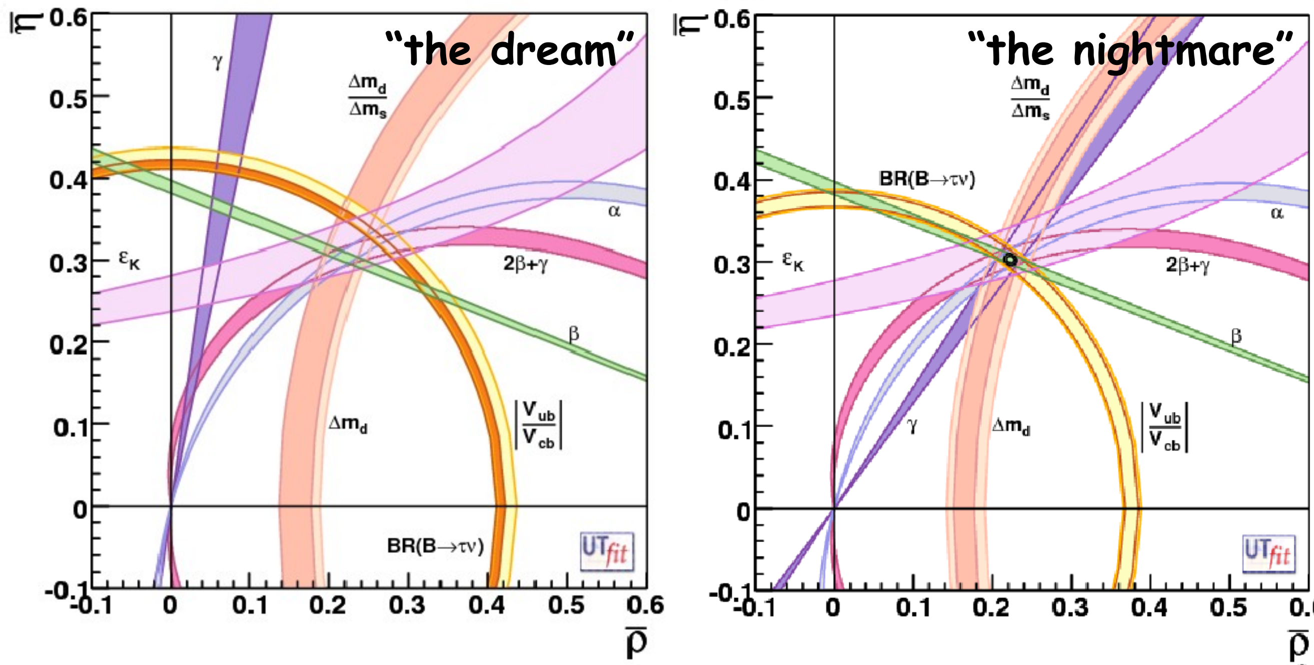
Theory is ready and working on NP contributions & SM uncertainties

Outlook

Today



End of next-generation flavour experiments



Let's see if the dream comes true…

Backup

Going BSM with flavour physics: why?

Indirect searches look for new physics through virtual effects of new particles in loops

* SM FCNCs and CPV occur at the loop level

* SM FV and CPV are governed by the weak interactions and suppressed by mixing angles

* SM quark CPV comes from a single source (neglecting θ_{QCD})

New Physics does not necessarily share the SM pattern of FV and CPV: very large NP effects are possible

Past (SM) successes anticipating heavy flavours:

1970: charm from $K^0 \to \mu^+\mu^-$ (GIM)

1973: 3rd generation from ϵ_K (Kobayashi & Maskawa)

mid 80s+: heavy top from semileptonic decays & Δm_B

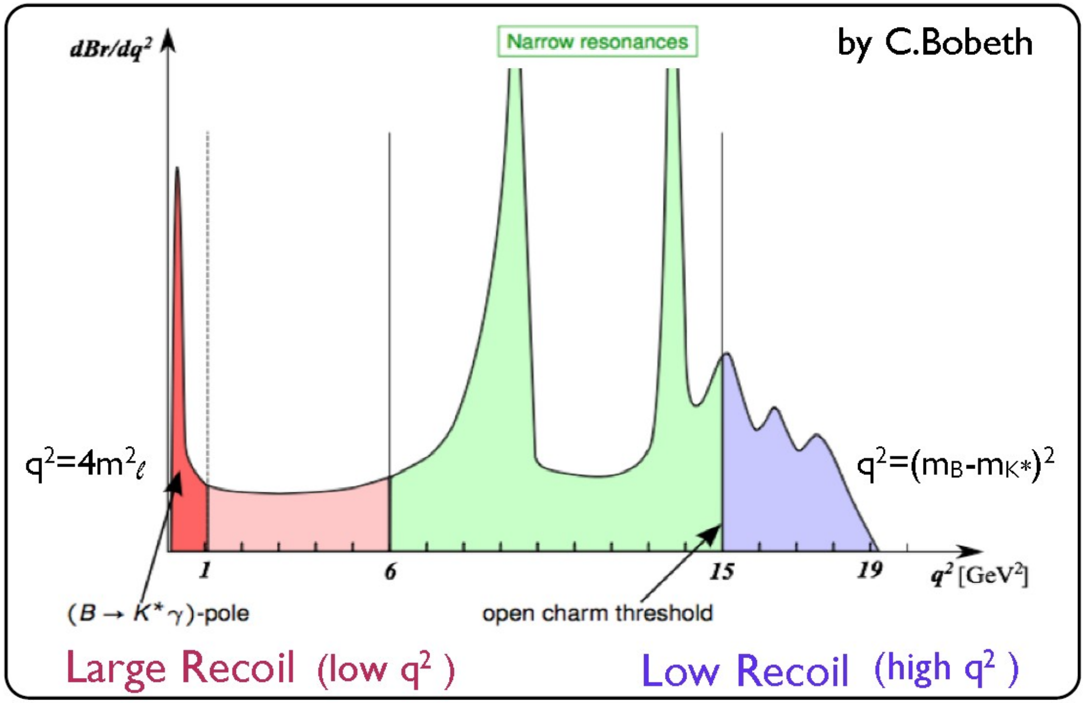
Going BSM with flavour physics: why now?

* next-generation flavour experiments will be able to improve the experimental precision/ sensitivity by almost one order of magnitude

* enough NP-insensitive observables to pin down the SM contribution with the required accuracy

* several NP-sensitive observables not limited by systematics or theoretical uncertainties

Overall, the NP sensitivity extends to (i) the TeV region for SM-like flavour violation and to (ii) 10-100 TeV or even more in less constrained cases



Experimental binning from latest data release, LHCb-CONF-2015-002:

Large Recoil	Low Recoil	
[0.1, 0.98], [1.1, 2.5], [2.5, 4.0] [4.0, 6.0], [6.0, 8.0], [1.1,6.0]	[15.0, 17.0] ,[17.0, 19.0], [15.0, 19.0]	[GeV^2]

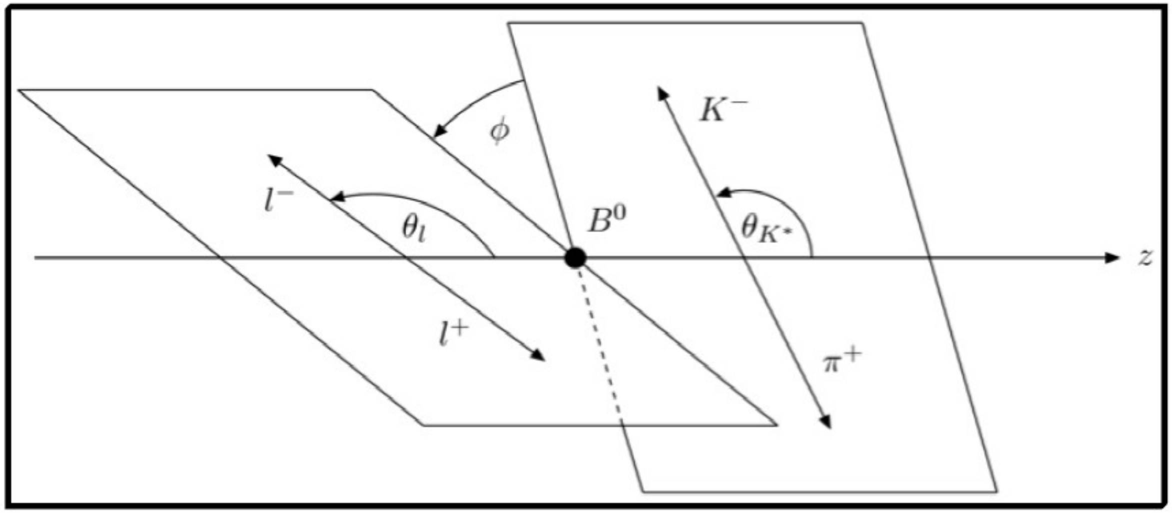
Angular Analysis

θ_K in K* rest frame

θ_l in dilepton CM frame

ϕ boost-invariant w.r.t. z-axis

$q^2 \equiv$ invariant dilepton mass



B to K* μμ decay belongs to b→ s transitions

$$\mathcal{H}_{\rm eff}^{\Delta B=1} = \mathcal{H}_{\rm eff}^{\rm had} + \mathcal{H}_{\rm eff}^{\rm sl}$$

@ dimension 6, 10 operators

$$Q_1^{q=u,c} = (\bar{s}_L \gamma_\mu T^a q_L)(\bar{q}_L \gamma^\mu T^a b_L)$$

$$Q_2^{q=u,c} = (\bar{s}_L \gamma_\mu q_L)(\bar{q}_L \gamma^\mu b_L)$$

$$P_3 = (\bar{s}_L \gamma_\mu b_L) \sum\nolimits_q (\bar{q}\gamma^\mu q)$$

$$P_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum\nolimits_q (\bar{q}\gamma^\mu T^a q)$$

$$P_5 = (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} b_L) \sum\nolimits_q (\bar{q}\gamma^{\mu 1}\gamma^{\mu 2}\gamma^{\mu 3} q)$$

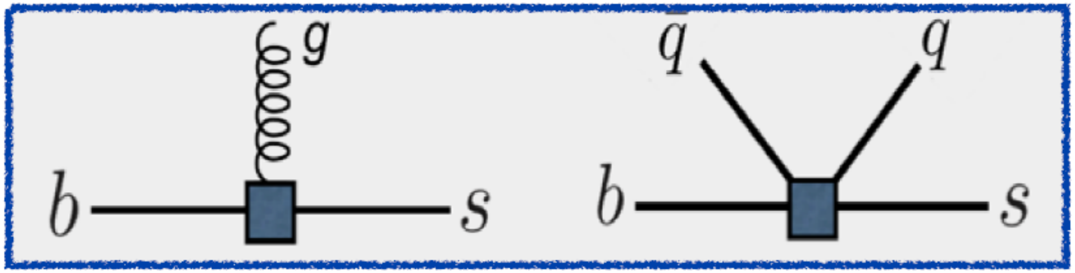
$$P_6 = (\bar{s}_L \gamma_{\mu 1} \gamma_{\mu 2} \gamma_{\mu 3} T^a b_L) \sum\nolimits_q (\bar{q}\gamma^{\mu 1}\gamma^{\mu 2}\gamma^{\mu 3} T^a q)$$

$$Q_{8g} = \frac{g_s}{16\pi^2} m_b \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b$$

$$Q_{7\gamma} = \frac{e}{16\pi^2} m_b \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b$$

$$Q_{9V} = \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$$

$$Q_{10A} = \frac{\alpha_{em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$



In the SM, $\langle M\,\ell\,\ell|\mathcal{H}_{\rm eff}^{\rm sl}|\bar{B}\rangle$ corresponds to the following helicity amplitudes:

$$H_V(\lambda) \propto C_9 \tilde{V}_{L\lambda} + \frac{2 m_b m_B}{q^2} C_7 \tilde{T}_{L\lambda}$$

$$H_A(\lambda) \propto C_{10} \tilde{V}_{L\lambda} \qquad (\lambda = 0, \pm)$$

$$H_P \propto \frac{2 m_l m_B}{q^2} C_{10} \left(1 + \frac{m_s}{m_B}\right) \tilde{S}$$

The angular coefficients $I^{(c,s)}$ are functions of these amplitudes, as well as the CP averaged observables we are ultimately interested in.

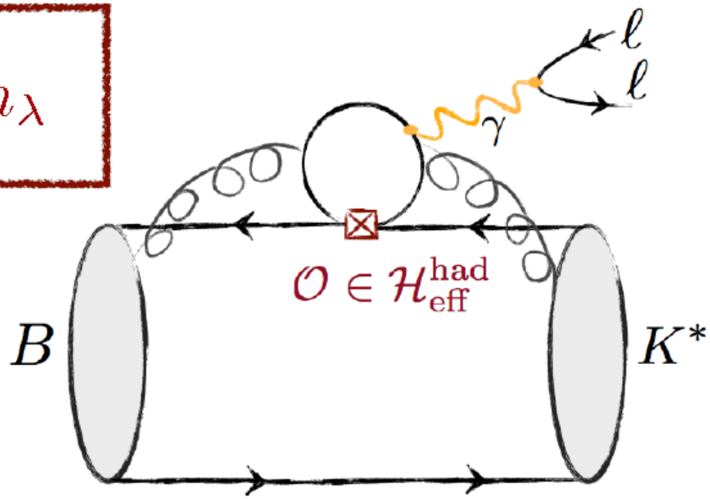
What about the hadronic part of the effective Hamiltonian?

It can contribute to $H_V(\lambda)$ through the insertion of E.M. currents!

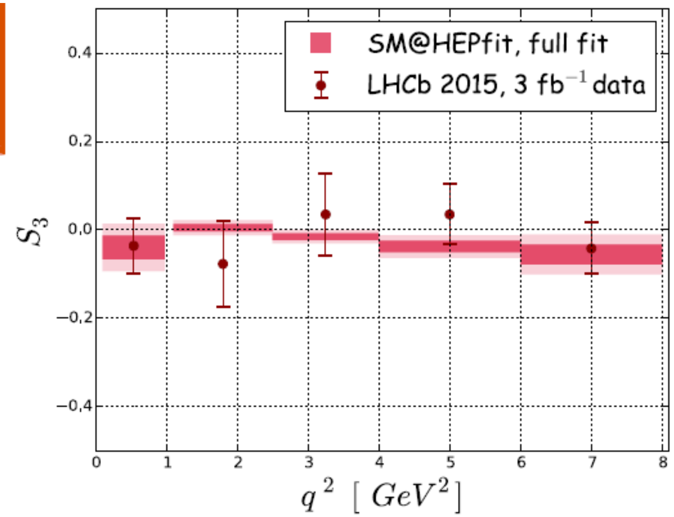
$$H_V(\lambda) \propto C_9 \tilde{V}_{L\lambda} + \frac{2 m_b m_B}{q^2} C_7 \tilde{T}_{L\lambda} - \frac{16\pi^2 m_B^2}{q^2} h_\lambda$$

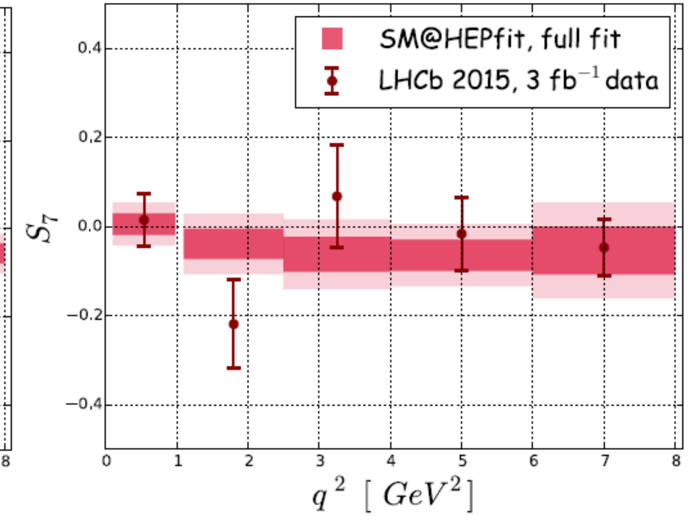
where the above hadronic contribution reads:

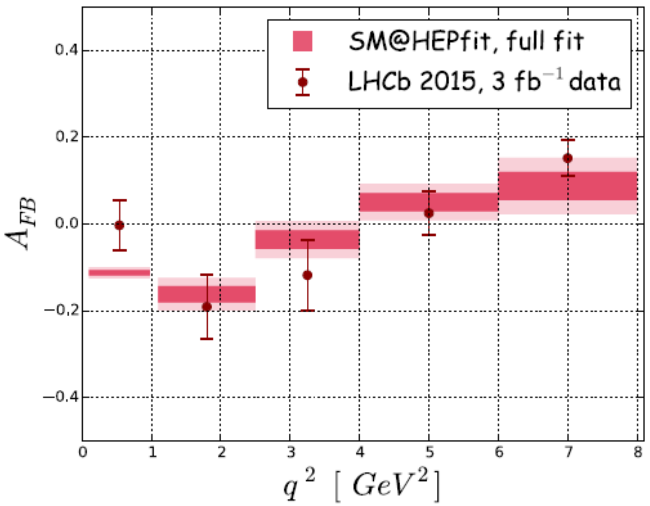
$$h_\lambda(q^2) = \frac{\epsilon_\mu^*(\lambda)}{m_B^2} \int d^4x e^{iqx} \langle \bar{K}^* | T\{ j_{\rm em}^\mu(x) \mathcal{H}_{\rm eff}^{\rm had}(0)\} | \bar{B}\rangle$$

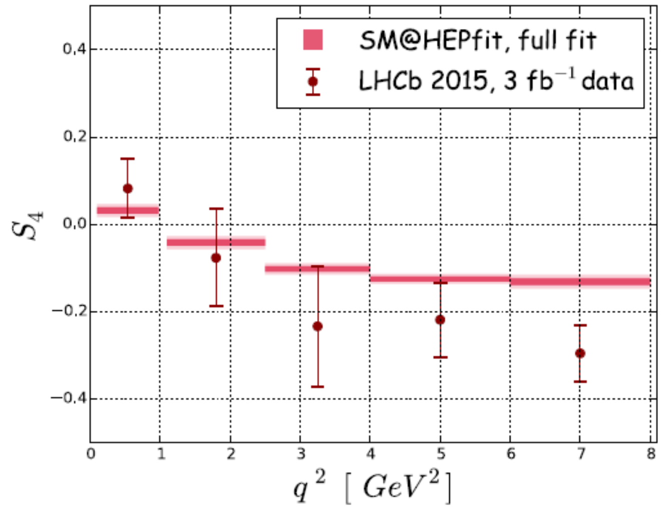


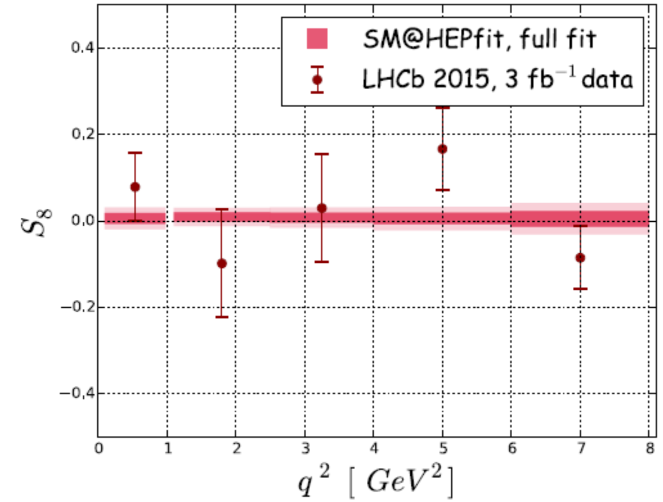
HEPfit full fit

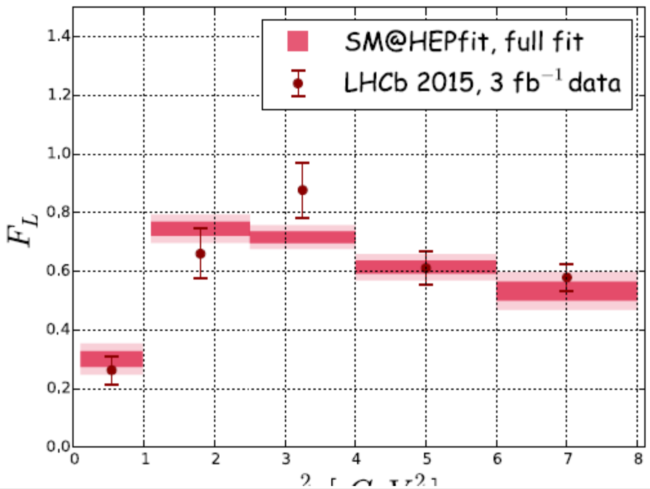


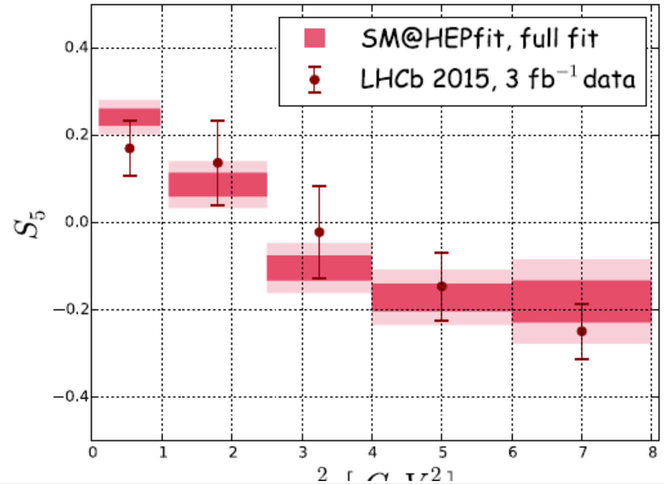


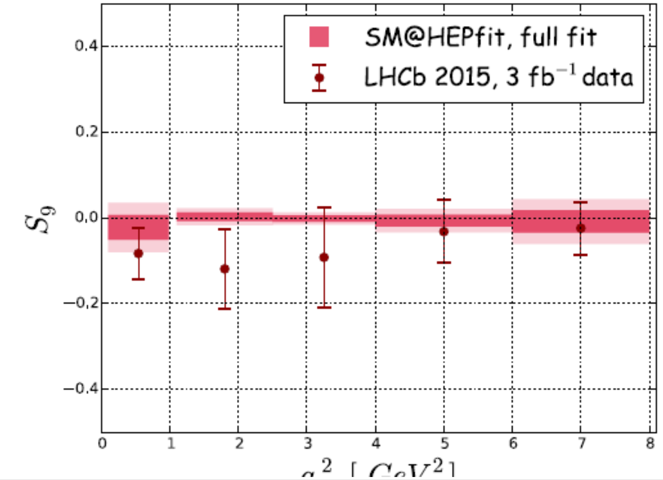










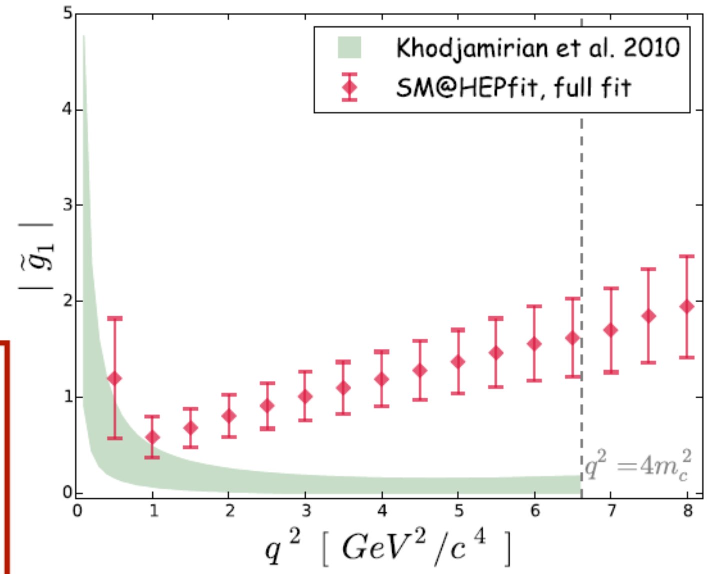


One can easily read the size of the hadronic contribution h_λ as a shift in C_9 .

Eventually, to compare with the literature:

$$\tilde{g} \equiv \Delta C_9^{(\text{non pert.})} / (2C_1)$$

hadronic contribution extracted is compatible with theory estimate order of magnitude for $q^2 \lesssim 1 GeV^2$ and grows for larger q^2 towards charm resonances ... it goes as expected!



DISCLAIMER:

Generic NP contribution in a Wilson coefficient would not bring any q^2 dependence.