Title: Anomalies in Flavour Physics

Date: Jun 14, 2017 10:00 AM

URL: http://pirsa.org/17060013

Abstract:

Flavour Anomalies

Roman Zwicky
Edinburgh University

CP³ Origins
Cosmology & Particle Physics

CENTRE FOR THEORETICAL PHYSICS · Higgs

RADIATIVE CORRECTIONS AT THE
INTENSITY FRONTIER OF PARTICLE PHYSICS

12-14 June 2017 — Perimeter

Overview

- 1. **Introduction** 15’

    [A] Overview Flavour Anomalies

    [B] Flavour Violation & Flavour Universality

    [C] Effective Hamiltonian(s)

    [D] Angular Distributions

Overview

- 1. **Introduction** 15’

  [A] Overview Flavour Anomalies

  [B] Flavour Violation & Flavour Universality

  [C] Effective Hamiltonian(s)

  [D] Angular Distributions

- 2. **Current tensions (anomalies)** SM-status - prospects 35’

  [A] Tree -level: $|V_{ub}|$ exclusive vs inclusive &

  [B] $b \to sll$ $B \to D^{(*)} l\nu$: $l=e,\mu$ vs τ

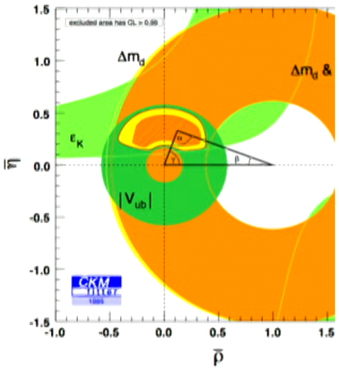
  (i) Theory Overview

  (ii) Experimental Results

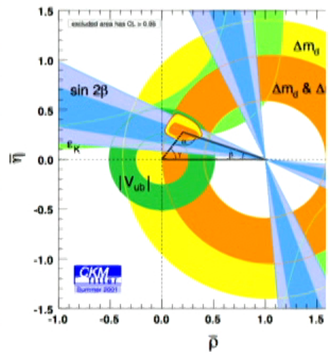
  (iii) Summary of global Fits

  (iv) Theoretical Reappraisal of Charm

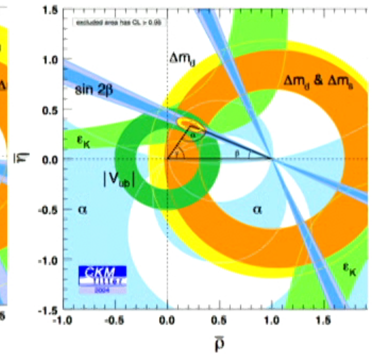
..not in the CKM mechanism



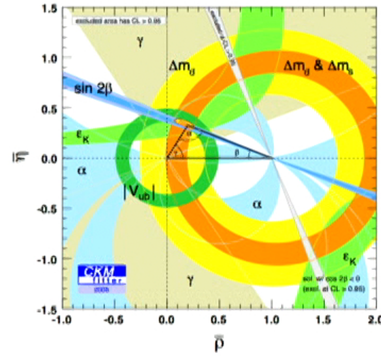
95' pre b-factory



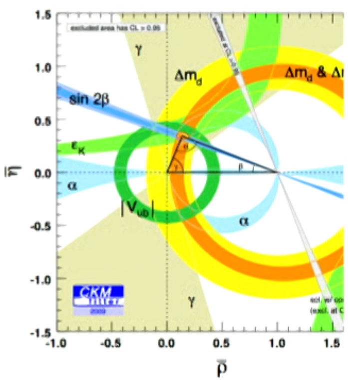
01'



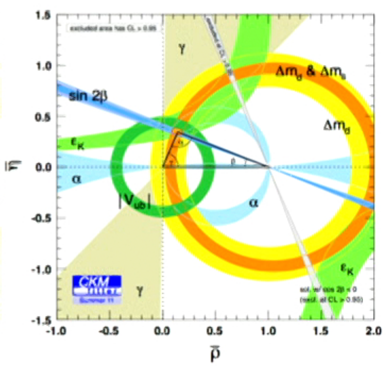
04'



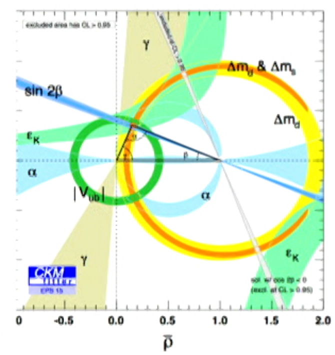
06'



09'



11'



15'

Area triangle =
strength CP-violation
NB: ca 10^3 below max.

Note: here CKM-fitter also U-fit group

… in a few (un)expected places

b→s FCNC's

Angular Observables
(e.g. $A_{\rm FB}$, P_5')

TD-CPV: $B_s \to \phi\gamma$

$$R^{\mu\mu}_{K^*/\phi} \equiv \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0_s \to \phi\mu\mu)}$$

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

… in a few (un)expected places

b→s FCNC's

Angular Observables
(e.g. A_{FB}, P_5')

TD-CPV: $B_s \to \phi\gamma$

$$R^{\mu\mu}_{K^*/\phi} \equiv \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0_s \to \phi\mu\mu)}$$

Tree-level

$|V_{\mathrm{ub}}|_{\mathrm{excl}}$ & global fit
vs $|V_{\mathrm{ub}}|_{\mathrm{incl}}$

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

$$R_{D^{(*)}} = \frac{\mathcal{B}[B \to D^{(*)}\tau\nu]}{\mathcal{B}[B \to D^{(*)}\ell\nu]}$$

Lepton Flavour Universality Violation (LFUV)?

$\ell = e, \mu$

New flavour physics and generic flavour structure?

- Anarchic flavour O(1) Wilson coefficients
  → most severe **constraints** from **mixing** i.e. $\Delta F=2$

… in a few (un)expected places

b→s FCNC's

Angular Observables
(e.g. $A_{\rm FB}$, P_5')

TD-CPV: $B_s \to \phi\gamma$

$$R^{\mu\mu}_{K^*/\phi} \equiv \frac{\mathcal{B}(B^0 \to K^{*0}\mu\mu)}{\mathcal{B}(B^0_s \to \phi\mu\mu)}$$

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

Tree-level

$|V_{\rm ub}|_{\rm excl}$ & global fit
vs $|V_{\rm ub}|_{\rm incl}$

$$R_{D^{(*)}} = \frac{\mathcal{B}[B \to D^{(*)}\tau\nu]}{\mathcal{B}[B \to D^{(*)}\ell\nu]}$$

$\ell = e, \mu$

New flavour physics and generic flavour structure?

- Anarchic flavour O(1) Wilson coefficients
  → most severe **constraints** from **mixing** i.e. ΔF=2

hadron	discovery	dim-6 operator	bound $\Lambda_{FV}/(10^3\text{TeV})]$
K_0	1964	$(\bar{s}d)_{\rm V-A}(\bar{s}d)_{\rm V-A}\,(\Lambda_{FV})^{-2}$	1
B_0	1999	$(\bar{b}d)_{\rm V-A}(\bar{b}d)_{\rm V-A}$	0.4
B_s	2006	$(\bar{b}s)_{\rm V-A}(\bar{b}s)_{\rm V-A}$	0.07
D_0	2007	$(\bar{c}u)_{\rm V-A}(\bar{c}u)_{\rm V-A}$	1

New flavour physics and generic flavour structure?

- Anarchic flavour O(1) Wilson coefficients
  → most severe **constraints** from **mixing** i.e. ΔF=2

hadron	discovery	dim-6 operator	bound $\Lambda_{FV}/(10^3\text{TeV})]$
K_0	1964	$(\bar{s}d)_{\rm V-A}(\bar{s}d)_{\rm V-A}\,(\Lambda_{FV})^{-2}$	1
B_0	1999	$(\bar{b}d)_{\rm V-A}(\bar{b}d)_{\rm V-A}$	0.4
B_s	2006	$(\bar{b}s)_{\rm V-A}(\bar{b}s)_{\rm V-A}$	0.07
D_0	2007	$(\bar{c}u)_{\rm V-A}(\bar{c}u)_{\rm V-A}$	1

⇒ new flavour better have a structure! (also more likely to explain old one)

- ***N.B.*** Constraints Lepton sector larger ΔF=1
  (since photon does not couple to ν)

ABC of Symmetry:
Flavour Universality (FU) & Flavour Conservation

- **Yukawa** = 0 global symmetry: $G_F = U(3)^5 = G_q \times G_l$, $G_q = U(3)_Q \times U(3)_{UR} \times U(3)_{DR}$

  Yukawa ≠0 breaking down: $G_q = U(3)_q^3 \rightarrow U(1)_{Baryon}$

ABC of Symmetry: Flavour Universality (FU) & Flavour Conservation

- **Yukawa** = 0 global symmetry: $G_F = U(3)^5 = G_q \times G_l$, $G_q = U(3)_Q \times U(3)_{UR} \times U(3)_{DR}$
  Yukawa $\neq 0$ breaking down: $G_q = U(3)_q^3 \to U(1)_{Baryon}$

- **SM: FU-broken** : $m_u \neq m_c \neq m_t$ but not couplings $g_{weak} = g_u = g_c = g_t$

SM: Flavour Violation (FV) by misalignment of Yukawa matrices:

$$V_{CKM} = S_D S_U^\dagger \neq 1$$

(i) charged FV $b \to W^* c$ (tree)

(ii) neutral FV (FCNC) $b \to s\gamma$

ABC of Symmetry: Flavour Universality (FU) & Flavour Conservation

- **Yukawa** = 0 global symmetry: $G_F = U(3)^5 = G_q \times G_l$, $G_q = U(3)_Q \times U(3)_{UR} \times U(3)_{DR}$
  Yukawa ≠0 breaking down: $G_q = U(3)_q^3 \rightarrow U(1)_{Baryon}$

- **SM: FU-broken** : $m_u \neq m_c \neq m_t$ but not couplings $g_{weak} = g_u = g_c = g_t$

  SM: Flavour Violation (FV) by misalignment of Yukawa matrices:

$$V_{CKM} = S_D S_U^\dagger \neq 1$$

(i) charged FV $b \rightarrow W^* c$ (tree)

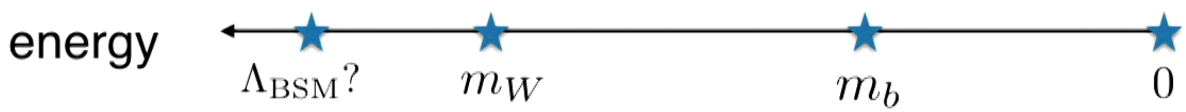
(ii) neutral FV (FCNC) $b \rightarrow s\gamma$

Flavour Universality is not a symmetry of the SM

- Yet for leptons: control the breaking in terms of (mainly) kinematic factors.

Make use of energy scales (eg. talk T.Becher)

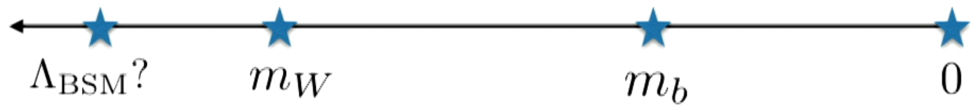
ABC of Dynamics: Effective Hamiltonian



Make use of energy scales (eg. talk T.Becher)

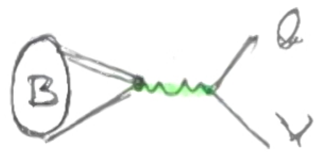
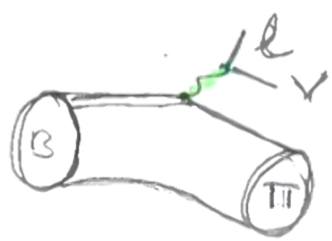
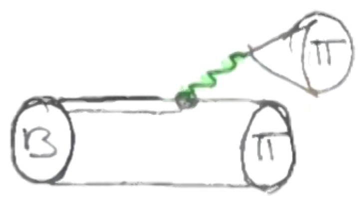
ABC of Dynamics: Effective Hamiltonian

energy



amplitude $$\mathcal{A} = \langle XYZ|H_{\rm eff}|B\rangle = \sum_i C_i(m_b)\langle XYZ|\underbrace{O_i(m_b)}_{\bar{q}_1\Gamma_1 q_2 \bar{b}\Gamma_2 q_3}|B\rangle$$

ΔF=1 topologies are (ΔF=2 mixing)

final hadron	type	topology	theory	methods
0	**leptonic**		decay constant f_B	lattice sum rules (SR)
1	**semi-leptonic**		form factors	lattice, slow π LCSR, fast π
	radiative FCNC		LD form factors multi-resonance →	↗ ***dualit y*** → Breit-Wigner
≥2	**non-leptonic**		factorisation (fast pions) pb: FSI size of Λ/m_b	QCDF: $1/m_b$

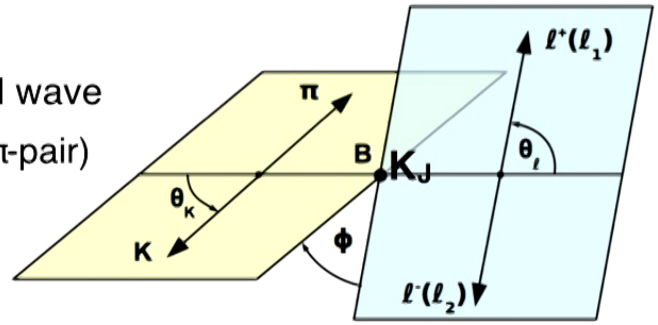
difficulty theory ↓

ABC of Kinematics: Angular Distributions

- **This talk** mostly: $B \to V(\to S_1 S_2) l_a l_b$ or $B \to S l_a l_b$ (semi-leptonic/radiative)

partial wave

l_K-(Kπ-pair)



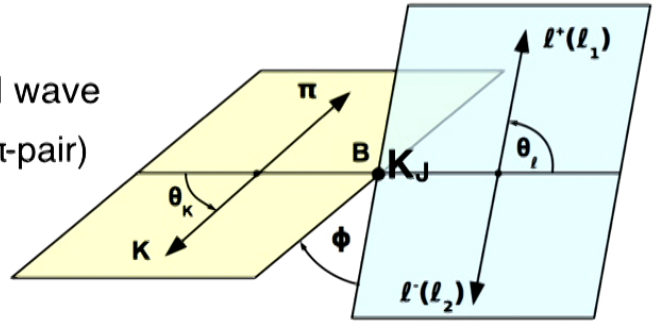
partial wave

l_l-(ll-pair)

ABC of Kinematics: Angular Distributions

- **This talk** mostly: B → V(→S_1S_2)$l_a l_b$ or B → S$l_a l_b$ (semi-leptonic/radiative)

partial wave l_K-(Kπ-pair)



partial wave l_l-(ll-pair)

Heff of dim=6 with 10 operators

$$H^{\rm eff} = -\frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}V_{\rm ts}V_{\rm tb}^* \sum_{i=V,A,S,P,\mathcal{T}} (C_i O_i + C_i' O_i') \ .$$

$$O_{S(P)} = \bar{s}_L b\, \bar{\ell}(\gamma_5)\ell\ , \qquad O_{V(A)} = \bar{s}_L \gamma^\mu b\, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

$$O_{\mathcal{T}} = \bar{s}_L \sigma^{\mu\nu} b\, \bar{\ell}\sigma_{\mu\nu}\ell\ , \qquad O' = O|_{s_L \to s_R}$$

→ **S-** and **P-wave**

$$\frac{d^4\Gamma}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \sum_{m,l_l=0..2,l_K=0..J_K} \underbrace{G_m^{l_k,l_l}}_{|\mathcal{A}_{S,P}|^2} Y_{l_k}(\theta_K,\phi) Y_{l_l,m}(\theta_l,0)$$

12-terms known for some time

"Jacob-Wick formalism" for effective theories

Sinha et al '99
Gratrex. Hopfer, RZ'15

... connection to dynamics

$$\frac{32\pi}{3}\frac{d^4\Gamma}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \mathrm{Re}\Big[G_0^{0,0}(q^2)\Omega_0^{0,0} + G_0^{0,1}(q^2)\Omega_0^{0,1} + G_0^{0,2}(q^2)\Omega_0^{0,2} + G_0^{2,0}(q^2)\Omega_0^{2,0} + G_0^{2,1}(q^2)\Omega_0^{2,1} + G_1^{2,1}(q^2)\Omega_1^{2,1} + G_0^{2,2}(q^2)\Omega_0^{2,2} + G_1^{2,2}(q^2)\Omega_1^{2,2} + G_2^{2,2}(q^2)\Omega_2^{2,2}\Big],$$

... connection to dynamics

$$\frac{32\pi}{3}\frac{d^4\Gamma}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \mathrm{Re}\Big[G_0^{0,0}(q^2)\Omega_0^{0,0} + G_0^{0,1}(q^2)\Omega_0^{0,1} + G_0^{0,2}(q^2)\Omega_0^{0,2} + G_0^{2,0}(q^2)\Omega_0^{2,0} + G_0^{2,1}(q^2)\Omega_0^{2,1} + G_1^{2,1}(q^2)\Omega_1^{2,1} + G_0^{2,2}(q^2)\Omega_0^{2,2} + G_1^{2,2}(q^2)\Omega_1^{2,2} + G_2^{2,2}(q^2)\Omega_2^{2,2}\Big],$$

$$G_2^{2,2} \sim \left(H_+^V\bar{H}_-^V + H_+^A\bar{H}_-^A - 2\left(H_+^T\bar{H}_-^T + 2H_+^{T_t}\bar{H}_-^{T_t}\right)\right)$$

Hadronic helicity amplitudes e.g. $H_\lambda^{V[A]} = \langle\bar{K}^*(\lambda)|\bar{s}\gamma^\mu[\gamma_5]b|\bar{B}\rangle\epsilon^*(\lambda)_\mu$

... connection to dynamics

$$\frac{32\pi}{3}\frac{d^4\Gamma}{dq^2\ d\cos\theta_\ell\ d\cos\theta_K\ d\phi} = \mathrm{Re}\Big[G_0^{0,0}(q^2)\Omega_0^{0,0} + G_0^{0,1}(q^2)\Omega_0^{0,1} + G_0^{0,2}(q^2)\Omega_0^{0,2} + G_0^{2,0}(q^2)\Omega_0^{2,0} + G_0^{2,1}(q^2)\Omega_0^{2,1} + G_1^{2,1}(q^2)\Omega_1^{2,1} + G_0^{2,2}(q^2)\Omega_0^{2,2} + G_1^{2,2}(q^2)\Omega_1^{2,2} + G_2^{2,2}(q^2)\Omega_2^{2,2}\Big],$$

$$G_2^{2,2} \sim \left(H_+^V\bar{H}_-^V + H_+^A\bar{H}_-^A - 2\left(H_+^T\bar{H}_-^T + 2H_+^{T_t}\bar{H}_-^{T_t}\right)\right)$$

Hadronic helicity amplitudes e.g. $H_\lambda^{V[A]} = \langle \bar{K}^*(\lambda)|\bar{s}\gamma^\mu[\gamma_5]b|\bar{B}\rangle\epsilon^*(\lambda)_\mu$

- Pause! Goal find info on microscopic theory

Tools: (1) angular analysis (moments) extract G's
(2) q^2-dependence - disentangle short from long-distance physics

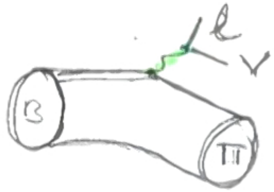
(2) Tensions

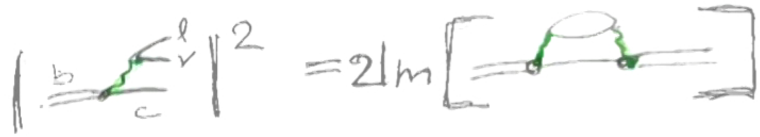
Tree-level tensions

(no sizeable long distance contamination!)

CKM-elements

exclusive **vs** **inclusive**



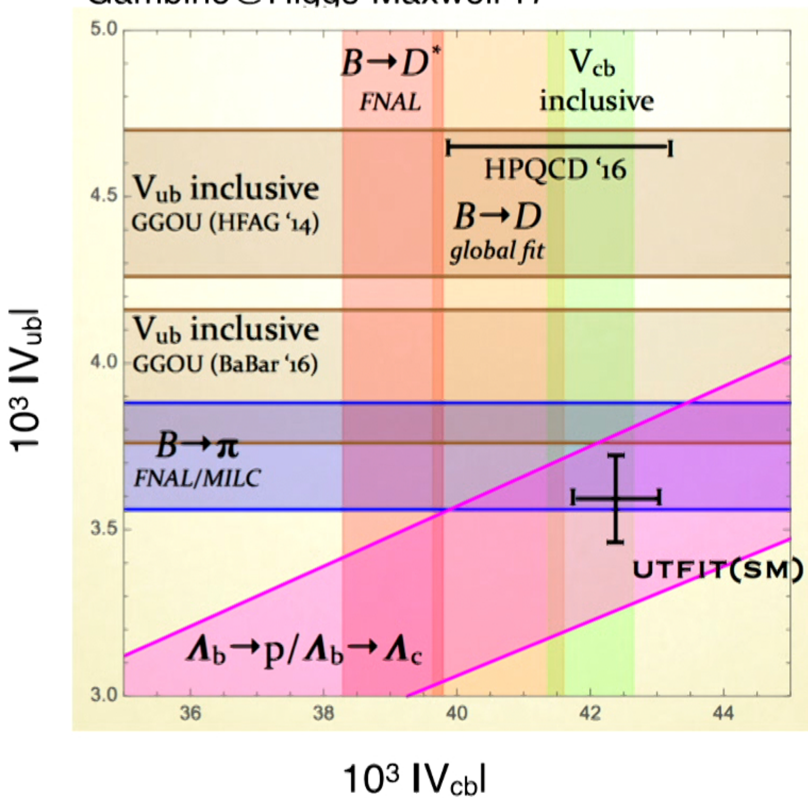


optical thm & OPE

$\lvert V_{\mathrm{ub}}\rvert$	$\lvert V_{\mathrm{cb}}\rvert$	non-perturbative Input
$B \to \pi\ell\nu$	$B \to D\ell\nu$	$\Gamma[\lvert V(q^2)\rvert^2, m_\ell^2\lvert S(q^2)\rvert^2]$
$B \to \rho\ell\nu$	$B \to D^*\ell\nu$	$\Gamma[\lvert V_{\pm,0}(q^2)\rvert^2, m_\ell^2\lvert S(q^2)\rvert^2]$
$\Lambda_b \to \Lambda\ell\nu$		
$b \to X_u\ell\nu$	$b \to X_c\ell\nu$	universal m-elements shape function (model, fit)

V_{cb} & V_{ub} inclusive vs exclusive

Gambino@Higgs-Maxwell'17



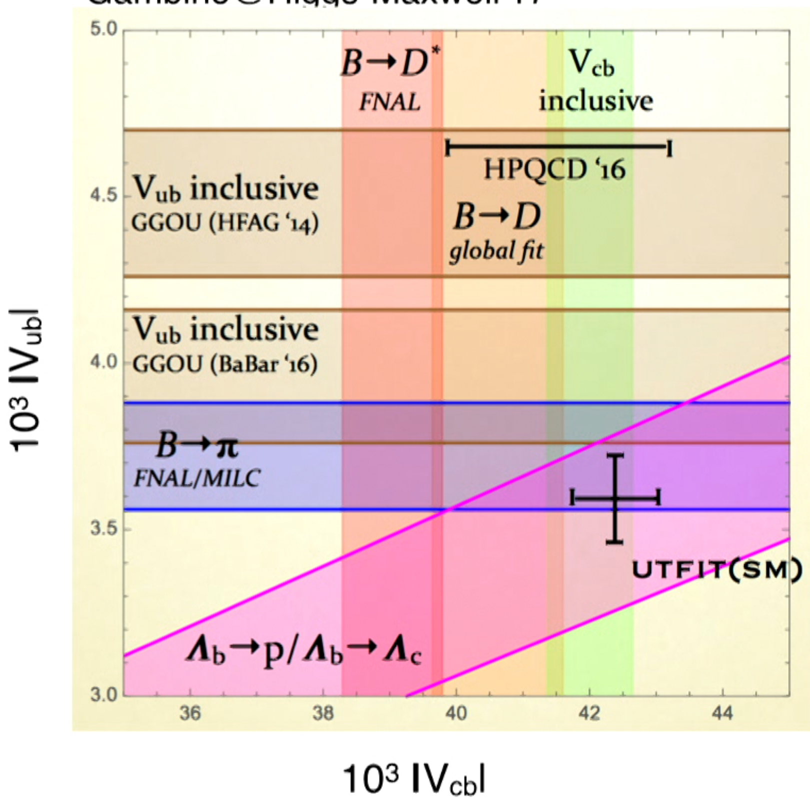
- $|V_{cb}|$-tension eased by angular data Belle'17 allowed to revisit assumption of CLN'97 (HQET):

$$|V_{\rm cb}|_{D^*} = 41.7(2) \cdot 10^{-3}$$

Bigi, Gambino, Schacht'17

V_{cb} & V_{ub} inclusive vs exclusive

Gambino@Higgs-Maxwell'17



- $|V_{cb}|$-tension eased by angular data Belle'17 allowed to revisit assumption of CLN'97 (HQET):

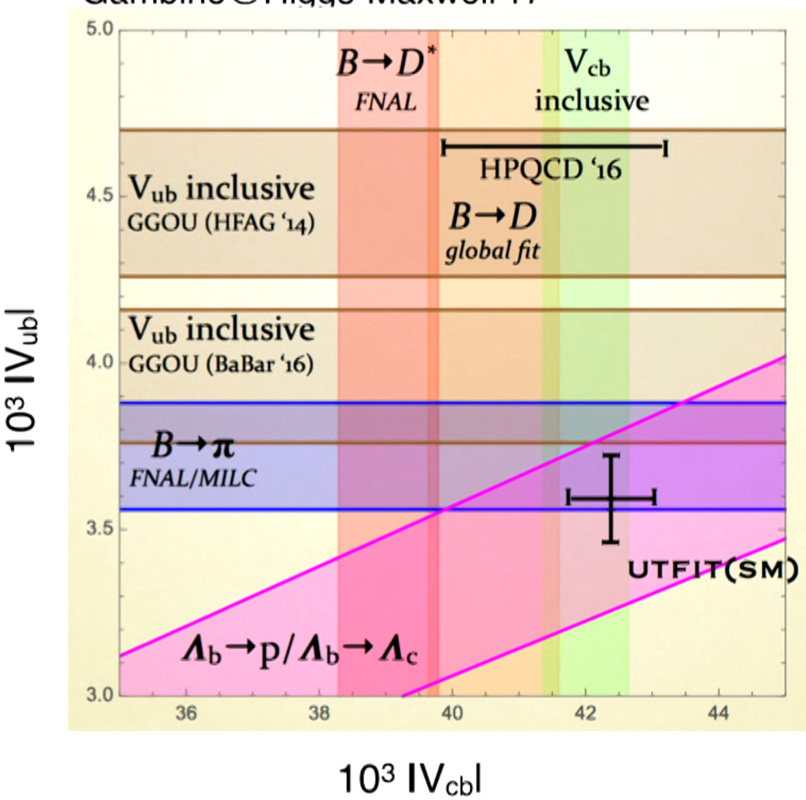
$$|V_{cb}|_{D^*} = 41.7(2)\cdot 10^{-3}$$

Bigi, Gambino, Schacht'17

- $|V_{ub}|$-tension eased by new BaBar analysis.
  "needs checks" Gambino'17

V_{cb} & V_{ub} inclusive vs exclusive

Gambino@Higgs-Maxwell'17



- $|V_{cb}|$-tension eased by angular data Belle'17 allowed to revisit assumption of CLN'97 (HQET):

$$|V_{\rm cb}|_{D^*} = 41.7(2) \cdot 10^{-3}$$

Bigi, Gambino, Schacht'17

- $|V_{ub}|$-tension eased by new BaBar analysis. "needs checks" Gambino'17

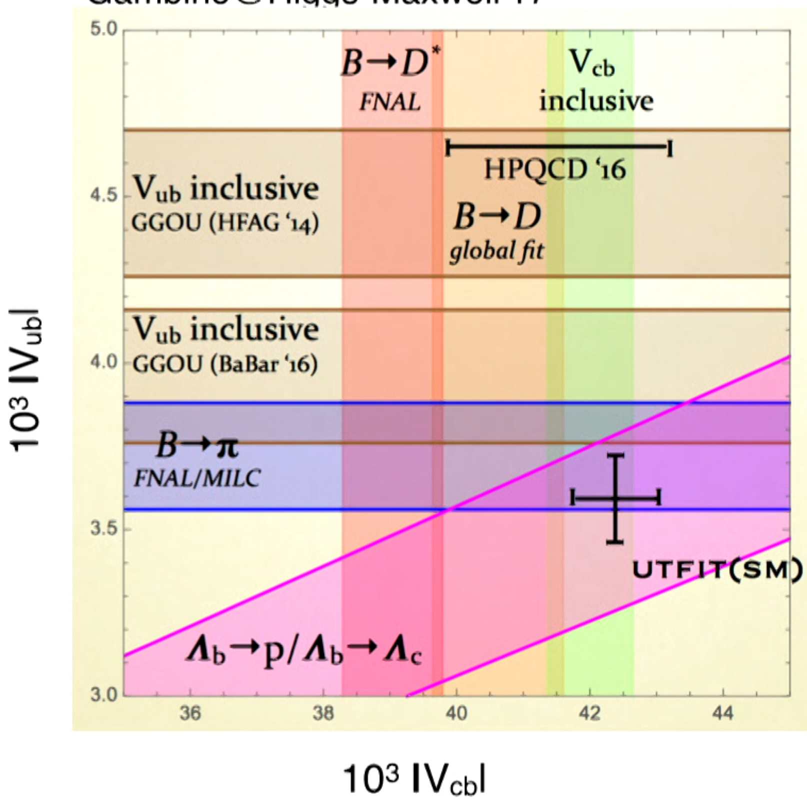
- Another Vub-mode

$$|V_{\rm ub}|_{\rho^*} = 32(3) \cdot 10^{-3}$$

Bharucha, Straub, RZ '15

V_{cb} & V_{ub} inclusive vs exclusive

Gambino@Higgs-Maxwell'17



- $|V_{cb}|$-tension eased by angular data Belle'17 allowed to revisit assumption of CLN'97 (HQET):

$$|V_{\rm cb}|_{D^*} = 41.7(2) \cdot 10^{-3}$$

Bigi, Gambino, Schacht'17

- $|V_{ub}|$-tension eased by new BaBar analysis. "needs checks" Gambino'17

- Another Vub-mode

$$|V_{\rm ub}|_{\rho^*} = 32(3) \cdot 10^{-3}$$

Bharucha, Straub, RZ '15

☆ **$|V_{ub}|$-tensions disappearing** in favour of **global fits**! (not fully sorted…)

- Yet instructive to **contemplate** on **right-handed currents ε_R**

V_{cb}

$$|V_{cb}|_{\text{incl}} = |V_{cb}|(1 + \tfrac{1}{2}\epsilon^2)$$
$$|V_{cb}|_{D^*} = |V_{cb}|(1 + \epsilon)$$
$$|V_{cb}|_D = |V_{cb}|(1 - \epsilon)$$

no good as D and D^*
in wrong direction

- Yet instructive to **contemplate** on **right-handed currents ε_R**

V_{cb}

$$|V_{cb}|_{\rm incl} = |V_{cb}|(1 + \tfrac{1}{2}\epsilon^2)$$
$$|V_{cb}|_{D^*} = |V_{cb}|(1 + \epsilon)$$
$$|V_{cb}|_{D} = |V_{cb}|(1 - \epsilon)$$

no good as D and D*
in wrong direction

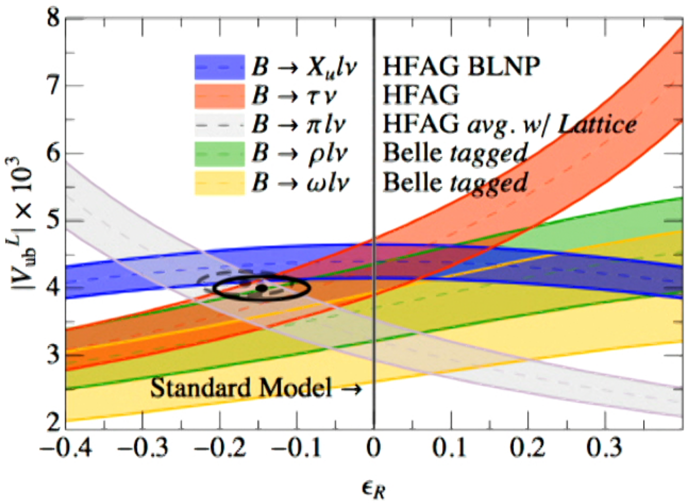
- Yet instructive to **contemplate** on **right-handed currents** ε_R

V_{cb}

$$|V_{cb}|_{\rm incl} = |V_{cb}|(1+\tfrac{1}{2}\epsilon^2)$$
$$|V_{cb}|_{D^*} = |V_{cb}|(1+\epsilon)$$
$$|V_{cb}|_D = |V_{cb}|(1-\epsilon)$$

no good as D and D* in wrong direction

V_{ub}



- Diagnosing better via angular distribution Bernlocher,Ligeti, Turczek'14
- General dim-6 RHC can explain (old) Vub-pattern but problems with Z->bb Crivellin, Pokorksi'14
- $\Lambda_b \to p l\nu$ from LHCb from '15 does not support right handed currents (not exclude them either)

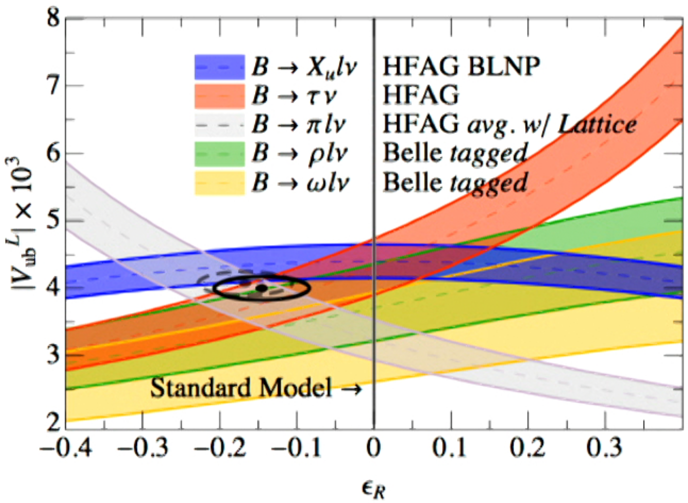
- Yet instructive to **contemplate** on **right-handed currents** ε_R

V_{cb}

$$|V_{cb}|_{\rm incl} = |V_{cb}|(1+\tfrac{1}{2}\epsilon^2)$$
$$|V_{cb}|_{D^*} = |V_{cb}|(1+\epsilon)$$
$$|V_{cb}|_{D} = |V_{cb}|(1-\epsilon)$$

no good as D and D^* in wrong direction

V_{ub}



- Diagnosing better via angular distribution Bernlocher,Ligeti, Turczek'14
- General dim-6 RHC can explain (old) Vub-pattern but problems with Z->bb Crivellin, Pokorksi'14
- $\Lambda_b \to p l\nu$ from LHCb from '15 does not support right handed currents (not exclude them either)

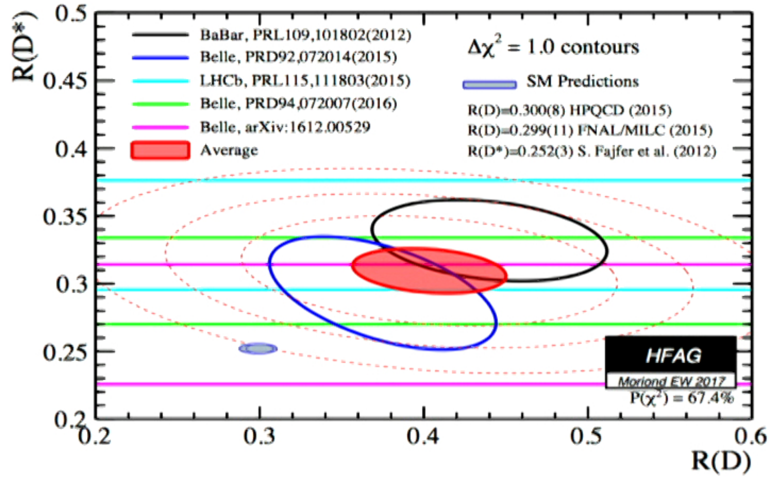
Flavour Universality I: τ vs μ,e

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

3.9σ

LHCb@FPCP'17

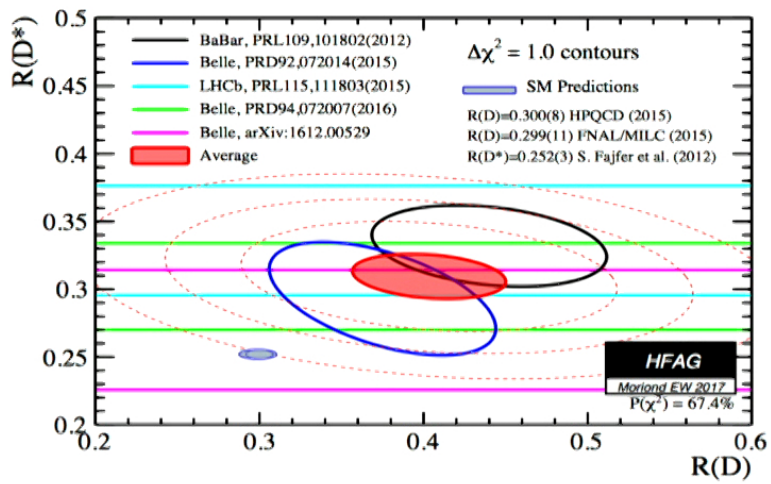
$$R_{D^*} = 0.285(19)(25)(14)$$



Flavour Universality I: τ vs μ,e

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

3.9σ



LHCb@FPCP'17

$$R_{D^*} = 0.285(19)(25)(14)$$

- SM: S,P wave form factors
  R_D lattice HPQCD Na et al'15
  R_{D^*} using Caprini, Lellouch, Neubert'97 expansion ($O(\alpha_s/m_b)$)

$$R_i(w) = R_i(1) + R_i'(1)(1-w) + R_i''(1)/2(1-w)^2$$

form factor

Belle'10 data assuming no NP l=e,μ

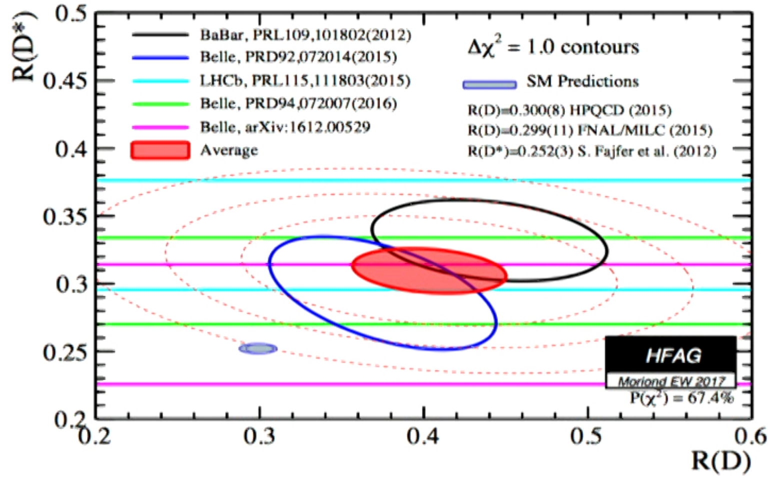
Flavour Universality I: τ vs μ,e

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

3.9σ

LHCb@FPCP'17

$R_{D^*} = 0.285(19)(25)(14)$



- SM: S,P wave form factors
  - R_D lattice HPQCD Na et al'15
  - R_{D^*} using Caprini, Lellouch, Neubert'97 expansion ($O(\alpha_s/m_b)$)

$$R_i(w) = R_i(1) + R_i'(1)(1-w) + R_i''(1)/2(1-w)^2$$

form factor

Belle'10 data assuming no NP l=e,μ

- R_{D^*} dominated by scalar form factor R_0 which is exp-unconstrained! Angular analysis $B \to D^*\tau\nu$ is investigated by LHCb ….

- Refined analysis using Belle’17 angular data with more reliable error R_{D^*}
  Schacht et al & Robinson et al to appear @LHC-workshop - anomaly persists

  $R_{D^*} = 0.258(10)$ [preliminary] compare $R_{D^*} = 0.252(3)$, Fajfer, Kamenik, Nisandizc’13

- Refined analysis using Belle'17 angular data with more reliable error R_{D^*}
  Schacht et al & Robinson et al to appear @LHC-workshop - anomaly persists

  R_{D^*} = 0.258(10) [preliminary] compare R_{D^*} = 0.252(3), Fajfer, Kamenik, Nisandizc'13

- **However** : **τ** difficult particle …

$$BF(B \to X_c \tau \nu) = \begin{cases} 2.42(06) \cdot 10^{-2} & \text{Ligeti, Tackman(theory)} \\ 2.41(23) \cdot 10^{-2} & \text{LEP(experiment)} \end{cases}$$

$$BF(B \to D \tau \nu) + BF(B \to D^* \tau \nu) = \begin{cases} Kamenik, Fajfer'12 & BaBar'12, LHCb'15 & Belle'15 \\ 2.01(7) \cdot 10^{-2} & 2.78(25) \cdot 10^{-2} & 2.39(32) \cdot 10^{-2} \end{cases}$$

looks like two modes experimentally saturate inclusive rate …

- Refined analysis using Belle'17 angular data with more reliable error R_{D^*}
  Schacht et al & Robinson et al to appear @LHC-workshop - anomaly persists

  R_{D^*} = 0.258(10) [preliminary] compare R_{D^*} = 0.252(3), Fajfer, Kamenik, Nisandizc'13

- **However** : **τ** difficult particle …

$$BF(B \to X_c \tau \nu) = \begin{cases} 2.42(06) \cdot 10^{-2} & \text{Ligeti, Tackman(theory)} \\ 2.41(23) \cdot 10^{-2} & \text{LEP(experiment)} \end{cases}$$

$$BF(B \to D\tau\nu) + BF(B \to D^*\tau\nu) = \begin{cases} Kamenik, Fajfer'12 & BaBar'12, LHCb'15 & Belle'15 \\ 2.01(7) \cdot 10^{-2} & 2.78(25) \cdot 10^{-2} & 2.39(32) \cdot 10^{-2} \end{cases}$$

looks like two modes experimentally saturate inclusive rate …

- Refined analysis using Belle'17 angular data with more reliable error R_{D^*}
  Schacht et al & Robinson et al to appear @LHC-workshop - anomaly persists

  R_{D^*} = 0.258(10) [preliminary] compare R_{D^*} = 0.252(3), Fajfer, Kamenik, Nisandizc'13

- **However** : **τ** difficult particle …

$$BF(B \to X_c \tau \nu) = \begin{cases} 2.42(06) \cdot 10^{-2} & \text{Ligeti, Tackman(theory)} \\ 2.41(23) \cdot 10^{-2} & \text{LEP(experiment)} \end{cases}$$

$$BF(B \to D\tau\nu) + BF(B \to D^*\tau\nu) = \begin{cases} Kamenik, Fajfer'12 & BaBar'12, LHCb'15 & Belle'15 \\ 2.01(7) \cdot 10^{-2} & 2.78(25) \cdot 10^{-2} & 2.39(32) \cdot 10^{-2} \end{cases}$$

  looks like two modes experimentally saturate inclusive rate …

- **Good 1**: BelleII@50/ab competitive with theory error
  LHCb Run2 4% on R_{D^*}

- Refined analysis using Belle'17 angular data with more reliable error R_{D^*}
  Schacht et al & Robinson et al to appear @LHC-workshop - anomaly persists

  $R_{D^*} = 0.258(10)$ [preliminary] compare $R_{D^*} = 0.252(3)$, Fajfer, Kamenik, Nisandizc'13

- **However** : τ difficult particle …

$$BF(B \to X_c \tau \nu) = \begin{cases} 2.42(06) \cdot 10^{-2} & \text{Ligeti, Tackman(theory)} \\ 2.41(23) \cdot 10^{-2} & \text{LEP(experiment)} \end{cases}$$

$$BF(B \to D\tau\nu) + BF(B \to D^*\tau\nu) = \begin{cases} Kamenik, Fajfer'12 & BaBar'12, LHCb'15 & Belle'15 \\ 2.01(7) \cdot 10^{-2} & 2.78(25) \cdot 10^{-2} & 2.39(32) \cdot 10^{-2} \end{cases}$$

  looks like two modes experimentally saturate inclusive rate …

- **Good 1**: BelleII@50/ab competitive with theory error
  LHCb Run2 4% on R_{D^*}
- **Good 2**: CLN-expansion can be partly improved $O(\alpha_s^2, \alpha_s/m_c, 1/m_c^2)$

☆ **Experimental prospects** to settle; it theory improvement possible

2.B.FCNC-level tensions

long distance contamination
except LFU

(i) quick theory overview
(ii) experimental results
(iii) summery of fits
(iv) theoretical reappraisal of charm

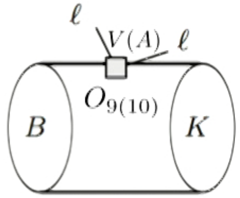
$B \to K^{(*)} ll$ under microscope

- SM Wilson-coeff: $\mathbf{C_S = C_P = C_T \simeq 0}$, $\mathbf{C_V = C_9 + \delta C_9^{eff}(q^2)}$, $\mathbf{C_A = C_{10}}$

B→K(*)ll under microscope

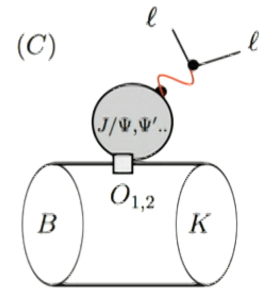
- SM Wilson-coeff: $C_S = C_P = C_T \simeq 0$, $C_V = C_9 + \delta C_9^{eff}(q^2)$, C

short distance



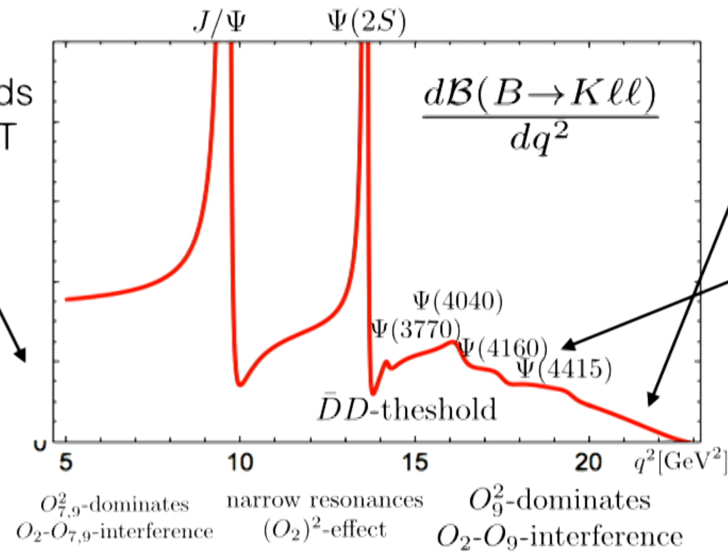
electroweak penguin (also O_7..)

Long distance



4-quark operators (also $O_{3..6}$)

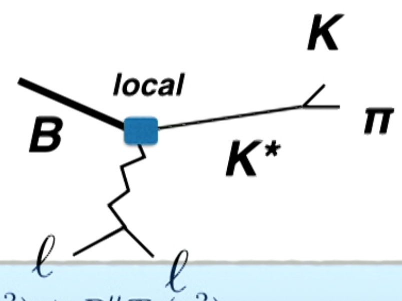
K **fast**:
- **light-cone** methods
LCSR, QCDF/SCET



K **slow**:
- high-q^2 **"OPE"**
-**endpoint relations**

diagnostic shape for charm

Short distance described Form Factors



- ***tensor* & *vector* form factors**

$$\langle K^*(p,\eta)|\bar{s} i q_\nu \sigma^{\mu\nu}(1\pm\gamma_5) b|\bar{B}(p_B)\rangle = P_1^\mu T_1(q^2) \pm P_2^\mu T_2(q^2) \pm P_3^\mu T_3(q^2)$$

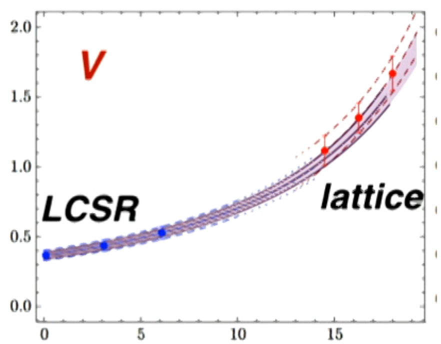
$$\langle K^*(p,\eta)|\bar{s}\gamma^\mu(1\mp\gamma_5) b|\bar{B}(p_B)\rangle = P_1^\mu \mathcal{V}_1(q^2) \pm P_2^\mu \mathcal{V}_2(q^2) \pm P_3^\mu \mathcal{V}_3(q^2) \pm P_P^\mu \mathcal{V}_P(q^2)$$

- **low q²** (large recoil) Light-cone sum rules

  K*-DA: Bharucha, Straub, RZ '15 (use of elms - backup)
  B-DA: Offen, Khodjamirian, Mannel '06

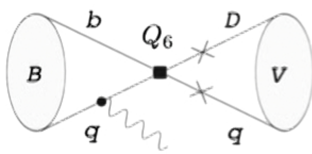
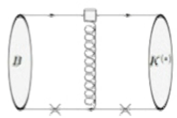
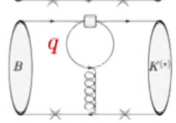
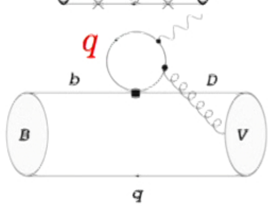
- **high q²** (low recoil) lattice Horgan, Meinel, Wingate, Liu'13

algebraically:
$T_1(0) = T_2(0)$
regularity:
$A_0(0) = A_3(0)$



- For Gil et al (💝):
  connects smoothly via z-expansion

long-distance brief overview status

	QCDF	LCSR
comments:	1) depends B-meson DA 2) at $1/m_b$ breakdown fac endpoint divergences	1) depend on spurious momentum and analytic continuation thereof 2) includes photon DA
	$1/m_b$ suppressed $O(a_s)$ accidental?	photon DA sizeable Khodjamirian et al'95 Ali Braun'95 Lyon, RZ'13
	the $1/m_b$ endpoint divergent	Dimou, Lyon, RZ'12
	idem	not done (some work)
	non-factorisable	various bits done Ball, Jones, RZ'06, Khodjamirian et al'10, ..later

Bosch, Buchalla'01

Beneke, Feldman, Seidel'01

Flavour Universality II: μ vs e

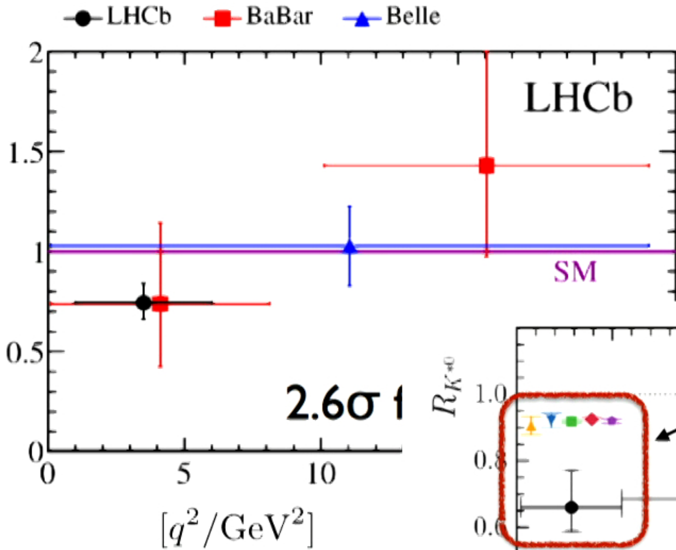
Hiller Kruger'03

$$R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2}$$

Flavour Universality II: μ vs e

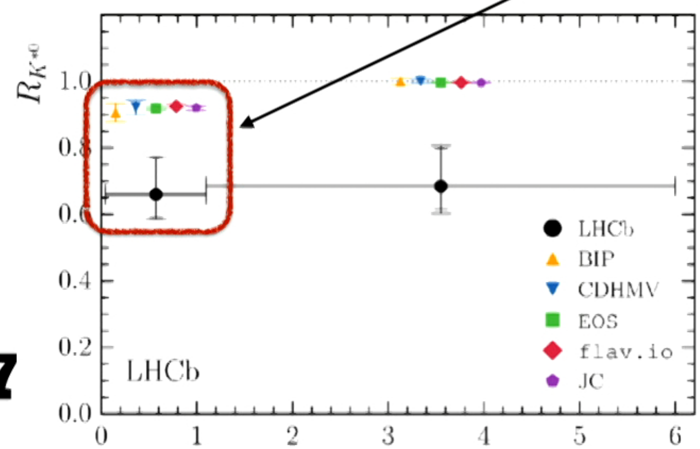
Hiller Kruger'03

$$R_H = \frac{\int \frac{d\Gamma(B \to H\mu^+\mu^-)}{dq^2}\, dq^2}{\int \frac{d\Gamma(B \to He^+e^-)}{dq^2}\, dq^2}$$



2014

dominated by photon pole!?!
(non-universality impossible unless light-resonance)



2017

Theory Crosschecks

- **hadronic** effects are **universal**, ought to cancel

some caveats
LHCb checked ..

- **non-universal** - phase space controlled
  - QED: O(few%) - unknown at time

$$\sim \alpha \ln^2 \left(\frac{m_e}{m_\mu} \right)$$

Theory Crosschecks

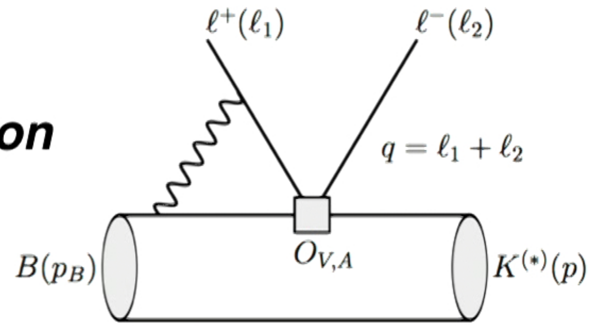
- **hadronic** effects are **universal**, ought to cancel   some caveats LHCb checked ..
- **non-universal** - phase space controlled
  - QED: O(few%) - unknown at time $\sim \alpha \ln^2\left(\frac{m_e}{m_\mu}\right)$

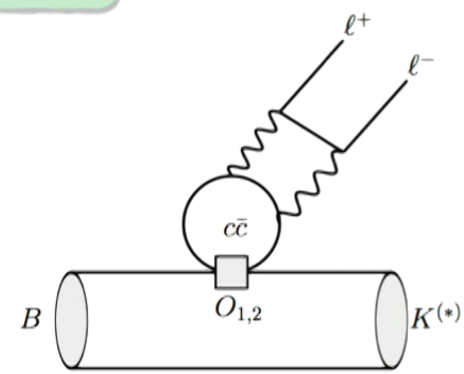
QED no factorisation → all partial waves!
estimate QED effect from D,F,..-waves
Gratrex. Hopfer, RZ'15 [ongoing LHCb analysis]

non-factorisable QED corrections

effects:
A_{FB} without axial interaction

photon

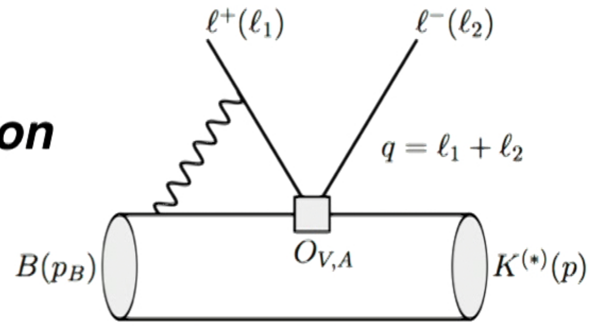


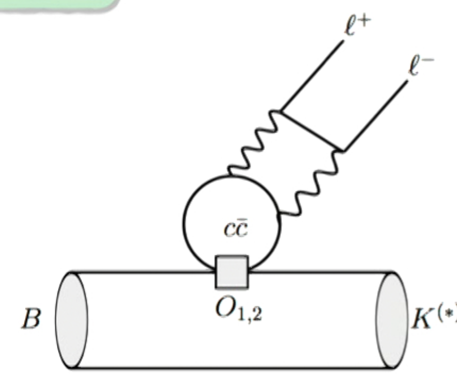


non-factorisable QED corrections

effects:
A_{FB} without axial interaction

photon





- Becomes a proper 1→3 process and by crossing a 2→2 with Mandelstam variables

$$B(p_B) + \ell^-(-\ell_1) \to K(p) + \ell^-(\ell_2) \ ,$$

$$s[u] = (p \pm \ell_2[\ell_1])^2 = \frac{1}{2}\left[(m_B^2 + m_K^2 + 2m_\ell^2 - q^2) \pm \beta_\ell \sqrt{\lambda} \cos\theta_\ell\right]$$

Experimental Crosschecks

- Available for K*-mode (K not public - awaited in update)

[1]

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to \mu^+ \mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi (\to e^+ e^-))} = 1.043 \pm 0.006 \pm 0.045$$

also compatible with Ψ(2S)

Experimental Crosschecks

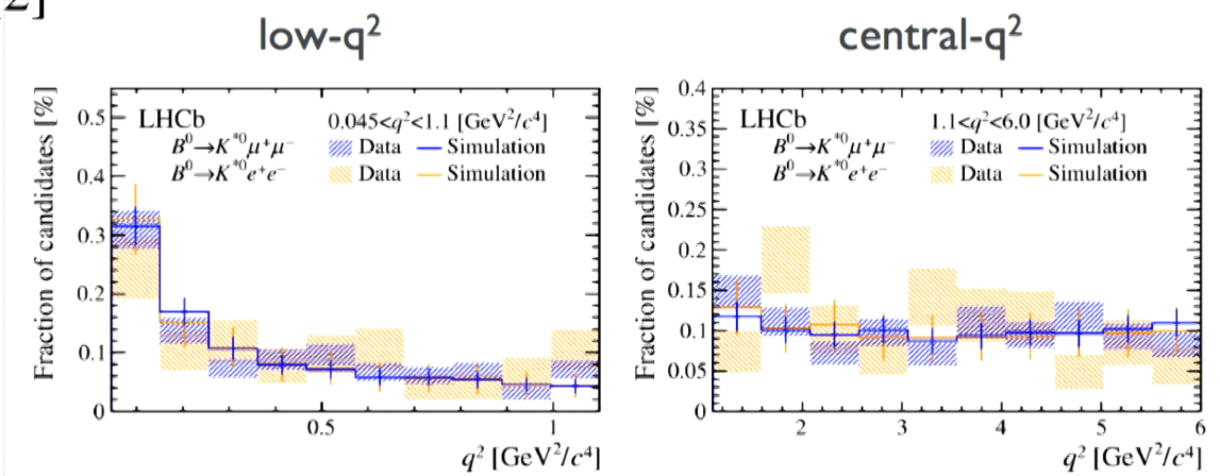
- Available for K*-mode (K not public - awaited in update)

[1]

$$r_{J/\psi} = \frac{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B^0 \to K^{*0} J/\psi(\to e^+e^-))} = 1.043 \pm 0.006 \pm 0.045$$

also compatible with Ψ(2S)

[2]



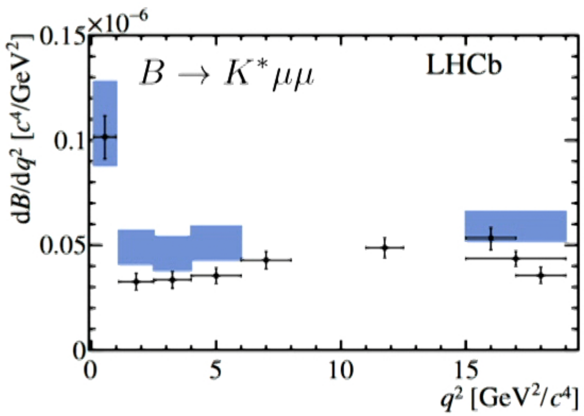
$B_s \to \phi$ vs $B \to K^*$ tension

- at q²=0 (i.e. to photon)

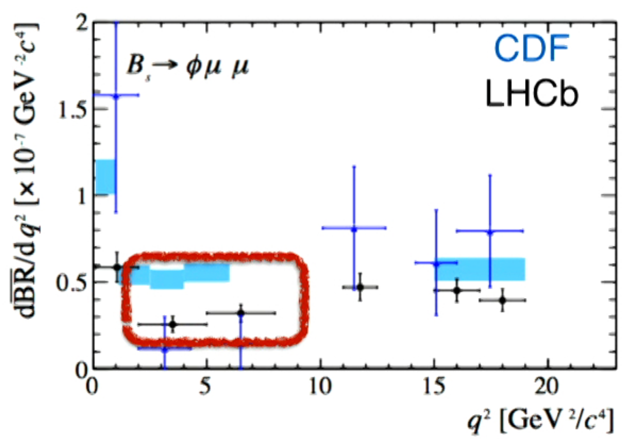
$$R^{(\gamma)}_{K^*\phi} \equiv \frac{\mathrm{BR}(B^0 \to K^{*0}\gamma)}{\mathrm{BR}(B_s \to \phi\gamma)}$$

Lyon, RZ '13	LHCb '12 1202.6267
$0.78(18)$	$1.23(32)$

- B→Vll look at q²-spectrum



reasonable agreement
(LHCb'16 corrected …)



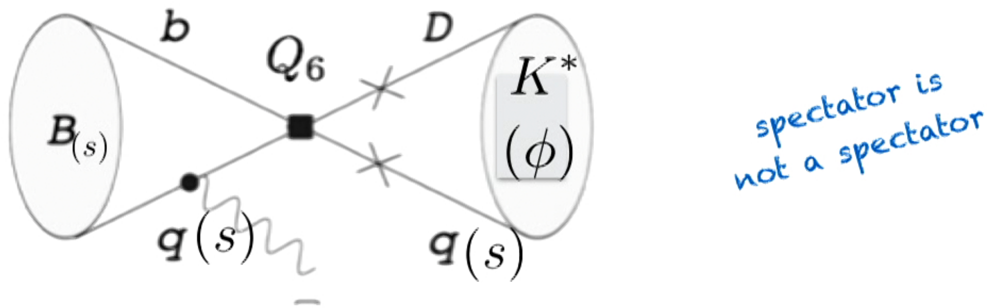
the sign of something?

“On the wrong side of one!” σ-wise not compelling …

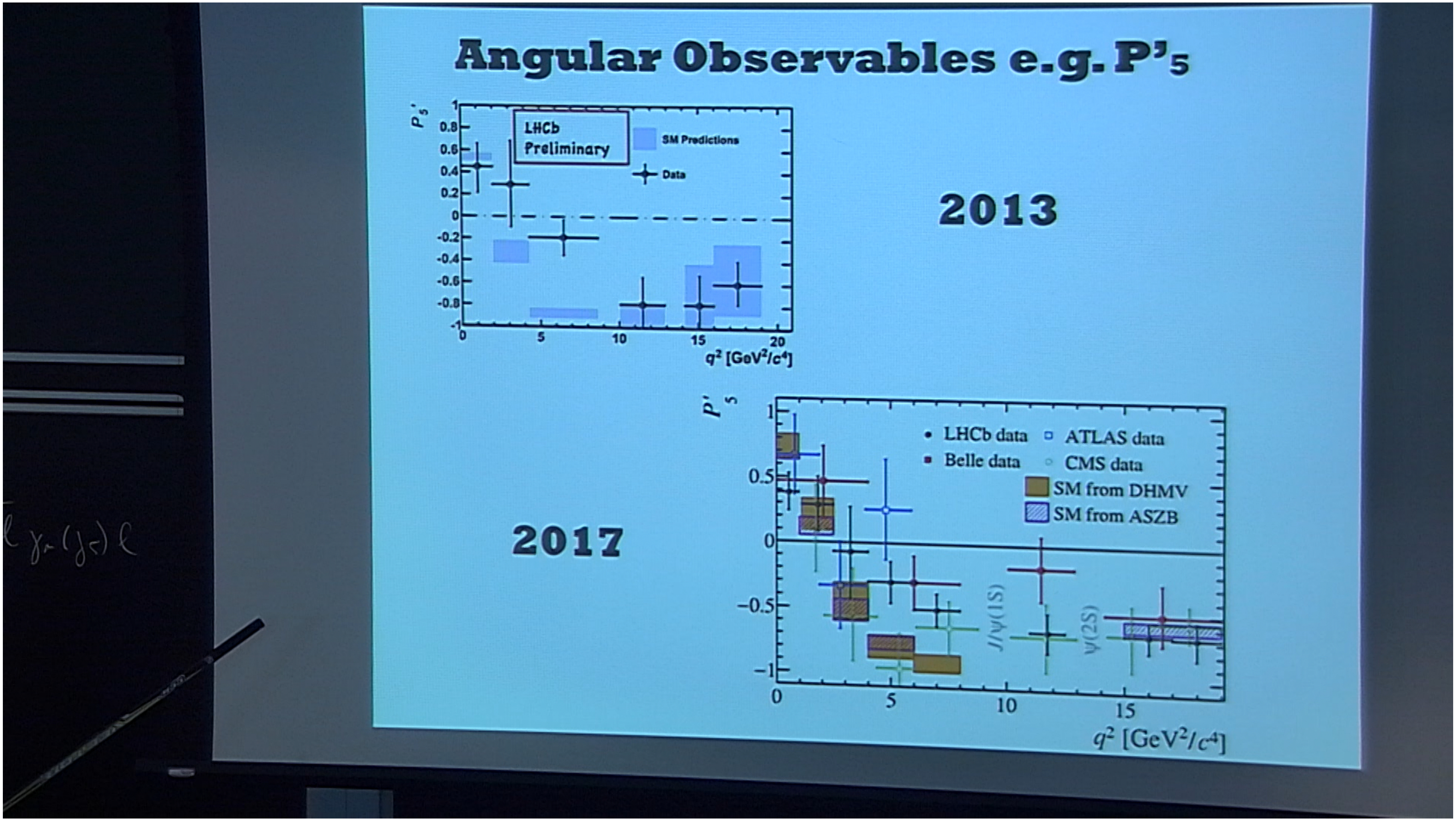
Decays differ by spectator

- lifetimes (effect small)
- form factors Bharucha,Straub,RZ ’15
  normalisation experimental **decay constants**…
  (yet another chapter, this is why $|V_{ub}|_{pl\nu}$ was important)

- **weak annihilation** LCSR or QCDF



- sensitive to $\bar{b}s\bar{s}s - operators$
  very little constraints elsewhere (mixing, non-leptonic)

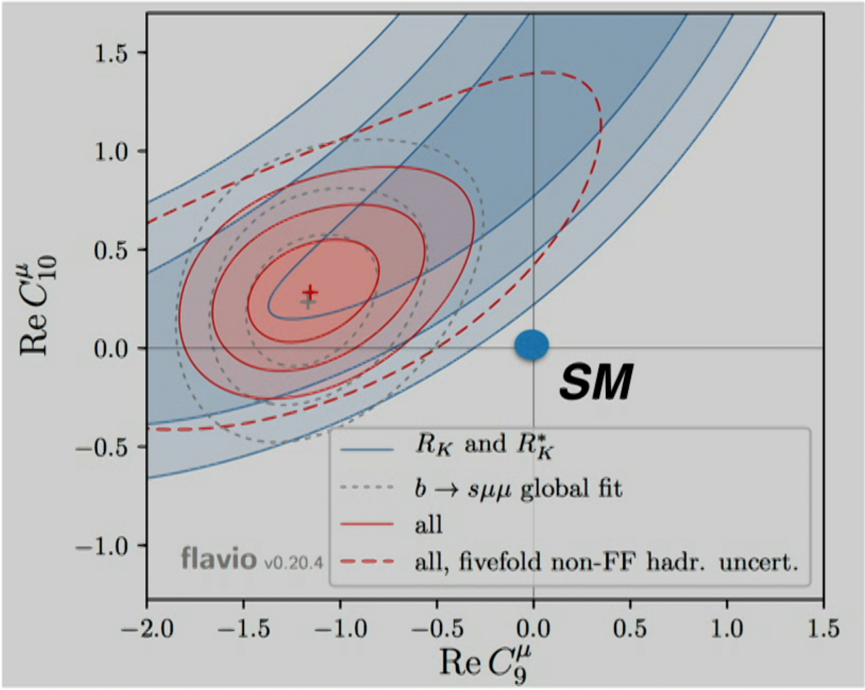

Angular Observables e.g. P'5
LHCb
Preliminary
SM Predictions
Data
2013
q^2 [GeV^2/c^4]
2017
LHCb data
ATLAS data
Belle data
CMS data
SM from DHMV
SM from ASZB
J/ψ(1S)
ψ(2S)
q^2 [GeV^2/c^4]

Summary of global fits b→sll

- Assume it's new physics: may perform fit to H^{eff}_{SM} (charm later ..)

  Several fit-groups: Altmanshofer, et al, Descotes et al, Bobeth et al, Hurth et al, Ciuchini et al

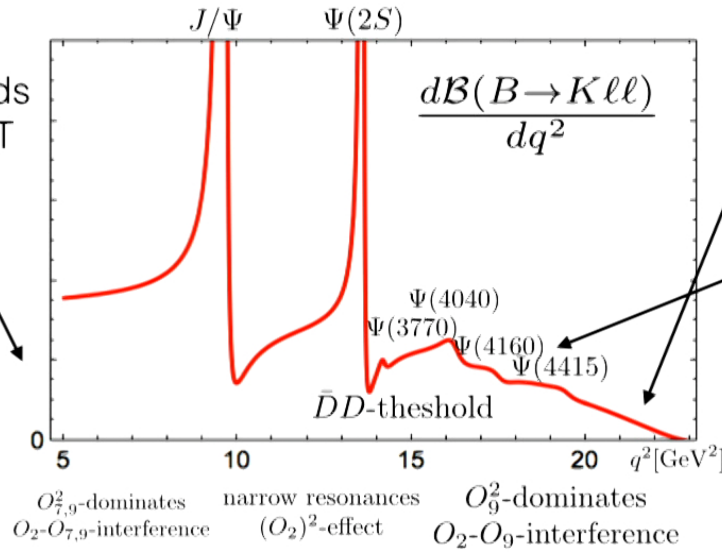
  - An example-fit: Altmanshofer, et al,



(iv) On the importance charm contribution

- Recall:

K **fast**:
- **light-cone** methods
LCSR, QCDF/SCET



K **slow**:
- high-q^2 **"OPE"**
-**endpoint relations**

diagnostic shape for charm

- low-q^2-OPE Expected to work below charmonium
- high-q^2-OPE Grinstein, Pirjol'04, Pirjol, Buchalla,Feldmann'11
  Idea: form factors, LD-suppressed parametrically except charm
  assuming charm is moderate e.g. **naive factorisation** ok
  this induces errors of the type 2% when averaged over high-q^2

Yet charm is virulent

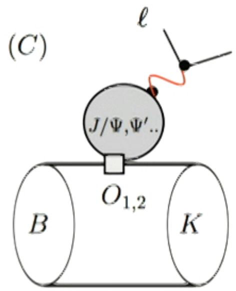
Lyon RZ'14

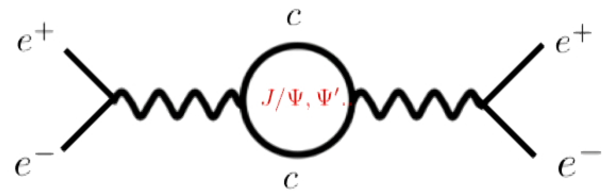
- Does (naive) factorisation describe $B \to Kll$ data? Answer: **not really**

Yet charm is virulent

Lyon RZ'14

- Does (naive) factorisation describe B→Kll data? Answer: **no** **ly**

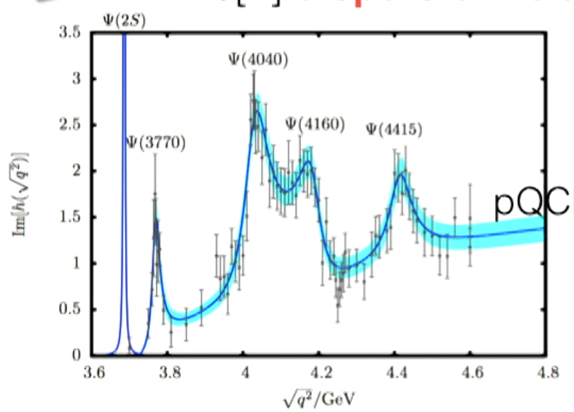




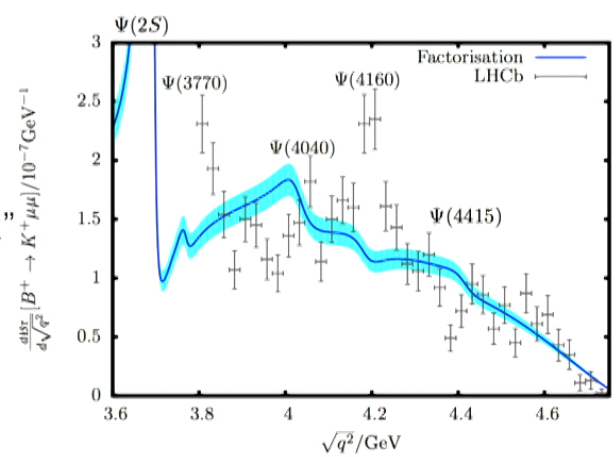
- **vac. pol. h(q²)** (for B->Kll) from e⁺e⁻→hadrons as for (g-2

Disc ~ Im[h]; BESII-data'PLB08

Re[h] **dispersion relation**



pQCD "ok"

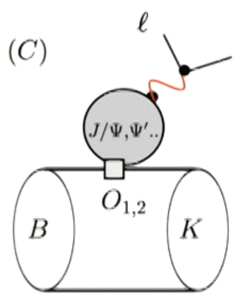


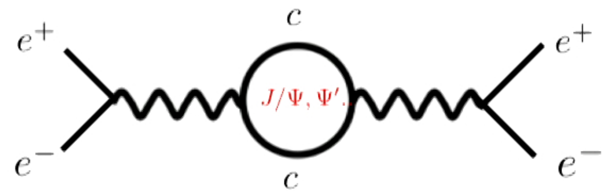
our **χ^2/dof = 1.015**

Yet charm is virulent

Lyon RZ'14

- Does (naive) factorisation describe $B \to Kll$ data? Answer: **no ly**

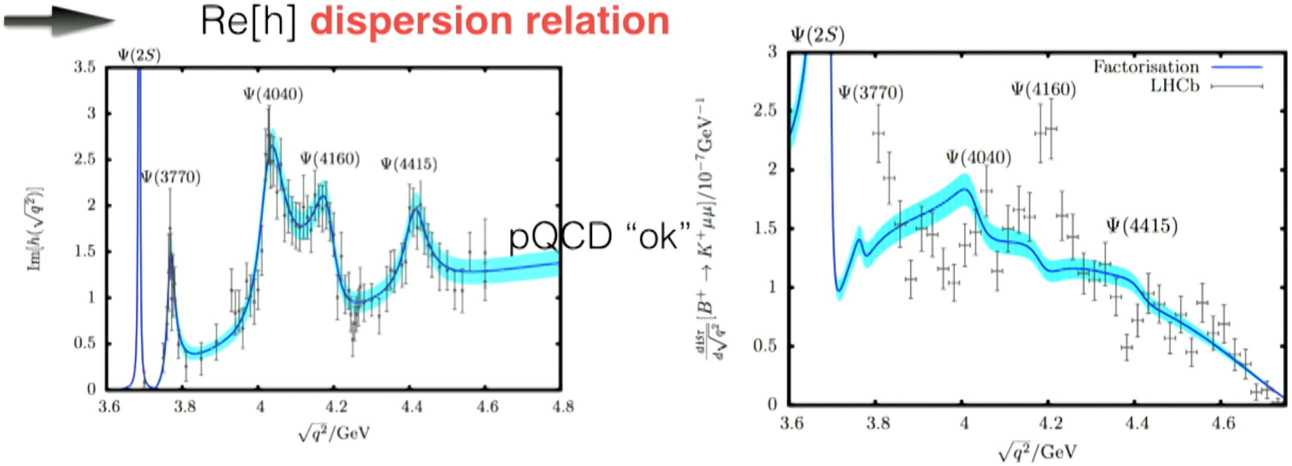




- **vac. pol. h(q²)** (for B->Kll) from $e^+e^- \to$hadrons as for (g-2

Disc ~ Im[h]; BESII-data'PLB08

Re[h] **dispersion relation**



our χ^2/dof = 1.015

Beyond naive factorisation

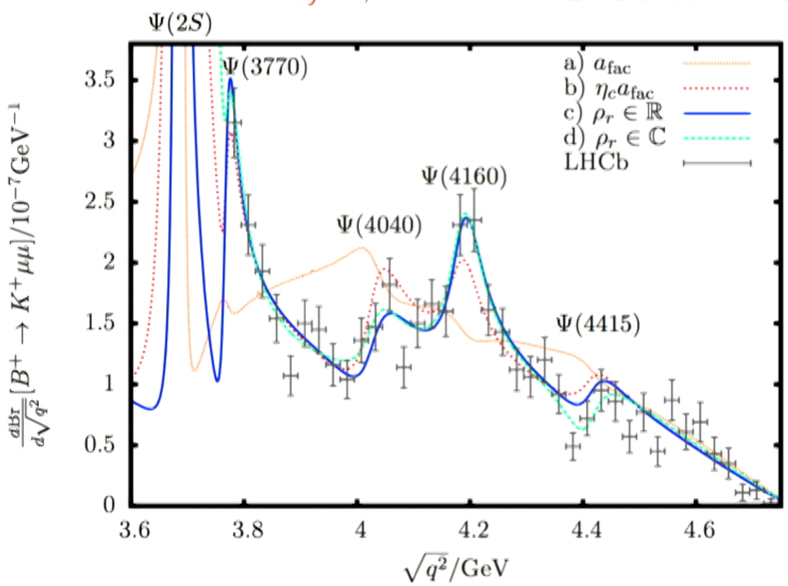
- Can were understand data? Answer: **yes**

Beyond naive factorisation

- Can were understand data? Answer: **yes**
- first principles: Breit-Wigner **residues** related to amplitudes

$$\mathcal{A}(B \to K\ell\ell)|_{q^2 \simeq m_\Psi^2} = \frac{\mathcal{A}(B \to \Psi K)\mathcal{A}^*(\Psi \to \ell\ell)}{q^2 - m_\Psi^2 + i m_\Psi \Gamma_\Psi} + ..$$

Lyon, RZ '14 fit to LHCb data **broad** charmonium resonances



results:

- fit for residues large and opposite in p
  to what people used to use for
  estimates (pQCD or e^+e^- -> hadrons)

What are the implications?

- factorisation badly broken (some history in b->css sector)*
  duality violation in the 10% range (not just 2%)

---

* There is **no duality** in **exclusive** processes for branching fraction since not related to n-point function

What are the implications?

- factorisation badly broken (some history in b->css sector)*
  duality violation in the 10% range (not just 2%)
- in order to give reliable predictions one needs to reconcile hadronic picture with partonic picture in charm.

---

* There is **no duality** in **exclusive** processes for branching fraction since not related to n-point function

What are the implications?

- factorisation badly broken (some history in b->css sector)*
  duality violation in the 10% range (not just 2%)
- in order to give reliable predictions one needs to reconcile hadronic picture with partonic picture in charm.
- the question may be raised as to whether there are more bscc-operators than we think …

---

* There is **no duality** in **exclusive** processes for branching fraction since not related to n-point function

What are the implications?

- factorisation badly broken (some history in b->css sector)*
  duality violation in the 10% range (not just 2%)
- in order to give reliable predictions one needs to reconcile hadronic picture with partonic picture in charm.
- the question may be raised as to whether there are more bscc-operators than we think …
- What is missing?

(1) interference phases $\boldsymbol{\delta_{J/\Psi K}}$, $\boldsymbol{\delta_{J/\Psi(2S)}}$ (absolute value of residue known)
LHCB'16 measured them with 4-fold degeneracy
$\delta_{J/\Psi K}=\pm\pi$ $\delta_{J/\Psi(2S)}=\pm\pi$ (narrow resonances harder than broader)

more analysis to follow

(2) a consistent & complete treatment of charm beyond heavy quark limit
sizeable important: (i) tree-level WC,
(ii) m-element $O(a_s)$ colour enhanced (N_c-enhanced)
Only partial results available

---

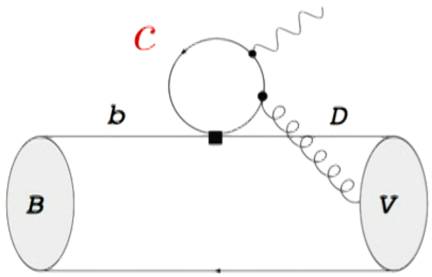
* There is **no duality** in **exclusive** processes for branching fraction since not related to n-point function

Non-factorisable charm

- Do with LCSR either K*-DA (RZ et al) or B-DA (Khodjamirian et al)

Non-factorisable charm

- Do with LCSR either K*-DA (RZ et al) or B-DA (Khodjamirian et al)



"known" (and in progress..)
important for RH-currents search

depends on normalisation
of m-elements (lattice cross-check!)

$$\langle K^* | \bar{s} G_{\alpha\beta} \gamma^\beta q | 0 \rangle$$

3. Model building

- A lot of activity …..

  Crivellin, d'Ambrosio, Jung, Gauld, Haisch, Cellis, Martin, Hofer, Straub, Gori, Altmanshofer, Hiller, Kamenik, Becirevic, Fajifer, Buras, Neubert, Bauer, Isidori, Buttazzo, Greillo, Guadagnoli, Glashow, Lane, …

3. Model building

- A lot of activity …..

  Crivellin, d'Ambrosio, Jung, Gauld, Haisch, Cellis, Martin, Hofer, Straub, Gori, Altmanshofer, Hiller, Kamenik, Becirevic, Fajifer, Buras, Neubert, Bauer, Isidori, Buttazzo, Greillo, Guadagnoli, Glashow, Lane, …

- Severe constraints LFV, LFUV from 1st & 2nd generation
  ⇒ single out **3rd generation**

  Artificial? Yes but no since **top** is **special**. E.g. top mass generation in **composite Higgs model** (partial compositeness)
  Georgi,Kaplan 90' Pomaorol. Wulzer, …'00+, Ferretti'14

3. Model building

- A lot of activity …..

  Crivellin, d'Ambrosio, Jung, Gauld, Haisch, Cellis, Martin, Hofer, Straub, Gori, Altmanshofer, Hiller, Kamenik, Becirevic, Fajifer, Buras, Neubert, Bauer, Isidori, Buttazzo, Greillo, Guadagnoli, Glashow, Lane, …

- Severe constraints LFV, LFUV from 1st & 2nd generation
  ⇒ single out **3rd generation**

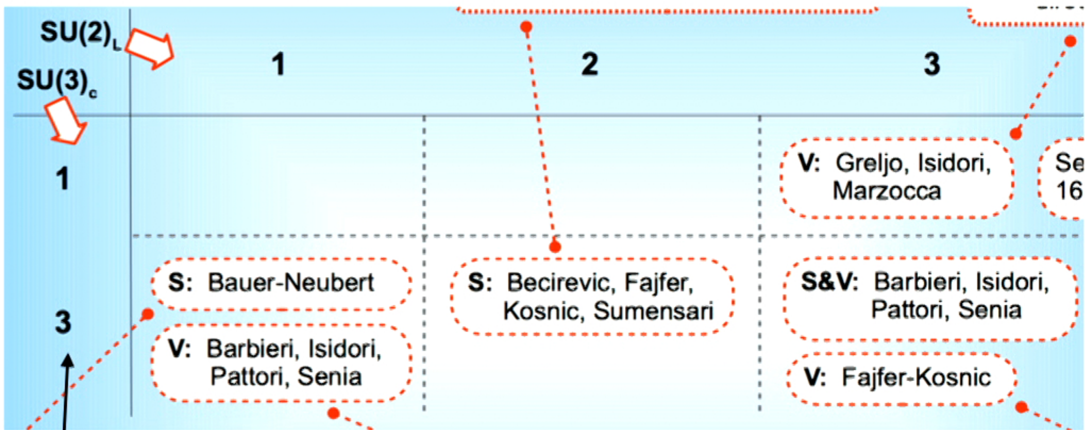
  Artificial? Yes but no since **top** is **special**. E.g. top mass generation in **composite Higgs model** (partial compositeness)
  Georgi,Kaplan 90' Pomaorol. Wulzer, …'00+, Ferretti'14

- People speculating on a **light-resonance** in connection with R_{K^*} deviating from SM in photon pole bin!

- One may distinguish 3 levels
  1) **flavour effective theory** (and RG-running)
  2) **mediator** particles (not UV complete)
  3) **UV-complete** models (e.g. anomaly free, renormalisable)

attempts to explain both b->sll & b->clν anomalies in one model

- Most models (2,3) have a mediator coupling to leptons & quarks e.g. leptoquarks, Z', charged Higgs



Guadagnoli@Higgs-Maxwell'17

Leptoquark

LFUV → LFV?

story of one model

- Consider 3rd generation coupling before EWSB

Glashow, Guadaognoli, Lane'14

$$H^{\rm eff} \sim \bar{b}'_L \gamma_\alpha b'_L \bar{\tau}' \gamma^\alpha (\delta C_9^\alpha + \delta C_{10}^\mu \gamma_5)\tau$$

LFUV → LFV?

story of one model

- Consider 3rd generation coupling before EWSB

Glashow, Guadaognoli, Lane'14

$$H^{\text{eff}} \sim \bar{b}'_L \gamma_\alpha b'_L \bar{\tau}' \gamma^\alpha (\delta C_9^\alpha + \delta C_{10}^\mu \gamma_5) \tau$$

- rotation to mass basis induces LFV*

$$\frac{\mathcal{B}(B \to K e\mu)}{\mathcal{B}(B \to K \mu\mu)} = 2 \frac{|\delta C_{10}|^2}{|C_{10} \delta C_{10}|^2} \left| \frac{(V_L^\ell)_{31}}{(V_L^\ell)_{32}} \right|^2$$

$< 3.7^2$ "weak bound"

- Make it $SU(2)_L$-invariant ⇒ relation to charged currents & b→clv

Bhattacharaya et al '15

- RG-running severe constraints from LFUV τ→lvv

Ferruglio, Paradisi, Pattori'16

---

* bypassed if flavour symmetry broken to $U(1)_e \times U(1)_\mu \times U(1)_\tau$ by aligning with mass Yukawa's

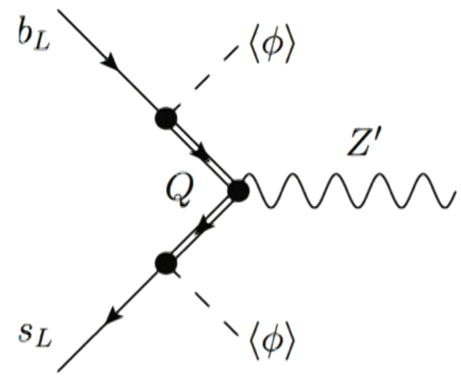
Alonso, Grinstein, Camalich '15

Z'-model

first Gauld et al'13 as 3-3-1 model
here Altmanshofer,Gori, PospelovYavin'14

story of another one

- U(1)' "higgsed" by ϕ (UV complete)
  Q heavy vector fermions (anomaly free)
  gauged L_μ-L_τ (attractive neutrino model building)

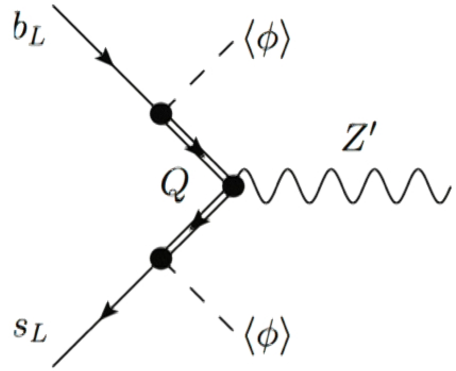


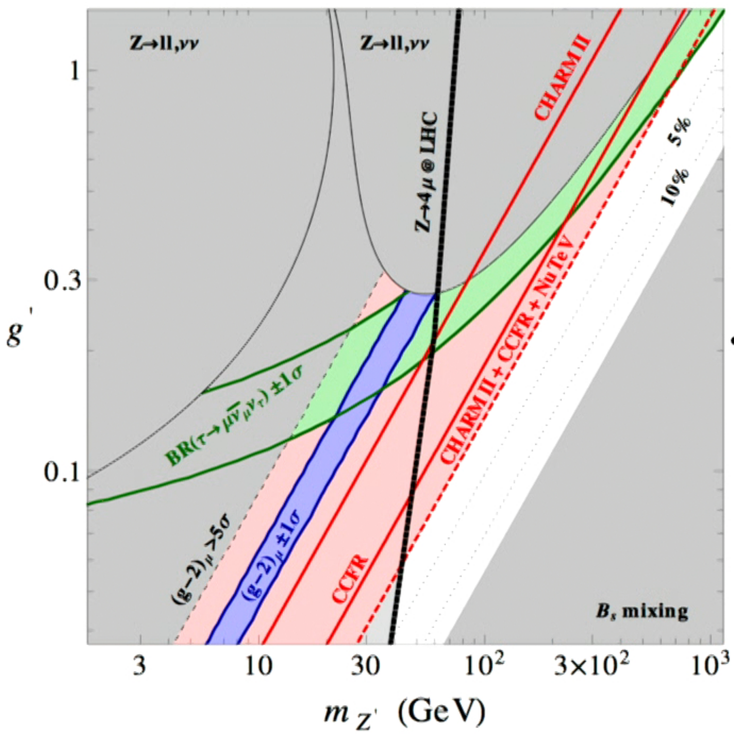
Z'-model

first Gauld et al'13 as 3-3-1 model
here Altmanshofer,Gori, PospelovYavin'14

story of another one

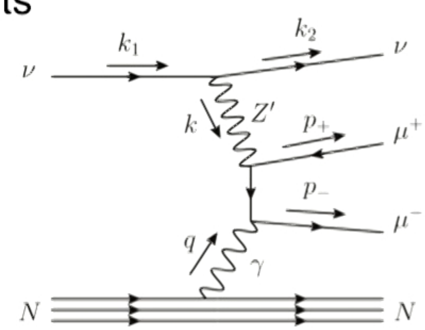
- U(1)' "higgsed" by ϕ (UV complete)
  Q heavy vector fermions (anomaly free)
  gauged L_μ-L_τ (attractive neutrino model building)





their model predicted LFUV just before R_K-anomaly!

- subjected their model to Trident contestants



Conclusions & Summary

some of my personal impressions

interesting anomalies 2-4σ anomalies
good news: will know more in the foreseeable future

- **Angular anomalies b->sll**:
  1) more q^2-bins also in fast recoil
  2) need to know residues of charmonium resonances
  3) desirable to connect charm partonic to hadronic picture

- **Angular anomalies b->sll**:
  1) more q^2-bins also in fast recoil
  2) need to know residues of charmonium resonances
  3) desirable to connect charm partonic to hadronic picture

  - Work out observables which **isolate WCs** with def. q-numbers
    - C^e_{10} non-QCD/QED LFU-sensitive coupling?
    - E.g. bscc and bsss-operators directly?

$$\mathcal{A}_\Delta \simeq -0.98(50)(20) \qquad \mathcal{A}_\Delta \simeq 0.047(28)$$

LHCb '16   theory

$$B_s \to \phi\gamma \text{ time-dependent CP-asymmetry}$$

- Are there observables where the charm can be eliminated?
- My impression: possibilities have not been fully exploited.