Survey of Flavour Anomalies

Roman Zwicky
Edinburgh University
& University of Zurich (visiting)

CP³ Origins
Cosmology & Particle Physics

Centre for Theoretical Physics · Higgs

Experimental talks: Pepe-Altarelli & Harnew
Global-Fit: Mahmoudi
BSM: Crivellin, King (next)

Workshop on Beyond the Standard Model Physics

2-10 September 2017 — Corfu

Overview

- 1. **Introduction** 8'

  [a] Overview Flavour Anomalies
  [b] ***Flavour Universality*** (FU)
  [c] Effective Hamiltonian(s) & Angular Distributions

- 2. **Tree-level** 8'

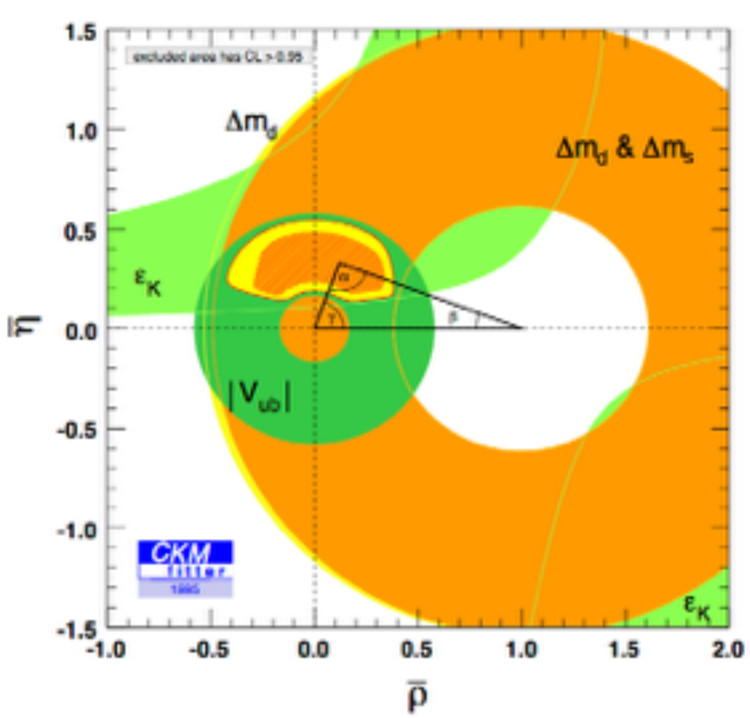
  [a] News on $B \to D^*$ form factors
  [b] $|V_{ub}|$, $|V_{cb}|$ exclusive vs inclusive - tension eases
  [c] $\boldsymbol{R_D, R_{D^*}}$ from $B \to D^{(*)} l \nu$: [l=e,μ vs τ]

- 3. **FCNC** 12'

  [a] $B \to K^* ll$-type angular analysis - missing pieces
  [b] $\boldsymbol{R_K, R_{K^*}}$ [e vs μ] & QED corrections

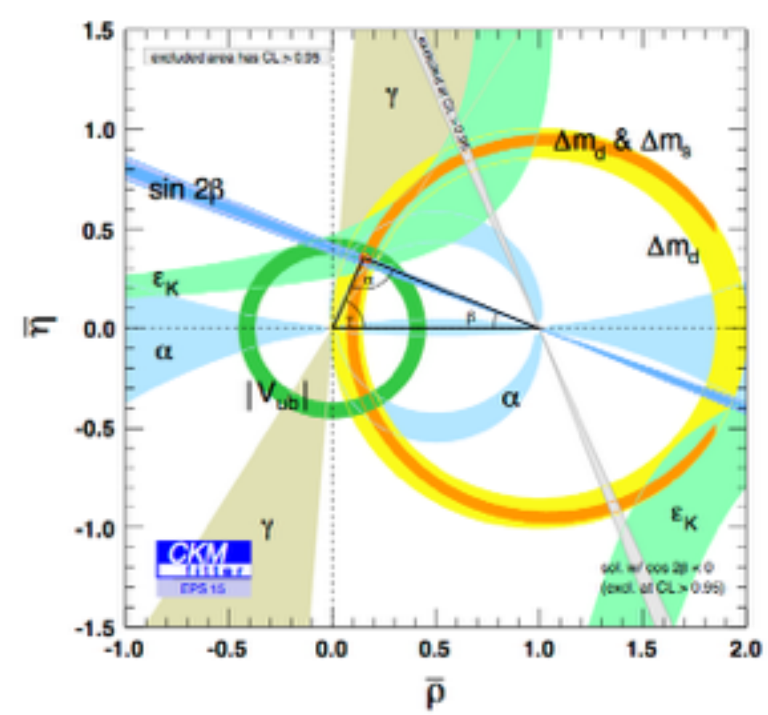
- **Outlook**

[A] Flavour Anomalies
in
expected (FCNC)
and
unexpected (tree) places



95' pre b-factory

..20 years..



15'

... 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 $|V_{\mathrm{ub}}|_{\mathrm{incl}}$

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

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

$\ell = e, \mu$

Lepton Flavour Universality Violation (LFUV)?

(b) Flavour Universality (FU)

- **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 (trivial) kinematic factors and QED corrections (size?)

(c) $H_{\rm eff}$ & angular distributions

- **Flavour physics:** = successful EFT integrating out dof a la Wilson

energy ← $\Lambda_{\rm BSM}?$ — m_W — m_b — 0

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

$C_i(m_b)$ → **perturb. calculable**
Wilson coefficient
UV physics (BSM?)

$O_i(m_b)$ → M-element
IR physics (**non-perturbative**)

- e.g. d=6 Heff of with 10 operators

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

$$O_{S(P)} = \bar{s}_L b \, \bar{\ell}(\gamma_5)\ell \,, \qquad O_{V(A)} = \bar{s}_L \gamma^\mu b \, \bar{\ell}\gamma_\mu(\gamma_5)\ell$$
$$O_{\mathcal{T}} = \bar{s}_L \sigma^{\mu\nu} b \, \bar{\ell}\sigma_{\mu\nu}\ell \,, \qquad O' = O|_{s_L \to s_R}$$

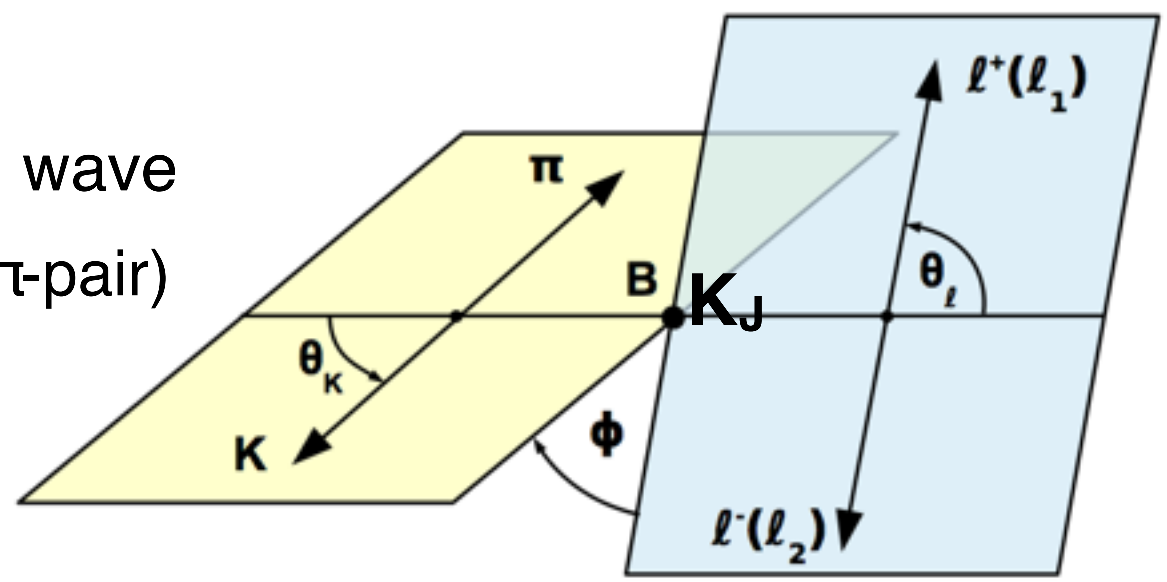
$\bar{\ell}\gamma_\mu(\gamma_5)\ell$ → **S-** and **P-wave** (**ℓ=0,1**)

- In $B \to V(\to S_1S_2)\ell_a\ell_b$ (semi-leptonic/radiative - this talk)

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

d=6 Heff
12 terms

partial wave ℓ_K-(Kπ-pair)



partial wave ℓ_l-($\ell\ell$-pair)

- higher partial waves D, F, .. - ℓ= 2,3, …?

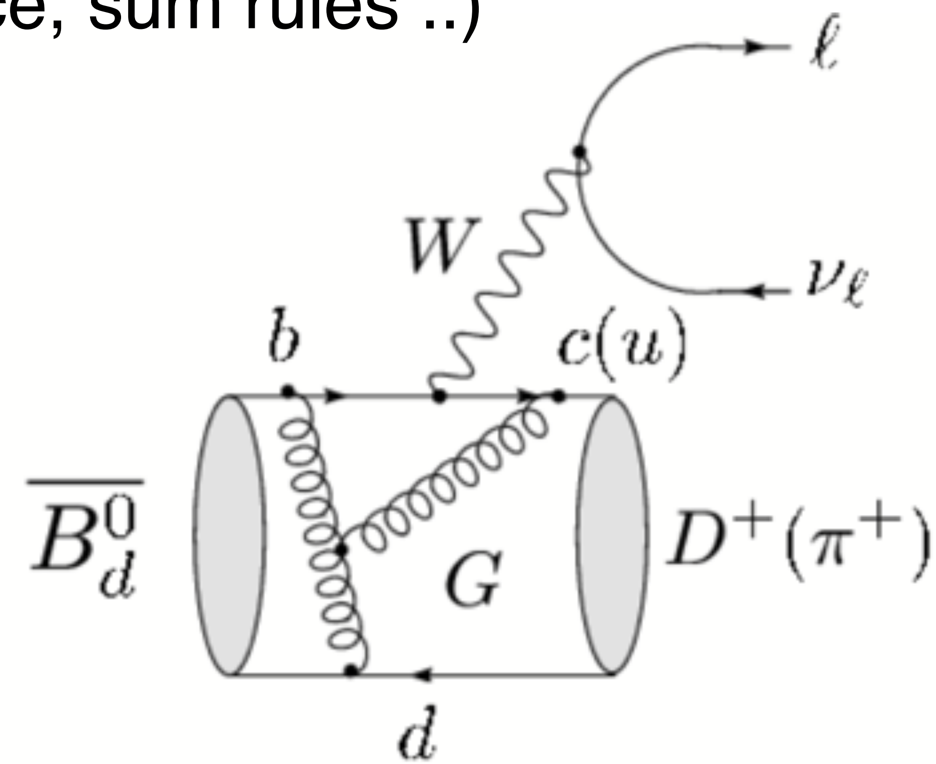
  1) higher dim operators - suppressed by further powers $(m_b/m_W)^{(\ell-1)}$

  2) QED no suppression of higher waves (IR effect) Gratrex. Hopfer, RZ'15

  ⇒ opportunity to probe QED-effects experimentally

Tree-level* tensions

- **Dynamics =** ***short distance*** (no sizeable long distance contributions)
  ➪ short distance **form factor(s)** (e.g. lattice, sum rules ..)



- Focus ***semi-leptonic*** decays

- Hadron Final state:

  J=0 ⇔ 1 scalar form factor

  J=1 ⇔ 3 vector form factors

  1 scalar form factor (enters proportional to lepton mass)

- flavour violation at tree-level of (V-A)-type in SM.

(a) News on $B \to D^*_{(j=1)}$ form factors

- **Not so easy** to compute.
  low recoil (endpt): lattice QCD with effective theories*
  large recoil (fast D^*): LCSR

statistically dominant

- **Low-recoil expansion** & HQET to compute exp.-parameters
  Caprini, Lellouch, Neubert'97

- **Belle** 1702.01521
  release (first-time) **angular distributions** for $\mathbf{B \to D^*(e,\mu)\nu}$

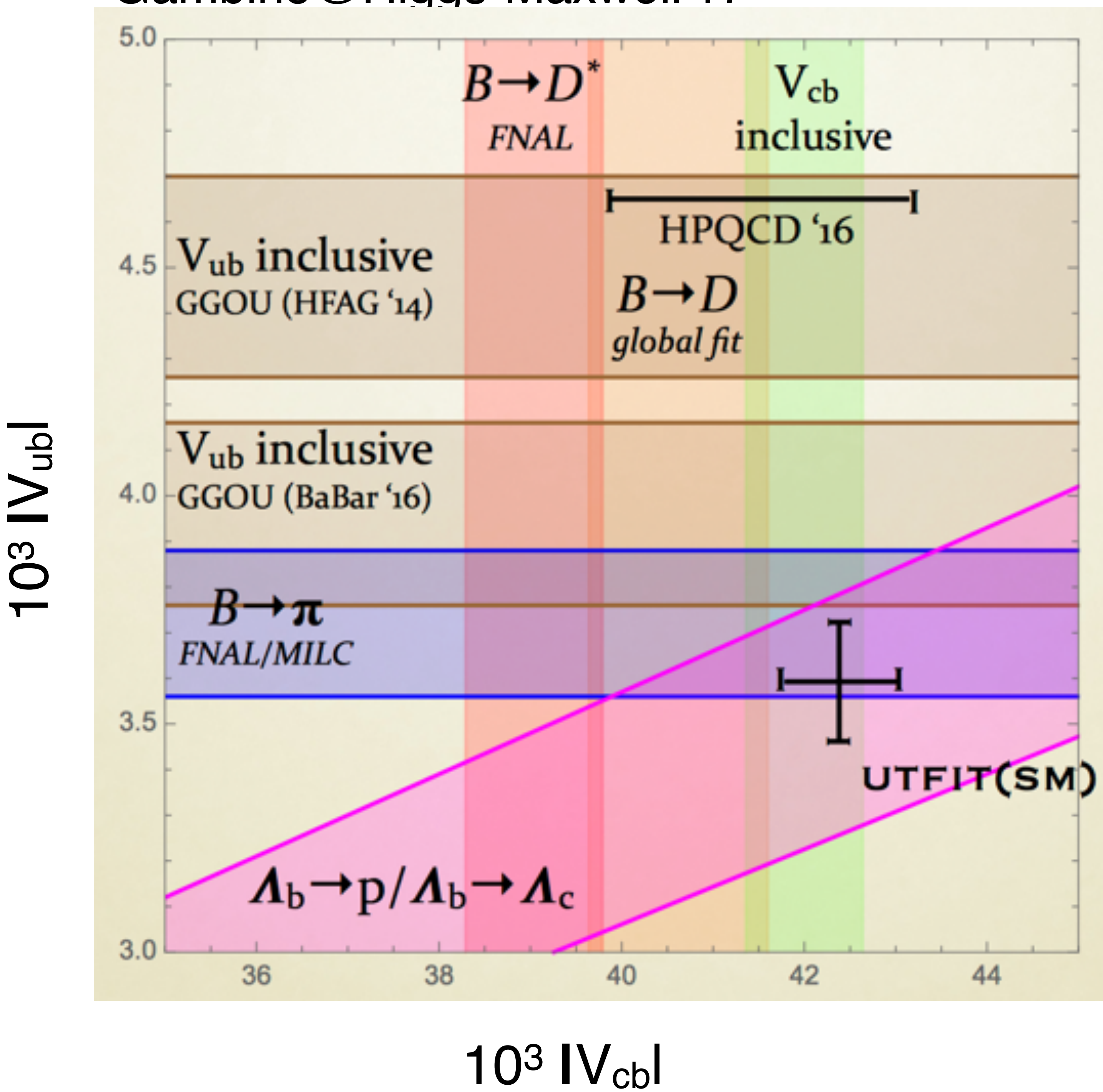
new-player in town

- Used by theorists to **reassess** the situation for
  $|V_{cb}|_{D^*}$: Bigi,Gambino,Schacht 1703.06124 Grinstein & Kobach 1703.08170
  Bernlocher, Ligeti, Papucci, Robinson 1708.07134
  R_{D^*} Gambino,Schacht 1707.09509

- a) finite width effect small
  b) quasi-stable $B \to D$ form factors lattice results HPQCD'15, FNAL'15
  c) only 1 form factor at zero recoil, beyond zero recoil on the way ,,,

(b) V_{cb} & V_{ub} inclusive (optical thm & OPE) vs exclusive

Gambino@Higgs-Maxwell'17



- $|V_{cb}|$-tension eased by angular data Belle'17

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

Bigi, Gambino, Schacht'17

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

- Another Vub-mode

$$|V_{\rm ub}|_{\rho\ell\nu} = 3.3(3)\cdot 10^{-3}$$

Bharucha, Straub, RZ '15

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

V_{cb}

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

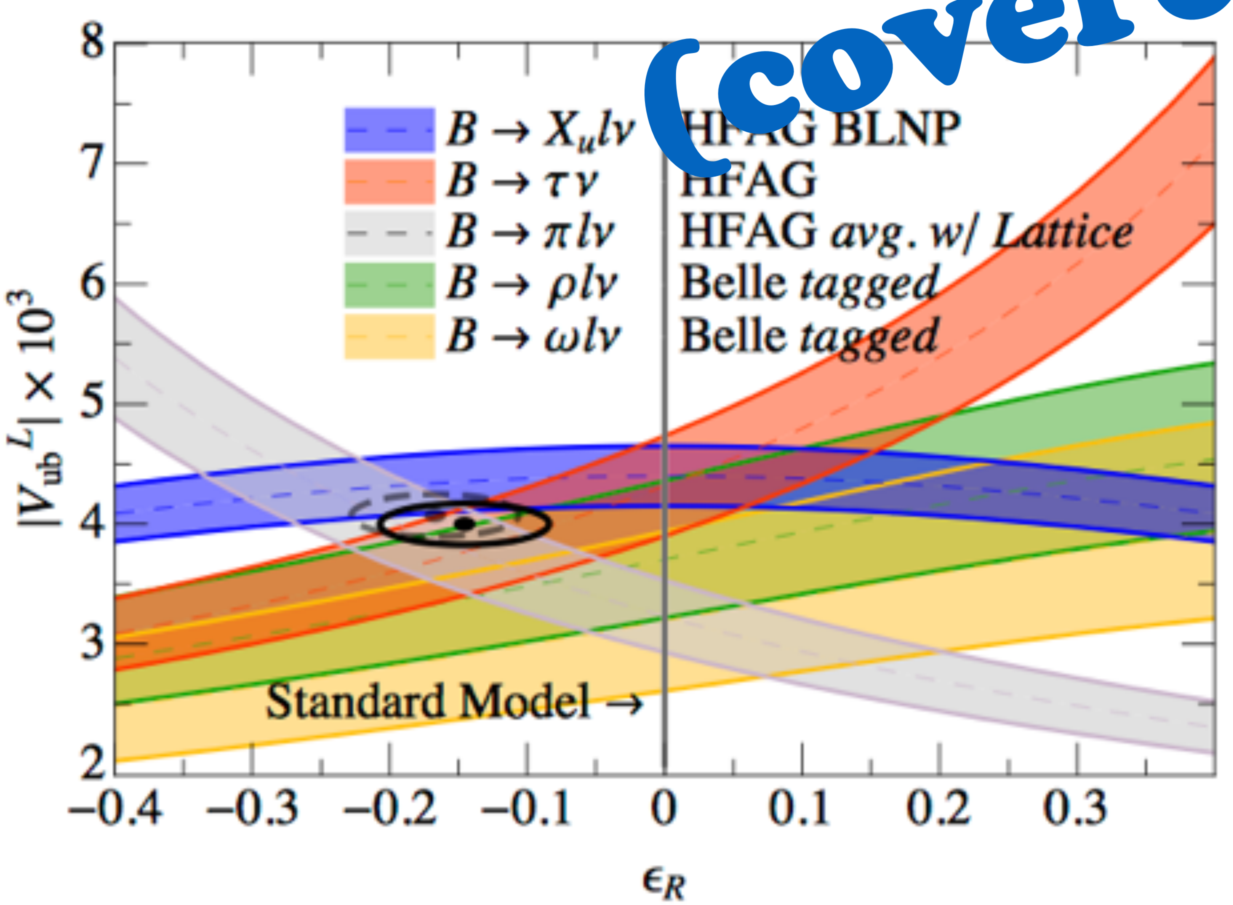
$$|V_{cb}|_{D^*} = |V_{cb}|(1 + \epsilon)$$

$$|V_{cb}|_{D} = |V_{cb}|(1 - \epsilon)$$

no good as D and D*
in wrong direction

SKIP (covered by others)

V_{ub}

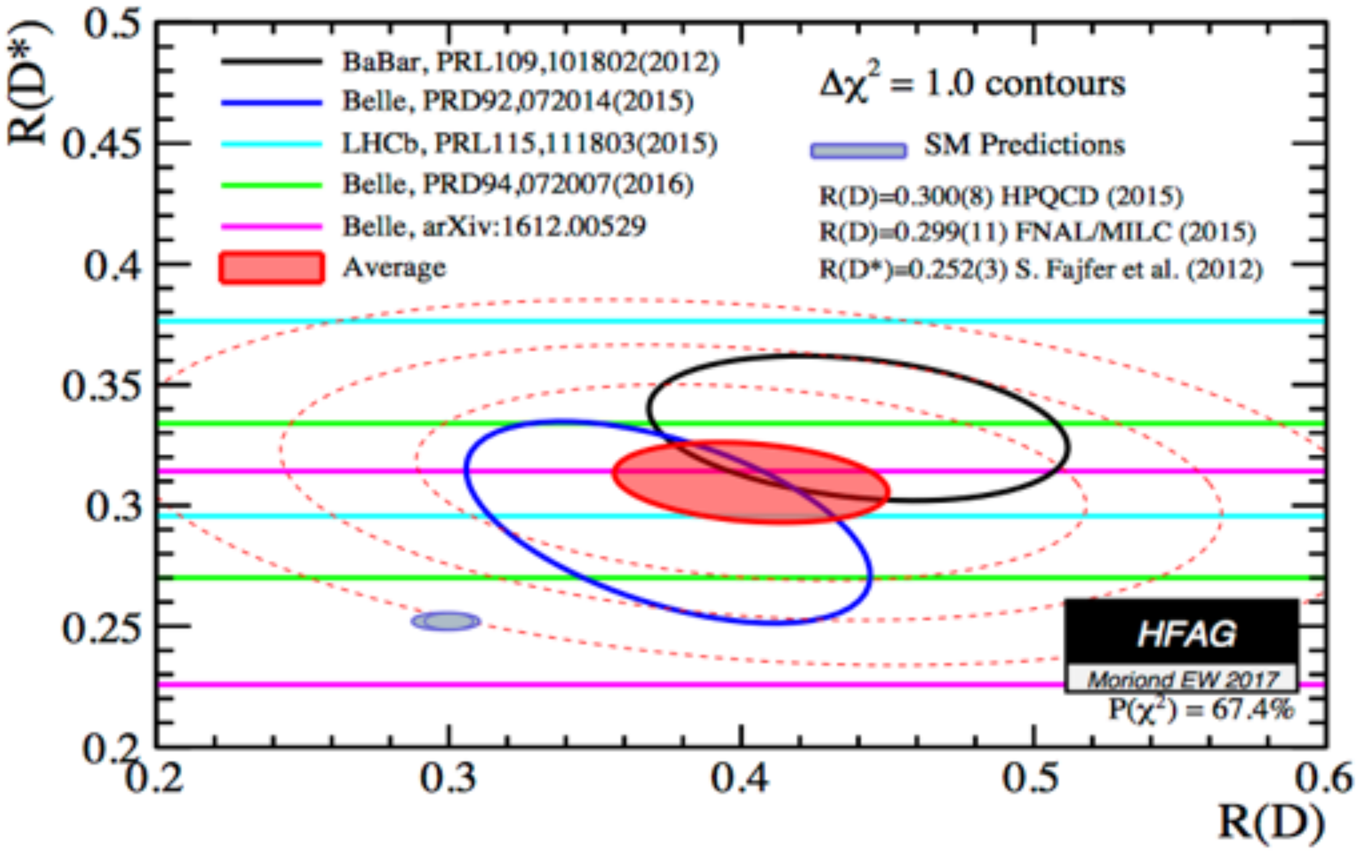


- Diagnosing better via angular distribution Bernlocher,Ligeti, Turczek'14
- General dim-6 RHC can explain (old) Vub-pattern but problems with Z->bb Crivellin, Pokorksi'14
- $\Lambda_b \to p l\nu$ from LHCb from '15 does not support right handed currents (not exclude them either)

(b) R_{D^*} Lepton Flavour Universality I

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

3.9σ



New results:

LHCb@FPCP'17

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

- **However,**

  1) Using **Bellell angular-data** Schacht et al (cf. Robinson et al 17xx.)

  R_{D^*} = 0.262(10) [as average of diff. methods/imputs]

  compare R_{D^*} = 0.252(3), Fajfer et al'13

  R_{D^*} = 0.304(13)(7) HFAG

  2) **τ** difficult particle: 2 exclusive modes saturate incl. rate?

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

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

  D(2400) states contribute ca 10% [PDG]

Perspectives (reducing errors)

- **Theory**:

  1) CLN-expansion can be partly improved $O(\alpha_s^2, \alpha_s/m_c, 1/m_c^2)$

  2) lattice computation on the way …

  3) $B \to D^* \tau \nu$ angular distributions (LHCb?) =

     info on unconstrained scalar form factor (contributes 10% to R_{D^*})

- **Experiment**:

  1) BelleII@50/ab competitive with theory error

  2) BelleII redo LEP's $B \to X_c \tau \nu$

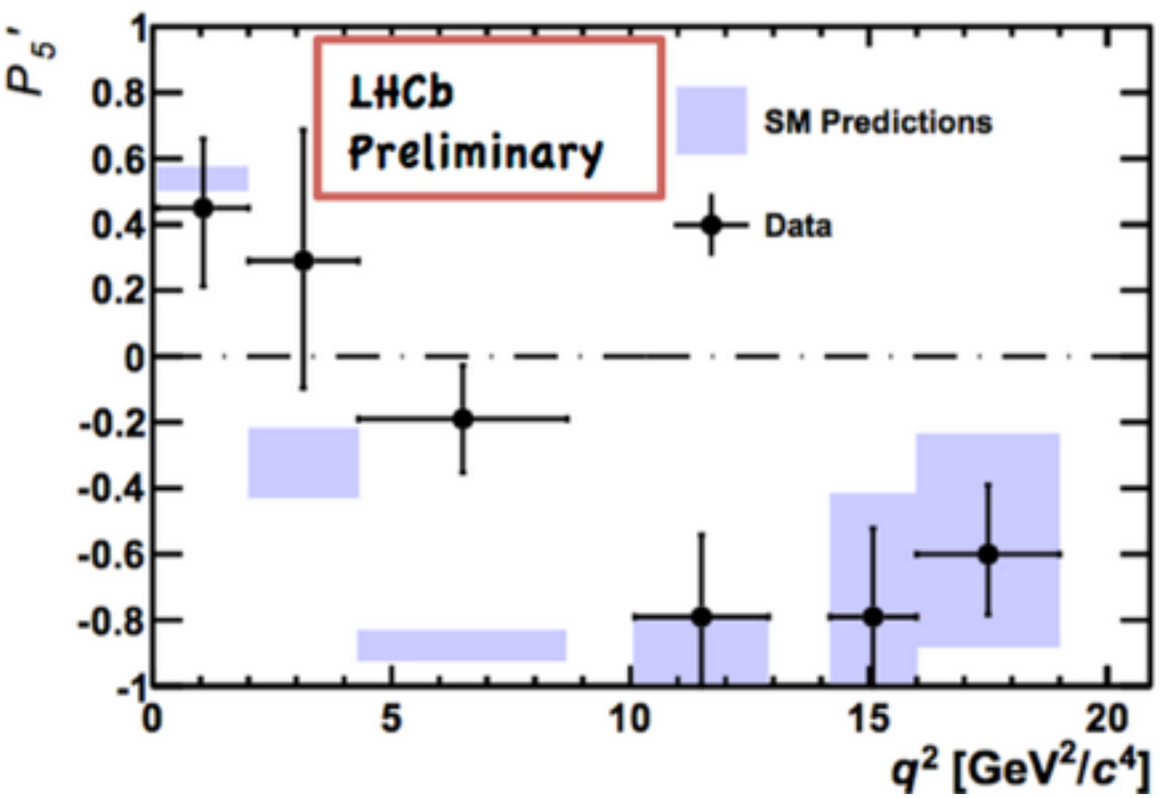
  3) LHCb Run2 4% on R_{D^*}

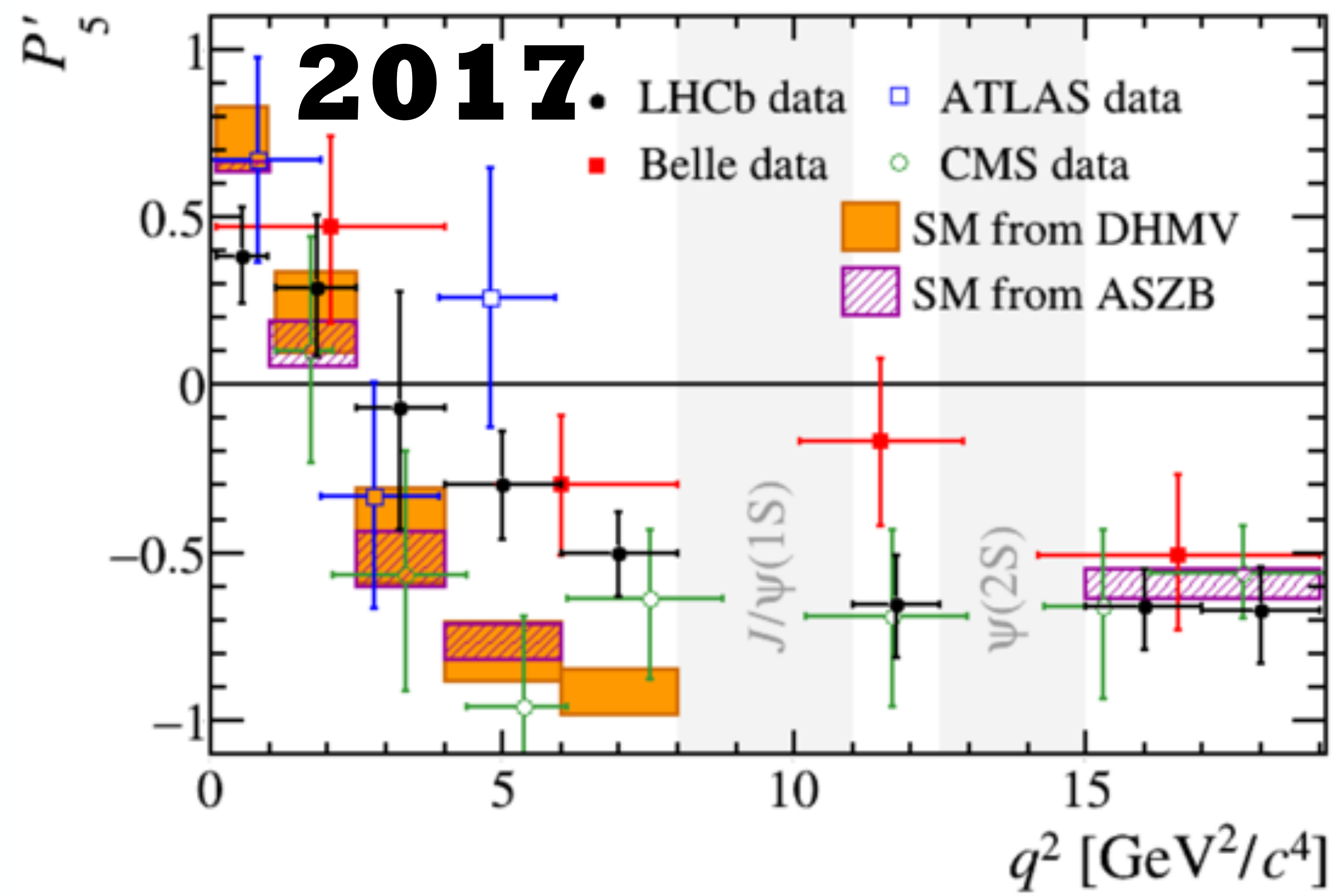
3.FCNC-tensions in b→s$\ell\ell$

long distance contamination
except LFU

(a) Tension angular observables $B \to K^* \mu\mu$

2013





- **e.g. P_5'** odd lepton partial wave A_{FB}-like

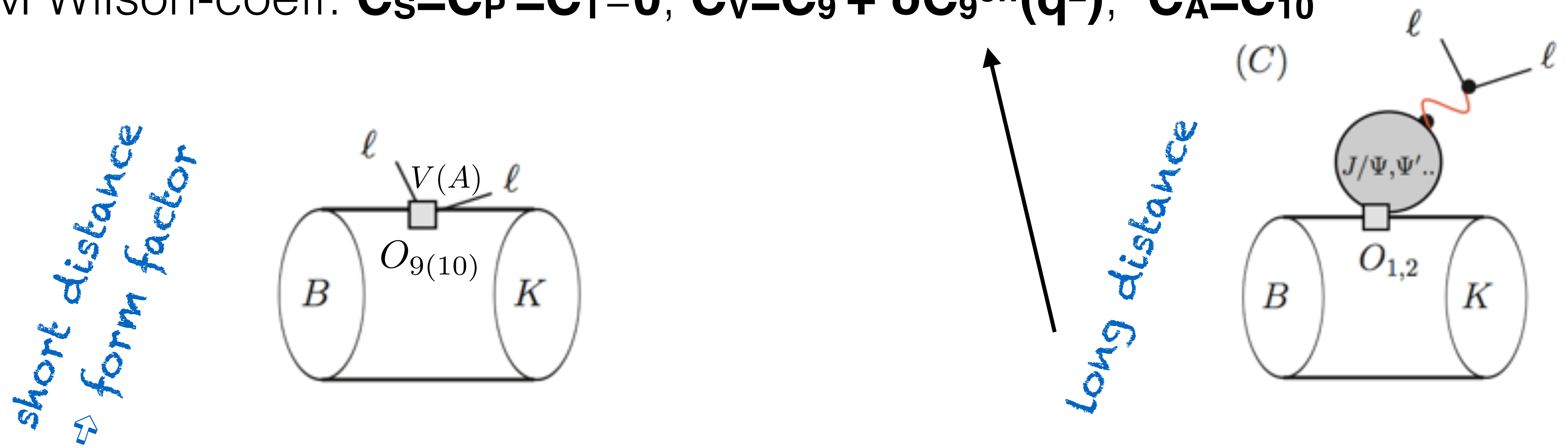
$$\langle P_5' \rangle_{\rm bin} \Big|_{\rm LHCb} = \frac{\left\langle {\rm Re}\left[G_1^{2,1}\right]\right\rangle_{\rm bin}}{2\sqrt{3}\mathcal{N}'_{\rm bin}}$$

very sensitive to polarisation

➪ need to understand what is behind polarisation (dynamics)

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

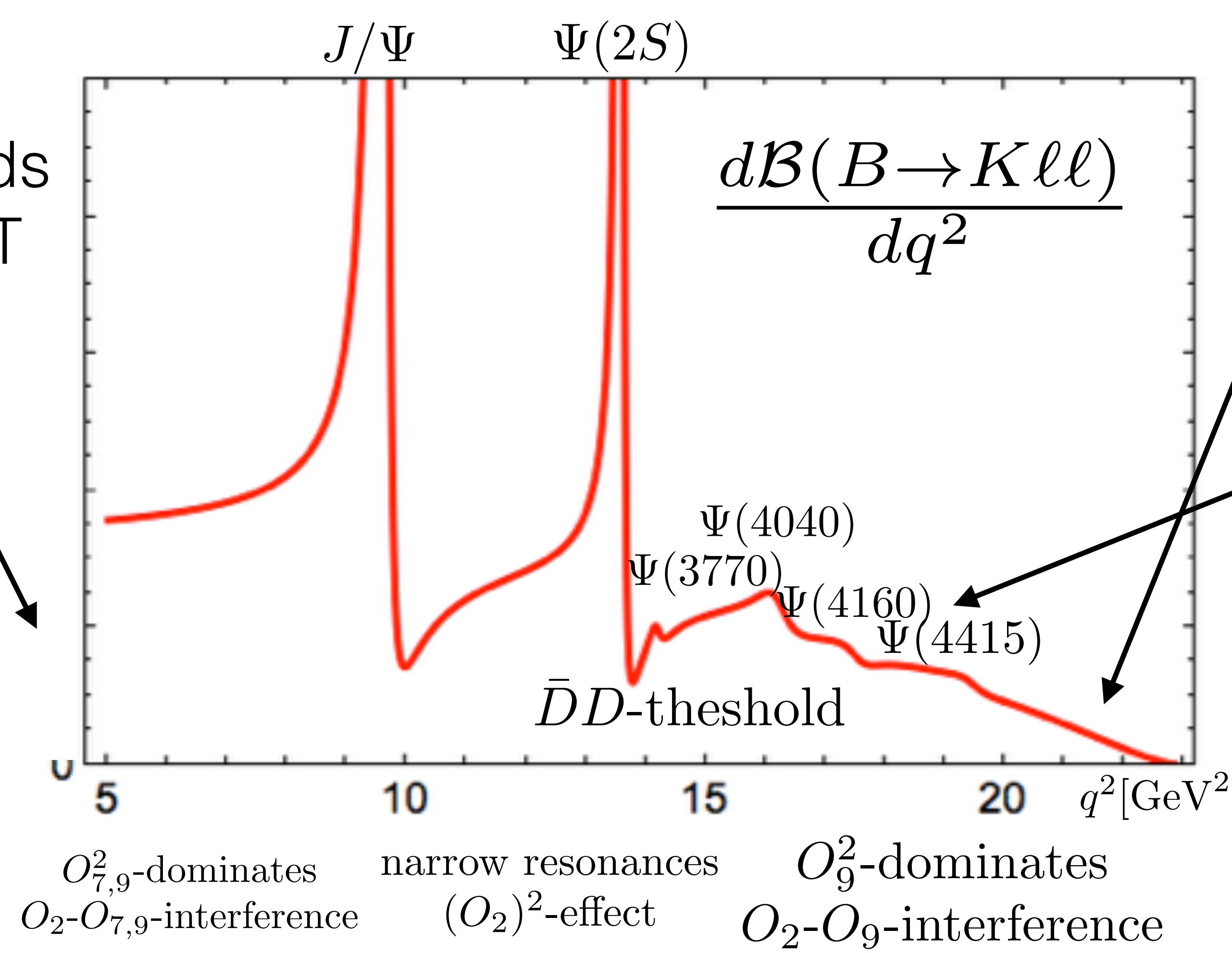
- SM Wilson-coeff: $\mathbf{C_S = C_P = C_T \simeq 0}$, $\mathbf{C_V = C_9 + \delta C_9^{eff}(q^2)}$, $\mathbf{C_A = C_{10}}$



bs$\ell\ell$-operators ($O_{7,9,10}$)

4-quark ($O_{1\text{-}6}$)

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



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

diagnostic shape for charm

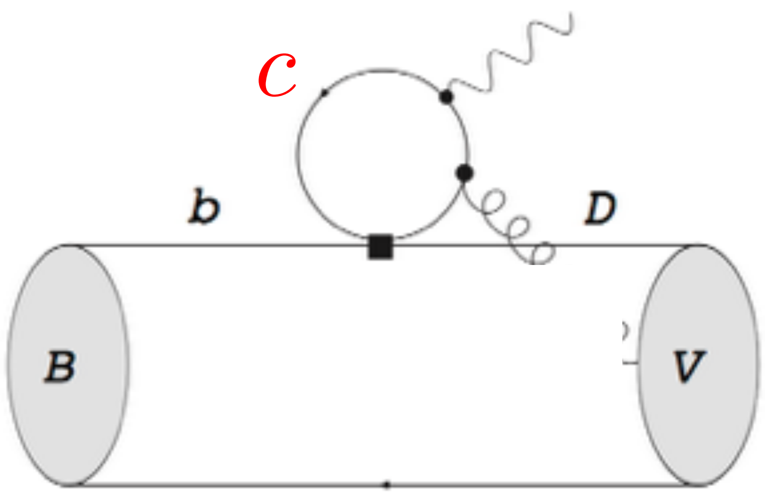
Theory outlook

e.g. cross-checks with semileptonics

- **Form factors:** believe to known reasonable well
- **Charm:** divides into partonic and hadronic methods
  and ideally we relate them via dispersion relation

partonic (below charm threshold)

known only in **factorisation-limit:**
LD(q²)xFormFactor(q²)



Comment: **problematic** as
polarisation-sensitive

Cure: **compute**
or argue polarisation dependence to be small

hadronic (above threshold)

- **Fact: no duality** in **exclusive** processes for branching fraction

Since not related to n-point function (duality at level of amplitude).
Note: Br($e^+e^- \to$ hadrons) is inclusive and a misleading example

- ➪ if we want to enter resonance region have to deal with hadrons

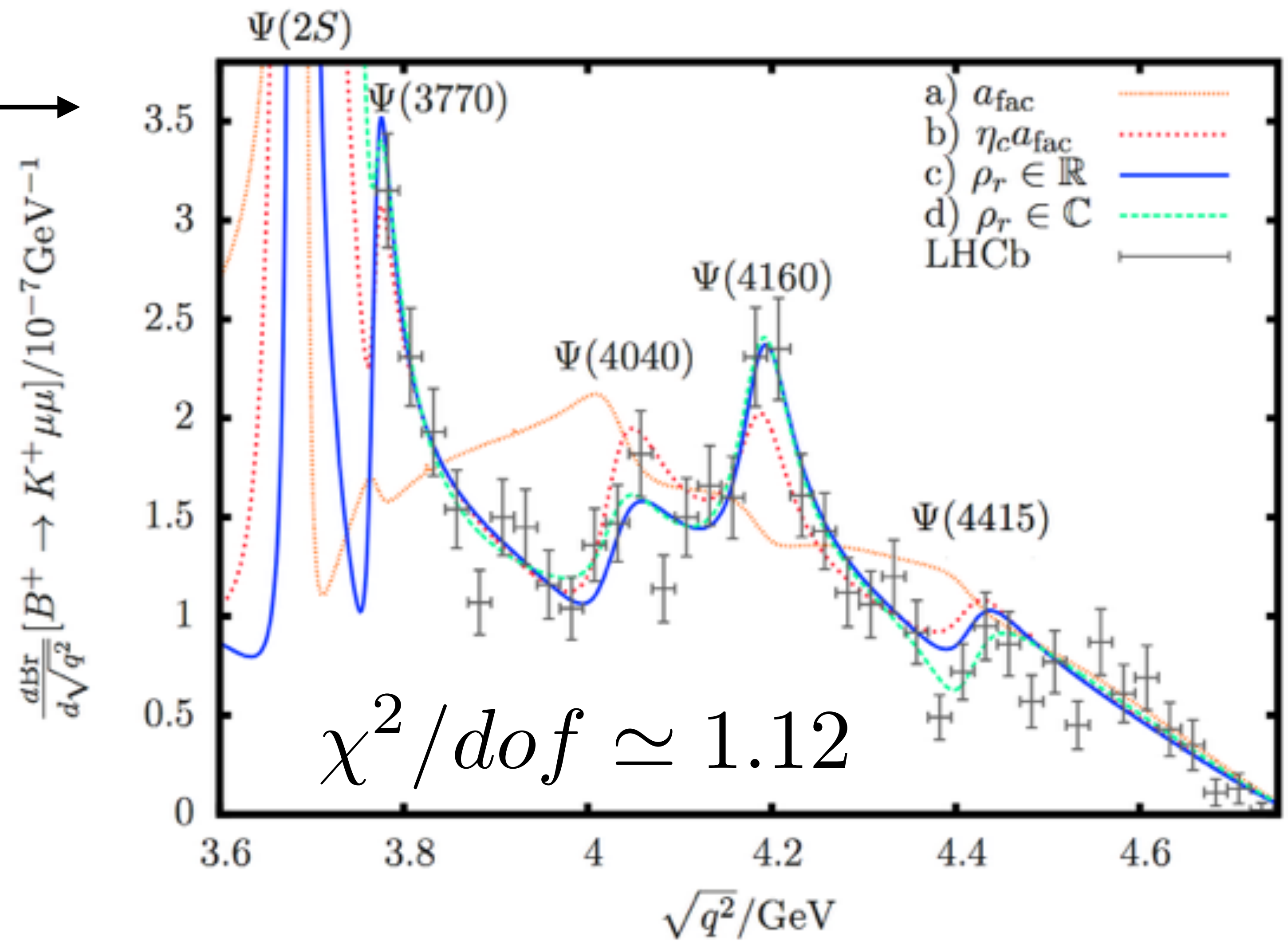
  ➪ charmonium-SD interference phases $\boldsymbol{\delta_{\psi K^{(*)}}}$ have to be fitted!

- B→Kμμ done for **broad resonances** Lyon, RZ ’14 →

  Results:

  1) large effects $\boldsymbol{\delta_{\psi \mathrm{broad} K} \simeq \pi}$

  2) severe violation of naive factorisation (using e^+e^- data)



- B→Kμμ redone LHCb’16 **& narrow resonances**

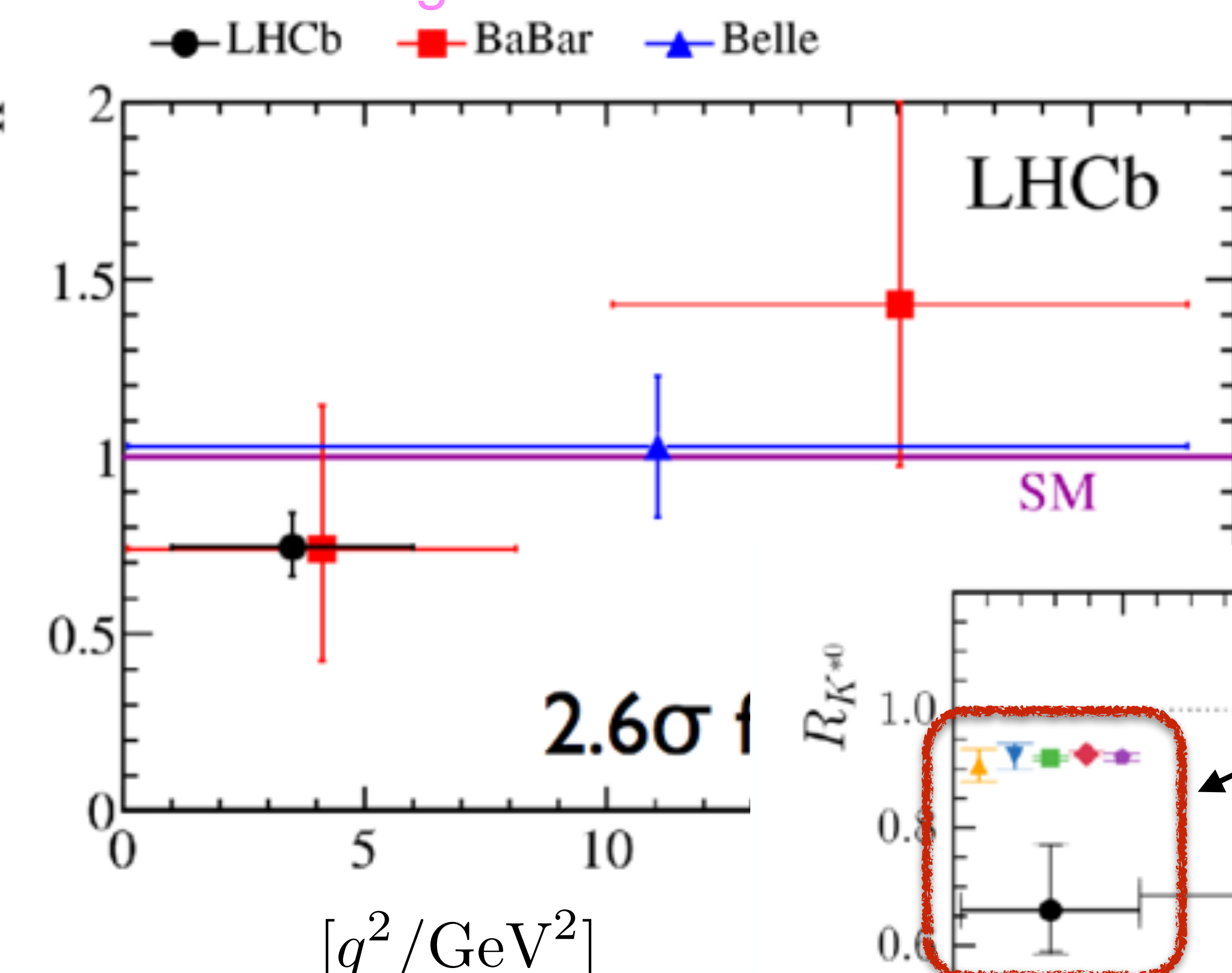
  4-fold degeneracy — $\delta_{J/\psi K} = \pm\pi = \delta_{\psi(2S)K} = \pm\pi$

- B→K*μμ ongoing LHCb better perspectives as more observables

(b) R_{K,K^*} Lepton Flavour Universality II

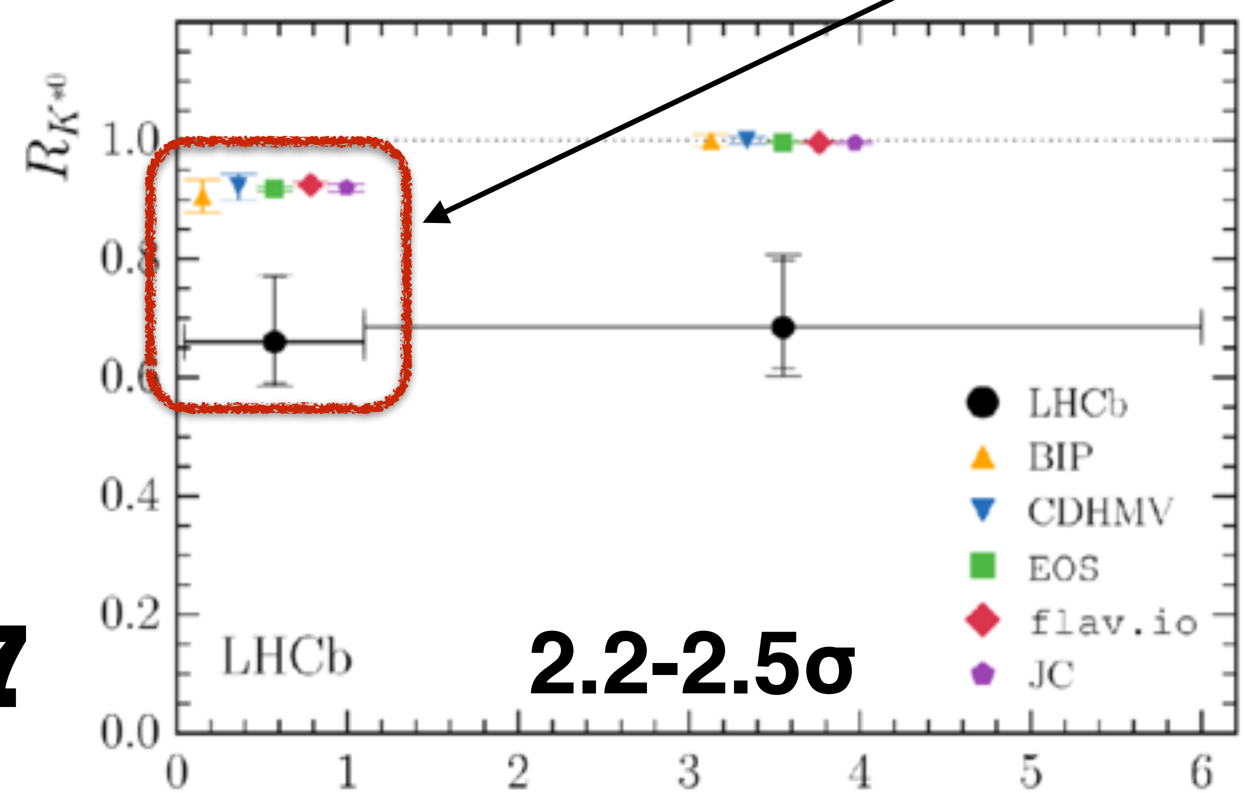
$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\,dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\,dq^2}$$

Hiller Kruger'03



2014

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



2017

Theory Crosschecks

- **hadronic** effects are **universal**, ought to cancel
- **non-universal** - phase space controlled
  - **QED**: O(few%) - unknown at time

collinear & soft log

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

- **QED** no factorisation (estimate QED effect from D,F,..-waves) mentioned before Gratrex. Hopfer, RZ'15

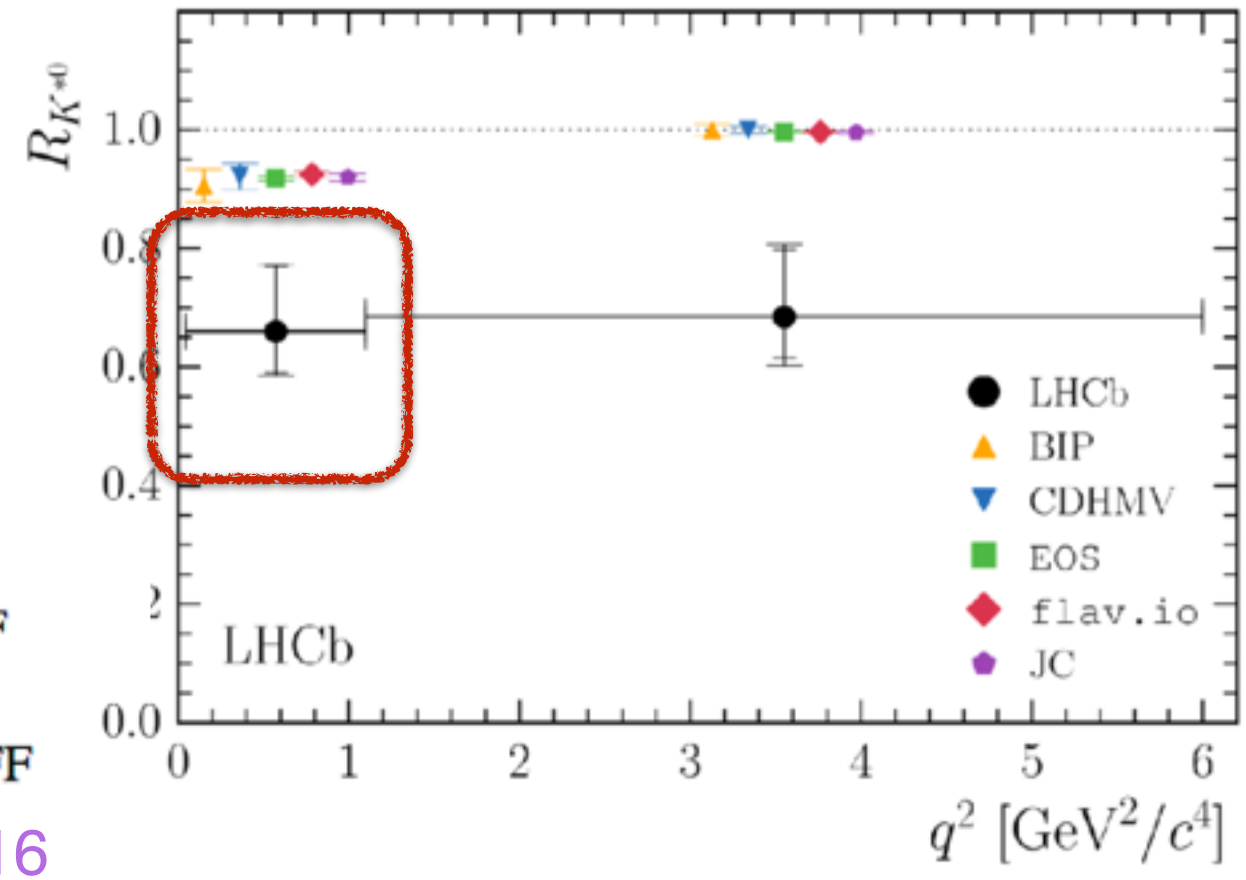
- Compute **soft & collinear QED logs** (structure independent) in real emission and by **Kinoshita, Lee & Nauenberg thm** fixes coefficients of leading virtual logs Bordone, Isidori, Pattori'16

1) Effects up to 15% for electrons (depending m_B-cuts)
2) These effects are captured by **PHOTOS** -Monte-Carlo!
3) Estimate structure dependent part to O(**1%**) for R_K,R_{K^*}

some point one has to check by computation

... further comments

- comment on **lowest K*-bin**
  - good idea to probe in photon-pole region
  - yet **maybe too close** to **muon-threshold**



$$R_{K^*}[0.045, 1.1]^{\rm SM} = 0.906 \pm 0.020_{\rm QED} \pm 0.020_{\rm FF}$$

$$R_{K^*}[0.1, 1.1]^{\rm SM} = 0.983 \pm 0.010_{\rm QED} \pm 0.010_{\rm FF}$$

Bordone, Isidori, Pattori'16

- **LFU-ratios of angular observables** interesting experimentally as some efficiency uncertainties cancel
  more tests R_ϕ, $R_{Bs \to \ell\ell\gamma}$

- Question: could LHCb **test electron/muon detection** in $D_s \to (\phi \to ee)\pi$ (Cabibbo-allowed tree) Pospelov private communication

Experimental Crosschecks

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

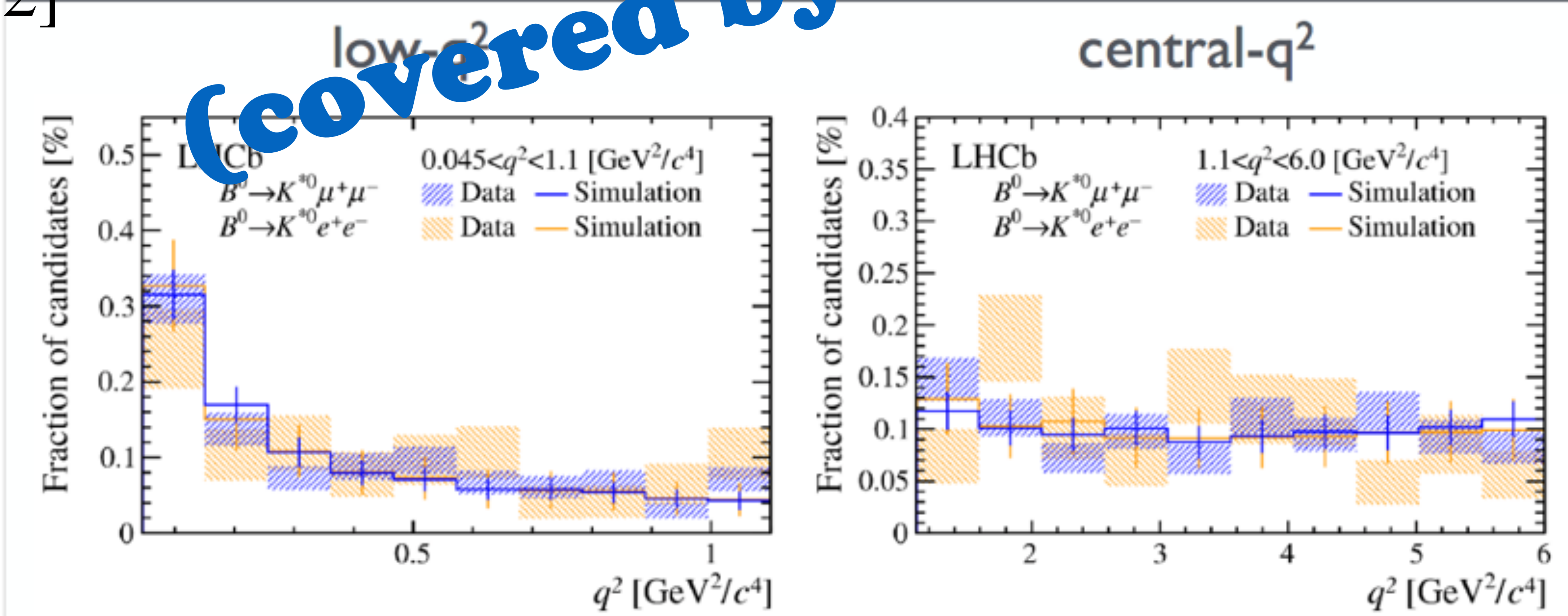
[1]

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

also compatible with Ψ(2S)

SKIP (covered by LHCb-talks)

[2]



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

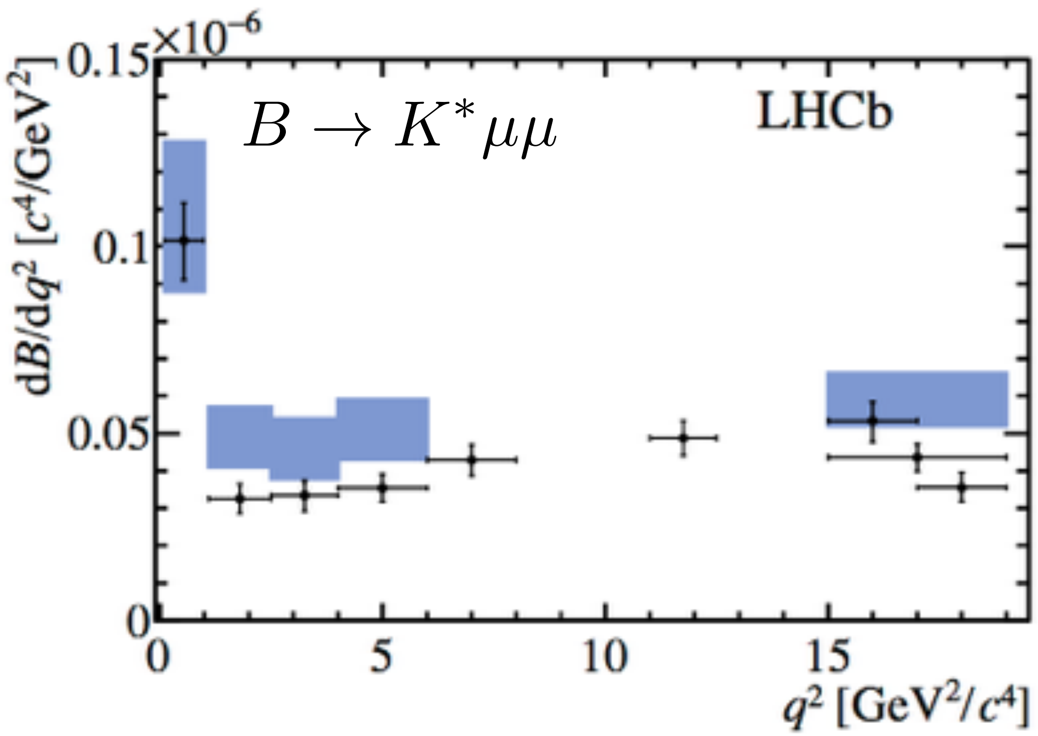
SKIP (no time)

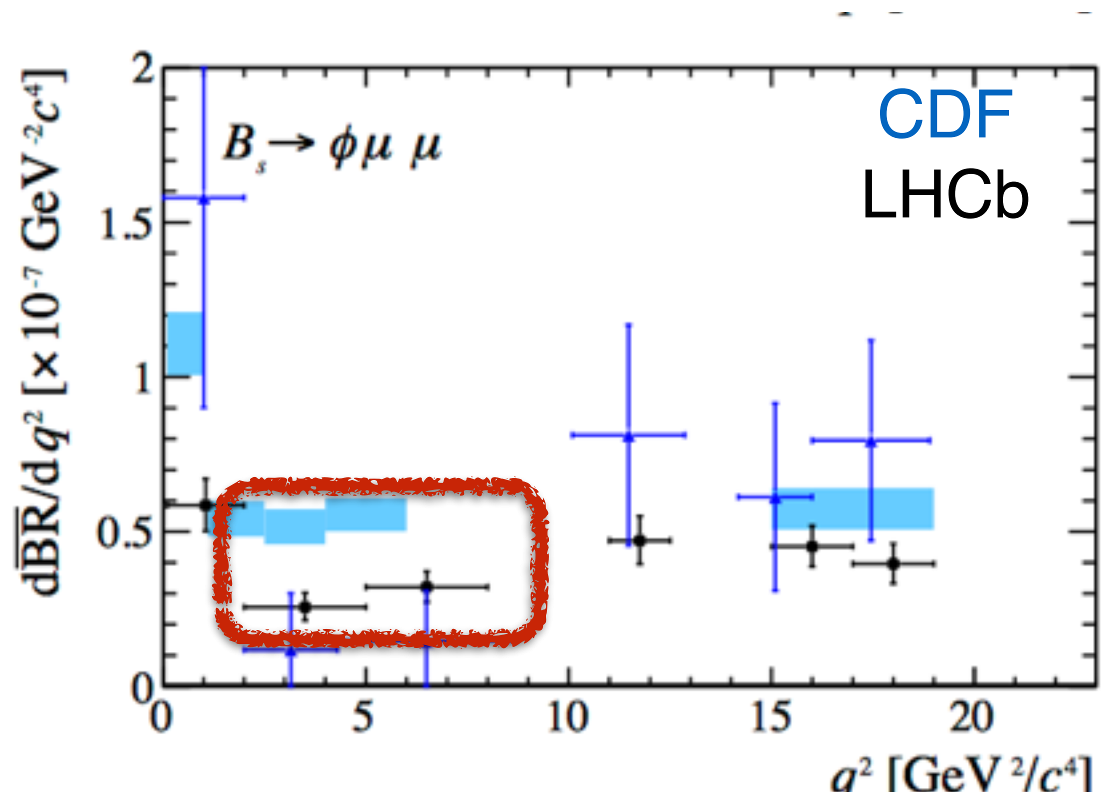
- at $q^2=0$ (i.e. to photon)

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

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

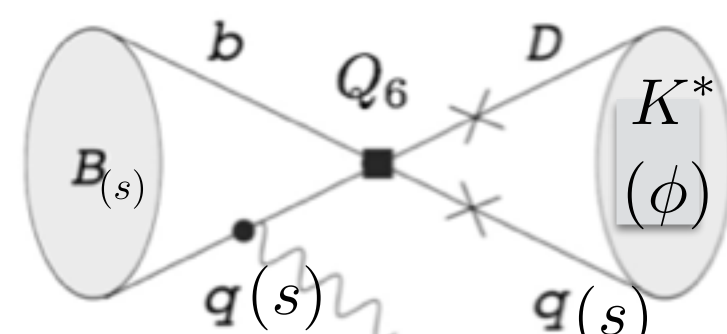
- persists in B→VII: q^2-spectrum





- puzzling as differ by spectator quark only
  form factor normalisation from decay constants (experiment)

- sensitive to $\bar{b}s\bar{s}s - operators$
  in **weak annihilation**



Conclusions & Summary

some of my personal impressions

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

- **CKM-corner:** $|V_{cb}|$ disappearing (Belle angular analysis)
  $|V_{ub}|$ signs of this happening
  impacts positively on many predictions (e.g. rare decays)!

- **Lepton Flavour Universality**:

  1) R_K, R_{K^*} -anomaly very interesting
     (i) photon pole bin puzzling
     (ii) Future: more data, crosschecks & Belle II

- 2) $R_D^{(*)}$: exp. BelleII, LHCb Run 2 good perspectives
  exp-th Angular data helps theorists..
  th: lattice $B \to D^*$ form factors from several groups

- **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

$B_s \to \phi\gamma$ time-dependent CP-asymmetry

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

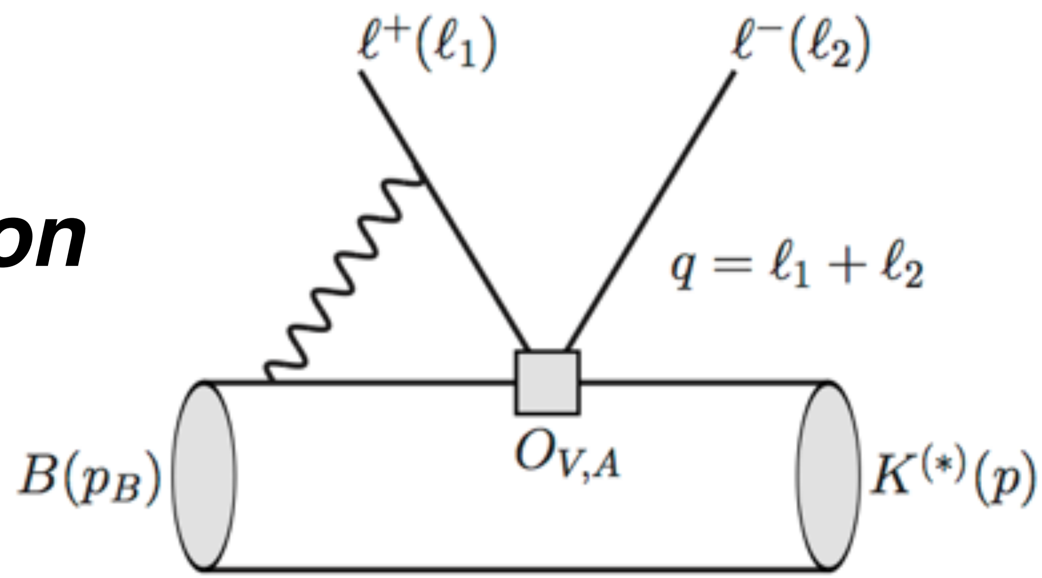
Thanks for your Attention !

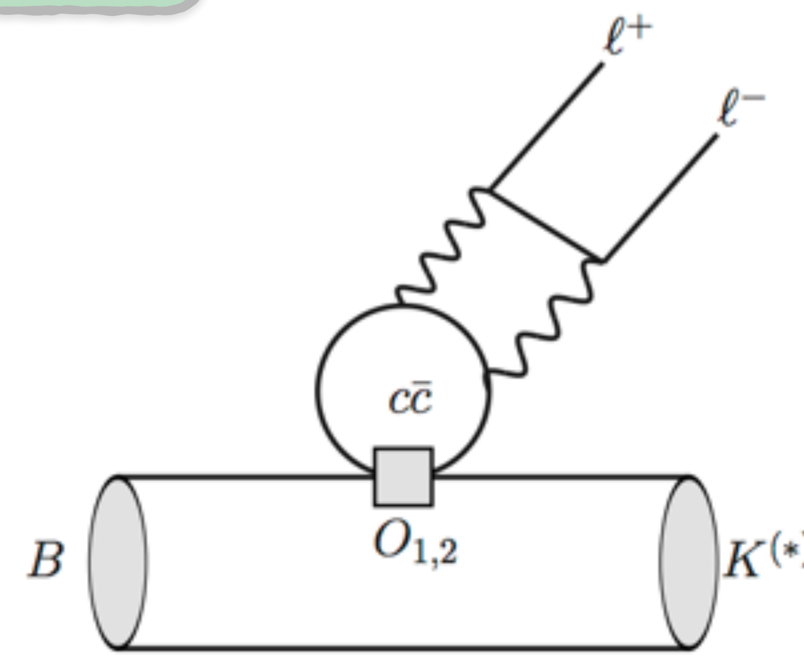
Backup Slides

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

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

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

- ⟹ s[u] enter logs ⟹ **no restriction sin(θ_l),cos(θ_l)-powers;** Legendre polynomial [or $\Omega_m^{|k,|l}$] serves as a complete basis (non-vanishing higher moments)

$$\frac{d^2\Gamma(B \to K\ell^+\ell^-)}{dq^2 \ d\cos\theta_\ell} = \sum_{l_\ell \geq 0} G^{(l_\ell)} P_{l_\ell}(\cos\theta_\ell)$$

More details QED-corrections

Bordone, Isidori, Pattori'16

$B \to K\ell^+\ell^-$	$\ell = e$	$\ell = \mu$
$m_B^{\text{rec}} = 4.880$ GeV	-7.6%	-1.8%
$m_B^{\text{rec}} = 5.175$ GeV	-16.9%	-4.6%

$B \to K^*\ell^+\ell^-$	$\ell = e$	$\ell = \mu$
$m_B^{\text{rec}} = 4.880$ GeV	-7.3%	-1.7%
$m_B^{\text{rec}} = 5.175$ GeV	-16.7%	-4.5%

Table 1 Relative impact of radiative corrections for $q^2 \in [1,6]$ GeV^2, with different cuts on the reconstructed mass and different lepton masses.

$m_B^{rec} = m_B$-Detector-Resolution

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

SKIP (covered by others)

V$_{cb}$

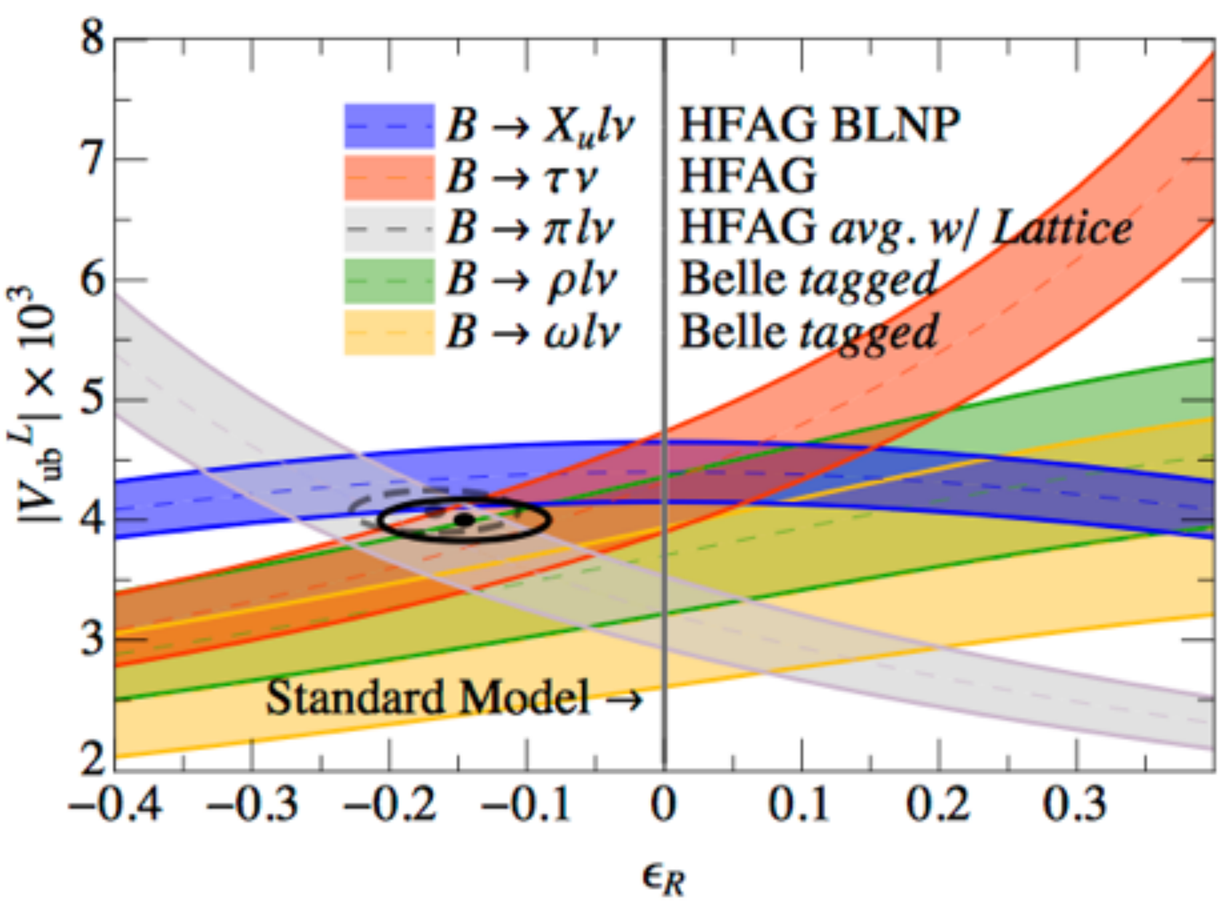
$$|V_{cb}|_{\rm incl} = |V_{cb}|(1+\tfrac{1}{2}\epsilon^2)$$

$$|V_{cb}|_{D^*} = |V_{cb}|(1+\epsilon)$$

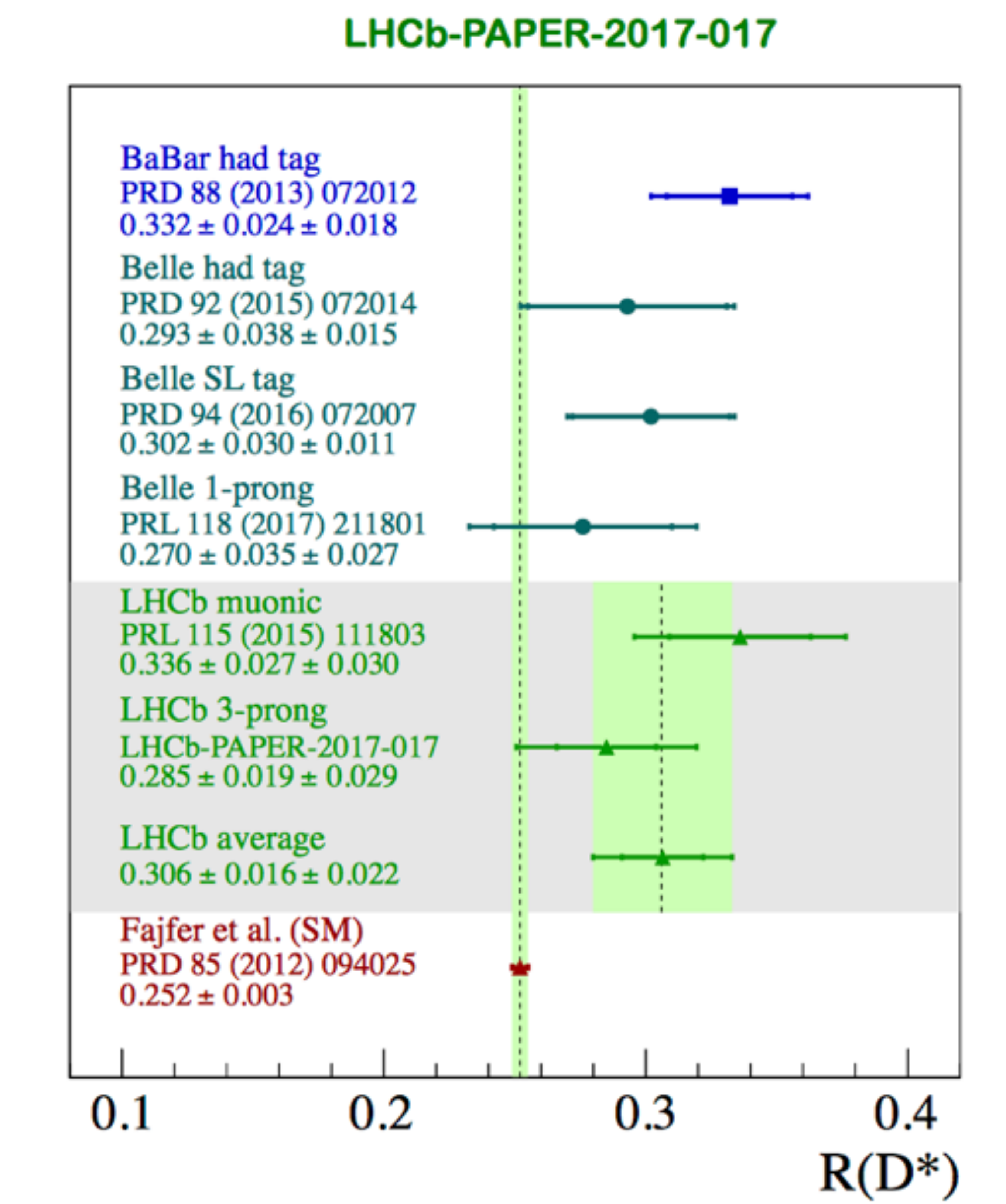
$$|V_{cb}|_D = |V_{cb}|(1-\epsilon)$$

no good as D and D* in wrong direction

V$_{ub}$

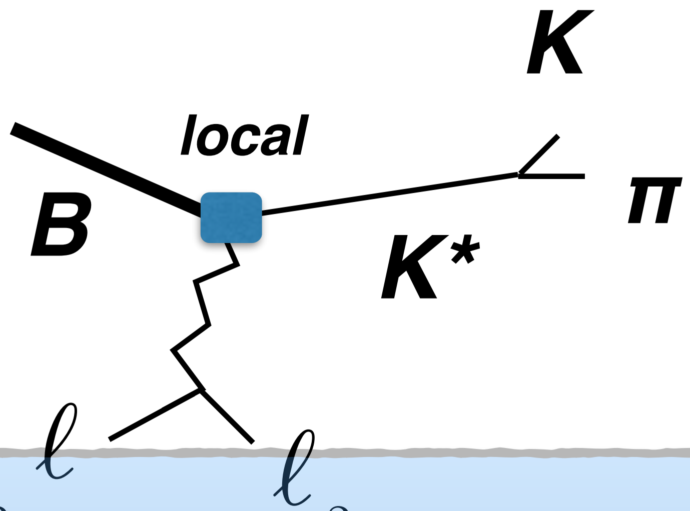


- Diagnosing better via angular distribution Bernlocher,Ligeti, Turczek'14
- General dim-6 RHC can explain (old) Vub-pattern but problems with Z->bb Crivellin, Pokorksi'14
- $\Lambda_b \to$ plv from LHCb from '15 does not support right handed currents (not exclude them either)



LHCb-PAPER-2017-017
BaBar had tag
PRD 88 (2013) 072012
0.332 ± 0.024 ± 0.018
Belle had tag
PRD 92 (2015) 072014
0.293 ± 0.038 ± 0.015
Belle SL tag
PRD 94 (2016) 072007
0.302 ± 0.030 ± 0.011
Belle 1-prong
PRL 118 (2017) 211801
0.270 ± 0.035 ± 0.027
LHCb muonic
PRL 115 (2015) 111803
0.336 ± 0.027 ± 0.030
LHCb 3-prong
LHCb-PAPER-2017-017
0.285 ± 0.019 ± 0.029
LHCb average
0.306 ± 0.016 ± 0.022
Fajfer et al. (SM)
PRD 85 (2012) 094025
0.252 ± 0.003
0.1
0.2
0.3
0.4
R(D*)

Short distance described Form Factors



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

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

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

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

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

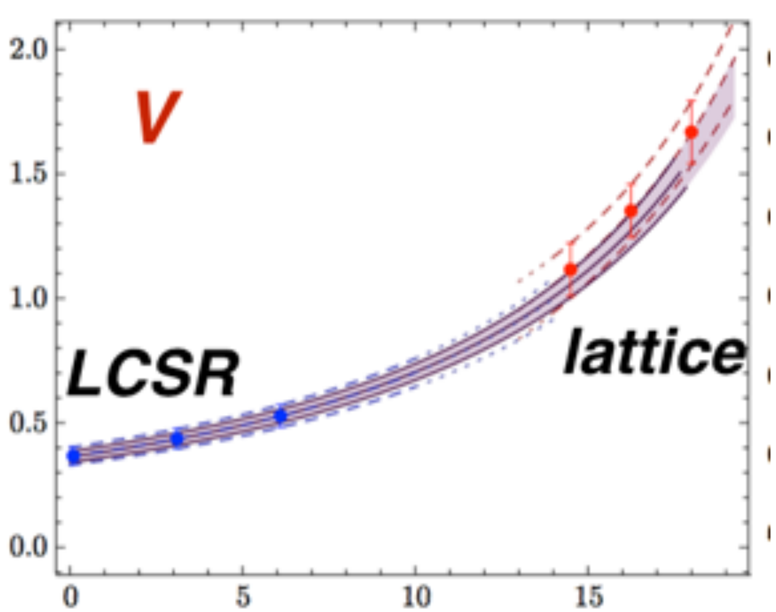
- **high q²** (low recoil) lattice Horgan, Meinel, Wingate, Liu'13

algebraically:

$T_1(0) = T_2(0)$

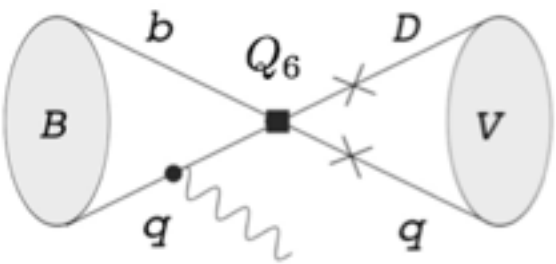
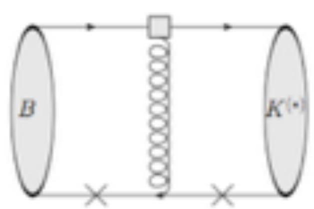
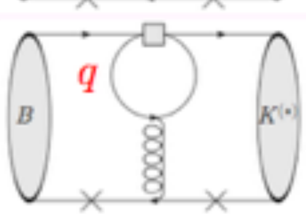
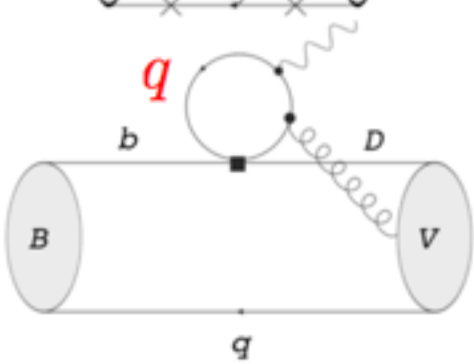
regularity:

$A_0(0) = A_3(0)$



- For Gil et al (💝):
  LCSR (K*-DA) & lattice
  connect smoothly via z-expansion

long-distance brief overview status

	QCDF	LCSR
comments:	1) depends B-meson DA 2) at 1/m endpoint divergences	1) depend on spurious momentum and analytic continuation thereof 2) includes photon DA
	1/m accidental?	photon DA sizeable Khodjamirian et al'95 Ali Braun'95 Lyon, RZ'13
	the 1/m 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

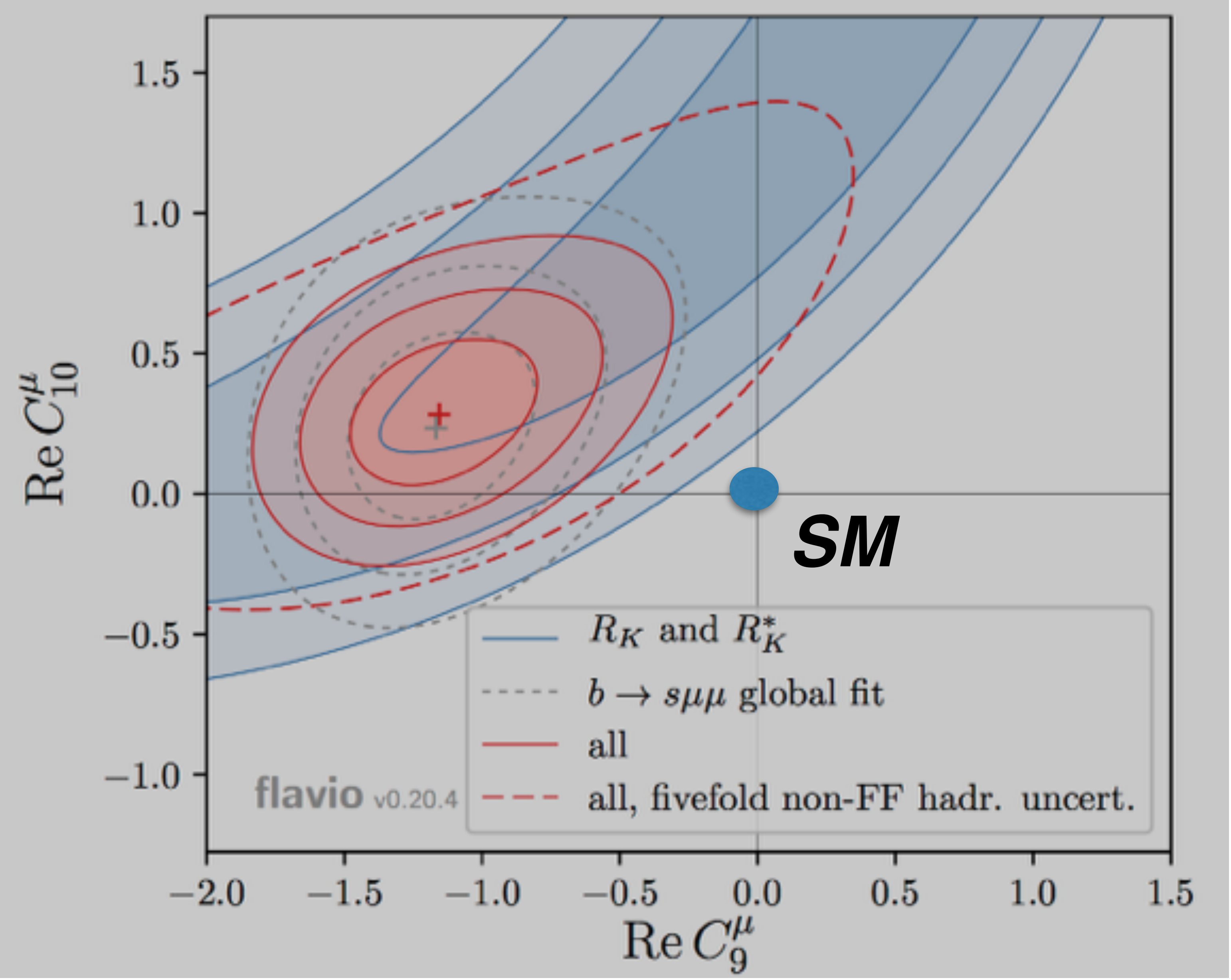
Beneke, Feldman, Seidel'01

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,



- no stringent signs of
  (i) RH-currents
  (ii) NP in b->see
  (iii) even non-QCD coupling C_{10}

- NP: $C_9 = - C_{10}$ often considered in model building

5σ > ..yet hadronics

EOM in QFT ⇔ relations between correlation functions

- ***the following equation valid on <K*|...|B>:***

$$i\partial^{\nu}(\bar{s}i\sigma_{\mu\nu}(\gamma_5)b) = -(m_s \pm m_b)\bar{s}\gamma_{\mu}(\gamma_5)b + i\partial_{\mu}(\bar{s}(\gamma_5)b) - 2\bar{s}i\overleftarrow{D}_{\mu}(\gamma_5)b\,,$$

- ***leads to 4 equation of motion***

$$T_1(q^2) + (m_b + m_s)\mathcal{V}_1(q^2) + \mathcal{D}_1(q^2) = 0\,,$$
$$T_2(q^2) + (m_b - m_s)\mathcal{V}_2(q^2) + \mathcal{D}_2(q^2) = 0\,,$$
$$T_3(q^2) + (m_b - m_s)\mathcal{V}_3(q^2) + \mathcal{D}_3(q^2) = 0\,,$$
$$(m_b - m_s)\mathcal{V}_P(q^2) + \left(\mathcal{D}_P(q^2) - \frac{q^2}{m_b + m_s}\mathcal{V}_P(q^2)\right) = 0\,.$$

where D_i's are form factors of derivative operator:

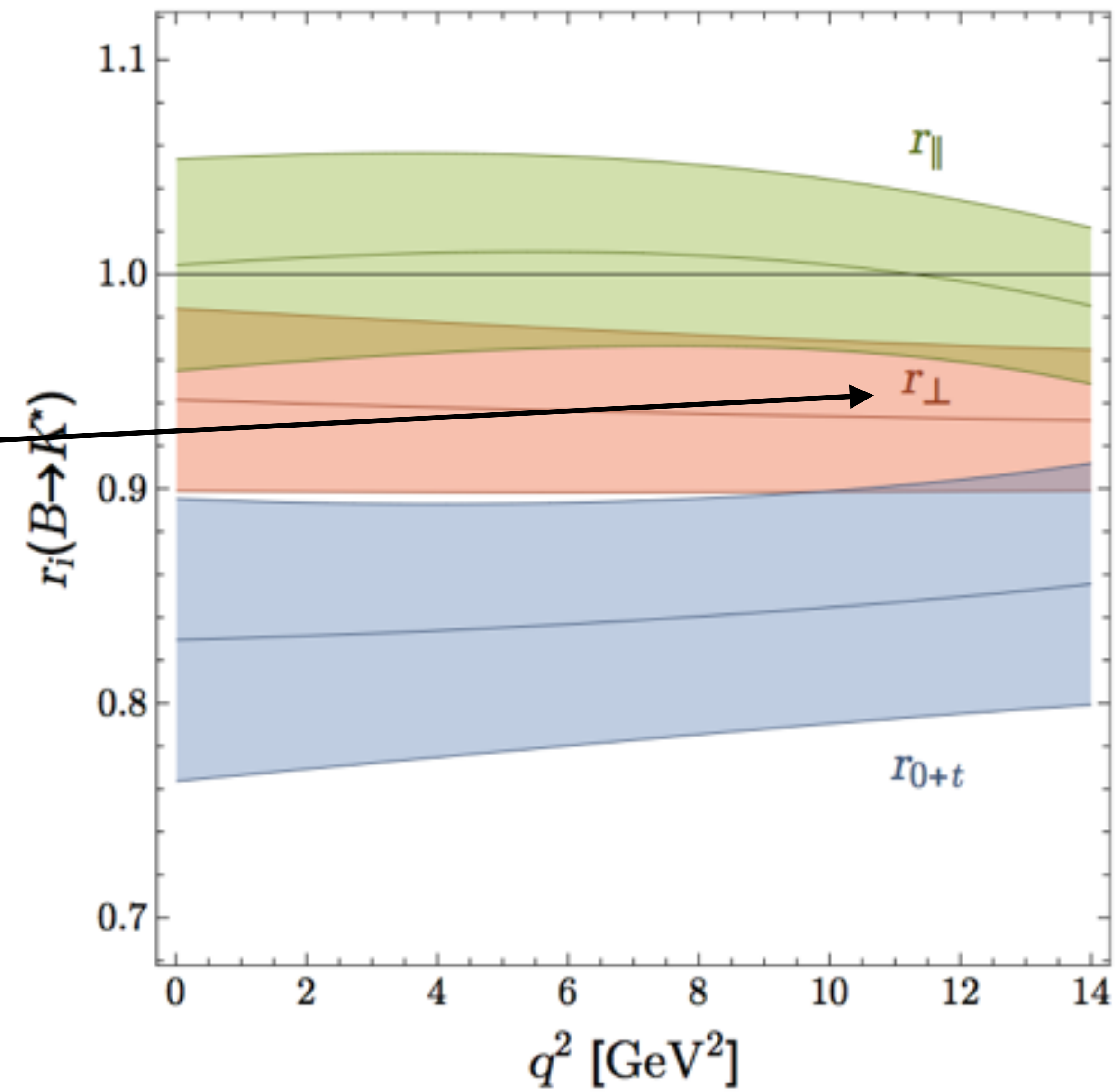
$$\langle K^*(p,\eta)|\bar{s}(2i\overleftarrow{D})^{\mu}(1\pm\gamma_5)b|\bar{B}(p_B)\rangle = P_1^{\mu}\,\mathcal{D}_1(q^2) \pm P_2^{\mu}\,\mathcal{D}_2(q^2) \pm P_3^{\mu}\,\mathcal{D}_3(q^2) \pm P_P^{\mu}\mathcal{D}_P(q^2)$$

- *Hence* ***if*** *D_1 is considered form factor then* $|s_0^{T_1} - s_0^V| < 1\,\mathrm{GeV}^2$

checked that **twist** and α_s -expansion is controlled
(⇒ more than a numerical accident)

- Vector-tensor form factor ratios determined up to 4-6%

$$r_\perp(q^2) = \frac{m_b + m_s}{m_B + m_{K^*}} \frac{V(q^2)}{T_1(q^2)}$$



B. probing non-factorisable effects

- think resonances described Breit-Wigner

N.B. 1) location of pole & 2) residue are **physical**!

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

- idea: **correct** for **Ψ-production** (residue physical)

$$\begin{aligned} \mathcal{A}(B \to \Psi K)|_{\text{fac}} \quad &\sim \quad f_+^{B\to K}(q^2)\mathcal{A}(\Psi \to \ell\ell) \\ &\to \quad f_+^{B\to K}(q^2) \underbrace{\eta_\Psi}_{1+\text{non}-\text{fac}} \mathcal{A}(\Psi \to \ell\ell) \sim \mathcal{A}(B \to \Psi K) \end{aligned}$$

- fits η_Ψ: b) global (scaled)fac; c) real-variable; d) complex-variable

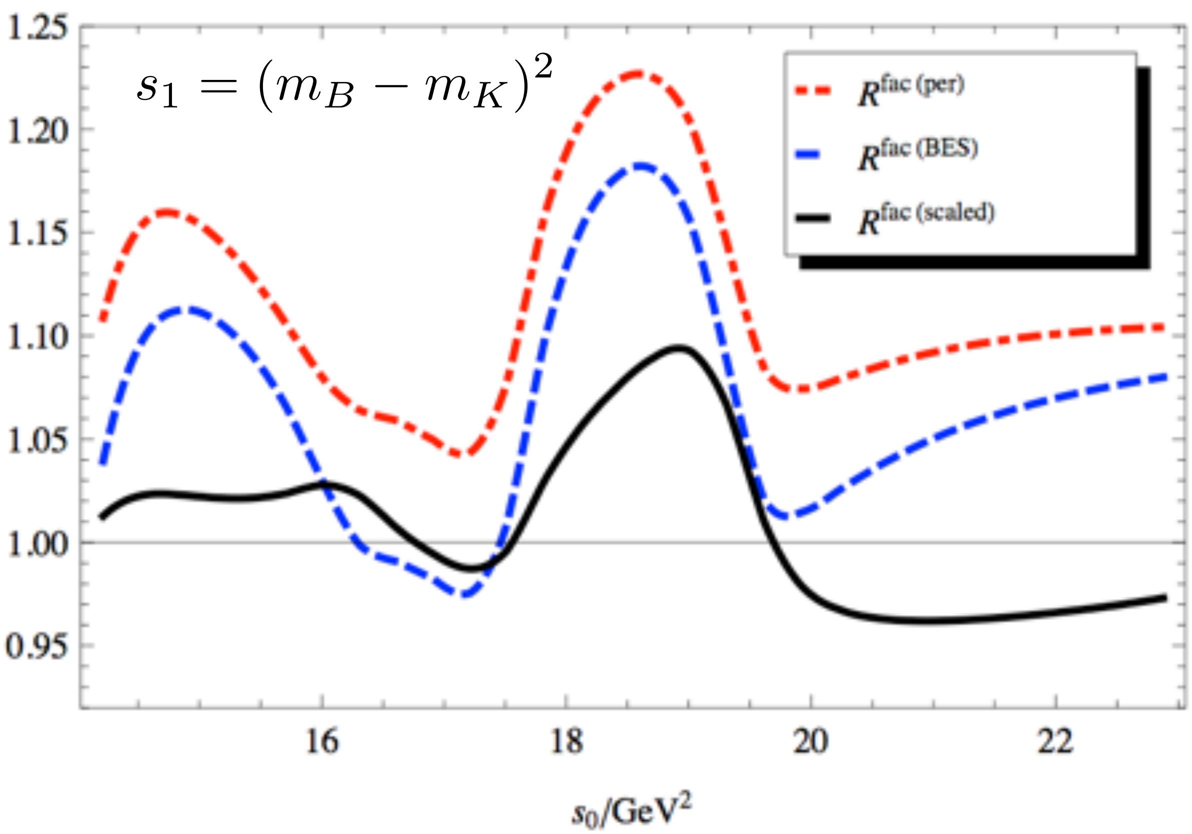
only option d) sensible a priori

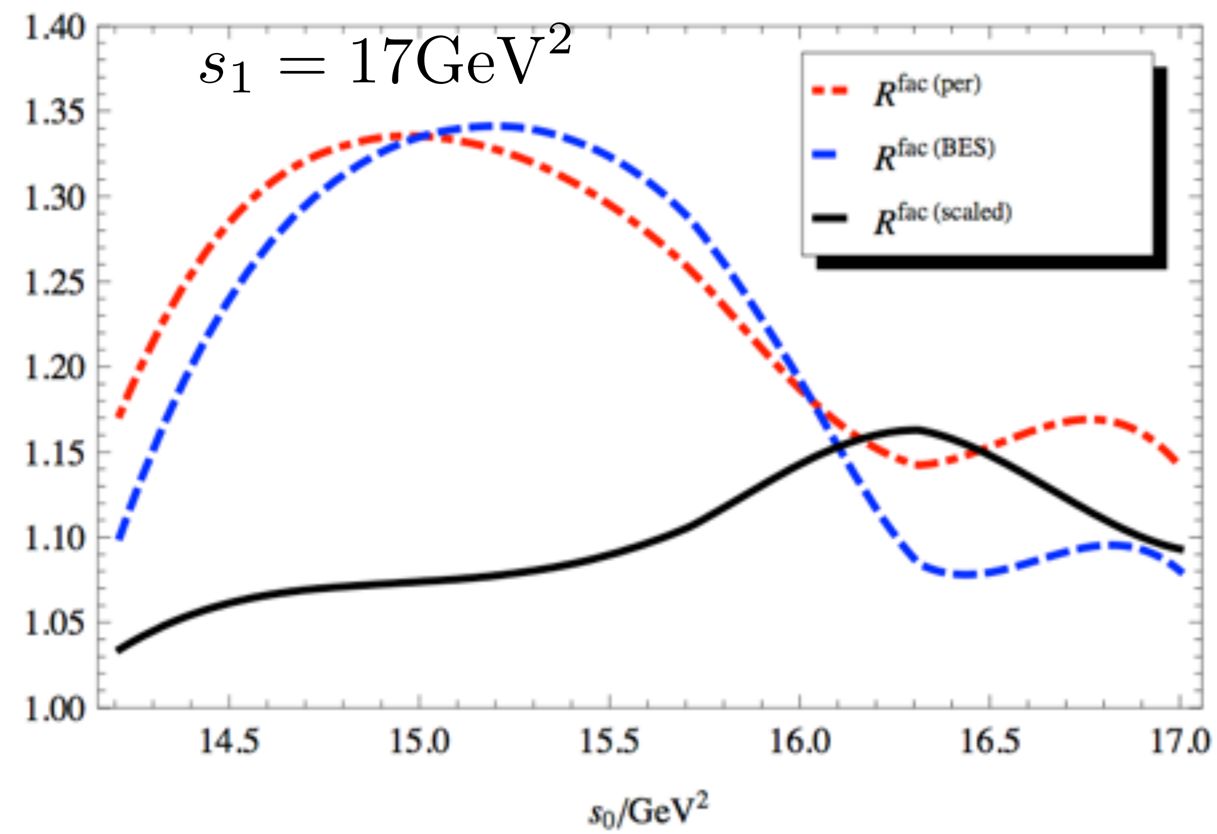
Binned Br(B→Kll) high q^2: a priori and a posteriori

- ratio of Br(B→Kll) using
  i) factorisation perturbative (no resonances)
  ii) factorisation (BES-data)
  vs data as function lower bin bdry s_0

$$\frac{\mathrm{Br}(B^+ \to K^+ \ell\ell)^{i),ii)}_{[s_0,s_1]}}{\mathrm{Br}(B^+ \to K^+ \ell\ell)^{fit-d)}_{[s_0,s_1]}}$$

basically as good as data (by construction)





for angular observables issue more subtle as their can be cancellations in ratio ……..

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, Greljo, 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

$Belle@1709.00129$

$$R(D^*) = 0.270 \pm 0.035(\text{stat})^{+0.028}_{-0.025}(\text{syst})$$

$$P_\tau(D^*) = -0.38 \pm 0.51(\text{stat})^{+0.21}_{-0.16}(\text{syst})$$

which is consistent with SM!