A glance at CP Violation, Status of Flavour Anomalies and all that-I

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Outline

- Introduction and Motivation.
- Assessing the CKM paradigm in the SM.
- Two tensions: $|V_{ub}|$ and $|V_{cb}|$.
- Bounding New Physics via FCNC ($\Delta F = 2$).
- Probing New Physics via Rare B decays: Present situation and description of Flavour Anomalies.
- The path to the $b \to s\ell\ell$ anomalies... why there? why now?

Even if the SM is extremely successful theory most likely is an effective theory, it does not explain...

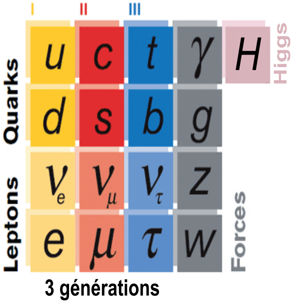
- why 3 generations of fermions? why their masses are so hierarchical.
- origin of the Baryon asymmetry in the universe? matter anti-matter asymmetry too small in SM.
- **lack of a candidate of the dark matter observed in the Universe**
- ...

$$\Downarrow$$

a more fundamental theory with new degrees of freedom (new particles)

This new theory defines what is usually called **New Physics**

Central question of QFT-based particle physics



$$\mathcal{L} = ?$$

i.e. which degrees of freedom, symmetries, scales ?

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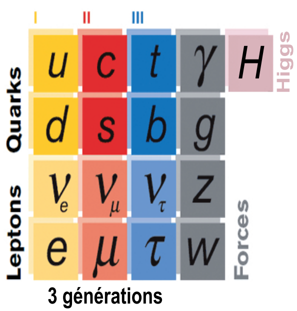

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Two ways of searching for New Physics:

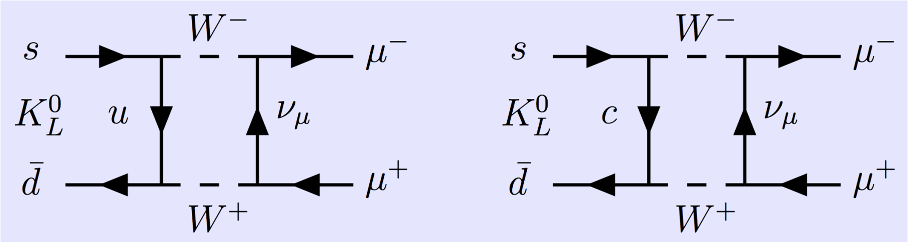
- **DIRECT** production of New Particles: so far nothing new....besides SM Higgs. It needs **Energy**.

- **INDIRECT** or VIRTUAL production of New Particles affecting (i.e. loops) couplings & **decays**
  $\Rightarrow$ It needs **Precision**. Energy scales not directly accessible at accelerators.
  $\Rightarrow$ If New Particles bring couplings with new phases, CP violating observables can detect them.

$\Rightarrow$ We test this second path with **Flavour Physics: Rare decays and CP Violation**

A historical example of indirect search

The $K_L^0 \to \mu^+\mu^-$ decay is forbidden at tree level



The unexpected non-observation was explained by Glashow, Iliopoulos and Maiani ("GIM mechanism"):

Idea of GIM mechanism: to understand the suppression besides the u quark loop a second loop with a new quark (c) with opposite sign that cancels in the limit $m_c - m_u = 0$.

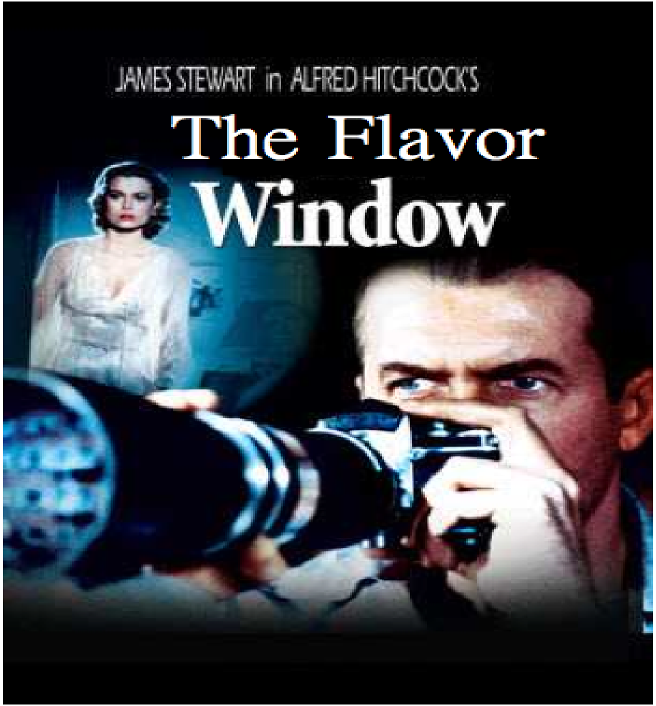
Example of an observation of New Physics mediated by a new virtual particle: charm particle.

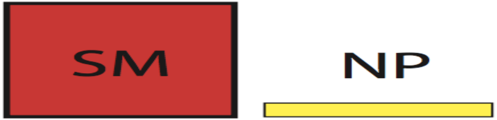
Our main tools (but not ONLY)

List of B mesons

B mesons

Particle	Symbol	Anti-particle	Quark content	Charge	Isospin (I)	Spin and parity (J^P)	Rest mass (MeV/c^2)	S	C	B'	Mean lifetime (s)
Strange B meson	B_s^0	$\overline{B}_s^0$	$s\bar{b}$	0	0	0^-	5,366.3 ±0.6	−1	0	+1	$1.470^{+0.027}_{-0.026} \times 10^{-12}$
B meson	B^0	$\overline{B}^0$	$d\bar{b}$	0	½	0^-	5,279.53 ±0.33	0	0	+1	$(1.530 \pm 0.009) \times 10^{-12}$
Charmed B meson	B_c^+	B_c^-	$c\bar{b}$	+1	0	0^-	6,276 ±4	0	+1	+1	$(0.46 \pm 0.07) \times 10^{-12}$
B meson	B^+	B^-	$u\bar{b}$	+1	½	0^-	5,279.15 ±0.31	0	0	+1	$(1.638 \pm 0.011) \times 10^{-12}$



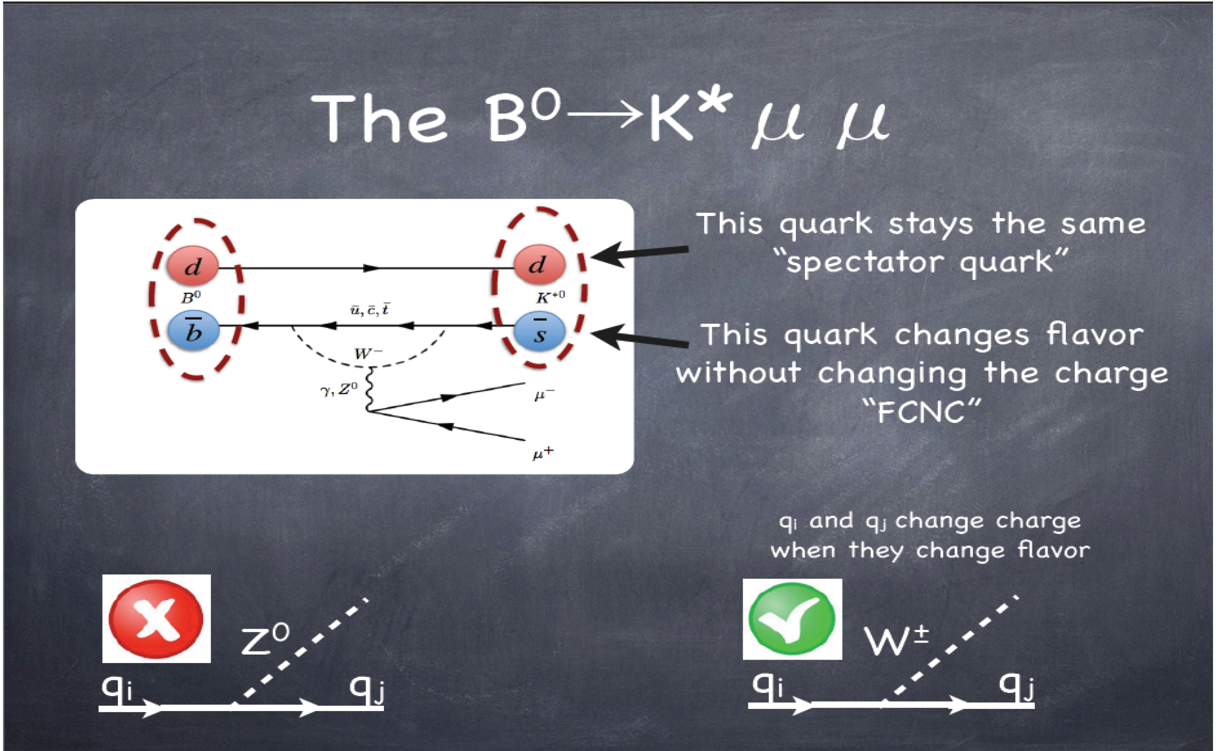


SM expected to be dominant
(tree dominated)
[semi/leptonic dec.] Metrology of SM
but there are unexpected exceptions...

SM and NP competing
(loop dominated)
[rare processes] Constraints on NP
FCNC Forbidden in SM at tree level

Subclass of observables (LFUV)
with little hadronic unc. **IN SM.**
$\rightarrow$ Smoking guns of NP

A relevant example of FCNC process



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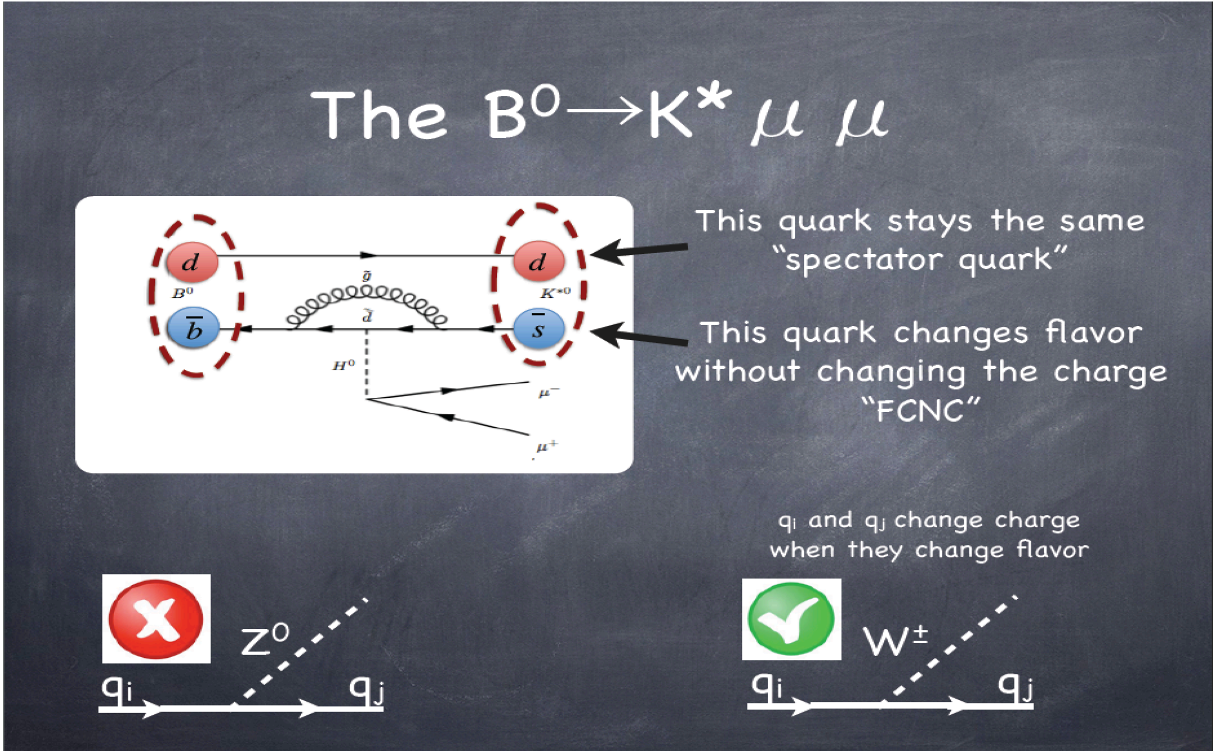
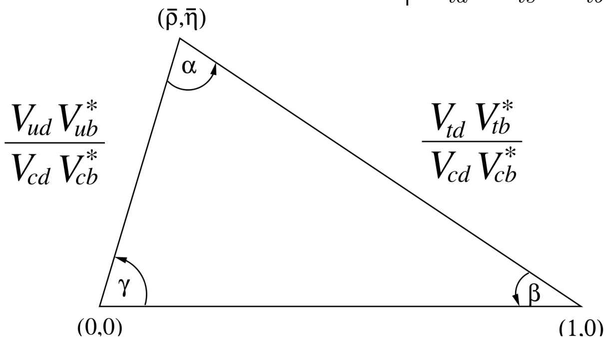


Assessing the CKM paradigm in the SM

CP-violation : the four parameters

In SM weak charged transitions mix quarks of different generations

Encoded in unitary CKM matrix $V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$. From off-diagonal $V_{CKM}^\dagger V_{CKM} = 1$



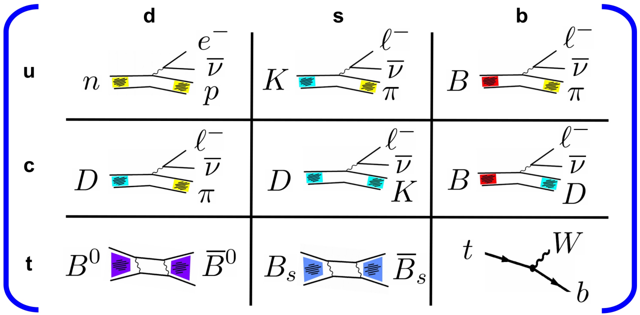
- 3 generations $\Longrightarrow$ 1 phase, only source of CP-violation in SM
- Wolfenstein parametrisation, defined to hold to all orders in λ and rephasing invariant

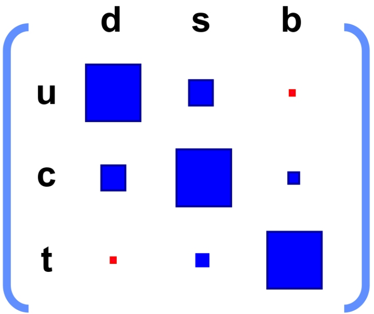
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \qquad \bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

$\Longrightarrow$ 4 parameters describing the CKM matrix,

to determine from data under the SM hyp.

Extracting the CKM parameters

$V =$ 



- CP-invariance of QCD to build hadronic-indep. CP-violating asym.
  or to determine hadronic inputs from data
- Statistical framework to combine data and assess uncertainties

	Exp. uncert.		Theoretical uncertainties	
Tree	$B \to DK$	γ	$B(b) \to D(c)\ell\nu$	$\lvert V_{cb}\rvert$ vs form factor (OPE)
			$B(b) \to \pi(u)\ell\nu$	$\lvert V_{ub}\rvert$ vs form factor (OPE)
			$M \to \ell\nu$	$\lvert V_{UD}\rvert$ vs f_M (decay cst)
Loop	$B \to J/\Psi K_s$	β	ϵ_K (K mixing)	$(\bar{\rho}, \bar{\eta})$ vs B_K (bag parameter)
	$B \to \pi\pi, \rho\rho$	α	$\Delta m_d, \Delta m_s$ (B_d, B_s mixings)	$\lvert V_{tb}V_{tq}\rvert$ vs $f_B^2 B_B$ (bag param)

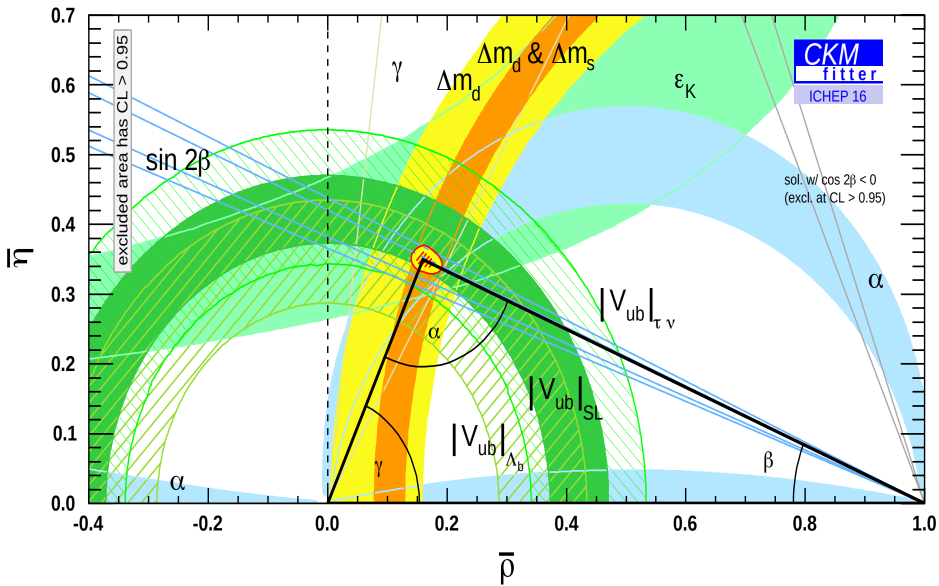
CKM matrix within a frequentist framework ($\simeq \chi^2$ minim.)

data = weak $\otimes$ QCD $\Longrightarrow$Need for hadronic inputs (mostly lattice)

$\lvert V_{ud}\rvert$	superallowed β decays	PRC91, 025501 (2015)
$\lvert V_{us}\rvert$	$K \to \pi\ell\nu$ (Flavianet)	$f_+(0) = 0.9681 \pm 0.0014 \pm 0.0022$
	$K \to \ell\nu, \tau \to K\nu_\tau$	$f_K = 155.2 \pm 0.2 \pm 0.6$ MeV
$\lvert V_{us}/V_{ud}\rvert$	$K \to \ell\nu/\pi \to \ell\nu, \tau \to K\nu_\tau/\tau \to \pi\nu_\tau$	$f_K/f_\pi = 1.1959 \pm 0.0010 \pm 0.0029$
ϵ_K	PDG	$\hat{B}_K = 0.7567 \pm 0.0021 \pm 0.0123$
$\lvert V_{ub}\rvert$	inclusive and exclusive	(see later)
$\lvert V_{cb}\rvert$	inclusive and exclusive	(see later)
Δm_d	B_d-$\bar{B}_d$ mixing	$B_{B_s}/B_{B_d} = 1.007 \pm 0.014 \pm 0.014$
Δm_s	B_s-$\bar{B}_s$ mixing	$B_{B_s} = 1.320 \pm 0.016 \pm 0.030$
β	$J/\psi K^{(*)}$	
α	$\pi\pi, \rho\pi, \rho\rho$	isospin
γ	$B \to D^{(*)}K^{(*)}$	GLW/ADS/GGSZ
$B \to \tau\nu$	$(1.08 \pm 0.21) \cdot 10^{-4}$	$f_{B_s}/f_{B_d} = 1.205 \pm 0.003 \pm 0.006$
		$f_{B_s} = 225.1 \pm 1.5 \pm 2.0$ MeV

How to search for New Physics

Frequentist approach (CKMfitter). See also UTfit approach.
Look for inconsistent determinations of UT-angles, UT- sides.
Small Yellow region: preferred region by all observables (C.L. $< 95.45\%$)



$|V_{ud}|, |V_{us}|$
$|V_{cb}|_{SL}, |V_{ub}|_{SL}$
$B \to \tau\nu$
$\Delta m_d, \Delta m_s$
ϵ_K
$\sin 2\beta$
α
γ

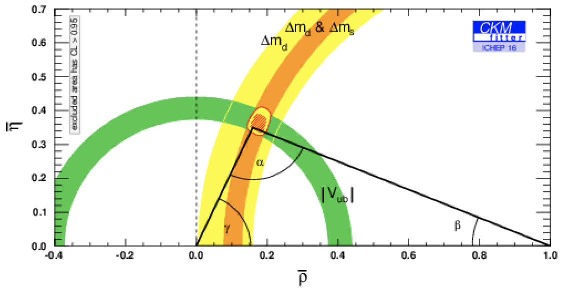
$A = 0.825^{+0.007}_{-0.012}$

$\lambda = 0.2251^{+0.0003}_{-0.0003}$

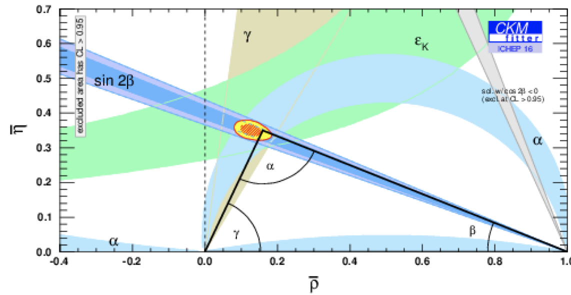
$\bar{\rho} = 0.160^{+0.008}_{-0.007}$

$\bar{\eta} = 0.350^{+0.006}_{-0.006}$

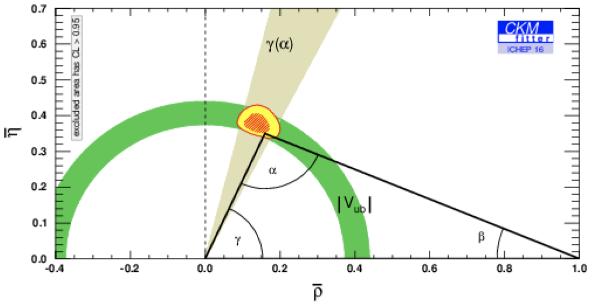
Consistency of the CKM mechanism: Many different determinations



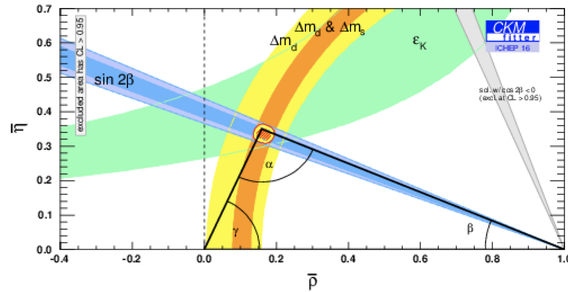
CP-conserving only



CP-violating only



Tree only



Loop only

Validity of Kobayashi-Maskawa picture of CP violation: No significant deviation observed

But two tensions: V_{ub} and V_{cb}

V_{ub} and V_{cb} affects the identification of NP.

Problem: Inclusive and Exclusive determinations in tension (different theory & experiment).

TABLE 1. Status of exclusive and inclusive $|V_{cb}|$ determinations

Exclusive decays	$\|V_{cb}\| \times 10^3$
$\bar{B} \to D^* l \bar{\nu}$	
FLAG 2016 [23]	$39.27 \pm 0.49_{\rm exp} \pm 0.56_{\rm latt}$
FNAL/MILC 2014 (Lattice $\omega = 1$) [20]	$39.04 \pm 0.49_{\rm exp} \pm 0.53_{\rm latt} \pm 0.19_{\rm QED}$
HFAG 2012 (Sum Rules) [27, 28, 21]	$41.6 \pm 0.6_{\rm exp} \pm 1.9_{\rm th}$
$\bar{B} \to D l \bar{\nu}$	
Global fit 2016 [35]	40.49 ± 0.97
Belle 2015 (CLN) [34, 29]	39.86 ± 1.33
Belle 2015 (BGL) [34, 29, 33]	40.83 ± 1.13
FNAL/MILC 2015 (Lattice $\omega \neq 1$) [29]	$39.6 \pm 1.7_{\rm exp+QCD} \pm 0.2_{\rm QED}$
HPQCD 2015 (Lattice $\omega \neq 1$) [33]	$40.2 \pm 1.7_{\rm latt+stat} \pm 1.3_{\rm syst}$
Inclusive decays	
Gambino et al. 2016 [100]	42.11 ± 0.74
HFAG 2014 [24]	42.46 ± 0.88
Indirect fits	
UTfit 2016 [101]	41.7 ± 1.0
CKMfitter 2015 (3σ) [102]	$41.80^{+0.97}_{-1.64}$

Refs from 1610.04387 (Giulia Ricciardi)

$$|V_{cb}|$$

- Most precise determinations:
  - 1st) Lattice determination in exclusive $B \to D^*$ channel,
  - 2nd) inclusive measurements,
  - 3rd) semileptonic $B \to D$.
- Tension among latest inclusive and latest $B \to D^*$ is 3σ. NO tension if Sum Rules used.
- Indirect Fit using CKM, CPV and flavour data (except direct decays) closer to **inclusive determination.**

But two tensions: V_{ub} and V_{cb}

TABLE 2. Status of exclusive $|V_{ub}|$ determinations and indirect fits

Exclusive decays	$|V_{ub}| \times 10^3$
$\bar{B} \to \pi l \bar{\nu}_l$	
FLAG 2016 [23]	3.62 ± 0.14
Fermilab/MILC 2015 [138]	3.72 ± 0.16
RBC/UKQCD 2015 [139]	3.61 ± 0.32
HFAG 2014 (lattice) [24]	3.28 ± 0.29
HFAG 2014 (LCSR) [145, 24]	3.53 ± 0.29
Imsong et al. 2014 (LCSR, Bayes an.) [150]	$3.32^{+0.26}_{-0.22}$
Belle 2013 (lattice + LCSR) [133]	3.52 ± 0.29
$\bar{B} \to \omega l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR) [153]	$3.31 \pm 0.19_{\rm exp} \pm 0.30_{\rm th}$
$\bar{B} \to \rho l \bar{\nu}_l$	
Bharucha et al. 2015 (LCSR) [153]	$3.29 \pm 0.09_{\rm exp} \pm 0.20_{\rm th}$
$\Lambda_b \to p \mu \nu_\mu$	
LHCb (PDG) [154]	3.27 ± 0.23
Indirect fits	
UTfit (2016) [101]	3.74 ± 0.21
CKMfitter (2015, 3σ) [102]	$3.71^{+0.17}_{-0.20}$

Inclusive decays ($|V_{ub}| \times 10^3$)	ADFR [190, 191, 192]	BNLP [193, 194, 195]	DGE [196]	GGOU [197]
HFAG 2014 [24]	$4.05 \pm 0.13^{+0.18}_{-0.11}$	$4.45 \pm 0.16^{+0.21}_{-0.22}$	$4.52 \pm 0.16^{+0.15}_{-0.16}$	$4.51 \pm 0.16^{+0.12}_{-0.15}$

$|V_{ub}|$

- Less precise module of CKM matrix elements.
- Inclusive determination more challenging theoretically than V_{cb}
- Lattice best exclusive determination $B \to \pi$ $(B \to \rho, \omega)$ systematically lower.
- Tension exclusive-inclusive at 2-3σ.
- Indirect Fit using CKM, CPV and flavour data (except direct decays) closer to **exclusive determination.**
- $|V_{ub}|$ from $\mathcal{B}(B^+ \to \ell^+ \nu_\ell)$ consistent with both inclusive and exclusive (not yet competitive).

Is there a New Physics solution for those tensions exclusive/inclusive?

Apparently there seems NOT to exist a NP solution [A. Crivellin et al.].

- Inclusive always larger than exclusive determinations (in both $|V_{cb}|$ and $|V_{ub}|$)
- EFT approach to test it in a model independent way.

Two possibilities NP can affect CKM from tree-level B decays:

$\Rightarrow$ via additional four-fermion operators (generated at tree level)

$$\mathcal{O}_R^S = \bar{\ell} P_L \nu \bar{q} P_R b \quad \mathcal{O}_L^S = \bar{\ell} P_L \nu \bar{q} P_L b \quad \mathcal{O}_L^T = \bar{\ell} \sigma_{\mu\nu} P_L \nu \bar{q} \sigma^{\mu\nu} P_L b$$

$q = u, c$. Lack of interference with SM at zero-recoil:

- Exclusive: $|C_L^T|^2$ (all), $|C_R^S + C_L^S|^2$ ($B \to D(\pi)$), $|C_R^S - C_L^S|^2$ ($B \to D^*(\rho)$).
- Inclusive: $|C_L^T|^2$ (all), $|C_R^S|^2 + |C_L^S|^2$.

$\rightarrow$ No way to explain Inclusive $>$ Exclusive.

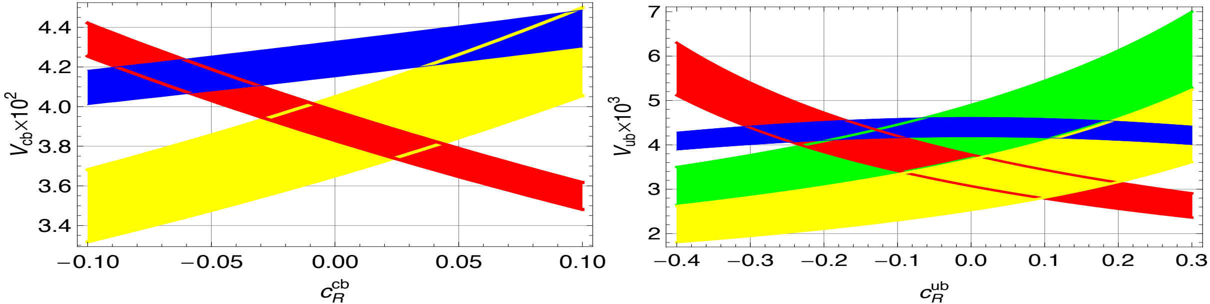
$\Rightarrow$ via operators modifying W-quark couplings (loop-effect)

$\Rightarrow$ affect the charged current after W boson is integrated out

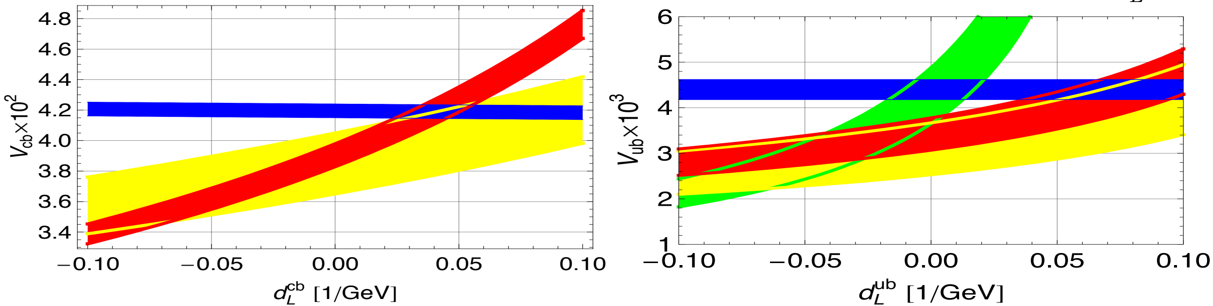
$$H_{eff} = \frac{4 G_F V_{qb}}{\sqrt{2}} \bar{\ell} \gamma^\mu P_L \nu \left((1 + c_L^{qb}) \bar{q} \gamma_\mu P_L b + g_L^{qb} \bar{q} i \overleftrightarrow{D}_\mu P_L b + d_L^{qb} i \partial^\nu \left(\bar{q} i \sigma_{\mu\nu} P_L b \right) + L \to R \right)$$

$$V_{cb} \to V_{cb}(c_{L,R}^{cb}, d_{L,R}^{cb}, g_{L,R}^{cb}) \text{ and } V_{ub} \to V_{ub}(c_{L,R}^{ub}, d_{L,R}^{ub}, g_{L,R}^{ub})$$

Only c_R can produce differences in exclusive and inclusive but not agreement between incl. (**blue**) and excl. $(B \to D^*(\pi)$ (**Red**), $(B \to D(\rho)$ (**Yellow**), $(B \to \tau\nu$ (**Green**).



Also the other coefficients fail to get a global agreement, except maybe d_L^{qb}



d_L^{qb}: Agreement between INCL. and EXCL., BUT tension with $B \to \tau\nu$. Also too large $Z - b\bar{b}$ coupling.

$\Rightarrow \beta$:

- Mode $B^0 \to J/\psi K_S^0$ access to φ_d (phase between decay and mixing+decay):
  SM: decay dominated by single CKM phase (neglect penguins)+ B_0-mixing: top-top box diagram.

$$\sin 2\beta^{\rm meas} = 0.691 \pm 0.017 < \sin 2\beta^{\rm indirect} = 0.740^{+0.020}_{-0.025}$$

$\to$ fit to $B \to J/\psi P$+SU(3) and SCET $\Rightarrow$ penguin small.
$\to$ 2nd solution of β disfavoured from $B^0 \to J/\psi K^{*0}$.
$\to \sin 2\beta^{q\bar{q}s} = 0.655 \pm 0.032$ from loop-induced $b \to q\bar{q}s$ transitions.

$\Rightarrow \alpha$

- $b \to u$ transitions ($B \to \rho\rho, \pi\pi, \pi\rho$) polluted by penguins.
- Challenging for th $\&$ exp. Unitary used. Isospin analysis for $B \to \pi\pi$ using all channels.

$$\alpha^{\rm measured} = (88.8^{+2.3}_{-2.3})^0 \quad \text{versus} \quad \alpha^{\rm fit} = (92.1^{+1.5}_{-1.1})^0$$

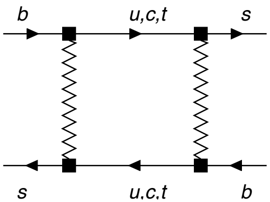
$\Rightarrow \gamma$

- Less precisely known angle. Tree $B \to DK$ decays; interference between $b \to c$ (CA) and $b \to u$ (CS) topologies. Important test of CKM paradigm. Different methods (GLW,GGSZ,ADS).

$$\gamma^{\rm measured} = (72.1^{+5.4}_{-5.8})^0 (\rm B - factories + LHCb) \quad \text{versus} \quad \gamma^{\rm fit} = (65.31^{+1.0}_{-2.5})^0$$

Bounding New Physics via FCNC ($\triangle F = 2$)

$\Delta F = 2$: neutral-meson oscillation observables



$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(M^q - \frac{i}{2}\Gamma^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

- Non-hermitian Hamiltonian (only 2 states) but M and Γ hermitian
- Mixing due to non-diagonal terms $M^q_{12} - i\Gamma^q_{12}/2$

$\Longrightarrow$Diagonalisation: physical $|B^q_{H,L}\rangle = p|B_q\rangle \mp q|\bar{B}_q\rangle$ of masses $M^q_{H,L}$, widths $\Gamma^q_{H,L}$

In terms of M^q_{12}, $|\Gamma^q_{12}|$ and $\phi_q = arg\left(-\frac{M^q_{12}}{\Gamma^q_{12}}\right)$ and determined from:

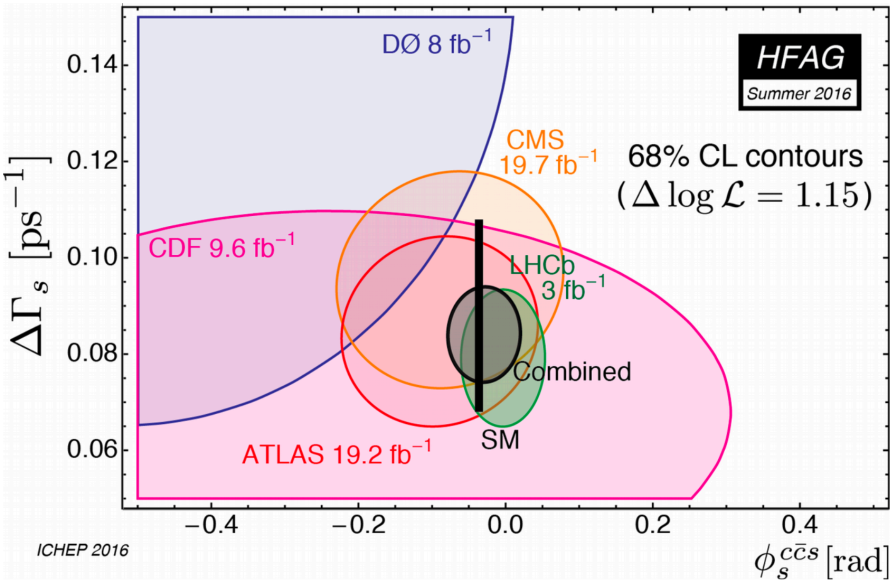
- Mass difference $\Delta m_q = M^q_H - M^q_L$
- Width difference $\Delta\Gamma_q = \Gamma^q_L - \Gamma^q_H$
- $a^q_{SL} = \frac{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)-\Gamma(B_q(t)\to\ell^-\nu X)}{\Gamma(\bar{B}_q(t)\to\ell^+\nu X)+\Gamma(B_q(t)\to\ell^-\nu X)}$ measures CP violation in mixing

Accessible for B_d and B_s at Babar, Belle, CDF, DØ, LHCb… Model-independent parametrisation under the assumption that NP only changes modulus and phase of M^d_{12} and M^s_{12} A. Lenz, U. Nierste, CKMfitter

$$M^q_{12} = (M^q_{12})_{SM} \times \Delta_q \qquad \Delta_q = |\Delta_q|e^{i\phi^\Delta_q} = (1 + h_q e^{2i\sigma_q})$$

Use Δm_d, Δm_s, β, ϕ_s, a^d_{SL}, a^s_{SL}, $\Delta\Gamma_s$ to constrain Δ_d and Δ_s

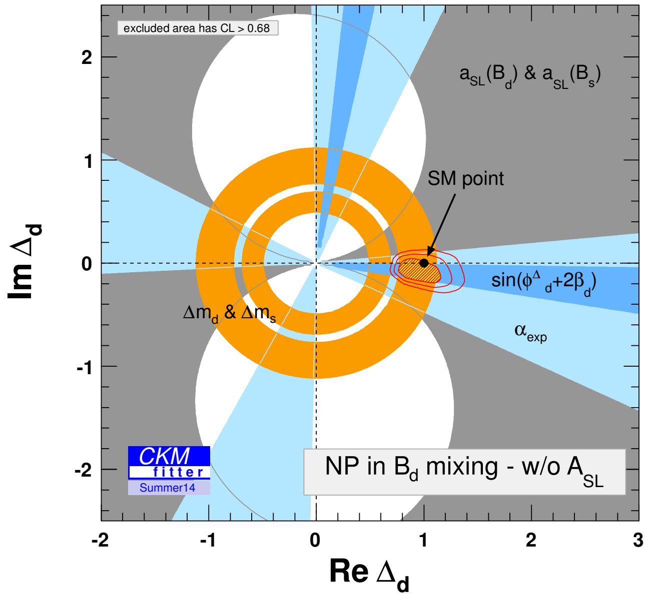
NP in B_s^0 oscillations?



Experimental errors are still larger than theory ones for ϕ_s ....

...but no much room left for NP here.

NP phases shift $2\beta \to 2\beta + \phi_d^\Delta$ in mixing-induced CP asymm. in $B^0 \to J/\psi K_s^0$ and a_{sl}^d



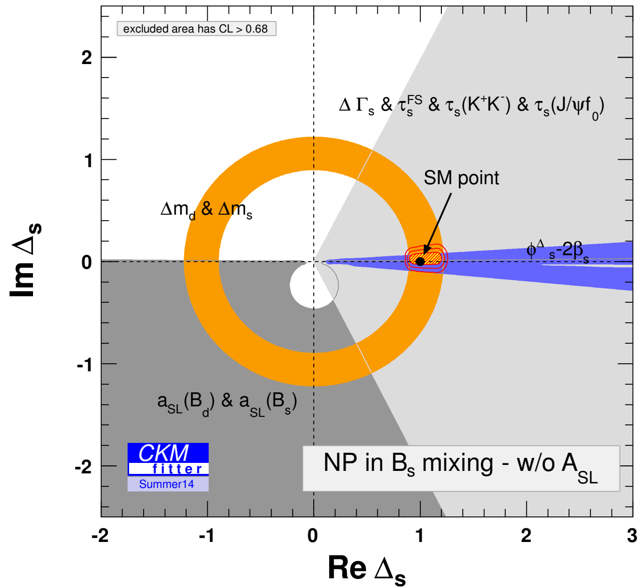
[Constraints @ 68% CL]

- Dominant constraint from β and Δm_d
- Good agreement with other constraints (α, $a_{SL}^{d,s}$)
- Compatible with SM

$\Delta_d = 0.94^{+0.18}_{-0.15} + i \cdot (-0.11^{+0.11}_{-0.05})$ 2D SM hyp. ($\Delta_d = 1 + i \cdot 0$): 0.9 σ

$\Delta F = 2$: B_s mixing

NP phases shift $2\beta_s \to 2\beta_s - \phi_s^\Delta$ in mixing-induced CP asymm. in $B_s^0 \to J/\psi\phi$ and a_{sl}^s



[Constraints @ 68% CL]

- Dominant constraints from Δm_s and ϕ_s
- ϕ_s favours SM situation
- A_{SL}, combining a^d_{SL} and a^s_{SL}, measured by $D\emptyset$ not included

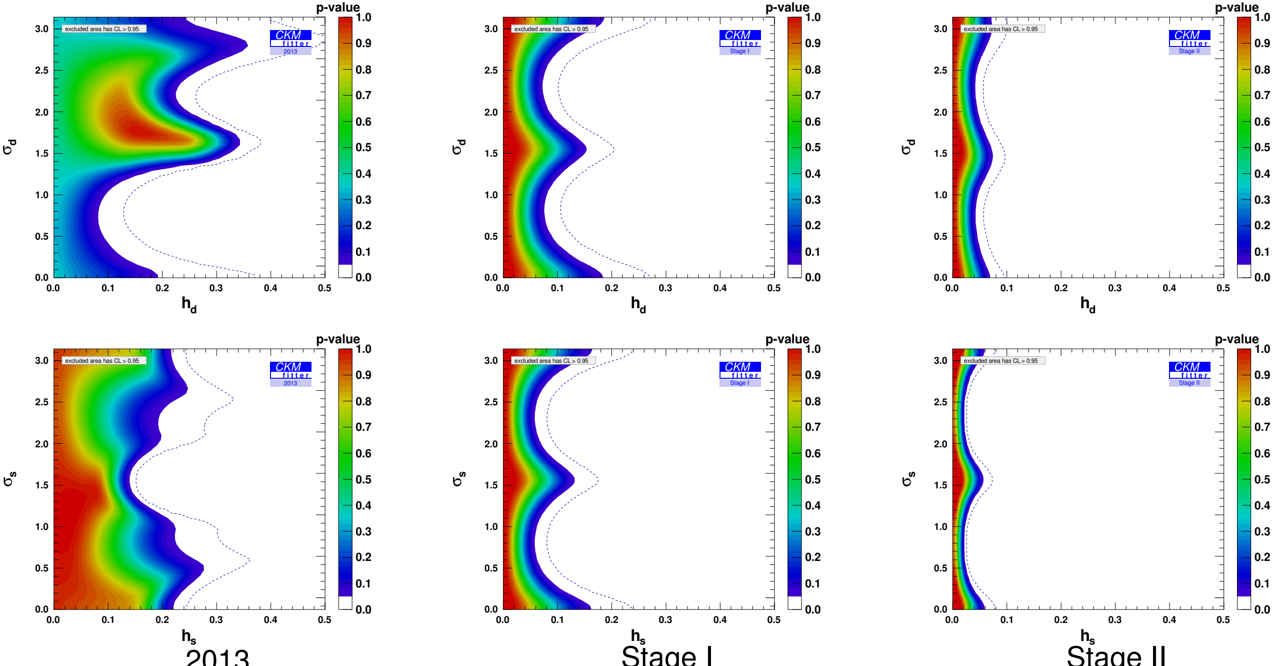
$\Delta_s = 1.05^{+0.14}_{-0.13} + i \cdot (-0.03^{+0.04}_{-0.04})$

2D SM hyp ($\Delta_s = 1 + i \cdot 0$): 0.3 σ

What are the bounds/prospects for New Physics at Stage I: 7 fb^{-1} LHCb data + 5 ab^{-1} Belle II and Stage II: 50 fb^{-1} LHCb data + 50 ab^{-1} Belle II

$\Delta F = 2$: bounds on $h_{d,s} = |\Delta_{d,s} - 1|$

What are the bounds/prospects for New Physics at Stage I: 7 fb^{-1} LHCb data + 5 ab^{-1} Belle II and Stage II: 50 fb^{-1} LHCb data + 50 ab^{-1} Belle II



Probing New Physics via Rare B decays:

Present situation

concerning New Physics in $b \to s\ell\ell$

and in $b \to c\tau\nu$

Goal of this talk

Messages to take home of this talk:

For the first time we see Coherence on a large set of deviations/anomalies

Nature seems to point towards first signals of violation of lepton flavour universality

...SM predicts LFU: interactions between gauge bosons and leptons being the same for different lepton families.

... soon we will have more observables to confirm it.

We still need a bit more **DATA** to solve some internal tensions and a few specific **NEW** inputs

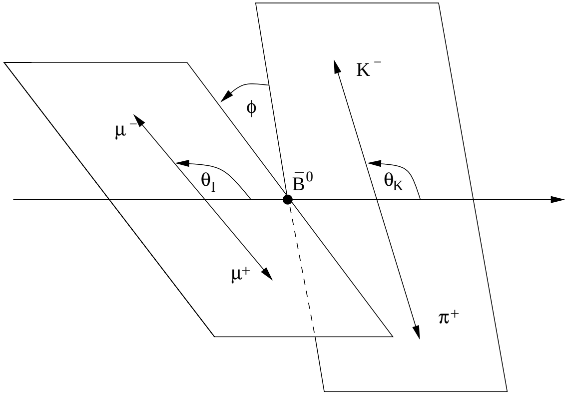
The path

to the anomalies

Why now? why there?

The starting point: Angular distribution of $B \to K^*(\to K\pi)\mu\mu$

4-body angular distribution $\mathbf{\bar{B}_d} \to \mathbf{\bar{K}^{*0}}(\to \mathbf{K}^-\pi^+)\mathbf{l^+l^-}$ with three angles, invariant mass of lepton-pair q^2.



θ_ℓ: Angle of emission between $\bar{K}^{*0}$ and μ^- in di-lepton rest frame.
$\theta_{\mathbf{K}}$: Angle of emission between $\bar{K}^{*0}$ and K^- in di-meson rest frame.
ϕ: Angle between the two planes.

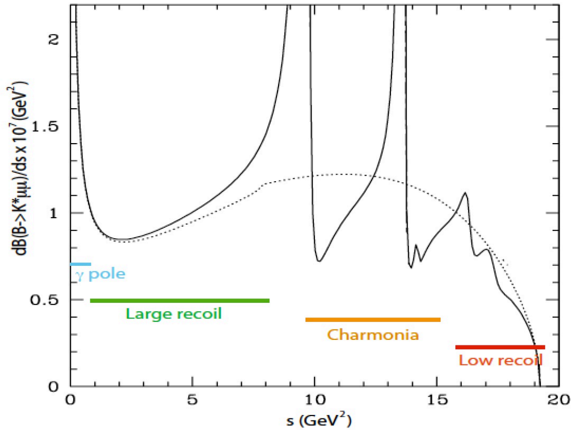
$\mathbf{q^2}$: dilepton invariant mass square.

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$

$J_i(q^2)$ function of transversity (helicity) amplitudes of K*: $A^{L,R}_{\perp,\|,0}$ but also A_t, A_S

$A^{L,R}_{\perp,\|,0}$= $\mathcal{C}_i$ (short) × Hadronic quantities (long)

Four regions in q^2 for the angular distribution $B \to K^*(\to K\pi)\mu^+\mu^-$

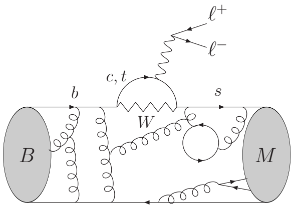


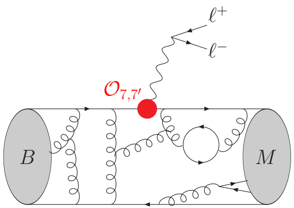
Four regions in q^2:

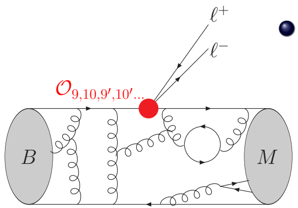
- **very large** K^*-recoil ($4m_\ell^2 < q^2 < 1$ GeV^2): γ almost real.
- **large K^*-recoil/low-q^2**: $E_{K^*} \gg \Lambda_{QCD}$ or $4m_\ell^2 \leq q^2 < 9$ GeV^2: LCSR-FF
- charmonium region ($q^2 = m^2_{J/\Psi}, ...$) betwen $9 < q^2 < 14$ GeV^2.
- **low K^*-recoil/large-q^2**: $E_{K^*} \sim \Lambda_{QCD}$ or $14 < q^2 \leq (m_B - m_{K^*})^2$: LQCD-FF

The amplitude of $B \to K^* \mu^+ \mu^-$

The framework: $b \to s\ell\ell$ effective Hamiltonian, **Wilson Coefficients**







$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\triangle F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

separate short and long distances ($\mu_b = m_b$)

- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \left(\bar{\mathbf{s}}\sigma^{\mu\nu}\mathbf{P_R}\mathbf{b}\right) \mathbf{F}_{\mu\nu}$ [real or soft photon]
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L}\mathbf{b}) \; (\bar{\ell}\gamma^\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{\mathbf{s}}\gamma_\mu \mathbf{P_L}\mathbf{b}) \; (\bar{\ell}\gamma^\mu \gamma_{\mathbf{5}} \ell)$

$$\mathcal{C}_7^{\rm SM} = -0.29, \; \mathcal{C}_9^{\rm SM} = 4.1, \; \mathcal{C}_{10}^{\rm SM} = -4.3$$

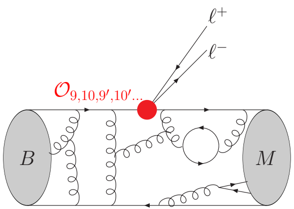
NP changes short-distance $\mathcal{C}_i = \mathcal{C}_i^{\rm SM} + \mathcal{C}_i^{\rm NP}$ for SM or involve additional operators $\mathcal{O}_i$

- Chirally flipped ($W \to W_R$) $\quad \mathcal{O}_{7'} \propto (\bar{s}\sigma^{\mu\nu} P_L\, b) F_{\mu\nu}, \; \mathcal{O}_{9'} \propto (\bar{s}\gamma_\mu P_R\, b)(\bar{\ell}\gamma^\mu \ell)$ ....
- (Pseudo)scalar ($W \to H^+$) $\quad \mathcal{O}_S \propto (\bar{s}P_R b)(\bar{\ell}\ell), \; \mathcal{O}_P \propto (\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell)$
- Tensor operators ($\gamma \to T$) $\quad \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5) b \; \bar{\ell}\sigma_{\mu\nu}\ell$

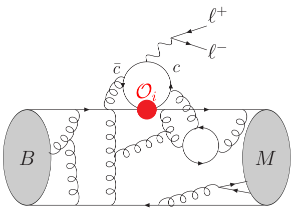
The framework: Hadronic structure of $B \to K^* \ell\ell$

$$A(B \to K^* \ell\ell) = \frac{G_F \alpha}{\sqrt{2}\pi} V_{tb} V_{ts}^* [(A_\mu + T_\mu) \bar{u}_\ell \gamma^\mu v_\ell + B_\mu \bar{u}_\ell \gamma^\mu \gamma_5 v_\ell]$$

Form factors (local)



Charm loop (non-local)



1 Local contributions: 7 form factors $\Rightarrow V, A_{0,1,2,}, T_{1,2,3}$

$$\begin{aligned} A_\mu &= -\frac{2 m_b q^\nu}{q^2} \mathcal{C}_7 \langle V_\lambda | \bar{s} \sigma_{\mu\nu} P_R b | B \rangle + \mathcal{C}_9 \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle \\ B_\mu &= \mathcal{C}_{10} \langle V_\lambda | \bar{s} \gamma_\mu P_L b | B \rangle \qquad \lambda: \ K^* \text{ helicity} \end{aligned}$$

2 Non-local contributions (charm loops): hadronic contribs.

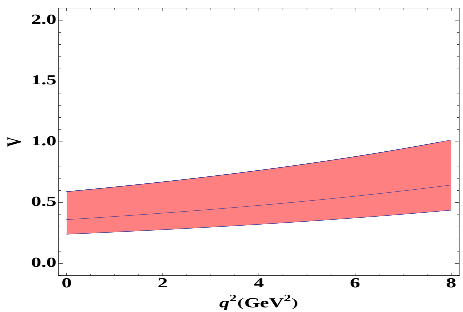
T_μ contributes like $\mathcal{O}_{7,9}$, but depends on q^2 and external states

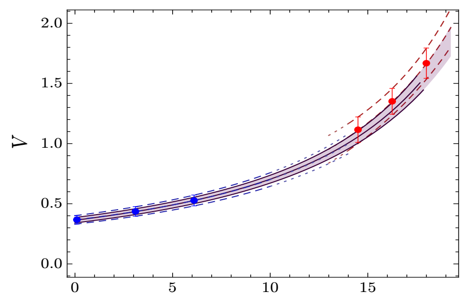
⇒ Different sets of form factors available: KMPW (LCSR, low q^2) or BSZ (fit LCSR + lattice).

- low K^* recoil: lattice, with correlations [Horgan, Liu, Meinel, Wingate]
- large K^* recoil: B-meson Light-Cone Sum Rule,
  - large error bars and no correlations [Khodjamirian, Mannel, Pivovarov, Wang]
  - reduce uncertainties and restore correlations among form factors using EFT correlations arising in $m_b \to \infty$, e.g., at large K^* recoil

$$\xi_\perp = \frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 = T_1 = \frac{m_B}{2E_{K^*}} T_2 \qquad +O(\alpha_s, \Lambda/m_b) \text{ corr}$$

- Alternatively: fit to K^*-meson LCSR + lattice, small errors bars, correlations [Bharucha, Straub, Zwicky]





Traditional experimental approach to

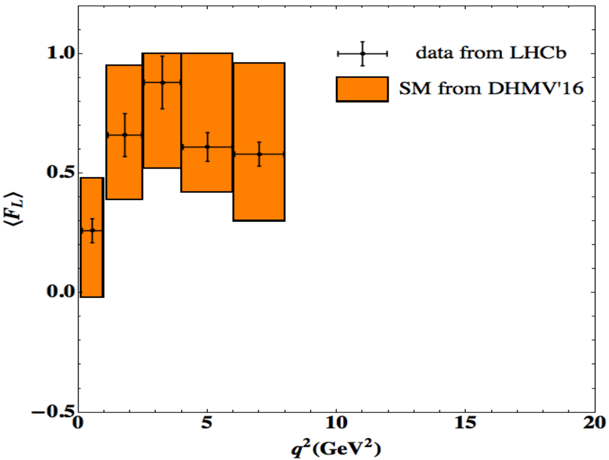
$$B \to K^* \mu^+ \mu^-$$

Till 2013 .... Traditional approach to $B \to K^* \mu^+ \mu^-$

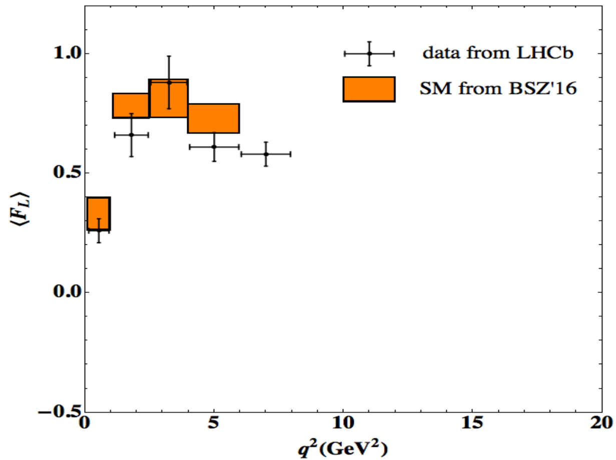
For a longtime only $\frac{dB}{dq^2}, F_L, A_{\rm FB}$ were the target of traditional analysis.

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_\ell} = -\left(\frac{3}{4}\mathbf{F_L}\sin^2\theta_\ell + \frac{3}{8}(1-\mathbf{F_L})(1+\cos^2\theta_\ell) + \mathbf{A_{FB}}\cos\theta_\ell\right)\frac{\mathbf{d\Gamma}}{\mathbf{dq^2}}$$

FF: KMPW



FF: BSZ



....in these observables hadronic uncertainties mask any possible sign of New Physics.

Two key observations:

- **THEORY**: At leading order in $1/m_b$, α_s and large-recoil ($E_{K^*} \to \infty$) FF fulfill:

$$\frac{m_B}{m_B+m_V}\mathbf{V(q^2)} = \frac{m_B+m_V}{2E}\mathbf{A_1(q^2)} = \mathbf{T_1(q^2)} = \frac{m_B}{2E}\mathbf{T_2(q^2)} = \xi_\perp(\mathbf{q^2})$$

$$\frac{m_B+m_V}{2E}\mathbf{A_1(q^2)} - \frac{m_B-m_V}{m_B}\mathbf{A_2(q^2)} = \frac{m_B}{2E}\mathbf{T_2(q^2)} - \mathbf{T_3(q^2)} = \xi_\parallel(\mathbf{q^2})$$

consequently the transversity amplitudes:

$$A_\perp^{L,R} = \sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} + \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} + \mathcal{C}_{10}^\prime) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} + \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\perp(E_{K^*})$$

$$A_\parallel^{L,R} = -\sqrt{2} N m_B (1-\hat{s}) \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^\prime) + \frac{2\hat{m}_b}{\hat{s}} (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\perp(E_{K^*})$$

$$A_0^{L,R} = -\frac{N m_B (1-\hat{s})^2}{2\hat{m}_{K^*}\sqrt{\hat{s}}} \left[(\mathcal{C}_9^{\rm eff} - \mathcal{C}_9^{\rm eff\prime}) \mp (\mathcal{C}_{10} - \mathcal{C}_{10}^\prime) + 2\hat{m}_b (\mathcal{C}_7^{\rm eff} - \mathcal{C}_7^{\rm eff\prime}) \right] \xi_\parallel(E_{K^*})$$

- **EXPERIMENT**: One can get access to new observables using the "folding technique". Identify $\phi \leftrightarrow -\phi$ and $\theta_\ell \leftrightarrow \pi - \theta_\ell$ leads to

$$d\Gamma = d\Gamma(\hat{\phi}) + d\Gamma(-\hat{\phi}) + d\Gamma(\hat{\phi}, \pi - \hat{\theta}_\ell) + d\Gamma(-\hat{\phi}, \pi - \hat{\theta}_\ell)$$

A new approach: new observables

Optimized observables: P_i

One can construct a new type of observables out of $A_{\perp,\|,0}$ based on two criteria: [F. Kruger, JM'05]

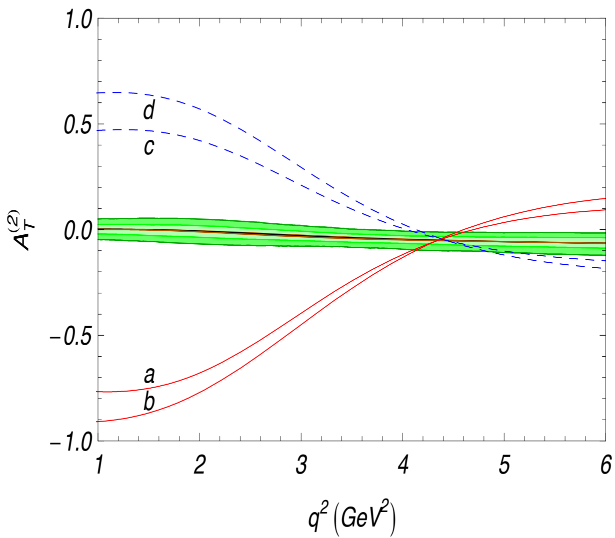
1 Exact Cancelation at LO of the SFF ($\xi_{\perp,\|}$):

$$A_T^{(2)} = P_1 = \frac{|A_\perp|^2 - |A_\||^2}{|A_\perp|^2 + |A_\||^2} = \mathcal{O}(\alpha_s \xi_\perp) + \ldots$$

compared to

$$F_L = \mathcal{O}(\xi_\perp^2/\xi_\|^2)$$

- The suppression of $H_{+1} = (A_\perp + A_\|)/\sqrt{2} \simeq 0$ due to LHS of SM implies $|A_\perp| \simeq |A_\||$.
- A contribution to C_7' induces a large-deviation (sign-sensitive: positive-down, negative-up).



2 Respect the symmetries of the distribution.

[Egede, Hurth, JM, Ramon, Reece'10]

An important step forward was the identification of the **symmetries** of the distribution:

Transformation of amplitudes leaving distribution invariant.

All the distribution can be rewritten in terms of $n_\| = (A_\|^L, A_\|^{R*})$, $n_\perp = (A_\perp^L, -A_\perp^{R*})$ and $n_0 = (A_0^L, A_0^{R*})$.

All physical information of the massless distribution encoded in 3 moduli + 3 complex scalar products - 1 constraint (**relation among n_i**): $3 + 3 \times 2 - 1 = 8$

$$|n_\||^2 = \frac{2}{3}J_{1s} - J_3\,, \qquad |n_\perp|^2 = \frac{2}{3}J_{1s} + J_3\,, \qquad |n_0|^2 = J_{1c}$$

$$n_\perp^\dagger n_\| = \frac{J_{6s}}{2} - iJ_9\,, \qquad n_0^\dagger n_\| = \sqrt{2}J_4 - i\frac{J_7}{\sqrt{2}}\,, \qquad n_0^\dagger n_\perp = \frac{J_5}{\sqrt{2}} - i\sqrt{2}J_8$$

How do we find the number of symmetries of the distribution?

Any $\vec{A}' = \vec{A} + \delta\vec{s}$ with $\vec{A} = \left(Re[A_\perp^L], ...\right)$ a 12-component vector is a symmetry that leaves the J_i coefficients unchanged if

$$\forall\, i\, \in J_i : \vec{\nabla}_i \perp \delta\vec{s}$$

Number of symmetries can be found by the directions ortogonal to the hyperplane of gradients.

Symmetries of Massless Case:

$$n_i' = U n_i = \begin{bmatrix} e^{i\phi_L} & 0 \\ 0 & e^{-i\phi_R} \end{bmatrix} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \cosh i\tilde{\theta} & -\sinh i\tilde{\theta} \\ -\sinh i\tilde{\theta} & \cosh i\tilde{\theta} \end{bmatrix} n_i \,.$$

Symmetries determine the minimal # observables for each scenario:

$$n_{obs} = 2n_A - n_S \qquad n_{obs} = n_{Ji} - n_{dep}$$

Case	Coefficients J_i	Amplitudes	Symmetries	Observables	Dependencies
$m_\ell = 0,\ A_S = 0$	11	6	4	**8**	3
$m_\ell = 0$	11	7	5	**9**	2
$m_\ell > 0,\ A_S = 0$	11	7	4	**10**	1
$m_\ell > 0$	12	8	4	**12**	0

All symmetries (massive and scalars) were found explicitly later on. [JM, Mescia, Ramon, Virto'12]

Symmetries ⇒ # of observables ⇒ determine a **basis:** ⇒ $\{\frac{dBr}{dq^2}, F_L, P_1, P_2, P_3, P_4', P_5', P_6'\}$

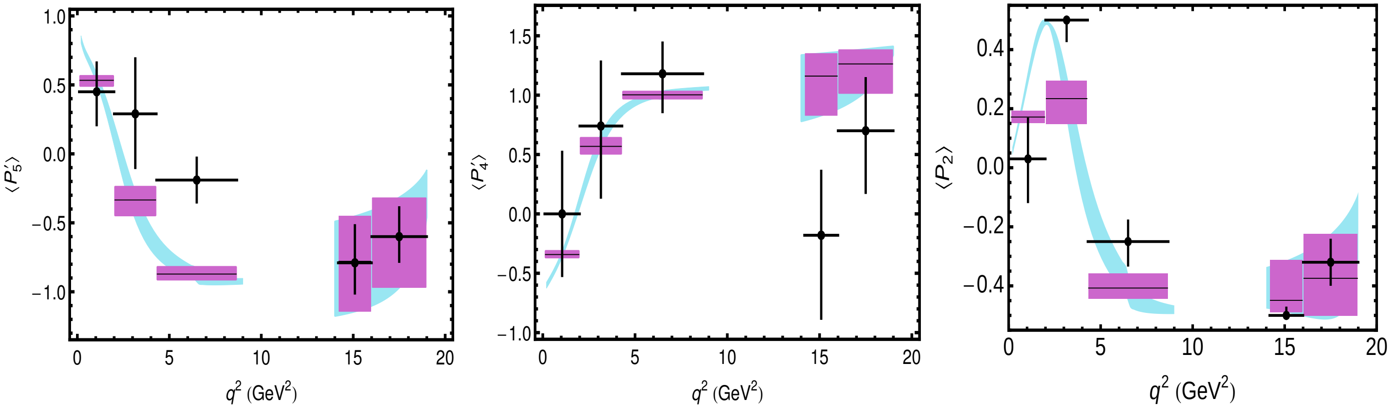
Example of non-trivial dependency:

$$P_2 = \frac{1}{2}\left[P_4' P_5' + \sqrt{\left(-1 + P_1 + P_4'^2\right)\left(-1 - P_1 + P_5'^2\right)}\right]$$

Brief flash on the anomalies: Back to 2013

Why so much excitement in Flavour Physics in that year?

First measurement by LHCb of the basis of optimized observables P_i with 1 fb^{-1}:



All the focus was on the optimized observable P_5' that deviated in the bin [4,8.68] GeV^2 near 4σ.

BUT the relevant point......indeed is the COHERENT PATTERN among the relevant observables [S. Descotes-Genon, J.M., J. Virto'13].

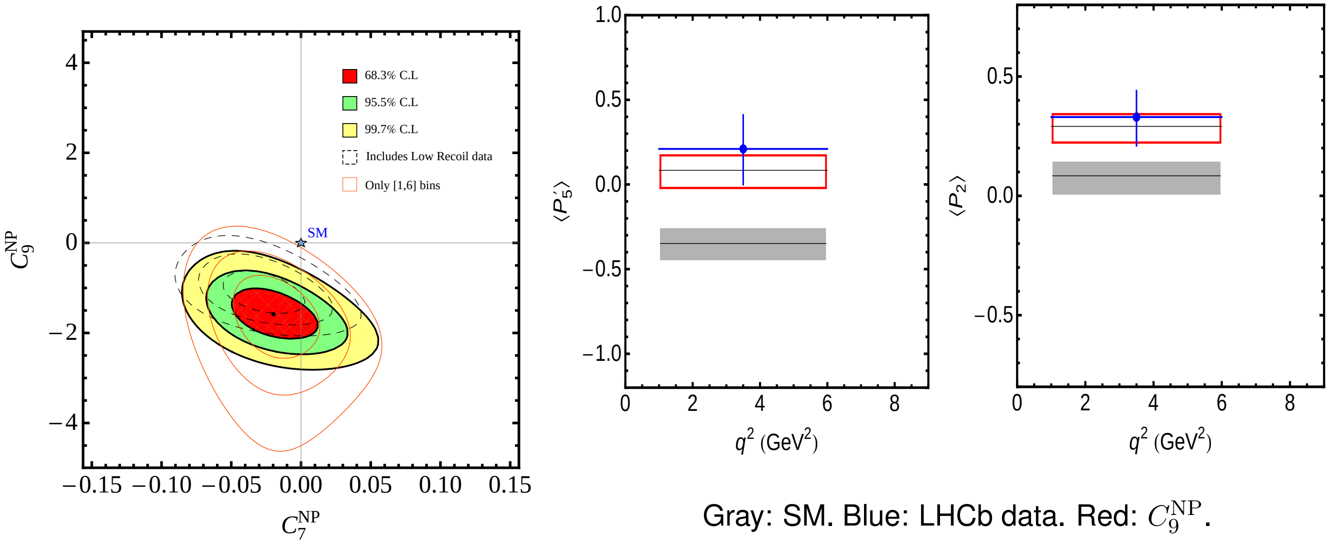
$\Rightarrow$ **Symmetries** among $A_{\perp,\|,0}$ [Egede, JM, Reece, Ramon'12] and [Serra, JM]

$\Rightarrow$ imply relations among the observables above.

How do we understand this anomaly? (Coherence I)

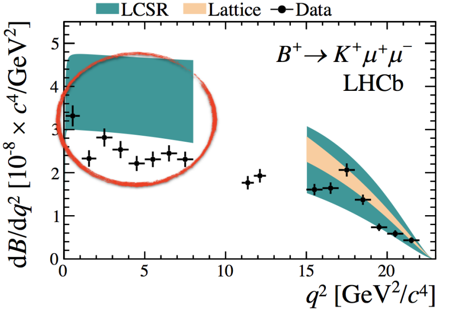
In [DMV'13] it was shown that a New Physics contribution to the coefficient C_9: $C_9^{\rm NP} \sim -1.5$

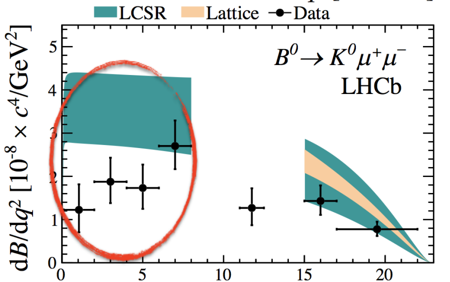
reduced the tension on P_5', but also in P_2.



Gray: SM. Blue: LHCb data. Red: $C_9^{\rm NP}$.

Systematic deficit of muons at large-recoil but also at low-recoil:





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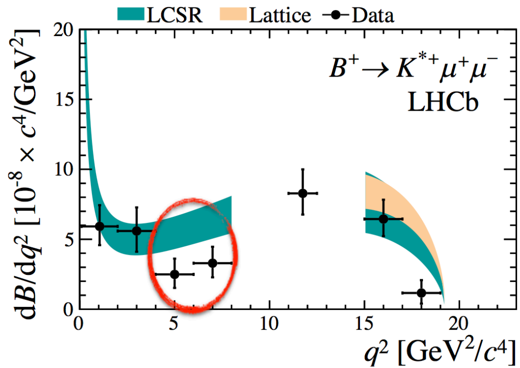
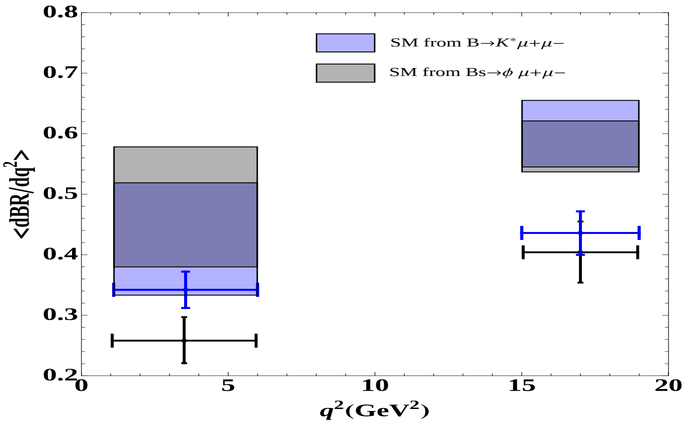


$b \to s\mu^+\mu^-$ $(\times 10^7)$	bin	SM	EXP	Pull
$\mathrm{BR}(B^0 \to K^0\mu^+\mu^-)$	[15,19]	0.91 ± 0.12	0.67 ± 0.12	+1.4
$\mathrm{BR}(B^0 \to K^{*0}\mu^+\mu^-)$	[16,19]	1.66 ± 0.15	1.23 ± 0.20	+1.7
$\mathrm{BR}(B^+ \to K^{*+}\mu^+\mu^-)$	[15,19]	2.59 ± 0.25	1.60 ± 0.32	**+2.5**
$\mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	[15,18.8]	2.20 ± 0.17	1.62 ± 0.20	**+2.2**

Let's take a look to the case of $B_s \to \phi\mu^+\mu^-$

Systematic low-recoil small tensions:

$10^7 \times \mathrm{BR}(B_s \to \phi\mu^+\mu^-)$	SM	EXP	Pull
[0.1,2]	1.56 ± 0.35	1.11 ± 0.16	+1.1
[2,5]	1.55 ± 0.33	0.77 ± 0.14	**+2.2**
[5,8]	1.89 ± 0.40	0.96 ± 0.15	**+2.2**

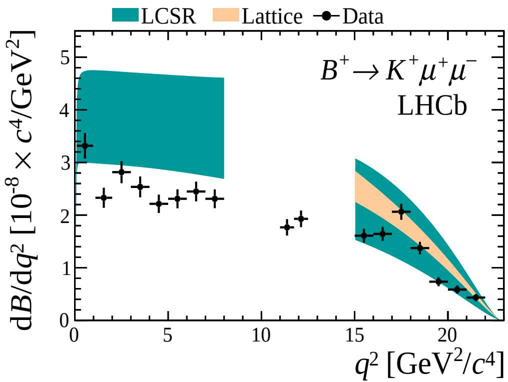


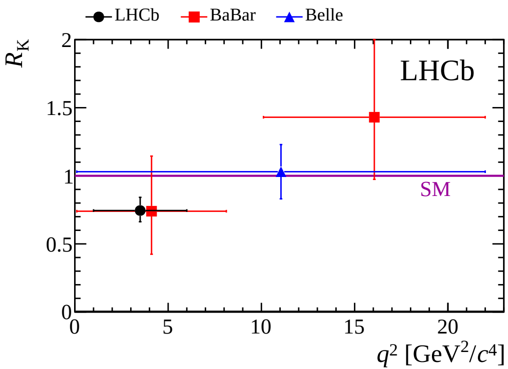
Form factors at low-q^2 for $B_s \to \phi$ (computed ONLY in BSZ) are larger than $B \to K^*$, so we would expect at low-q^2 an INVERTED hierarchy.

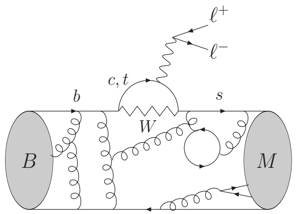
... more data required.

or problem of BSZ FF? No cross check from KMPW.

In the meanwhile (2014) new deviations appear...LFUV anomalies







$$R_K = \frac{\mathrm{Br}\,(B^+ \to K^+\mu^+\mu^-)}{\mathrm{Br}\,(B^+ \to K^+e^+e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

⇒ It deviates $\mathbf{2.6}\sigma$ from SM.

⇒ equals to 1 in SM (universality of lepton coupling).

⇒ NP coupling $\neq$ to μ and e.

Conceptually R_K very relevant:

1 **Tensions in R_K cannot be explained in the SM by neither factorizable power corrections* nor long-distance charm*.**

New category of LFUV observables: $Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$ (BELLE)

[S. Wehle et al. PRL118 (2017)]

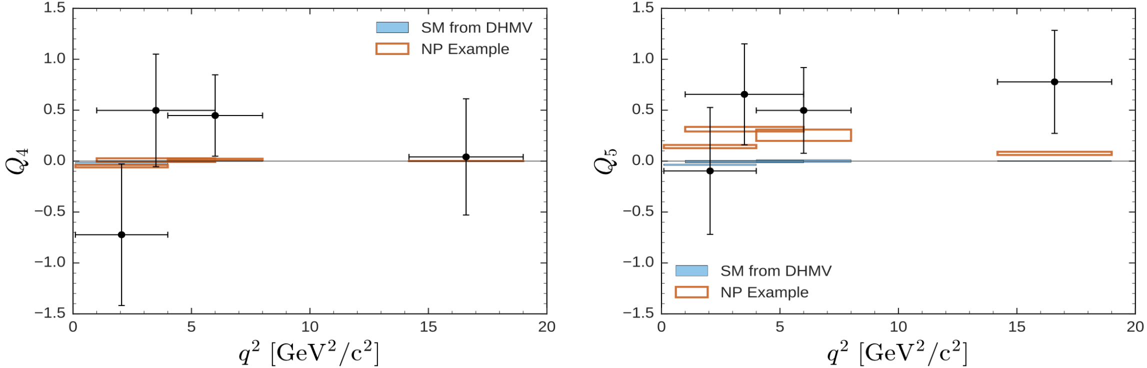


Figure 3: Q_4 and Q_5 observables with SM and favored NP "Scenario 1" from Ref. [6].

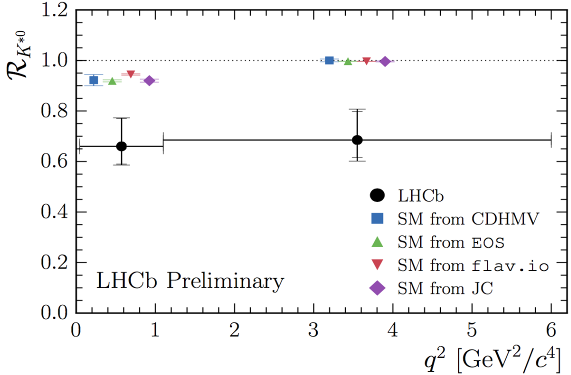
Table 2: Results for the lepton-flavor-universality-violating observables Q_4 and Q_5. The first uncertainty is statistical and the second systematic.

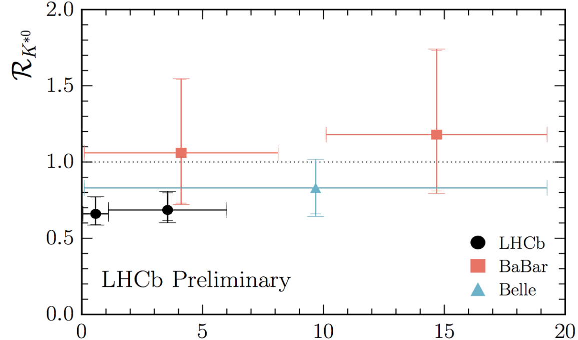
q^2 in GeV$^2/c^2$	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

and a new LFUV surprise ... R_{K^*}

$$R_{K^\star} = \frac{Br(B^0 \to K^{*0}\mu^+\mu^-)}{Br(B^0 \to K^{*0}e^+e^-)}$$

pulls	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01





- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

- Both R_K and R_{K^*} are very clean **in the SM and for** $q^2 \geq 1$ **GeV**^{2}.
  - Lepton mass effects even in the SM are important in the first bin.
    $\to$ Our error size in 1st and 2nd bin in agreement with Isidori et al. (including QED $\to 0.03$).
- In presence of New Physics or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.**
  - Typical wrong statement "R_{K^*} is ALWAYS a very clean observable", indeed it is substantially less clean and more FF dependent than any optimized observable.