XX Lomonosov conference, 16th August 2021

Update and progress with B-Flavour Anomalies

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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.

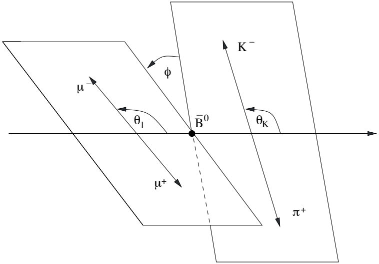
... soon we will have more observables to confirm it.

Not my goal HERE to focus on a specific UV completion
...but to SHOW that there is a **SIGNAL**.

The path to the anomalies

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

4-body angular distribution $\mathbf{B_d} \to \mathbf{K}^{*\mathbf{0}}(\to \mathbf{K}^-\pi^+)\mathbf{l}^+\mathbf{l}^-$ 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.

large K^***-recoil/low-q**^{2}: $E_{K*} \gg \Lambda_{QCD}$ or $4m_\ell^2 \leq q^2 < 9$ GeV^2:
low K^***-recoil/large-q**^{2}: $E_{K*} \sim \Lambda_{QCD}$ or $14 < q^2 \leq (m_B - m_{K^*})^2$

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

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

$\searrow$

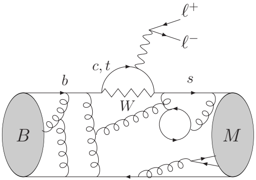
$A^{L,R}_{\perp,\|,0} = \mathcal{C}_i$ (short) $\times$ Hadronic quantities (long)

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

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

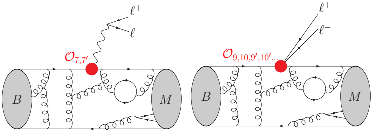
$$b \to s\gamma(^*) : \mathcal{H}^{SM}_{\triangle F=1} \propto \sum V^*_{ts} V_{tb} \mathcal{C}_i \mathcal{O}_i + \ldots$$

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



- $\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}$
- $\mathcal{O}_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell)$
- $\mathcal{O}_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

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



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

- 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 ($\gamma \to T$) $\quad \mathcal{O}_T \propto \bar{s}\sigma_{\mu\nu}(1-\gamma_5) b\, \bar{\ell}\sigma_{\mu\nu}\ell$

Diagnosis of $b \to s\, \mu^+\mu^-$ Anomalies

$b \to s\,\mu^+\mu^-$ anomalies: P_5'

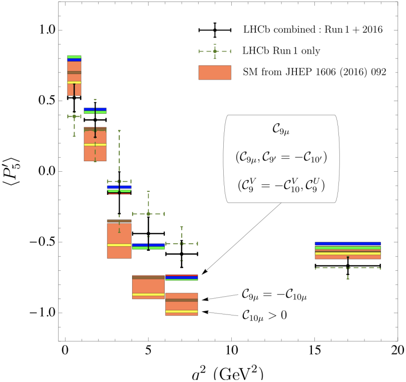
LHCb, Belle, ATLAS measurements deviate from Standard model (SM) predictions:

- Angular observable P_5' in $B \to K^*\mu^+\mu^-$ (two anomaly bins $\sim 3\,\sigma$ each)

  LHCb, arXiv:2003.04831, arXiv:2012.13241

  - **Exact** cancellation of soft FF at LO: optimized observable.
  - Most tested anomaly, now including charged channel: $B^+ \to K^{*+}\mu^+\mu^-$.
  - Latest LHCb update increased significantly the coherence w.r.t. other observables.

  Eur.Phys.J.C 80 (2020) 6, 511 (addendum)



All P_i's are constructed to cancel exactly at LO the dependence on SFF: **7 FFs (V, A_i, T_i)** $\to$ $\xi_{\perp,\parallel}$ **(SFF)**

JHEP 04 (2012) 104, JHEP 01 (2013) 048

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} = \sqrt{2}\,\frac{\mathrm{Re}[A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}]}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}}$$

It enters the 4-body distribution:

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma_P}{dq^2\,d\Omega} = \frac{9}{32\pi}\left[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K + \ldots\right.$$
$$\left. + \sqrt{\mathbf{F_T F_L}}\,\mathbf{P_5'}\sin 2\theta_K \sin\theta_l \cos\phi + \ldots\right.$$

$b \to s\,\mu^+\mu^-$ anomalies

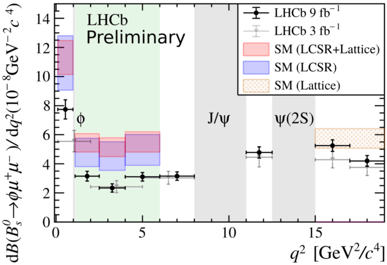
Several other LHCb measurements deviate from Standard model (SM) predictions:

- Branching ratios of $B \to K\mu^+\mu^-$, $B \to K^*\mu^+\mu^-$, and $B_s \to \phi\mu^+\mu^-$ ($\sim 2\,\sigma$).

LHCb, arXiv:1403.8044, arXiv:1506.08777, arXiv:1606.04731

BRs like S_i observables differently from P_i
are very sensitive to the choice and treatment of FFs.

[LHCB-PAPER-2021-014, in preparation]



Bin[1.1,6.0]:

$$\frac{d\mathcal{B}(B_s^0 \to \phi\mu^+\mu^-)}{dq^2} = (2.88\pm0.21)\times10^{-8}\,\frac{\mathrm{GeV}^2}{c^4}$$

Tension with SM at 1.8σ (LCSR-Zwicky et al.) and 3.6σ (LCSR+Lattice)

$\to$**systematic deficit in muons in all measured channels**

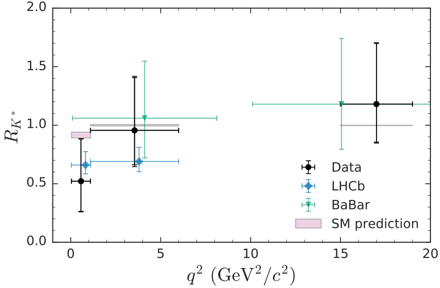
Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurements of lepton flavour universality (LFU) ratios $R_{K^*}^{[0.045,1.1]}$, $R_{K^*}^{[1.1,6]}$ show deviations from SM by about 2.5σ each.

LHCb, arXiv:1705.05802
Belle, arXiv:1904.02440

- Cancellation of all uncertainties in SM (up to lepton masses) but strongly FF sensitive in presence of NP.

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



Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

Measurement of LFU ratio $R_K^{[1.1,6]}$ shows deviation from SM by 3.1σ.

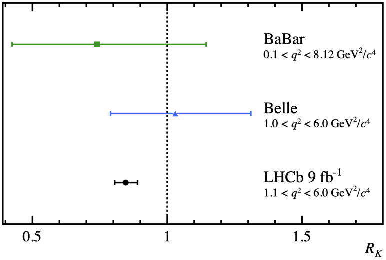
LHCb, arXiv: 2103.11769, Belle, arXiv:1908.01848

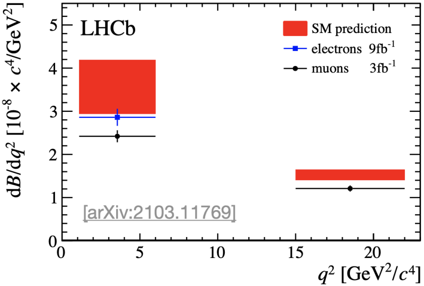
- Cancellation of all uncertainties in SM and in presence of NP (up to m_ℓ).

$$R_K = \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}$$: Experimental value $R_K^{\rm LHCb} = 0.846^{+0.042+0.013}_{-0.039-0.012}$

$$\int_{q^2=1.1\ \mathrm{GeV}^2}^{q^2=6\ \mathrm{GeV}^2} \frac{d\mathcal{B}(B^+ \to K^+e^+e^-)}{dq^2} dq^2 = (28.6^{+1.5}_{-1.4}\ (\mathrm{stat.})\ \pm 1.3\ (\mathrm{syst.})\ ) \times 10^{-9}$$

... Electrons seem more SM-like than muons.





Hints for LFU violation in $b \to s\,\ell^+\ell^-$ decays

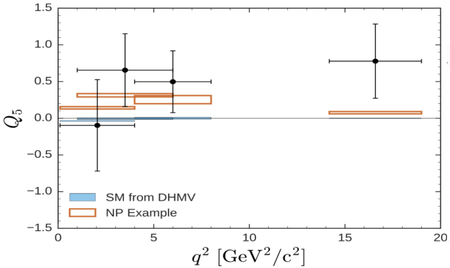
Measurement of LFU observable $Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$ **by Belle**.

S. Wehle et al (Belle), PRL 118 (2017)

- Cancellation of all uncertainties in SM (up to lepton masses) like other LFUV R_{K,K^*}, **and** optimized in presence of NP, contrary to the case of R_{K^*}.
- Isospin averaged but lepton-flavour dependent channels:

$$P'^{\ell}_i = \sigma_+ P'^{\ell}_i(B^+) + (1-\sigma_+)P'^{\ell}_i(\bar{B}^0) \qquad \sigma_+ = 0.5 \pm 0.5$$

- Also electronic and muonic channel analysis, show electrons more SM-like.

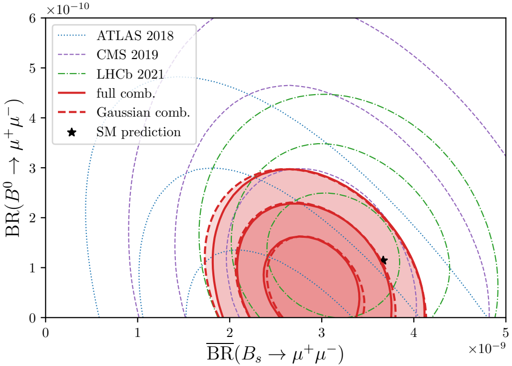


q^2 in GeV$^2/c^2$	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

Combination of $B_{s,d} \to \mu^+\mu^-$ measurements

Measurements of BR($B_{s,d} \to \mu^+\mu^-$) by LHCb, CMS, and ATLAS show combined deviation from SM by about 2σ.

ATLAS, arXiv:1812.03017
CMS, arXiv:1910.12127
LHCb seminar 23 March 2021
Altmannshofer, PS, arXiv:2103.13370



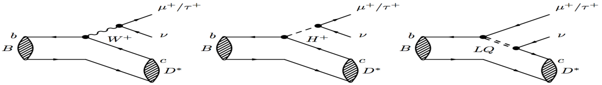
We take the average of ATLAS, CMS, LHCb (now closer to SM)

$\mathcal{B}_{B_s\to\mu^+\mu^-} = (2.85^{+0.34}_{-0.31}) \times 10^{-9}$ [Diego Martinez, private communication]

Hints for LFU violation in $b \to c\,\ell\,\nu$ decays

Measurements of LFU ratios R_D and R_{D^*} by BaBar, Belle, and LHCb show combined deviation from SM by about 3σ.

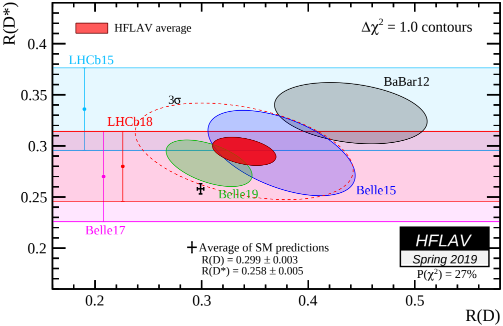
BaBar, arXiv:1205.5442, arXiv:1303.0571
LHCb, arXiv:1506.08614, arXiv:1708.08856
Belle, arXiv:1507.03233, arXiv:1607.07923, arXiv:1612.00529, arXiv:1904.08794



SM NP

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

$$\ell \in \{e, \mu\}$$

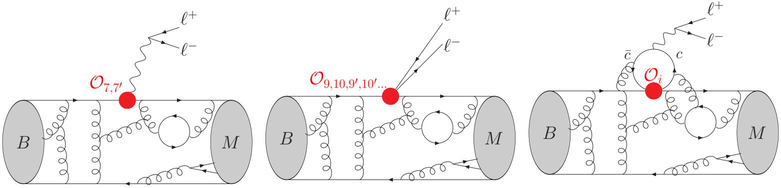


HFLAV, hflav.web.cern.ch

Hadronic Uncertainties for exclusive $b \to s\ell\ell$ decays

Two sources of hadronic uncertainties

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



Form factors (local) Form factors (local) (non-local) Charm loop

- Local contributions (more terms if NP in non-SM $\mathcal{C}_i$): form factors

$$A_\mu = -\frac{2m_b q^\nu}{q^2} \mathcal{C}_7 \langle M|\bar{s}\sigma_{\mu\nu}P_R b|B\rangle + \mathcal{C}_9 \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

$$B_\mu = \mathcal{C}_{10} \langle M|\bar{s}\gamma_\mu P_L b|B\rangle$$

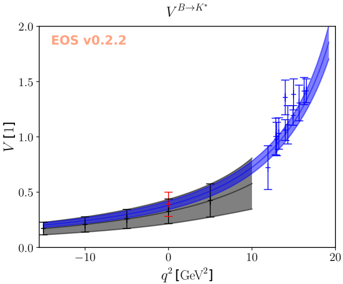
- Non-local contributions (charm loops): hadronic contribs.

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

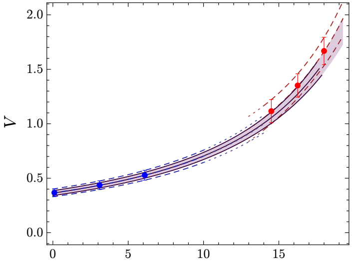
Hadronic uncertainties: form factors

3 form factors for K, 7 form factors for K^* and ϕ

- low recoil: lattice QCD [Horgan, Liu, Meinel, Wingate; HPQCD collab]
- large recoil: Light-Cone Sum Rules (B-meson or light-meson DAs)
  [Khodjamirian, Mannel, Pivovarov, Wang; Bharucha, Straub, Zwicky; Gubernari, Kokulu, van Dyk]



B-meson LCSR + lattice

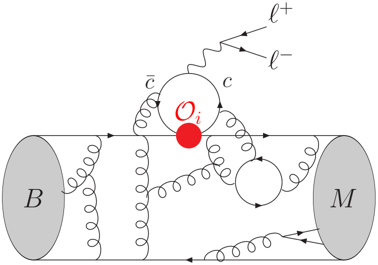


Light-meson LCSR + lattice

- correlations among the form factors needed
  - recovered from EFT with $m_b \to \infty$ + $O(\alpha_s)$ + $O(1/m_b)$
    [Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- optimised observables P_i to reduce the impact of form factor uncertainties

Hadronic uncertainties: charm loops

- important for resonance regions (charmonia)
- SM effect contributing to $\mathcal{C}_{9\ell}$
- depends on q^2, lepton univ.



Hadronic uncertainties: charm loops

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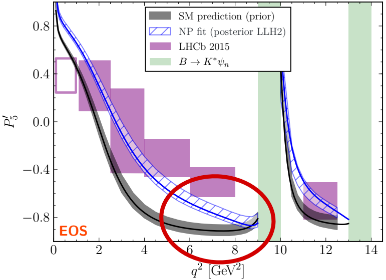


Several approaches agree at low-q^2

- LCSR explicit estimates (LO+NLO) [Khodjamirian, Mannel, Pivovarov, Wang; Gubenari, Van Dyk]
- We include to LCSR computation a nuisance parameter s_i to allow for constructive/destructive interference between charm and short-distance for each amplitude widening theo uncertainties [Crivellin, Capdevila, SDG, Hofer, Matias; Straub, Altmannshoffer; Hurth, Mahmoudi]
- fit of sum of resonances to the data [Blake, Egede, Owen, Pomery, Petridis]
- dispersive representation + $J/\psi, \psi(2S)$ data [Bobeth, Chrzaszcz, van Dyk, Virto]

Is charm-loop **overestimated** instead of **underestimated**?

The global $b \to s\ell\ell$ analysis

To focus just on one single anomaly (R_K or R_{K^*}) at the very beginning of the analysis make you lose the general view of the forest of anomalies... and may probably lead you to the wrong conclusions....

Setup

- Likelihood taking into account experimental and theoretical uncertainties and correlations in Gaussian approximation

[Algueró, Capdevila, Crivellin, SDG, Masjuan, Matias, Novoa-Brunet, Virto]

We fit $C_i = C_i^{\rm SM} + C_i^{\rm NP}$

Two statistical quantities of interest to asses a NP scenario/hypothesis:

- p-value of a given hypothesis: $\chi^2_{\rm min}$ considering N_{dof} (in %)
  goodness of fit: does the hypothesis give an overall good fit ?
  and if not, can we exclude it ?

- $\text{Pull}_{\rm SM}$: $\chi^2(\mathcal{C}_i = 0) - \chi^2_{min}$ considering N_{dof} (in σ units)
  metrology: how well does the hypothesis solve SM deviations ?

Experimental inputs

- LFUV: R_K, R_{K^*} and $\mathbf{Q_{4,5}} = \mathbf{P'^{\mu}_{4,5}} - \mathbf{P'^{e}_{4,5}}$ isospin average* (large- low-recoil bins)
- $B \to K^* \mu\mu$ (Br and ang obs)
- $B_s \to \phi\mu\mu$ (Br and ang obs)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\mu\mu$ (Br and ang obs)
- $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (Br, effective $B_s \to \mu\mu$ lifetime $\tau_{\rm eff}$)
- $B \to K^* ee$ (ang obs)
- $B \to X_s\gamma$, $B_s \to \phi\gamma$, $B \to K^*\gamma$ (Br)

including LHCb, ATLAS, CMS, Babar and Belle data whenever available

Total: 246 obs (Global) of which LFUV (R_K, R_{K^*}, $Q_{4,5}$) from LHCb, Belle, ATLAS, CMS

* It is important not to miss any LFUV observable (like Q_i observables) for a complete analysis.

Updates

- **Update**: Experimental value $R_K^{\rm LHCb} = 0.846^{+0.042+0.013}_{-0.039-0.012}$ [LHCb 2103.11769]
- **Update**: Exp value $BR(B_s \to \mu\mu) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ [LHCb at LHC Seminar]
- **Update**: Experimental value $R_K^{\rm Belle}$ [Belle 1908.01848]
- **New**: Optimised angular distribution $B^+ \to K^{*+}\mu\mu$ [LHCb 2012.13241]
- **Update**: Angular analysis at low $B^0 \to K^{*0}ee$ [LHCb 2010.06011]
- **New**: Angular analysis $B^+ \to K^+\mu\mu$ (F_H, A_{FB}) [CMS 1806.00636]
- **New**: Angular analysis $B^+ \to K^{*+}\mu\mu$ (F_L, A_{FB}) [CMS 2010.13968]
- **New**: $BR(B^{0,+} \to K^{0,+}\mu\mu)$ partners to $R_K^{\rm Belle}$ [Belle 1908.01848]

Theoretical inputs

- **Form factors:** B-meson DA LCSR + lattice + EFT for correlations
- **Charm-loop corrections**: Perturbative contribution + magnitude of long-distance contrib inspired by [Khodjamirian, Mannel, Pivovarov, Wang]
- **Quark-duality violation at high q^2**: conservative 10% effect at the level of the amplitude

  (explicit estimates [Feldman, Buchalla] at the level of 2%)
- $Br(B_s \to \mu\mu)$ modified to include latest corrections from

  [Misiak ; Beneke, Bobeth, Szafron]
- $Br(B^+ \to K^{*+}\ell\ell)$ and P_i^+ include mass and lifetime differences, annihilation graphs, hard spectator interactions with $\mathcal{O}_8$ and $\mathcal{O}_{1-6}$

Results and Outlook

1D Scenarios for $\mathcal{C}_{i\mu}$ [2021]

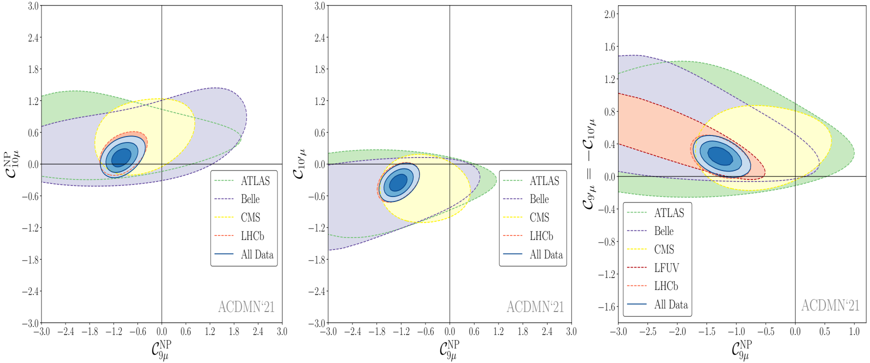
Updated results in: M. Algueró et al. arXiv: 2104.08921

		All			LFUV	
1D Hyp.	Best fit	1 σ	Pull$_{\rm SM}$	p-value	1 σ	Pull$_{\rm SM}$
$\mathcal{C}_{9\mu}^{\rm NP}$	-1.06	$[-1.20, -0.91]$	**7.0**	39.5 %	$[-1.06, -0.60]$	4.0
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{10\mu}^{\rm NP}$	-0.44	$[-0.52, -0.37]$	**6.2**	22.8 %	$[-0.46, -0.29]$	4.6
$\mathcal{C}_{9\mu}^{\rm NP} = -\mathcal{C}_{9'\mu}$	-1.11	$[-1.25, -0.96]$	6.5	28.0 %	$[-2.13, -0.96]$	3.0
$\mathcal{C}_{9\mu}^{\rm NP} = -3\mathcal{C}_{9e}$	-0.89	$[-1.03, -0.75]$	6.7	32.2 %	$[-0.78, -0.44]$	4.0

- LFUV fit: R_K, R_{K^*}, $\mathbf{Q_{4,5}}$ (updated isospin average), $B_s \to \mu\mu$, $b \to s\gamma$
- All : all $b \to s\ell\ell$ and $b \to s\gamma$ observables
- Pull$_{\rm SM}$ in σ units increased compare to [2020], scenario $\mathcal{C}_{10\mu}^{\rm NP}$ still marginal. Time-ev. of Pull$_{\rm SM}(\mathcal{C}_{9\mu}^{\rm NP})$: 4.5 [2016], 5.8 [2018], 5.6 [2019], 6.3 [2020], 7.0 [2021].
- *p*-value of SM hyp from 11% (2019) to 1.4% (2020) to 1.1% (2021) for the fit "All" 12.6% (2020) to 1.4% (2021) for the fit "LFUV"
- Tension between All fit preference by $C_{9\mu}^{\rm NP}$ and LFUV-fit by $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP}$.

Same hierarchy of main scenarios was found by other groups, for instance: Hurth, Mahmoudi, Neshatpour, arXiv:2012.12207

2D Scenarios for $\mathcal{C}_{i\mu}$ [2021]: Hints for RHC?



- Now $\mathcal{C}_{10\mu}^{\rm NP}$ compatible with zero at 1σ in ($\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10\mu}^{\rm NP}$) due to $B_s \to \mu^+\mu^-$.
- RHCs appear quite naturally: large increase in scenario ($\mathcal{C}_{9\mu}^{\rm NP}, \mathcal{C}_{10'\mu}$) and Hyp. V ([$C_{9\mu}, C_{9'\mu} = -C_{10'\mu}$]) due to R_K at level of 3σ w.r.t. RHCs.

2D and 6D Scenarios for $\mathcal{C}_{i\mu}$ [2021]

	All			LFUV		
2D Hyp.	Best fit	Pull_{SM}	p-value	Best fit	Pull_{SM}	p-value
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10\mu}^{\text{NP}})$	(-1.00,+0.11)	6.8	39.4 %	(-0.12,+0.54)	4.3	65.6 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu})$	(-1.22,+0.56)	7.2	49.8 %	(-1.80,+1.12)	4.1	53.6 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{10'\mu})$	(-1.26,-0.35)	**7.4**	55.9 %	(-1.82,-0.59)	4.7	84.1 %
$(\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$	(-1.26,+0.25)	**7.4**	55.8 %	(-2.08,+0.51)	4.7	86.0 %
$(\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$	(-0.48,+0.11)	**6.0**	24.0 %	(-0.46,+0.15)	4.5	74.5 %

- No change in the hierarchy of scenarios w.r.t. 2020.
- From last two rows: Vector preference in left sector ($C_{9\mu}^{\text{NP}}$) (vs $C_{9\mu}^{\text{NP}} = -C_{10\mu}^{\text{NP}}$) and $C_{9'\mu} = -C_{10'\mu}$ preference in right sector.

	$\mathcal{C}_7^{\text{NP}}$	$\mathcal{C}_{9\mu}^{\text{NP}}$	$\mathcal{C}_{10\mu}^{\text{NP}}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Bfp	+0.01	-1.21	+0.15	+0.01	+0.37	-0.21
$1\,\sigma$	$[-0.02, +0.04]$	$[-1.38, -1.01]$	$[+0.00, +0.34]$	$[-0.02, +0.03]$	$[-0.12, +0.80]$	$[-0.42, +0.02]$
$2\,\sigma$	$[-0.04, +0.06]$	$[-1.52, -0.83]$	$[-0.11, +0.49]$	$[-0.03, +0.05]$	$[-0.51, +1.12]$	$[-0.60, +0.23]$

- Pull_{SM}: 5.1σ [2019] $\to$ 5.8σ [2020] $\to$ 6.6σ [2021] (49.9%)
- 6D Fit shows coherence and stability with time.

Solution of the tension between All fit and LFUV fit: LFU New Physics

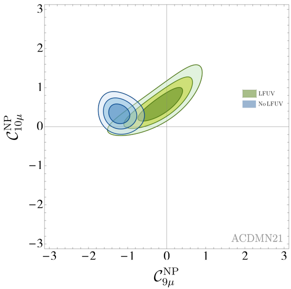
In [Algueró, Capdevila, Descotes-Genon, Masjuan, JM, PRD'19, 1809.08447] it was proposed:
... to remove hypothesis that NP is purely LFUV

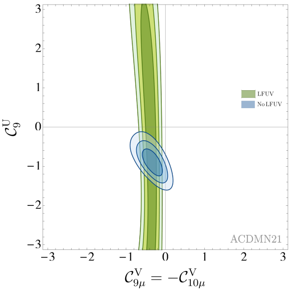
$$C_{ie}^{\mathrm{NP}} = C_i^{\mathrm{U}}$$
$$C_{i\mu}^{\mathrm{NP}} = C_{i\mu}^{\mathrm{V}} + C_i^{\mathrm{U}}$$

- Common New Physics contribution C_i^{U} to charged leptons.
- Allow to accommodate that LFUV-NP prefers $SU(2)_L$ and LFU-NP is vectorial.

$[C_{9\mu}, C_{10\mu}]$

TENSION between LFUV and non-LFUV. Pull$_{SM}$ $= 6.8\sigma$.





$[C_{9\mu}^V = -C_{10\mu}^V, C_9^U]$

PERFECT agreement and higher Pull$_{SM}$ significance of 7.3σ.

(see more LFU scenarios in back-up)

Solution of the tension between All fit and LFUV fit: LFU New Physics

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... to remove hypothesis that NP is purely LFUV

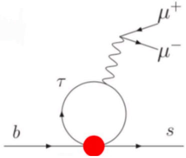
$$C_{ie}^{\rm NP} = C_i^{\rm U}$$
$$C_{i\mu}^{\rm NP} = C_{i\mu}^{\rm V} + C_i^{\rm U}$$

- Common New Physics contribution $C_i^{\rm U}$ to charged leptons.
- LFU naturally generated by τ-loop linking it to future $b \to s\tau\tau$ and R_{D,D^*} anomalies (discussed later)

[Capdevila, Crivellin, Descotes-Genon, Hofer, Matias, PRL'18, arxiv 1712.01919]

[Crivellin, Greub, Muller, Saturnino, PRL'19, arxiv 1807.02068]

[Algueró et al. EPJC79 (2019) 8,714.]



Assuming a generic flavour structure and NP at the scale Λ:

* Notice that C_9^U should not be confused with the q^2- dependent, amplitude and process dependent charm-loop.

An EFT interpretation: SMEFT

Connect $b \to s\ell\ell$ and $b \to c\ell\nu$ anomalies within SMEFT ($\Lambda_{NP} \gg m_{t,W,Z}$)

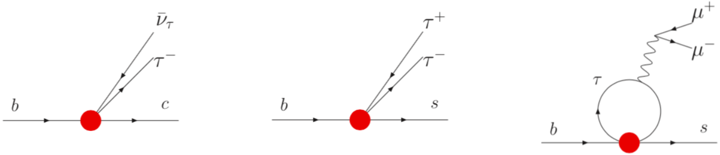
$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}_{d>4}$ with higher-dim ops involving only SM fields

[Grzadkowski, Iskrzynski, Misiak, Rosiek ; Alonso, Grinstein, Camalich]

- Two ops. with left-handed doublets

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l] \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu \vec{\sigma} Q_j][\bar{L}_k\gamma^\mu \vec{\sigma} L_l]$$

- FCCC part of $\mathcal{O}^{(3)}_{2333}$ can describe $R_{D^{(*)}}$ (rescaling of G_F for $b \to c\tau\nu$)
- FCNC part of $\mathcal{O}^{(1,3)}_{2333}$ with $C^{(1)}_{2333} = C^{(3)}_{2333}$ [Capdevila, Crivellin, SDG, Hofer, Matias]
  - Large NP contribution $b \to s\tau\tau$ through $\mathcal{C}^{\rm V}_{9\tau} = -\mathcal{C}^{\rm V}_{10\tau}$
  - Avoids bounds from $B \to K^{(*)}\nu\nu$, Z decays, direct production in $\tau\tau$
  - Through radiative effects, (small) NP contribution to $\mathcal{C}^{\rm U}_9$

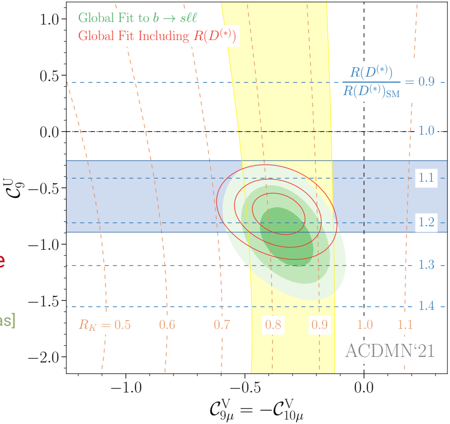


An EFT interpretation B anomalies in Scenario 8: $\mathcal{C}_9^V = -\mathcal{C}_{10}^V, \mathcal{C}_9^U$

- $\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}$ from small $\mathcal{O}_{2322}$ [$b \to s\mu\mu$]
- $\mathcal{C}^{\rm U}_9$ from radiative corr from large $\mathcal{O}_{2333}$ [$b \to c\tau\nu$ and $b \to s\mu\mu$]
- Agreement with (R_D, R_{D^*}) for $\Lambda = 1 - 10$ TeV
- Scenario 8 has $\text{Pull}_{\rm SM}$ of 8.1 σ once R_{D^*} included. Global fit $b \to s\ell\ell$ would prefer slightly higher tension in $R_{D^{(*)}}$ or large Λ scale
- Huge enhancement of $b \to s\tau\tau$ modes $O(10^{-4})$ [Capdevila, Crivellin, SDG, Hofer, Matias]

$$\text{Br}(B_s \to \tau^+\tau^-)_{\rm LHCb} \leq 6.8 \times 10^{-3},$$

$$\text{Br}(B \to K\tau^+\tau^-)_{\rm Babar} \leq 2.25 \times 10^{-3}$$

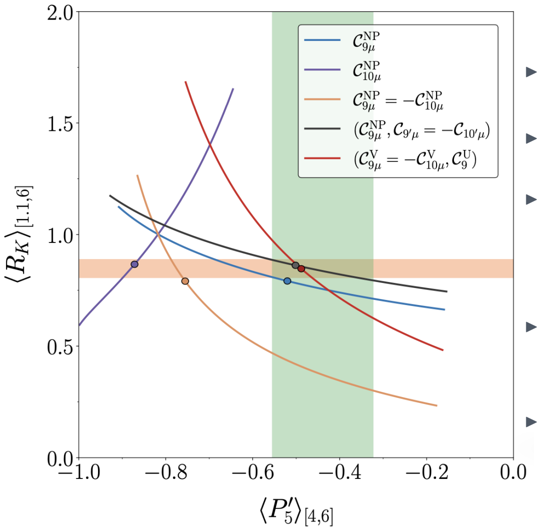


$\Lambda = 2$ TeV

Scenario 8 LFU fits & $R(D^{(*)})/R(D^{(*)})_{\rm SM}$

Scenario	Best fit	1σ	$\text{Pull}_{\rm SM}$ (σ)	p-value (%)
$(\mathcal{C}^{\rm V}_{9\mu} = -\mathcal{C}^{\rm V}_{10\mu}, \mathcal{C}^{\rm U}_9)$	(-0.36, -0.74)	([-0.43, -0.28], [-0.86, -0.61])	8.1	51.4

Consistency of scenarios with $B \to K^*\mu\mu$: $\langle P_5' \rangle_{[4,6]}$ vs $\langle R_K \rangle_{[1.1,6]}$



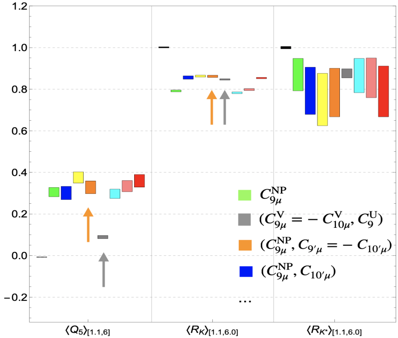
- Bfps not significantly changed in 2021.
- Increase of significance for some scenarios, but same hierarchies
- Better internal coherences of the fit
  - for P_5'
  - between P_5' and R_K

  for some of the scenarios
- $C_{9\mu}$ on the edge with R_K. $C_{9\mu} = -C_{10\mu}$ and $C_{10\mu}$ completely fail to explain P_5'.
- **RHCs counterbalance a very large and negative $C_{9\mu}$ in R_K**

Summary of dominant scenarios and future outlook

Hypotheses	Param.	$P_5'^{[4,6]}$	R_K	$Q_5^{[1,6]}$	Pull_{SM}
$\mathcal{C}_{9\mu}^{\text{NP}}$	1	✓	✓	$+0.29$	7.0
$\to [\mathcal{C}_{9\mu}^{\text{V}} = -\mathcal{C}_{10\mu}^{\text{V}}, \mathcal{C}_9^{\text{U}}]^*$	2	✓	✓	$+0.09$	7.3
$\to [\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu}]$	2	✓	✓	$+0.31$	7.4

With only 1 or 2 parameters one gets excellent fit to data. Scenario (*) moreover link with $b \to c\tau\nu$ anomaly and naturally generates LFU in C_9+imply large $b \to s\tau\tau$.



Can we disentangle the two most interesting ones?:

1) $[\mathcal{C}_{9\mu}^{\text{NP}}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu}] \Rightarrow \text{Pull}_{\text{SM}} = 7.4\sigma$
2) $[\mathcal{C}_{9\mu}^{V} = -\mathcal{C}_{10\mu}^{V}, \mathcal{C}_9^{U}] \Rightarrow \text{Pull}_{\text{SM}} = 7.3\sigma$

- R_K and R_{K^*} **cannot**.
- Q_5 **can**. It is a discriminator that can tell us if NP prefers a $SU(2)_L$ structure $C_{9\mu}$=-$C_{10\mu}$ or a vector one $C_{9\mu}$.

Outlook: a) large $b \to s\tau\tau$ would point in favour of LFU (C_9^{U}). b) large and $Q_5 > 0$ would point in favour of large $C_{9\mu}^{\text{NP}} < 0$ + possible RHCs.

What else?

Further work...

[M. Algueró et al., arXiv: 2107.05301]

I. We are now opening a new direction, turning nuisance parameters into signal.

The complete angular distribution

$$\frac{d^5\Gamma}{dq^2\, dm^2_{K\pi}\, d\Omega} = \frac{d^5\Gamma_P}{dq^2\, dm^2_{K\pi}\, d\Omega} + \frac{d^5\Gamma_S}{dq^2\, dm^2_{K\pi}\, d\Omega}$$

New observables from the S-wave piece $B \to K_0^*(\to K\pi)l^+l^-$ (K_0^* a broad scalar resonance).

- Strong bounds on each individual new observable and globally < 0.3 from symmetries.
- Two new S-wave optimized observables $W_{1,2}$ defined and predicted from P-wave.
- Experimental present and future prospects at LHCb are presented.

II. In non-leptonic B decays ($B_{d,s} \to K^{*0}\bar{K}^{*0}$) we build a new observable **L** based on a ratio of longitudinal amplitudes of $b \to$ **s**/$b \to$ **d** transitions analog of R_K ($b \to s\mu^+\mu^-/b \to s$**e**$^+$**e**$^-$).

- $L^{exp}_{K^*\bar{K}^*} = 4.43 \pm 0.92$ vs $L^{SM}_{K^*\bar{K}^*} = 19.5^{+9.3}_{-6.8} \Rightarrow$ **2.6**σ **tension**. [M. Algueró et al., JHEP 04 (2021) 066]
- We identified the most probable responsible model-independently:

$$\mathcal{Q}_{4s} = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V-A}$$

- Natural candidate: Tree level massive $SU(3)_c$ octet vector particle (KK gluon).
  ...but significant fine-tuning due to ΔM_{Bs}, dijet searches, ...
- Possible link to $b \to s\ell\ell$?: KK gluon part of spectrum of composite model+Z' boson.

Conclusions

We observe for the first time in particle physics a large set of **coherent** anomalies.

- Increase in the Pull_{SM} of the favoured scenarios, no change in hierarchy of scenarios.
- Three dominant scenarios:
  - $\mathcal{C}_{9\mu}$ this basically rules out any scenario not including it: 7.0 σ.
  - **RHC**s in several scenarios: **Hypothesis V** ($\mathcal{C}_{9\mu}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu}$): 7.4 σ.
  - **LFU contributions**, in good agreement with simple EFT interpretations combining $b \to c\ell\nu$ and $b \to s\ell\ell$ anomalies: **Scenario 8** ($\mathcal{C}_9^U, \mathcal{C}_9^V = -\mathcal{C}_{10}^V$): 7.3 σ.

Outlook and future directions:

We extended the analysis of $B \to K\pi\mu\mu$ including **new S-wave observables**. We pointed out the relevance of two measurements:

- $\mathbf{b} \to \mathbf{s}\tau\tau$ governed decays that if enhanced favours LFU NP in C_9^U (Scenario 8).
- $\mathbf{Q_5}$ that can disentangle between Hypothesis V (RHCs) and Scenario 8 (LFU).

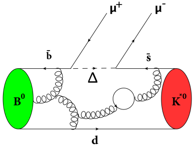
A very **promising** new B-flavour anomaly in the non-leptonic sector has emerged showing a 2.6σ tension w.r.t. SM in a new observable called **L-observable**
... the dominant Wilson coefficients are identified and a possible first model...

Backup slides

A possible successful candidate?

A very promising candidate is:

Vector leptoquark SU(2) singlet:
$U_1(3, 1, 2/3)$
Coupled mainly to 3rd generation

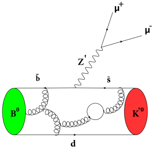


- It can explain both charged and neutral anomalies
- $C_9^V = -C_{10}^V$ pattern
- No tree level effect for $b \to s\nu\bar{\nu}$
- No conflict with direct searches

Good solution, but challenging UV completion.

Examples: $SU(4) \times U(2)_L \times SU(2)_R$+vector like ferm (Calibbi, Crivellin, Li),
$SU(4) \times U(2) \times SU(2)_R$ in RS (Blanke, Crivellin),...

Many realizations of LFUV Z' models (if only $b \to s\ell\ell$ is considered).



Pati-Salam extended $PS^3 \equiv PS_1 \times PS_2 \times PS_3$ with $PS_i = SU(4)_i \times [SU(2)_L]_i \times [SU(2)_R]_i$
(Bordone et al.) TeV LQ associated to 3rd gen.

A complete basis of optimized observables for the distribution

JHEP 04 (2012) 104, JHEP 01 (2013) 048

The most relevant ones are:

$$\mathbf{P_1} = \frac{J_3}{2J_{2s}} = \frac{|A_\perp|^2 - |A_\parallel|^2}{|A_\perp|^2 + |A_\parallel|^2} \qquad \mathbf{P_2} = \frac{J_{6s}}{8J_{2s}} = \frac{\mathrm{Re}[A_\perp^{L*}A_\parallel^L - A_\perp^R A_\parallel^{R*}]}{|A_\perp|^2 + |A_\parallel|^2}$$

$$\mathbf{P_4'} = \frac{J_4}{\sqrt{-J_{2s}J_{2c}}} = \sqrt{2}\frac{\mathrm{Re}[A_0^L A_\parallel^{L*} + A_0^R A_\parallel^{R*}]}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}} \qquad \mathbf{P_5'} = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}} = \sqrt{2}\frac{\mathrm{Re}[A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}]}{\sqrt{|A_0|^2(|A_\perp|^2 + |A_\parallel|^2)}}$$

and the angular distribution:

$$\frac{1}{\Gamma'_{full}}\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K + (\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - \mathbf{F_L}\cos^2\theta_K)\cos 2\theta_l$$

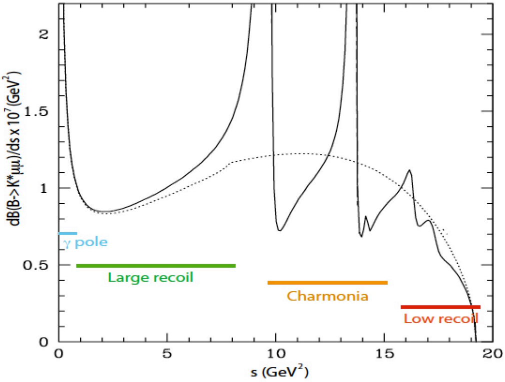
$$+\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\frac{1}{2}\mathbf{P_4'}\sin 2\theta_K \sin 2\theta_l \cos\phi + \mathbf{P_5'}\sin 2\theta_K \sin\theta_l\cos\phi\right) + 2\mathbf{P_2}\mathbf{F_T}\sin^2\theta_K\cos\theta_l + \frac{1}{2}\mathbf{P_1}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\cos$$

$$-\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\mathbf{P_6'}\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\mathbf{P_8'}\sin 2\theta_K\sin 2\theta_l\sin\phi\right) - \mathbf{P_3}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big](1-\mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

All P_i's are constructed to cancel exactly at LO the dependence on SFF: **7 FFs (V, A_i, T_i)** $\to$ $\xi_{\perp,\parallel}$ **(SFF)**

Our computation includes soft FF + α_s factorizable from QCDF + power corrections to FFs + non-factorizable α_s corrections from QCDF + long distance charm contributions (KMPW).

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



- **very large** K^*-recoil ($4m_\ell^2 < q^2 < 1\,\text{GeV}^2$): 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 ($q^2 = m_{J/\Psi}^2, ...$) between $9 < q^2 < 14$ 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

Soft Form Factors to parametrize $B \to K^*$

$\Rightarrow$ Different sets of form factors ($V, A_{1,2}, T_{1,2,3}$) available:

KMPW (LCSR B meson DA, low q^2) or BSZ (fit LCSR light meson DA + lattice).

- low q^2 region: using EFT correlations arising in $m_b \to \infty$, e.g., at large K^* recoil

$$\begin{aligned}
\xi_\perp &= \frac{m_B}{m_B + m_{K^*}} V = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 = T_1 = \frac{m_B}{2E_{K^*}} T_2 \\
\xi_{||} &= \frac{m_{K^*}}{E_{K^*}} A_0 = \frac{m_B + m_{K^*}}{2E_{K^*}} A_1 - \frac{m_B - m_{K^*}}{m_B} A_2 = \frac{m_B}{2E_{K^*}} T_2 - T_3
\end{aligned}$$

$\xi_{\perp,\|}$ are the *soft FF*.

Our analysis includes soft FF + α_s factorizable from QCDF + power corrections + non-factorizable α_s corrections and long distance charm (KMPW).

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 properties**)

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

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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**

  $\Rightarrow$ Energy scales not directly accessible at accelerators.

  $\Rightarrow$ This is the approach of **Flavour Physics**