$B \to \pi \ell^- \ell^+$ and $B \to K \ell^- \ell^+$

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Beyond the Flavour Anomalies Workshop 2026

INSTITUTO GALEGO DE FÍSICA DE ALTAS ENERXÍAS IGFAE

XUNTA DE GALICIA | CONSELLERÍA DE EDUCACIÓN, CIENCIA, UNIVERSIDADES E FORMACIÓN PROFESIONAL

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Santiago de Compostela

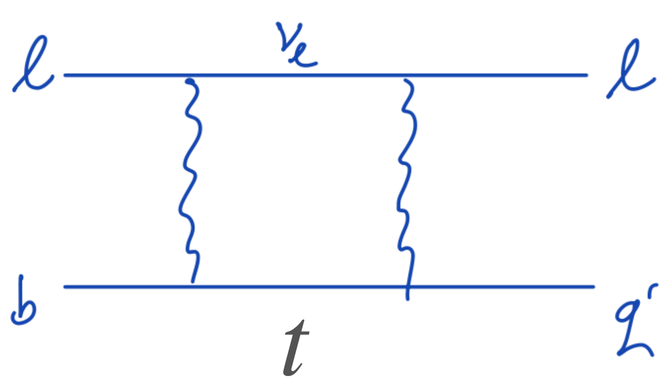
17 April 2026

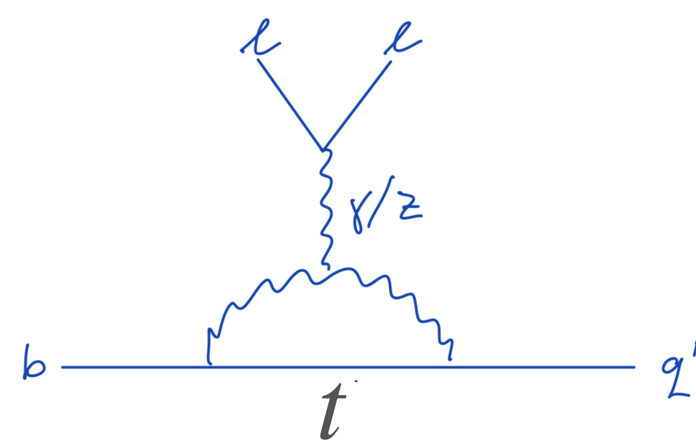
UNIVERSITY OF LJUBLJANA | FMF Faculty of Mathematics and Physics

INTRODUCTION

- Rare semileptonic B-meson decays are excellent probes of (B)SM flavour structure

- SM FCNC amplitudes are severely suppressed. Consider $b \to s\ell\ell$ or $b \to d\ell\ell$





$$\mathcal{A}_{\rm SM} \sim \frac{G_F^2 V_{tb} V_{tq'}^*}{(4\pi)^2}\, m_t^2$$

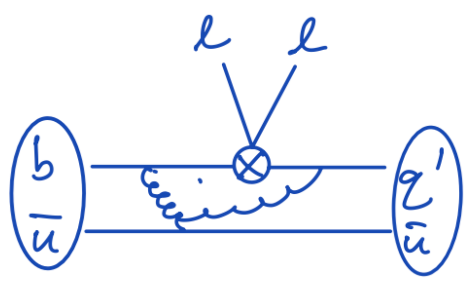
- Loop and CKM suppressed
- b hadrons are ideal testing ground for FCNCs and possible NP
- Visible short distance effect due to $m_t \sim v$, lifting GIM cancellation

$$\lambda_t^{(s)} = V_{tb} V_{ts}^* \sim \lambda^2$$

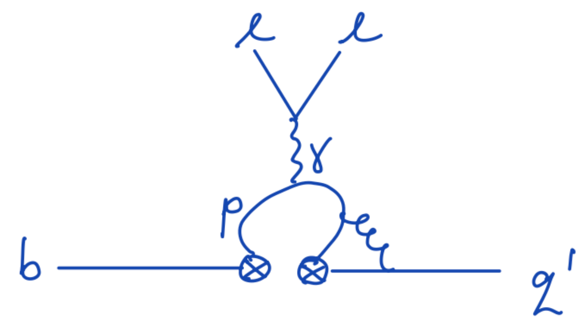
$$\lambda_t^{(d)} = V_{tb} V_{td}^* \sim \lambda^3$$

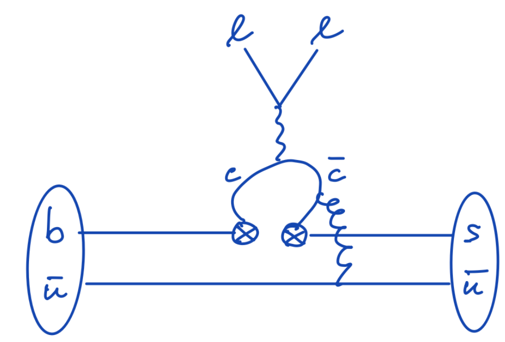
INTRODUCTION

- **Effects of QCD obstruct the view at scale m_B**



Short distance local form factors - single quark current insertion





non-local and (non)-factorisable QCD effects

- Notoriously difficult to calculate nonlocal effects of light quark propagation ($c\bar{c}, u\bar{u}$)
  - Light-cone sum rules
  - Experimental fits to a series of known intermediate resonances (à la Breit-Wigner) or via dispersive approach
  - Lattice QCD

- **Can we disentangle the effects of long-distance QCD from short distance SM?**

see yesterday's talks by Zak, Simon, Nico, Alex, Luca

WEAK EFFECTIVE THEORY

- Describing transitions $b \to q'\ell\ell$ with $q' = d, s$

$$\mathcal{L}_{\text{eff}}^{(q')} = \frac{4G_F\lambda_t^{(q')}}{\sqrt{2}}\sum_{i=3}^{10}\mathcal{C}_i\mathcal{O}_i^{(q')} + \frac{4G_F}{\sqrt{2}}\sum_{p=u,c}\lambda_p^{(q')}\sum_{i=1,2}\mathcal{C}_i\mathcal{O}_{i,p}^{(q')}$$

$$\lambda_p^{(q')} = V_{pb}V_{pq'}{}^*$$

semileptonic operators

$$\mathcal{O}_7^{(q')} = \frac{em_b}{(4\pi)^2}\bar{q}'_L\sigma_{\mu\nu}b_R\,F^{\mu\nu}$$

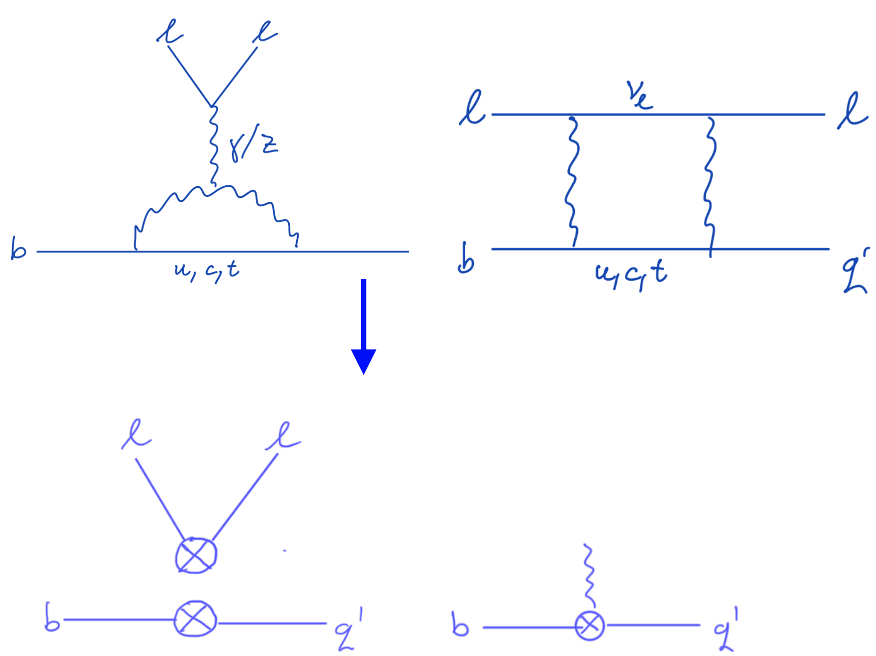
$$\mathcal{O}_9^{(q')} = \frac{\alpha}{4\pi}(\bar{q}'_L\gamma_\mu b_L)\,(\bar{\ell}\gamma^\mu\ell)$$

$$\mathcal{O}_{10}^{(q')} = \frac{\alpha}{4\pi}(\bar{q}'_L\gamma_\mu b_L)\,(\bar{\ell}\gamma^\mu\gamma^5\ell)$$

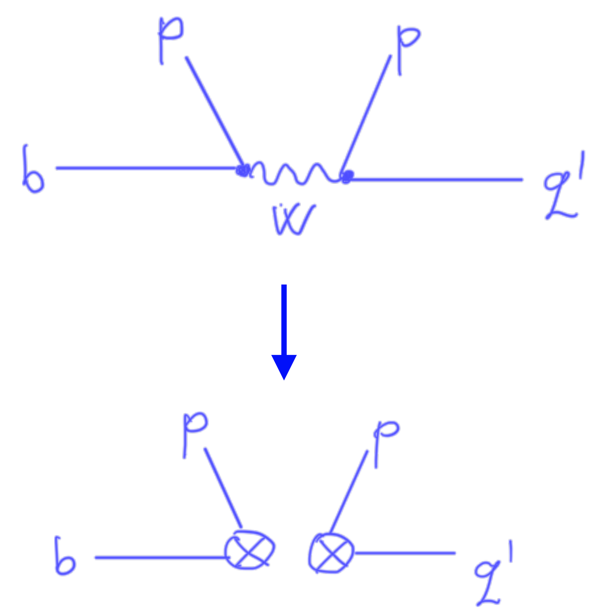
4-quark operators

$$\mathcal{O}_{1,p}^{(q')} = (\bar{q}'_{L\alpha}\gamma^\mu p_{L\beta})(\bar{p}_{L\beta}\gamma_\mu b_{L\alpha})$$

$$\mathcal{O}_{2,p}^{(q')} = (\bar{q}'_L\gamma^\mu p_L)(\bar{p}_L\gamma_\mu b_L)$$



local, short distance



non-local QCD

$m_p < m_b$

$p = u, c$

(NON)LOCAL QCD

- Differential rate for $B^- \to P^- \ell\ell$

$$\frac{d\Gamma_P}{dq^2} = \mathcal{N}_P \left(f_+^{(P)}\right)^2 \left(|\mathcal{C}_{10}|^2 + \left|\mathcal{C}_9^{\rm eff} + \tilde{f}_T^{(P)}\mathcal{C}_7\right|^2\right)$$

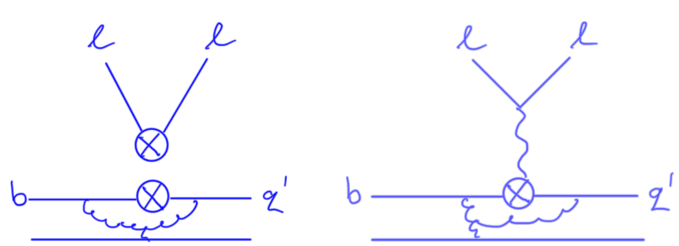
$$\mathcal{N}_P = \frac{G_F^2 \alpha^2 |\lambda_t^{(q')}|^2}{3 \cdot 512 \pi^5 m_B^3} \lambda_P^{3/2}(q^2)$$

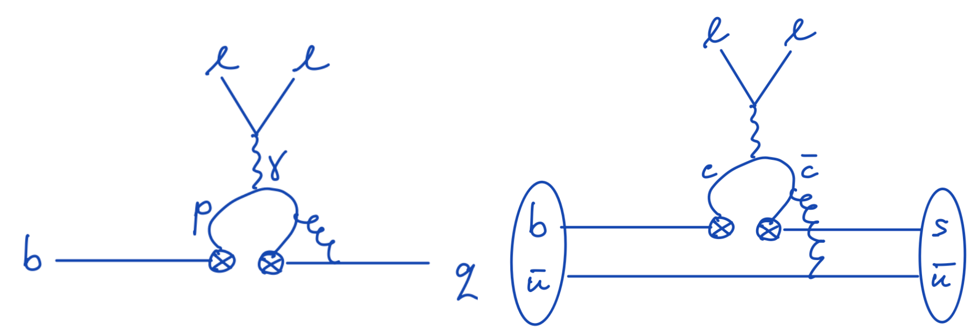
- All long-distance (non-FF) effects can be absorbed in $C_9^{\rm eff}(q^2)$

C_7, C_{10}

$$\mathcal{C}_9^{\rm eff}(q^2) = \mathcal{C}_9 - \underbrace{\tilde{\lambda}_c^{(q')} Y_{c\bar{c}}(q^2) - \tilde{\lambda}_u^{(q')} Y_{u\bar{u}}(q^2)}$$

$$\tilde{\lambda}_p^{(q')} = \lambda_p^{(q')}/\lambda_t^{(q')}$$

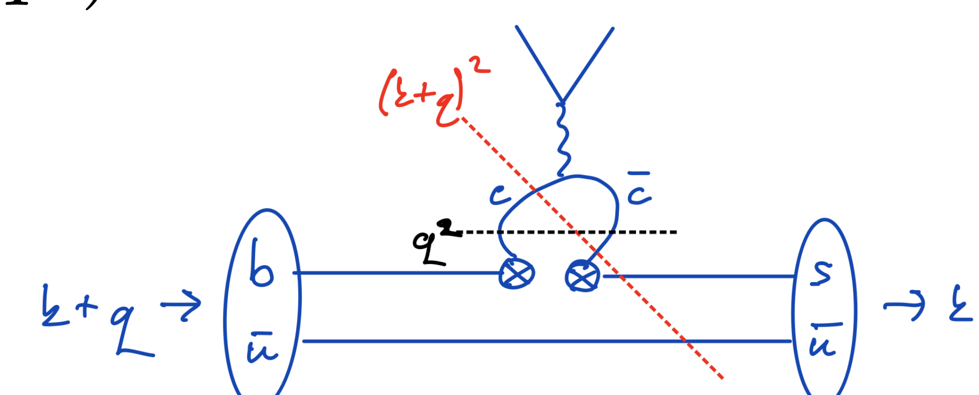




$$\sim f_+^{(P)} Y_{p\bar{p}}(q^2)$$

- local form factors
  Gubernari et al., 2305.06301

- Analytic structure implies complex $Y_{q\bar{q}}$ for any q^2, due to cuts in $(k+q)^2$



See talk by Simon Mutke, Khodjamirian, Mannel, Wang, 1211.0234
Asatrian, Greub, Virto, 1912.09099

ASSUMPTIONS

- Differential rate for $B^- \to P^- \ell\ell$

$$\frac{d\Gamma_P}{dq^2} = \mathcal{N}_P \left(f_+^{(P)}\right)^2 \left(|\mathcal{C}_{10}|^2 + \left|\mathcal{C}_9^{\text{eff}} + \tilde{f}_T^{(P)}\mathcal{C}_7\right|^2\right)$$

- $m_\ell = 0$
- real constant Wilson coefficients $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$
- dominantly SM valued $\mathcal{C}_7^{\text{SM}} = -0.292\,,\ \mathcal{C}_9^{\text{SM}} = 4.07\,,\ \mathcal{C}_{10}^{\text{SM}} = -4.31$
- complex valued $Y_{q\bar{q}}$, independent in each bin, $|Y_{q\bar{q}}| \lesssim 1$
- power counting in $\lambda_p^{(q')}$ and $Y_{q\bar{q}}$, , neglect $\lesssim 1\,\%$ effects

RATES

- CP-averaged (even) differential decay rate

$$\frac{(d\Gamma_P + d\bar{\Gamma}_P)/2}{dq^2} = \mathcal{N}_P \left(f_+^{(P)}\right)^2 \Big[\mathcal{C}_{10}^2 + (\mathcal{C}_9 + \tilde{f}_T^{(P)}\mathcal{C}_7)^2$$ local^2

$$- 2(\mathcal{C}_9 + \tilde{f}_T^{(P)}\mathcal{C}_7)\left\{\mathrm{Re}(\tilde{\lambda}_c^{(q')})\,(\mathrm{Re}Y_{c\bar{c}} - \mathrm{Re}Y_{u\bar{u}}) - \mathrm{Re}Y_{u\bar{u}}\right\}$$ local × LD

$$- 2\left(|\tilde{\lambda}_c^{(q')}|^2 + \mathrm{Re}\tilde{\lambda}_c^{(q')}\right)\mathrm{Re}(Y_{c\bar{c}}Y_{u\bar{u}}^*) + |\tilde{\lambda}_c^{(q')}|^2|Y_{c\bar{c}}|^2 + |\tilde{\lambda}_u^{(q')}|^2|Y_{u\bar{u}}|^2\Big]$$ LD^2

- Local contribution captures most of the CP-even rate.

Relative sizes (a.u.):

- local^2 $\sim$ 30
- local × LD $\sim \mathrm{Re}(\tilde{\lambda}_c)\mathrm{Re}(Y_{cc}) \lesssim 10$
- LD^2 $\lesssim 1$

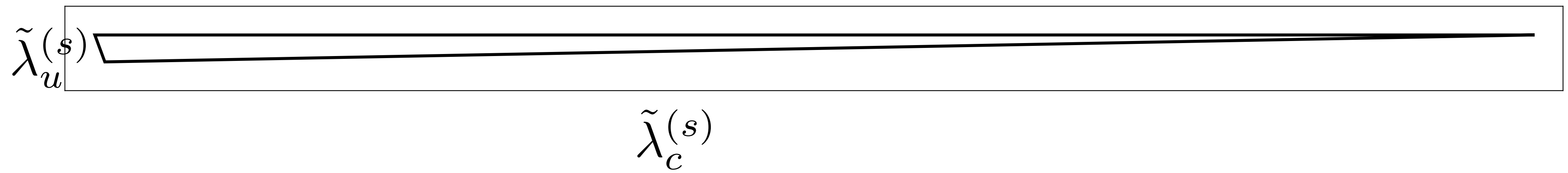
- Differential CP-difference of rates. Sensitive to interference of CP-even and CP-odd phase

$$\frac{d\Gamma_P - d\bar{\Gamma}_P}{dq^2} = 4\mathcal{N}_P \left(f_+^{(P)}\right)^2 \underbrace{\mathrm{Im}\tilde{\lambda}_c^{(q')}}_{\text{CP-odd phase}} \underbrace{\Big[\underbrace{(\mathcal{C}_9 + \tilde{f}_T^{(P)}\mathcal{C}_7)\,(\mathrm{Im}Y_{c\bar{c}} - \mathrm{Im}Y_{u\bar{u}})}_{\text{local × LD}} + \underbrace{\mathrm{Im}(Y_{c\bar{c}}Y_{u\bar{u}}^*)}_{\text{LD}^2}\Big]}_{\text{CP-even (strong) phases}}$$

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

- Degenerate unitarity triangle with negligible u-quark real part contribution

$$\tilde{\lambda}_c^{(s)} = -1 + \lambda^2(\rho - i\eta)$$
$$\tilde{\lambda}_u^{(s)} = -\lambda^2(\rho - i\eta)$$



$< 2\,\%$ effect

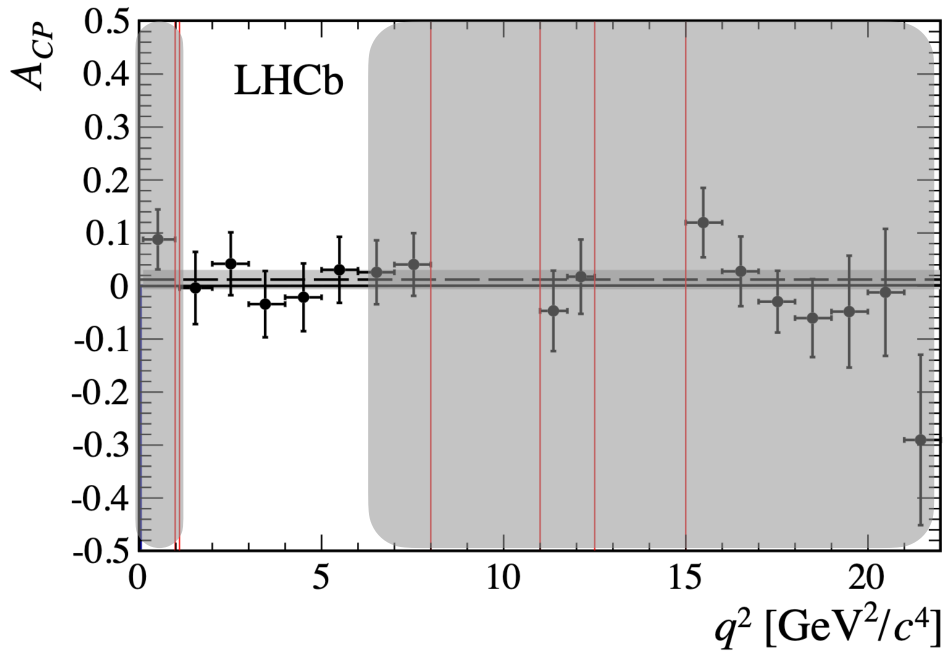
$$\frac{(d\Gamma_K + d\bar{\Gamma}_K)/2}{dq^2} = \mathcal{N}_K \left(f_+^{(K)}\right)^2 \left[\mathcal{C}_{10}^2 + \left(\mathcal{C}_9 + \tilde{f}_T^{(K)}\mathcal{C}_7\right)^2 + 2\left(\mathcal{C}_9 + \tilde{f}_T^{(K)}\mathcal{C}_7\right)\mathrm{Re}Y_{c\bar{c}} + |Y_{c\bar{c}}|^2\right]$$

- In CP-odd rate $\mathrm{Im}\tilde{\lambda}_c^{(s)} = -\,\mathrm{Im}\tilde{\lambda}_u^{(s)}$ imply opposite sign $u\bar{u}$ and $c\bar{c}$ contributions

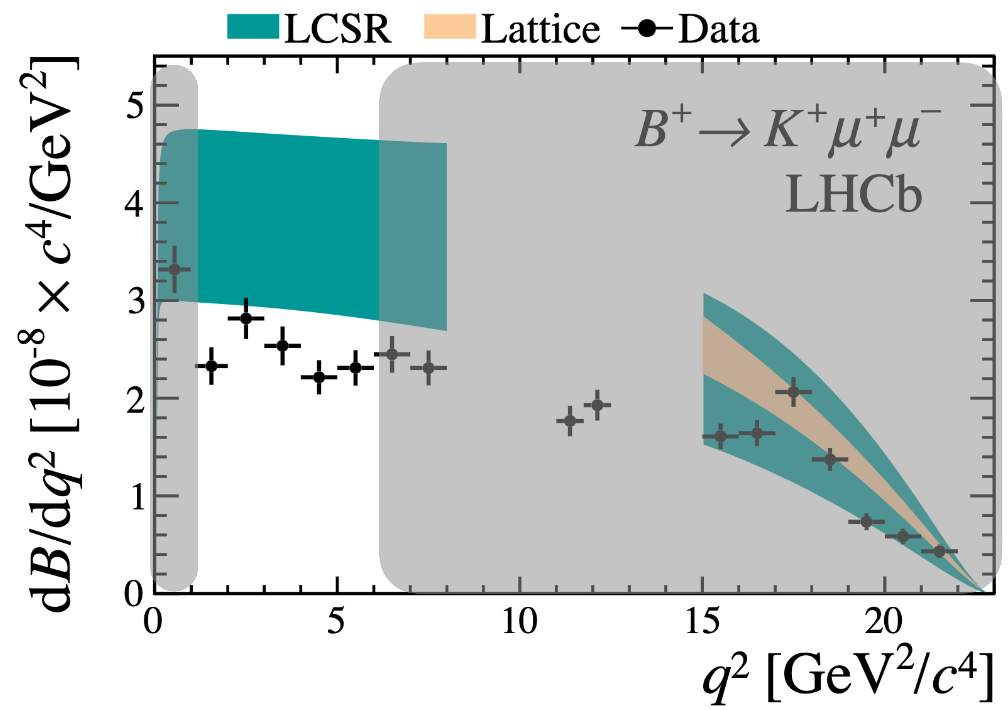
$$\frac{d\Gamma_K - d\bar{\Gamma}_K}{dq^2} = 4\mathcal{N}_K \left(f_+^{(K)}\right)^2 \eta\lambda^2 \left[\left(\mathcal{C}_9 + \tilde{f}_T^{(K)}\mathcal{C}_7\right) \underbrace{\mathrm{Im}(Y_{u\bar{u}} - Y_{c\bar{c}})}_{\text{dominant effect}} - \mathrm{Im}(Y_{c\bar{c}}Y_{u\bar{u}}^*)\right] \sim \lambda^6$$

DATA DRIVEN APPROACH

- Consider differential (binned) CP-averaged rates and CP-asymmetries



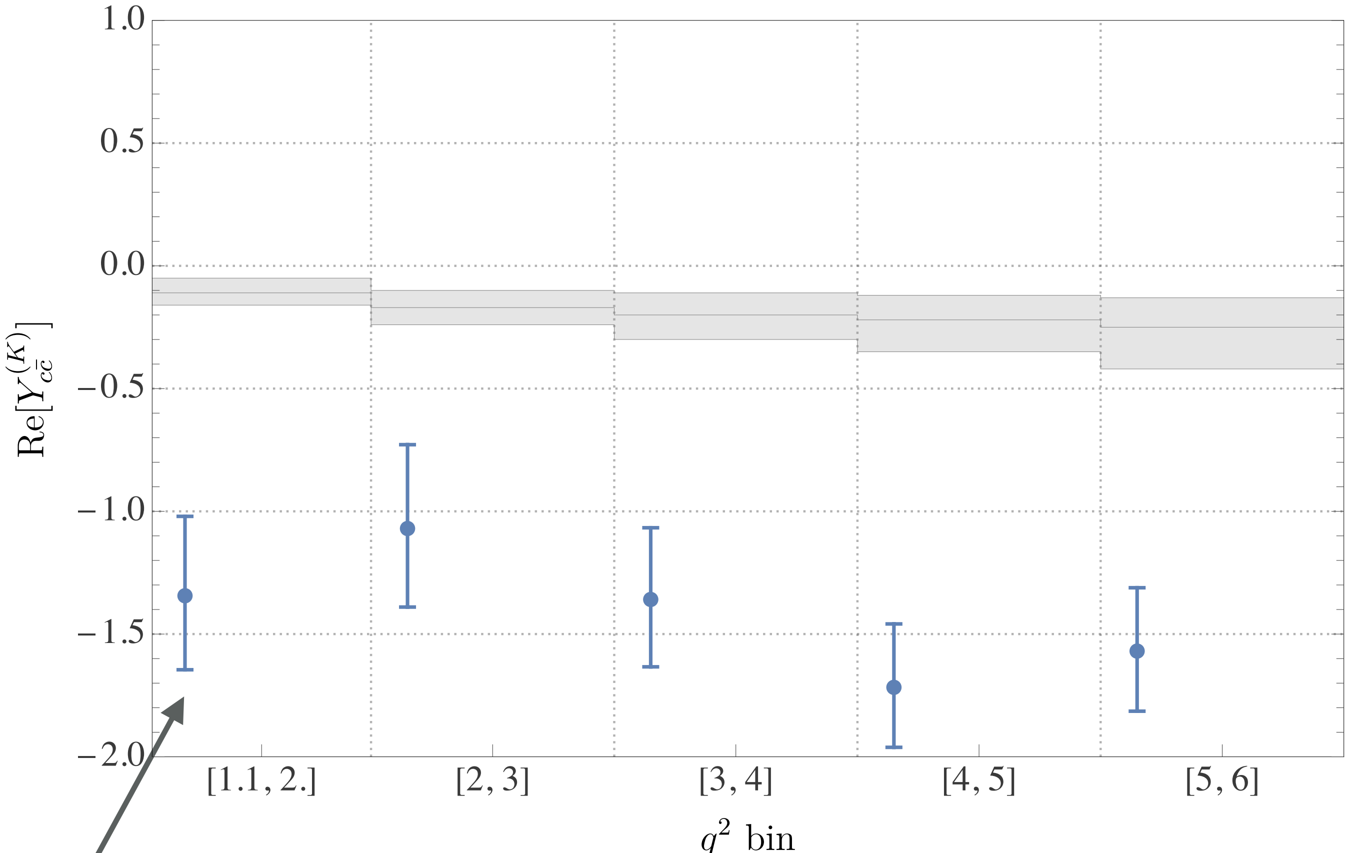
LHCb, 1408.0978



LHCb, 1403.8044

- bins $[1.1,2]$ - $[5,6]\,\mathrm{GeV}^2$, between ρ/ω and $c\bar{c}$ peaks
- compare the CP averaged rates and A_{CP} in each bin
- set $C_i = C_i^{\mathrm{SM}}$
- can we extract nonlocal functions $\mathrm{Re}Y_{c\bar{c}}$ and $\mathrm{Im}(Y_{c\bar{c}} - Y_{u\bar{u}})$ in each bin?

CP AVERAGED $B \to K\mu\mu$



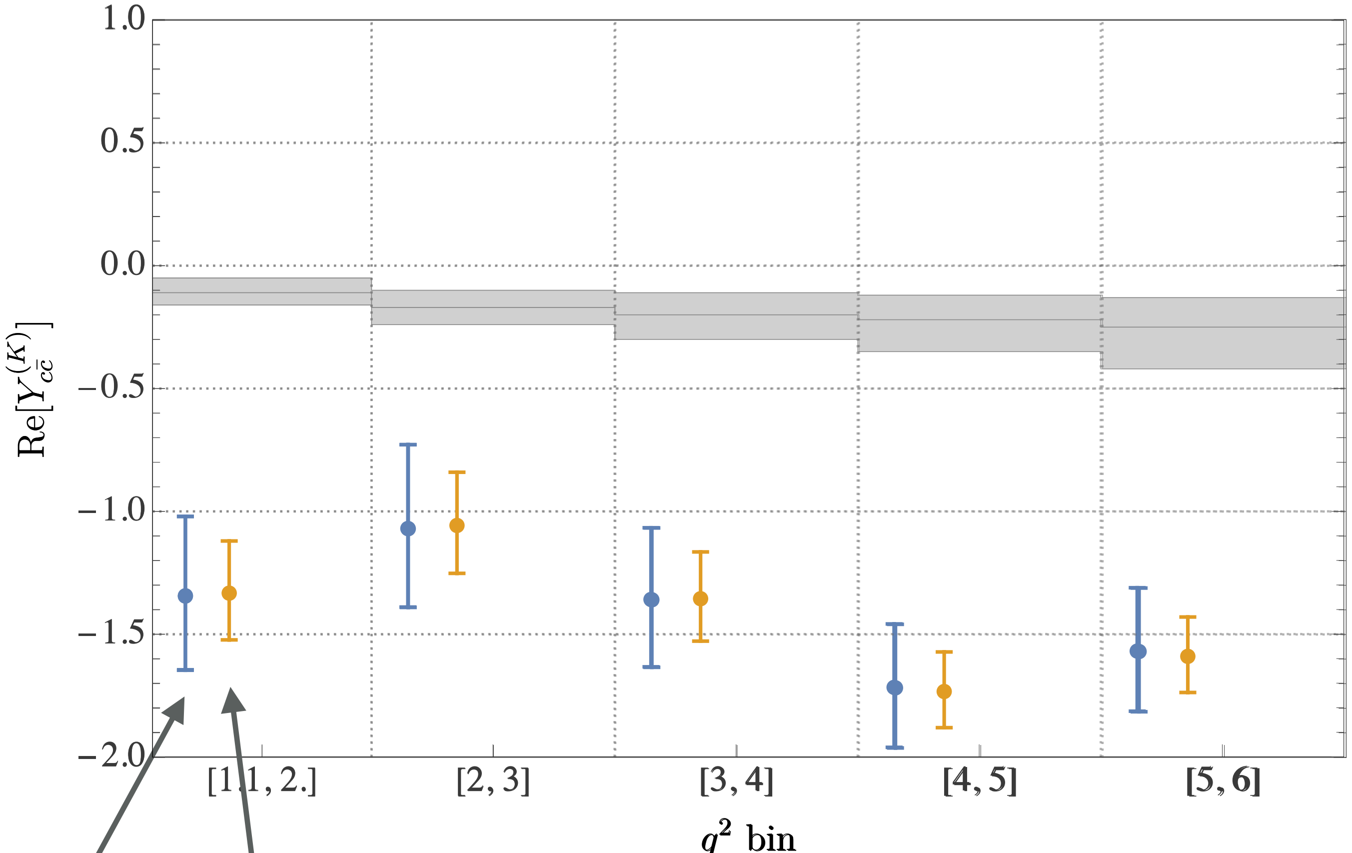
local form factors by Gubernari et al., 2305.06301, D. Leljak et al, 2102.07233

Khodjamirian, Mannel, Wang, 1211.0234

current data

CP AVERAGED $B \to K\mu\mu$

local form factors by Gubernari et al., 2305.06301, D. Leljak et al, 2102.07233



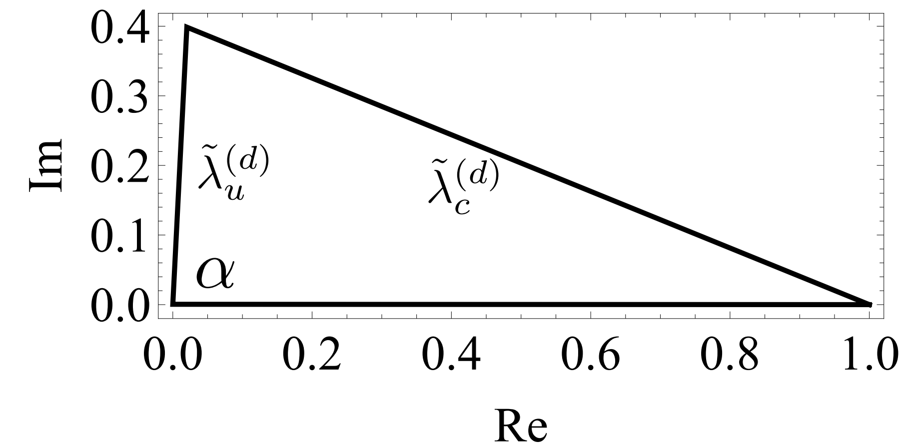
Khodjamirian, Mannel, Wang, 1211.0234

current data

reduced exp. error

$B^- \to \pi^- \ell\ell$

- Similar sizes of $\tilde\lambda_c^{(d)}$ and $\tilde\lambda_u^{(d)}$, large CPV phase
- $\tilde\lambda_u^{(d)}$ almost imaginary
- small expansion parameter $\rho(1-\rho)-\eta^2 = -0.022$



$$\tilde\lambda_c^{(d)} = \frac{\rho-1+i\eta}{(1-\rho)^2+\eta^2} \approx 0.4\,i - 1$$

$$\tilde\lambda_u^{(d)} = \frac{\rho(1-\rho)-\eta^2-i\eta}{(1-\rho)^2+\eta^2} \approx -0.4\,i$$

$< 2\,\%$ effect

$$\frac{(d\Gamma_\pi + d\bar\Gamma_\pi)/2}{dq^2} = \mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \left[\mathcal{C}_{10}^2 + (\mathcal{C}_9 + \tilde f_T^{(\pi)}\mathcal{C}_7)^2 + 2(\mathcal{C}_9 + \tilde f_T^{(\pi)}\mathcal{C}_7)\mathrm{Re}Y_{c\bar c} + \cancel{|Y_{c\bar c}|^2} + \cancel{(\mathrm{Im}\tilde\lambda_u^{(d)})^2|Y_{u\bar u} - Y_{c\bar c}|^2}\right]$$

Hambrock, Khodjamirian, Rusov, 1506.07760

see also A. Mclean Marshall et al, 2310.06734

- CP-odd rate of same order as CP-even rate and $B \to K$ CP-odd rate

$$\frac{d\Gamma_\pi - d\bar\Gamma_\pi}{dq^2} = 4\mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \frac{(-\eta)}{(1-\rho)^2+\eta^2}\left[\left(\mathcal{C}_9 + \tilde f_T^{(\pi)}\mathcal{C}_7\right)\underbrace{\mathrm{Im}(Y_{u\bar u} - Y_{c\bar c})}_{\text{dominant effect}} - \mathrm{Im}(Y_{c\bar c}Y_{u\bar u}^*)\right] \sim \lambda^6$$

- Implicit flavor and state dependence: $Y_{q\bar q}^{(K)} \neq Y_{q\bar q}^{(\pi)}$ due to U-spin breaking

No binned data for $B^- \to \pi^- \ell\ell$ at this time.

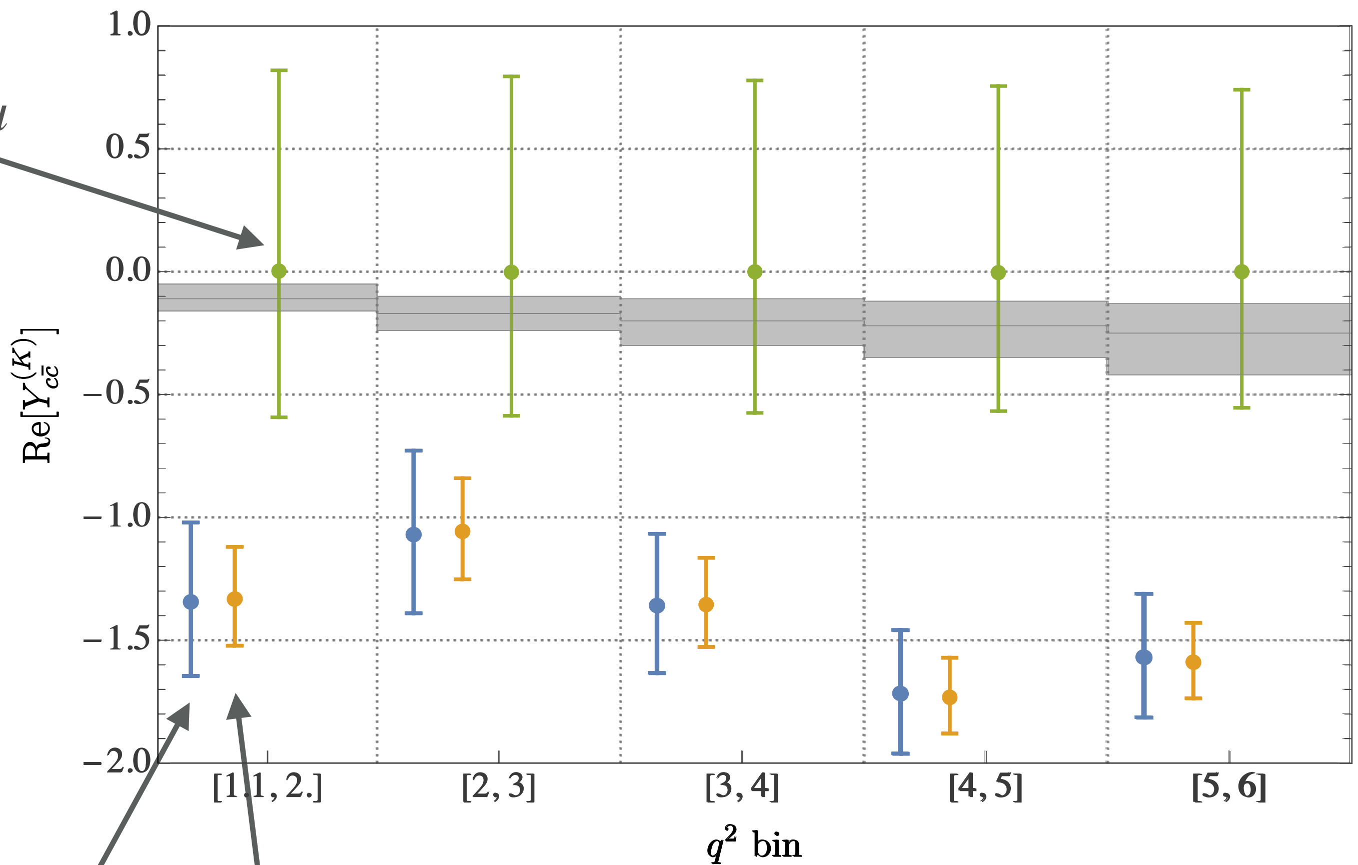
$$\mathrm{Br}(B \to \pi\mu\mu) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$
$$A_{\rm CP}(B \to \pi\mu\mu) = (-0.11 \pm 0.12 \pm 0.01)$$

LHCb, 1509.00414

ADDING $B \to \pi\mu\mu$ PROJECTION

local form factors by Gubernari et al., 2305.06301, D. Leljak et al, 2102.07233

adding $B \to \pi\mu\mu$ with 20% exp. error



Khodjamirian, Mannel, Wang, 1211.0234

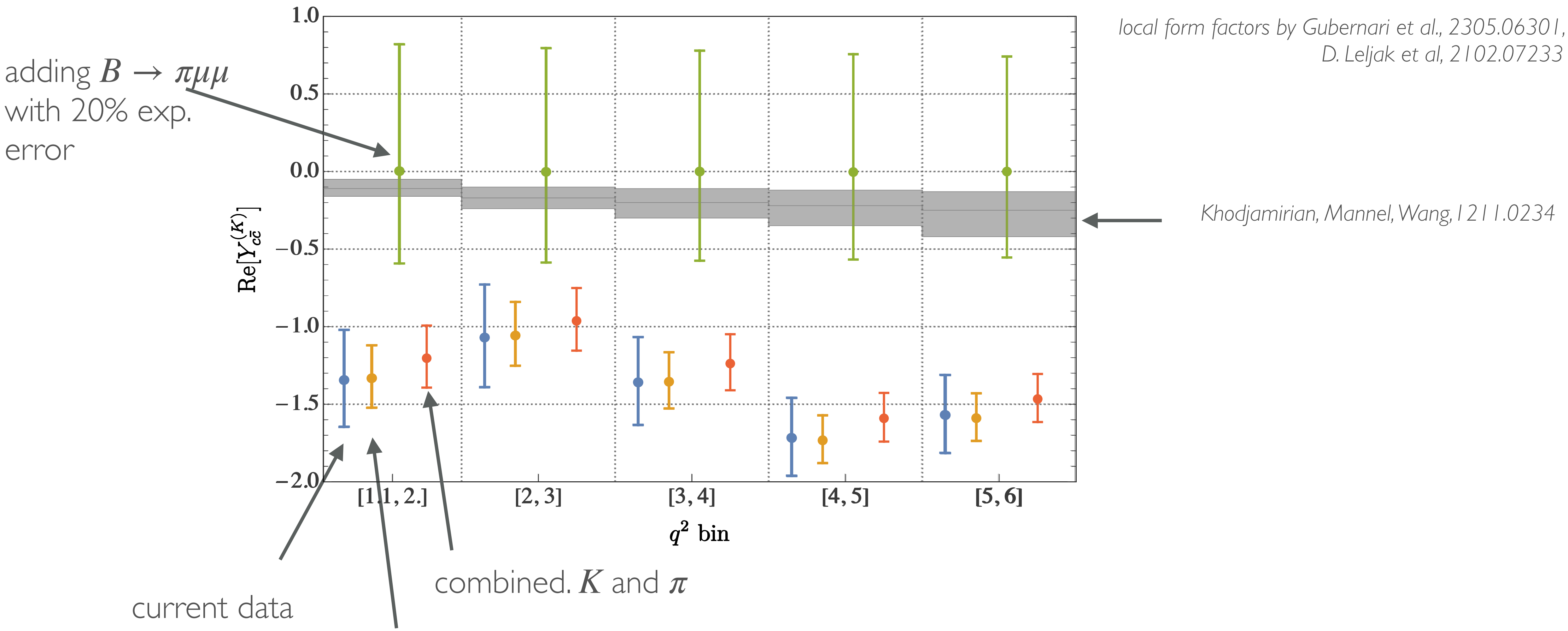
current data

reduced exp. error

Assuming U-spin relation $\mathrm{Re}Y_{c\bar{c}}^{(K)} = (1 \pm 0.3)\,\mathrm{Re}Y_{c\bar{c}}^{(\pi)}$

Kamenik, NK, Novoa-Brunet, 2403.13056

ADDING $B \to \pi\mu\mu$ PROJECTION



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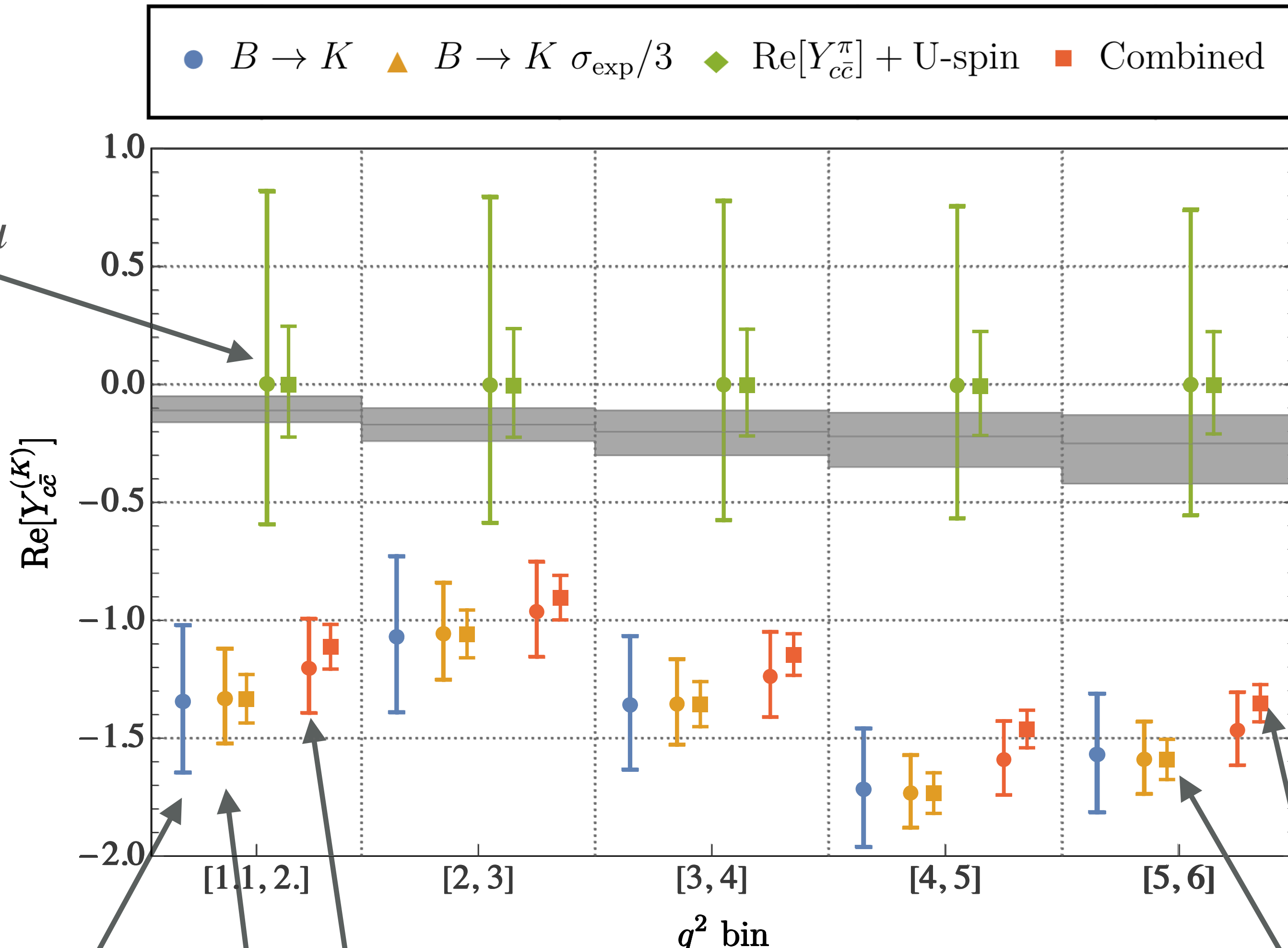
Kamenik, NK, Novoa-Brunet, 2403.13056

ADDING $B \to \pi\mu\mu$ PROJECTION

adding $B \to \pi\mu\mu$ with 20% exp. error



local form factors by Gubernari et al., 2305.06301, D. Leljak et al, 2102.07233

Khodjamirian, Mannel, Wang, 1211.0234

current data

reduced exp. error

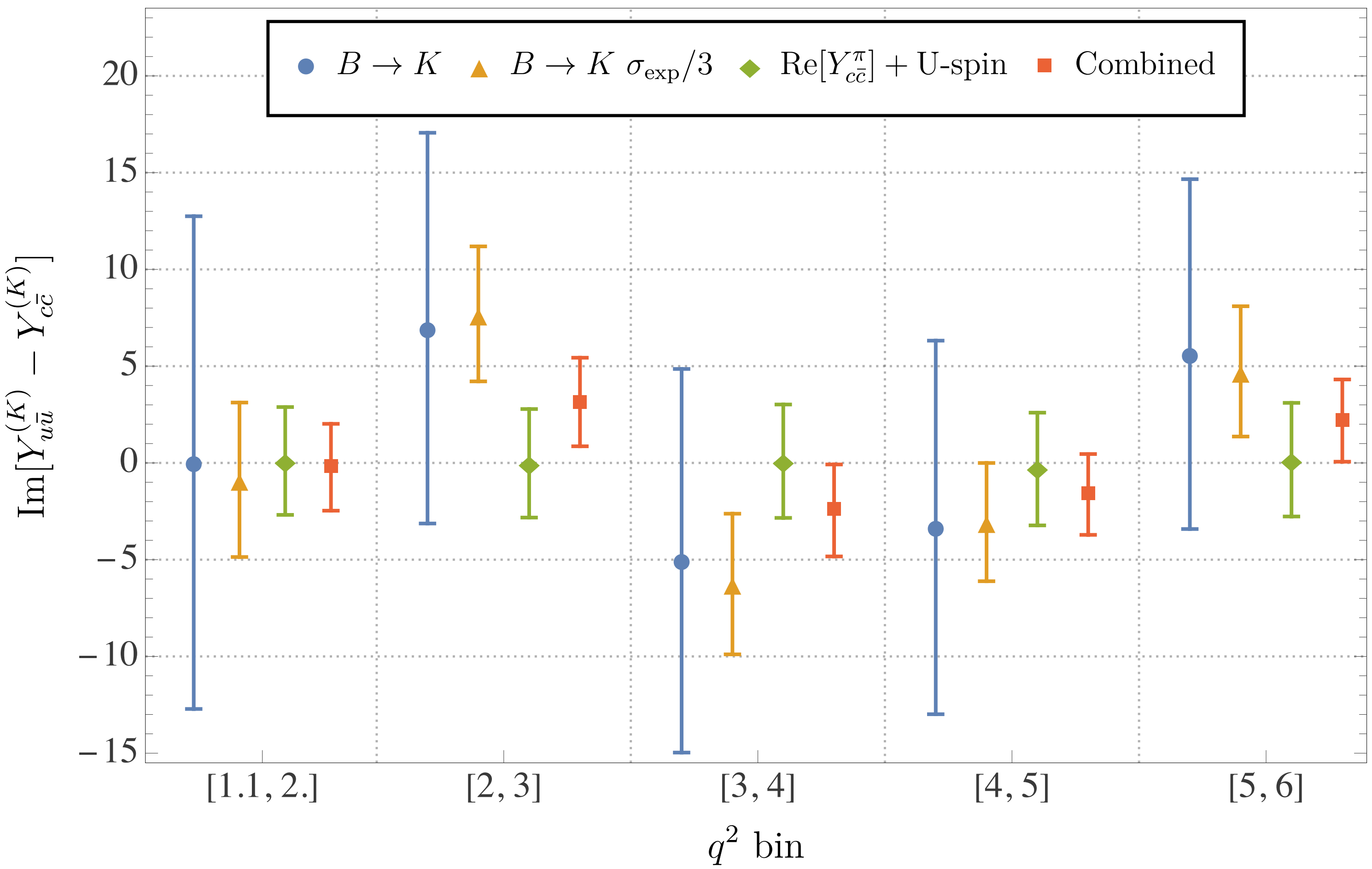
combined. K and π

reduced th. error

Assuming U-spin relation $\text{Re}Y_{c\bar{c}}^{(K)} = (1 \pm 0.3)\,\text{Re}Y_{c\bar{c}}^{(\pi)}$

Kamenik, NK, Novoa-Brunet, 2403.13056

CONSTRAINTS FROM A_{CP}



- Only the combined $B \to K\mu\mu$ and $B \to \pi\mu\mu$ give a reasonable bound.
- Caveat: omitted quadratic terms in $Y_{q\bar{q}}$.

$B^- \to K^-\ell\ell$ AND $B^- \to \pi^-\ell\ell$ CPV RATES

- Consider the ratio of CP-odd rates

$$R^{\mathrm{CP}}_{K/\pi} \equiv -\frac{(d\Gamma_K - d\Gamma_K)/dq^2}{(d\Gamma_\pi - d\bar{\Gamma}_\pi)/dq^2}$$

- CPV rates are comparable

$$R^{\mathrm{CP}}_{K/\pi}\big|_{\mathrm{SM}} = \underbrace{\left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2}\left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2}_{\text{known } U\text{-spin breaking}}\left[1 - \underbrace{\frac{\mathcal{C}_7^{\mathrm{SM}}(\tilde{f}_T^{(\pi)} - \tilde{f}_T^{(K)})}{\mathcal{C}_9^{\mathrm{SM}} + \mathcal{C}_7^{\mathrm{SM}}\tilde{f}_T^{(K)}}} - \epsilon_{uc}\right] = \mathcal{O}(1)$$

unknown U-spin breaking

CP-even quantity

- *U*nknown U-spin breaking parameter: $|\epsilon_{uc}| < 0.3$

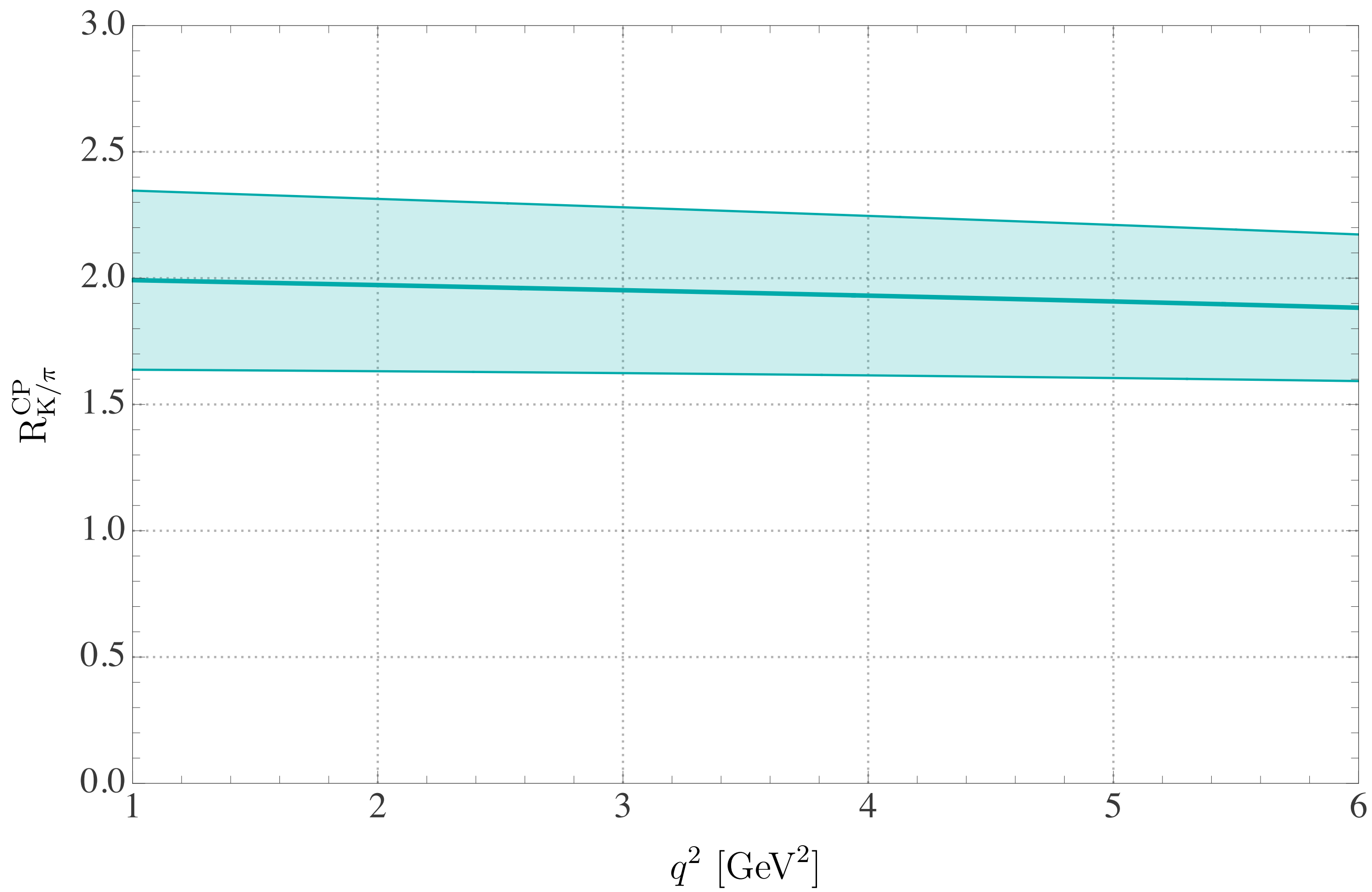
$$\mathrm{Im}\left(Y_{u\bar{u}}^{(\pi)} - Y_{c\bar{c}}^{(\pi)}\right) = (1+\epsilon_{uc})\,\mathrm{Im}\left(Y_{u\bar{u}}^{(K)} - Y_{c\bar{c}}^{(K)}\right)$$

- Experimental sanity check of U-spin breaking (at J/ψ peak):

$$\left|\frac{Y_{c\bar{c}}^{(K)}}{Y_{c\bar{c}}^{(\pi)}}\right|_{q^2=m_{J/\psi}^2} = \left|\frac{\lambda_c^{(d)}}{\lambda_c^{(s)}}\right|\sqrt{\frac{|\boldsymbol{k}_\pi|}{|\boldsymbol{k}_K|}\frac{\Gamma(B^+ \to J/\psi K^+)}{\Gamma(B^+ \to J/\psi\pi^+)}} = 1.2$$

U-SPIN RATIO

$$R^{\mathrm{CP}}_{K/\pi}|_{\mathrm{SM}} = \left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2}\left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2\left[1 - \frac{\mathcal{C}_7^{\mathrm{SM}}(\tilde{f}_T^{(\pi)} - \tilde{f}_T^{(K)})}{\mathcal{C}_9^{\mathrm{SM}} + \mathcal{C}_7^{\mathrm{SM}}\tilde{f}_T^{(K)}} - \cancel{\epsilon_{uc}}\right]$$



- $Y_{q\bar{q}}$ values cancel out
- Local quantity (modulo *U*-spin breaking)

- Accounts for known *U*-spin breaking (kinematics, form factors)
- Remains valid in the CP-conserving *U*-spin symmetric New Physics case ($\delta C_i^{(s)} = \delta C_i^{(d)}$)
- We need better *U*-spin breaking estimates.

U-SPIN RATIO AND NEW PHYSICS

- CP-conserving NP in $B \to K\ell\ell$: $C_{7,9}^{(s)} = C_{7,9}^{\rm SM} + \delta C_{7,9}^{(s)}$

$$R_{K/\pi}^{\rm CP}|_{\rm NP} = \left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2}\left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2\left[1 - \frac{\mathcal{C}_7^{\rm SM}(\tilde{f}_T^{(\pi)} - \tilde{f}_T^{(K)})}{\mathcal{C}_9^{\rm SM} + \mathcal{C}_7^{\rm SM}\tilde{f}_T^{(K)}} - \epsilon_{uc}\right] \times \left(1 + \frac{\delta\mathcal{C}_9^{(s)} + \delta\mathcal{C}_7^{(s)}\tilde{f}_T^{(K)}}{\mathcal{C}_9^{\rm SM} + \mathcal{C}_7^{\rm SM}\tilde{f}_T^{(K)}}\right)$$

- Ratio probes NP contribution without the value of $\mathrm{Re}Y_{c\bar{c}}$

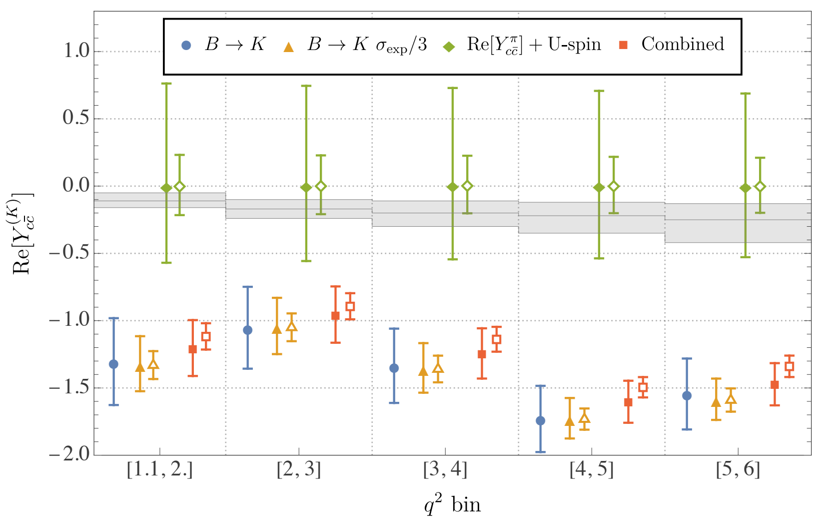
Sensitive observable if $\dfrac{\delta C_9}{C_9^{\rm SM}} \gtrsim \epsilon_{uc}$

- $R_{K/\pi}^{\rm CP}$ not suitable for CP-violating NP. For this case consider either direct CP closer to resonances, time dependent CP (see talk by Martín and Camille), or angular CP asymmetries in $B \to V\mu\mu$ (e.g. Altmannshofer, Stangl 2603.27753)

SUMMARY

- CKM structure enables extraction of non-local form factor $\mathbf{Re}Y_{c\bar{c}}(q^2)$ for $B^- \to K^-\ell\ell$ and $B^- \to \pi^-\ell\ell$.

- *U*-spin ratio of CP-odd rates is an indicator of validity of CKM mechanism. Provides orthogonal handle on CP-even New Physics. Estimate of U-spin breaking needed!



$$R^{\rm CP}_{K/\pi}|_{\rm NP} = \left(\frac{\lambda_K}{\lambda_\pi}\right)^{3/2}\left(\frac{f_+^{(K)}}{f_+^{(\pi)}}\right)^2\left[1 - \frac{\mathcal{C}_7^{\rm SM}(\tilde{f}_T^{(\pi)} - \tilde{f}_T^{(K)})}{\mathcal{C}_9^{\rm SM} + \mathcal{C}_7^{\rm SM}\tilde{f}_T^{(K)}} - \epsilon_{uc}\right] \times \left(1 + \frac{\delta\mathcal{C}_9^{(s)} + \delta\mathcal{C}_7^{(s)}\tilde{f}_T^{(K)}}{\mathcal{C}_9^{\rm SM} + \mathcal{C}_7^{\rm SM}\tilde{f}_T^{(K)}}\right)$$

- Benefits of common analysis of $B \to K\mu\mu$ and $B \to \pi\mu\mu$ is clear.

- Can we come up with realistic estimates of U-spin breaking?

$b \to d\ell\ell$ experimental

Michael McCann
On behalf of LHCb

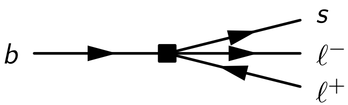
Imperial College London

17 April 2026

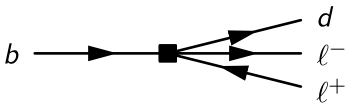
Beyond Flavour Anomalies,
Santiago de Compostela

$b \to d\ell^-\ell^+$ experimentally

Superficially identical to $b \to s\ell^-\ell^+$

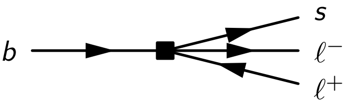


$\Rightarrow$



$b \to d\ell^-\ell^+$ experimentally

Superficially identical to $b \to s\ell^-\ell^+$



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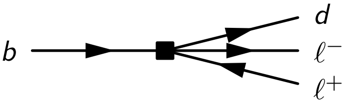

Good measurements of $b \to s\ell\ell$ processes

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

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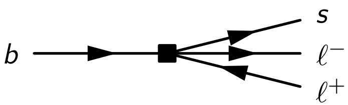

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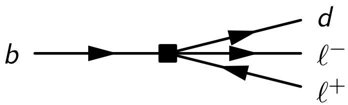

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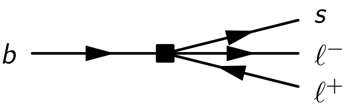

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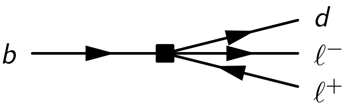

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Surely experimentally “easy” too ???

The joys of down quarks

Expect SM suppression $\left|\frac{V_{td}}{V_{ts}}\right|^2 \sim 0.04$

- $\sim 25\times$ less signal than $b \to s\ell\ell$ modes
  - Correspondingly lower statistical precision

but also. . .

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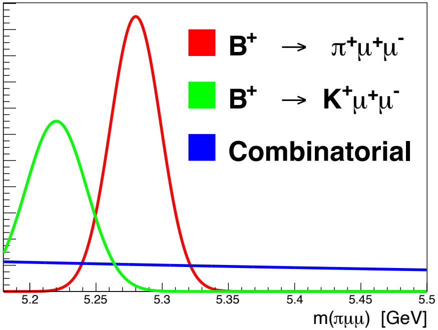
Looking at $B^+ \to \pi^+\mu\mu$ as an example ...

Dealing with the kaons

After (excellent) PID selections



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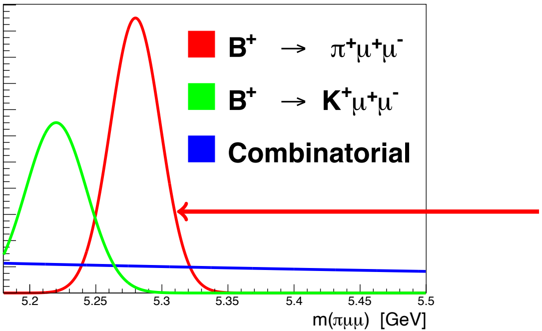
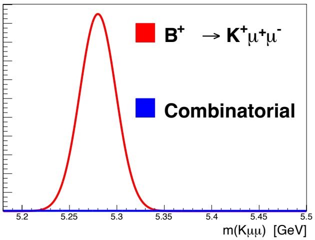
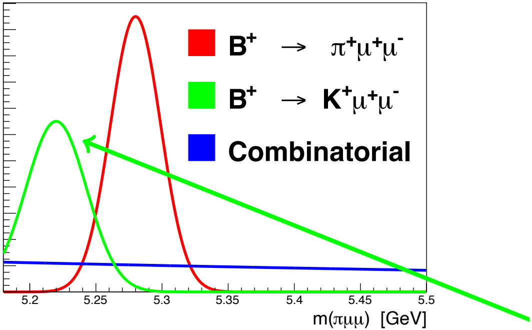


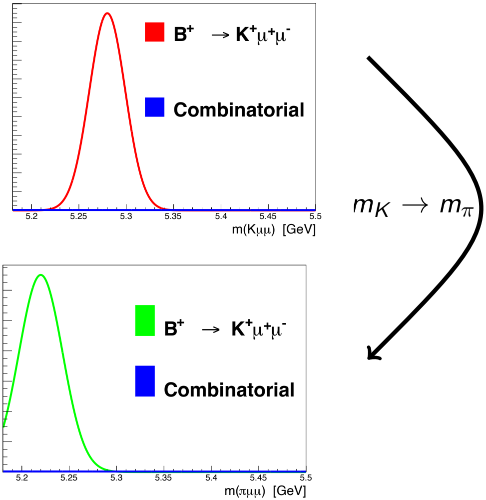


- Select kaon mode tightly (very clean)
  - Gives signal shape
  - Corrected for K/π resolution difference

Dealing with the kaons

After (excellent) PID selections





- Reconstruct kaon as pion
  - Gives misID shape and yield
  - Corrected for K vs π selection

Dealing with the hadrons

- hadron $\rightarrow$ muon misID is a bit trickier than hadron $\rightarrow$ hadron
  - Decays-in-flight and non-fully-contained hadronic showers
  - Not necessarily described at level required using well reconstructed calibration samples

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- hadron $\rightarrow$ muon misID is a bit trickier than hadron $\rightarrow$ hadron
  - Decays-in-flight and non-fully-contained hadronic showers
  - Not necessarily described at level required using well reconstructed calibration samples
- Need to consider backgrounds from $B \rightarrow \pi\pi\pi$, $\pi\pi K$, πKK, KKK
- Once again can use data driven approach

	h_1 looks like π	h_2 looks like μ	h_3 looks like μ
Fit 3-particle states in $\pi\mu\mu$ mass	✓	X	X
	✓	X	✓
	✓	✓	X
Compute:	✓	✓	✓

- Correct for potential correlations using $D^0 \rightarrow K\pi$ and $K_S \rightarrow \pi\pi$ samples

Things coming "soon"

Three $B^+ \to \pi^+ \ell\ell$ analyses with Run1+Run2 data sets

- Branching fraction of $B^+ \to \pi^+ e^+ e^-$
  - High and low wide bins in q^2

- Angular analysis of $B^+ \to \pi^+ \mu^+ \mu^-$
  - High and low wide bins in q^2
  - A_{FB} and F_H

- Differential branching fraction and CP asymmetry of $B^+ \to \pi^+ \mu^+ \mu^-$
  - 2 GeV^2 wide q^2 bins
  - Simultaneous measurement of $\mathcal{B}(B^+ \to \pi^+ \mu\mu)$, A_{CP} and $\frac{\mathcal{B}(B \to \pi\mu\mu)}{\mathcal{B}(B \to K\mu\mu)}$

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Preliminary

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Not here (soz)

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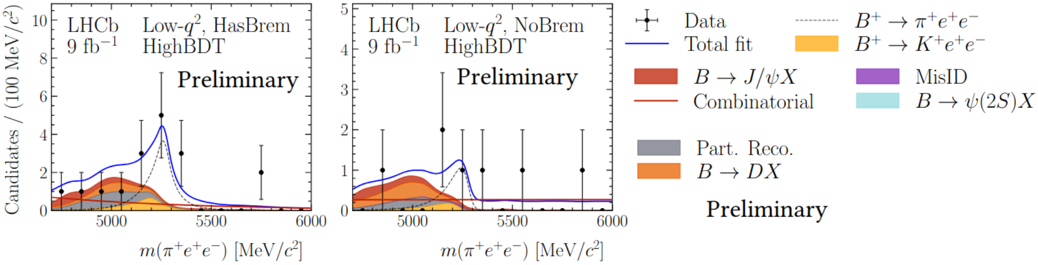
  - Simultaneous measurement of $\mathcal{B}(B^+ \to \pi^+ \mu\mu)$, A_{CP} and $\frac{\mathcal{B}(B \to \pi\mu\mu)}{\mathcal{B}(B \to K\mu\mu)}$
- Honourable mention: Search for $B^+ \to \pi^+ \mu^\pm e^\mp$
  - $BF(B^+ \to \pi^+ \mu^\pm e^\mp) < 1.8 \times 10^{-9}$ at 90% [arXiv:2604.08396]

$B^+ \to \pi^+ e^+ e^-$ Preliminary [LHCb-PAPER-2025-50 in preparation]

Simultaneous fit to BDT and Bremsstrahlung photon categories



$$\mathcal{B}(B^+ \to \pi^+ e^+ e^-)^{[0.045<q^2<6.000\mathrm{GeV}^2]} = (0.76^{+0.30+0.14}_{-0.27-0.08}) \times 10^{-8}$$

$$\mathcal{B}(B^+ \to \pi^+ e^+ e^-)^{[15<q^2<25\mathrm{GeV}^2]} = (0.40^{+0.52+0.24}_{-0.45-0.22}) \times 10^{-8}$$

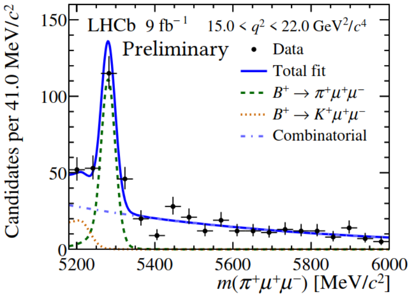
$$\boxed{\mathcal{B}(B^+ \to \pi^+ e^+ e^-) = (2.4^{+0.9+0.4}_{-0.8-0.2}) \times 10^{-8}}$$

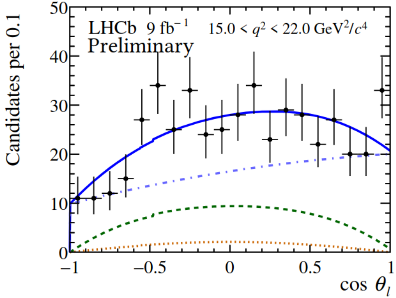
- Total (and low q^2 bin) at 3.2σ signal significance
  - First evidence for this decay

Angular $B^+ \to \pi^+\mu^+\mu^-$ Preliminary [LHCb-PAPER-2026-15 in prep.]

- Angular distribution in $1.1 < q^2 < 6.0\,\mathrm{GeV}^2$ and $15 < q^2 < 22\,\mathrm{GeV}^2$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_\ell} = \frac{3}{4}(1-F_H))(1-\cos^2\theta_\ell) + \frac{1}{2}F_H + A_{\mathrm{FB}}\cos\theta_\ell$$





To be on arXiv imminently

Things on the horizon

Same again with Run 3

- Still stats dominated, so anticipate considerable improvements
- Finer binning should be possible

What else can we do?

- Unbinned analysis of $B^+ \to \pi^+\mu^+\mu^-$ – pion equivalent of kaon analyses (see Zak's talk for kaon mode for example)
  - As discussed in Phys. Rev. D 109, 116013 (Marshall, McCann, Patel, Petridis, Reboud, van Dyk)
  - Constraints from $-$ve q^2
  - With Run 1+2 can't float everything suspect $|C_9|$ and $\arg(C_9)$
  - Can apply constraint to C_{10}
  - Likely restrict q^2 below open charm region

- Thoughts about extracting $B_s^0 \to \overline{K}^{*0}\mu\mu$ angular observables

Conclusions

- Lots of interesting $b \to d\ell\ell$ results in the process of dropping
- With the upgrade data set, can really push the resolution on these modes
- Any other interesting measurements to make here?