CP-ODD OBSERVABLES IN $B \to P\ell^-\ell^+$

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INTRODUCTION

Flavor in the SM

$$\mathcal{L}_{\rm SM} = \underbrace{|D_\mu H|^2 + \mu^2|H|^2 - \lambda|H|^4 + \sum_f \bar{f} i \not{D} f - \frac{1}{4}\sum_X {\rm tr}(X_{\mu\nu}X^{\mu\nu})}_{\text{flavor blind/symmetric}} + \underbrace{\mathcal{L}_{\rm Yuk}}_{\text{fla}\!\!\!/\text{vor}}$$

global
$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$

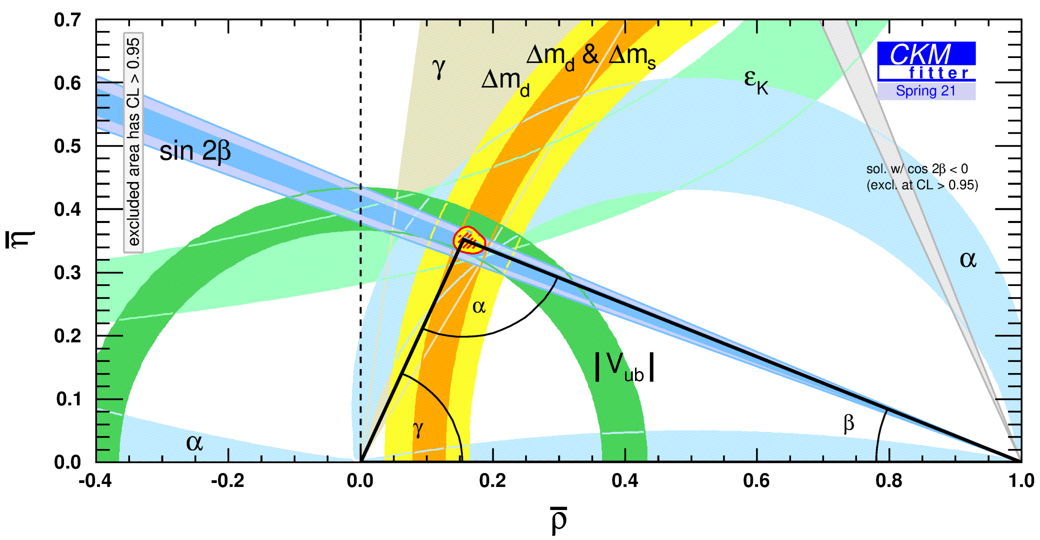
Higgs Yukawa couplings distinguish generations.

$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$

- 13 parameters of the SM Yukawa sector: 9 masses, 3 mixing angles, 1 CP phase
- SM effective theory predicts $\sim 10^3$ additional flavour breaking parameters

SM(EFT) FLAVOUR

$$\mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i C_i Q_i$$



1 CPV + 18 CP even parameters

$$\det(i[M_d, M_u]) = J(m_t - m_c)(m_t - m_u)\ldots$$

$$J \approx 3\times 10^{-5}$$ *Jarlskog '85*

	$(\bar L L)(\bar L L)$
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$\cdots$

At dim-6:

- 1149 CPV + 1350 CP even flavor couplings

  Grzadkowski et al '10
  Alonso et al '13

- 699 Jarlskog-like invariants

  Bonnefoy et al. '21

RARE SEMILEPTONIC *B*-DECAYS

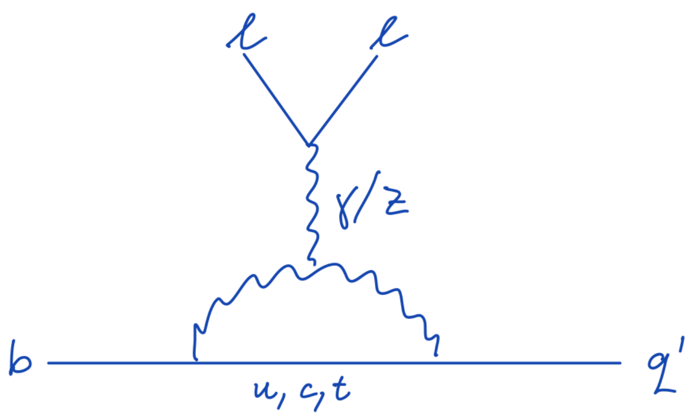
- Rare semileptonic *B*-meson decays are excellent probes of (B)SM flavour structure

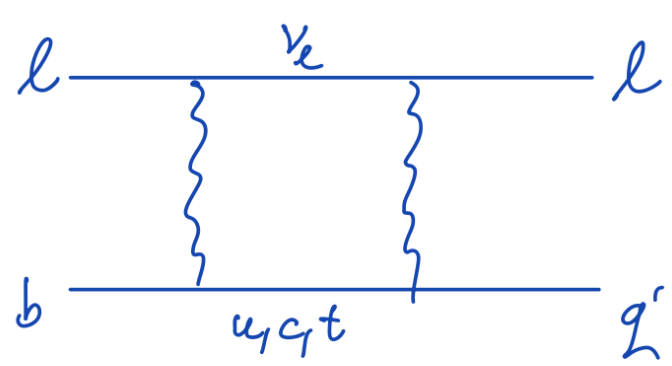
$$B \to K\ell^+\ell^- \qquad B \to \pi\ell^+\ell^-$$

- At short distances SM amplitudes are severely suppressed

$$\mathcal{A}_{\rm SM} \sim \frac{g^4 V_{tb}V_{ts}^*}{(4\pi)^2}\,\frac{m_t^2}{v^2}$$

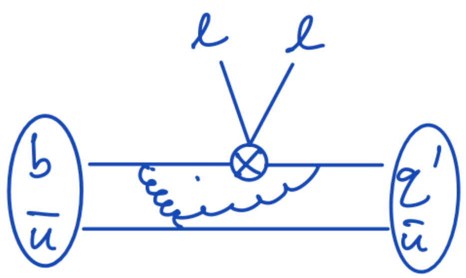
- CKM suppression (GIM suppression broken by m_t)
- Loop suppression



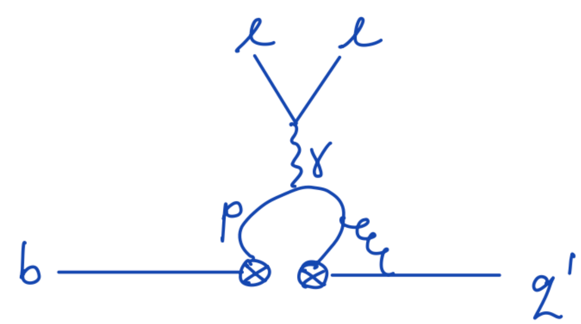


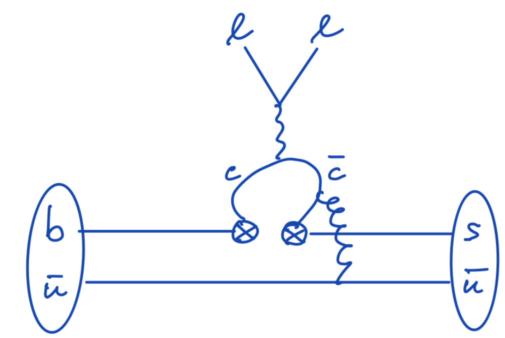
RARE SEMILEPTONIC *B*-DECAYS

- Effects of QCD obstruct the view at scale m_B



local form factors -
single current insertion





non-local (non)-factorisable QCD effects

- Can we disentangle the effects of long-distance QCD from short distance SM and potential NP contributions ?

- 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

see talk by Eluned

OUTLINE

- CP-even and CP-odd parts of $B \to P\ell^+\ell^-$ spectra

- Use experimental data to:
  - ✳ extract non-local amplitudes from data (assuming SM)
  - ✳ relation between CP-odd $B^- \to \pi^-\ell^+\ell^-$ and $B^- \to K^-\ell^+\ell^-$

- Direct CPV in $B \to K\ell^+\ell^-$, enhanced by narrow charmonium resonance (J/ψ)

CP-EVEN/ODD RATES

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

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

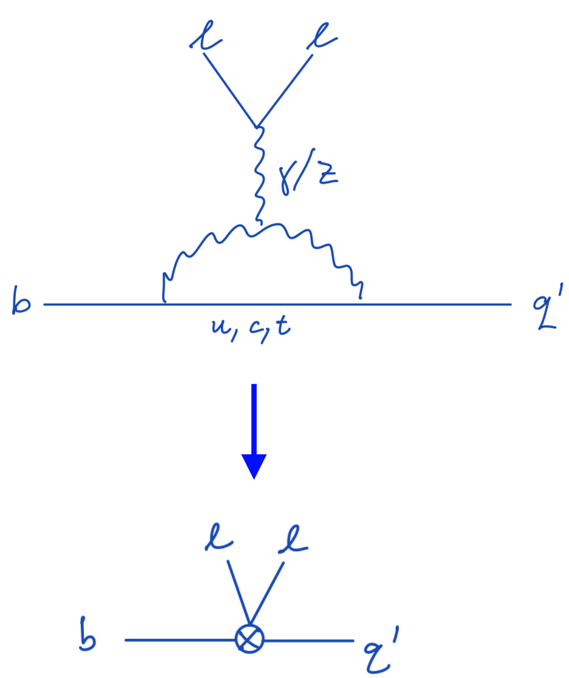
$$\lambda_p^{(q')} = V_{pb} V_{pq'}{}^*$$

semileptonic operators

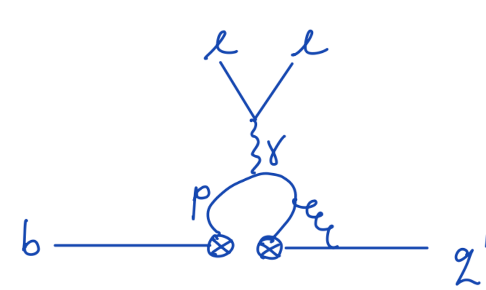
$$\mathcal{O}_7^{(q')} = \frac{e m_b}{(4\pi)^2} \bar{q}'_L \sigma_{\mu\nu} b_R F^{\mu\nu}$$
$$\mathcal{O}_9^{(q')} = \frac{\alpha}{4\pi} (\bar{q}'_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$
$$\mathcal{O}_{10}^{(q')} = \frac{\alpha}{4\pi} (\bar{q}'_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma^5 \ell)$$

hadronic 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

(NON)LOCAL AMPLITUDE

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

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

$f_+^{(P)}(q^2)$ = vector form factor

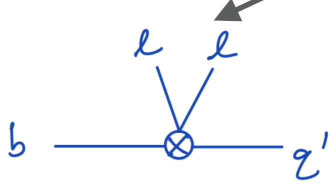
$$\mathcal{N}_P = \frac{G_F^2 \alpha^2 |\lambda_t^{(q')}|^2}{3 \cdot 512 \pi^5 m_B^3} \lambda_P^{3/2}(q^2)$$

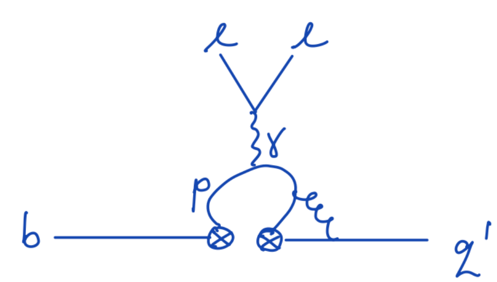
$$\tilde{f}_T^{(P)} \equiv \frac{2 f_T^{(P)}(q^2)(m_b + m_{q'})}{f_+^{(P)}(q^2)(m_B + m_P)}$$

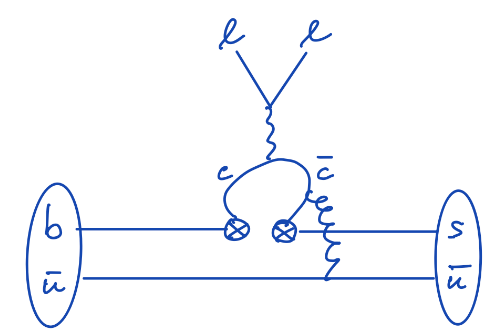
- All long-distance effects can be absorbed in $\mathcal{C}_9^{\rm eff}(q^2)$

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

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







- local form factors
  Gubernari et al., 2305.06301

$$f_+^{(P)} Y_{p\bar{p}}(q^2) \equiv \frac{(8\pi)^2 Q_p}{\lambda_P(q^2)} \int d^4x \, e^{iq\cdot x} \langle P(k)| \mathcal{T}\left\{\bar{p}\not{k}p(x), \sum_{i=1,2} \mathcal{C}_i \mathcal{O}_{i,p}^{(q')}(0)\right\} |\overline{B}(q+k)\rangle$$

Khodjamirian, Mannel, Wang, 1211.0234

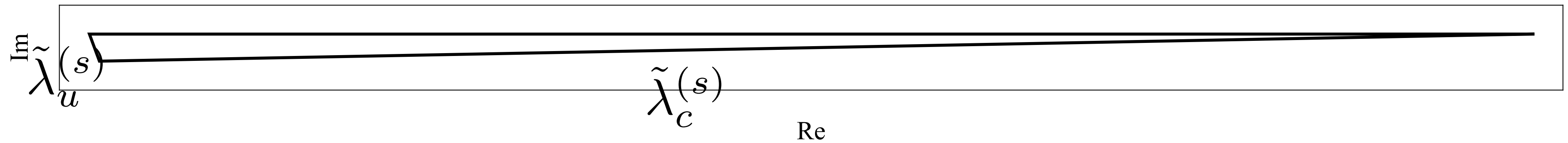
Assumptions

- $m_\ell = 0$
- real local coefficients $\mathcal{C}_7, \mathcal{C}_9, \mathcal{C}_{10}$
- with SM values $\mathcal{C}_7^{\rm SM} = -0.292\,,\ \mathcal{C}_9^{\rm SM} = 4.07\,,\ \mathcal{C}_{10}^{\rm SM} = -4.31$
- complex valued $Y_{q\bar{q}}$, independent in each bin

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

- In CP-even rate quirky CKM hierarchy selects the charm quark non-local contribution

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



$< 2\,\%$ effect

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

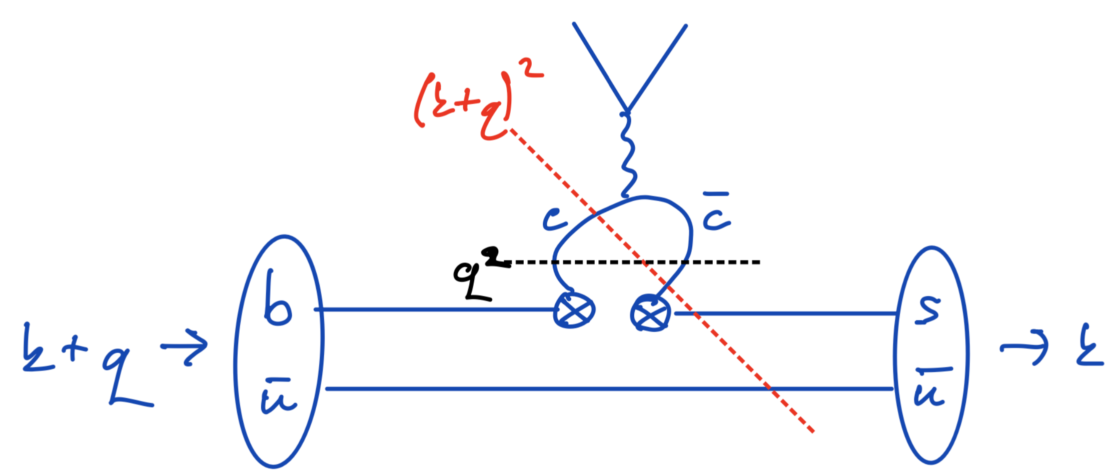
Kamenik, NK, Novoa-Brunet, 2403.13056

- CP-odd rate proportional to $\mathrm{Im}\tilde\lambda_c^{(s)} = -\,\mathrm{Im}\tilde\lambda_u^{(s)}$, both $u\bar u$ and $c\bar c$ contribute

$$\frac{d\Gamma_K - d\bar\Gamma_K}{dq^2} = 4\mathcal{N}_K \left(f_+^{(K)}\right)^2 \eta\lambda^2 \left[\left(\mathcal{C}_9 + \tilde f_T^{(K)}\mathcal{C}_7\right)\mathrm{Im}(Y_{u\bar u} - Y_{c\bar c}) - \mathrm{Im}(Y_{c\bar c}Y_{u\bar u}^*)\right]$$

$< 30\,\%$ effect

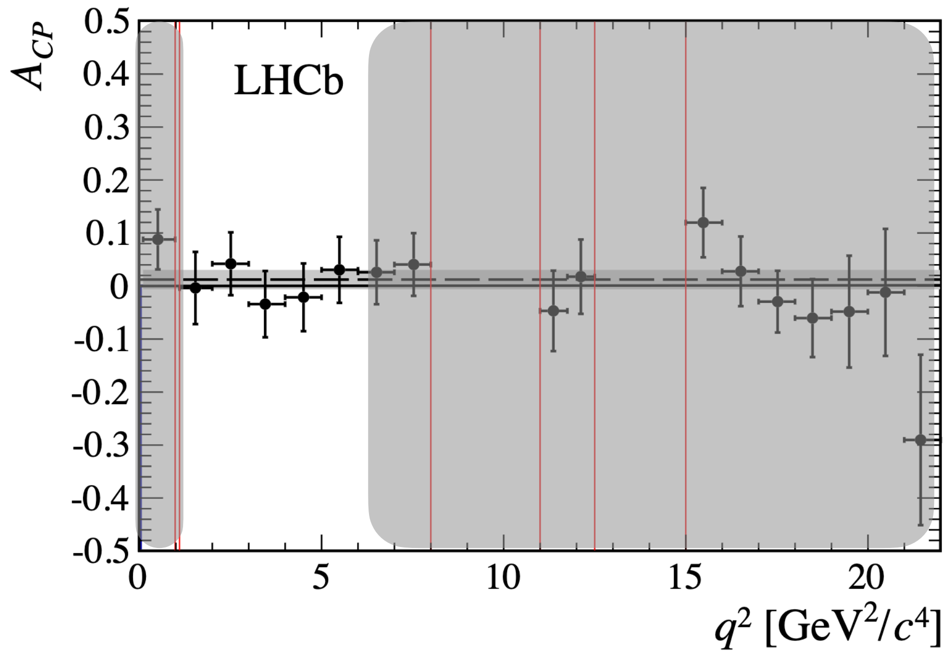
- Analytic structure implies complex $Y_{q\bar q}$ - due to cuts in q^2 and $(k+q)^2$



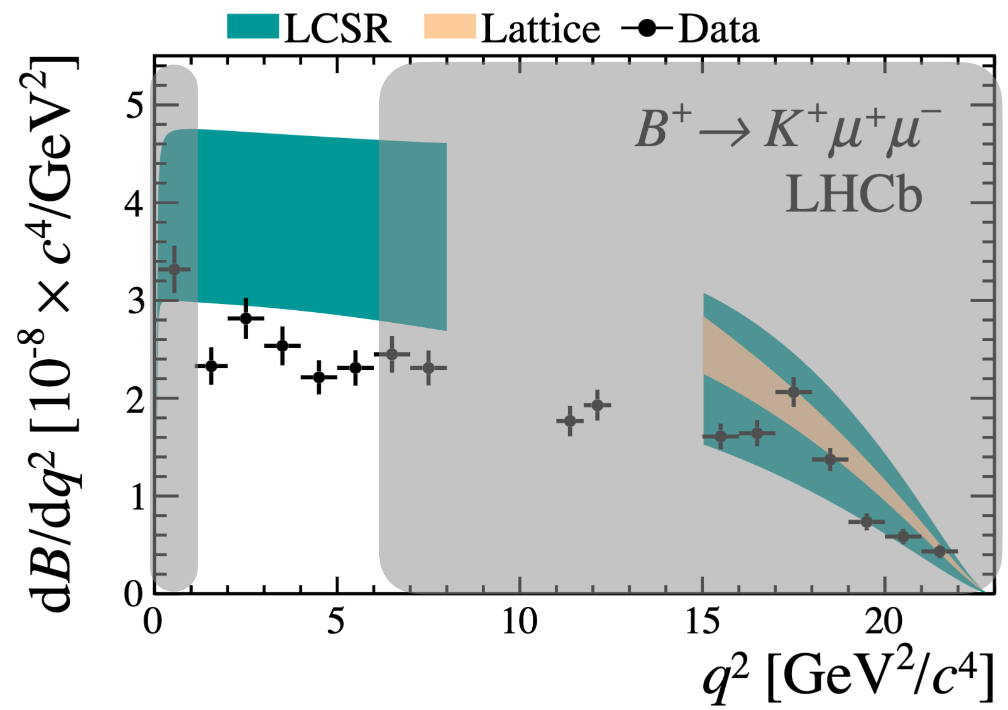
Khodjamirian, Mannel, Wang, 1211.0234
Asatrian, Greub, Virto, 1912.09099

DATA DRIVEN APPROACH

- Consider binned CP-averaged rates and CP-asymmetries



LHCb, 1408.0978

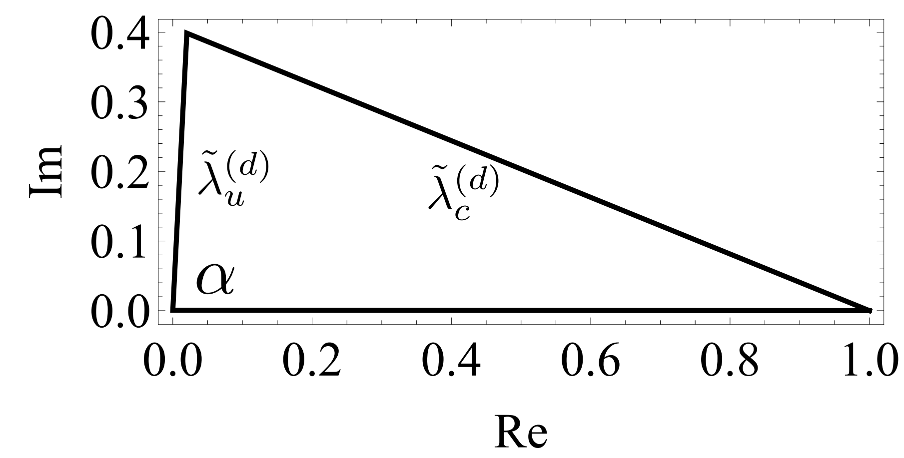


LHCb, 1403.8044

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

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

- 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

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

Hambrock, Khodjamirian, Rusov, 1506.07760

- CP-odd rate is large

$$\frac{d\Gamma_\pi - d\bar{\Gamma}_\pi}{dq^2} = 4\mathcal{N}_\pi \left(f_+^{(\pi)}\right)^2 \frac{(-\eta)}{(1-\rho)^2+\eta^2}\left[\left(\mathcal{C}_9 + \tilde{f}_T^{(\pi)}\mathcal{C}_7\right)\mathrm{Im}(Y_{u\bar{u}} - Y_{c\bar{c}}) - \mathrm{Im}(Y_{c\bar{c}}Y_{u\bar{u}}^*)\right]$$

< 30 % effect

- Note: $Y_{q\bar{q}} = Y_{q\bar{q}}^{(P)}$ and $Y_{q\bar{q}}^{(K)} \neq Y_{q\bar{q}}^{(\pi)}$

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

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

- Consider the ratio of CP-odd rates

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

Kamenik, NK, Novoa-Brunet, 2403.13056

Sensitive to U-spin breaking:

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

known U-spin breaking

subleading

unknown U-spin breaking

- Unknown U-spin breaking parameter: $\epsilon_{uc} < 0.3$

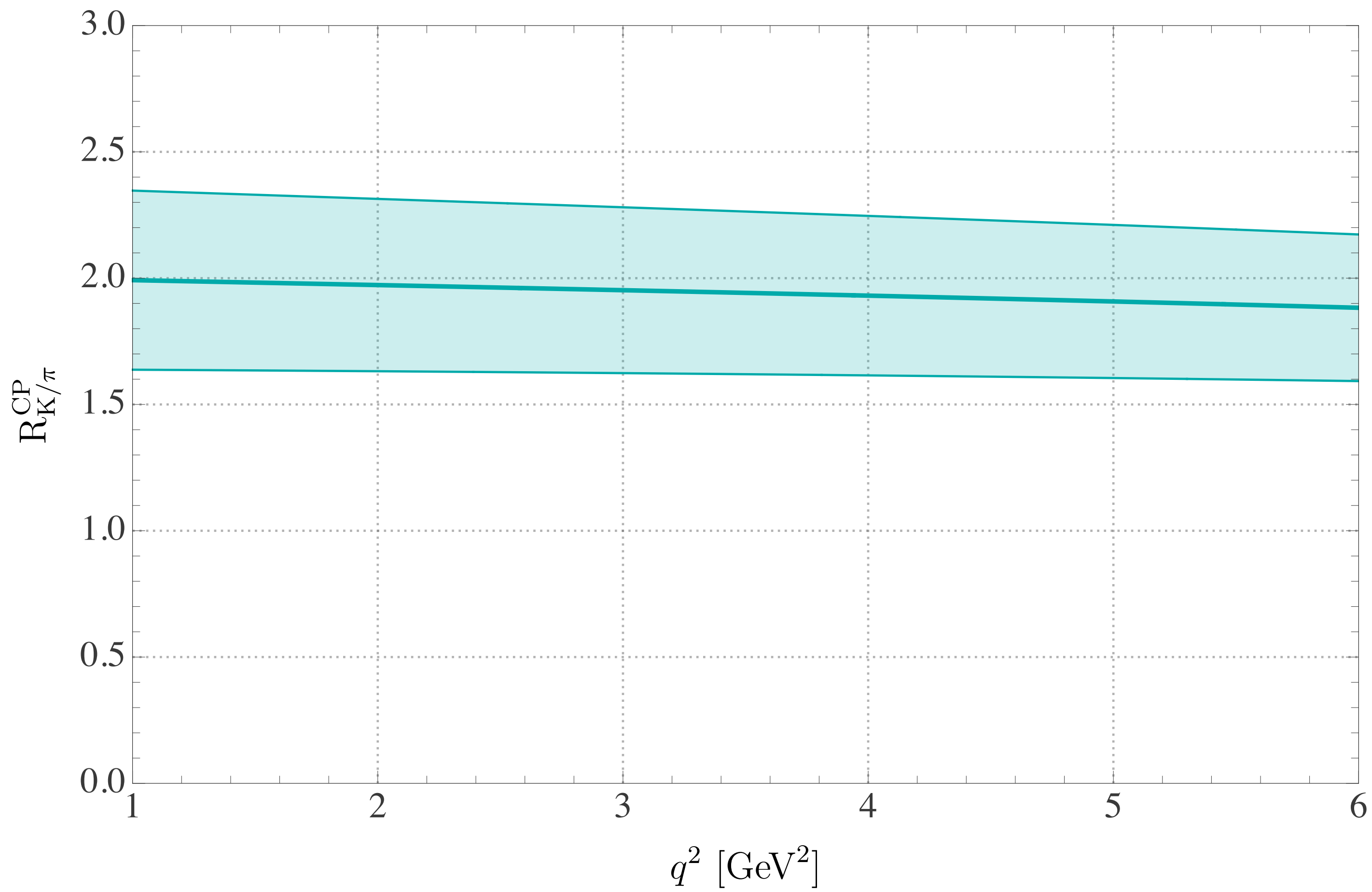
$$\mathrm{Im}\left(Y_{u\bar{u}}^{(\pi)} - Y_{c\bar{c}}^{(\pi)}\right) = (1 + \epsilon_{uc})\,\mathrm{Im}\left(Y_{u\bar{u}}^{(K)} - Y_{c\bar{c}}^{(K)}\right)$$

- Experimental check of U-spin:

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

U-SPIN RATIO

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

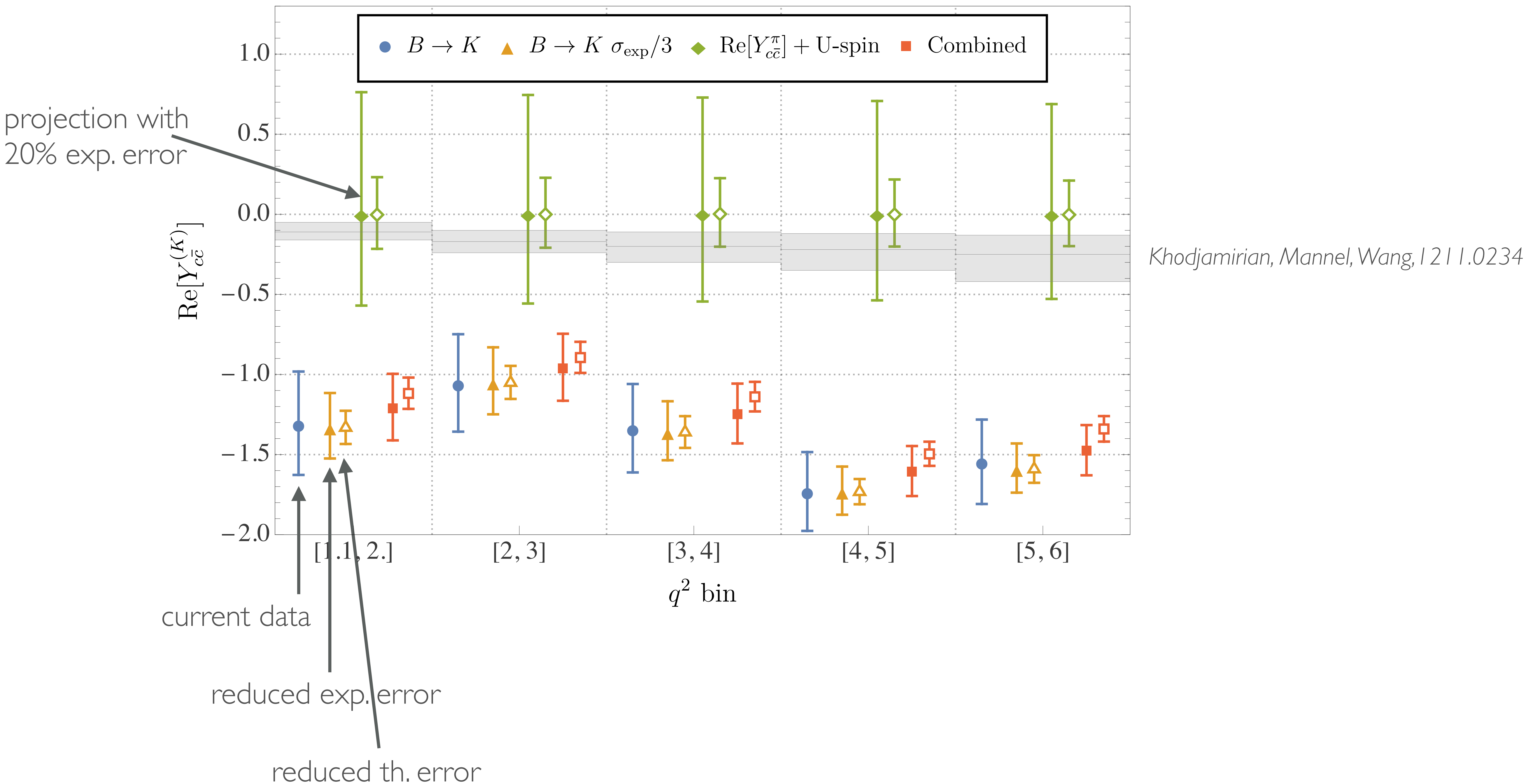


Independent of $Y_{q\bar{q}}$ values!

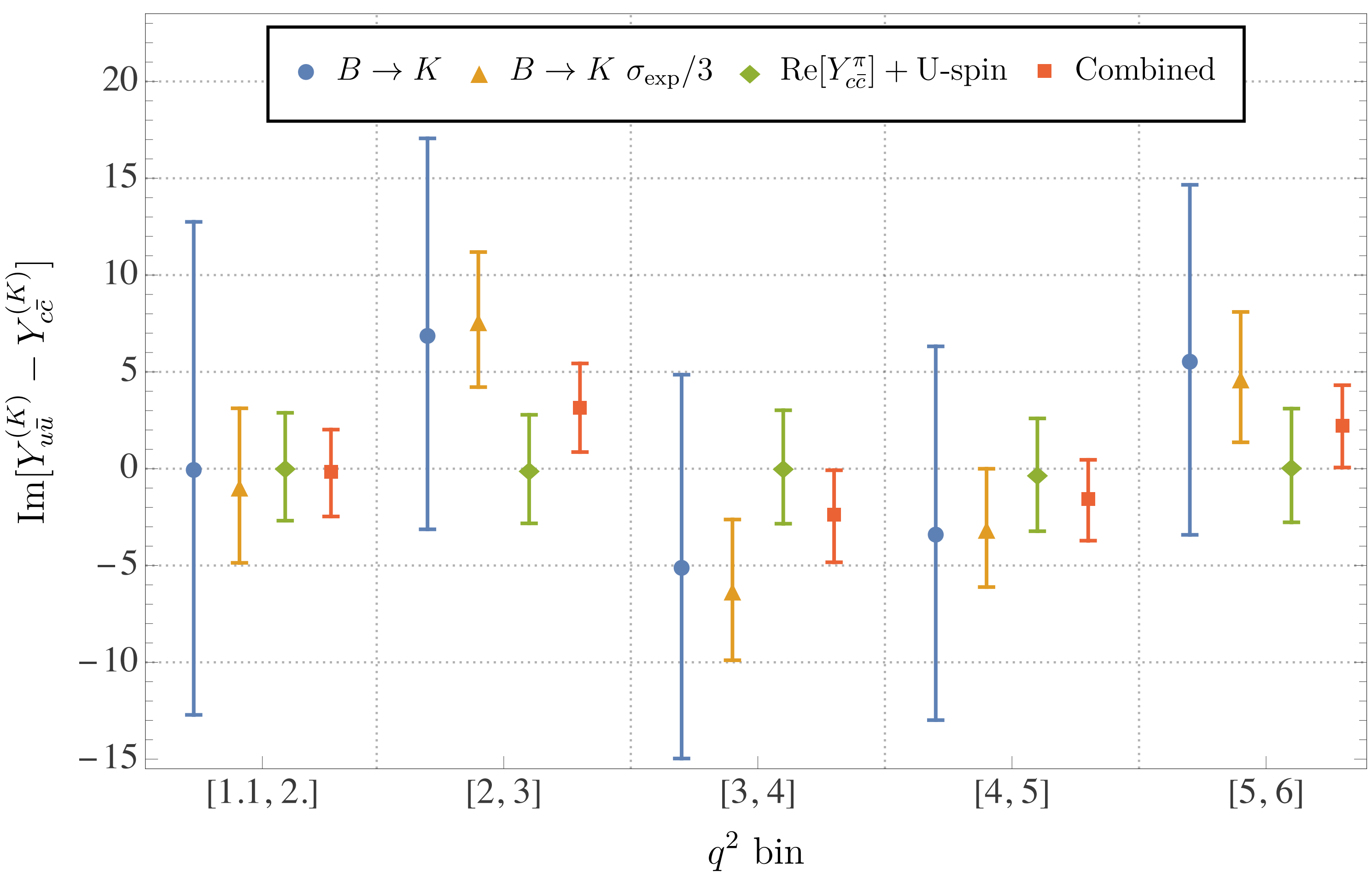
Accounts for known U-spin breaking

Remains valid in the CP-conserving U-spin symmetric New Physics case ($\delta C_i^{(s)} = \delta C_i^{(d)}$)

REAL PARTS OF NONLOCAL AMPS



IM. PARTS OF NONLOCAL AMPS



Caveat: omitted quadratic terms in $Y_{q\bar{q}}$

U-SPIN RATIO AND NEW PHYSICS

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

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

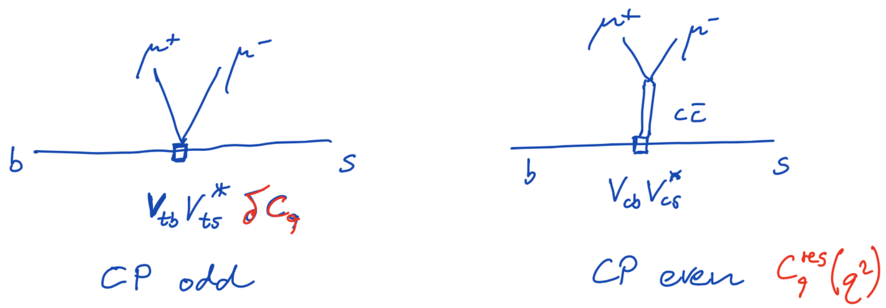
- Ratio probes CP-conserving contribution in orthogonal direction (relative to the CP-averaged rate)

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

$$\frac{(d\Gamma_K - d\bar{\Gamma}_K)_{\rm ImNP}}{(d\Gamma_K - d\bar{\Gamma}_K)_{\rm SM}} = -\frac{{\rm Im}\delta\mathcal{C}_9^{(s)}}{\eta\lambda^2} \times \frac{{\rm Im}Y_{c\bar{c}}^{(K)}}{(\mathcal{C}_9^{\rm SM} + \tilde{f}_T^{(K)}\mathcal{C}_7^{\rm SM})({\rm Im}Y_{c\bar{c}}^{(K)} - {\rm Im}Y_{u\bar{u}}^{(K)}) + {\rm Im}(Y_{c\bar{c}}^{(K)}Y_{u\bar{u}}^{(K)*})}$$

- CP-violating NP interferes with CP-even $c\bar{c}$ absorbtive amplitude. Additional U-spin breaking parameter makes $R_{K/\pi}^{\rm CP}$ less useful.

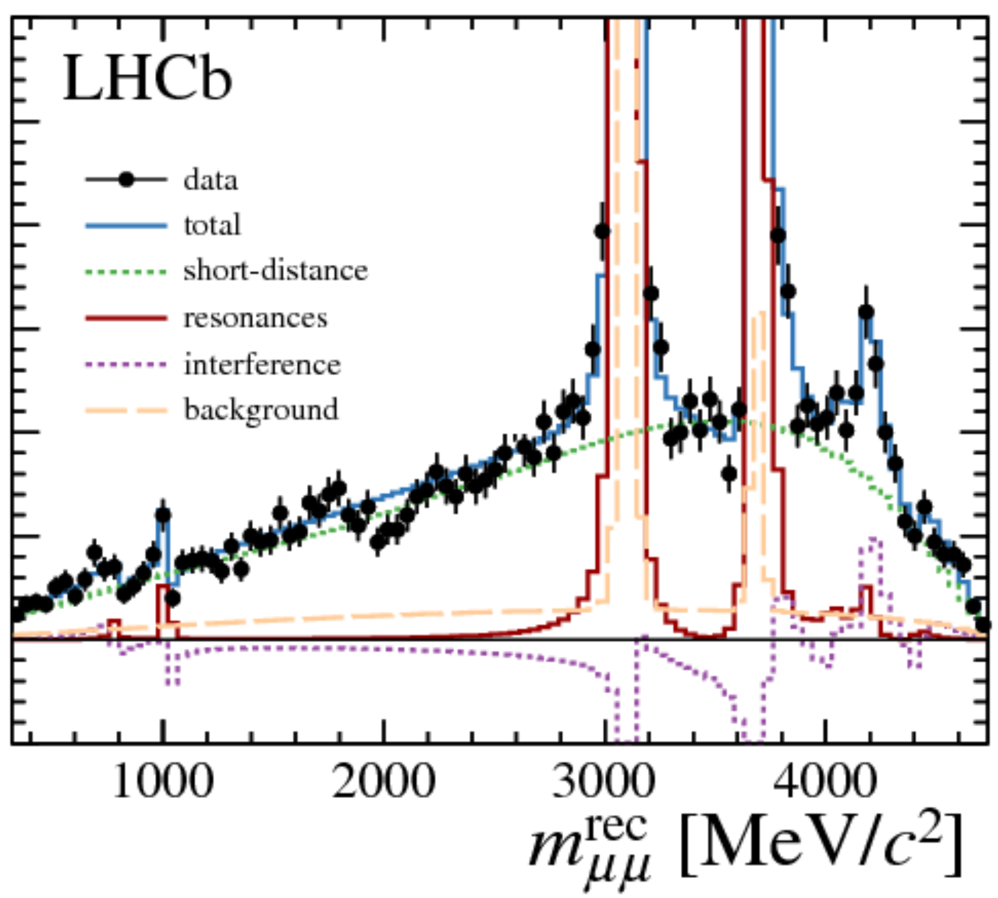
RESONANT STRONG PHASE



$\sim Y_{c\bar{c}}(q^2)$

$$C_9^{\rm res}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j}$$

δ_j : extract from CP-averaged non-blinded spectrum



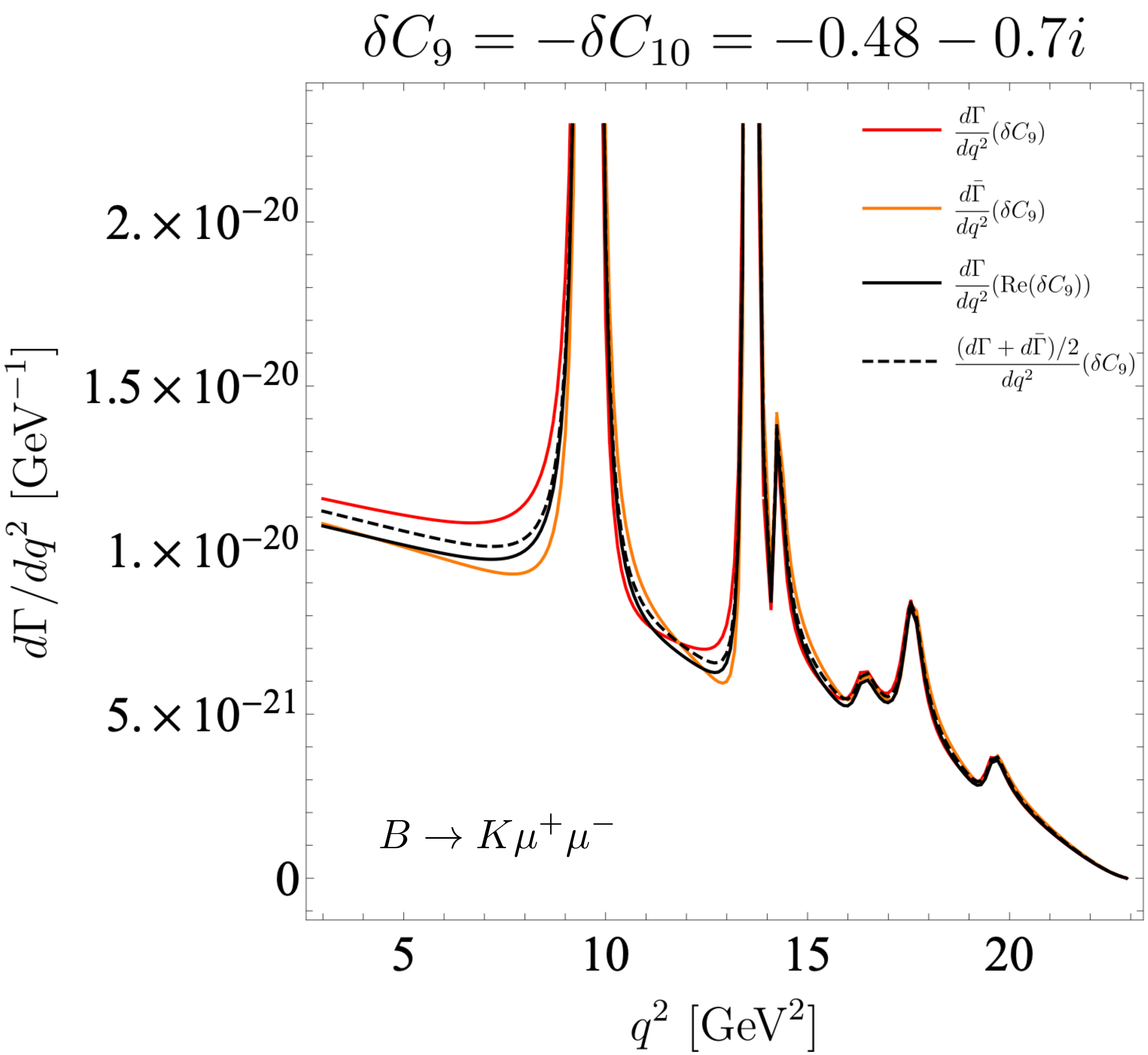
4-fold degeneracy of fit to the spectrum:

$$\begin{aligned} &\text{Branch 1:} \quad \delta_{J/\psi} = -1.66\,, \quad \delta_{\psi(2S)} = -1.93\,, \\ &\text{Branch 2:} \quad \delta_{J/\psi} = -1.50\,, \quad \delta_{\psi(2S)} = 2.08\,. \end{aligned}$$

Branch 3,4 ~ Branch 1,2

LHCb '16
see also Blake, Egede, Owen, Petridis, Pomery '17

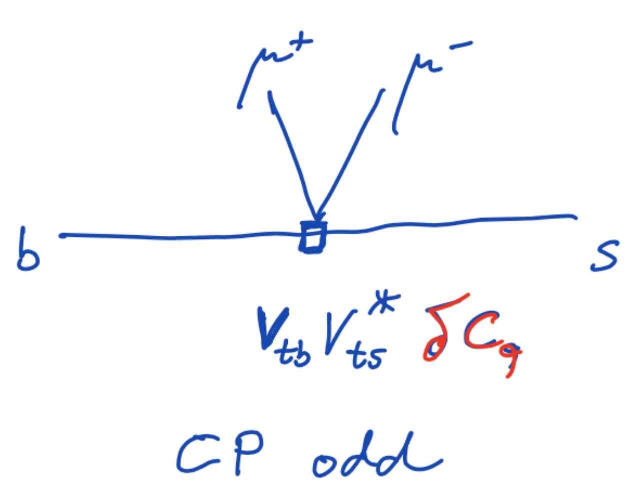
NO CP VS. CP-AVERAGE

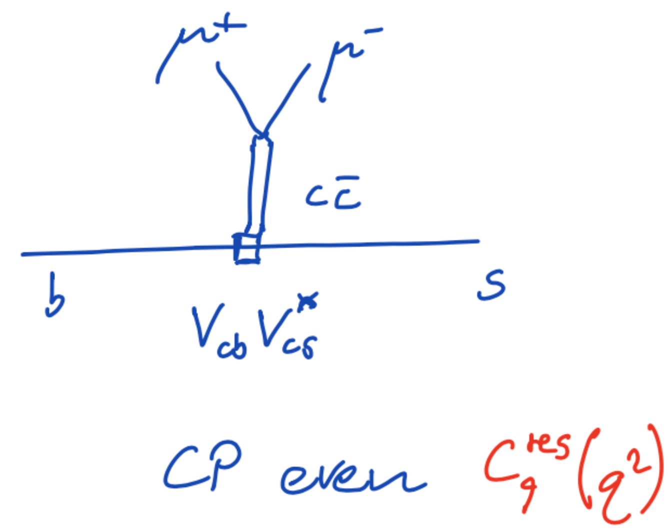


Resonant parameters taken from the LHCb fit to CP averaged rates.

CP-averaged fit is not sensitive to CPV phases

DIRECT ASYMMETRIES



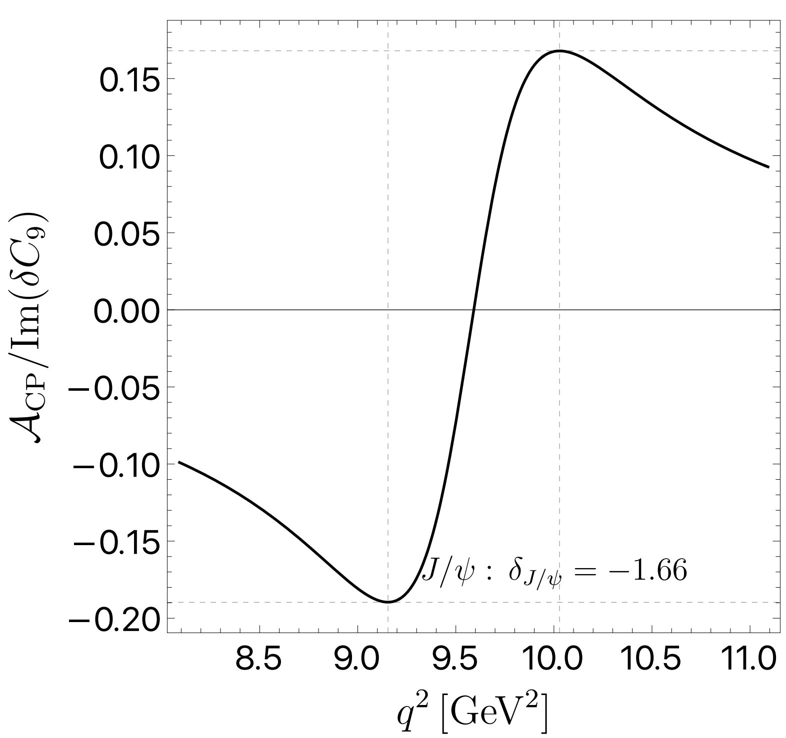


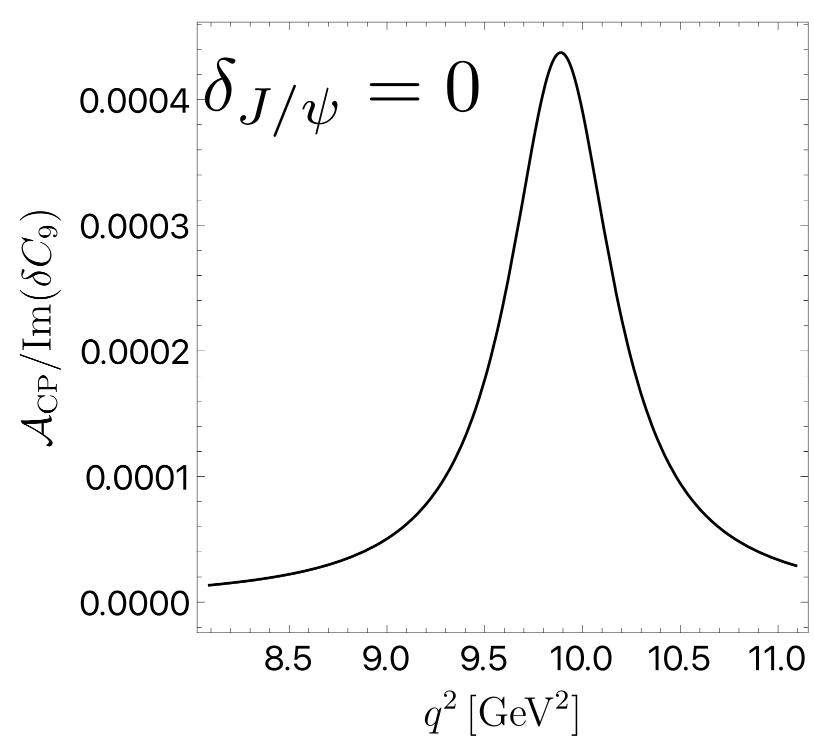
$$C_9^{\rm res}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j}$$

$$\mathcal{A}_{\rm CP} = {\rm Im}(\delta C_9)\, \frac{2\eta_j\left(\cos\delta_j - x\sin\delta_j\right)}{\eta_j^2 - 2\eta_j B\left[\sin\delta_j + x\cos\delta_j\right] + A\left[1+x^2\right]}$$

$$x \equiv (q^2 - m_j^2)/(m_j\Gamma_j)$$

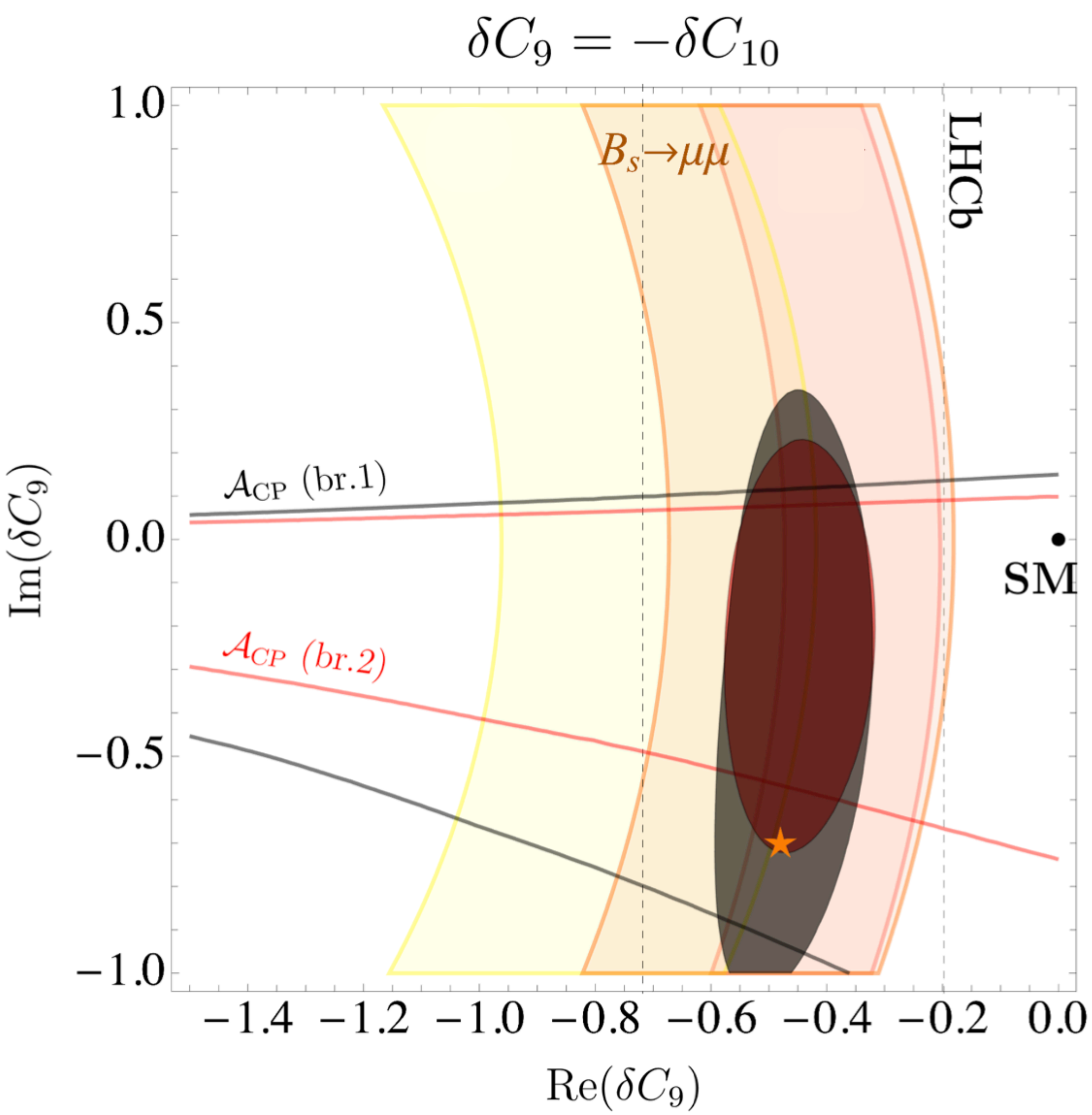
Input: strong phase δ_j





Sensitive to CPV in δC_9

ALLOWED CPV IN NP



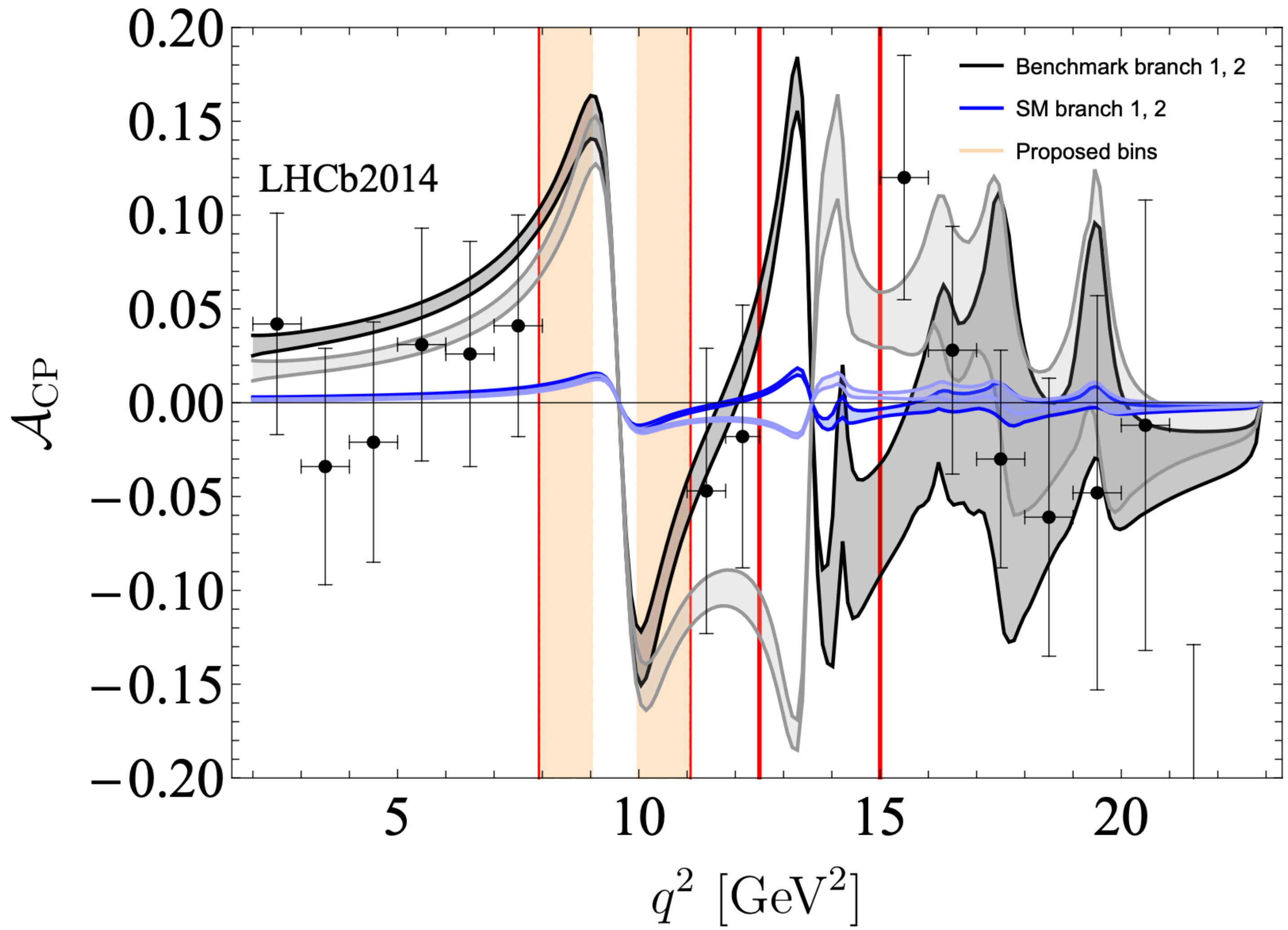
Orthogonality of constraints

- Br(Bs → $\mu\mu$) and rates
- A_{CP} (2-8 GeV^2)

★ $\delta C_9 = -\delta C_{10} = -0.46 - 0.71i$ benchmark scenario allows large imaginary part

RESONANT CPV

$\delta C_9 = -\delta C_{10} = -0.46 - 0.71i$



A. Smolkovic thesis '21
Becirevic et al, 2008.09064

Interesting region to look for direct CPV

$$\Delta\mathcal{A}_{\rm CP} \equiv \frac{\bar\Gamma_{[8,9]} - \Gamma_{[8,9]} - \bar\Gamma_{[10,11]} + \Gamma_{[10,11]}}{\bar\Gamma_{[8,9]} + \Gamma_{[8,9]} + \bar\Gamma_{[10,11]} + \Gamma_{[10,11]}}$$

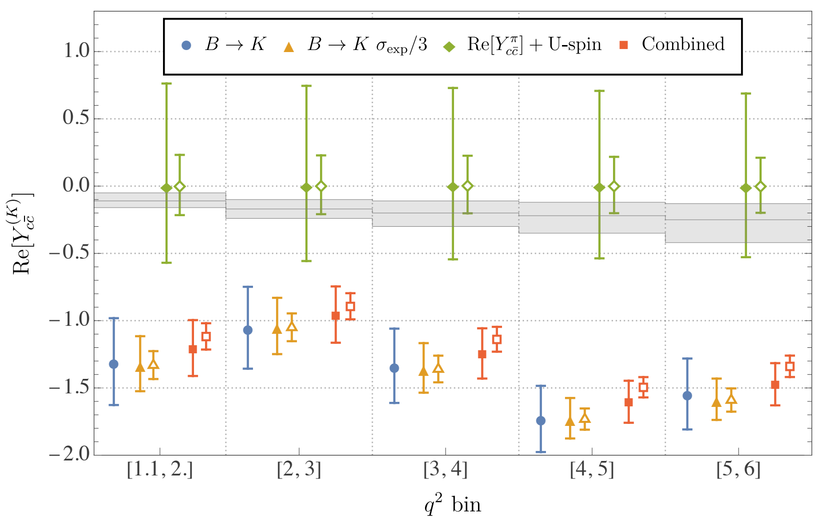
$$\Delta\mathcal{A}_{\rm CP} = \frac{0.0108(2) - 0.139(3)\,\mathrm{Im}(\delta C_9)}{1 + 0.414(5)\,\mathrm{Re}(\delta C_9) - 0.0082(1)\,\mathrm{Im}(\delta C_9) + 0.054(1)\,|\delta C_9|^2}$$

NK, A.Smolkovic, 2108.11929
for other CPV constraints see also
Descotes-Genon, Novoa-Brunet, Vos, 2008.08000
Carvunis, Dettori, Gangal, Guadagnoli, Normand, 2102.13390

SUMMARY

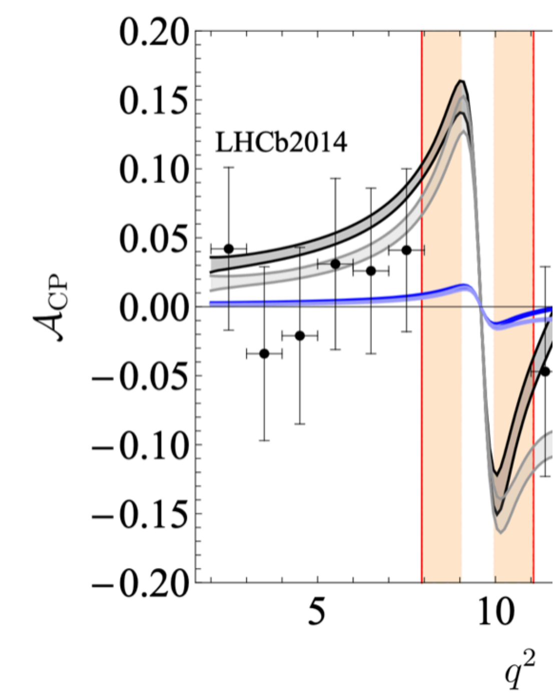
- CKM structure enables extraction of non-local form factor $\mathrm{Re}Y_{c\bar{c}}(q^2)$ for $B^- \to K^- \ell\ell$ and $B^- \to \pi^- \ell\ell$.

- *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!



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

- New Physics with CPV in rare decays relies on absorbtive $c\bar{c}$ amplitude, present close to the J/ψ resonance.



Thank you!