Flavour physics and CP violation

Lecture 2: Phenomenology of K and B meson decays

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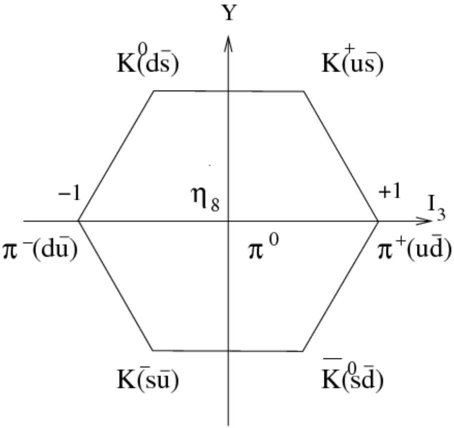
Outline

1. **Flavour physics in the Standard Model (SM)**
   - CKM matrix
   - flavour changing neutral currents
   - effective Hamiltonian
2. **Phenomenology of K and B meson decays**
   - neutral meson mixing
   - rare K decays
   - $b \to s$ transitions
3. **Flavour physics beyond the SM**
   - constraints on the scale of new physics
   - Minimal Flavour Violation
   - flavour hierarchies from partial compositeness

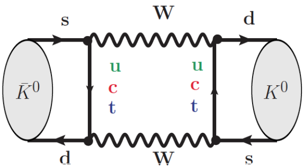
Pseudoscalar meson octet



two neutral K mesons: $|K^0\rangle = |d\bar{s}\rangle$ and $|\bar{K}^0\rangle = |s\bar{d}\rangle$

Neutral kaon mixing

Recall from Monday: K^0 and $\bar{K}^0$ can mix



➢ time evolution of $K^0 - \bar{K}^0$ system described by Schrödinger equation

$$i\frac{d\psi(t)}{dt} = \hat{H}\psi(t) \qquad \psi(t) = \begin{pmatrix} K^0(t) \\ \bar{K}^0(t) \end{pmatrix}$$

with the 2×2 Hamiltonian

$$\hat{H} = \hat{M} - i\frac{\hat{\Gamma}}{2} = \begin{pmatrix} M_{11} - i\frac{\Gamma_{11}}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{21} - i\frac{\Gamma_{21}}{2} & M_{22} - i\frac{\Gamma_{22}}{2} \end{pmatrix}$$

From flavour to mass eigenstates

Using

- CPT invariance: $M_{11} = M_{22} \equiv M$, $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$
- hermiticity: $M_{21} = M_{12}^*$, $\Gamma_{21} = \Gamma_{12}^*$

the Hamiltonian simplifies to

$$\hat{H} = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^* - i\frac{\Gamma_{12}^*}{2} & M - i\frac{\Gamma}{2} \end{pmatrix}$$

Diagonalisation yields the mass eigenstates

$$K_{L,S} = \frac{(1+\bar{\varepsilon})K^0 \pm (1-\bar{\varepsilon})\bar{K}^0}{\sqrt{2(1+|\bar{\varepsilon}|^2)}} \qquad \frac{1-\bar{\varepsilon}}{1+\varepsilon} = \sqrt{\frac{M_{12}^* - i\frac{\Gamma_{12}^*}{2}}{M_{12} - i\frac{\Gamma_{12}}{2}}} = \frac{\Delta M - \frac{i}{2}\Delta\Gamma}{2M_{12} - i\Gamma_{12}}$$

exp.: $\bar{\varepsilon} = \mathcal{O}(10^{-3})$ ➢ $\Delta M \simeq 2\mathrm{Re}M_{12}$, $\Delta\Gamma \simeq 2\mathrm{Re}\Gamma_{12}$

CP Properties

$$CP|K^0\rangle = -|\bar{K}^0\rangle \qquad CP|\bar{K}^0\rangle = -|K^0\rangle$$

➢ CP eigenstates

$$K_1 = \frac{1}{\sqrt{2}}(K^0 - \bar{K}^0) \qquad CP \text{ even: } CP|K_1\rangle = +|K_1\rangle$$

$$K_2 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0) \qquad CP \text{ odd: } CP|K_2\rangle = -|K_2\rangle$$

mass eigenstates $K_{S,L}$ are not CP eigenstates:

$$K_S = \frac{K_1 + \bar{\varepsilon} K_2}{\sqrt{1+|\bar{\varepsilon}|^2}} \qquad K_L = \frac{K_2 + \bar{\varepsilon} K_1}{\sqrt{1+|\bar{\varepsilon}|^2}}$$

➢ **CP violation**

$K_{L,S}$ lifetimes

if CP symmetry was unbroken:

- $K_S = K_1$ is CP even, hence decays to two pions
- $K_L = K_2$ is CP odd, hence decays to three pions ➢ suppressed

lifetime difference (hence $K_{\text{Short}}, K_{\text{Long}}$)

$$\tau(K_S) \sim 90\,\text{ps} \qquad \tau(K_L) \sim 5 \cdot 10^3\,\text{ps}$$

➢ CP is (approximately) conserved

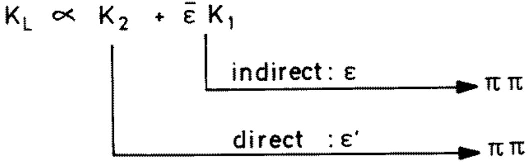
Application: how to get a K_L beam
neutral kaon beam contains superposition of K_S and K_L states
➢ wait until K_S have decayed

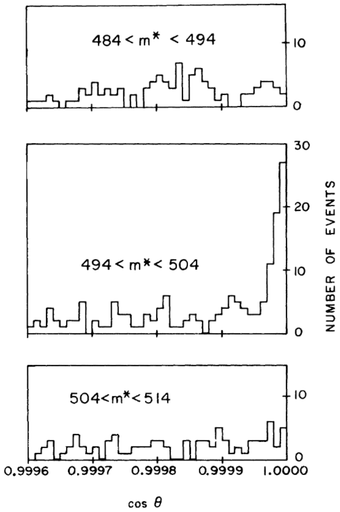
Observation of CP violation

observation of $K_L \to \pi^+\pi^-$ in 1964
$=$ first observation of CP violation

➢ Nobel Prize 1980

. . . but is is direct or indirect?





Christenson et al. (1964)

Classification of CP violation

Standard classification

- indirect CP violation: mass eigenstates are not CP eigenstates
- direct CP violation: transition (decay) of CP-odd to CP-even state (or vice versa)

➢ How to distinguish between the two?

Idea: direct CP violation depends on decay channel, but indirect does not

For $K \to \pi\pi$ we can study the modes

$$K_L \to \pi^0\pi^0 \qquad K_L \to \pi^+\pi^-$$
$$K_S \to \pi^0\pi^0 \qquad K_S \to \pi^+\pi^-$$

ε and ε' from isospin amplitudes

$\pi\pi$ final state can be isospin $I = 0$ or $I = 2$ with amplitudes A_0 and A_2:

$$A(K^0 \to \pi^+\pi^-) = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

$$A(K^0 \to \pi^0\pi^0) = \sqrt{\frac{2}{3}} A_0 e^{i\delta_0} - 2\sqrt{\frac{1}{3}} A_2 e^{i\delta_2}$$

$\delta_{0,2}$: strong phases

Defining the ratios

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \qquad \eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

one can show that

$$\varepsilon \simeq \frac{1}{3}\left(\eta_{00} + 2\eta_{+-}\right) \qquad \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) \simeq \frac{1}{6}\left(1 - \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2\right)$$

Status of $|\varepsilon|$ and ε'/ε

experimentally:

$$\begin{aligned} |\varepsilon| &= (2.228 \pm 0.011) \cdot 10^{-3} \\ \mathrm{Re}(\varepsilon'/\varepsilon) &= (16.6 \pm 2.3) \cdot 10^{-4} \end{aligned}$$

in the SM:

- CP violation governed by phase of the CKM matrix
- three generations necessary

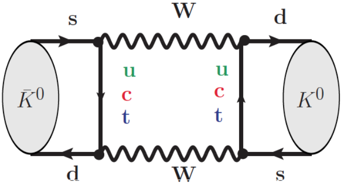
➢ CP violation in the K sector driven by

$$\mathrm{Im}(V_{ts}^* V_{td}) \simeq \mathcal{O}(10^{-4})$$

new physics: CKM suppression could be absent
➢ outstanding new physics sensitivity, even within flavour physics

$|\varepsilon|$ in the SM

$$\varepsilon = \frac{\kappa_\varepsilon e^{i\varphi_\varepsilon}}{\sqrt{2}\Delta M_K}\mathrm{Im}M_{12}^K$$



- $\kappa_\varepsilon = 0.94 \pm 0.02$: estimate of long-distance corrections
- $\varphi_\varepsilon = 43.51°$ from data
- $\Delta M_K = (0.5292 \pm 0.0009) \cdot 10^{-2}\,\mathrm{ps}^{-1}$ from data
- M_{12}^K from box diagram, including higher oder perturbative corrections and non-perturbative parameter from lattice QCD

➢ $|\varepsilon|_{\mathrm{SM}} = (1.90 \pm 0.26) \cdot 10^{-3}$

a bit lower, but consistent with data

ε'/ε in the SM

simple phenomenological expression:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = \frac{\mathrm{Im}(V_{ts}^* V_{td})}{1.4 \cdot 10^{-4}} \cdot 10^{-4} \cdot \Big(\underbrace{-3.6 + 21.4 B_6^{(1/2)}}_{A_0:\ \text{QCD penguins}} + \underbrace{1.2 - 10.4 B_8^{(3/2)}}_{A_2:\ \text{EW penguins}} \Big)$$

- large cancellation between A_0 and A_2 amplitudes
- hadronic matrix elements from the lattice (RBC-UKQCD):

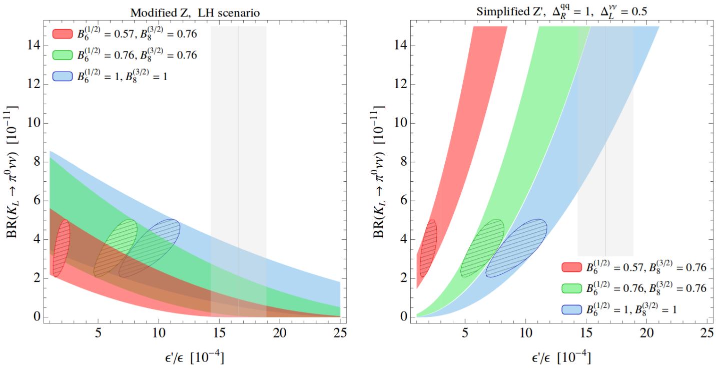
$$B_6^{(1/2)} = 0.57 \pm 0.19 \qquad B_8^{(3/2)} = 0.76 \pm 0.05$$

➢ $\mathrm{Re}(\varepsilon'/\varepsilon)_{\mathrm{SM}} = (1.4 \pm 4.6) \cdot 10^{-4}$ $\sim 3\sigma$ tension with the data!

ε'/ε in the presence of new physics

example: two simplified models (flavour changing Z or Z' couplings)

Buras et al. (2015)



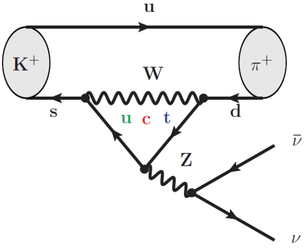
- tension in $|\varepsilon'/\varepsilon|$ can be removed
- simultaneous large effects in $K_L \to \pi^0 \nu\bar{\nu}$

The $K \to \pi\nu\bar{\nu}$ decays – a unique opportunity

Standard Model:

- governed by Z penguin and box diagrams
- hadronic uncertainties well under control
- main uncertainty from CKM determination

➢ **theoretically extremely clean & very rare!**



$K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$ are an ideal place to hunt for new physics!

Experimental prospects:

NA62 (CERN), KOTO (J-PARC), ORKA & Project X (Fermilab)

$K \to \pi\nu\bar{\nu}$ and new physics

effective Hamiltonian for $K \to \pi\nu\bar{\nu}$

$$\mathcal{H}_{\text{eff}} \propto \Big[\underbrace{V_{cs}^* V_{cd} X_{\text{NNL}}(x_c)}_{\text{charm contribution}} + \underbrace{V_{ts}^* V_{td} |X| e^{i\theta_X}}_{\text{short distance new physics!}} \Big] (\bar{s}\gamma^\mu d)(\bar{\nu}\gamma_\mu(1-\gamma_5)\nu)$$

short-distance physics described model-independently by complex function

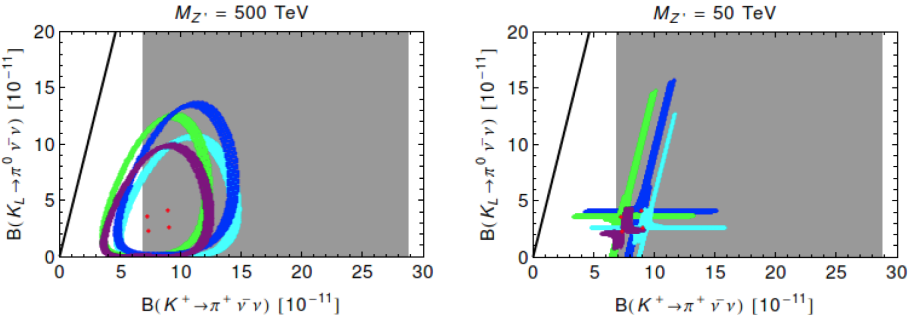
$$X = |X| e^{i\theta_X} \qquad \text{where } |X|^{\text{SM}} = X(x_t)\,, \theta_X^{\text{SM}} = 0$$

$K^+ \to \pi^+\nu\bar{\nu}$ mode is CP-conserving ➢ sensitive to $|X|^2$
$K_L \to \pi^0\nu\bar{\nu}$ mode is CP-violating ➢ measures $(\text{Im}X)^2$

➢ **both measurements needed to determine $|X|$ and θ_X**

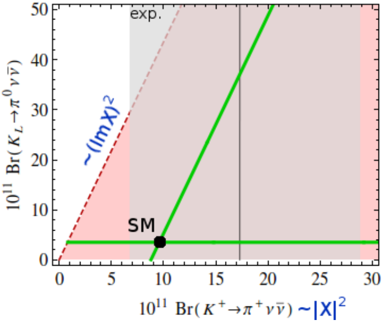
$K \to \pi\nu\bar{\nu}$ with a flavour changing Z'

Buras et al. (2014)



- NP reach beyond 10^3 TeV in the presence of LH and RH couplings
- smaller reach for chiral theory (only LH oder RH couplings) distinctive correlation (2 branches)
- strong dependence on CKM input (plot colours)

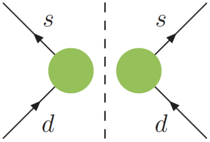
$K \to \pi\nu\bar{\nu}$ – model-independent considerations



➢ **test of new physics structure $K^0 - \bar{K}^0$ mixing** MB (2009)

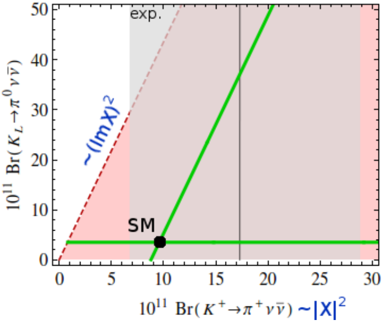
purely left-handed structure:

- ε_K **constrains phase** of $s \to d$ transition
- **same phase** enters $K \to \pi\nu\bar{\nu}$



➢ only two branches are allowed

$K \to \pi\nu\bar{\nu}$ – model-independent considerations



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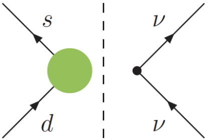

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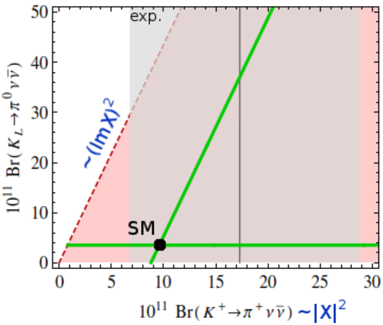

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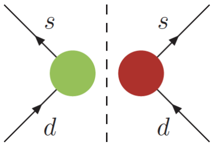


both left- and right-handed:

- $\mathcal{Q}_{LR}$ **dominates** in ε_K
- **connection** between $\Delta S = 2$ and $\Delta S = 1$ is **spoiled**

➢ full $K \to \pi\nu\bar{\nu}$ plane possible

Summary – What makes kaons so special?

The past

- prediction of charm quark from $K_L \to \mu^+\mu^-$ branching ratio
- first observation of CP violation in neutral kaon mixing
  ➢ prediction of three generations

The presence

- ε among the most stringent constraints on flavour beyond the SM
- recent progress on lattice calculations entering ε'/ε
  ➢ tension between data and SM

The future

- measurement of $K \to \pi\nu\bar{\nu}$ branching ratios will offer an extremely clean probe of new physics
- more precise prediction for ε'/ε should become available soon, possibly sharpening the tension

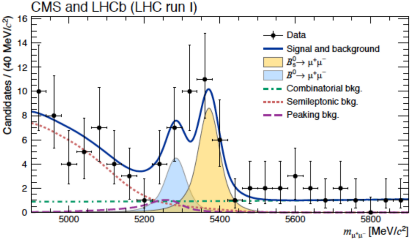
B physics

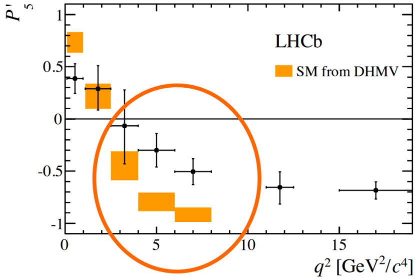
We are in an era of B physics experiments!

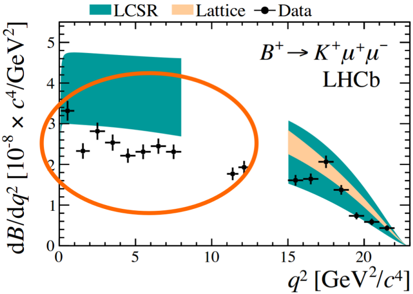
but also BaBar, Belle, CMS, ATLAS. . .

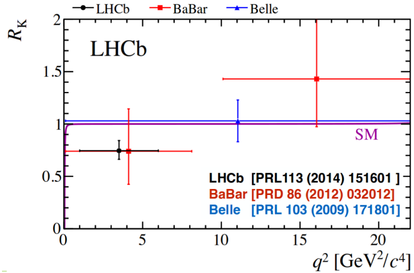
➢ hundreds of interesting observables, and we've already seen a few anomalies!

Some recent results









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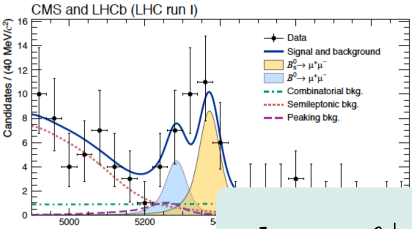
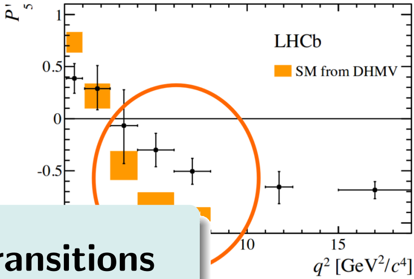
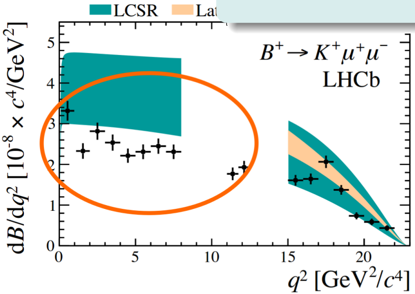
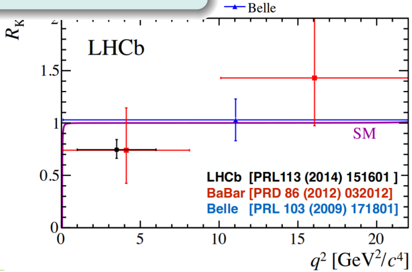




$b \to s\ell^+\ell^-$ **transitions**



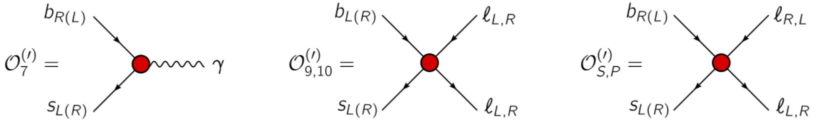


Radiative and semileptonic $b \to s$ transitions

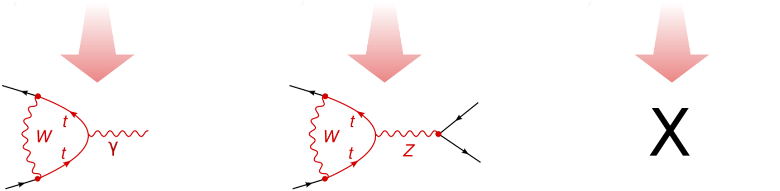
$b \to s\ell^+\ell^-$ and $b \to s\gamma$ transitions described by effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_\rangle + C_i' \mathcal{O}_\rangle') + h.c.$$

where the operators most sensitive to new physics are



SM:



Sensitivity to Wilson coefficients

Complementary sensitivity:

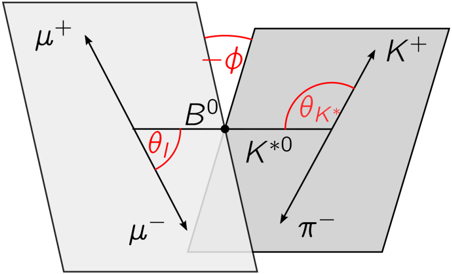
Decay	$C_7^{(\prime)}$	$C_9^{(\prime)}$	$C_{10}^{(\prime)}$	$C_{S,P}^{(\prime)}$
$B \to X_s\gamma$	X			
$B \to K^*\gamma$	X			
$B \to X_s\ell^+\ell^-$	X	X	X	
$B \to K^{(*)}\ell^+\ell^-$	X	X	X	
$B_s \to \mu^+\mu^-$			X	X

- different observables constrain different operators
- global analysis can be used to resolve ambiguities
- apparent deviation from the SM in one observable can be cross-checked in related modes

Angular observables in $B \to K^* \mu^+ \mu^-$

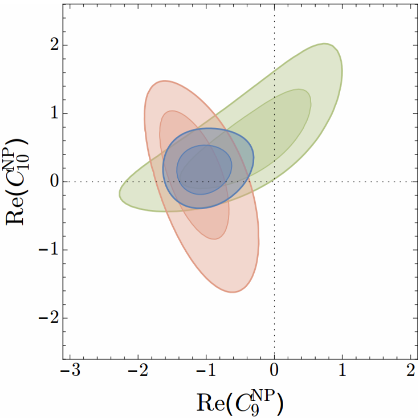
$B \to K^* (\to K\pi) \mu^+ \mu^-$:

- four body final state ➢ 3 angles and $\mu^+\mu^-$ invariant mass q^2
- different parametrisations on the theory market

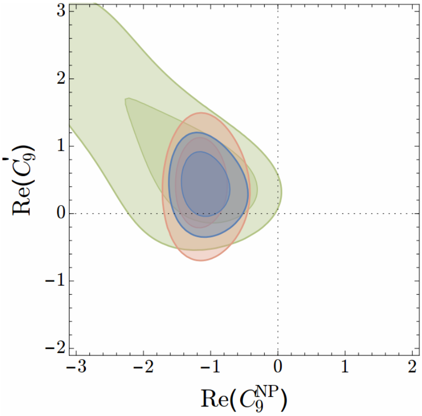


➢ one of these observables: P_5'

Global fit to Wilson coefficients



Altmannshofer, Straub (2015) and others



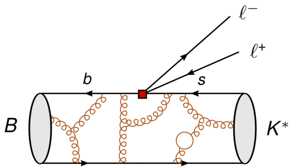
➢ $\sim 4\sigma$ **evidence for a new contribution to** C_9

What could it be?

New physics!

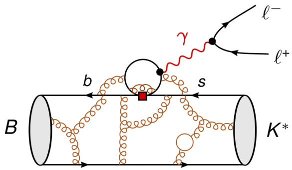
. . . or some underestimated theory contribution?

$B \to K^*$ form factor



- from lattice QCD and light-cone sume rules
- systematic improvements possible

non-factorisable corrections



- "charm loops" at low q^2 and broad $c\bar{c}$ resonances
- dominant uncertainty, no systematic theory description

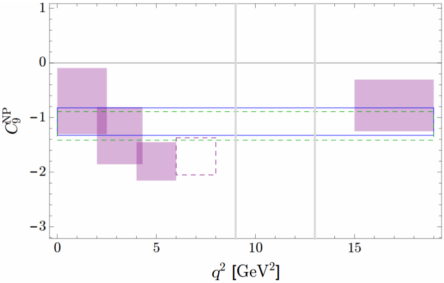
How can we tell?

Hadronic effects

- q^2 dependence expected
- lepton flavour universal

New physics contribution

- q^2 independent
- can be lepton flavour specific



Altmannshofer, Straub (2015)

test of lepton flavour universality:

$$R_K = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)}$$

and other similar ratios

Summary

- quark flavour physics has a very rich phenomenology
  ➢ only few examples highlighted here
- K physics: highest potential new physics sensitivity
- B physics: currently lots of activity
  ➢ interesting anomalies to be understood