SM (quark) flavour theory

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Outline

- Basics: quark flavour and CKM matrix
- Hadron flavour and QCD
- Selected observables

Basics: flavour physics with quarks

Flavours of quarks

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{matrix} u_R \\ d_R \end{matrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{matrix} c_R \\ s_R \end{matrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$\begin{matrix} t_R \\ b_R \end{matrix}$	$\begin{matrix} Q = +2/3 \\ Q = -1/3 \end{matrix}$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{matrix} - \\ e_R \end{matrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{matrix} - \\ \mu_R \end{matrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$\begin{matrix} - \\ \tau_R \end{matrix}$	$\begin{matrix} Q = 0 \\ Q = -1 \end{matrix}$

Quarks are those elementary particles in the Standard Model that have spin 1/2 and strong interactions.

They come in 3 colours and six different mass eigenstates, called **flavours**: up, down, strange, charm, bottom, top in order of increasing mass. (The historical origin is ice-cream, which also carries colour and flavour, as observed by Fritzsch & Gell-Mann.)

3 of the quarks have charge +2/3 e, called “up-type” quarks

3 have charge -1/3 e, called “down-type” quarks

Only the left-chiral parts of the quark fields have SU(2) gauge interactions and couple to the W bosons

Flavour symmetry

In modern parlance, the flavour symmetry group of a gauge theory is the largest global symmetry group (that commutes with the gauge group) of a gauge theory.

Gauge theory part of the SM Lagrangian

$$\mathcal{L}_{\text{gauge}} = \sum_f \bar{\psi}_f \gamma^\mu D_\mu \psi_f - \sum_{i,a} \frac{1}{4} g_i F^{ia}_{\mu\nu} F^{ia\mu\nu}$$

$$f = Q_{Lj}, u_{Rj}, d_{Rj}, L_{Lj}, e_{Rj} \quad j = 1, 2, 3$$

3 parameters only, no masses

invariant under transformations (3x3 matrices)

$$Q_L \to e^{i(b/3+a)} V_{Q_L} Q_L,\ u_R \to e^{i(b/3-a)} V_{u_R} u_R,\ d_R \to e^{i(b/3-a)} V_{d_R} d_R$$

$$G_{\text{flavor}} = SU(3)^5 \times U(1)_B \times U(1)_A \times U(1)_L \times U(1)_E$$

[Chivukula & Georgi 1987]

nb - anomalies reduce the 4 U(1) factors to $U(1)_{B\text{-}L}$

broken by Yukawa couplings to Higgs field

$$\mathcal{L}_Y = -\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L$$

to

$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

(ignoring anomalies)

To go to mass eigenstates, need to diagonalise the Yukawa matrices. Achieved by simultaneous U(3) transformations:

$$u_L \to V_{u_L} u_L \qquad u_R \to V_{u_R} u_R \qquad Y_U \to V_{u_R} Y_U V_{u_L}^\dagger = Y_U^{\text{diag}}$$

$$d_L \to V_{d_L} d_L \qquad d_R \to V_{d_R} d_R \qquad Y_D \to V_{d_R} Y_D Y_{D_R}^\dagger = Y_D^{\text{diag}}$$

If V_{uL} and V_{dL} are different, this is **not** a flavour symmetry transformation. W couplings become non-diagonal:

$$W_\mu^+ \bar{u}_L \gamma^\mu d_L \to W_\mu^+ \bar{u}_L \underbrace{V_{u_L}^\dagger V_{d_L}}_{\text{CKM matrix}} \gamma^\mu d_L$$

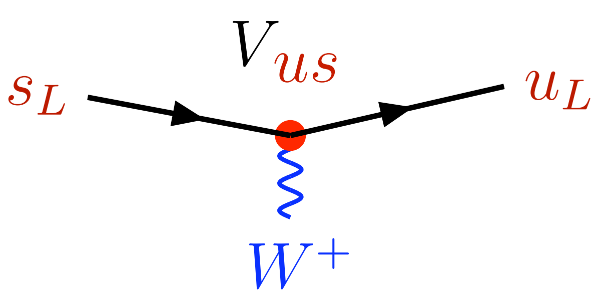
weak interactions violate flavour

Quiz

1) Why do the Z couplings remain generation diagonal?

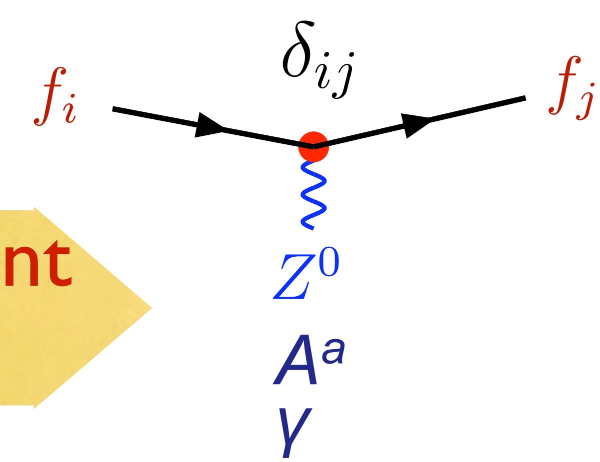
2) What would happen if there were only one quark SU(2) doublet and one further left-handed down-type singlet s'_L ? (Plus right-handed singlets)

SM flavour: CKM matrix



all flavour violation in charged current

(tree) neutral current conserves flavor



$$V_{\rm CKM} \;=\; \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$ unitary matrix

phase changes $$u_{Li} \to e^{i\alpha_i} u_{Li}, \quad u_{Ri} \to e^{i\alpha_i} u_{Ri}$$
$$d_{Li} \to e^{i\beta_i} d_{Li}, \quad d_{Ri} \to e^{i\beta_i} d_{Ri}$$

change CKM (eg can use to make some CKM elements real+)

9	independent parameters in a unitary matrix
- (6 - 1)	rephasings (1 universal rephasing is symmetry)
= 4	physical CKM parameters (3 angles, 1 phase)

weak interactions violate CP

Quiz

3) Why can the work of Kobayashi and Maskawa (1972) be viewed as a prediction of a third SM generation?
(CP violation was first observed in 1964.)

Parameterisations

Standard parameterisation in terms of three angles $\theta_{12},\theta_{13},\theta_{23}$ similarly to Euler angles, and a phase δ (Particle data group)

$$V_{\rm CKM} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

empirically, $s_{13} \ll s_{23} \ll s_{12} \ll 1$, $V_{\rm CKM}$ not far from diagonal

Wolfenstein parameters (phase convention independent)

$$\lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2+|V_{us}|^2}} \qquad A = \frac{1}{\lambda}\frac{|V_{cb}|}{|V_{us}|} \qquad \bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

[L Wolfenstein; Buras et al; PDG]

One can expand the CKM matrix in these:

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\bar\rho - i\bar\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\bar\rho-i\bar\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda = 0.22457^{+0.00186}_{-0.00014}, \quad A = 0.823^{+0.012}_{-0.033}, \quad \bar\rho = 0.1289^{+0.0176}_{-0.0094}, \quad \bar\eta = 0.348^{+0.012}_{-0.012}$$

nucl. beta decay, K decays, semileptonic b->c decays very precisely determined

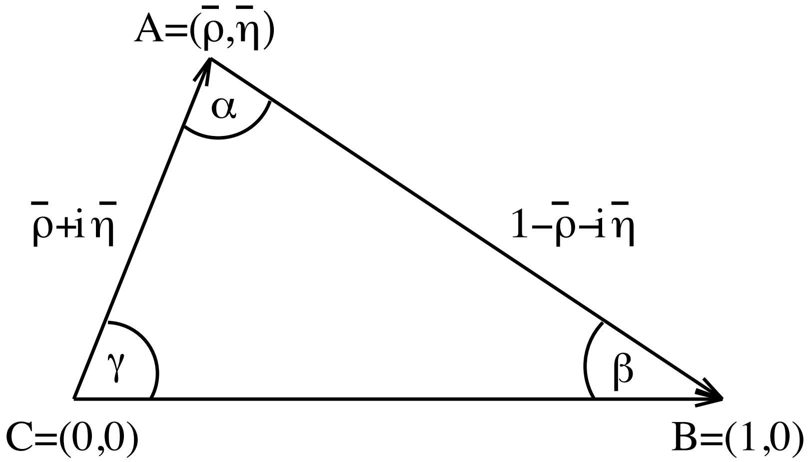
[CKMfitter collaboration, FPCP13]

Unitary triangle

Unitarity implies orthogonality of any two rows or columns of CKM

Each such relation can be viewed as a closed triangle in the complex plane

$$
\begin{array}{rcrcl}
V_{ud}V_{ub}^* & + & V_{cs}V_{cb}^* + V_{ts}V_{tb}^* & = & 0 \\
-\dfrac{V_{ud}V_{ub}^*}{V_{cs}V_{cb}^*} & & -\dfrac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} & = & 1 \\
\bar{\rho} + i\bar{\eta} & + & (1 - \bar{\rho} - i\bar{\eta}) & = & 1
\end{array}
$$

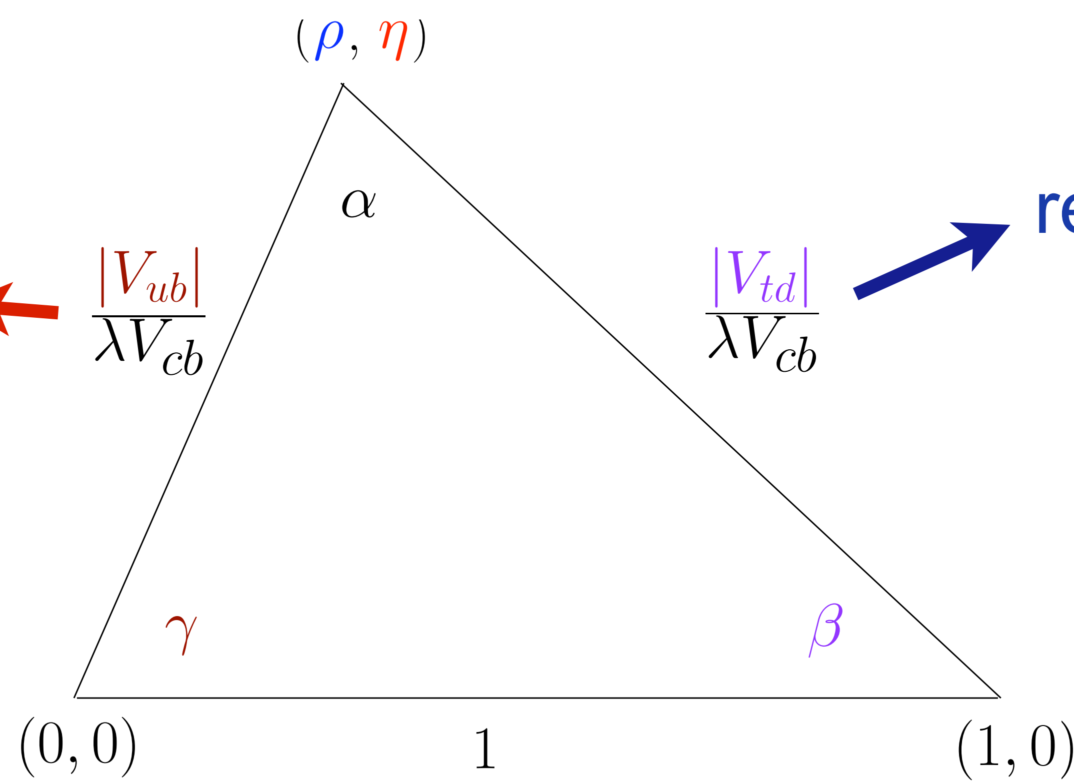


[fig. A Buras]

The form with one side normalised to 1 is most common and justified as the rescaling factor is quite precisely known (and largely insensitive to beyond-SM physics)

Unitarity triangle determination

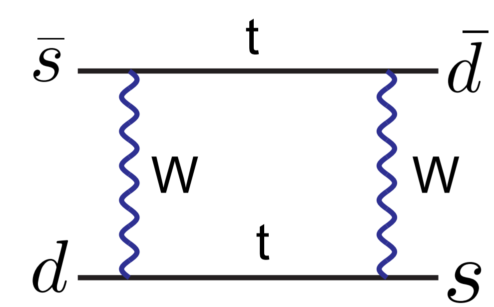
b →u l v
b →u q q
(tree-level
Weak int.)

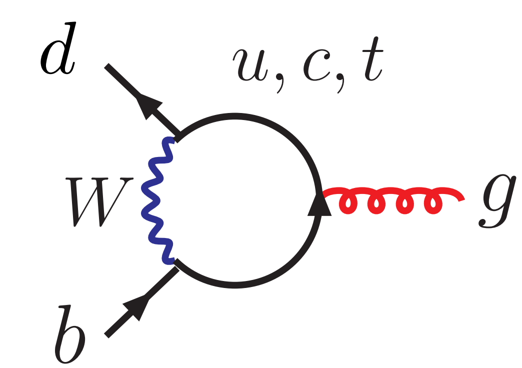


requires top loop

$$V_{ub} = |V_{ub}|e^{-i\gamma}$$

$$V_{td} = |V_{td}|e^{-i\beta}$$





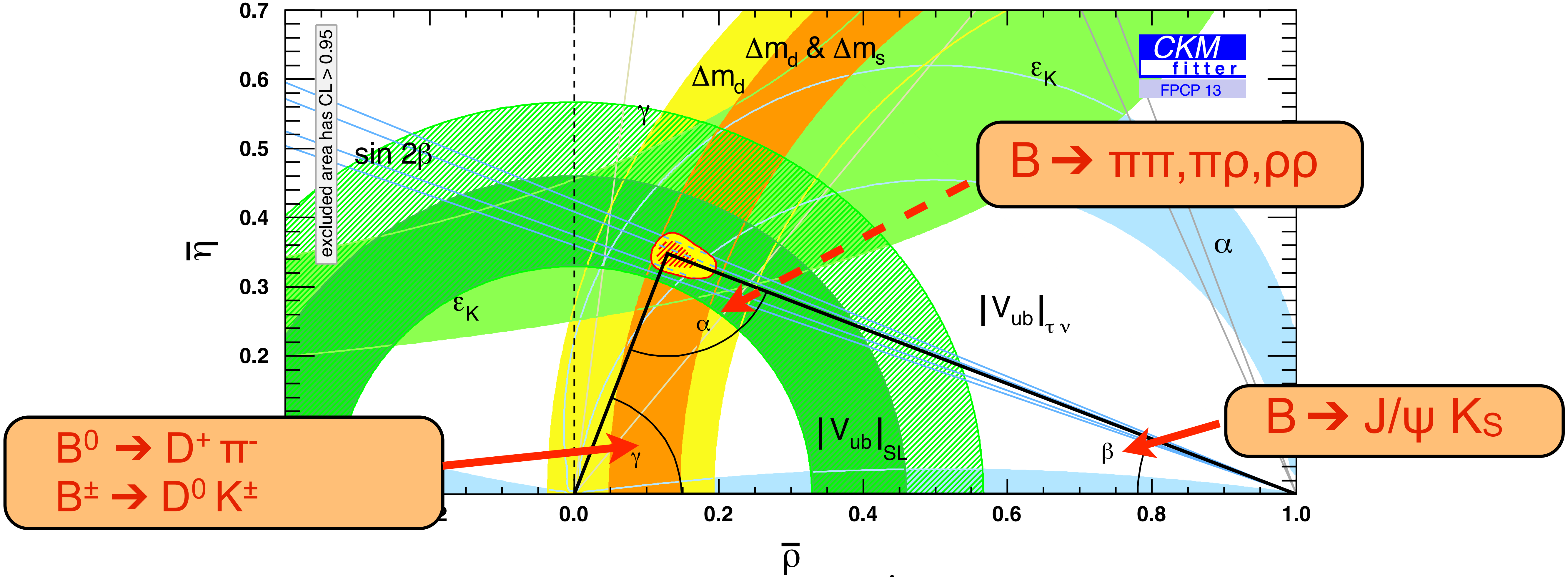
suppression of FCNC by loops and CKM hierarchy

This makes them sensitive to new physics!

Global fits to the CKM matrix by two expert groups

CKMfitter http://ckmfitter.in2p3.fr/

UTfit http://utfit.org/



Each observable constrains $\bar{\rho} + i\bar{\eta}$ to lie on a one-dimensional set (one or more lines). Bands due to uncertainties (theory & expt)

No apparent inconsistencies, CKM paradigm appears to work

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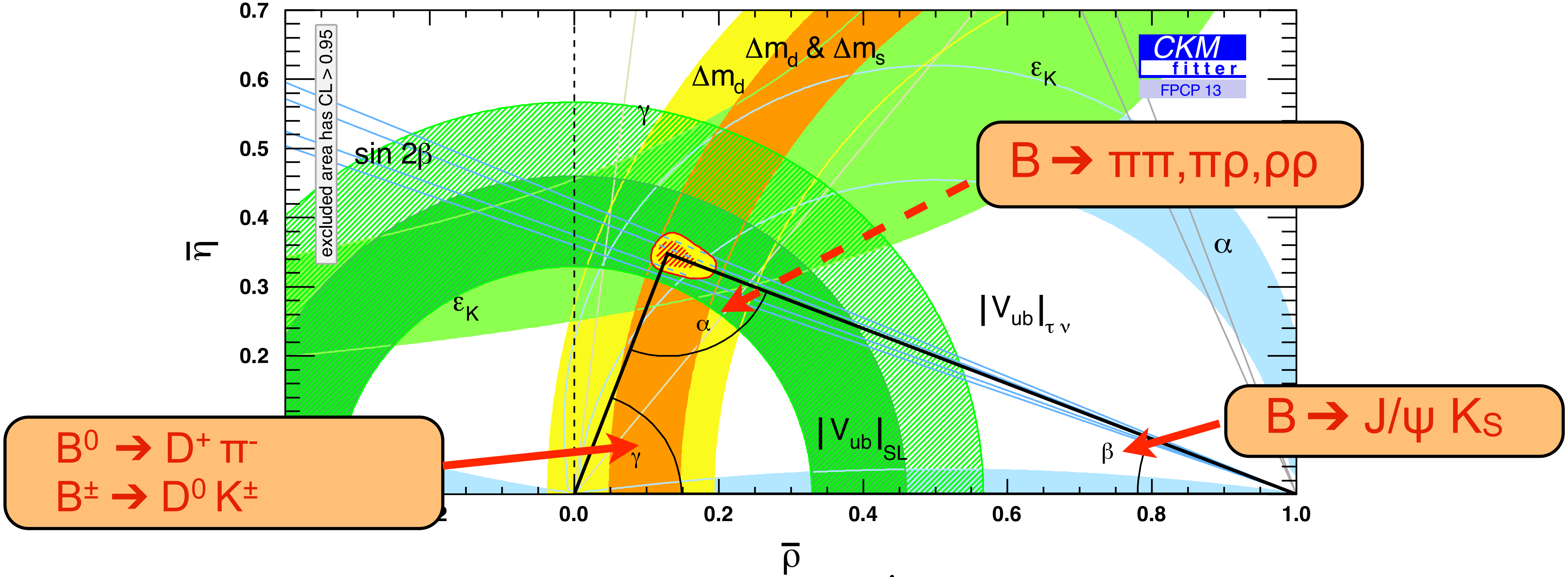

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Of all constraints, **only** the γ and $|V_{ub}|$ determinations are robust against new physics as they do not involve loops.

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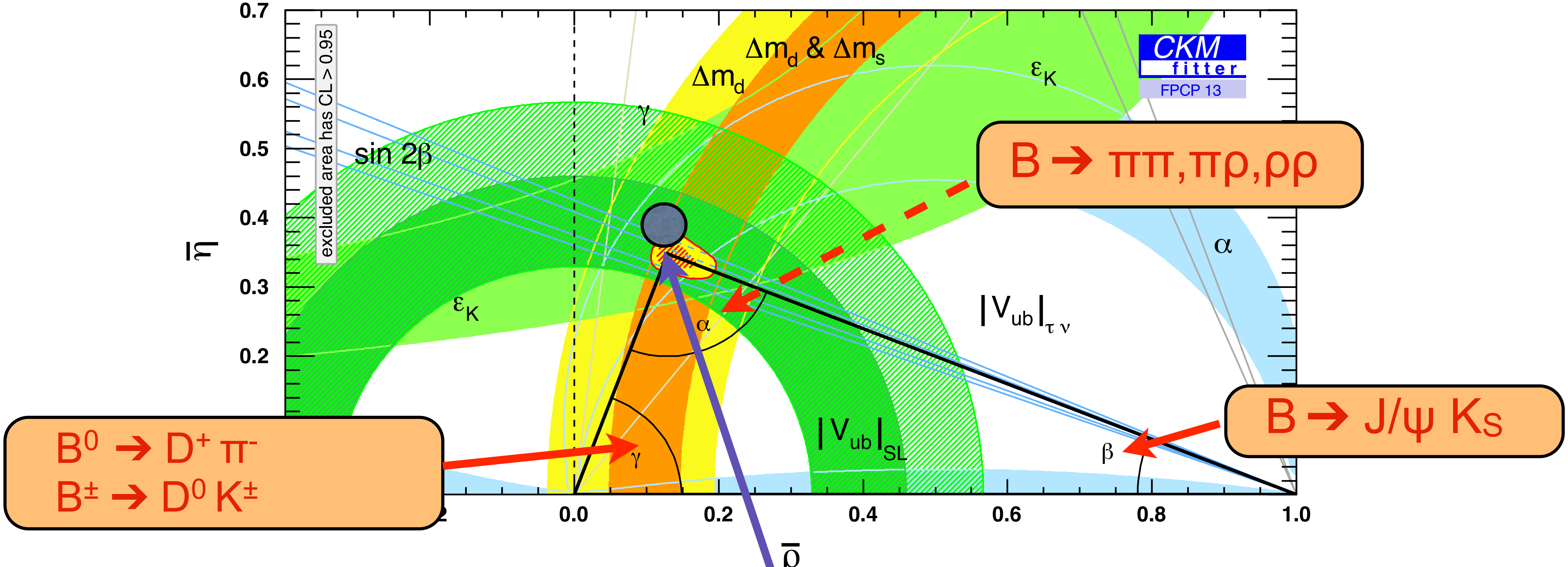

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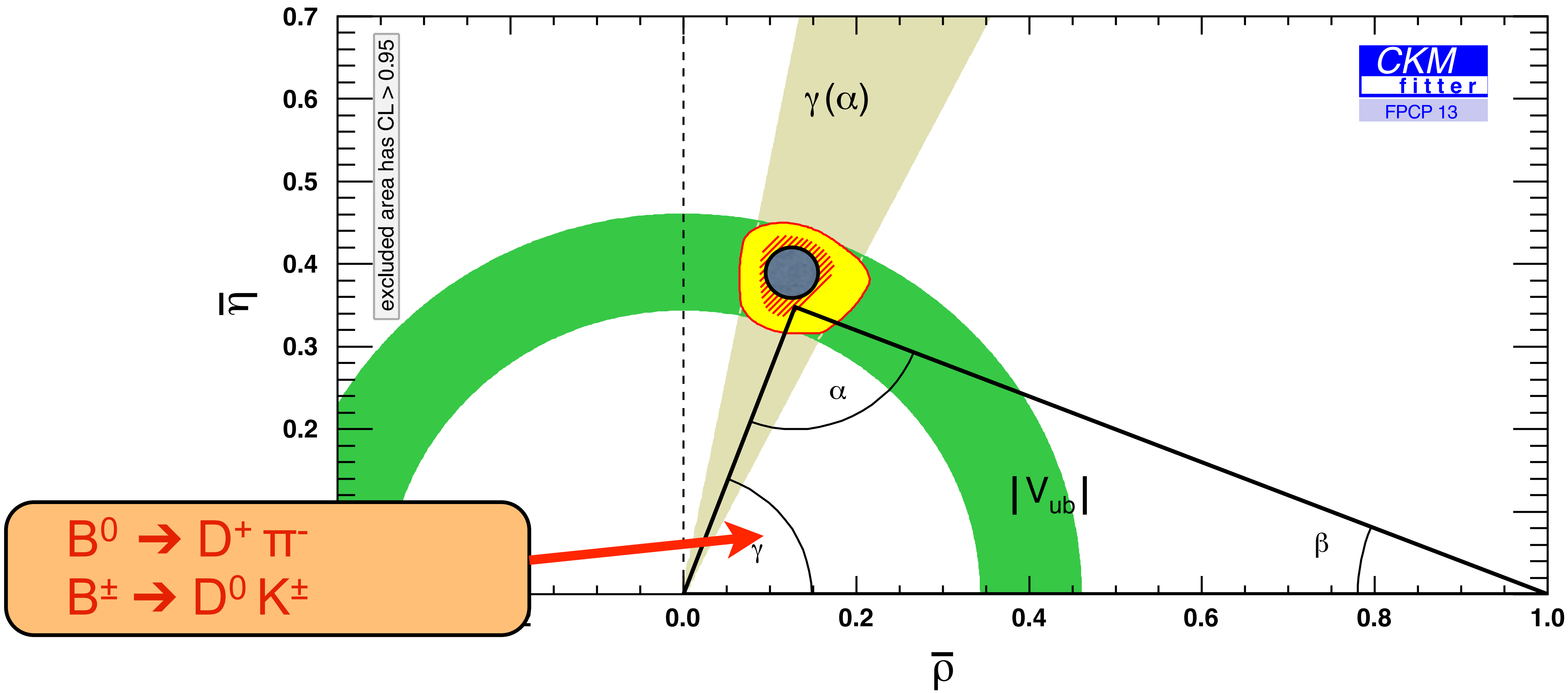
Of all constraints, **only** the γ and $|V_{ub}|$ determinations are robust against new physics as they do not involve loops.

It is possible that the TRUE $(\bar{\rho}, \bar{\eta})$ lies here (for example)

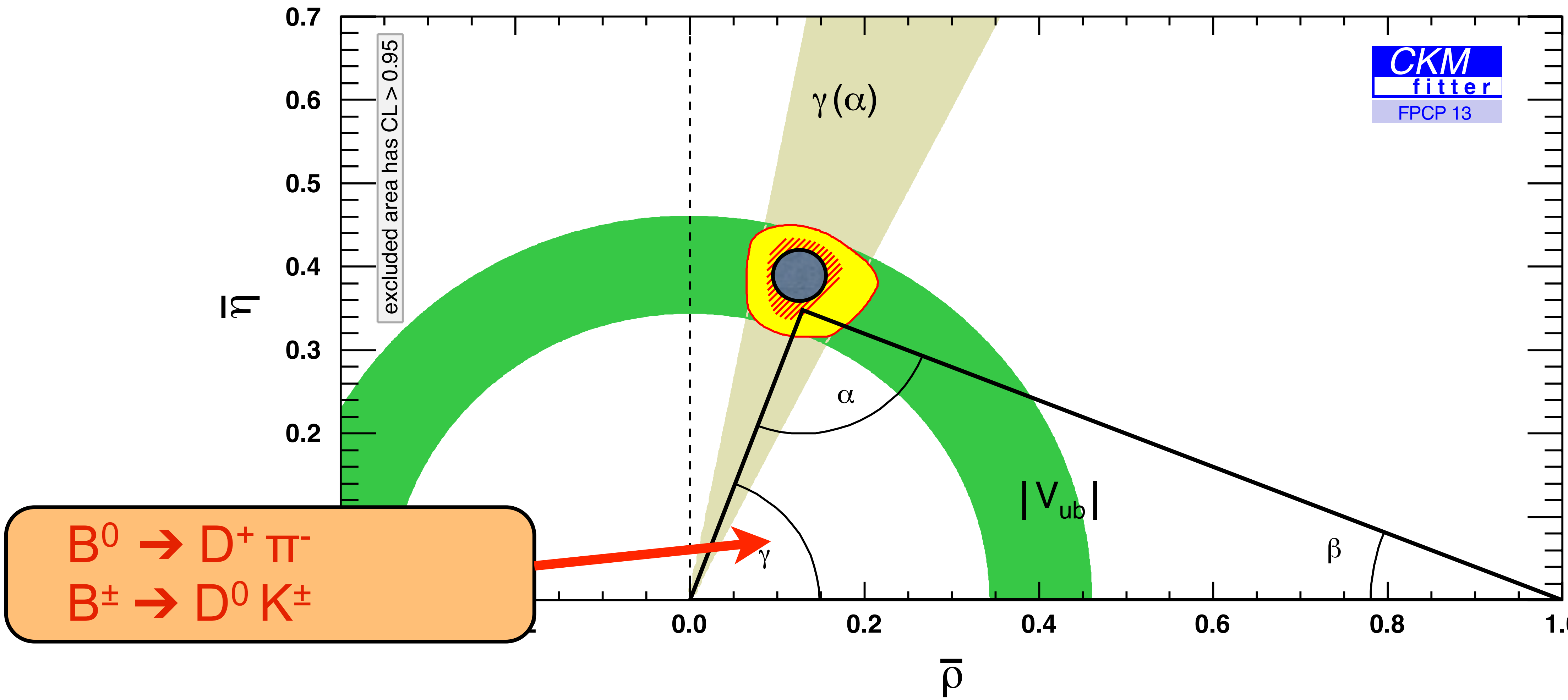
“Tree” determinations



Plot showing only “NP-robust” measurements of γ and $|V_{ub}|$.

Note: the γ(α) constraint shown depends on assumptions (absence of BSM ΔI=3/2 contributions in B->ππ); the “pure tree-level” γ determination (grey band) is more robust. Such determinations will be greatly improved by LHCb.

“Tree” determinations



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Certainly there is room for O(10%) NP in loop processes as far as UT fits are concerned, moreover UT fit mainly constrains b->d

Reality: flavour physics with hadrons

using mixing as example

observables
short and long distances
effective Hamiltonian

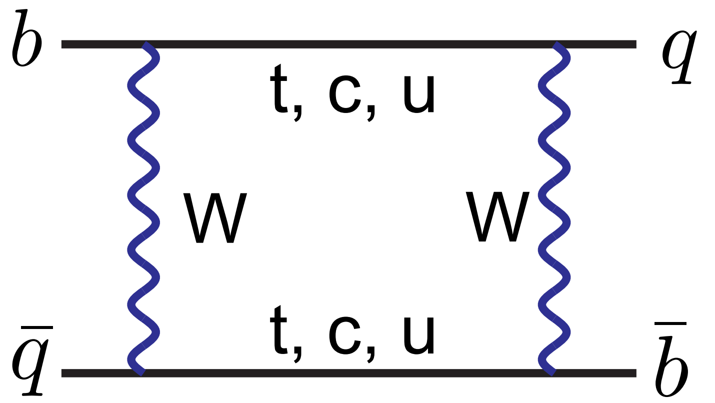
Meson mixing

flavour violation implies particle-antiparticle mixing:

$$i\frac{\partial}{\partial t}\begin{pmatrix} B_q^0(t) \\ \bar{B}_q^0(t) \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2}\hat{\Gamma}^q\right)\begin{pmatrix} B_q^0(t) \\ \bar{B}_q^0(t) \end{pmatrix}$$

$$\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$$

if we view a B meson as a quark-antiquark two-particle state:



similarly for K^0, D^0 mixing

The diagram is easy to calculate.

However, mesons are complicated QCD bound states,
so QCD corrections must be understood

Mixing: observables

$$\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$$

Three physical parameters (for each neutral meson system)

$$|M_{12}|, |\Gamma_{12}|, \phi \equiv \arg \frac{-M_{12}}{\Gamma_{12}}$$

give rise to three independent observables

$\Delta M \approx 2|M_{12}|,$	$\Delta\Gamma \approx 2|\Gamma_{12}| \cos\phi,$	$a_{\rm fs} = \frac{\Delta\Gamma}{\Delta M} \tan\phi$
mass difference	width difference (lifetime difference)	flavour-specific CP asymmetry

a_{fs} can be measured from the CP asymmetry in any “flavour-specific” decay, ie one which vanishes in the absence of mixing.

$$B \to \bar{B} \to f$$

$$a_{\rm fs}^q = \frac{\Gamma(\bar{B}_q^0(t) \to f) - \Gamma(B_q^0(t) \to \bar{f})}{\Gamma(\bar{B}_q^0(t) \to f) + \Gamma(B_q^0(t) \to \bar{f})}$$

(nb - time dependence cancels between numerator and denominator)

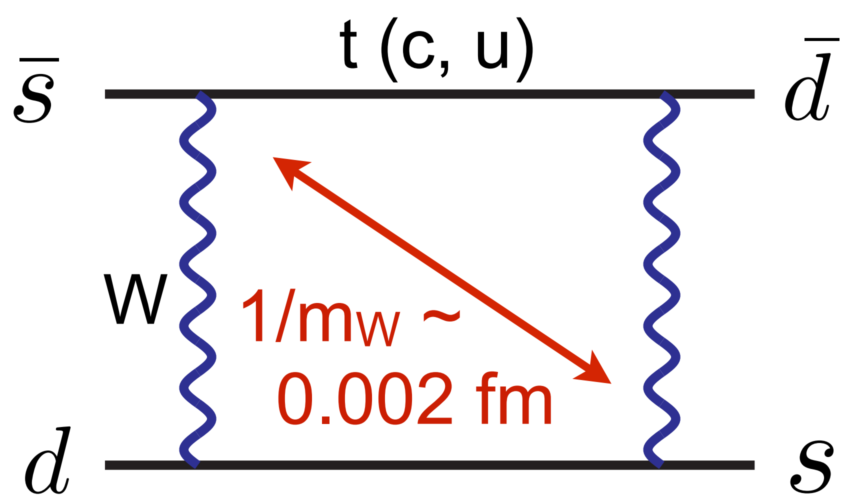
Often $f=X\mu^+$ - self-tagging. Hence “semileptonic CP as.” $a_{sl} = a_{fs}$

short distance

vs

long distance

Digression: $K^0 - \bar{K}^0$ mixing



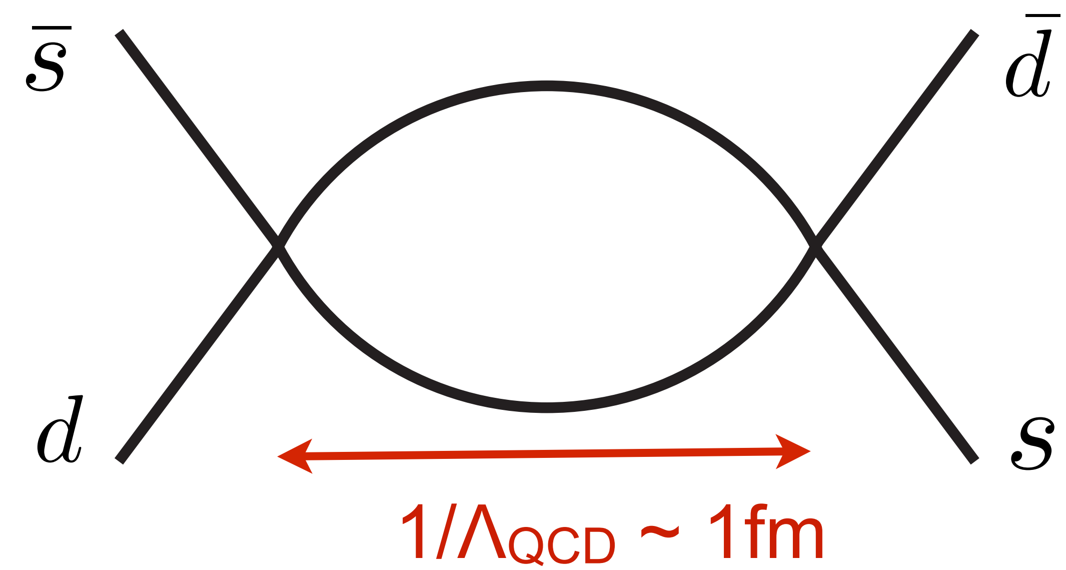
short distance

perturbation theory applies

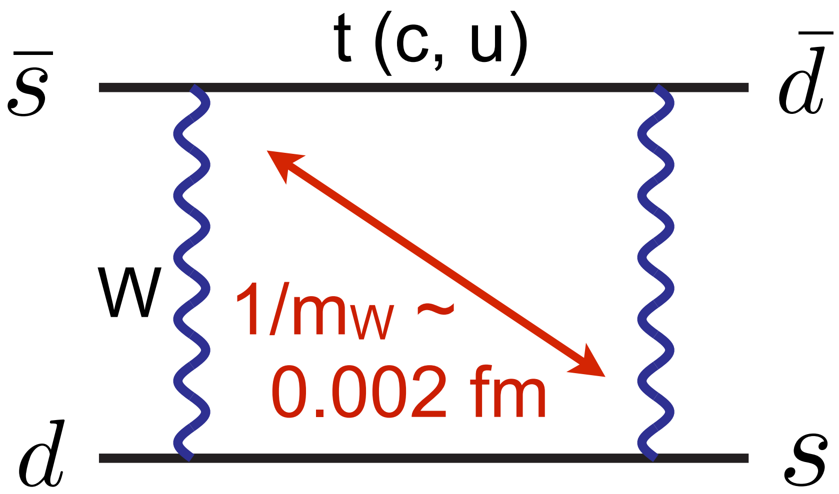
vs

long distance

non-perturbative QCD essential



Digression: $K^0 - \bar{K}^0$ mixing



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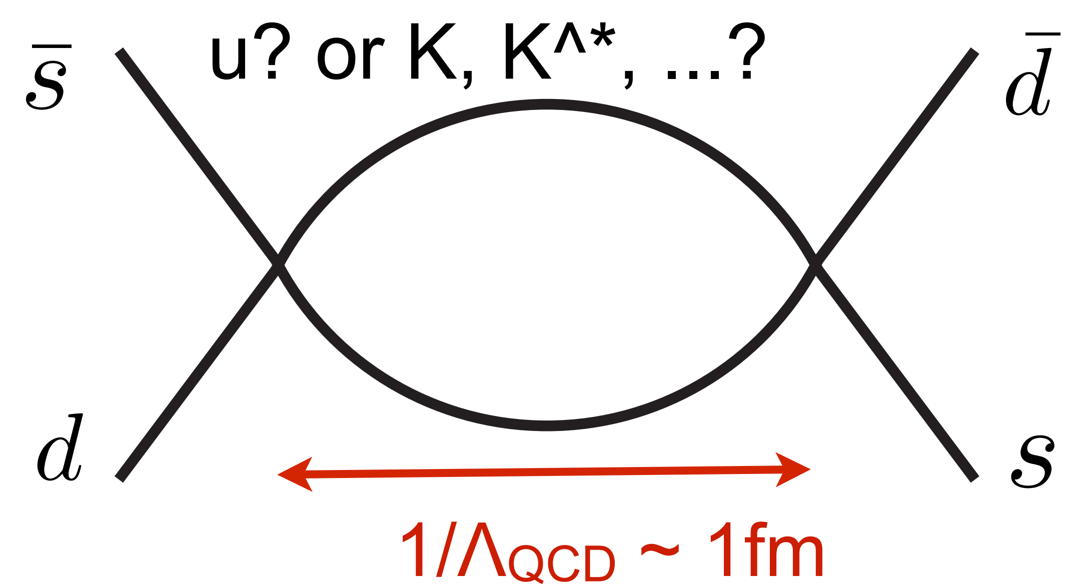

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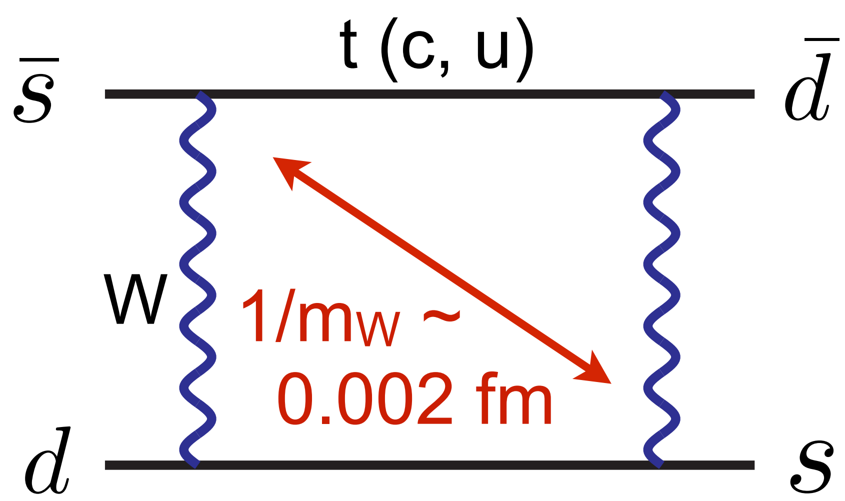

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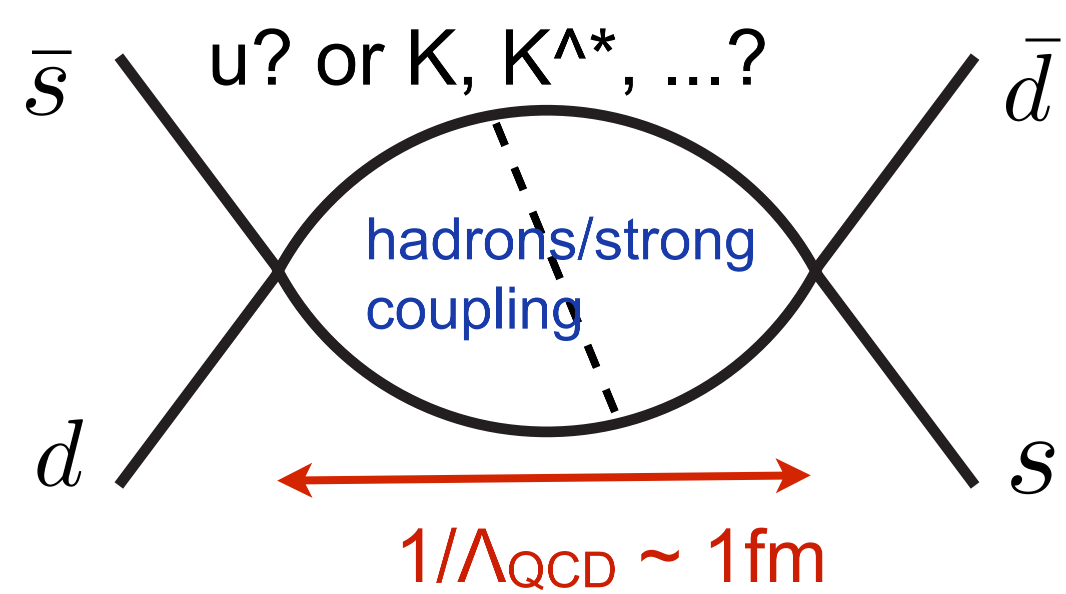

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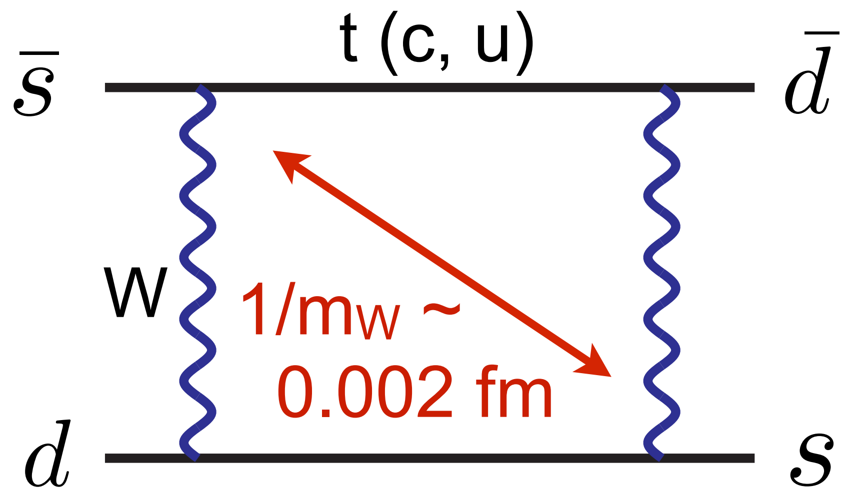
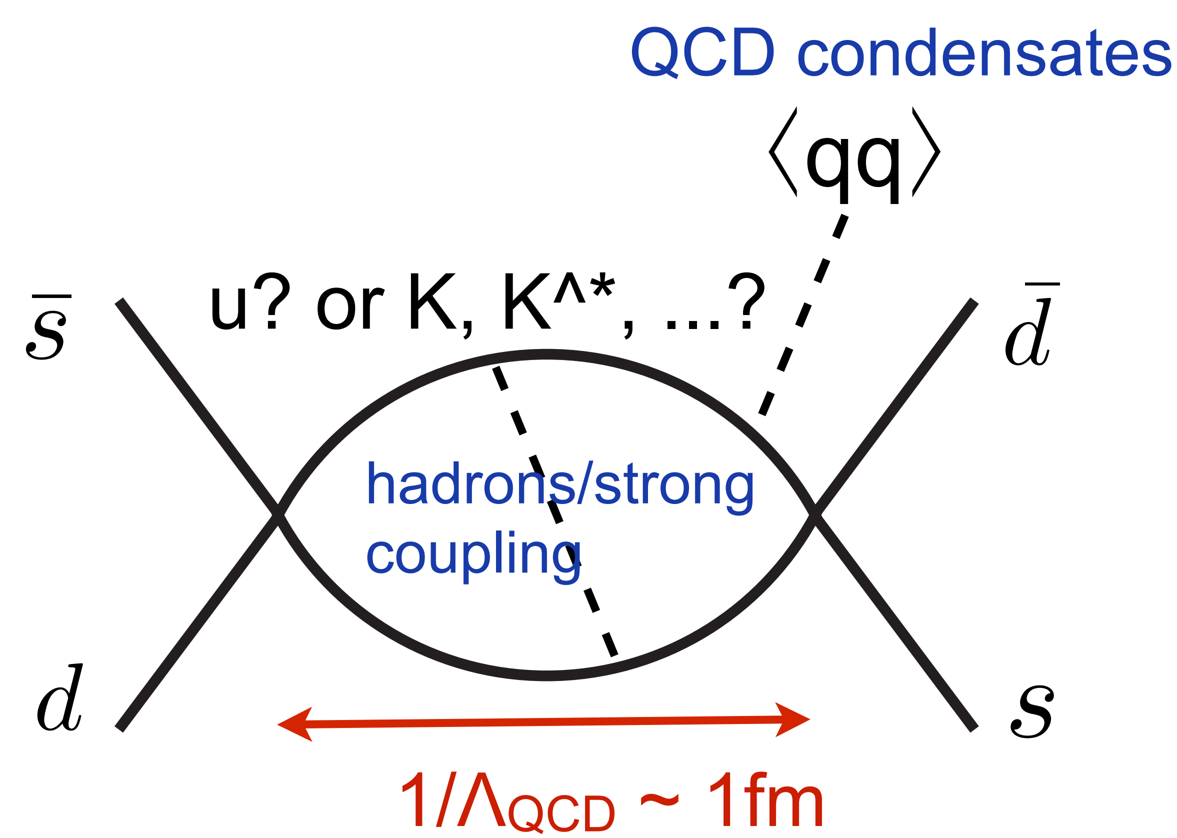


short distance

perturbation theory applies

vs



long distance

non-perturbative QCD essential

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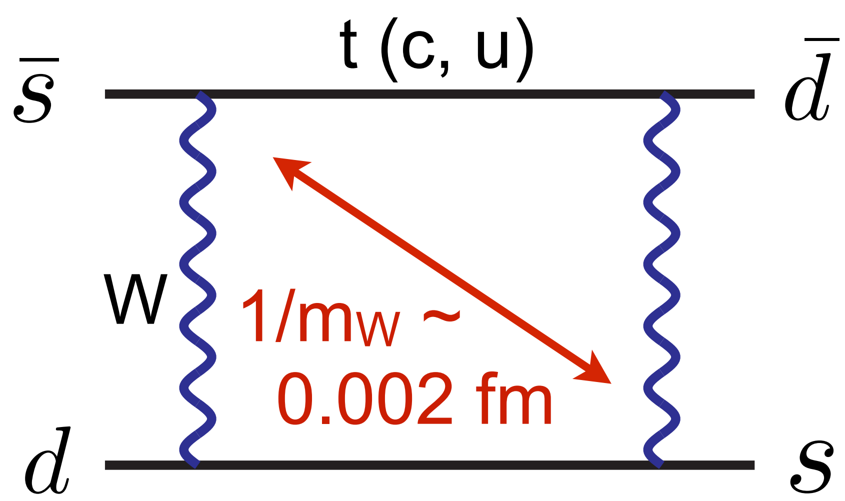
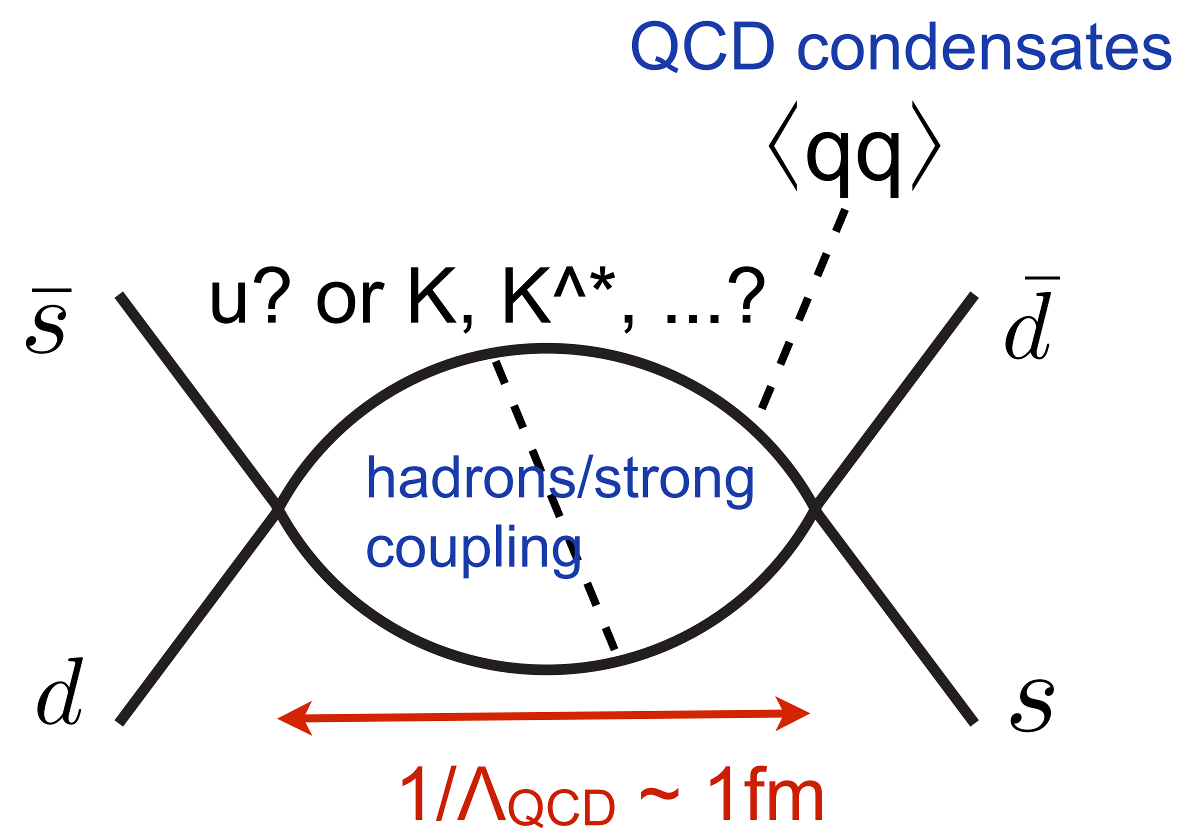


short distance

perturbation theory applies

vs

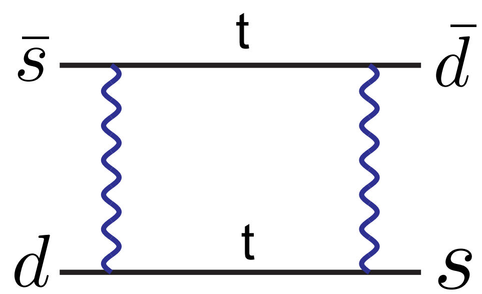


long distance

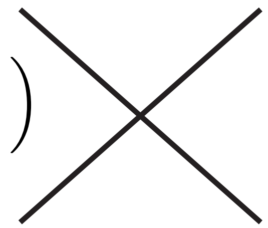
non-perturbative QCD essential

which dominates ?

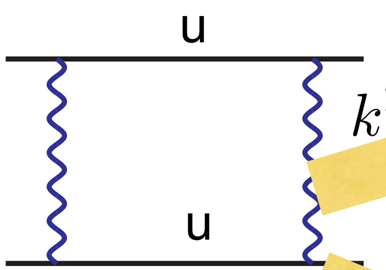
$K^0 - \bar{K}^0$ mixing



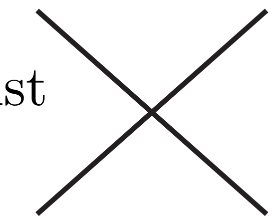
$\propto (V_{ts}V_{td}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2}\left(\frac{m_t^2}{M_W^2} + \dots\right)$



$\sim \frac{10^{-6}}{M_W^2}$ top quark loop
CKM-suppressed

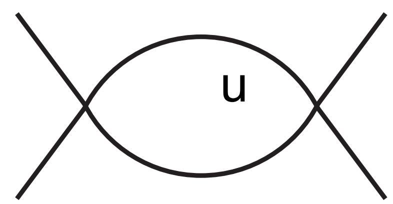


$k^2 \sim M_W^2$ $\propto (V_{us}V_{ud}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2} \times \text{const}$



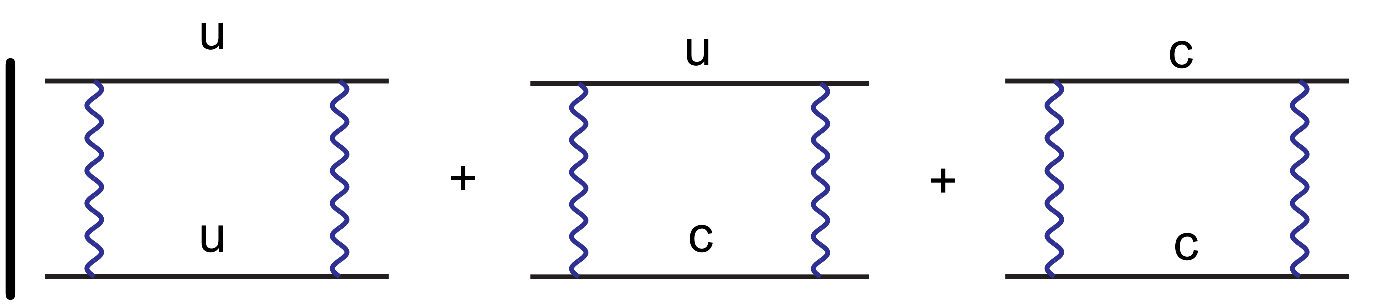
$\sim \frac{10^{-4}}{M_W^2}$ light quark loop
CKM-enhanced

$k^2 \sim \Lambda_{\text{QCD}}^2$ $\propto (V_{us}V_{ud}^*)^2 \frac{1}{M_W^4}$



$\propto (V_{us}V_{ud}^*)^2 \frac{\Lambda_{\text{QCD}}^2}{M_W^4}$ long-distance
power-suppressed
but CKM-enhanced

currently incalculable



$= \mathcal{O}(\Delta m_K^{\text{exp}})$ if $m_c \lesssim \text{GeV}$

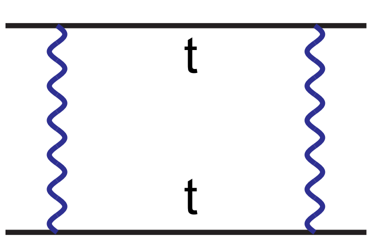
Δm_K long-distance dominated

$$(V_{us}V_{ud}^*)^2 + 2\,(V_{us}V_{ud}^*)(V_{cs}V_{cd}^*) + (V_{cs}V_{cd}^*)^2 = (V_{ts}V_{td}^*)^2$$

unitarity / GIM cancellation

CPV vanishes for 2 generations, so **must** involve top in the loop

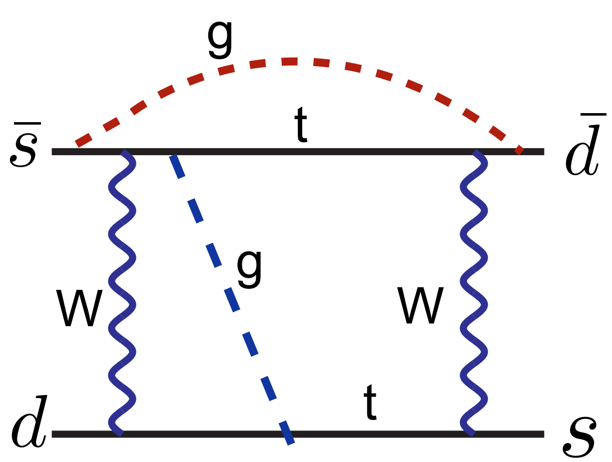
CPV in mixing short-distance dominated

Im 

=> $\epsilon_K = \mathcal{O}(10^{-3})$ constraint on V_{td}

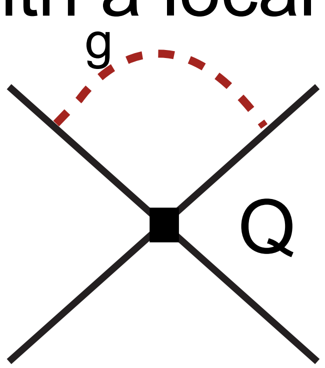
Higher-order corrections

We can draw QCD (gluon) corrections to the top loop diagram



As before, we should be wary of the loop integration region where k ~ Λ and perturbation theory doesn't apply. However, it turns out that these configurations can all be mimicked by diagrams with a local 4-quark vertex ("operator")

$C(\alpha_s,\mu)$

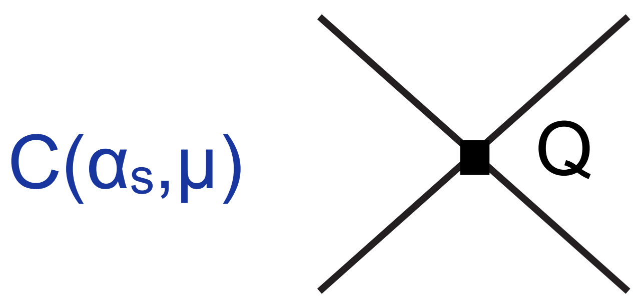


$$Q \equiv Q_1(\mu) = (\bar{s}\gamma^\mu P_L d)(\bar{s}\gamma_\mu P_L d)$$

multiplied by a **Wilson coefficient** which mimics the contributions from $k \sim m_W \sim m_t$. This works to all orders in perturbation theory and is presumed to still apply when quarks are replaced by hadrons

Renormalisation group & hadronic matrix elements

The Wilson coefficients depend on a renormalisation scale μ which enters in the course of renormalising divergences appearing from two loops. It has a physical, Wilsonian, interpretation as a cut-off on a low-energy effective theory, wherein a new coupling constant C(μ) contains the physics from quantum fluctuations with k>μ. We can lower μ changing C(μ) in a calculable manner (analogous to the running gauge couplings)



At μ~2 GeV, you can now ask your lattice theory friend to calculate the matrix element $\langle M|Q(\mu)|\bar{M}\rangle \equiv \frac{2}{3} f_M^2 m_M^2 B_M(\mu)$

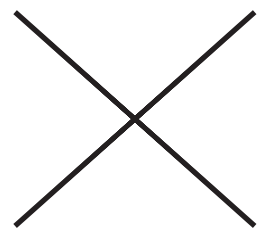
and subsequently you can calculate the local part of the mixing amplitude as $\mathcal{A}(\bar{M} \to M) = C(\mu)\langle M|Q(\mu)|\bar{M}\rangle$

This largely carries over to leptonic and semileptonic decays.

CP violation in $K^0 - \bar{K}^0$ mixing

For CP violation in Kaon mixing,

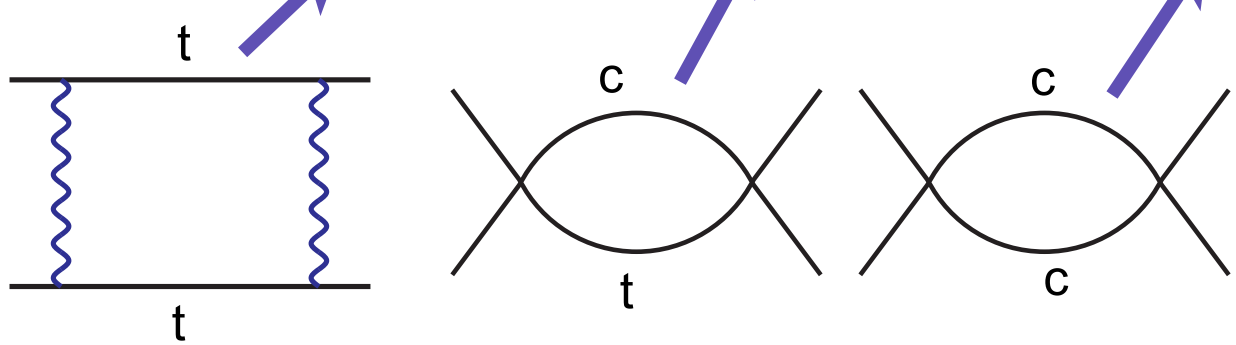
$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi \right)$$

$\hat{B}_K \propto \langle \bar{K}|$  $|K\rangle$

hadronic matrix element of the local operator Q (nonperturbative)

lattice calculation & (typically) perturbative continuum conversion

$$|\epsilon_K^{\mathrm{SM}}| = \kappa_\epsilon C_\epsilon \hat{B}_K |V_{cb}|^2 \lambda^2 \overline{\eta} \times$$
$$\left(|V_{cb}|^2 (1-\overline{\rho}) \eta_{tt} S_0(x_t) + \eta_{ct} S_0(x_c, x_t) - \eta_{cc} x_c \right)$$



short-distance “local” contributions including higher-order perturbative QCD corrections

correction factor from non-local contributions

$\kappa_\epsilon = 0.94 \pm 0.02$ Buras, Guadagnoli, Isidori 10

B physics

In B_d physics the CKM hierarchy is mild, and in B_s physics it is reversed. Hence, the nonlocal contributions are small enough to allow for a calculation of the mass differences.

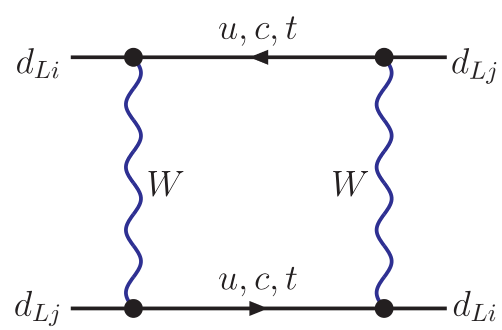
Moreover, the b quark mass is large enough for an expansion in Λ/m_b

This allows theoretical access to the lifetime difference, and is applicable to certain types of B decays with one or two hadrons in the final state.

$B_{(s)} - \bar{B}_{(s)}$ mixing

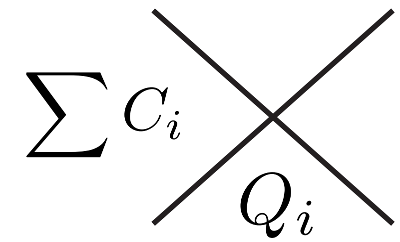
mixing-induced CP violation

- flavour violation: $\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$



+ ?

OPE (m_B/m_W)



M_{12}

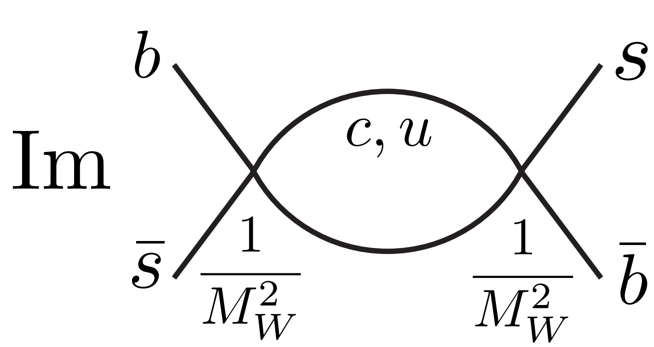
$\Delta M = 2|M_{12}|$

$$Q_1 = (\bar{s}^a_L \gamma_\mu b^a_L)(\bar{s}^b_L \gamma^\mu b^b_L),$$

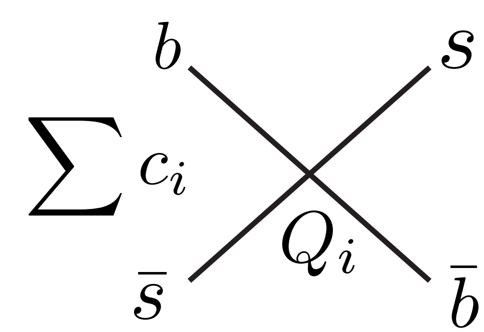
only operator present in SM

$$Q_2 = (\bar{s}^a_R b^a_L)(\bar{s}^b_R b^b_L),$$
$$Q_3 = (\bar{s}^a_R b^b_L)(\bar{s}^b_R b^a_L),$$
$$Q_4 = (\bar{s}^a_R b^a_L)(\bar{s}^b_L b^b_R),$$
$$Q_5 = (\bar{s}^a_R b^b_L)(\bar{s}^b_L b^a_R)$$

+ 3 more



OPE (Λ_{QCD}/m_B)



Γ_{12}

$\Delta\Gamma$

no NP contribution to Γ_{12} unless NP lighter than m_B or NP significantly affects b->c decays (which are tree-level size in the SM)

Time-dependent CP asymmetry

decay into CP eigenstate:

$$A_f = \langle f | B \rangle \qquad B \to f$$

$$M_{12}^q = |M_{12}^q| e^{-i\phi_{B_q}} \qquad B \to \bar{B} \to f \qquad \bar{A}_f = \langle f | \bar{B} \rangle$$

$$\lambda_f = e^{i\phi_{B_q}} \frac{\langle f | \bar{B}_q^0 \rangle}{\langle f | B_q^0 \rangle}$$

CP-violation parameter

$$\mathcal{A}_f^{\rm CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = S_f \sin(\Delta M t) - C_f \cos(\Delta M t)$$

$$S_f = \frac{2\,{\rm Im}\,\lambda_f}{1 + |\lambda_f|^2} \qquad C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$$

if only one decay amplitude:

$$A_f = A e^{i\theta} \qquad \bar{A}_f = A e^{-i\theta} \qquad C_f = 0 \qquad -\eta_{\rm CP}(f) S_f = \sin(\phi_{B_q} + 2\theta)$$

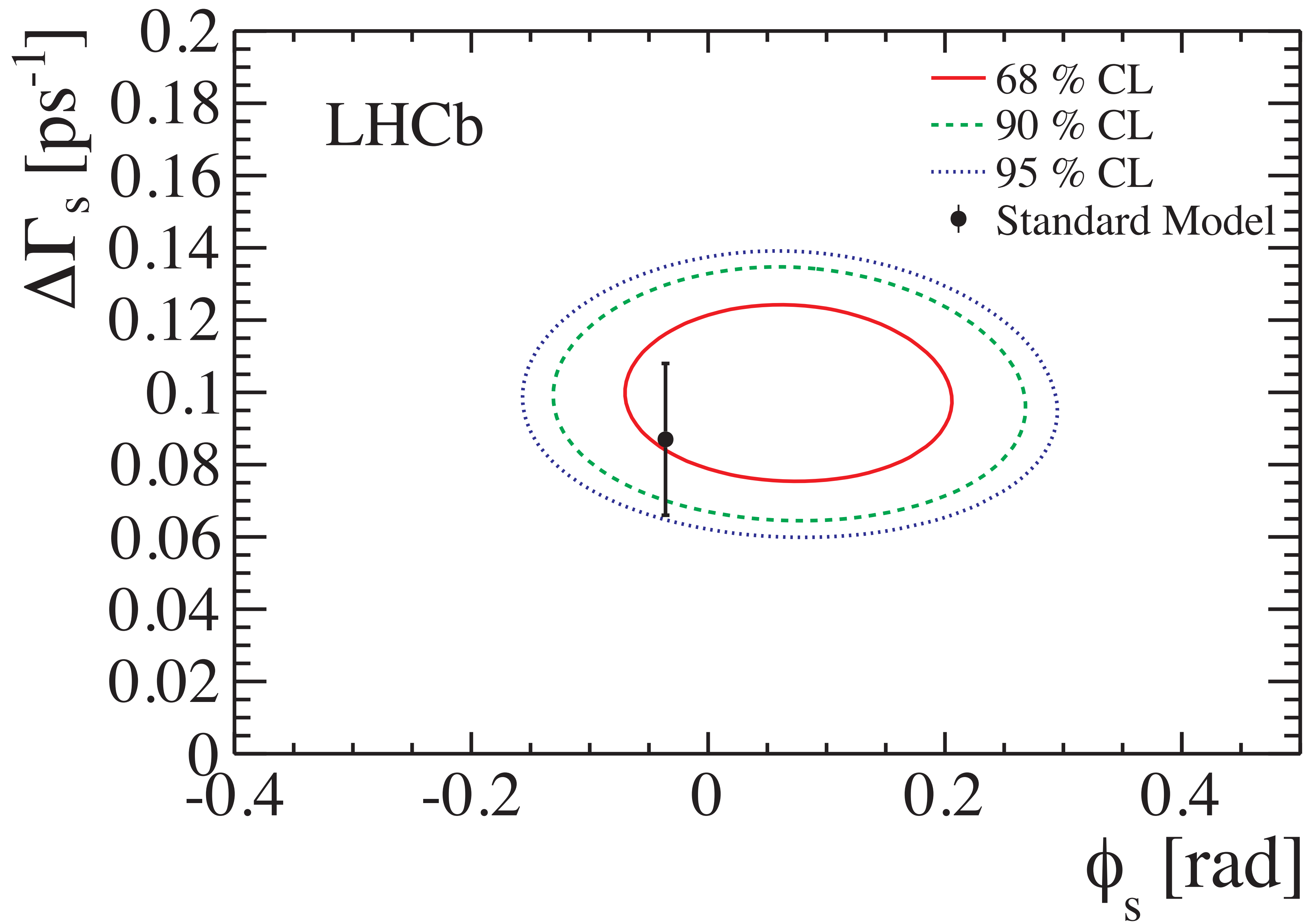
$B_d^0 \to \psi K_S \qquad S = \sin(\phi_{B_d}) = \sin(2\beta)$ — Beyond SM $\phi_{B_d} \neq 2\beta$

$B_d^0 \to \pi\pi, \pi\rho, \rho\rho \qquad S = \sin(\phi_{B_d} + 2\gamma) = -\sin(2\alpha)$

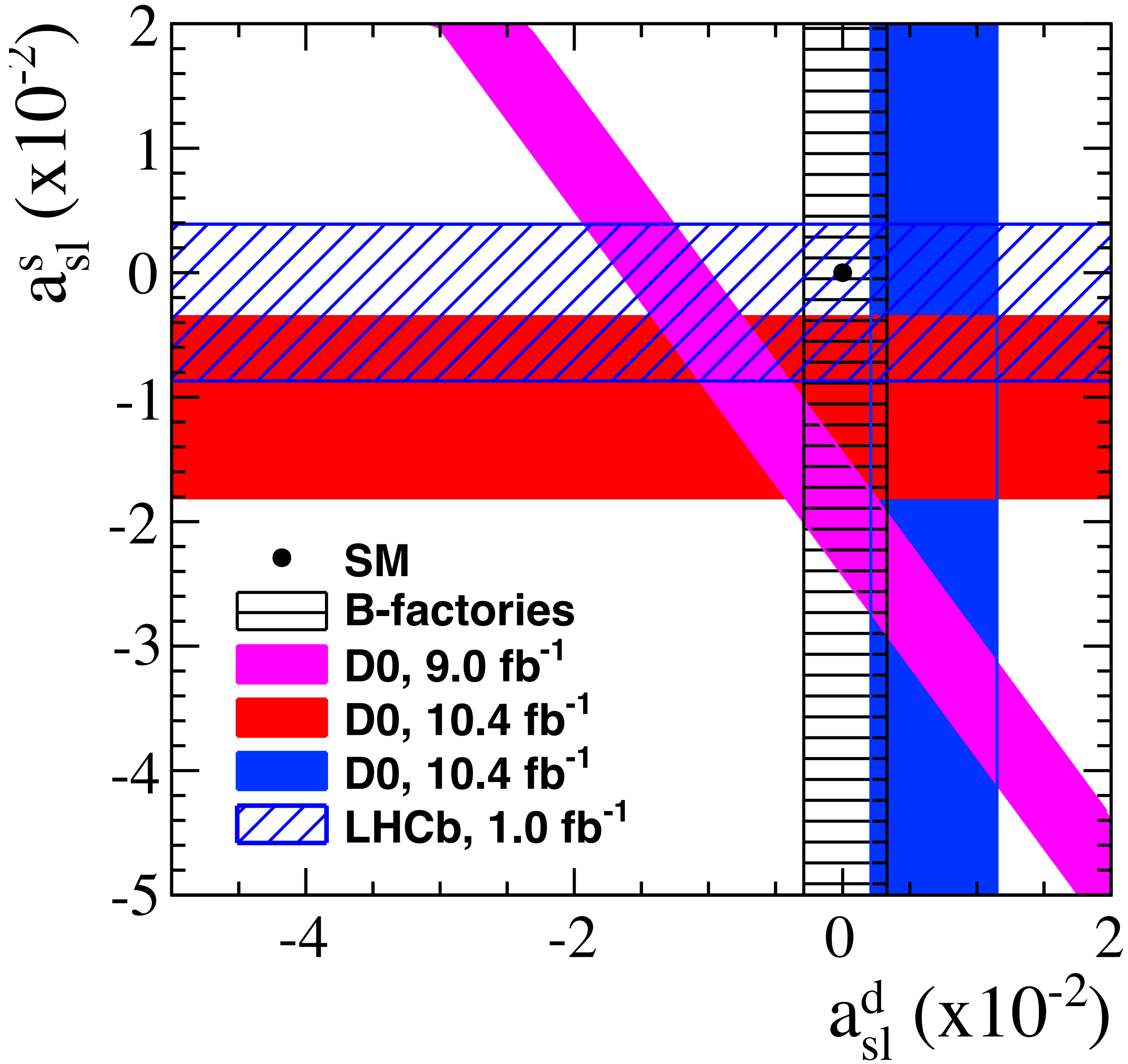
$B_s^0 \to J/\psi\,\phi \qquad \pm S = \sin\phi_{B_s} \approx 0$ — Beyond SM $\phi_{B_s} \neq 0$

can be generalized to non-CP final states $\qquad \phi_{B_{d,s}} + \gamma$ from $B_{(s)}^0 \to D_{(s)} K$

Note: The phase ϕ_{B_q} on this slide is the phase of M_{12} in the standard parameterisation. For B_s, this is very close to ϕ entering a_{fs} (also beyond SM)



[LHCb, arXiv:1304.2600v3]



[LHCb, arXiv:1306.0092v1]

Outlook

This was but a brief introduction to a huge and active field.

On the technical side:

- BSM effects in Wilson coefficients (see David Straub's lecture)
- Factorisation methods (based on Λ/m_B expansions)
- Flavour symmetry ($SU(3)_F$) methods

Key observables include
- many B decays accessible at LHCb,
eg exclusive leptonic & semileptonic (e.g. $B \to K^* \mu^+ \mu^-$, which shows interesting features in exp. data - sadly no time to cover)
- CP violation in K decays, D decays

Another area that has seen (and is seeing) enormous theoretical activity are inclusive B decays such as $B \to X_s \gamma$. Accessible at lepton colliders (Babar, Belle, future Belle2)

These, as mixing, provide powerful constraints on, and vehicles to discovery of BSM physics (see David Straub's lecture)

Reading

Here are a few examples out of many useful resources
Conventions and data:

PDG review “The CKM quark mixing matrix”, http://pdg.lbl.gov/ (go to Reviews,Tables,Plots -> Standard Model and Related Topics)
CKM fitter site: http://ckmfitter.in2p3.fr/
UTfit web site: http://utfit.org/
Heavy flavour averaging group: http://www.slac.stanford.edu/xorg/hfag/

Technicalities of weak Hamiltonian, RGE, etc

A Buras, Les Houches lectures “Weak Hamiltonian, CP violation and Rare decays”, arXiv:hep-ph/984071, very detailed and pedagogical

G Buchalla, A Buras, M Lautenbacher, Rev Mod Phys 68 (1996) 1125

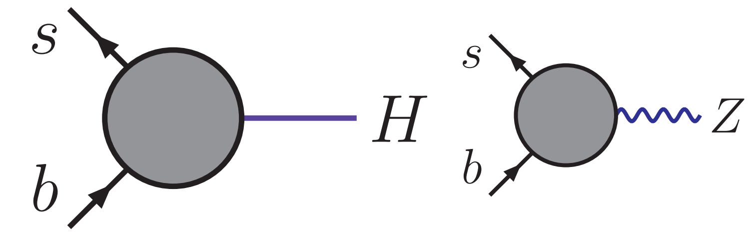
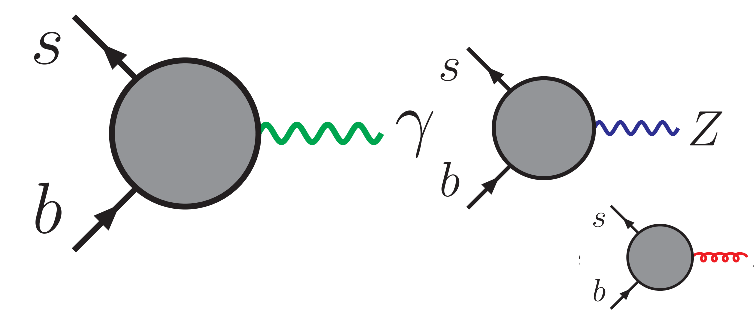
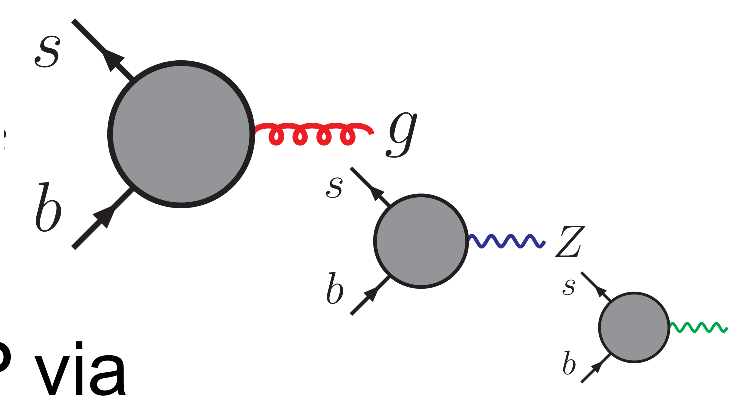
More recent, with more of a new-physics focus

Y Nir, lectures at the 2007 CERN summer school, arXiv:0708.1872

G Isidori, lectures at the 2011 CERN summer school, arXiv:1302.0661

Backup

Exclusive decays at LHCb

final state	strong dynamics	#obs	NP enters through
Leptonic $B \rightarrow l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \rightarrow K^* l^+ l^-$, $K^* \gamma$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \rightarrow \pi\pi$, πK, $\rho\rho$, ...	matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$	O(100)	

All non-radiative modes are also sensitive to NP via four-fermion operators

Decay constants and form factors are essential. Accessible by QCD sum rules and, increasingly, by lattice QCD.

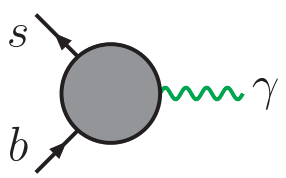
weak ΔB=ΔS=1 Hamiltonian

= EFT for ΔB=ΔS=1 transitions (up to dimension six)

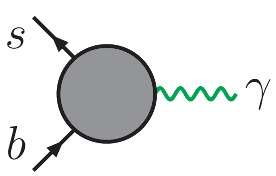
$$\mathcal{H}_{\rm eff}^{\rm had} = \frac{4G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left[C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3\ldots6} C_i P_i + C_{8g} Q_{8g} \right]$$

$$C_i \sim g_{\rm NP} \frac{m_W^2}{M_{\rm NP}^2}$$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} \lambda_t \Big[C_7 Q_{7\gamma} + C_7' Q_{7\gamma}' + C_9 Q_{9V} + C_9' Q_{9V}' + C_{10} Q_{10A} + C_{10}' Q_{10A}' + C_S Q_S + C_S' Q_S' + C_P Q_P + C_P' Q_P' + C_T Q_T + C_T' Q_T' \Big].$$



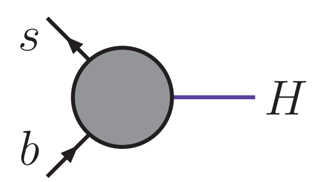
$$\mathcal{O}_7 = \frac{e}{16\pi^2}\, \hat{m}_b\, \bar{s} \sigma_{\mu\nu} P_R F^{\mu\nu} b\,,$$



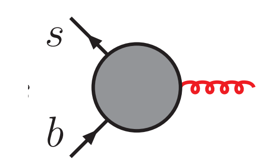
$$\mathcal{O}_V = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)\,,$$

$$\mathcal{O}_S = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l} l)\,,$$

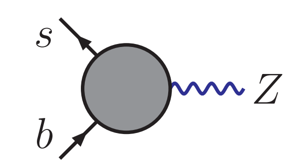
$$\mathcal{O}_T = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s}\sigma_{\mu\nu} P_R b)(\bar{l}\sigma^{\mu\nu} P_R s)\,,$$



$$\mathcal{O}_8 = \frac{g_s}{16\pi^2}\, \hat{m}_b\, \bar{s} \sigma_{\mu\nu} P_R G^{\mu\nu} b\,,$$



$$\mathcal{O}_A = \frac{\alpha_{\rm em}}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma^5 l)_A$$

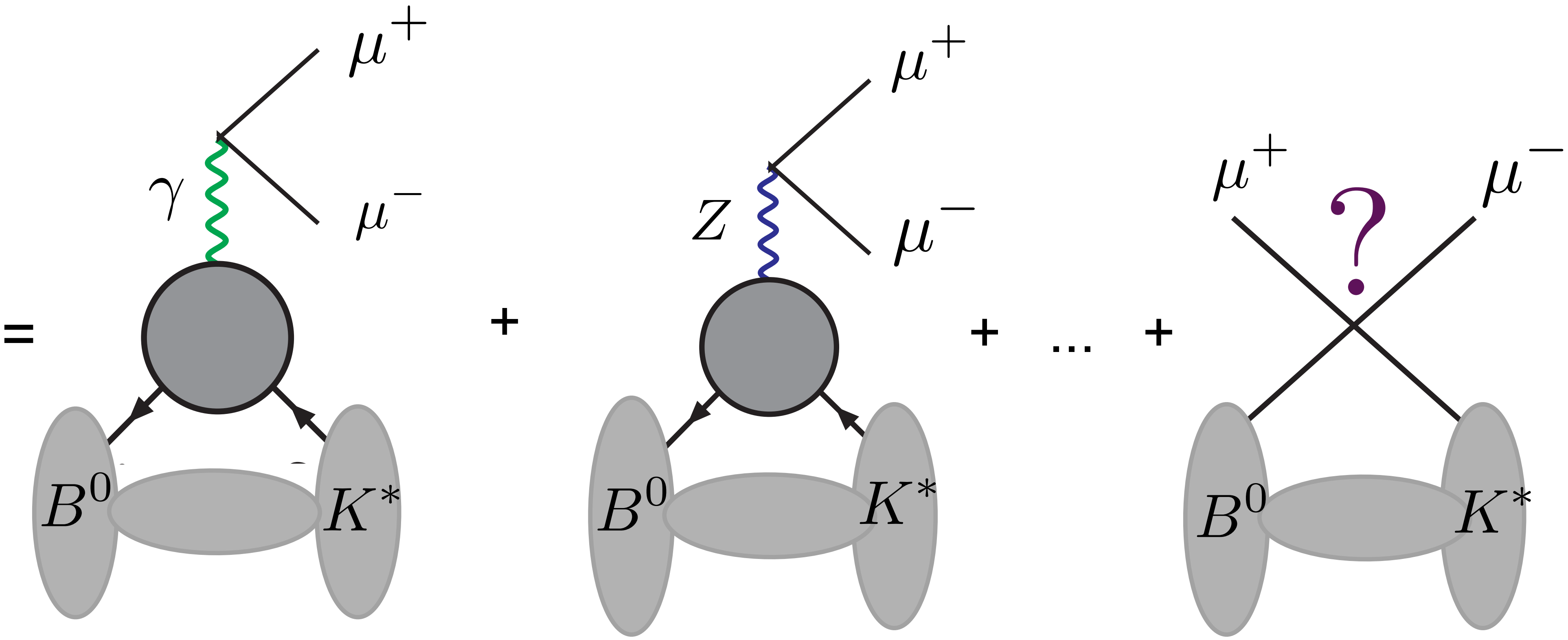


$$\mathcal{O}_P = \frac{\alpha_{\rm em}}{4\pi} \hat{m}_b (\bar{s} P_R b)(\bar{l}\gamma^5 l)\,,$$

look for observables sensitive to C_i's, specifically
those that are suppressed in the SM

Semileptonic decay

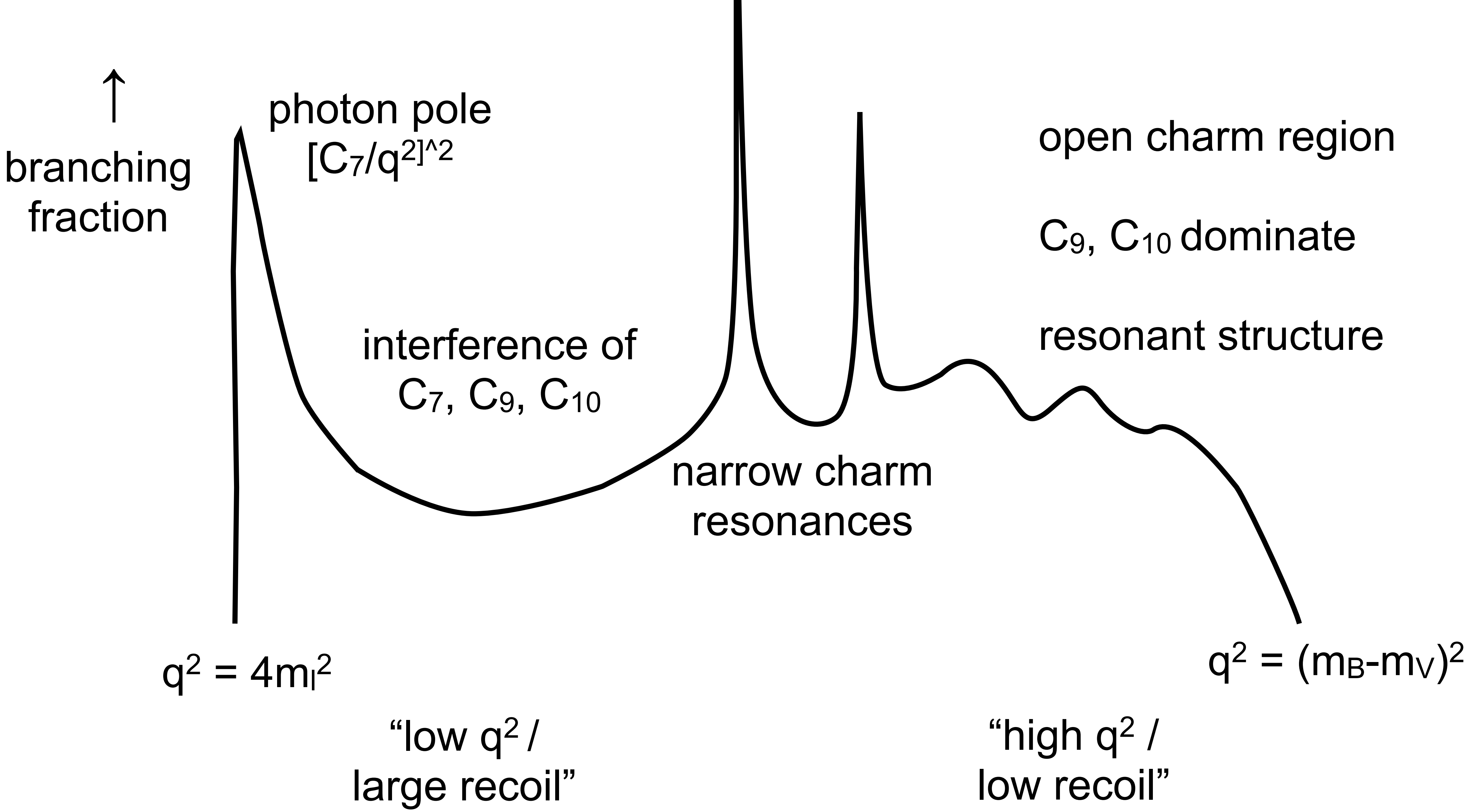
$A(B \rightarrow K^* l^+ l^-)$ =



- kinematics described by dilepton invariant mass q^2 and three angles
- Systematic theoretical description based on heavy-quark expansion (Λ/m_b) for $q^2 << m^2(J/\psi)$ (SCET) Beneke, Feldmann, Seidel 01
  also for $q^2 >> m^2(J/\psi)$ (OPE) Grinstein et al; Beylich et al 2011
  Theoretical uncertainties on form factors, power corrections

SJ, J Martin Camalich 1212.2263

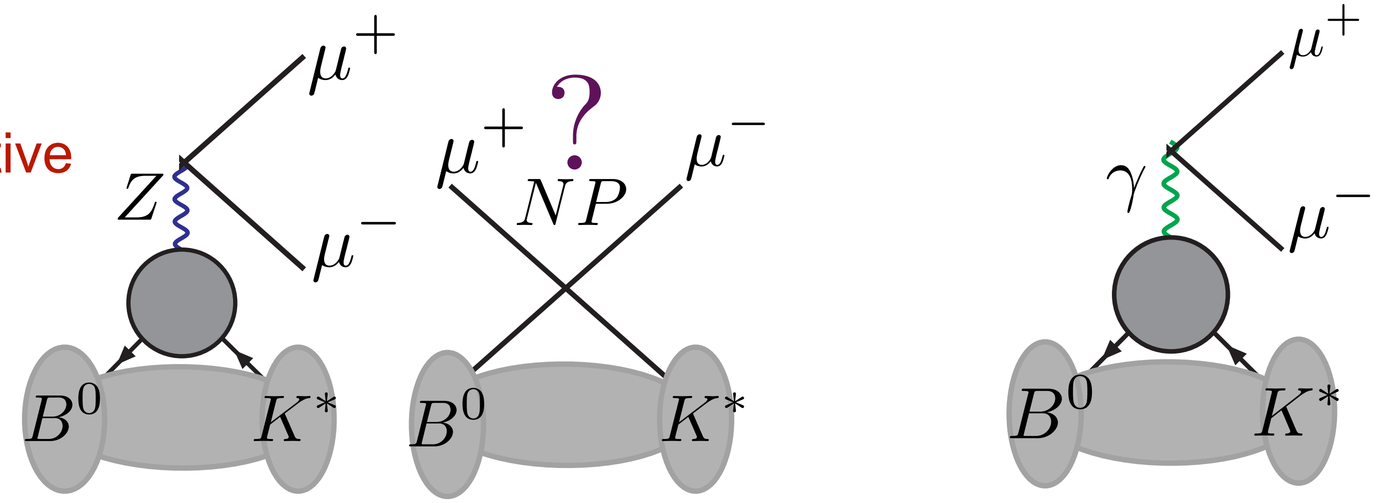
q^2 dependence (qualitative)



Note - artist's impression only.
LHCb has not yet published sufficiently fine binning to show the resonant features
[open charm resonances are however visible in published B->K l l data]

B->K*l+ l-   decay amplitude

matrix elements of semileptonic/radiative Hamiltonian factorize "naively"

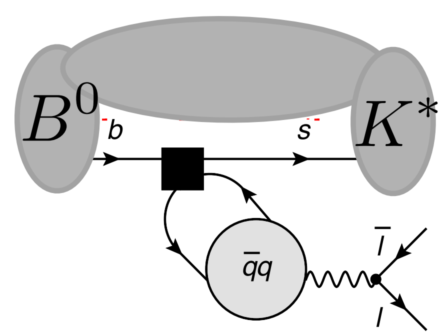


lepton current   form factor   lepton current   form factor

$$\mathcal{A}(\bar B \to V\ell^-\ell^+) = \sum_i C_i \langle \ell^-\ell^+|\bar l \Gamma_i l|0\rangle\langle V|\bar s\Gamma_i' b|\bar B\rangle + C_7^{(\prime)}\frac{e^2}{q^2}\langle \ell^+\ell^-|\bar l\gamma^\mu l|0\rangle\langle V|\bar s\sigma_{\mu\nu}P_{R(L)}b|\bar B\rangle$$

B^0

$$+\frac{e^2}{q^2}\langle\ell^-\ell^+|\bar l\gamma^\mu l|0\rangle F.T.\langle V|T(j^{\rm had}_{\mu,\rm em}(x)\mathcal{H}_W^{\rm had}(0))|\bar B\rangle$$



nonlocal "quark loops"

do **not** factorize naively

correct to lowest order in electromagnetism
exact in QCD - no assumptions (yet)

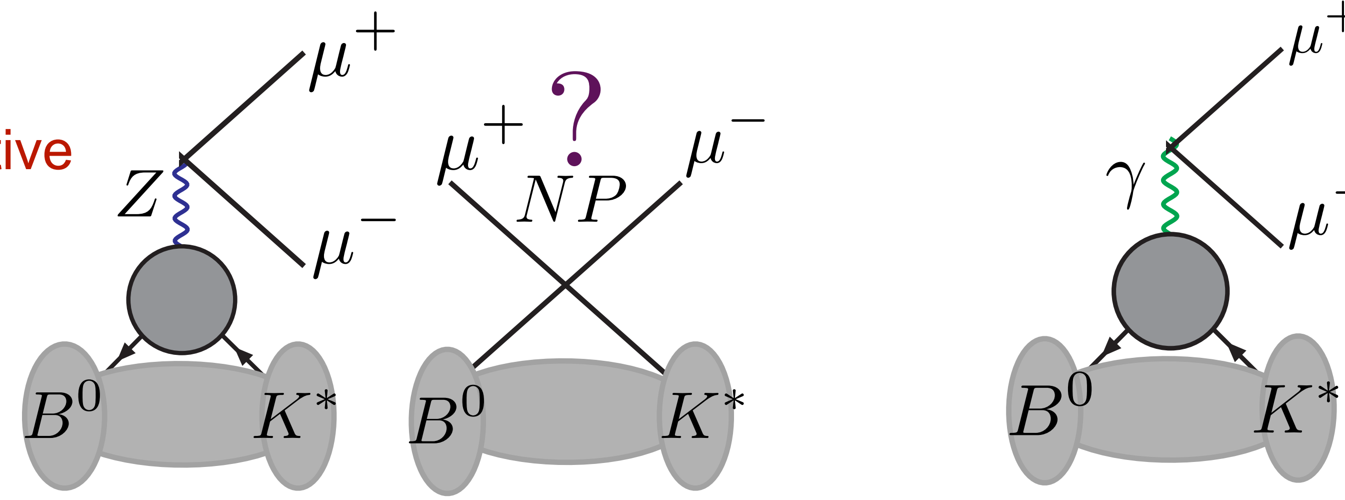
three helicity states for V=K*
dilepton can have J=0 or J=1
several leptonic currents

} 7 (14) helicity amplitudes in SM (BSM)

photon couples only to **vector** leptonic current. At $q^2 = 0$ photon pole

B->K*l$^+$ l$^-$ decay amplitude

matrix elements of semileptonic/radiative Hamiltonian factorize “naively”



lepton current form factor lepton current form factor

$$\mathcal{A}(\bar B\to V\ell^-\ell^+) = \sum_i C_i\langle \ell^-\ell^+|\bar l\Gamma_i l|0\rangle\langle V|\bar s\Gamma'_i b|\bar B\rangle + C_7^{(\prime)}\frac{e^2}{q^2}\langle\ell^+\ell^-|\bar l\gamma^\mu l|0\rangle\langle V|\bar s\sigma_{\mu\nu}P_{R(L)}b|\bar B\rangle$$

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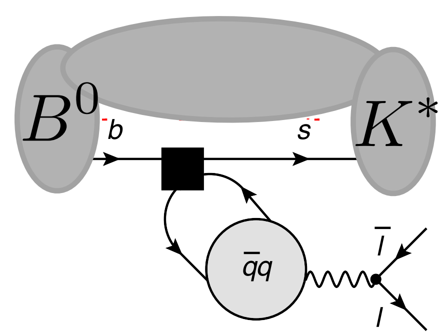

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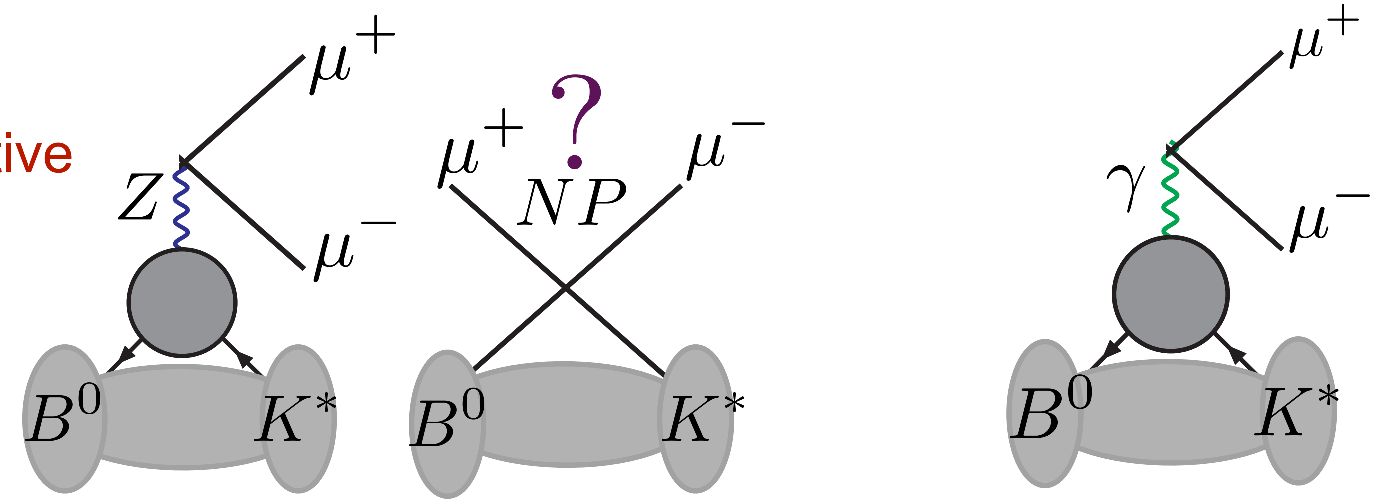

lepton current | form factor | lepton current | form factor

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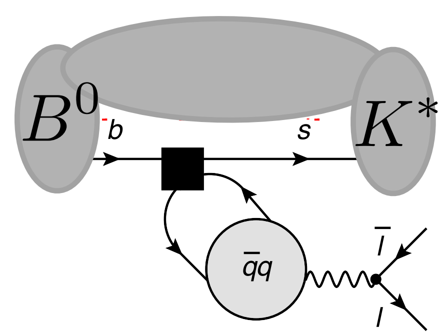
B^0

$$+\frac{e^2}{q^2}\langle\ell^-\ell^+|\bar l\gamma^\mu l|0\rangle F.T.\langle V|T(j^{\rm had}_{\mu,\rm em}(x)\mathcal{H}_W^{\rm had}(0))|\bar B\rangle$$



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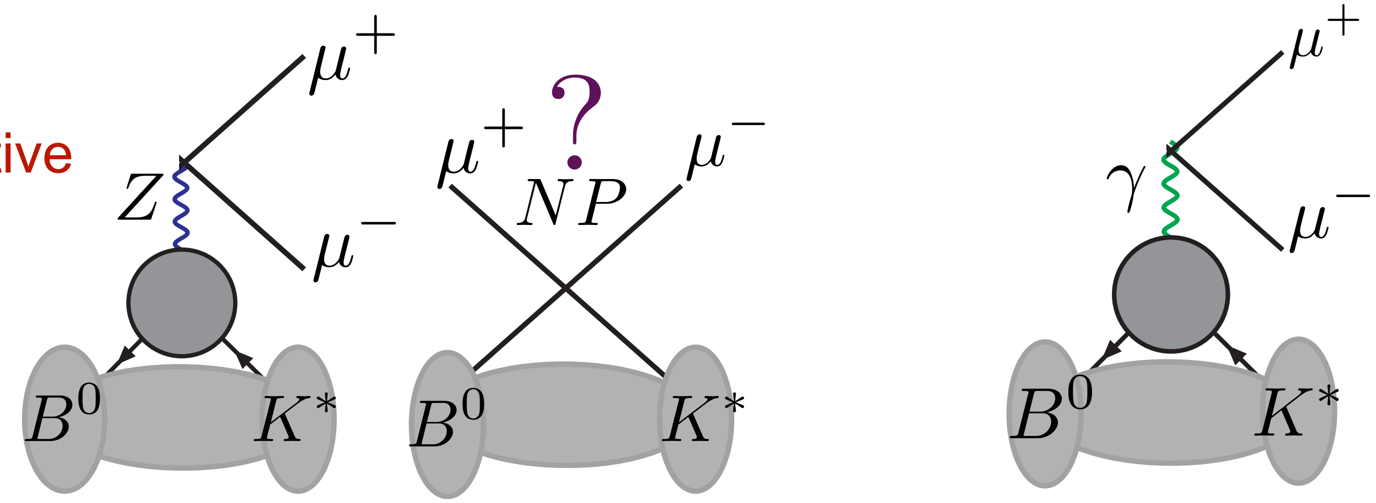

lepton current　form factor　lepton current　form factor

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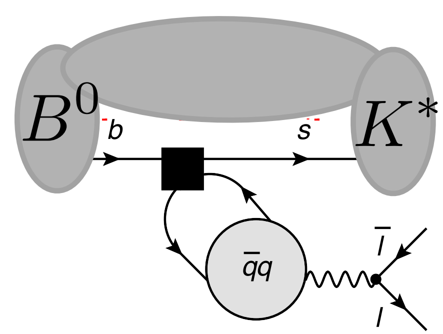
B^0

$$+ \frac{e^2}{q^2} \langle \ell^- \ell^+ | \bar{l} \gamma^\mu l | 0 \rangle F.T. \langle V | T(j^{\rm had}_{\mu,\rm em}(x) \mathcal{H}^{\rm had}_W(0)) | \bar{B} \rangle$$



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In the news

- PRL **111,** 191801 (2013) PHYSICAL REVIEW LETTERS week ending 8 NOVEMBER 2013

Measurement of Form-Factor-Independent Observables in the Decay $B^0 \to K^{*0}\mu^+\mu^-$

R. Aaij *et al.**
(LHCb Collaboration)
(Received 9 August 2013; published 4 November 2013)

We present a measurement of form-factor-independent angular observables in the decay $B^0 \to K^*(892)^0\mu^+\mu^-$. The analysis is based on a data sample corresponding to an integrated luminosity of 1.0 fb^{-1}, collected by the LHCb experiment in pp collisions at a center-of-mass energy of 7 TeV. Four observables are measured in six bins of the dimuon invariant mass squared q^2 in the range $0.1 < q^2 < 19.0\ \mathrm{GeV}^2/c^4$. Agreement with recent theoretical predictions of the standard model is found for 23 of the 24 measurements. A local discrepancy, corresponding to 3.7 Gaussian standard deviations is observed in one q^2 bin for one of the observables. Considering the 24 measurements as independent, the probability to observe such a discrepancy, or larger, in one is 0.5%.

DOI: 10.1103/PhysRevLett.111.191801 PACS numbers: 13.20.He, 11.30.Rd, 12.60.−i

Descotes-Genon, Matias, Virto e PRD 88,074002 claim 3.9 *global*

further model-independent fits: Altmannshofer&Straub; Beaujean, Bobeth, van Dyk

interpretation in NP models: Gauld,Goertz,Haisch; Buras&Girrbach; Buras, DeFazio, Girrbach

In the news

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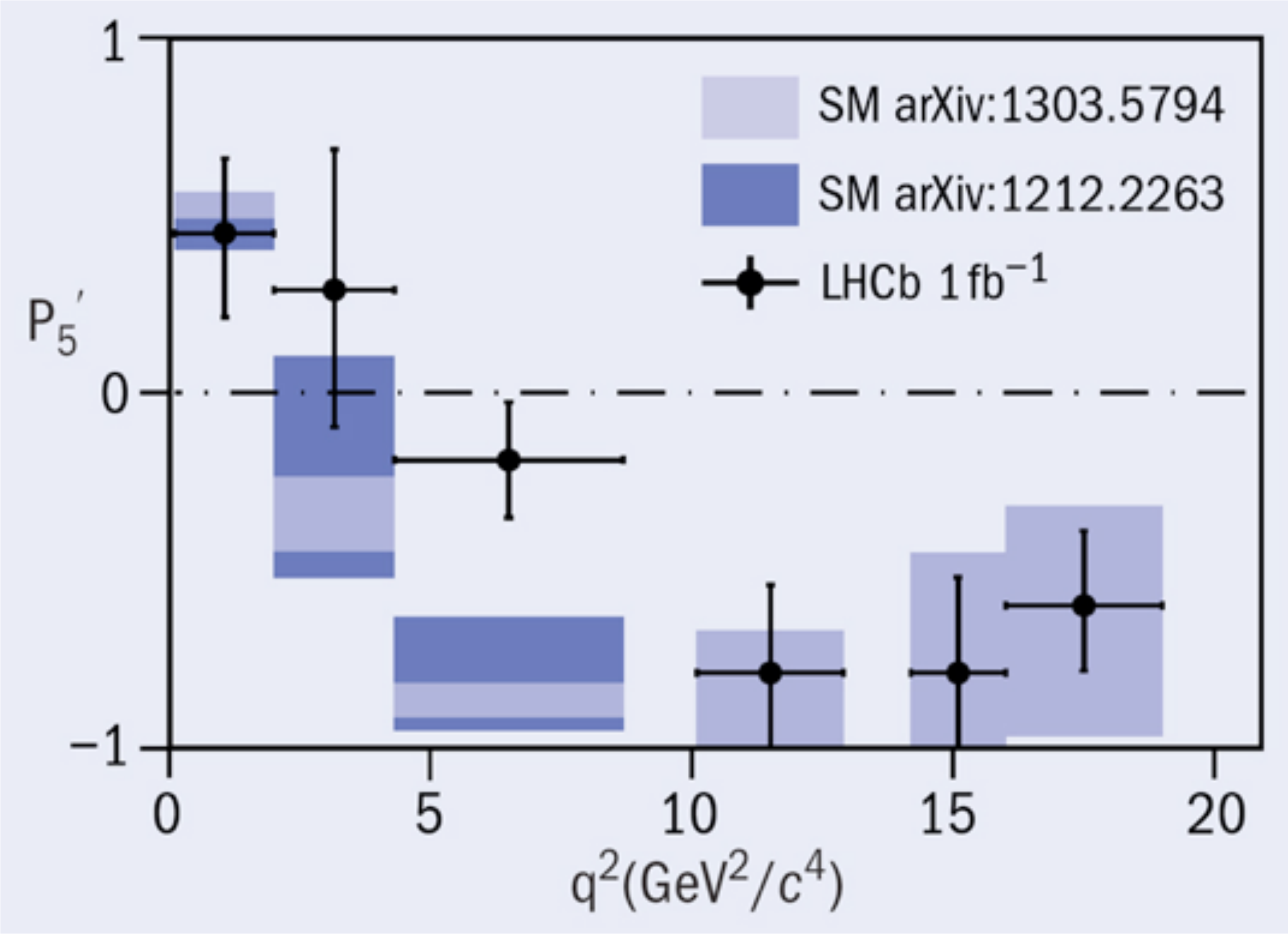
P_5' "anomaly"

$$\langle P_5' \rangle = \frac{\langle \beta(\mathrm{Re}[(H_V^- - H_V^+)H_A^{0*} + (H_A^- - H_A^+)H_V^{0*})\rangle}{\sqrt{\langle \beta^2 |H_V^0|^2 + |H_A^0|^2)\rangle \langle \beta^2(|H_V^+|^2 + |H_V^-|^2 + |H_A^+|^2 + |H_A^-|^2)\rangle}}$$

CERN Courier, December 2013



Descotes-Genon, Matias, Virto [DMV]

SJ, J Martin Camalich (4.3..8.68 bin actually a private update, not stated in paper)

P_5' has strong sensitivity to long-distance power corrections. Ongoing discussion.

Flavour:
the glorious past ...
template for the future?

A very brief history of flavour

1934 Fermi proposes Hamiltonian for beta decay

$$H_W = -G_F(\bar{p}\gamma^\mu n)(\bar{e}\gamma_\mu \nu)$$

1956-57 Lee&Yang propose parity violation to explain "θ-τ paradox".
Wu et al show parity is violated in β decay
Goldhaber et al show that the neutrinos produced in ^{152}Eu K-capture always have negative helicity

1957 Gell-Mann & Feynman, Marshak & Sudarshan

$$H_W = -G_F(\bar{\nu}_\mu \gamma^\mu P_L \mu)(\bar{e}\gamma_\mu P_L \nu_e) - G(\bar{p}\gamma^\mu P_L n)(\bar{e}\gamma_\mu P_L \nu_e) + \ldots$$

V-A current-current structure of weak interactions.
Conservation of vector current proposed
Experiments give G = 0.96 G_F (for the vector parts)

1960-63 To achieve a universal coupling, Gell-Mann&Levy and Cabibbo propose that a certain superposition of neutron and Λ particle enters the weak current. Flavour physics begins!

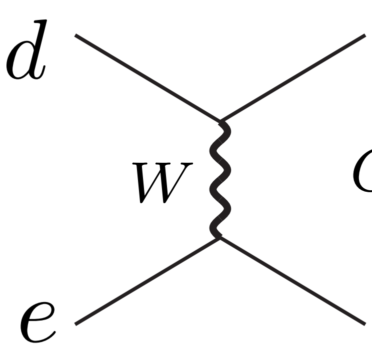
1964 Gell-Mann gives hadronic weak current in the quark model

$$H_W = -G_F J^\mu J_\mu^\dagger$$

$$J^\mu = \bar{u}\gamma^\mu P_L(\cos\theta_c d + \sin\theta_c s) + \bar{\nu}_e\gamma^\mu P_L e + \bar{\nu}_\mu\gamma^\mu P_L \mu$$

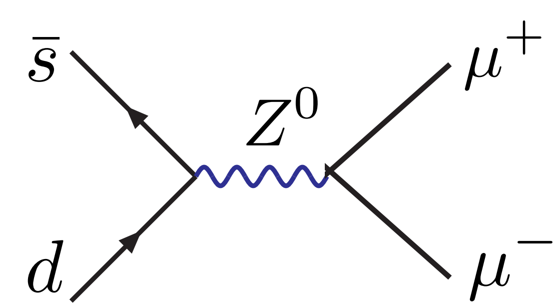
1964 CP violation discovered in Kaon decays (Cronin&Fitch)

1960-1968 J_μ part of triplet of weak gauge currents. Neutral current interactions predicted and, later, observed at CERN.



$$G_F = \frac{g^2}{4\sqrt{2}M_W^2}$$

However, the predicted flavour-changing neutral current (FCNC) processes such as $K_L \to \mu^+\mu^-$ are *not* observed!

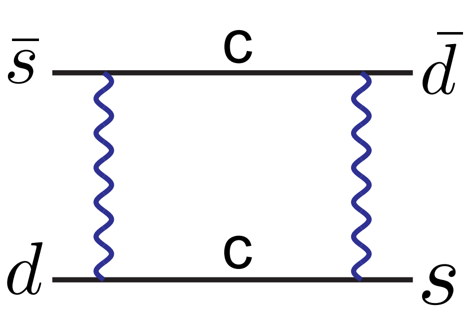


1970 To explain the absence of $K_L \rightarrow \mu^+\mu^-$, Glashow, Iliopoulos & Maiani (GIM) couple a "charmed quark" to the formerly "sterile" linear combination
$-\sin\theta_c d_L + \cos\theta_c s_L$
The doublet structure eliminates the Zsd coupling!

1971 Weak interactions are renormalizable ('t Hooft)

1972 Kobayashi & Maskawa show that CP violation requires extra particles, for example a third doublet. CKM matrix

1974 Gaillard & Lee estimate loop contributions to the K_L-K_S mass difference
Bound m_c < 5 GeV



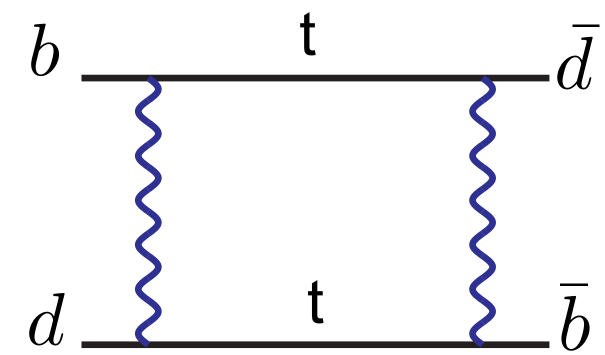
1974 Charm quark discovered

1977 τ lepton and bottom quark discovered

1983 W and Z bosons produced

1987 ARGUS measures B_d - B_d mass difference
First indication of a heavy top

The diagram depends quadratically on m_t



1995 top quark discovered at CDF & D0

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	u_R d_R	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	c_R s_R	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	t_R b_R	$Q = +2/3$ $Q = -1/3$
$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$-$ e_R	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$-$ μ_R	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	$-$ τ_R	$Q = 0$ $Q = -1$

Precision measurements: masses, running coupling, direct CP violation, B factories, determination of CKM elements, neutrino oscillations, search for electric dipole moments, proton decay, ...