Flavour at the TeV scale

Sebastian Jäger

University of Sussex

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Contents

Flavour:
the story so far...

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

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

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!

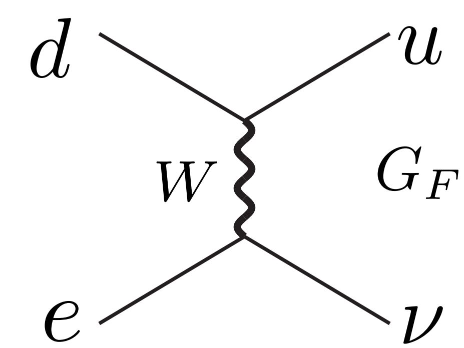
1964 Gell-Mann gives hadronic weak current in the quark model

$$H_W = -G_F J^\mu J^\dagger_\mu$$

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

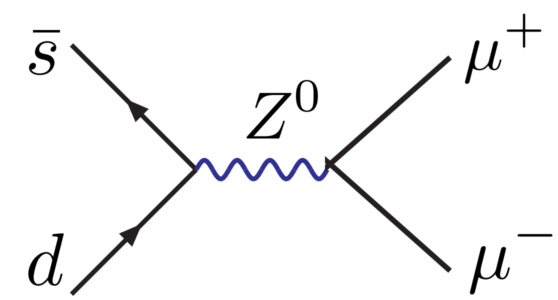
1964 CP violation discovered in Kaon decays

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 $K_L \rightarrow \mu^+\mu^-$ are *not* observed!

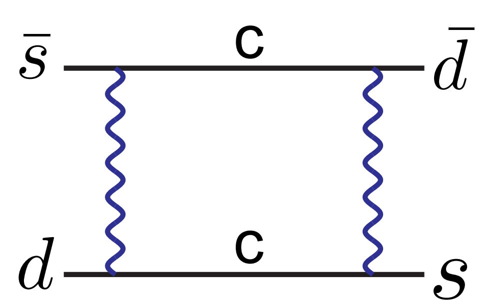


1970 To explain the absence of $K_L \rightarrow \mu^+\mu^-$, Glashow, Iliopoulos & Maiani (GIM) invent the charmed quark and couple it to the formerly “sterile” linear combination $-\sin\theta_c d_L + \cos\theta_c s_L$
The doublet structure eliminates the Zsd coupling!

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



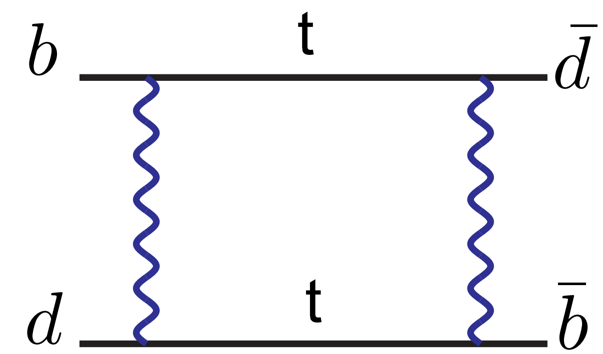
1974 Charm quark discovered

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

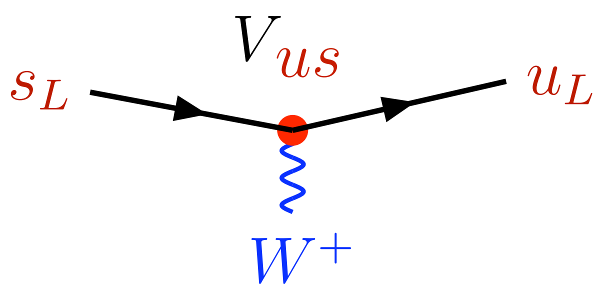


1995 top quark discovered at CDF & D0

$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	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	$Q = 0$ $Q = -1$

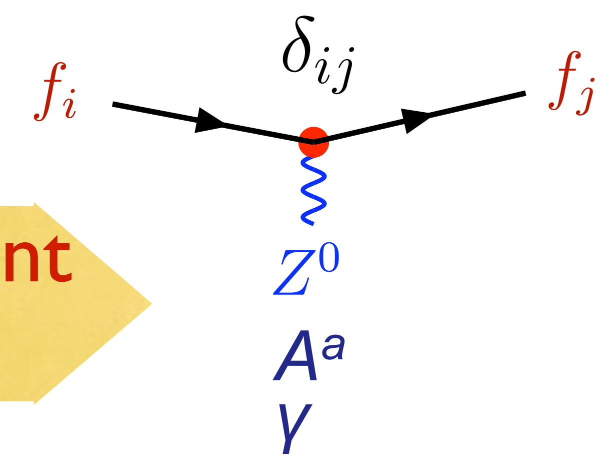
Precision measurements: masses, running coupling, direct CP violation, B factories, determination of CKM elements, neutrino oscillations, search for electric dipole moments, proton decay, ...

SM flavour: CKM matrix



all flavour violation in charged current

(tree) neutral current conserves flavor



$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\lambda \equiv \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}} = 0.2255 \pm 0.0029$$ nucl. beta decay, n lifetime

$$|V_{cb}| = A\lambda |V_{us}| = (41.2 \pm 1.1) \times 10^{-3}$$ excl. & incl. b->c decay

$$\bar{\rho} + i\bar{\eta} \equiv -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \rho + i\eta + \mathcal{O}(\lambda^2)$$

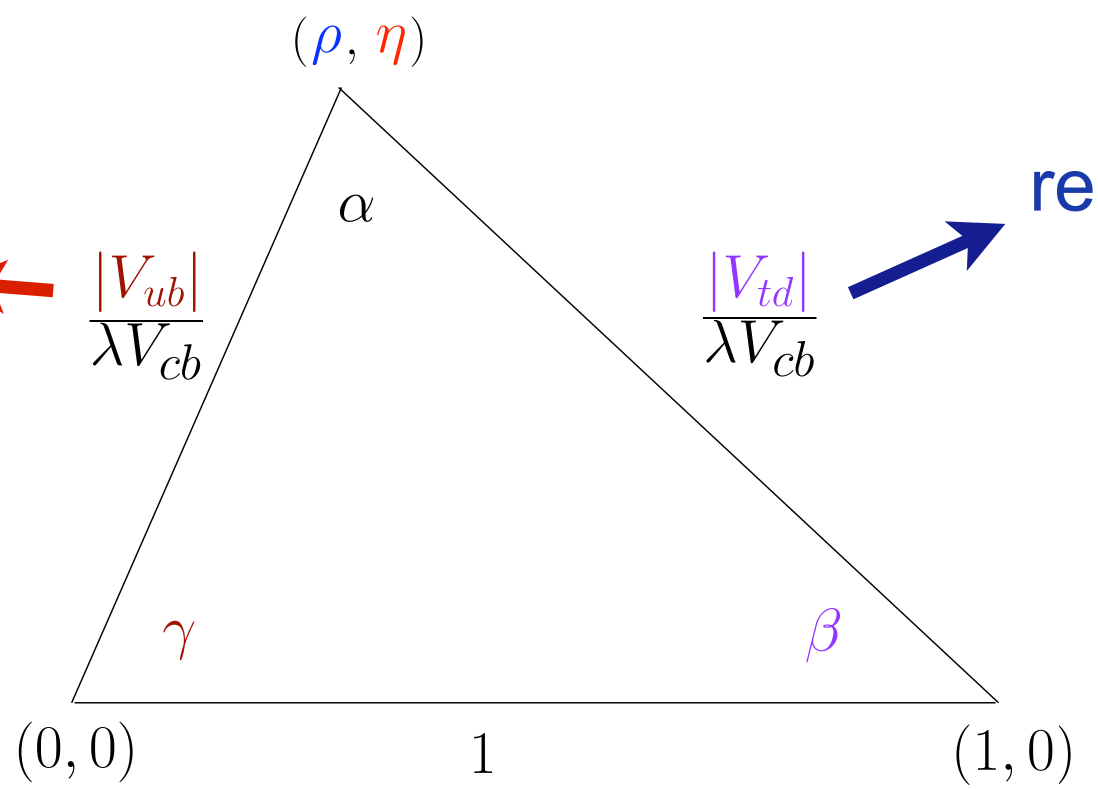
2 parameters to be determined
one complex - CP violating

Unitarity triangle

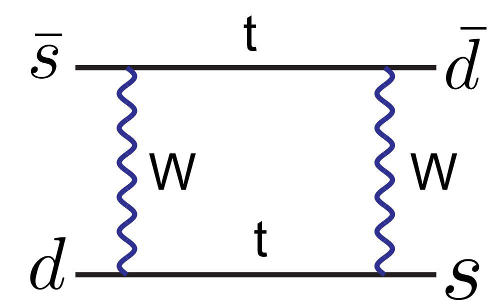
Unitarity of V $\Rightarrow$
$$\begin{aligned} V_{ub}^* V_{ud} \quad &+ \quad V_{cb}^* V_{cd} \quad + \quad V_{tb}^* V_{td} &= 0 \\ A\lambda^3(\rho + i\eta) \quad &- \quad A\lambda^3 \quad + \quad A\lambda^3(1-\rho-i\eta) &= 0 \end{aligned}$$

Graphically,

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

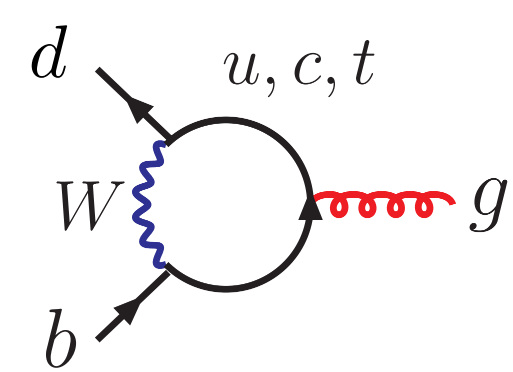


requires top loop



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

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

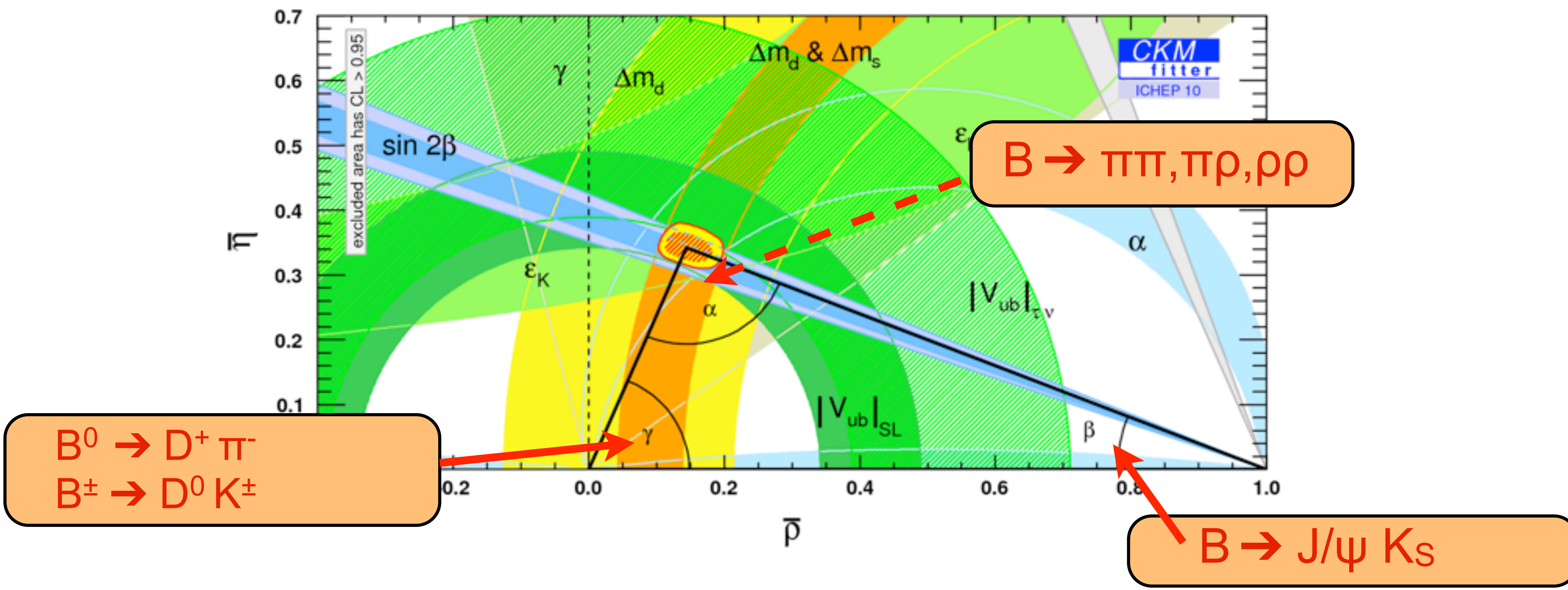


suppression of FCNC by loops and CKM hierarchy

This makes them sensitive to new physics!

Unitarity Triangle 2010

apologies to UTfit, who obtain consistent results



The CKM picture of flavour & CP violation is consistent with observations.

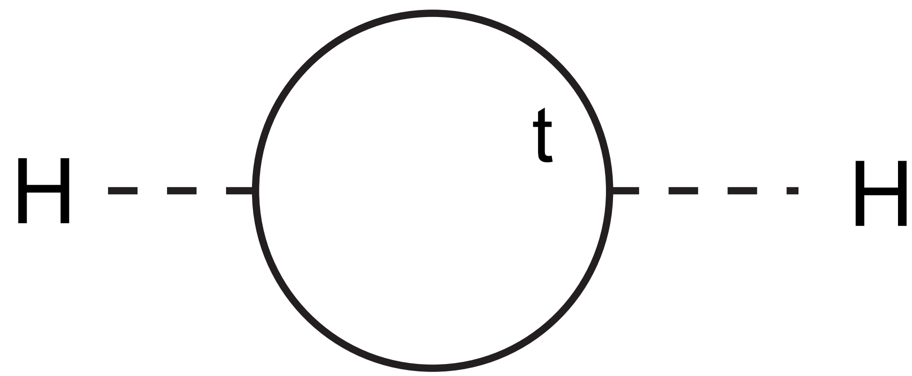
Within the Standard Model, all parameters (except higgs mass) including CKM have been determined, most to at least few percent accuracy.

However, this is unlikely to be the whole story

Flavour at the TeV scale

- Much of present theory activity - and of LHC - is motivated by exploring the weak scale and by its sensitivity to radiative corrections

- This derives in part from



$$\propto y_t^2 \Lambda_{\rm UV}^2$$

hence physics that stabilizes weak scale should contain new flavoured particles. This is what happens in
SUSY (stop),
warped extra dimensions (KK modes),
little Higgs (heavy T),
technicolour,
etc.

- Such particles will always contribute to FCNC

SUSY flavour

Supersymmetry associates a scalar with every SM fermion

Squark mass matrices are 6x6 with independent flavour structure:

3x3 flavour-violating

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} \hat{m}^2_{\tilde{Q}} + m_d^2 + D_{dLL} & v_1 \hat{T}_D - \mu^* m_d \tan\beta \\ v_1 \hat{T}_D^\dagger - \mu m_d \tan\beta & \hat{m}^2_{\tilde{d}} + m_d^2 + D_{dRR} \end{pmatrix} \equiv \begin{pmatrix} (\mathcal{M}^2_{\tilde{d}})^{LL} & (\mathcal{M}^2_{\tilde{d}})^{LR} \\ (\mathcal{M}^2_{\tilde{d}})^{RL} & (\mathcal{M}^2_{\tilde{d}})^{RR} \end{pmatrix}$$

LR mass terms are $SU(2)_W$-breaking - related to trilinear scalar couplings

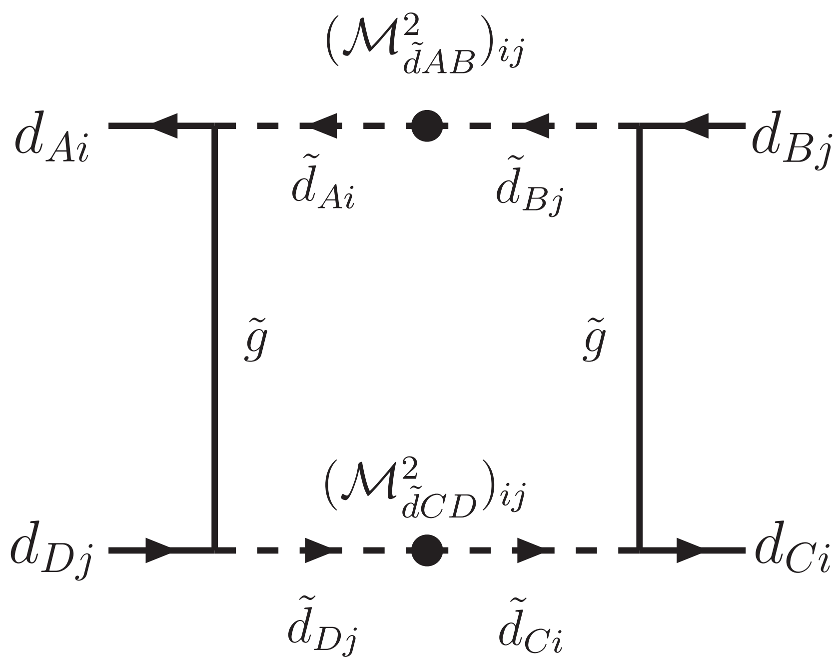
similar for up squarks, charged sleptons. 3x3 LL for sneutrinos

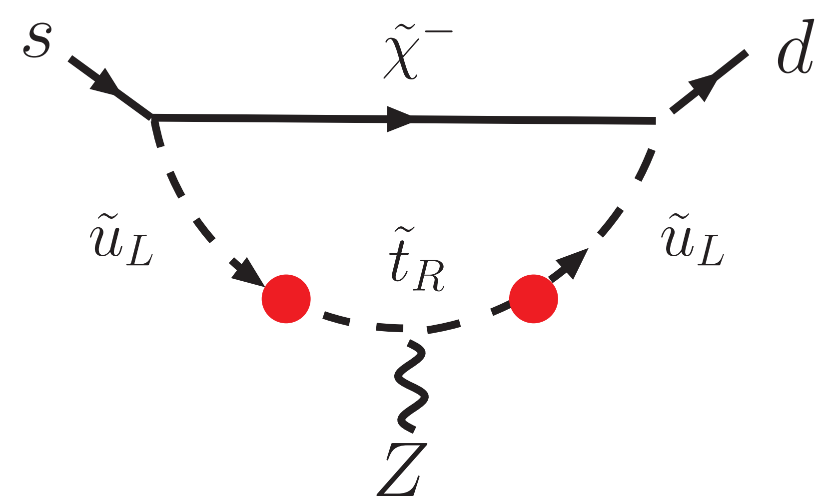
$$(\delta^{u,d,e,\nu}_{ij})_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

33 flavour-violating parameters

45 CPV (some flavour-conserving)

SUSY flavour (2)





K-$\overline{K}$, B_d-$\overline{B}_d$, B_s-$\overline{B}_s$ mixing

$\Delta F=1$ decays

$B \to K^* \mu^+ \mu^-$
$B \to K^* \gamma$
$B \to K\pi$
$B_{s,d} \to \mu^+ \mu^-$
$K \to \pi\nu\nu$
...

SUSY flavour puzzle

$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

where are their effects?

Quantity	upper bound
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{ds})^2_{LL}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{ds})^2_{RR}\rvert}$	4.0×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{ds})^2_{LR}\rvert}$	4.4×10^{-3}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{ds})_{LL}(\delta^{\tilde{d}}_{ds})_{RR}\rvert}$	2.8×10^{-3}
$\sqrt{\lvert \mathrm{Im}(\delta^{\tilde{d}}_{ds})^2_{LL}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert \mathrm{Im}(\delta^{\tilde{d}}_{ds})^2_{RR}\rvert}$	3.2×10^{-3}
$\sqrt{\lvert \mathrm{Im}(\delta^{\tilde{d}}_{ds})^2_{LR}\rvert}$	3.5×10^{-4}
$\sqrt{\lvert \mathrm{Im}(\delta^{\tilde{d}}_{ds})_{LL}(\delta^{\tilde{d}}_{ds})_{RR}\rvert}$	2.2×10^{-4}

Quantity	upper bound
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{db})^2_{LL}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{db})^2_{RR}\rvert}$	9.8×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{db})^2_{LR}\rvert}$	3.3×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{db})_{LL}(\delta^{\tilde{d}}_{db})_{RR}\rvert}$	1.8×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{sb})^2_{LL}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{sb})^2_{RR}\rvert}$	4.8×10^{-1}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{sb})^2_{LR}\rvert}$	1.62×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{d}}_{sb})_{LL}(\delta^{\tilde{d}}_{sb})_{RR}\rvert}$	8.9×10^{-2}

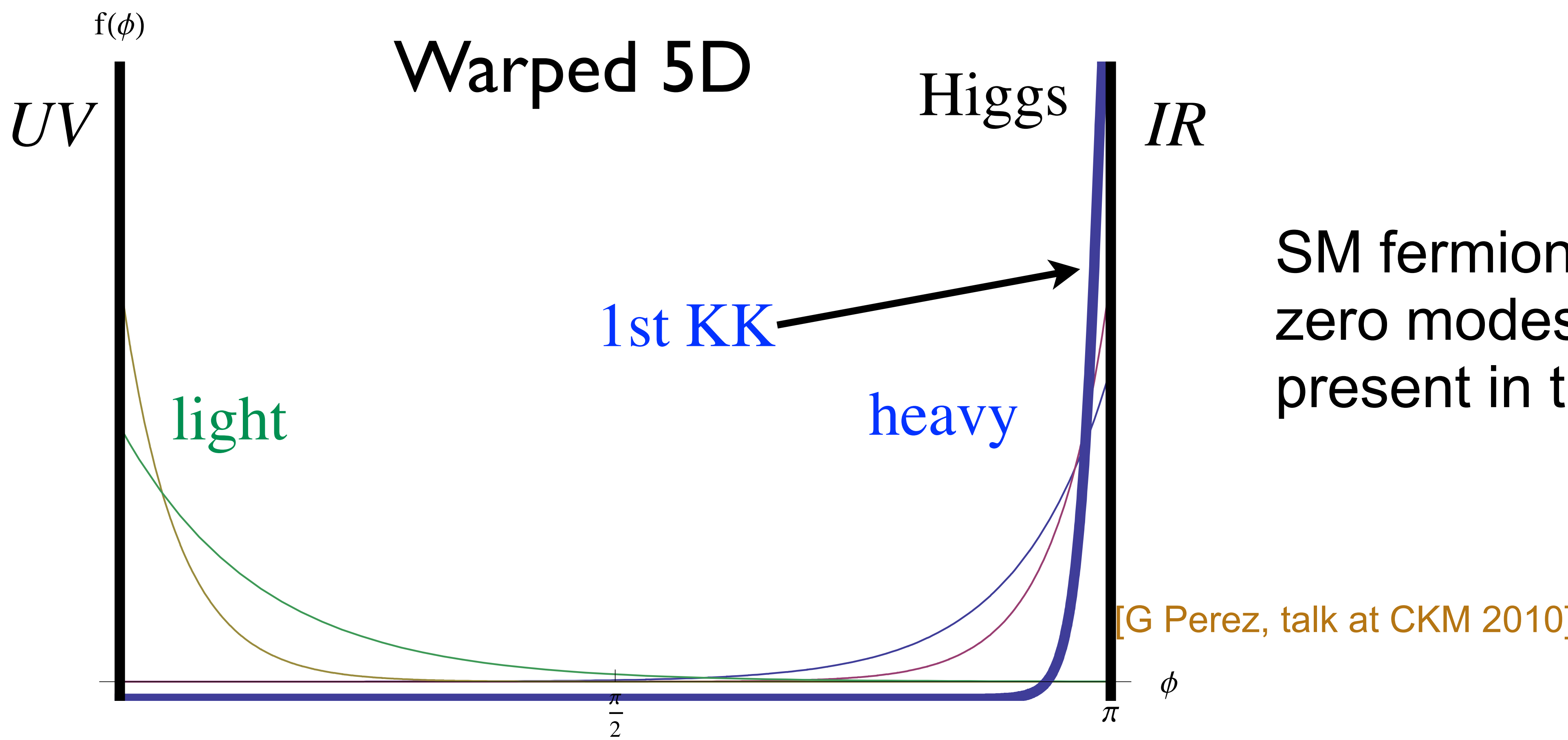
Quantity	upper bound
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LL}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{ud})^2_{RR}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LR}\rvert}$	1.20×10^{-2}
$\sqrt{\lvert \mathrm{Re}(\delta^{\tilde{u}}_{uc})_{LL}(\delta^{u}_{uc})_{RR}\rvert}$	6.6×10^{-3}

[Gabbiani et al 96; Misiak et al 97]
these numbers from [SJ, 0808.2044]

- elusiveness of deviations from SM in flavour physics seems to make MSSM look unnatural

- pragmatic point of view: flavour physics highly sensitive to many MSSM parameters

Flavour - warped ED

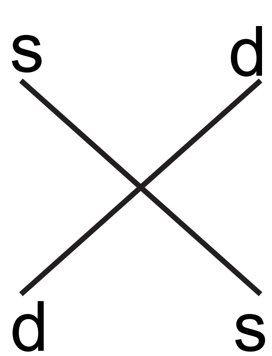


SM fermions are zero modes of fields present in the bulk

Higgs localized on IR brane

light (heavy) fermions localized near UV (IR) brane

hierarchical SM fermion masses

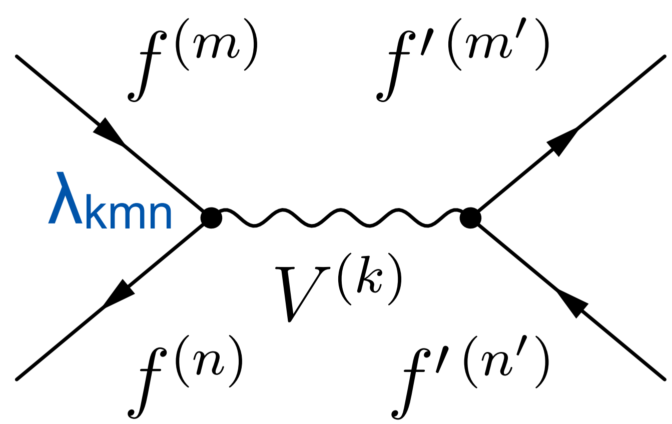


dangerous four-fermion operators with TeV suppression are "natural" on the IR brane

not so dangerous after taking into account localization of SM fermions ("RS-GIM")

Flavour - warped ED (2)

- dominant contribution to FCNC usually not from brane contact terms but from tree-level KK boson exchange



$$\lambda_{kmn} = \int d\phi \, w(\phi) f^{(m)}(\phi) f^{(n)}(\phi) f_V^{(k)}(\phi)$$

$$Y_{mn} \propto f^{(m)}(\pi) f^{(n)}(\pi)$$

non-minimal flavour violations !

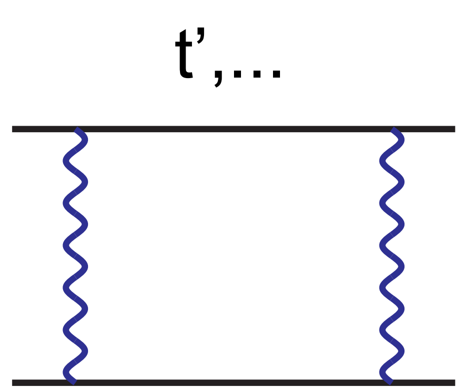
- where are their effects?

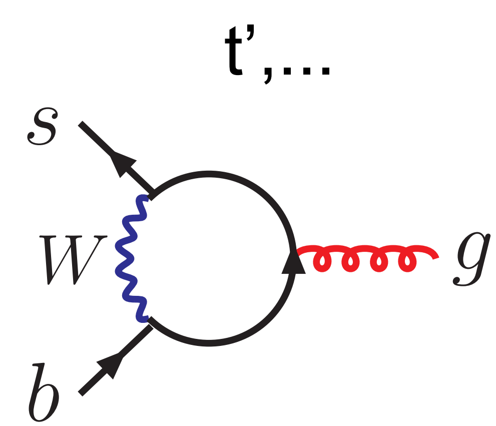
Other scenarios

- fourth SM generation
  CKM matrix becomes 4x4, giving new sources of flavour and CP violation

- little(st) higgs model with T parity
  (higgs light because a pseudo-goldstone boson)
  finite, calculable 1-loop contributions due to new heavy particles with new flavour violating couplings

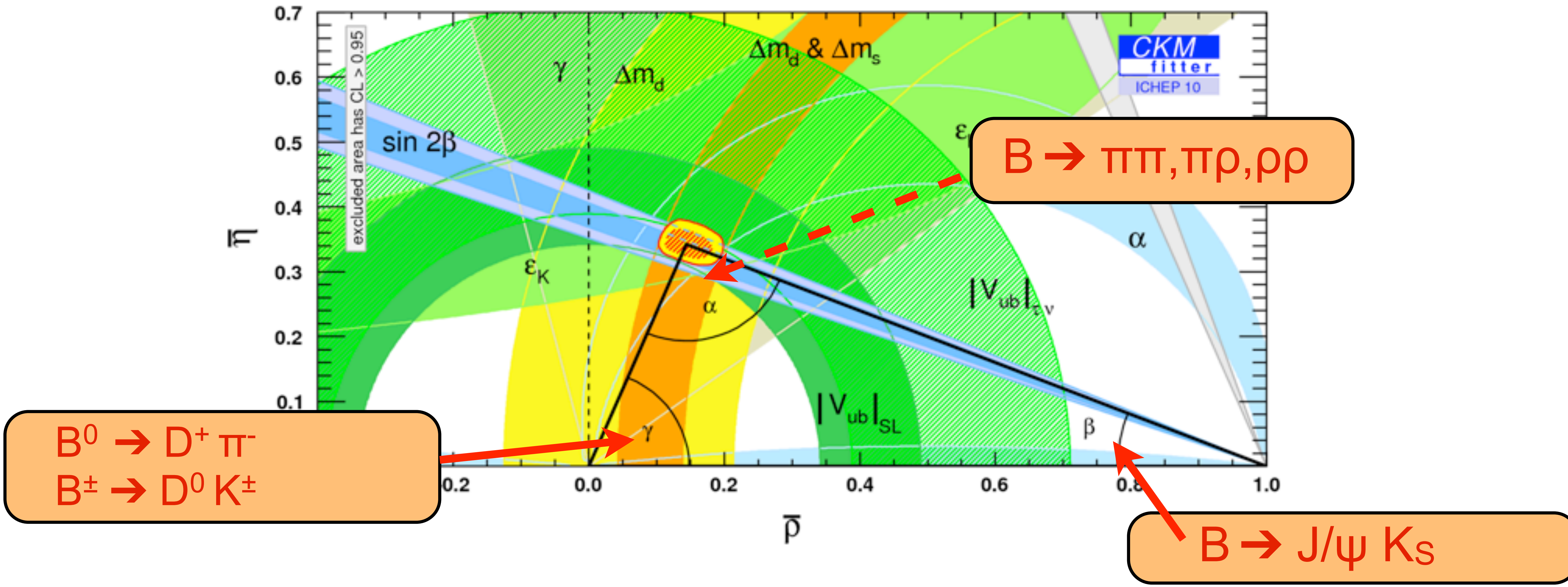
- ...



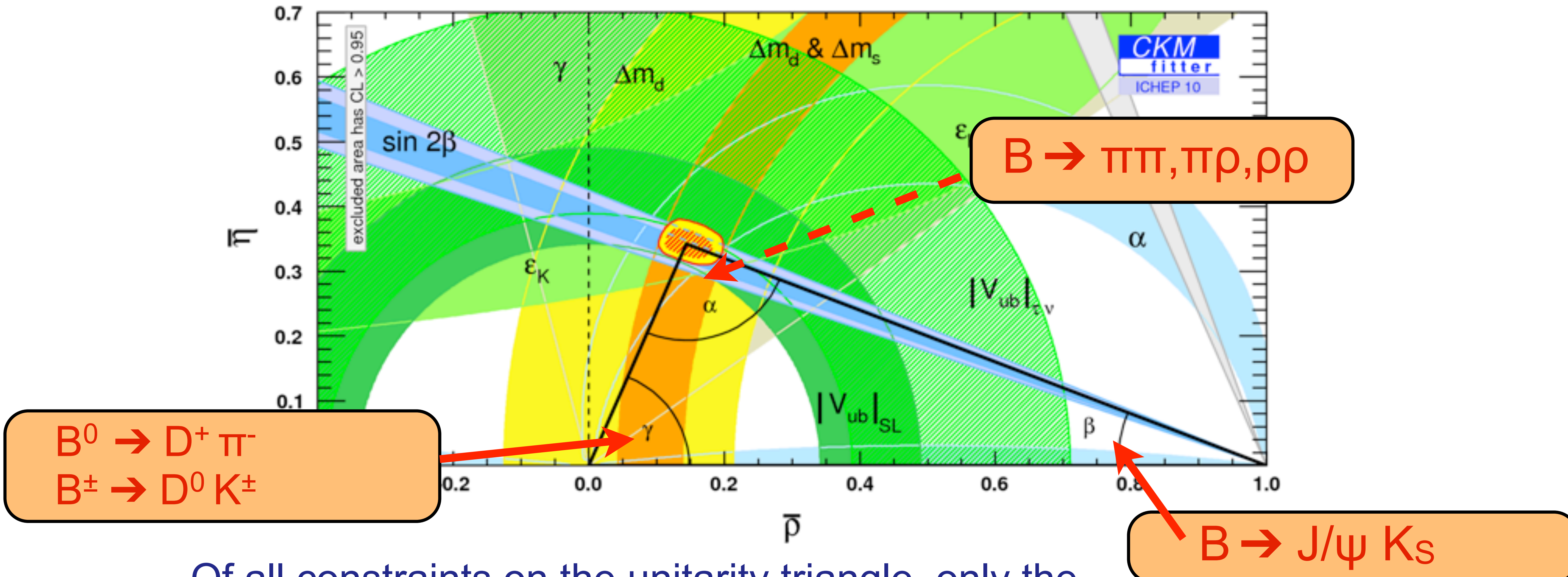


non-minimal flavour violation !

Unitarity Triangle revisited

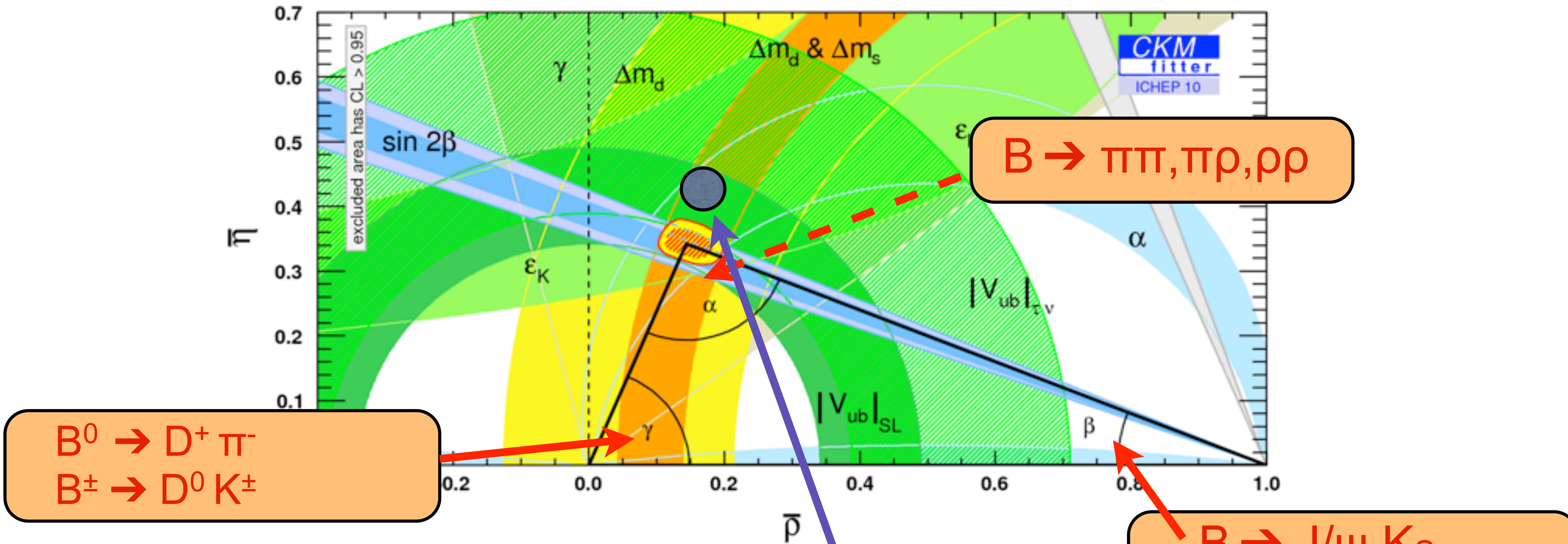


Unitarity Triangle revisited



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

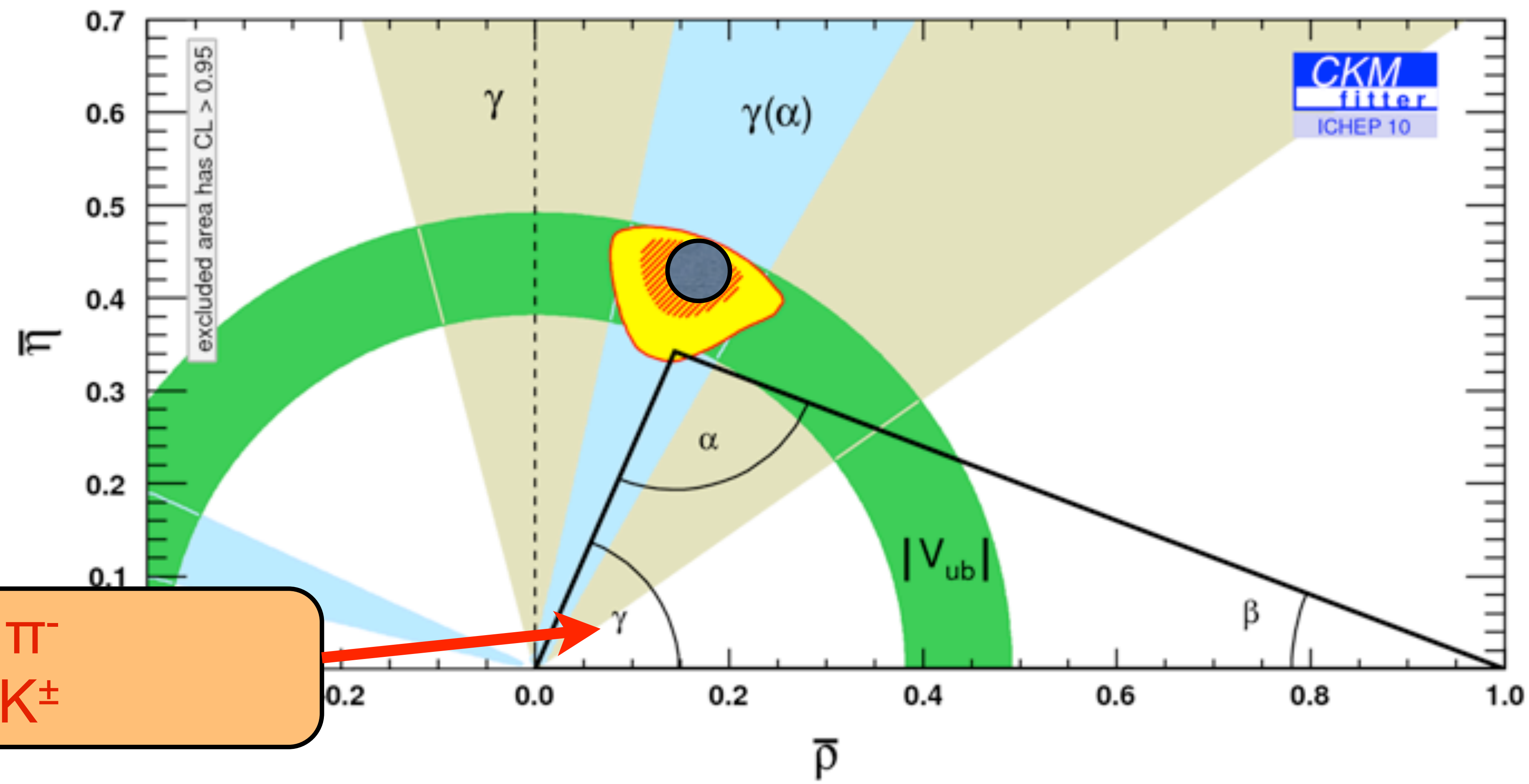
Unitarity Triangle revisited



Of all constraints on the unitarity triangle, 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)

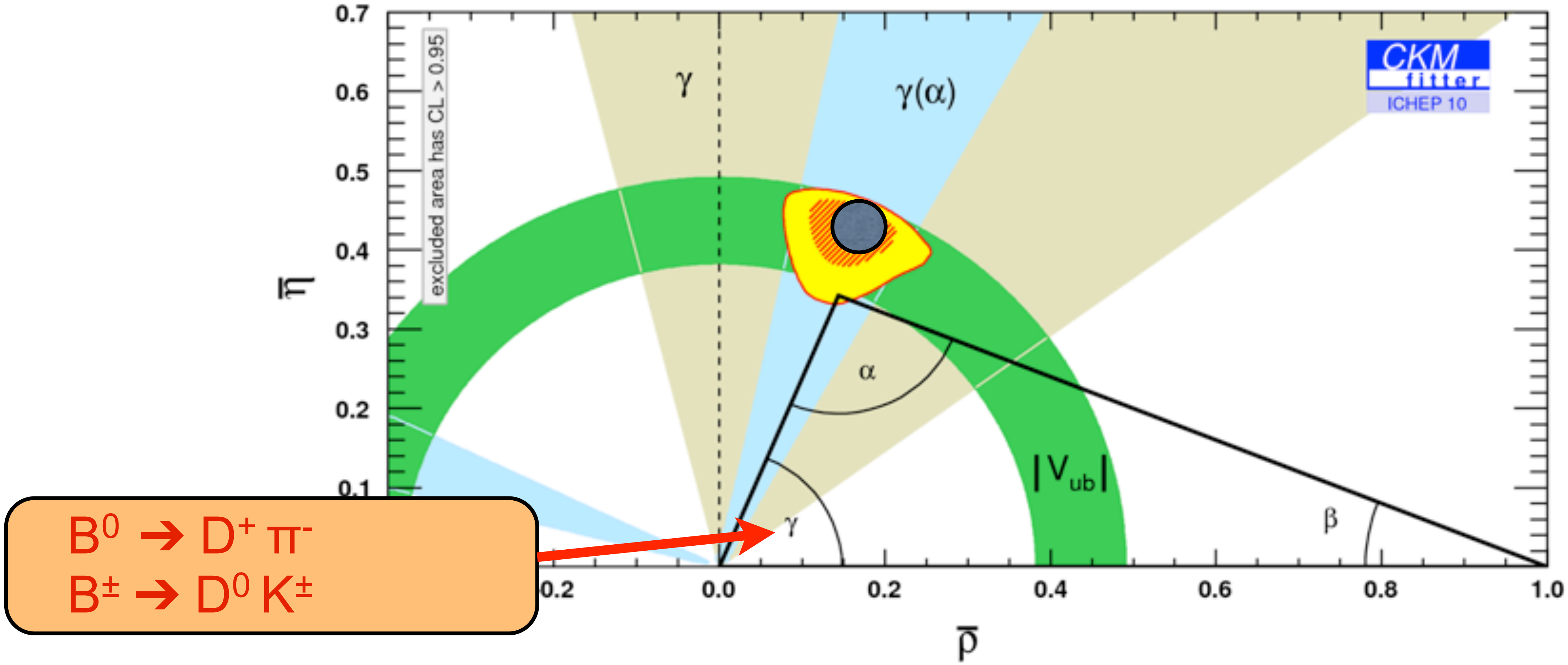
“Tree” determinations



$B^0 \rightarrow D^+ \pi^-$
$B^\pm \rightarrow D^0 K^\pm$

Only “robust” measurements of γ and $|V_{ub}|$. Note: the γ(α) constraint depends on assumptions about new physics

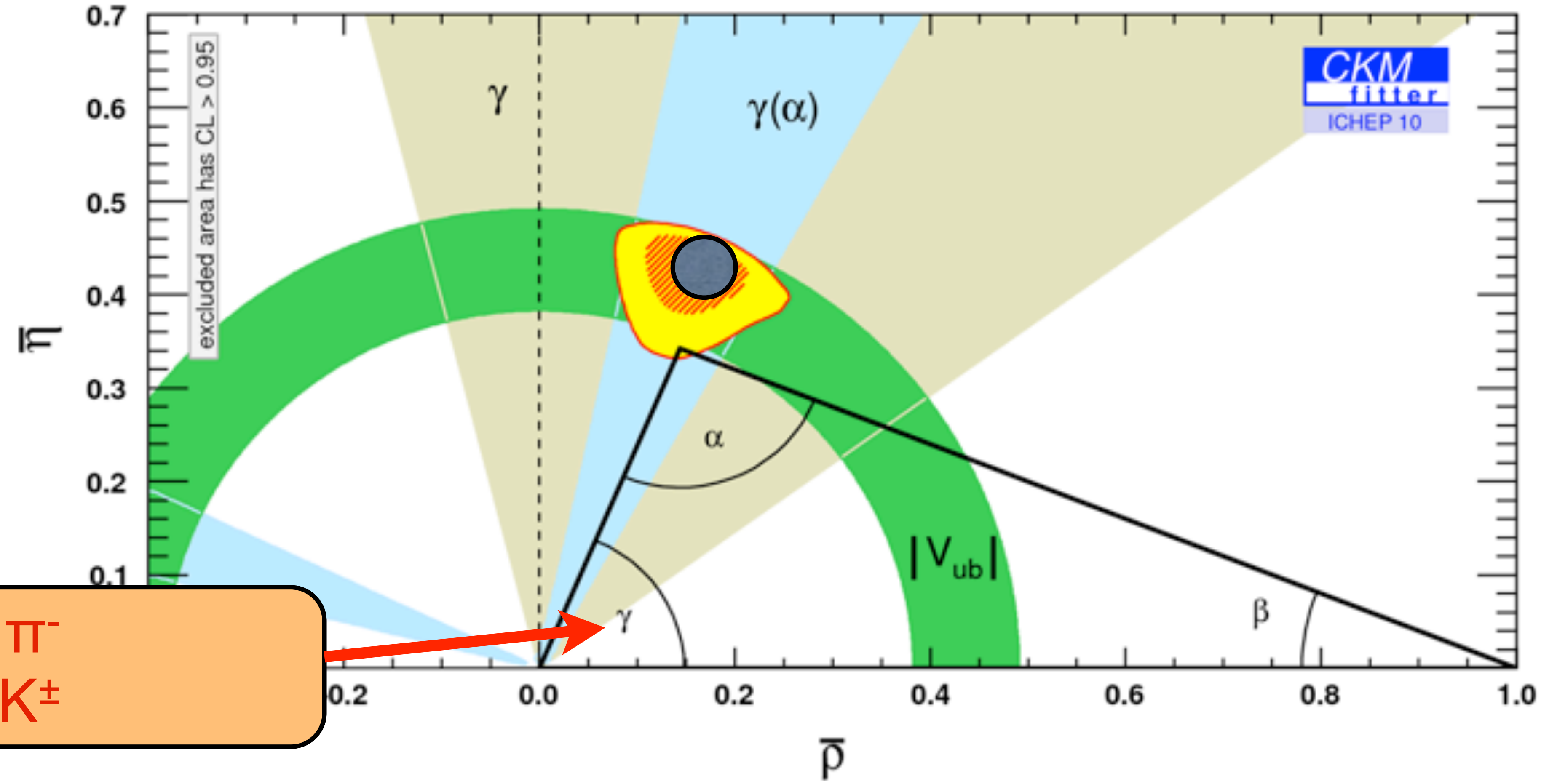
“Tree” determinations



Only “robust” measurements of γ and $|V_{ub}|$. Note: the γ(α) constraint depends on assumptions about new physics

Certainly there is room for O(10%) NP in b->d transitions

"Tree" determinations



$B^0 \rightarrow D^+ \pi^-$
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Only "robust" measurements of γ and $|V_{ub}|$. Note: the γ(α) constraint depends on assumptions about new physics

Certainly there is room for O(10%) NP in b->d transitions

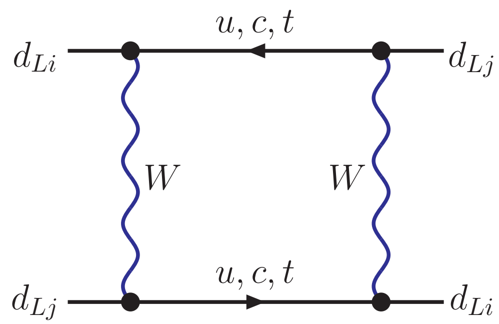
Moreover, b->s transitions are almost unrelated to (ρ,η). They are the domain of the Tevatron and of LHCb

Where to look

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

mixing-induced CP violation

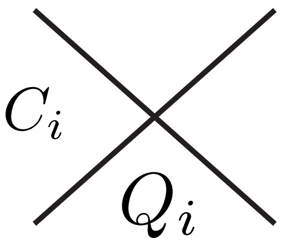
- flavour violation: $\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$



+ ?

OPE (m_B/m_W)

$\sum C_i$



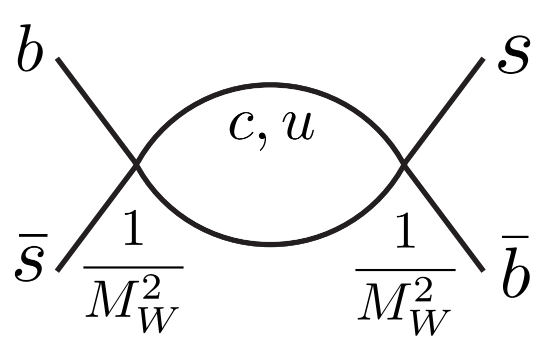
M_{12}

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

$$
\begin{aligned}
Q_1 &= (\bar{s}^a_L \gamma_\mu b^a_L)(\bar{s}^b_L \gamma^\mu b^b_L), \\
Q_2 &= (\bar{s}^a_R b^a_L)(\bar{s}^b_R b^b_L), \\
Q_3 &= (\bar{s}^a_R b^b_L)(\bar{s}^b_R b^a_L), \\
Q_4 &= (\bar{s}^a_R b^a_L)(\bar{s}^b_L b^b_R), \\
Q_5 &= (\bar{s}^a_R b^b_L)(\bar{s}^b_L b^a_R)
\end{aligned}
$$

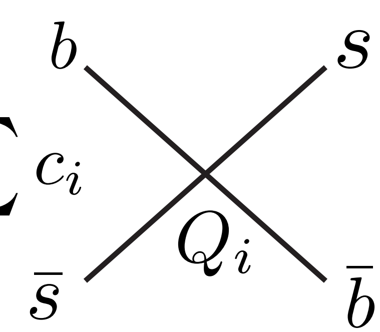
+ 3 more

Im



OPE (Λ_{QCD}/m_B)

$\sum c_i$



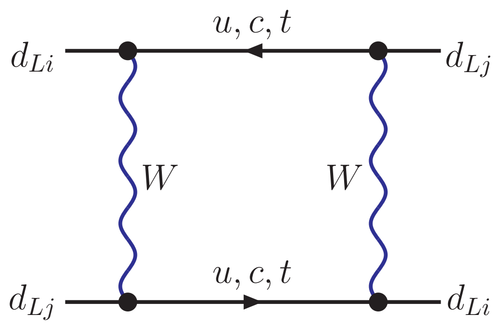
Γ_{12}

$\Delta\Gamma$

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

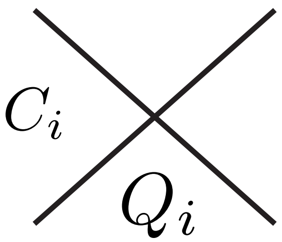
mixing-induced CP violation

- 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) $\sum C_i$



M_{12}

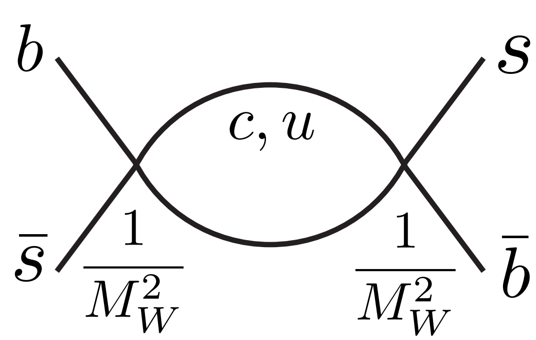
$$\boxed{Q_1 = (\bar{s}^a_L \gamma_\mu b^a_L)(\bar{s}^b_L \gamma^\mu b^b_L),}$$

only operator present in SM

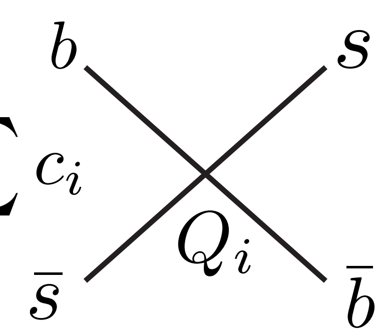
$\Delta M = 2|M_{12}|$

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

+ 3 more

Im


OPE (Λ_{QCD}/m_B) $\sum c_i$



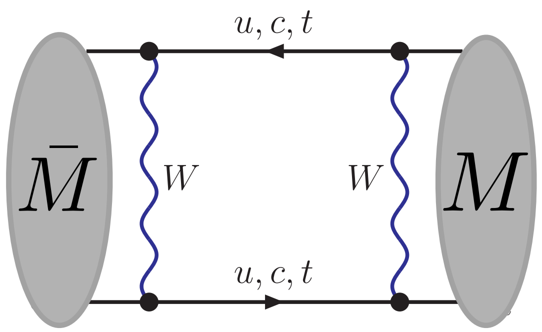
Γ_{12}

$\Delta\Gamma$

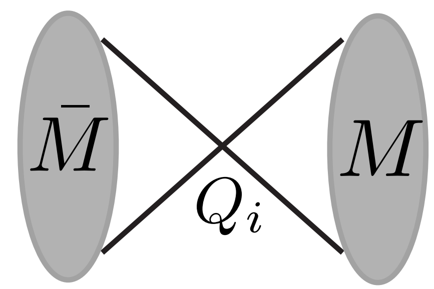
no NP contribution unless lighter than m_B

QCD corrections

- apply OPE to hadronic states



+ NP + QCD $= \sum C_i$



$= \sum C_i \langle \bar{M} | Q_i | M \rangle$

(factorization)

$\Delta M = 2 | \sum C_i \langle \bar{M} | Q_i | M \rangle |$ (similarly for ΔΓ)

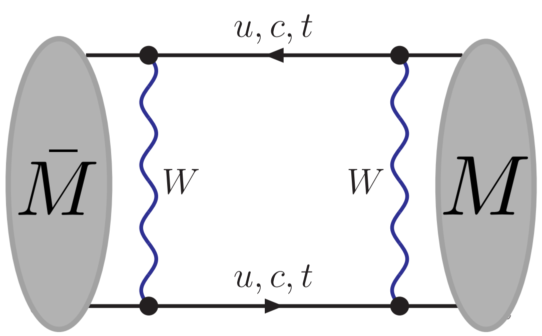
- hadronic matrix elements $\langle \bar{M} | Q_i | M \rangle$ require nonperturbative methods (lattice QCD). Huge progress being made! Big UK participation

- if only one operator (as in SM for B mixing), *phase* $\arg M_{12} \equiv \phi_M$ theoretically clean (matrix element real)

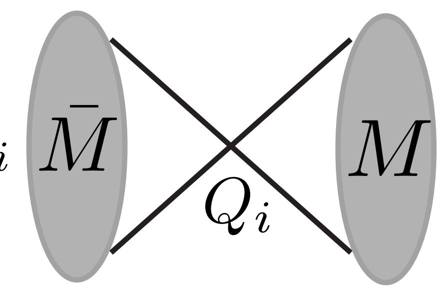
$\phi_{B_d} \approx \arg(V_{td}^2) = 2\beta$ $\phi_{B_s} \approx \arg(V_{ts}^2) = -2\beta_s = (2.2 \pm 0.6)^\circ$

QCD corrections

- apply OPE to hadronic states



$+$ NP $+$ QCD $= \sum C_i$



$= \sum C_i \langle \bar{M} | Q_i | M \rangle$

(factorization)

$\Delta M = 2 | \sum C_i \langle \bar{M} | Q_i | M \rangle |$ (similarly for $\Delta\Gamma$)

- hadronic matrix elements $\langle \bar{M} | Q_i | M \rangle$ require nonperturbative methods (lattice QCD). Huge progress being made! Big UK participation

- if only one operator (as in SM for B mixing),
phase $\arg M_{12} \equiv \phi_M$ theoretically clean (matrix element real)

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close to zero in Standard Model

Time-dependent CP asymmetry

decay into CP eigenstate:

$$\begin{tikzcd}[column sep=huge, row sep=large]
B \arrow[rr, "A_f = \langle f|B\rangle"] \arrow[dr, "M_{12}^q = |M_{12}^q| e^{-i\phi_{B_q}}"'] & & f \\
& \bar{B} \arrow[ur, "\bar{A}_f = \langle f|\bar{B}\rangle"'] &
\end{tikzcd}$$

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

CP-violation parameter

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

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

if only one decay amplitude:

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

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

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

$\phi_{B_{d,s}} + \gamma$ from $B_{(s)}^0 \to D_{(s)} K$

Time-dependent CP asymmetry

decay into CP eigenstate:

$$\begin{tikzcd} B \arrow[rr, "A_f = \langle f|B\rangle"] \arrow[dr, "M_{12}^q = |M_{12}^q| e^{-i\phi_{B_q}}"'] & & f \\ & \bar{B} \arrow[ur, "\bar{A}_f = \langle f|\bar{B}\rangle"'] & \end{tikzcd}$$

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

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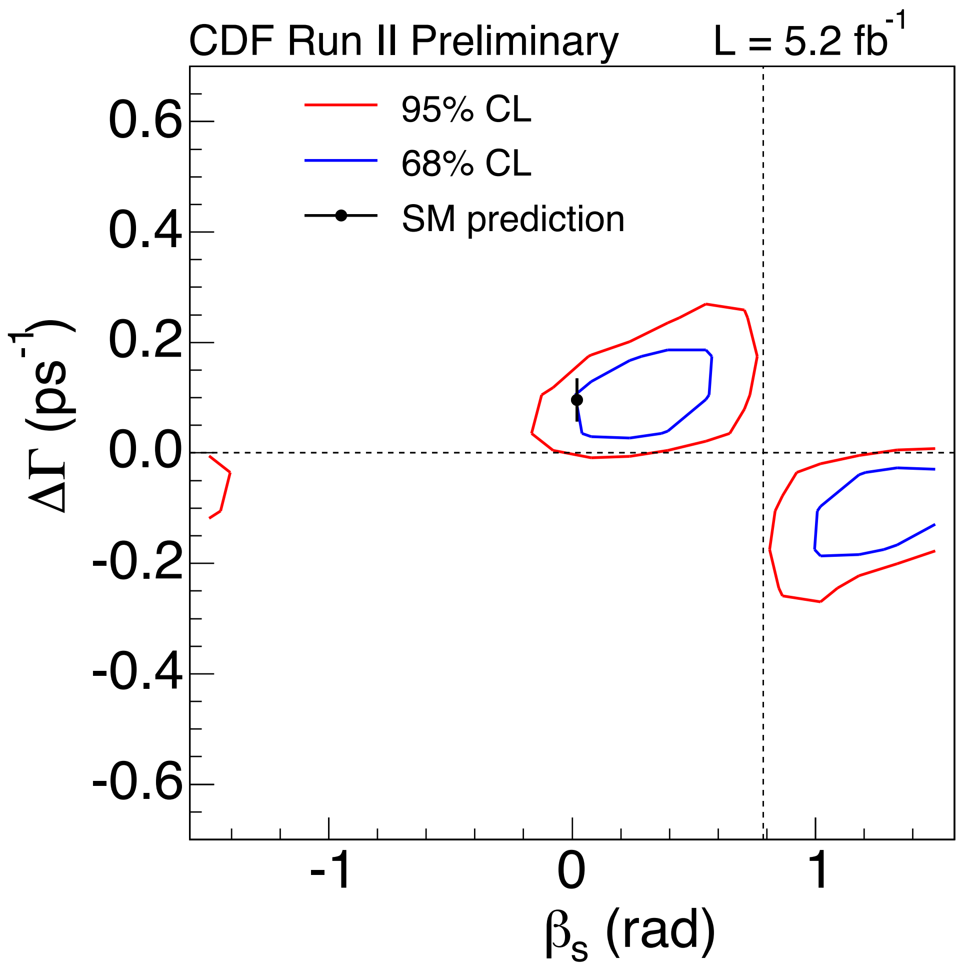
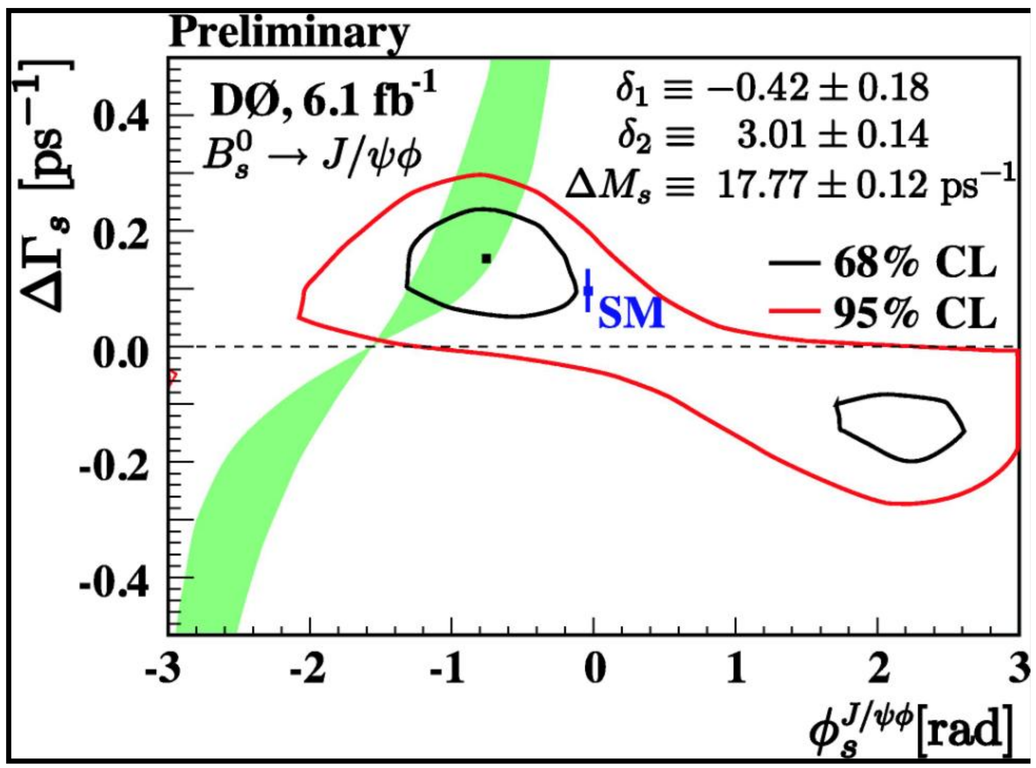
$B_s^0 \to J/\psi\,\phi$ $\quad \pm S = \sin\phi_{B_s} \approx 0$ $\quad$ Beyond SM $\phi_{B_s} \neq 0$

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

$\sin(2\phi_{Bs})$ measurement

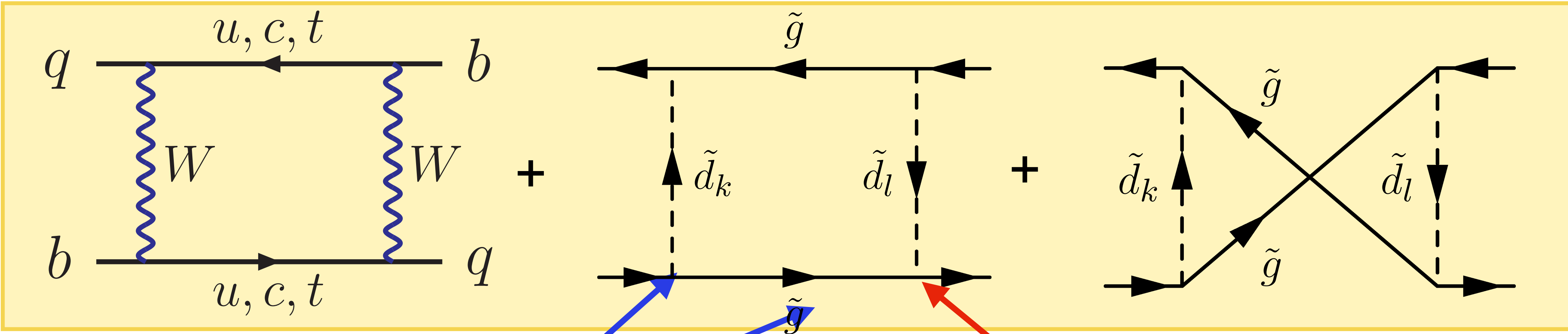
- CDF, D0 measured mixing-induced CPV in $B_s \to J/\psi\phi$





- low significance at present (previously higher)
- LHCb expects few ° sensitivity with 1 fb^{-1}

CP violation in B_s mixing?



- in general, three parameters $|M_{12}^s|,\ |\Gamma_{12}^s|,\ \phi_s = \arg \dfrac{-M_{12}^s}{\Gamma_{12}^s}$
- CP is violated in mixing if $\phi_s \neq 0$ $\qquad \phi_s^{\mathrm{SM}} \approx \phi_{B_s}^{\mathrm{SM}} \approx 0$
- three observables:

$$\Delta M_s \approx 2|M_{12}^s|,\ \Delta\Gamma_s \approx 2|\Gamma_{12}^s| \cos\phi_s,\ a_{\mathrm{fs}}^s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

mass difference $\qquad$ width difference

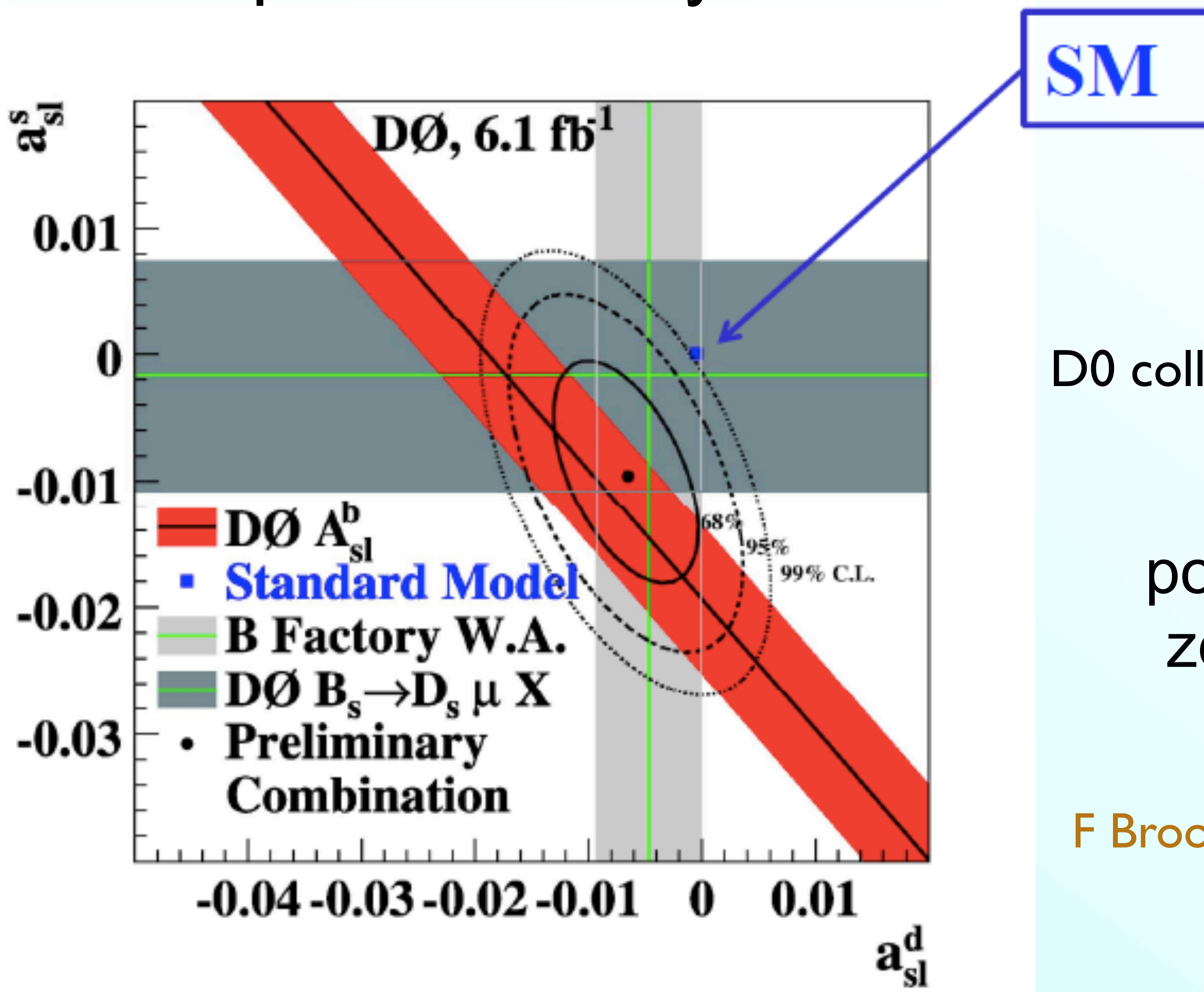
- a_{fs}^s CP asymmetry in (any) flavour-specific B-decay, e.g.

$$B_s \longrightarrow \bar{B}_s \longrightarrow X l^+ \nu$$

(semileptonic CP asymmetry)

Semileptonic CP asymmetries

- D0 and B factories measured (combinations of) semileptonic CP asymmetries



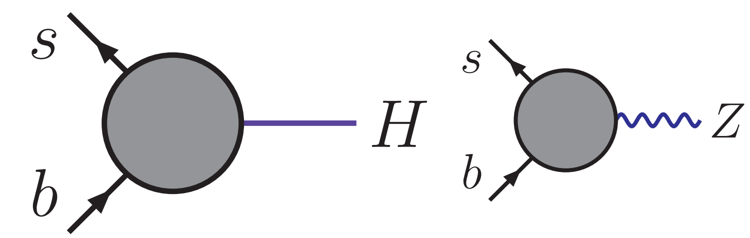
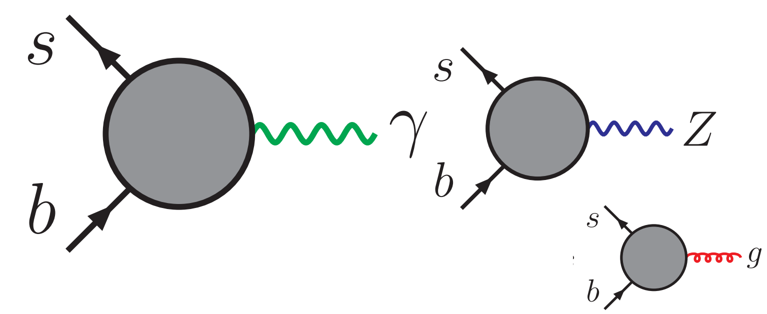
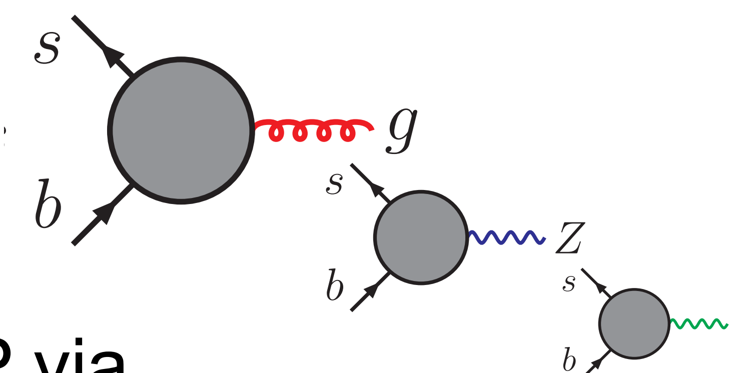
D0 collaboration, arXiv:1005.2757

points to non-zero a^s_{sl} / ϕ_s

F Brooijmans @ FCPC2010

These are functions of the same mixing phases as enter the time-dependent CPV, so a consistent picture must eventually emerge
LHCb will give complementary info in the above plane

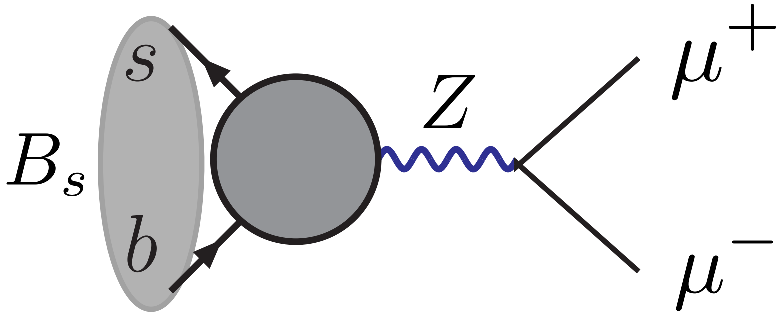
Exclusive decays at LHCb

final state	strong dynamics	#obs	NP enters through
Leptonic $B \to l^+ l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$	O(1)	
semileptonic, radiative $B \to K^* l^+ l^-, K^* \gamma$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$	O(10)	
charmless hadronic $B \to \pi\pi, \pi K, \rho\rho, \ldots$	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 in more and more cases by lattice QCD!

Leptonic decay, NP and LHC

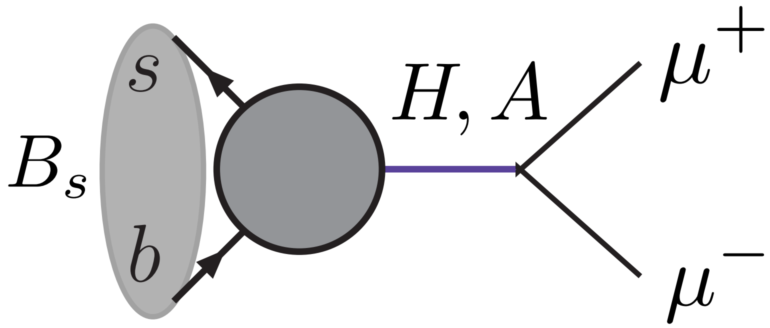


$\propto \frac{m_\mu^2}{M_W^2}$

loop and helicity suppressed in SM

$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$

Buras et al 2010

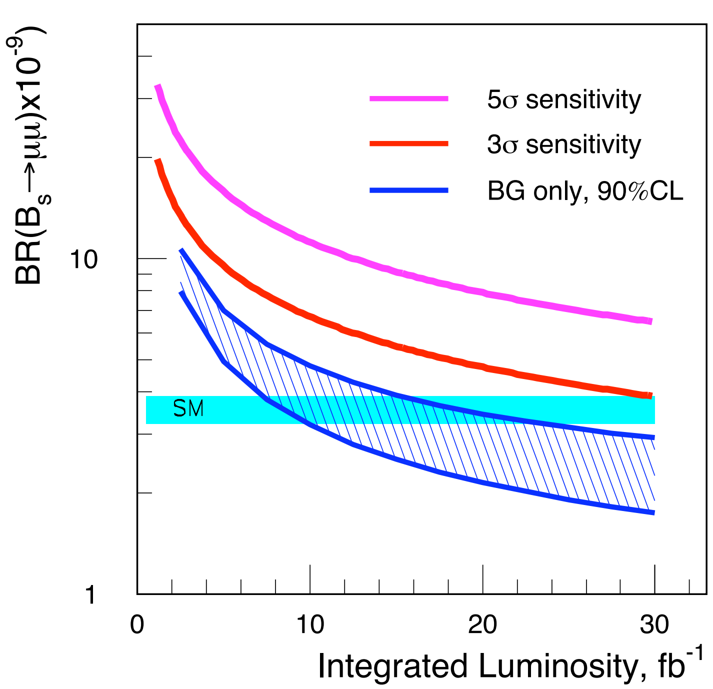


$\propto \frac{m_b^2 m_\mu^2}{M_W^4} \tan^6\beta$

Yukawa suppressed in SM

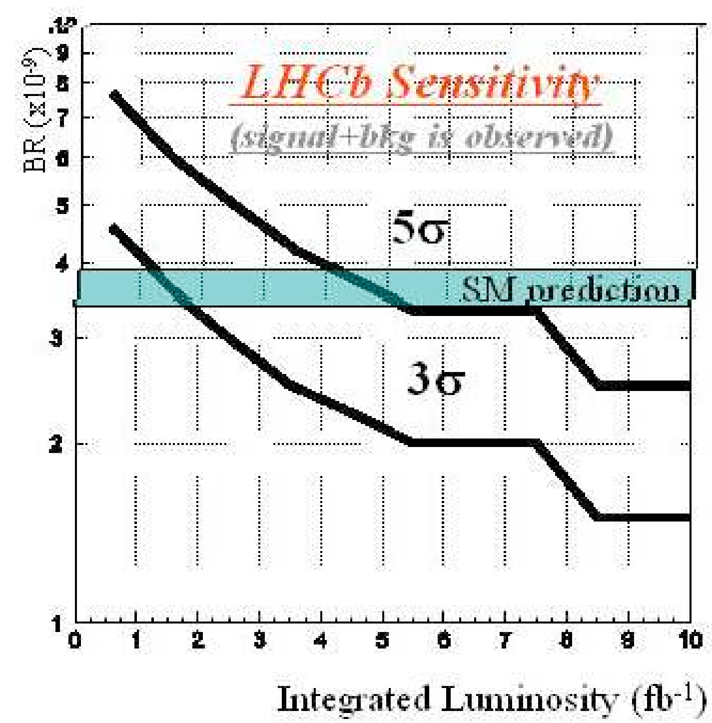
in 2HDM (or MSSM) Yukawas can be very large

Loop suppression and possible removal of helicity/Yukawa suppression imply strong sensitivity to new physics



ATLAS/CMS

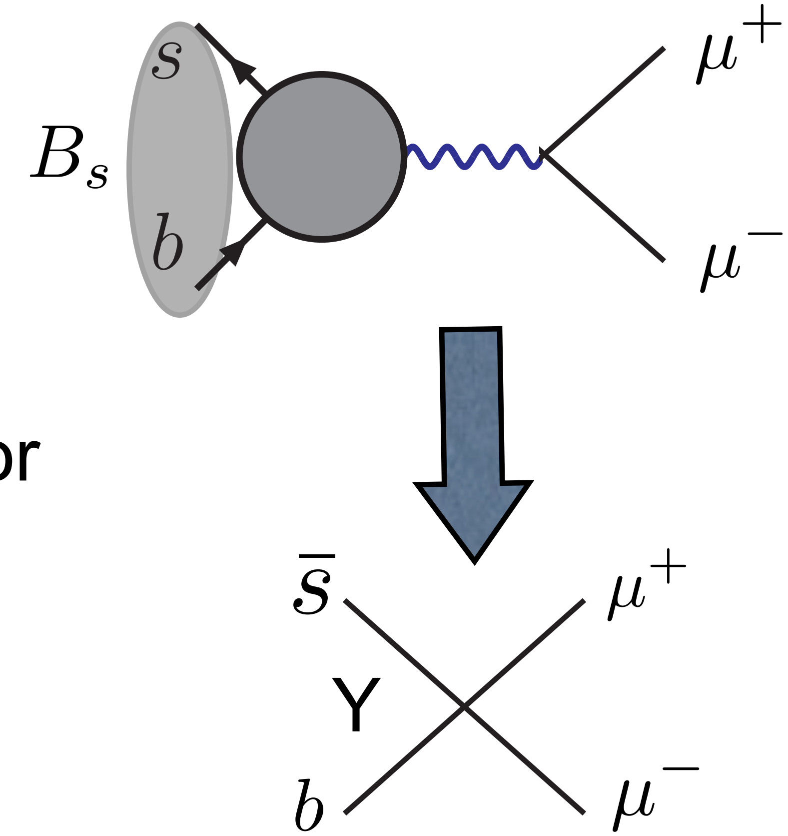
[Artuso et al 0801.1833]



LHCb

$B_s \to \mu^+\mu^-$: Standard Model

- Mediated by short-distance
  Z penguin and box - long distance
  strongly CKM / GIM suppressed



- including QCD corrections, matches onto single relevant effective operator

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2\theta_W} V_{tb}^* V_{tq} Y Q_A$$

$$Y\left(\bar{m}_t(m_t)\right) = \quad 0.9636 \left[\frac{80.4 \text{ GeV}}{M_W} \frac{\overline{m}_t}{164 \text{ GeV}}\right]^{1.52}$$

$$Q_A \quad = \quad \bar{b}_L \gamma^\mu q_L \, \bar{\ell} \gamma_\mu \gamma_5 \ell$$

(approximates NLO to $<10^{-4}$)

[Buchalla&Buras 93,
Misiak&Urban 99;
Artuso et al 0801.1833]

higher orders negligible

- branching fraction

$$B(B_s \to l^+ l^-) = \tau(B_s) \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2\Theta_W}\right)^2 F_{B_s}^2 m_l^2 m_{B_s} \sqrt{1 - 4\frac{m_l^2}{m_{B_s}^2}} |V_{tb}^* V_{ts}|^2 \, Y^2$$

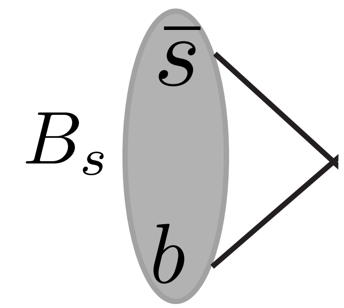
main uncertainties: decay constant, CKM
for D or K decays long-distance contributions are important

$B_s \to \mu^+\mu^-$: Standard Model

- F_{Bs} = (238.8 ± 9.5) MeV

  Lunghi, Laiho, van de Water 2009

  lattice QCD average



- error can be reduced by normalizing to $B_s - \bar{B}_s$ mixing

$$B(B_q \to \ell^+\ell^-) = C\frac{\tau_{B_q}}{\hat{B}_q}\frac{Y^2(\overline{m}_t^2/M_W^2)}{S(\overline{m}_t^2/M_W^2)}\Delta M_q$$

Buras 2003

  where S is the ΔF=2 box function and C a numerical const and in the bag factor $\hat{B}_{B_s} = 1.33 \pm 0.06$, some systematic uncertainties cancel. Then

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

Buras et al 2010

- Very precise test of SM from hadronic observables at LHC!
- same trick for $B_d \to \mu^+\mu^-$, $B_{s,d} \to e^+e^-$, $e^+\mu^-$, etc
- not for $D \to \mu^+\mu^-$ or $K \to \mu^+\mu^-$ as mixing is not calculable

Experiment

- present upper bounds

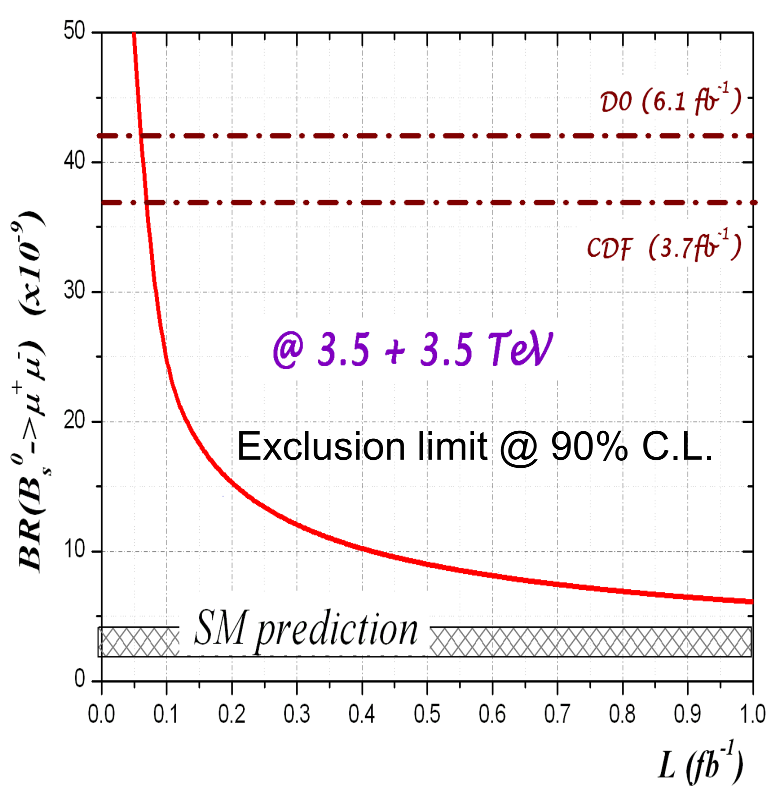
	CDF	D0	SM theory
$B_s \rightarrow \mu^+\mu^-$	$4.3\ 10^{-8}$ 95% CL	$5.2\ 10^{-8}$ 95% CL	$(3.2\pm0.2)\ 10^{-9}$
$B_d \rightarrow \mu^+\mu^-$	$7.6\ 10^{-9}$ 95% CL		$(1.0\pm0.1)\ 10^{-10}$
$D \rightarrow \mu^+\mu^-$	$3.0\ 10^{-7}$ 95% CL		$\sim 10^{-13}$

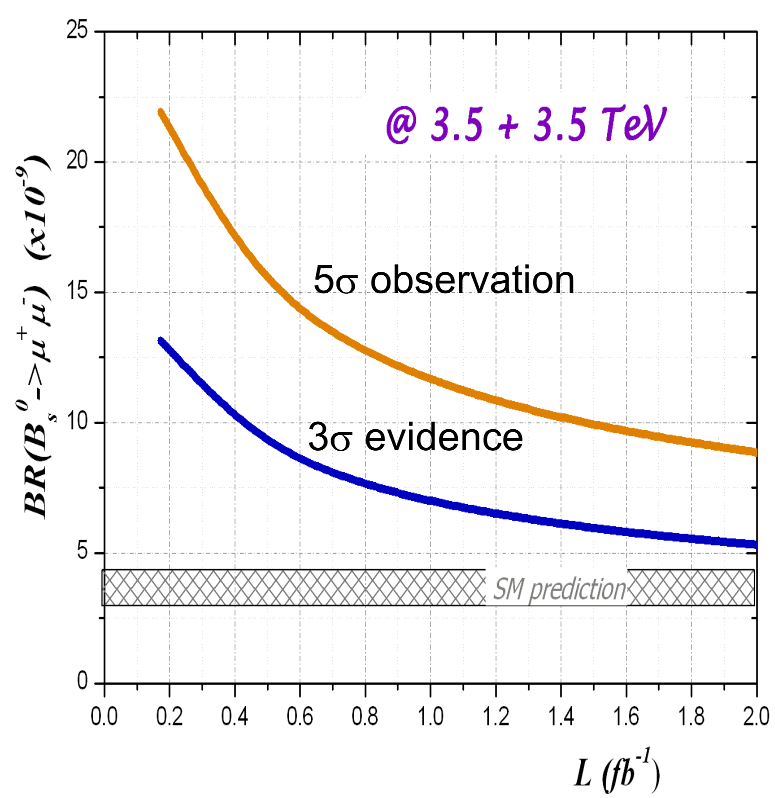
CDF public note 9892 D0 arXiv:1006.3469 D0 arXiv:1008.5077

Kreps arXiv:1008.0247 Buras et al arXiv:1007.1993

Burdman et al 2001

- early LHCb prospects

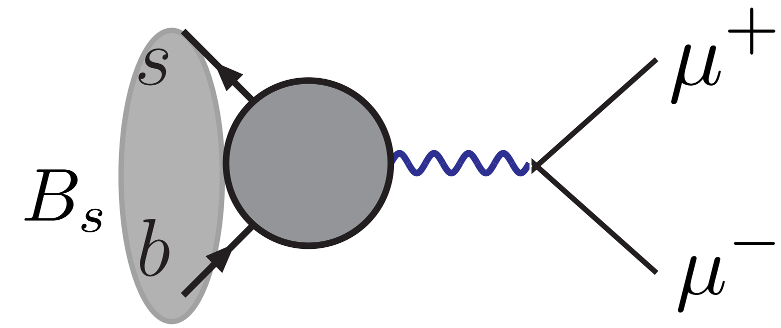




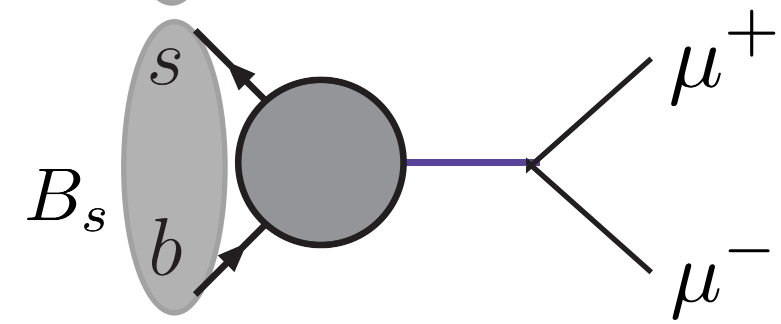
(Guy Wilkinson at CKM2010)

Beyond the SM

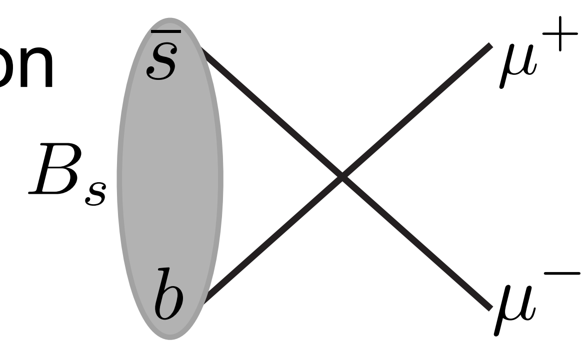
- New physics can modify the Z penguin ....



... induce a Higgs penguin ...



... or induce (or comprise) four-fermion contact interactions directly



could also violate lepton flavour

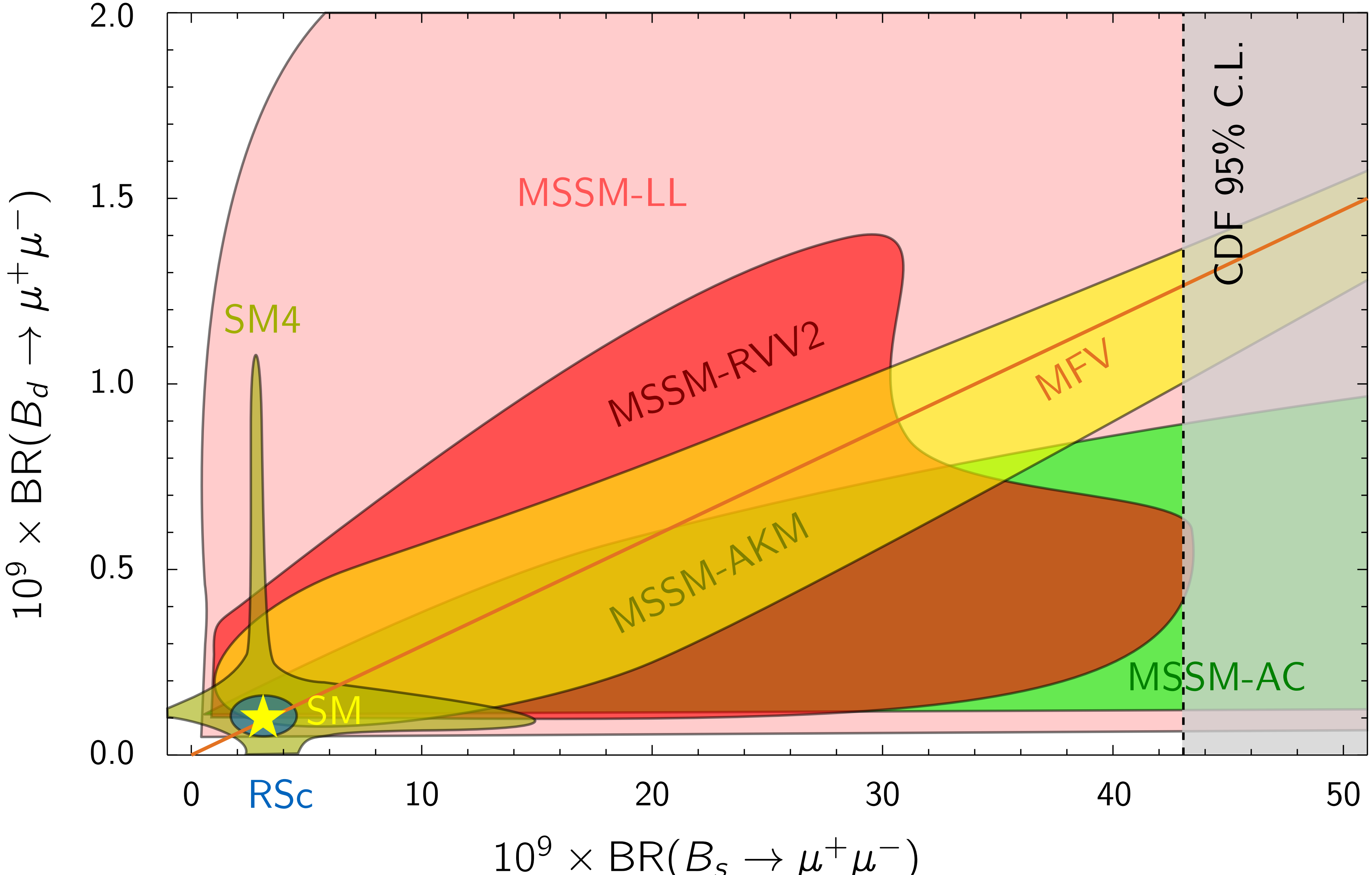
- most general effective hamiltonian

$$\frac{G_F}{\sqrt{2}} \frac{\alpha}{\pi \sin^2 \theta_W} V_{tb}^* V_{tq} \left[C_S Q_S + C_P Q_P + C_A Q_A \right] \text{ + parity reflections}$$

$$B\left(B_q \to \ell^+ \ell^-\right) = \frac{G_F^2 \, \alpha^2}{64 \, \pi^3 \sin^4 \theta_W} \left|V_{tb}^* V_{tq}\right|^2 \tau_{B_q} M_{B_q}^3 f_{B_q}^2 \sqrt{1 - \frac{4 m_\ell^2}{M_{B_q}^2}} \times \left[\left(1 - \frac{4 m_\ell^2}{M_{B_q}^2}\right) M_{B_q}^2 C_S^2 + \left(M_{B_q} C_P - \frac{2 m_\ell}{M_{B_q}} C_A\right)^2 \right]$$

could violate lepton flavour !

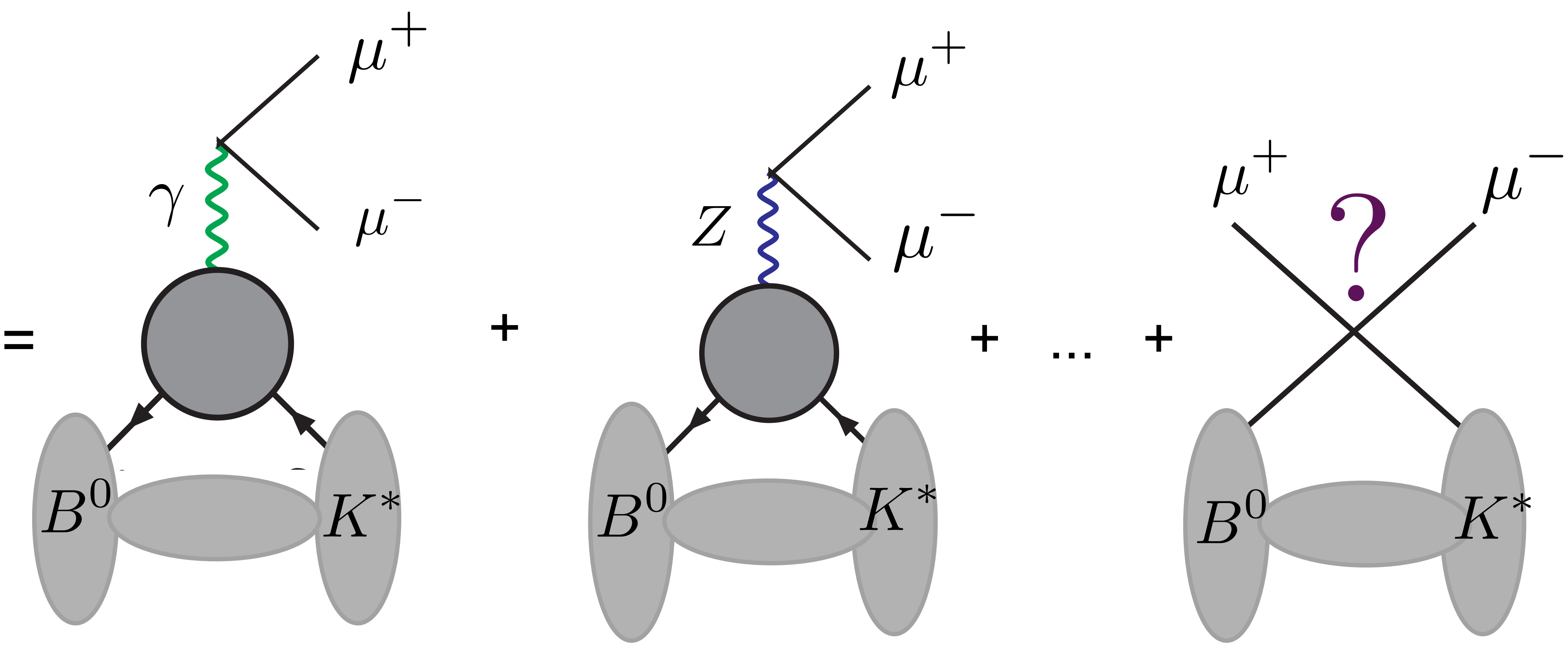
BSM model comparison



David Straub at CKM 2010

Semileptonic decay

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



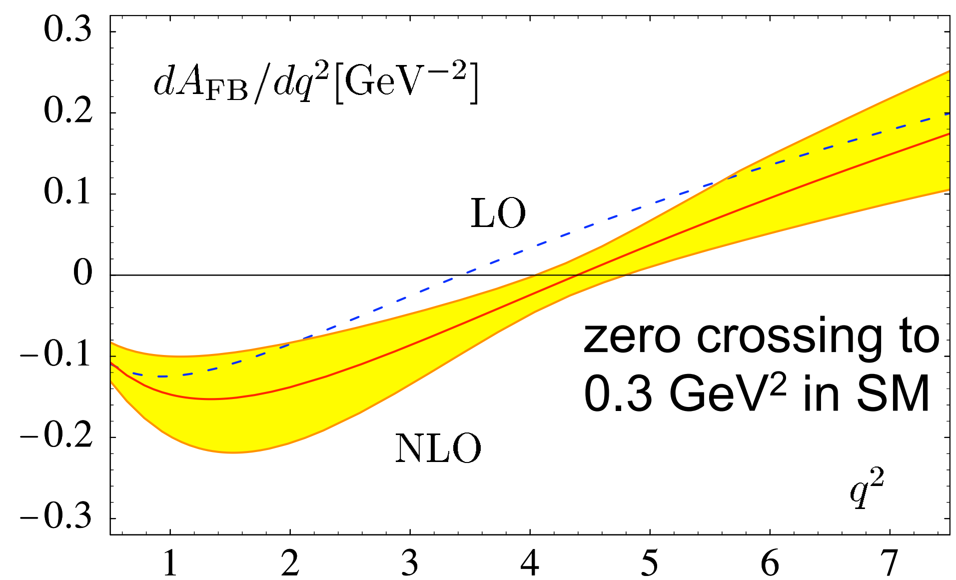
- kinematics described by dilepton invariant mass q^2 and two angles

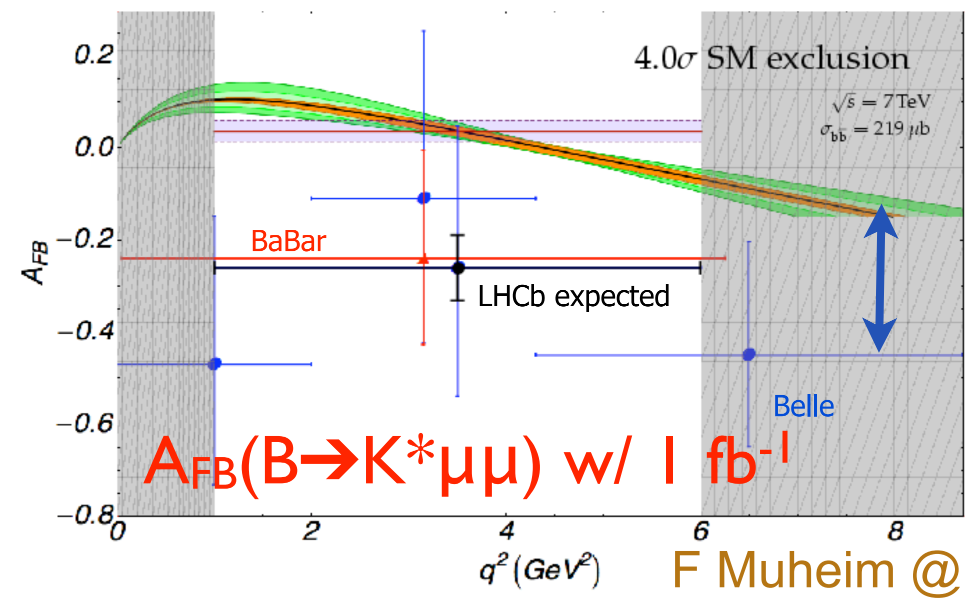
- Systematic theoretical description based on heavy-quark expansion (Λ/m_b) for $q^2 << m^2(J/\psi)$ (SCET) Beneke, Feldmann, Seidel 01
  also for $q^2 >> m^2(J/\psi)$ (HQET) Grinstein et al
  Theoretical uncertainties on form factors, power corrections

$B_d \rightarrow K^* \mu^+ \mu^-$

Ali et al ; Beneke et al; ...

- Most well-known observable: forward-backward asymmetry





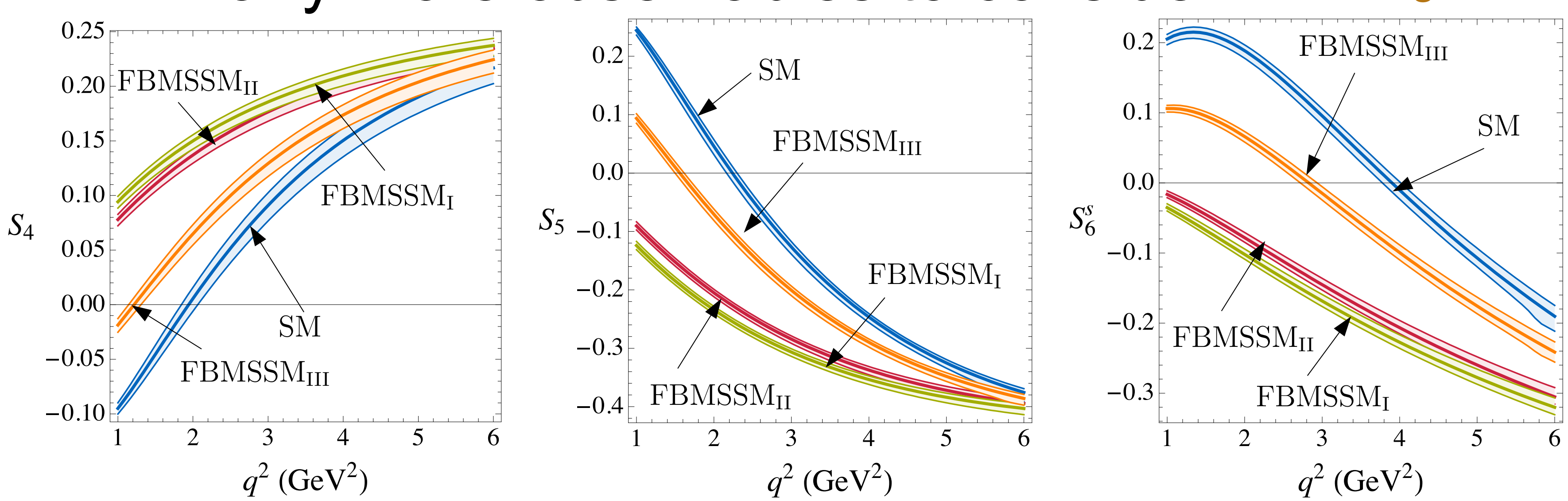
F Muheim @ FPCP2010

$$q_0^2[K^{*0}] = 4.36^{+0.33}_{-0.31}\,\mathrm{GeV}^2, \qquad q_0^2[K^{*+}] = 4.15^{+0.27}_{-0.27}\,\mathrm{GeV}^2$$

Beneke et al Eur Phys J C 41 (2005) 173

- Many more observables to consider

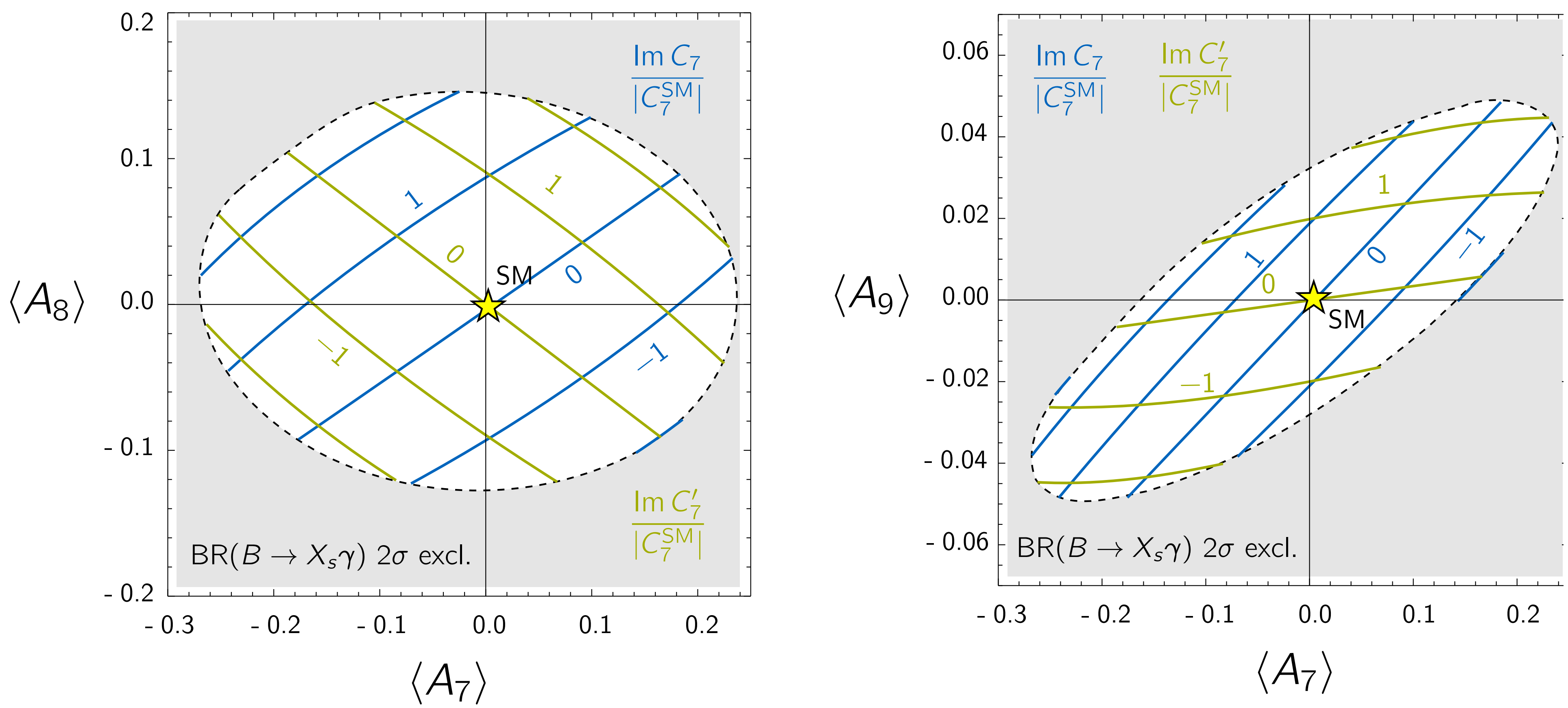
Krueger, Matias; ...



Altmannshofer et al
0811.1214v3

see also Bobeth et al 2008,10; Egede et al 2009,2010; Alok et al 2010 for recent analyses

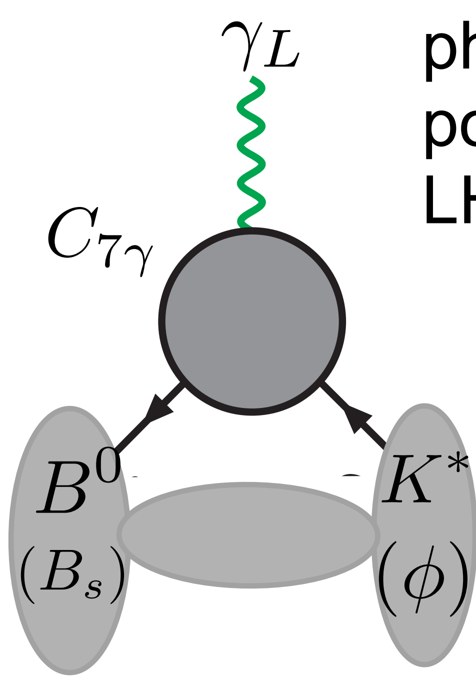
Right-handed currents?



Altmannshofer et al 0811.1214v3

D Straub @ CKM 2010

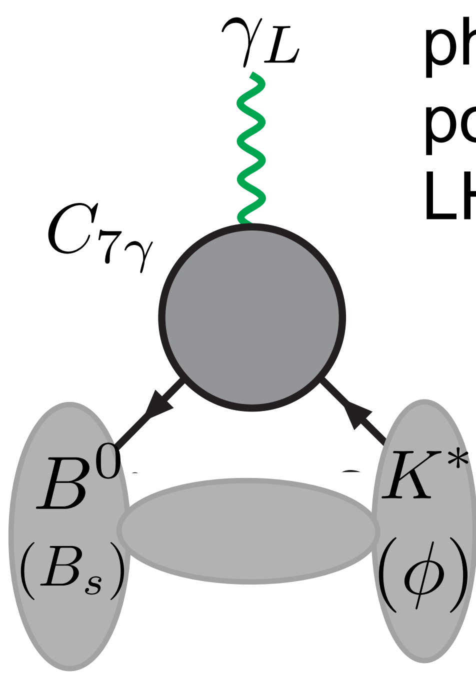
$B_d \to K^* \gamma$, $B_s \to \phi\gamma$



photon left-handed in SM;
polarization not observable at LHCb

$S(B \to K^* \gamma) = -0.16 \pm 0.22$
HFAG average of B factory data
(SM: ≈0)

$B_d \rightarrow K^* \gamma$, $B_s \rightarrow \phi\gamma$



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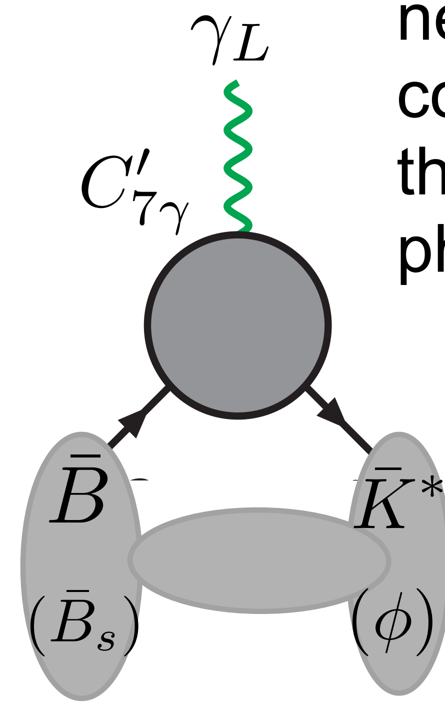

new physics might induce coupling to right-handed photon; this will produce left-handed photons in **anti**particle decay

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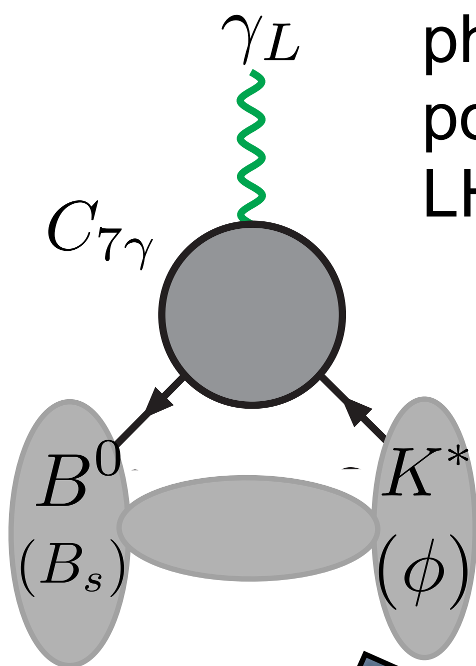

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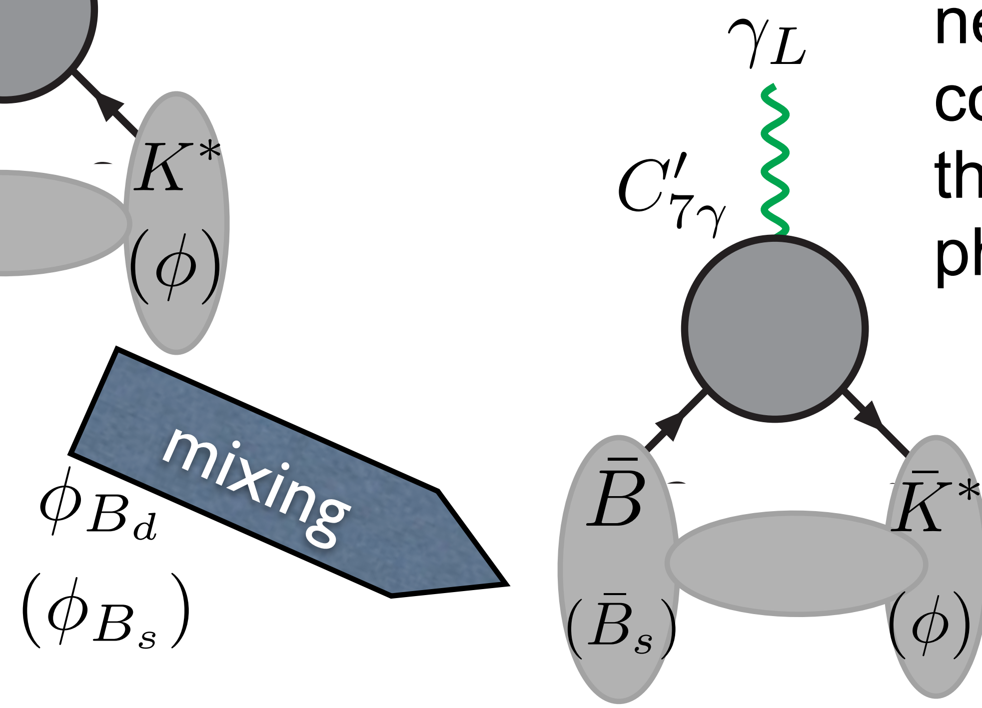

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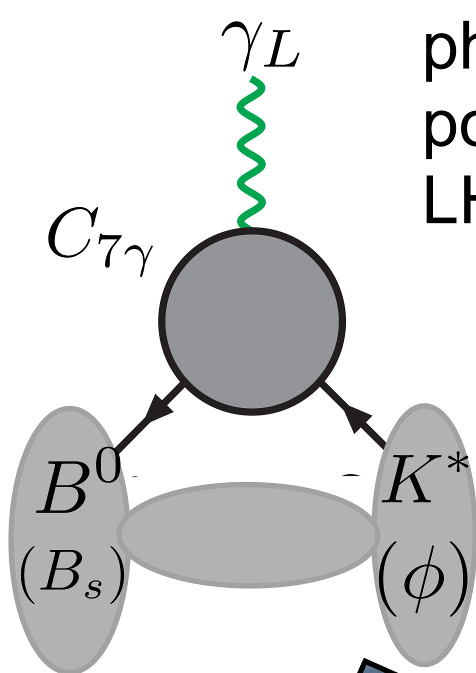
mixing-decay interference & time-dependent CP asymmetry
LHCb has sensitivity for $S(B_s \rightarrow \phi \gamma)$

$B_d \to K^*\gamma$, $B_s \to \phi\gamma$



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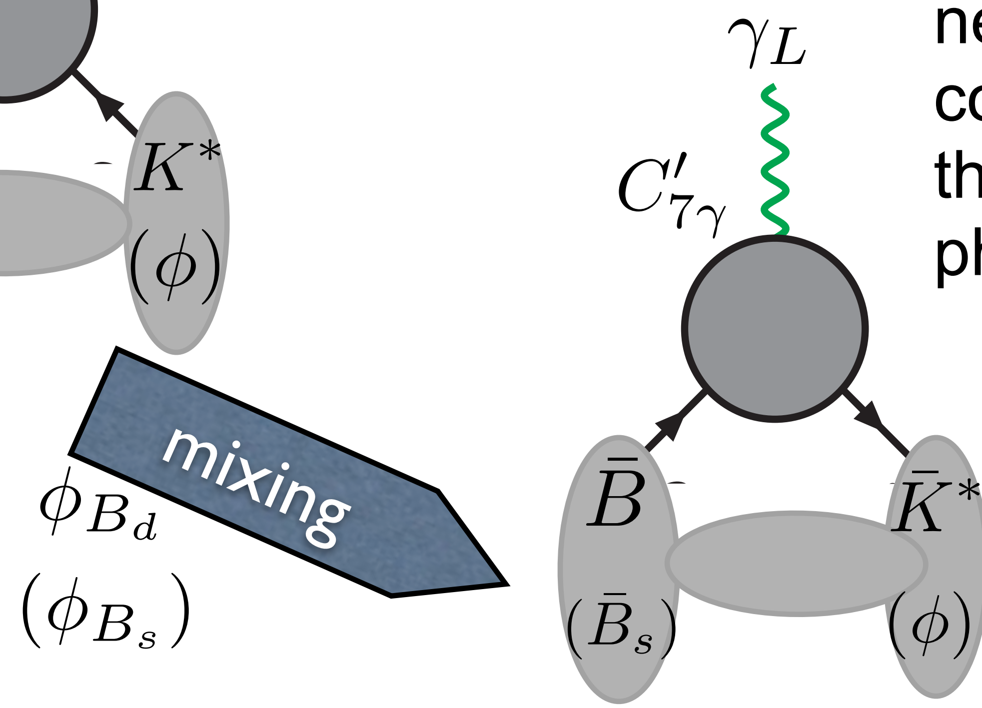

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mixing-decay interference & time-dependent CP asymmetry
LHCb has sensitivity for $S(B_s \to \phi\gamma)$

- Theoretical description based on heavy-quark expansion, similar to semileptonic case

Bosch & Buchalla 01

Beneke, Feldmann, Seidel 01

Conclusion

- Theories of the electroweak scale bring in new particle that contribute to flavour-violating observables
- Some interesting results on CP violation in B_s mixing
- LHCb should give a clear picture on mixing, and would see large NP effects in a number of observables soon
- Many important topics not covered, in particular

  - improved determination of “true” CKM angle γ from tree decays
  - charmless hadronic B decays

  both of which have impact on the new-physics search