New physics at LHCb

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Outline

- Flavour at the weak scale
- Flavour at the TeV scale
- Where to look at LHCb

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

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

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!

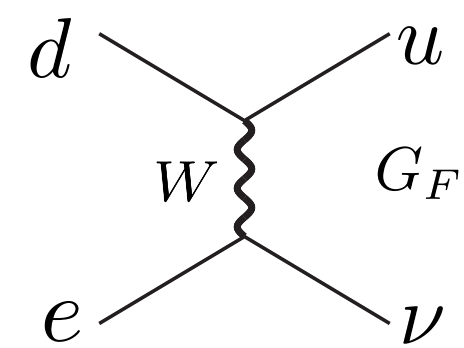
1964 Gell-Mann gives hadronic weak current in the quark model

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

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

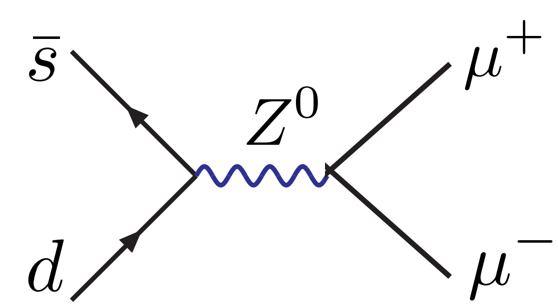
1964 CP violation discovered in Kaon decays (Cronin&Fitch)

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

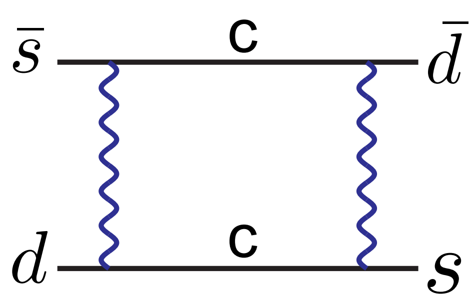


1970 To explain the absence of $K_L \rightarrow \mu^+\mu^-$, Glashow, Iliopoulos & Maiani (GIM) couple a “charmed quark” to the formerly “sterile” linear combination
$-\sin\theta_c d_L + \cos\theta_c s_L$
The doublet structure eliminates the Zsd coupling!

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



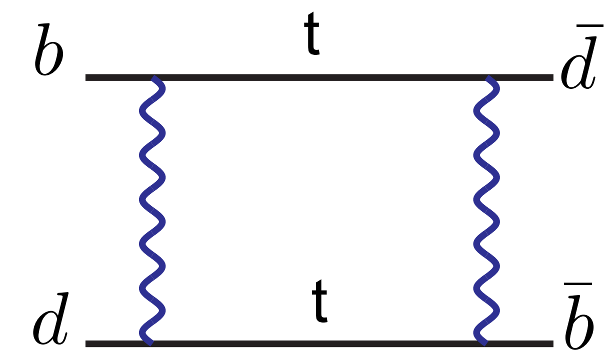
1974 Charm quark discovered

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

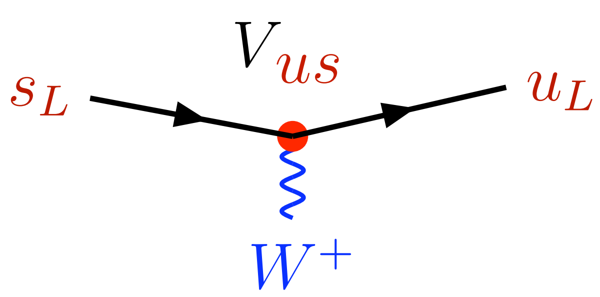


1995 top quark discovered at CDF & D0

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

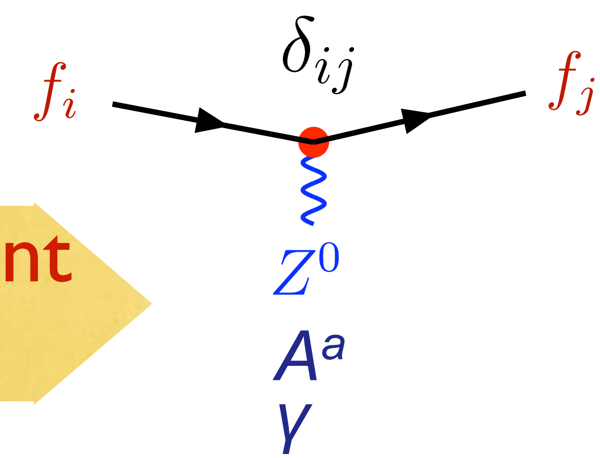
Precision measurements: masses, running coupling, direct CP violation, B factories, determination of CKM elements, neutrino oscillations, search for electric dipole moments, proton decay, ...

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

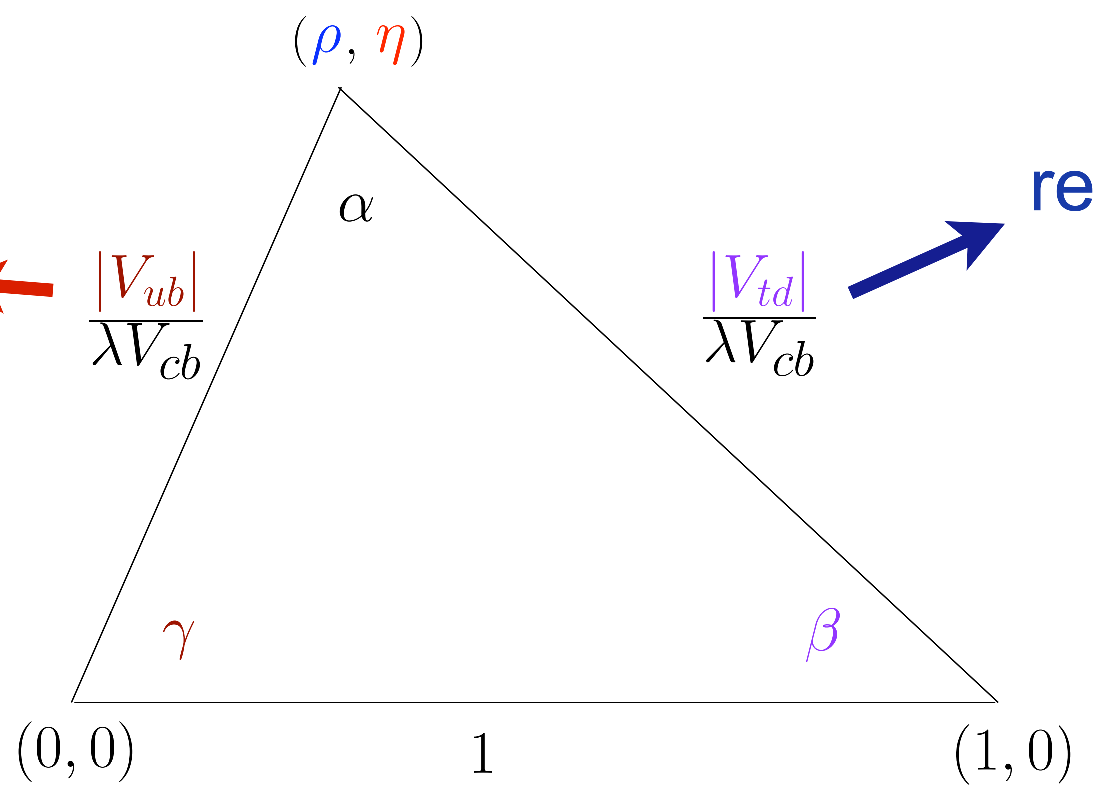
Unitarity triangle

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,

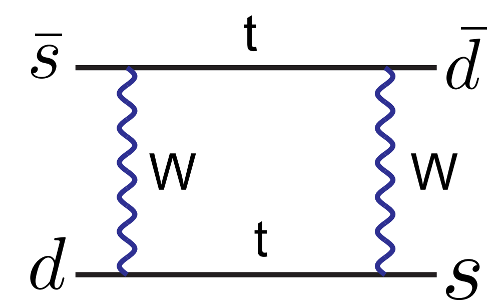
b → u l v
b → u q q
(tree-level Weak int.)

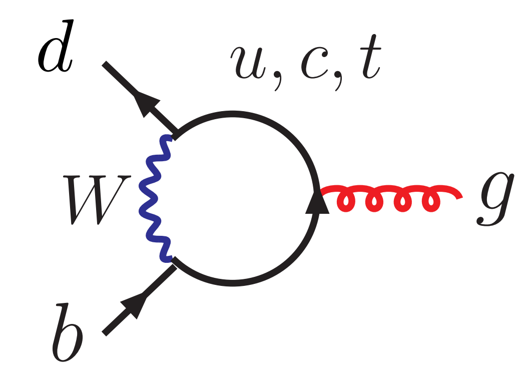


requires top loop

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

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



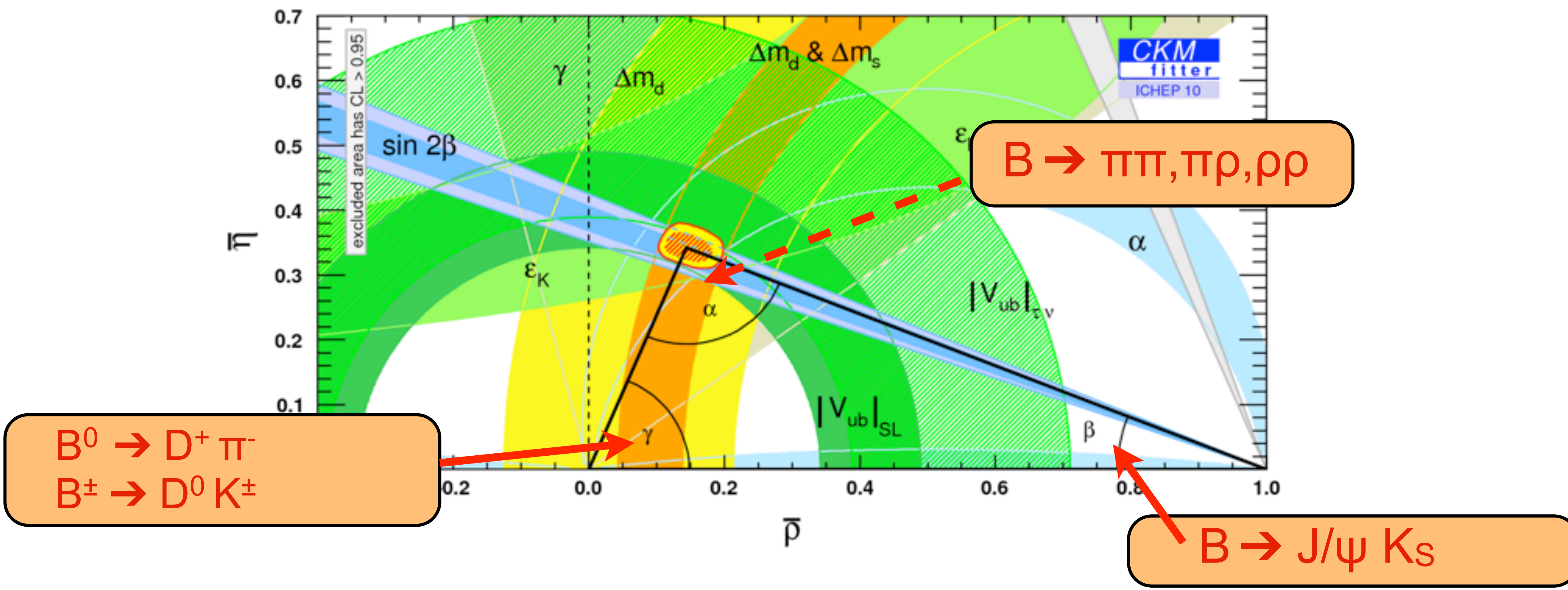


suppression of FCNC by loops and CKM hierarchy

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.

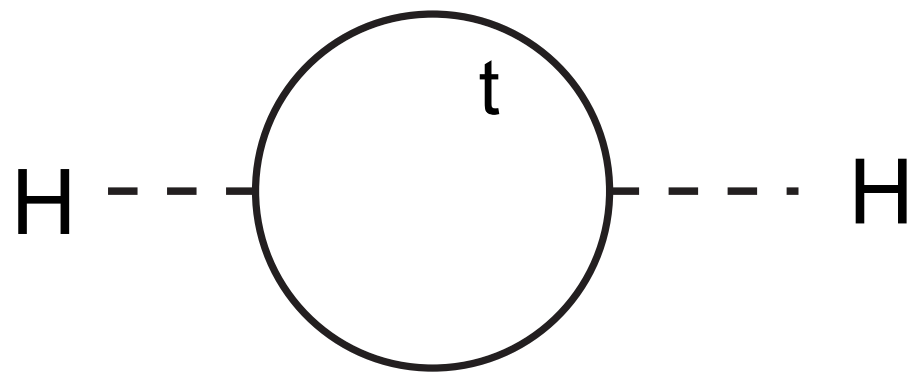
Within the Standard Model, all parameters (except higgs mass) including CKM have been determined, most to at least few percent accuracy.

However, this is unlikely to be the whole story

Flavour at the TeV scale

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

- This derives in part from



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

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

- Such particles will always contribute to FCNC, which become a probe of the *details* of TeV scale dynamics

Flavour group

SM gauge interactions

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

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

have a large global (= flavour) symmetry group

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

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

[Chivukula & Georgi 1987]

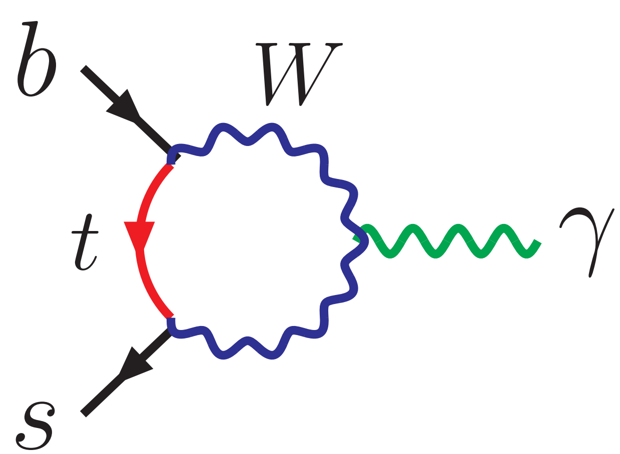
broken (only) by Yukawa couplings to the Higgs

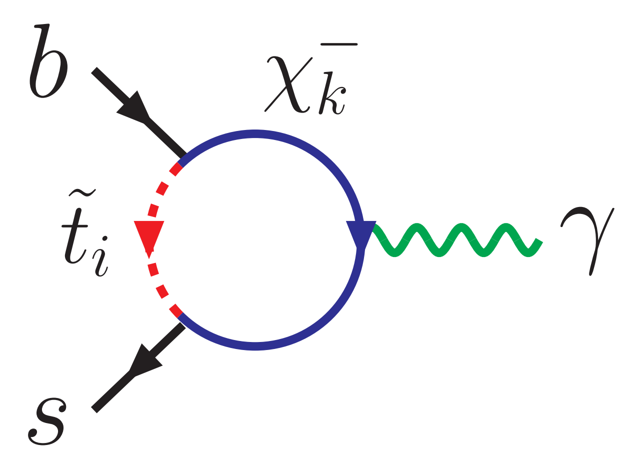
$$\mathcal{L}_Y = -\bar{u}_R Y_U \phi^{c\dagger} Q_L - \bar{d}_R Y_D \phi^\dagger D_L - \bar{e}_R Y_E \phi^\dagger E_L$$

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

Minimal flavour violation (MFV)

- At least, a top partner relevant to the hierarchy problem will have CKM-like flavour violations



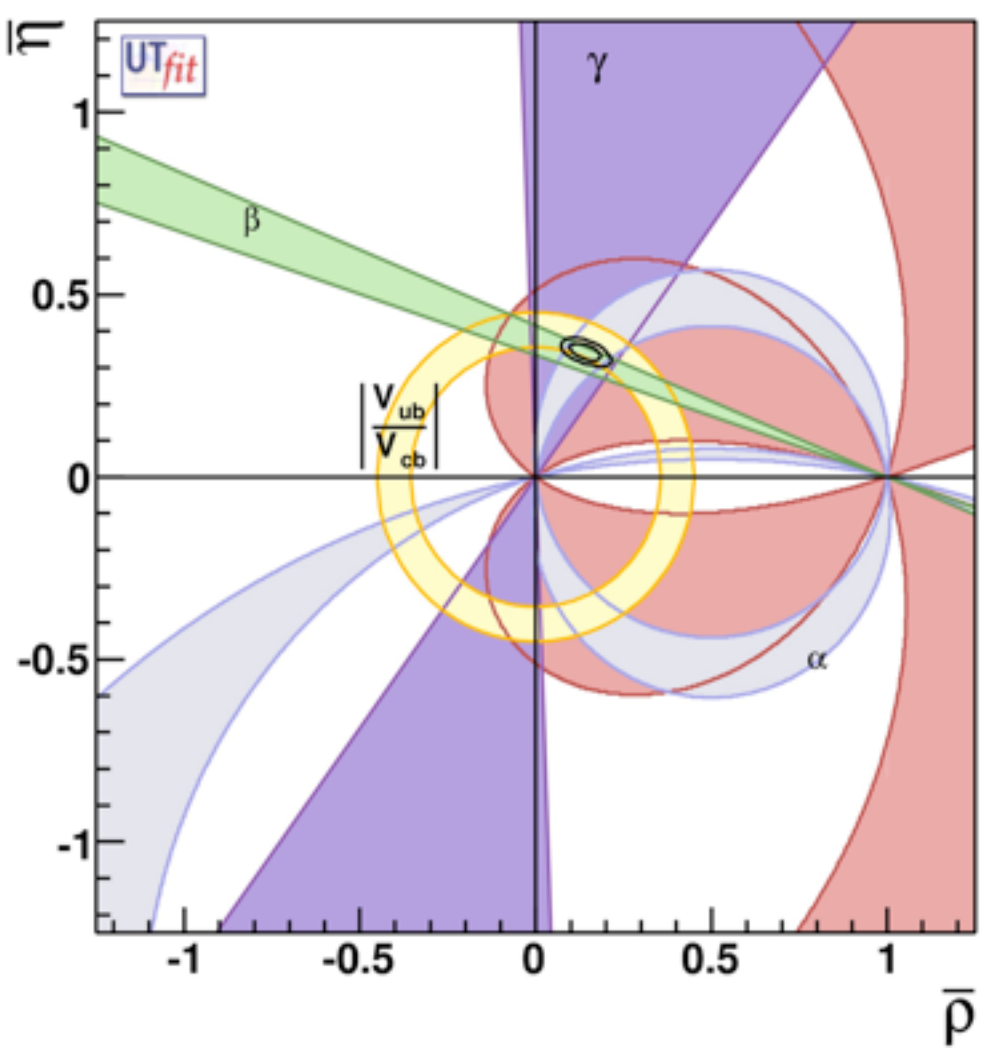


- can be formalized:
  MFV = new physics is invariant under the flavour group once Yukawas are treated as spurions (i.e. transformed like fields under flavour group).
  d'Ambrosio et al 2002

  this means NP flavour violations are functions of SM Yukawas multiplied by numbers, e.g. $c Y_U^\dagger Y_U Y_D^\dagger$

Minimal flavour violation

- in this case, CKM parameters can be extracted unambiguously beyond the Standard Model



Universal unitarity triangle (UUT)

Buras, Gambino, Gorbahn, SJ, Silvestrini 2000

independent of details of new physics (particle content, masses, couplings)

UTfit collaboration (Bona et al)

- however, this is a very restrictive scenario; typically does not apply to dynamical BSM models

- can be generalized (relaxed) eg Kagan et al 2009

SUSY flavour

Supersymmetry associates a scalar with every SM fermion

Squark mass matrices are 6x6 with independent flavour structure:

3x3 flavour-violating - and *supersymmetry-breaking*

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

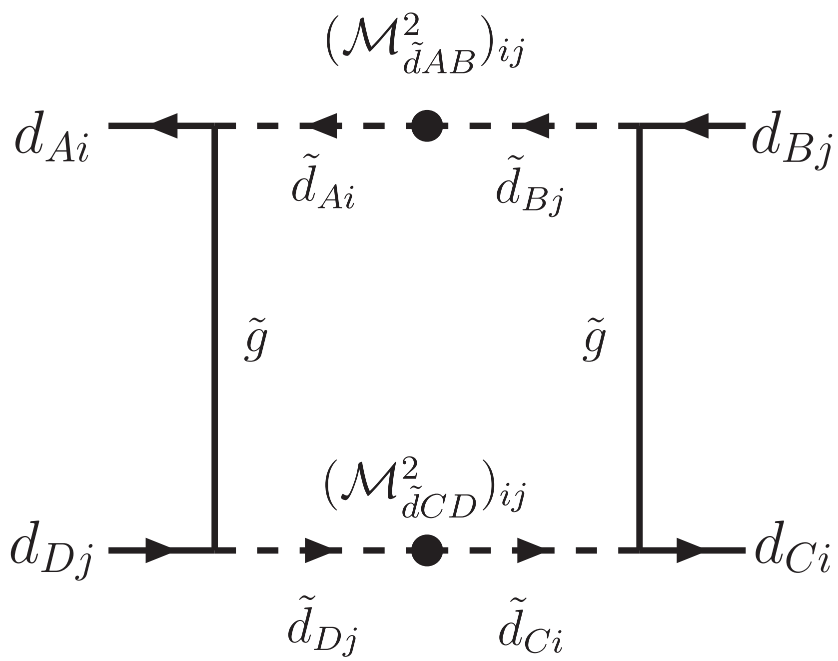
similar for up squarks, charged sleptons. 3x3 LL for sneutrinos

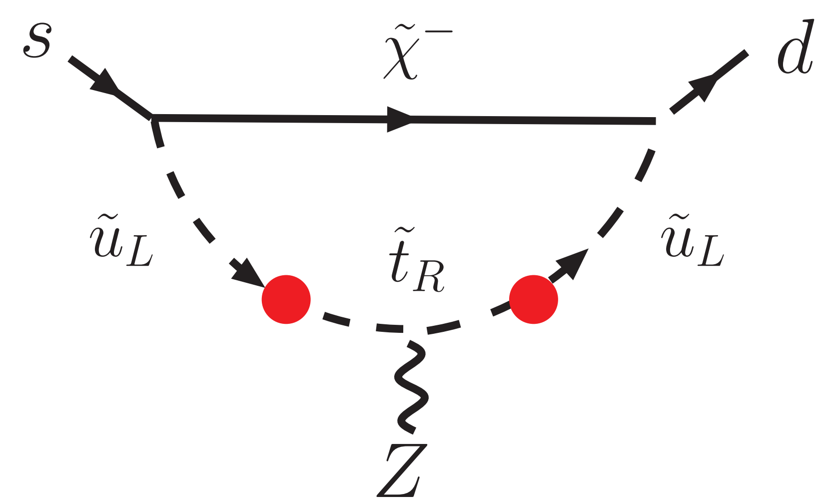
$$\left(\delta_{ij}^{u,d,e,\nu}\right)_{AB} \equiv \frac{\left(\mathcal{M}^2_{\tilde{u},\tilde{d},\tilde{e},\tilde{\nu}}\right)^{AB}_{ij}}{m^2_{\tilde{f}}}$$

33 flavour-violating parameters

45 CPV (some flavour-conserving)

SUSY flavour (2)





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

ΔF=1 decays

B ➔$K^*\mu^+\mu^-$
B ➔$K^*\gamma$
B ➔Kπ
$B_{s,d}$ ➔$\mu^+\mu^-$
K ➔πνν
...

SUSY flavour puzzle

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

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}

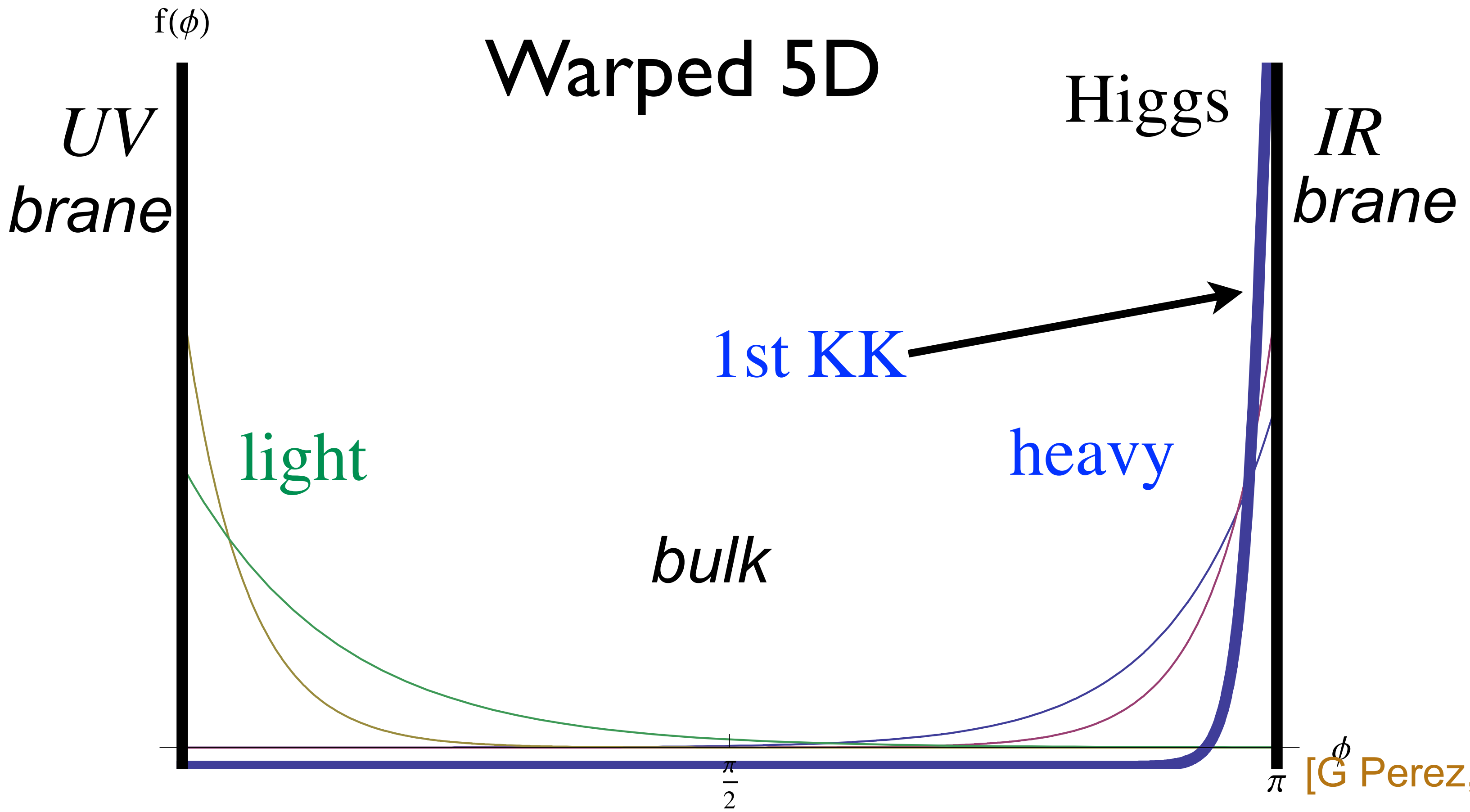
Quantity	upper bound
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LL}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{ud})^2_{RR}\rvert}$	3.9×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})^2_{LR}\rvert}$	1.20×10^{-2}
$\sqrt{\lvert\mathrm{Re}(\delta^{\tilde{u}}_{uc})_{LL}(\delta^{u}_{uc})_{RR}\rvert}$	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 MSSM parameters - and SUSY breaking mechanism in particular

Flavour - warped ED



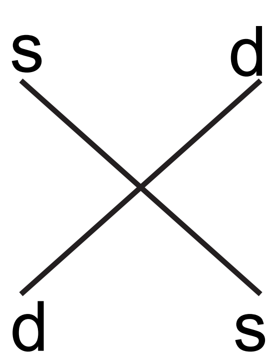
SM fermions are zero modes (~ ground state waves of a particle in a box) of fields present in the bulk.
They also have infinitely many massive modes (KK modes, ~higher states of particle in box)

[G Perez, talk at CKM 2010]

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

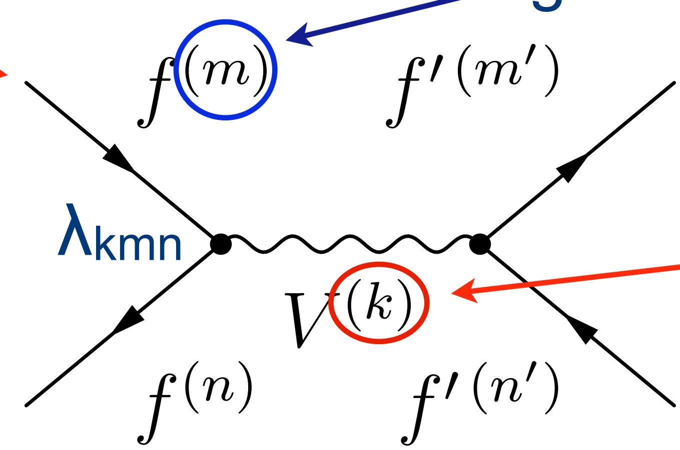
→ not so dangerous after taking into account localization of SM fermions ("RS-GIM")

Flavour - warped ED (2)

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

zero modes
=SM particles

generation



KK mode number

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

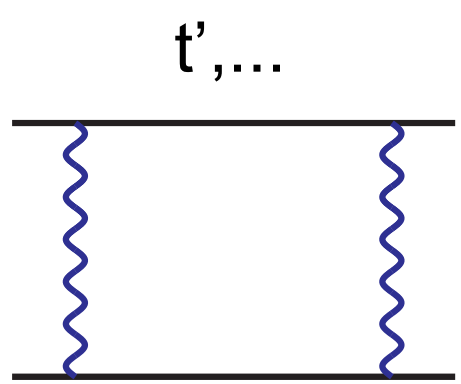
SM Yukawa coupling
$$Y_{mn} \propto f^{(m)}(\pi) f^{(n)}(\pi)$$

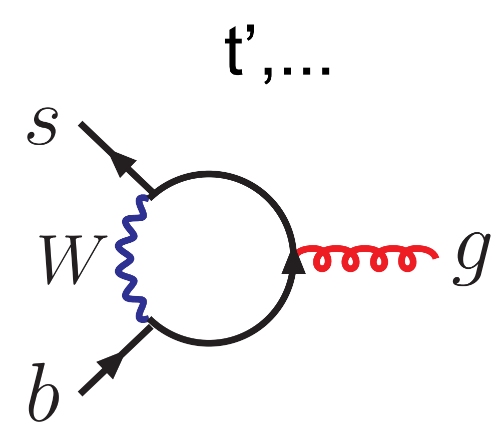
non-minimal flavour violations !

- where are their effects?

Other scenarios

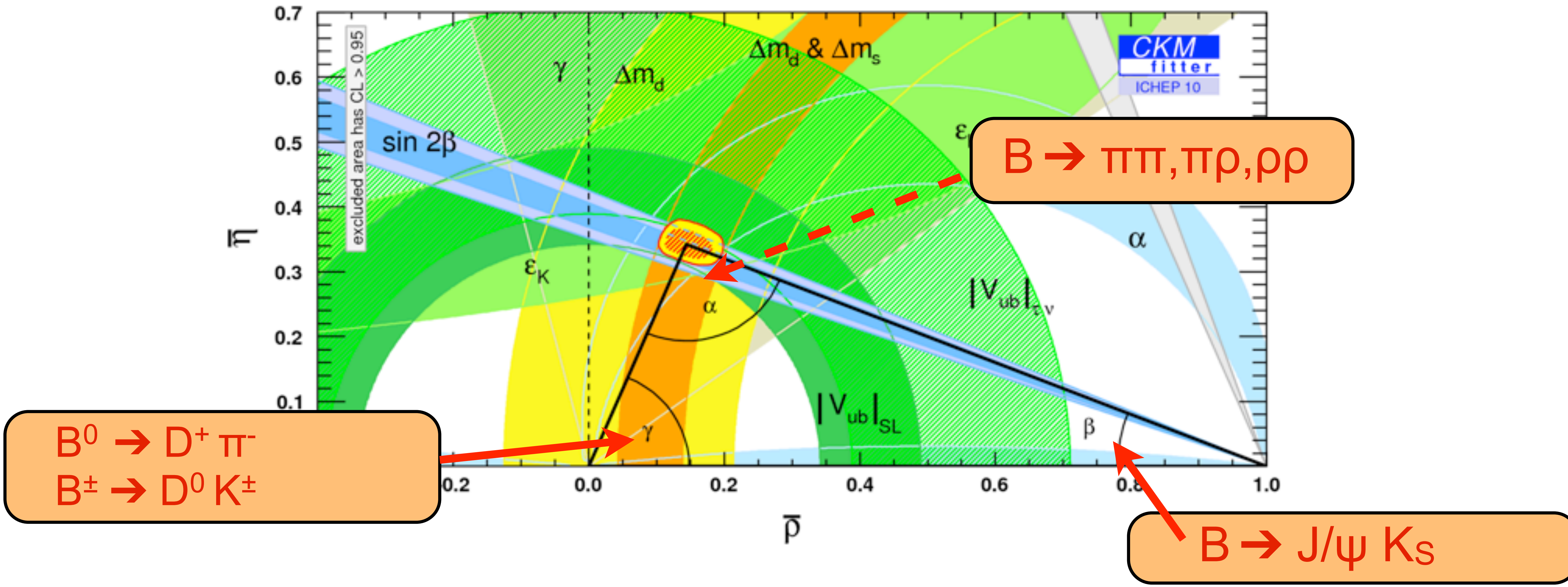
- fourth SM generation
  CKM matrix becomes 4x4, giving new sources of flavour and CP violation
- little(st) higgs model with T parity
  (higgs light because a pseudo-goldstone boson)
  finite, calculable 1-loop contributions due to new heavy particles with new flavour violating couplings
- ...



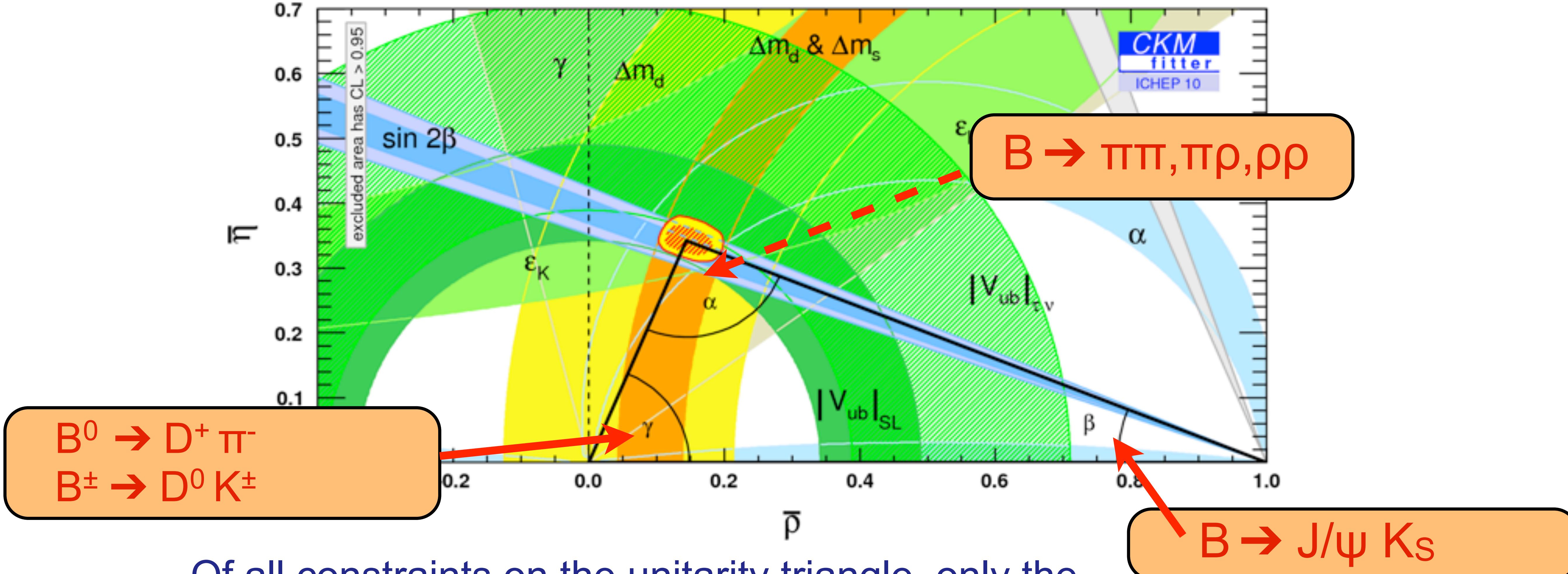


non-minimal flavour violation !

Unitarity Triangle revisited

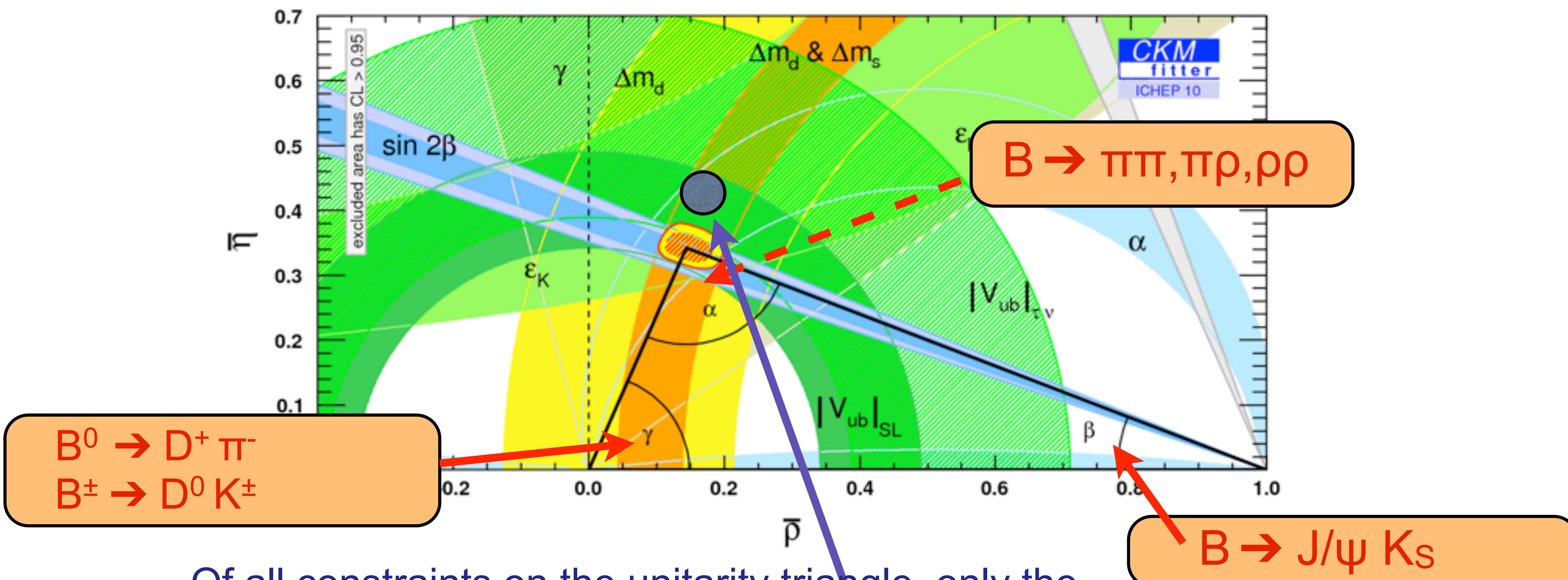


Unitarity Triangle revisited



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.

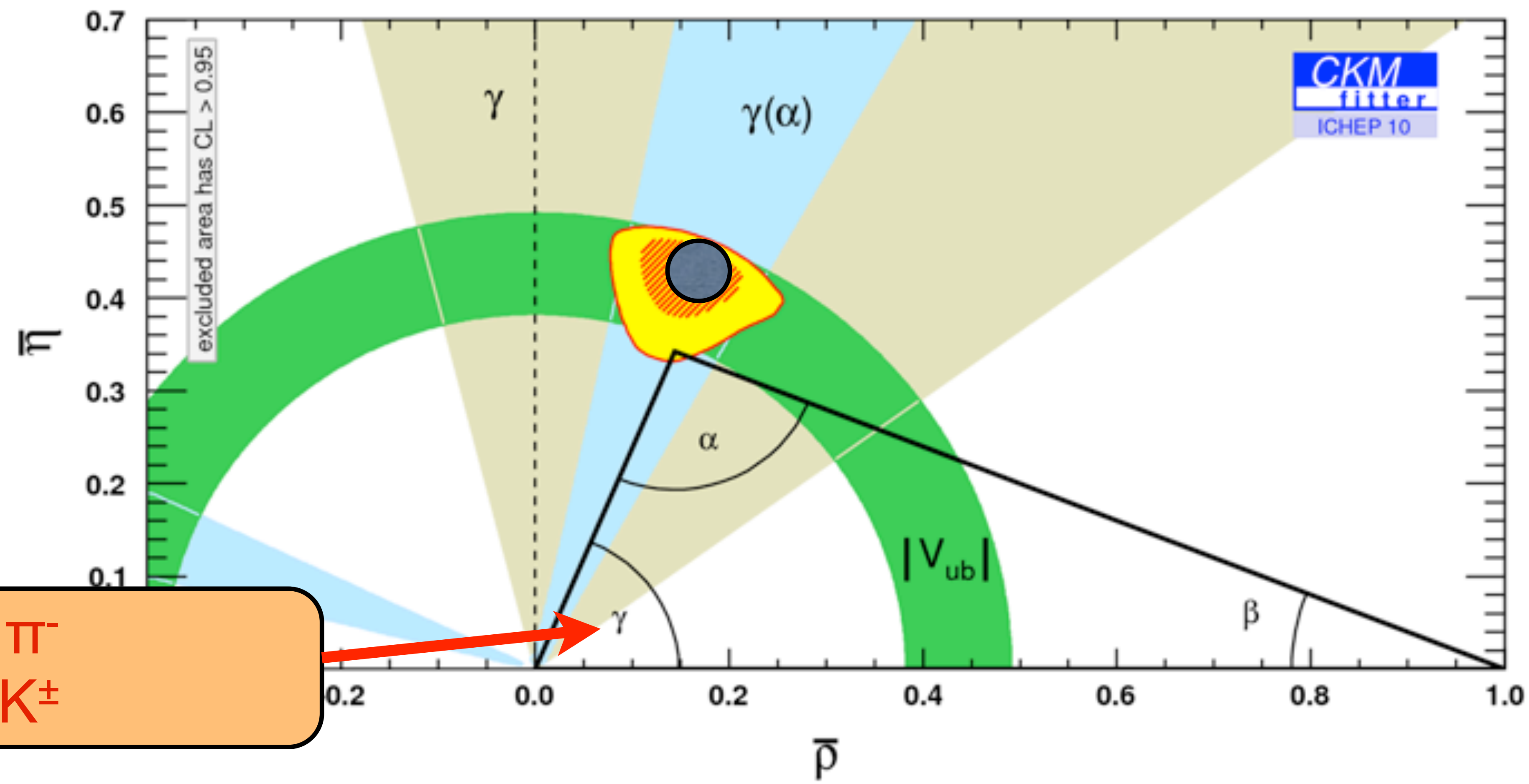
Unitarity Triangle revisited



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)

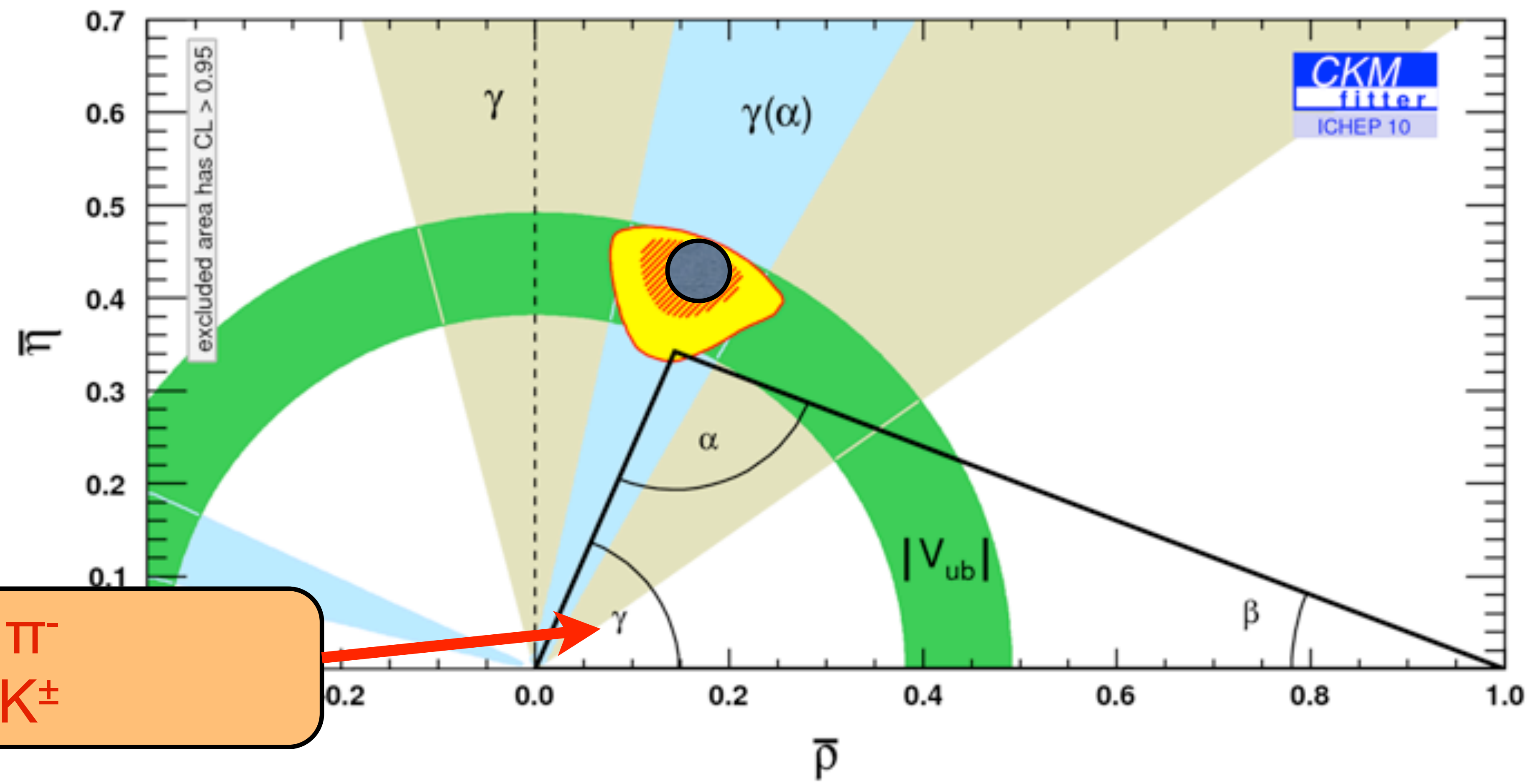
"Tree" determinations



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

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

“Tree” determinations



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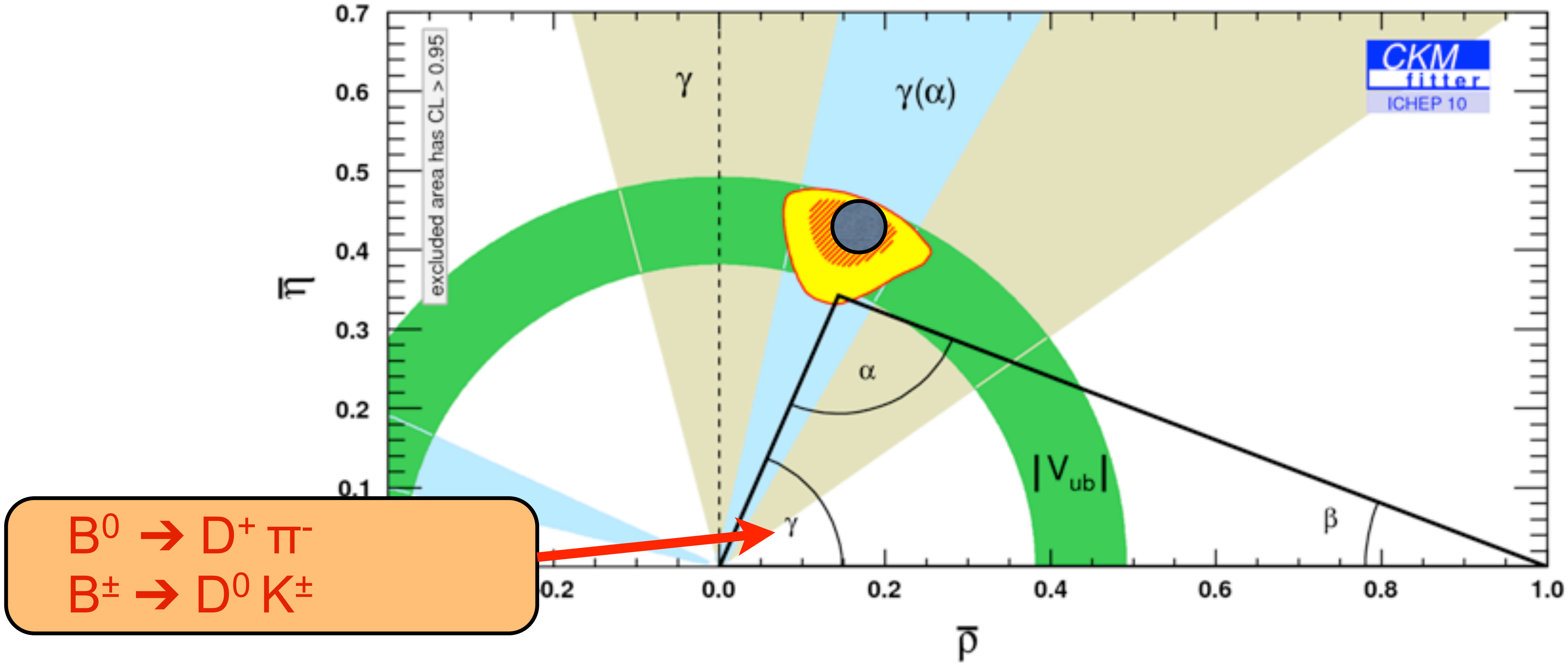
Certainly there is room for O(10%) NP in b->d transitions

“Tree” determinations



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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

B factories vs LHC

- B-factories: dedicated asymmetric e^+e^- colliders
  -SLAC/Babar
  -KEK/Belle -> Belle 2
  operating from end of 1990s, providing $O(10^9)$ B decays so far - almost exclusively at Upsilon(4S) resonance, which cannot decay to B_s mesons

- LHCb dedicated B-physics experiment 10^{12} $b\bar{b}$ pairs/year
  will run close to design lumi early on (2011)
  huge statistics advantage

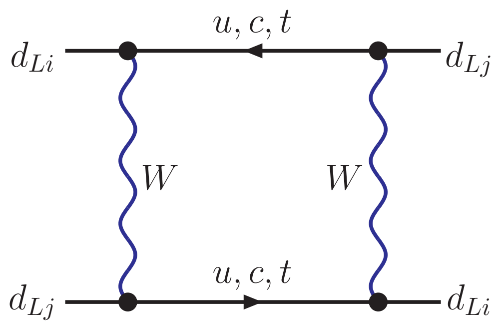
- ATLAS & CMS will also do B-physics, especially while running at low luminosity

- inclusive measurements ($B \to X_s\gamma$, ...) not feasible at hadron collider; many exclusive modes possible

Where to look

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

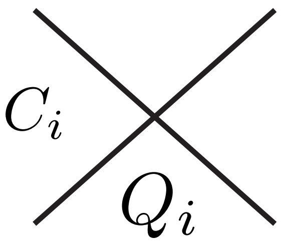
- flavour violation: $\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$



+ ?

OPE (m_B/m_W)

$\sum C_i$



M_{12}

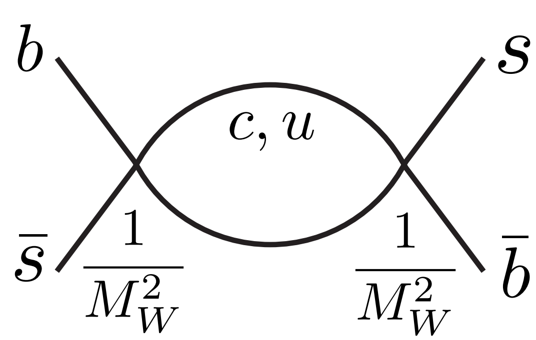
mixing-induced CP violation

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

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

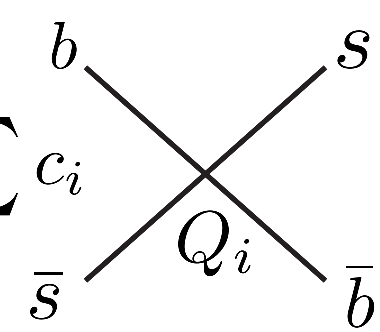
+ 3 more

Im



OPE (Λ_{QCD}/m_B)

$\sum c_i$



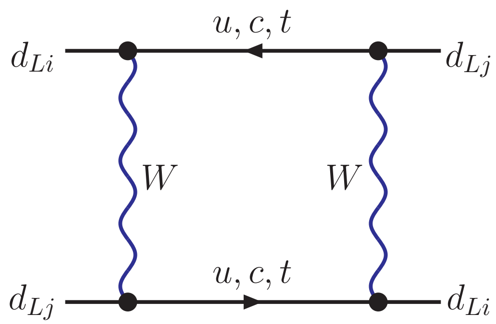
Γ_{12}

$\Delta\Gamma$

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

mixing-induced CP violation

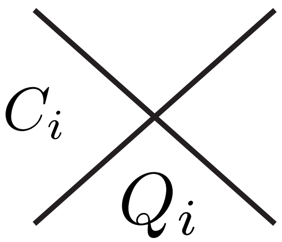
- flavour violation: $\mathcal{A}(\bar{M}^0 \to M^0) \propto M_{12} - \frac{i}{2}\Gamma_{12} \neq 0$



+ ?

OPE (m_B/m_W)

$\sum C_i$



M_{12}

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

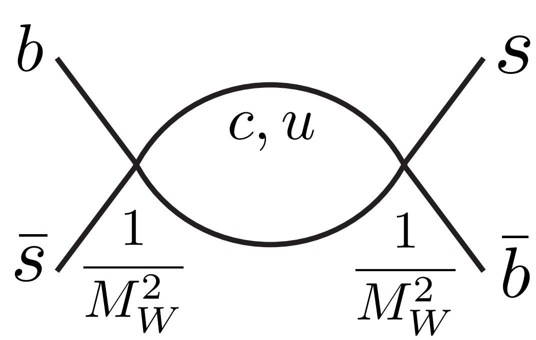
$$Q_1 = (\bar{s}^a_L \gamma_\mu b^a_L)(\bar{s}^b_L \gamma^\mu b^b_L),$$

only operator present in SM

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

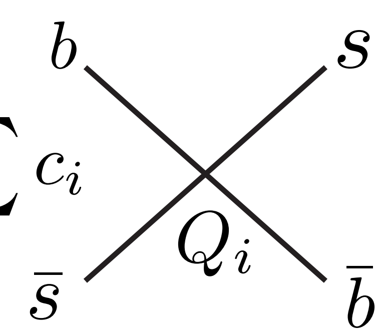
+ 3 more

Im



OPE (Λ_{QCD}/m_B)

$\sum c_i$



Γ_{12}

$\Delta\Gamma$

no NP contribution unless lighter than m_B

Time-dependent CP asymmetry

decay into CP eigenstate:

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

$$M_{12}^q = |M_{12}^q| e^{-i\phi_{B_q}} \qquad B \rightarrow \bar{B}$$

$$\bar{A}_f = \langle f | \bar{B} \rangle \qquad \bar{B} \rightarrow f$$

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

CP-violation parameter

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

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

if only one decay amplitude:

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

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

Beyond SM $\phi_{B_d} \neq 2\beta$

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

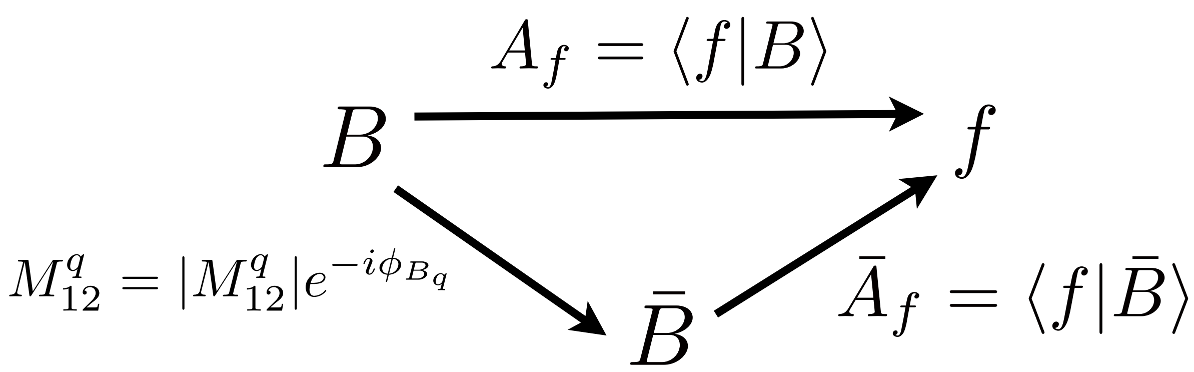
$$B_s^0 \to J/\psi\,\phi \qquad \pm S = \sin\phi_{B_s} \approx 0$$

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:



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

CP-violation parameter

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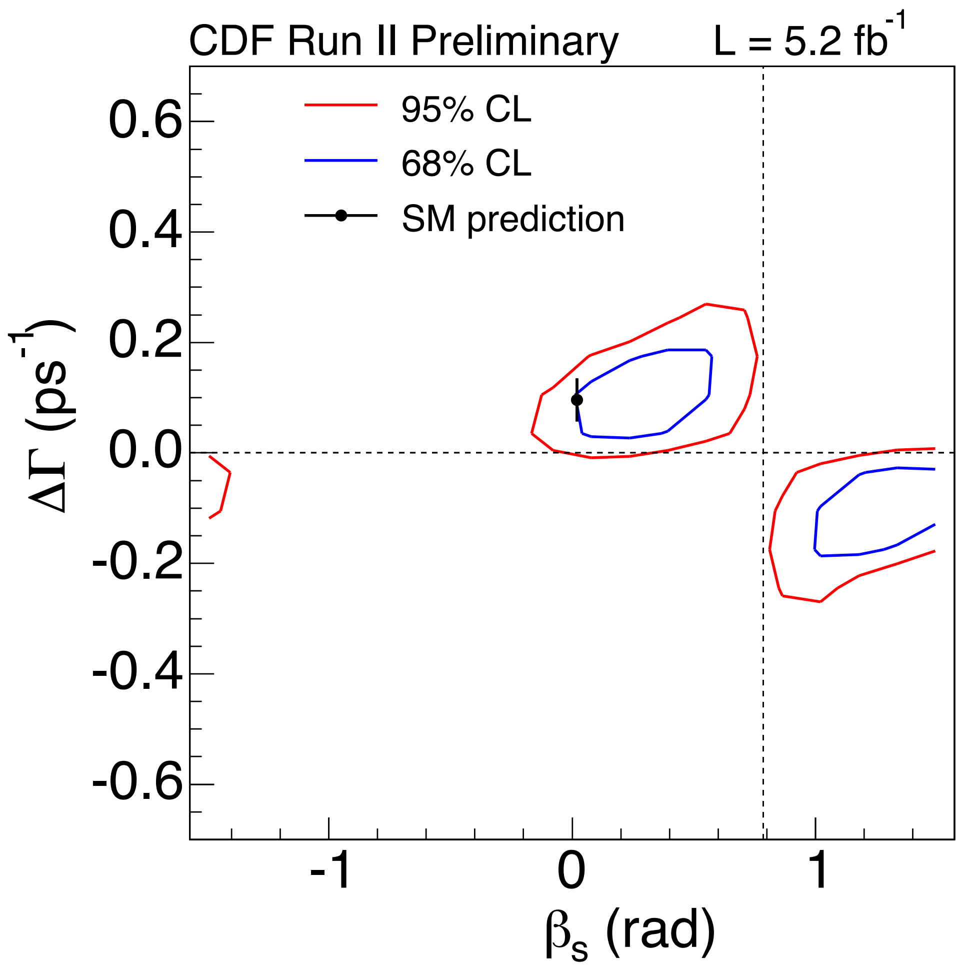
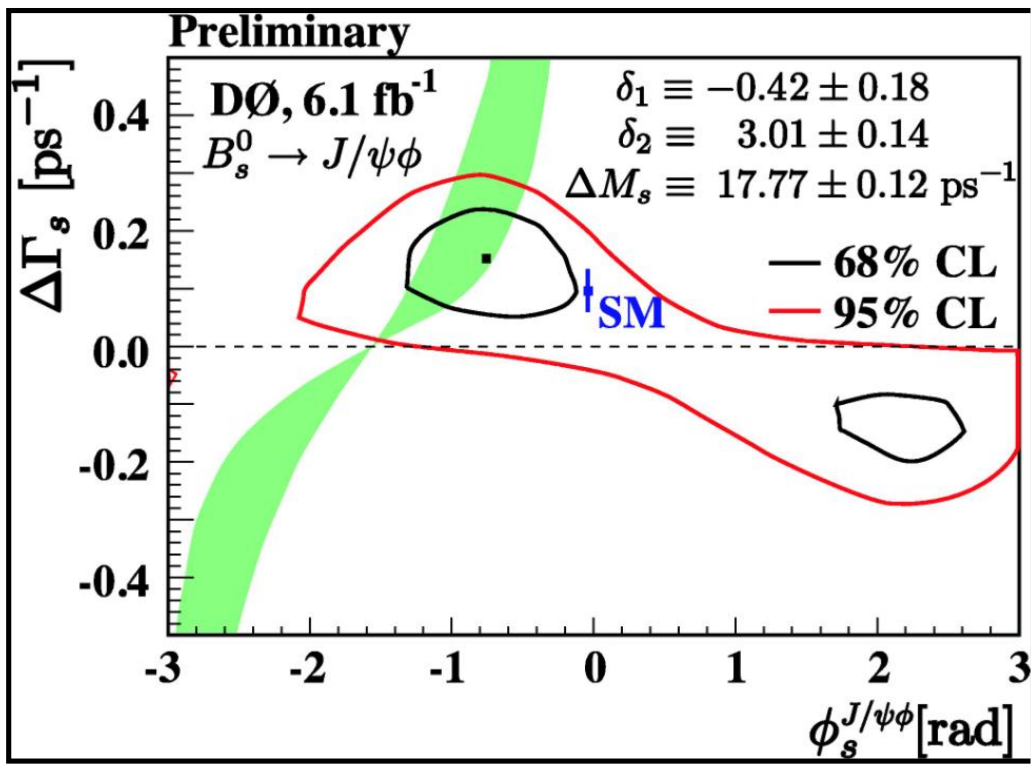
can be generalized to non-CP final states $\quad \phi_{B_{d,s}} + \gamma$ from $B_{(s)}^0 \to D_{(s)} K$

sin(2 ϕBs) measurement

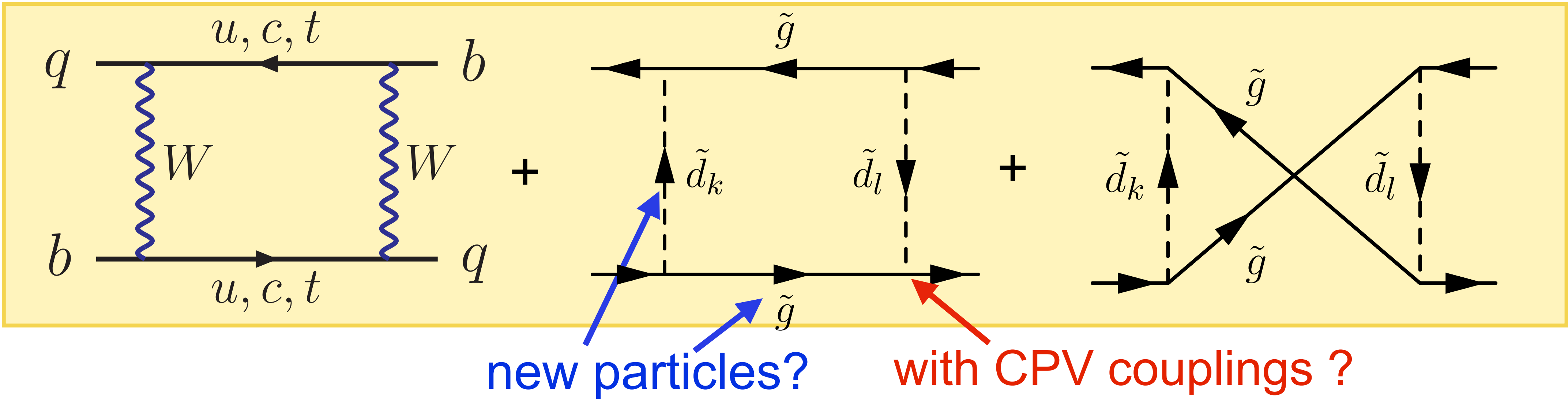
- CDF, D0 measured mixing-induced CPV in $B_s \to J/\psi\phi$





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

CP violation in B_s mixing?



- in general, three parameters $|M_{12}^s|, \; |\Gamma_{12}^s|, \; \phi_s = \arg \frac{-M_{12}^s}{\Gamma_{12}^s}$
- 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:

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

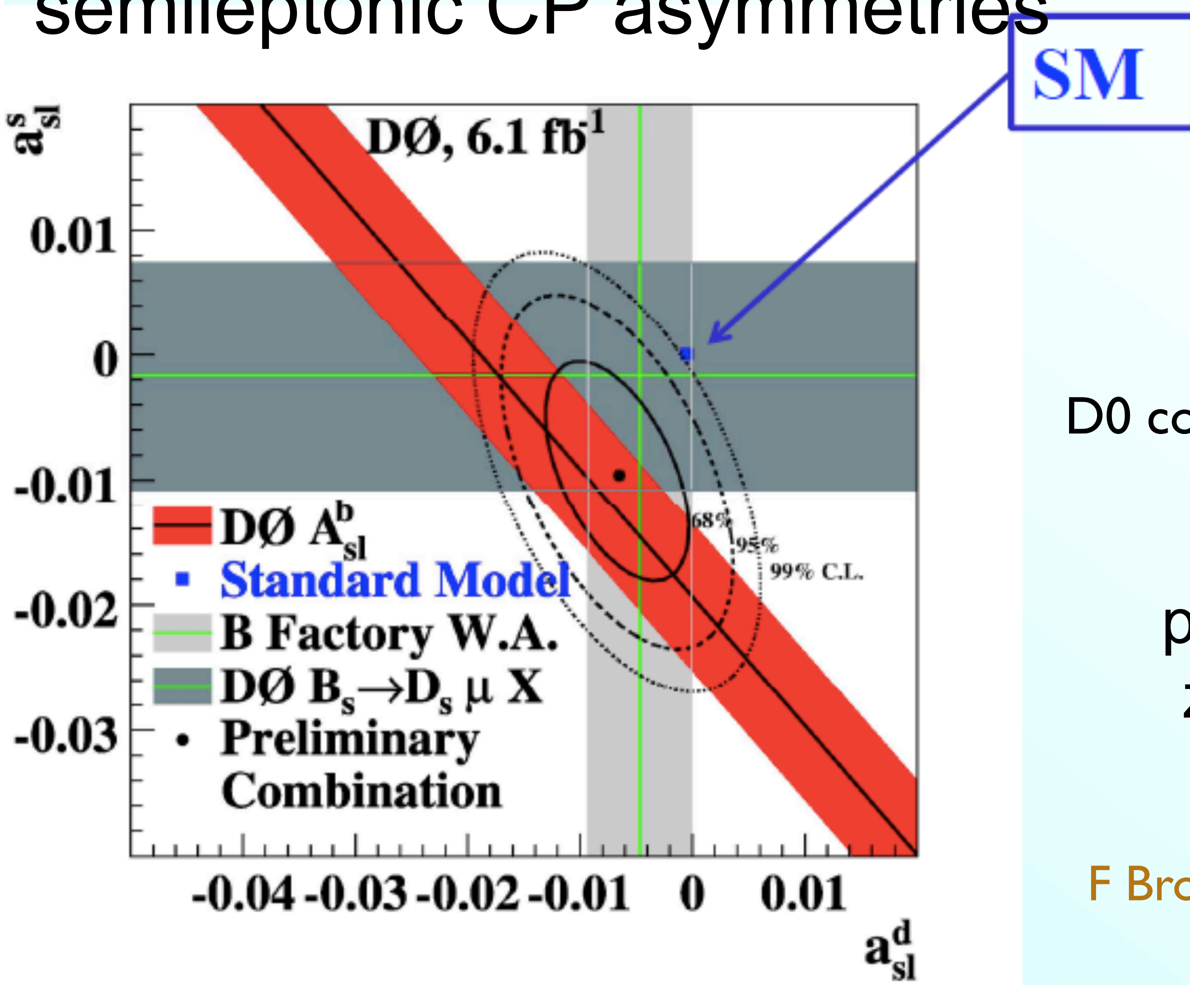
mass difference $\qquad$ width difference

- 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

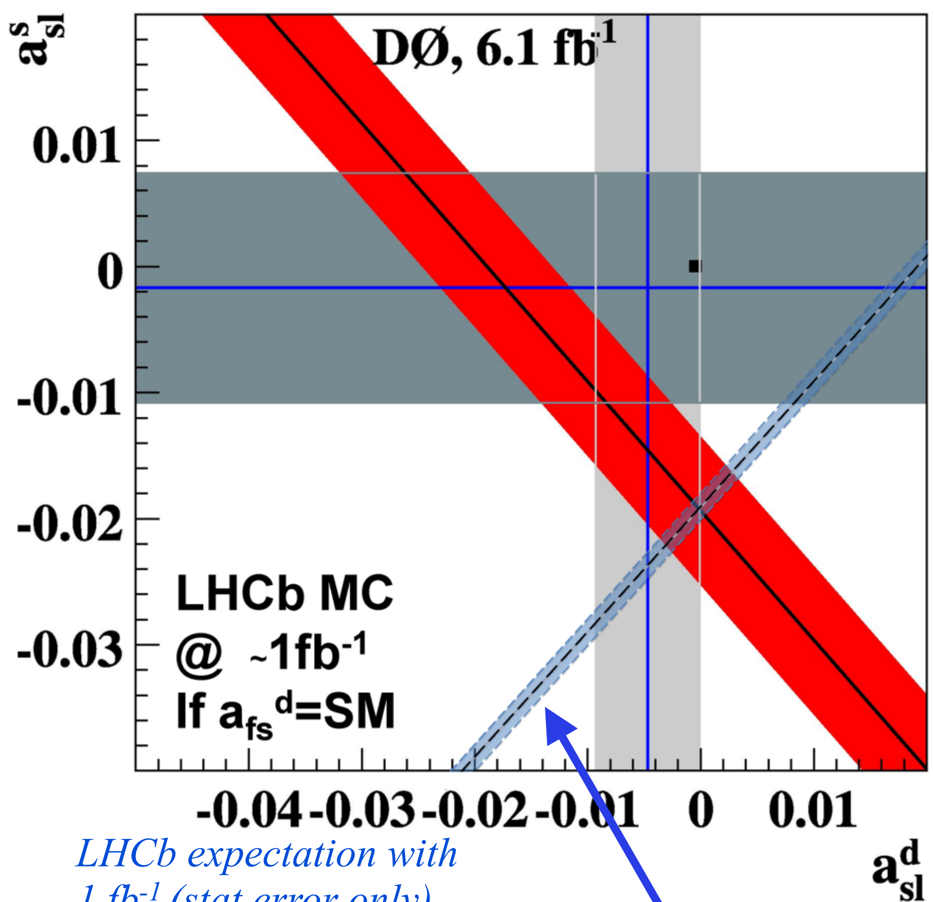
points to non-zero a^s_{sl} / ϕ_s

F Brooijmans @ FCPC2010

These are functions of the same mixing phases as enter the time-dependent CPV, so a consistent picture must eventually emerge

Semileptonic CP asymmetries

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



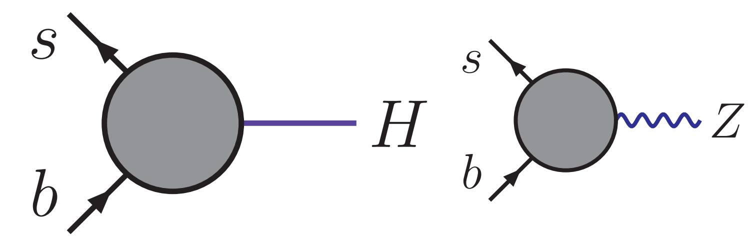
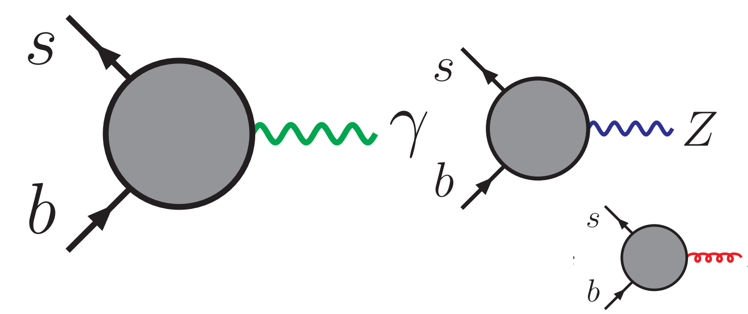
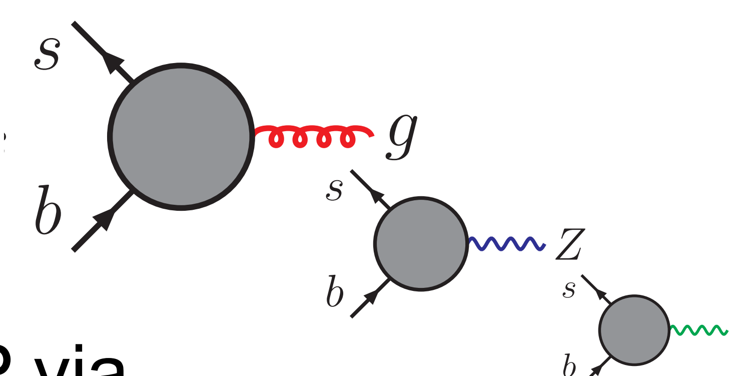
LHCb expectation with 1 fb^{-1} (stat error only), assuming D0 central value and no NP in a^d_{sl}

J Rademacker @ iNExT 2010

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 plane

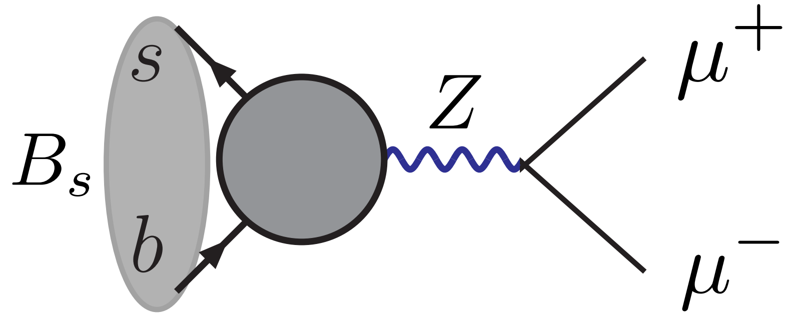
Exclusive decays at LHCb

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 $B \to \pi\pi$, 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.

Leptonic decay, NP and LHC

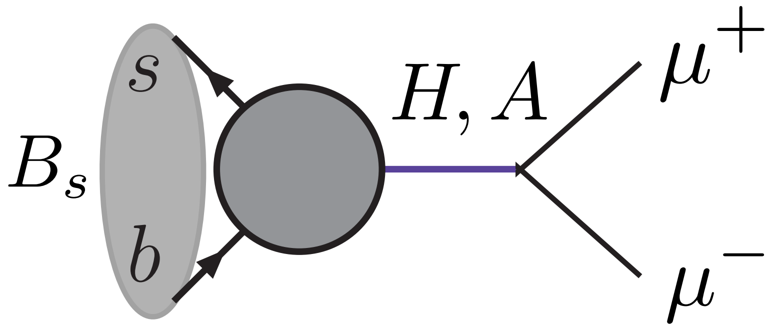


$\propto \frac{m_\mu^2}{M_W^2}$

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

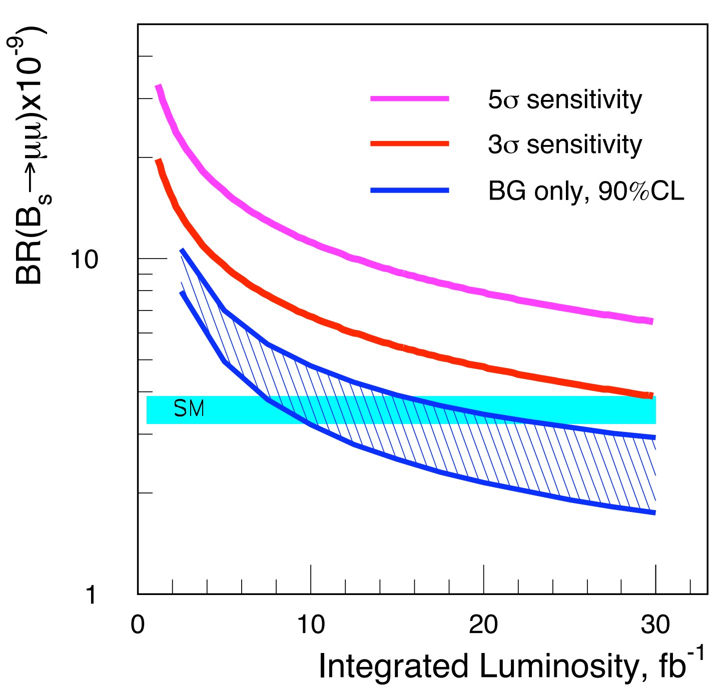


$\propto \frac{m_b^2 m_\mu^2}{M_W^4} \tan^6 \beta$

Yukawa suppressed in SM

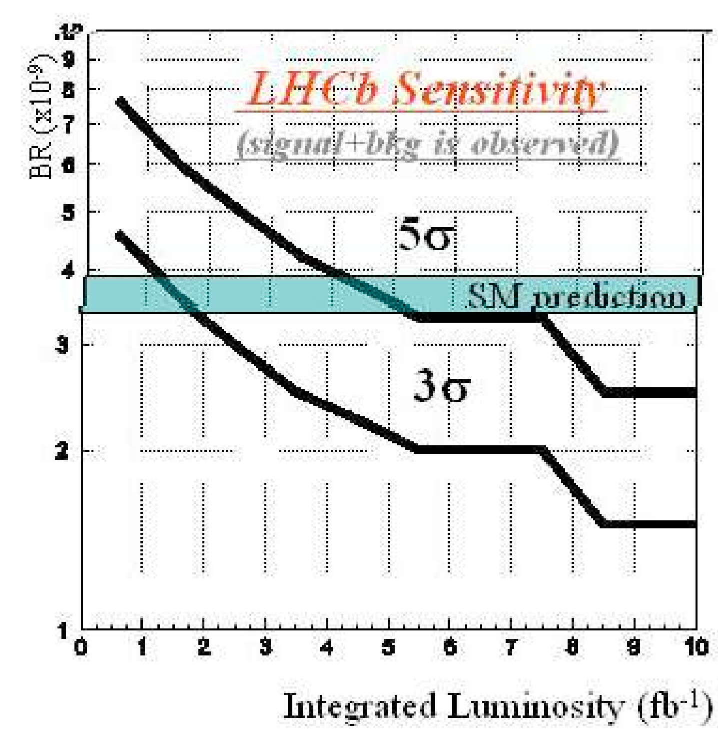
in 2HDM (or MSSM) Yukawas can be very large

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



ATLAS/CMS

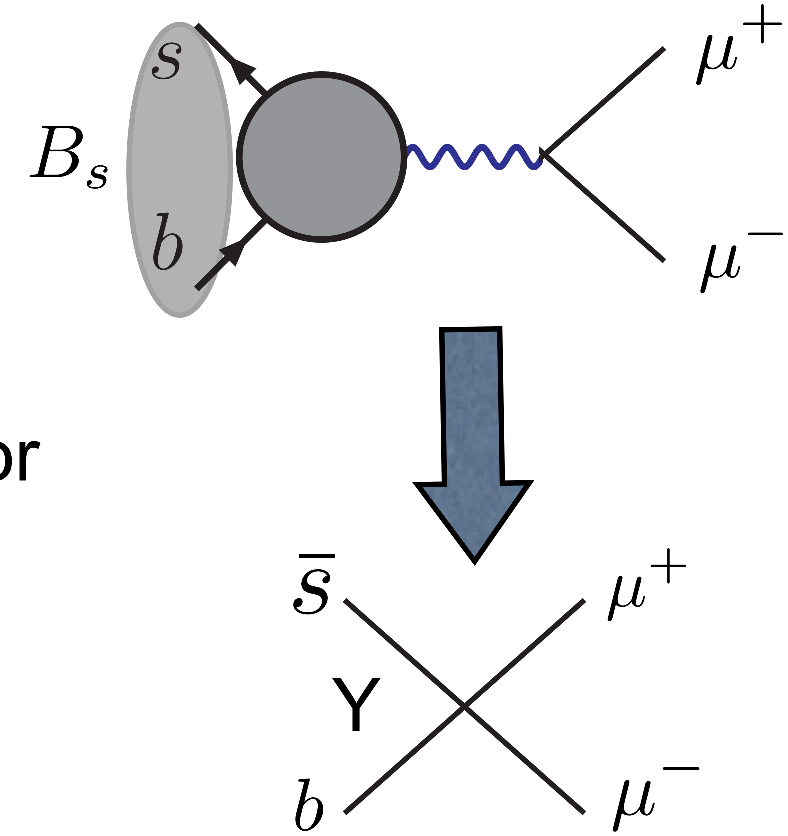
[Artuso et al 0801.1833]



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

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

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

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

(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

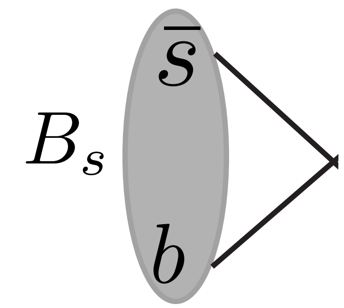
for D or K decays long-distance contributions are important

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

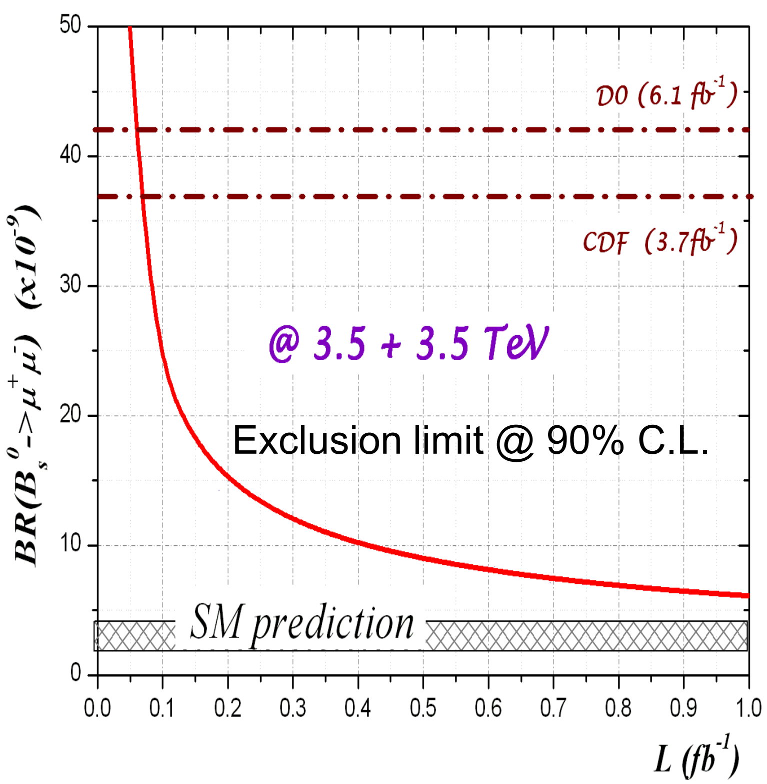
	CDF	D0	SM theory
$B_s \to \mu^+\mu^-$	$4.3\ 10^{-8}$ 95% CL	$5.2\ 10^{-8}$ 95% CL	$(3.2\pm0.2)\ 10^{-9}$
$B_d \to \mu^+\mu^-$	$7.6\ 10^{-9}$ 95% CL		$(1.0\pm0.1)\ 10^{-10}$
$D \to \mu^+\mu^-$	$3.0\ 10^{-7}$ 95% CL		$\sim 10^{-13}$

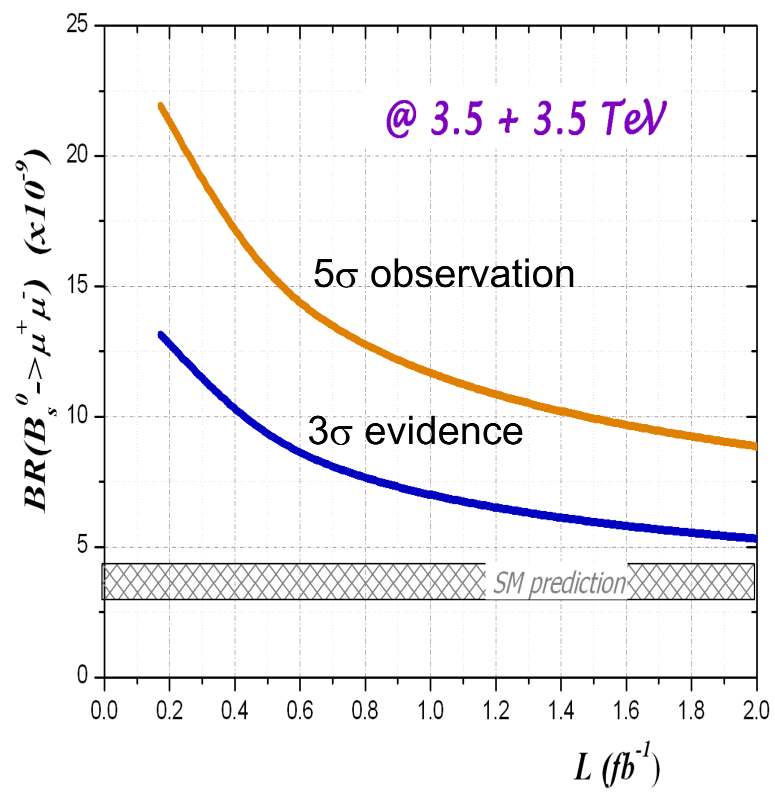
CDF public note 9892 D0 arXiv:1006.3469 D0 arXiv:1008.5077

Kreps arXiv:1008.0247 Buras et al arXiv:1007.1993

Burdman et al 2001

- early LHCb prospects





(Guy Wilkinson at CKM2010)

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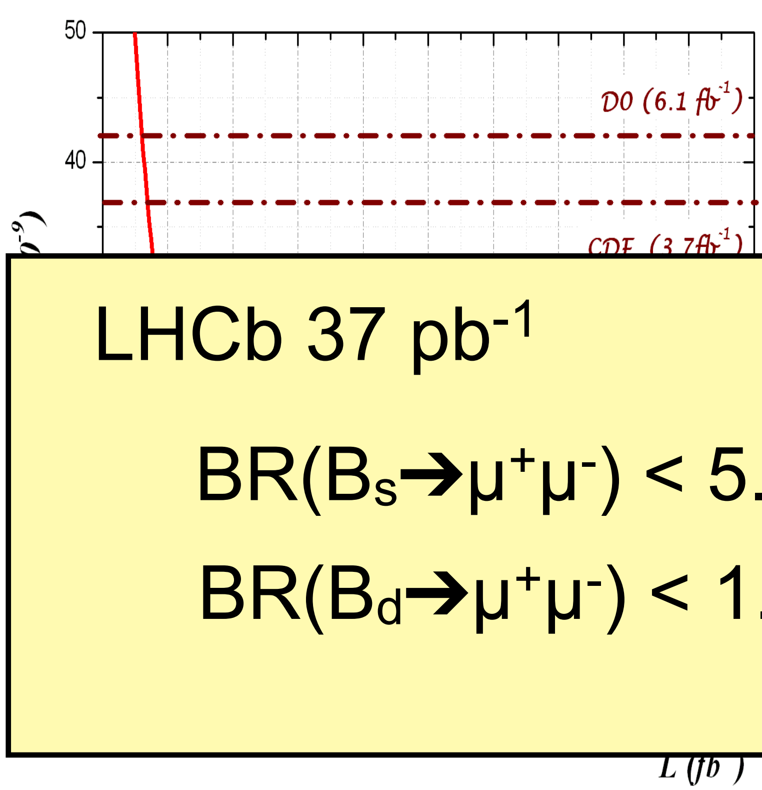
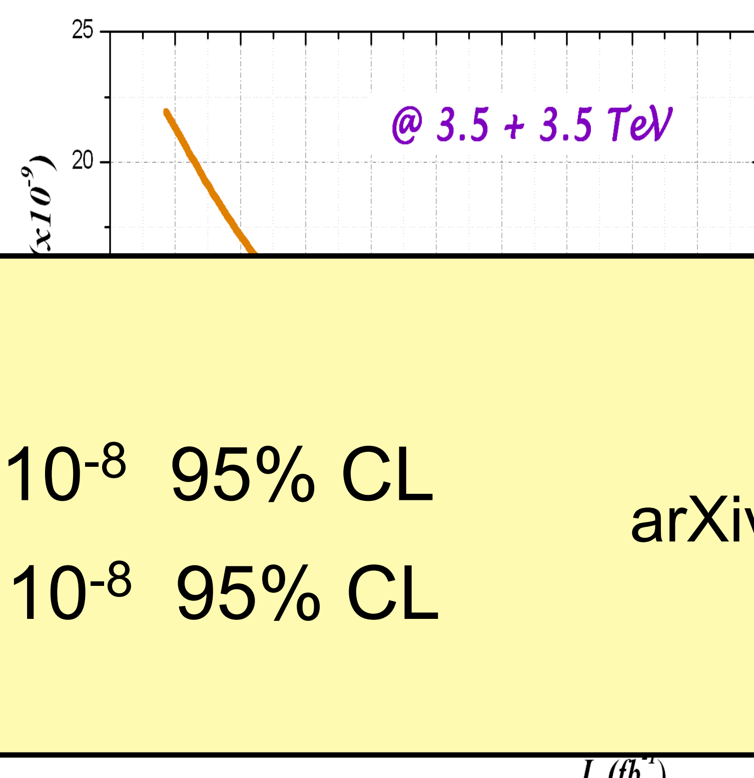




(Guy Wilkinson at CKM2010)

LHCb 37 pb^{-1}

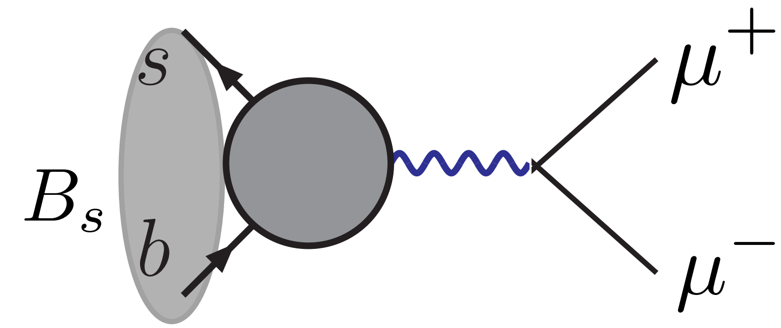
$BR(B_s \to \mu^+\mu^-) < 5.6\ 10^{-8}$ 95% CL

$BR(B_d \to \mu^+\mu^-) < 1.5\ 10^{-8}$ 95% CL

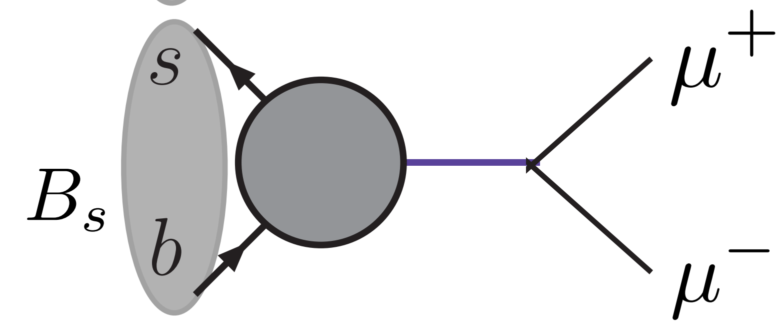
arXiv:1103.2465

Beyond the SM

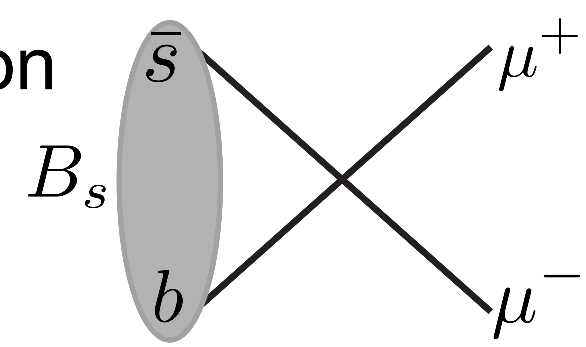
- New physics can modify the Z penguin ....



... induce a Higgs penguin ...



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



could also violate lepton flavour

- most general effective hamiltonian

$$\frac{G_F}{\sqrt{2}}\,\frac{\alpha}{\pi\sin^2\theta_W}\,V_{tb}^*V_{tq}\,\left[\,C_SQ_S+C_PQ_P+C_AQ_A\,\right]$$ + parity reflections

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

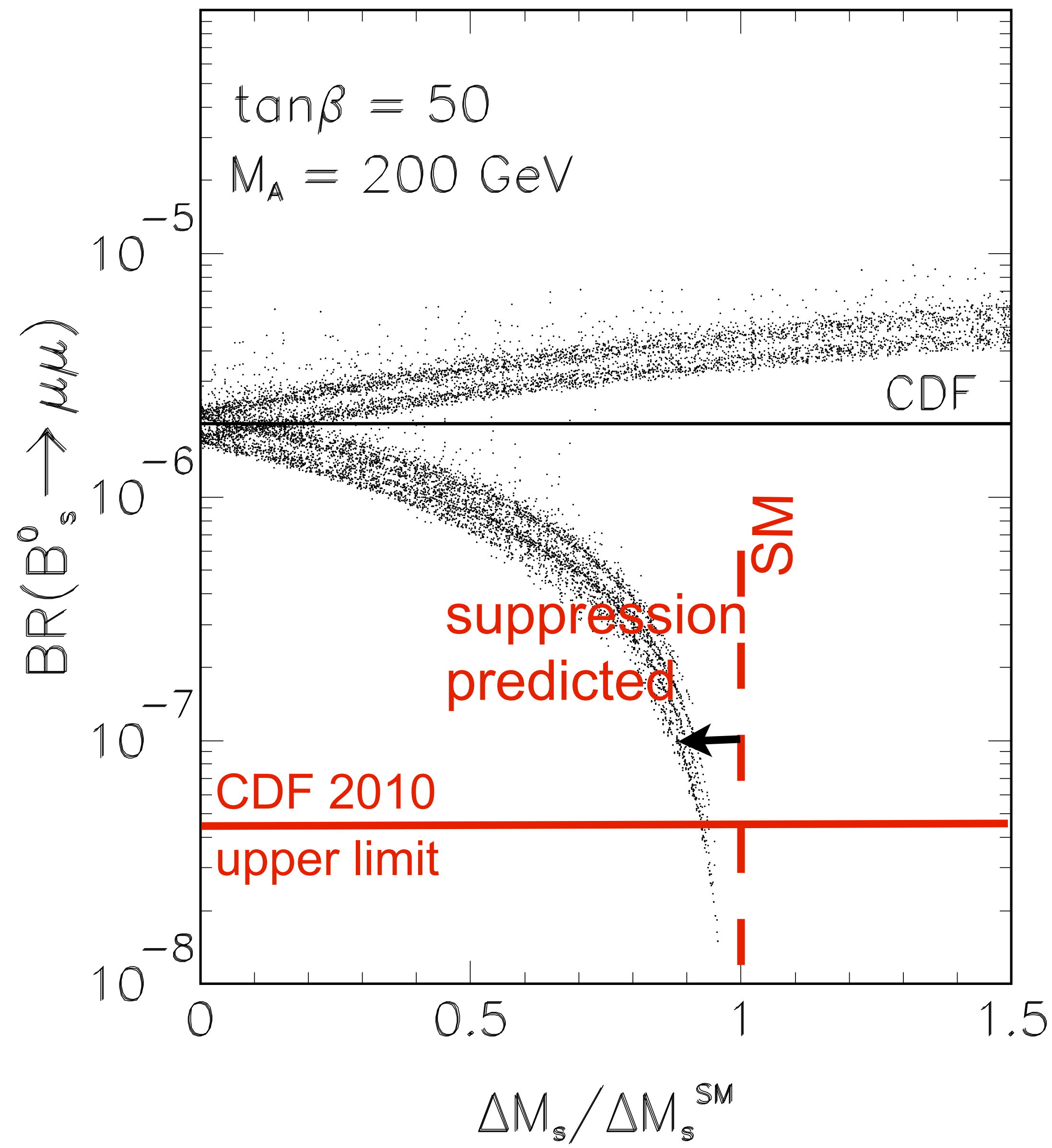
could violate lepton flavour !

MSSM - large tan β - MFV

- huge rates possible, even for minimal flavour violation (MFV) (via heavy-Higgs penguin)

- correlation (for MFV) with ΔM_{B_s} [Buras et al 2002] [Gorbahn, SJ, Nierste, Trine 2009]

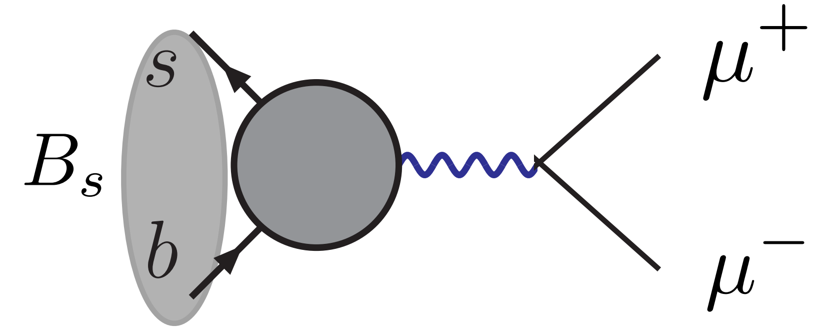
  bound on BR($B_s \to \mu^+\mu^-$) in these models implies closeness of ΔM_{B_s} to SM. In turn, ΔM_{B_s} at present does not constrain $B_s \to \mu^+\mu^-$



- beyond MFV, no correlations !
  not necessarily suppression of $B_d \to \mu^+\mu^-$ with respect to $B_s \to \mu^+\mu$

MSSM - small tan β

- Z penguin contributions now relatively more important and interference effects possible

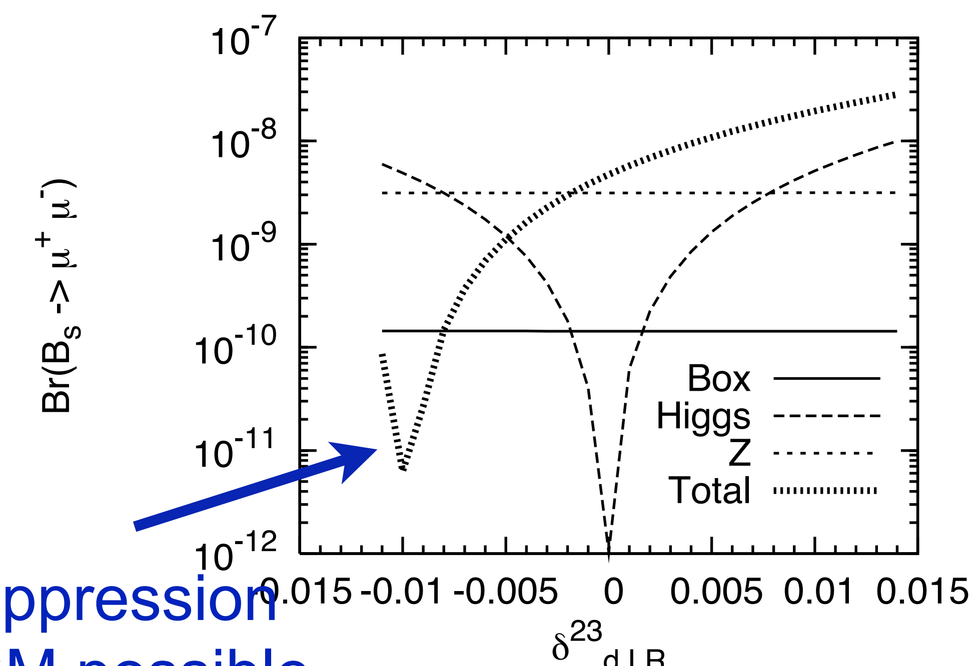


complete 1-loop calculation in general MSSM

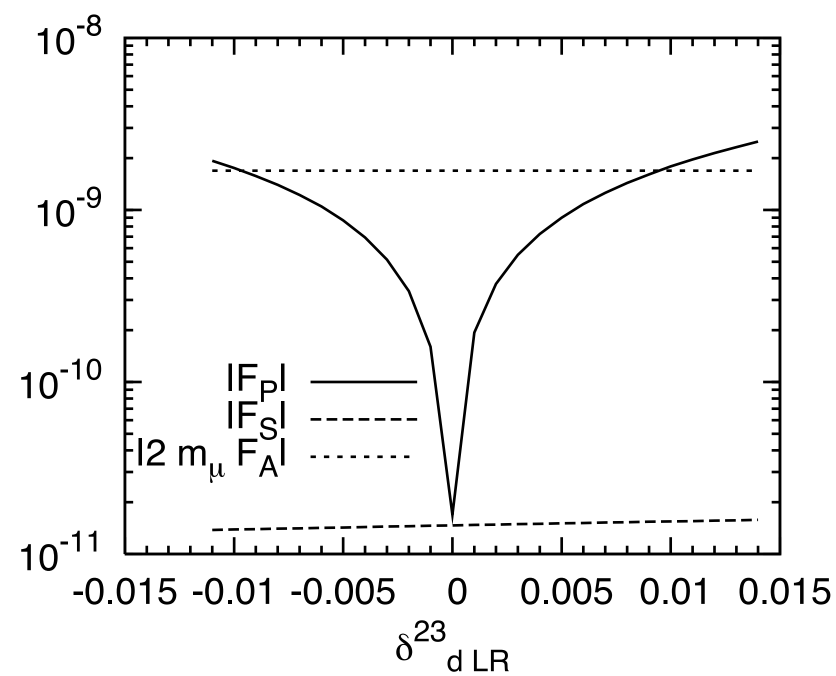
[Dedes, Rosiek, Tanedo 2008]

implemented in public computer program “SUSY_FLAVOR”

[Rosiek, Chankowski, Dedes, SJ, Tanedo 2010]

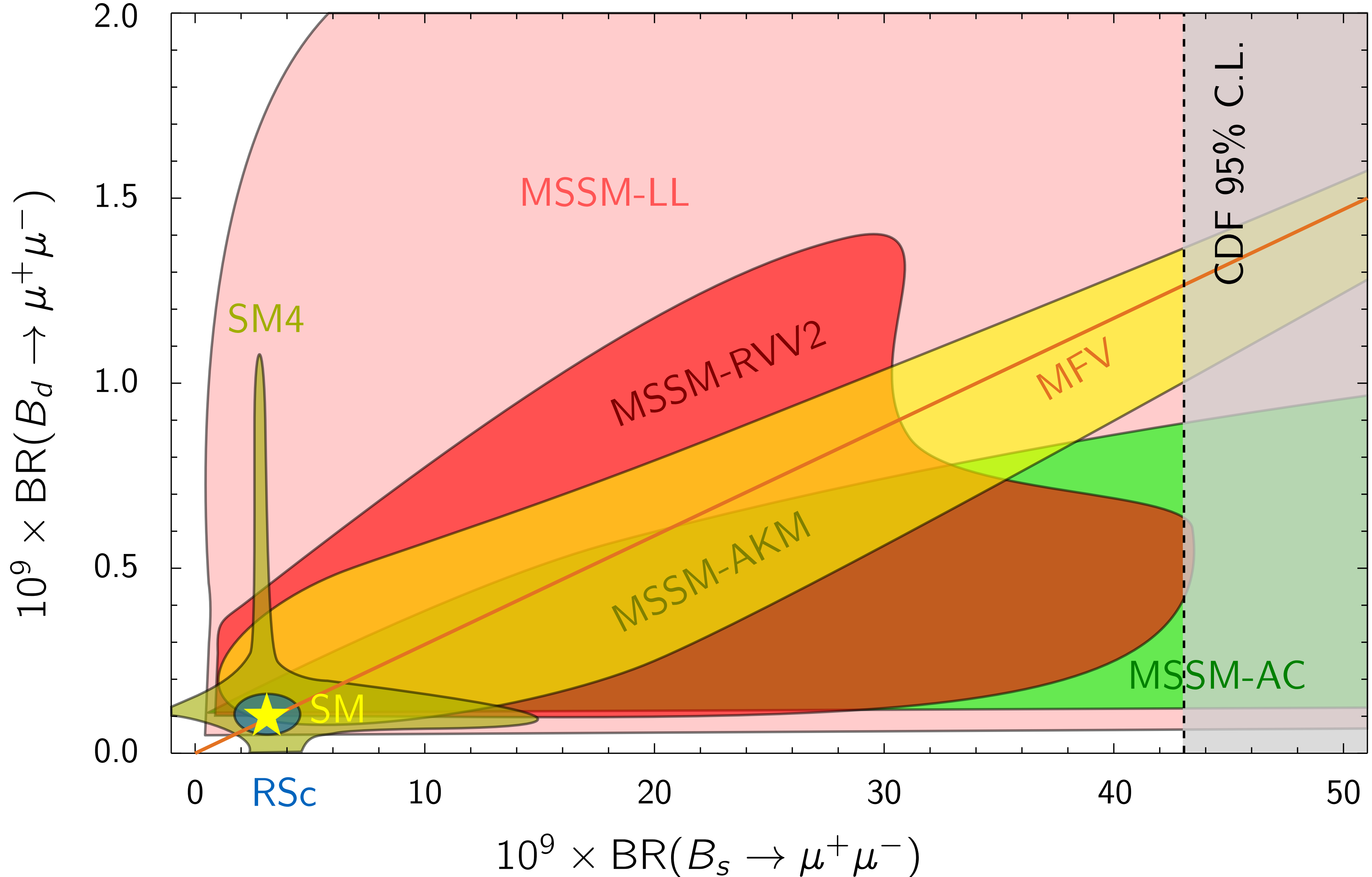


even suppression below SM possible



(in this plot the Z penguin does not receive large contributions, in general it can)

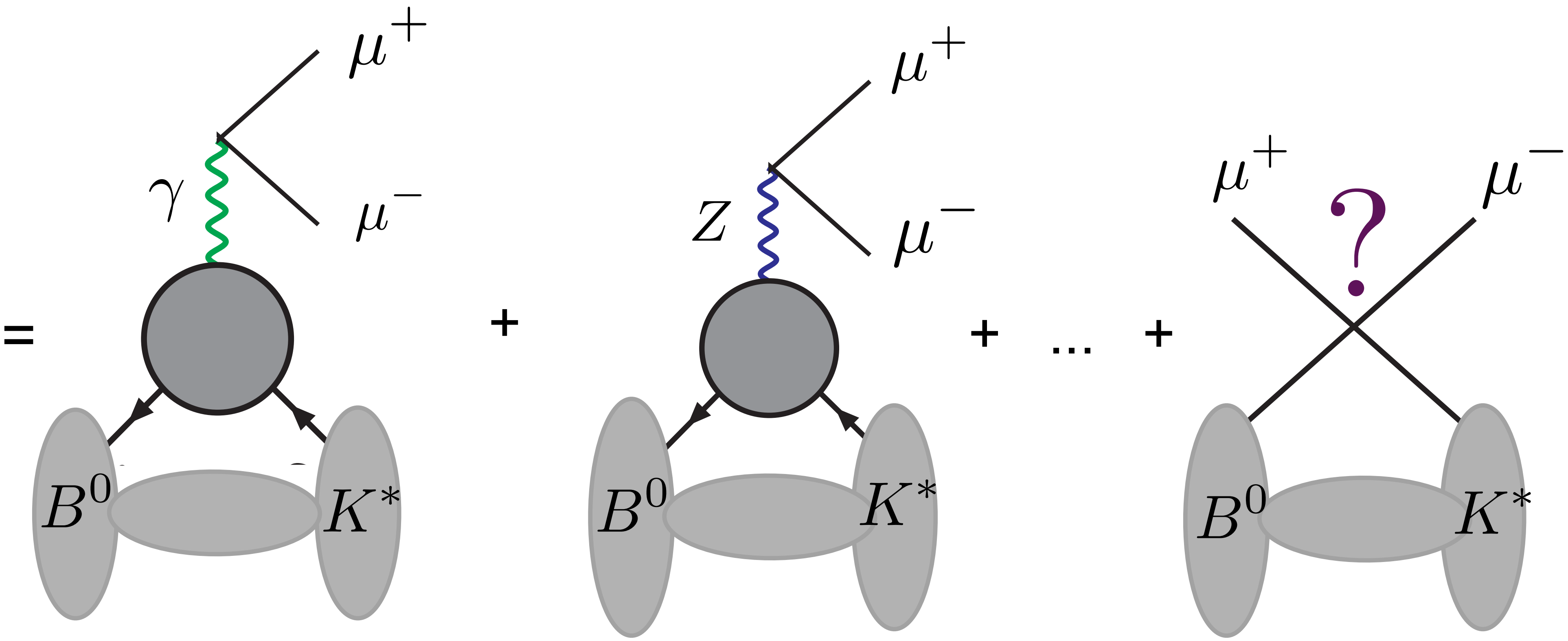
BSM model comparison



David Straub at CKM 2010

Semileptonic decay

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

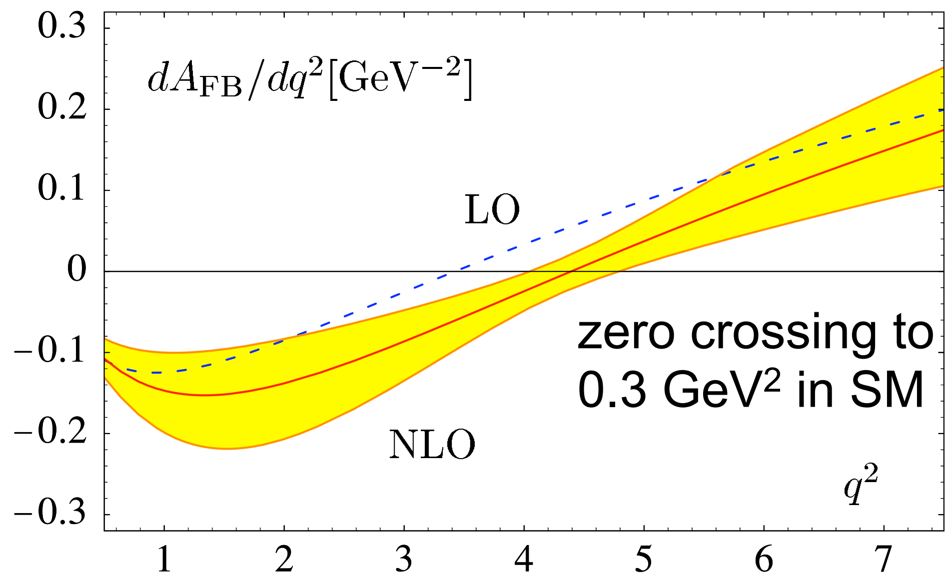


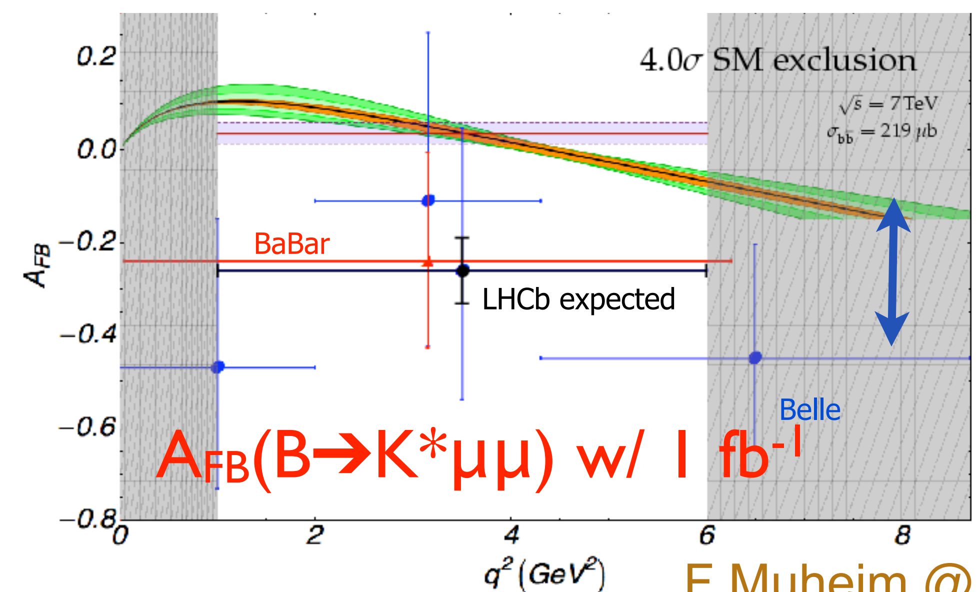
- kinematics described by dilepton invariant mass q^2 and three angles
- Systematic theoretical description based on heavy-quark expansion (Λ/m_b) for $q^2 << m^2(J/\psi)$ (SCET) Beneke, Feldmann, Seidel 01
  also for $q^2 >> m^2(J/\psi)$ (OPE) Grinstein et al; Beylich et al 2011
  Theoretical uncertainties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

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

Ali et al ; Beneke et al; ...

- Most well-known observable: forward-backward asymmetry





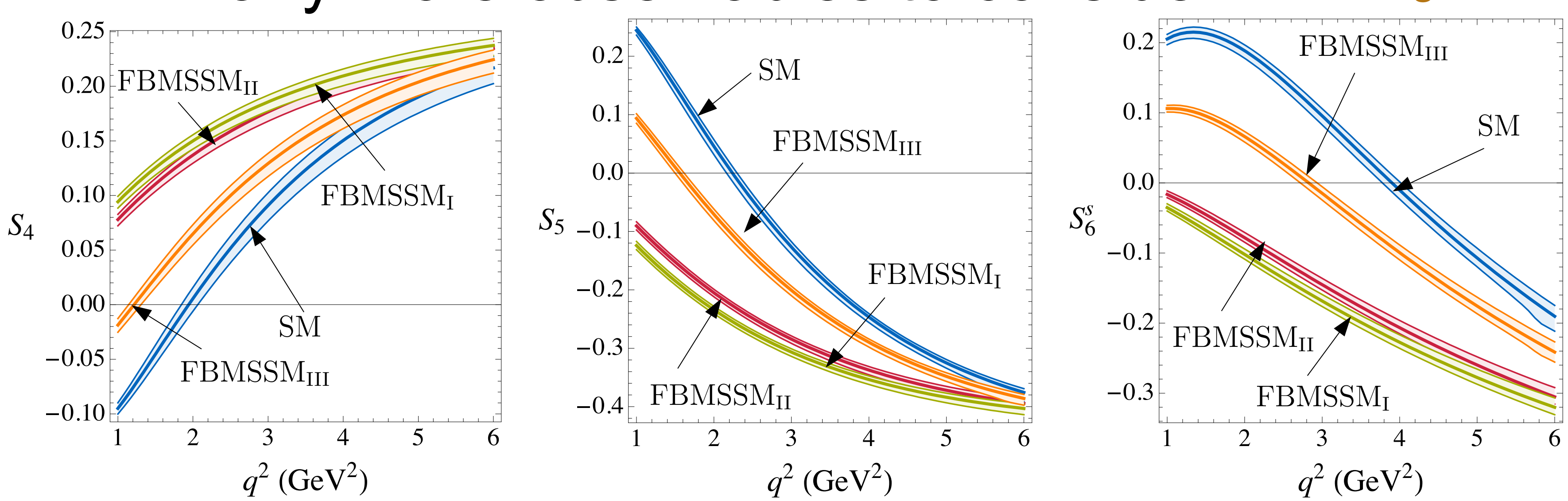
F Muheim @ FPCP2010

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

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

- Many more observables to consider

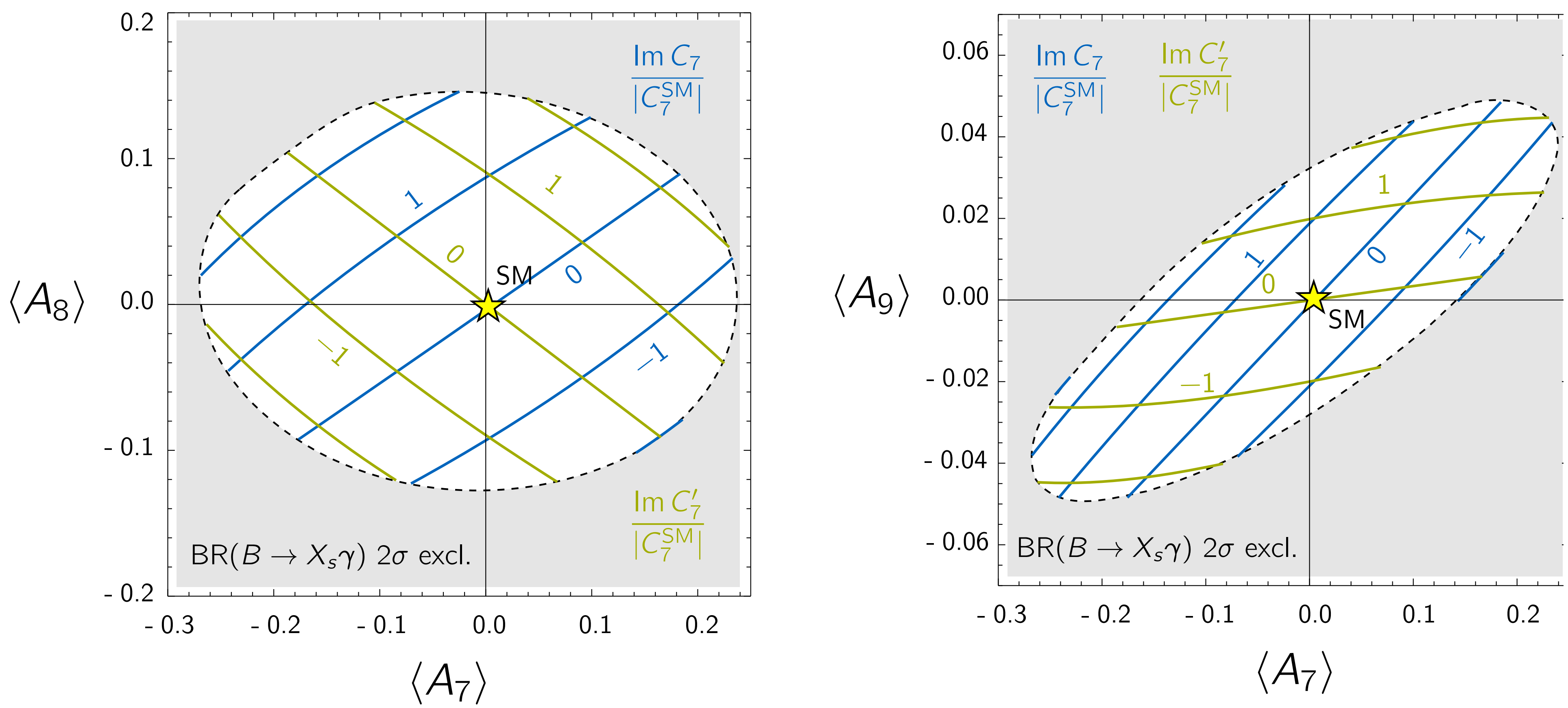
Krueger, Matias; ...



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?

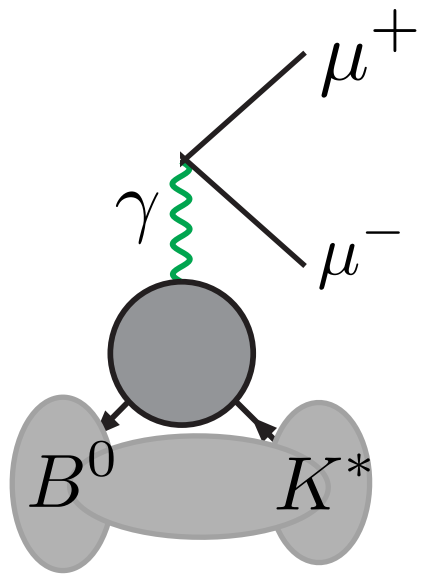


Altmannshofer et al 0811.1214v3

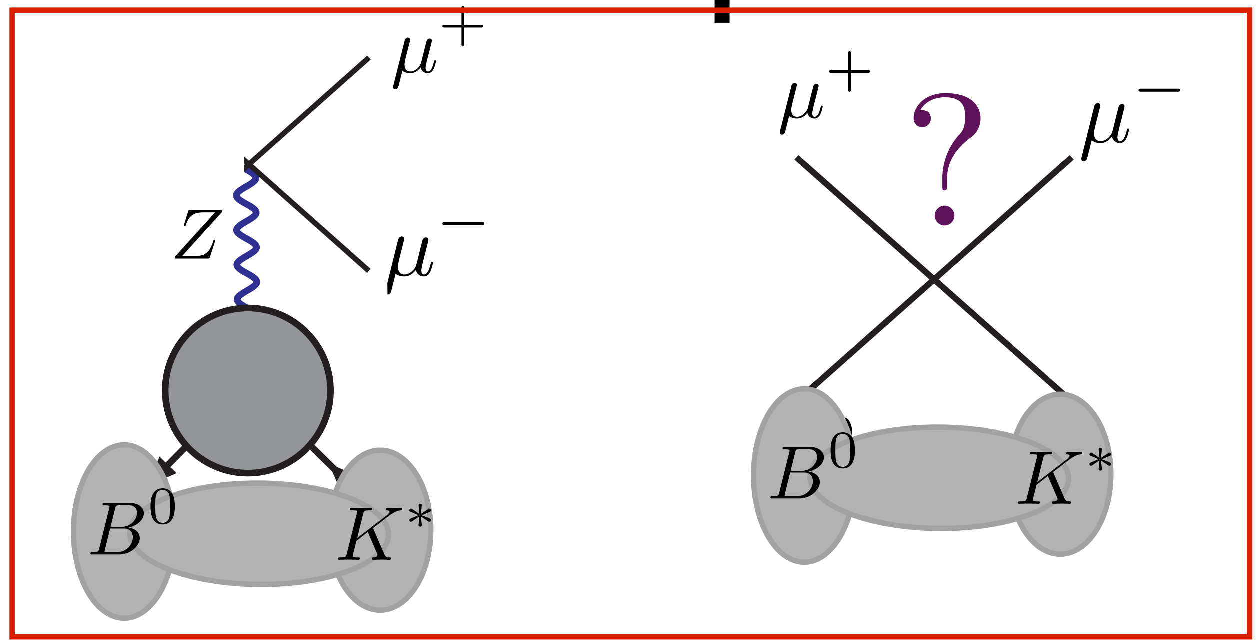
D Straub @ CKM 2010

Theoretical description

- $A(B \to K^{*}l^{+}l^{-})$ =

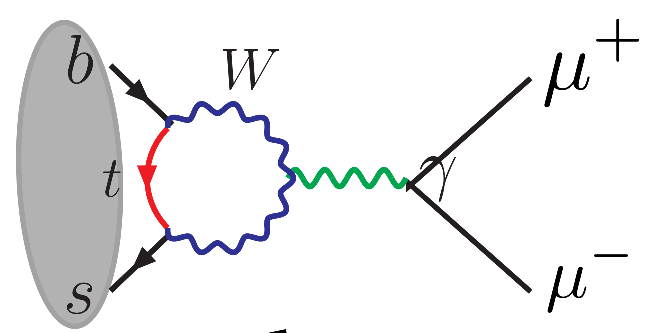


+



“naively” factorize into form factors and
“effective” Wilson coefficients C_{9eff} , C_{10}

partly short distance

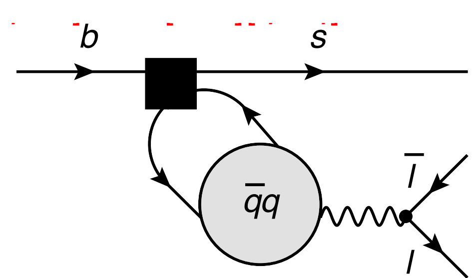


Form factor $T_{1,2,3}$ x C_7

(lattice, QCD sum rules)

Wilson coefficient (may receive NP corrections)

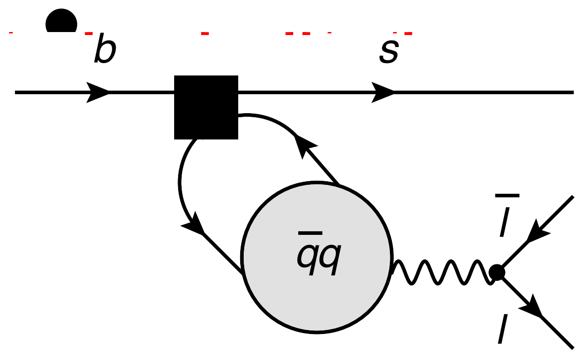
partly long distance



[Fig C Bobeth]

q = charm / u / d / s
not calculable in terms of form factors

Long-distance effects



no known way to treat charm resonance region to the necessary precision (would need << 1% to see short-distance contribution)
"solution": cut out 6 GeV^2 < q^2 < 14 GeV^2

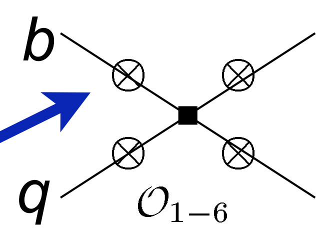
above (high-q^2) charm loops calculable in OPE

Grinstein et al; Beylich et al 2011

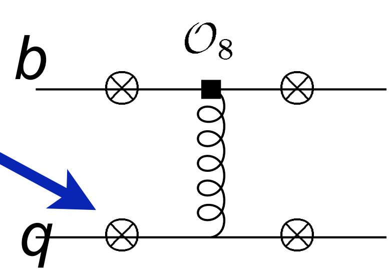
at *low* q^2 , long-distance charm effects also suppressed, but photon can now be emitted from *spectator* withouth power suppression

Beneke, Feldmann, Seidel 01

possible photon attachments



small Wilson coefficients



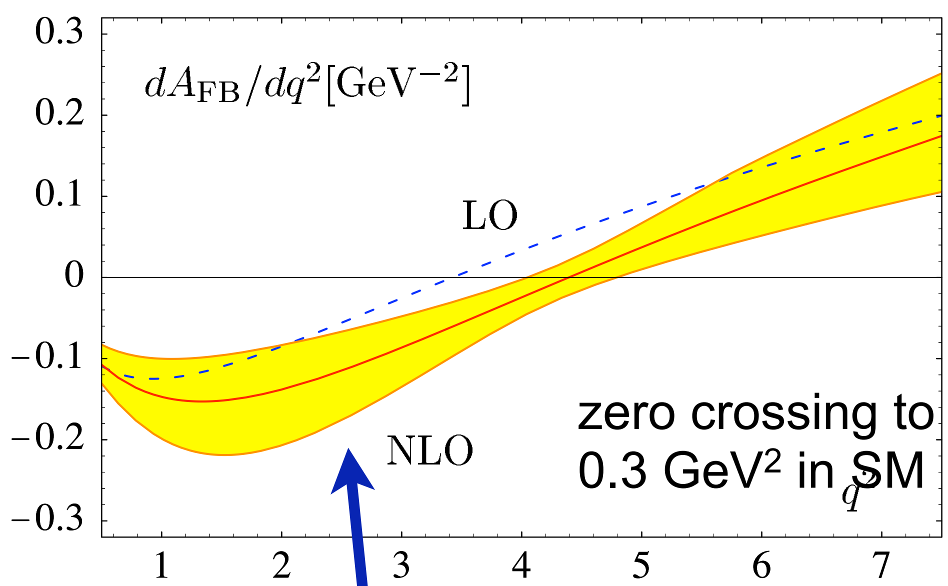
more significant for b ➔s transitions

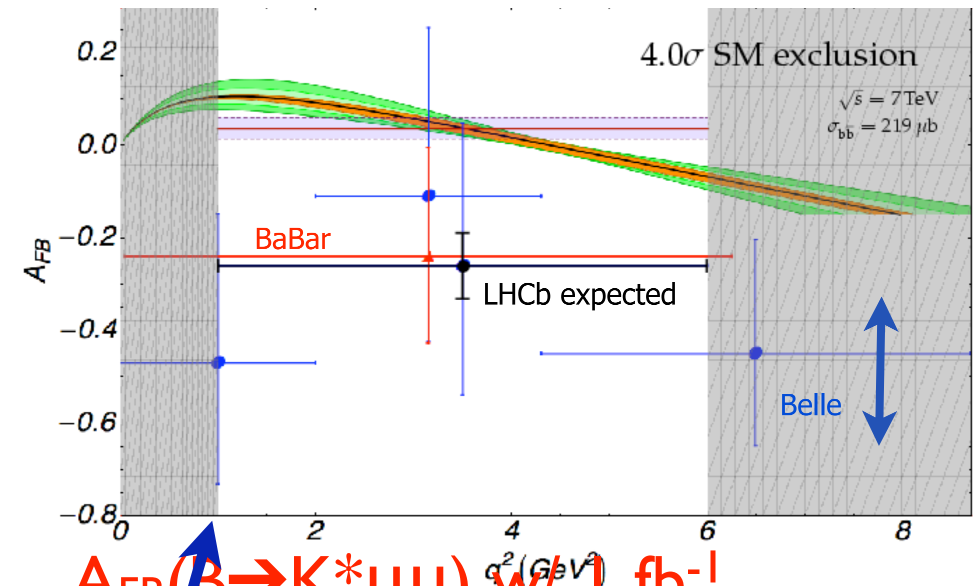
$$\frac{\pi^2}{N_c}\,\frac{f_B f_{K^*,a}}{M_B}\,\Xi_a \sum_{\pm}\int \frac{d\omega}{\omega}\,\Phi_{B,\pm}(\omega)\int_0^1 du\,\Phi_{K^*,a}(u)\,T_{a,\pm}(u,\omega)$$

light-cone wave functions

calculable

long-distance "resonance" effects as in top figure (q=u,d,s) CKM and power suppressed





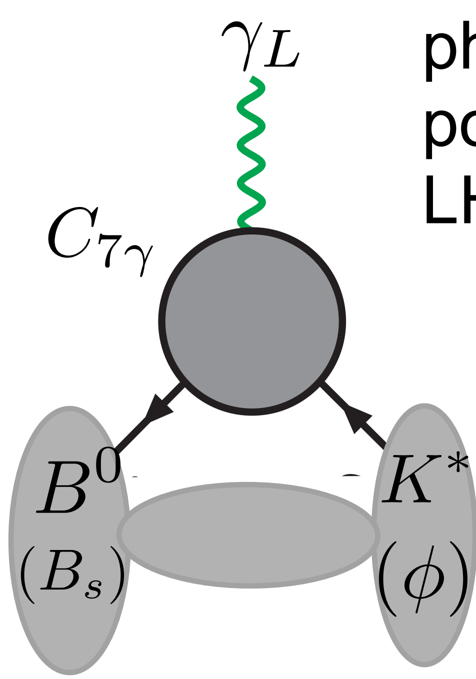
$A_{FB}(B \to K^*\mu\mu)$ w/ 1 fb^{-1}

F Muheim @ FPCP2010

- uncertainty due to mainly form factor precision (will improve); light cone distribution amplitudes (will to some degree improve)

cut at 1 GeV^2 is an ad-hoc procedure to remove/ reduce uncertainty from 'light resonances' however interesting physics in this region (C_7, C_7')

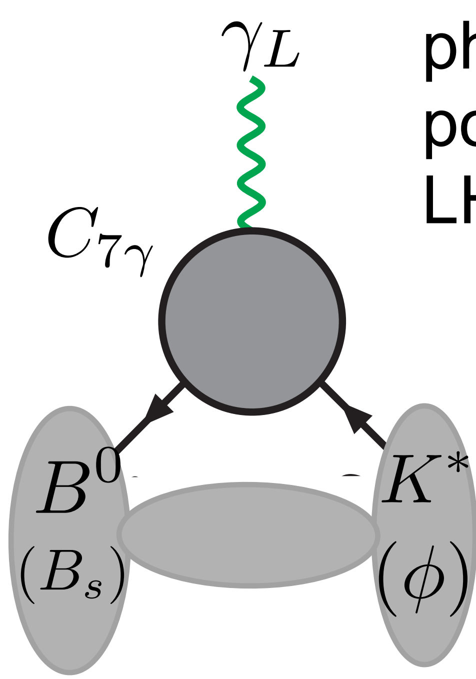
$B_d \rightarrow K^* \gamma$, $B_s \rightarrow \phi\gamma$



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

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

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



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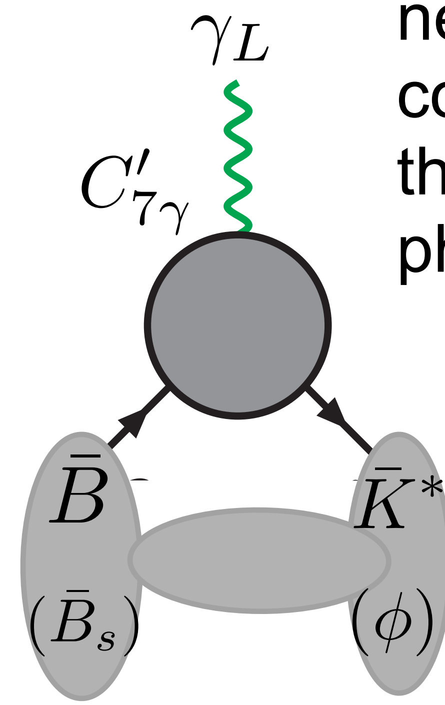

new physics might induce coupling to right-handed photon; this will produce left-handed photons in **anti**particle decay

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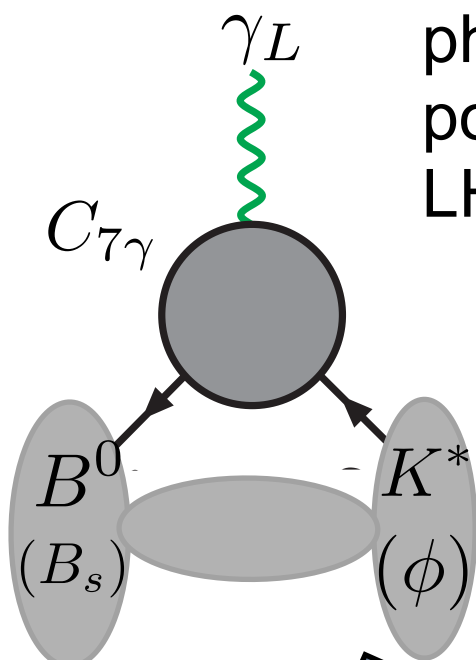

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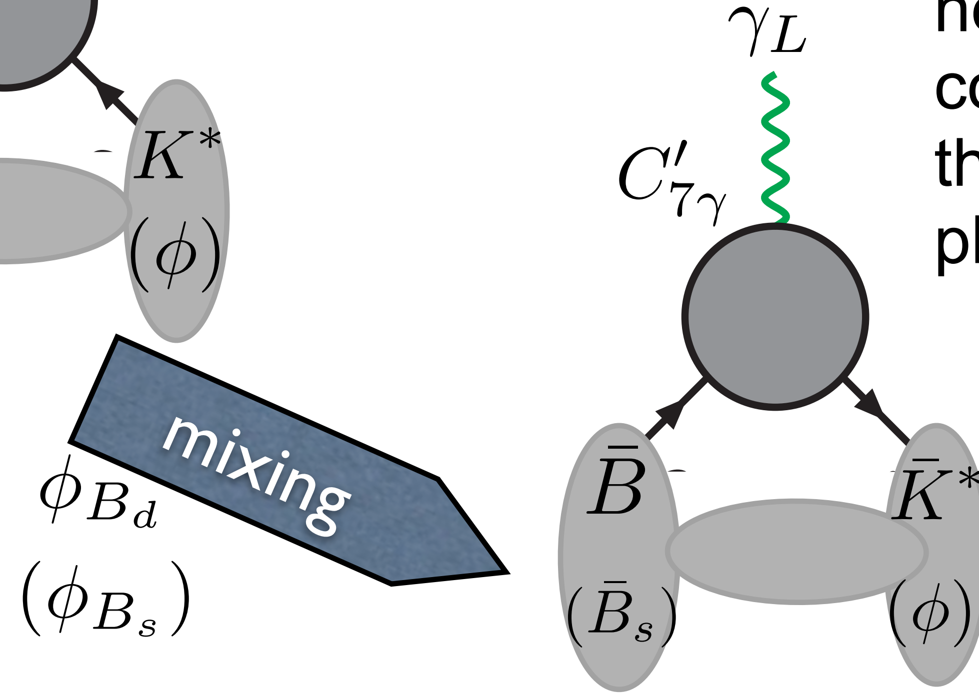

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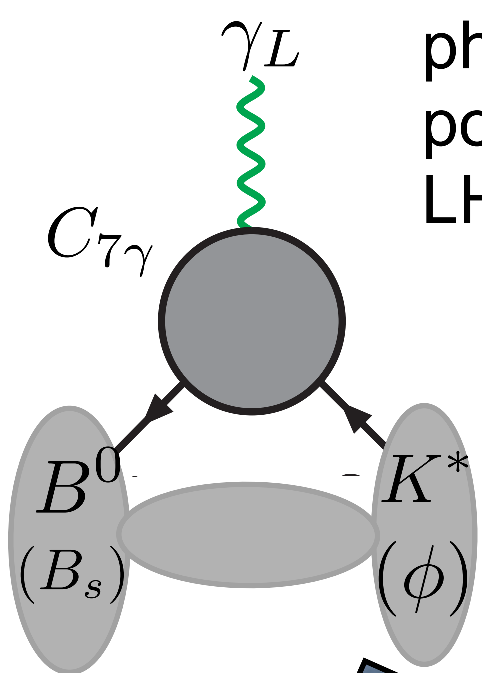
HFAG average of B factory data
(SM: ≈0)

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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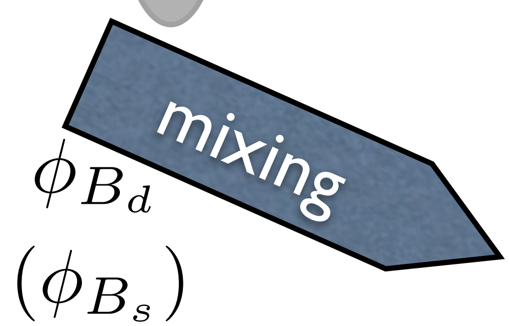

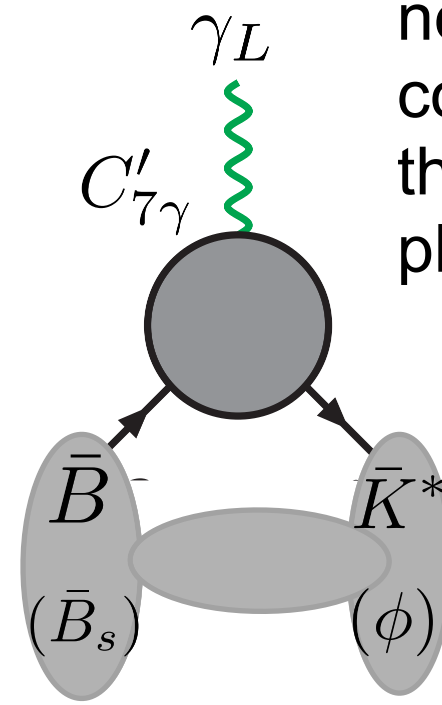

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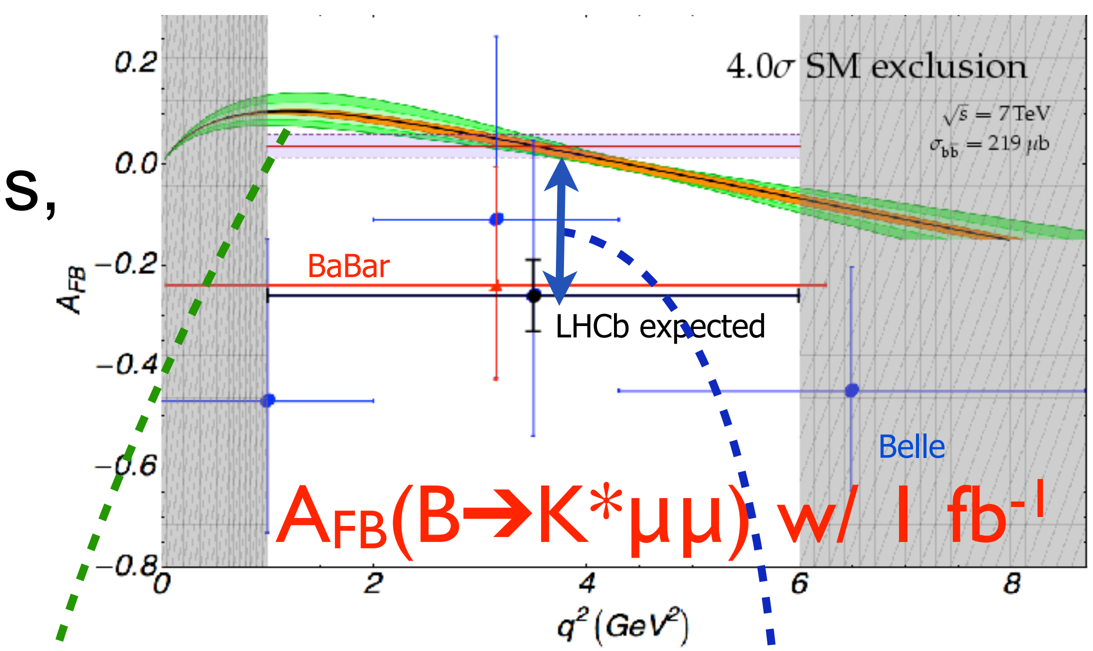
mixing-decay interference & time-dependent CP asymmetry
LHCb has sensitivity for $S(B_s \to \phi\gamma)$

- Theoretical description based on heavy-quark expansion, similar to semileptonic case   Bosch & Buchalla 01
  Beneke, Feldmann, Seidel 01

Connecting LHCb to theories of the weak scale

- LHCb to run close to design lumi in 2011&2012 ➔ early discoveries?
- UK: 10 LHCb experimental groups, focus: rare semileptonic/radiative decays, CKM angles, mixing. (Few theorists.)
- for exploiting physics potential, want "bottom-up" approach



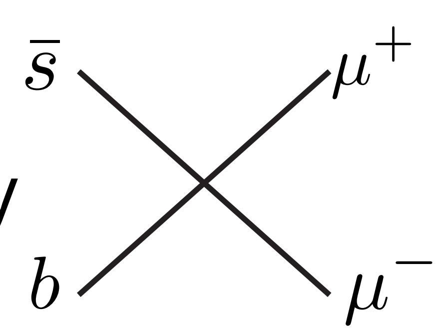
F Muheim (Edinburgh) @ FPCP2010

How is a possible SM exclusion best translated to New Physics ?
- *not* assuming a model (eg SUSY)

how to reliably quantify theory uncertainty ?

observables

effective theory



BSM particle content (from high-pT expt)

theory of the weak scale

Hadronic modes, etc

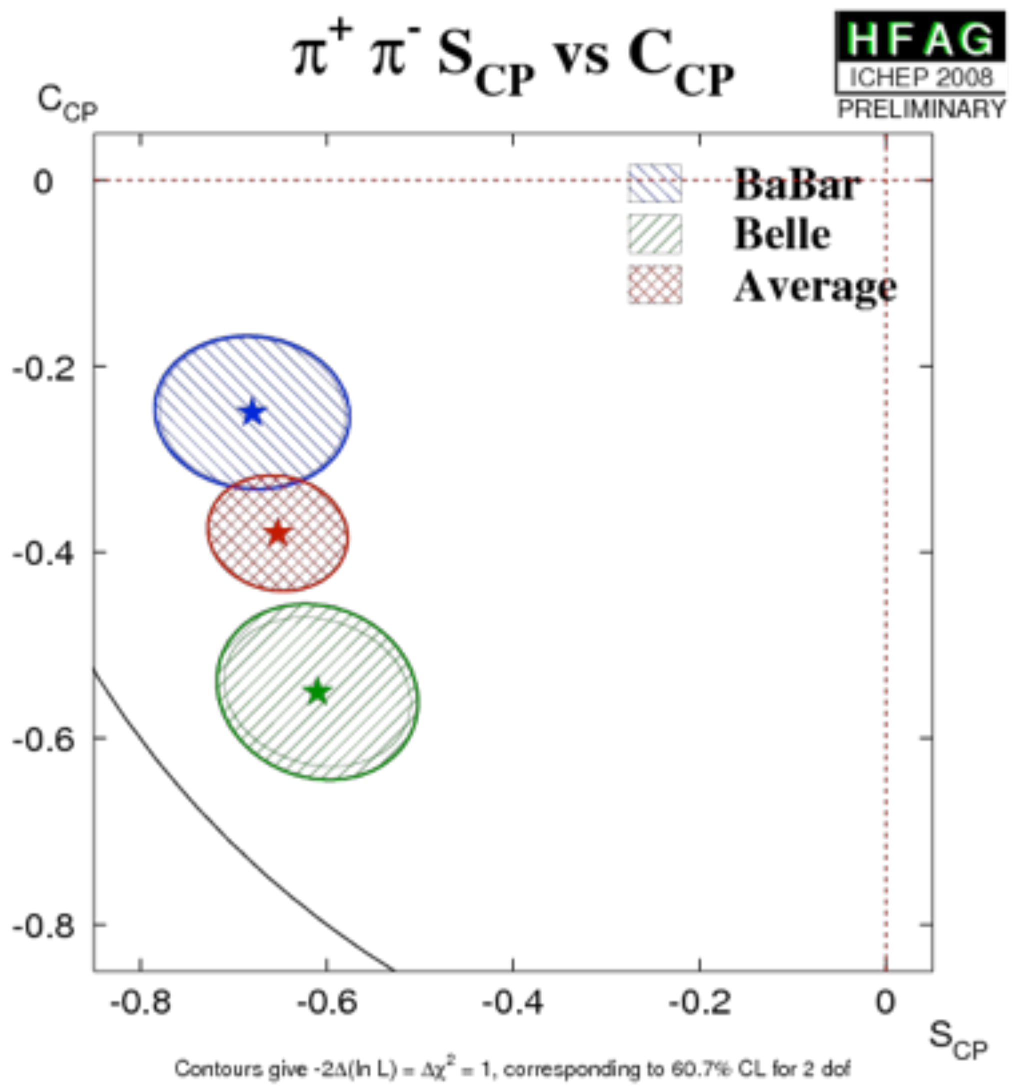
Hadronic decays at LHCb

Guy Wilkinson at CKM2010

	Current knowledge	LHCb stat sensitivity with 200 pb^{-1}
$\mathcal{A}^{CP}_{K^+\pi^-}$	$-0.098^{+0.012}_{-0.011}$	0.008
$\mathcal{A}^{CP}_{\pi^+K^-}$	$0.39 \pm 0.15 \pm 0.08$	0.05
$\mathcal{A}^{CP}_{p\pi^-}$	$0.03 \pm 0.17 \pm 0.05$	0.05
$\mathcal{A}^{CP}_{pK^-}$	$0.37 \pm 0.17 \pm 0.03$	0.03
$\mathcal{A}^{dir}_{\pi^+\pi^-}$	0.38 ± 0.06	0.13
$\mathcal{A}^{mix}_{\pi^+\pi^-}$	-0.65 ± 0.07	0.13
$\mathrm{Corr}(\mathcal{A}^{dir}_{\pi^+\pi^-}, \mathcal{A}^{mix}_{\pi^+\pi^-})$	0.08	-0.03
$\mathcal{A}^{dir}_{K^+K^-}$	**Still unmeasured**	0.15
$\mathcal{A}^{mix}_{K^+K^-}$		0.11
$\mathrm{Corr}(\mathcal{A}^{dir}_{K^+K^-}, \mathcal{A}^{mix}_{K^+K^-})$		0.02
$\frac{\mathcal{BR}(B^0\to\pi^+\pi^-)}{\mathcal{BR}(B^0\to K^+\pi^-)}$	0.264 ± 0.011	0.006
$\frac{\mathcal{BR}(B^0\to K^+K^-)}{\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.020 \pm 0.008 \pm 0.006$	0.005
$\frac{f_s\,\mathcal{BR}(B^0_s\to K^+K^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.347 \pm 0.020 \pm 0.021$	0.006
$\frac{f_s\,\mathcal{BR}(B^0_s\to \pi^+K^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.071 \pm 0.010 \pm 0.007$	0.004
$\frac{f_s\,\mathcal{BR}(B^0_s\to \pi^+\pi^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.007 \pm 0.004 \pm 0.005$	0.002
$\frac{f_{\Lambda_b}\,\mathcal{BR}(\Lambda_b\to p\pi^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.0415 \pm 0.0074 \pm 0.0058$	0.0016
$\frac{f_{\Lambda_b}\,\mathcal{BR}(\Lambda_b\to pK^-)}{f_d\,\mathcal{BR}(B^0\to K^+\pi^-)}$	$0.0663 \pm 0.0089 \pm 0.0084$	0.0018

LHCb to surpass B factory statistics early on, for those modes it can access

should resolve long-standing experimental puzzle



Hadronic decays - theory

- Any SM 2-light-hadron amplitude can be written

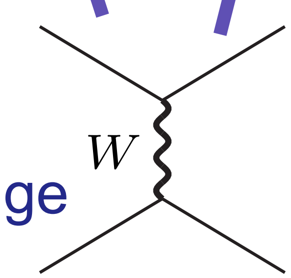
$$\mathcal{A}(\bar{B} \to M_1 M_2) = e^{-i\gamma} T_{M_1 M_2} + P_{M_1 M_2}$$

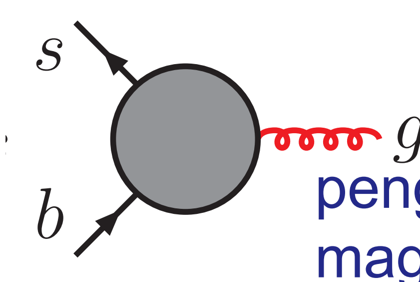
$$T_{M_1 M_2} = V_{uD} |V_{ub}| \Big[C_1 \langle Q_1^u \rangle + C_2 \langle Q_2^u \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \Big]$$ "tree"

$$P_{M_1 M_2} = V_{cD} |V_{cb}| \Big[C_1 \langle Q_1^c \rangle + C_2 \langle Q_2^c \rangle + \sum_{i=3}^{12} C_i \langle Q_i \rangle \Big]$$ "penguin"

CKM factor (D=d or s)

tree W exchange



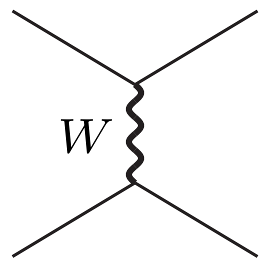


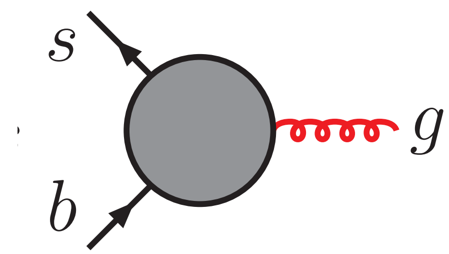
penguins (QCD, magnetic, EW)

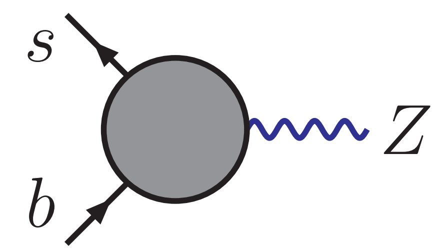
Q_i: operators in weak hamiltonian
C_i: QCD corrections from short distances (< hc/m_b) & new physics
$\langle Q_i \rangle = \langle M_1\ M_2 \mid Q_i \mid B \rangle$: QCD at distances > hc/$m_b$, strong phases

B➔πK direct CP puzzle

$A(B^0 \to \pi^- K^+) \;=\; T\,e^{i\gamma} \;+\; P \;+\; P^c_{EW}$







$-A(B^+ \to \pi^0 K^+) \;=\; (T+C)\,e^{i\gamma} \;+\; P \;+\; P_{EW} \;+\; P^c_{EW}$

data: $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

[Belle collab: in Nature (2008)]

In general, only isospin relation [Gronau 2005; Gronau & Rosner 2006]

$A_{CP}(B^+ \to \pi^0 K^+) + A_{CP}(B^0 \to \pi^0 K^0) \approx A_{CP}(B^0 \to \pi^- K^+) + A_{CP}(B^+ \to \pi^0 K^0)$

how small are the “small” amplitude ratios C/T and P_{EW}/T

$B \to \pi K$ direct CP puzzle

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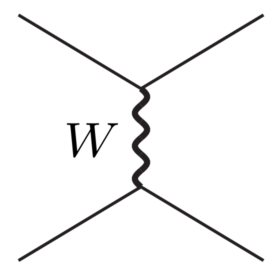

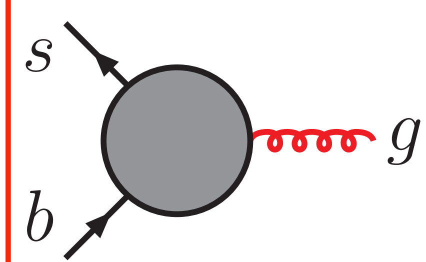

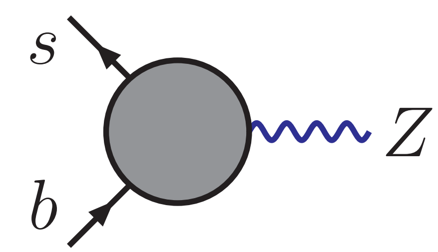

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(QCD) penguin amplitudes

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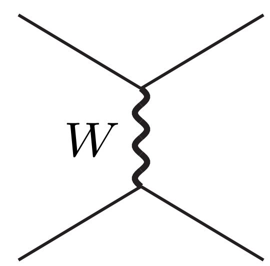
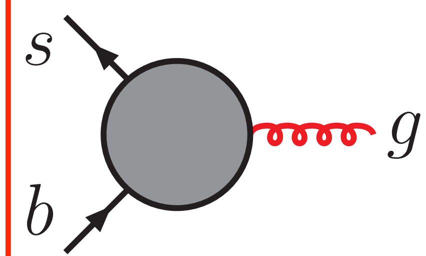
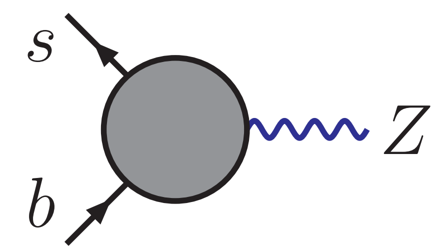
B→πK direct CP puzzle

$A(B^0 \to \pi^- K^+) = T e^{i\gamma} + P + P^c_{EW}$

tree amplitudes







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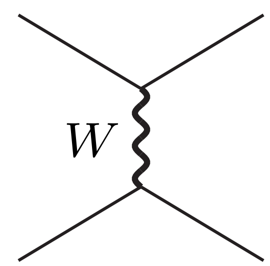

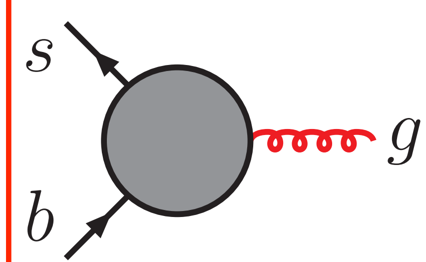

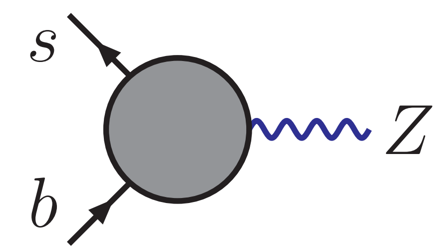

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(QCD) penguin amplitudes

EW penguin amplitudes

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how small are the “small” amplitude ratios C/T and P_{EW}/T

Theory of hadronic amplitudes

- 1/N expansion (only counting rules)
- expansion in Λ_{QCD}/m_B ~0.2 (QCDF/SCET; "pQCD"): reduce amplitudes to simpler objects (form factors etc)

	T/a_1	C/a_2	P	E/b_1	A/b_1
1/N	1	1/N	1/N	1/N	1 [?]
Λ/m_B	1	1	1	Λ/m_B	Λ/m_B

- QCD light-cone sum rules: partly complementary set of calculable amplitudes; constrain "inputs" to heavy-quark expansion
- SU(3) / U-spin relates $\Delta D=1$ and $\Delta S=1$ amplitudes
  $T(B\to\pi K)\approx T(B\to\pi\pi)$; $P(B\to\rho\rho)\approx P(B\to\rho K^*)$, etc.
  (corrections in m_s/Λ_{QCD} ~0.3 uncontrolled; annihilation amplitudes spoil simple relations)

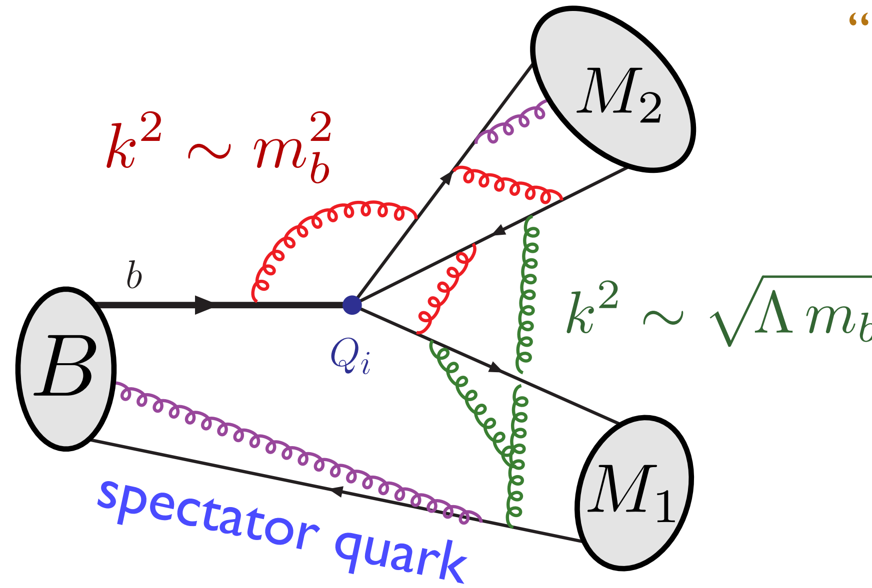
QCD factorization

Beneke, Buchalla, Neubert, Sachrajda 99-01
SCET: Bauer, Pirjol, Rothstein, Stewart 04

"pQCD": Keum, Li, Sanda 00

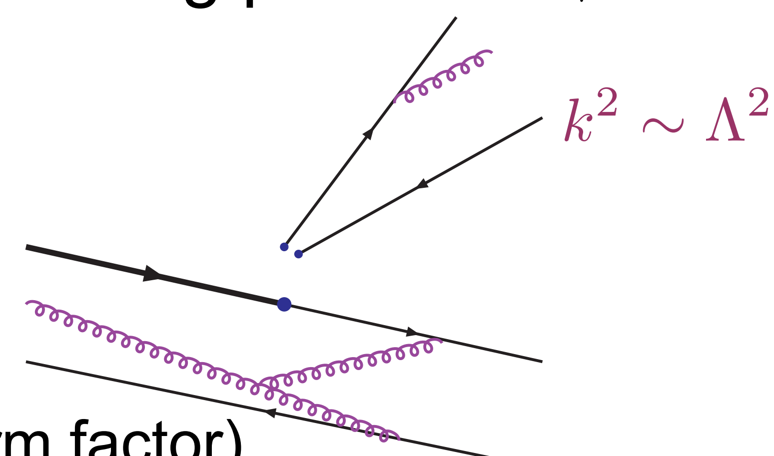
"nonfactorizable" gluons are perturbative

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle =$$



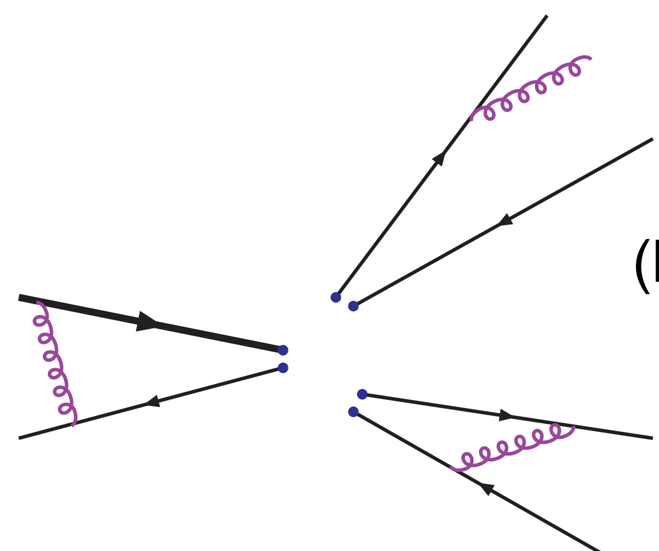
$$+ \ldots$$

To leading power in Λ/m_b *long-distance* interactions look like



soft overlap (form factor)

or



(hard) spectator scattering

model dependence enters (only) at subleading power (factorization breaks at O(Λ/m) for some amplitudes)

(This is generic - applies to semileptonic and radiative decays, too)

$$\langle M_1 M_2 | Q_i | \bar{B} \rangle =$$

perturbative, includes strong phases

non-perturbative QCD

$$f_+^{BM_1}(0) f_{M_2} \int du\, T_i^{\mathrm{I}}(u) \phi_{M_2}(u) + f_B f_{M_1} f_{M_2} \int du\, dv\, d\omega\, T_i^{\mathrm{II}}(u, v, \omega)\, \phi_{B_+}(\omega) \phi_{M_1}(v) \phi_{M_2}(u)$$

soft overlap (form factor) hard spectator scattering

$$T_i^{\mathrm{I}} \sim 1 \; + \; t_i\, \alpha_s \; + \; \mathcal{O}(\alpha_s^2)$$

"naive factorization" BBNS 99-01 Bell 07, 09 (trees), Beneke et al 09 (trees)

$$T_i^{\mathrm{II}} \sim H_i \star J$$

$$\sim \left(1 + h_i\, \alpha_s + \mathcal{O}(\alpha_s^2)\right) \left(j^{(0)} \alpha_s + j^{(1)} \alpha_s^2 + \mathcal{O}(\alpha_s^3)\right)$$

BBNS 99-01 BBNS 99-01

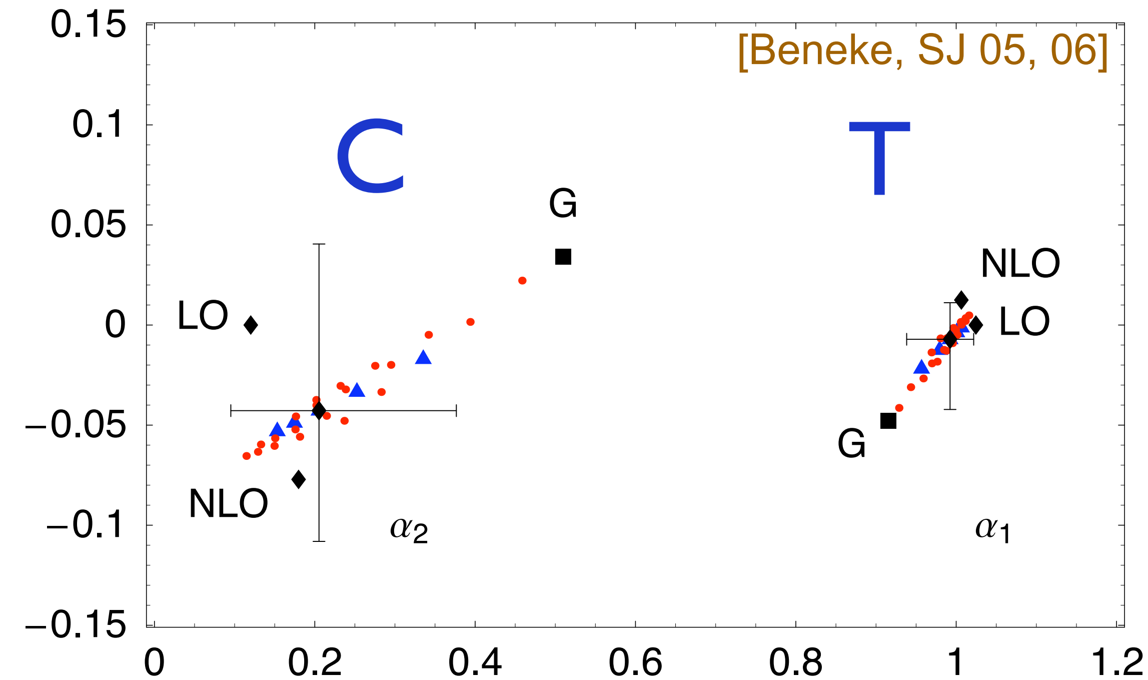
Hill, Becher, Lee, Neubert 2004; Beneke, Yang 2005; Kirilin 2005

Beneke, SJ 2005 (trees), 2006 (penguins); Kivel 2006; Pilipp 2007 (trees);
Jain, Rothstein, Stewart 2007 (penguins)

phenomenological summary

- Corrections to naive factorization small for T and P_{EW}, stable perturbation series ; small uncertainties

- Corrections O(1) for C (and P_{EW}^c), stable perturbation series
  large uncertainties (hadronic inputs; large incalculable power correction for final states with pseudoscalars)



parameter set "G" (fit hadronic parameters to B➔ππ BR's):
$C/T \sim 0.69 + 0.17\,i$
large magnitude, small phase

- (physical) penguin amplitudes moderately affected by power-suppressed incalculable penguin annihilation (&charm penguin) terms. Spoils precise predictions for direct CP asymmetries

- certain SU(3)-type relations satisfied in good approximation

$B \to \pi K$ direct CPV

- QCDF, with usual estimate of uncertainties (in particular BBNS model of power corrections), cannot accomodate data:

  $A_{CP}(B^+ \to \pi^0 K^+) - A_{CP}(B^0 \to \pi^- K^+) = 0.14 \pm 0.03$ (expt)

  $= 0.03 \pm 0.03$ (QCDF) [Beneke 08]

  reason: small arg(C/T); if it were large, could accomodate data

  [eg Baek, Chiang, London 09]

- one possibility: new physics with the structure of an electroweak penguin amplitude (modified Zsb vertex, Z' boson etc)

  [Buras, Fleischer, Recksiegel, Schwab; Baek et al; Imbeault, Baek, London; Kim et al; Lunghi, Soni; Arnowitt et al; Khalil, Kou; Hou; Soni et al; Barger et al; Khalil, Masiero, Murayama; Ciuchini et al ...]

- $S_{\pi K}$ (time-dependent CP asymmetry): no significant deviation; direct CP asymmetry interpretation depends on a model of power corrections, which may (plausibly) underestimate C

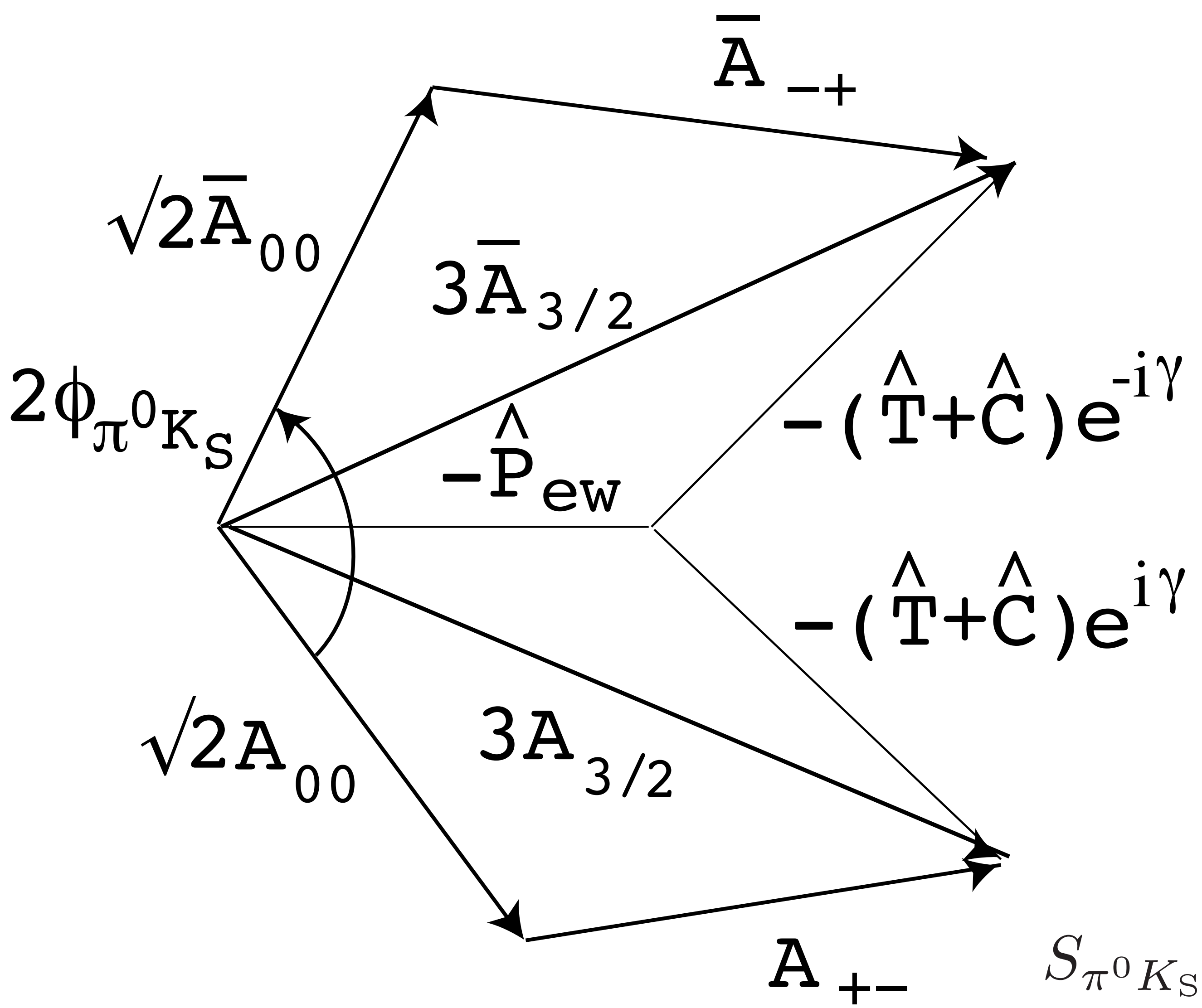
- can we better use the data to reduce the theory uncertainty?

$B\to\pi K$ isospin analysis

Fleischer, SJ, Pirjol, Zupan 08

Gronau, Rosner 08

The two B^0 decay amplitudes add up to a pure ΔI=3/2 amplitude.
(The two B^+ decay amplitudes add up to the *same amplitude.)*
The situation for the four CP-conjugate modes is analogous.



In the SM, $A_{3/2}$ stems solely from tree and electroweak penguin amplitudes (QCD penguins are ΔI=3/2)

The ratio $P_{EW}/(T+C)$ is known in the SU(3) limit. Neubert, Rosner 98

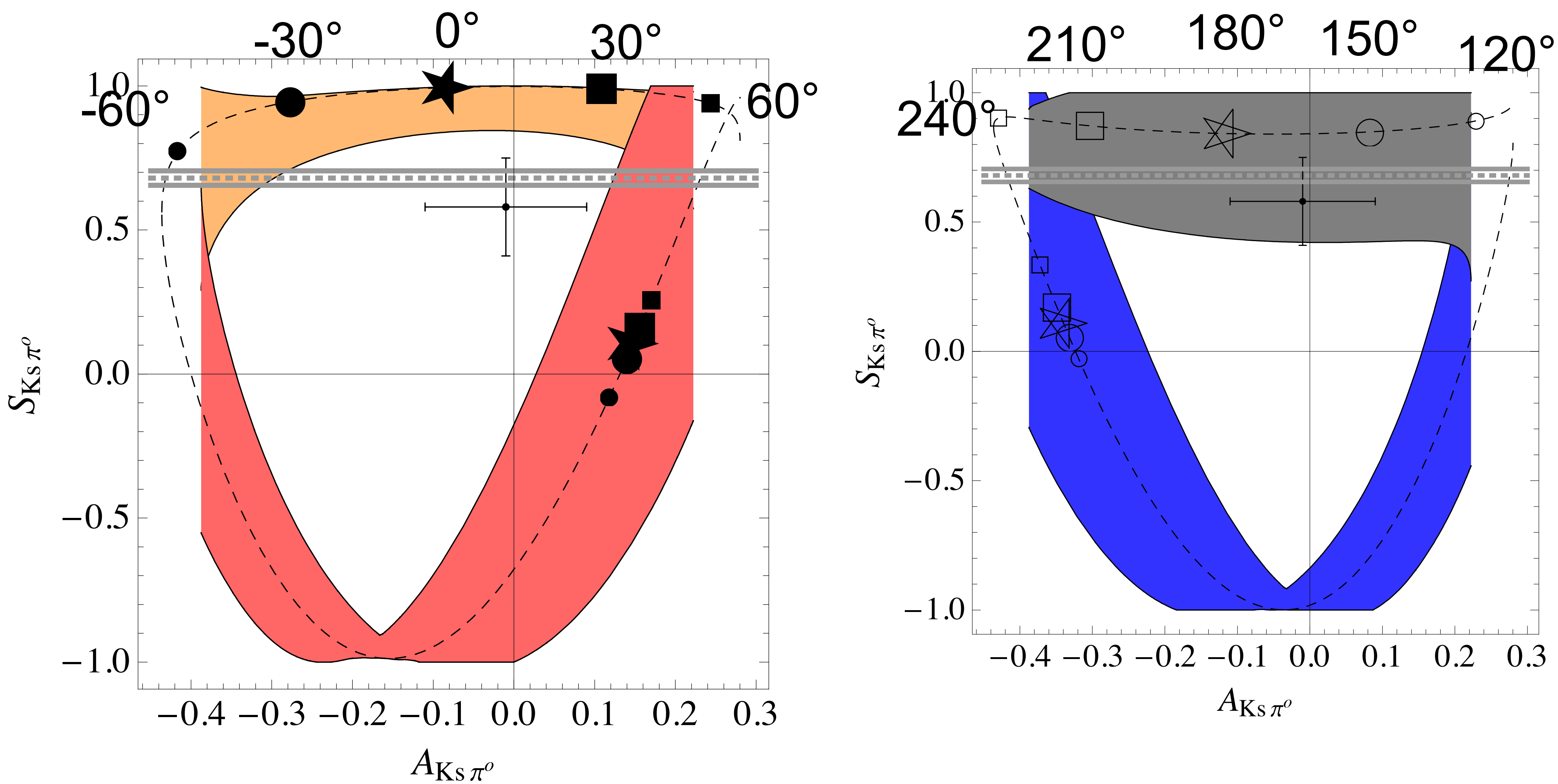
T+C is SU(3)-related to BR($B^0 \to \pi^0\pi^0$)

$$S_{\pi^0 K_S} = \frac{2|\bar{A}_{00}A_{00}|}{|\bar{A}_{00}|^2 + |A_{00}|^2}\sin(2\beta - 2\phi_{\pi^0 K_S})$$

One relation between 4 decay rates (all measured) and $S_{\pi K}$

Mode	BR $[10^{-6}]$	A_{CP}
$\bar{B}^0 \to \pi^+ K^-$	19.4 ± 0.6	-0.098 ± 0.012
$\bar{B}^0 \to \pi^0 \bar{K}^0$	9.8 ± 0.6	-0.01 ± 0.10

four-fold ambiguity: resolve by considering strong phase of P/(T+C)



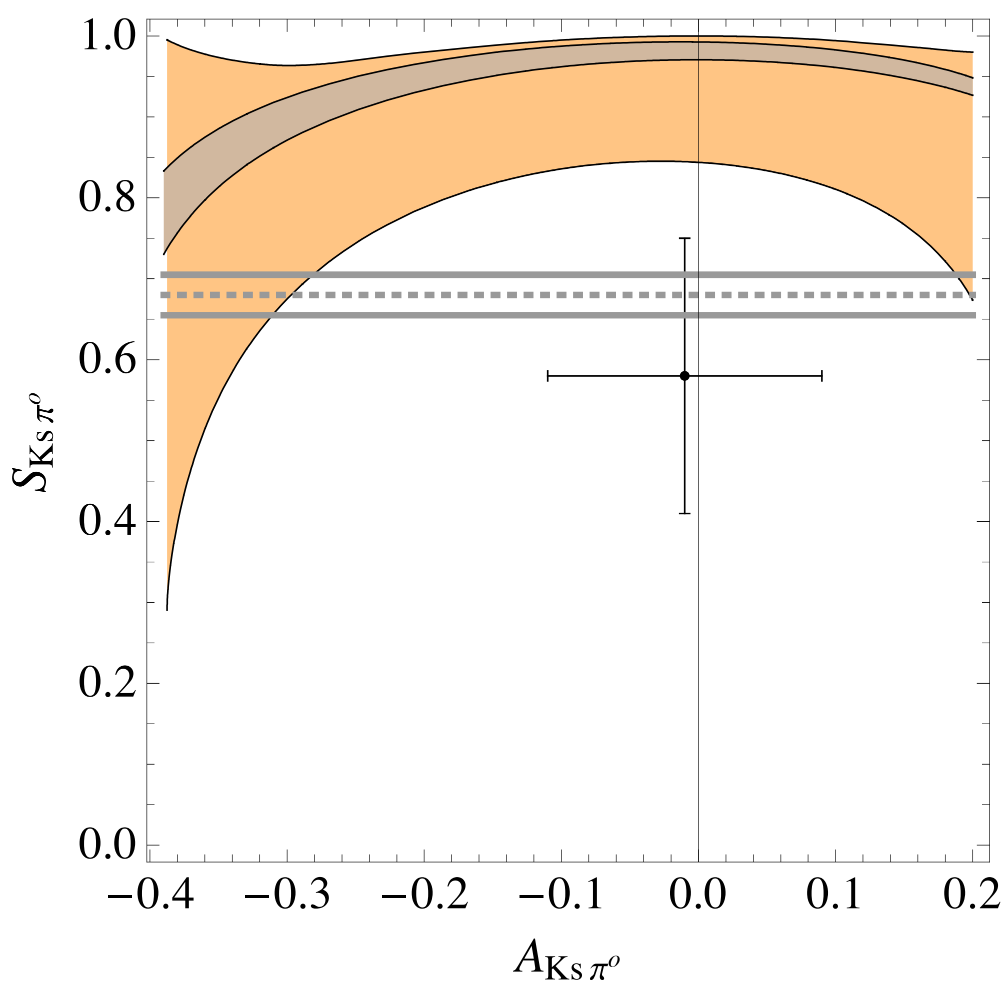
Fleischer, SJ, Pirjol, Zupan 08

heavy-quark limit predicts ≈0°

SU(3) relation with B➔ππ gives ≈0°

both exclude the solution in the red band

- use QCD factorization only to estimate SU(3) breaking



Fleischer, SJ, Pirjol, Zupan 08

also Gronau&Rosner 08, Ciuchini et al 08

$$S_{\pi^0 K_S} = 0.99^{+0.01}_{-0.08}\Big|_{\mathrm{exp.}}{}^{+0.000}_{-0.001}\Big|_{R_{T+C}}{}^{+0.00}_{-0.11}\Big|_{R_q}{}^{+0.00}_{-0.07}\Big|_{\gamma}$$

error dominated by form-factor ratio $F^{B\to K}(0)/F^{B\to\pi}(0)$

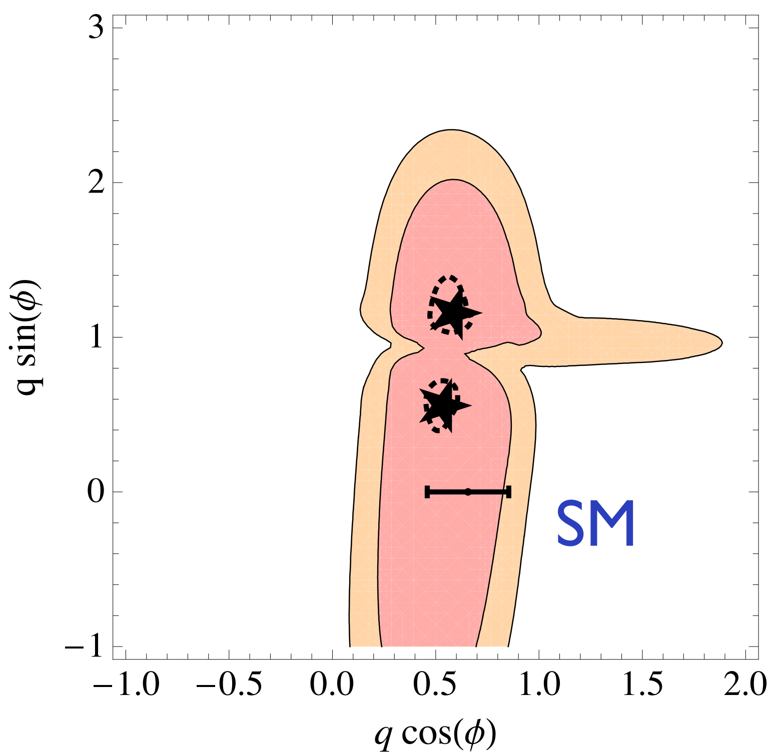
$$R_q = (1.02^{+0.27}_{-0.22})e^{i(0^{+1}_{-1})^\circ}$$

assuming 30% error on future lattice calculation of SU(3) breaking in $F^{B\to K}(0)/F^{B\to\pi}(0)$ together with 10 x more statistics would reduce error:

$$R_q = (0.908^{+0.052}_{-0.043})e^{i(0^{+1}_{-1})^\circ}$$

[arbitrary central value]

- can be explained a modified electroweak penguin

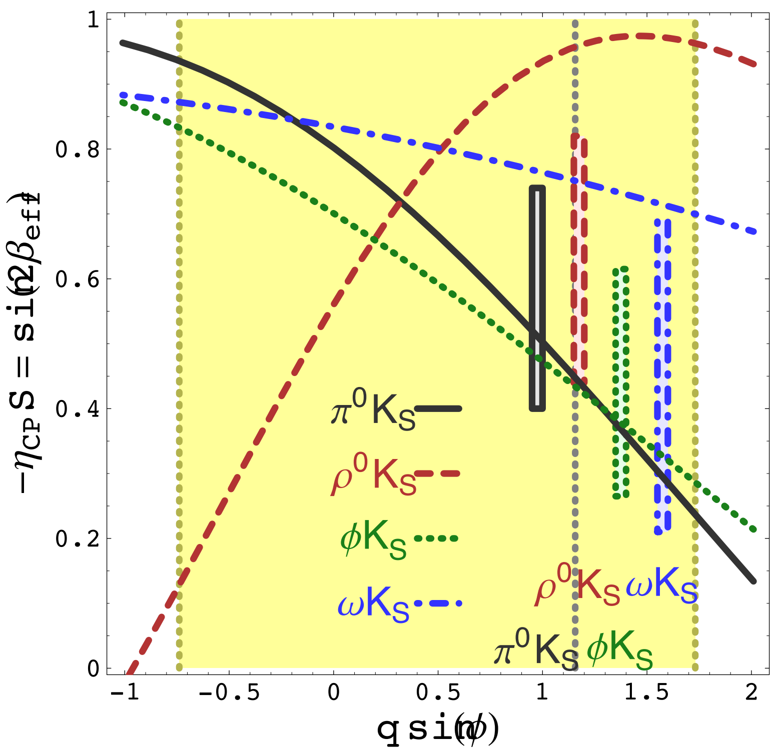


$$qe^{i\phi} = \frac{\hat{P}_{ew}}{0.66\,\hat{T}}$$

Fleischer, SJ, Pirjol, Zupan 08

Barger et al 09

- best fit works a bit better for (other) time-dependent CP asymmetries than SM - details depend on how EW Wilson coefficients are modified

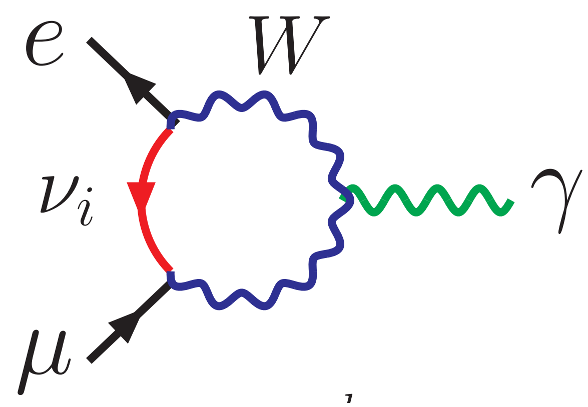


Conclusion

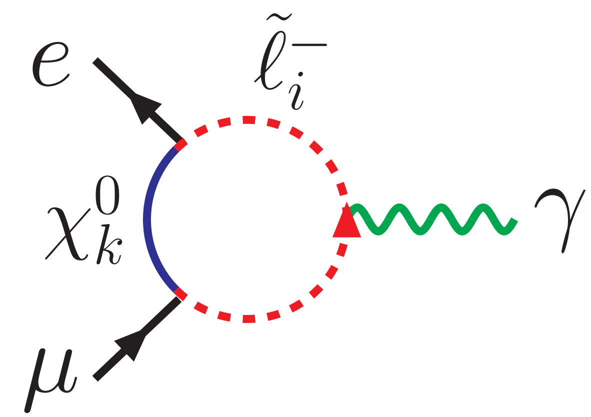
- Theories of the electroweak scale bring in new particles which contribute to flavour-violating observables
- LHCb should give a clear picture on mixing, and would see large NP effects in a number of observables soon
  - already now (37 pb^{-1}) world leading on $B_s \rightarrow \mu^+\mu^-$
- quantitative interpretation of LHCb results suggests bottom-up approach; requires attention to theory uncertainties

Lepton flavour violation

1) Very suppressed in the SM
$(m_\nu \approx 0)$



2) New flavour violation in SUSY

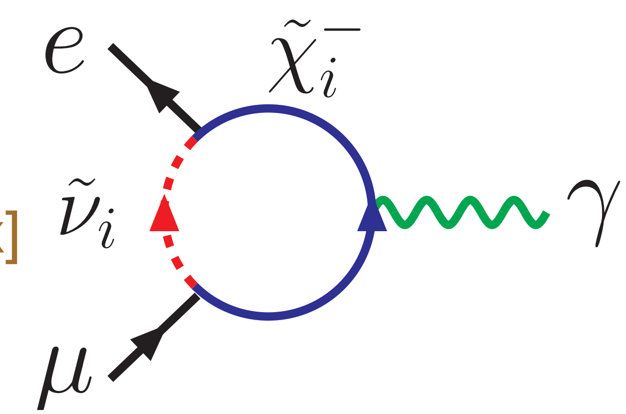


(6x6 charged slepton mass matrix and 3x3 sneutrinos masses).

Easy to saturate current experimental bounds e.g.

$BR(\tau \to \mu\gamma) < 4.4 \cdot 10^{-8}$ Babar 1006.0314 [hep-ex]

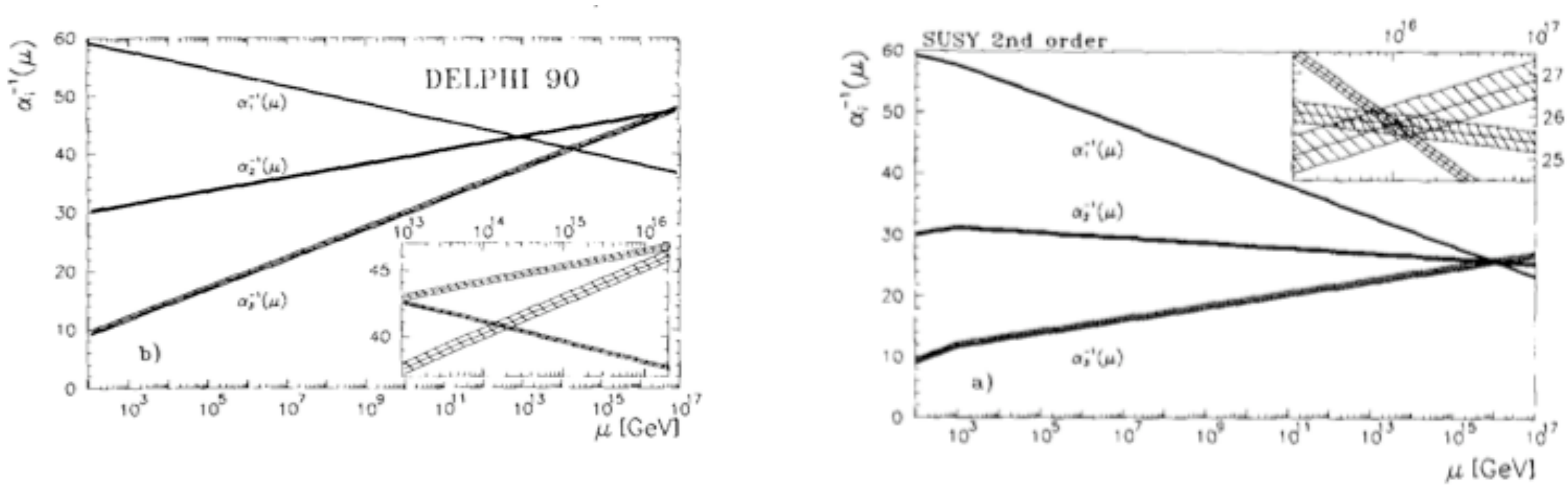
$BR(\tau \to \mu\gamma) < 4.5 \cdot 10^{-8}$ Belle 0705.0650 [hep-ex]



also $\tau \to e\gamma$, $\mu \to e\gamma$, $\tau \to 3\ell, \mu \to e$ conversion in nuclei, etc

Grand unification

- The MSSM strongly hints at grand unification:



Amaldi, de Boer, Furstenau

- SUSY GUTs unify different fermion fields

  - left & right chiral -> peculiar, nonminimal flavour violation

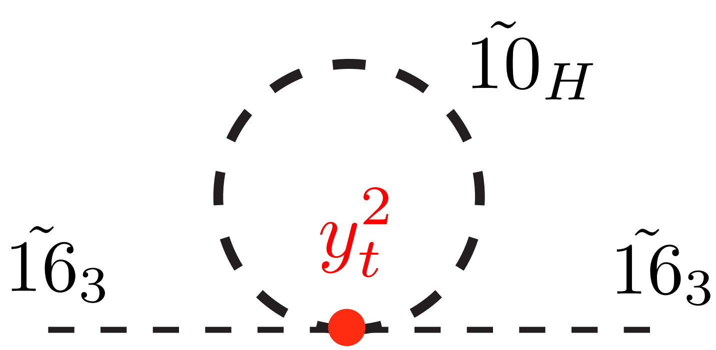
  - quarks & leptons -> leptonic and hadronic flavour violation correlated

“msugra GUTs”

1. Assume that SUSY breaking is Planck-mediated and flavour blind (like msugra) with universal parameters m_0, a_0 $m_{1/2}$, sgn μ at or near the Planck scale, and with unification (here, SO(10)).
2. Furthermore assume that only one Yukawa matrix (Y_U) contains large entries. Choose a GUT basis where it is diagonal

Then radiative corrections lead to a nonuniversal but diagonal sfermion mass matrix at the GUT scale

[Hall, Kostelecky, Raby 86; Barbieri, Hall, Strumia 95]



$$m^2_{\tilde{16}_3} = m_0^2 - \Delta$$

$$m^2_{\tilde{16}_1} \approx m^2_{\tilde{16}_2} = m_0^2 + \delta$$

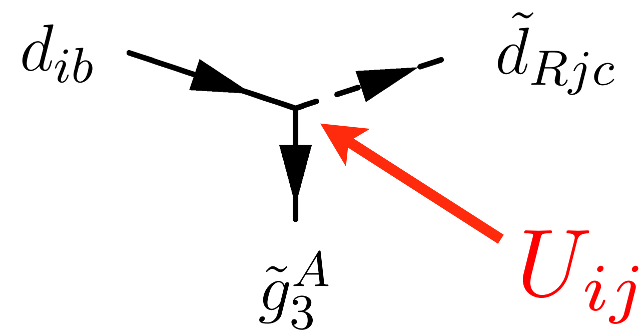
Θ_{atm} in hadronic physics

At M_W, there exists a basis for MSSM superfields where Y_U and *all sfermion mass matrices* are still (nearly) diagonal.
If Y_D, Y_E are nondiagonal in this basis, there are FCNC

Concrete model: Y^U and M_R simultaneously diagonal and SU(5) type embedding of SM into SO(10) [Chang, Masiero, Murayama 03]

$$Y_E = U_E^T \hat{Y}_E U_{\text{PMNS}}, \; Y_D = U_D^T \hat{Y}_D V_{\text{CKM}}^\dagger, \; M_\nu = \hat{M}_\nu$$

$$Y_D = Y_E^T \Rightarrow U_D \approx U_{\text{PMNS}} \equiv U$$



strong impact on B physics
correlations of hadronic and leptonic observables

[Harnik et al 03; SJ, Nierste 03, ...,
Girrbach, SJ, Knopf, Martens, Nierste, Scherrer, Wiesenfeldt 1101.6047]

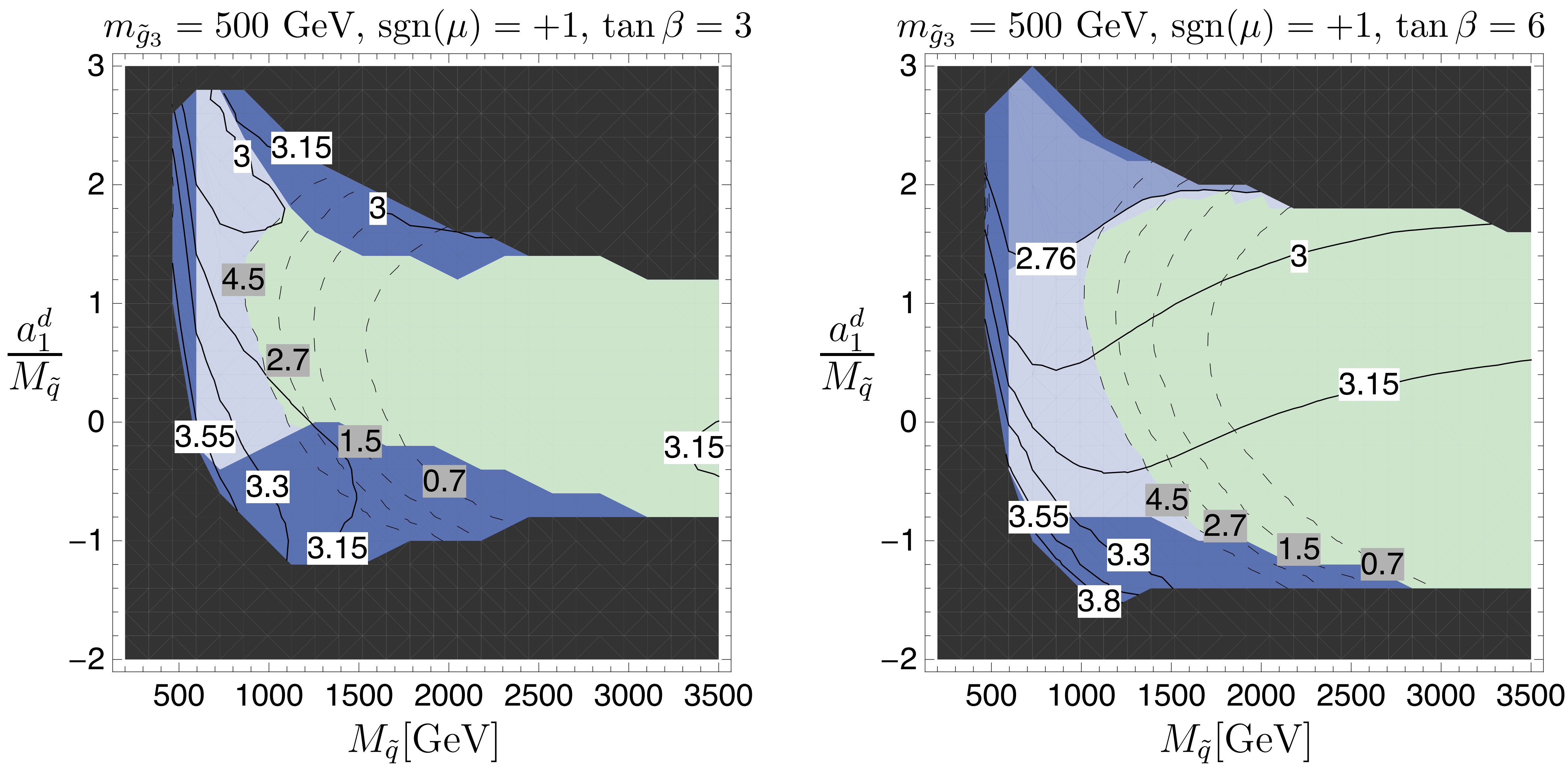
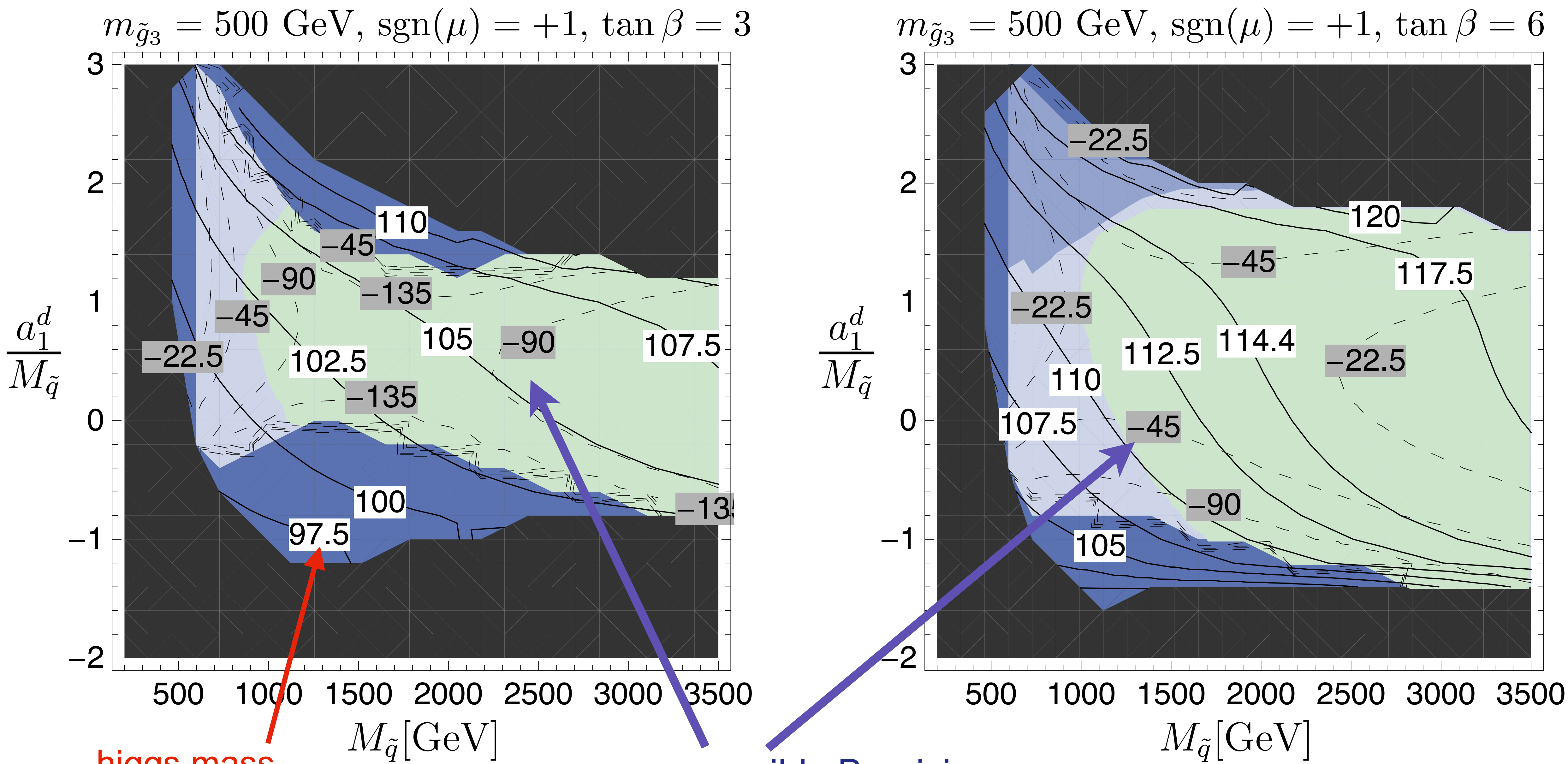


Figure 4: Correlation of FCNC processes as a function of $M_{\tilde{q}}(M_Z)$ and $a_1^d(M_Z)/M_{\tilde{q}}(M_Z)$ for $m_{\tilde{g}_3}(M_Z) = 500$ GeV and $\operatorname{sgn}\mu = +1$ with $\tan\beta = 3$ (left) and $\tan\beta = 6$ (right). $\mathcal{B}(b \to s\gamma)[10^{-4}]$ solid lines with white labels; $\mathcal{B}(\tau \to \mu\gamma)[10^{-8}]$ dashed lines with gray labels. Black region: $m_{\tilde{f}}^2 < 0$ or unstable $|0\rangle$; dark blue region: excluded due to $B_s - \overline{B}_s$; medium blue region: consistent with $B_s - \overline{B}_s$ but excluded due to $b \to s\gamma$; light blue region: consistent with $B_s - \overline{B}_s$ and $b \to s\gamma$ but inconsistent with $\tau \to \mu\gamma$; green region: compatible with all three FCNC constraints.

from 1101.6047

Higgs mass & CPV in B_s mixing



higgs mass

excludes whole green region at $\tan\beta = 3$

max possible B_s mixing phase (degrees)

higgs mass bound can be satisfied for $\tan\beta = 6$ (or greater)

Can accomodate large B_s mixing.
Such large effects would suggest BR($\tau \to \mu\gamma$) at O($10^{-8..9}$)