B-physics theory for LHC & the quest for new physics

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CERN theoretical seminar, 24 September 2008

Outline

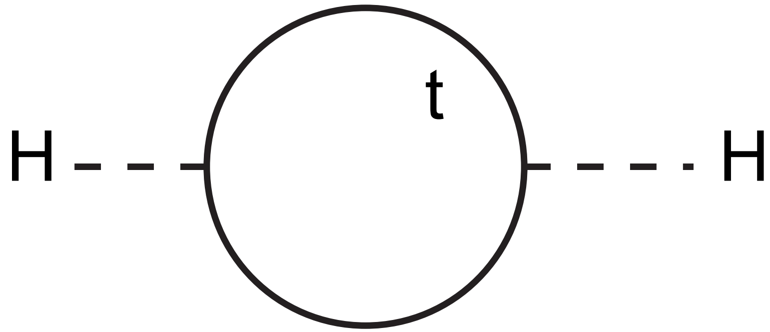
- Motivation
- Role of B physics in the SM
- New physics in mixing
- Disentangling SM and BSM in B decays

- not much discussion of concrete NP models - sorry of course there is no shortage of models providing the potential signals I will discuss

Flavour at the TeV scale

- Much of LHC is motivated by exploring the weak scale and, from a theoretical perspective, by 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. This is what happens in SUSY (stop), warped extra dimensions (KK modes), little Higgs (heavy T), technicolour, etc.

NP flavour puzzle

- Naturalness suggests

$$\mathcal{L}_{\text{eff}} = \Lambda_{\text{UV}}^2 H^2 + \mathcal{L}_{\text{gauge,Yukawa}} + \frac{1}{\Lambda_{\text{UV}}}(H^\dagger L)^2 + \frac{1}{\Lambda_{\text{UV}}^2}\left[(\bar{s}\gamma_\mu d)^2 + \cdots\right]$$

v ~ 246 GeV => Λ < TeV

generic --->	MSSM	WED	generic
EWP bound	weak	3 TeV	$10^{1\text{-}2}$ TeV
flavour bound	$10^{3\text{-}4}$ TeV	20 TeV	10^4 TeV

Ellis, Nanopoulos 82
Gabbiani et al 96

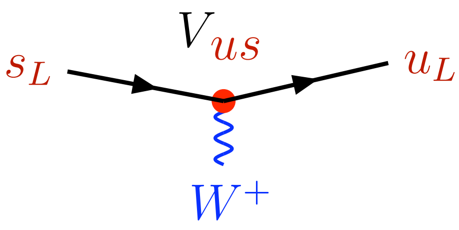
Agashe,Delgado,May,Sundrum 03
Csaki,Falkowski,Weiler 08

Bona et al (UTfit) 06

- flavour violation in SM “unnaturally” small: weak coupling, highly non-generic structure (CKM, GIM)

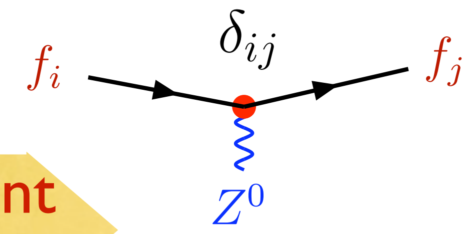
$$\Delta M_K, \epsilon_K \sim \frac{1}{16\pi^2}(V_{td}V_{ts})^2$$ (gives strong NP constraint)

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

PDG08, no unitarity used

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

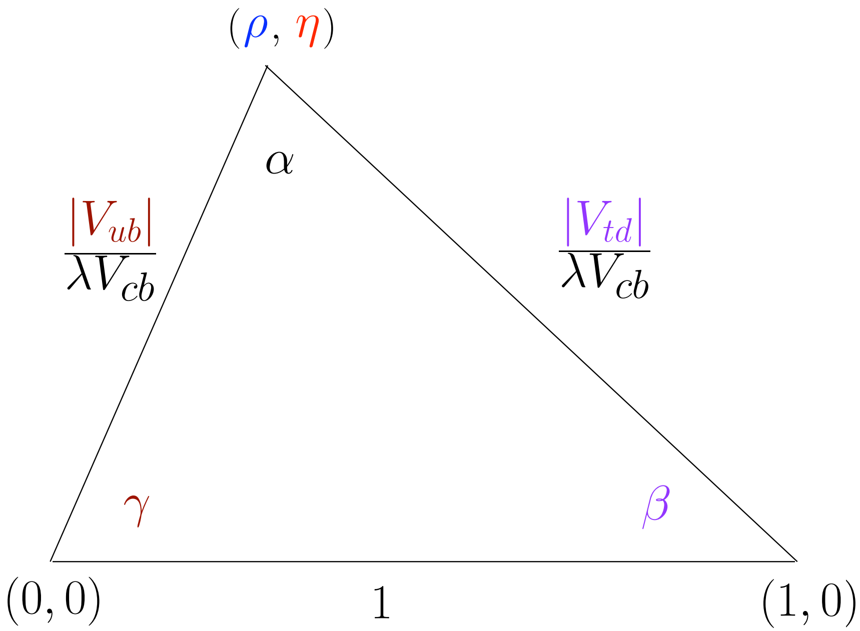
2 parameters to be determined
one complex - CP violating

Unitarity triangle

Unitarity of $V \Rightarrow$

$$
\begin{array}{ccccccccc}
V_{ub}^* V_{ud} & + & V_{cb}^* V_{cd} & + & V_{tb}^* V_{td} & = & 0 \\
A\lambda^3(\rho + i\eta) & - & A\lambda^3 & + & A\lambda^3(1 - \rho - i\eta) & = & 0
\end{array}
$$

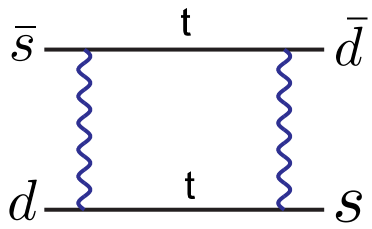
Graphically,



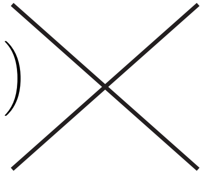
$$V_{ub} = |V_{ub}| e^{-i\gamma}$$

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

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

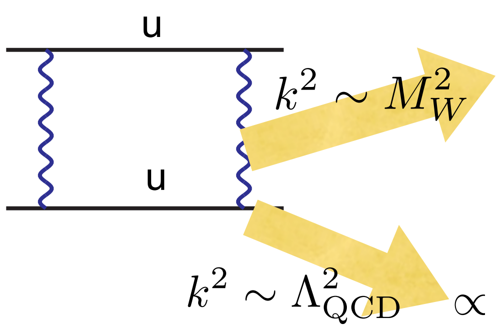


$$\propto (V_{ts}V_{td}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2}\left(\frac{m_t^2}{M_W^2}+\ldots\right)$$

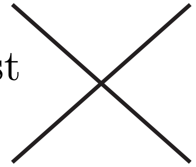


$$\sim \frac{10^{-6}}{M_W^2}$$

top quark loop
CKM-suppressed



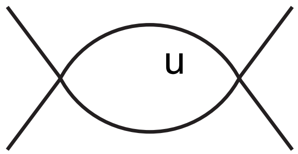
$$\propto (V_{us}V_{ud}^*)^2 \frac{1}{16\pi^2}\frac{1}{M_W^2} \times \text{const}$$



$$\sim \frac{10^{-4}}{M_W^2}$$

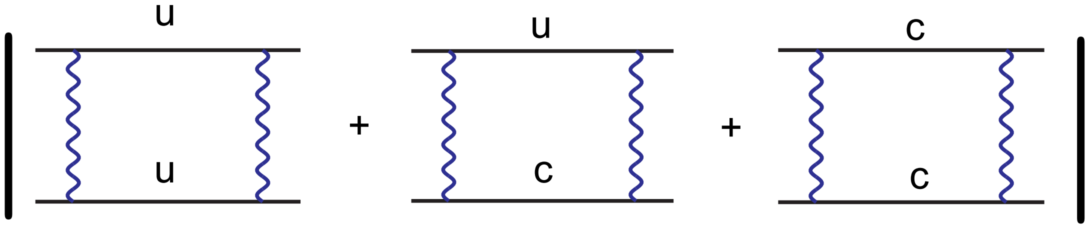
light quark loop
CKM-enhanced

$$\propto (V_{us}V_{ud}^*)^2 \frac{1}{M_W^4}$$



$$\propto (V_{us}V_{ud}^*)^2 \frac{\Lambda_{\rm QCD}^2}{M_W^4}$$

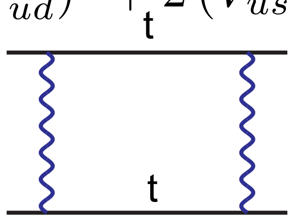
long-distance
CKM-enhanced
but power-
suppressed



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

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

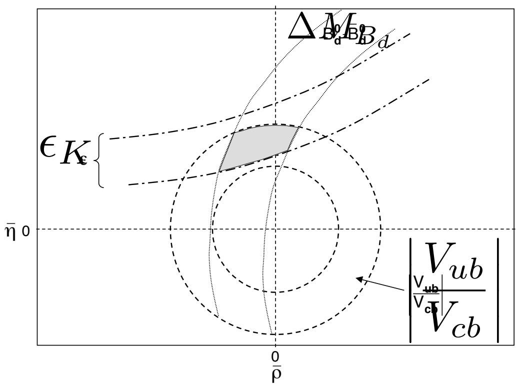
unitarity / GIM
cancellation

Im 

=> $\epsilon_K = \mathcal{O}(10^{-3})$

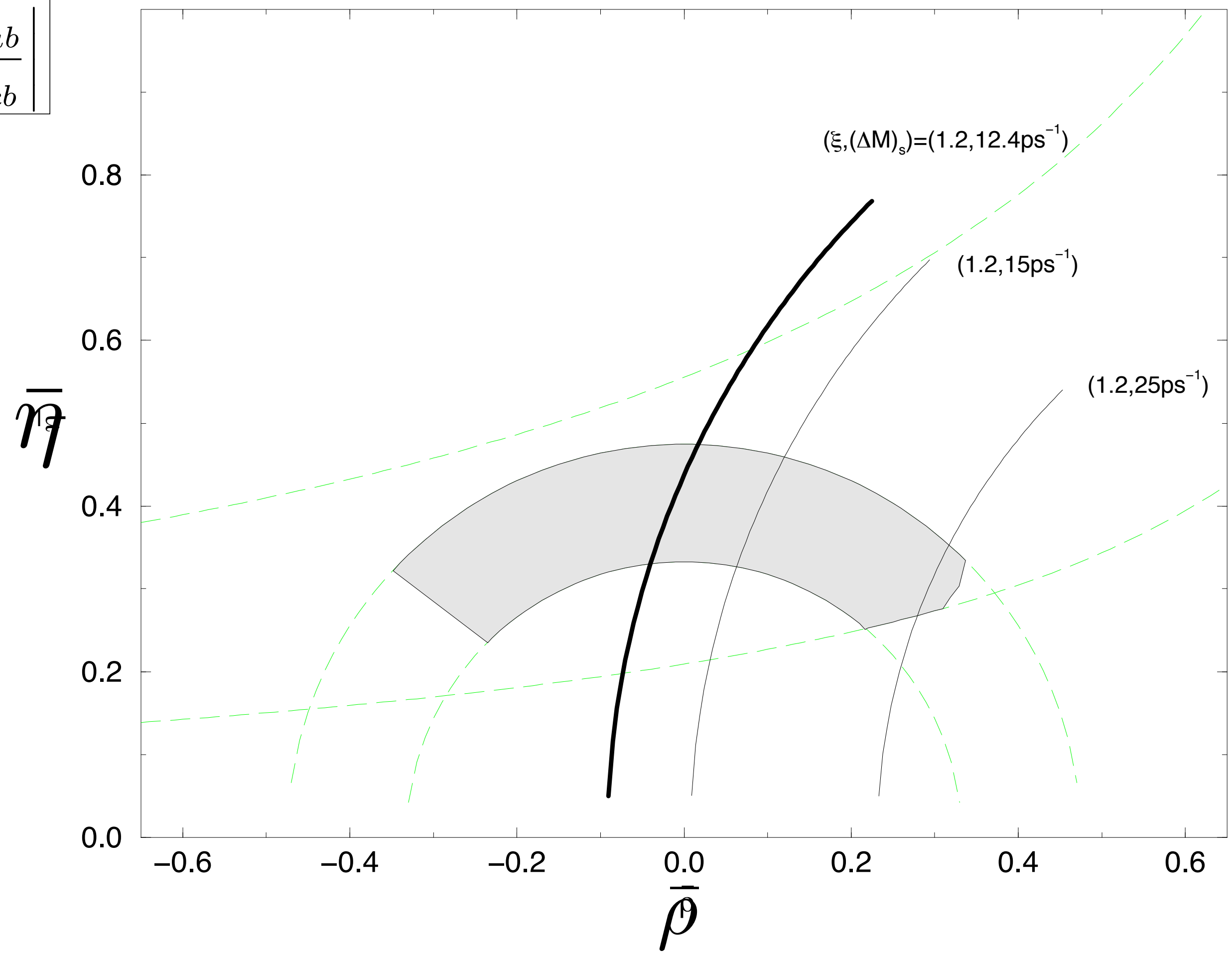
constraint on V_{td}

UT ~ 1999



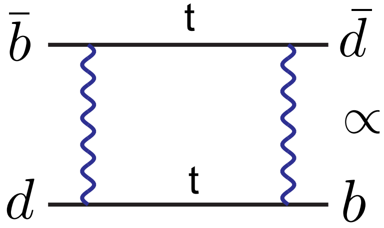
from Buras, hep-ph/9905437

also Grossman et al, Paganini et al, Stocchi, Ali et al, ...

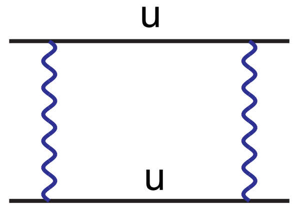


why B physics?

- CKM hierarchy in mixing is removed (w.r.t. Kaons)



$\propto (V_{tb}V_{td}^*)^2 \sim \lambda^6$



$\propto (V_{ub}V_{ud}^*)^2 \sim \lambda^6$

  power suppression of long-distance effects now effective, short-distance dominates

- clean prediction of mixing-induced CP violation $\arg \mathcal{A}(\bar{B}_d \to B_d) = -2\beta$, survives QCD corrections

- theoretical tools available to compute, estimate or contain non-perturbative corrections (mixing,decays)

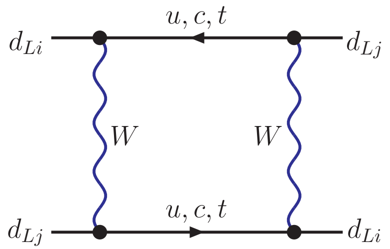
- many observables, look for deviations from SM

B factories

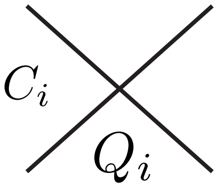
- 2 dedicated asymmetric e^+e^- colliders
  -SLAC/Babar
  -KEK/Belle
  operating from end of 1990s, providing $O(10^9)$ B decays so far
- running (almost) exclusively at Upsilon(4S) resonance, which cannot decay to B_s mesons
- measure time-dependent CP violation
- excellent statistics: many rare B decay modes measured

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

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



(+ NP ?) OPE (m_B/m_W) → $\sum C_i$



→ M_{12} → $\Delta M = 2|M_{12}|$

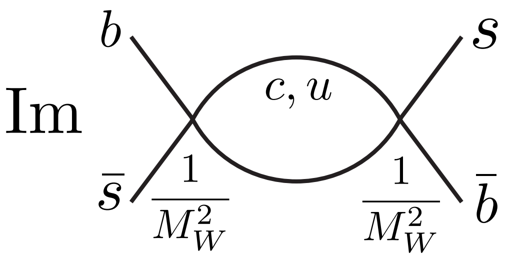
$Q_1 = (\bar{s}^a_L \gamma_\mu b^a_L)(\bar{s}^b_L \gamma^\mu b^b_L)$, only operator present in SM

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

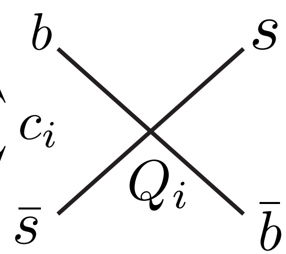
$Q_3 = (\bar{s}^a_R b^b_L)(\bar{s}^b_R b^a_L)$, + 3 more

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

$Q_5 = (\bar{s}^a_R b^b_L)(\bar{s}^b_L b^a_R)$



OPE (Λ_{QCD}/m_B) → $\sum c_i$

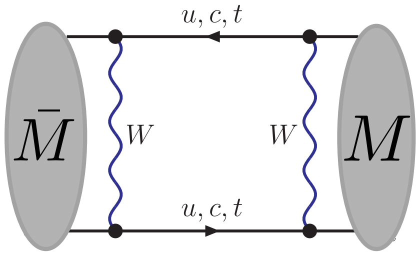


→ Γ_{12} → $\Delta\Gamma$

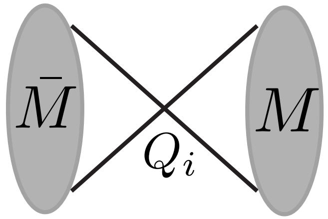
no NP contribution unless lighter than m_B

QCD corrections

- apply OPE to hadronic states



+ NP + QCD $= \sum C_i$



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

(factorization)

$$\Delta M = 2 \left| \sum C_i \langle \bar{M} | Q_i | M \rangle \right|$$

- hadronic matrix elements $\langle \bar{M} | Q_i | M \rangle$ require nonperturbative methods (such as lattice QCD)

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

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

Time-dependent CP asymmetry

decay into CP eigenstate:

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

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

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

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

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:

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

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

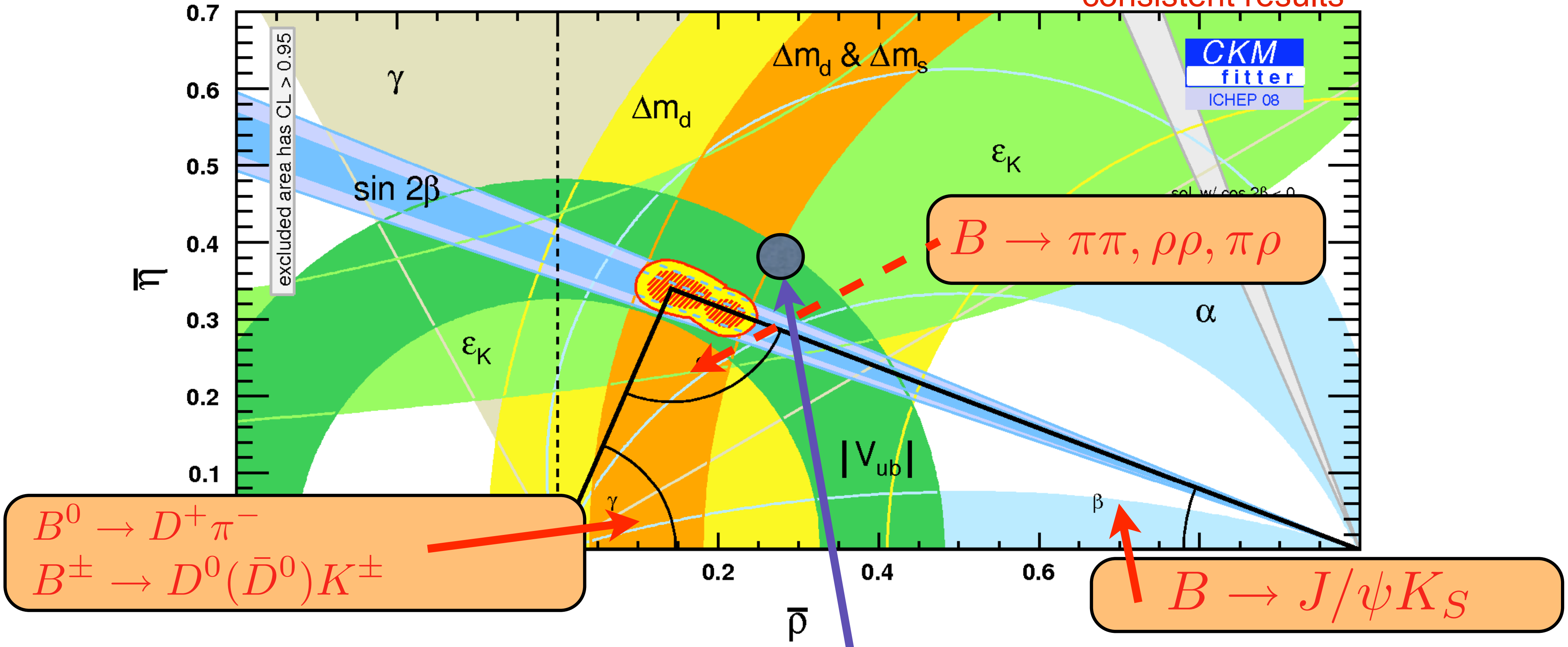
$B_d^0 \to \pi\pi, \pi\rho, \rho\rho$ $\qquad S = \sin(\phi_{B_d} + 2\gamma) = -\sin(2\alpha)$

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

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

UT 2008

apologies to UTfit, who obtain consistent results

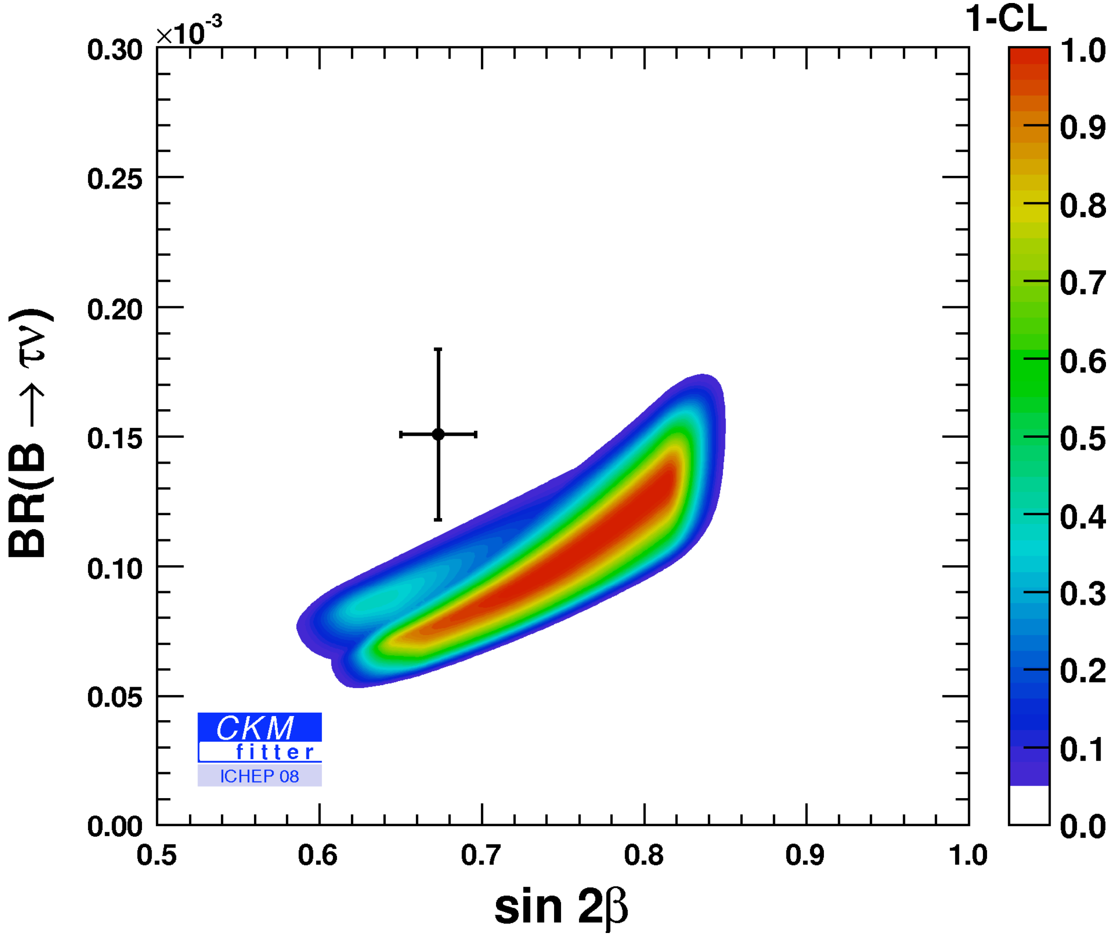


- consistency of CKM picture established by B factories
- sin(ϕ_d) = 0.67±0.02 ($b \to c\bar{c}s$) vs sin(2β) = $0.815^{+0.015}_{-0.045}$ (fit)
- γ= $(67^{+32}_{-25})^\circ$ ("tree" decays) vs $(55.4^{+2.5}_{-2.2})^\circ$ or $(67.4^{+3.3}_{-5.6})^\circ$ (fit)

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

b→s transitions (particularly B_s mixing) only weakly sensitive to $(\bar{\rho}, \bar{\eta})$

NP in B_d mixing?



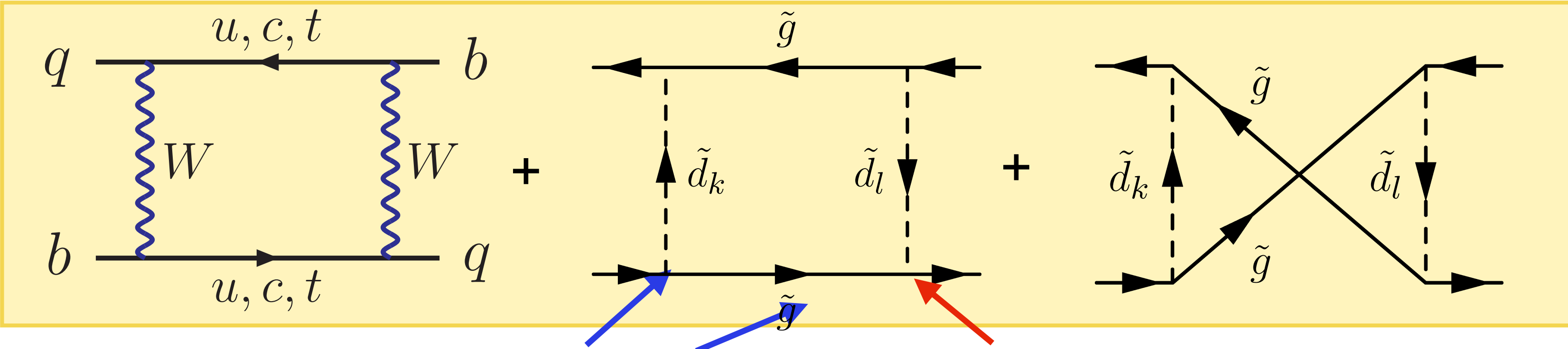
2.1 σ

hadronic uncertainties almost cancel out in correlation

$B \to \tau\nu$ a tree process - NP should be small

two-Higgs doublet model (II): $BR(B \to \tau\nu) = BR(B \to \tau\nu)_{\rm SM} \times \left|1 - \frac{M_B^2 \tan^2\beta}{M_{H^+}^2}\right|^2$

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 $\phi_s \neq 0$ $\qquad \phi_s^{\rm SM} \approx \phi_{B_s}^{\rm SM} \approx 0$
- three observables:

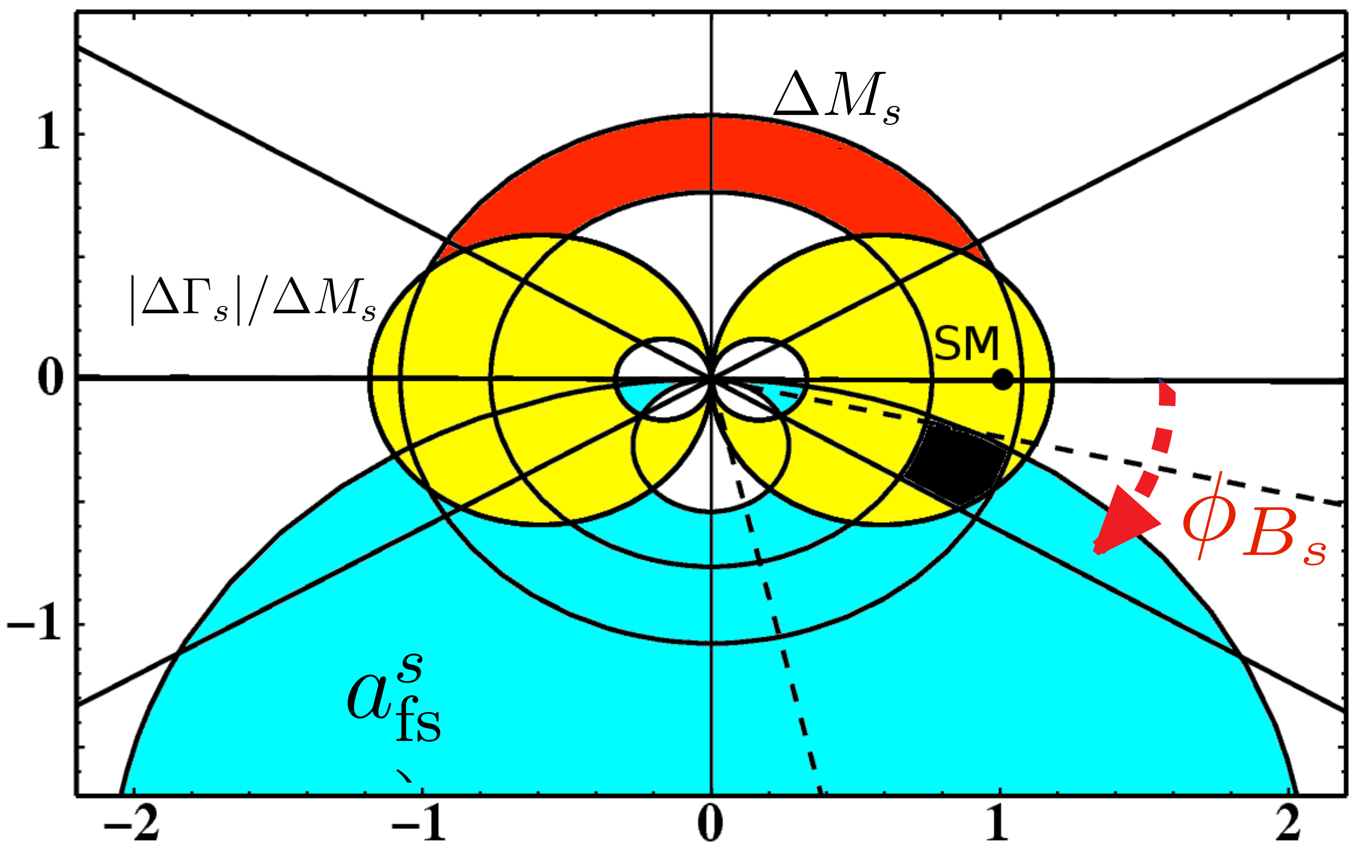
$$\Delta M_s \approx 2|M_{12}^s|, \ \Delta\Gamma_s \approx 2|\Gamma_{12}^s| \cos\phi_s, \ a_{\rm fs}^s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

mass difference   width difference

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

$$B_s \longrightarrow \bar{B}_s \longrightarrow X l^+ \nu$$ (semileptonic CP asymmetry)

complex $\frac{M_{12}^{s}}{M_{12}^{s,\mathrm{SM}}}$ plane end 2006



Lenz, Nierste hep-ph/0612167

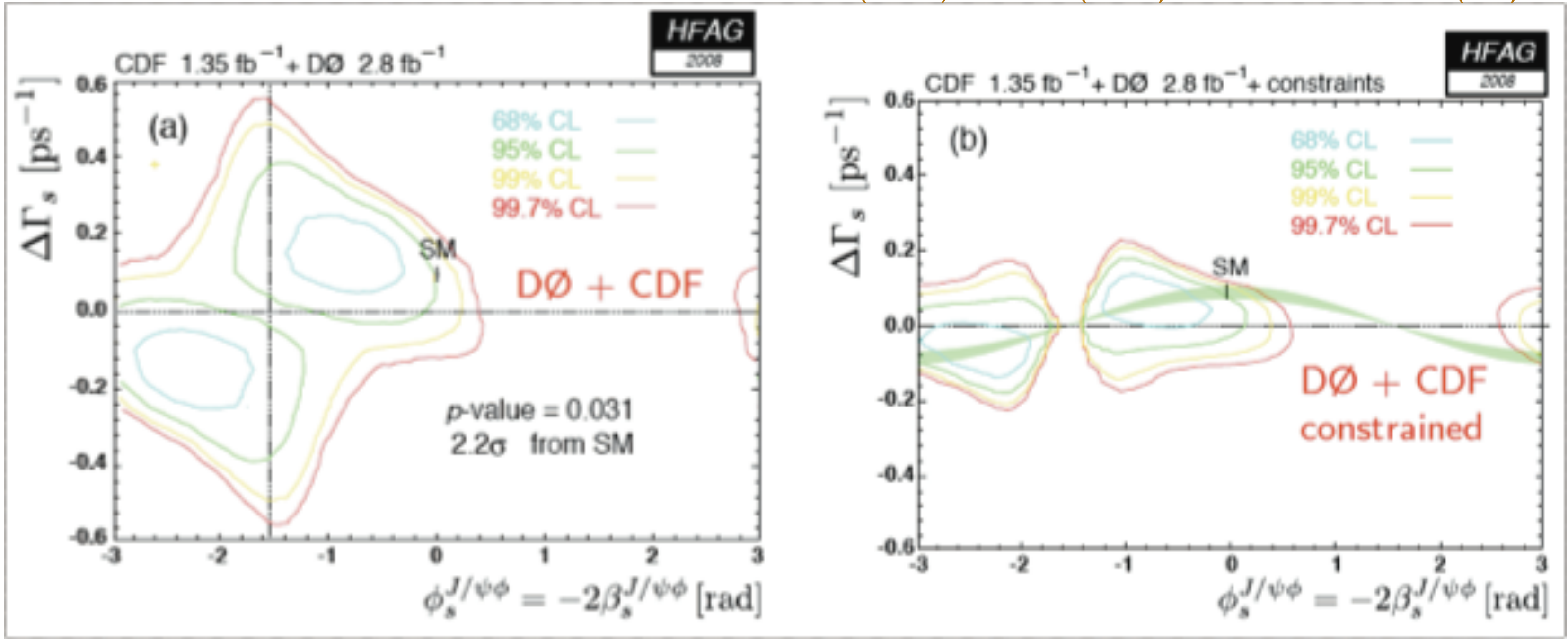
combination of $\Delta\Gamma_s$, ΔM_s , $a_{\mathrm{sl}}^{s,\mathrm{dimuon}}$ from Tevatron

approx 2σ deviation from SM prediction

sin(2 ϕ_s) measurement

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

PRL100 (2008)161802 (CDF), arXiv:0802.2255 (D0)



- CDF & D0 consistent, $-65^\circ < \phi_s < -28^\circ$ or $-151^\circ < \phi_s < -136^\circ$

L Sonnenschein(D0) talk at CKM2008

- ~4x statistics, better tagging, may reach 5σ by 2010

D Tonelli (CDF), talk at CKM2008

- LHCb expects ~ 1° sensitivity with 2 fb^{-1} data (1 nom. yr)

M Merk(LHCb), talk at CERN TH institute

see also Bona et al (UTfit), arXiv:0803.0659

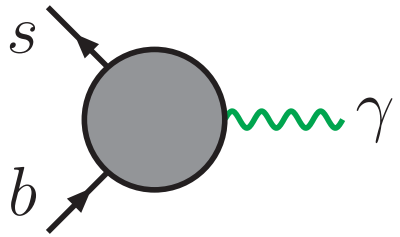
B physics at LHC

- LHCb dedicated B-physics experiment
  10^{12} $b\bar{b}$ pairs/year (compared to 10^9 at B-factories)
- 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, however high statistics for many exclusive modes - a challenge for theory
- Exploration of B_s system (huge improvement on mixing parameters over Tevatron)
- precise determination of ϕ_s and of true CKM γ
- rare decays

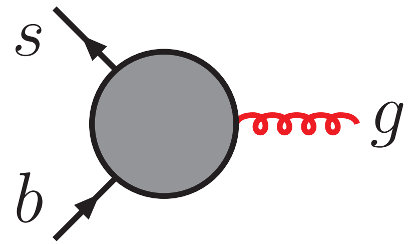
Decays

Penguins

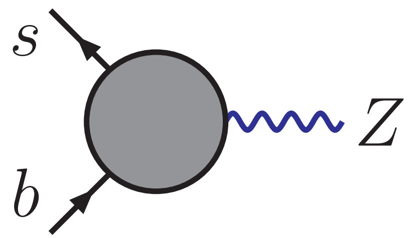
require chirality flip



$\bar{s}_L b_R \gamma$	$\bar{s}_R b_L \gamma$	magnetic penguin
$\bar{s}_L b_L \gamma^*$	$\bar{s}_R b_R \gamma^*$	QED penguin



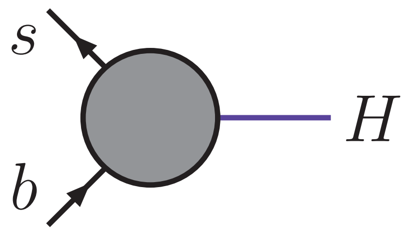
$\bar{s}_L b_R g$	$\bar{s}_R b_L g$	chromomagnetic penguin
$\bar{s}_L b_L g^*$	$\bar{s}_R b_R g^*$	QCD penguin



$\bar{s}_L b_L Z$	$\bar{s}_R b_R Z$	Z-penguin

SU(2)$_W$-breaking

negligible in SM



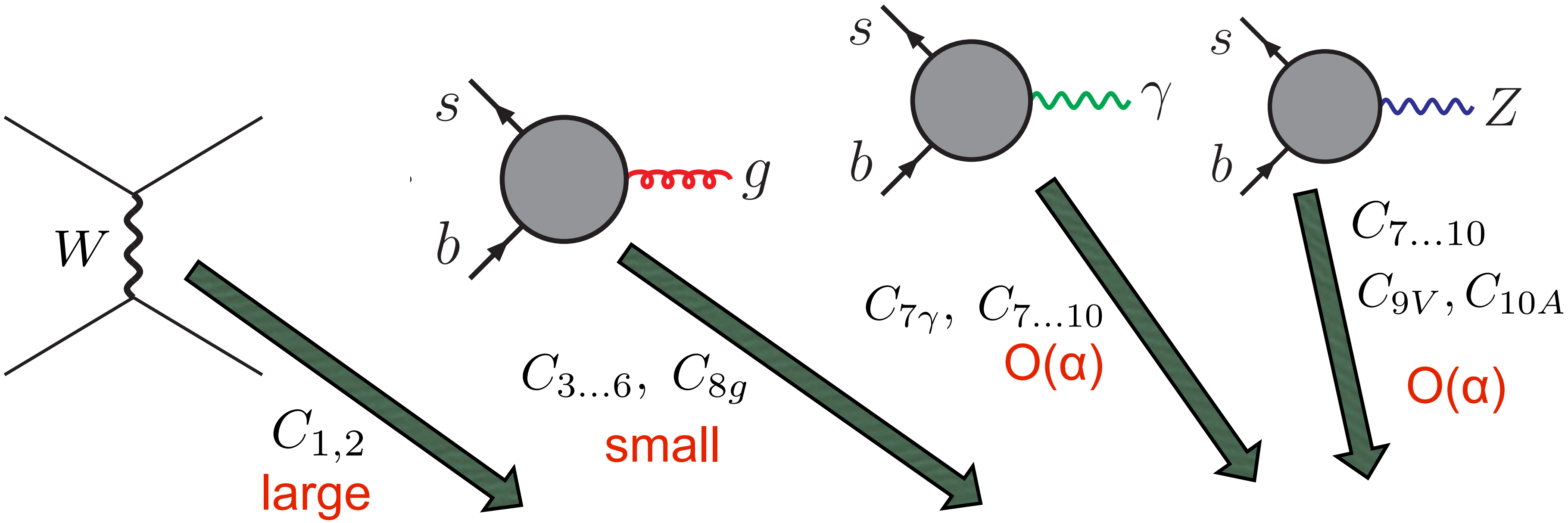
$\bar{s}_L b_R H$

$\bar{s}_R b_L H$

important in 2HDM at large tan(β)

as with mixing (ΔF=2), GIM cancellations enhance sensitivity to heavy particles

Weak $\Delta F = 1$ hamiltonian



$$\mathcal{H}^{\rm SM}_{{\rm eff},b\to D} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} V^*_{pD} V_{pb} \Big(C_1(\mu) Q_1^p(\mu) + C_2(\mu) Q_2^p(\mu) + \sum_{i=3\ldots10,7\gamma,8g} C_i(\mu) Q_i(\mu) \Big)$$

BSM: modified C_i, possibly more Q_i

$C_1(m_b) \sim 1.1 \qquad |C_{3\ldots6}(m_b)| \sim 0.01\ldots0.04$

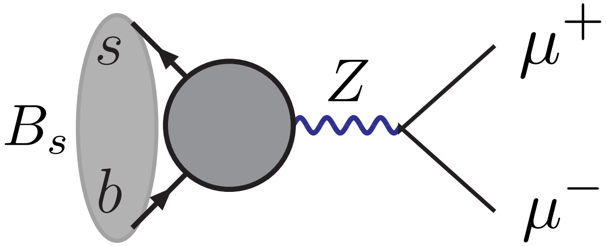
$C_2(m_b) \sim -0.2 \qquad C_{8g}(m_b) \sim -0.15$

Exclusive decays

	need (th)		# observables
Leptonic $B \to l\nu$, $B \to l^+l^-$	decay constant $\langle 0 \vert j^\mu \vert B \rangle \propto f_B$		O(1)
(Certain) semileptonic $B \to \pi l \nu, \rho l \nu, \ldots$	form factors $\langle \pi \vert j^\mu \vert B \rangle \propto f^{B\pi}(q^2)$		O(10)
Nonleptonic $B \to \pi\pi, \pi K, \rho\rho \ldots$	full matrix element $\langle \pi\pi \vert Q_i \vert B \rangle$		O(100)

Decay constants and form factors accessible to present first-principles methods (lattice QCD),
nonleptonic matrix elements are not

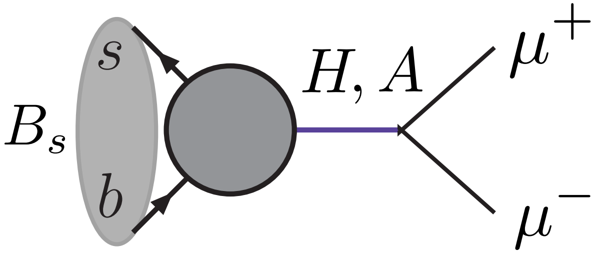
Leptonic decay



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

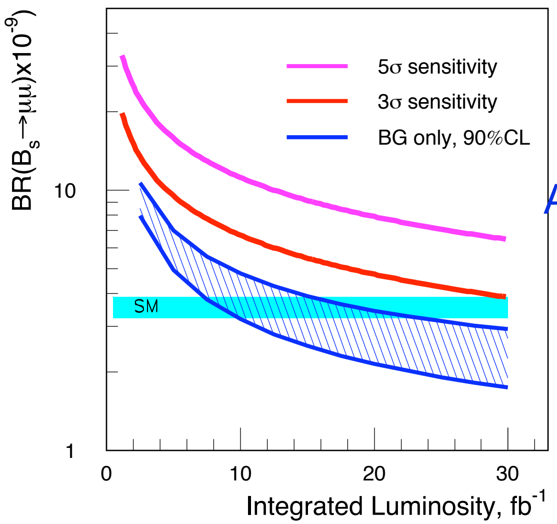
helicity suppressed
theoretically clean in SM
(normalize to ΔM_s) Buras 03

$$BR(B_s \to \mu^+\mu^-)_{\rm SM} = (3.5 \pm 0.5) \times 10^{-9}$$

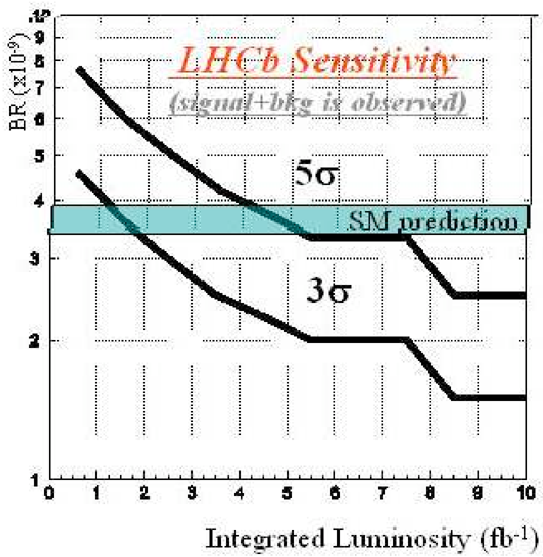


$$\propto \frac{m_b^2 m_\mu^2}{M_W^4} \tan^6\beta$$

Yukawa suppressed in SM
strong enhancement in 2HDM
(or MSSM) possible



ATLAS/CMS



LHCb

SUSY large tan(β) B physics

assume $M_{SUSY} \gg M_{H,A,h} \sim v=246$ GeV ; effective 2HDM description

$$M^d_{ij} = v_d Y^d_{ij} + v_u \Delta_{ij}$$

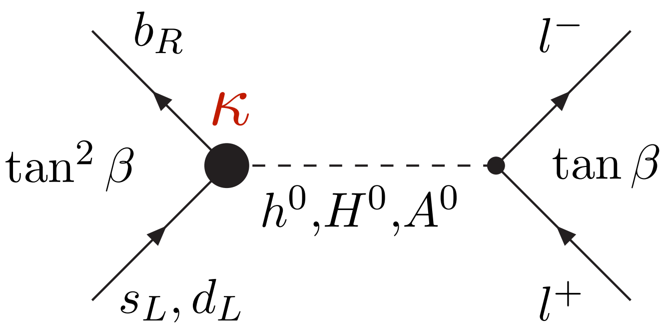
parametrically large if $v_u \gg v_d$

rediagonalization of M^d rotates Y^d out of diagonal form:

$$\mathcal{L}_{\rm eff} \supset \kappa(\cos\beta h_u^{0*} - \sin\beta h_d^0)[y_b \bar{b}_R s_L + y_s \bar{s}_R b_L]$$

$$\kappa \propto \frac{\tan\beta}{16\pi^2}$$

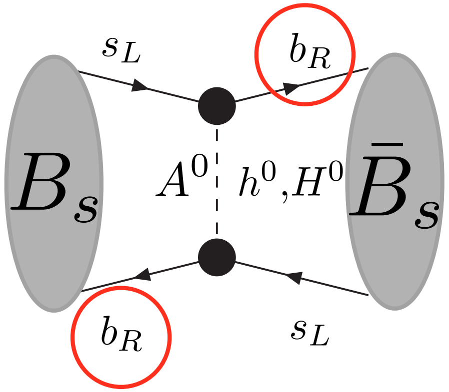
(minimal flavour violation; non-MFV: flavour-dependent)



$$BR(B_s \to \mu\mu) \propto \tan^6\beta$$

[Choudhury&Gaur 99; Hamzaoui, Pospelov, Toharia 99; Babu, Kolda 99; Isidori, Retico; Buras et al 02; Foster et al 04-06,...]

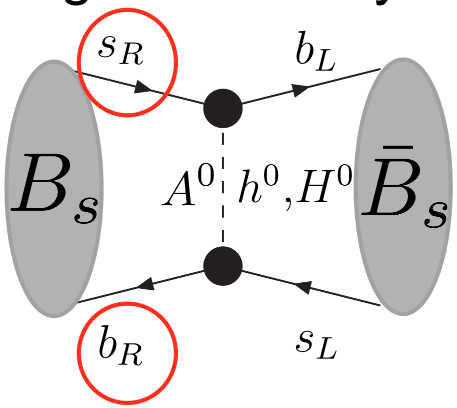
SUSY large tan (β) B physics (MFV)



$$\propto \kappa^2 y_b^2 \left[\frac{\sin^2(\alpha-\beta)}{M_H^2} + \frac{\cos^2(\alpha-\beta)}{M_h^2} - \frac{1}{M_A^2} \right] = 0$$

[LO higgs masses & mixing angle α]

Flipping the chirality of one b (hence one s) quark,

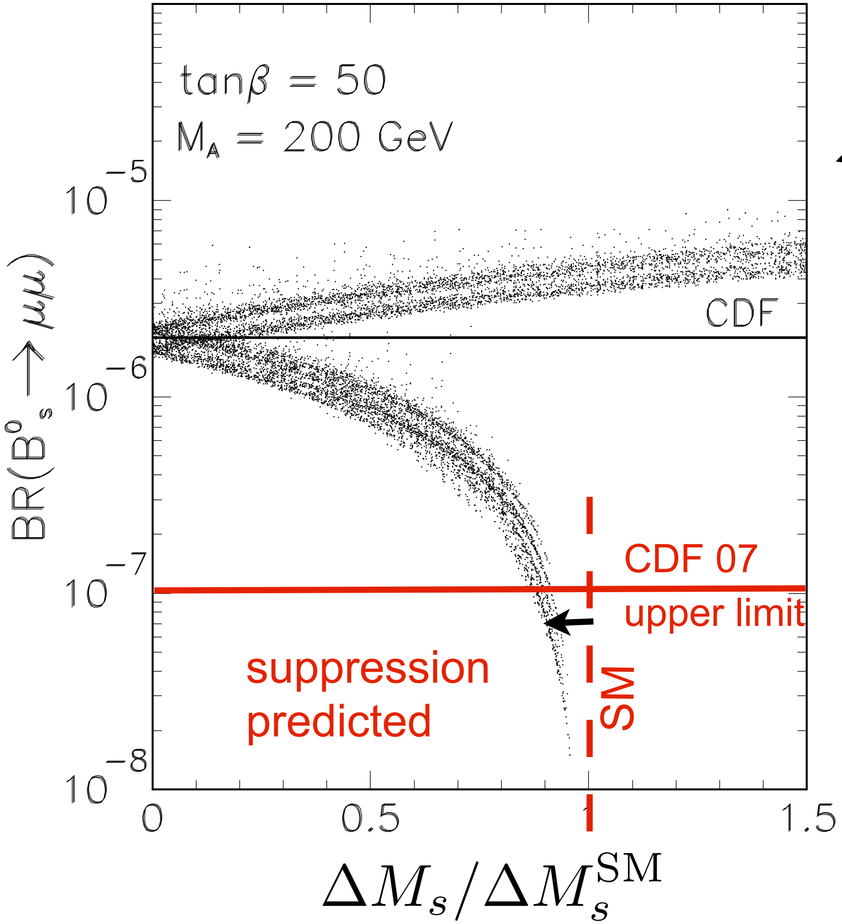


$$\propto |\kappa^2| y_b y_s \left[\frac{\sin^2(\alpha-\beta)}{M_H^2} + \frac{\cos^2(\alpha-\beta)}{M_h^2} + \frac{1}{M_A^2} \right] \neq 0$$

costs a factor m_s/m_b (in $B_d - \bar{B}_d$ mixing: m_d/m_b - negligible)

But this is only one of several small parameters!

$$1/(16\pi^2) \sim m_s/m_b \sim 1/\tan\beta \sim 10^{-2}$$



Strong correlation between ΔM_{B_s} and $BR(B_s \to \mu^+\mu^-)$

[Buras et al 02]

$$(\Delta M_s)_{\rm exp} = (17.77 \pm 0.12)\mathrm{ps}^{-1}$$

$$\Delta M_s^{\rm SM} \approx 16 \ldots 27\,\mathrm{ps}^{-1}$$

(recent claims of CP violation, ~ zero in SM)

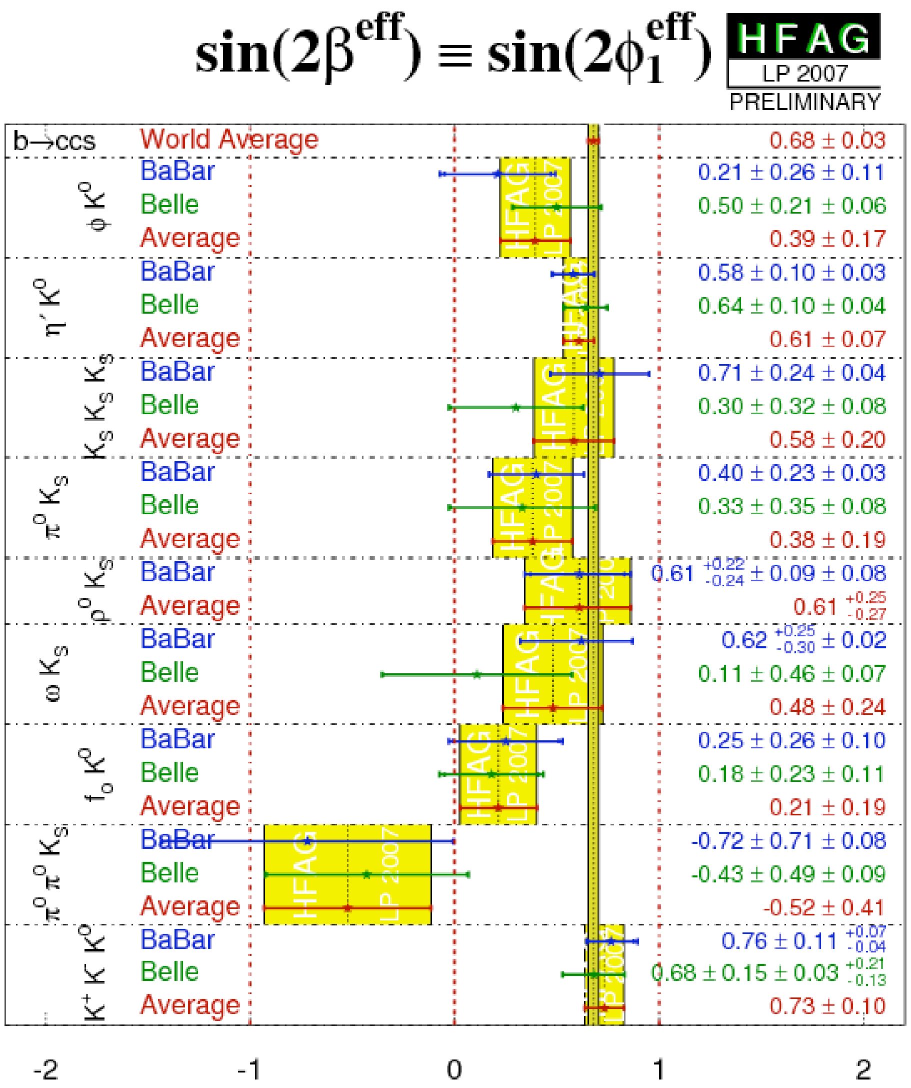
A (naively) subleading effect: arises at first order in m_s/m_b

Can more loops or 1/tan(β) corrections remove m_s/m_b suppression? claims of large effects from Higgs self-energies both in ΔM_d and ΔM_s in recent literature [Parry 06; Freitas,Gasser,Haisch 07]

A more systematic investigation shows that this does not happen

[Gorbahn, SJ, Nierste, Trine, in prep.]

b→s penguin transitions



In the SM, expect

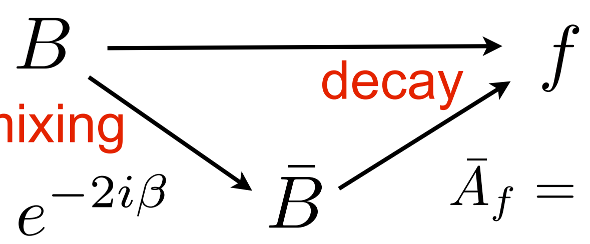
$$\sin(2\beta^{\rm eff}) \approx \sin(2\beta)$$

several modes seem to have

$$\sin(2\beta^{\rm eff}) \neq \sin(2\beta)$$

SM QCD corrections or new physics?

a generic issue in flavour (as in collider) physics

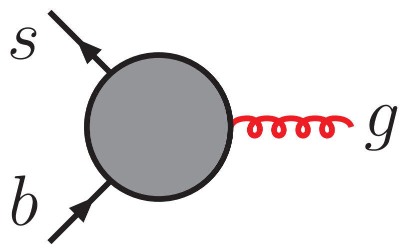


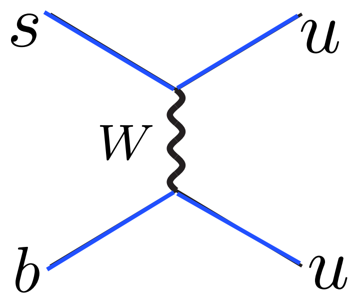
f CP eigenstate

$$\frac{BR(B^0(t)\to f) - BR(\bar{B}^0(t)\to f)}{BR(B^0(t)\to f) + BR(\bar{B}^0(t)\to f)} = -S_f \sin(\Delta m_B t) + C_f \cos(\Delta m_B t)$$

time-dependent CP asymmetry

$$\overbrace{-\eta_{CP}(f)\cdot S_f}^{\sin(2\beta^{\rm eff})} \approx \sin(2\beta) + 2\cos(2\beta)\sin\gamma\,{\rm Re}\frac{T_f + P_f^u}{P_f^c} + S_f^{\rm N.P.}$$





?

what is the size of the subleading amplitudes?

Charmless hadronic amplitudes

Any decay amplitude can be written in the form

weak phases (CP odd)

$$\mathcal{A}(\bar{B} \to M_1 M_2) = |V_{ub} V_{uD}| e^{-i\gamma} T_{M_1 M_2} + V_{cb} V_{cD} P_{M_1 M_2} + e^{i\delta_{\rm NP}} P^{\rm NP}_{M_1 M_2}$$

Sensitive to V_{ub}, γ and new flavour parameters beyond the SM

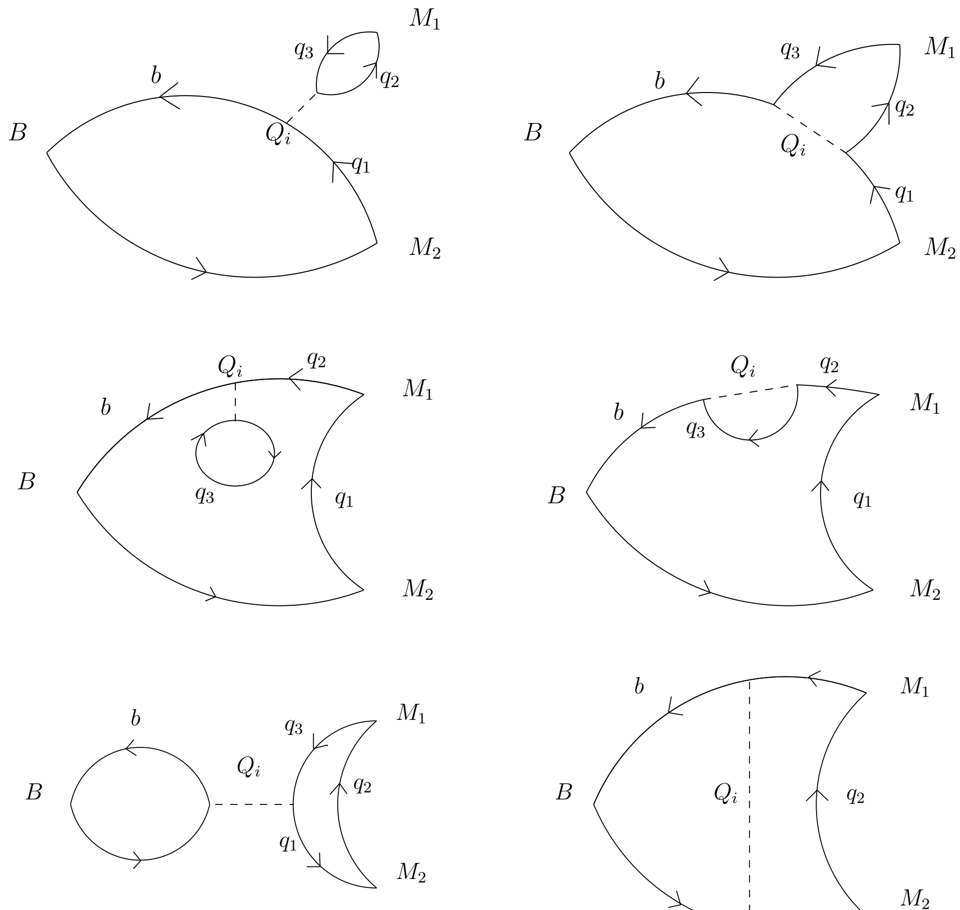
Theorist's job: Eliminate or compute amplitudes |P|, |T|, which include strong (rescattering) phases arg(P/T), arg(P^{NP}/T)

$$T_{M_1 M_2} = \frac{G_F}{\sqrt{2}} \Big(\sum_{i=1,2} C_i \langle M_1 M_2 | Q_i^u | \bar{B} \rangle + \sum_{i=3\ldots 8,7\gamma,8g} C_i \langle M_1 M_2 | Q_i | \bar{B} \rangle \Big) \quad \text{“tree”}$$

$$P_{M_1 M_2} = \frac{G_F}{\sqrt{2}} \Big(\sum_{i=1,2} C_i \langle M_1 M_2 | Q_i^c | \bar{B} \rangle + \sum_{i=3\ldots 8,7\gamma,8g} C_i \langle M_1 M_2 | Q_i | \bar{B} \rangle \Big) \quad \text{“penguin”}$$

$$e^{i\delta_{\rm NP}} P^{\rm NP}_{M_1 M_2} = \sum C_k \langle M_1 M_2 | Q_k | \bar{B} \rangle$$

Topological amplitudes



[from Buras&Silvestrini hep-ph/9812392]

$Q_i = Q_{1,2}^u$ → $a_{1,2}$ $[T, C][E_{1,2}]$

color-allowed/
-suppressed tree

$Q_i = Q_{3...}$ → α_4^u $[P_{ut}][P_1 - P_1^{\mathrm{GIM}}]$

$Q_i = Q_{1,2}^{u(c)}, Q_{3...}$ → up-penguin
(charming penguin)

$Q_i = Q_{1,2}^u$ → $b_{1,2}$ $[E, A][A_{2,1}]$

tree annihilation

ex.: $-\mathcal{A}(\bar{B}^0 \to \pi^0\pi^0) = V_{ud}^* V_{ub} \left[A_{\pi\pi} \left(a_2(\pi\pi) - \alpha_4^u(\pi\pi)\right) + B_{\pi\pi} b_1(\pi\pi)\right]$

$$+V_{cd}^* V_{cb} \text{ terms} + \text{EWP terms}$$

Theory approaches

- 1/N expansion (only counting rules)
- Λ_{QCD}/m_B expansion (QCDF/SCET; pQCD): computation of important pieces possible

	a_1/T/E_1	a_2/C/E_2	α_4^u	b_1/E/A_2	b_2/A/A_1
1/N	1	1/N	1/N	1/N	1 [?]
Λ/m_B	1	1	1	Λ/m_B	Λ/m_B

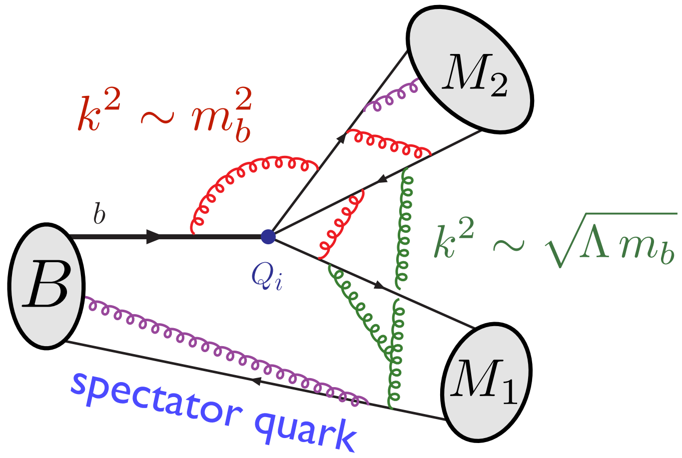
- QCD light-cone sum rules: partly complementary set of calculable amplitudes; constrain "inputs" to Λ/m_B
- SU(3) [U-spin] relates $\Delta D=1$ and $\Delta S=1$
  T(πK)≈ T(ππ); P(ρρ) ≈ P(ρK^*), etc.
  (m_s/Λ_{QCD} corrections; annihilation amplitudes)

QCD factorization

Beneke, Buchalla, Neubert, Sachrajda

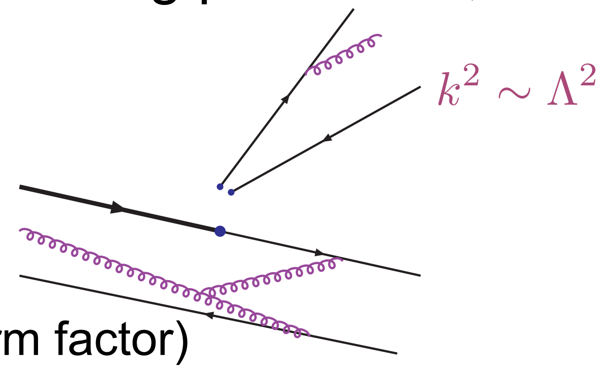
"nonfactorizable" gluons
are perturbative

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



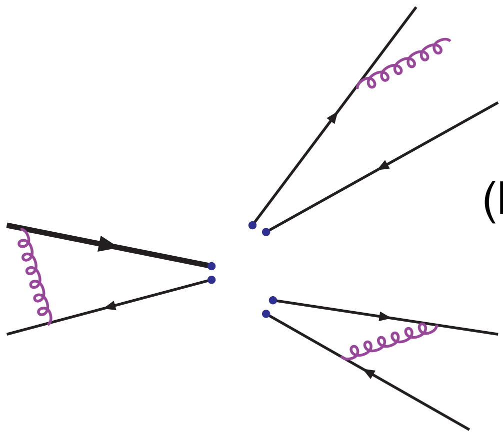
$$+ \ldots$$

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



soft overlap (form factor)

or



(hard) spectator scattering

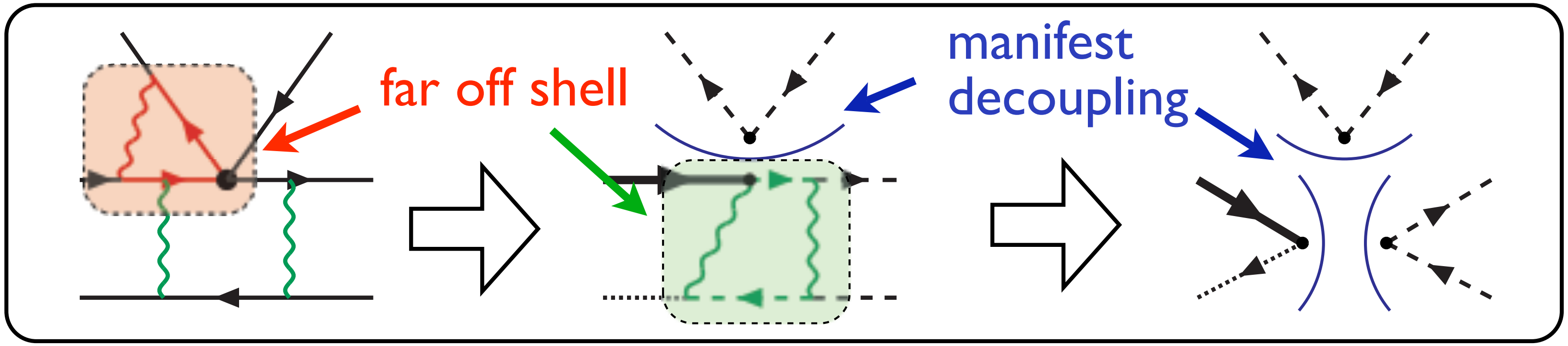
model dependence enters (only) at subleading power
(factorization breaks at O(Λ/m) for some amplitudes)

SCET representation

["SCET" = soft-collinear effective theory]

[Bauer et al; Chay et al; Beneke et al; Williamson & Zupan; Beneke, SJ; many more]

- Hierarchy $m_b \gg \Lambda_{\rm QCD}$ suggests EFT description
- Spectator interactions induce 3rd scale $\sqrt{\Lambda_{\rm QCD} m_b}$



hard scale ⇒ coefficients H^{II} (several topologies)

intermediate scale ⇒ "jet function" J (universal)

- $T^{II} = H^{II} * J$ (starts at $O(\alpha_s)$, so NLO is α_s^2)
- J known to NLO
- recent NLO computations of H^{II}

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

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 (partial)

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

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

BBNS 99-01 — BBNS 99-01

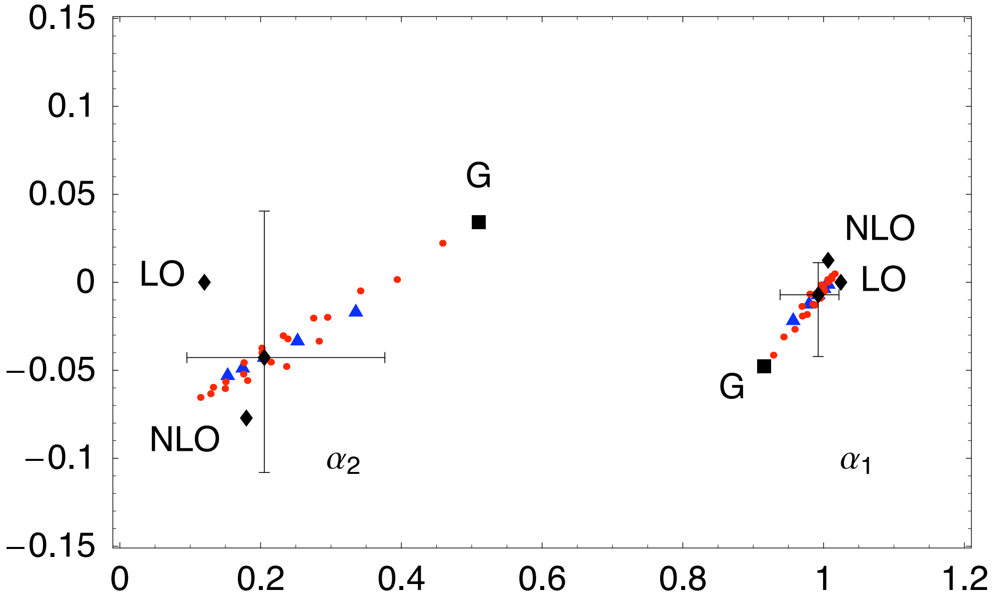
Hill, Becher, Lee, Neubert 2004; Beneke, Yang 2005; Kirilin 2005

Beneke, SJ 2005, 2006; Kivel 2006; Pilipp 2007; Jain, Rothstein, Stewart 2007

Implementations of factorization

	BBNS Beneke, Buchalla,Neubert, Sachrajda	BPRS ("SCET") Bauer, Pirjol, Rothstein, Stewart
hard scale (m_b)	perturbative; identical kernels [up to basis]	
hardcollinear scale ($\sqrt{m_b \Lambda}$)	perturbative	fit to data (possible for LO hard kernels)
charm penguin	no special treatment (generally) small perturbative phase	introduce extra complex parameter (fit to data)
most important theory inputs	QCD form factor, B & light meson LCDA	2 soft form factors, light meson LCDA
power corrections	calculate or model potentially large ones	typically omitted

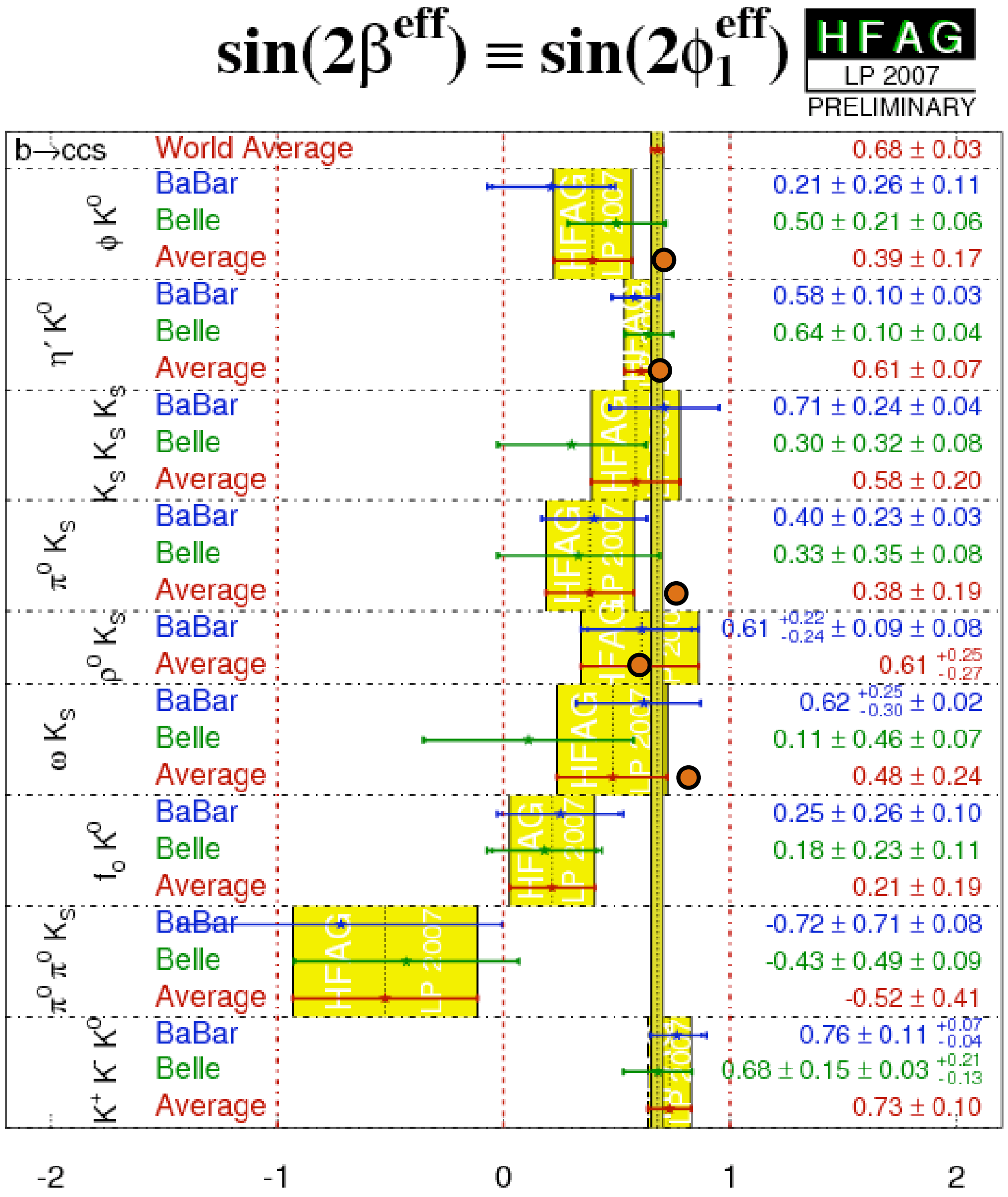
Jain et al 2007 pursue a hybrid approach



- bulk of uncertainties due to universal hadronic parameters (B decay constant, wave function) and to poorly known form factors

- colour-allowed tree close to naive factorization, so is colour-allowed electroweak penguin (not shown)

- colour-suppressed tree: large departure from naive factorization



[Beneke 2005] (NLO QCDF)

Subleading SM amplitudes tend to worsen the agreement

similar conclusion in BPRS approach [Williamson, Zupan 2006]

$S_{\pi^\circ K_S}$ and isospin

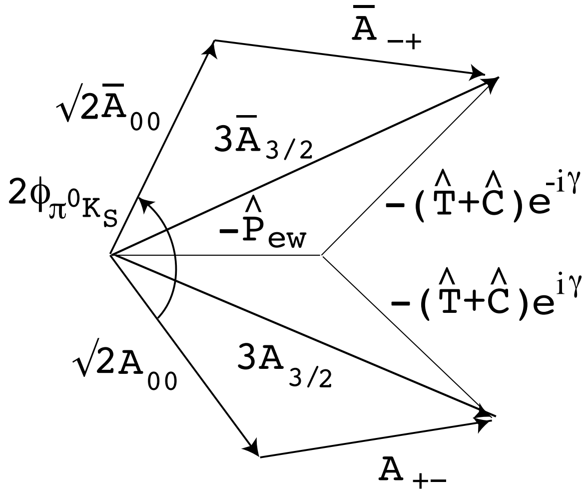
- pattern of CP asymmetries (and BRs) in B→πK has been much studied
  Gronau et al; Buras, Fleischer, Recksiegel, Schwab; Baek et al; Yoshikawa; Gronau, Rosner; Agashe et al; Grossman et al; Feldmann et al;...

- can use isospin relations to find the shift of $S_{\pi K}$ from the remaining B°→πK data (BR & CP asymmetries) requires knowledge of the (unique) isospin-3/2 amplitude. Then

Fleischer, SJ, Pirjol, Zupan 08

Gronau, Rosner 08

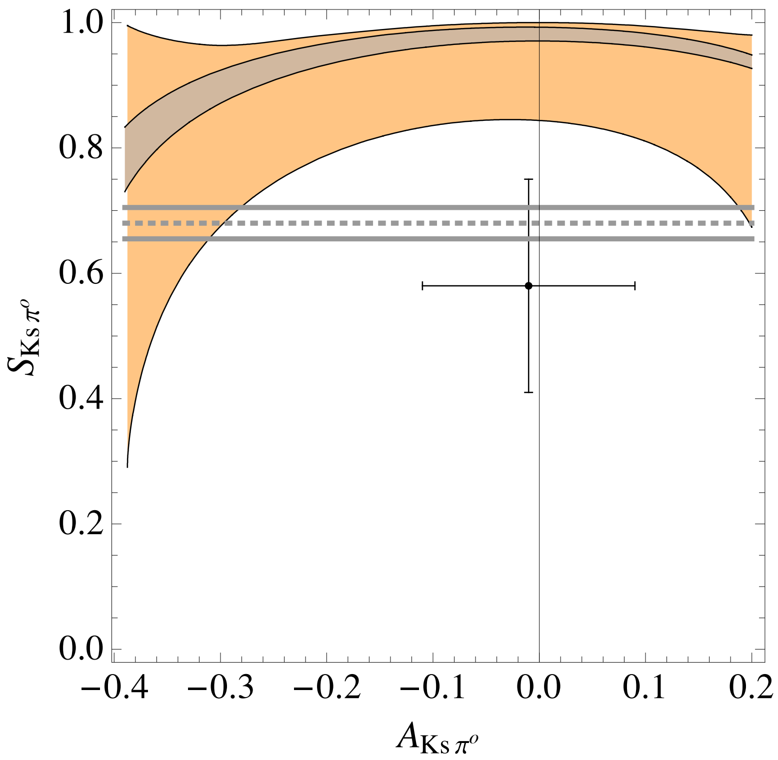
Mode	BR $[10^{-6}]$	$A_{\rm CP}$
$\bar{B}^0 \to \pi^+ K^-$	19.4 ± 0.6	-0.098 ± 0.012
$\bar{B}^0 \to \pi^0 \bar{K}^0$	9.8 ± 0.6	-0.01 ± 0.10



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

- $A_{3/2}$ from BR($B^+ \to \pi^+\pi^\circ$) and two SU(3) relations use QCD factorization only to estimate SU(3) breaking Fleischer, SJ, Pirjol, Zupan 08

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



error dominated by form-factor ratio

$$F^{B\to K}(0)/F^{B\to\pi}(0)$$

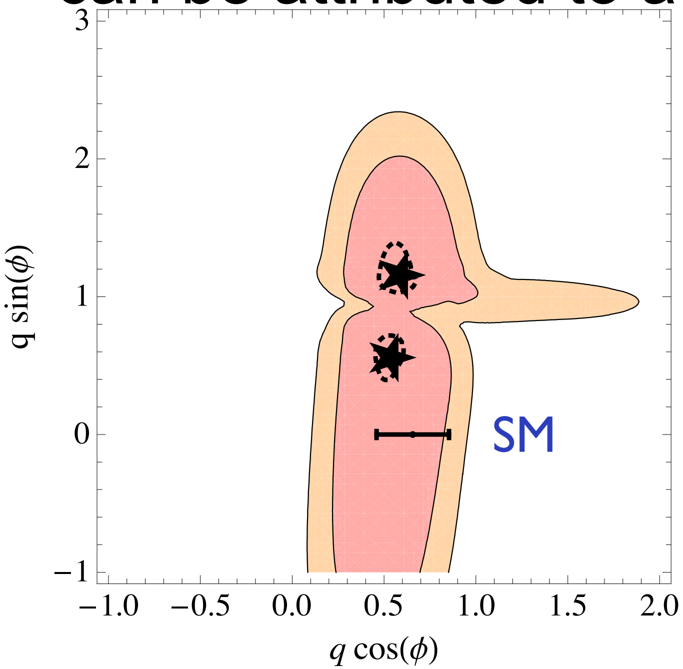
$$R_q = (1.02^{+0.27}_{-0.22})e^{i(0^{+1}_{-1})^\circ}$$

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

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

[arbitrary central value]

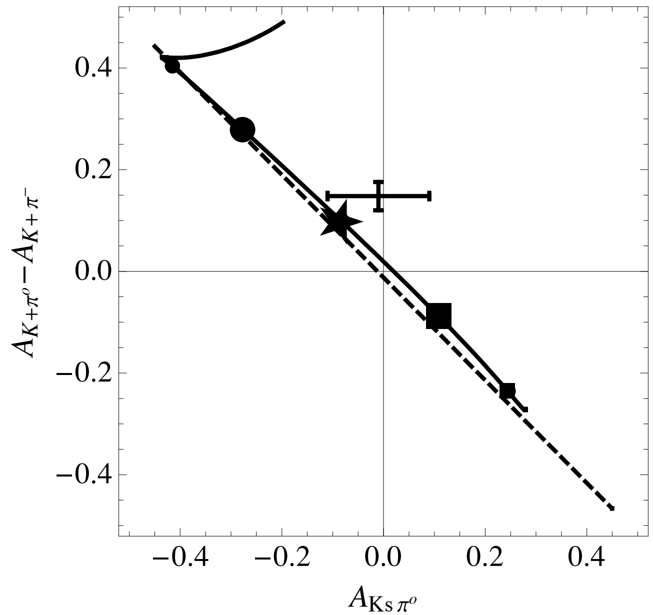
- can be attributed to a modified electroweak penguin



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

- Direct CP asymmetries $A_{\pi^0 K^+}$ and $A_{\pi^- K^+}$ differ by 5 σ, but interpretation less clear (could be large C/T in SM, or modified electroweak penguin, or other new physics)

  e.g. Belle collaboration, Nature, 2008

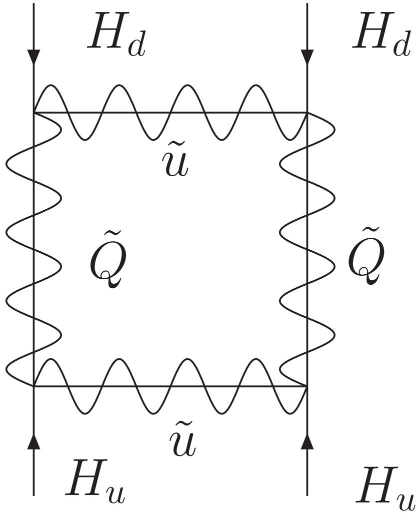


Conclusions

- SM CKM picture consistent with present data
- There is, however, room for new physics, particularly in $b \to s$ transitions
- Several interesting signals (CP violation in B_s mixing, CP asymmetries in $B \to \pi K$).
- could potentially turn into high-significance falsification of the SM at LHC
- there are many other promising modes I did not discuss ($B \to K^* \gamma$ - test magnetic penguin, $B \to K^* l^+ l^-$ - test Z penguin, ...) which may just as well show signs of BSM physics at LHC

BACKUP

Loop corrected Higgs potential



Sparticle loops generate most general quartics

break tree-level relation giving zero O(1) amplitude

previous calculations [Haber, Hempfling unpublished; Carena et al. ; ...?]
in the context of Higgs masses & mixings
here: complete computation including arbitrary MSSM flavour structure

$$V = m_{11}^2 H_d^\dagger H_d + m_{22}^2 H_u^\dagger H_u + \{m_{12}^2 H_u \cdot H_d + h.c.\}$$

$$+ \frac{\lambda_1}{2}(H_d^\dagger H_d)^2 + \frac{\lambda_2}{2}(H_u^\dagger H_u)^2 + \lambda_3 (H_u^\dagger H_u)(H_d^\dagger H_d) + \lambda_4 (H_u^\dagger H_d)(H_d^\dagger H_u)$$

$$+ \left\{ \frac{\lambda_5}{2} (H_u \cdot H_d)^2 - \lambda_6 (H_d^\dagger H_d)(H_u \cdot H_d) - \lambda_7 (H_u^\dagger H_u)(H_u \cdot H_d) + \text{h.c.} \right\}$$

allowed in a model II

not present in tree-level MSSM

$$\lambda_1^{(0)} = \lambda_2^{(0)} = -\lambda_3^{(0)} = (g^2 + g'^2)/4 \equiv \tilde{g}^2/4, \qquad \lambda_4^{(0)} = g^2/2$$

Symmetries at large tan (β)

Investigate systematically corrections to the $B - \bar{B}$ cancellations:
expand in loops, in 1/tanβ, in $y_{s(d)}/y_b$ [and in v/M_{SUSY}, via EFT construct]

- loop-corrected effective 2HDM Yukawa Lagrangian

$$\mathcal{L}_{\rm eff} \supset \kappa(\cos\beta h_u^{0*} - \sin\beta h_d^0)[y_b \bar{b}_R s_L + y_s \bar{s}_R b_L]$$

has approximate U(1) symmetry $h_d \to e^{i\alpha} h_d, b_R \to e^{i\alpha} b_R,$
exact for $\cos\beta = 0\,(\tan\beta = \infty),\ y_s = 0$ in down sector

- leading-order Higgs potential respects same symmetry at $\tan\beta = \infty$
even if electroweak symmetry broken : also constrains Higgs trees&loops

$$V_{\rm ltb}^{(2)} = \left[m_A^2 + \frac{\lambda_5^r}{2}v^2\right] H_d^\dagger H_d + \frac{\lambda_4}{2}v^2|h_d^-|^2 + \frac{\lambda_2}{2}v^2\phi_u^2$$

preserves U(1)

$$+\left[\frac{\lambda_5}{4}(h_d^{0*})^2 + \frac{\lambda_7}{\sqrt{2}}\phi_u h_d^{0*} + \text{h.c.}\right]v^2,$$

breaks U(1) but loop suppressed

All U(1) breaking in EFT proportional to one of the small parameters.

U(1) classification of mixing amplitudes

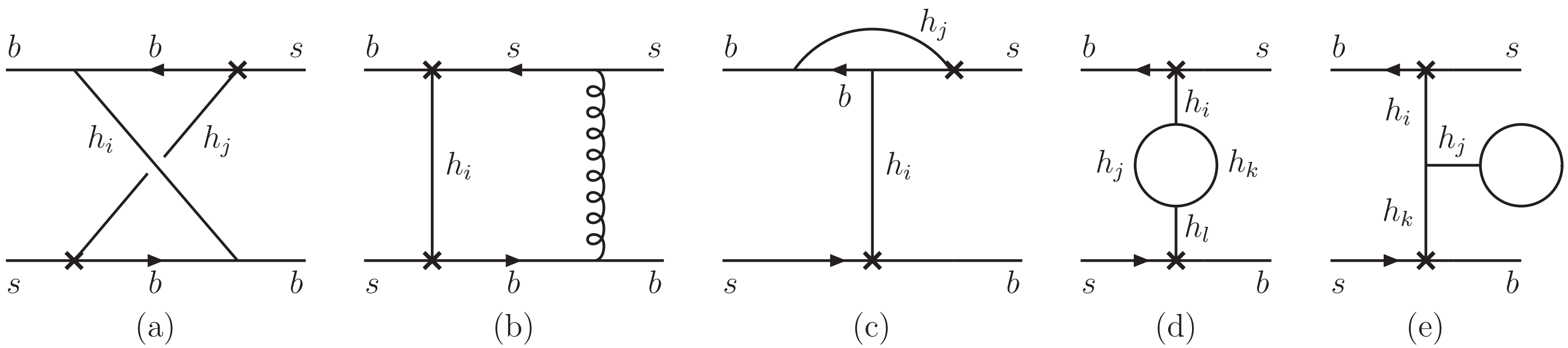
$$\mathcal{A}(B \to \bar{B}) = \sum_i C_i \langle \bar{B} | \mathcal{O}_i | B \rangle$$

operator(s)	U(1) charge	suppression of leading Higgs contribution		
$\mathcal{O}(\bar{b}_R s_L \bar{b}_R s_L)$	$\Delta Q = 2$	λ_5 / sparticle loop	new	formally of same size
$\mathcal{O}(\bar{b}_R s_L \bar{b}_L s_R)$	$\Delta Q = 1$	y_s	known	
$\mathcal{O}(\bar{b}_L s_L \bar{b}_L s_L)$ (SM)	$\Delta Q = 0$	2HDM loop (no scalar tree)	new	
$\mathcal{O}(\bar{b}_R s_R \bar{b}_R s_R)$	$\Delta Q = 2$	$(y_s)^2$ and 2HDM loop		tiny, ignore
$\mathcal{O}(\bar{b}_L s_R \bar{b}_L s_R)$	$\Delta Q = 0$ $[\Delta Q' = -2]$ [modified assignment]	$(y_s)^2$ and λ_5/sparticle loop		

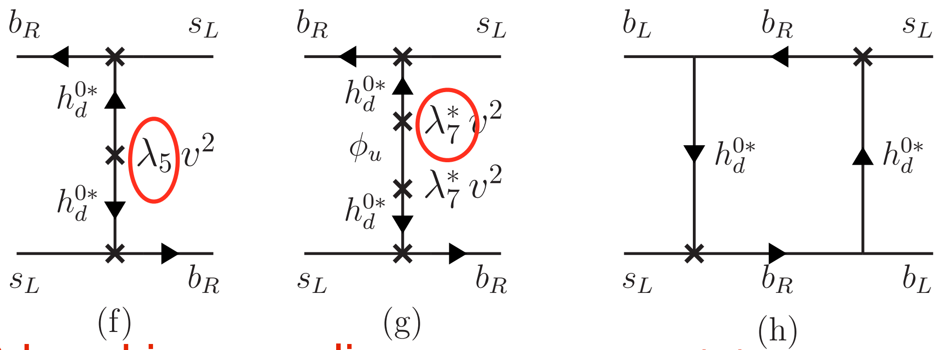
Effective loops

Large tan(beta) effective Lagrangian allows to compute in terms of complex fields and symmetry-breaking insertions

$$h_d = H_0 - iA_0 + \mathcal{O}(\text{loop};\ 1/\tan\beta)$$



small subset of diagrams that cancel due to the symmetry



only one loop diagram remains (3-loop in MSSM)

U(1) breaking couplings (sfermion-loop suppressed)

$$\longrightarrow \mathcal{O}(\bar{b}_R s_L \bar{b}_R s_L)$$

U(1) preserving Higgs loop

$$\longrightarrow \mathcal{O}(\bar{b}_L s_L \bar{b}_L s_L)$$

Some technicalities

- consistent tanβ matching 2HDM / MSSM possible (e.g. "$\tan\beta^{\overline{\rm DR}}$")
  freedom of 2HDM Higgs field basis: renormalize such
  that no tanβ-enhanced matching corrections

$$\begin{pmatrix} v_u^{\rm eff} \\ v_d^{\rm eff} \end{pmatrix} = \begin{pmatrix} 1+\delta Z_{uu}/2 & \delta Z_{ud}/2 \\ 0 & 1+\delta Z_{dd}/2 \end{pmatrix} \begin{pmatrix} v_u \\ v_d \end{pmatrix}$$

- v/M corrections

U(1)-breaking

$$Q^{(6)} = \frac{1}{M^2_{\rm SUSY}} (H_u^\dagger H_u)(\bar b_R H_u^\dagger Q_{2L}) \Longrightarrow \frac{2\sqrt{2}\, v_u^3}{M^2_{\rm SUSY}} \bar b_R s_L + \frac{2\, v_u^2}{M^2_{\rm SUSY}} (\bar b_R s_L h_u^0 + 2\, \bar b_R s_L h_u^{0*})$$

  would contribute, but loop-suppressed due to R-parity, not tanβ enh'd

- "Leading-order" cancellation exact for finite tanβ
  broken by leading log(v/$M_{\rm SUSY}$)s at O(1/tanβ^2):

$$\lambda_1(\mu)\lambda_2(\mu) - \lambda_3(\mu)^2 \neq 0$$

(a subleading effect)

Phenomenology

nonperturbative QCD effects

$$(\Delta M - \Delta M_{\rm SM})_{s/d} = \left\{ \begin{array}{c} -14\mathrm{ps}^{-1} \\ \sim 0\mathrm{ps}^{-1} \end{array} \right\} X \left[\frac{m_s}{0.06\mathrm{GeV}}\right] \left[\frac{m_b}{3\mathrm{GeV}}\right] \left[\frac{P_2^{\rm LR}}{2.56}\right]$$

known effect

$$+ \left\{ \begin{array}{c} 4.4\mathrm{ps}^{-1} \\ .13\mathrm{ps}^{-1} \end{array} \right\} X \left[\frac{M_W^2 \left(-\lambda_5 + \frac{\lambda_7^2}{\lambda_2}\right) 16\pi^2}{M_A^2}\right] \left[\frac{m_b}{3\mathrm{GeV}}\right]^2 \left[\frac{P_1^{\rm SLL}}{-1.06}\right]$$

new effect

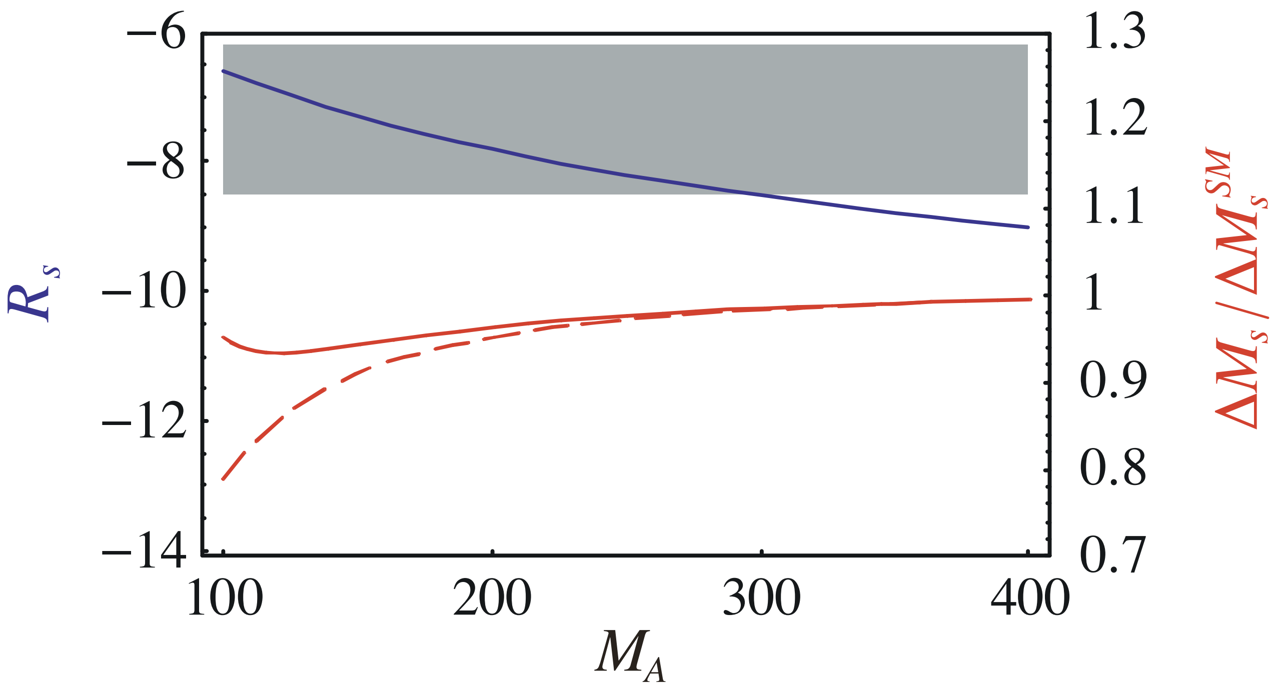
numerically small

$$X = \frac{m_t^4}{M_W^2 M_A^2} \frac{(\epsilon_Y 16\pi^2)^2}{(1+\tilde{\epsilon}_3 \tan\beta)^2 (1+\epsilon_0 \tan\beta)^2} \left[\frac{\tan\beta}{50}\right]^4$$

All new effects numerically somewhat (accidentally) suppressed

$$(\Delta M_s)_{\rm exp} = (17.77 \pm 0.12)\mathrm{ps}^{-1} \qquad (\Delta M_d)_{\rm exp} = (0.507 \pm 0.005)\mathrm{ps}^{-1}$$

$$\Delta M_s^{\rm SM} \approx 16 \ldots 27\,\mathrm{ps}^{-1}$$



[Gorbahn, SJ, Nierste, Trine, in progress]

excluding

including

new corrections

$\tan\beta = 40$

$a_{t,b} = 2000\,\mathrm{GeV}$,

$M_{\tilde{g}} = \mu = 1500\,\mathrm{GeV}$

$M_{\tilde{q}} = M_2 = 1000\,\mathrm{GeV}$

$M_1 = 500\,\mathrm{GeV}$

- $R_s = \log_{10}[BR(B_s \to \mu^+\mu^-)/\Delta M_{B_s}\,\mathrm{ps}]$
- $\Delta M_s / \Delta M_s^{\mathrm{SM}}$

main features - and correlations - of ΔM_{B_s} and $BR(B_s \to \mu^+\mu^-)$ are preserved