Plan of the lectures:

- An introduction to flavour physics
- Phenomenology of B and D decays
  - Time evolution and time-dependent asymmetries of $B_{d,s}$
  - CPV in B_s mixing
  - Time-dependent studies of "penguin modes"
  - CPV in charged B decays [measuring γ]
  - Rare B decays
  - Exclusive rare B decays
  - CP violation in the charm system
  - The puzzle of Δa_{CP}
- Flavour physics beyond the SM

▸ *Time evolution and time-dependent asymmetries of $B_{d,s}$*

$B_{d,s}$ mass eigenstates: $|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle \qquad |B_H\rangle = p|\overline{B}^0\rangle + q|B^0\rangle$

$$i \frac{d}{dt} \begin{bmatrix} B^0 \\ \overline{B}^0 \end{bmatrix} = [\, M - i\,\Gamma/2 \,] \begin{bmatrix} B^0 \\ \overline{B}^0 \end{bmatrix}$$

The time evolution can be described in full generality by means of a non-Hermitian Hamiltonian

▶ Time evolution and time-dependent asymmetries of $B_{d,s}$

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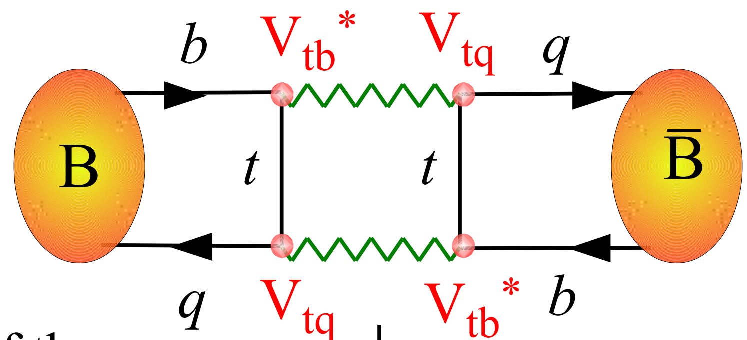
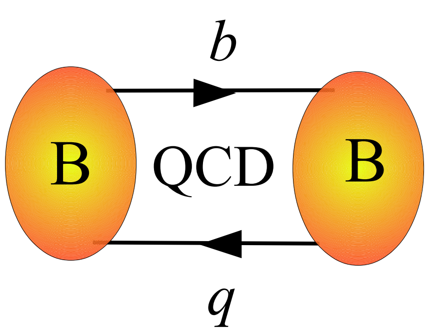
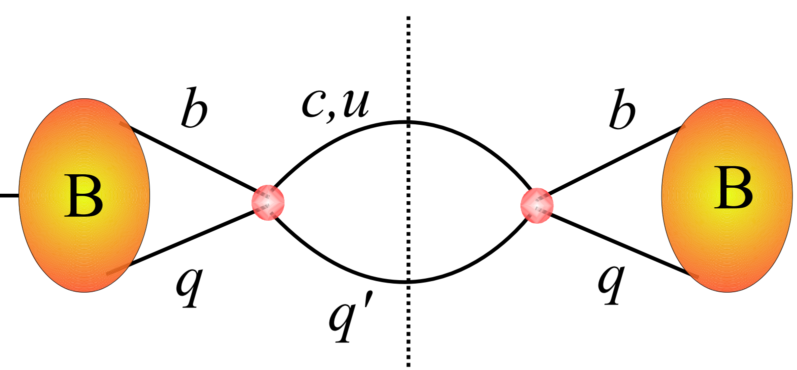


off-diagonal elements of the mass matrix

$M_{11} = M_{22}$





Time evolution and time-dependent asymmetries of $B_{d,s}$

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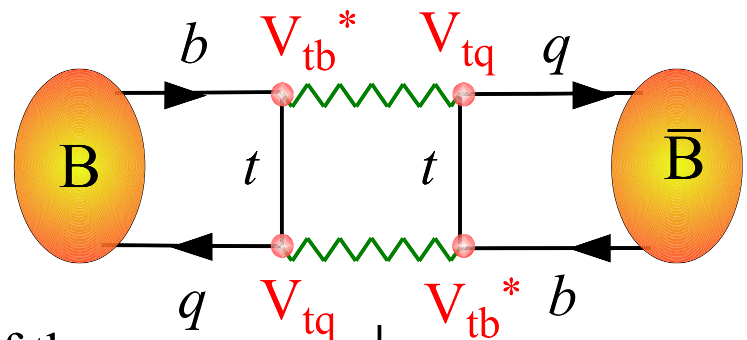

off-diagonal elements of the mass matrix

$$\frac{q}{p} = \arg(A_{box}) + O(10^{-3} \text{ due to } \Gamma)$$

theoretically very clean

$$\Delta m_B \propto |A_{box}| \times |\langle \bar{B}|\, (\bar{b}_L \gamma_\mu q_L)^2 \,|B\rangle|$$

O(10%-30%) theory error

Time evolution and time-dependent asymmetries of $B_{d,s}$

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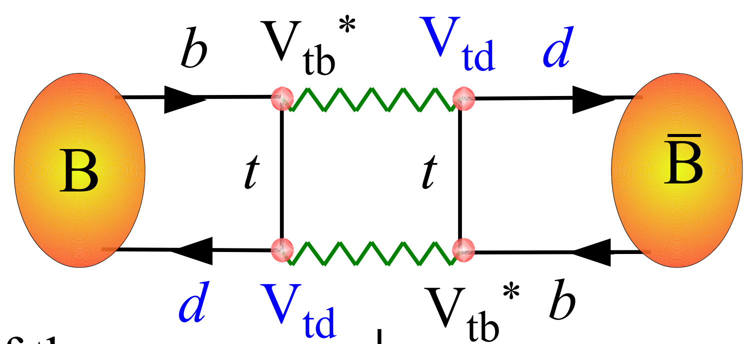

off-diagonal elements of the mass matrix

$$\frac{q}{p} = \frac{(V_{tb}^* V_{td})^2}{|(V_{tb} V_{td}^*)^2|} = e^{-2i\beta}$$

B_d

Large CPV phase
(in the standard CKM phase convention)

Time evolution and time-dependent asymmetries of $B_{d,s}$

$B_{d,s}$ mass eigenstates: $|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \qquad |B_H\rangle = p|\bar{B}^0\rangle + q|B^0\rangle$

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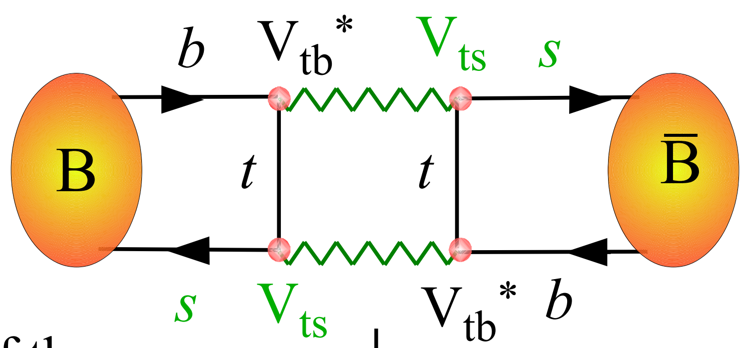

off-diagonal elements of the mass matrix

$$\frac{q}{p} = \frac{(V_{tb}^* V_{ts})^2}{|(V_{tb} V_{ts}^*)^2|} = \underbrace{1 + i\,O(\lambda^2)}_{e^{-2i\beta_s}}$$

B_s

Negligible CPV phase and large oscillaction freqency:

$$|\Delta m_{Bs}| \sim \lambda^{-2}\, |\Delta m_{Bd}|$$

$\sim 18\ \mathrm{ps}^{-1}$ $\qquad \sim 0.5\ \mathrm{ps}^{-1}$

The study of time-dependent decays of neutral B into CP eigenstates is a a marvelous tool to extract CPV phases in a clean way:

$$
\begin{tikzcd}[column sep=huge]
{[\ \mathrm{t{=}0}\ ]\quad B^0} \arrow[r, "q/p"] \arrow[rr, bend right, "A_f"'] & \bar{B}^0 \arrow[r, "\bar{A}_f"] & f \quad [\ \mathrm{t}\ ]
\end{tikzcd}
$$

$$\mathrm{CP}\,|f\rangle = \eta_f\,|f\rangle$$

$$\boxed{\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}}$$

Phase-convention independent quantity [$\rightarrow$ observable]

If $|\lambda_f| = 1$ (i.e. if A_f is dominated by a single weak phase) & $\Delta\Gamma = 0$ then :

$$\Gamma\left(B^0(t)\to f\right) \propto e^{-\Gamma_B t}\left[1-\eta_f\,\mathrm{Im}(\lambda_f)\,\sin\left(\Delta m_B t\right)\right]$$

$$\Gamma\left(\bar{B}^0(t)\to f\right) \propto e^{-\Gamma_B t}\left[1+\eta_f\,\mathrm{Im}(\lambda_f)\,\sin\left(\Delta m_B t\right)\right]$$

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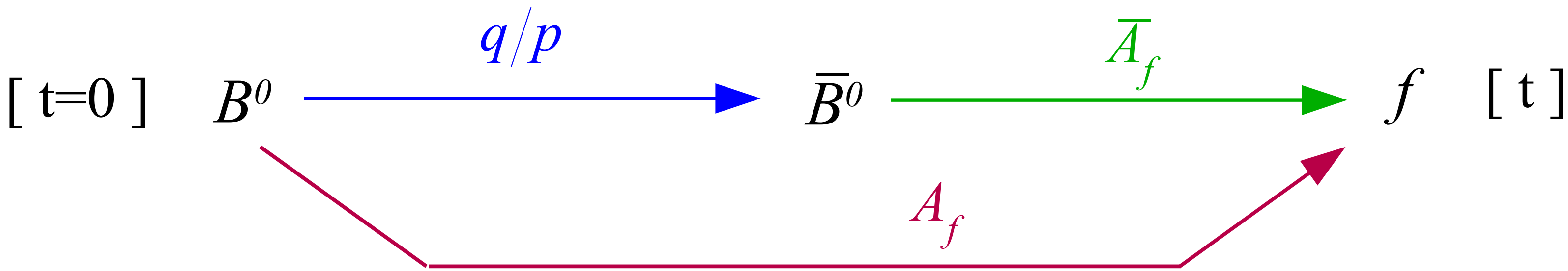

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Phase-convention independent quantity [$\rightarrow$ observable]

If $|\lambda_f| = 1$ (i.e. if A_f is dominated by a single weak phase) & $\Delta\Gamma \neq 0$ then :

$$\Gamma(B^0(t)\rightarrow f) \propto e^{-\Gamma_B t}\left[e^{\Delta\Gamma t/2}(1+c_f)+e^{-\Delta\Gamma t/2}(1-c_f)-\eta_f s_f \sin(\Delta m_B t)\right]$$

$s_f = \mathrm{Im}(\lambda_f)$ $c_f = \mathrm{Re}(\lambda_f)$

The study of time-dependent decays of neutral B into CP eigenstates is a a marvelous tool to extract CPV phases in a clean way:

$$[\,t=0\,]\quad B^0 \xrightarrow{q/p} \bar{B}^0 \xrightarrow{\bar{A}_f} f \quad [\,t\,]$$

$$B^0 \xrightarrow{A_f} f$$

$$\mathrm{CP}|f\rangle = \eta_f |f\rangle$$

$$\boxed{\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}}$$

Phase-convention independent quantity [$\rightarrow$ observable]

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Key points to successfully use this method:

$s_f = \mathrm{Im}(\lambda_f)$ $\quad c_f = \mathrm{Re}(\lambda_f)$

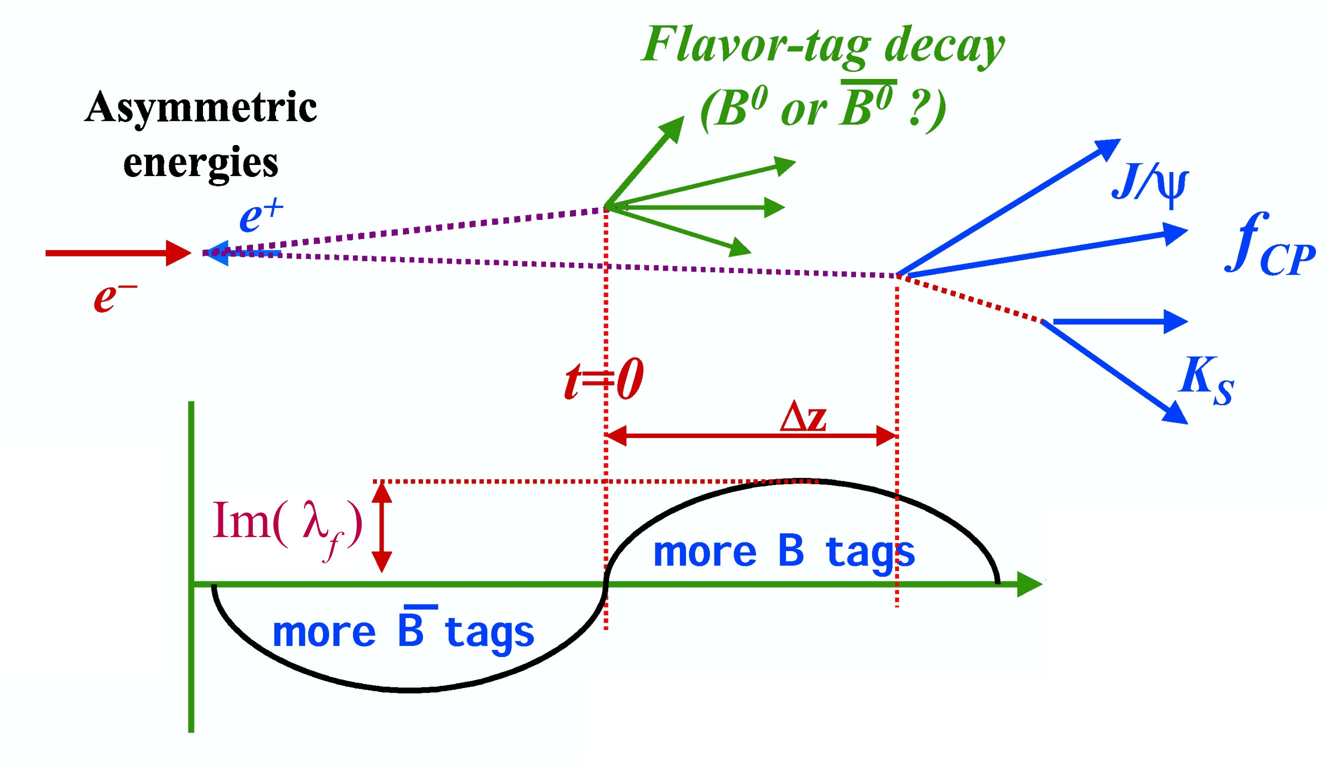
- [EXP]: flavour tagging and time-dependent resolution are essential ingredients
- [TH]: identify final states such that A_f is dominated by a single weak phase

A few words about flavour tagging: B factories vs. hadron colliders

B factories:

$e^+ + e^- \rightarrow \Psi(4S) \rightarrow B\,\bar{B}$

- clean environment [$\sigma(B)/\sigma(bkg) \sim 0.3$]
- coherent quantum state for neutral B
- low stat. [~ 10^8 B pairs / 100 fb^{-1}]
- no B_s [*unless running at higher energies with lower luminosity*]



A few words about flavour tagging: B factories vs. hadron colliders

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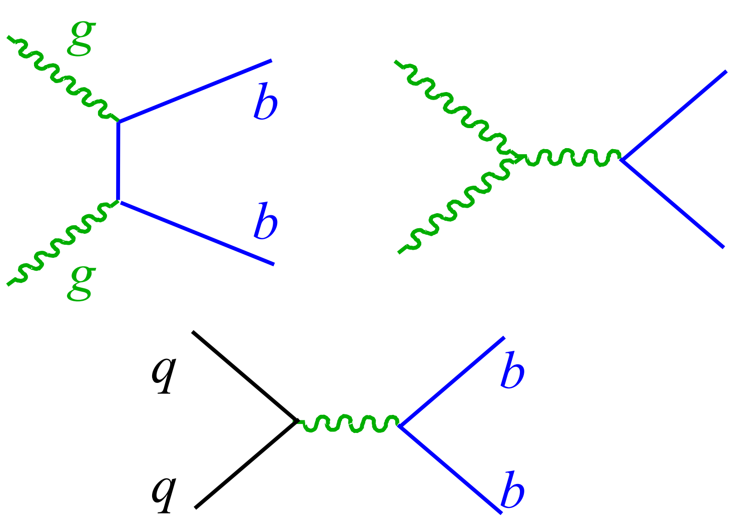
- coherent quantum state for neutral B

- low stat. [$\sim 10^8$ B pairs / 100 fb^{-1}]
- no B_s [*unless running at higher energies with lower luminosity*]

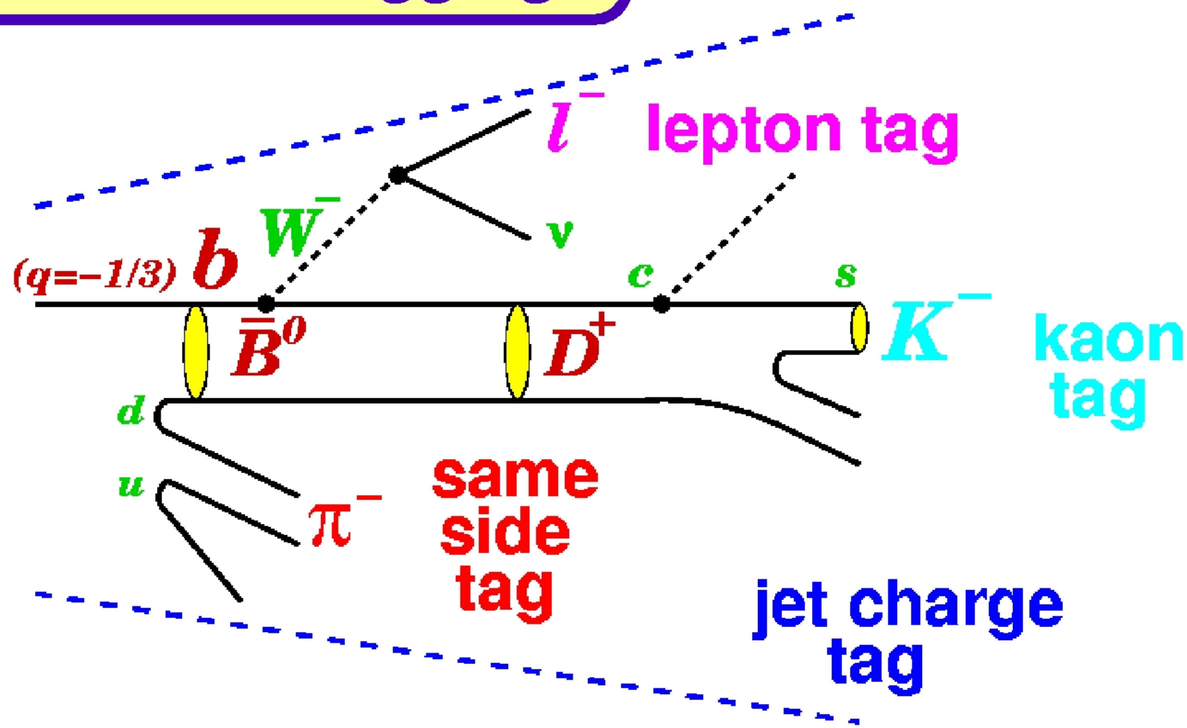
Hadron colliders:



- dirty environment [$\sigma(B)/\sigma(bkg) < 0.01$]
- incoherent quantum state

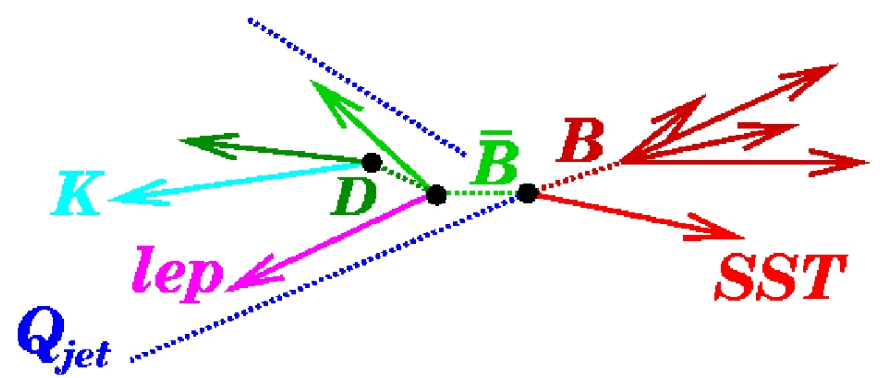
- high stat. [$\sim 10^{12}$ B pairs / 1 fb^{-1}]
- all hadrons with b-quarks produced

B Flavour Tagging



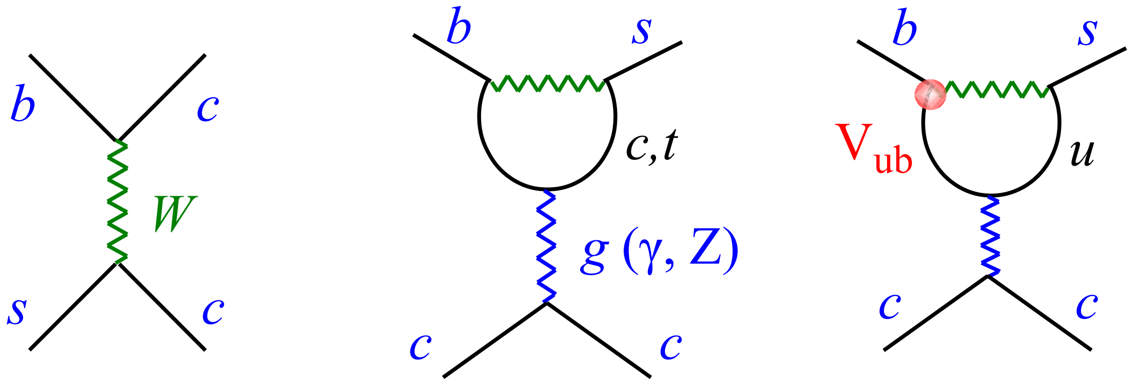
<u>**B flavour tagging methods:**</u>

- Opposite side lepton tag
- Jet charge tag
- Same side tag
- Opposite side kaon tag



When is A_f dominated by a single weak phase?

$|B_d\rangle \to |\psi K_S\rangle$ [$b+d \to c\bar{c}s+d$]



real $O(\lambda^2)$ real $O(\alpha_S\ \lambda^2)$ $O(\alpha_S\ \lambda^5)$

dominant amplitude pollution $\lesssim 1\ \%$

$\mathrm{Im}(\lambda_f) = \sin(2\beta)$

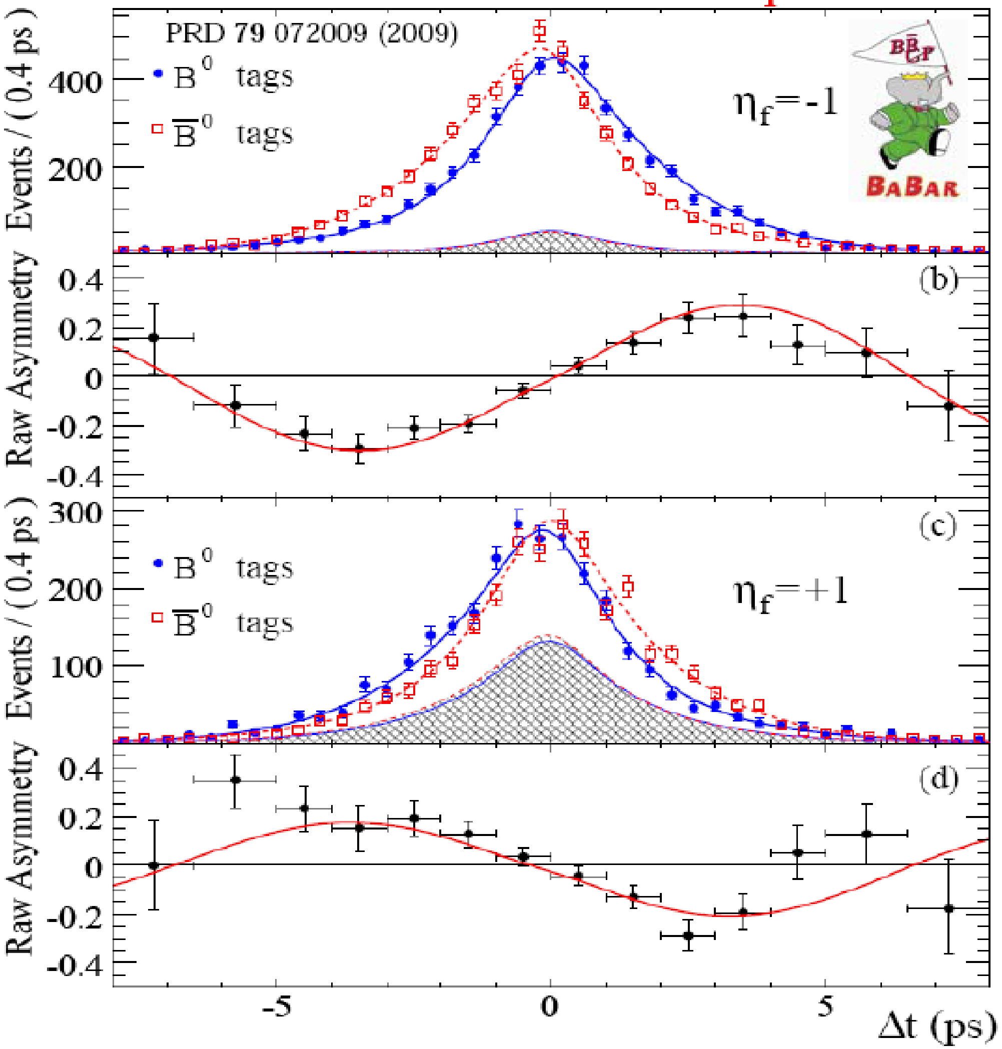
(from the mixing)

$$\boxed{V_{tb}^{*}V_{ts} = -V_{cb}^{*}V_{cs} - V_{ub}^{*}V_{us}}$$

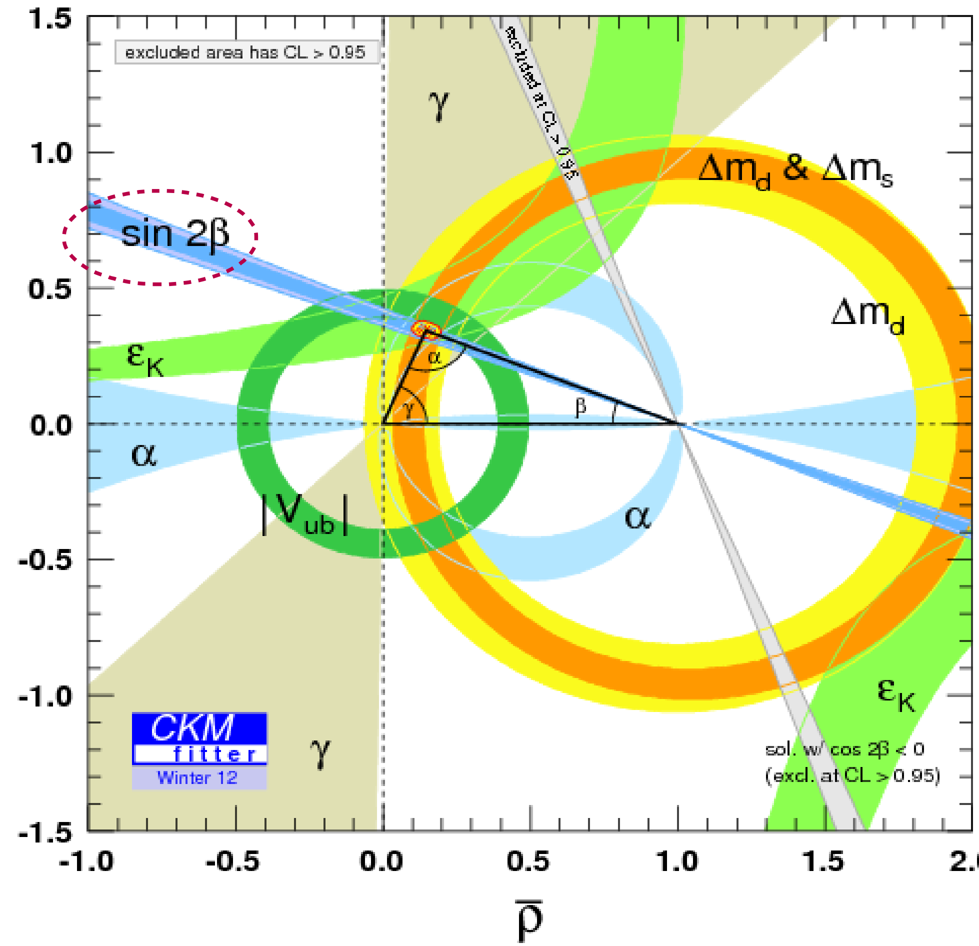
flat triangle

extremely precise constraint in the ρ−η plane ➡ *Golden channel* for B factories

BaBar's final result has been published:



A. Bevan, Lepton-Photon 2009

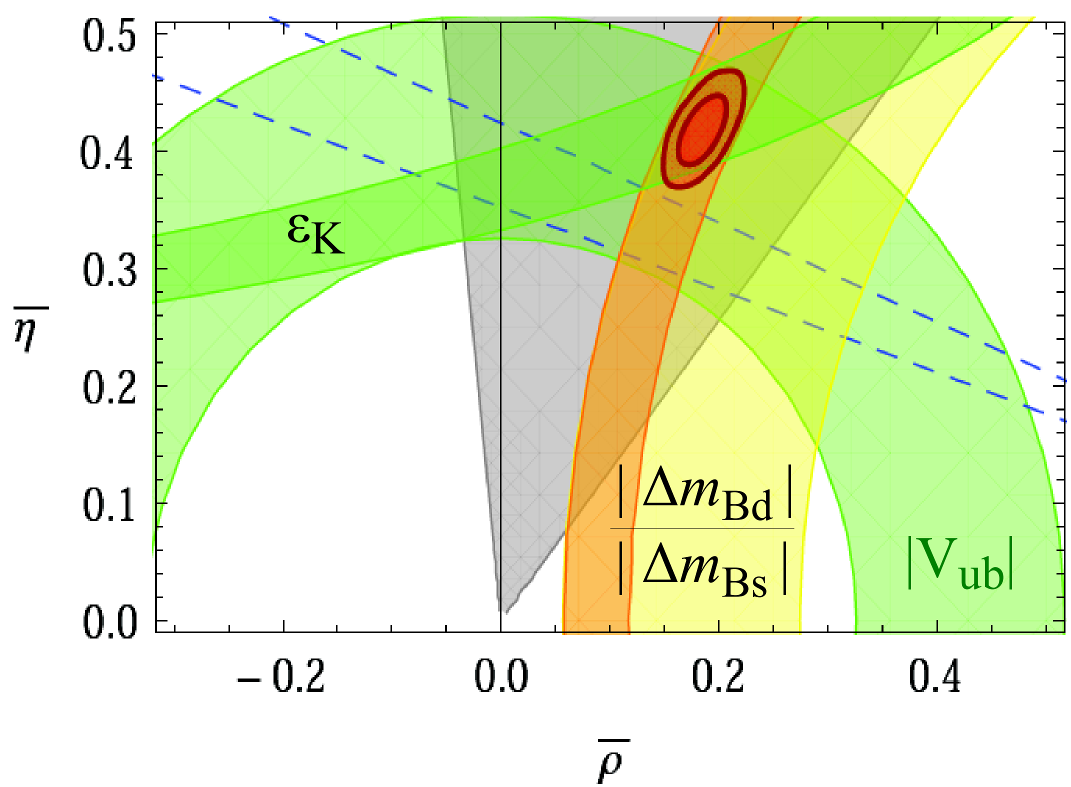


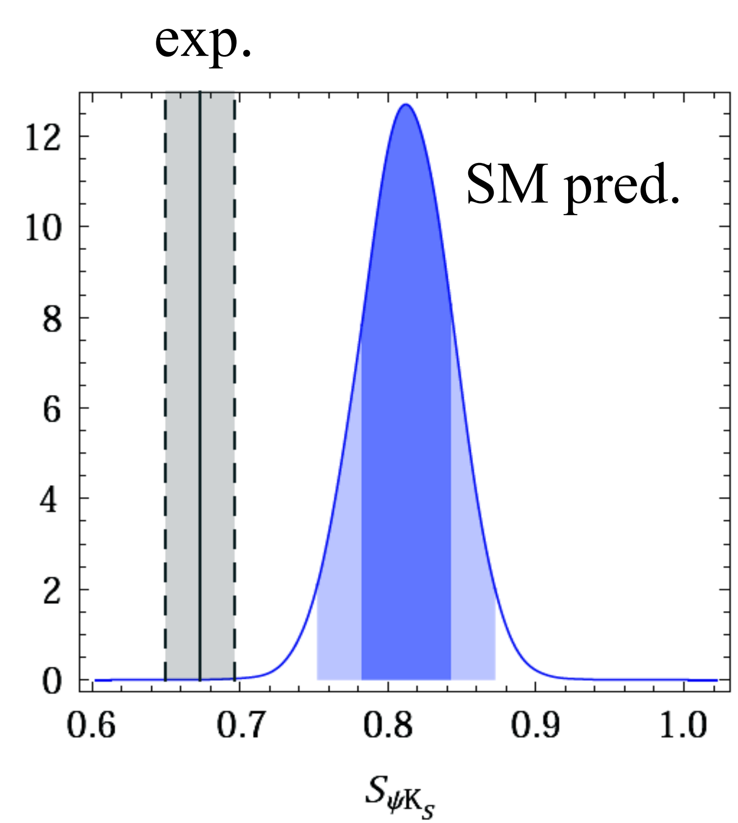
extremely precise
constraint in the ρ−η plane

N.B.: Despite the overall consistency of the CKM picture, looking more closely the agreement of the various constraints is not so good. At present there is a ~2σ tension between

- the value of ε_K (CPV in K^0 mixing) [*or* $|V_{ub}|$ *extracted from* $B\to\tau\nu$]
- the value of $\sin(2\beta)$ extracted from $B_d \to \psi K$

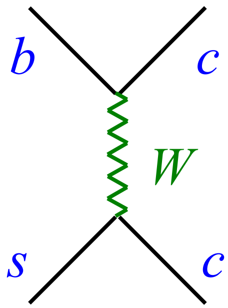
SM fit, no $S_{\psi K}$ (no B_d mixing phase):

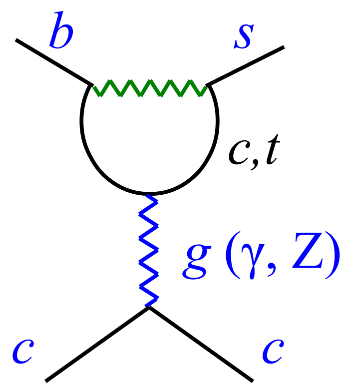


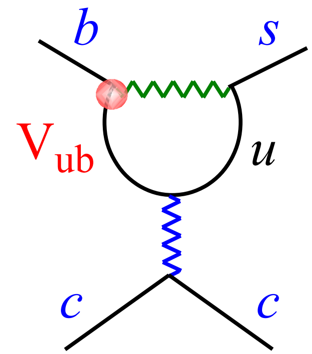


The golden channel for B_s mixing is

$$|B_s\rangle \rightarrow |\psi\,\phi\rangle \qquad [\ b+s \rightarrow c\bar{c}s+s\ ]$$







real $O(\lambda^2)$ real $O(\alpha_S\,\lambda^2)$ $O(\alpha_S\,\lambda^5)$

dominant amplitude pollution $\lesssim 1\ \%$

$$\mathrm{Im}(\lambda_f) = \sin(2\beta_s) = 0 + O(\lambda^2) \approx 0.04$$

It is not a constraint in the ρ-η plane
but is a very significant test of the SM

Golden channel for
hadron machines

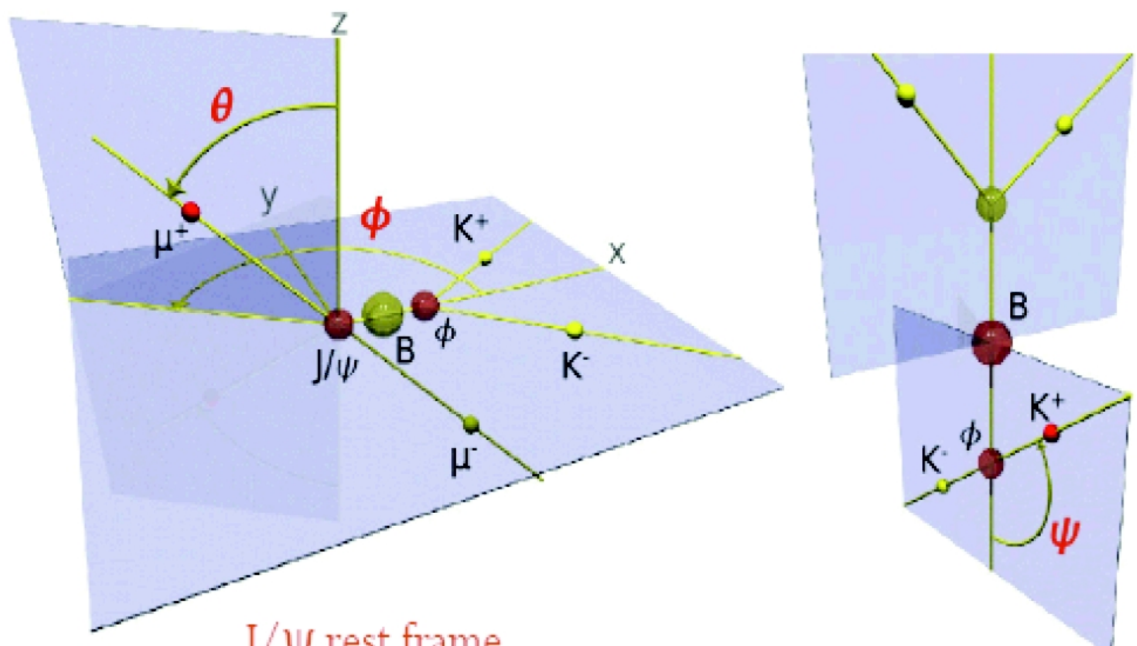
▸ Measuring CPV in B_s mixing

The extraction of the B_s mixing phase differs (and is somehow more challenging) with respect to the B_d case for three main reasons:

- $|\psi\, \phi\rangle$ is not a CP eigenstate and a complete angular analysis of the 4-body final state is needed in order to disentangle the amplitudes with different CP

- Since $\Delta\Gamma_s \neq 0$, a simultaneous fit of the width difference and the mixing phase is needed

- The flavour tag is much more involved at hadron machines



J/ψ rest frame

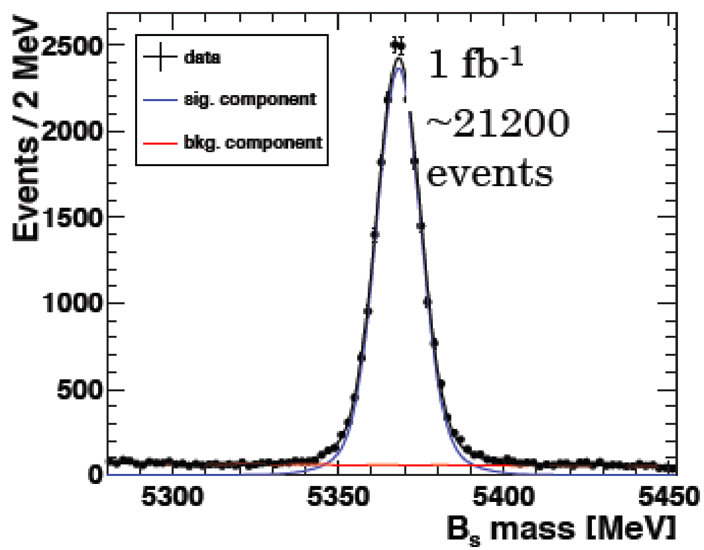
φ rest frame

$B_s \to J/\psi\varphi$: LHCb latest result [1 fb^{-1}]

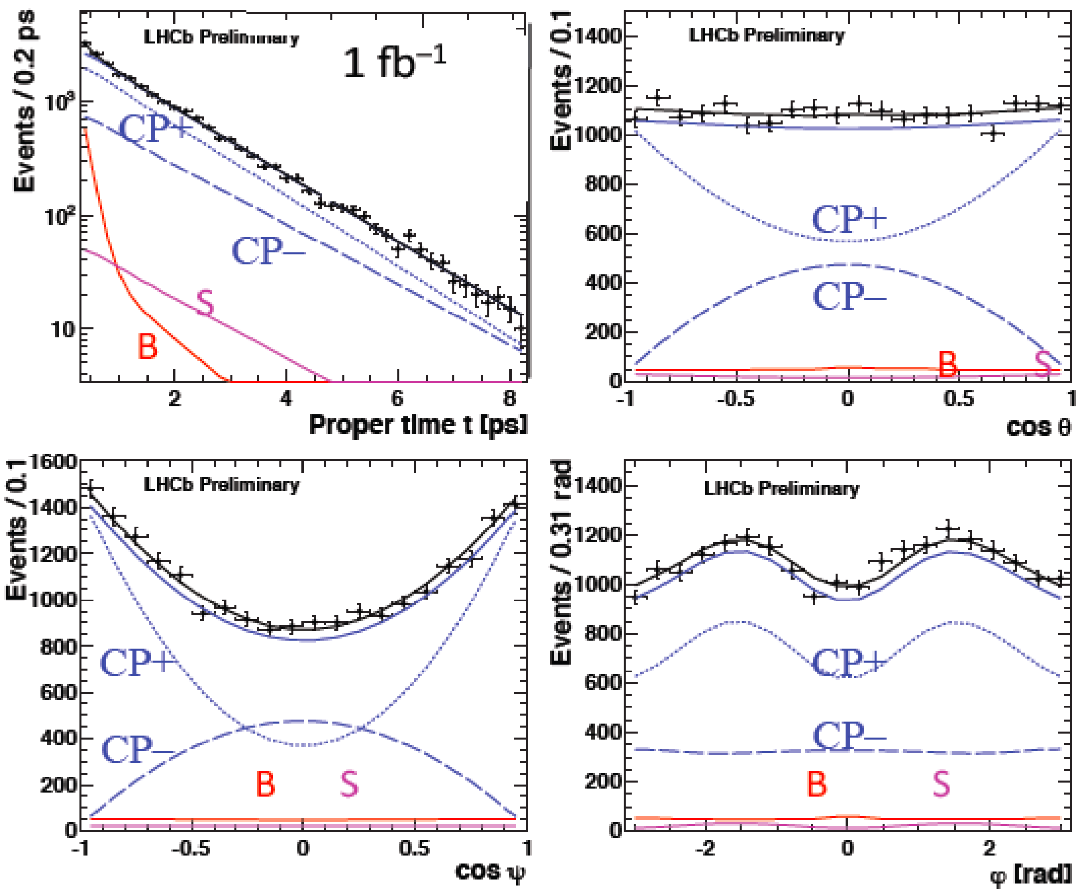
Full fit of tagged and untagged rates as a function of B_s mass, proper time and transversity angles:

LHCb-CONF-2012-002, 1/fb

$B_s \to J/\psi$ KK final state is a mixture of CP-even and CP-odd eigenstates so angular analysis needed



G. Lanfranchi, Blois 2012



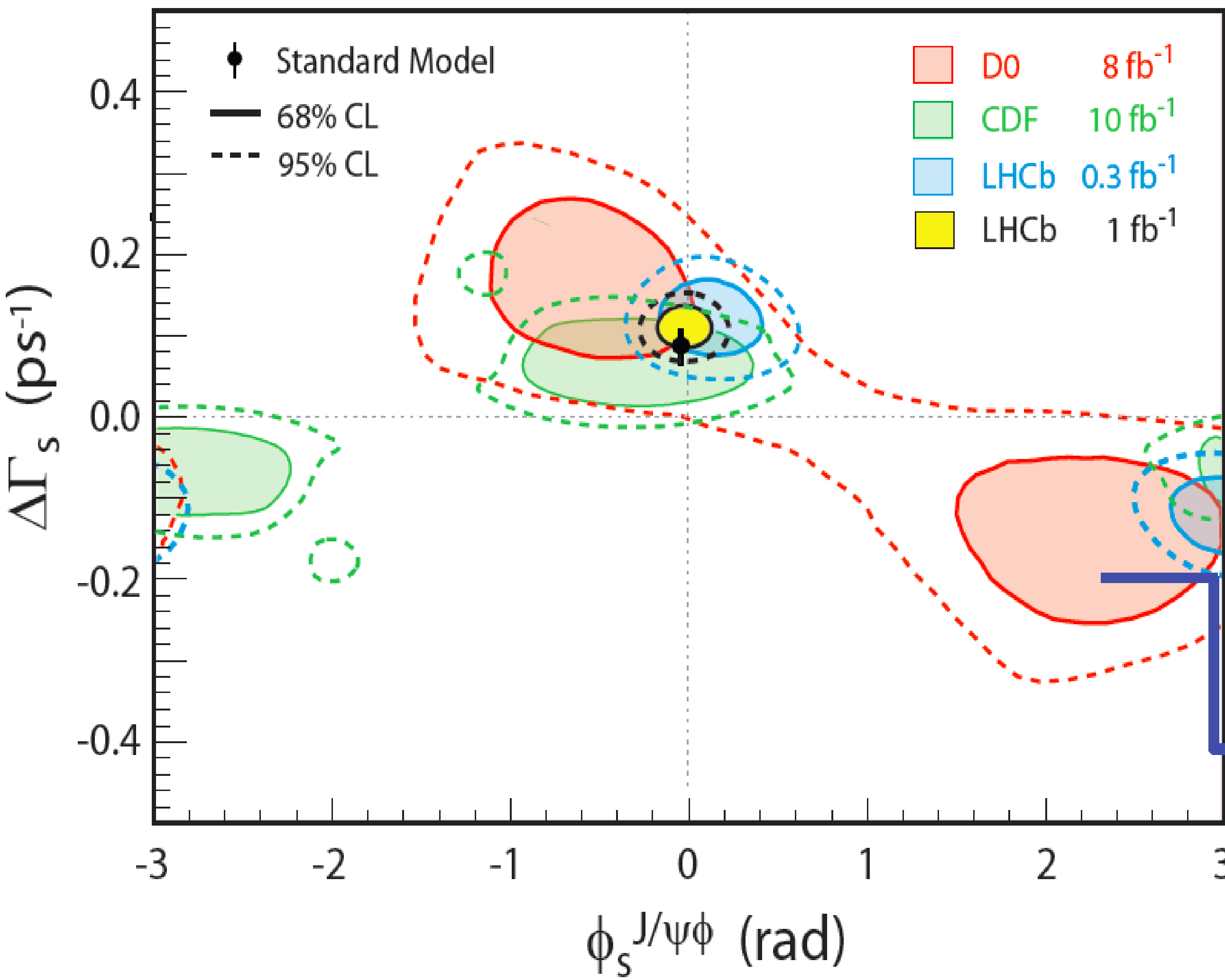
CP+ : $B_s \to J/\psi\varphi$ signal with CP-even final state

CP– : $B_s \to J/\psi\varphi$ signal with CP-odd final state

S : $B_s \to J/\psi KK$ signal with $J_{KK}= 0$ (S-wave, CP-odd)

B : combinatorial background

So far there is an excellent agreement with the SM:



PRD 85 (2012) 032006

CDF note 10778

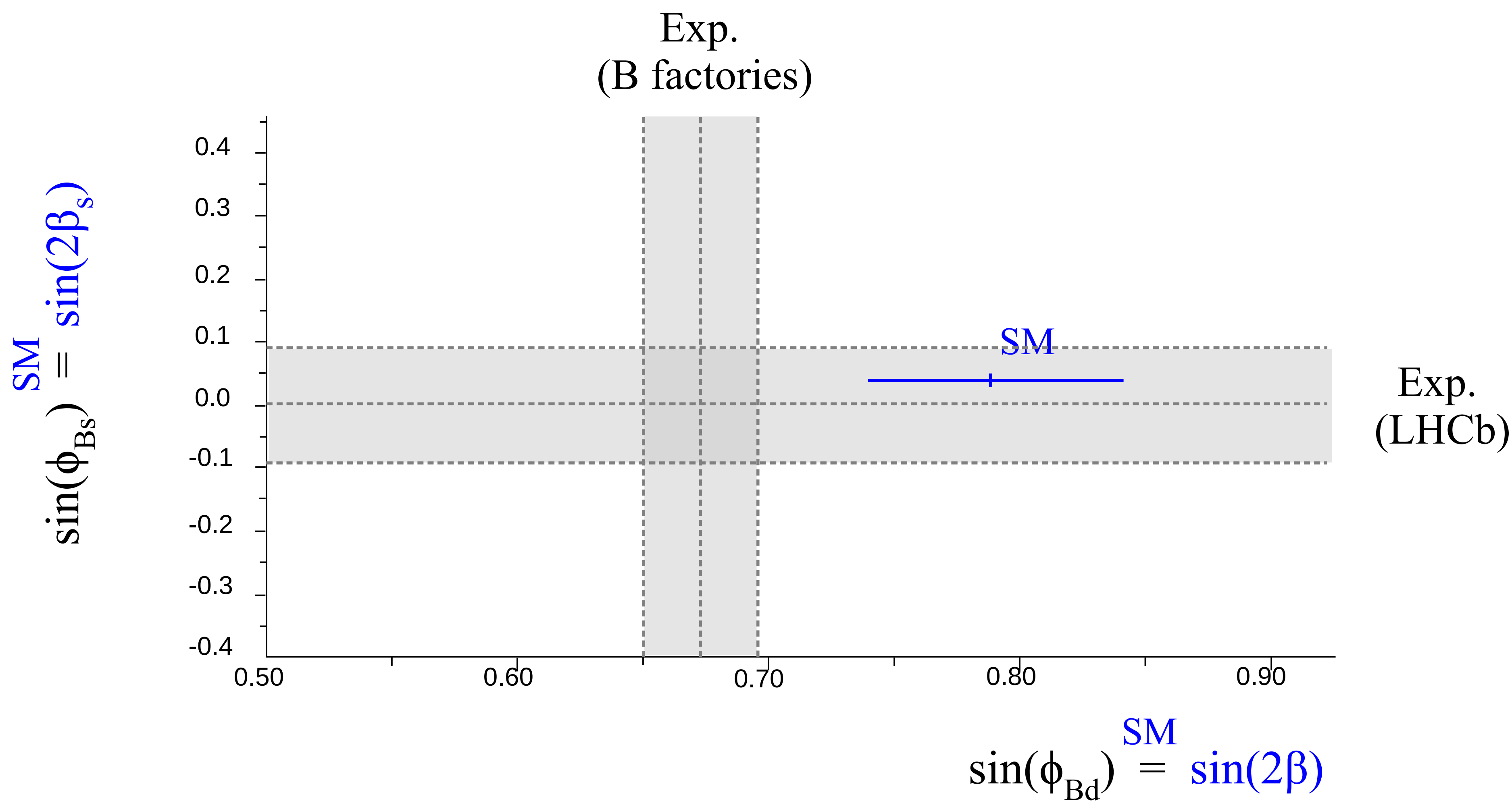
arXiv:1112.3183

LHCb-CONF-2012-002

Ambiguity removed by LHCb

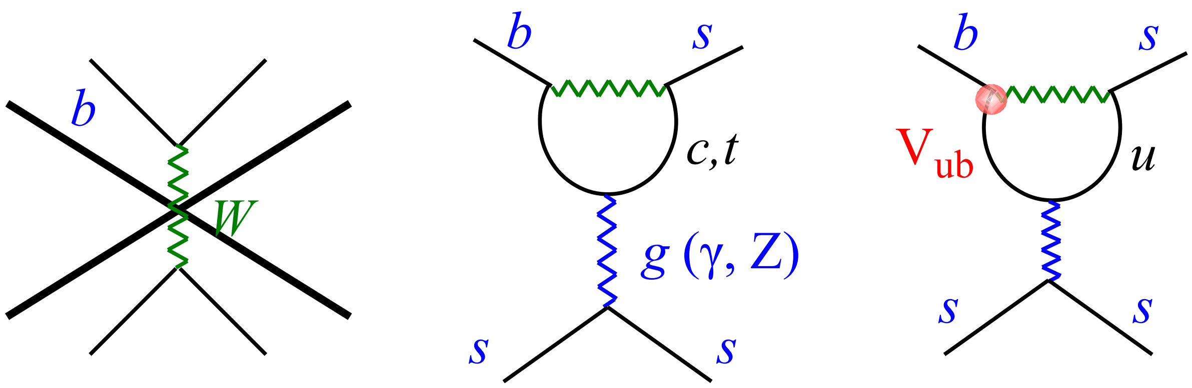
So far there is an excellent agreement with the SM.

But we cannot exclude surprises with more precise measurements, especially given the "tension" in the B_d case. *There is still a lot to learn...*



Time-dependent studies in "penguin" modes

E.g.: $|B_d\rangle \rightarrow |\phi K\rangle$ [$b+d \rightarrow s\bar{s}s+s$]



real $O(\alpha_S \lambda^2)$ dominant

$O(\alpha_S \lambda^5)$ pollution $< 10\ \%$

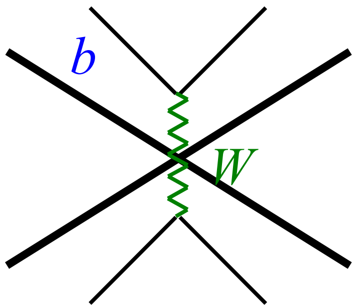
$$|\ \mathrm{Im}\,(\lambda_{\psi K})\ -\ \mathrm{Im}\,(\lambda_{\phi K})\ | \ <\ 0.1 \quad \text{(within SM)}$$

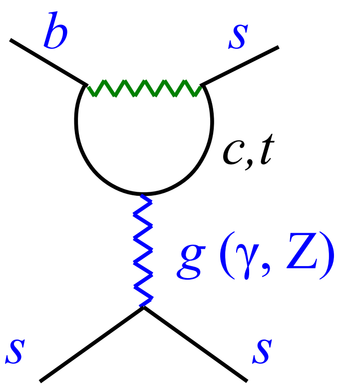
These modes are not interesting for precise determinations of CKM elements, neither for very precise tests of the SM, but are potentially sensitive to NP:

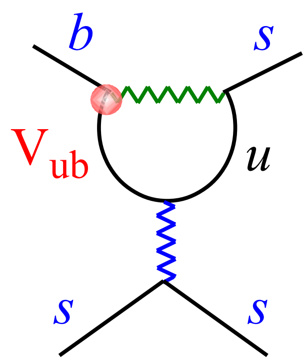
$$|\ \mathrm{Im}\,(\lambda_{\psi K})\ -\ \mathrm{Im}\,(\lambda_{\phi K})\ | \ \gg\ 0.1 \quad \Rightarrow \quad \text{New Physics !}$$

Time-dependent studies in "penguin" modes

E.g.: $|B_d\rangle \rightarrow |\phi\, K\rangle$ [$b+d \rightarrow s\bar{s}s+s$]







real $O(\alpha_S\, \lambda^2)$ dominant

$O(\alpha_S\, \lambda^5)$ pollution < 10 %

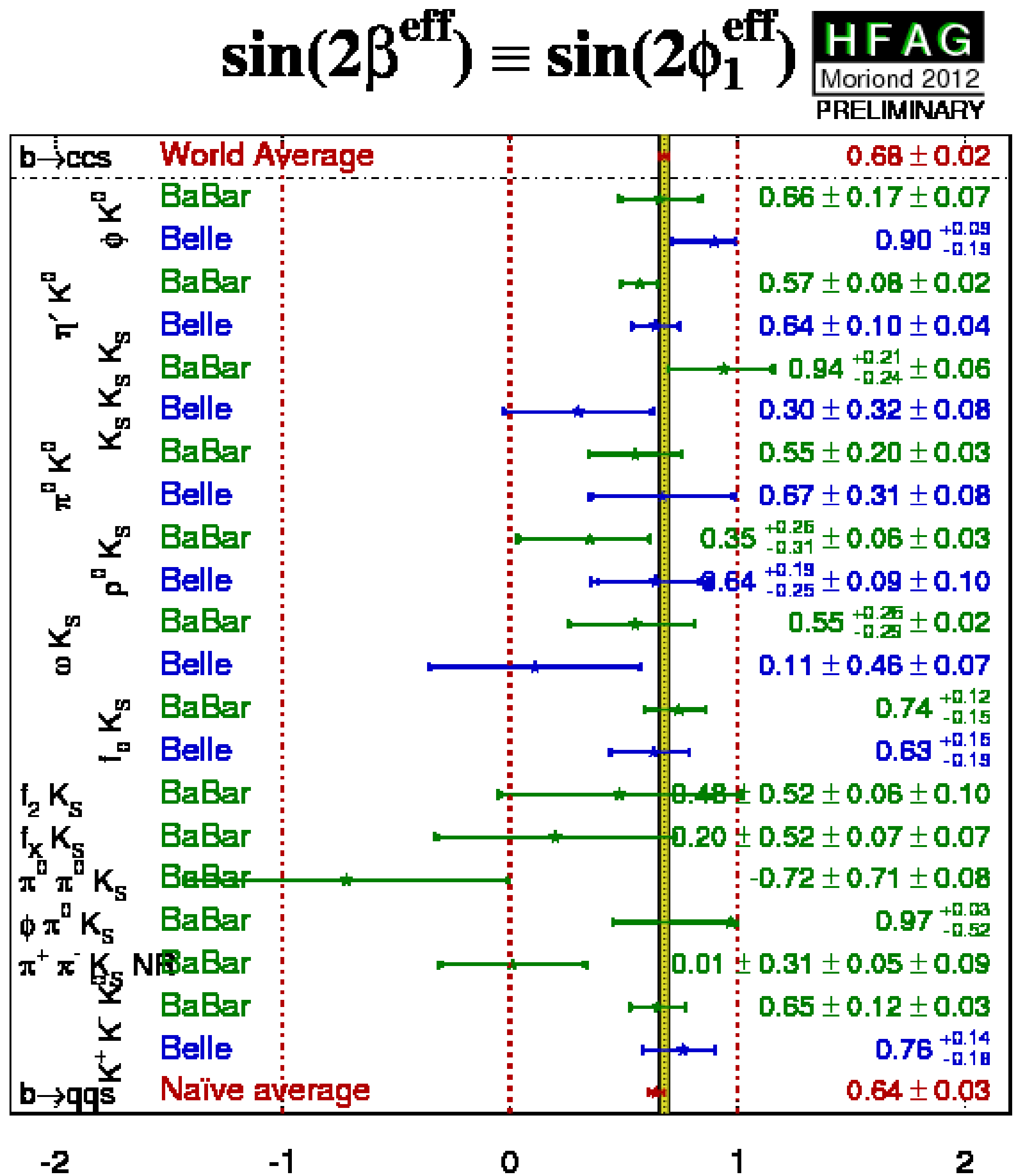
$$|\,\mathrm{Im}\,(\lambda_{\psi K})\; - \mathrm{Im}\,(\lambda_{\phi K})\,| \;<\; 0.1 \quad \text{(within SM)}$$

Unfortunately there are not many *pure penguin* channels of this type, moreover, even for pure penguin modes, it is very difficult to control the theory error below the ~ 10% level

Time-dependent studies in "penguin" modes

A few years ago there was a lot of (partly unjustified...), "excitement". Right now:

- The most clean observables show no significant deviations.
- In most cases the exp. precision is already below the level of the irreducible th. errors.



CPV in charged B decays

CP violation in charged modes is usually easy from the experimental point of view, but it is hard to be predicted/interpreted from the theoretical point of view [no control on non-perturbative hadronic amplitudes]

$$\Gamma(B^+ \to f^+) = |A_1 + e^{i\gamma} e^{i\delta} A_2|^2 \qquad \Gamma(B^- \to f^-) = |A_1 + e^{-i\gamma} e^{i\delta} A_2|^2$$

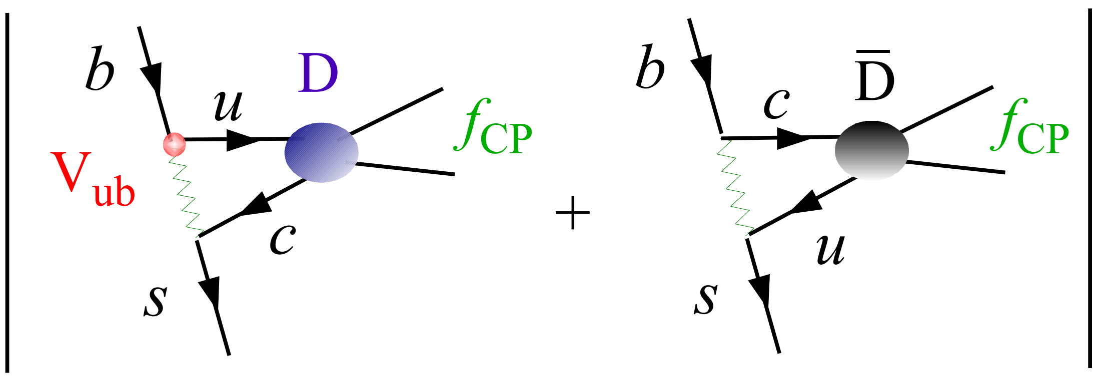
weak phase

strong phase

CPV in charged B decays

CP violation in charged modes is usually easy from the experimental point of view, but it is hard to be predicted/interpreted from the theoretical point of view [no control on non-perturbative hadronic amplitudes]

A notable exception are the $B^\pm \to D\,(\bar{D}) + K^\pm \to f_{CP} + K^\pm$ decays



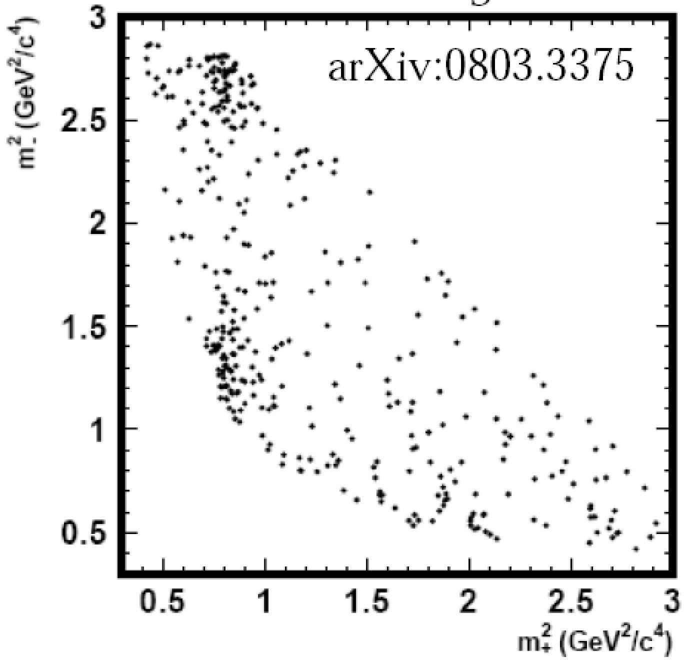
- Neutral D mixing weak phase measured to be small
- Relative weight and phase of the two strong amplitudes measured by looking at different CP eigenstates

Clean way to extract phase $\gamma = \arg(V_{ub})$:

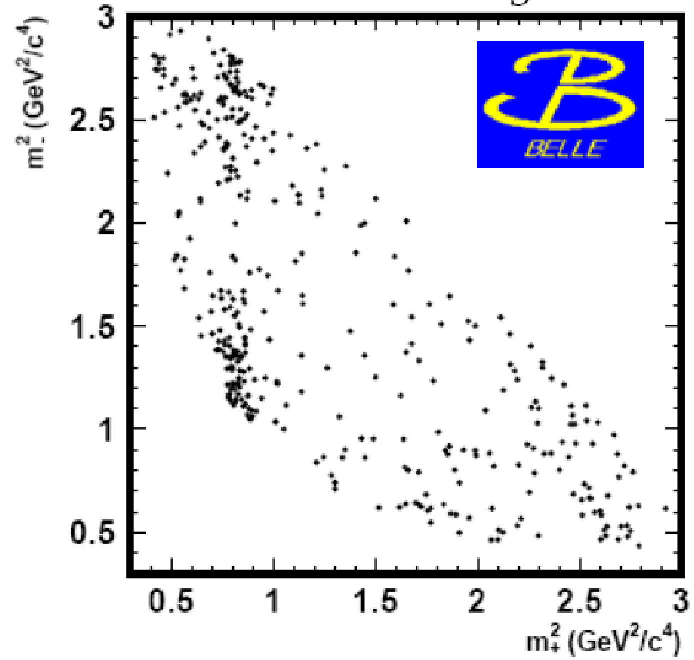
- Gronau-London-Wyler/Atwood-Dunietz-Soni methods: $B^\pm \to (K\pi,\ \pi\pi) + K^\pm$
- Giri-Grossman-Soffer-Zupan method: $B^\pm \to (K_S\,\pi^+\pi^-) + K^\pm$

full Dalitz-Plot analysis

$$B^- : \bar{D}^0 \to K^0_S \pi^+ \pi^-$$



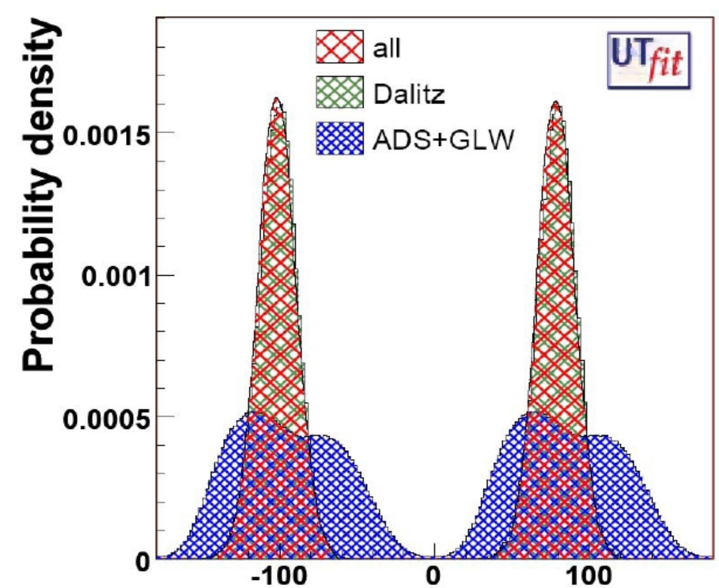
$$B^+ : \bar{D}^0 \to K^0_S \pi^+ \pi^-$$



Method shown to work at B factories:
no theoretical limitations,
only statistically limited

⬇

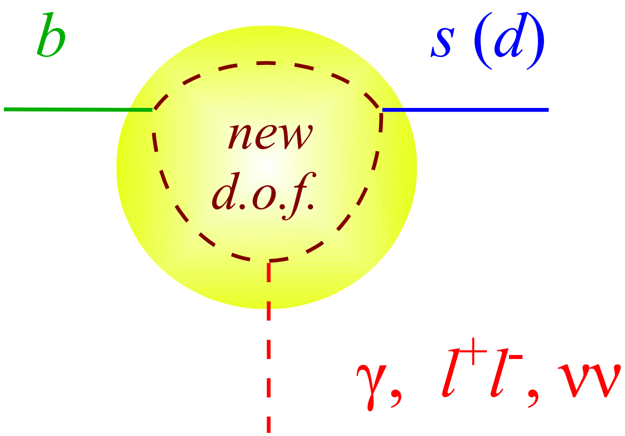
Substantial room for improvements
at LHCb



$$\gamma(UTFit) = (78 \pm 12)^\circ$$

Rare B decays

Similarly to $\Delta F=2$ mixings, rare decays mediated by *Flavour Changing Neutral Current* (FCNC) amplitudes are useful probes for *precision* tests of flavor dynamics beyond the SM



- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the partonic level: NNLO pert. calculations available for all the main B modes ($m_b \gg \Lambda_{QCD}$)

The ΔF=1 sector is, in principle, much more reach:

FLAVOUR COUPLING:

ELECTROWEAK STRUCTURE

	$b \to s$ $(\sim\lambda^2)$	$b \to d$ $(\sim\lambda^3)$	$s \to d$ $(\sim\lambda^5)$
ΔF=2 box	$(Q_L^b \Gamma Q_L^s)^2$	…	
ΔF=1 4-quark box	⋮		
gluon penguin			
γ penguin			
Z^0 penguin			
H^0 penguin			

The FCNC matrix:

each box correspond to an independent combination of dimension-6 SU(3)× SU(2)×U(1)-invariant operators

$$\mathscr{L}_{\rm eff} = \mathscr{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{\,d}$$

...although not all observables are theoretically very clean

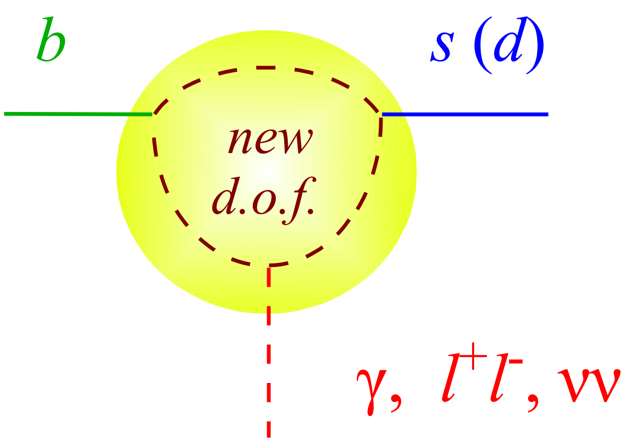
FLAVOUR COUPLING:

ELECTROWEAK STRUCTURE

	$b \to s\ (\sim\lambda^2)$	$b \to d\ (\sim\lambda^3)$	$s \to d\ (\sim\lambda^5)$
$\Delta F=2$ box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$	ΔM_K, ε_K
$\Delta F=1$ 4-quark box	$B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to \pi\pi$, $B_d \to \rho\pi$, ...	ε'/ε, $K \to 3\pi$, ...
gluon penguin	$B_d \to X_s \gamma$, $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d \gamma$, $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, ...
γ penguin	$B_d \to X_s l^+ l^-$, $B_d \to X_s \gamma$ $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d l^+ l^-$, $B_d \to X_d \gamma$ $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, ...
Z^0 penguin	$B_d \to X_s l^+ l^-$, $B_s \to \mu\mu$ $B_d \to \phi K$, $B_d \to K\pi$, ...	$B_d \to X_d l^+ l^-$, $B_d \to \mu\mu$ $B_d \to \pi\pi$, ...	ε'/ε, $K_L \to \pi^0 l^+ l^-$, $K \to \pi\nu\nu$, $K \to \mu\mu$, ...
H^0 penguin	$B_s \to \mu\mu$	$B_d \to \mu\mu$	$K_{L,S} \to \mu\mu$

Rare B decays

Similarly to $\Delta F=2$ mixings, rare decays mediated by *Flavour Changing Neutral Current* (FCNC) amplitudes are useful probes for *precision* tests of flavor dynamics beyond the SM



- No SM tree-level contribution
- Strong suppression within the SM because of CKM hierarchy
- Predicted with high precision within the SM at the partonic level: NNLO pert. calculations available for all the main B modes ($m_b \gg \Lambda_{QCD}$)

- The key point is the relation between patonic & hadronic worlds

Fully inclusive decays
usually good precision thanks to heavy-quark symmetry

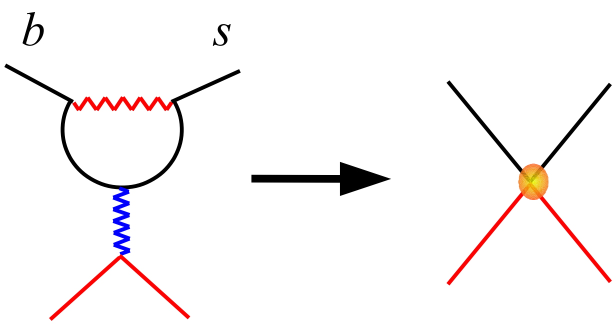
$$\Gamma(b \to s\gamma) \xrightarrow{m_b \to \infty} \Gamma(B \to X_s \gamma)$$

Exclusive decays
generally more difficult than inclusive, with some notable exceptions:

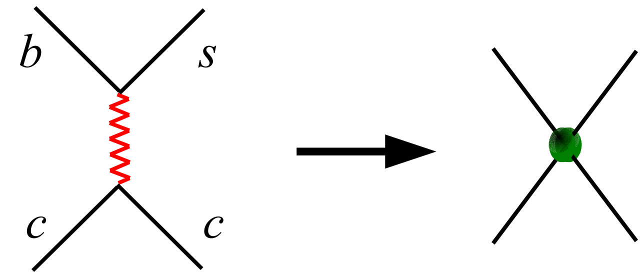
$$B \to (0, K, K^*) + \mu^-\mu^+$$

Three-step procedure to deal with the various scales of the problem:

1st step: Construction of a local eff. Hamiltonian at the electroweak scale integrating out all the heavy fields around m_W (including the heavy SM fields)



$$H_{\rm eff} = \Sigma_{\rm i}\, C_i(M_W)\, Q_i$$



FCNC operators:

$$Q_6 = (b\,s)_{V-A}(q\,q)_V \qquad \text{[Gluon penguins]}$$
$$\vdots$$
$$Q_{9V} = Q_f (b\,s)_{V-A}(f\,f)_V \qquad \text{[E.W. penguins]}$$
$$Q_{10A} = Q_f (b\,s)_{V-A}(f\,f)_A$$

Four-quark (tree-level) ops.:

$$Q_1 = (b\,s)_{V-A}(c\,c)_{V-A}$$
$$Q_2 = (b\,c)_{V-A}(c\,s)_{V-A}$$
$$\vdots$$

The interesting short-distance info is encoded in the $C_i(M_W)$ (*initial conditions*) of the Wilson coefficients of the FCNC operators

2nd step: Evolution of $H_{\rm eff}$ down to low scales using RGE

Penguin operators:

$$Q_6 = (b s)_{V-A}(q q)_V$$
$$\vdots$$
$$Q_{9V} = Q_f (b s)_{V-A}(f f)_V$$
$$Q_{10A} = Q_f (b s)_{V-A}(f f)_A$$

$$\boxed{H_{\rm eff} = \Sigma_i\, C_i(M_W)\, Q_i}$$
$$\downarrow$$
$$\boxed{H_{\rm eff} = \Sigma_i\, C_i(\mu \sim m_b)\, Q_i}$$

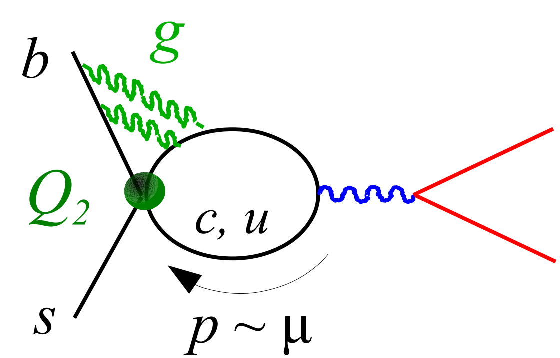
Four-quark (tree-level) ops.:

$$Q_1 = (b s)_{V-A}(c c)_{V-A}$$
$$Q_2 = (b c)_{V-A}(c s)_{V-A}$$
$$\vdots$$

Sources of long-distance effects:
[*dilution of the interesting short-distance info*]:

- Mixing of the four-quark Q_i into the FCNC Q_i
  [perturbative long-distance contribution]

e.g.:



- Small in the case of electroweak penguins (Q_{10A}) because of the power-like GIM mechanism [mixing parametrically suppressed by $O(m_c^2/m_t^2)$]
- Large for gluon penguins

3rd step: Evaluation of the hadronic matrix elements

$$A(B \to f) = \Sigma_i\, C_i(\mu)\ \langle f |\, Q_i\, | B \rangle\, (\mu) \qquad\qquad [\ \mu \sim m_b\ ]$$

- sensitivity to long-distances (cc threshold, m_c dependence,...)
- distinction between inclusive (OPE + $1/m_{b,c}$ expansion) and exclusive modes (hadronic form factors)
- irreducible large theory errors in the case of exclusive non-leptonic final states

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- irreducible large theory errors in the case of exclusive non-leptonic final states

Putting all the ingredients together in the case of $B \to X_s \gamma$ [best inclusive mode so far]:

NNLO SM th. estimate:

$$\mathcal{B}(B \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$$

[Misiak *et al.* '07]

To be compared with:

$$\mathcal{B}(B \to X_s \gamma) = (3.57 \pm 0.24) \times 10^{-4}$$

[present exp. W.A.]

A great success for the SM...

...and a great challenge for many of its extensions !

Exclusive rare B decays

The accuracy on *exclusive* FCNC *B* decays of the type $B \to H+(\gamma, l^+l^-)$ depends on the th. control of $B \to H$ *hadronic form factors* :

$$A(B \to f) = \sum_i C_i(\mu) \langle f | Q_i | B \rangle (\mu) \qquad \mu \sim m_b$$

- Several progress in the last few years [Light-cone sum rules, Heavy-quark expansion, Lattice] but typical errors still ~ 30%

The most difficult exclusive observables are the total branching ratios however, *f.f.* uncertainties can be considerably reduced in appropriate ratios or differential distributions, or considering very peculiar final states.

- Notable examples:

I. $\mathcal{B}(B_{s,d} \to \mu^+\mu^-)$

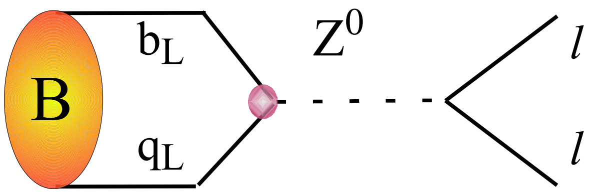
II. Differential distributions in $B \to K^* \mu^+\mu^-$

$B_{s,d} \to \mu^+\mu^-$

A special case among exclusive *B* decays:

- No vector-current contribution [th. error of the short-distance calculation ~ 1%]
- Hadronic matrix element relatively simple [f_B within the SM]

$$\langle 0 |\, \bar{b}\, \gamma_\mu \gamma_5\, u \,|\, B(p) \rangle = i f_B\, p_\mu$$



$B_{s,d} \to \mu^+\mu^-$

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$$\langle 0|\, \bar{b}\, \gamma_\mu \gamma_5\, u \;|\, B(p) \rangle = i\, f_B\, p_\mu$$

- Very clean signature
- <u>Strong sensitivity to scalar currents beyond the SM</u> [*Higgs penguin*]

  Sizable deviations possible in multi-Higgs models,
  even without new flavor structures [SUSY @ large tanβ]

<u>SM expectations:</u>

$B(B_s \to \mu\mu)_{SM} = 3.2(2)\times 10^{-9}$
$B(B_s \to \mu\mu)_{SM} = 1.0(1)\times 10^{-10}$

e channels suppressed by $(m_e/m_\mu)^2$
τ channels enhanced by $(m_\tau/m_\mu)^2$

$B_{s,d} \to \mu^+\mu^-$

A special case among exclusive *B* decays:

- No vector-current contribution [th. error of the short-distance calculation ~ 1%]
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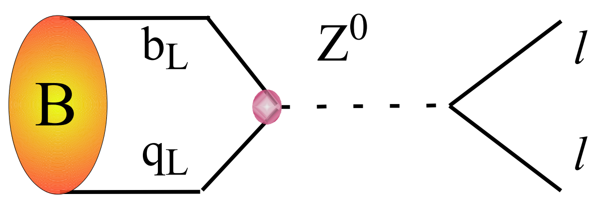
- Strong sensitivity to scalar currents beyond the SM [*Higgs penguin*]

Exercise [to understand why $B_{s,d} \to ll$ is interesting]:

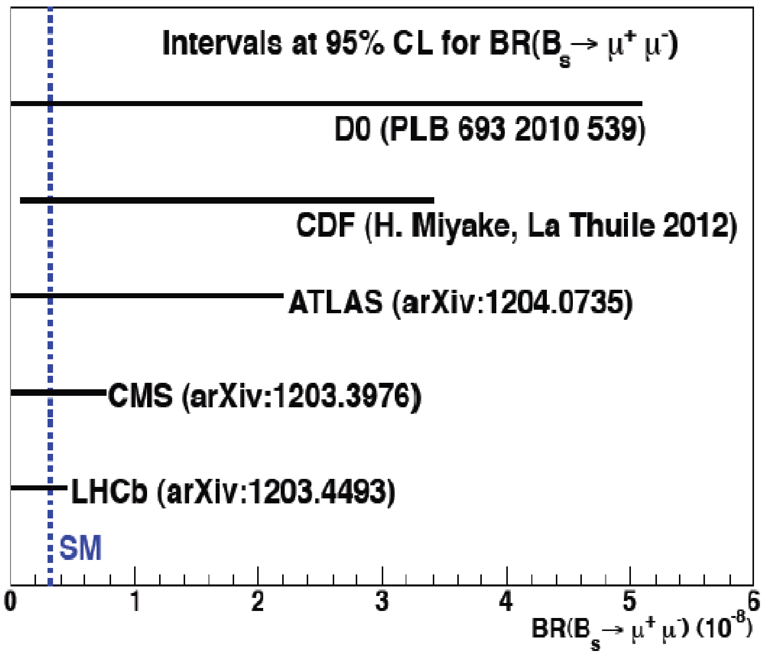
- Compute $B_u \to l\nu$ at the tree-level and compare it with the result obtained in the *gauge-less* limit
- Help: $\langle 0|\, \bar{b}\, \gamma_\mu \gamma_5\, u \;|\, B(p) \rangle \;=\; i\, f_B\, m_B^2/m_b$ & neglect m_B/M_W

$B_{s,d} \to \mu^+\mu^-$

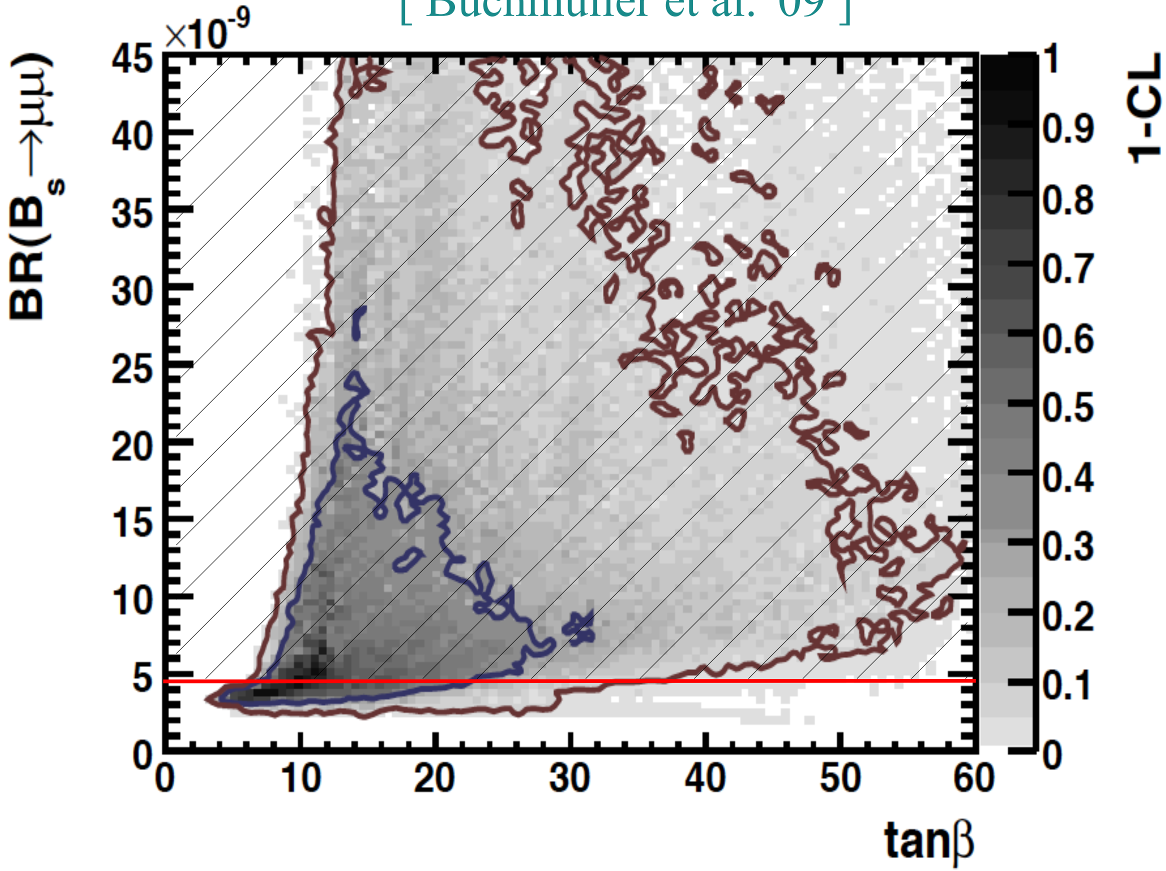


The amplitude is dominated by the longitudinal component of the Z (*or the contribution of the Goldstone bosons*) $\to$ particularly sensitive to possible modifications of the Higgs sector.

The recent exp. bounds:



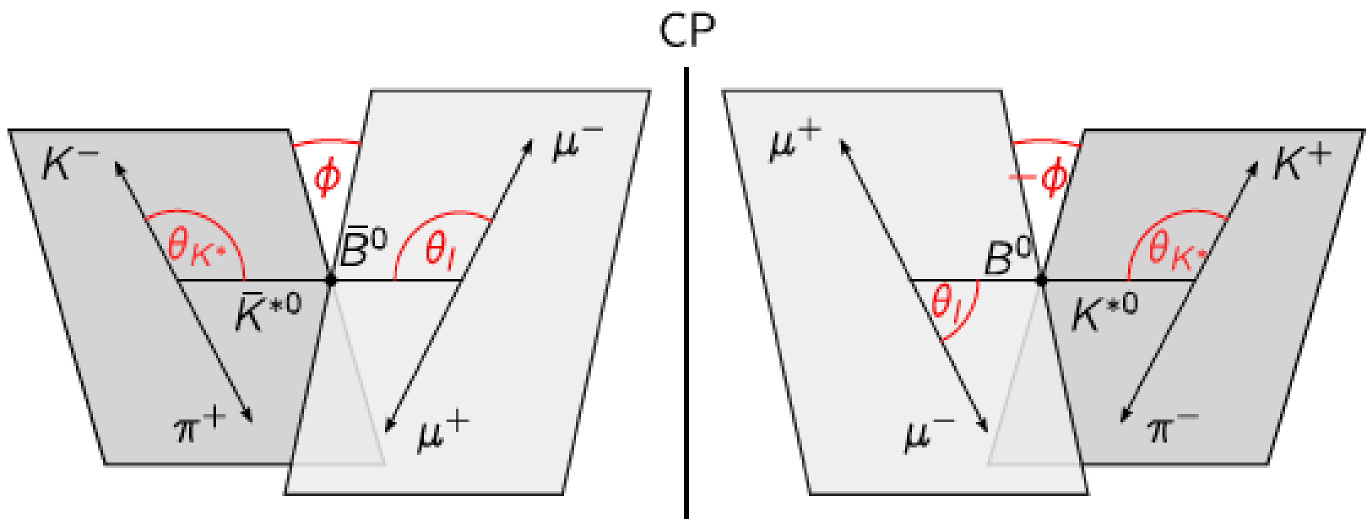
E.g.: MSSM with NUHM
[Buchmuller et al. '09]



Have strongly restricted the large tanβ scenario of minimal SUSY models

Differential distributions in $B \to K^* \mu^+\mu^-$

$B^0 \to K^{0*} (\to K^+\pi^-)\, \mu^+\mu^-$ $\qquad$ $\bar{B}^0 \to \bar{K}^{0*} (\to K^-\pi^+)\, \mu^+\mu^-$



$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} J(q^2, \theta_l, \theta_K, \phi)$$

$$\downarrow$$

$$J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l + J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$+ J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi + (J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l$$
$$+ J_7\sin 2\theta_K\sin\theta_l\sin\phi + J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi$$

- The angular distribution give access to several observables (12 indep. terms !)
- Self-tagging mode: easy to measure CP asymmetries

E.g.: The FB asymmetry

$$A_{FB} = \int \frac{d^2 B(B \to K^* \mu^+ \mu^-)}{ds\, d\cos\theta} sgn(\cos\theta) \quad \propto \quad \Re\left\{C_{10}^*\left[s C_9 + r(s) C_7\right]\right\}$$

θ = angle between μ^+ & B momenta in the dilepton rest frame

th. errror ~5 %

- Direct access to the *relative phases* of the C_i
- Proportional to C_{10} (→ interference of axial & vector currents → small QCD corrections)
- Particularly clean prediction: $A_{FB}(s) = 0$ for $s = q^2/m_b^2 \sim C_7/C_9$
- Hadronic uncertainties substantially decreased with a proper normalization.

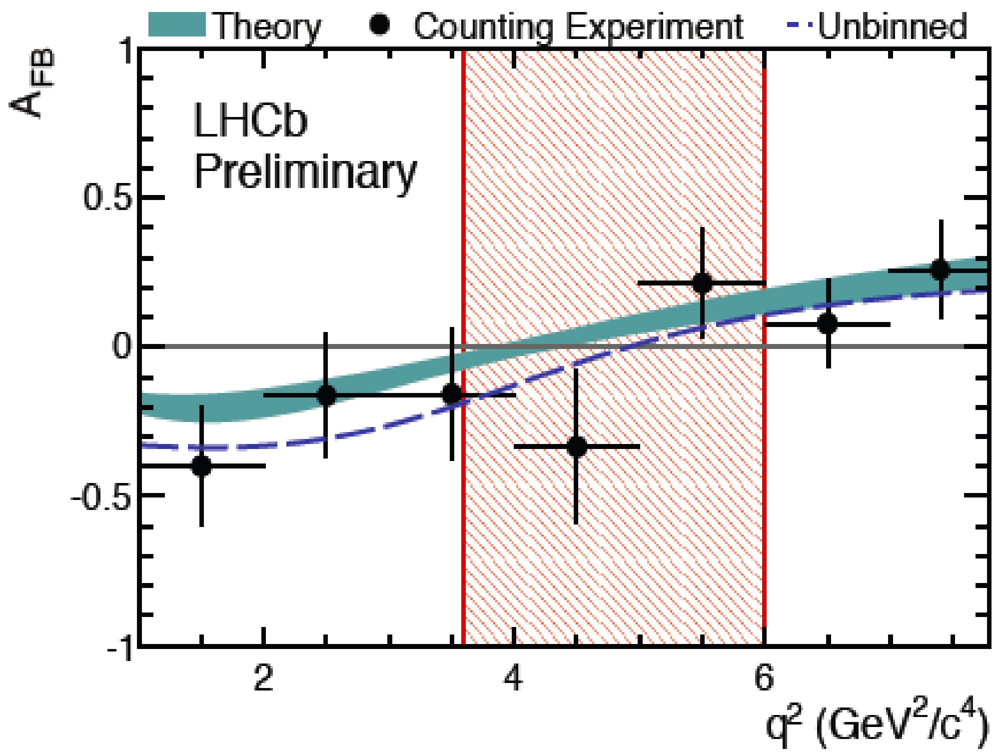
E.g.: The FB asymmetry

The clean prediction:

$A_{FB}(s) = 0$ for $s = q^2/m_b^2 \sim C_7/C_9$

Has recently been tested with good precision by LHCb, but there are many more observables that could be studied in this mode.

LHCb: LHCb-CONF-2012-008



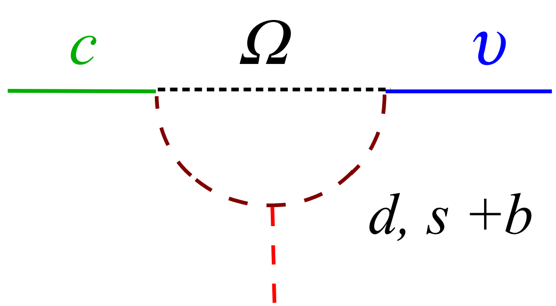
CP violation in the charm system

The physics of charm mixing and charm decays (c⟶u transitions) is quite different with respect to the $B_{s,d}$ (b⟶s,d) and K (s⟶d) systems.

No top-enhancement of FCNC amplitudes (both ΔF=2 & ΔF=1):

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

- In all CP-conserving amplitudes we can safely approximate the CKM matrix to a *2x2 real mixing matrix*, and long-distance contributions are largely dominant



- CP-violating amplitudes are not calculable with high-accuracy within the SM, but are expected to be very small because of the CKM hierarchy ⇒ possible interesting null-tests of the SM

CP violation in the charm system

The *news of the year* in flavour physics is the evidence of CP violation in two-body Cabibbo-suppressed charm decays $D \to KK, \pi\pi$ ($c \to u + s\bar{s}, d\bar{d}$) observed by LHCb & CDF:

$$\Delta a_{CP} = a_{CP}(K^+K^-) - a_{CP}(\pi^+\pi^-) = (0.67 \pm 0.16)\%$$

- Unambiguos evidence of direct CP violation:

$$a_{CP}^{(\mathrm{dir})} = \frac{\Gamma(D \to PP) - \Gamma(\bar{D} \to PP)}{\Gamma(D \to PP) + \Gamma(\bar{D} \to PP)}$$

- Totally unexpected, at least according to all the pre-LHCb predictions of the last 20 years: direct CPV in charm above 0.1% quoted as "clear signal of physics beyond the SM"...

▶ The puzzle of Δa_{CP}

Let's consider the relevant SM effective Hamiltonian ($|\Delta c|=1$, $|\Delta s|=0$) renormalized at a scale $m_c < \mu < m_b$

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} = \lambda_d\, \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s\, \mathcal{H}^{s}_{|\Delta c|=1} + \lambda_b\, \mathcal{H}^{\rm peng}_{|\Delta c|=1}$$

$$\mathcal{H}^{q}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C^q_i Q^s_i + \text{H.c.}\,,$$

$$Q^q_1 = (\bar u q)_{V-A}\,(\bar q c)_{V-A}$$

$$Q^q_2 = (\bar u_\alpha q_\beta)_{V-A}\,(\bar q_\beta c_\alpha)_{V-A}$$

O(1) Wilson coeff.

Standard basis of QCD penguin operators

Tiny coefficients for μ in the perturbative regime: $C_i \sim \alpha_s(\mu)/\pi$

$$\lambda_q = V^*_{cq} V_{uq} = \begin{cases} +\lambda + \ldots & (q=d) \\ -\lambda + \ldots & (q=s) \\ A^2\lambda^5 e^{-i\gamma} & (q=b) \end{cases}$$

$$\lambda_d + \lambda_s + \lambda_b = 0$$

The puzzle of Δa_{CP}

To a good approximation, for sufficiently heavy μ:

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} \approx \lambda_d\, \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s\, \mathcal{H}^{s}_{|\Delta c|=1}$$

The puzzle of Δa_{CP}

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$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} \approx \lambda_d \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s \mathcal{H}^{s}_{|\Delta c|=1}$$

$$= +\lambda_d \left(\mathcal{H}^{d}_{|\Delta c|=1} - \mathcal{H}^{s}_{|\Delta c|=1} \right) - \lambda_b \, \mathcal{H}^{s}_{|\Delta c|=1}$$

$$= -\lambda_s \left(\mathcal{H}^{d}_{|\Delta c|=1} - \mathcal{H}^{s}_{|\Delta c|=1} \right) - \lambda_b \, \mathcal{H}^{d}_{|\Delta c|=1}$$

- CKM-suppressed
- No tree-level in K^+K^- or $\pi^+\pi^-$
- *Penguin contractions allowed*

- Cabibbo-leading structure
- Tree-level amplitude in both K^+K^- and $\pi^+\pi^-$
- No penguin contractions in the SU(3) limit

The puzzle of Δa_{CP}

To a good approximation, for sufficiently heavy μ:

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} \approx \lambda_d \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s \mathcal{H}^{s}_{|\Delta c|=1}$$

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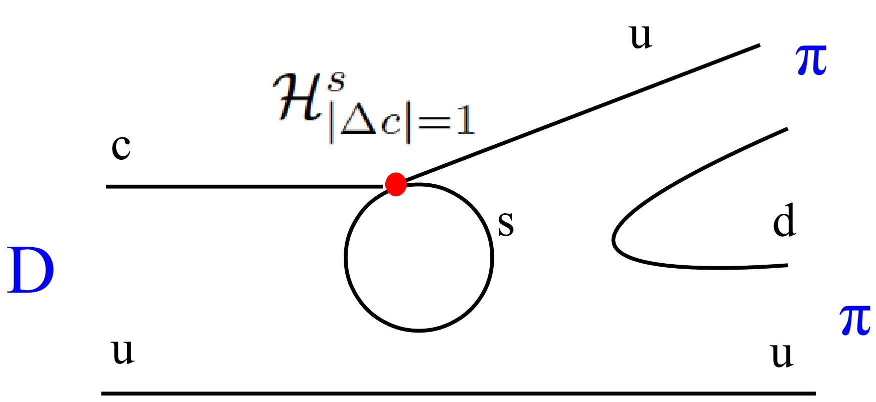
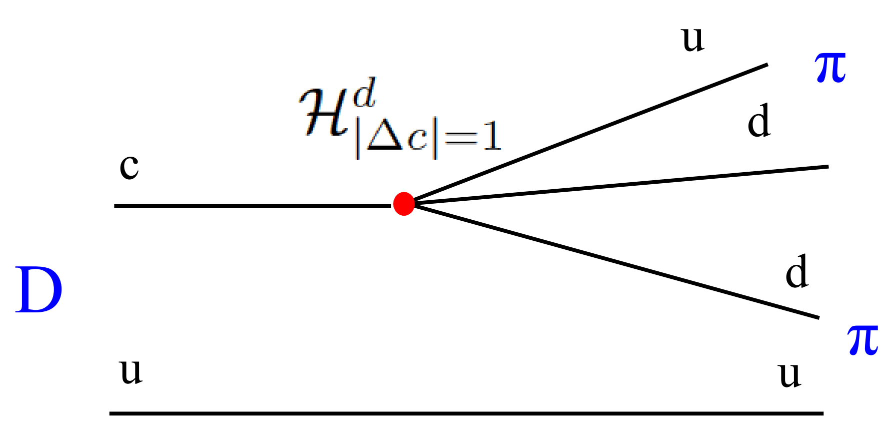


"Penguin contractions"



"Tree-level topologies"

The puzzle of Δa_{CP}

The observed Δa_{CP} is large compared to its "natural" SM expectation, but is not large enough, compared to SM uncertainties, to be considered a clear signal of NP:

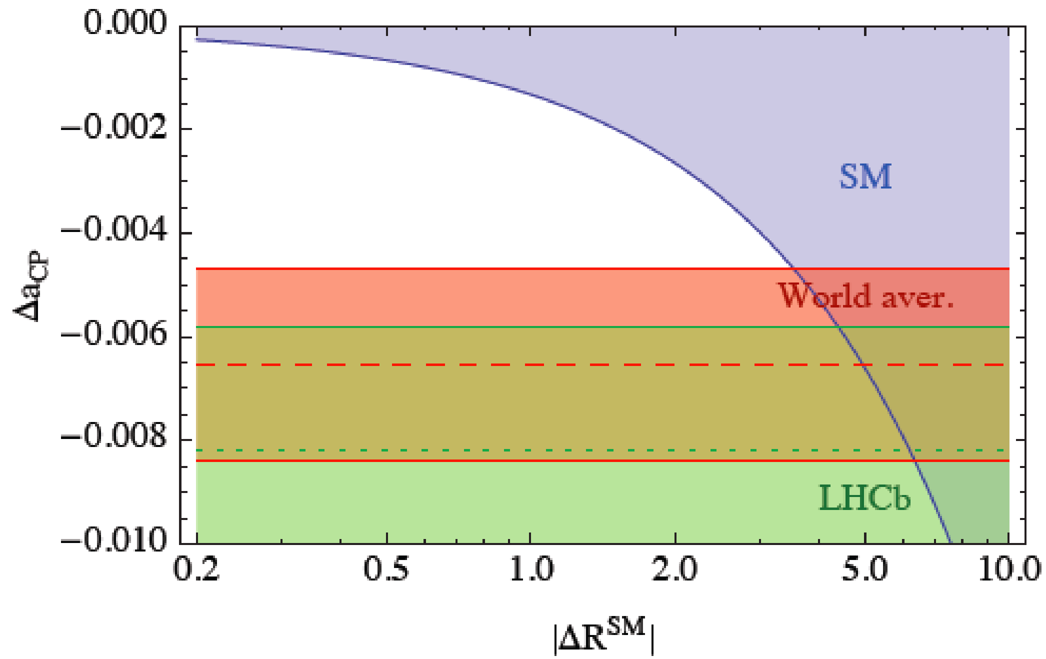
$$\Delta a_{CP} \approx (0.13\%)\ \mathrm{Im}(\Delta R^{SM})$$

CKM suppression:

$$\arg\left(\frac{V_{cs}{}^{*}V_{us}}{V_{cd}{}^{*}V_{ud}}\right) = O(\lambda^4)$$

matrix-element ratio:

$$\frac{\text{"penguin"}}{\text{"tree"}}$$



$\Delta R>1$ is not what we expect for $m_c >> \Lambda_{QCD}$, but is not impossible treating the charm as a light quark (*possible connection with the* $\Delta I=1/2$ *rule in Kaons*)

More works (and especially more observables) needed in order to clarify the situation.