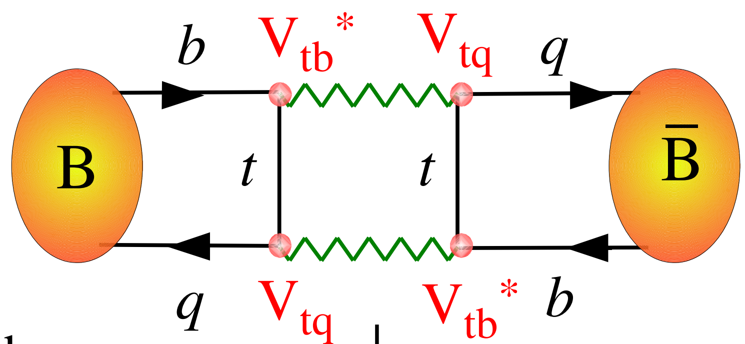
Plan of the lectures:

- Flavour physics in the LHC era
- B-physics phenomenology: mixing, CP violation, and rare decays
  - Time evolution and time-dependent asymmetries of $B_{d,s}$
  - Production & tagging @ hadron colliders
  - CPV in B_s mixing
  - CPV in charged B decays [measuring γ]
  - Rare FCNC B decays
  - The $\Delta F=1$ effective Hamiltonian
  - Exclusive rare B decays [$B \to K^* \mu^+ \mu^-$ & $B \to \mu^+ \mu^-$]
- Flavour physics beyond the SM: models and predictions

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

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

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



off-diagonal elements of the mass matrix

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

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

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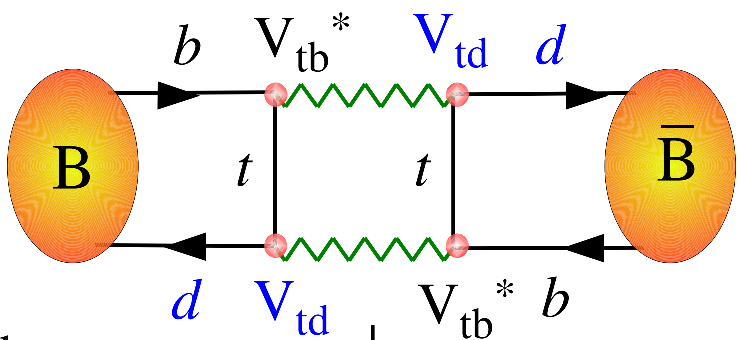

off-diagonal elements of the mass matrix

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

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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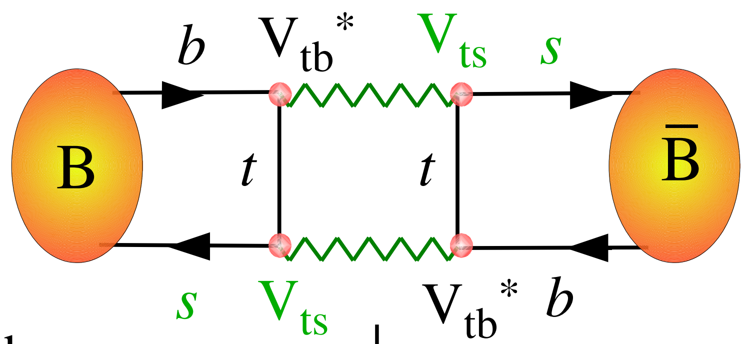


off-diagonal elements of the mass matrix

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

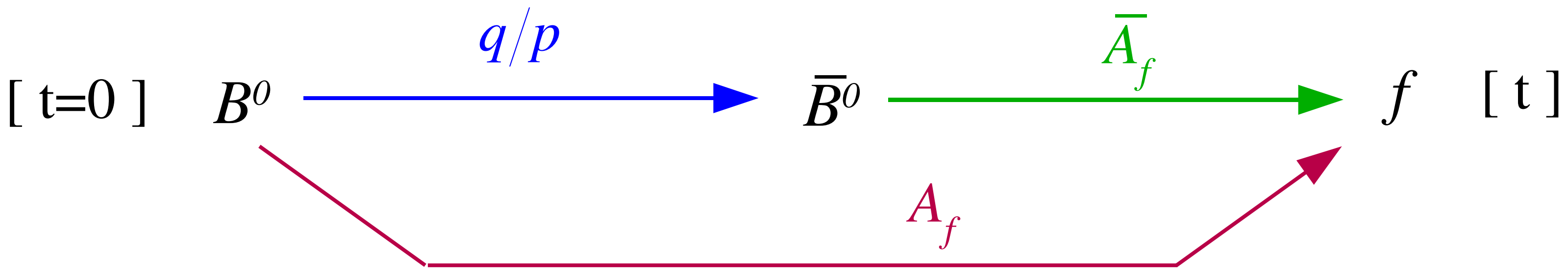
B_s

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:



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

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

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

If $|\lambda_f| = 1$, i.e. if A_f is dominated by a single weak phase, then :

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

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:

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

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

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

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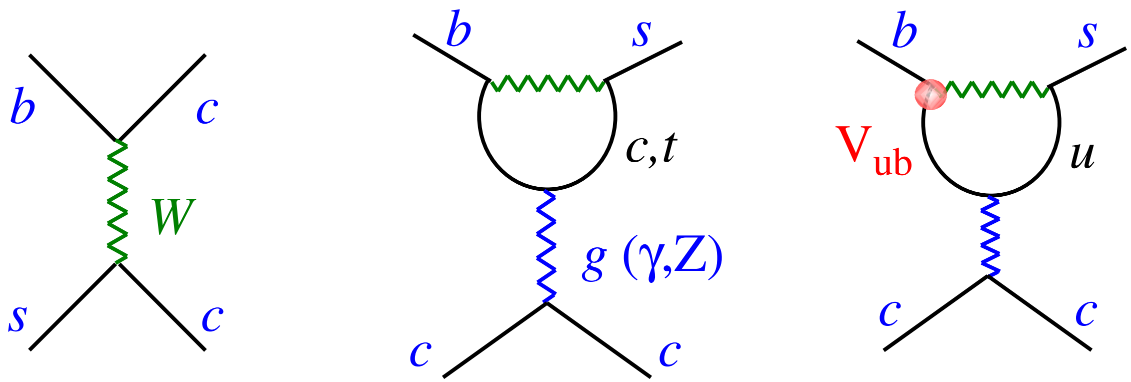
Key points to successfully use this method:

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

When is A_f dominated by a single weak phase ?

I. $|B_d\rangle \rightarrow |\Psi K_S\rangle$ [$b+d \rightarrow c\bar{c}s+d$]



real $O(\lambda^2)$ real $O(\alpha_s \lambda^2)$ $O(\alpha_s \lambda^4)$

dominant amplitude pollution $\lesssim 1\ \%$

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

(from the mixing)

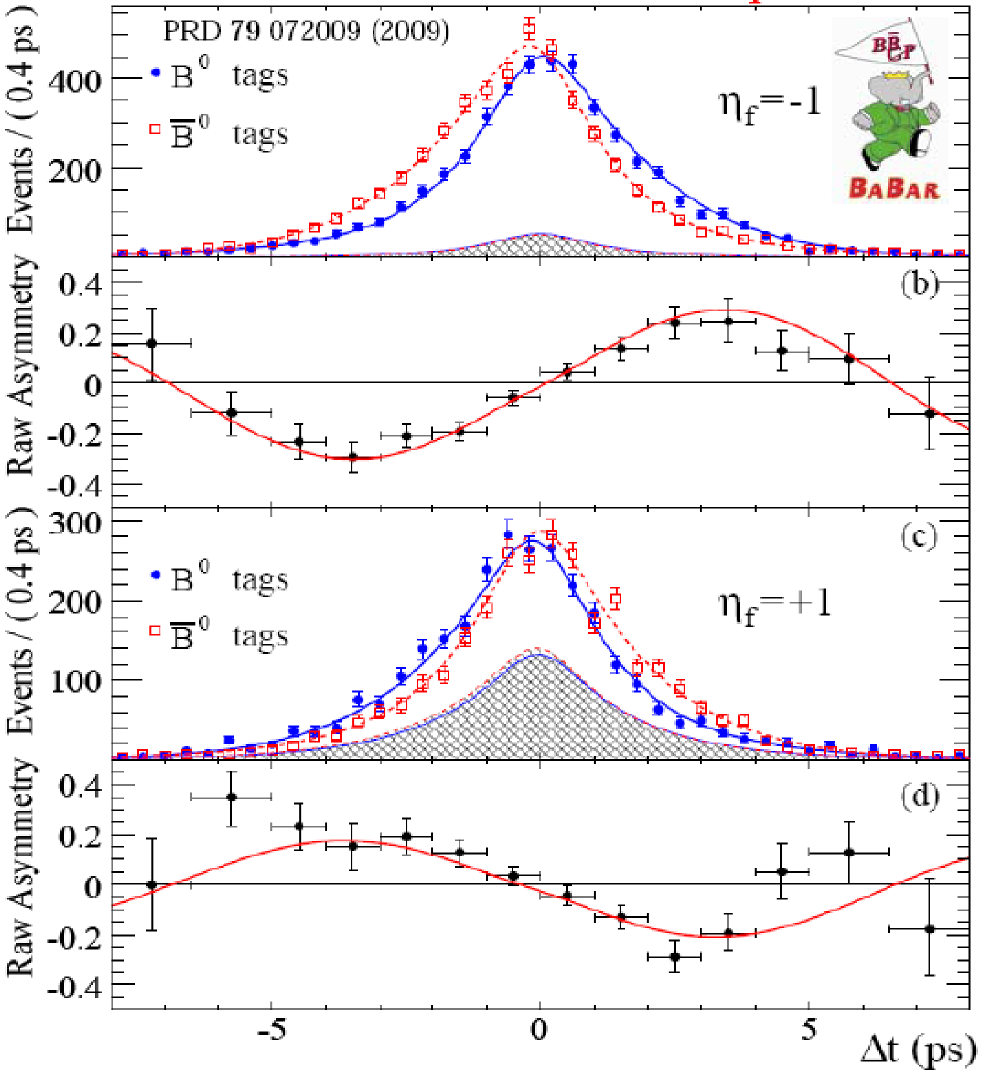
$$\boxed{V_{tb}^{\ *}V_{ts} = -V_{cb}^{\ *}V_{cs} - V_{ub}^{\ *}V_{us}}$$

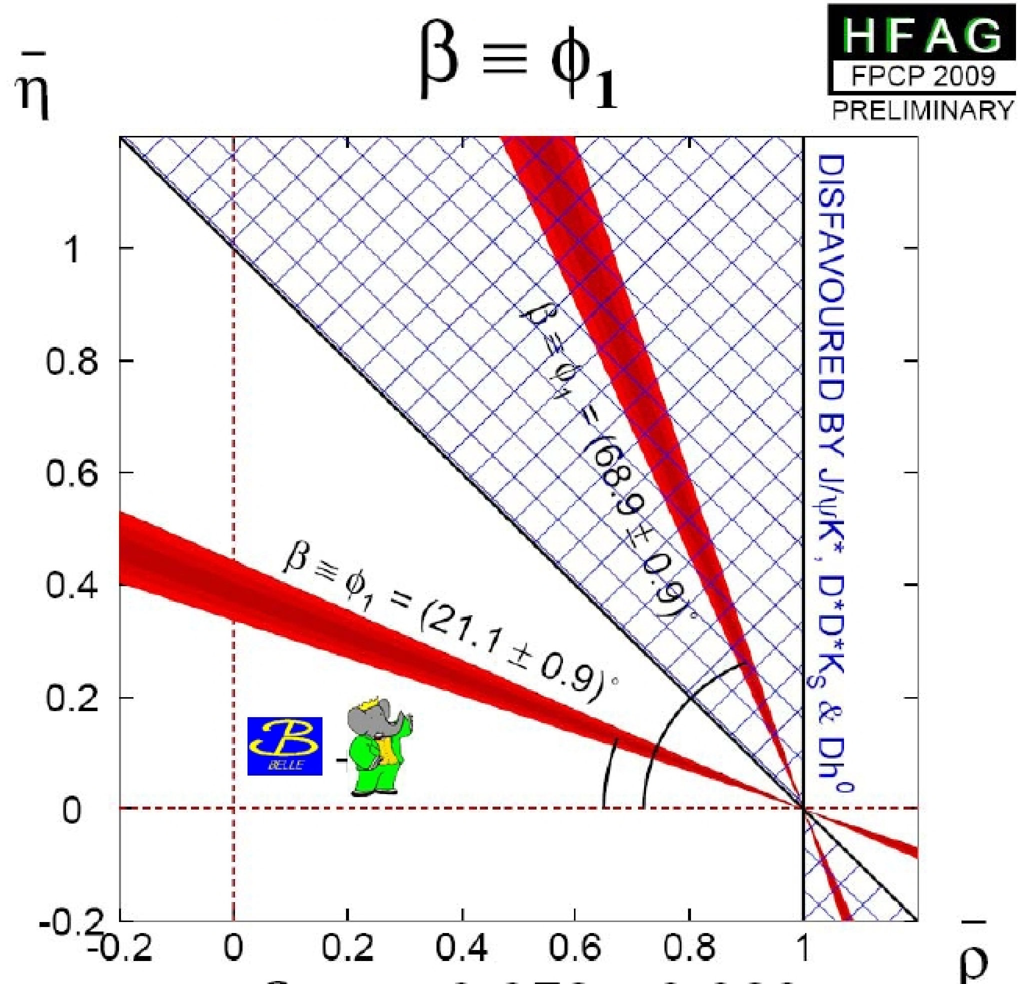
flat triangle

extremely precise
constraint in the ρ–η plane

➡ *Golden channel* for B factories

BaBar's final result has been published:





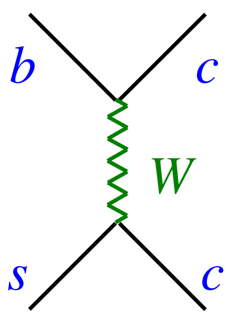
$$S_{WA} = -0.672 \pm 0.023$$

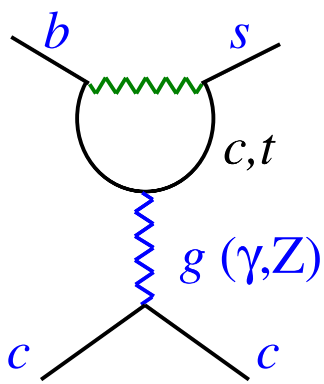
$$C_{WA} = 0.004 \pm 0.019$$

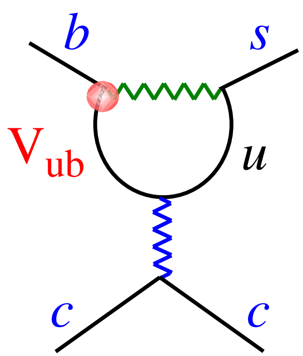
A. Bvan, Lepton-Photon 2009

The golden channel for B_s mixing is

I.a $|B_s\rangle \to |\Psi\phi\rangle$ $[\ b+s \to c\bar{c}s+s\ ]$







real $O(\lambda^2)$ real $O(\alpha_S \lambda^2)$ $O(\alpha_S \lambda^4)$

dominant amplitude pollution $\lesssim 1\ \%$

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

- No constraint in the $\rho-\eta$ plane
- But very significant constraint on NP

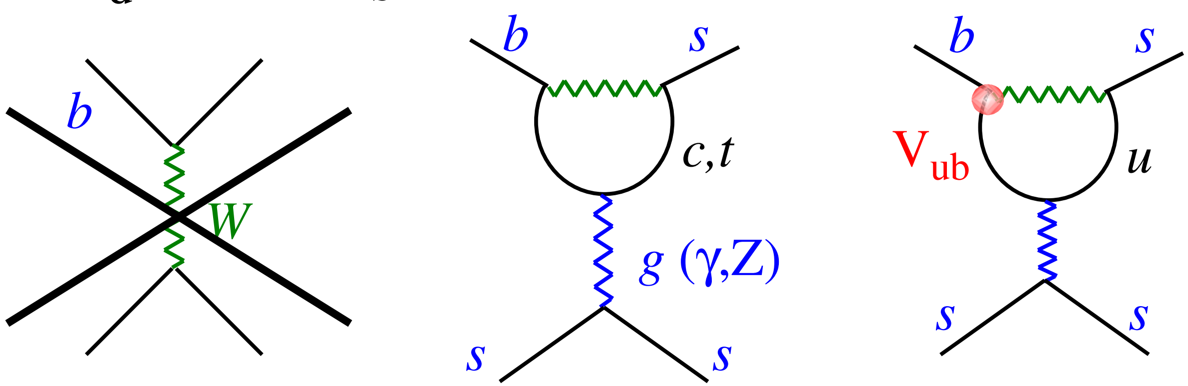
➡ *Golden channel* for hadron machines

N.B.: $|\Psi\phi\rangle$ is not a CP eigenstate (different angular-momentum states)

$\Rightarrow$ angular analysis required to extract the CPV phase

An interesting category are the so-called b→s penguin modes:

II. $|B_d\rangle \rightarrow |\phi K_S\rangle$ [b+d → s$\bar{s}$s+d]



real $O(\alpha_S \lambda^2)$ $O(\alpha_S \lambda^4)$

dominant pollution < 10 %

↓

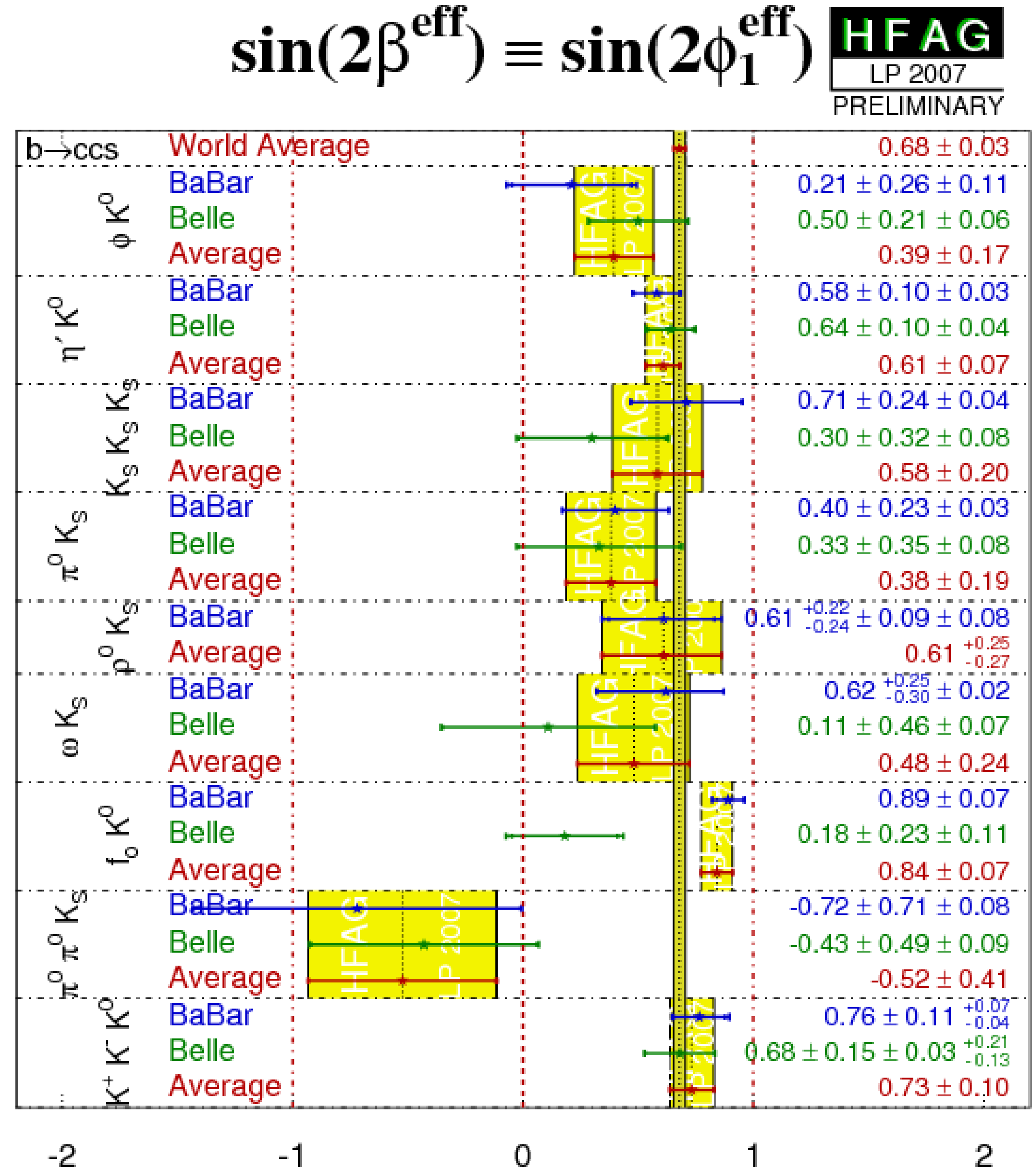
$|\,\mathrm{Im}\,(\lambda_{\psi K}) - \mathrm{Im}\,(\lambda_{\phi K})\,| > 0.1$ ⇒ New Physics !

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

An interesting category ~~are~~ were the so-called b→s penguin modes:

- Best observables [high stat. + full Dalitz Plot analysis] show no significant effect

- We are already close to the level of irredcible th. errors [remember the ε'/ε lesson...]

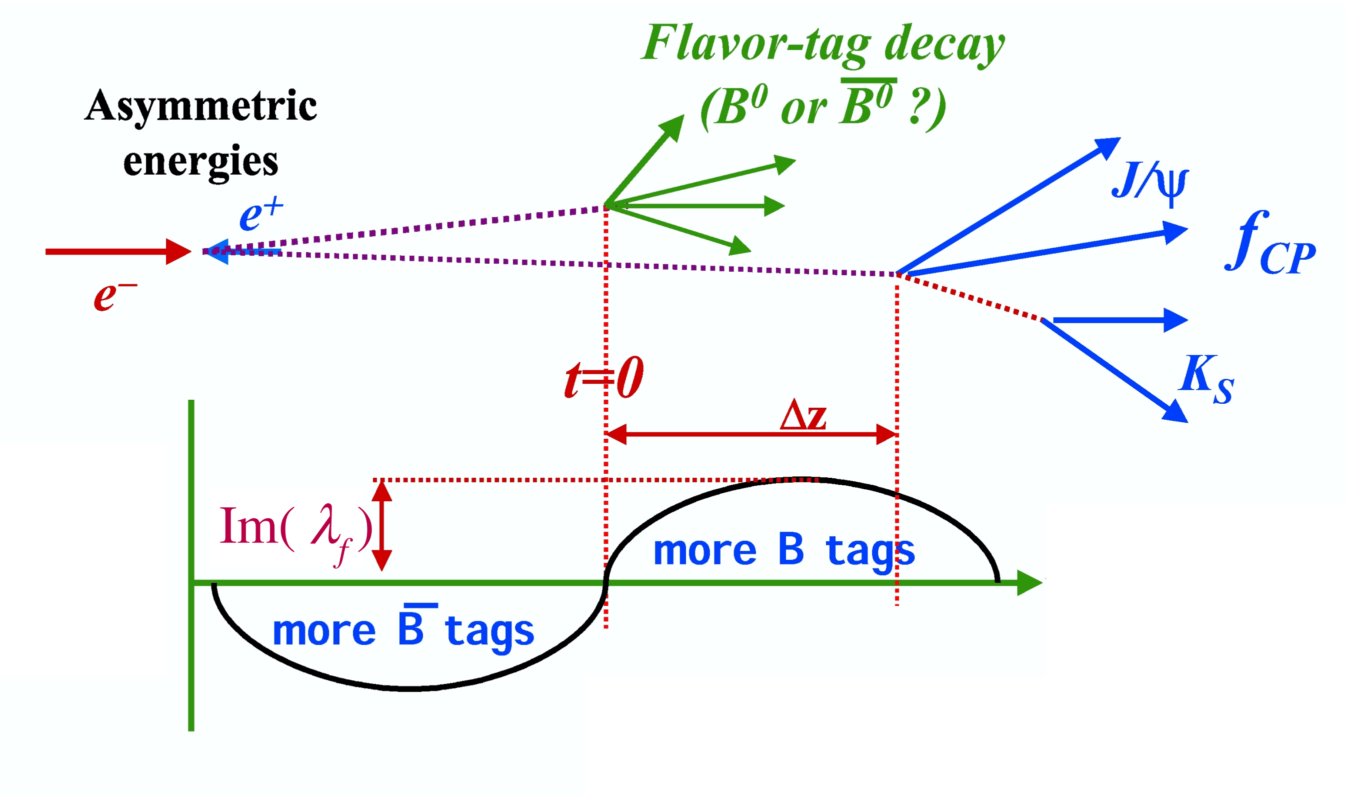


Production & flavour tagging @ hadron colliders

@ 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



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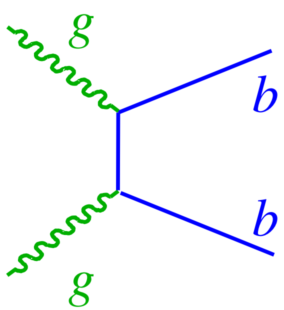
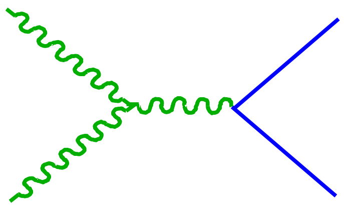
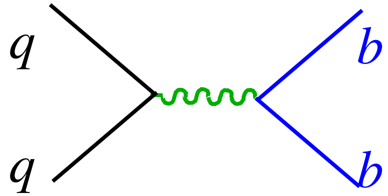
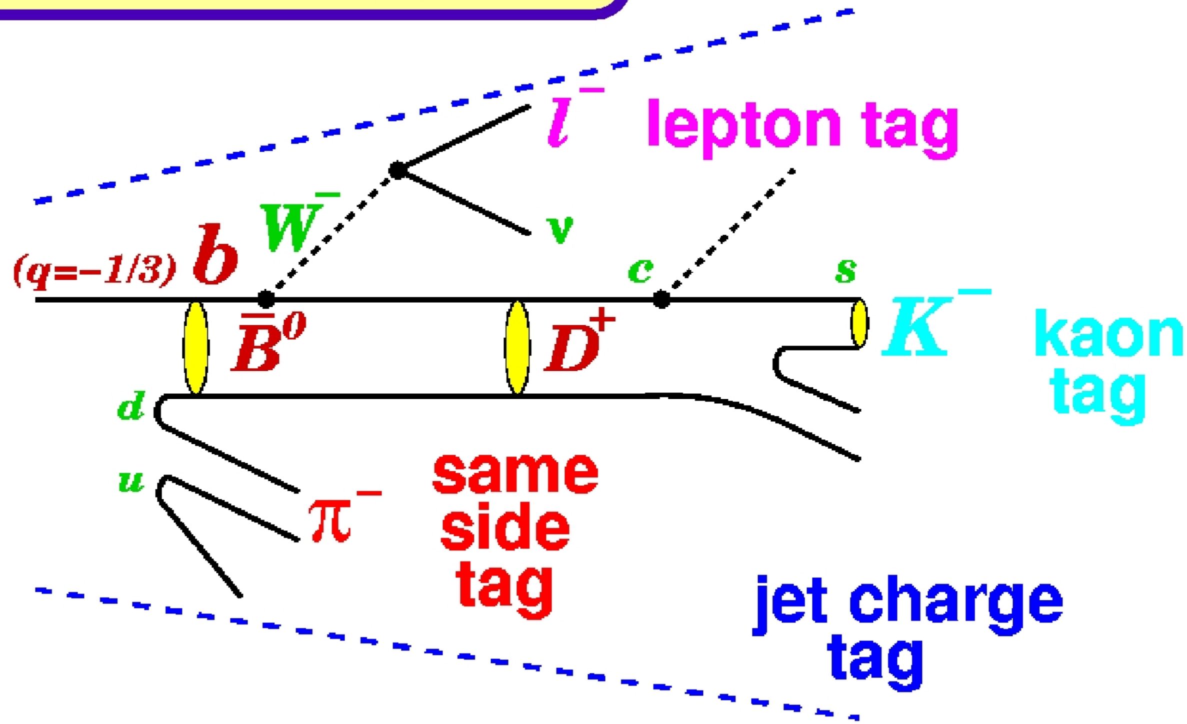






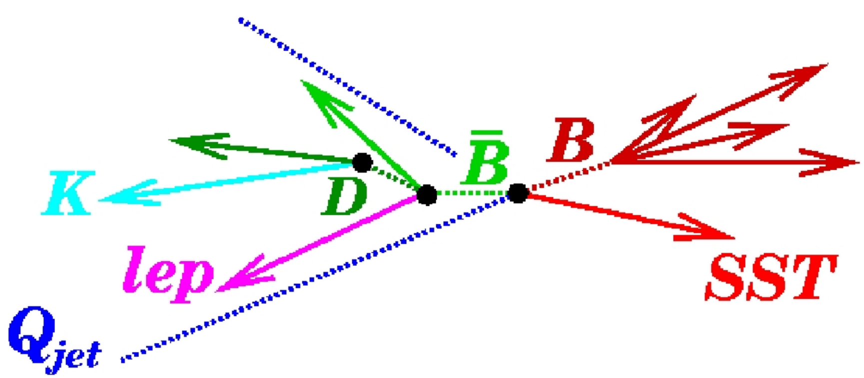
- dirty environment [$\sigma(B)/\sigma(bkg) < 0.01$]
- incoherent quantum state
- high stat. [~ 10^{12} B pairs / 1 fb^{-1}]
- all hadrons with b-quarks produced

B Flavour Tagging



B flavour tagging methods:

- Opposite side lepton tag
- Jet charge tag
- Same side tag
- Opposite side kaon tag
- Forward-backward asymmetry



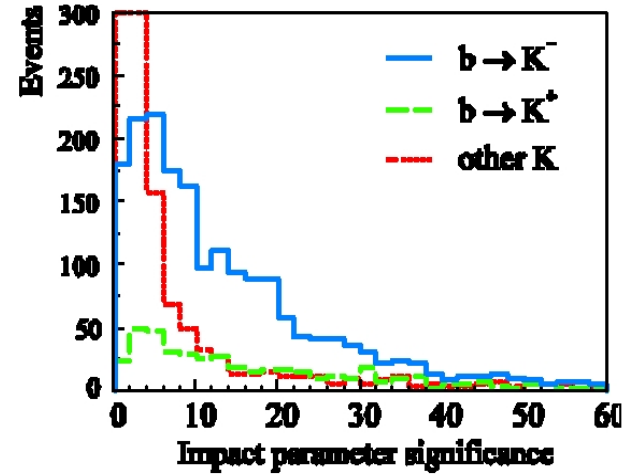
Manfred Paulini – CP Violation School , Prerow, 22./23. Sept. 2003

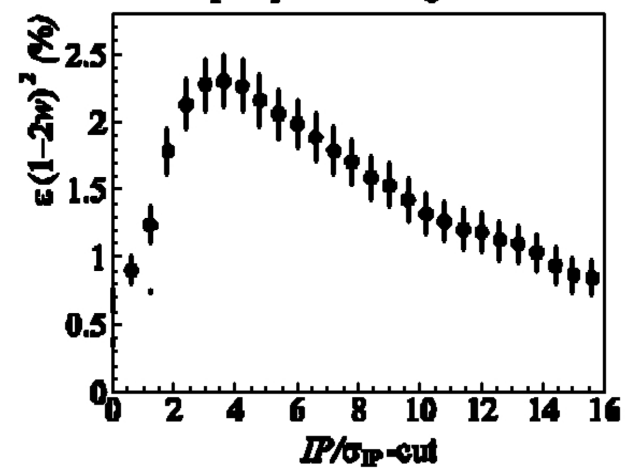
Flavour tagging at LHC:

- Kaon tagging most powerful for LHCb ($K^\pm$ from the "opposite side" $b \to c \to s$)

Tagging power $\varepsilon D^2 = \varepsilon(1-2w)^2$ (in %)

Tag	LHCb	CMS	ATLAS
Muon	1.0	0.7	0.7
Electron	0.4	0.5	0.3
Kaon	2.4	–	–
Jet/vertex charge	1.0	2.3	1.6
Same side	2.1	2.2	2.1





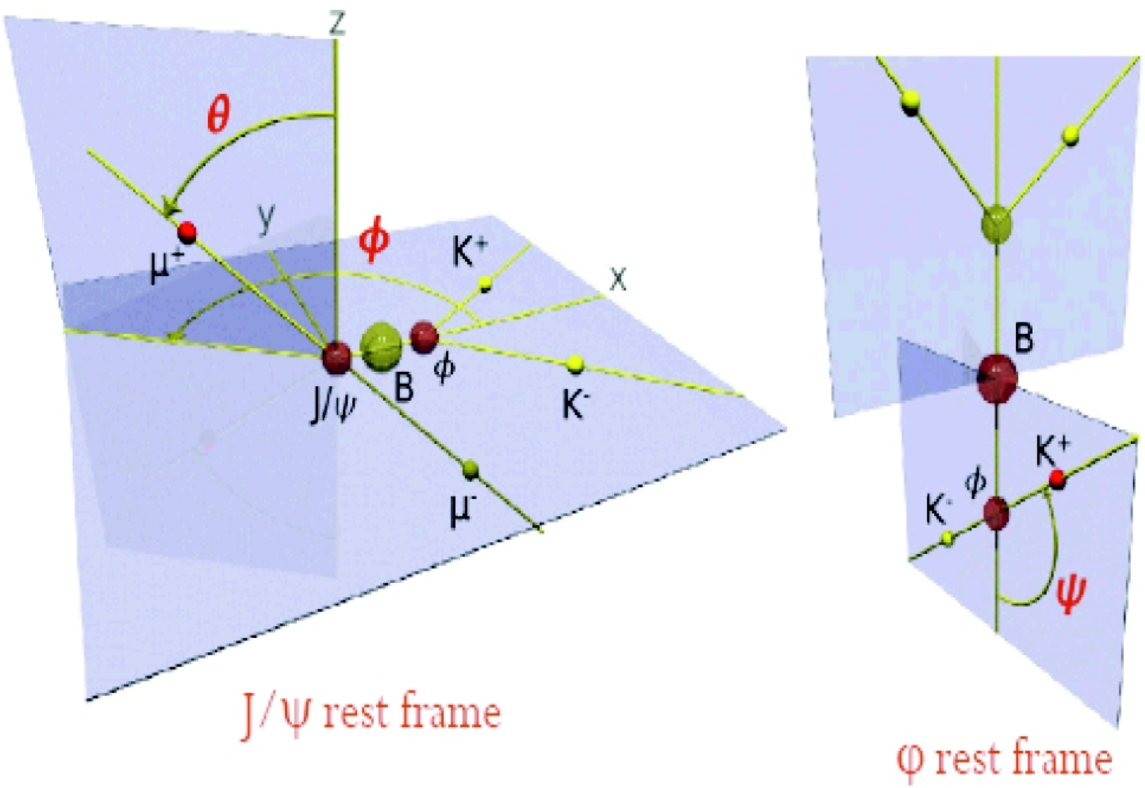
- Combined power for B_s ~ 6% (LHCb)
(*cf* ~ 1% at CDF/D0, ~ 30% at B Factories)
Lower for B^0 (~ 4%) due to reduced same-side tagging power

CPV in B_s mixing

The CP-violating phase of the B_s mixing amplitude is the last missing ingredients about down-type $\Delta F=2$ transitions [K, B_d, B_s]: a key element to understand if there is room for new sources of flavour symmetry breaking beyond the SM.

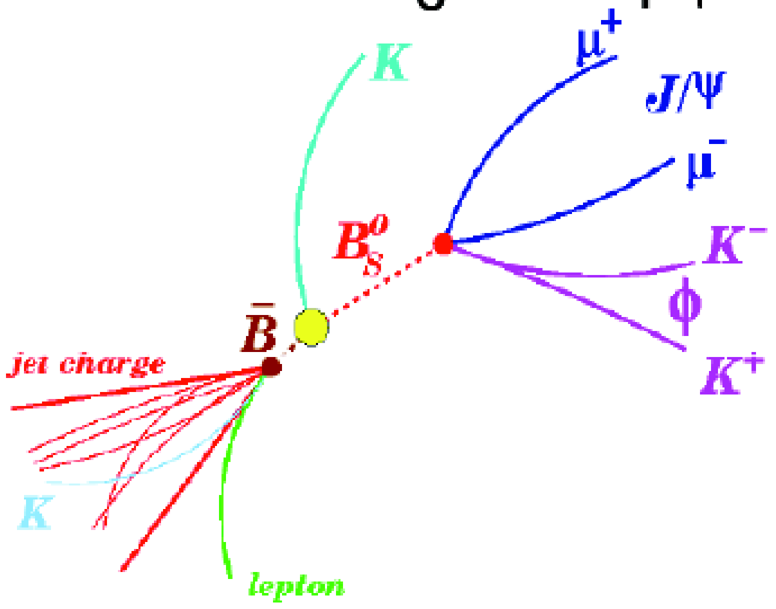
Experimentally quite challenging:

- Non-trivial angular analysis needed to separate the various decay amplitudes
- Fast oscillations
- Simultaneous fit of the width difference ($\Delta\Gamma_s$) and the mixing phase



Measuring mixing parameters with $B_s \to J/\psi\phi$

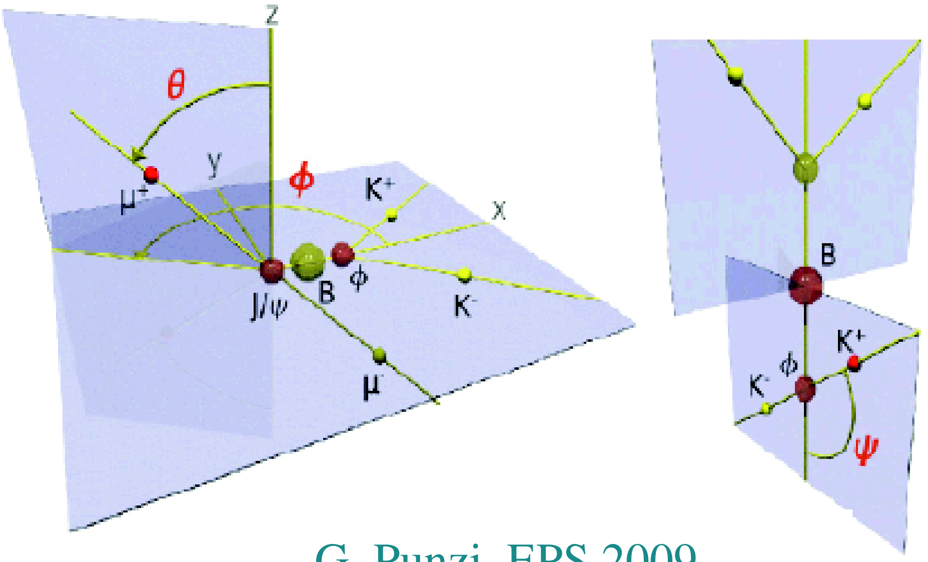
1. Reconstruct decays from stable products:
   - $B_s \to J/\Psi[\mu^+\mu^-]\ \Phi[K^+K^-]$
   - $B_d \to J/\Psi[\mu^+\mu^-]\ K^{*0}[K^+\pi^-]$ (control sample)



2. Measure lifetime $ct = m_B * L_{xy}/p_T$
   - Proper time resolution essential to resolve oscillations

3. Measure decay angles in transversity base:

$$\vec{w} = (\vartheta, \phi, \psi)$$



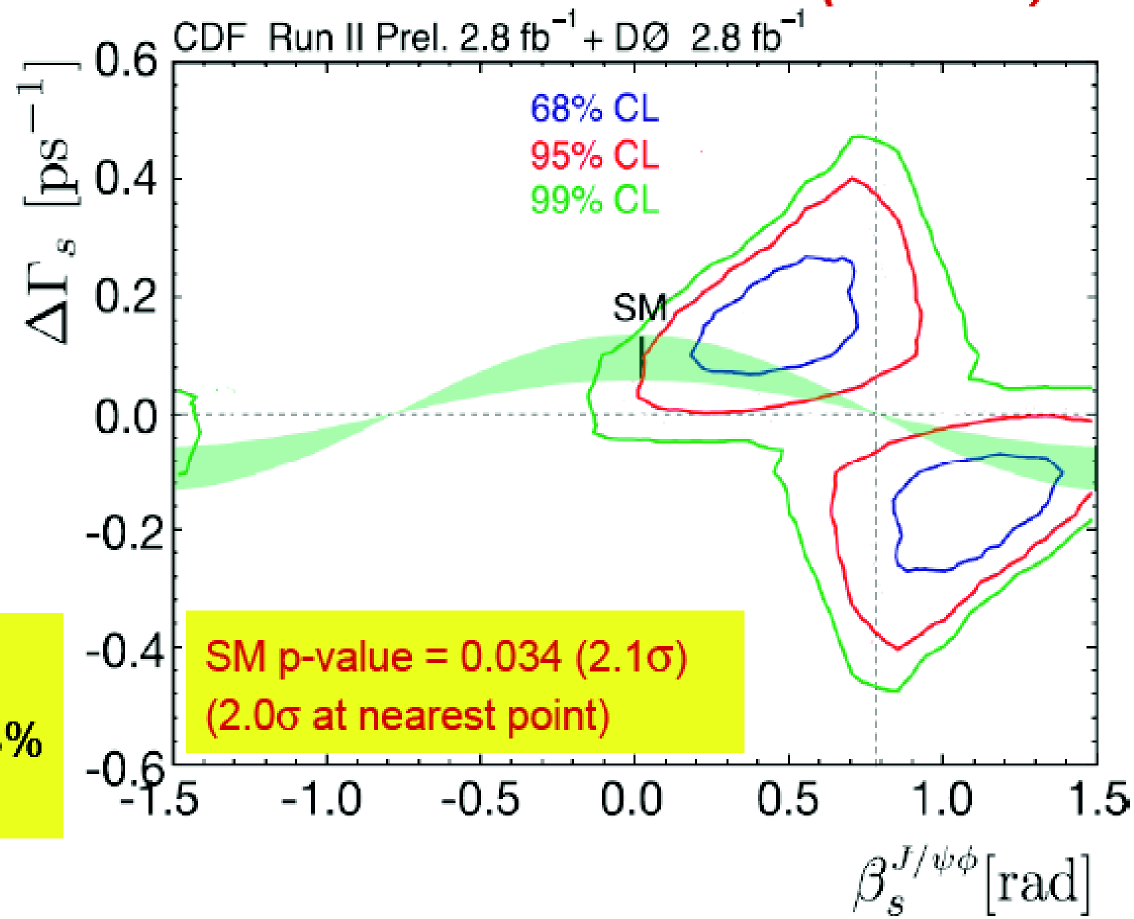
4. Identify Bs flavor at production time:
   - Flavor Tagging (Tag decision ξ)

5. Perform maximum likelihood fit:
   - Likelihood in m, ct, w , ξ

G. Punzi, EPS 2009

Combined Tevatron result *(NEW)*

- Full inclusion of systematics and non-Gaussian effects
- No constraints. Make available to combination groups.



$\beta_s^{J/\psi\phi}$ range:
[0.27,0.59] U [0.97,1.30] @68%
[0.10,1.42] @95%

- Compared to HFAG 2008:
  Larger CDF sample + Better accounting for tails ⇒ same level of SM agreement.
- Both CDF and D0 currently working on **2x** samples.
- Expect improved precision by ***simultaneous fit*** of CDF and D0 samples.

G. Punzi, EPS 2009

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]

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

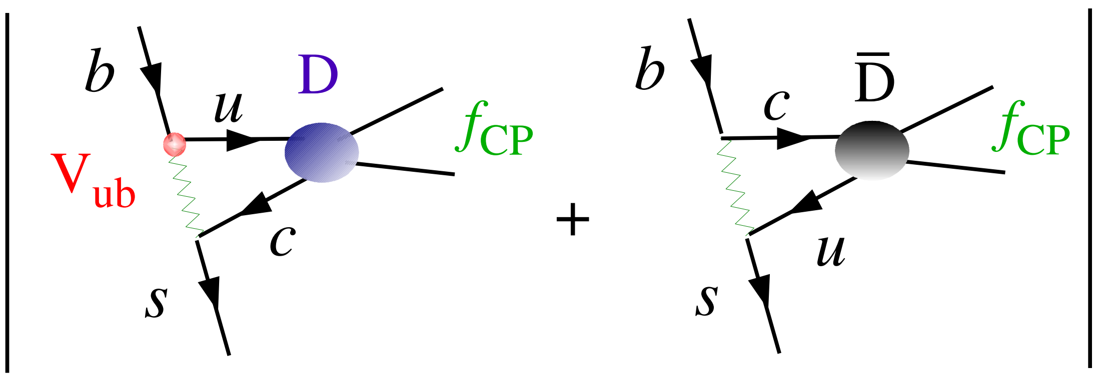
weak phase

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



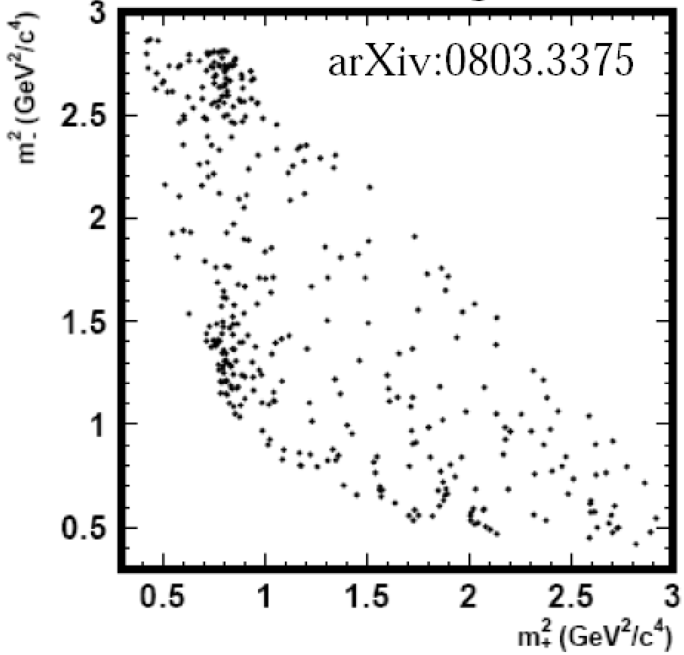
- Neutral D mixing weak phase measured to be small
- Relative weight and phase of the two strong amplitudes measured by looking at different CP eigenstates

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

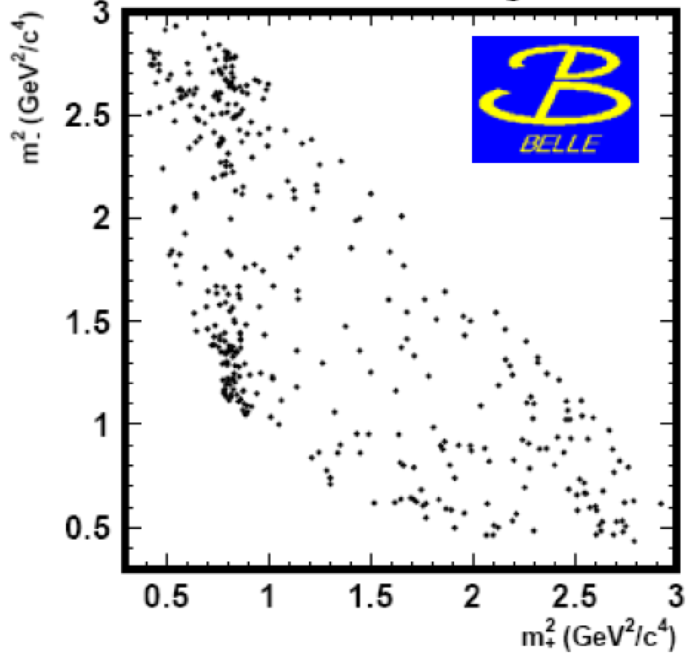
- Gronau-London-Wyler/Atwood-Dunietz-Soni methods: $B^\pm \to (K\pi,\ \pi\pi\ ) + K^\pm$
- Giri-Grossman-Soffer-Zupan method: $B^\pm \to (K_S\pi^+\pi^-) + K^\pm$

full Dalitz-Plot analysis

$B^- : \overline{D}^0 \to K_S^0 \pi^+ \pi^-$

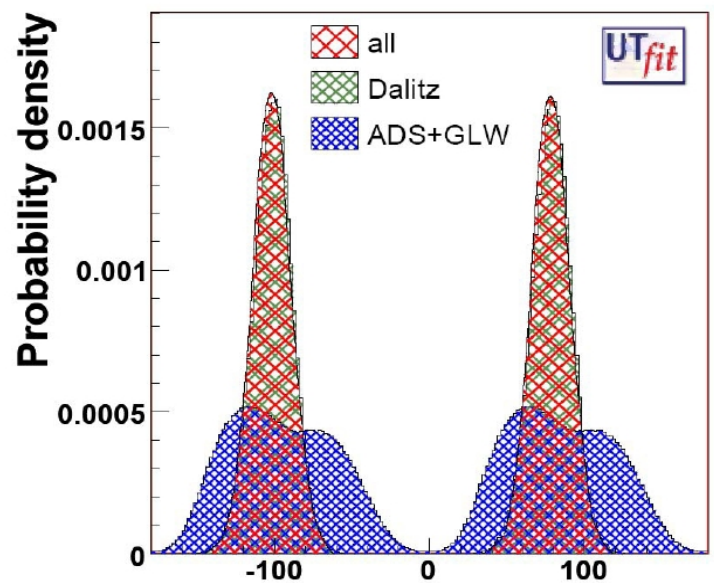


$B^+ : \overline{D}^0 \to K_S^0 \pi^+ \pi^-$



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

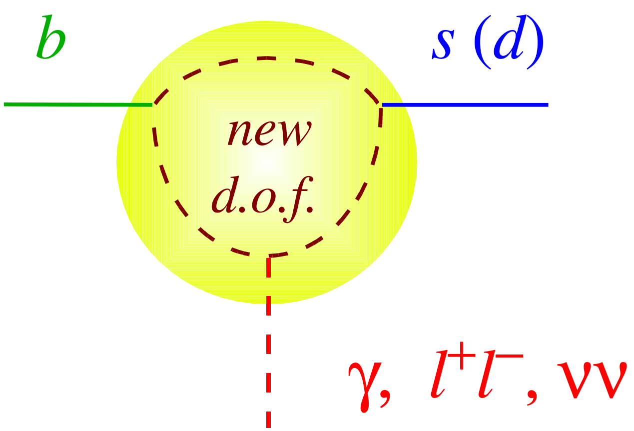
Clear room for improvements at LHCb



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

Rare FCNC B decays

Similarly to ΔF=2 mixing amplitudes, rare decays mediated by *FCNC amplitudes* are very interesting to perform *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 ($m_b \gg \Lambda_{QCD}$)

And the ΔF=1 sector is much more rich...

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	$(Q_L^b \Gamma Q_L^s)^2$	$\ldots$	
ΔF=1 4-quark box	$\vdots$		
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

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

FLAVOUR COUPLING:

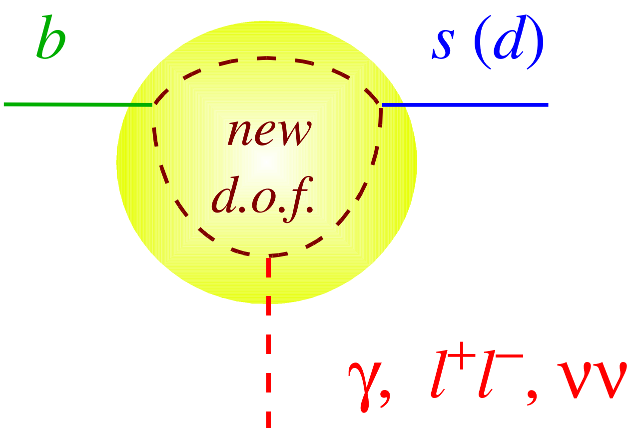
ELECTROWEAK STRUCTURE

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

Rare FCNC B decays

Similarly to ΔF=2 mixing amplitudes, rare decays mediated by *FCNC amplitudes* are very interesting to perform *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

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

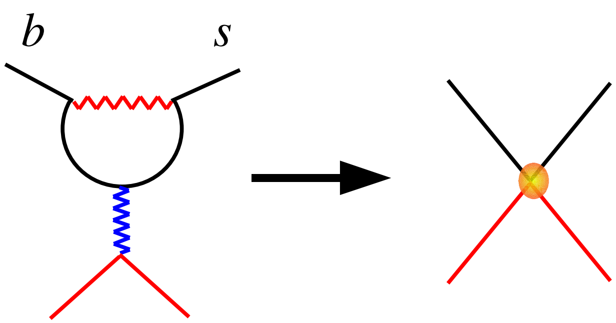
Exclusive decays
generally more difficult than inclusive, with notable exceptions:

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

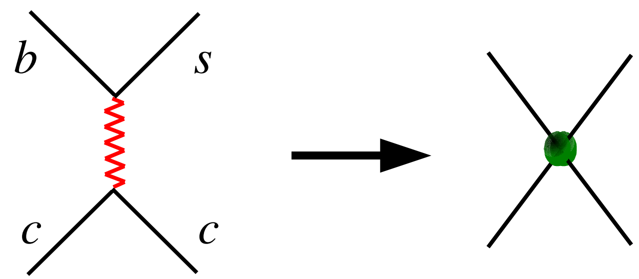
The ΔF=1 effective Hamiltonian

The most efficient tool to deal with the various scales of the problem is the construction of an effective Hamiltonian

1st step: Integrating out all the heavy d.o.f around or above the electroweak scale (including the heavy SM fields)



$$H_{\text{eff}} = \Sigma_i\, C_i(\mu)\, Q_i$$



FCNC operators:

$$Q_6 = (b\,s)_{V-A}(q\,q)_V \qquad \text{[Gluon penguins]}$$

$$\vdots$$

$$Q_{9V} = Q_f (b\,s)_{V-A}(f\,f)_V$$

$$Q_{10A} = Q_f (b\,s)_{V-A}(f\,f)_A$$

[E.W. penguins / FCNC ops.]

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

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

$$\downarrow$$

$$H_{\rm eff} = \Sigma_{\rm i}\, C_i(\mu \sim m_b)\, Q_i$$

Penguin operators:

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

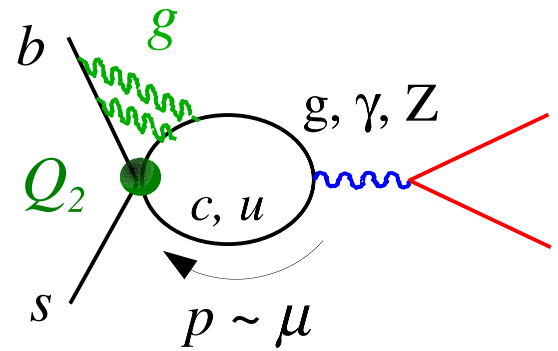
Four-quark (tree-level) ops.:

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

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

$$A(B \to f) = \langle f | \sum_i C_i(\mu)\, Q_i \ | K \rangle$$

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

Putting all the ingredients together in the case of $B \to X_s \gamma$
[at present the only case which allows a significant theory vs. exp. comparison]:

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:

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

[2009 exp. WA]

A great success for the SM...

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

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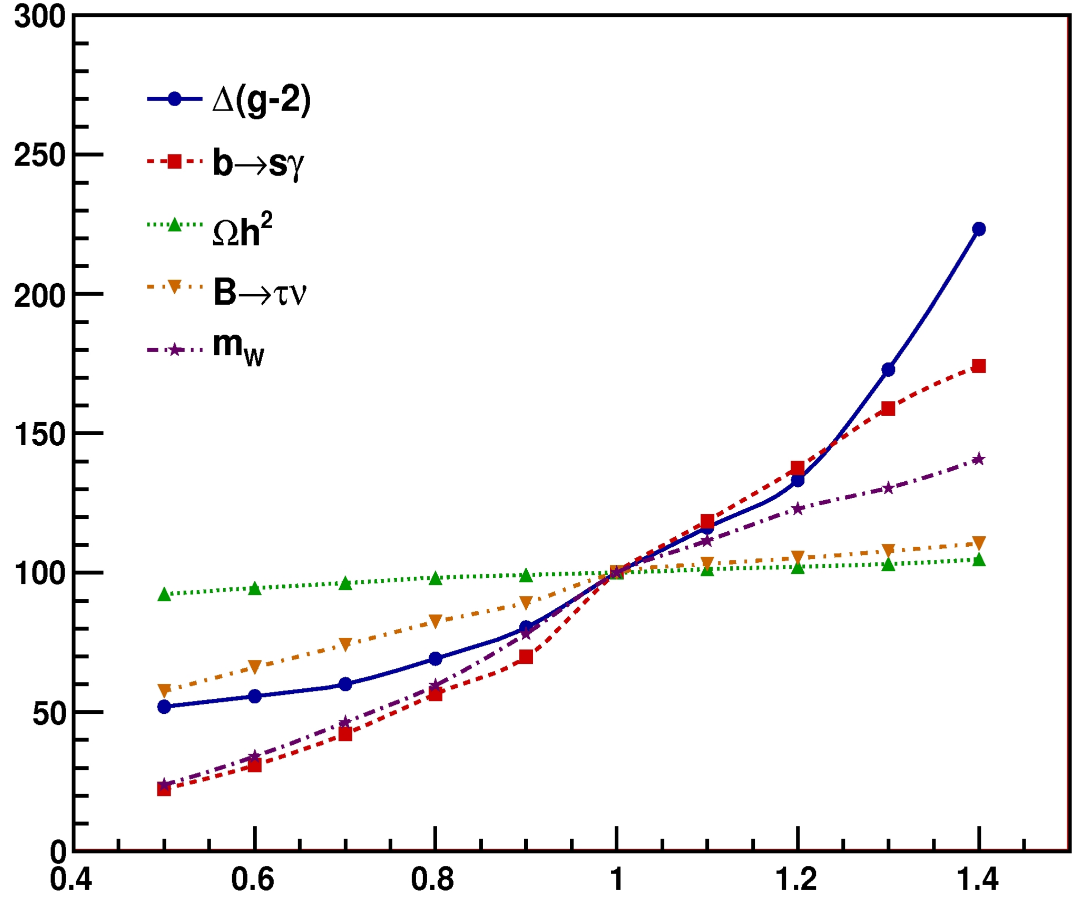
E.g.: relative reduction (%) of the preferred area in the M_0–$\tan\beta$ plane for the CMSSM, as a function of the current error on various indirect observables [Buchmuller et al. '08.4128]



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* :

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

⇒ several progress in the last few years [SCET, LCSR, 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.

⇒ Two notable examples:

I. $A_{FB}(B \to K^* l^+ l^-)$ II. $\Gamma(B \to l^+ l^-)$

I. The lepton FB asymmetry in $B \to K^* l^+ l^-$

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

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

th. error ~5 %

- Direct access to the *relative phases* of the C_i
- Proportional to C_{10} (interf. of axial & vector currents)
  $\Rightarrow$ small QCD corrections
- Very useful probe of non-standard scenarios
- Hadronic uncertainties substantially decreased with a proper normalization:

$$\bar{A}_{FB} = \frac{d\Gamma(\cos\theta>0)/ds - d\Gamma(\cos\theta<0)/ds}{d\Gamma(\cos\theta>0)/ds + d\Gamma(\cos\theta<0)/ds}$$

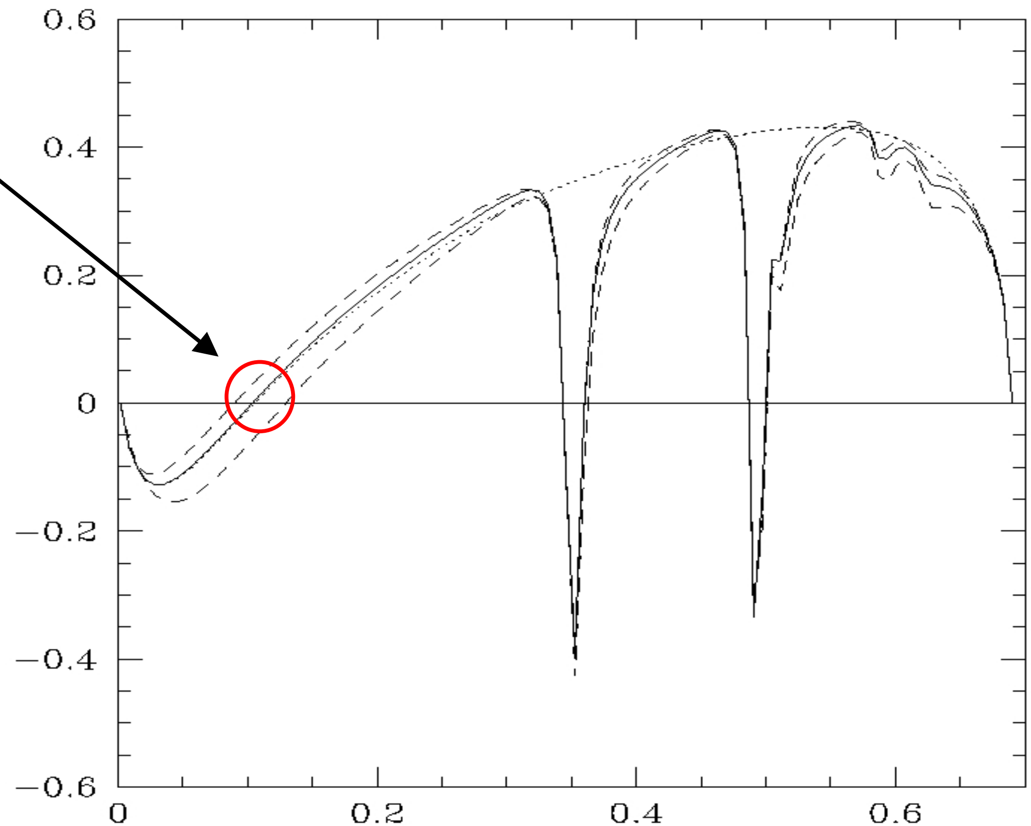
I. The lepton FB asymmetry in $B \to K^* l^+ l^-$

The following main features turns out to be independent from the details of the form factors:

$$\bar{A}_{FB} = \frac{d\Gamma(\cos\theta>0)/ds - d\Gamma(\cos\theta<0)/ds}{d\Gamma(\cos\theta>0)/ds + d\Gamma(\cos\theta<0)/ds}$$

- $A_{FB}(s) = 0$ for $s = q^2/m_b^2 \sim C_7/C_9$
- $\int ds\, A_{FB}[B] > 0$
- $\int ds\, A_{FB}[B] + A_{FB}[\bar{B}] < 0.1\%$

CPV observable



$\bar{A}_{FB}(s)$ within the SM for the $\bar{B} = |b\bar{d}\rangle$ mode

Much more interesting than CP asym. in the rates, since $A_{FB} \sim \mathrm{Re}[C_{10}^* C_9]$

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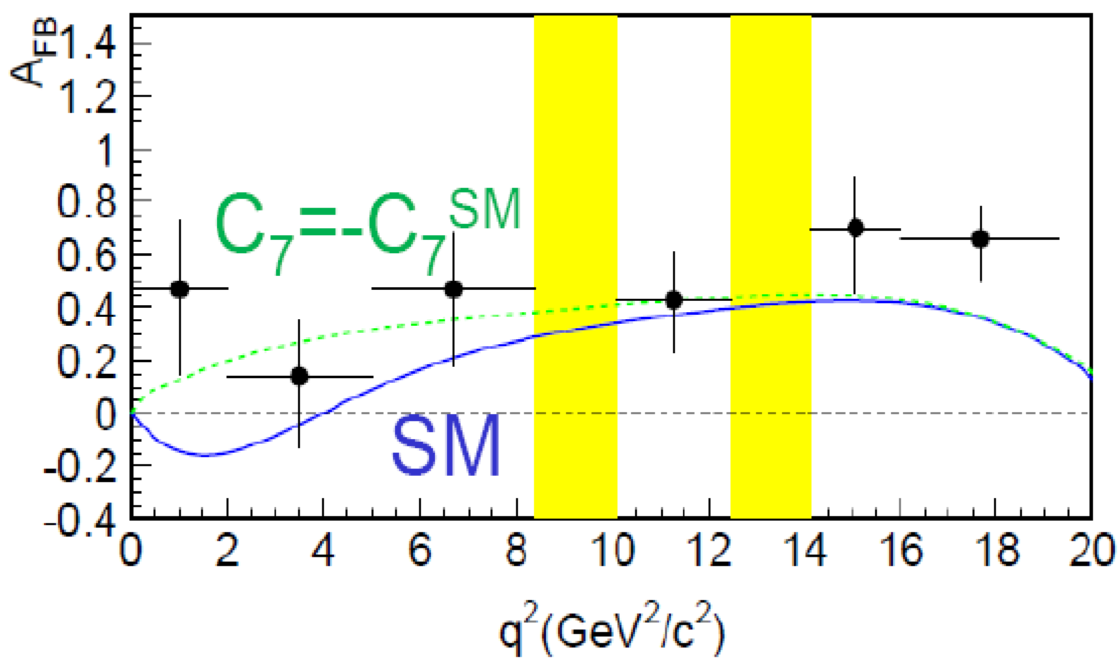
657 M BB,
submitted to PRL, arXiv: 0904.0770



Results from B factories, limited by statistics, still allow large room for non-standard effects

II. $B_{s,d} \to l^+ l^-$

A special case among exclusive *B* decays:

- No vector-current contribution [th. error of the s.d. calculation ~ 1%]
- Hadronic matrix element relatively simple [f_B within the SM]
- Very clean signature
- Strong sensitivity to scalar currents beyond the SM [Higgs penguin]

$\Rightarrow$ order-of-magnitude enhancements possible in multi-Higgs models, even without new flavor structures [SUSY @ large $\tan\beta$]

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

$$B(B_d \to \mu\mu)_{SM} \approx 1.0 \times 10^{-10}$$

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

τ channles enhanced by $(m_\tau/m_\mu)^2$

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Exercise [to understand why $B_{s,d} \to l^+ l^-$ 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: $\langle 0|\, \bar{b}\gamma_\mu\gamma_5 u \,|\, B(p) \rangle = i\, f_B\, p_\mu$ $\qquad \langle 0|\, \bar{b}\gamma_5 u \,|\, B(p) \rangle = i\, f_B\, m_B^2/m_b$