Measurements of the CKM angles at the B Factories

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Outline

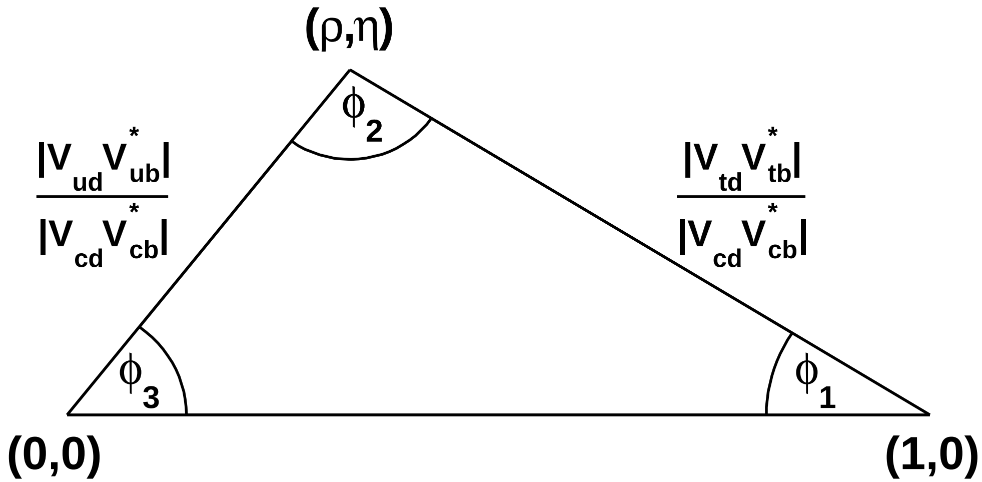
~~Motivation~~

Principles of the Measurements

Measurements of ϕ_1

Measurements of ϕ_2

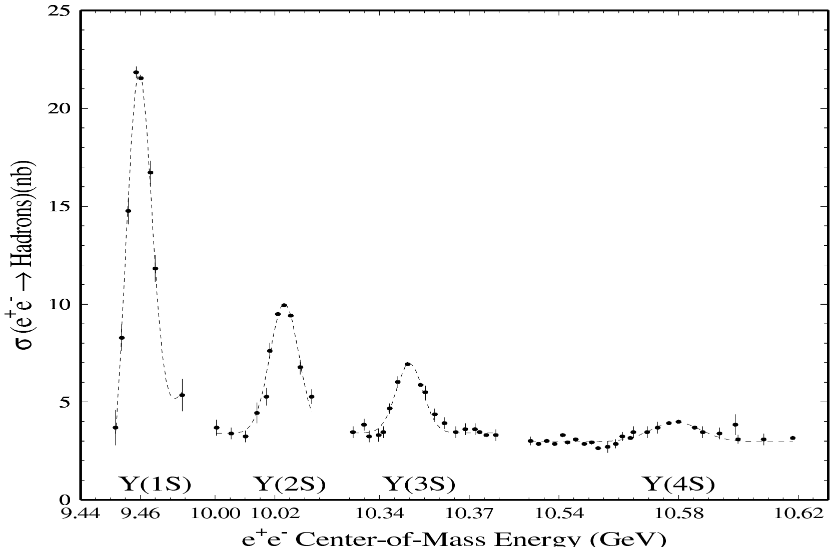
~~Measurements of ϕ_3~~



Prospects at the Super Flavour Factories

Measurement Principles

$B\bar{B}$ pairs produced in the reaction $e^+e^- \to \Upsilon(4S) \to B\bar{B}$



The Υ resonances are $b\bar{b}$ bound states

$\Upsilon(4S)$ is the first resonance just above the $B\bar{B}$ production threshold

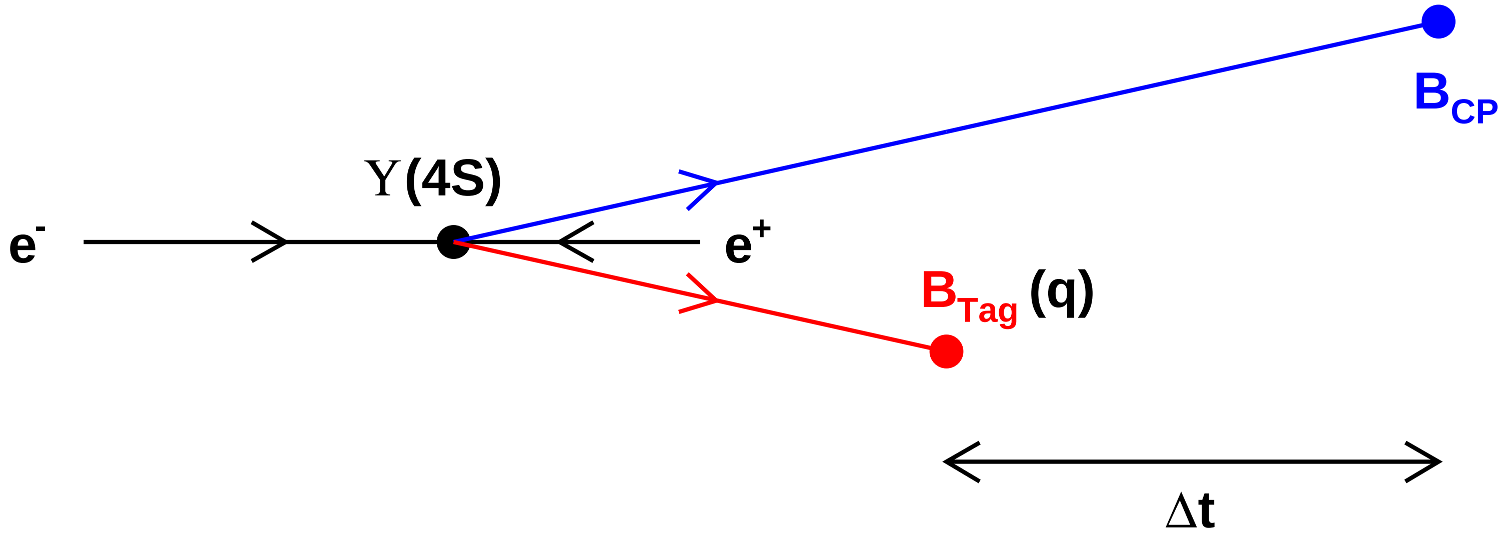
- Only $B\bar{B}$ pairs are produced, and are $\approx$ at rest in the $\Upsilon(4S)$ frame

In addition, the $B\bar{B}$ pairs are correlated (produced and evolve with opposite flavour)

- This makes B flavour identification (B^0 or $\bar{B}^0$) possible which is vital for CP measurements

Very convenient experimental environment

Measurement Principles

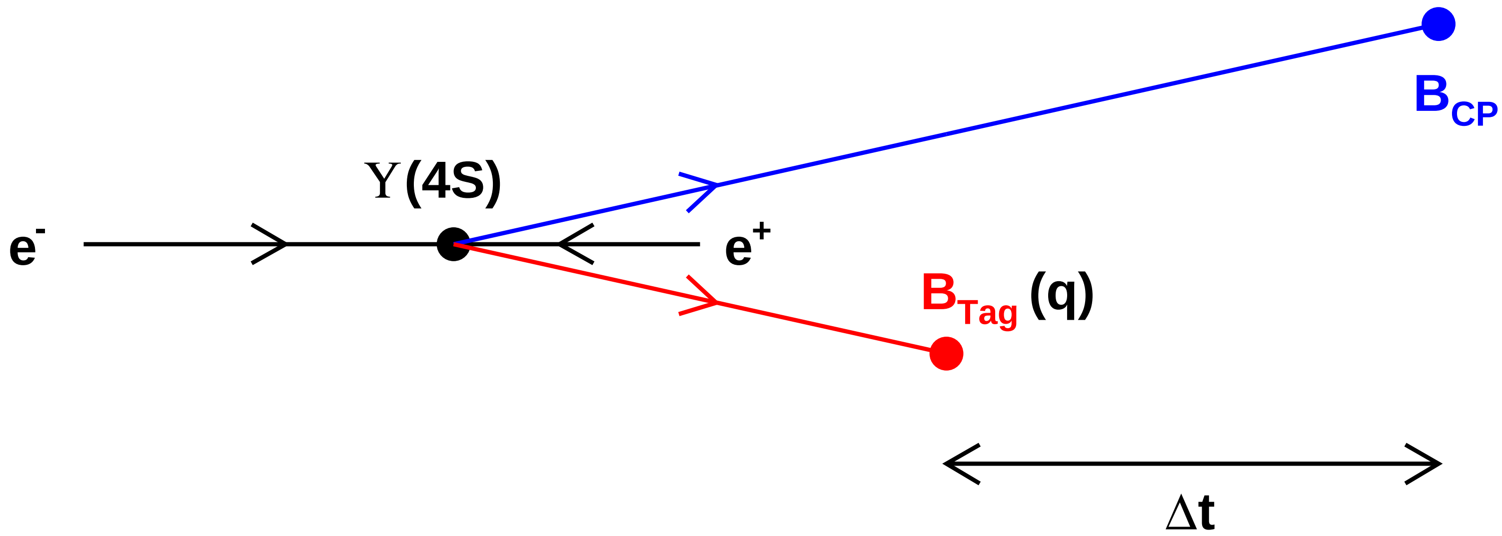


Time measurements are essential to finding CP violation in B decays

Matter (B^0) and anti-matter ($\bar{B}^0$) can have different time evolution

But average time difference between $B\bar{B}$ decays is ~ 1 ps

Measurement Principles



Use asymmetric e^+e^- beams to produce $\Upsilon(4S)$ with a Lorentz boost

Boost increases mean separation of $B\bar{B}$ pairs to something we can measure

$B\bar{B}$ pairs almost at rest in CMS, Δt accessed through separation measurement in 1D

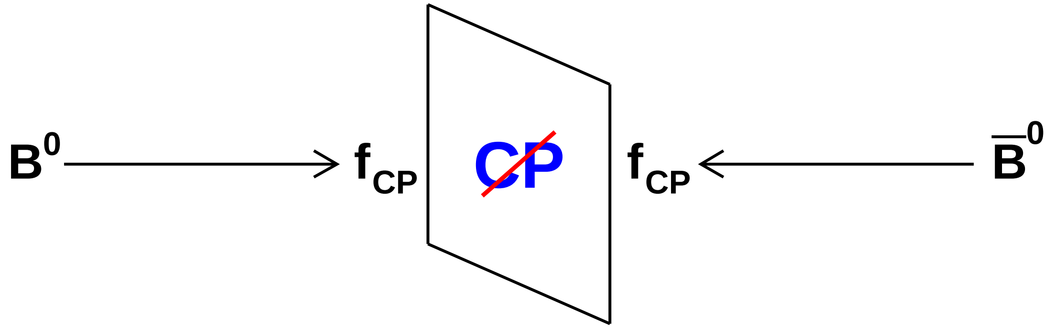
Precise vertex measurement is the key to acccessing CP violation in B decays

CP Measurement

Two types of CP violation can be measured from the data

Direct CP violation

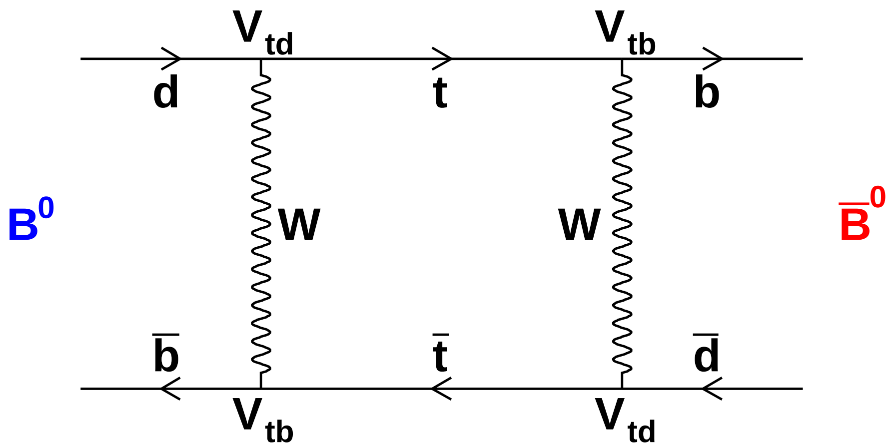
Different decay rates

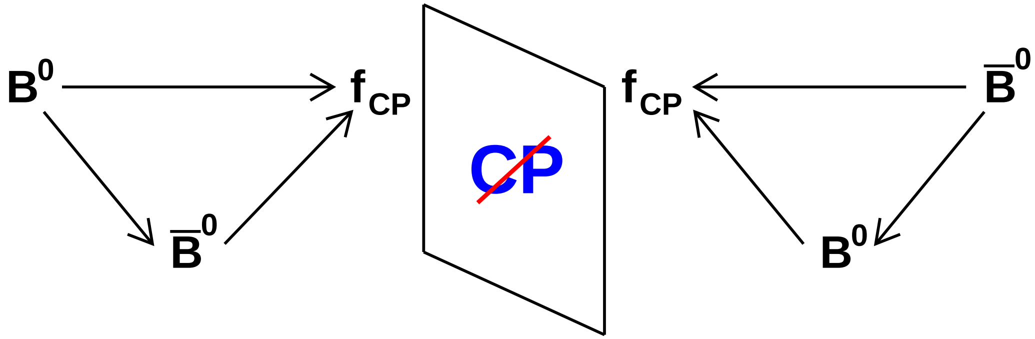


Mixing-induced (Indirect) CP violation

Arises from an interference between $B^0 - \bar{B}^0$ mixing and the final state

Feynman Diagram





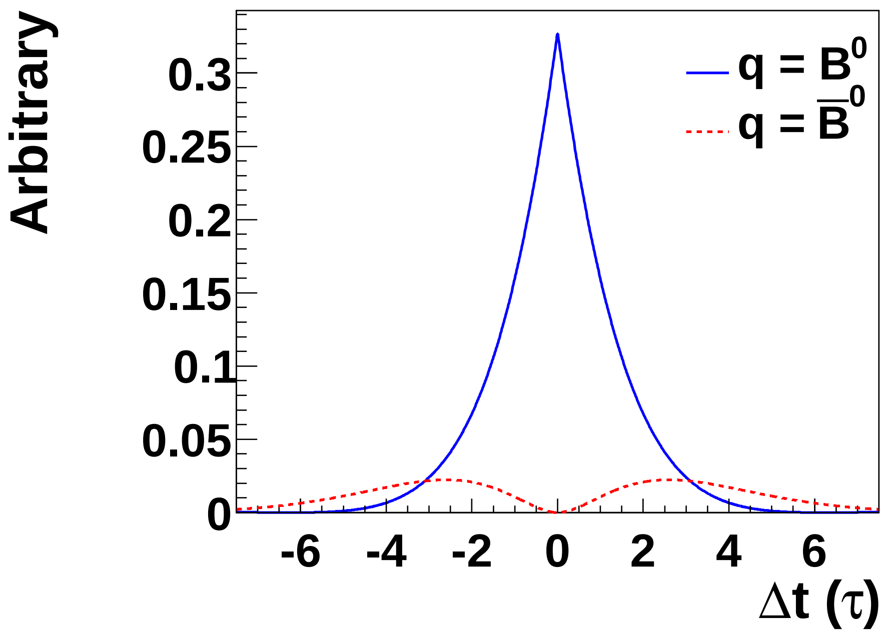
CP Violation in Δt

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d\Delta t + \mathcal{S}_{CP}\sin\Delta m_d\Delta t\right)\right]$$

$q = +1(-1)$ for $B^0(\bar{B}^0)$

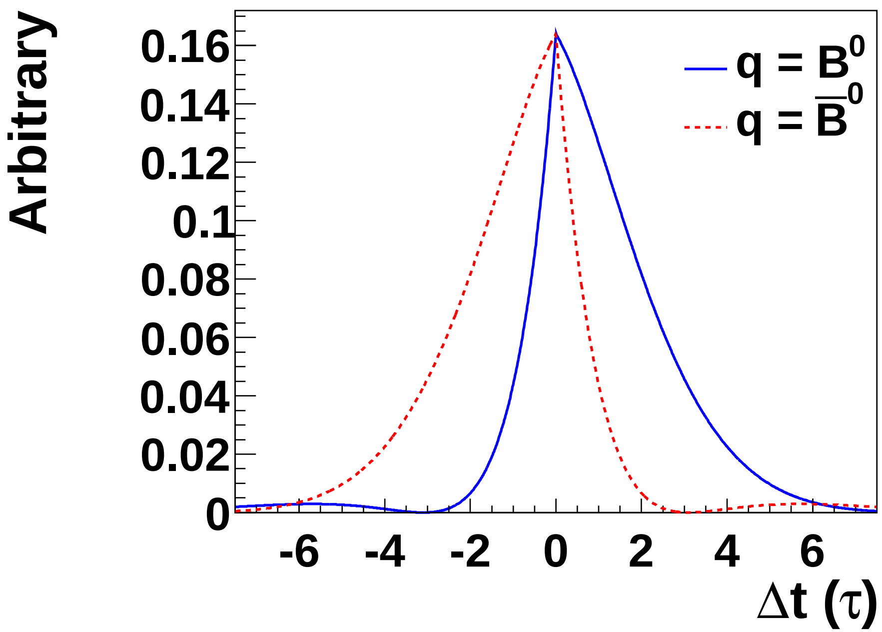
If no CP violation, Δt distributions are identical

$(\mathcal{A}_{CP}, \mathcal{S}_{CP}) = (1, 0)$



Don't need Δt to see $\mathcal{A}_{CP}$

$(\mathcal{A}_{CP}, \mathcal{S}_{CP}) = (0, 1)$



Need Δt to see $\mathcal{S}_{CP}$

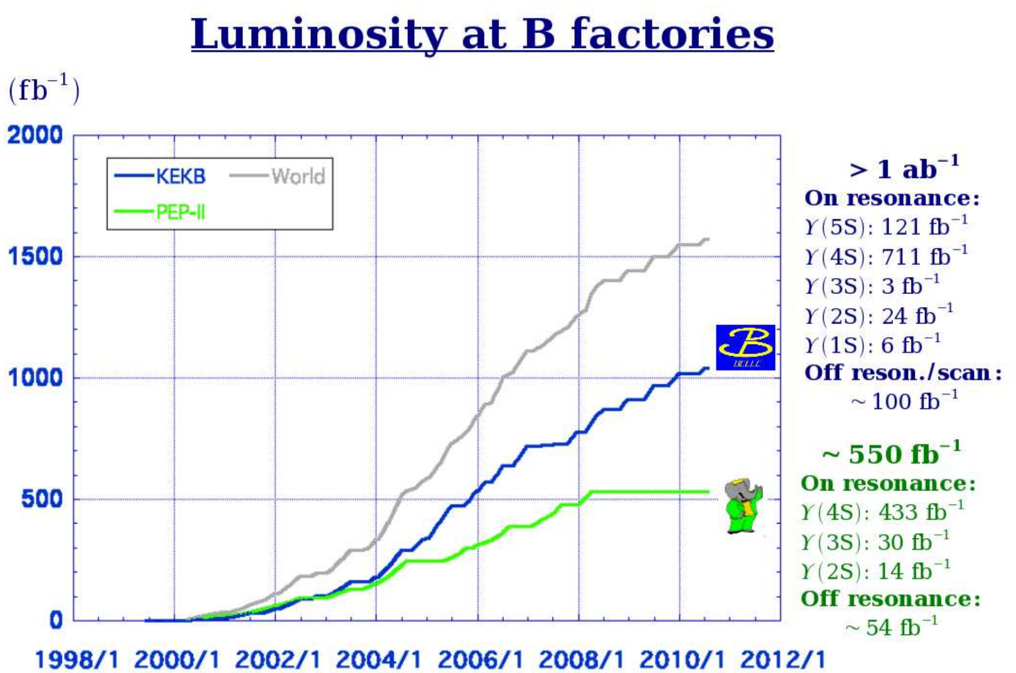
KEKB Accelerator

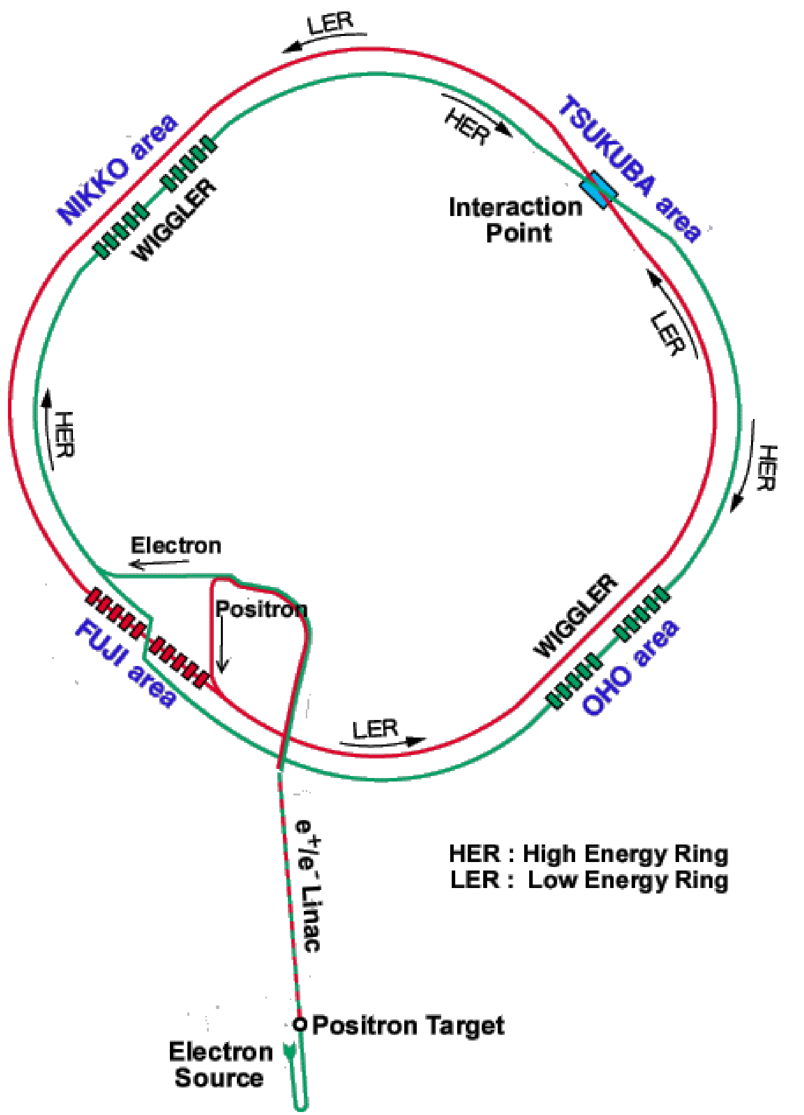
Asymmetric energy e^+e^- (3.5 on 8 GeV) collider

- $B\bar{B}$ separation increased to $\sim 200\ \mu\mathrm{m}$

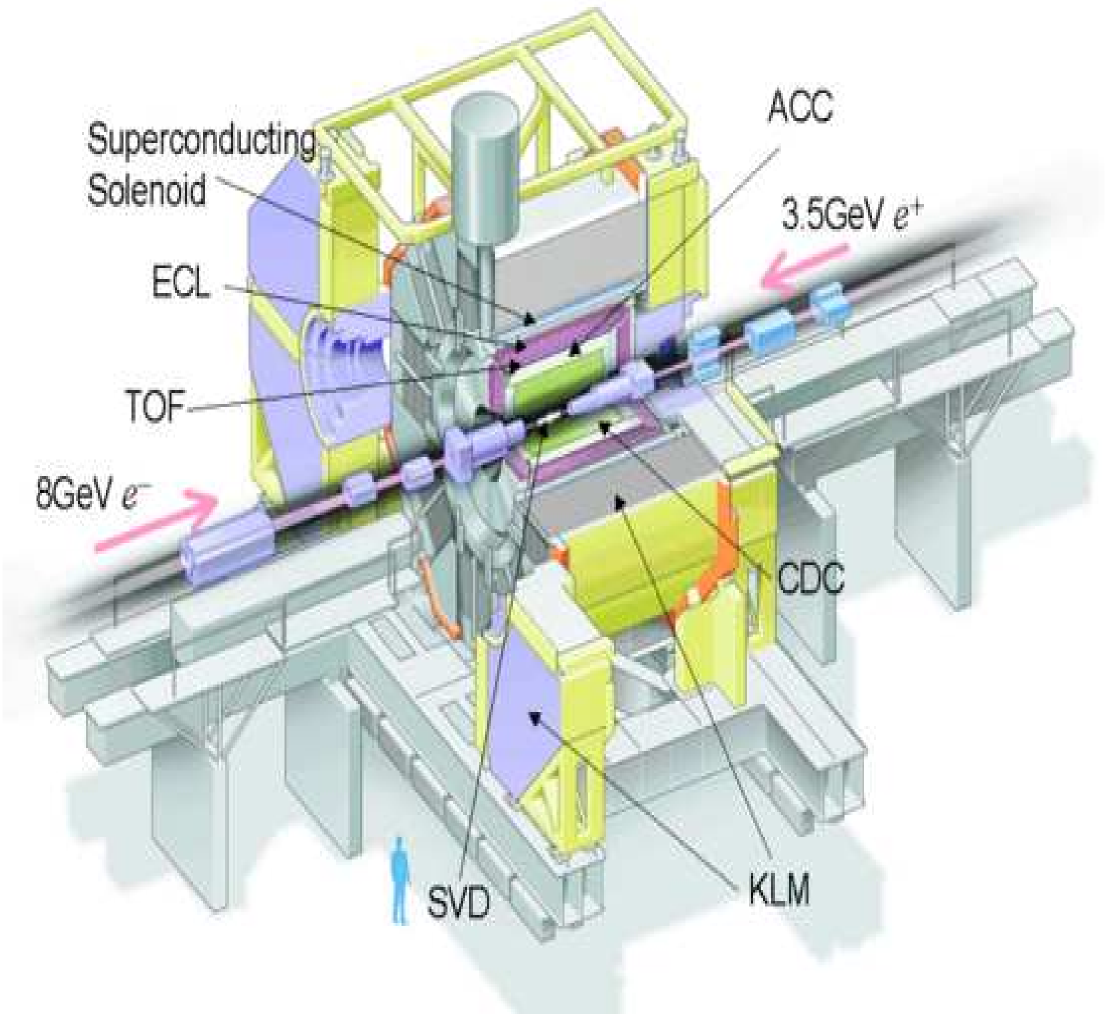
World record peak luminosity $2.1 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Largest sample of $772 \times 10^6\ B\bar{B}$ pairs





Belle Detector



Silicon Vertex Detector (SVD)

Precision vertexing

Central Drift Chamber (CDC)

Tracking, p measurement, particle ID

Aerogel Čerenkov Counter (ACC)

High momentum particle ID

Time of Flight Counter (TOF)

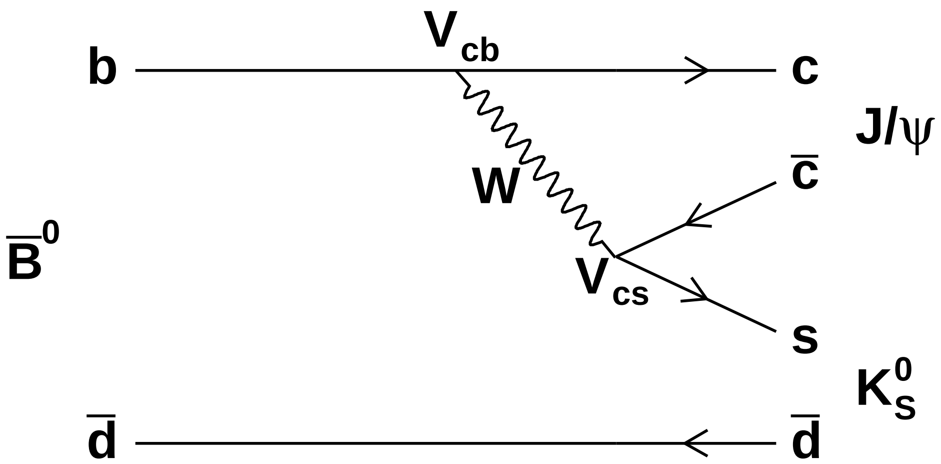
Low momentum particle ID

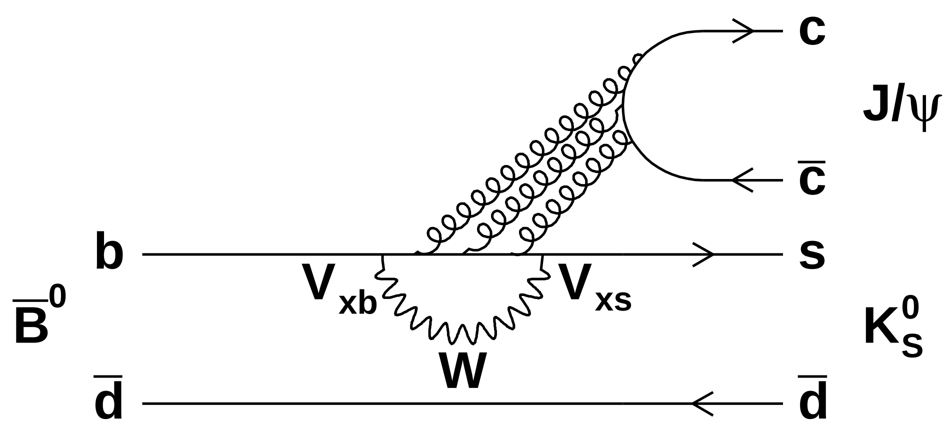
Electromagnetic Calorimeter (ECL)

e, γ ID

K_L^0 and Muon Detector (KLM)

$b \to c\bar{c}s$

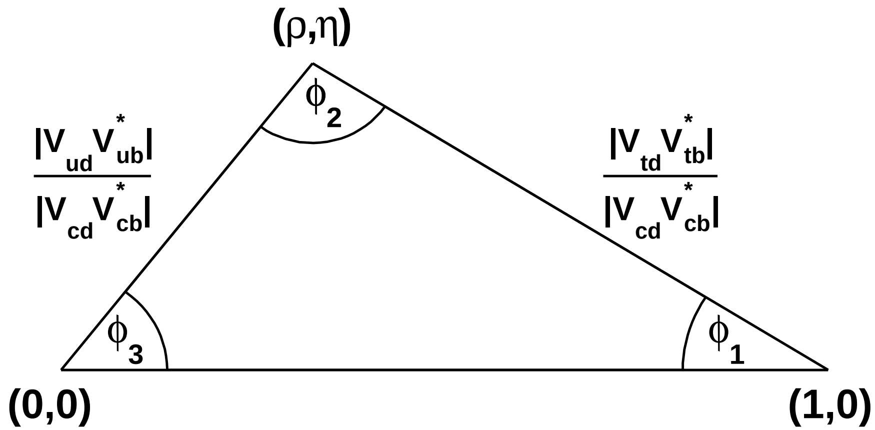




Theoretically clean, relatively free from penguins

Experimentally clean, relatively free from background

$$\begin{aligned}\lambda_{CP} &= \left(\frac{q}{p}\right)_{B^0}\left(\frac{\overline{A}_f}{A_f}\right)\left(\frac{q}{p}\right)_{K^0} \\ &= \frac{V_{td}V_{tb}^*}{V_{td}^*V_{tb}}\;\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\;\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}} \\ &= e^{-i2\phi_1}\end{aligned}$$



$b \to c\bar{c}s$

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\Big(\mathcal{A}_{CP}\cos\Delta m_d\Delta t + \mathcal{S}_{CP}\sin\Delta m_d\Delta t\Big)\right]$$

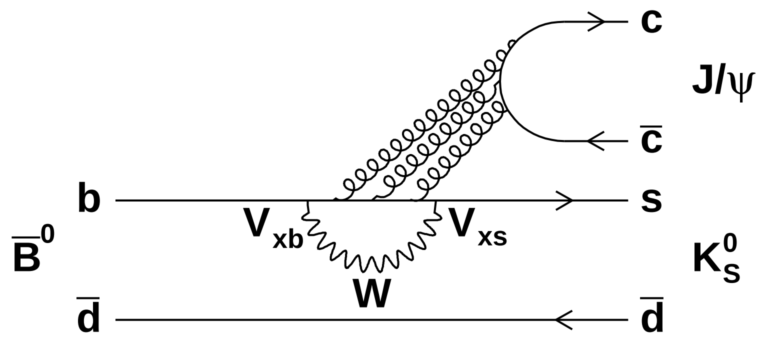
For tree amplitude,

$$\mathcal{A}_{CP} \equiv \frac{|\lambda_{CP}|^2 - 1}{|\lambda_{CP}|^2 + 1} = 0, \qquad \mathcal{S}_{CP} \equiv \frac{2\Im(\lambda_{CP})}{|\lambda_{CP}|^2 + 1} = \sin 2\phi_1$$

Important to note that measured $\mathcal{S}_{CP}$ is not strictly $\sin 2\phi_1$

Some penguin amplitudes carry a different weak phase

Non-zero $\mathcal{A}_{CP}$ possible and $\mathcal{S}_{CP}$ shifted from $\sin 2\phi_1$

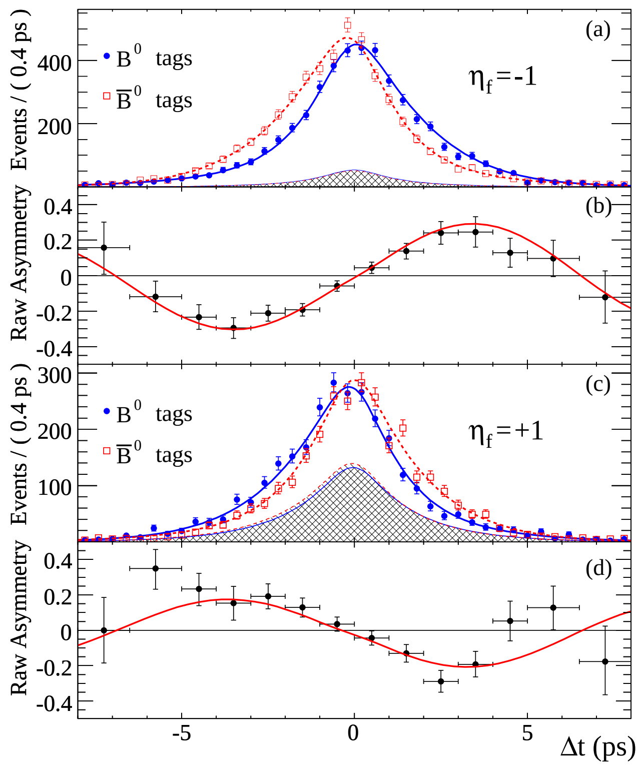


$b \to c\bar{c}s$

CP violation in the B sector first seen in $B^0 \to J/\psi K_S^0$

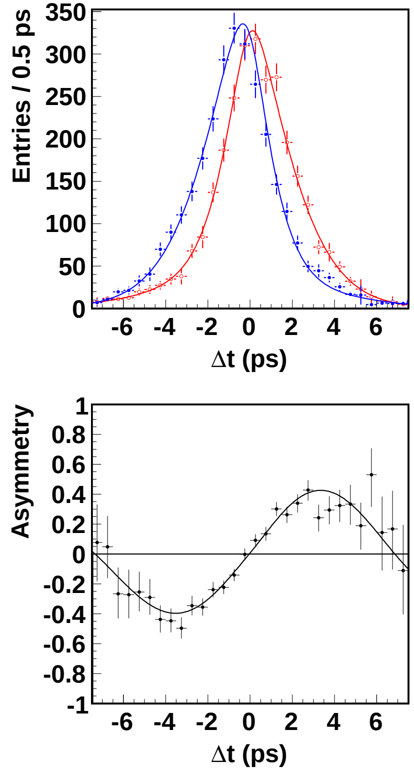
Final results from the B factories

BaBar, PRD **79** 072009 (2009)



$$\mathcal{S}_{CP} = 0.691 \pm 0.031$$

Belle, Moriond EW (2011)

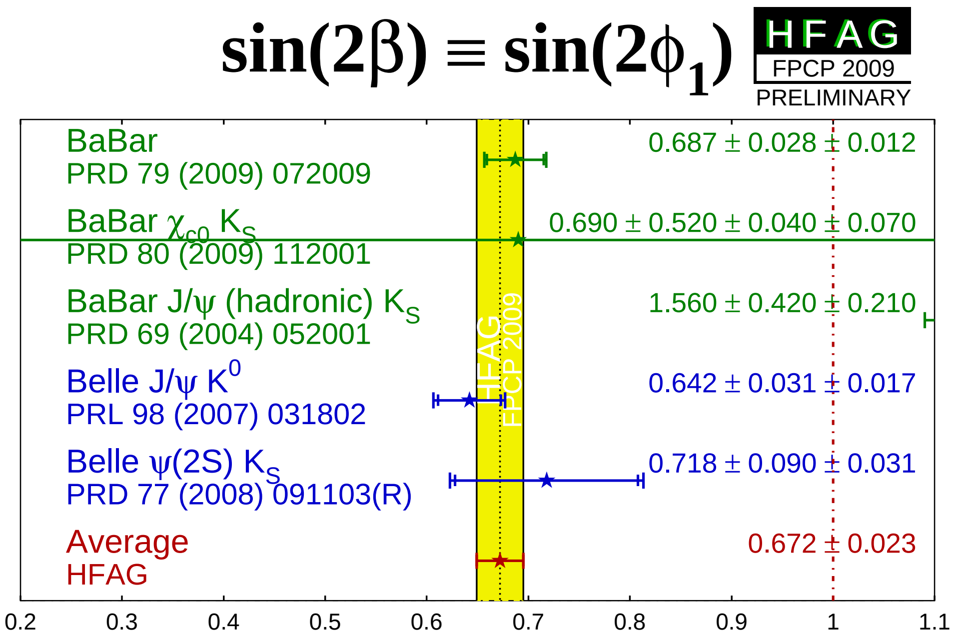


$$\mathcal{S}_{CP} = 0.671 \pm 0.029$$

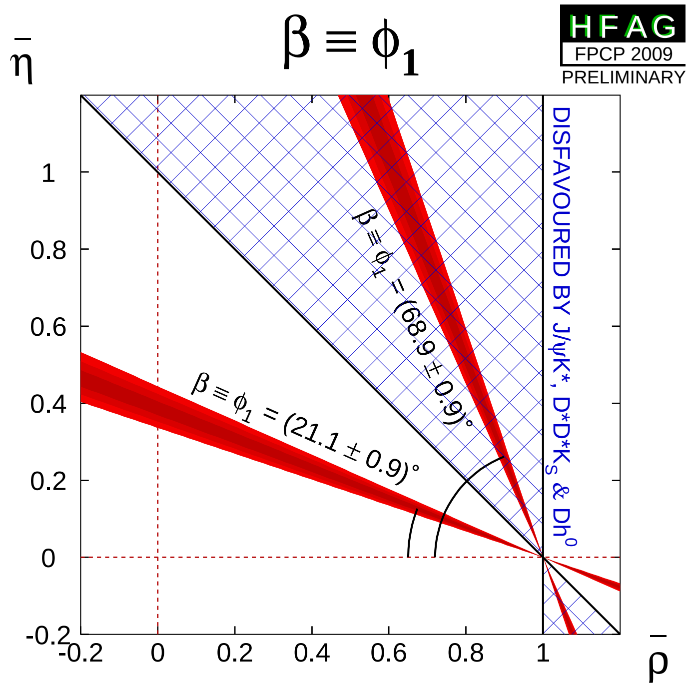
The Super Flavour Factories will push the uncertainty down to 1%

$b \to c\bar{c}s$

World average $\sin 2\phi_1$ from the B factories



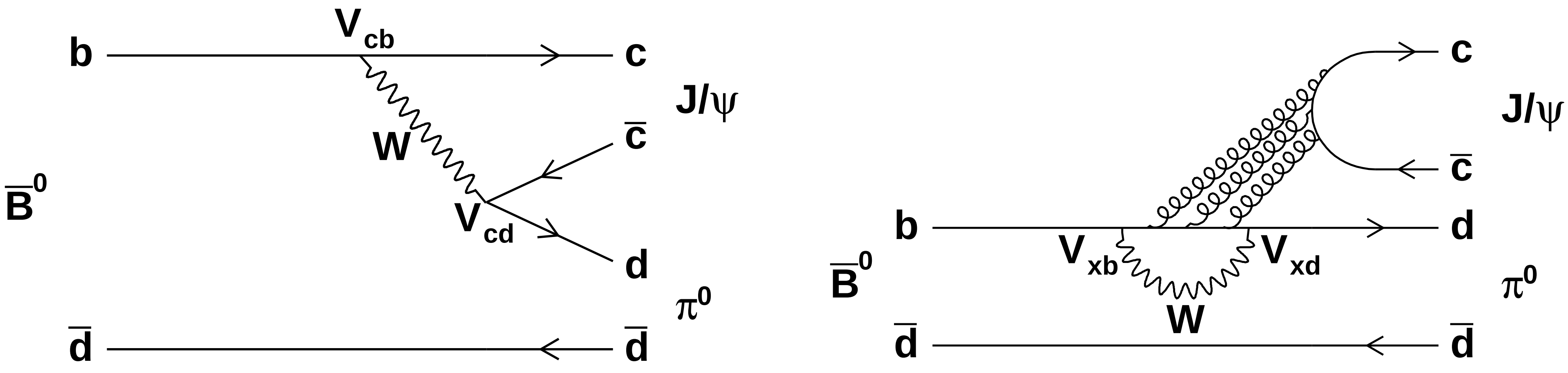
Measured $\sin 2\phi_1$ gives 2 solutions for ϕ_1



Ambiguity resolved by measuring $\cos 2\phi_1$

We (Martin Ritter :P) will talk about $B^0 \to D^{*+}D^{*-}K_S^0$ at DPG 2012

$b \to c\bar{c}d$



Sensitive to ϕ_1, just like $b \to c\bar{c}s$

For tree amplitude, expect $\mathcal{A}_{CP} = 0$, $\mathcal{S}_{CP} = \sin 2\phi_1$

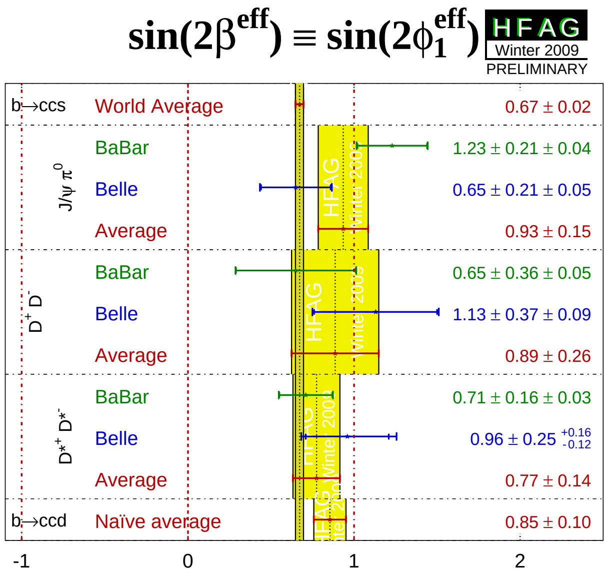
Additional motivation for studying charmonium $b \to (c\bar{c})d$

Using the results from $B^0 \to J/\psi\pi^0$ and $SU(3)$ symmetry, the penguin pollution in $B^0 \to J/\psi K_S^0$ can be estimated

We (Elena Nedelkovska-Cousins :P) will talk about $B^0 \to \psi(2S)\pi^0$ at DPG 2012

$b \to c\bar{c}d$

The B factories have evidence for CP violation in $b \to c\bar{c}d$



Color allowed $b \to c\bar{c}d$ modes covered by Karlsruhe

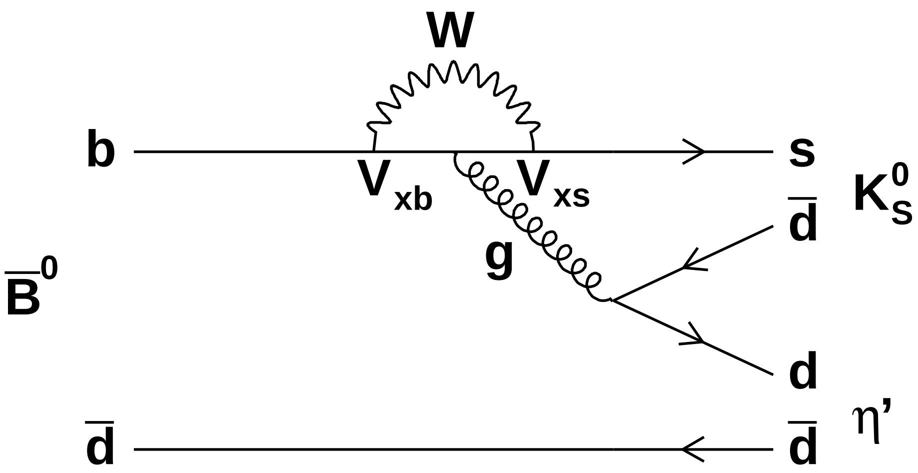
$B^0 \to D^+ D^-$ by Marcus Röhrken

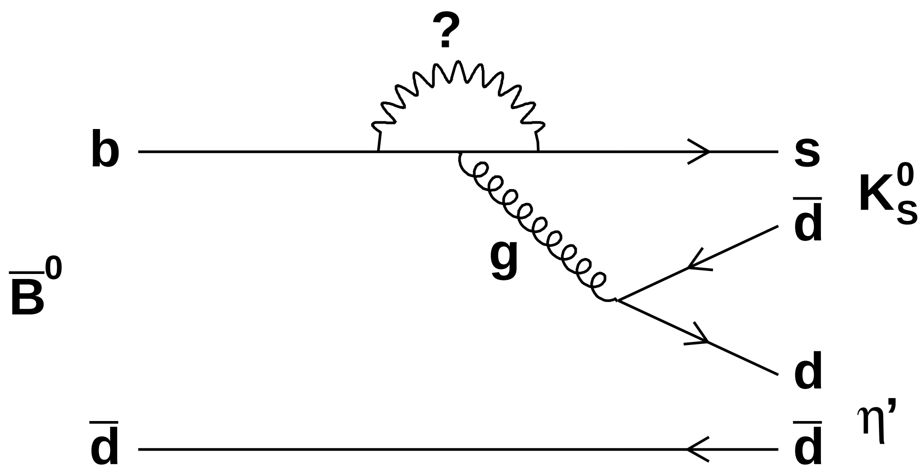
$B^0 \to D^{*+} D^{*-}$ by Bastian Kronenbitter

$B^0 \to D^{*\pm} D^{\mp}$ by Daniel Stemmer

$b \to sq\bar{q}$

Flavour Changing Neutral Currents forbidden at tree level





Penguin amplitudes highly sensitive to New Physics

Could be affected by a heavy unknown particle in the loop

Standard Model: $A_f = \sum_{q=u,c,t} V_{qb}^* V_{qs} P_q$, Apply unitarity constraint: $\sum_{q=u,c,t} V_{qb}^* V_{qs} = 0$

$$V_{ub}^* V_{us} \ll V_{cb}^* V_{cs} \text{ and } t\text{-quark dominance} \Rightarrow \frac{\bar{A}_f}{A_f} = \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}$$

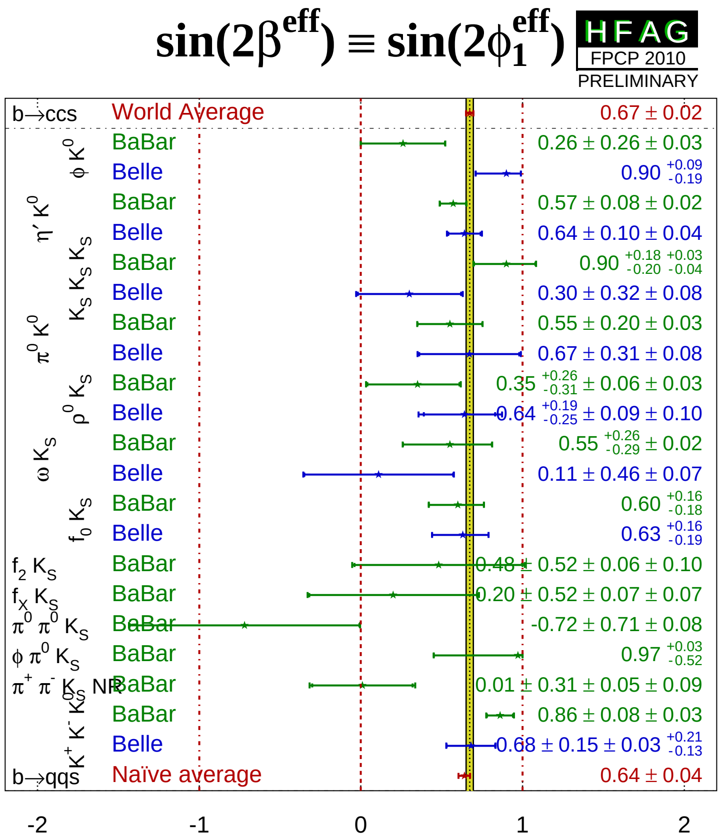
$\mathcal{S}_{CP} = \sin 2\phi_1$, same as $b \to c\bar{c}s$

$b \to sq\bar{q}$

Predicted in SM to have higher CP asymmetries than $b \to c\bar{c}s$

hep-ph/0707.1323, hep-ph/0702252

Mode	$\mathcal{S}_{CP} - \sin 2\phi_1$
$B^0 \to \eta' K^0_S$	0.01 ± 0.01
$B^0 \to \phi K^0_S$	0.02 ± 0.01
$B^0 \to \omega K^0_S$	0.13 ± 0.08
$B^0 \to \rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$
$B^0 \to K^0_S \pi^0$	$0.07^{+0.05}_{-0.04}$
$B^0 \to K^+ K^- K^0_S$	$0.03^{+0.02}_{-0.03}$
$B^0 \to K^0_S K^0_S K^0_S$	$0.02^{+0.02}_{-0.03}$
$B^0 \to K^0_S \pi^0 \pi^0$	$0.03^{+0.02}_{-0.03}$



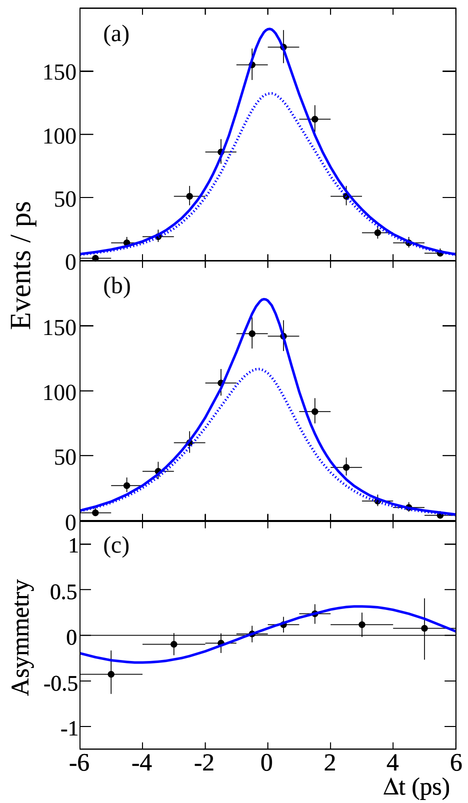
But most $b \to sq\bar{q}$ measurements below $b \to c\bar{c}s$ measurements

More experimental precision required

$b \to sq\bar{q}$

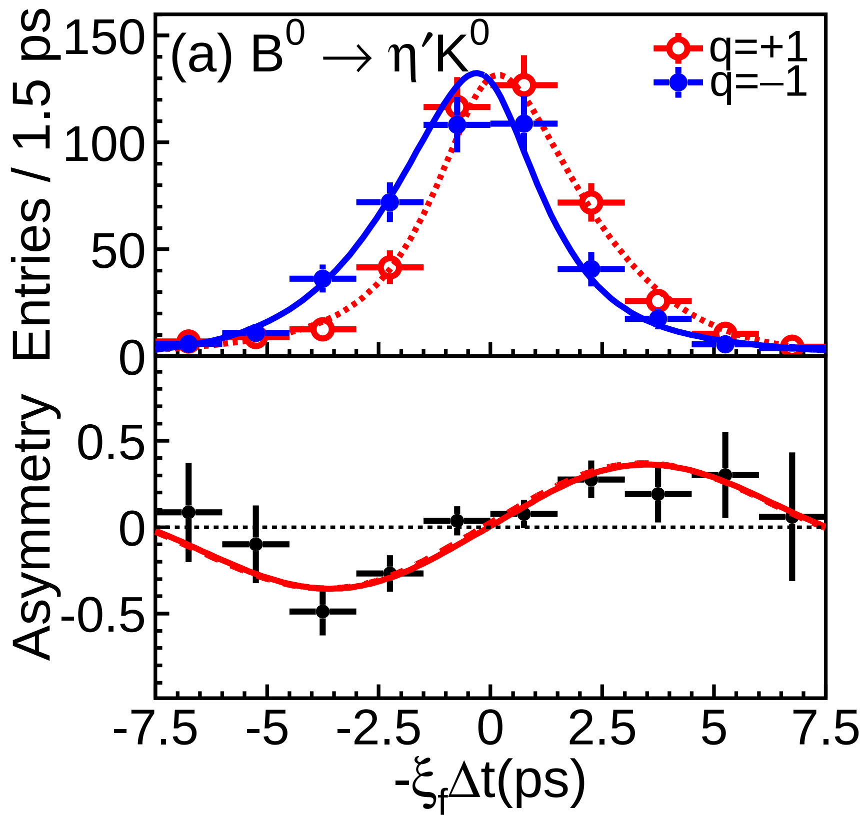
The B factories have observed CP violation in 1 mode, $B^0 \to \eta' K^0_S$

BaBar, PRD **79** 052003 (2009)



$$\mathcal{S}_{CP} = 0.57 \pm 0.08 \pm 0.02$$

Belle, PRL **98** 031802 (2007)



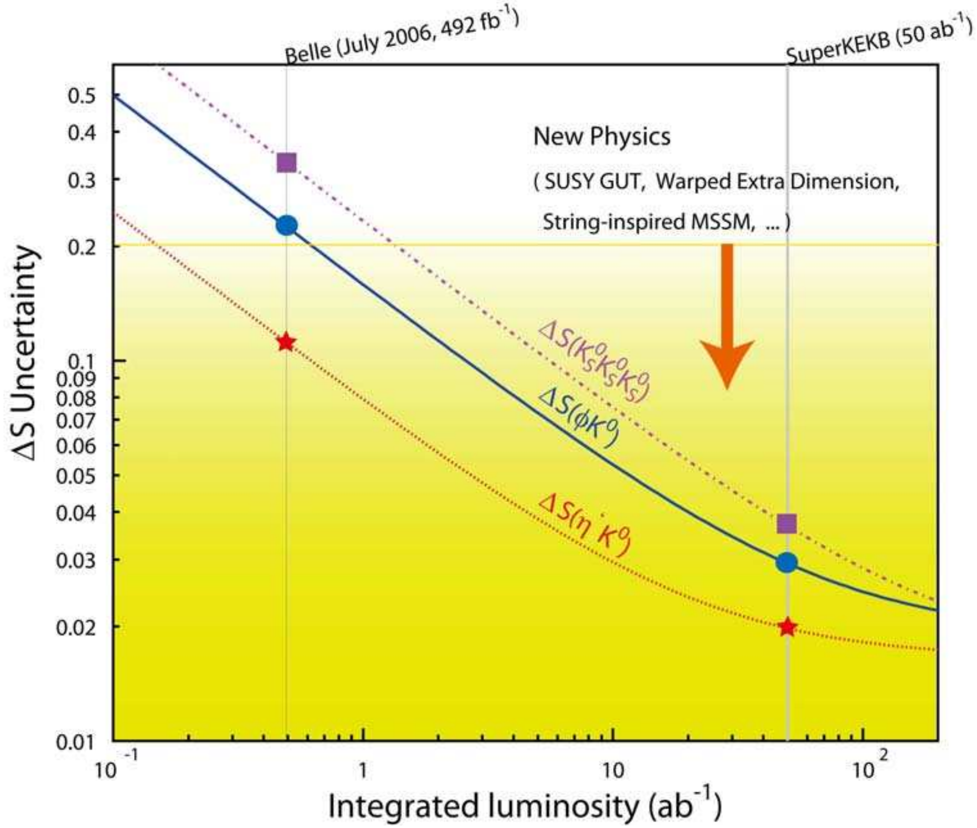
$$\mathcal{S}_{CP} = 0.64 \pm 0.10 \pm 0.04$$

We (Ver :P) will talk about $B^0 \to \omega K^0_S$ tomorrow

$b \to sq\bar{q}$

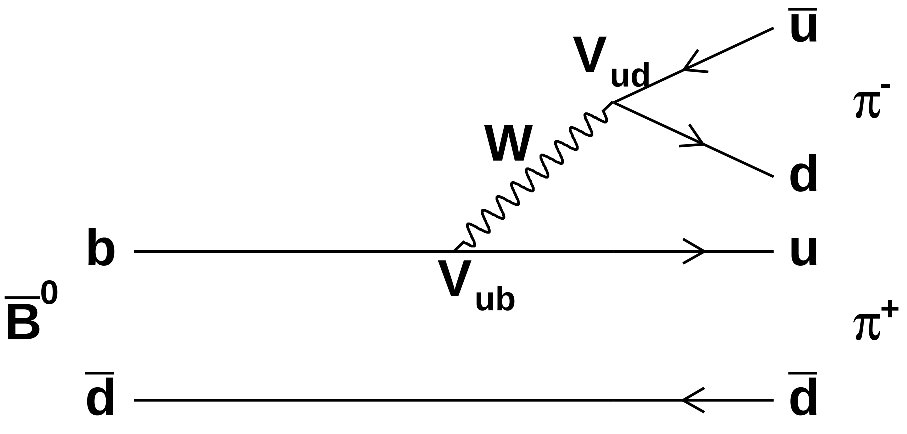
Search for a NP phase with the variable,

$$\Delta\mathcal{S} \equiv \mathcal{S}_{CP}(b \to sq\bar{q}) - \mathcal{S}_{CP}(B^0 \to J/\psi K_S^0)$$

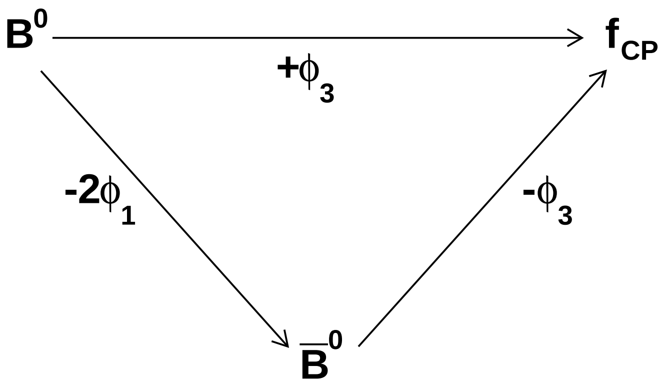


We will be sensitive to a deviation as small as $\Delta\mathcal{S} \sim 0.1$

$b \to u\bar{u}d$



V_{ub} carries the phase $e^{-i\phi_3}$



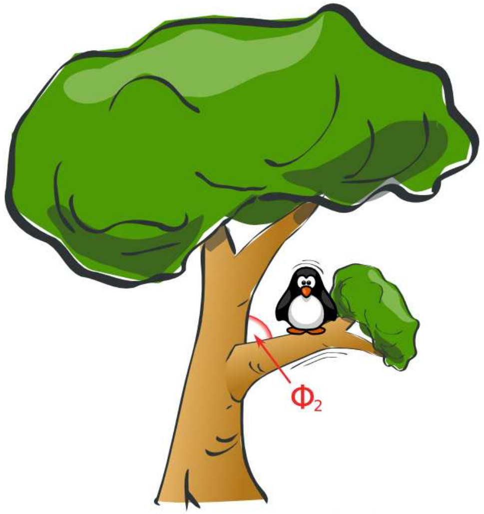
For tree amplitude,

The phase difference is $-2\phi_1 - \phi_3 - \phi_3$

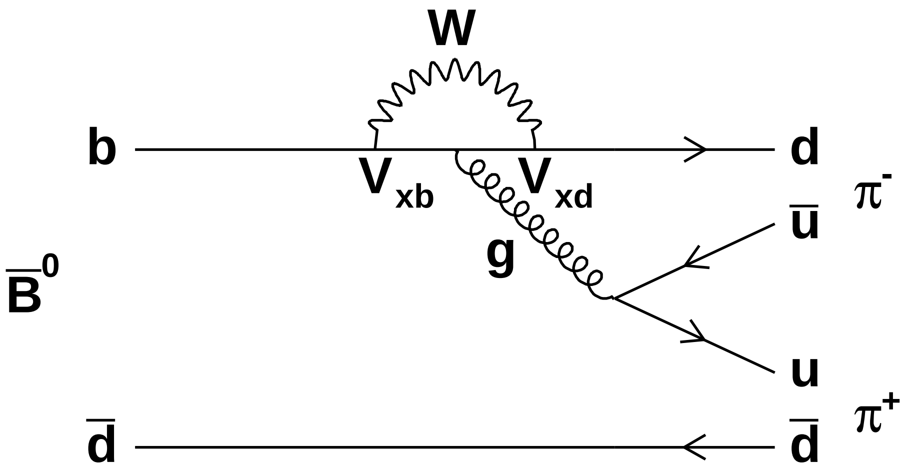
Assuming a closed triangle, $2\phi_1 + 2\phi_3 = 2\pi - 2\phi_2$

Expect $\mathcal{A}_{CP} = 0, \mathcal{S}_{CP} = \sin 2\phi_2$

$b \to u\bar{u}d$



How the penguin distorts the tree level measurement



Both tree and penguin amplitudes may contribute to the final state

Tree and penguin amplitudes carry different strong and weak phases

Direct CP violation, $\mathcal{A}_{CP} \neq 0$, is possible

Measure an effective ϕ_2

$$\mathcal{S}_{CP} = \sqrt{1 - \mathcal{A}_{CP}^2}\sin(2\phi_2 - 2\Delta\phi_2) = \sqrt{1 - \mathcal{A}_{CP}^2}\sin 2\phi_2^{\rm eff}$$

$b \to u\bar{u}d$

Can recover ϕ_2 with an SU(2) isospin analysis

M. Gronau and D. London, PRL **65**, 3381 (1990)

Neglecting isospin breaking effects

Set of $B \to \pi^+\pi^-, \pi^+\pi^0, \pi^0\pi^0$ decays obey the amplitude relations

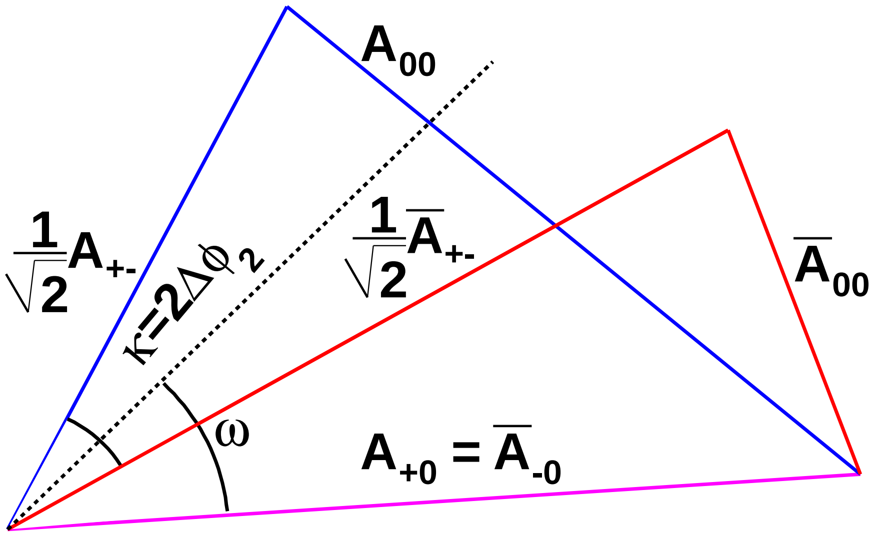
$$A_{+0} = \frac{1}{\sqrt{2}}A_{+-} + A_{00}, \quad \bar{A}_{-0} = \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00}$$

$B^0 \to \pi^+\pi^0$ is a pure tree

Triangle bases align

$\Delta\phi_2$ can be measured

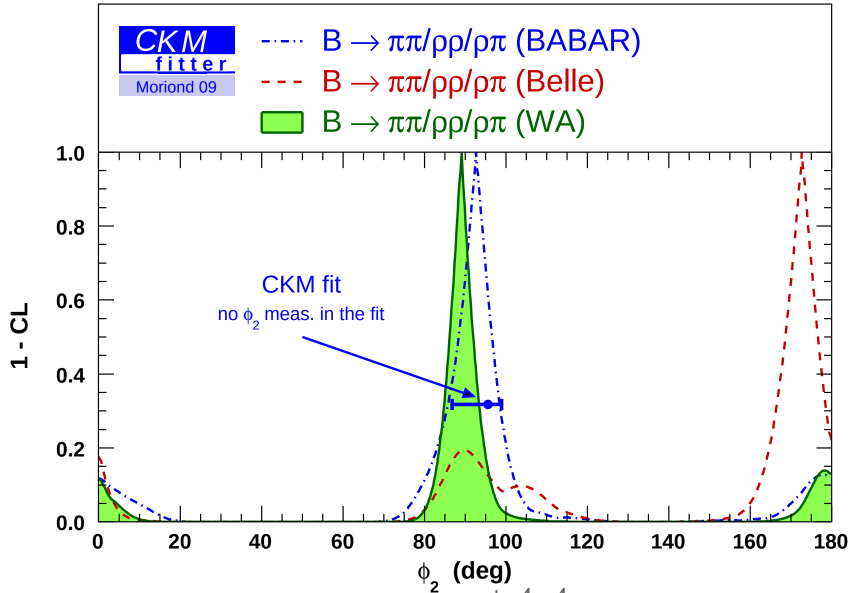
ϕ_2 determined up to an 8-fold ambiguity



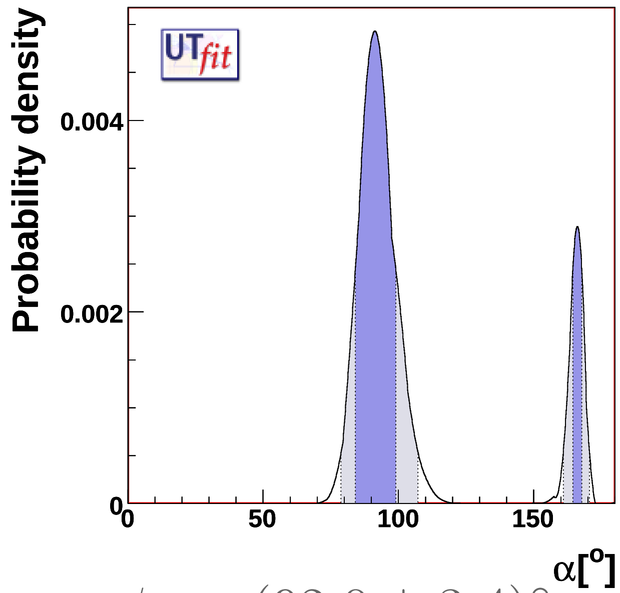
$b \to u\bar{u}d$

ϕ_2 measurements highlight the success of the Standard Model

Measured ϕ_2 in good agreement with SM prediction



$\phi_2 = (89.0^{+4.4}_{-4.2})^\circ$



$\phi_2 = (92.0 \pm 3.4)^\circ$

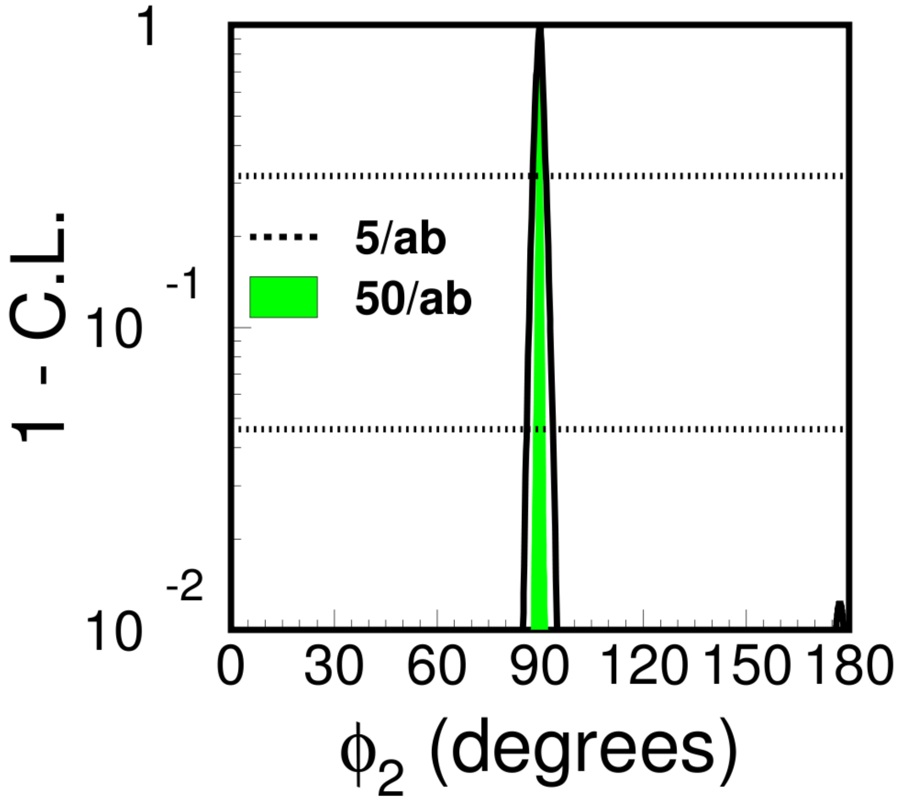
Other $b \to u\bar{u}d$ modes covered by MPI

$B^0 \to \pi^+\pi^-$ by Kolja Prothmann

$B^0 \to \rho^0\rho^0$ by Pit Vanhoefer

$b \to u\bar{u}d$

Expected ϕ_2 with $50\ \mathrm{ab}^{-1}$



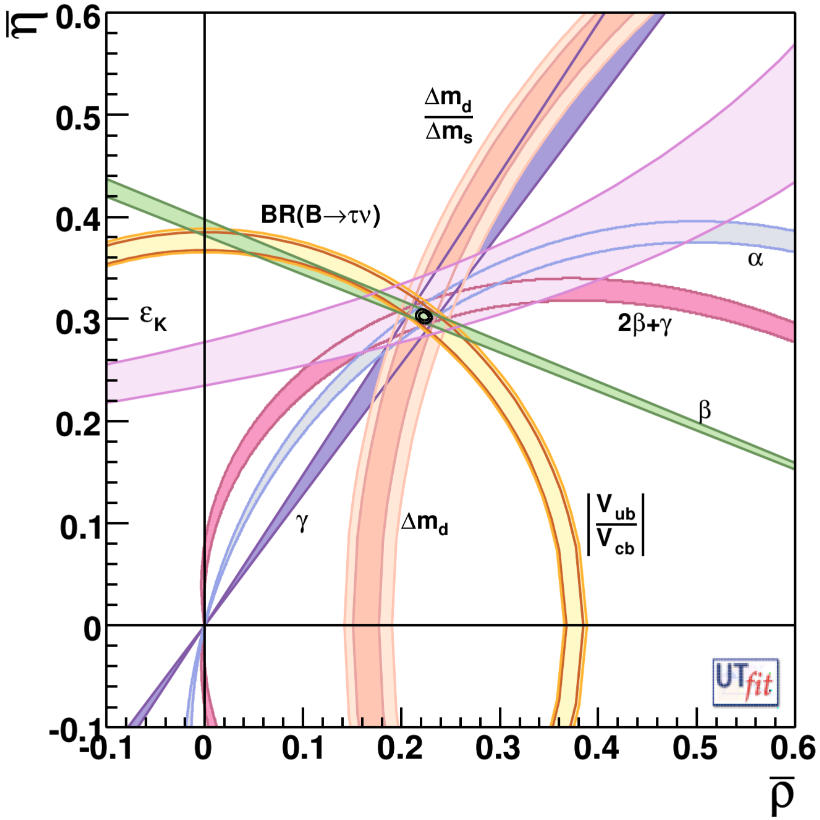
The uncertainty will go down to $\sim 1^\circ$

Roughly the same order as isospin breaking effects

After the Super Flavour Factories ...

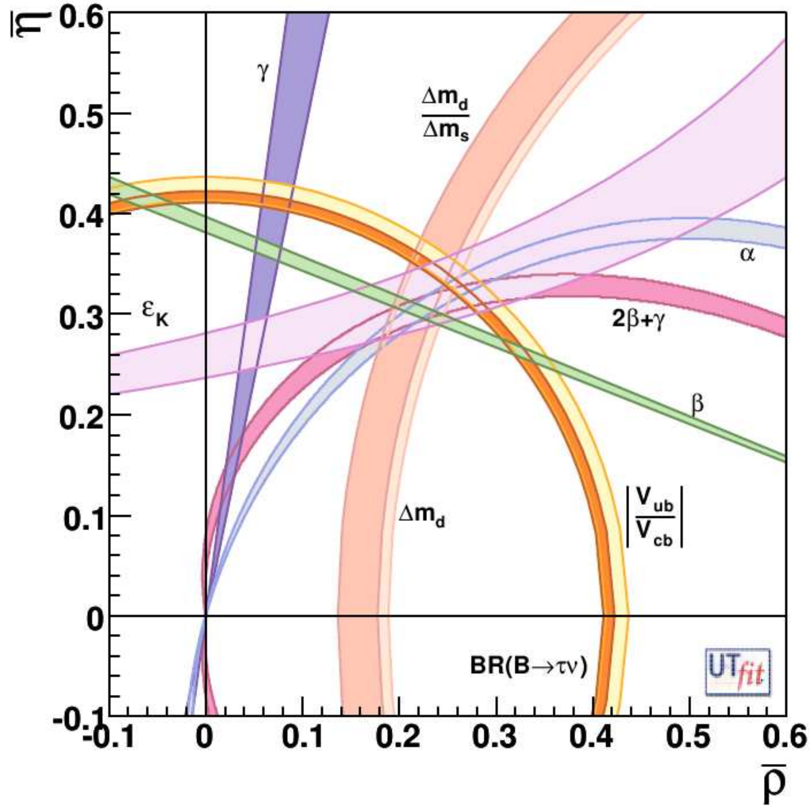
The CKM paradigm is correct

Measurements move to Standard Model expectations



New Physics is found!

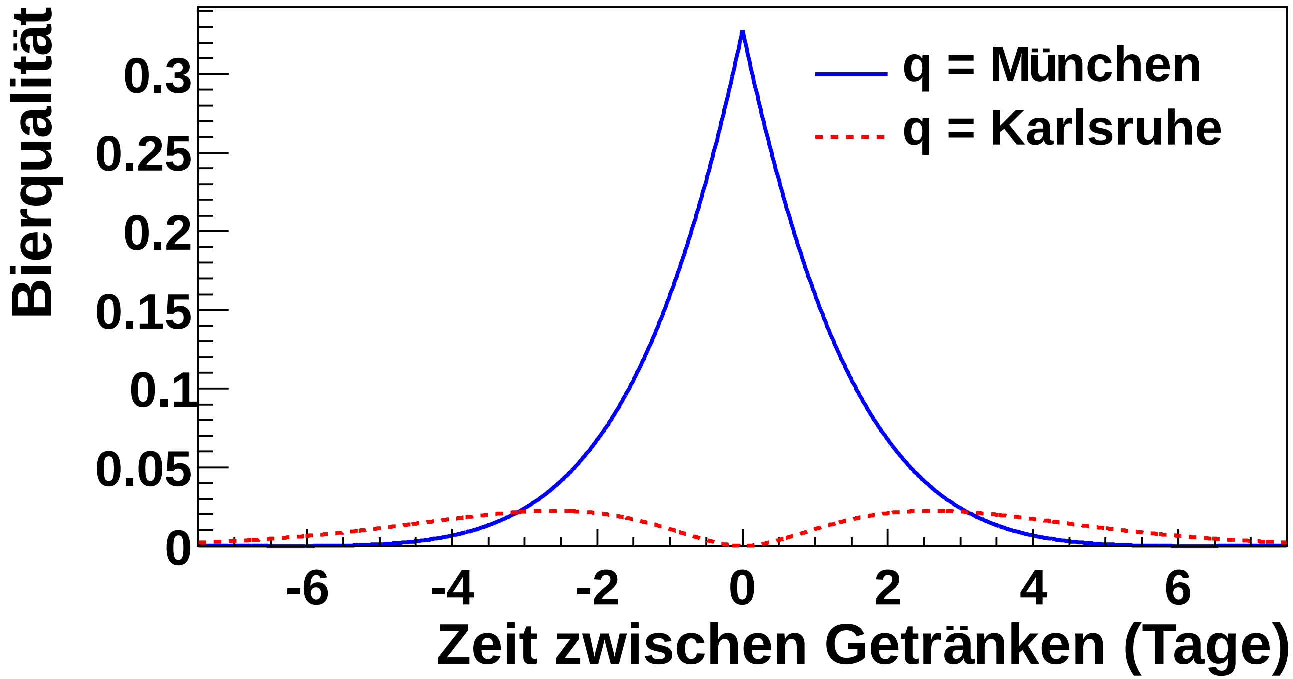
Disagreement between constraints in the Standard Model



Backup

Summary

Maximal Direct CP violation has been found in the Beer system (B system)!



Bayern des samma mir, Bayern und des bayrische Bier!

It is a direct consequence of the Bavarian Reinheitsgebot