Stiftung Preußischer Kulturbesitz

406. WE-HERAEUS-SEMINAR
PHYSICS AT THE TERASCALE

Heavy Flavour Physics at B-Factories and LHCb: Results and Plans

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GEFÖRDERT VOM
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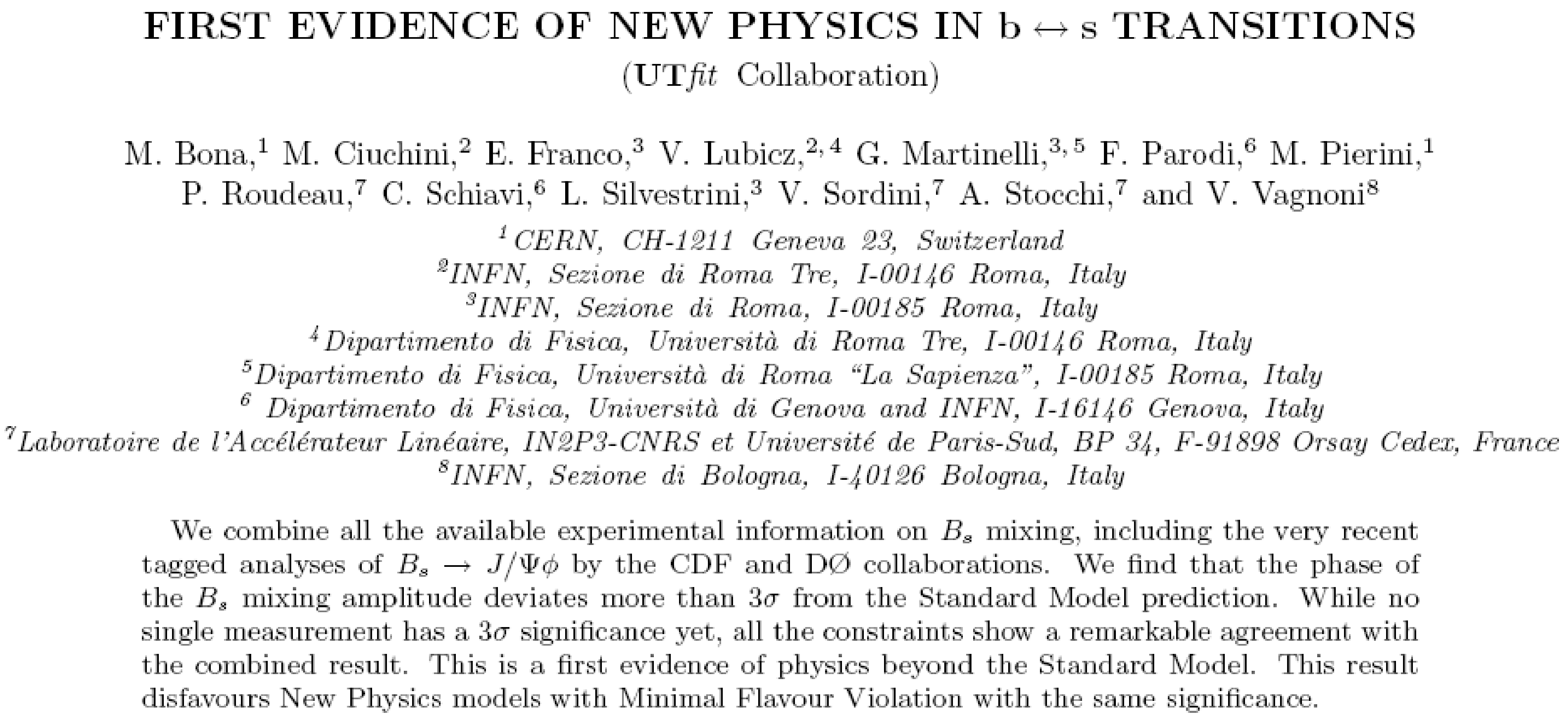
für Bildung
und Forschung

Motivation I



FIRST EVIDENCE OF NEW PHYSICS IN b $\leftrightarrow$ s TRANSITIONS

(**UT***fit* Collaboration)

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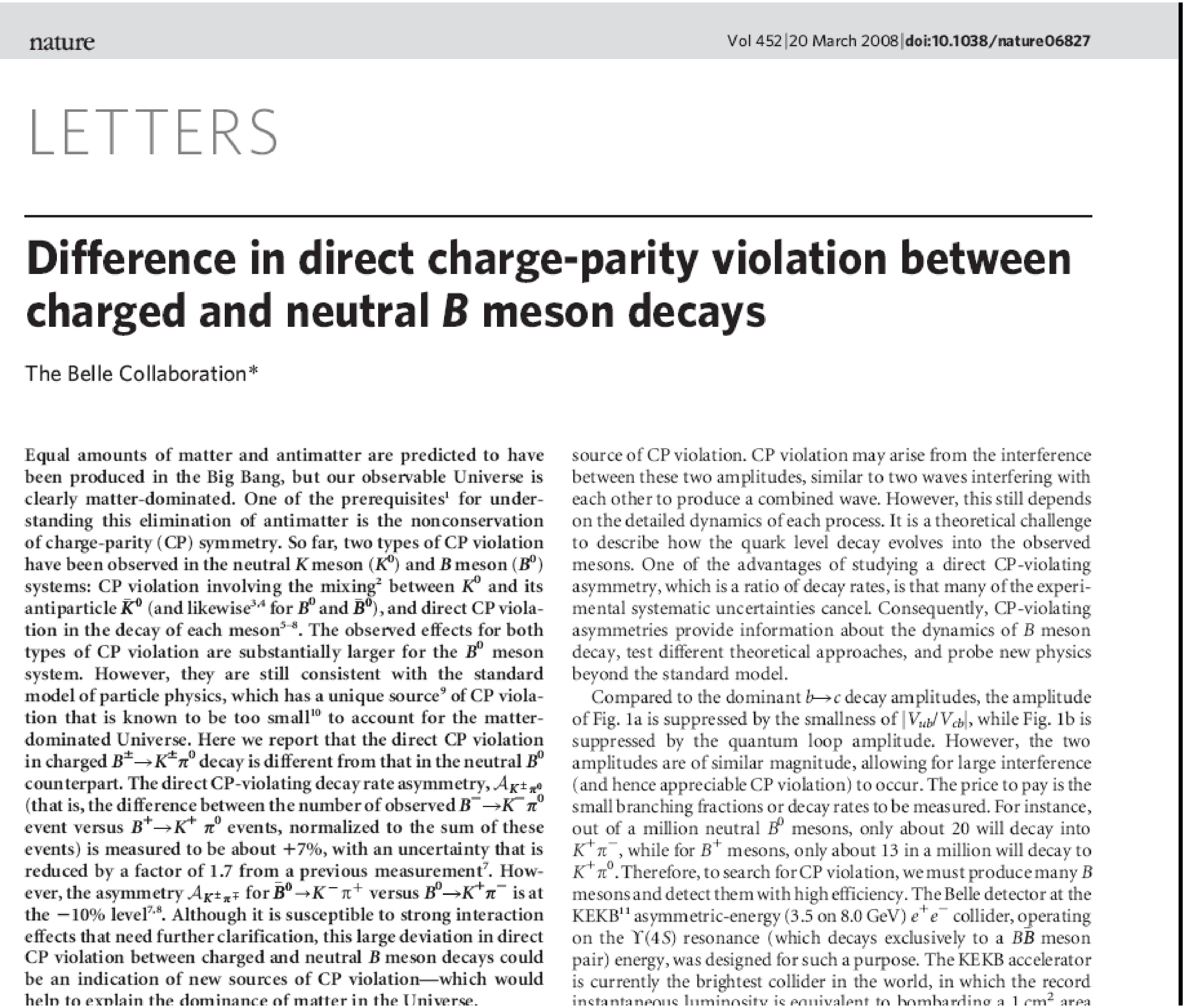
We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

Motivation II



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LETTERS

Difference in direct charge-parity violation between charged and neutral *B* meson decays

The Belle Collaboration*

Equal amounts of matter and antimatter are predicted to have been produced in the Big Bang, but our observable Universe is clearly matter-dominated. One of the prerequisites[1] for understanding this elimination of antimatter is the nonconservation of charge-parity (CP) symmetry. So far, two types of CP violation have been observed in the neutral K meson (K^0) and B meson (B^0) systems: CP violation involving the mixing[2] between K^0 and its antiparticle $\bar{K}^0$ (and likewise[3,4] for B^0 and $\bar{B}^0$), and direct CP violation in the decay of each meson[5–8]. The observed effects for both types of CP violation are substantially larger for the B^0 meson system. However, they are still consistent with the standard model of particle physics, which has a unique source[9] of CP violation that is known to be too small[10] to account for the matter-dominated Universe. Here we report that the direct CP violation in charged $B^\pm \to K^\pm \pi^0$ decay is different from that in the neutral B^0 counterpart. The direct CP-violating decay rate asymmetry, $\mathcal{A}_{K^\pm \pi^0}$ (that is, the difference between the number of observed $B^- \to K^- \pi^0$ event versus $B^+ \to K^+ \pi^0$ events, normalized to the sum of these events) is measured to be about +7%, with an uncertainty that is reduced by a factor of 1.7 from a previous measurement[7]. However, the asymmetry $\mathcal{A}_{K^\pm \pi^\mp}$ for $\bar{B}^0 \to K^- \pi^+$ versus $B^0 \to K^+ \pi^-$ is at the −10% level[7,8]. Although it is susceptible to strong interaction effects that need further clarification, this large deviation in direct CP violation between charged and neutral B meson decays could be an indication of new sources of CP violation—which would help to explain the dominance of matter in the Universe.

source of CP violation. CP violation may arise from the interference between these two amplitudes, similar to two waves interfering with each other to produce a combined wave. However, this still depends on the detailed dynamics of each process. It is a theoretical challenge to describe how the quark level decay evolves into the observed mesons. One of the advantages of studying a direct CP-violating asymmetry, which is a ratio of decay rates, is that many of the experimental systematic uncertainties cancel. Consequently, CP-violating asymmetries provide information about the dynamics of B meson decay, test different theoretical approaches, and probe new physics beyond the standard model.

Compared to the dominant $b \to c$ decay amplitudes, the amplitude of Fig. 1a is suppressed by the smallness of $|V_{ub}/V_{cb}|$, while Fig. 1b is suppressed by the quantum loop amplitude. However, the two amplitudes are of similar magnitude, allowing for large interference (and hence appreciable CP violation) to occur. The price to pay is the small branching fractions or decay rates to be measured. For instance, out of a million neutral B^0 mesons, only about 20 will decay into $K^+\pi^-$, while for B^+ mesons, only about 13 in a million will decay to $K^+\pi^0$. Therefore, to search for CP violation, we must produce many B mesons and detect them with high efficiency. The Belle detector at the KEKB[11] asymmetric-energy (3.5 on 8.0 GeV) e^+e^- collider, operating on the $\Upsilon(4S)$ resonance (which decays exclusively to a $B\bar{B}$ meson pair) energy, was designed for such a purpose. The KEKB accelerator is currently the brightest collider in the world, in which the record instantaneous luminosity is equivalent to bombarding a 1 cm^2 area

Motivation III

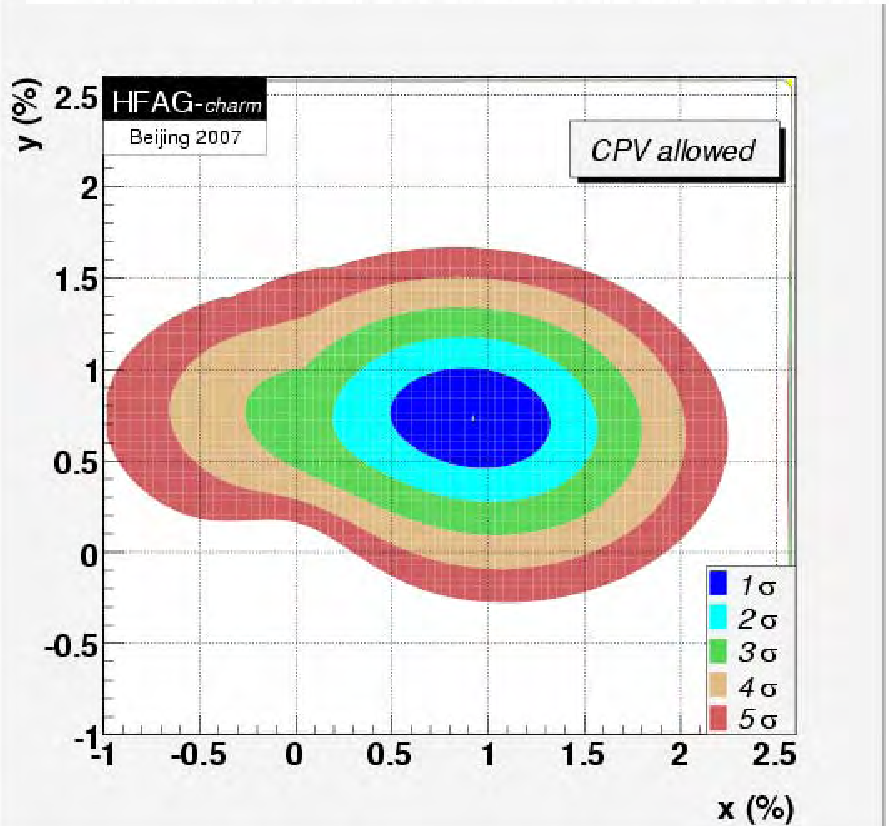
SLAC today

Tuesday - March 13, 2007

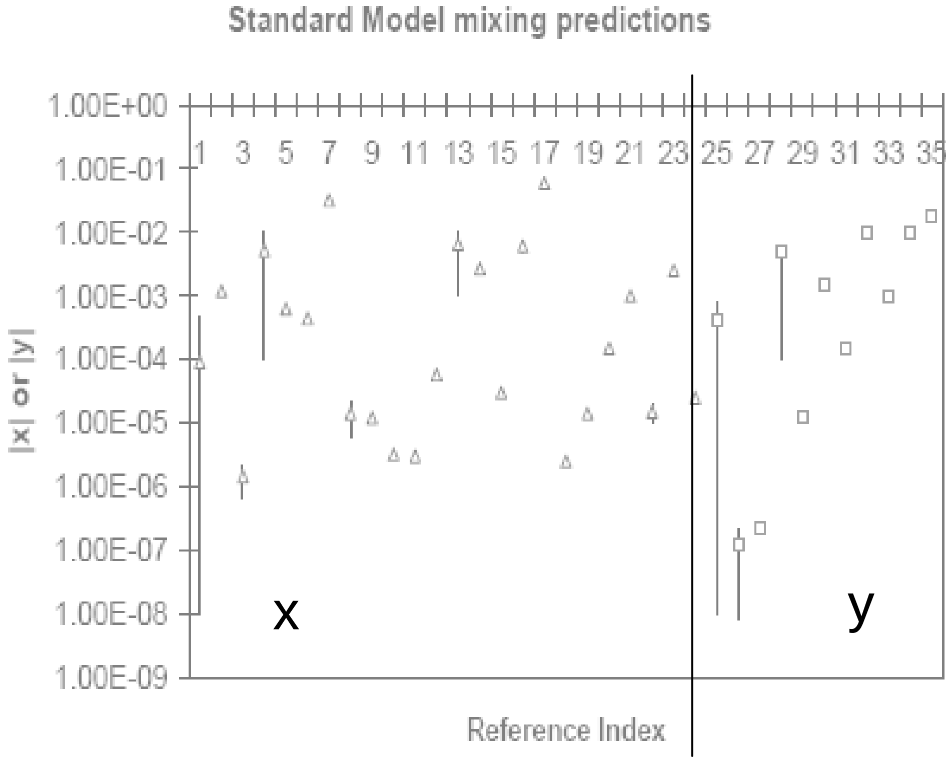
New Form of Matter-antimatter Transformation Observed

by Kelen Tuttle

For the first time, BaBar researchers have observed the transition of one type of particle, the neutral D-meson, into its antimatter particle. This observation will now be used as a test



D-Mixing may be compatible with high end of SM predictions

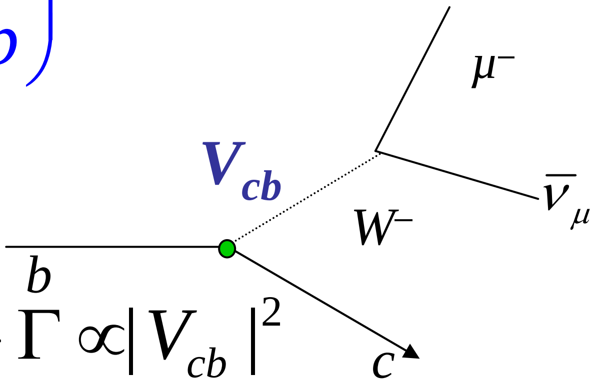


The Heart of SM Flavour Physics:
The Cabibbo Kobayashi Maskawa Matrix

weak eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

mass eigenstates



$$\Rightarrow \Gamma \propto |V_{cb}|^2$$

Origin of the CKM-Matrix: Higgs-Sector

- consequence of mass generation of fermions
- source of SM CP Violation

Fermion-Masses in the Standard Model

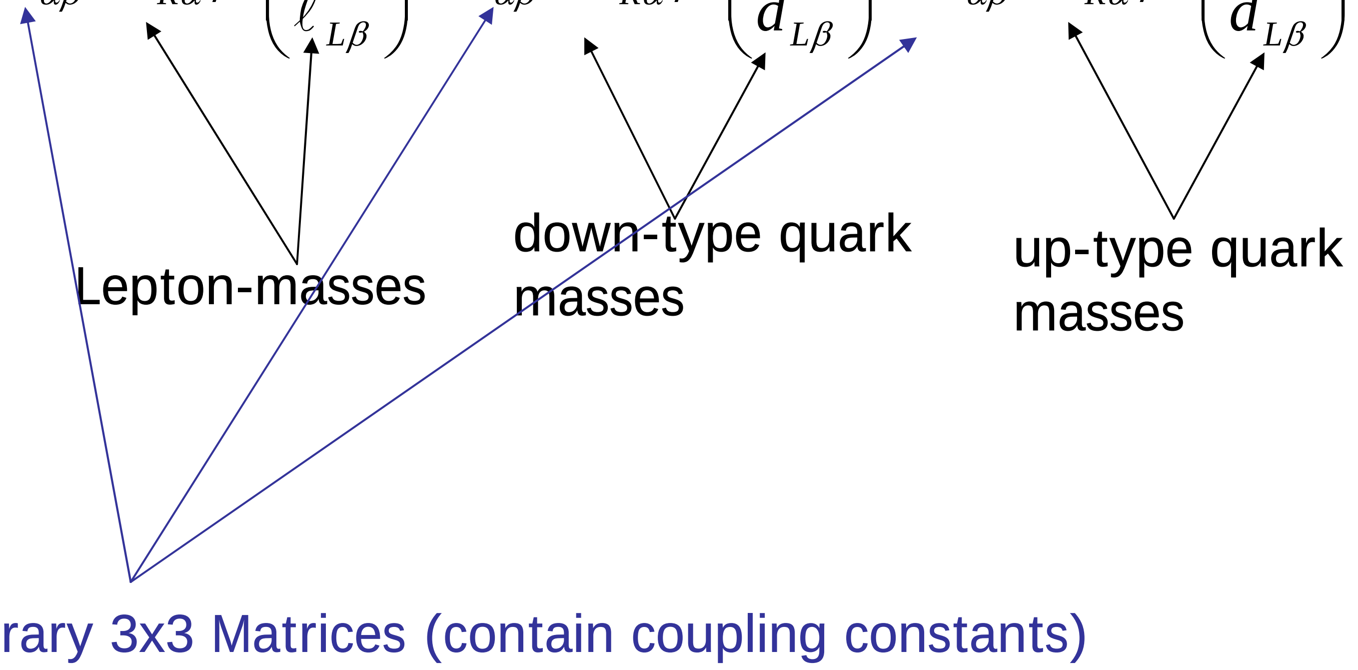
Gauge invariance requires that fermion mass terms in the Standard Model Lagragian enter via a Yukawa coupling to the Higgs field

Erweiterung auf 3 Familien: (masselose Neutrinos)

$$\mathcal{L}_{Yukawa} = -\left[C^{(\ell)}_{\alpha\beta} \cdot \overline{\ell}_{R\alpha}\phi^{\dagger}\begin{pmatrix}\nu_{L\beta}\\ \ell_{L\beta}\end{pmatrix} + C^{(d)}_{\alpha\beta} \cdot \overline{d}_{R\alpha}\phi^{\dagger}\begin{pmatrix}u_{L\beta}\\ d_{L\beta}\end{pmatrix} + C^{(u)}_{\alpha\beta} \cdot \overline{u}_{R\alpha}\overline{\phi}^{\dagger}\begin{pmatrix}u_{L\beta}\\ d_{L\beta}\end{pmatrix} + h.c. \right]$$

$$\phi = \begin{pmatrix}\phi_1\\ \phi_2\end{pmatrix};$$

$\alpha, \beta = 1,2,3.$
(3 families)



Lepton-masses

down-type quark masses

up-type quark masses

arbitrary 3x3 Matrices (contain coupling constants)

$$\mathcal{L}_{\text{Yukawa}} = -\left[C^{(\ell)}_{\alpha\beta}\cdot \bar{\ell}_{R\alpha}\phi^\dagger \begin{pmatrix} \nu_{L\beta} \\ \ell_{L\beta}\end{pmatrix} + C^{(d)}_{\alpha\beta}\cdot \bar{d}_{R\alpha}\phi^\dagger \begin{pmatrix} u_{L\beta} \\ d_{L\beta}\end{pmatrix} + C^{(u)}_{\alpha\beta}\cdot \bar{u}_{R\alpha}\bar{\phi}^\dagger \begin{pmatrix} u_{L\beta} \\ d_{L\beta}\end{pmatrix} + h.c. \right]$$

Invariant under unitary transformations in the 3-Families-space:

Leptons: $\ell_R \to U_1 \ell_R$ $\begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} \to U_2 \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix}$ $C_\ell \to U_1 C_\ell U_2^+$

Assuming massless neutrinos

➡ One can always find 2 transformations which diagonalize C_ℓ !

$$C^\ell = \begin{pmatrix} c_e & 0 & 0 \\ 0 & c_\mu & 0 \\ 0 & 0 & c_\tau \end{pmatrix} = \sqrt{\frac{2\lambda}{\mu^2}} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

Leptons:
mass-eigenstates
are
weak eigenstates!
(m_ν=0 assumed)

Quarks: up-type and down-type quarks have masses!

$$\mathcal{L}^{Quarks}_{Yukawa} = C^{(d)}_{\alpha\beta} \cdot \overline{d}'_{R\alpha}\phi^{\dagger}\begin{pmatrix} u'_{L\beta} \\ d'_{L\beta} \end{pmatrix} + C^{(u)}_{\alpha\beta} \cdot \overline{u}'_{R\alpha}\overline{\phi}^{\dagger}\begin{pmatrix} u'_{L\beta} \\ d'_{L\beta} \end{pmatrix}$$

3 unitary Transformations:

$$u'_R \to U_3 u'_R$$

$$d'_R \to U_4 d'_R$$

$$\begin{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \\ \begin{pmatrix} c_L \\ s_L \end{pmatrix} \\ \begin{pmatrix} t_L \\ b_L \end{pmatrix} \end{pmatrix} \to U_5 \begin{pmatrix} \begin{pmatrix} u_L \\ d_L \end{pmatrix} \\ \begin{pmatrix} c_L \\ s_L \end{pmatrix} \\ \begin{pmatrix} t_L \\ b_L \end{pmatrix} \end{pmatrix}$$

4 transformations are needed to diagonalize both matrices

Convention: diogonalize up-type matrix:

Additional matrix diagonalizes Down-type matrix

$$C_u = \begin{pmatrix} c_u & 0 & 0 \\ 0 & c_c & 0 \\ 0 & 0 & c_t \end{pmatrix} = \sqrt{\frac{2\lambda}{\mu^2}}\begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix}$$

$$C^{(d)} = V\begin{pmatrix} c_d & 0 & 0 \\ 0 & c_s & 0 \\ 0 & 0 & c_b \end{pmatrix}V^{+}$$

$$\mathcal{L}_{Yukawa} = -\left[\begin{pmatrix} \bar{e} & \bar{\mu} & \bar{\tau} \end{pmatrix} \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} + \begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix} \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} \begin{pmatrix} u \\ c \\ t \end{pmatrix} \right.$$

$$\left. + \begin{pmatrix} \bar{d}' & \bar{s}' & \bar{b}' \end{pmatrix} V \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix} V^\dagger \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} \right] \cdot \left(1 + \sqrt{\frac{\lambda}{\mu^2}} h \right)$$

Cabibbo Kobayashi Maskawa Matrix CKM

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V\,V^\dagger = 1$$

CP-Violation in the Standard Model

Standard model: Origin of CP-Violation: Higgs-Sector!
by **C**abibbo **K**obayashi **M**askawa (CKM) Matrix

weak eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

mass eigenstates

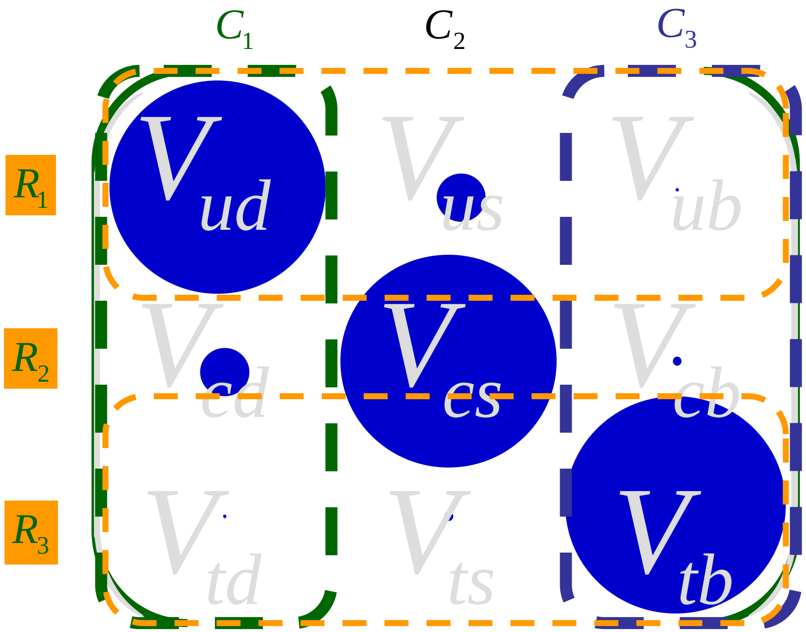
CKM Matrix:

- complex
- unitary
  - 4 parameters:
    - 3 Euler angles
    - 1 Phase → **~~CP~~**

⇒ difference for quarks and antiquarks $V_{ij} \rightarrow V_{ij}^*$
⇒ origin of CP violation
⇒ CP violation will only show up due to interference

CP-Violation in the Standard Model

Unitarity test of the CKM-Matrix:



6 unitarity conditions:

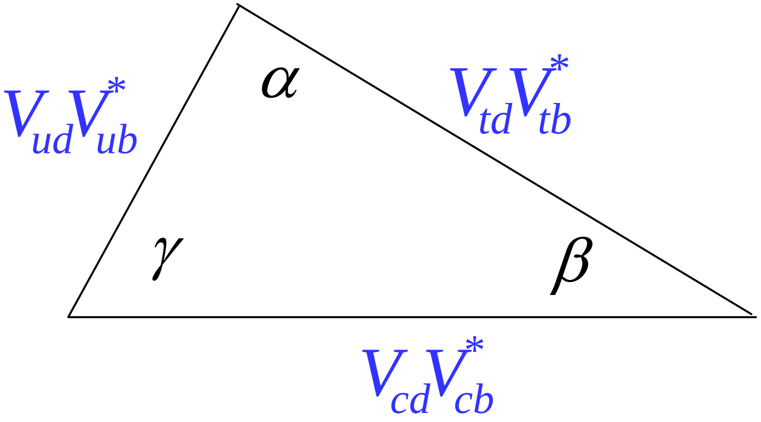
$$V^+V=1 \Rightarrow \begin{array}{l} \vec{R}_i\cdot\vec{R}^*_{j\neq i}=0 \\ \vec{C}_i\cdot\vec{C}^*_{j\neq i}=0 \end{array}$$

$$\boxed{\vec{C}_1}\cdot\boxed{\vec{C}_3^*}=0$$

$$\Downarrow$$

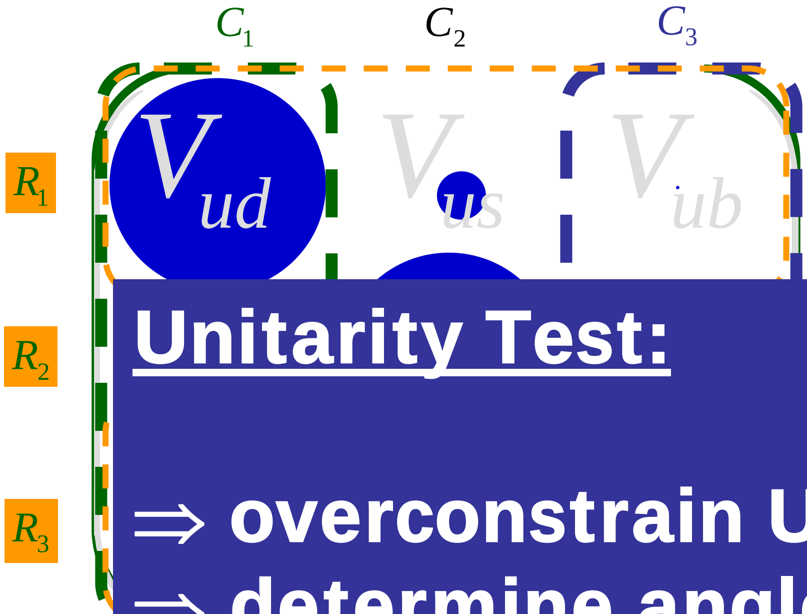
$$\boxed{V_{ud}}\cdot\boxed{V_{ub}^*}+\boxed{V_{cd}}\cdot\boxed{V_{cb}^*}+\boxed{V_{td}}\cdot\boxed{V_{tb}^*}=0$$

$$\Rightarrow$$



CP-Violation in the Standard Model

Unitarity test of the CKM-Matrix:



6 unitarity conditions:

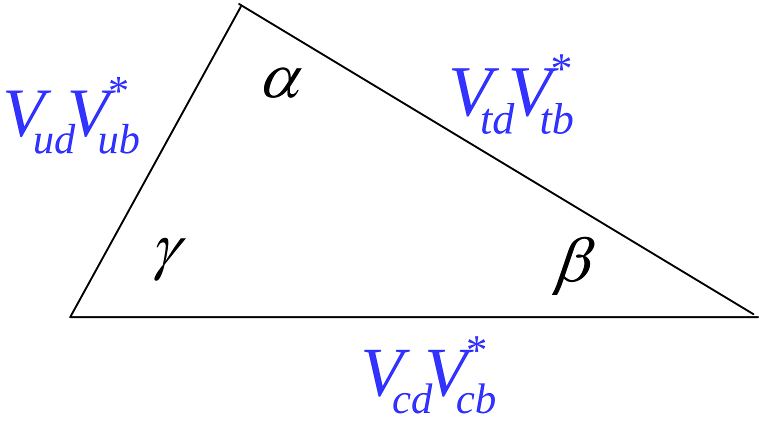
$$V^+V = 1 \Rightarrow \vec{R}_i \cdot \vec{R}^*_{j\neq i} = 0$$

Unitarity Test:

⇒ overconstrain Unitarity Triangles

⇒ determine angles and magnitude of sides

$$\boxed{\vec{C}_1} \cdot \boxed{\vec{C}^*_3} = 0$$



$$\boxed{V_{ud}} \cdot \boxed{V^*_{ub}} + \boxed{V_{cd}} \cdot \boxed{V^*_{cb}} + \boxed{V_{td}} \cdot \boxed{V^*_{tb}} = 0$$

CKM Parametrizations

V has 4 observable parameters and an infinite number of choices for these 4

L. Wolfenstein 1983:

λ, A, ρ, η

$J \approx A^2\lambda^6\overline{\eta}$

$\lambda \approx 0.2235$ ($\approx \sin\theta_C$)
$A\lambda^2 \approx 0.04$
$A\lambda^3\sqrt{\rho^2+\eta^2} \approx 0.004$
$\mathrm{atan}(\eta/\rho) \approx 60^o$

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \delta V$$

relevant for B_s

Tiny imaginary correction for V_{cd}

$$\delta V = \begin{pmatrix} 0 & 0 & 0 \\ \boxed{-iA^2\lambda^5\eta} & 0 & 0 \\ A\lambda^5(\rho+i\eta)/2 & \boxed{-A\lambda^4(1/2-\rho-i\eta)} & 0 \end{pmatrix}$$

Expect sizeable „phases“ for: V_{ub}, V_{td}, and V_{ts}

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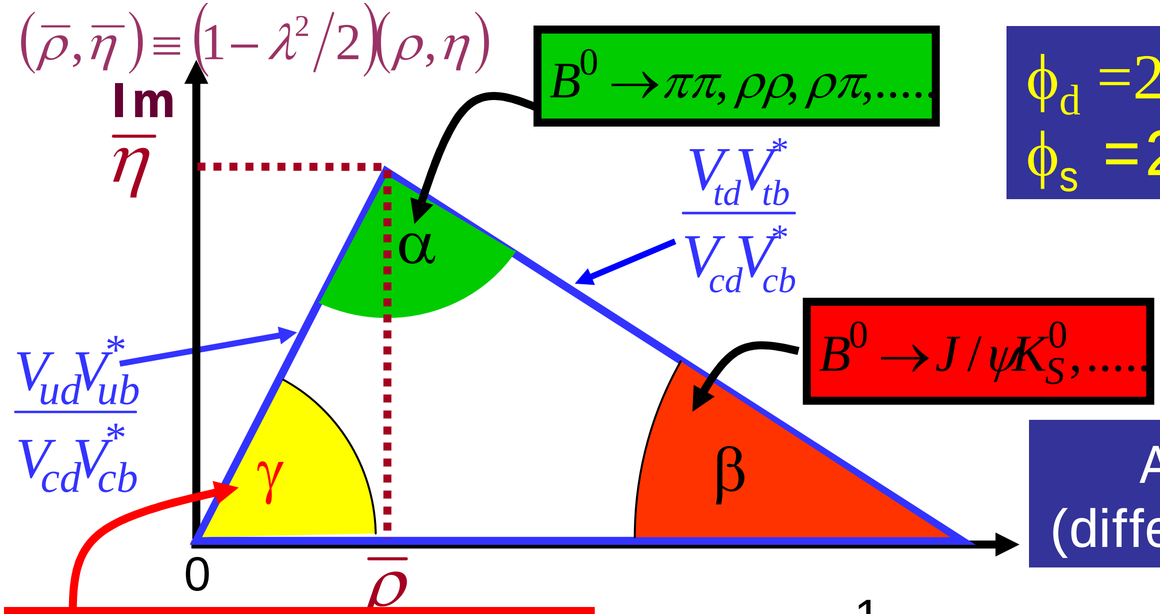
Expect sizeable „phases“ for: V_{ub}, V_{td}, and V_{ts}

Unitarity Triangles

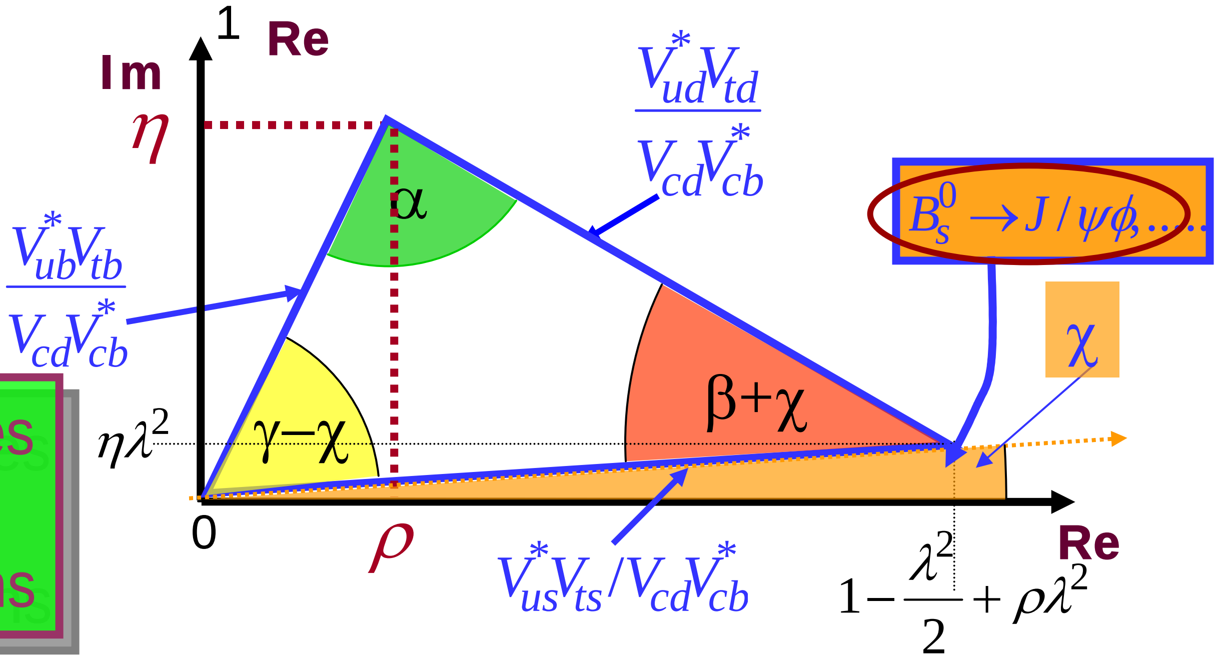


ϕ_d =2β: B$_d$ mixing phase
ϕ_s =2χ=2β$_s$: B$_s$ mixing phase

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

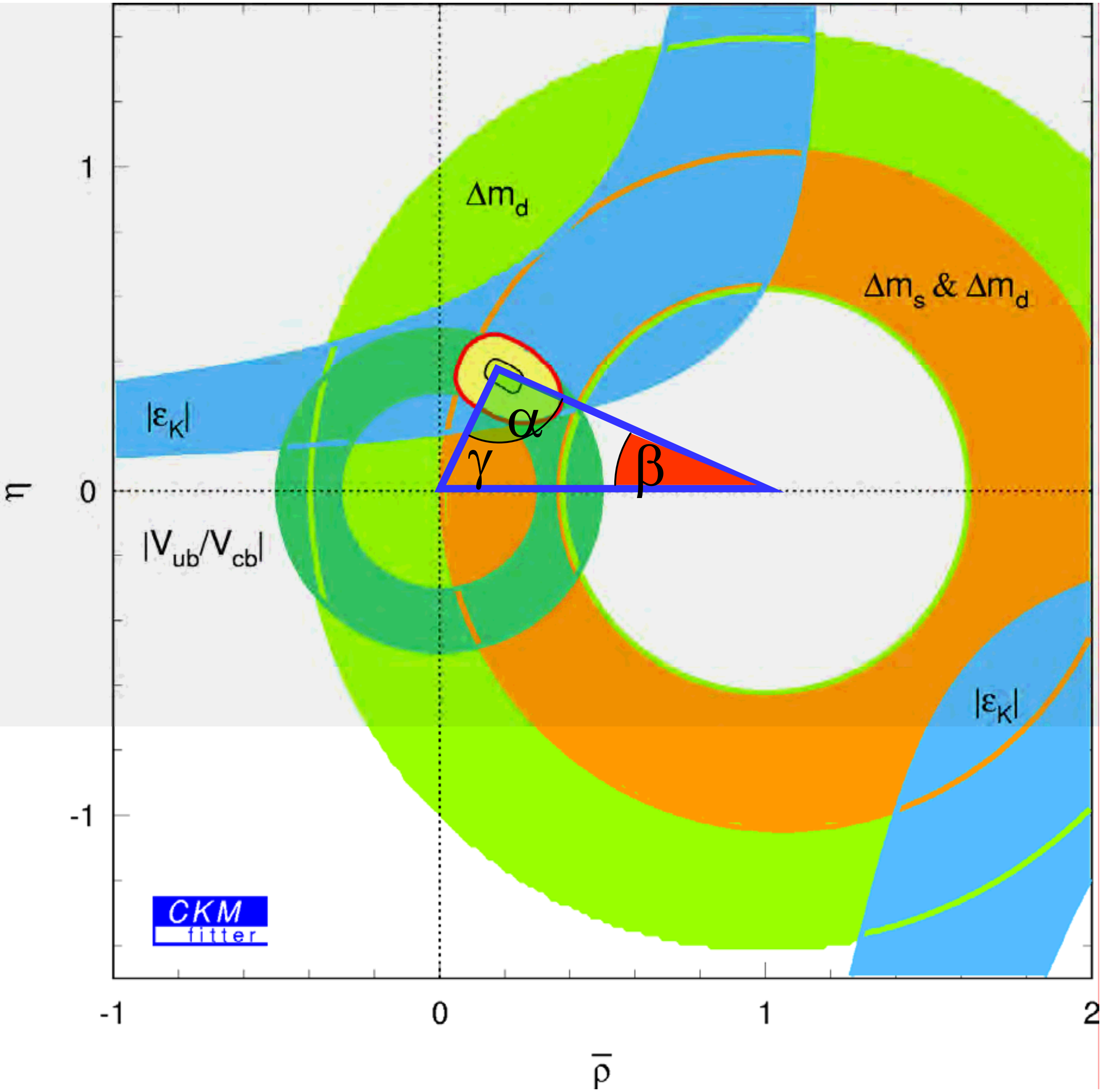
Almost identical triangles
(differences at the percent level)

$B_d\rightarrow DK, DK^*, K\pi,...$
$B_d\rightarrow\pi^+\pi^-$ and $B_s^0\rightarrow K^+K^-$
$B_s\rightarrow D_sK$ $(\gamma-2\chi)$
$B_d\rightarrow D^*\pi$ $(\gamma+2\beta)$



Precision Test requires measurements with B_u-, B_d-, and B_s-mesons

Constraints



B-Mesons (e.g. $B^0 \equiv \bar{b}d$):

Measurement of:

$V_{ub}, V_{cb}, V_{td}, \beta, \alpha, \gamma$

possible!

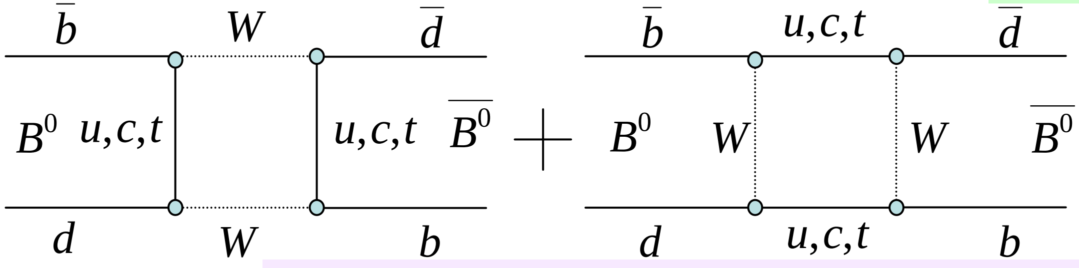
⇒sensitive Unitarity test

CP Violation

Three types of CP Violation:

- CP Violation in Mixing → „Indirect“ CP Violation
  - ⇨Neutral decays

$$\Gamma(K^0 \to \overline{K^0}) \neq \Gamma(\overline{K^0} \to K^0)$$



don‘t expect large effect in B-System

K^0,B^0 ⇒ particle ⇔ antiparticle oscillations

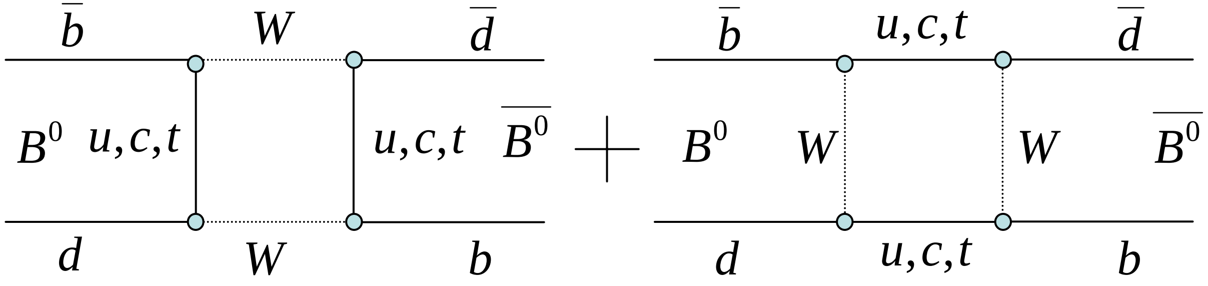
- CP Violation in Decay → „Direct“ CP Violation
  - ⇨Charged and neutral decays

$$\Gamma(A \to B) \neq \Gamma(\overline{A} \to \overline{B})$$

K-System: $\to \varepsilon'$

- CP Violation in Interference between Decays with and without Mixing
  - ⇨ neutral B-meson-system: e.g. sin2β measurement at B-Factories

$B^0\bar{B}^0$-Oscillations



mass eigenstates:

$$|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle$$

$|p|^2 + |q|^2 = 1$ complex coefficients

L : light, H : heavy

⇒**mass eigenstates**

B_H and B_L with Δm and $\Delta\Gamma$

($m_H > m_L$, sign of $\Delta\Gamma$ not defined)

Loop dominated by Top-Quark ⇒ Oscillation frequency depends on V_{td}, V_{tb}, m_t

$$\boxed{\Delta m_d = m_{B_H} - m_{B_L} = \frac{G_F^2}{6\pi^2}\eta_B m_B f_B^2 B_B |V_{tb}^* V_{td}|^2 \, m_t^2 F\left(\frac{m_t^2}{m_W^2}\right)}$$

Pert. QCD $\eta_B = 0.55 \pm 0.01$

lattice QCD $f_B^2 B_B = (223 \pm 33 \pm 12)^2 MeV^2$

$B^0\,\overline{B}{}^0$-Oscillations

Time evolution of rates:

$$\underbrace{P(B^0 \to B^0) = P(\overline{B^0} \to \overline{B^0})} = \frac{1}{4}\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} + 2e^{-(\Gamma_L + \Gamma_H)t/2}\cos\Delta m t\right]$$

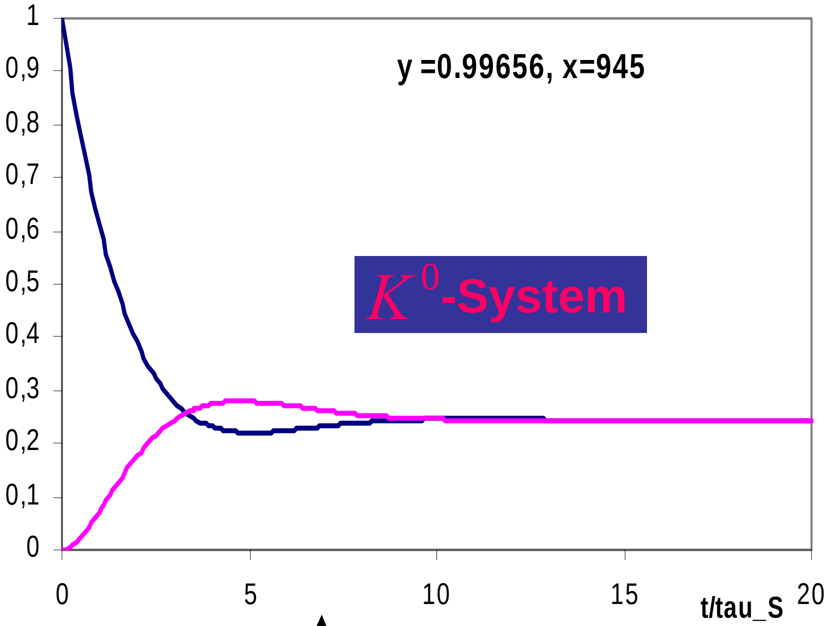
CPT !

$$P(B^0 \to \overline{B^0}) = \frac{1}{4}\left|\frac{p}{q}\right|^2\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L + \Gamma_H)t/2}\cos\Delta m t\right]$$

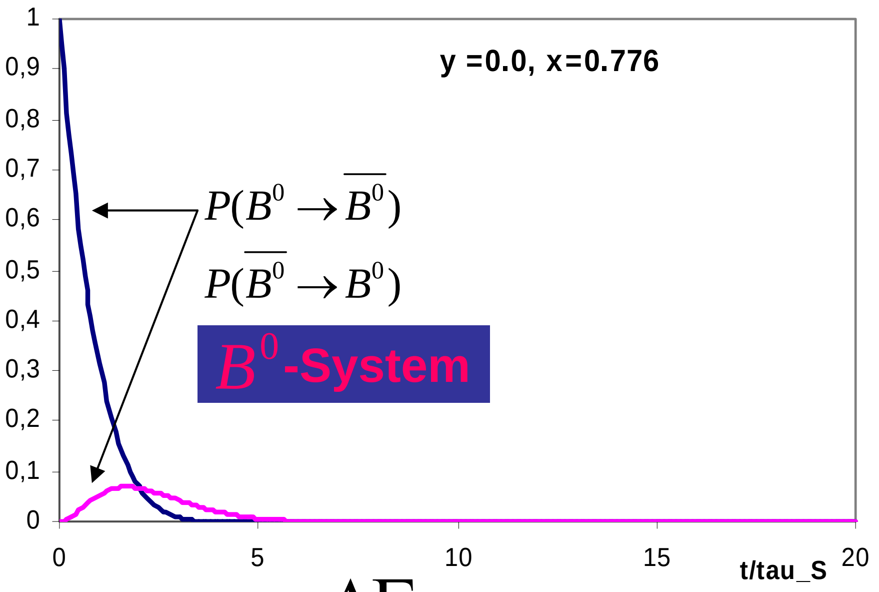
$$P(\overline{B^0} \to B^0) = \frac{1}{4}\left|\frac{q}{p}\right|^2\left[e^{-\Gamma_L t} + e^{-\Gamma_H t} - 2e^{-(\Gamma_L + \Gamma_H)t/2}\cos\Delta m t\right]$$

CP, T- Violation:

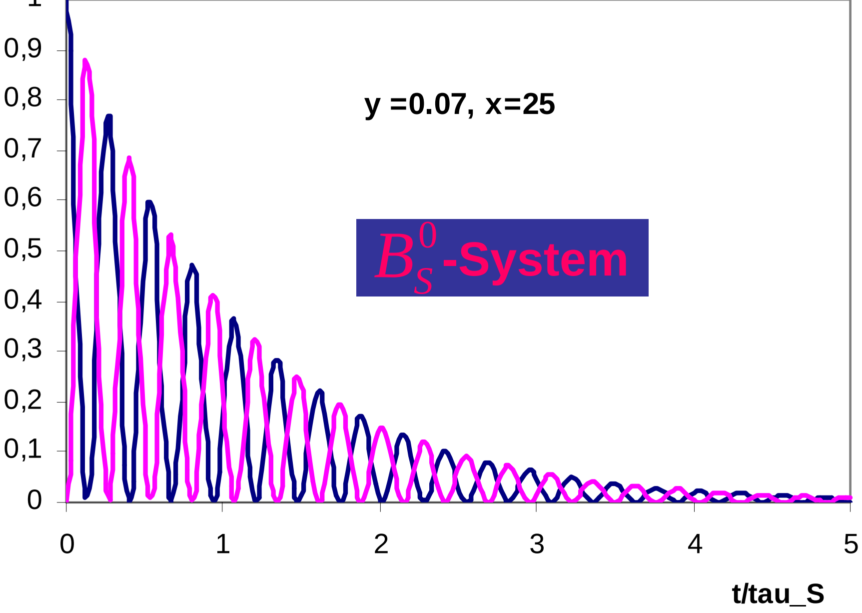
$$P(B^0 \to \overline{B^0}) \neq P(\overline{B^0} \to B^0) \Rightarrow \left|\frac{q}{p}\right| \neq 1$$

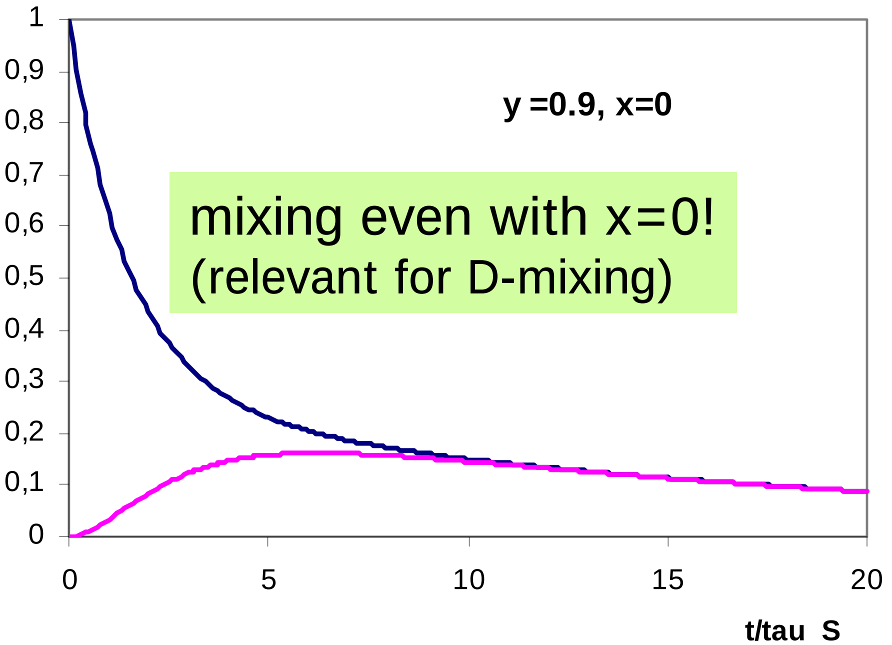


$$x = \frac{\Delta m}{\Gamma}$$



$$y = \frac{\Delta\Gamma}{2\Gamma}$$



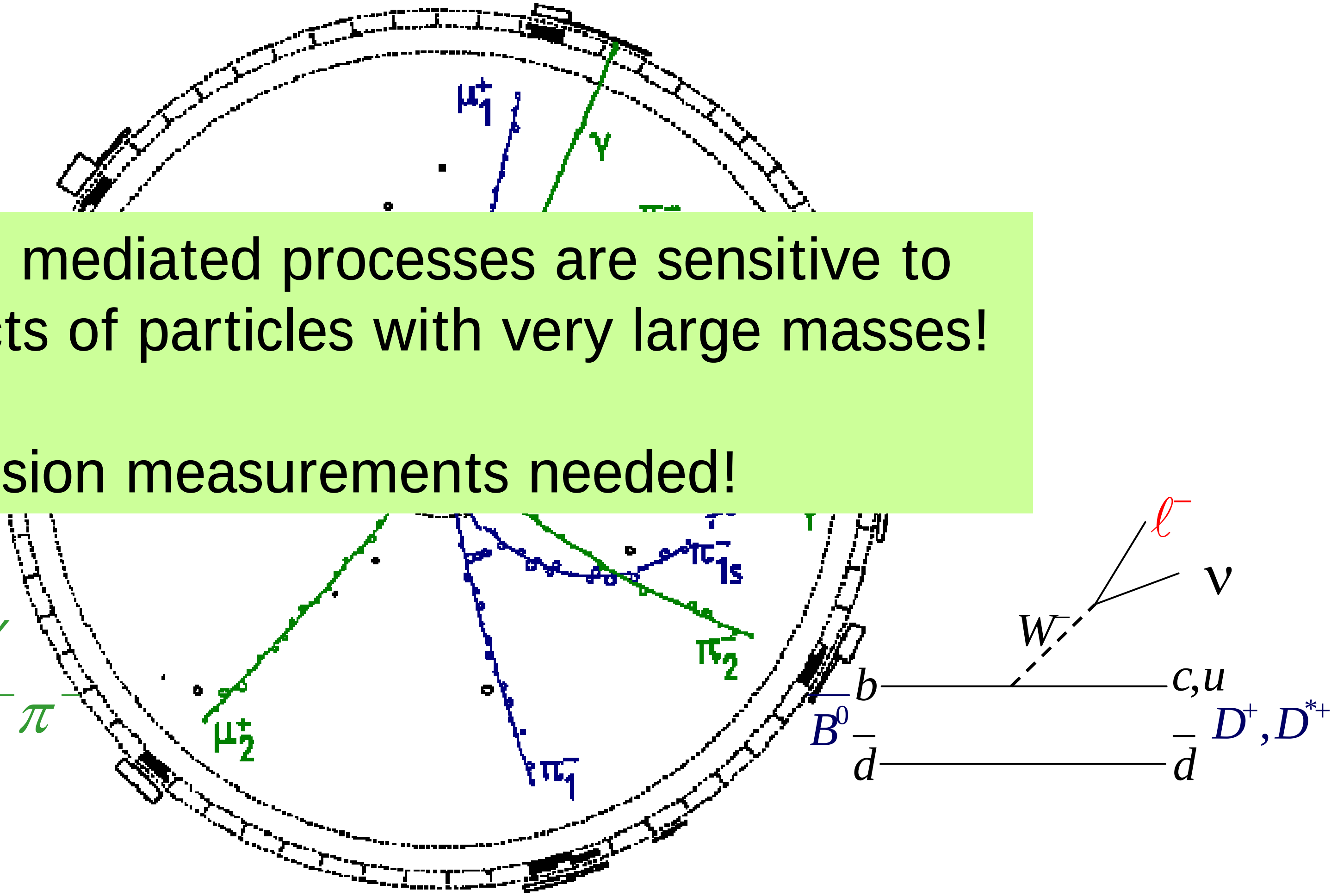


mixing even with x=0!
(relevant for D-mixing)

$B^0\overline{B}{}^0$-Oscillations

$B^0 \to D^{*-}\mu^+\nu_\mu$

$\quad \hookrightarrow \overline{D}{}^0\pi_s^-$



Loop mediated processes are sensitive to effects of particles with very large masses!

Precision measurements needed!

$B^0 \to D^{*-}\mu$

$\quad \hookrightarrow D^-\pi^0$

$\qquad \hookrightarrow \gamma\gamma$

$\quad \hookrightarrow K^+\pi^-\pi^-$

ARGUS 1987
(H. Schröder)

⇨ $M_{top} > 52$ GeV/c^2

~~CP~~ in Interference between Mixing and Decay

Consider decays into CP-eigenstates $f_{CP} \Rightarrow$ define $\lambda_{CP} = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = \eta_{CP}\frac{q}{p}\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$

$$\begin{tikzcd} & \bar{B}^0 \arrow[dr] & \\ B^0 \arrow[ur] \arrow[rr] & & f \end{tikzcd}$$

Oscillation

Decay

CP-eigenvalue of f_{CP}

Assume no CP violation in mixing & decay

Good approximation in $B \to J/\psi K_S$

$$\frac{q}{p} = -\left|\frac{q}{p}\right| e^{2i\phi_M} \approx -e^{2i\phi_M}$$

$$A_{f_{CP}} = |A| e^{i\phi_A} e^{i\delta_A}$$

$$\bar{A}_{\bar{f}_{CP}} = \eta_{CP} |\bar{A}| e^{-i\phi_A} e^{i\delta_A}$$

$$\lambda_{CP} = -\eta_{CP} e^{2i(\phi_M - \phi_A)}$$

Mixing Phase

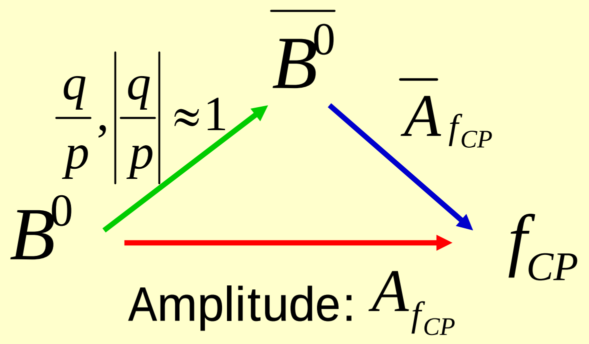
Weak Decay Phase

In general: $\lambda_{CP} = -\eta_{CP} \cdot \left|\frac{q}{p}\right| \cdot \left|\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right| \cdot e^{2i(\phi_M - \phi_A)}$

~~CP~~ in Interference between Mixing and Decay

***B* mesons**

$$\lambda_{CP} = -\eta_{CP} \cdot \left|\frac{q}{p}\right| \cdot \left|\frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}\right| \cdot e^{2i(\phi_M - \phi_A)}$$



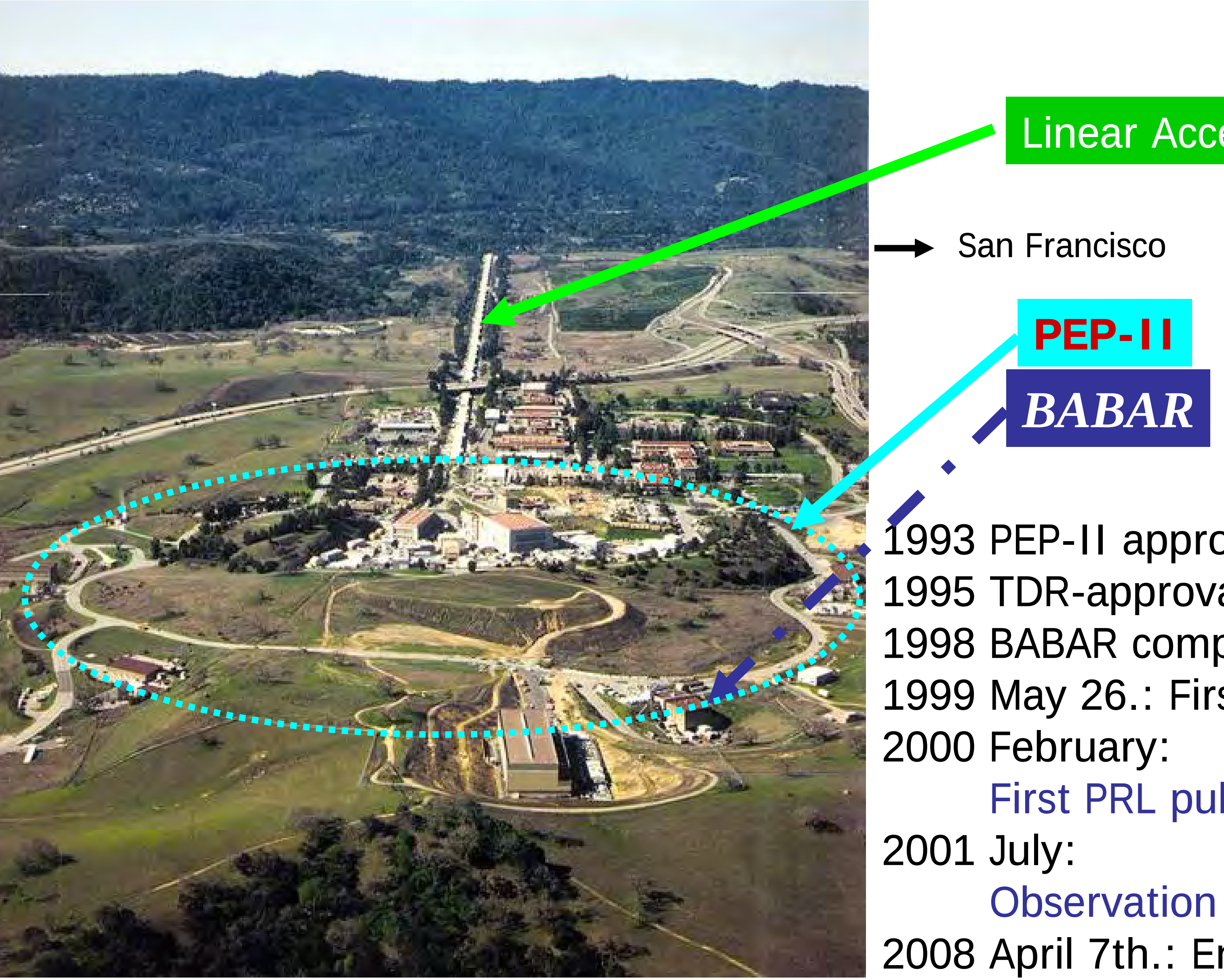
$$\Gamma(B^0 \to f_{CP}) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} + \mathrm{Im}(\lambda_{CP})\sin(\Delta m_d t) - \frac{1-|\lambda_{CP}|^2}{2}\cos(\Delta m_d t)\right]$$

$$\Gamma(\bar{B}^0 \to f_{CP}) \propto \frac{e^{-|\Delta t|/\tau_{B^0}}}{\left(1+|\lambda_{CP}|^2\right)} \times \left[\frac{1+|\lambda_{CP}|^2}{2} - \mathrm{Im}(\lambda_{CP})\sin(\Delta m_d t) + \frac{1-|\lambda_{CP}|^2}{2}\cos(\Delta m_d t)\right]$$

Interference
= sin2β for e.g. $B^0 \to J/\psi K_S$
≈ $\sin 2\alpha_{(\mathrm{eff})}$ for e.g. $B^0 \to \pi^+\pi^-$

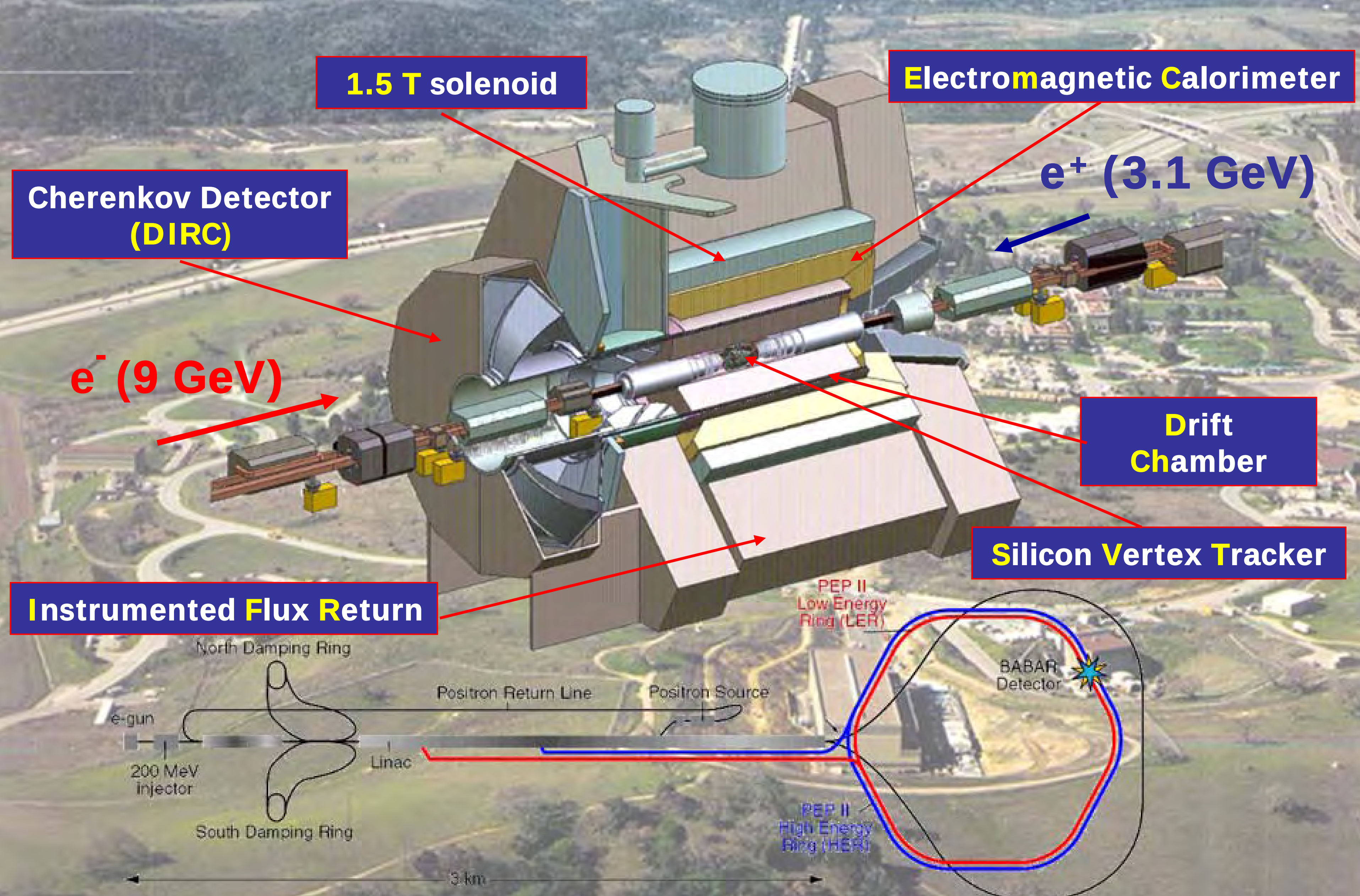
indicates direct CP violation if $|q/p|=1$

SLAC, PEP-II & BABAR



1993 PEP-II approval
1995 TDR-approval
1998 BABAR completed
1999 May 26.: First collision data
2000 February:
First PRL publication
2001 July:
Observation of CP violation
2008 April 7th.: End of Running

BABAR at SLAC



1.5 T solenoid

Electromagnetic Calorimeter

Cherenkov Detector (DIRC)

e^+ (3.1 GeV)

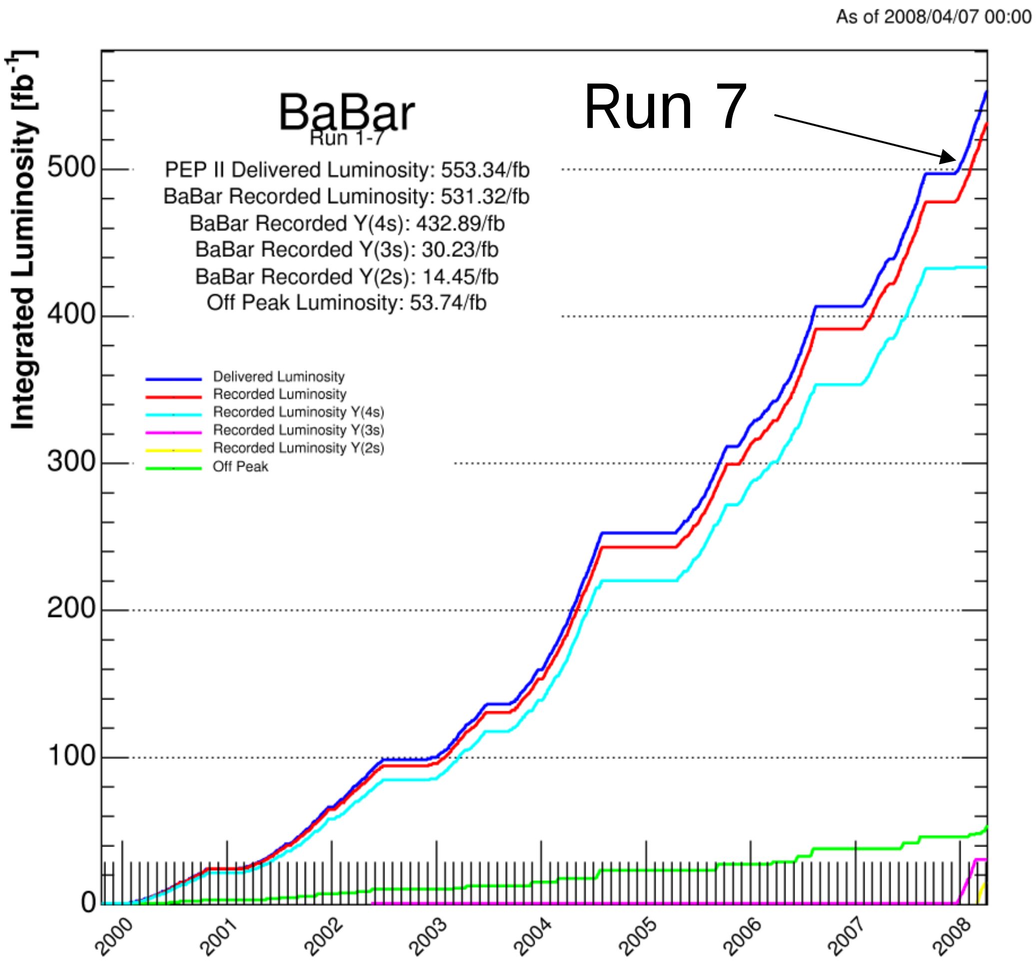
e^- (9 GeV)

Drift Chamber

Silicon Vertex Tracker

Instrumented Flux Return

BaBar Data Taking



Data collected

Run 1-6:

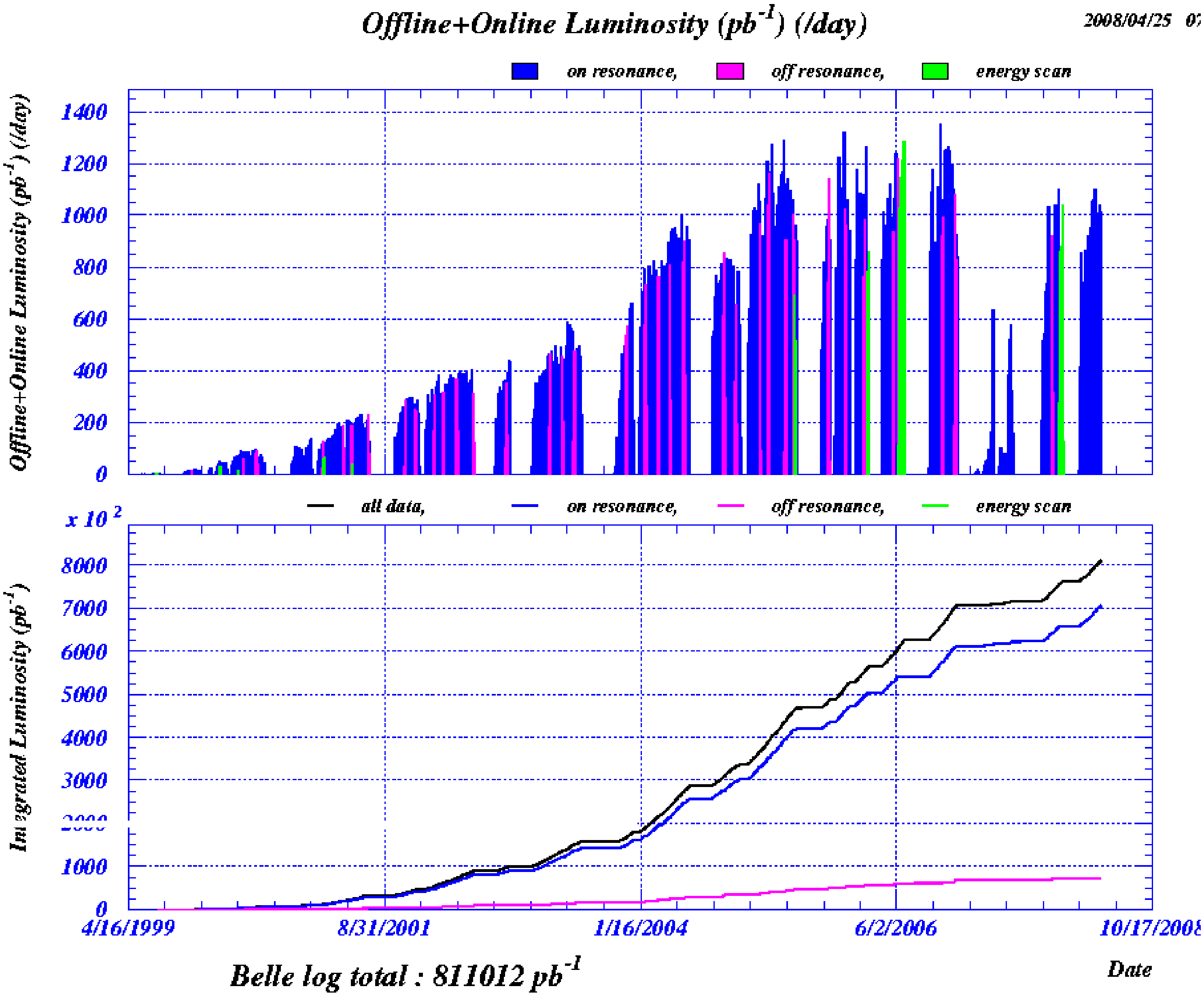
- 480M $B\overline{B}$ pairs,
- 630M $c\overline{c}$ events,
- 880M $\tau^+\tau^-$, etc.

Run 7:

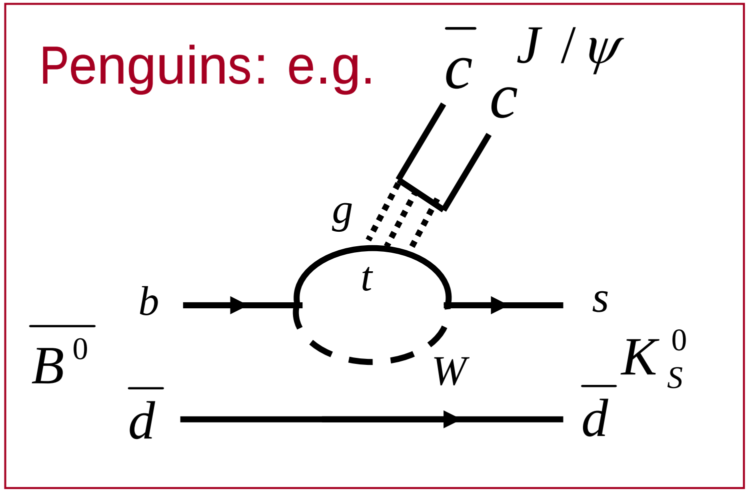
- 30/fb at $\Upsilon(3S)$
- 14/fb at $\Upsilon(2S)$ and above 4S scan

>340 paper submitted !

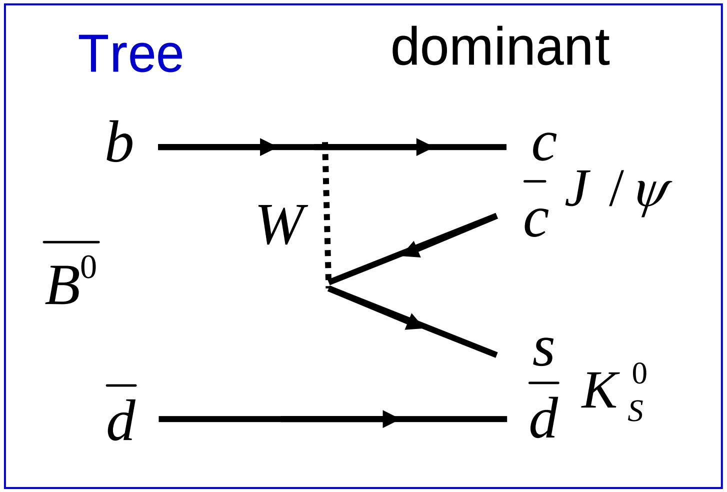
KEKB


Offline+Online Luminosity (pb^{-1}) (/day)
2008/04/25 0
on resonance,
off resonance,
energy scan
Offline+Online Luminosity (pb^{-1}) (/day)
1400
1200
1000
800
600
400
200
0
all data,
on resonance,
off resonance,
energy scan
x 10^2
8000
7000
6000
5000
4000
3000
2000
1000
0
Integrated Luminosity (pb^{-1})
4/16/1999
8/31/2001
1/16/2004
6/2/2006
10/17/2008
Belle log total : 811012 pb^{-1}
Date

sin2β from $B^0 \to J/\psi K_S$



Penguins: e.g.



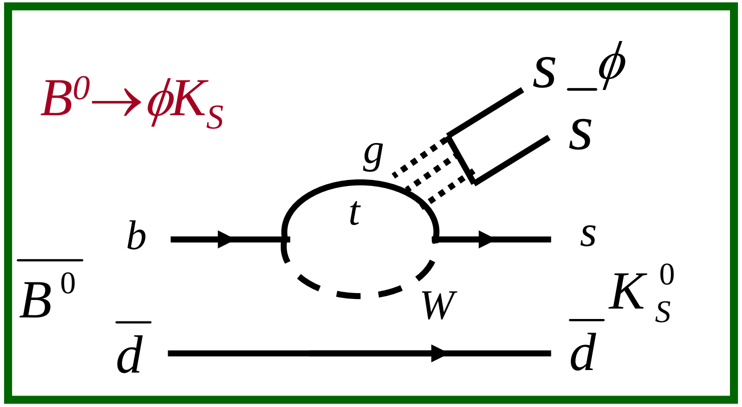
Tree dominant

same weak phases⇒ measure sin2β

$$BF(B^0 \to J/\psi K_S^0) \cong 4{,}5\times 10^{-4}$$

$$BF(J/\psi \to e^+e^-) \cong 6\%$$

$$BF(B^0 \to \phi K_S^0) \cong 4{,}5\times 10^{-6}$$



$B^0 \to \phi K_S$

Time Resolved Measurements

$B_{tag} = \overline{B}^0(t_0)$

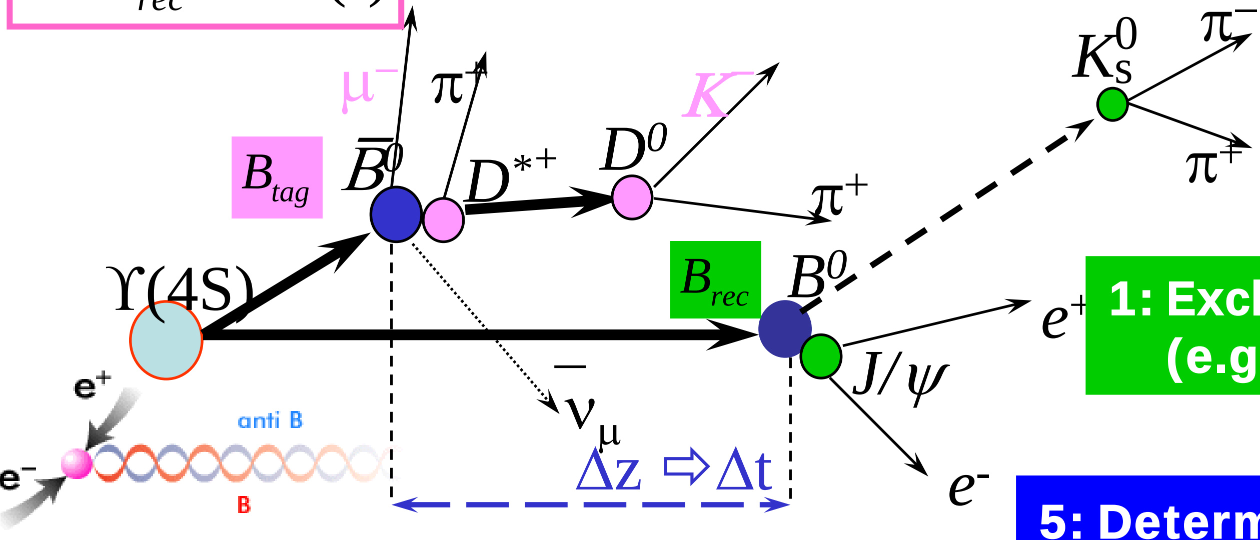
$\Rightarrow B_{rec} = B^0(t)$

2: Flavour-determination of other B meson („tag“)

3: Determination of mistag fraction w

$\Rightarrow$Dilution D: $D = (1\text{-}2w)$

reduces visible asymmetry



1: Exclusive B-reconstruction (e.g. CP Eigenstates)

5: Determination of Δz (Δt) resolution function R

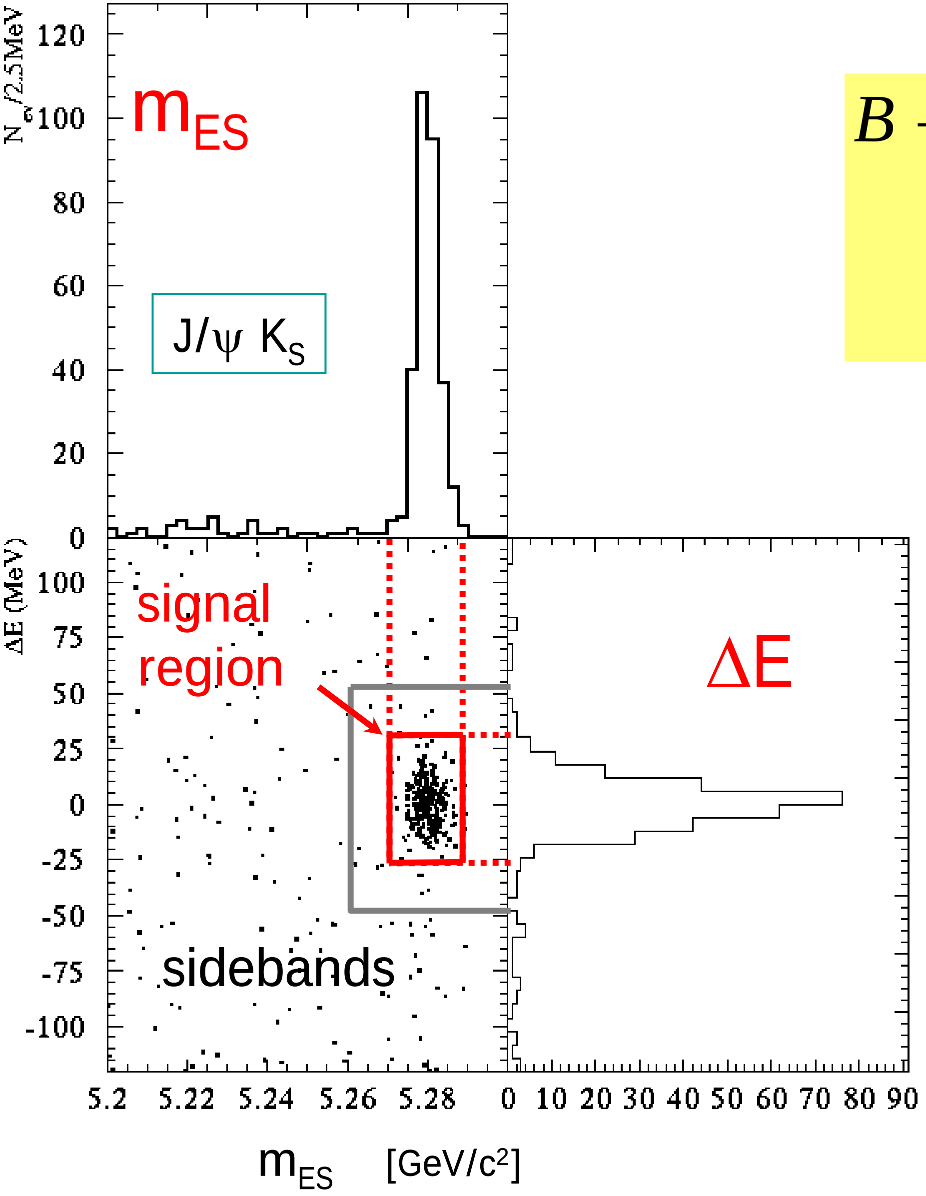
4: Determination of Δt = $\Delta z / \beta\gamma c$

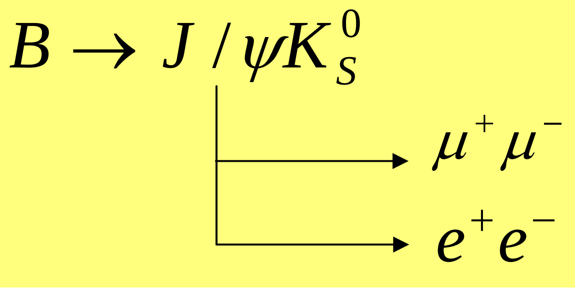
6: fit to Δt distribution

$B^0_{rec} = B^0_{flav}$ (flavor eigenstates) ➡ lifetime, mixing analyses

$B^0_{rec} = B^0_{CP}$ (CP eigenstates) ➡ CP analysis

Reconstruction of B-Mesons





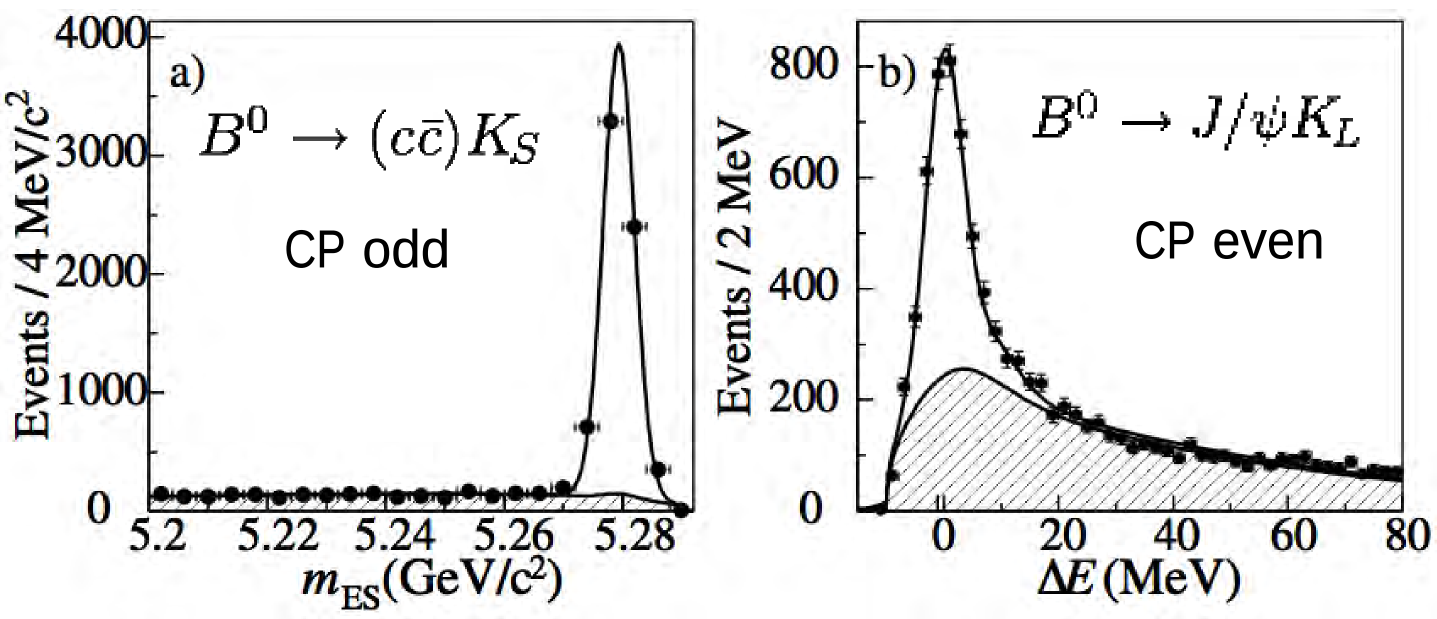
$$m_{ES} = \sqrt{E_{beam}^{cms2} - p_B^{cms2}}$$

$$\Delta E = E_B^{cms} - E_{beam}^{cms}$$

$$E_B^{cms} = E_{J/\psi}^{cms} + E_{K_S^0}^{cms}$$

$$p_B^{cms} = \left| \vec{p}_{J/\psi}^{\,cms} + \vec{p}_{K_S^0}^{\,cms} \right|$$

Reconstruction of CP-Eigenstates



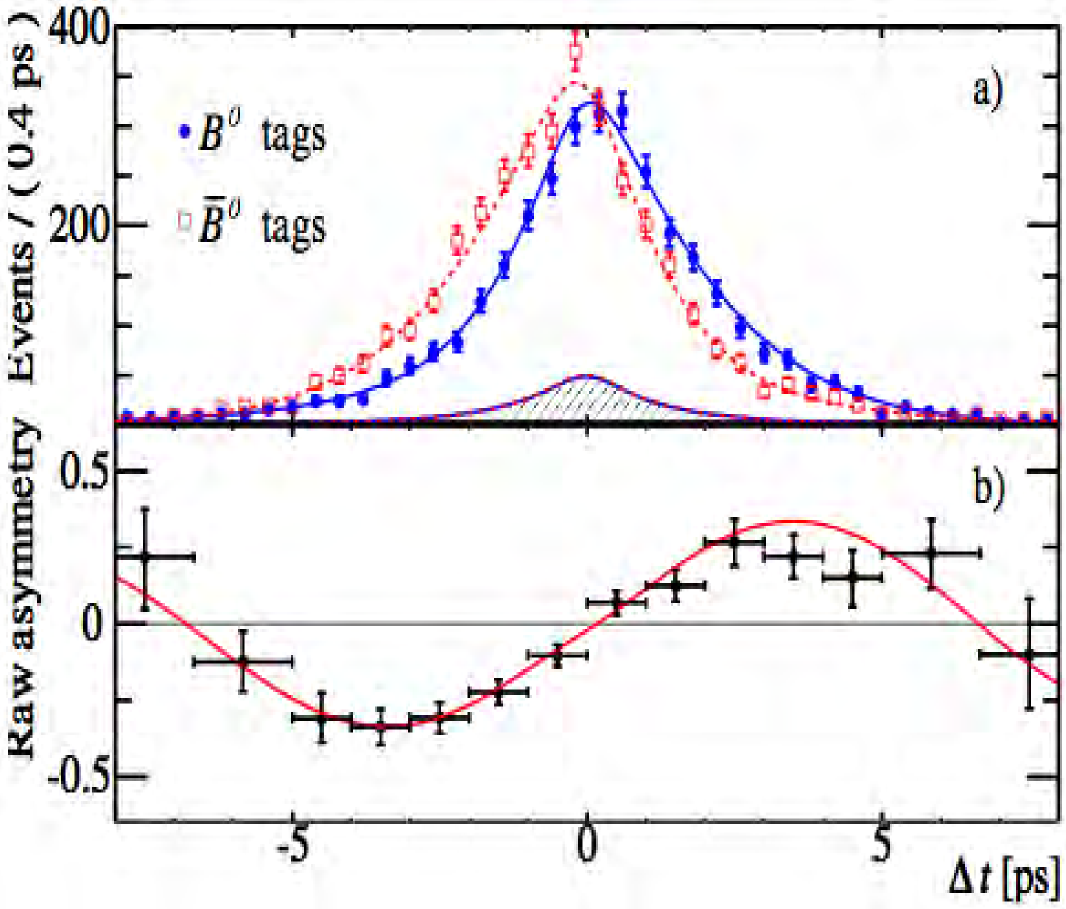
CP odd

CP even

$383 \times 10^6 B\bar{B}$

	CP Odd	CP even
N signal (purity)	6900 (92%)	3700 (55%)

sin2β - Measurement



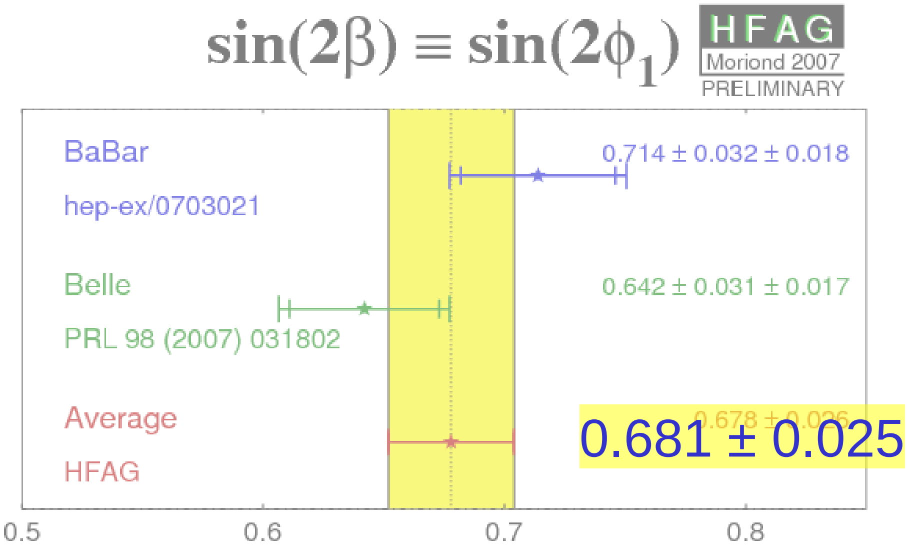
$383 \cdot 10^6\, B\bar{B}$ -Pairs

& no evidence for direct CP-Violation

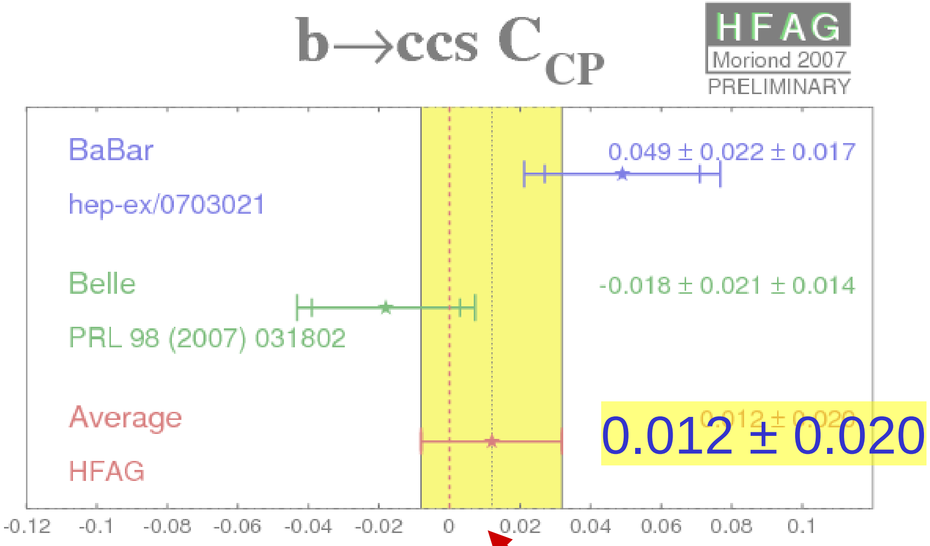
PRL 99,171803 (2007)

$$\sin 2\beta = +0.714 \pm 0.032 \pm 0.018$$

Summary: sin2β measurements from $(c\bar{c})K^0$



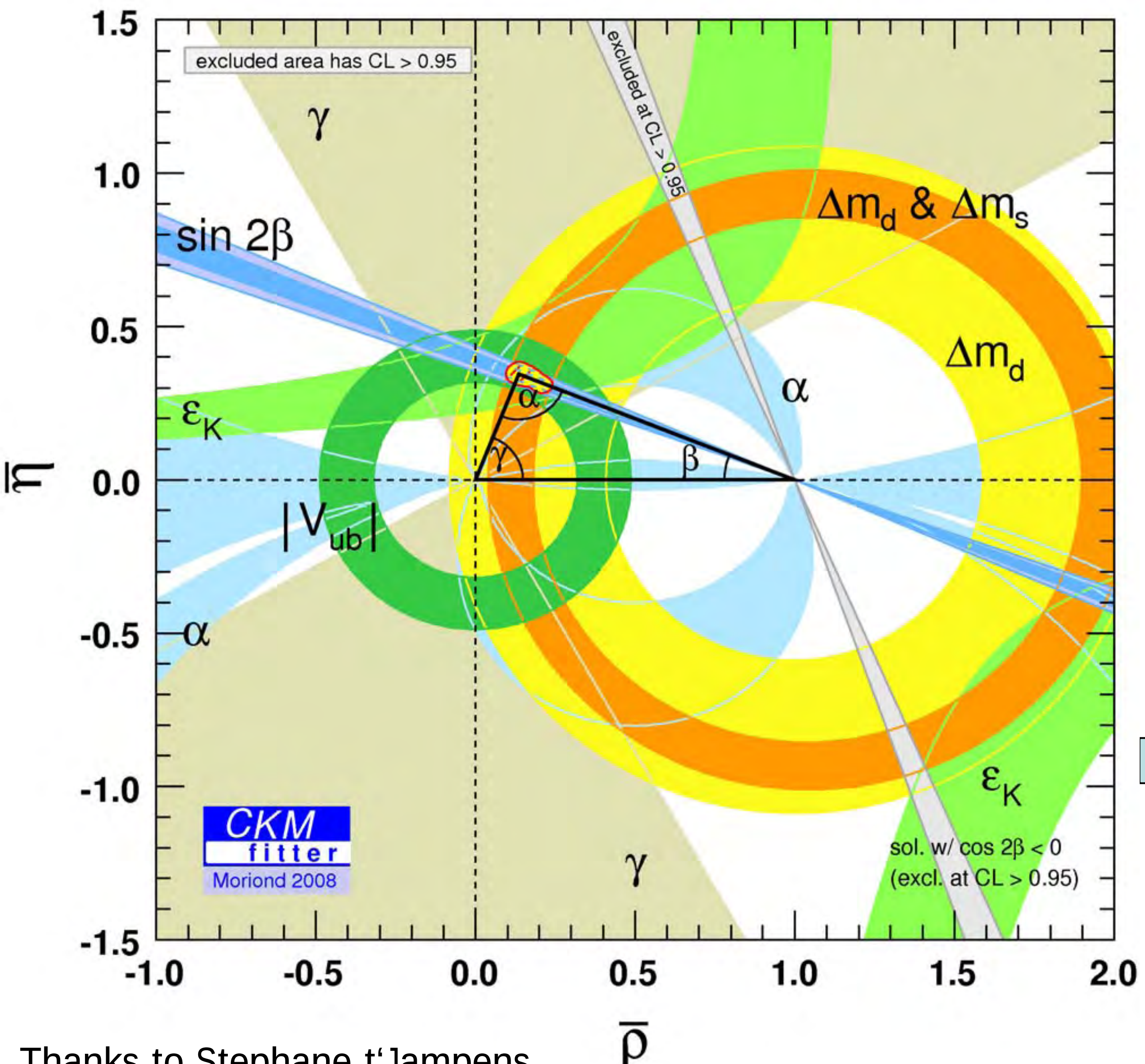
0.681 ± 0.025



0.012 ± 0.020

- Both experiments agree very well
- Experimental uncertainty on sin2β ~ 4% == Precision Experiment
- Small theoretical uncertainty in the Standard Model
- No evidence for direct CP-Violation

Unitarity Triangle



Excellent agreement with Standard Model ☹

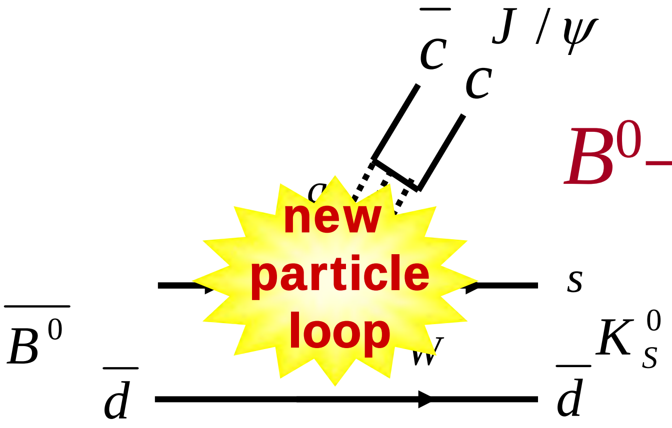
γ: will remain a challenge for the B-factories

New Experiments needed!

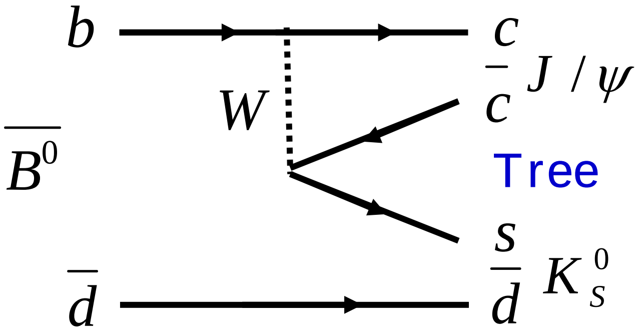
Super-B?

Thanks to Stephane t'Jampens

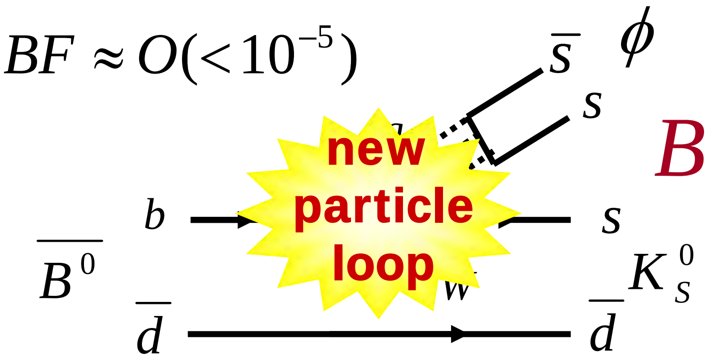
Penguins & Co



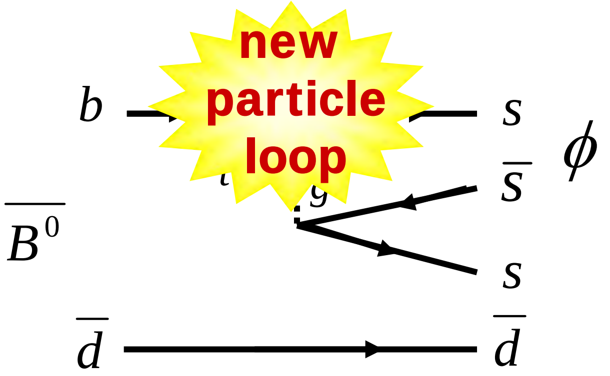
$B^0 \rightarrow J/\psi K_S$



rare $BF \approx O(<10^{-5})$



$B^0 \rightarrow \phi K_S$



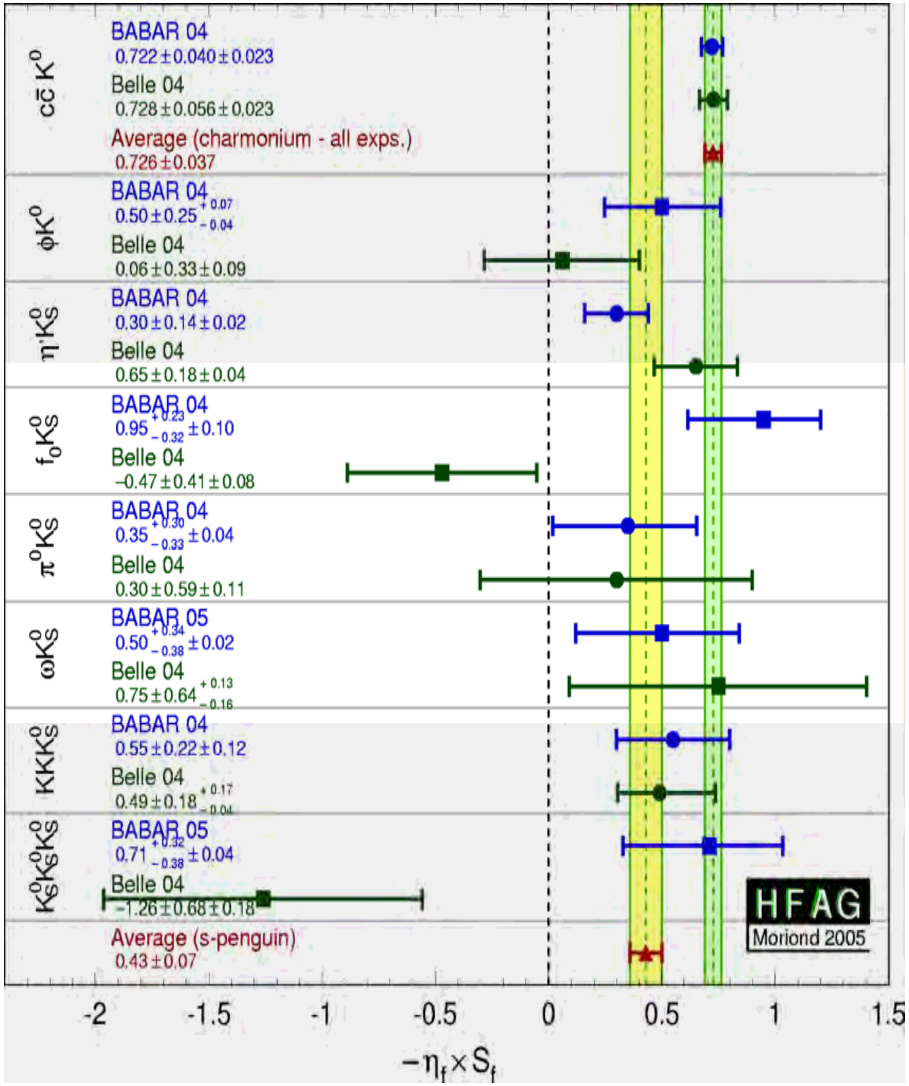
Pure Penguin ($b\rightarrow s\bar{s}s$) – same weak phase as in $b\rightarrow c\bar{c}s$ → should yield sin2β

- Difference to sin2β from $B\rightarrow J/\psi K_S \Rightarrow$ Hints for New Physics??

⇒ large potential for detection of New Physics in modes with penguin contribution ⇒ need high statistics ⇒ LHCb, Super-B

$b \to c\bar{c}s$ vs $b \to q\bar{q}s$ (Penguin)

Winter 2005

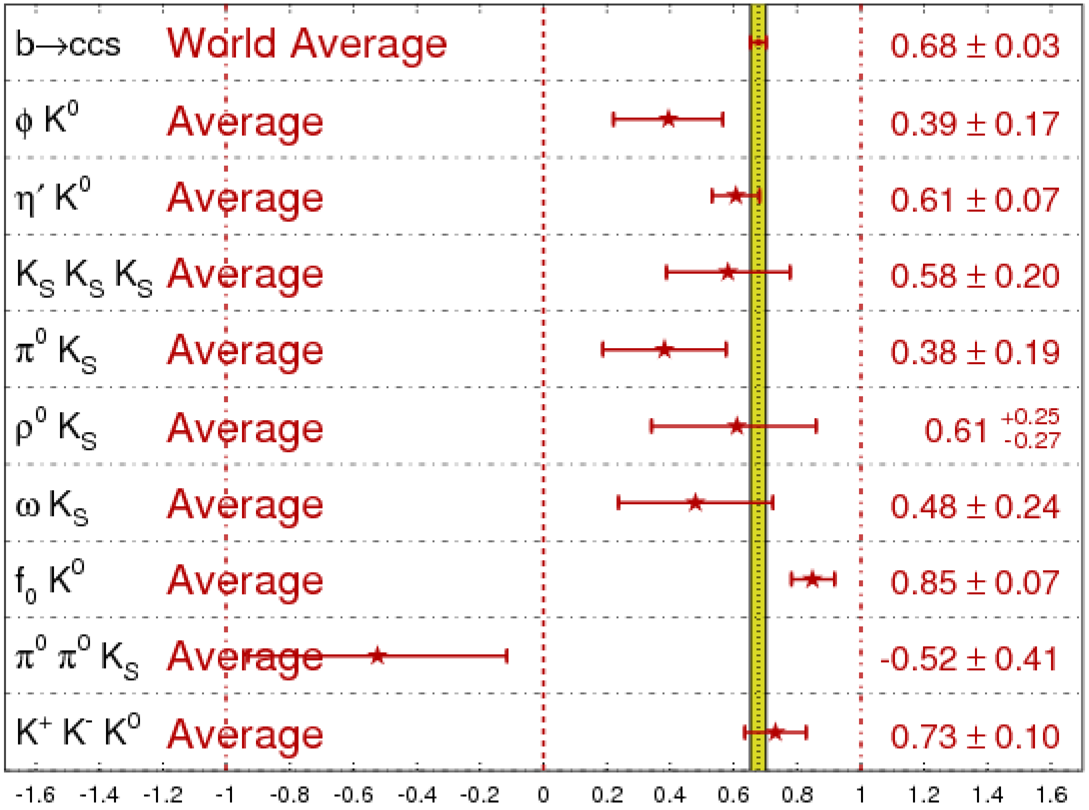


Naïve average $\sin 2\beta_{\mathrm{eff}} \cong 0.43 \pm 0.07$ 3.7σ Discrepancy

$b\to c\bar{c}s$ vs $b\to q\bar{q}s$ (Penguin)

$\sin(2\beta^{\mathrm{eff}}) \equiv \sin(2\phi_1^{\mathrm{eff}})$

HFAG
LP 2007
PRELIMINARY



Need more precision!

LHCb

Naïve average $\sin 2\beta^{avg}_{b\to q\bar{q}s} = 0.68 \pm 0.04$

Excluding f^0K^0 $\sin 2\beta^{avg}_{b\to q\bar{q}s} = 0.56 \pm 0.05$

$\Delta\sin2\beta \cong 2.1\sigma$

Direct CP Violation

Consider decay amplitudes for a decays into final state *f*

e.g. $$\begin{array}{l} B \to f \Rightarrow A_f \\ \bar{B} \to \bar{f} \Rightarrow \bar{A}_{\bar{f}} \end{array} \quad \Rightarrow \text{ CP Violation if } \left|\frac{\bar{A}_{\bar{f}}}{A_f}\right| \neq 1 \quad \Rightarrow \quad \text{Prob}(\bar{B} \to \bar{f}) \neq \text{Prob}(B \to f)$$

Several possible contributions to A_f and $\bar{A}_{\bar{f}}$

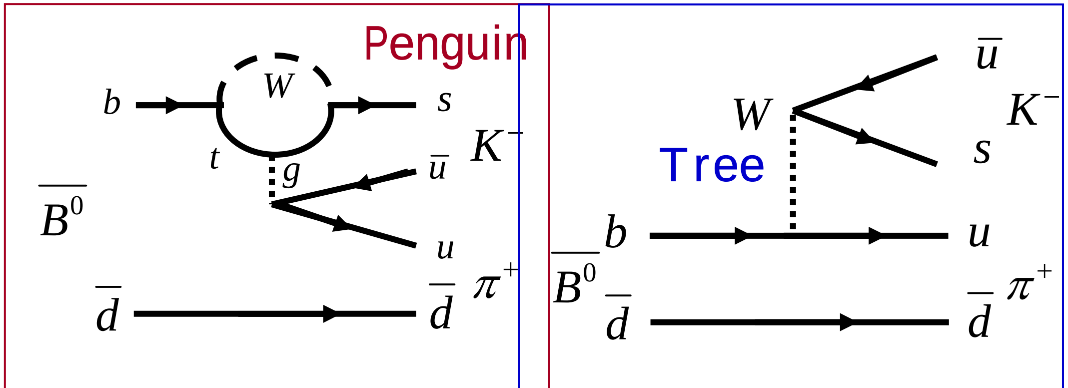
$$\Rightarrow |A_f|^2 - |\bar{A}_{\bar{f}}|^2 = -2\sum_{i,j} A_i A_j \underbrace{\sin(\phi_i - \phi_j)} \underbrace{\sin(\delta_i - \delta_j)}$$

Phases: weak & strong

Direct CP violation requires ≥ 2 different contributions with different weak phases and different strong phases

For neutral modes, direct ~~CP~~ competes with other types of CP violation

e.g. $B^0 \to K^+\pi^-$



direct CP violation possible!

CP Mirror

$$A_1 = |A_1|$$

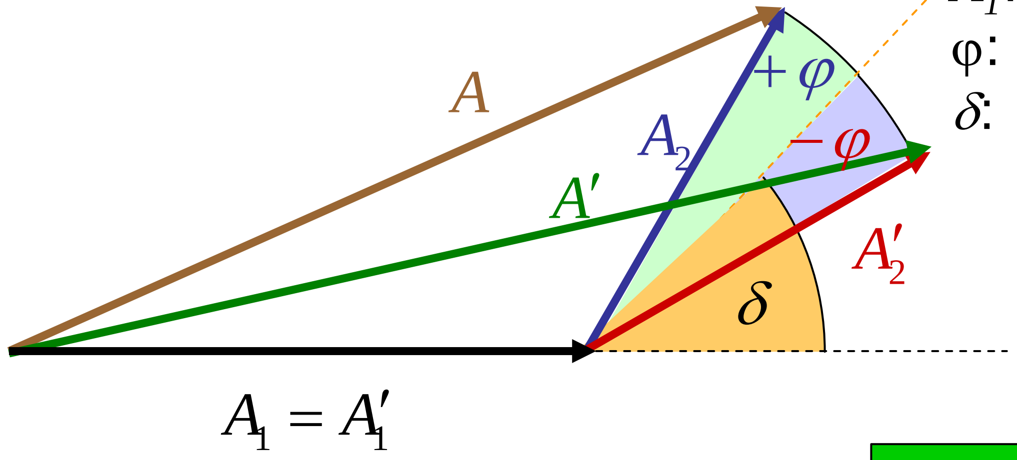
$$A_2 = |A_2| e^{i\varphi} e^{i\delta}$$

$$A = A_1 + A_2$$

$$A_1' = |A_1|$$

$$A_2' = |A_2| e^{-i\varphi} e^{i\delta}$$

$$A' = A_1' + A_2'$$



O.b.d.A.:
A_1: real
φ: weak phase difference
δ: strong phase difference

$$A_1 \leftrightarrow A_2$$

$$|\delta| \neq 0 \,\&\, |\varphi| \neq 0 \Rightarrow |A| \neq |A'|$$

Direkte CP-violaton!

CP Mirror

$$A_1 = |A_1|$$

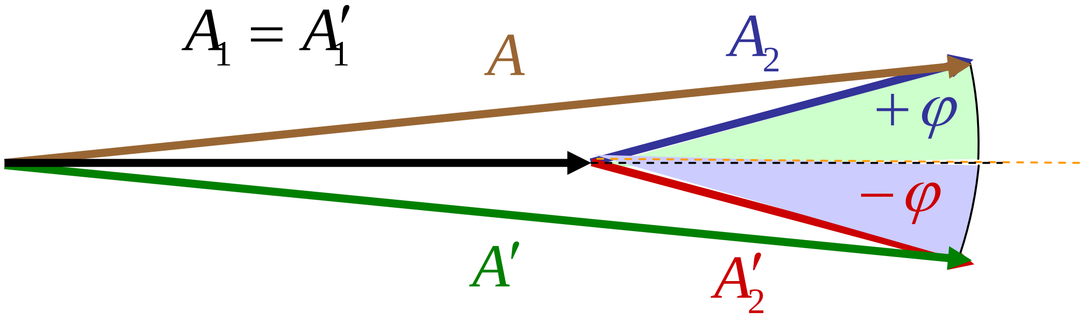
$$A_2 = |A_2| e^{i\varphi} e^{i\delta}$$

$$A = A_1 + A_2$$

$$A_1' = |A_1|$$

$$A_2' = |A_2| e^{-i\varphi} e^{i\delta}$$

$$A' = A_1' + A_2'$$



$$|\delta| = 0 \,||\, |\varphi| = 0 \Rightarrow |A| = |A'|$$

no direct CP-violation!

Direct CP Violation

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

$$A_{CP} = \frac{N(\bar{B}^0 \rightarrow K^-\pi^+) - N(B^0 \rightarrow K^+\pi^-)}{N(\bar{B}^0 \rightarrow K^-\pi^+) + N(B^0 \rightarrow K^+\pi^-)}$$

BABAR

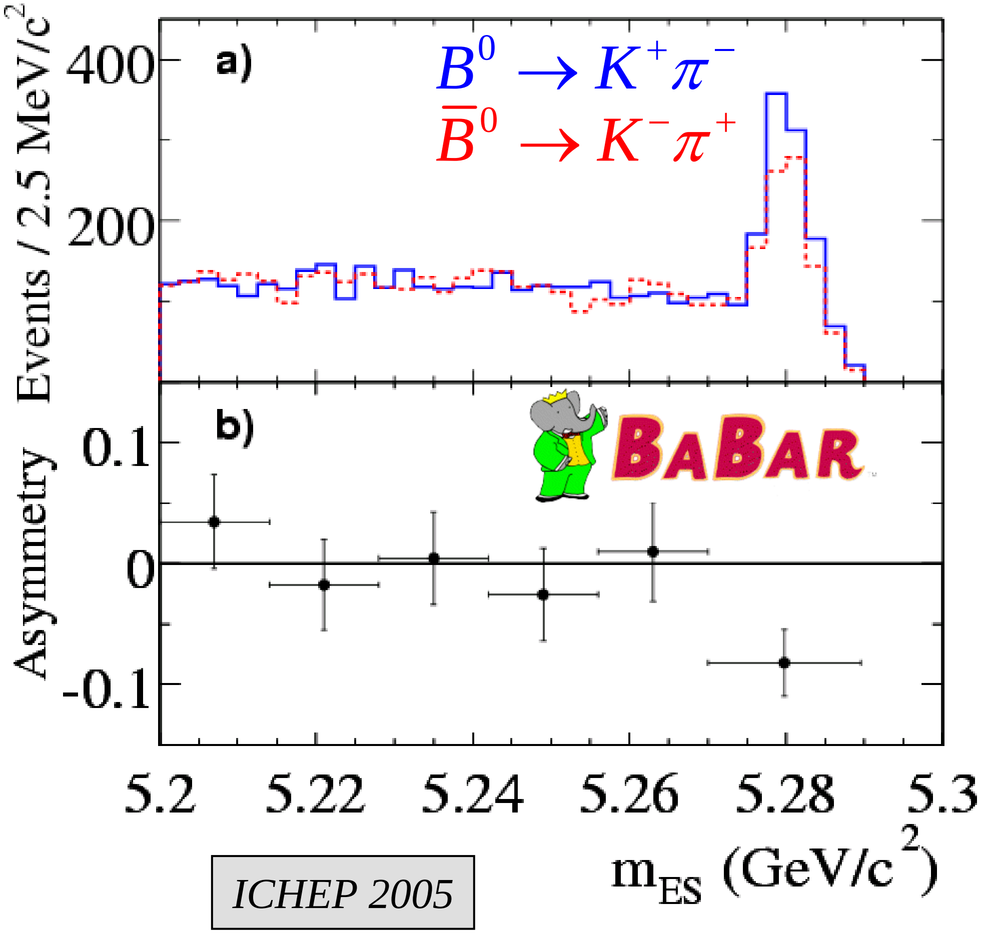
4.2σ

$$A_{CP} = -0.133 \pm 0.030 \pm 0.009$$

Phys. Rev Lett. 93 (131801) 2004.

First Observation of direct CP-Verletzung!

$$K^0 - \text{System}: \frac{\varepsilon'}{\varepsilon}$$



ICHEP 2005

BELLE

$$A_{CP} = -0.113 \pm 0.022 \pm 0.008$$

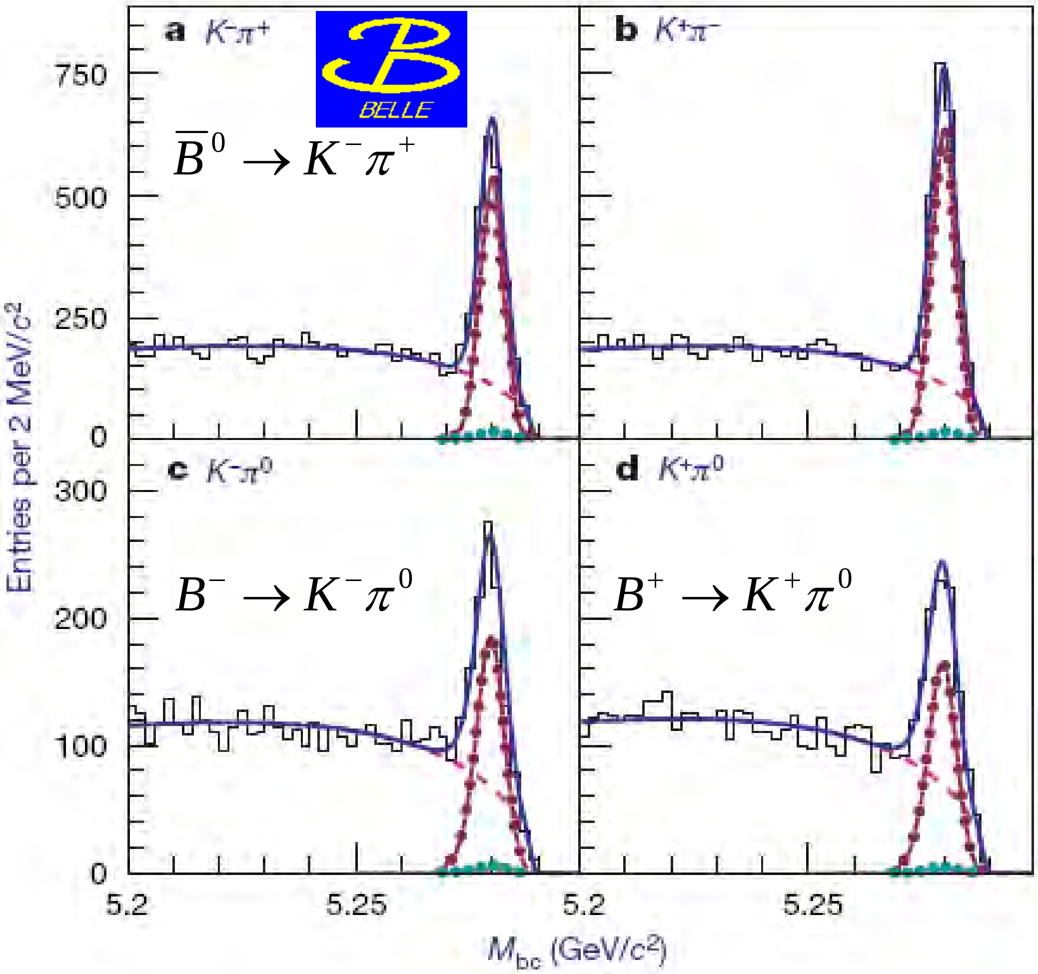
Moriond 2006

CDF II

$$A_{CP} = -0.058 \pm 0.039 \pm 0.007$$

Direct CP violation

535 M $B\overline{B}$



$$A_{K^\pm\pi^\mp} = \frac{N(B^- \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(B^- \to K^-\pi^+) + N(B^0 \to K^+\pi^-)}$$

$$= -0.094 \pm 0.018 \pm 0.018$$

$$A_{K^\pm\pi^0} = 0.07 \pm 0.03 \pm 0.01$$

$$\Delta A = A_{K^\pm\pi^0} - A_{K^\pm\pi^\mp} = 0.164 \pm 0.037$$

Vol 452|20 March 2008|**doi:10.1038/nature06827**

Conclusion: different direct CP violation for charged and neutral B‘s!
is this New Physics?

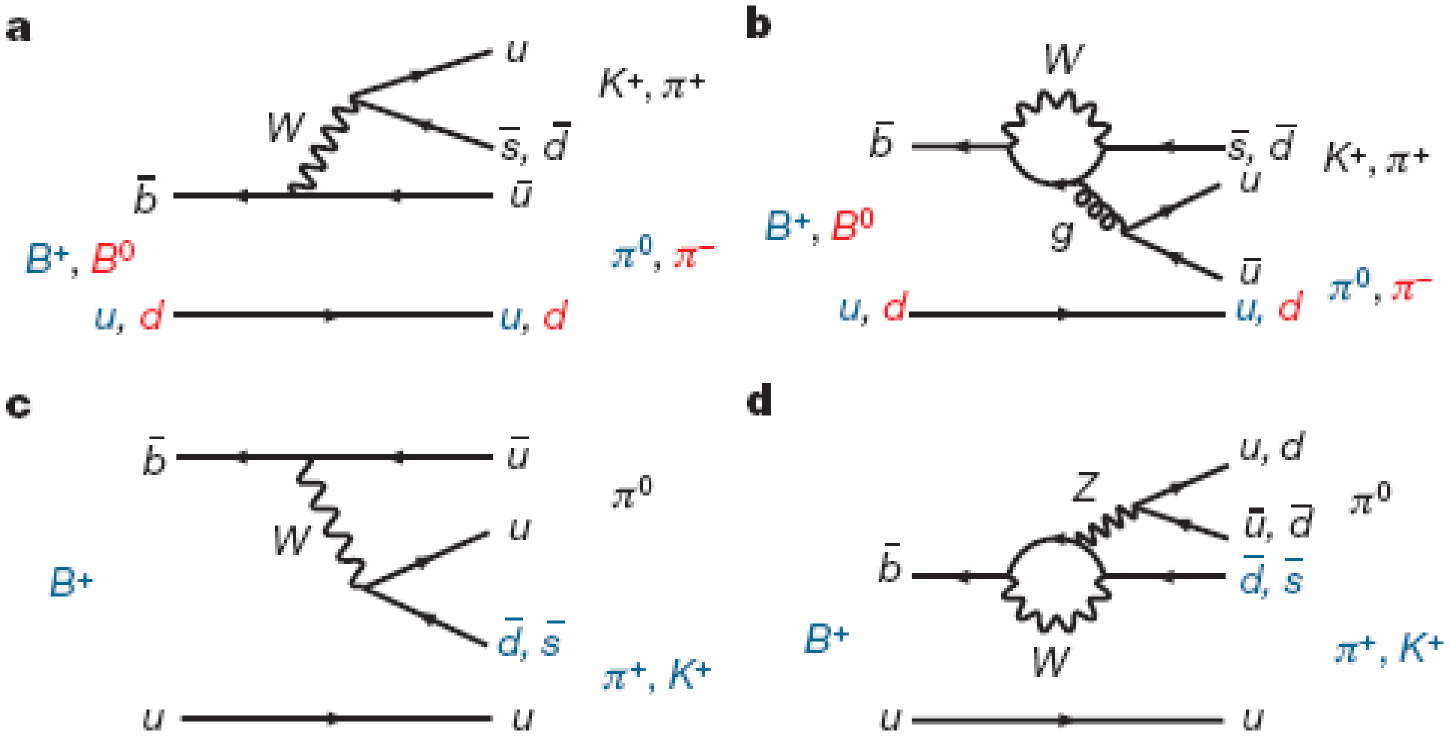
Direct CP Violation

Perhaps....

But:

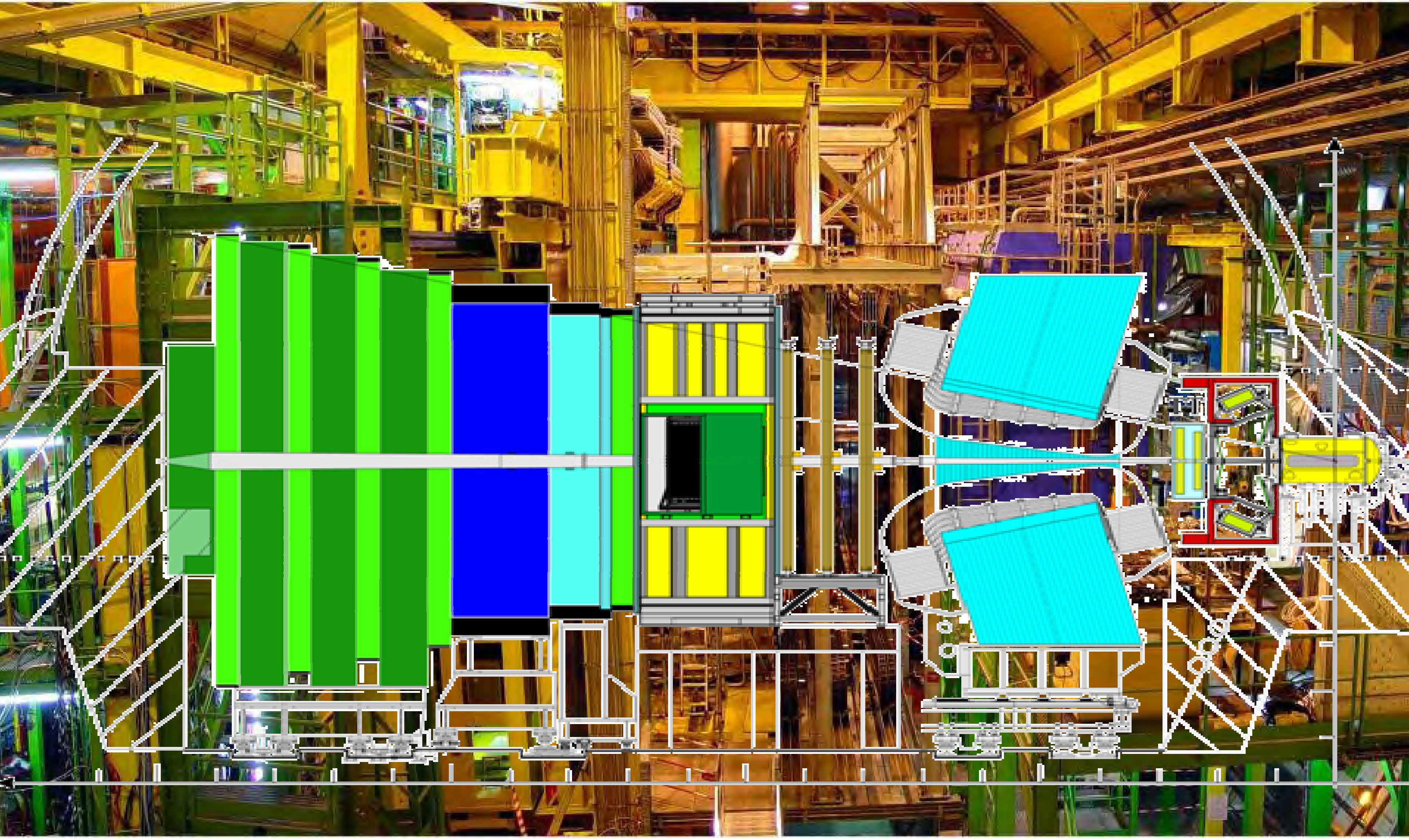
domiant

suppressed



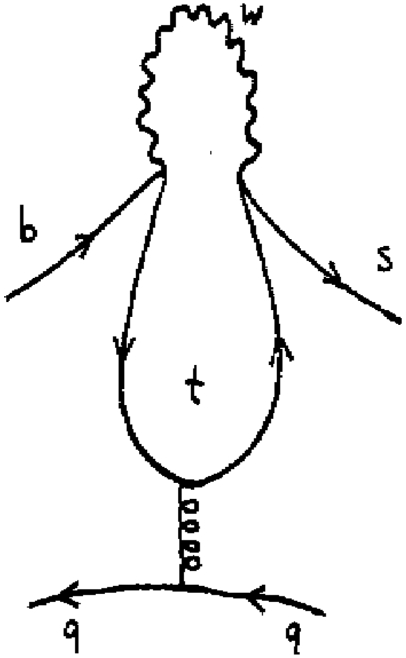
Electroweak Penguin contributes only to charged B's. It does not carry a different weak phase but potentially different strong phases. Although suppressed it may be responsible for the effect.

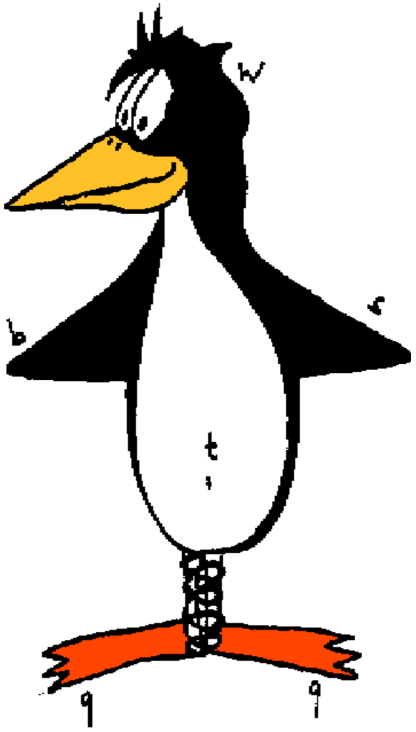
LHCb



Searches for New Physics

Large potential for detecting New Physics: Penguin Modes



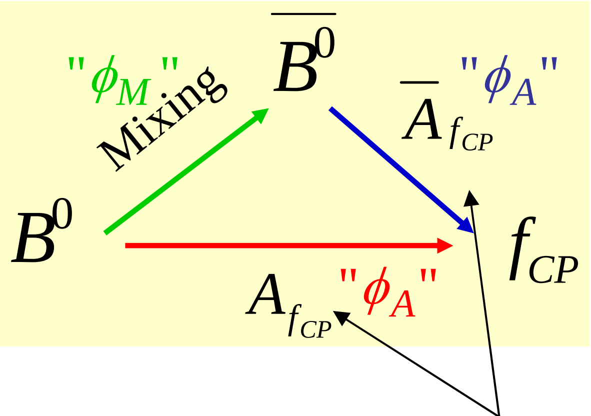


T. Hurth

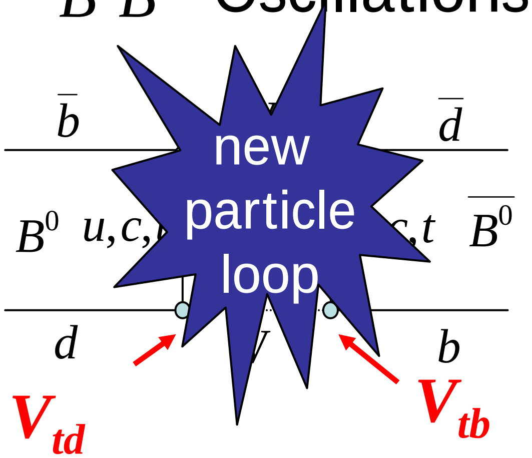
Many attemps are being made to look inside the penguin.....

~~CP~~ in Interference between Mixing and Decay

$B^0 \to J/\psi K_S$ vs $B_s \to J/\psi \phi$



$B^0\overline{B}^0$ Oscillations



dominated by top quark

$+$

$\phi_M \propto \arg V_{tb}^* V_{td}$ $\quad B_d^0$

$\phi_M \propto \arg V_{tb}^* V_{ts}$ $\quad B_s^0$

Wolfenstein: only „real“ CKM elements in decay → no weak phase

$$\Rightarrow \phi_M - \phi_A \approx \arg(V_{td}) \to -\beta$$

$$\Rightarrow \phi_M - \phi_A \approx \arg(V_{ts}) \to \chi + \pi$$

need to consider δV

Time resolved measurements!

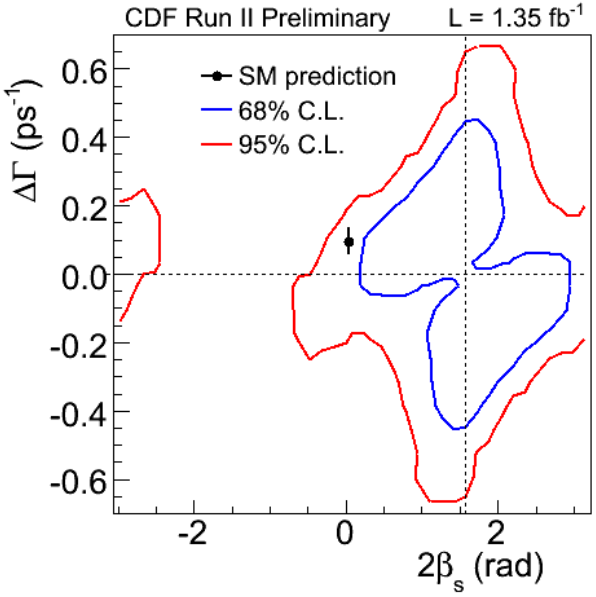
$A_{CP} \propto \sin 2\chi \sin \Delta m t$ tiny!

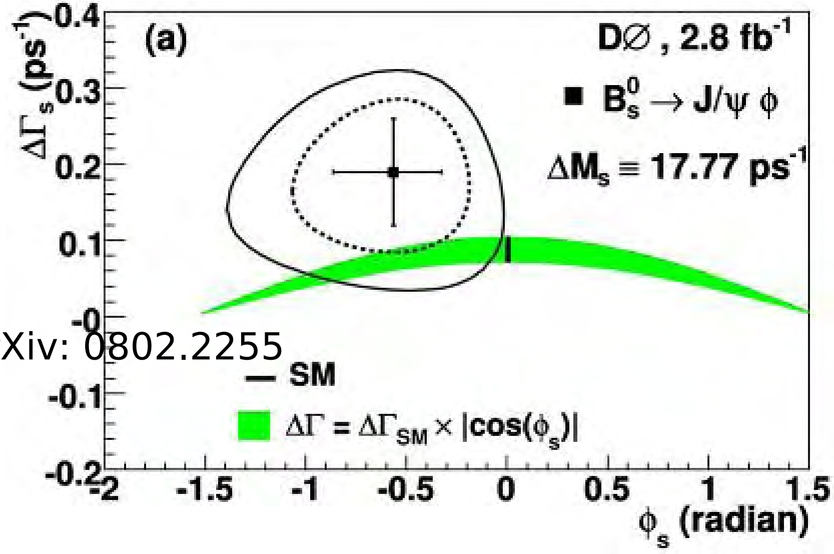
New Physics may influence mixing Phase! ⇒β shifted!

$B_s \to J/\psi \phi$, $B_s \to \phi\phi$

Not trivial to extract information!

- Time resolved measurements of CP-Asymmetries needed
  - take into account lifetime difference
- Pseudoscalar decaying into two Vector states
  - ℓ=0,1,2 possible (different CP eigenstates for ℓ=0, 2 and ℓ=1
    - requires full angular analysis („transversity basis“)
- Strong phases are around
  - can be dealt with as shown by measurements of $B \to J/\psi K^{*0}$





arXiv: 0802.2255

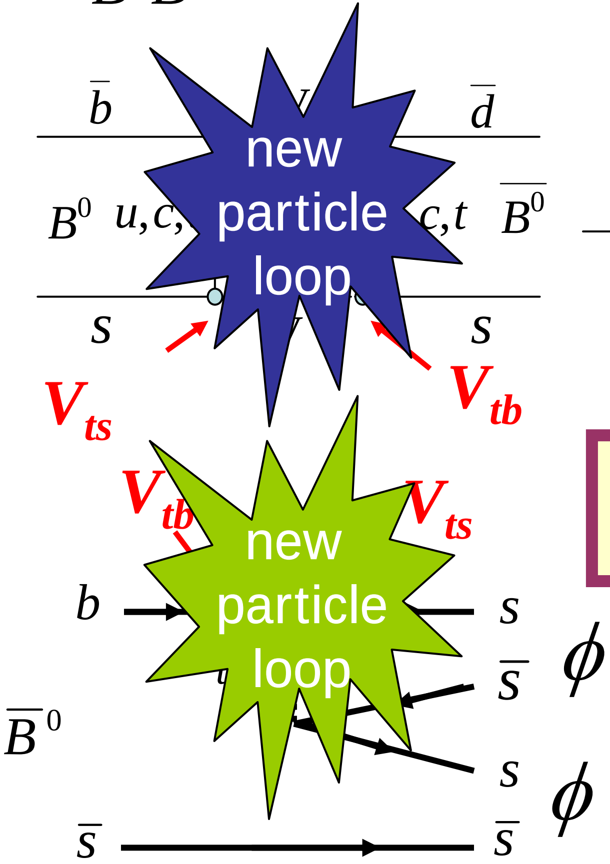
Interference between Mixing and Decay

$B_s \to \phi\phi$

$B^0\overline{B}^0$ Oscillations

dominated by top quark

$"\phi_M"$



$+\ \phi_M \propto \arg V_{tb}^* V_{ts} \quad B_s^0$

Even better!

$$\boxed{\Rightarrow \phi_M - \phi_A = 0}$$

$"\phi_A"$

$\phi_A \propto \arg V_{tb}^* V_{ts}$

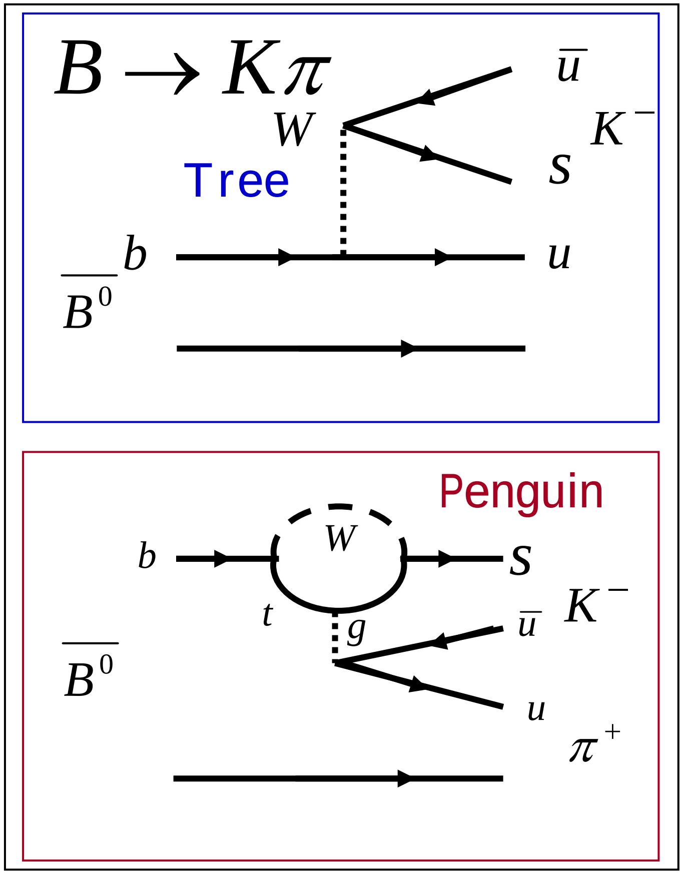
An Observation of CP Violation ⇒ New Physics!

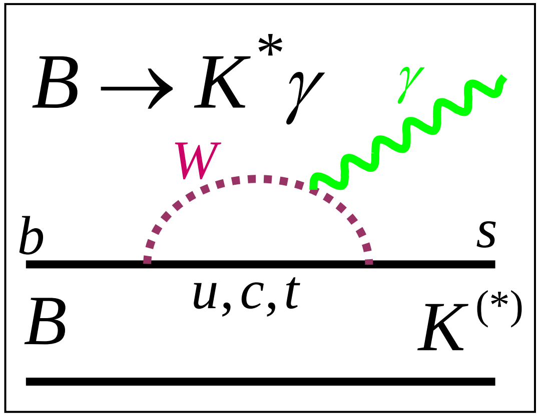
Rare decays

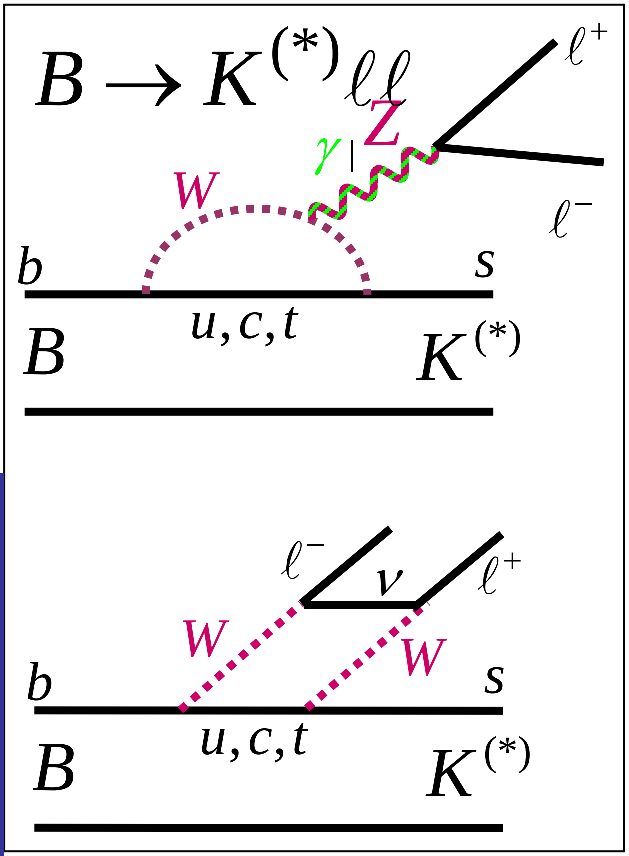
Small Branching Fractions

More interesting penguin mediated modes:

e.g. $B \to K\pi, K^{*}\gamma, K^{(*)}\ell\ell, \ldots.$







Need huge statistics!
⇒LHCb

+ look for other rare Decays e.g. $B\to\mu^+\mu^-$

LHCb Physics Programme

precision measurements
of CKM angles

rare decays

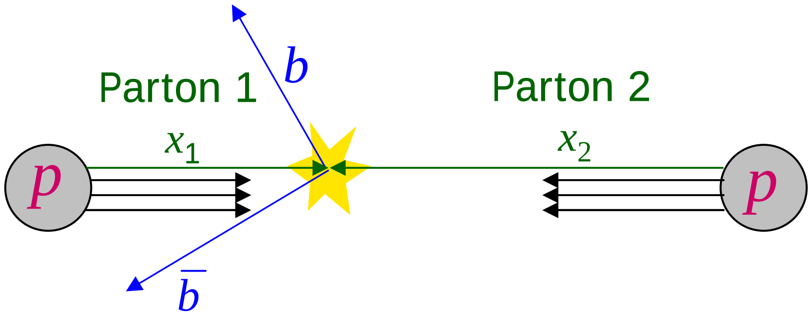
Search for New Physics

measure rates, CP-Asymmetries, Forward-Backward-Asymmetries etc.

+

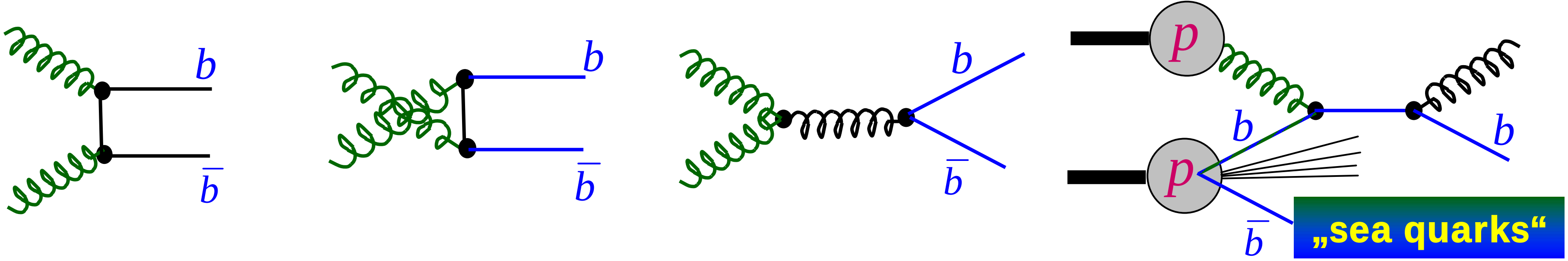
B production,
B_c , b-baryon physics
Charm decays (e.g. D-mixing)
Tau Lepton flavour violation
e.g. search for $\tau \rightarrow 3\mu$

B production in pp Collisions at $\sqrt{s}$ = 14 TeV (LHC)



Interactions of 2 partons (quarks, gluons) with fractional momenta x_i

Examples:



all b-hadron species are produced:

$$B^+, B_d^0\ , B_s^0, B_c, \Lambda_b, ...$$

~40% ~40% ~10% ~10%

$$\sigma_{b\bar{b}} \approx 500 \mu b$$

$$\sigma_{inelastic} \approx 80 mb$$

Challenge

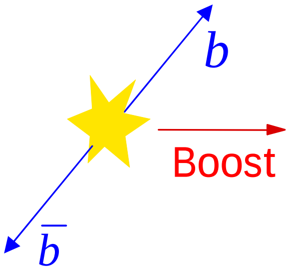
$$\Rightarrow \frac{\sigma_{b\bar{b}}}{\sigma_{inelastic}} \approx 0.006$$

compare with

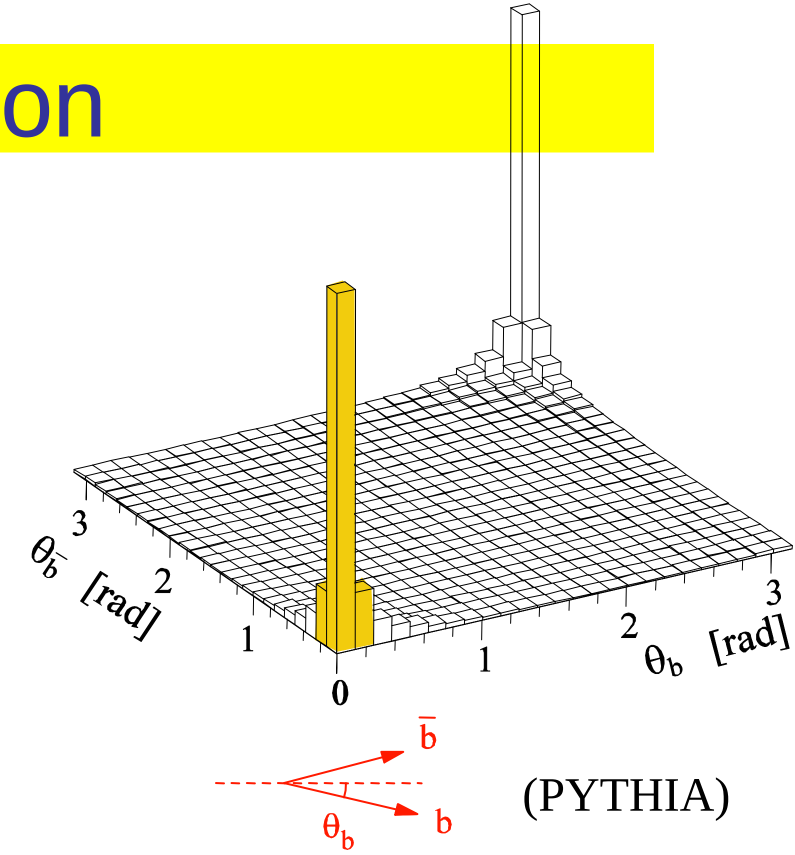
≈ 0.000001@

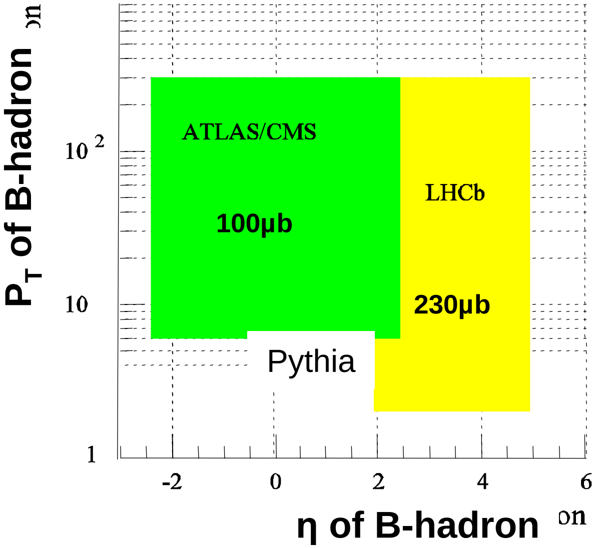
B production

- B hadrons are mostly produced in the forward (beam) direction



- Choose a forward spectrometer 10–≈300 mrad
- Both b and $\bar{b}$ in the acceptance: important for tagging the production state of the B hadron
- Efficient Trigger needed



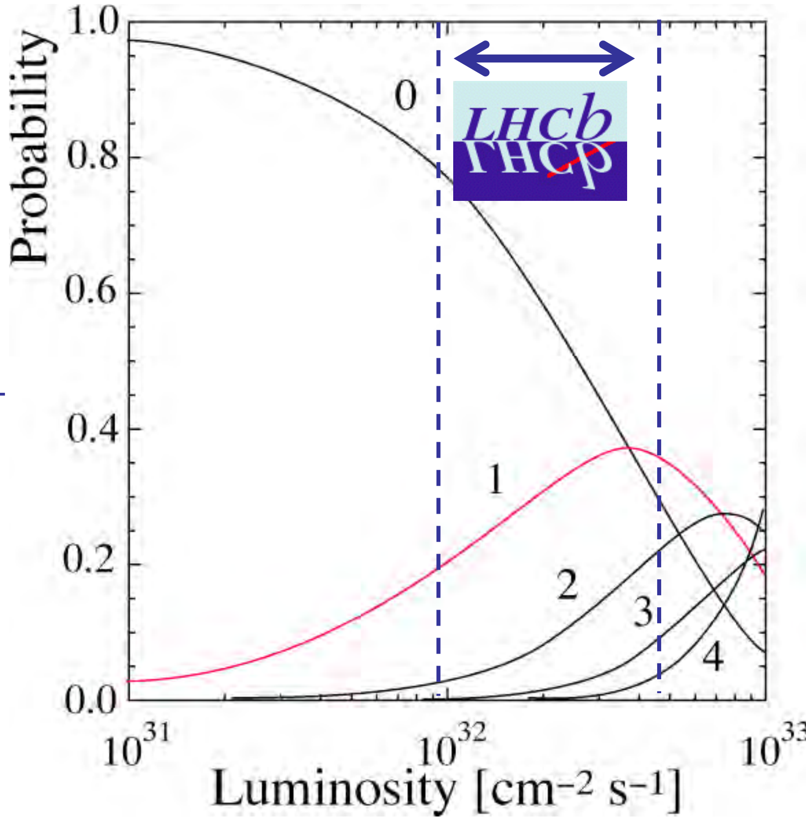


LHC environment

- Bunch crossing frequency: 40 MHz
- $\sigma_{inelastic}$ = 80 mb
  → at high L >> 1 pp collision/crossing
  ⇒ run at $<L>$ ~ 2 × 10^{32} $cm^{-2}s^{-1}$
  → dominated by single interactions
- in acceptance region: $\sigma_{b\bar{b}} \cong 230\ \mu b$
  ⇒ collect 10^{12} $b\bar{b}$ events/a

- Beams are less focused locally to maintain optimum luminosity even when ATLAS and CMS run at $<L>$ ~ 10^{34} $cm^{-2}s^{-1}$
- Reconstruction easier
  - e.g. b-quark vertex identification
- Lower radiation level
- LHCb-detector must be able to operate in a high rate and high multiplicity environment

Inelastic pp collisions/crossing



From U. Nierste

Why B_s physics?

i) CKM elements in $\mathrm{B_s}-\overline{\mathrm{B}}_\mathrm{s}$ mixing are well-known.

ii) Most CP asymmetries are small in the Standard Model.

iii) The mixing–induced CP asymmetries in $b \to s$ penguin modes can be studied in B_s decays into any final state, while the B_d penguin decays require a neutral K meson. Study $B_s \to \phi\phi$ and $B_s \to K^+K^-$!

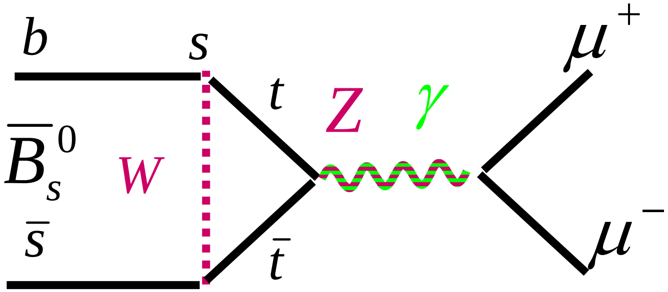
iv) $Br(B_s \to \ell^+\ell^-) \gg Br(B_d \to \ell^+\ell^-)$ in all MFV scenarios.

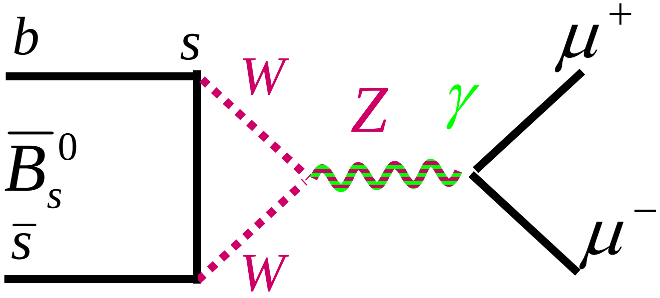
v) GUT models can naturally put large new effects into $b \to s$ transitions.

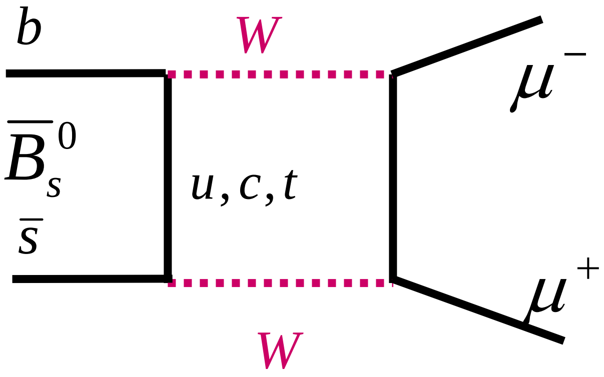
6. A theorist's wishlist for LHCb

1. $a_{\mathrm{mix}}^{\mathrm{CP}}(B_s \to J/\psi\phi)$
2. $Br(B_s \to \mu^+\mu^-)$
3. a_{fs}^{s} and a_{fs}^{d}
4. angular analysis of tagged $B_s \to \phi\phi$
5. tagged $B_s \to K_SK_S$, $B_s \to K_SK^{*0}$, $B_s \to \overline{K}^{*0}K_S$ and (with angular analysis) $B_s \to K^{*0}\overline{K}^{*0}$
6. Can you do $B \to D\tau\overline{\nu}$? (→ charged Higgs effects)
7. branching fraction and $a_{\mathrm{mix}}^{\mathrm{CP}}$ in $B_s \to \phi\rho^0$ (→ electroweak penguin physics)
8. $Br(B_s \to X\ell^+\ell^-)$ and $Br(B_d \to X\ell^+\ell^-)$

Example: $B_S \rightarrow \mu^+\mu^-$

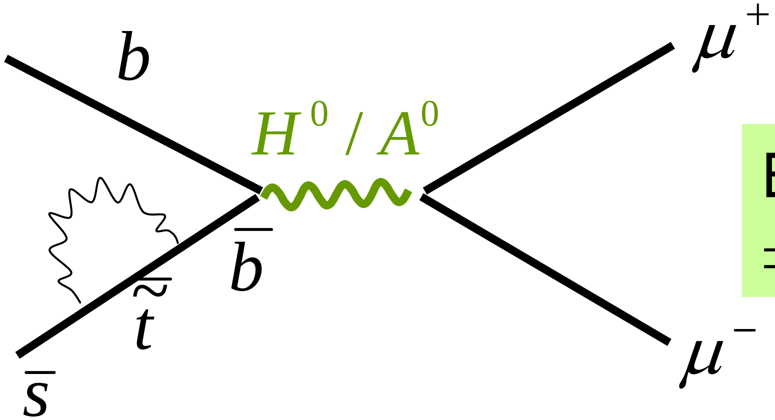






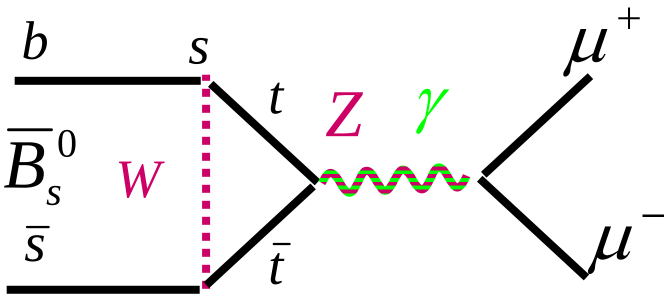
SM Prediction
(3.4 ± 0.5) x 10^{-9}

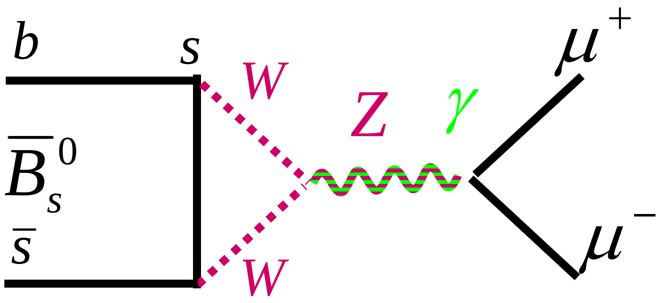
This decay could be strongly enhanced in some SUSY models. Example: MSSM:

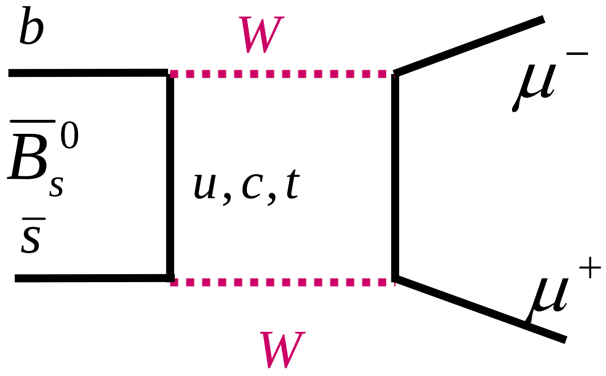


Branching ratio is $\propto \tan^6\beta$
$\Rightarrow$Enhancement of 100 is possible

$B_S \to \mu^+\mu^-$





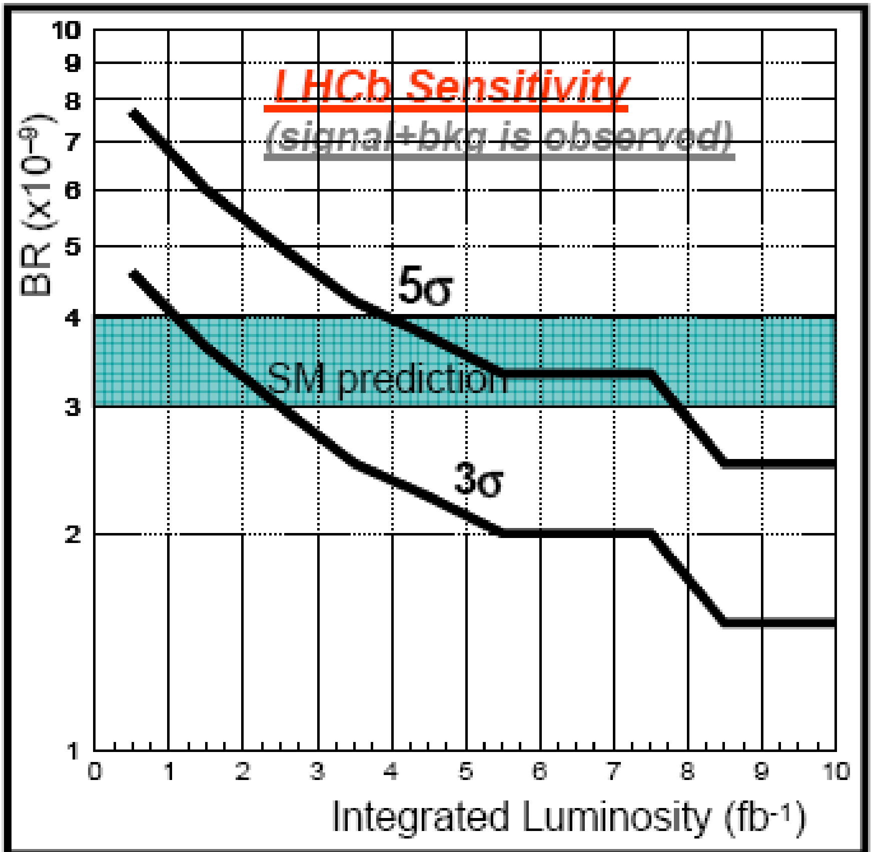


SM Prediction
$(3.4 \pm 0.5) \times 10^{-9}$

Current limit from CDF
BR($B_s \to \mu\mu$) < 5.8×10^{-8}

0.05/fb ⇒ overtake CDF, D0
0.5/fb ⇒ 90% exclusion of BR values down to Standard Model

2/fb ⇒ 3σ sensitivity to Standard Mode Branching Ratio



Performance figures (1 year, 2 fb^{-1})

	Channel	**Yield**	**B/S**	**Precision**
γ	$B_s \rightarrow D_s^{-+} K^{+-}$	5.4k	< 1.0	$\sigma(\gamma)$ ~ 14°
	$B_d \rightarrow \pi^+ \pi^-$	36k	0.46	$\sigma(\gamma)$ ~ 4°
	$B_s \rightarrow K^+ K^-$	36k	< 0.06	
	$B_d \rightarrow D^0 (K\pi, KK) K^{*0}$	3.4 k, 0.5 k, 0.6 k	<0.3, <1.7, < 1.4	$\sigma(\gamma)$ ~ 7° - 10°
	$B^- \rightarrow D^0 (K^-\pi^+, K^+\pi^-) K^-$	28k, 0.5k	0.6, 4.3	$\sigma(\gamma)$ ~ 5° - 15°
	$B^- \rightarrow D^0 (K^+K^-, \pi^+\pi^-) K^-$	4.3 k	2.0	
	$B^- \rightarrow D^0 (K_S\pi^+\pi^-) K^-$	1.5 - 5k	< 0.7	$\sigma(\gamma)$ ~ 8° - 16°
α	$B_d \rightarrow \pi^+ \pi^- \pi^0$	14k	< 0.8	$\sigma(\alpha)$ ~ 10°
	$B \rightarrow \rho^+\rho^0, \rho^+\rho^-, \rho^0\rho^0$	9k, 2k, 1k	1, <5, < 4	
β	$B_d \rightarrow J/\psi(\mu\mu)K_S$	216k	0.8	$\sigma(\sin 2\beta)$ ~ 0.022
Δm_s	$B_s \rightarrow D_s^- \pi^+$	80k	0.3	$\sigma(\Delta m_s)$ ~ 0.01 ps^{-1}
ϕ_s	$B_s \rightarrow J/\psi(\mu\mu)\phi$	131k	0.12	$\sigma(\phi_s)$ ~ 1.3°
Rare decays	$B_s \rightarrow \mu^+\mu^-$	17	< 5.7	
	$B_d \rightarrow K^{*0} \mu^+\mu^-$	7.7 k	0.4	$\sigma(C_7^{eff}/C_9^{eff})$ ~0.13
	$B_d \rightarrow K^{*0} \gamma$	35k	< 0.7	$\sigma(A_{CP})$ ~0.01
	$B_s \rightarrow \phi \gamma$	9.3 k	< 2.4	
charm	$D^{*+} \rightarrow D^0 (K^-\pi^+) \pi^+$	100 M		

Conclusions

- B-Physics will remain an exciting field for many years coming!

- BABAR: data taking up to April 2008
  - Many exciting results still expected
  - Standard Model still holds…….

- LHCb: new Quality
  - production rates
  - B_s sector accessible with high precision
    - has higher sensitivity to New Physics
  - Complententary program to direct NP-searches at ATLAS, CMS
  - waiting for data!