Collider Particle Physics
- Chapter 11 -

CP Violation in the B^0 System

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Chapter Summary

- Mixing in the neutral mesons
- Mixing in the B^0 mesons
- CKM matrix and CP violation
- CP violation in the B^0 mesons
- Pep II asymmetric B-factory at SLAC
- Quantum entanglement in the B^0B^0 system
- Measurement of the CP violation in the B^0 mesons
- Direct CP violation in the B^0 mesons

Is CP violated only in the K^0 system?

- In 1964 was discovered the CP violation in the mixing of the neutral K system (people were invoking a superweak interaction that intervenes in the transitions with $\Delta S=2$).

- **The direct CP violation (with $\Delta S=1$) was experimentally verified more than 30 years later.**

- In 1973 Kobayashi and Maskawa made the hypothesis of the existence of 3 quark families in order to accomodate a phase in the quark mixing matrix that would be responsible of the CP violation in the weak interactions.

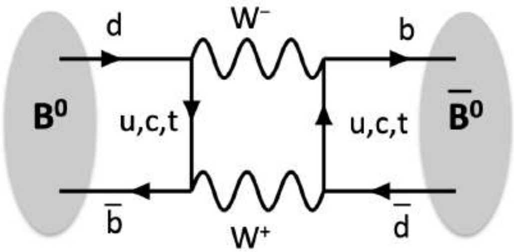
- **In 1974 was discovered the quark c and in 1977 the quark b**

- In the 80s start the search for the quark mixing in the B^0 system.

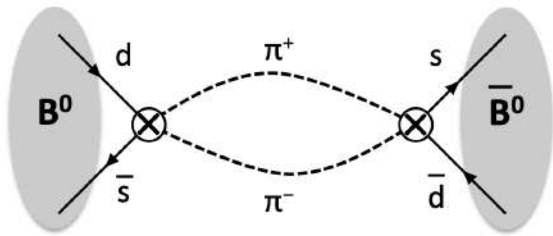
- **In the late 90s start the search of the CP violation in the B^0 system.**

Meson Mixing

Meson Mixing



"short-distance"
(=virtual particle exchange)



"long-distance"
(=real particle exchange)

- **Besides K^0, other neutral mesons can "mix":**

1) **Need to be neutral and have distinct anti-particle (x)**
2) **Needs to have a non-zero lifetime**
   - **top is so heavy, it decays long before it can even form a meson (◆)**

- **That leaves four distinct cases …**

	u	c	t
$\overline{u}$	$\times$	D^0	$\diamond$
$\overline{c}$	$\overline{D^0}$	$\times$	$\diamond$
$\overline{t}$	$\diamond$	$\diamond$	$\times$

	d	s	b
$\overline{d}$	$\times$	$\overline{K^0}$	$\overline{B^0}$
$\overline{s}$	K^0	$\times$	$\overline{B_s}$
$\overline{b}$	B^0	B_s	$\times$

B Mesons

Symbol	Quark	isospin	Mass (GeV)	S	C	B	Lifetime (s)
B^+	$u\bar{b}$	½	5.279	0	0	1	1.64×10^{-12}
B^0	$d\bar{b}$	½	5.279	0	0	1	1.52×10^{-12}
B^0_S	$s\bar{b}$	0	5.366	-1	0	1	1.51×10^{-12}
B^+_C	$c\bar{b}$	0	6.275	0	1	1	0.51×10^{-12}

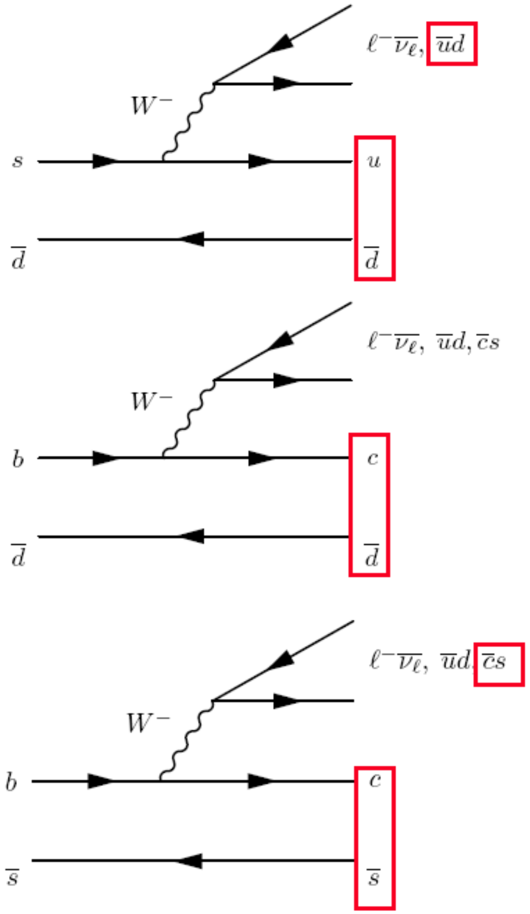
Mixing: Kaons versus B mesons

- The difference between K mixing and 'the rest': Γ_{12}

$$\Gamma_{12} = \Gamma_1 - \Gamma_2$$

- A *large* fraction of Kaon decays produce CP eigenstates:
  - all decays *without* leptons are CP eigenstates..
- the CP even ones have more phase-space
  - Hence the lifetime difference (large Γ_{12}!)

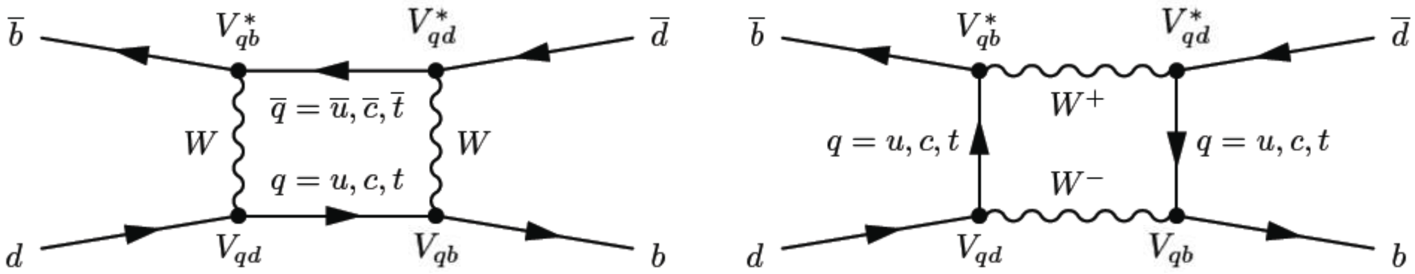
- For B^0, (and, to a somewhat lesser extent, B_s), the dominant decays are *not* CP eigenstates
  - hence $\Delta\Gamma$=0 (smallish), and Γ_{12} does *not* contribute to B^0 mixing
  - note: as a result labeling eigenstates as 'S'hort and 'L'ong doesn't make sense -- hence the 'H'eavy and 'L'ight



Dominant decay amplitudes

Mixing: box diagrams

N.B. We get the coupling in every vertex through CKM matrix elements



$t-\bar{t}: \quad \propto m_t^2 \left|V_{tb}V_{td}^*\right|^2 \quad \propto m_t^2 \lambda^6$

$c-\bar{c}: \quad \propto m_c^2 \left|V_{cb}V_{cd}^*\right|^2 \quad \propto m_c^2 \lambda^6$

$c-\bar{t}, \bar{c}-t: \quad \propto m_c m_t V_{tb} V_{td}^* V_{cb} V_{cd}^* \propto m_c m_t \lambda^6$

GIM(V_{CKM} unitarity):
if u,c,t same mass, everything cancels *by construction*!

$\lambda = \sin\theta_C$

Dominated by top quark mass: $\Delta m_B \approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2}\right)^2 \mathrm{ps}^{-1}$

reference: $\tau_B \sim 1.5$ ps

B^0 mixing: Argus, 1987

- Produce an $b\bar{b}$ bound state, $\Upsilon(4S)$, in e^+e^- collisions:
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\overline{B^0}$
- and then observe:

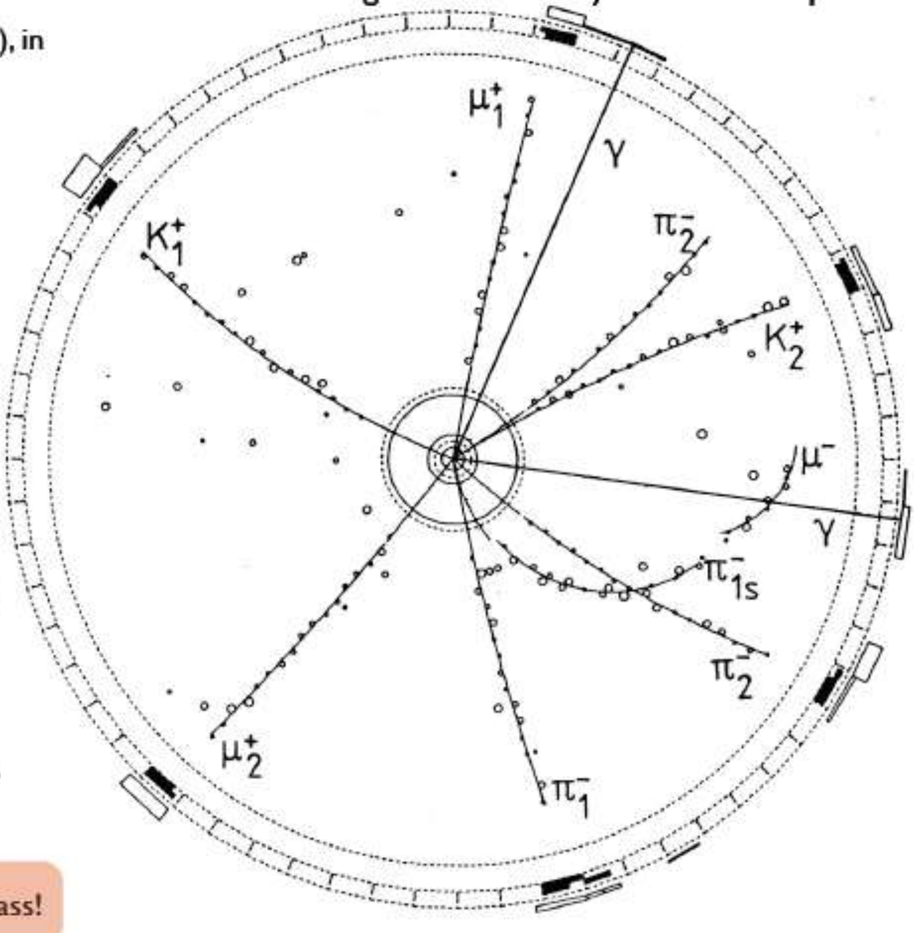
$$
\begin{aligned}
B_1^0 \rightarrow\ & D_1^{*-}\mu_1^+\nu_1 \\
& D_1^{*-} \rightarrow \overline{D^0}\pi_{1s}^- \\
& \overline{D^0} \rightarrow K_1^+\pi_1^-
\end{aligned}
$$

$$
\begin{aligned}
B_2^0 \rightarrow\ & D_2^{*-}\mu_2^+\nu_2 \\
& D_2^{*-} \rightarrow D^-\pi^0 \\
& D^- \rightarrow K_2^+\pi_2^-\pi_2^- \\
& \pi^0 \rightarrow \gamma\gamma
\end{aligned}
$$

- measure that ~17% of B^0 and $\overline{B^0}$ mesons oscillate before they decay
  - $\tau_B \sim 1.5$ ps $\Rightarrow$ $\Delta m_d \sim 0.5$/ps,

First evidence of a really large top mass!

Integrated luminosity 1983-87: 103 pb^{-1}



ARGUS
(**A** **R**ussian-**G**erman-**U**nited States-**S**wedish Collaboration) ran at the e+e- collider DORIS II at DESY.
Its aim was to explore properties of c and b quarks.
Its construction started in 1979, the detector was commissioned in 1982 and operated until 1992

Meson mixing: time dependence

Time evolution of particle given by Schrödinger-like equation:

$$i\frac{\partial}{\partial t}|\Psi\rangle = H|\Psi\rangle = (M - \frac{i}{2}\Gamma)|\Psi\rangle$$

mass

(real part of potential
– conserves probability)

decay rate (=1/τ)

(imaginary part of potential
– allows decays to be included)

For two-meson system, replace M,Γ with 2×2 matrices: $|\Psi\rangle = \begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & 0 \\ 0 & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

Meson mixing: time dependence

"CPT theorem": $M_{11} = M_{22} = M$
$\Gamma_{11} = \Gamma_{22} = \Gamma$

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & 0 \\ 0 & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

But… particles mix between states by above processes… need off-diagonal elements

$$i\frac{\partial}{\partial t}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{21} - \frac{i}{2}\Gamma_{21} & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} B^0 \\ \bar{B}^0 \end{pmatrix}$$

⇒ Flavour states are not eigenstates of Hamiltonian – no well defined mass or lifetime

Meson mixing: time dependence

⇒ Flavour states are not eigenstates of Hamiltonian…

Orthogonality

But… can express mass eigenstates in flavour basis:

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

Define parameters:

$\Delta m = m_H - m_L$

$\Delta\Gamma = \Gamma_L - \Gamma_H$

Heavy and light eigenstates then have energies:

$E_H = M + \frac{1}{2}\Delta m + \frac{1}{2}i(\Gamma - \Delta\Gamma)$

$E_L = M - \frac{1}{2}\Delta m + \frac{1}{2}i(\Gamma + \Delta\Gamma)$

So we can write time-dependent solutions for stationary states:

$|B(t)\rangle = |B(0)\rangle\, e^{-iEt}$

$$|B_H(t)\rangle = |B_H\rangle e^{-i(M+\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma-\Delta\Gamma))t}$$
$$|B_L(t)\rangle = |B_L\rangle e^{-i(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma))t}$$

Meson mixing: time dependence

We care about time-dependence of flavor states B^0 and $\bar{B}^0$. Can determine this from:

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \qquad |B_H(t)\rangle = |B_H\rangle e^{-i(M+\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma-\Delta\Gamma))t}$$

and

$$|B_L\rangle = p|B^0\rangle - q|\bar{B}^0\rangle \qquad |B_L(t)\rangle = |B_L\rangle e^{-i(M-\frac{1}{2}\Delta m+\frac{i}{2}(\Gamma+\Delta\Gamma))t}$$

$$\cosh x = \frac{e^x + e^{-x}}{2}$$

$$\sinh x = \frac{e^x - e^{-x}}{2}$$

With a bit of algebra, we get:

B^0 at t=0
$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \left(\frac{q}{p}\right) g_-(t)|\bar{B}^0\rangle$$

$\bar{B}^0$ at t=0
$$|\bar{B}^0(t)\rangle = \left(\frac{p}{q}\right) g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

where $g_\pm(t)$ gives time dependence:

$$g_+(t) = e^{-imt}e^{-\Gamma/2t}\left[\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right],$$

$$g_-(t) = e^{-imt}e^{-\Gamma/2t}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right]$$

Meson mixing: time dependence (example)

Take the simple case:

- We identify the production flavor of the meson as B^0
- What is the probability of observing the meson as $\bar{B}^0$ as a function of time?

$$|B^0(t)\rangle = g_+(t)|B^0\rangle + \left(\frac{q}{p}\right) g_-(t)|\bar{B}^0\rangle$$

$$|\bar{B}^0(t)\rangle = \left(\frac{p}{q}\right) g_-(t)|B^0\rangle + g_+(t)|\bar{B}^0\rangle$$

$$P(B^0 \rightarrow \bar{B}^0) = |\langle \bar{B}^0(t)|B^0\rangle|^2$$

$$\Rightarrow \quad P(B^0 \rightarrow \bar{B}^0) = |g_+(t)\underbrace{\langle \bar{B}^0|B^0\rangle}_{=0} + (p/q)^* g_-(t)^* \underbrace{\langle B^0|B^0\rangle}_{=1}|^2$$

= 0 (orthonormal basis) = 1 (orthonormal basis)

Plug in $g_-(t)$ from last slide

$$= |p/q|^2 |g_-(t)|^2$$

$$= \tfrac{1}{2} |p/q|^2 e^{-\Gamma t} \left[\cosh(\Delta\Gamma t/2) - \cos(\Delta m t)\right]$$

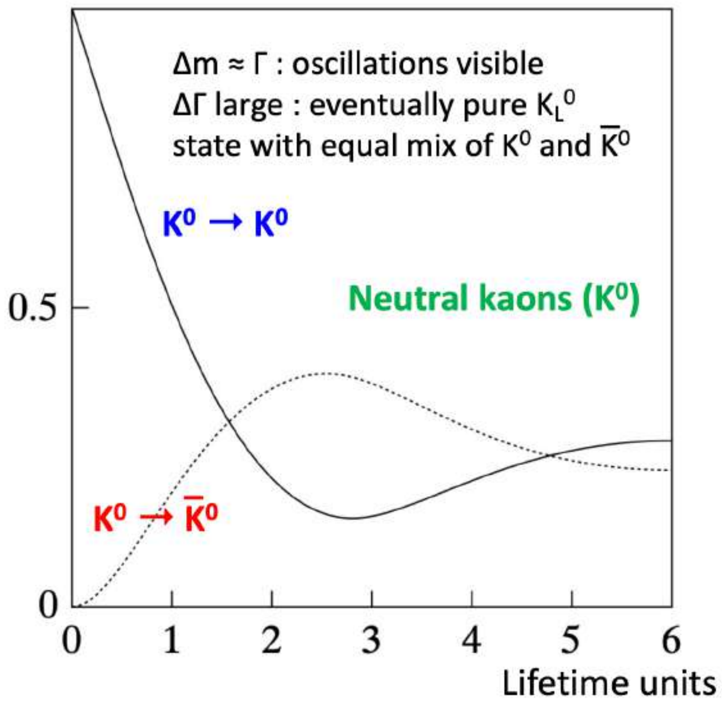
Exponential decay with lifetime $1/\Gamma$

Oscillation with angular frequency Δm

Meson mixing: four different systems

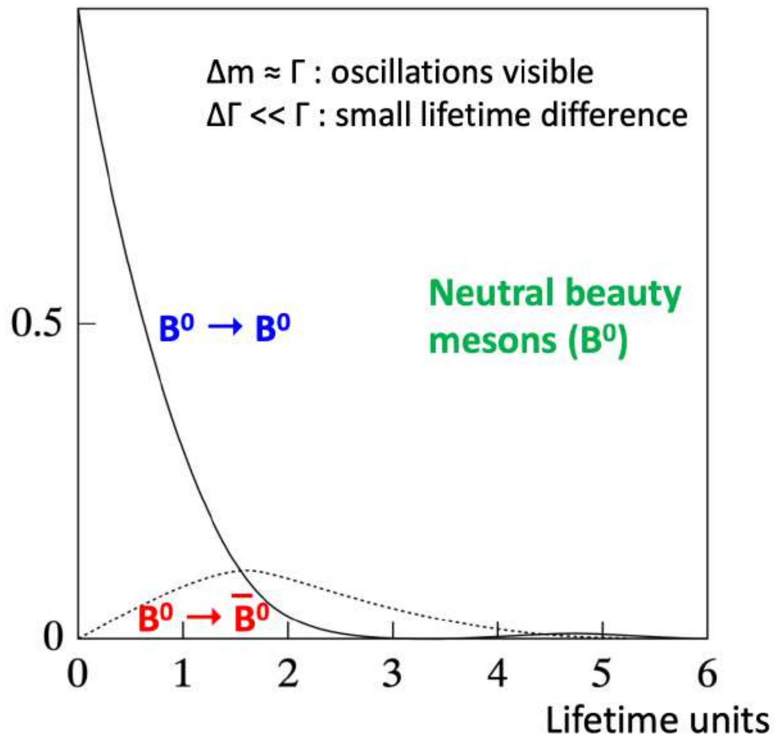
K^0 mixing

- Discovered implicitly in 1950s (K_L^0 and K_S^0 clearly different particles)



B^0 mixing

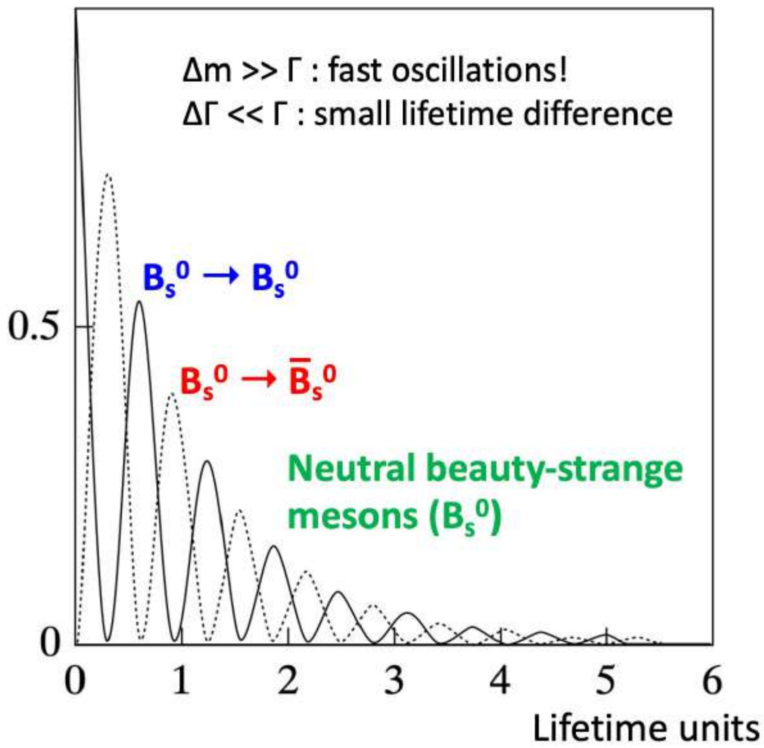
- Discovered in 1987 by Argus experiment



Meson mixing: four different systems

B_s^0 mixing

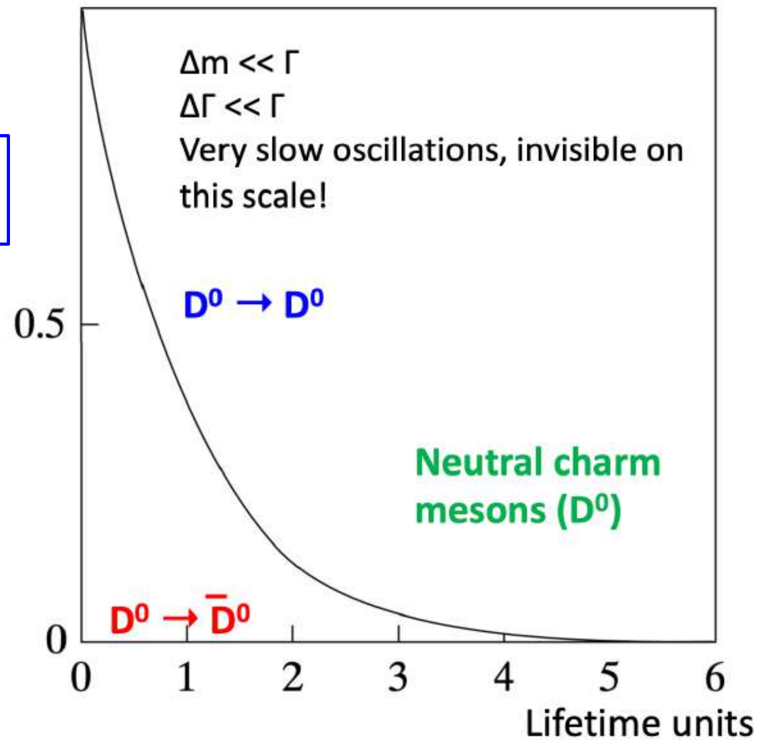
- Discovered in 2006 by CDF experiment



$$T = \frac{2\pi}{\Delta m}$$

D^0 mixing

- $\Delta\Gamma \neq 0$ discovered by Belle/Babar/LHCb in 2007-2013
- **In 2021**: Δm measured >5σ from zero



Meson mixing: kaon experiments

Production: $p\bar{p} \rightarrow K^0\pi^+K^-$ ($\bar{K}^0\pi^-K^+$)

Decay (e.g.): $K^0 \rightarrow \pi^-e^+\nu_e$

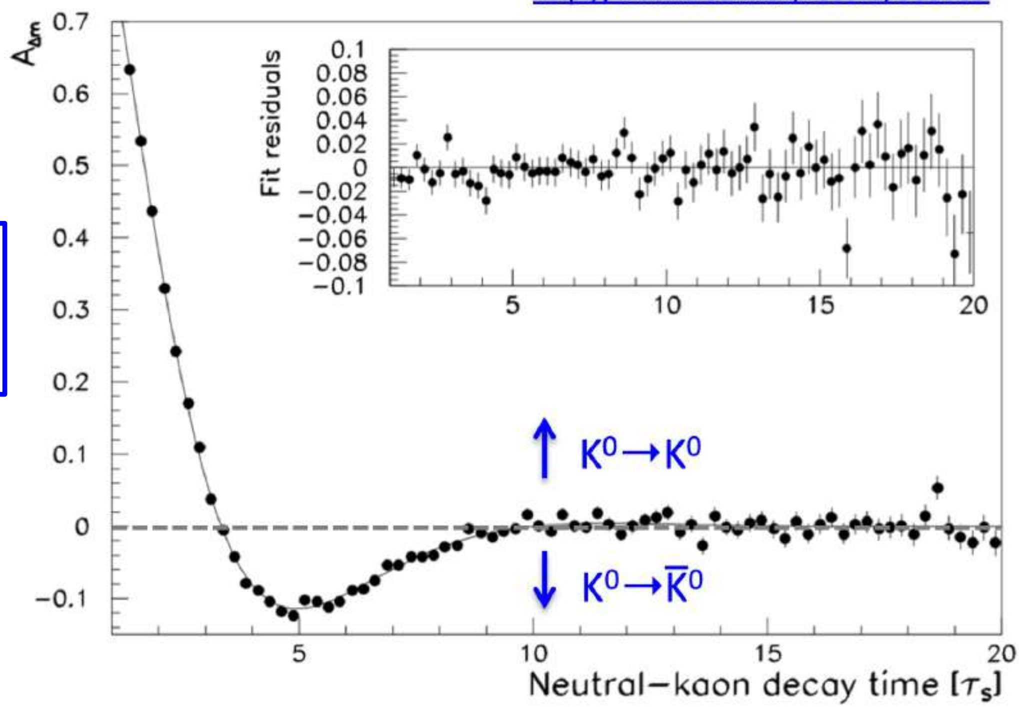
Identify final and initial kaon flavour states

CPLEAR Experiment
(results from 1998)

http://weblib.cern.ch/record/368703

The **CPLEAR experiment** used the antiproton beam of the LEAR facility - Low-Energy Antiproton Ring which operated at CERN from 1982 to 1996 – to produce neutral kaons through proton-antiproton annihilation at rest in order to study CP, T and CPT violation in the neutral kaon system.

At long decay times, only K_L^0 remains - equal probability to decay as K^0 or $\bar{K}^0$



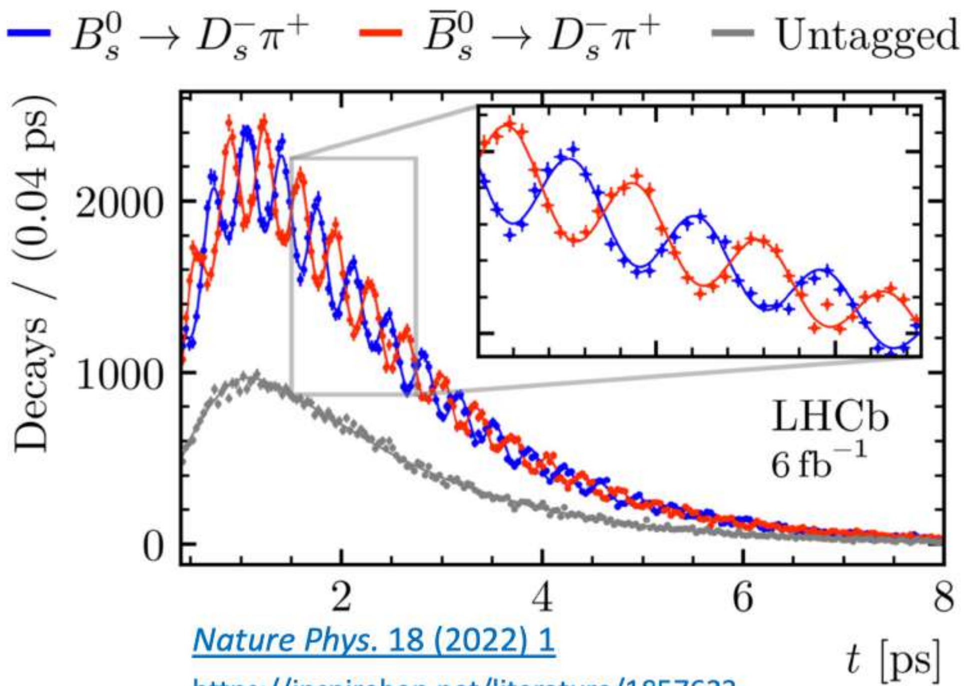
Meson mixing: beauty experiments

Same principles used for studies of B^0 and B_s^0 mixing
⇒ need to 'tag' flavour at production and decay

$\Delta m_s = (17.7656 \pm 0.0057)\ ps^{-1}$
(0.03% precision!)

B_s^0 case special due to very fast oscillations – need detector with very precise time reconstruction

LHCb designed to have excellent time resolution
⇒ could have seen oscillations up to Δm_s = 60ps^{-1}



[Nature Phys. 18 (2022) 1](https://inspirehep.net/literature/1857623)
https://inspirehep.net/literature/1857623

CKM Matrix

CP Violation in the Standard Model

CP violation experimentally verified in weak interaction, but couldn't fit into existing theory…

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

KM realised that **we need 3 generations** to allow CP violation…

Cabibbo

$$\begin{bmatrix} d' \\ s' \end{bmatrix} = \begin{bmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{bmatrix} \begin{bmatrix} d \\ s \end{bmatrix}$$

1 (real) parameter: mixing angle θ_c

Cabibbo Kobayashi Maskawa (CKM)

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

4 parameters: 3 real mixing angles

1 complex phase!

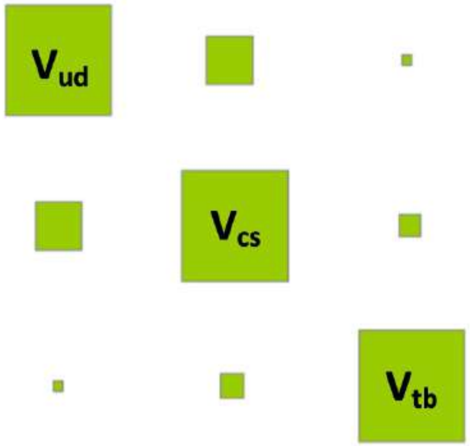
CKM Structure

Current experimental status:

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-ckm-matrix.pdf

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{bmatrix}$$

Magnitudes $|V_{ij}|^2$ appear in probabilities (=rates) of decays.



Magnitudes have suggestive pattern
No known reason!

Transitions within same generation : "**Cabibbo Favoured**" (CF)

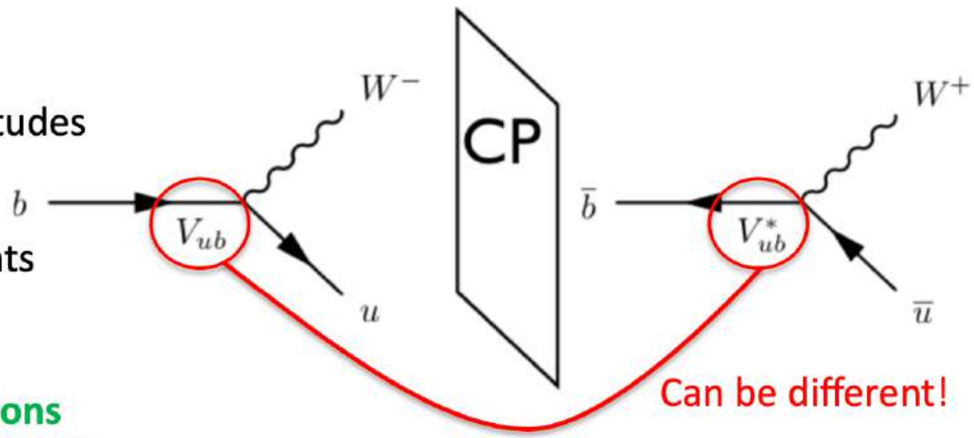
Processes with 1 (2) off-diagonal elements :
"**Singly (doubly) Cabibbo Suppressed**" (SCS / DCS)

CKM and CP Violation

CP operator
⇒ complex conjugation of amplitudes

With 3 generations, CKM elements V_{ij} can be complex

A universe with 2 (or 1) generations could not have CP violation this way!



Highly predictive (= good theory!)

- Can make many independent measurements of V_{ij} from different systems
- Test if these are self-consistent

Next job: measure the magnitudes and phases of these complex parameters V_{ij}

CKM parameterization: 'PDG'

$s_{ij} = \sin\theta_{ij}$

$c_{ij} = \cos\theta_{ij}$

Decompose into three rotation matrices:

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Parameters:

- 3 rotation angles $\theta_{12},\theta_{13},\theta_{23}$
- CP-violating phase δ

Observed hierarchy motivates an alternative parameterisation…

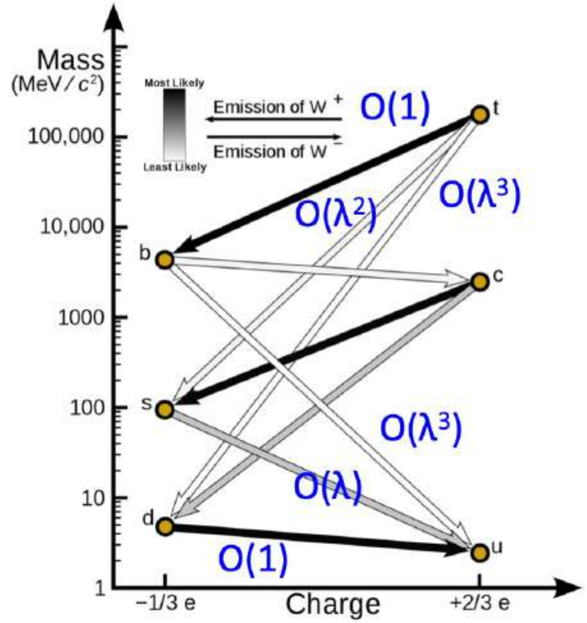
CKM parameterization: Wolfenstein

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

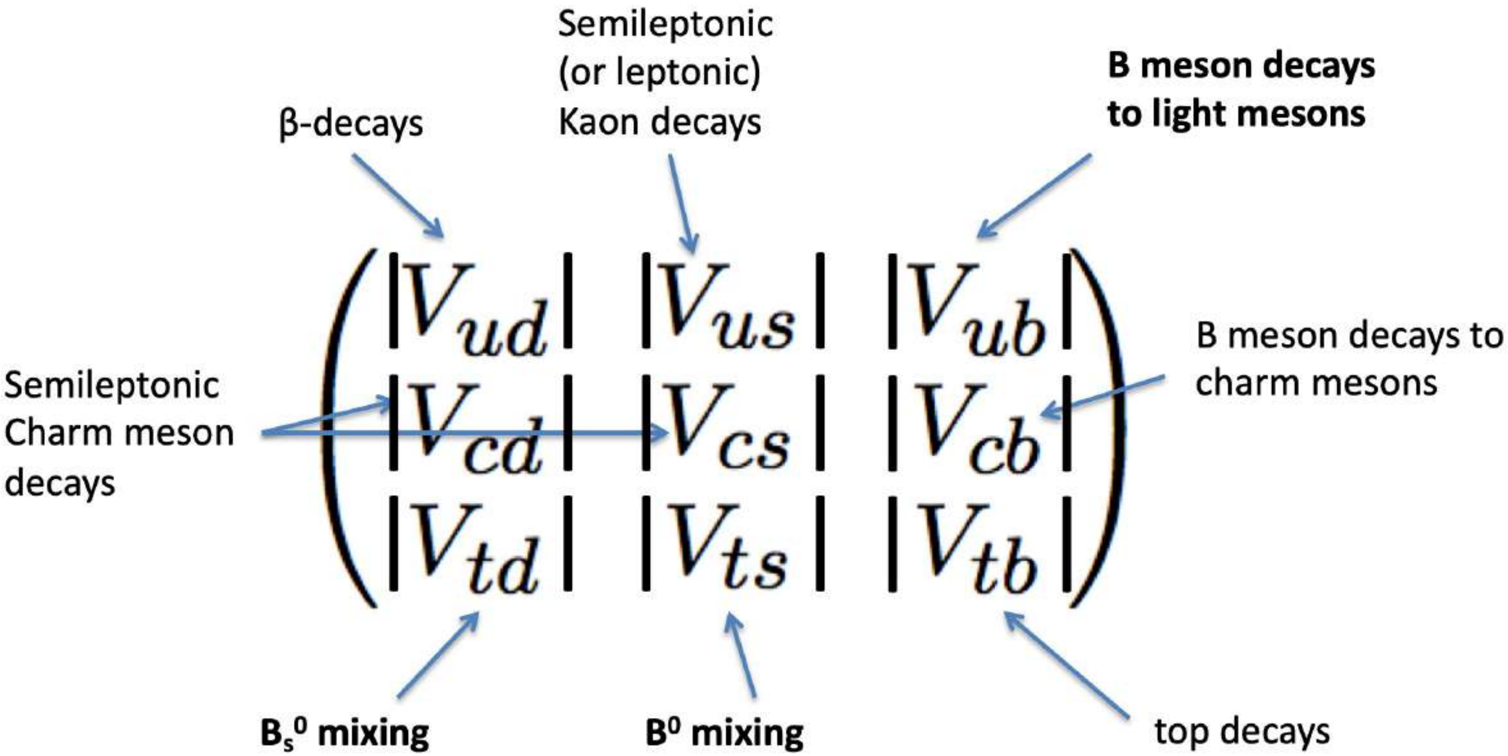
Expand CKM matrix elements in powers of $\lambda \approx 0.22$ (i.e. $\sin\theta_c$)

Here shown to order λ^3

Parameters: A, λ, ρ, η — Quantify CP violation



Testing the CKM mechanism



Often require theory inputs to relate hadron measurements to quark-level CKM

CKM matrix and CP Violation

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

Weak interactions eigenstates are not equal to strong interactions eigenstates

- **Let's write the CKM matrix in the Wolfstein formulation, useful to describe the CP violation in the B system (there is a phase only between the third and the first family):**

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \overbrace{A\lambda^3(\rho - i\eta)}^{V_{ub}} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \underbrace{A\lambda^3(1-\rho-i\eta)}_{V_{td}} & -A\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} + O(\lambda^4)$$

$$\lambda = \sin\theta_c$$

V_{td} and V_{ub} provide the weak phase necessary to have CP violation in the B mesons decays.

Unitarity of the matrix: $V^\dagger V=1$

$$|V_{ud}|^2+|V_{cd}|^2+|V_{td}|^2=1$$
$$|V_{us}|^2+|V_{cs}|^2+|V_{ts}|^2=1$$
$$|V_{ub}|^2+|V_{cb}|^2+|V_{tb}|^2=1$$

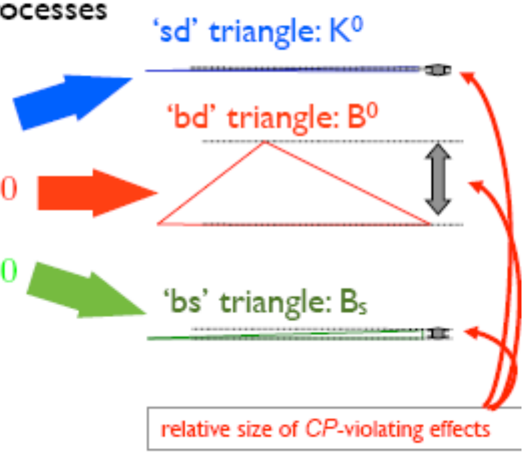
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The 6 complex "**Unitarity Triangles**" involve different physics processes

$$V_{us}^*V_{ud}+V_{cs}^*V_{cd}+V_{ts}^*V_{td}=0 \qquad \mathcal{O}(\lambda)+\mathcal{O}(\lambda)+\mathcal{O}(\lambda^5)=0$$

$$V_{ub}^*V_{ud}+V_{cb}^*V_{cd}+V_{tb}^*V_{td}=0 \qquad \mathcal{O}(\lambda^3)+\mathcal{O}(\lambda^3)+\mathcal{O}(\lambda^3)=0$$

$$V_{ub}^*V_{us}+V_{cb}^*V_{cs}+V_{tb}^*V_{ts}=0 \qquad \mathcal{O}(\lambda^4)+\mathcal{O}(\lambda^2)+\mathcal{O}(\lambda^2)=0$$



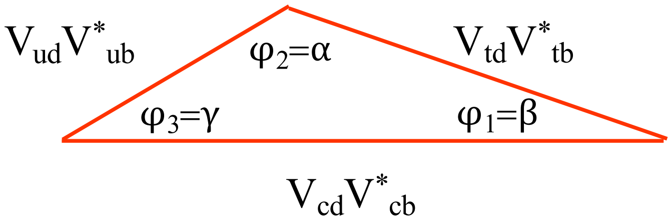
$$V_{ud}V_{cd}^*+V_{us}V_{cs}^*+V_{ub}V_{cb}^*=0$$
$$V_{ud}V_{td}^*+V_{us}V_{ts}^*+V_{ub}V_{tb}^*=0$$
$$V_{cd}V_{td}^*+V_{cs}V_{ts}^*+V_{cb}V_{tb}^*=0$$

These relations can be represented as a triangle in a complex plane

Unitarity triangle

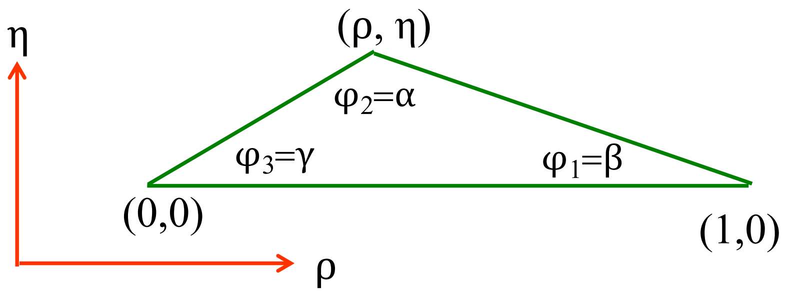
- **Let's take the triangle involving B_d mesons:**

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



$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right),$$
$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right),$$
$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right).$$

It is convenient to normalize all unitarity triangle sides to the base of the triangle ($V_{cd}V^{*}_{cb} = A\lambda^3$).
In the plane (ρ,η) the triangle becomes:



Another way to verify the CP violation in the B system is to verify that the area of this triangle is different from zero.
For instance by measuring the angle β

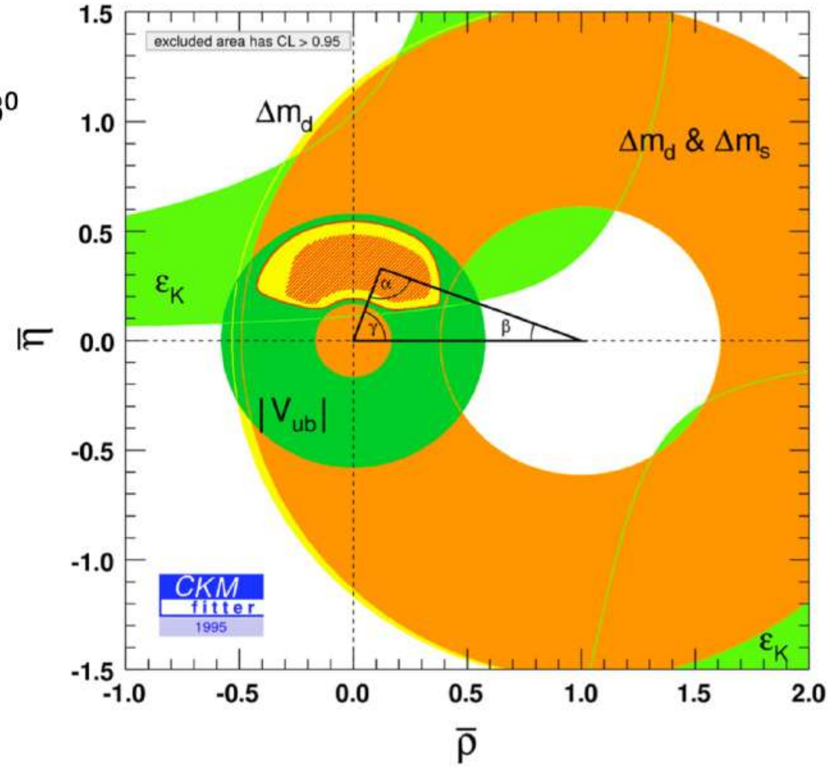
By measuring in an independent way all sides and angles of the triangle, we can check experimentally if the triangle "closes". If this were not the case then it would be the evidence of new physics not foreseen by the Standard Model.

Unitarity triangle in 1995 …

Top quark just discovered
⇒ CKM constraint can be derived from B^0 meson mixing measurements (ΔM)

First constraints on $|V_{ub}|$ from LEP, ARGUS, CLEO experiments

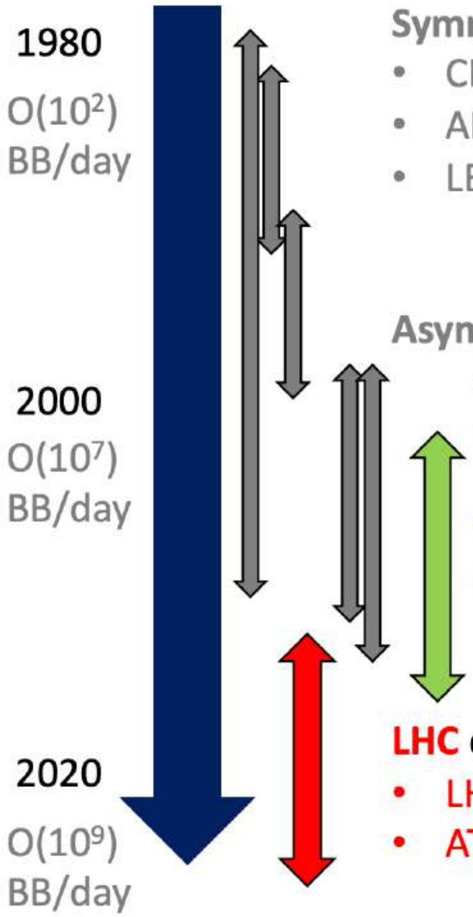
Minimum number of measurements needed to locate apex, and large uncertainties – **no measurements of angles**



Lots of work ahead! Sets the stage for the next phase in flavour physics…

The era of the B factories!

Timeline of b experiments



Symmetric e^+e^- collider experiments: "Cleopatra" and "Caesar"

- CLEO experiments (CESR, Cornell, USA), 1980 – 2008
- ARGUS (DORIS II storage ring, DESY, Hamburg), 1982 – 1992
- LEP experiments (CERN), 1989 – 2000
  ALEPH, DELPHI, OPAL, L3

"**A R**ussian-**G**erman-**U**nited States-**S**wedish Collaboration"

Asymmetric B-factories (1999–2011):

- BaBar (PEP-II ring, SLAC, Stanford)
- Belle (KEK, Japan)

Tevatron Run II experiments ($p\bar{p}$ @ 2 TeV) at Fermilab, Chicago

- CDF and D0 (2001 – 2011)

LHC experiments, CERN, 2009 – (pp @ 7–14 TeV):

- LHCb dedicated to flavour physics
- ATLAS and CMS also doing B physics

B factories versus hadron colliders

	B Factories *Belle (1999-2010)* *BaBar (1999-2008)*	**Hadron colliders** *Tevatron (<2 TeV, 1983–2011)* *LHC (<14 TeV, 2008–)*
Collision environment	Asymmetric $e^+e^- \rightarrow \Upsilon(4S)$ Clean! Pure $B\bar{B}$ event ✓	pp or $p\bar{p}$ (also ions…) Messy! Proton remnants give background particles
Flavour tagging (initial B^0 or $\bar{B}^0$)	Excellent ✓ (30% 'tagging power')	Challenging (~5%)
Production σ(B)	1 nb	~100–500 μb
B hadron boost	Small (βγ ≈ 0.5)	Large (βγ ≈ 100)
B hadrons created	B^+B^- (50%), $B^0\bar{B}^0$ (50%)	$B^\pm$ (40%), B^0 (40%), B_s^0 (10%) ✓ b baryons (10%)

CP Violation

How to measure CP Violation in the B^0?

- Let's recall the technique that was used to measure CP violation in the K^0 system:

1. We get a pure K_2 beam (this is possible due to huge difference in lifetime between the two CP K_1 and K_2, so we only need a long decay tunnel to get rid of the K_1 component)
2. We look for K_2 decays in the "wrong" CP eigenstate.

- The same technique can not be used to study CP violation in the B^0 system, because the lifetime of the two CP eigenstates is about the same; so there is no way to separate the two components "by waiting long enough".

- So we need another "trick". CP violation is due to a phase in the CKM matrix and the only way to measure a phase is through an interference phenomenon. We need to find observables that are sensitive to the CP violating phase.

How to measure α, β and γ?

Observables are rates, i.e. $|A|^2 \Rightarrow$ not sensitive to phases $|Ae^{i\phi}|^2 = A^2$

Need two amplitudes with different phases
– then rate sensitive to their difference…

$$|A_1 e^{i\phi_1} + A_2 e^{i\phi_2}|^2 = A_1^2 + A_2^2 + 2A_1A_2\cos(\delta\phi)$$

$$\delta\phi = \phi_1 - \phi_2$$

Unitarity triangle angles are phase differences between CKM elements

e.g. β is angle between $V_{cd}V_{cb}^*$ and $V_{td}V_{tb}^*$

top quark – must be in loop!

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

Need >1 amplitudes to reach same final state (interference)
One of these must include a top quark loop…

B^0 mixing?

N.B. any ``new'' particles could run in the loop

Condition for CP violation

Consider a process with two interfering amplitudes – can it violate CP symmetry?

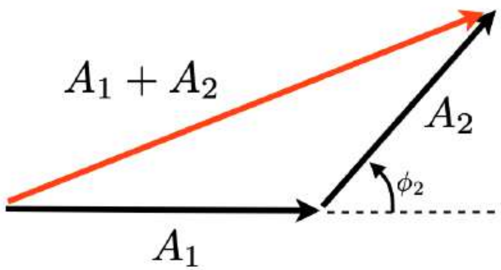
Amplitude $A = A_1 e^{i\phi_1} + A_2 e^{i\phi_2}$

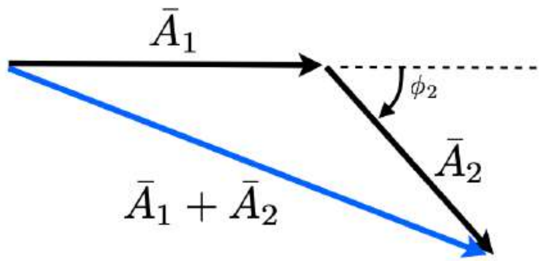
Rate $= |A_1 e^{i\phi} + A_2 e^{i\phi'}|^2$
$= A_1^2 + A_2^2 + 2A_1A_2\cos(\delta\phi)$

Amplitude $A^* = A_1 e^{-i\phi_1} + A_2 e^{-i\phi_2}$

Rate $= |A_1 e^{-i\phi} + A_2 e^{-i\phi'}|^2$
$= A_1^2 + A_2^2 + 2A_1A_2\cos(-\delta\phi)$
$= A_1^2 + A_2^2 + 2A_1A_2\cos(\delta\phi)$

No! Obvious in Argand diagram…





There is a second condition to allow CP violation…

Condition for CP violation

There is a second condition to allow CP violation…

Different strong phase (i.e. CP conserving – no sign change) between amplitudes

$A = A_1 e^{i\phi_1} e^{i\kappa_1} + A_2 e^{i\phi_2} e^{i\kappa_2}$

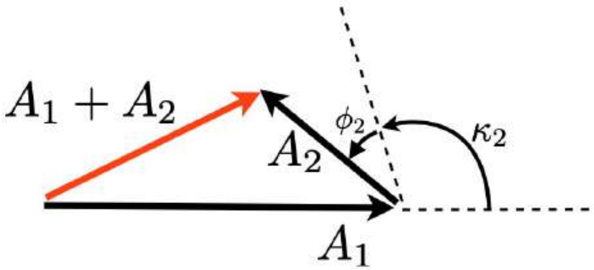
Rate

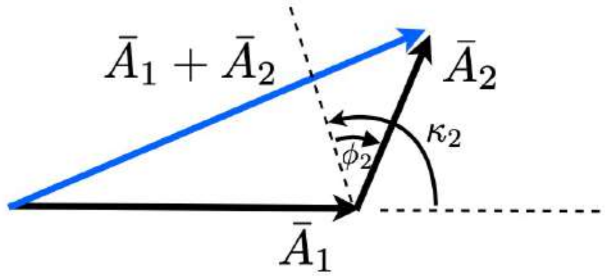
$= A_1^2 + A_2^2 + 2A_1A_2\cos(\delta\phi + \delta\kappa)$

$A = A_1 e^{-i\phi_1} e^{i\kappa_1} + A_2 e^{-i\phi_2} e^{i\kappa_2}$

Rate

$= A_1^2 + A_2^2 + 2A_1A_2\cos(\delta\phi - \delta\kappa)$





CP violation! Difference in rates: $\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f}) = -4A_1A_2 \sin(\delta\phi) \sin(\delta\kappa)$

CP violation in the B^0 mesons

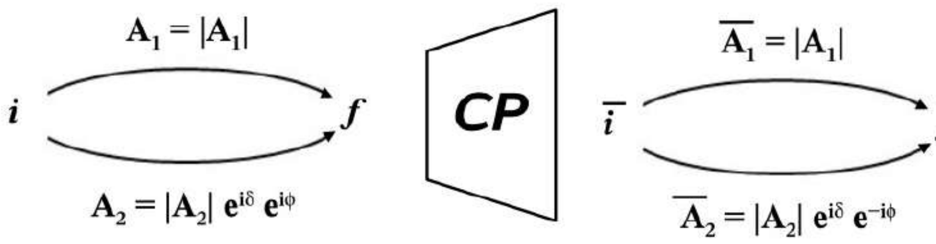
- **We have three mechanism that can give rise to CP violation in the B0 system:**

1. **CP violation purely in mixing:**

$$|B_H\rangle = p|B\rangle + q|\bar{B}\rangle \qquad |B_L\rangle = p|B\rangle - q|\bar{B}\rangle \qquad \text{if} \quad \left|\frac{p}{q}\right| \neq 1 \;\Rightarrow\; \text{CP is violated in mixing}$$

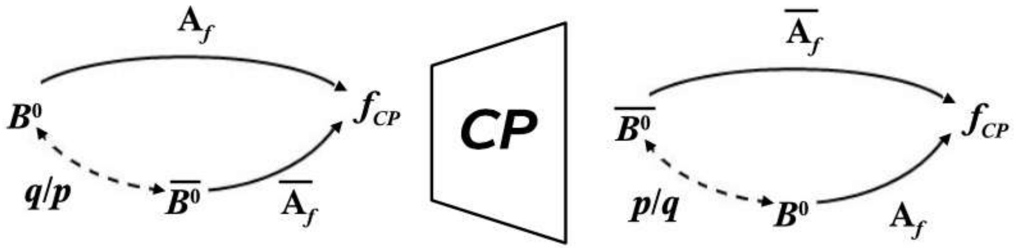
this is the main effect in the K^0 system but it is expected to be very small in the B decays

2. **CP violation in decay (often referred to as direct CP violation)**



$$\left|\frac{A_f}{\bar{A}_{\bar{f}}}\right| \neq 1 \;\Rightarrow\; \text{CP is viol.}$$

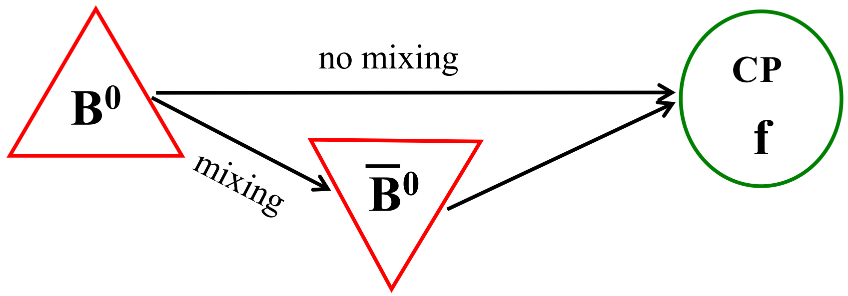
3. **CP violation in the interference between decays of mixed and unmixed mesons (the final state is a CP eigenstate).**



CP violation in the interference

- In order to measure the phase difference we use as interference phenomenon the B^0 decay in a final state f that is a CP eigenstate, that can proceed through two channels:

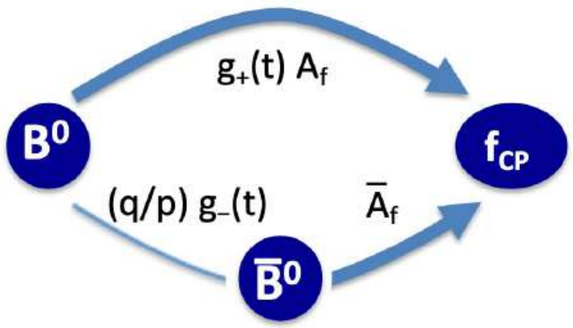
  - the direct decay of B^0 in the state f;
  - first the mixing B^0–anti B^0, then the decay of the anti B^0 in the state f:



- In this case the two amplitudes do interfere with each other;
- N.B. we can also have direct CP violation if the two decay amplitudes of the B^0 and of the anti-B^0 in the same state f are different.

CP violation in the interference

Consider the process $B^0 \to \bar{B}^0 \to f_{CP}$



We have seen that, for B^0 at time t=0

$$|B^0(t)\rangle \;=\; g_+(t)|B^0\rangle + \left(\frac{q}{p}\right) g_-(t)|\bar{B}^0\rangle$$

⇒ Total amplitude = $\langle f_{CP}|B^0(t)\rangle$

$$= A_{f_{CP}}\left[g_+(t) + \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}\, g_-(t)\right] \quad \text{where} \quad \overset{(-)}{A}_{CP} = \langle f_{CP}|\overset{(-)}{B^0}\rangle$$

$$= A_{f_{CP}}\left[g_+(t) + \lambda_{f_{CP}}\, g_-(t)\right] \qquad \lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

Now plug-in $g_\pm(t)$ terms and take the squared module to get the rate …

Reminder:

$$g_+(t) \;=\; e^{-imt}e^{-\Gamma/2t}\left[\cosh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} - i\sinh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right],$$

$$g_-(t) \;=\; e^{-imt}e^{-\Gamma/2t}\left[-\sinh\frac{\Delta\Gamma t}{4}\cos\frac{\Delta M t}{2} + i\cosh\frac{\Delta\Gamma t}{4}\sin\frac{\Delta M t}{2}\right]$$

CP violation in the interference

B^0 at t=0: $\Gamma(B(t) \to f) \propto e^{-\Gamma t}$
$\times$ [$\cosh(\Delta\Gamma t/2)$ **+** $A^{dir}_{CP} \cos(\Delta m t)$ + $A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2)$ **+** $A^{mix}_{CP} \sin(\Delta m t)$]

$\bar{B}^0$ at t=0: $\Gamma(\bar{B}(t) \to f) \propto e^{-\Gamma t}$
$\times$ [$\cosh(\Delta\Gamma t/2)$ **−** $A^{dir}_{CP} \cos(\Delta m t)$ + $A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2)$ **−** $A^{mix}_{CP} \sin(\Delta m t)$]

where:

$$\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

$$A^{dir}_{CP} = C_{CP} = \frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$$

CPV in decay

$$A_{\Delta\Gamma} = \frac{2\,\Re(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

CP conserving part

$$A^{mix}_{CP} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

CPV in interference between mixing & decay

CP violation in the interference

B^0 at t=0: $\Gamma(B(t) \to f) \propto e^{-\Gamma t}$

$$\times [\, \cosh(\Delta\Gamma t/2) + A_{CP}^{dir} \cos(\Delta m t) + A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2) + A_{CP}^{mix} \sin(\Delta m t)\,]$$

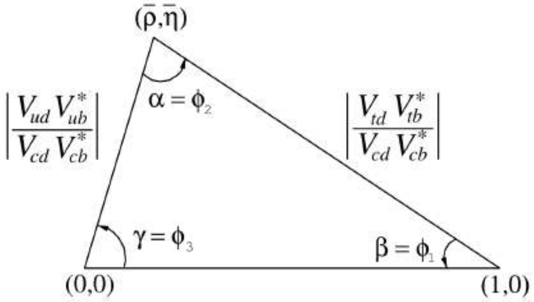
$\bar{B}^0$ at t=0: $\Gamma(\bar{B}(t) \to f) \propto e^{-\Gamma t}$

$$\times [\, \cosh(\Delta\Gamma t/2) - A_{CP}^{dir} \cos(\Delta m t) + A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2) - A_{CP}^{mix} \sin(\Delta m t)\,]$$

✗ For B^0 case, $\Delta\Gamma$ small – can be neglected…

✗ For 'golden mode' $B^0 \to J/\psi K_S^0$: No direct CPV ($A_{CP}^{dir} = 0$)

and $A_{CP}^{mix} = -\sin(2\beta)$



CP violation in the interference

$\bar{B}^0$ at t=0: $\Gamma(B(t) \rightarrow f) \propto e^{-\Gamma t} \times [\, 1 - \sin(2\beta) \sin(\Delta m t) \,]$

$\bar{B}^0$ at t=0: $\Gamma(\bar{B}(t) \rightarrow f) \propto e^{-\Gamma t} \times [\, 1 + \sin(2\beta) \sin(\Delta m t) \,]$

⇒ By time-dependent analysis, can extract β from amplitude of oscillations

⇒ Even cleaner using CP asymmetry:

$$\frac{\Gamma(t)\,[B^0 \rightarrow J/\psi K_S^0] - \Gamma(t)\,[\bar{B}^0 \rightarrow J/\psi K_S^0]}{\Gamma(t)\,[B^0 \rightarrow J/\psi K_S^0] + \Gamma(t)\,[\bar{B}^0 \rightarrow J/\psi K_S^0]} = -\sin(2\beta)\sin(\Delta m t)$$

Hence,
"Golden mode"

But note: asymmetry integrates to zero over time

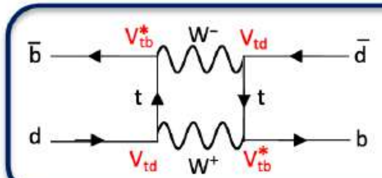
Golden channel: B⟶ J/Ψ Ks

Why is $A_{CP}^{mix} = -\sin(2\beta)$ for $B^0 \to J/\psi\, K_S^0$?

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

(1) remember: $$A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$ so this is satisfied if $\lambda_{CP} = -e^{-2i\beta}$
$= -\cos(2\beta) - i\sin(2\beta)$

(2) remember: $$\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*} \quad \ldots$$



$$\frac{V_{tb}^* V_{td}}{V_{tb}V_{td}^*}$$

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

Golden channel: B→ J/Ψ Ks

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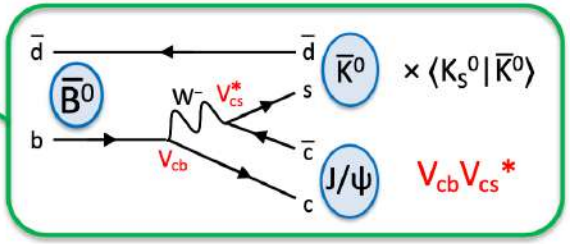

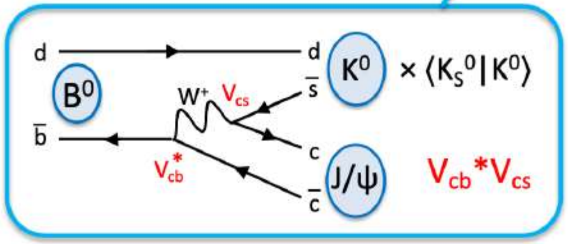

Golden channel: B⟶ J/Ψ Ks

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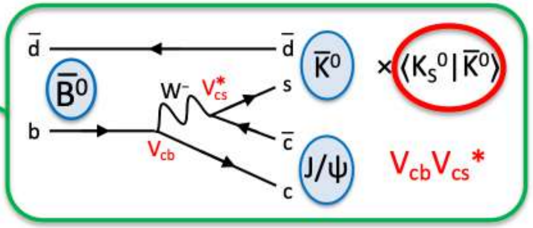
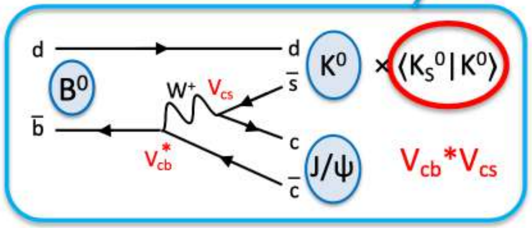
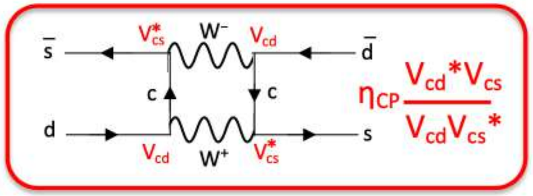






Golden channel: $B \rightarrow J/\Psi\ K_S$

Why is $A^{mix}_{CP} = -\sin(2\beta)$ for $B^0 \rightarrow J/\psi\ K_S^0$?

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

(1) remember: $$A^{mix}_{CP} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

so this is satisfied if $\lambda_{CP} = -e^{-2i\beta}$
$= -\cos(2\beta) - i\sin(2\beta)$

(2) remember: $$\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} = \frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\eta_{CP}\frac{V_{cd}^*V_{cs}}{V_{cd}V_{cs}^*}$$

$$= -\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cd}^*}{V_{cb}^*V_{cd}}$$

Cancel terms, and
$\eta_{CP} = -1$ for $J/\psi K_S^0$

$$= -\frac{V_{cb}V_{cd}^*}{V_{tb}V_{td}^*}\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}}$$

Rearrange

Golden channel: $B \to J/\Psi\ K_S$

Why is $A_{CP}^{mix} = -\sin(2\beta)$ for $B^0 \to J/\psi\ K_S^0$?

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$
$$\Rightarrow Ae^{i\beta} = \left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

(1) remember: $$A_{CP}^{mix} = S_{CP} = \frac{2\,\Im(\lambda_{CP})}{1+|\lambda_{CP}|^2}$$

so this is satisfied if $\lambda_{CP} = -e^{-2i\beta}$
$= -\cos(2\beta) - i\sin(2\beta)$

(2) remember: $$\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = \frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\eta_{CP}\frac{V_{cd}^*V_{cs}}{V_{cd}V_{cs}^*}$$

$$= -\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\frac{V_{cb}V_{cd}^*}{V_{cb}^*V_{cd}}$$

Cancel terms, and
$\eta_{CP} = -1$ for $J/\psi K_S^0$

$$= \left[-\frac{V_{cb}V_{cd}^*}{V_{tb}V_{td}^*}\right]\left[\frac{V_{tb}^*V_{td}}{V_{cb}^*V_{cd}}\right]$$

Rearrange

$= [Ae^{i\beta}]^*$
$= Ae^{-i\beta}$

$= [-Ae^{i\beta}]^{-1}$
$= -A^{-1}e^{-i\beta}$

$\Rightarrow \lambda_{J/\psi KS0} = -e^{-2i\beta}$ Q.E.D

(Quod Erat Demonstrandum)

CP violation measurement

- ❑ **Measure the asymmetry:**

$$\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B^0} \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)$$

- ❑ **Final state is very easy to identify and reconstruct.**

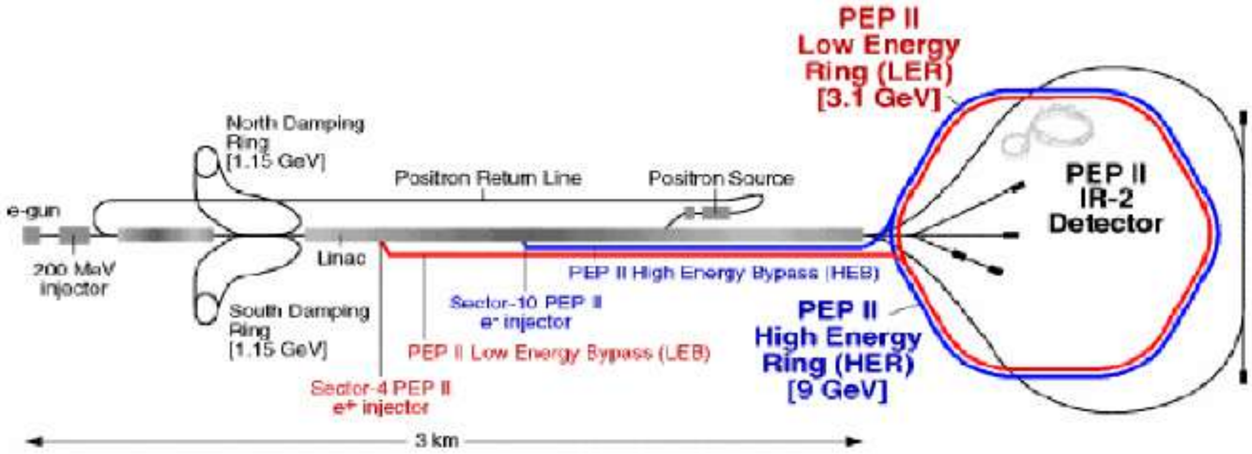
- ❑ **Problem: how to identify the initial meson? That is, if it is a B^0 or a $\overline{B^0}$?**

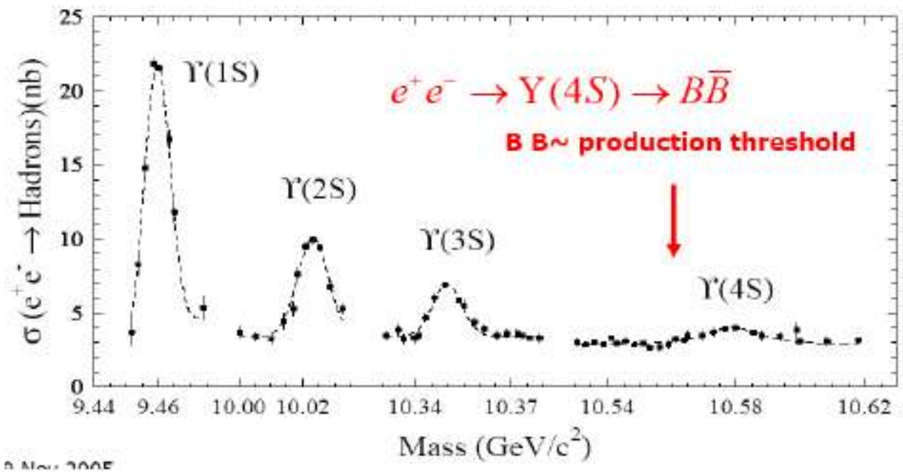
- ❑ **Solution: asymmetric B factory**
  - ➢ **Babar experiment at SLAC (California)**
  - ➢ **Belle experiment at KEK (Japan)**

Pier Oddone, father of asymmetric e^+e^- colliders

Asymmetric B Factories

PEP-II Asymmetric B-Factory at SLAC





- 9 GeV e^- on 3.1 GeV e^+
- $\Upsilon(4S)$ boost in lab frame
  - $\beta\gamma = 0.55$

1999-2008: 514 fb^{-1}

Quantum entanglement in $Y(4S) \rightarrow B^0\bar{B}^0$ decays

$$\Upsilon(4s) \rightarrow B^0 \bar{B}^0$$

With $L = 1$

Spin = 1 0 0

- Strong interaction: CP and flavor beauty number are conserved
  - Must have one **b** and one **anti-b** quarks in final state

$$|B^0_{\text{phys}} \overline{B}^0_{\text{phys}}\rangle = \frac{a}{\sqrt{2}} |B_L B_H\rangle + \frac{b}{\sqrt{2}} |B_H B_L\rangle$$

- Time evolution given by mass eigenstates

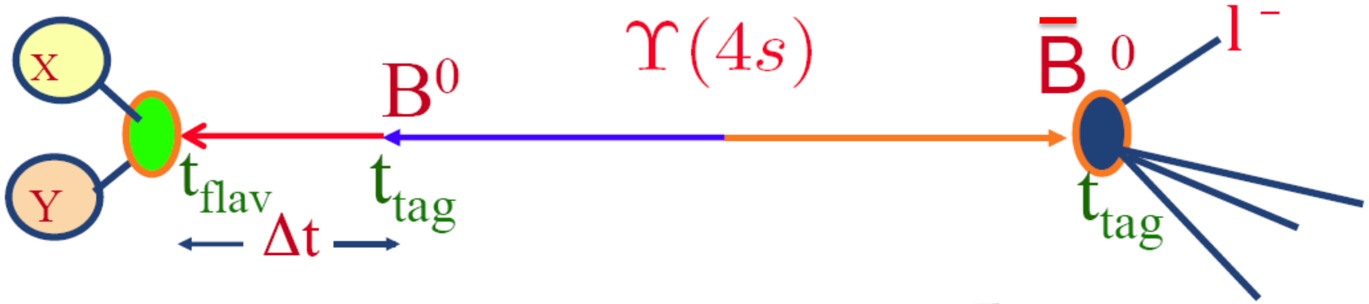
$$|B^0_{\text{phys}} \overline{B}^0_{\text{phys}}; t_1, t_2\rangle = a\, \mathrm{e}^{i\lambda_+ t_1} \mathrm{e}^{i\lambda_- t_2} |B_L B_H\rangle + b\, \mathrm{e}^{i\lambda_- t_1} \mathrm{e}^{i\lambda_+ t_2} |B_H B_L\rangle$$

- Bose-Einstein Statistics requires wave function $|\Psi\rangle$ to be symmetric at all times

$$|\Psi\rangle = |\Psi_{\text{flavor}}\rangle |\Psi_{\text{space}}\rangle$$

- L=-1 implies asymmetric spatial wave function
- We need a=-b which means a B^0 and a $\bar{B}^0$ meson at all times until one of them decays!
  - Example of Einstein-Podolsky-Rosen Paradox

Quantum correlation at Υ(4S)



- Decay of first B (B^0) at time t_{tag} ensures the other B is $\bar{B}^0$
  - End of Quantum entanglement ! Defines a ref. time (clock)

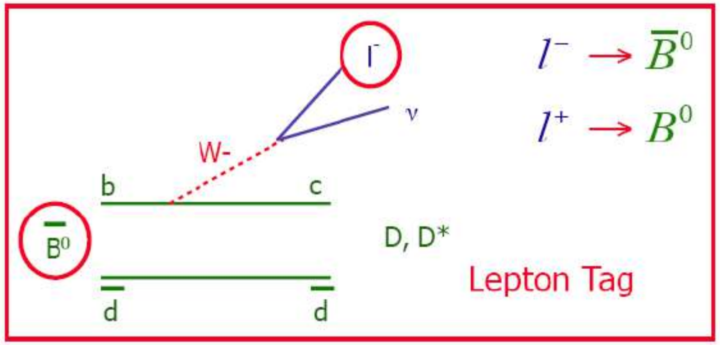
- At $t > t_{tag}$, B^0 has some probability to oscillate into $\bar{B}^0$ before it decays at time t_{flav} into a flavor specific state

- Two possibilities in the $\Upsilon(4S)$ event depending on whether the 2nd B oscillated or not:

$$\text{no oscillation/mixing} \Rightarrow B^0\,\bar{B}^0 \text{ in final state}$$

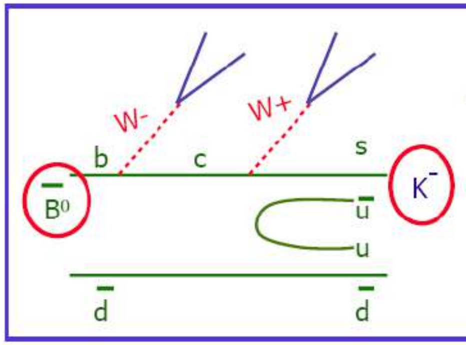
$$\text{oscillation/mixing} \Rightarrow \bar{B}^0\,\bar{B}^0 \text{ in final state}$$

Separating $\bar{B}^0$ and B^0 mesons



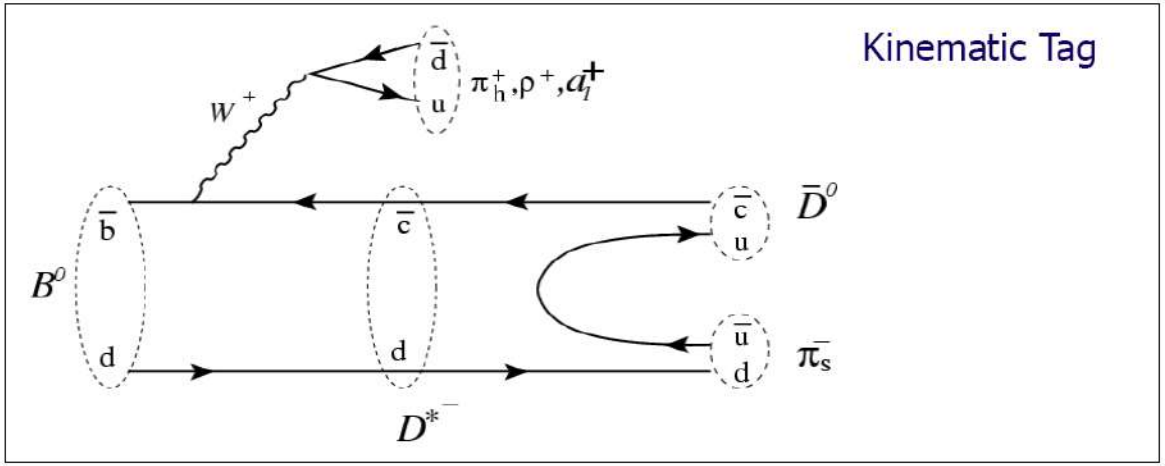
$l^- \rightarrow \bar{B}^0$

$l^+ \rightarrow B^0$

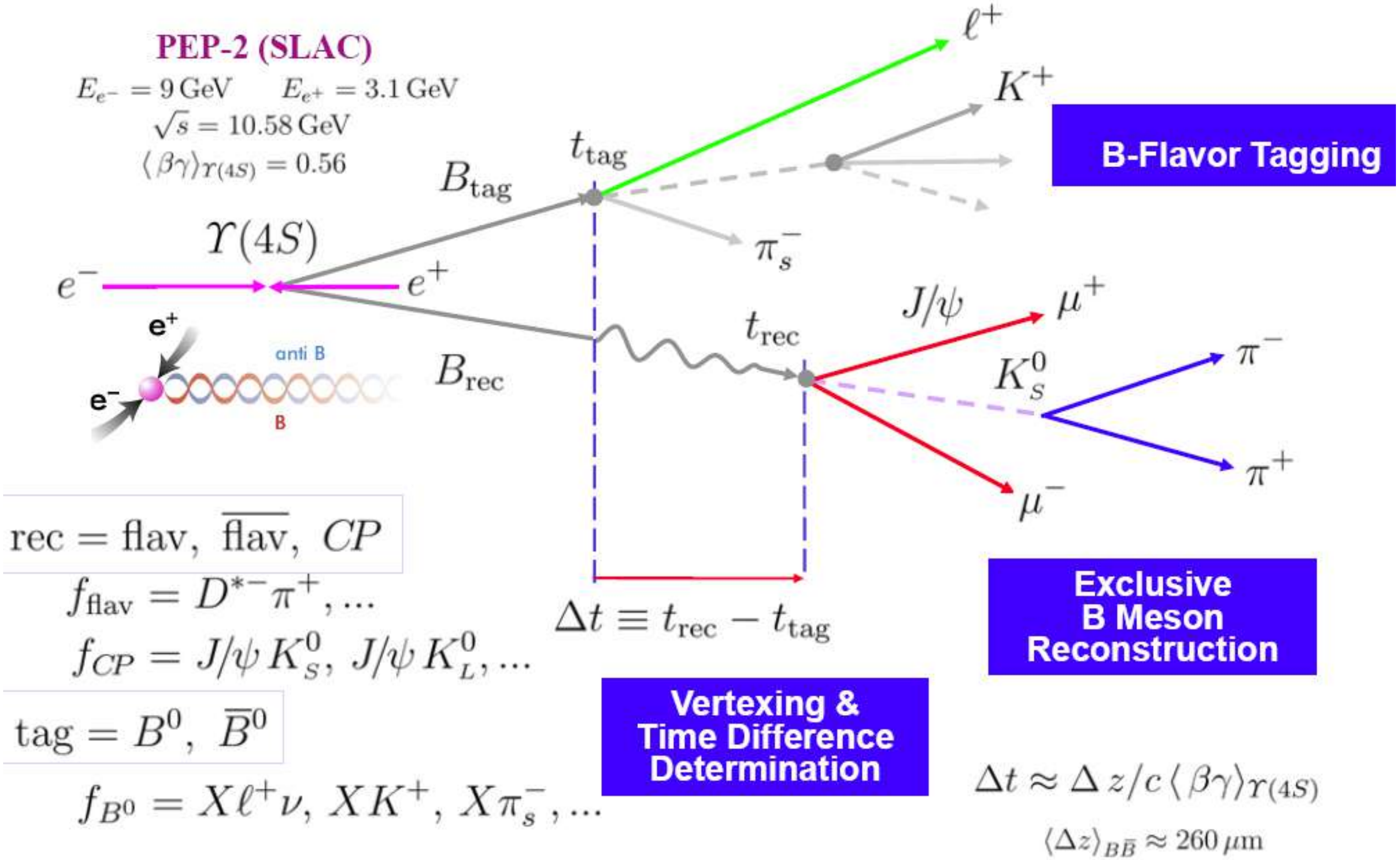


$\sum_{kaons} Q < 0 \Rightarrow \bar{B}^0$

$\sum_{kaons} Q > 0 \Rightarrow B^0$



Ingredients of the measurement

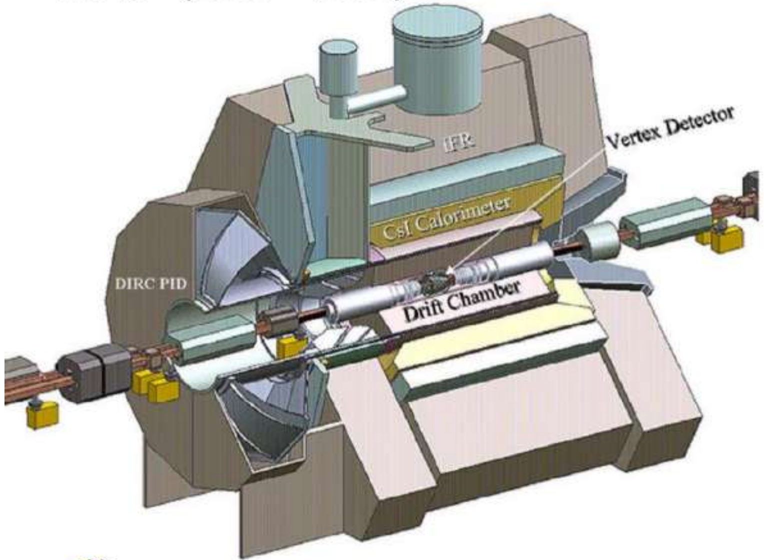


Babar and Belle Detectors

BaBar: on PEP-II @ SLAC, USA

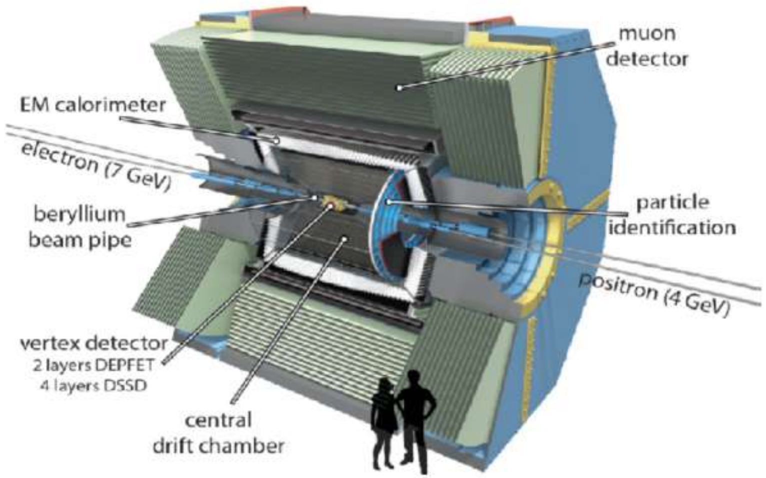
9 GeV e^- $\leftrightarrow$ 3.1 GeV e^+

433 fb^{-1} (1999 – 2008)



Different detectors, same ideas:

- Vertex + tracking detectors
- Particle ID
- Calorimetry

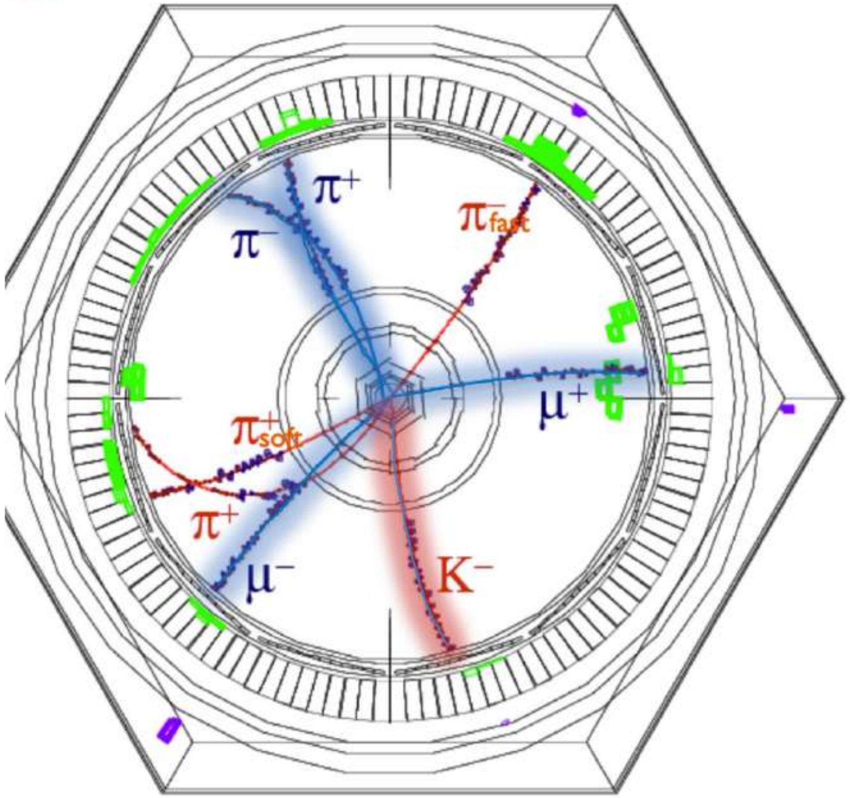


Belle: on KEKB accelerator (Japan)

8 GeV e^- $\leftrightarrow$ 3.5 GeV e^+

711fb^{-1} (1999 – 2010)

Example of a typical event



Tagging side: $\bar{B}^0 \rightarrow D^{*+} \pi^-_{fast}$

$\hookrightarrow D^0 \pi^+_{soft}$

$\hookrightarrow K^- \pi^+$

K^- tags initial flavor as $\bar{B}^0$

$\Rightarrow$ Signal must be B^0 at "t=0"

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

$K_S^0 \hookrightarrow \pi^+\pi^-$

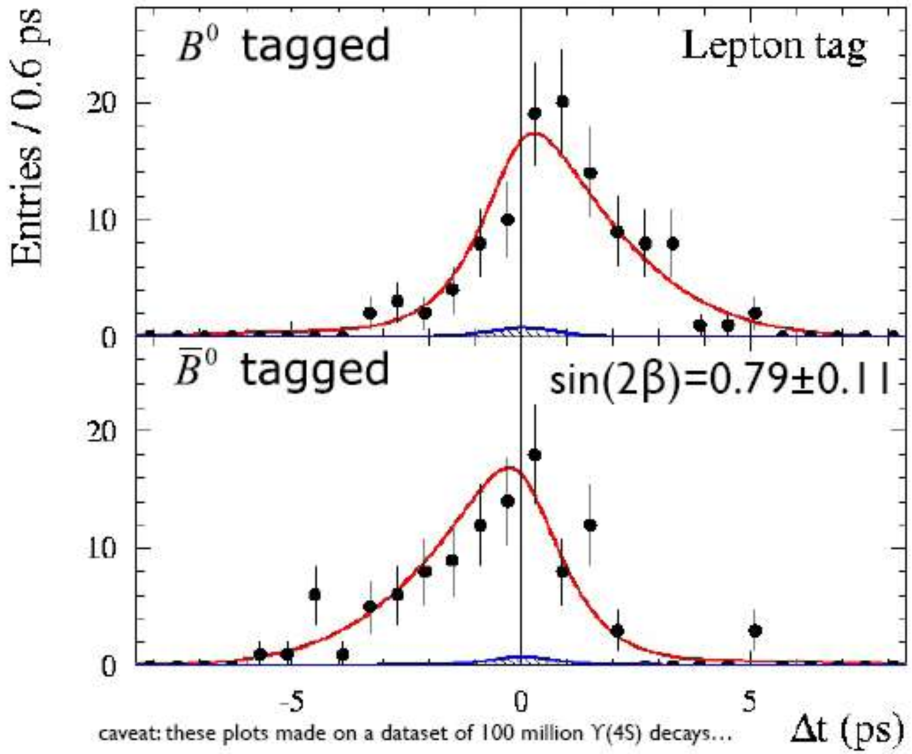
$J/\psi \hookrightarrow \mu^+\mu^-$

Sin 2β

First Babar result

CP violation in B system!

$$e^+e^- \to \Upsilon(4S) \to B_{\text{rec}}B_{\text{tag}} \qquad \begin{array}{l} B_{\text{rec}} \to J/\psi K_S \\ B_{\text{tag}} \to \ell^\pm X \end{array}$$



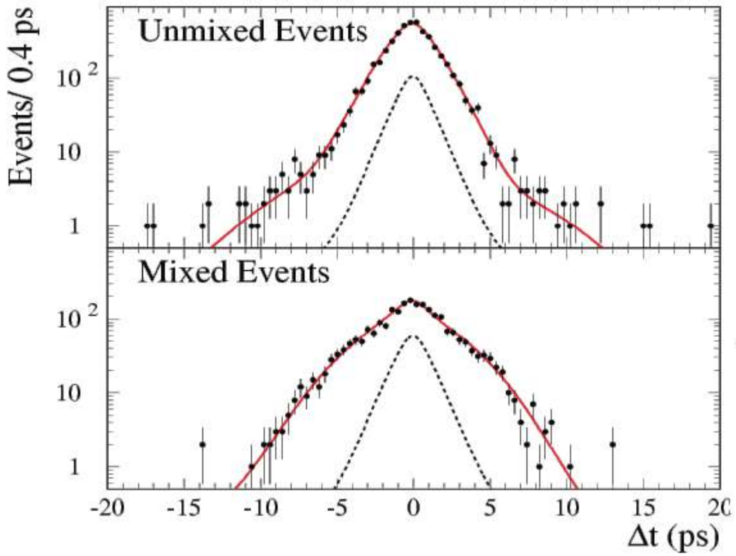
caveat: these plots made on a dataset of 100 million Υ(4S) decays…

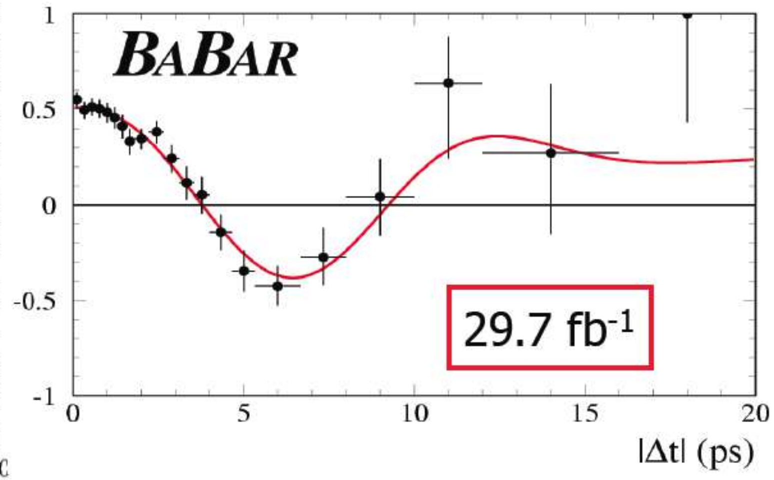
220 events

98% signal purity!
3.3% mistag rate!
20% better Δt resolution!

$B^0\bar{B}^0$ mixing: first BaBar result

$$Asym\,(\Delta t) = \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)} \sim (1 - 2\langle w \rangle) \times \cos\,(\Delta m_d \Delta t)$$



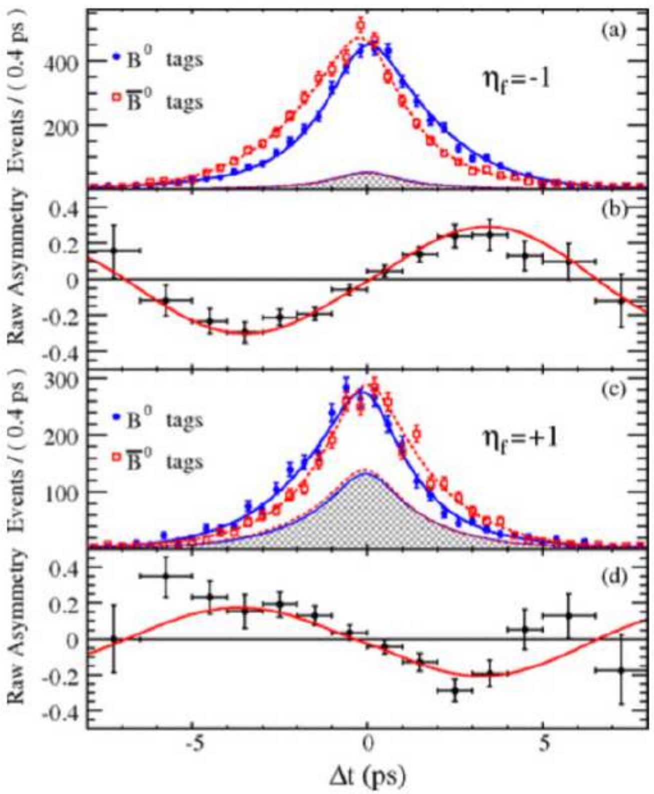


$\Delta m_d = 0.516 \pm 0.016\ (stat) \pm\ 0.010\ (syst)\ ps^{-1}$

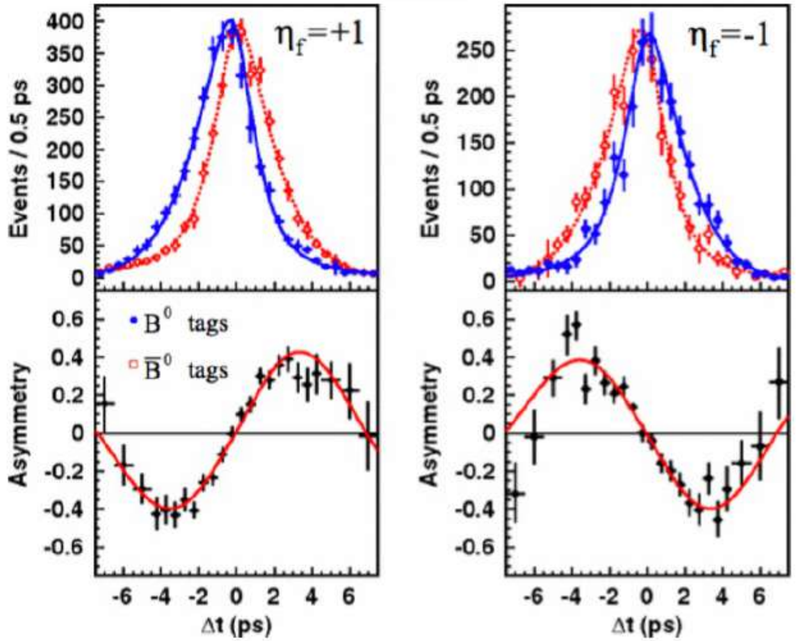
hep-ex/0112044
Published in PRL

Golden mode results

BaBar https://arxiv.org/abs/0902.1708



Belle https://arxiv.org/abs/1201.4643



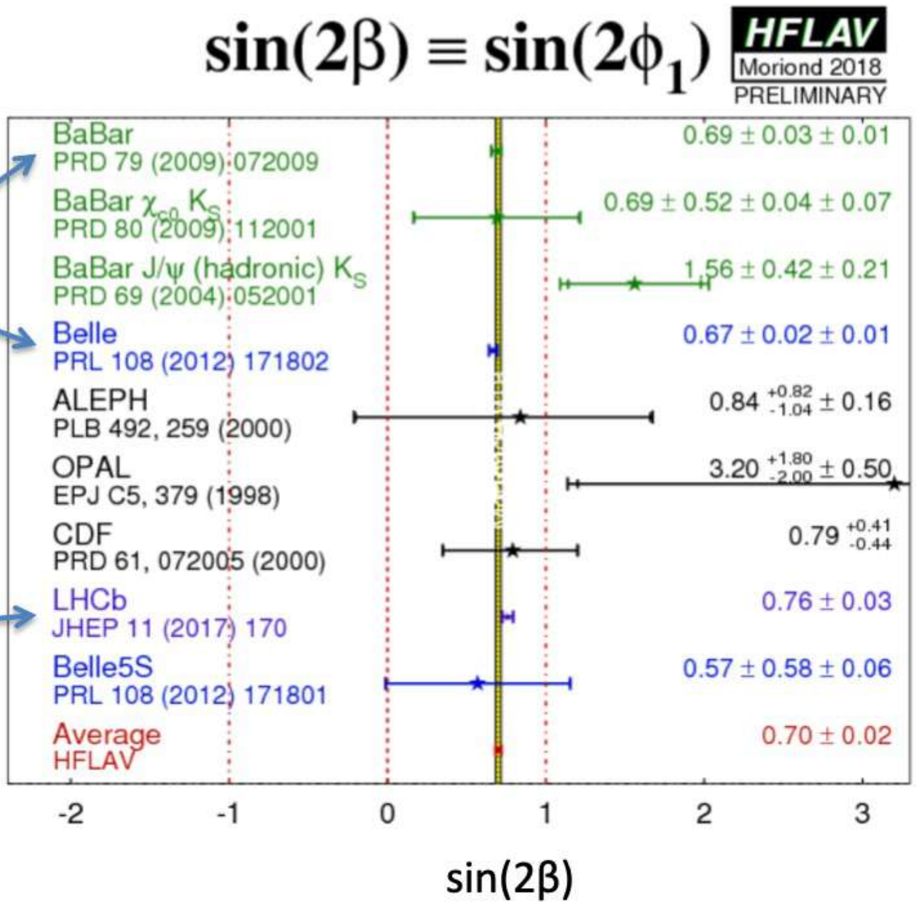
⇒ Clear CP-asymmetry! Measure sin(2β)

Actually use many different channels
(both CP-odd and CP-even, $\eta_f = \pm 1$)

~ K_L^0 **~K_S^0**

Summary table

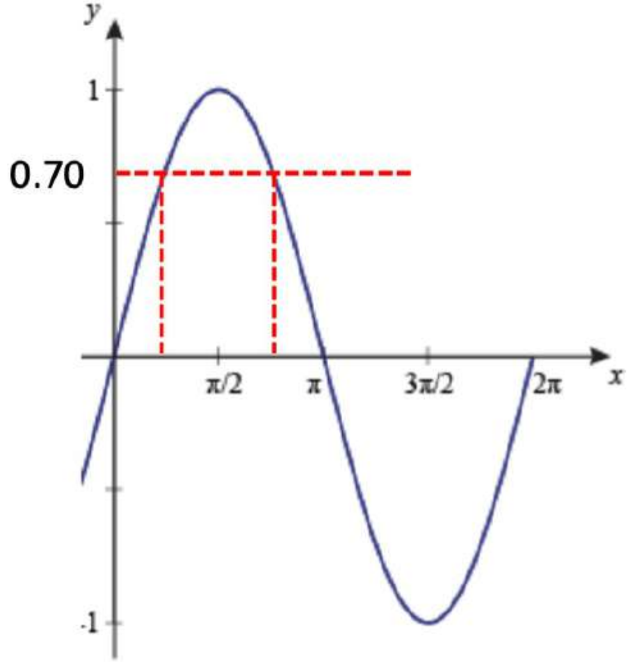
Results on previous slide



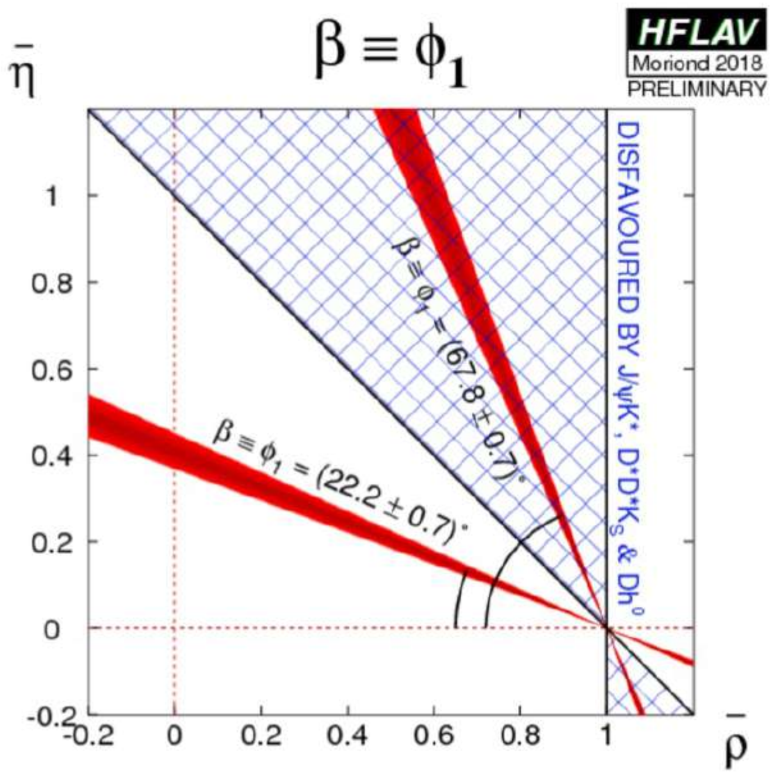
LHCb now competitive with B-factories!

CP asymmetry and sin2β

$A_{CP}^{mix} = -\sin(2\beta)$

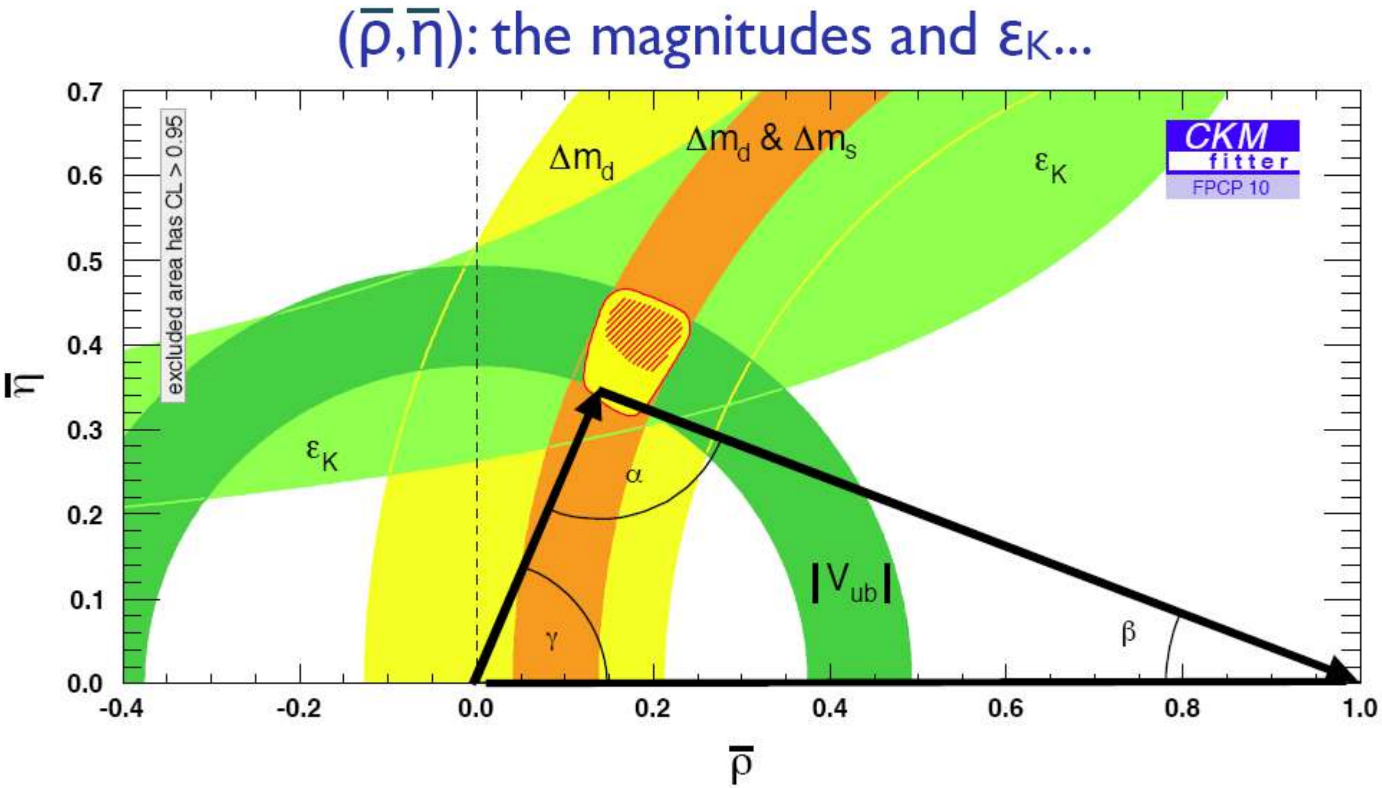


Two-fold ambiguity on β, but second solution ruled-out by other inputs



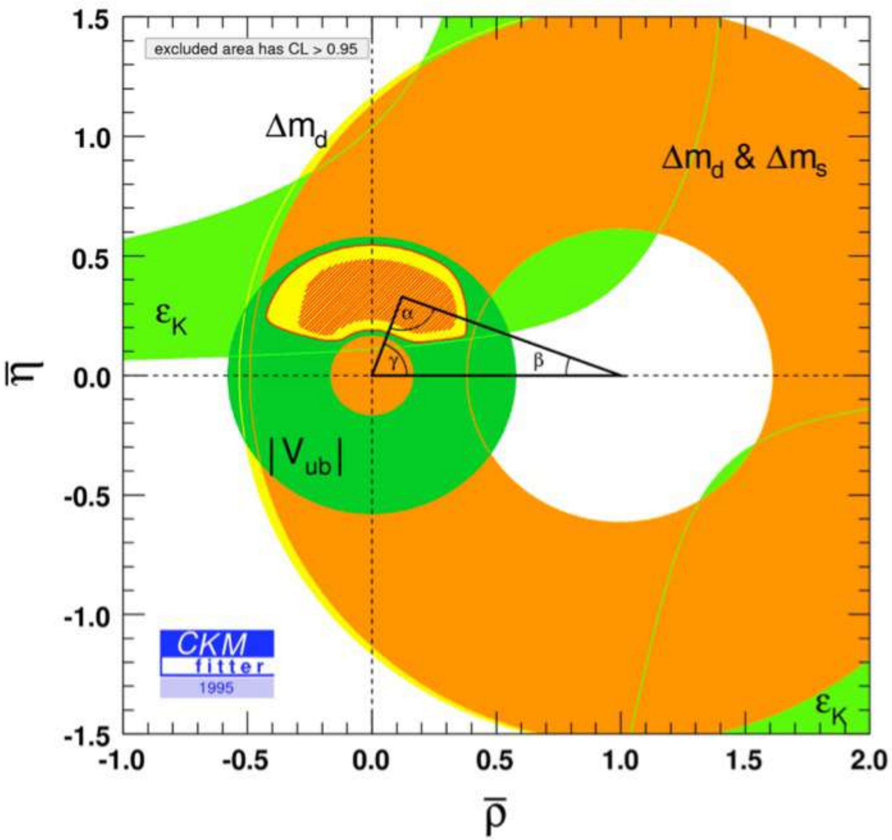
Global fit to unitarity triangle

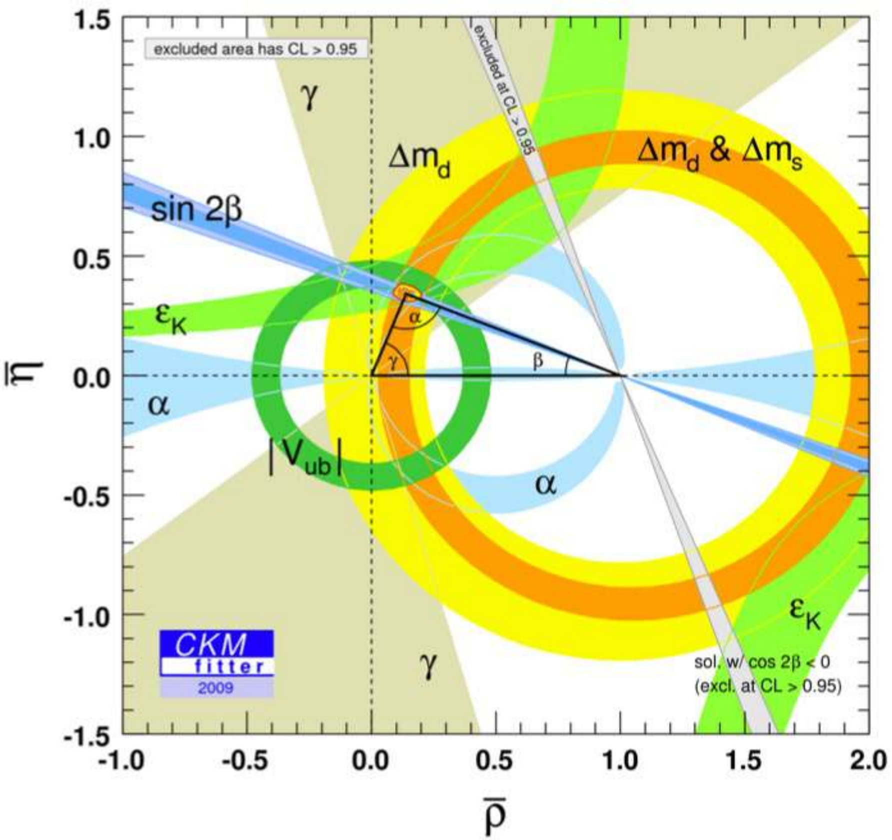
Several independent measurements, including some ones about K^0 system, are consistent with the "same" vertex of the triangle → no hints of new physics beyond SM



The impact of the B factories on the CKM triangle

1995 → **2009**





On the Eve of LHC

All constraints consistent with single point for apex

Direct measurements of angles:

$$\beta = (21.15 \pm 0.90)^\circ$$

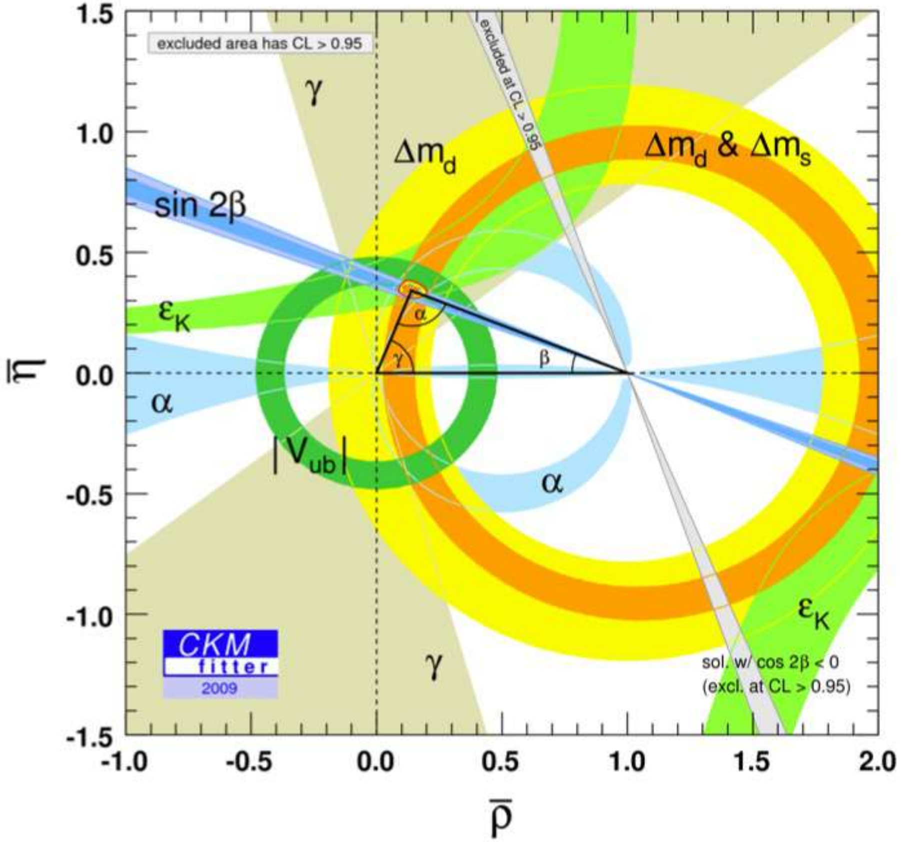
$$\alpha = (89.0^{+4.4}_{-4.2})^\circ$$

$$\gamma = (73^{+22}_{-25})^\circ$$

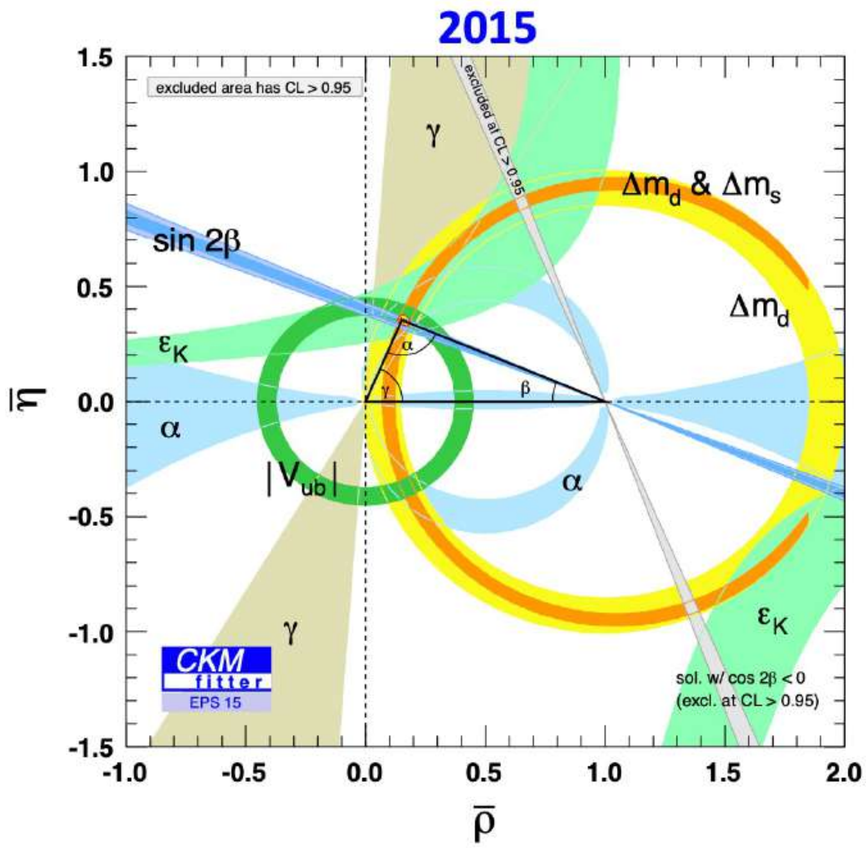
⇒ Need to improve γ measurement!

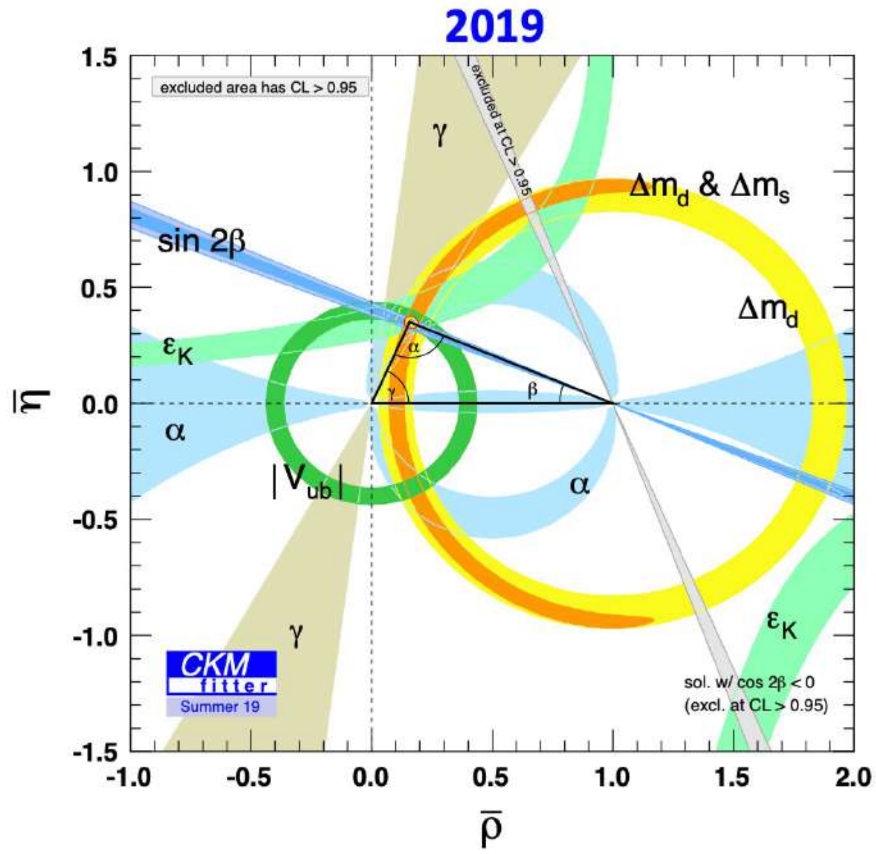
Brings us to the LHC era of flavour

2009



Unitarity triangle latest results



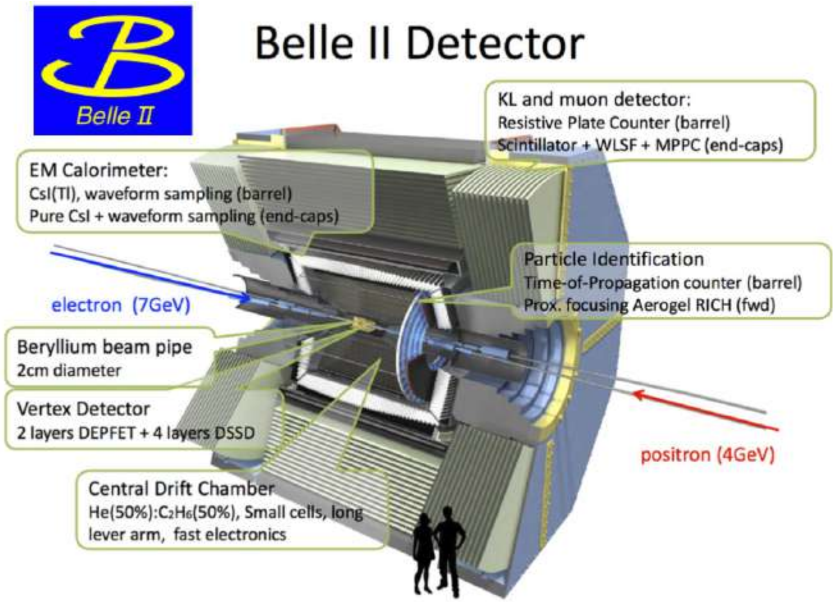


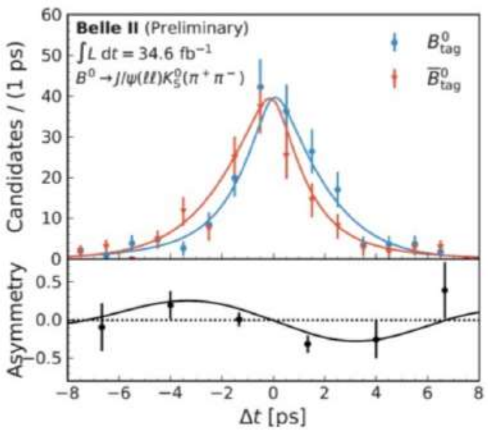
The future (actually now): Belle II (2019 – 2022)

Will collect 40× more data than Belle (already a world record luminosity!)

Major accelerator and detector upgrades to reach **50 ab^{-1}**

First physics run with complete detector started in March 2019

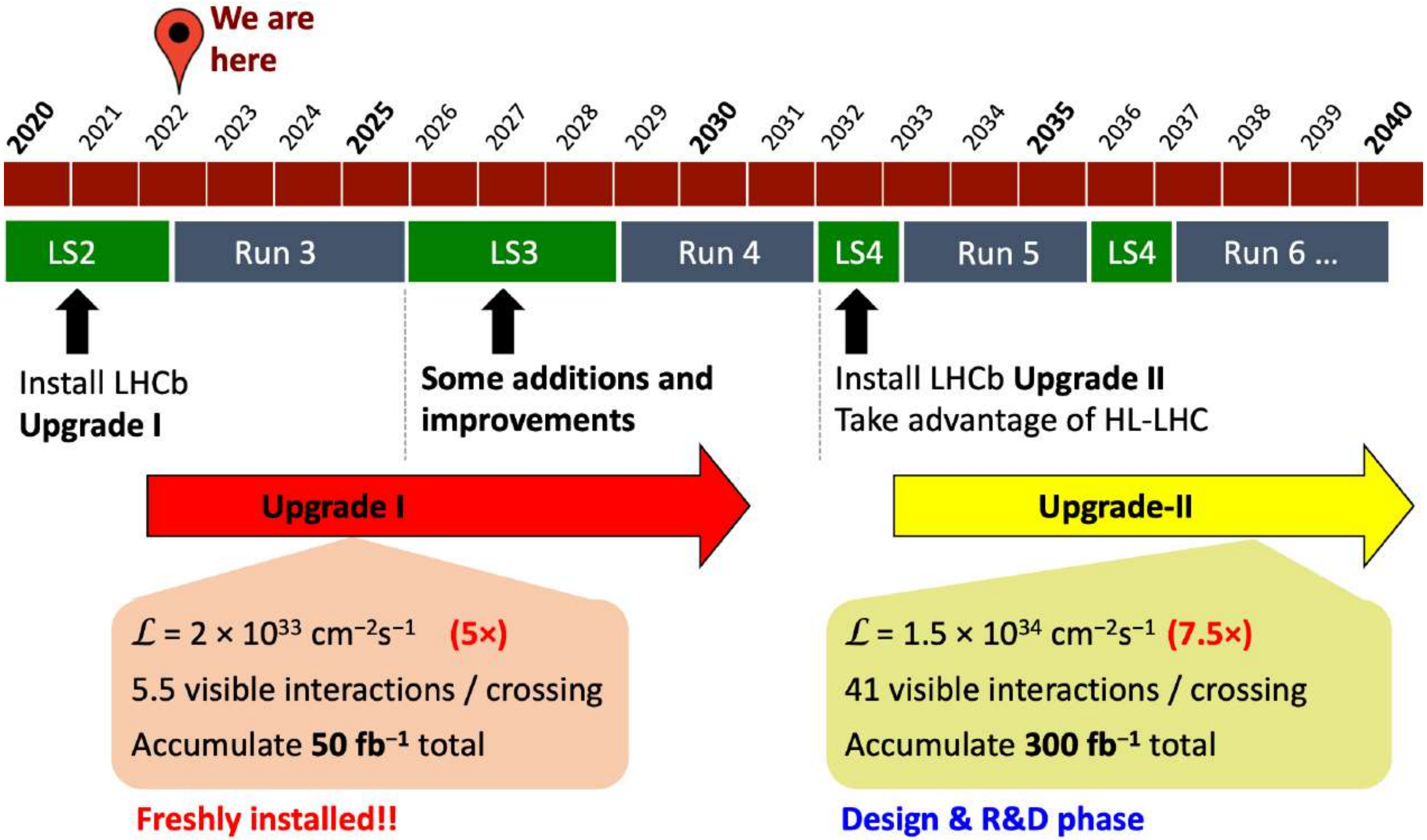




Already surpassing original Belle precision in several areas (with fraction of data)

Complementary to LHCb programme

LHCb Upgrade (2022-2040)



Direct CP Violation

Direct CP violation

$$B.R.\left(B^0 \rightarrow f\right) \neq B.R.\left(\bar{B}^0 \rightarrow \bar{f}\right)$$

- If the decay amplitudes contains a phase that changes sign under CP transformation, then:

$$A = |A|\, e^{i\phi} \quad \xrightarrow{CP} \quad \bar{A} = |A|\, e^{-i\phi}$$

- but this is not sufficient to have CP violation because:

$$A^* A = |A|\, e^{-i\phi}\, |A|\, e^{i\phi} = \bar{A}^* \bar{A} = |A|\, e^{i\phi}\, |A|\, e^{-i\phi} = |A|^2$$

- In order to have CP violation we must have:
  - a) two amplitudes;
  - b) two phases (weak phase, strong phase);
  - c) only one phase change sign under CP (weak phase).

$$A = A_1 + A_2 = |A_1|\, e^{i\phi_W} e^{i\phi_s} + |A_2| \qquad \bar{A} = \bar{A}_1 + \bar{A}_2 = |A_1|\, e^{-i\phi_W} e^{i\phi_s} + |A_2|$$

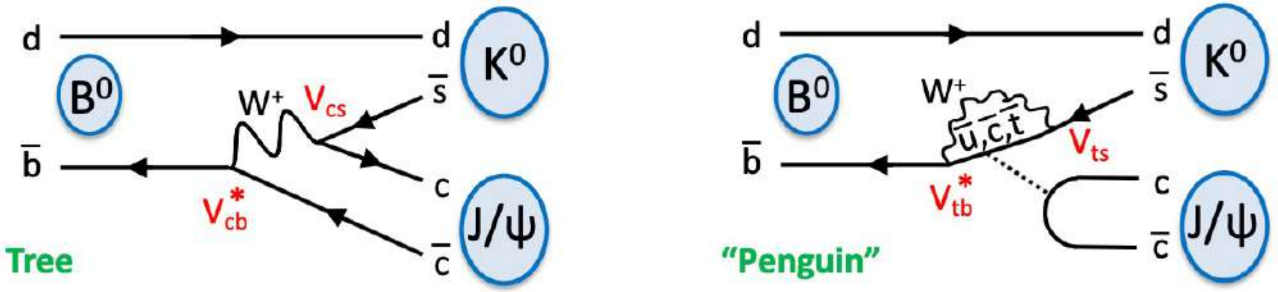
$$A^* A = |A_1|^2 + |A_2|^2 + 2\, |A_1|\, |A_2| \cos(\phi_s + \phi_W)$$

$$\bar{A}^* \bar{A} = |A_1|^2 + |A_2|^2 + 2\, |A_1|\, |A_2| \cos(\phi_s - \phi_W)$$

The Γ of the two processes depend on the phases, that are different

Penguin pollution

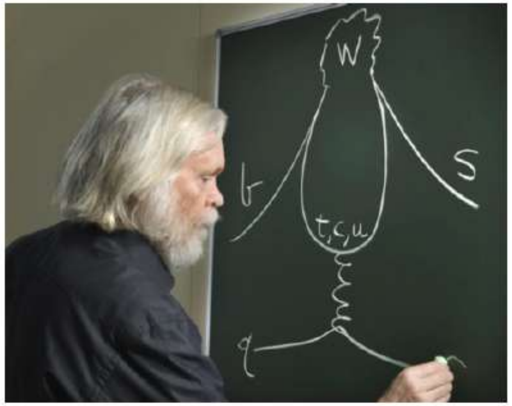
Beyond tree-level…



Can have penguin diagrams with different weak phase

For $B^0 \rightarrow J/\psi\, K_S^0$, tree-level process dominates
⇒ penguin can be ignored (<1% effect)

With sufficient experimental precision, these penguin contributions must be included.



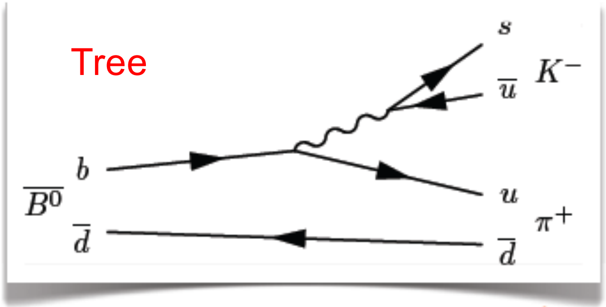
Penguin contribution could be enhanced having other particles, besides W, running in the loop

Direct CP violation: $\Gamma(B^0 \rightarrow f) \neq \Gamma(\overline{B}^0 \rightarrow \overline{f})$

needs (at least!) 2 interfering amplitudes

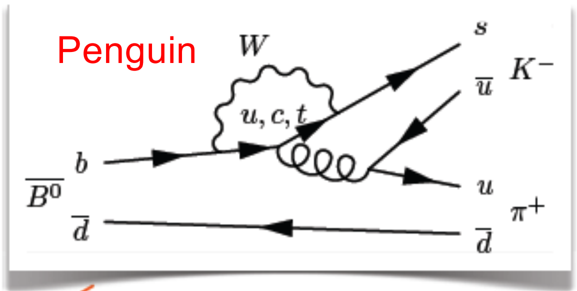
$B^0 \rightarrow K^- \pi^+$

Amplitude 1



+

Amplitudes 2,3 and 4...



$$A_{\overline{B^0}\rightarrow K^-\pi^+} = V_{ub}V_{us}^*(T + P_u - P_t) + V_{cb}V_{cs}^*(P_c - P_t)$$

$$=\mathcal{O}(\lambda^4) \qquad\qquad =\mathcal{O}(\lambda^2)$$

relative phase: γ

Now the otherwise dominant tree diagram is suppressed by λ^2!

potentially ~equal amplitudes with *both* different strong and weak phases !

➔ $\Gamma(B^0 \rightarrow f) \neq \Gamma(\overline{B}^0 \rightarrow \overline{f})$

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

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

Observation of direct CP V. in $B^0 \rightarrow K^-\pi^+$

First evidence from BaBar

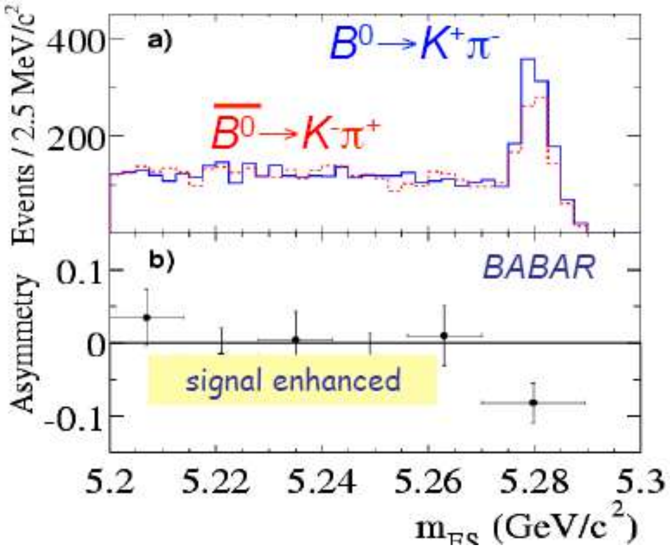
$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)}$$

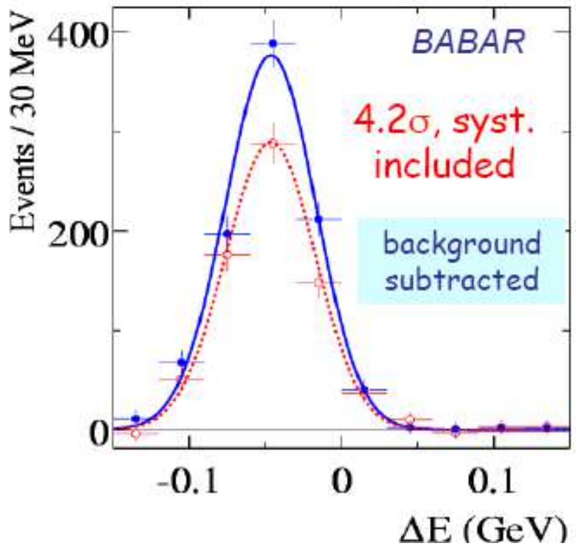
$$n_{K\pi} = 1606 \pm 51$$

$$A_{K\pi} = -0.133 \pm 0.030 \pm 0.009$$

$$n\left(B^0 \to K^+\pi^-\right) = 910$$

$$n\left(\overline{B}^0 \to K^-\pi^+\right) = 696$$

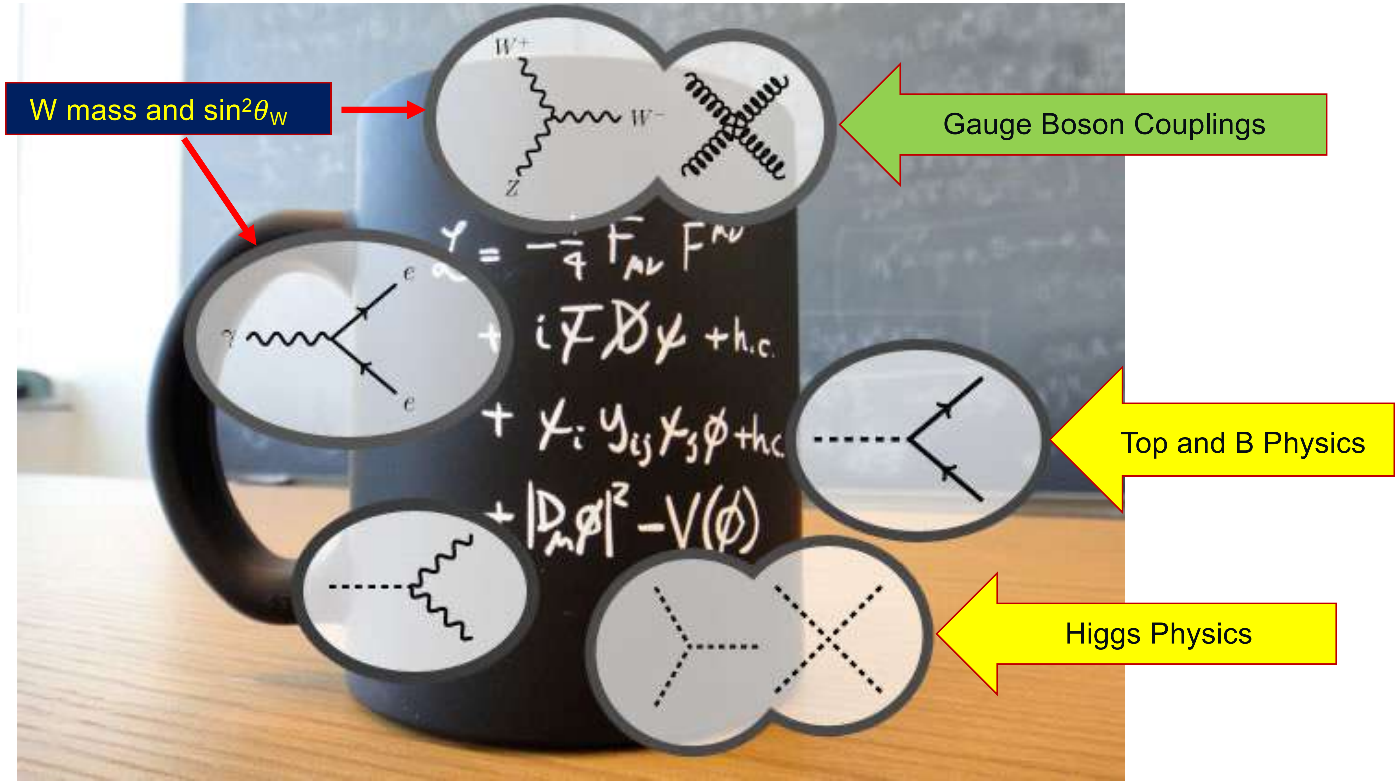




Conclusions

Standard Model is getting popular

- The Standard Model in a nutshell (actually in a coffee mug)



We are again in the precision era

Lord Kelvin at British Association for the Advancement of Science in 1900:

"There is nothing new to be discovered in physics now.

All that remains is more and more precise measurements."

(actually Kelvin never pronounced this sentence. Something similar was said by Michelson six years earlier)

Collider Particle Physics is following the road pointed by "Kelvin/Michelson" in the hope to be wrong as well.

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End of chapter 11