Flavour oscillations and CP violation in neutral mesons

(a.k.a. a biased introduction to heavy flavour physics)

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Part 2.b

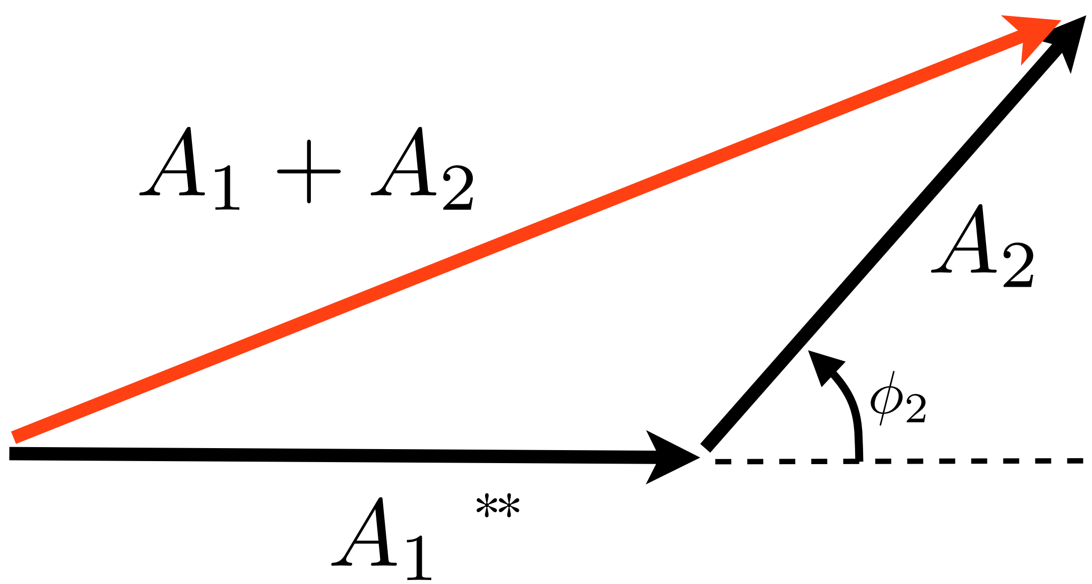
Roma — May 31st & Jun 1st, 2016

So far (so good?)

- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy…)
- ★ Matter-antimatter oscillations: K^0 can turn into anti-K^0;
  the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations
- ★ A very rich phenomenology of mixing of K, D, and B mesons
- ★ CP is broken!
- ★ Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).
- ★ We can measure CP violation in 3 ways: decays, mixing, interference
- ★ (time-dependent) CP in interference allows to measure phases (difference)

Two interfering amplitudes

$$\begin{aligned} A_j &= \langle \text{final} | H_j | \text{initial} \rangle \\ &= |A_j| e^{+i\phi_j^{\text{weak}}} \end{aligned}$$



$$P(i \to f) = |A_1 + A_2|^2$$

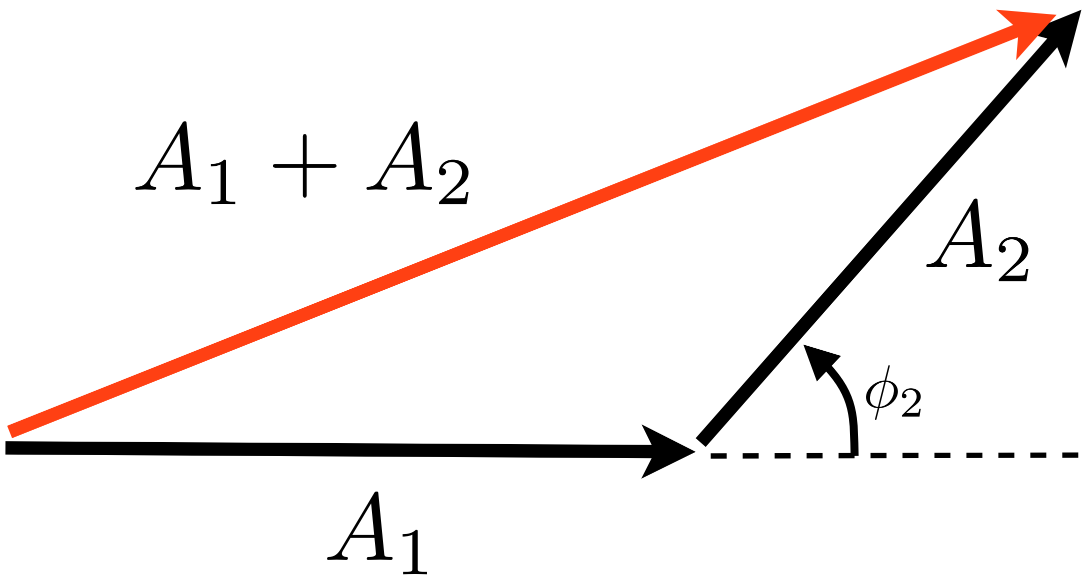
**take A1 real for simplicity

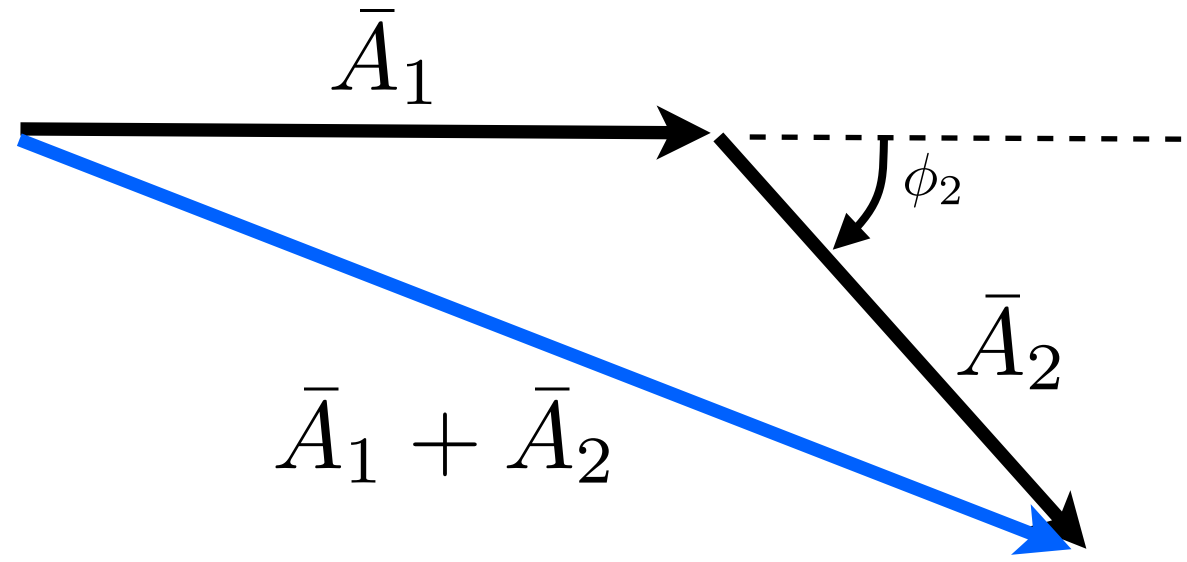
Two interfering amplitudes

$$\begin{aligned} A_j &= \langle \text{final}|H_j|\text{initial}\rangle \\ &= |A_j|e^{+i\phi_j^{\text{weak}}} \end{aligned}$$

CP

$$\begin{aligned} \bar{A}_j &= A_j^* \\ &= |A_j|e^{-i\phi_j^{\text{weak}}} \end{aligned}$$





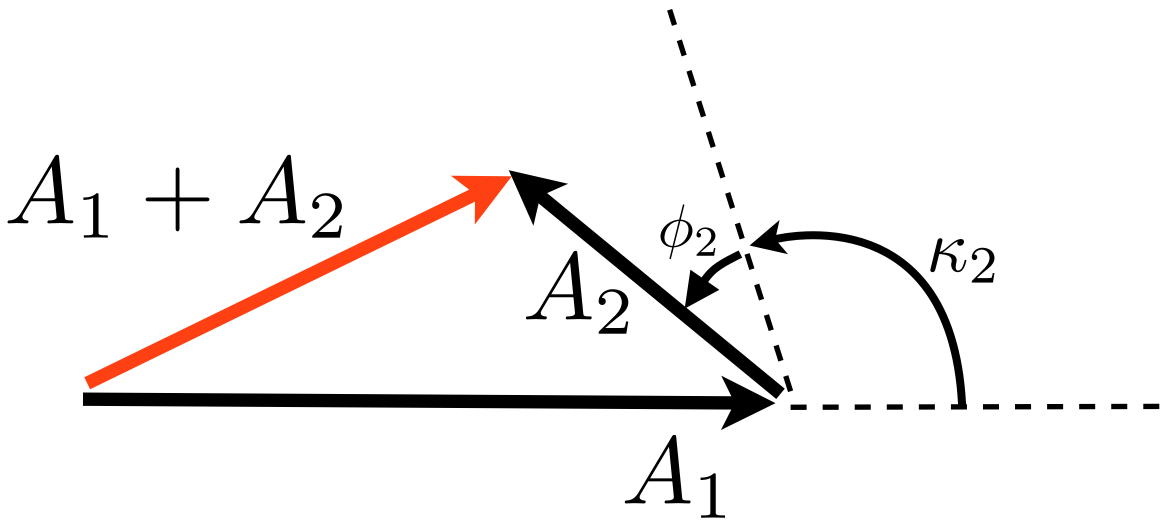
$$P(i \to f) = |A_1 + A_2|^2$$

$$P(\bar{i} \to \bar{f}) = |\bar{A}_1 + \bar{A}_2|^2$$

$$= |A_1|^2 + 2|A_1||A_2|\cos\phi_2 + |A_2|^2$$

Two interfering amplitudes

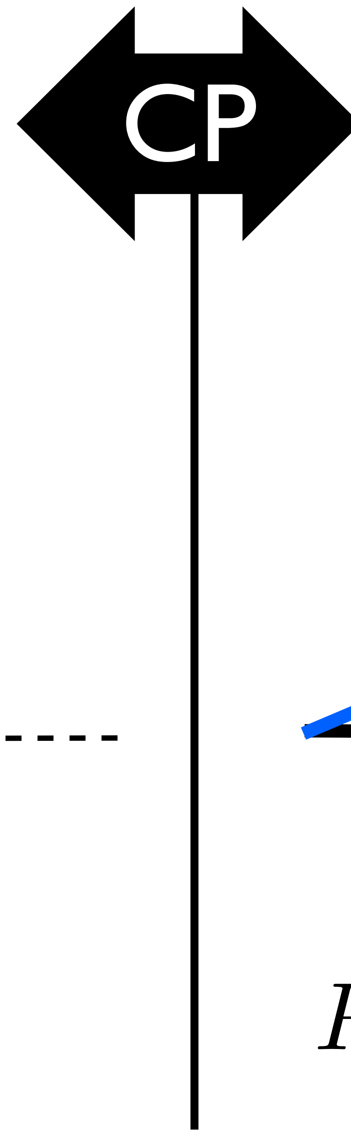
$$A_j = |A_j| e^{i\left(+\phi_j^{\mathrm{weak}} + \kappa_j\right)}$$



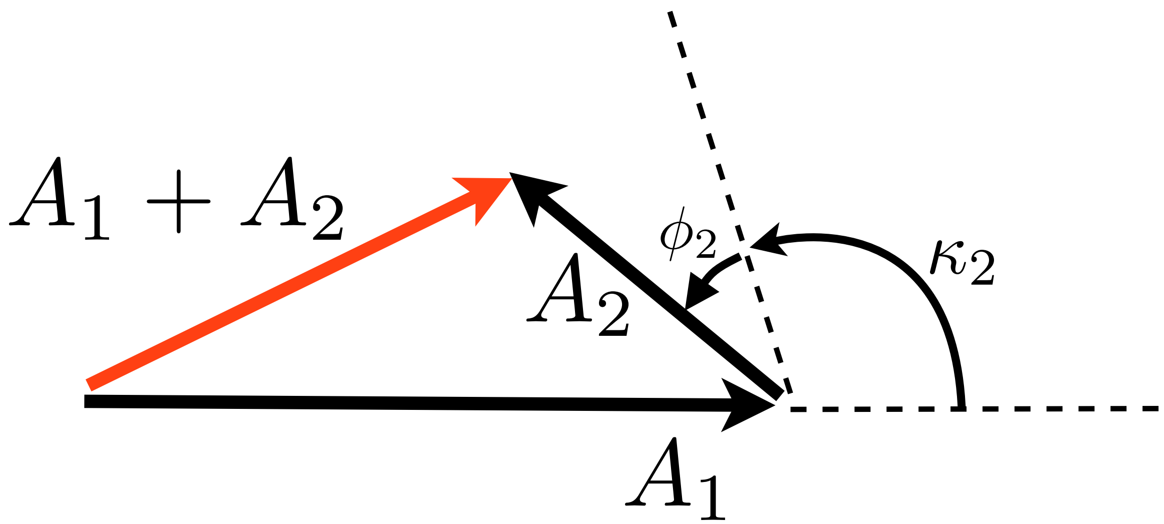
$$P(i \to f) = |A_1 + A_2|^2$$

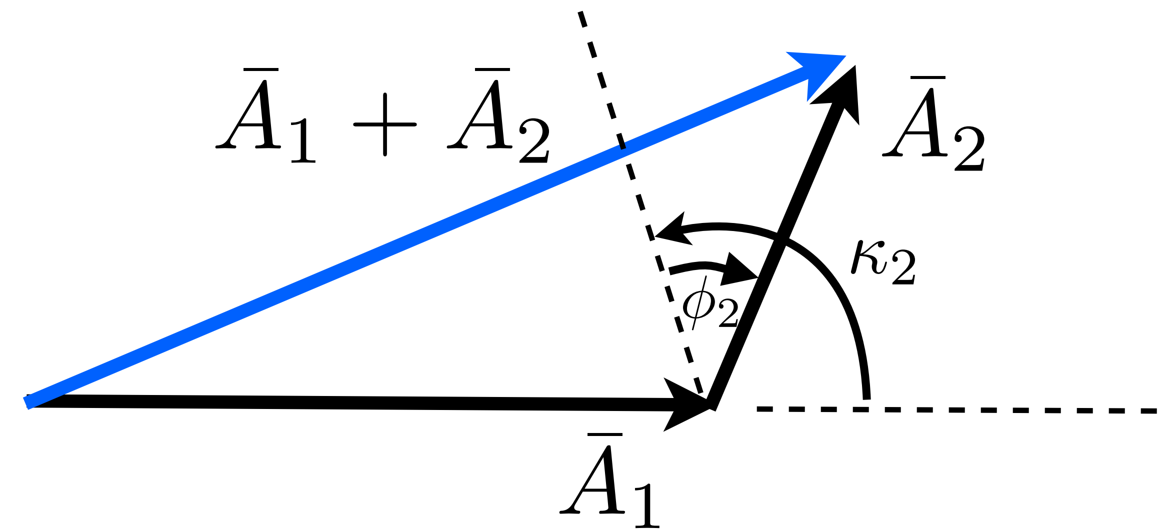
Need a CP conserving phase

$$A_j = |A_j| e^{i\left(+\phi_j^{\text{weak}} + \kappa_j\right)}$$



$$\bar{A}_j = |A_j| e^{i\left(-\phi_j^{\text{weak}} + \kappa_j\right)}$$





$$P(i \to f) = |A_1 + A_2|^2$$

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$$= |A_1|^2 + 2|A_1||A_2| \cos\left(\phi_2 \pm \kappa_2\right) + |A_2|^2$$

$$P(i \to f) - P(\bar{i} \to \bar{f}) = -4|A_1||A_2| \sin\left(\phi_2\right) \sin\left(\kappa_2\right)$$

Where is it?

$$g_\pm(t) = \frac{e^{-i\omega_H t} \pm e^{-i\omega_L t}}{2}$$

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

$t = 0$	t	Amplitude

$$\begin{tikzcd}
 & B^0 \arrow[d, "A_f"] \\
B^0 \arrow[ur, bend left, "g_+(t)"] \arrow[dr, bend right, "\frac{q}{p} g_-(t)"'] & f_{CP} \\
 & \overline{B^0} \arrow[u, "\overline{A}_f"']
\end{tikzcd}$$

$$A_{f_{CP}} [\, g_+(t) + \lambda_{f_{CP}} \; g_-(t) \,]$$

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\end{tikzcd}$$

$$\overline{A}_{f_{CP}} \left[g_+(t) + \frac{1}{\lambda_{f_{CP}}} \; g_-(t) \right]$$

Where is it?

$$g_+(t) = e^{-imt} e^{-\Gamma t/2} \cos\frac{\Delta m t}{2} \;^{**}$$

$$g_-(t) = e^{-imt} e^{-\Gamma t/2} i \sin\frac{\Delta m t}{2} \;^{**}$$

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$t = 0$	t	Amplitude
B^0	$B^0 \xrightarrow{A_f} f_{CP} \xleftarrow{\overline{A}_f} \overline{B^0}$	$A_{f_{CP}}[\,g_+(t) + \lambda_{f_{CP}}\, g_-(t)\,]$
$\overline{B^0}$	$\overline{B^0} \xrightarrow{\overline{A}_f} f_{CP} \xleftarrow{A_f} B^0$	$\overline{A}_{f_{CP}}\left[g_+(t) + \frac{1}{\lambda_{f_{CP}}}\, g_-(t)\right]$

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**for simplicity, considered the case $\Delta\Gamma=0$, i.e. B^0 meson

And the CP-violating phase

$$g_+(t) = e^{-imt} e^{-\Gamma t/2} \cos\frac{\Delta m t}{2} \quad {}^{**}$$

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$$\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}} = e^{-i\phi_{\mathrm{weak}}} \quad {}^{***}$$

$t = 0$	t	Amplitude
B^0	$B^0 \xrightarrow{g_+(t)}$ $B^0 \xrightarrow{A_f} f_{CP}$; $B^0 \xrightarrow{\frac{q}{p} g_-(t)} \overline{B^0} \xrightarrow{\overline{A}_f} f_{CP}$	$A_{f_{CP}}[\, g_+(t) + \lambda_{f_{CP}}\, g_-(t)\,]$
$\overline{B^0}$	$\overline{B^0} \xrightarrow{g_+(t)} \overline{B^0} \xrightarrow{\overline{A}_f} f_{CP}$; $\overline{B^0} \xrightarrow{\frac{p}{q} g_-(t)} B^0 \xrightarrow{A_f} f_{CP}$	$\overline{A}_{f_{CP}}\left[g_+(t) + \frac{1}{\lambda_{f_{CP}}}\, g_-(t) \right]$

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*** for B^0 $|q/p|=1$, and we choose a decay with $|\overline{A}_f/A_f|=1$

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$t=0$	t	Amplitude
B^0	$B^0 \xrightarrow{g_+(t)}$ $B^0 \xrightarrow{A_f} f_{CP}$; $B^0 \xrightarrow{\frac{q}{p}g_-(t)} \overline{B^0} \xrightarrow{\overline{A}_f} f_{CP}$	$A_{f_{CP}}e^{-imt}e^{-\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + ie^{-i\phi_{\mathrm{weak}}}\sin\frac{\Delta m t}{2}\right)$
$\overline{B^0}$	$\overline{B^0} \xrightarrow{g_+(t)} \overline{B^0} \xrightarrow{\overline{A}_f} f_{CP}$; $\overline{B^0} \xrightarrow{\frac{p}{q}g_-(t)} B^0 \xrightarrow{A_f} f_{CP}$	$\overline{A}_{f_{CP}}e^{-imt}e^{-\Gamma t/2}\left(\cos\frac{\Delta m t}{2} + ie^{+i\phi_{\mathrm{weak}}}\sin\frac{\Delta m t}{2}\right)$

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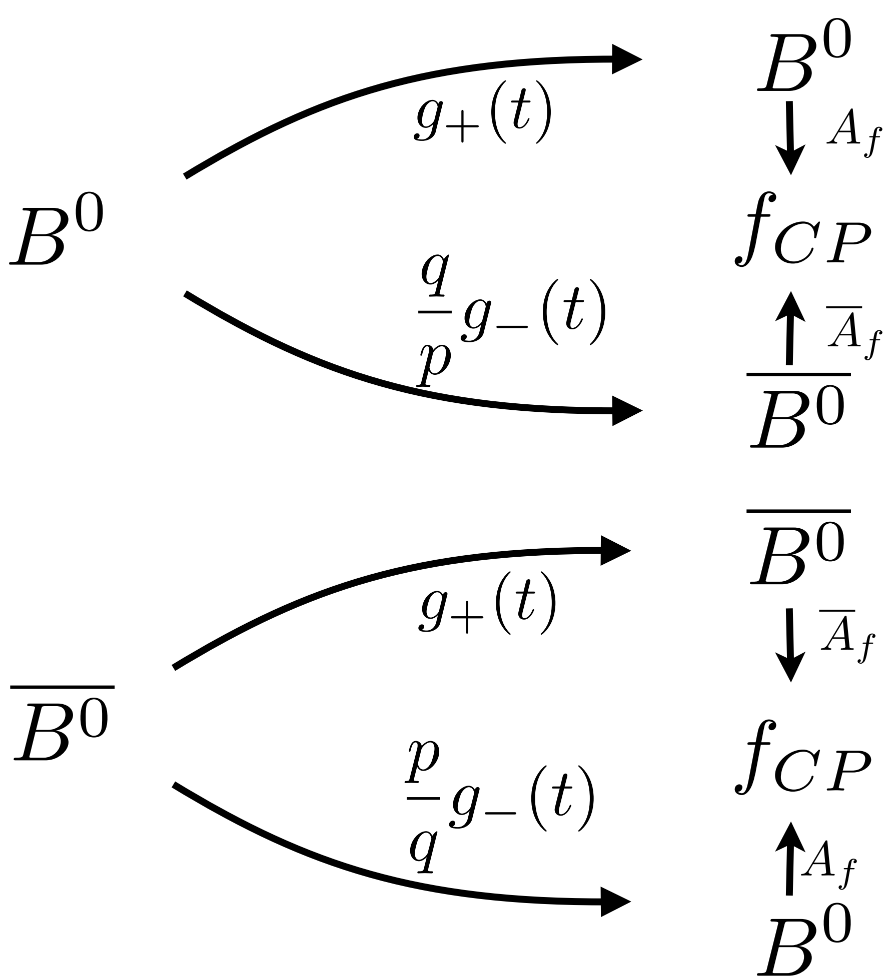
$t = 0$	t	Rate



$$\propto e^{-\Gamma t} \left[1 + \sin(\phi_{\text{weak}}) \sin(\Delta m t)\right]$$

$$\propto e^{-\Gamma t} \left[1 - \sin(\phi_{\text{weak}}) \sin(\Delta m t)\right]$$

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***for B^0 $|q/p|$=1, and we choose a decay with $|\overline{A}_f/A_f|$=1

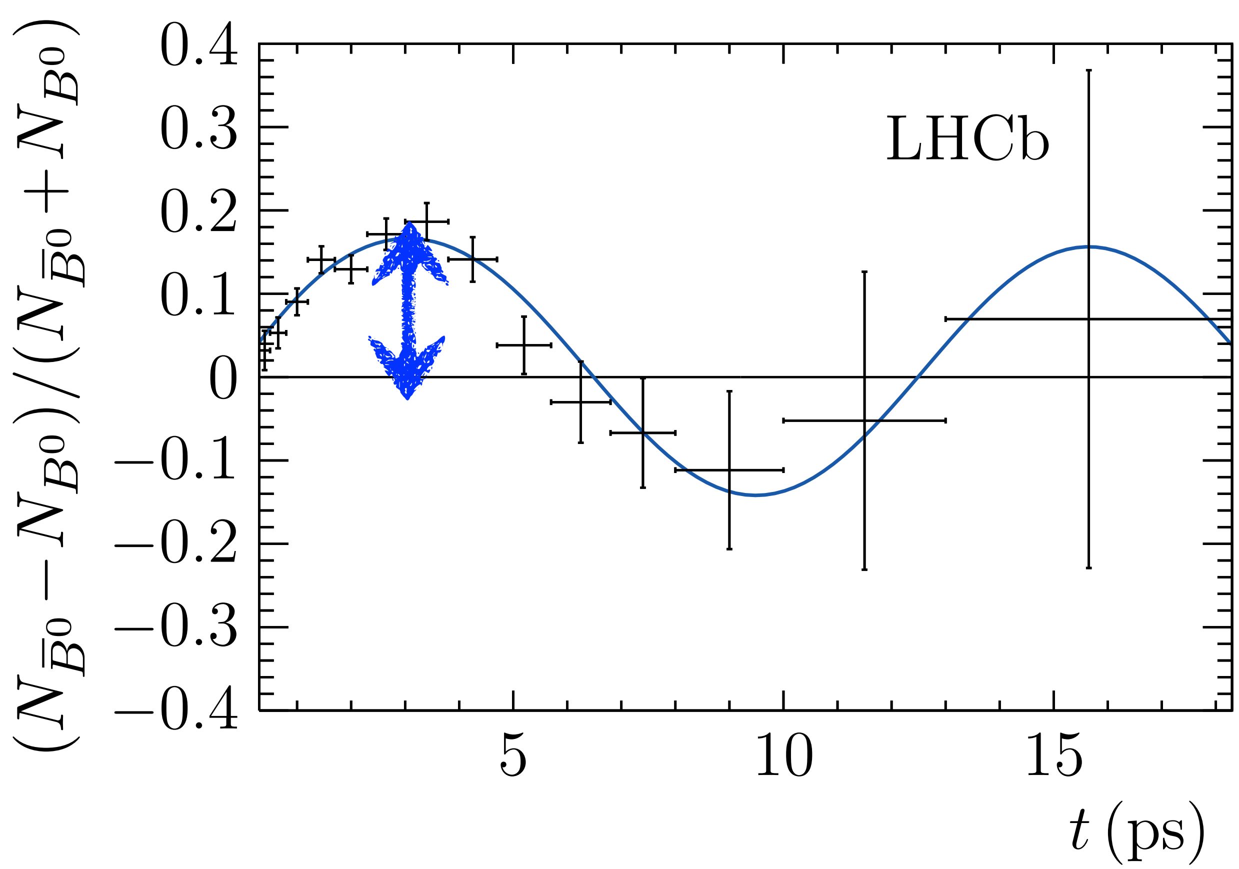
Time-dependent CP asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\overline{B^0} \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B^0} \to f_{CP}) + \Gamma(B^0 \to f_{CP})}$$
$$= -\sin\phi_{\text{weak}} \sin(\Delta m t)$$

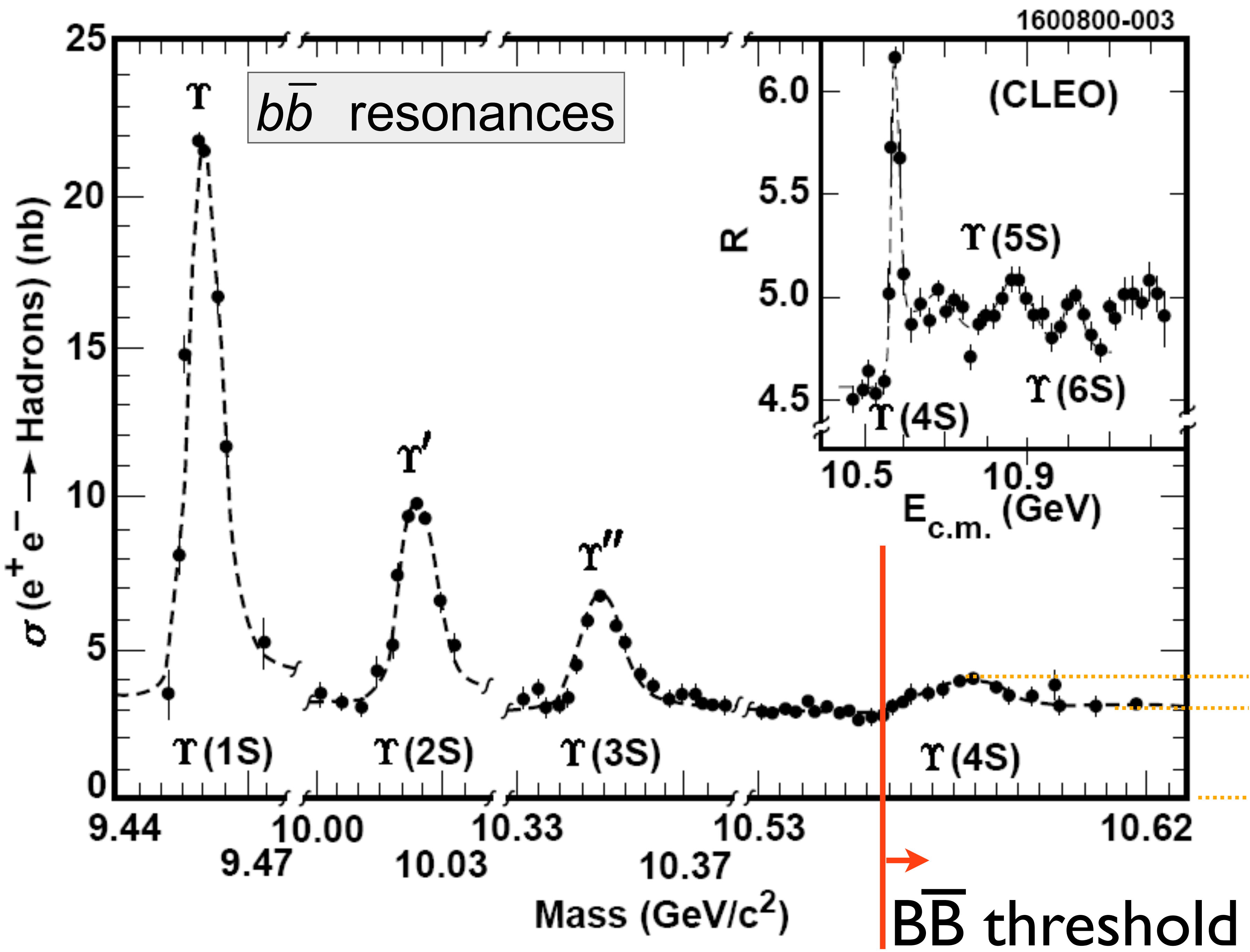
Use the decay
$B^0 \to J/\psi(\to\mu^+\mu^-)\, K_S(\to\pi^+\pi^-)$

Need flavour tagging:
the actual amplitude of the oscillation seen is
$(1\text{-}2\omega)\sin\phi_{\text{weak}}$

Phys. Rev. Lett. 115 (2015) 031601



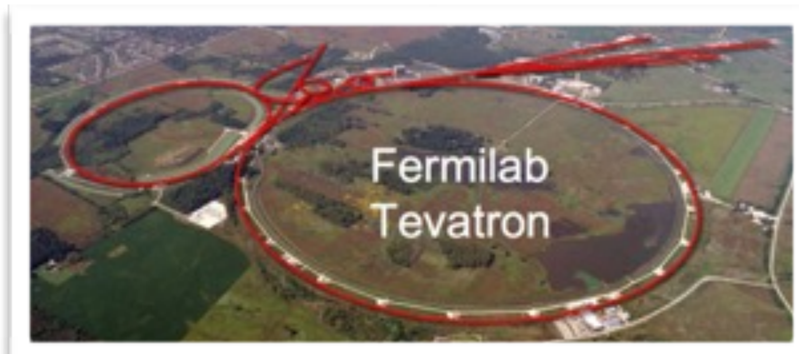
B-factories: Belle and Babar



$$\frac{\sigma(b\bar{b})}{\sigma(hadrons)} = 0.28$$

$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$

Hadron colliders vs. B-factories



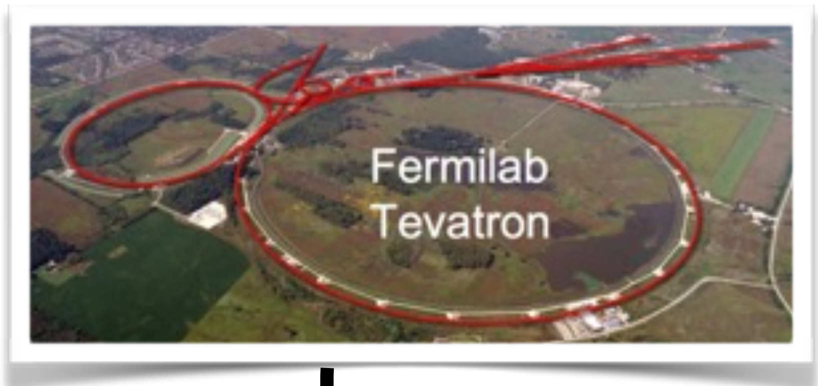
$e^+e^- \to \Upsilon(4S) \to B$ anti-B

p anti-p → b anti-b X
sqrt(s) = 2 TeV

pp → b anti-b X
sqrt(s) = 7,8,13 TeV

production x-section	~1 nb	~100 μb	~500 μb
b hadron mixture	B^+B^-(50%) B^0 anti-B^0 (50%)	B^+(40%) B^0 (40%) B_s^0 (10%) Λ_b^0 (10%), others (<1%)	
b hadron boost	$\beta\gamma$~0.5 (small)	$\beta\gamma$~100 (large)	
underlying event	only BB pairs	many additional particles	

Hadron colliders vs. B-factories



	$e^+e^- \to \Upsilon(4S) \to B$ anti-B	p anti-p → b anti-b X sqrt(s) = 2 TeV	pp → b anti-b X sqrt(s) = 7,8,13 TeV
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	B-factories	Tevatron	LHC
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b hadron boost	$\boxed{\beta\gamma\sim0.5 \text{ (small)}}$	$\beta\gamma\sim100$ (large)	
underlying event	only BB pairs	many additional particles	

Need asymmetric beams!

P. Oddone

Flavour tagging at B-factories: entanglement

– t=0: Decay of Υ(4s) into 2 B mesons

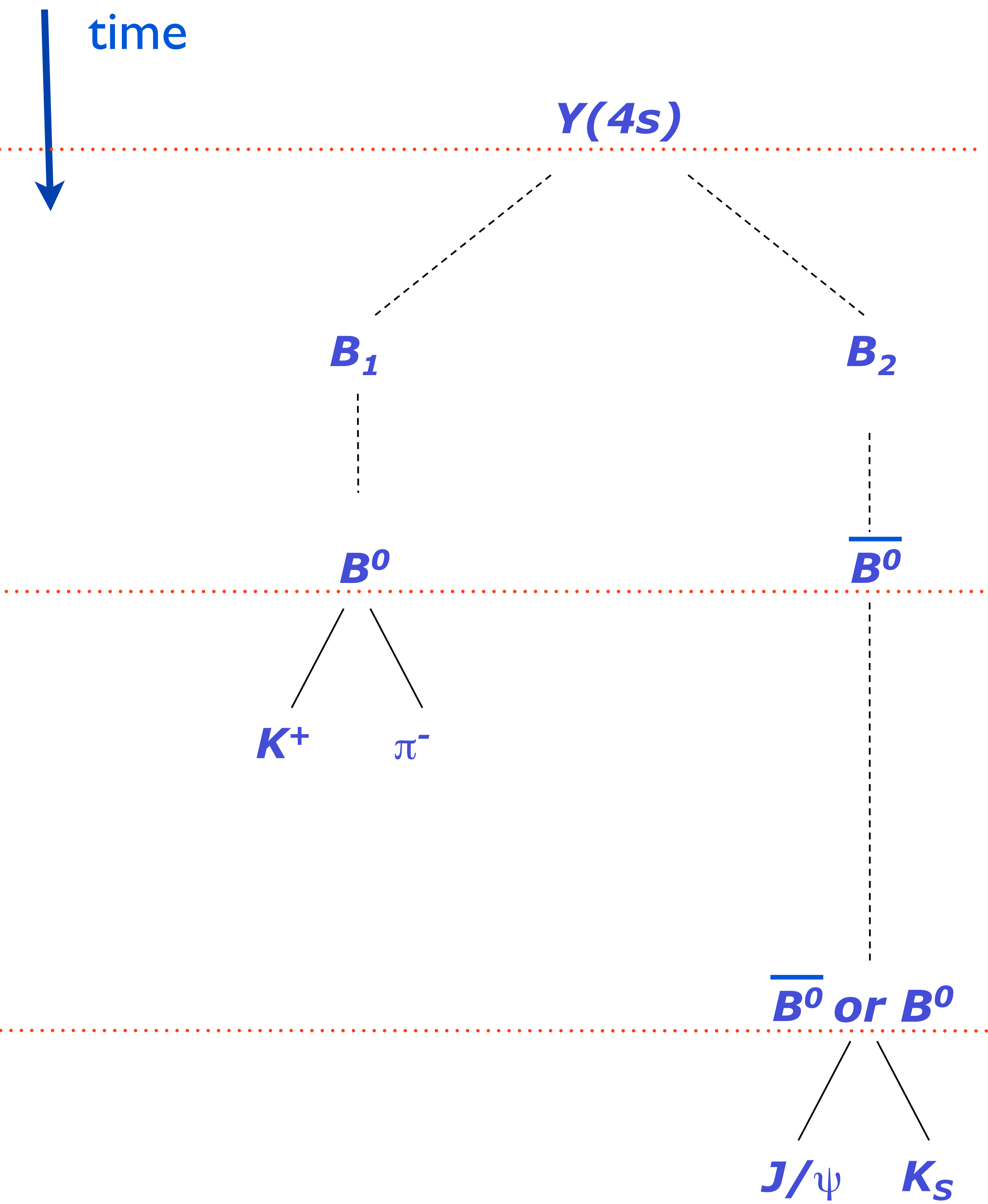
Neither B is in a specific eigenstate,
but B_1B_2 system evolves *coherently*,
i.e. flavor *anti*-correlation preserved during evolution

– $t=t_{tag}$ One of the two mesons (B_1) decays.

If it decays into a flavor eigenstate, flavor conservation in the coherent B_1B_2 system requires that also *B_2 goes into a flavor eigenstate, even though it has not decayed yet*!

– $t=t_{CP}$ The other B meson decays

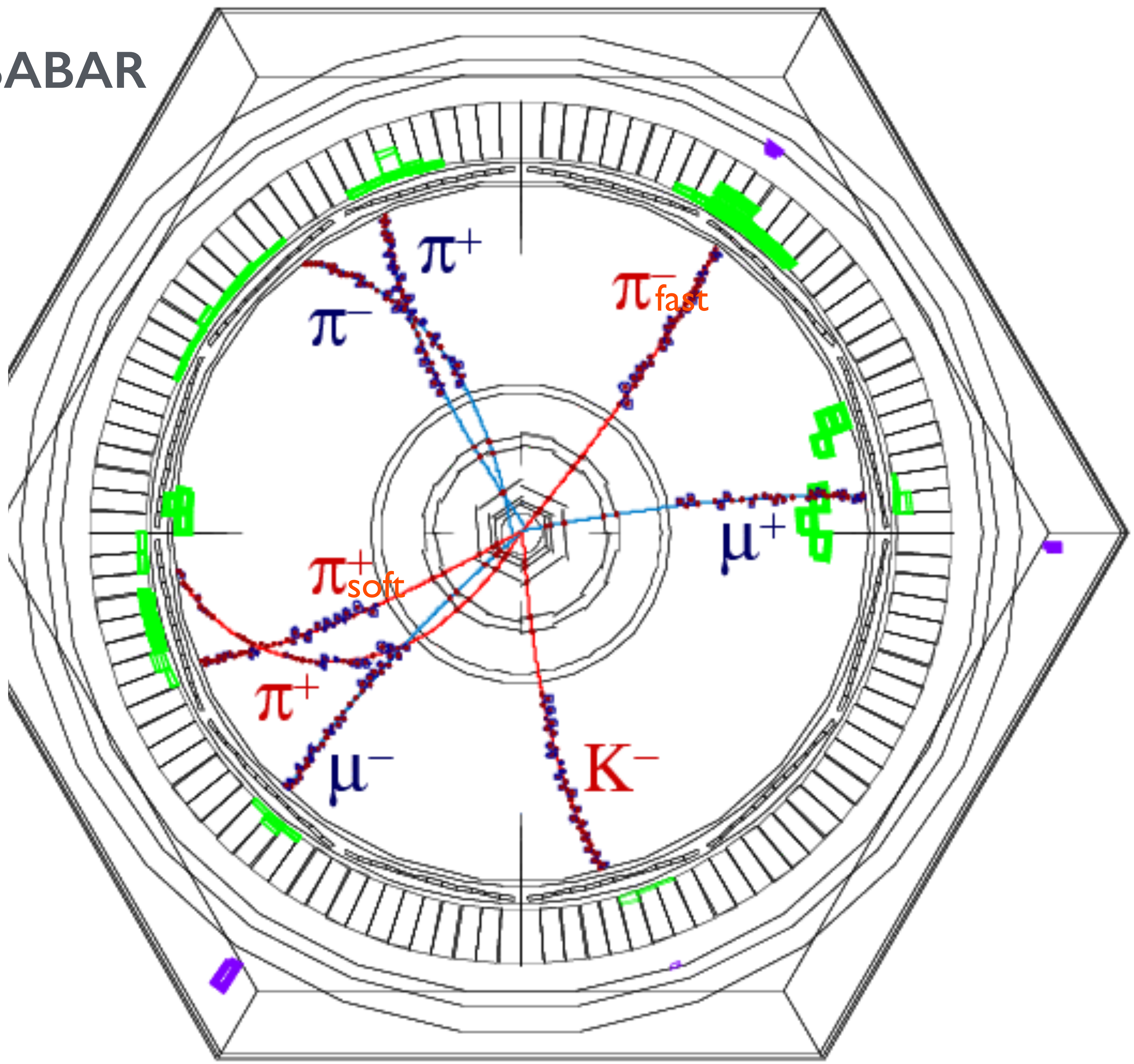
mixing took place *between* t_{CP} and t_{tag}.



Tagging power O(30%) (remember 2-3% at hadron colliders!)

Very clean environment!

BABAR



$\overline{B}^0 \rightarrow D^{*+}\ \pi^-_{fast}$

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

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

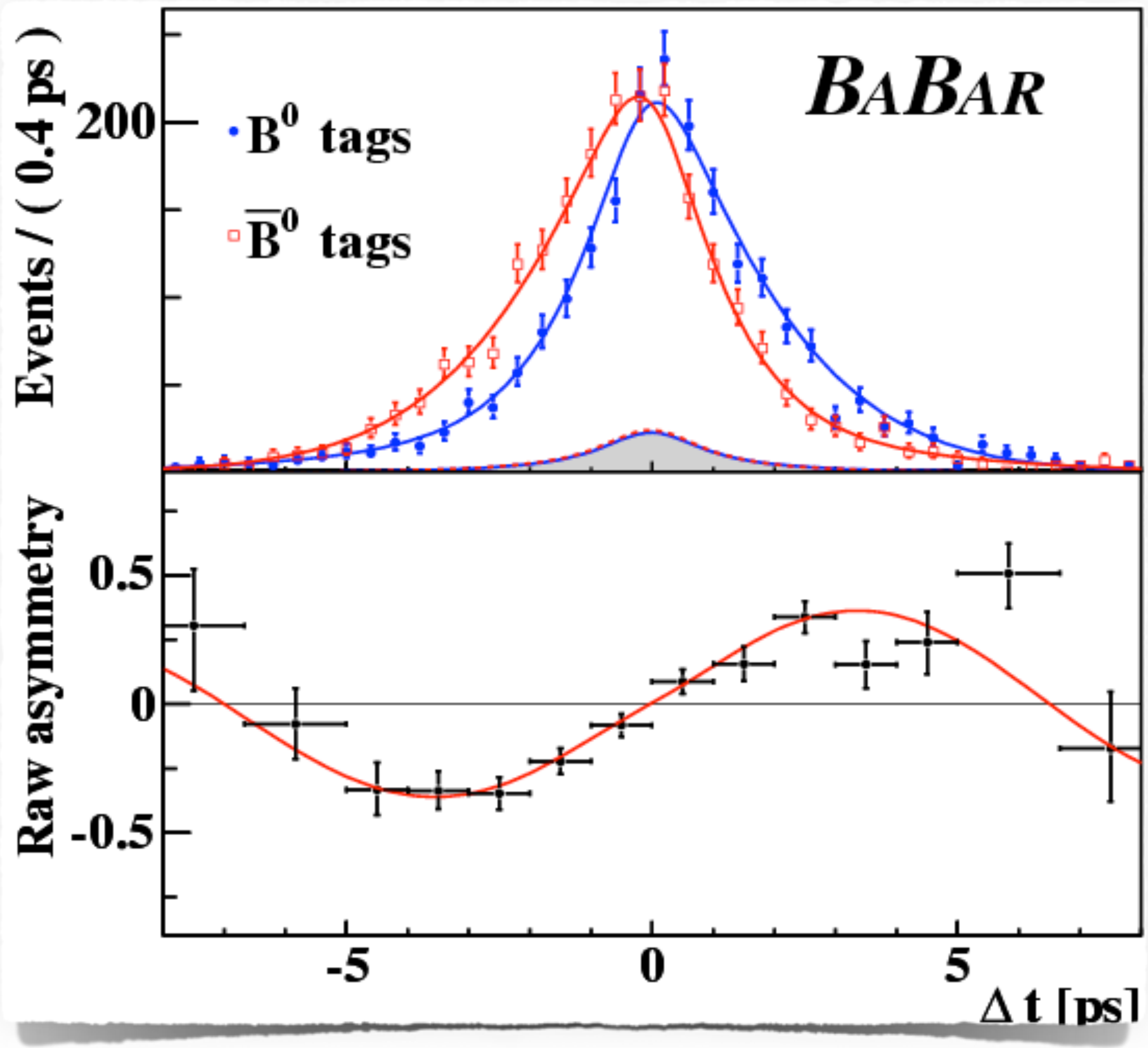
$\Updownarrow$

$B^0(\Delta t) \rightarrow \psi(2S)\ K_s$

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

At Δt=0 (i.e. when the D*π decay happened), the 'CP' B was/would have been a B^0

CP violation in B^0 meson



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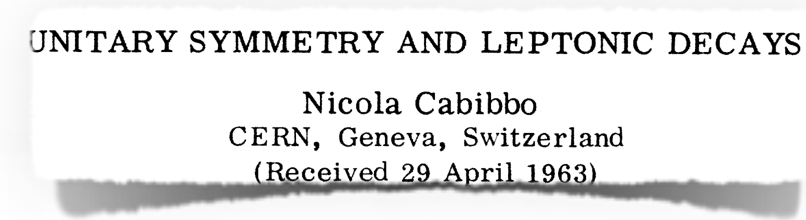
- ★ We can measure CP violation in 3 ways: decays, mixing, interference
- ★ (time-dependent) CPV in interference allows to measure phases (difference). Need two interfering amplitudes with CP-violating and CP conserving phases.
- ★ Large CPV in interference for B^0 mesons

Towards CP in the SM

In the '60s:
4 types of lepton: e, ν_e, μ, ν_μ
3 types of quarks: u, d, s


UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

1963 to preserve universality of weak interactions, Cabibbo introduces a rotation between d and s quarks

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

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Weak Interactions with Lepton-Hadron Symmetry*

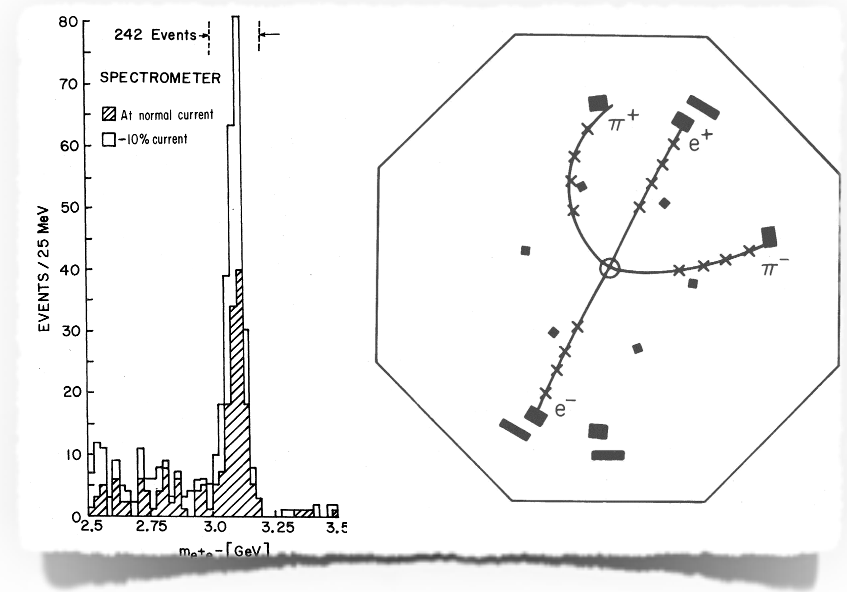
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$
$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

Towards CP in the SM

1974 Ting and Richter discover the J/ψ resonance.



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In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

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Department of Physics, Kyoto University, Kyoto

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1977 Discovery of the bottom quark

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

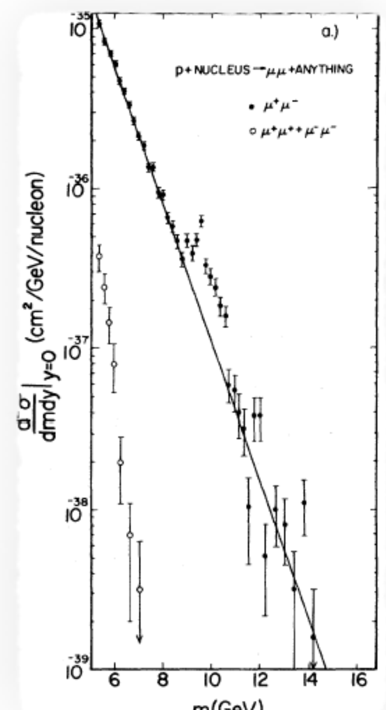
J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974
(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-}$ > 5 GeV.



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1973 Kobayashi and Maskawa introduce a new fields to accomodate CP violation in the theory

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq.

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CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

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

The CKM matrix

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

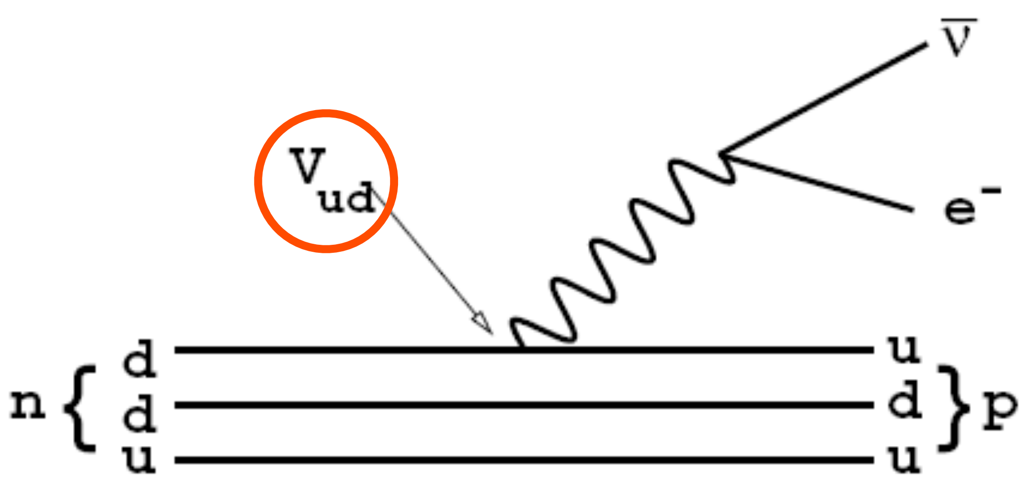
with $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$
so with four parameters $\theta_{12}, \theta_{23}, \theta_{13}, \delta$

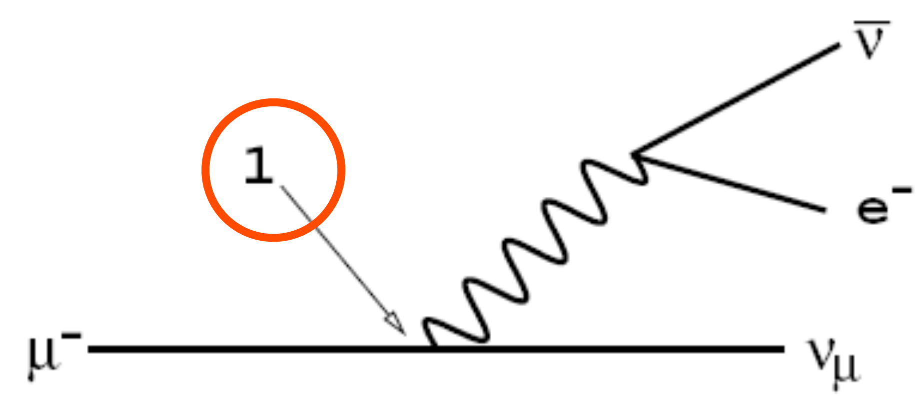
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

How do we measure the couplings?

Magnitudes are typically determined from *ratio* of decay rates

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





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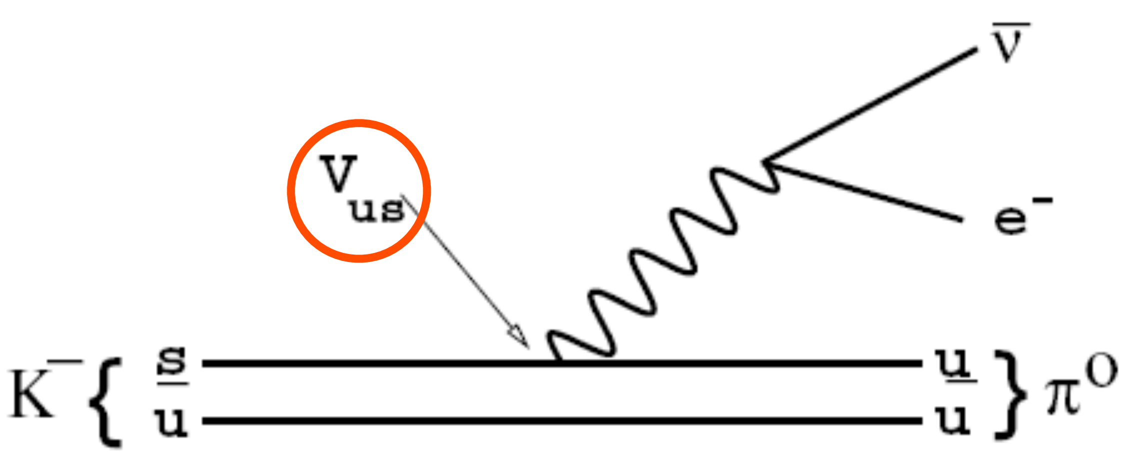

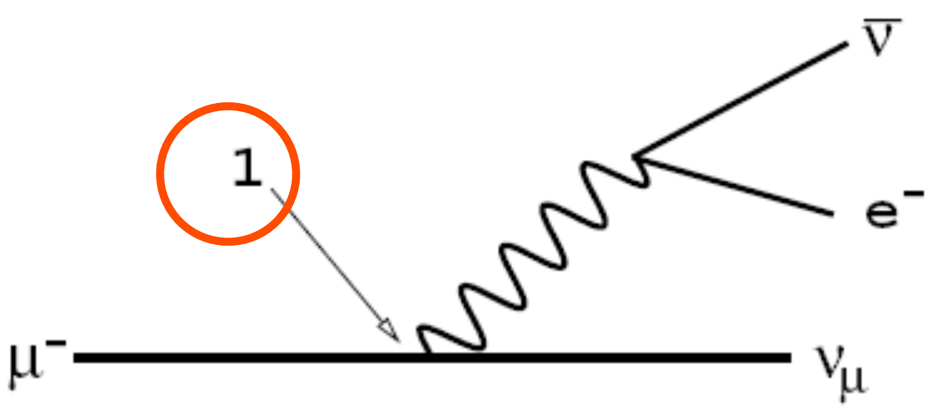

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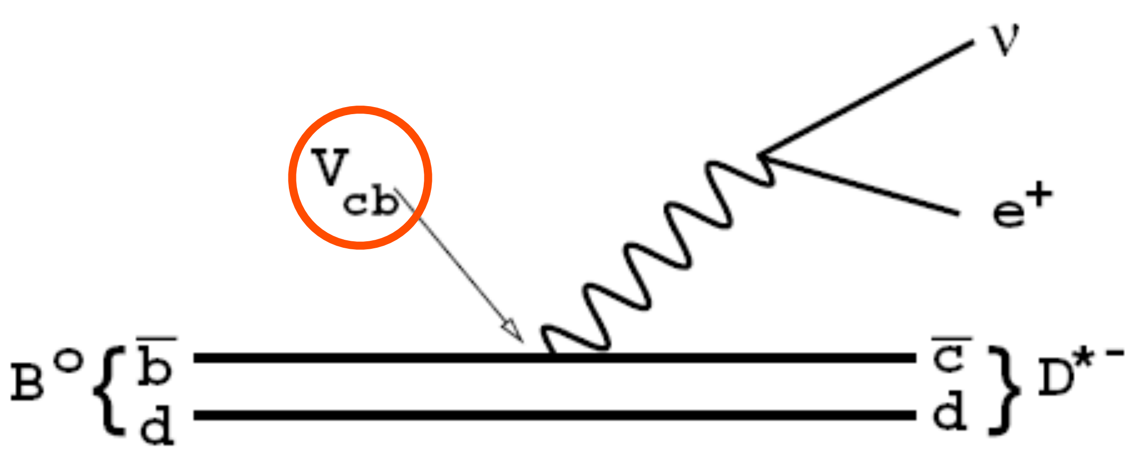

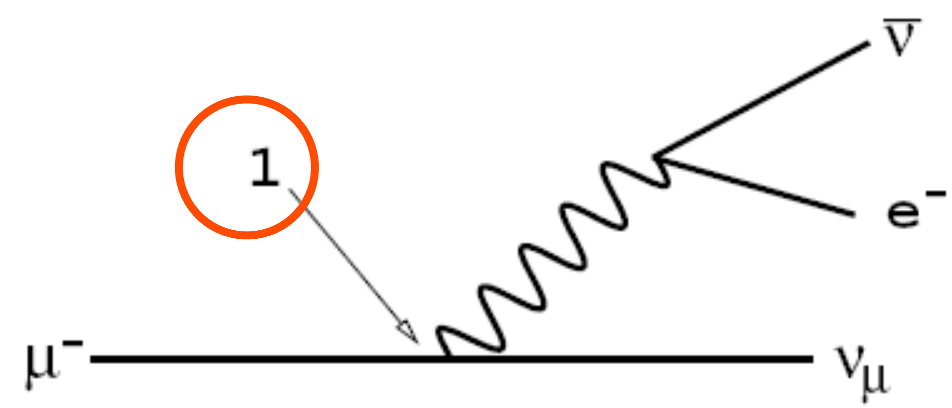

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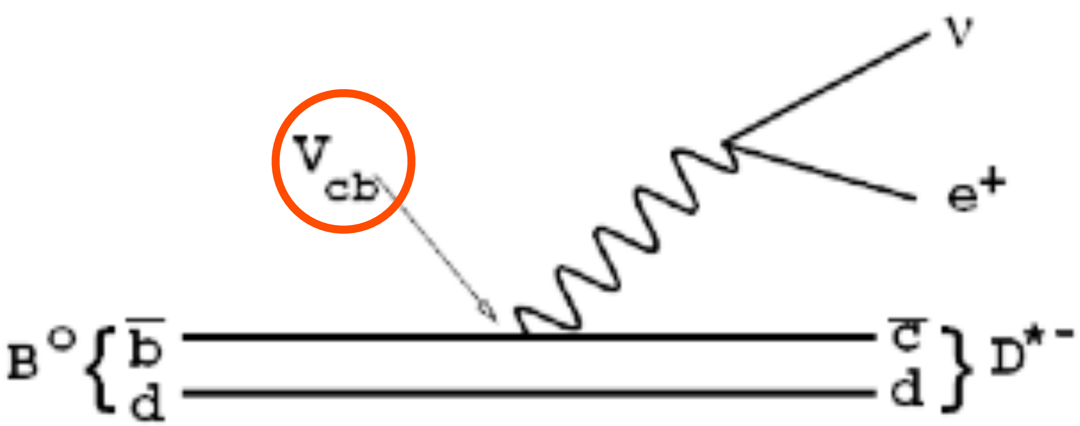

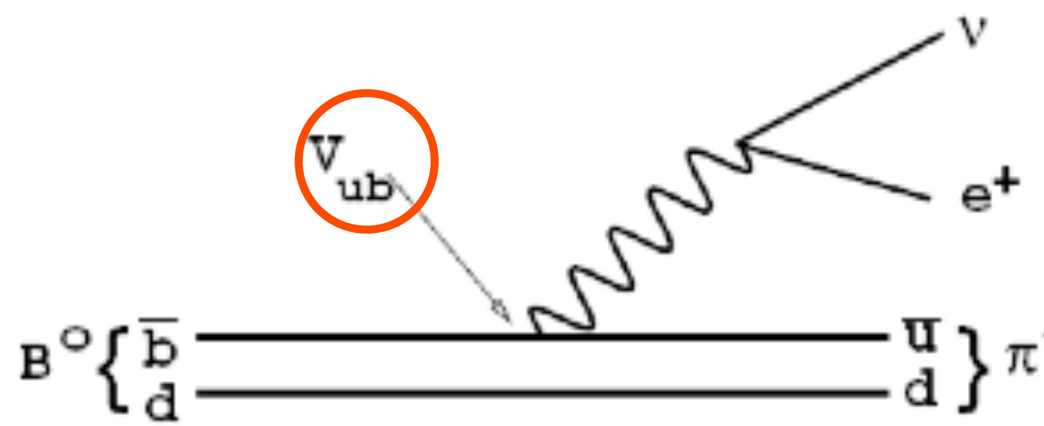

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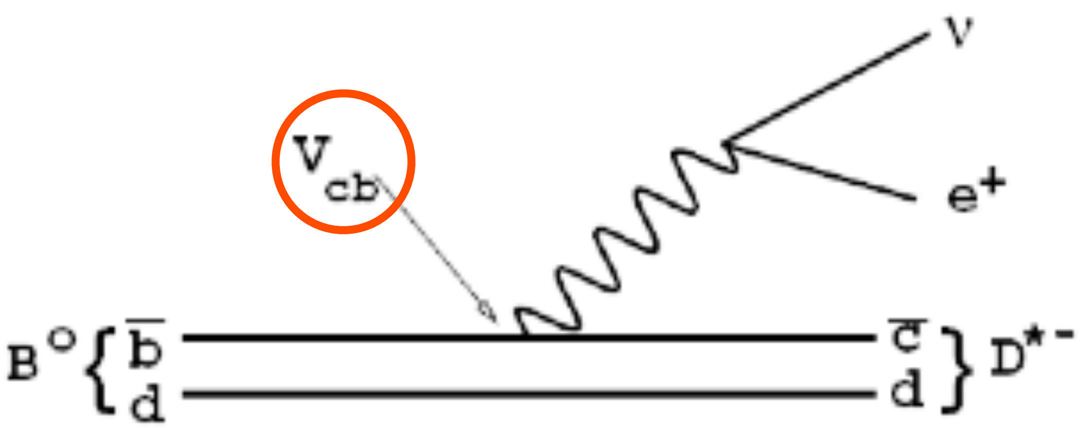

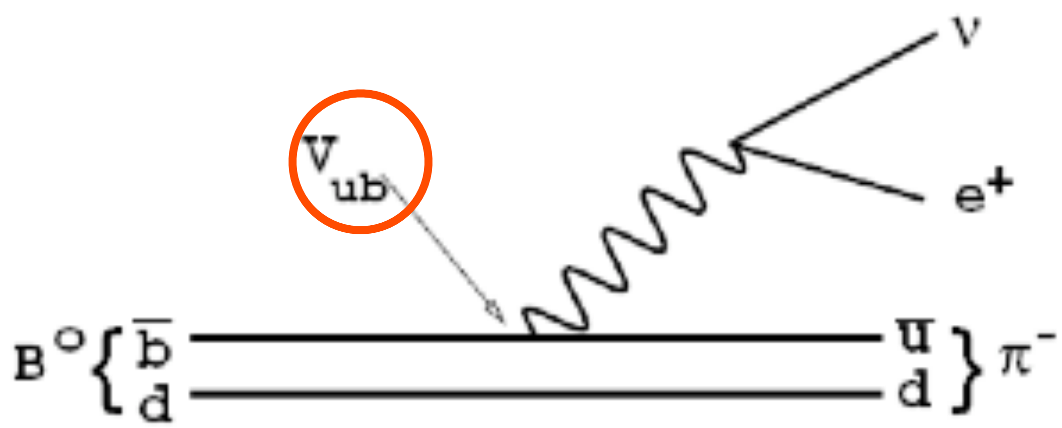

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

Wolfenstein parameterisation

Parametrization of the Kobayashi-Maskawa Matrix

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Department of Physics, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 22 August 1983)

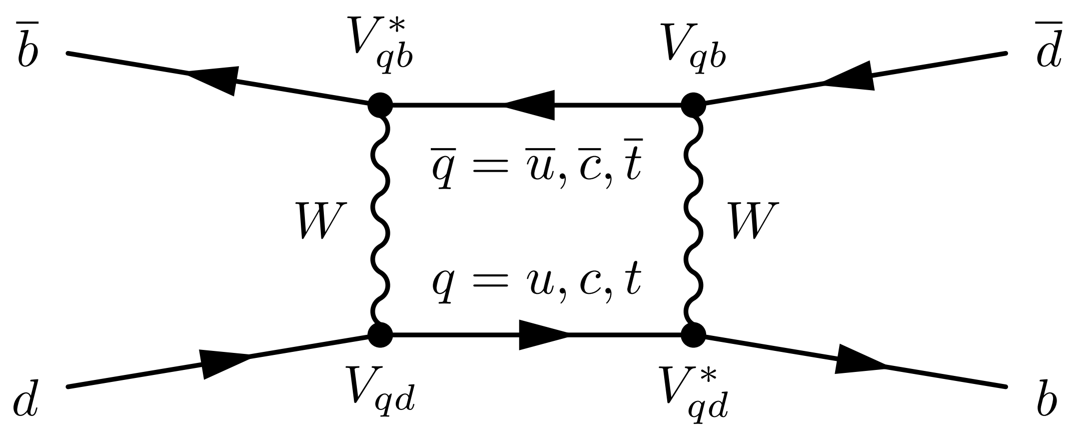
The quark mixing matrix (Kobayashi-Maskawa matrix) is expanded in powers of a small parameter λ equal to $\sin\theta_c = 0.22$. The term of order λ^2 is determined from the recently measured B lifetime. Two remaining parameters, including the *CP*-nonconservation effects, enter only the term of order λ^3 and are poorly constrained. A significant reduction in the limit on ϵ'/ϵ possible in an ongoing experiment would tightly constrain the *CP*-nonconservation parameter and could rule out the hypothesis that the only source of *CP* nonconservation is the Kobayashi-Maskawa mechanism.

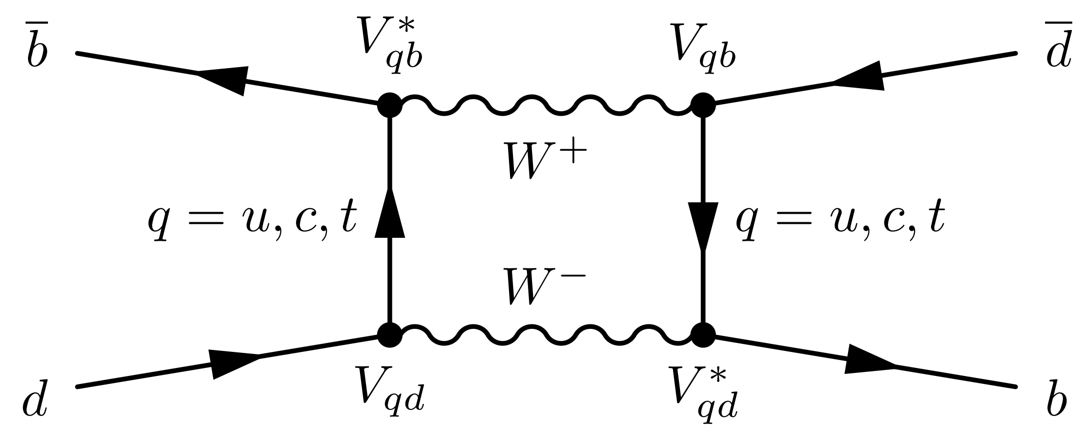
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

[do you remember Charm mixing and WS, RS: why $D^0 \to K^-\pi^+$ is favoured w.r.t to $D^0 \to K^+\pi^-$?]

How do we measure $|V_{td}|$ and $|V_{ts}|$?





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

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

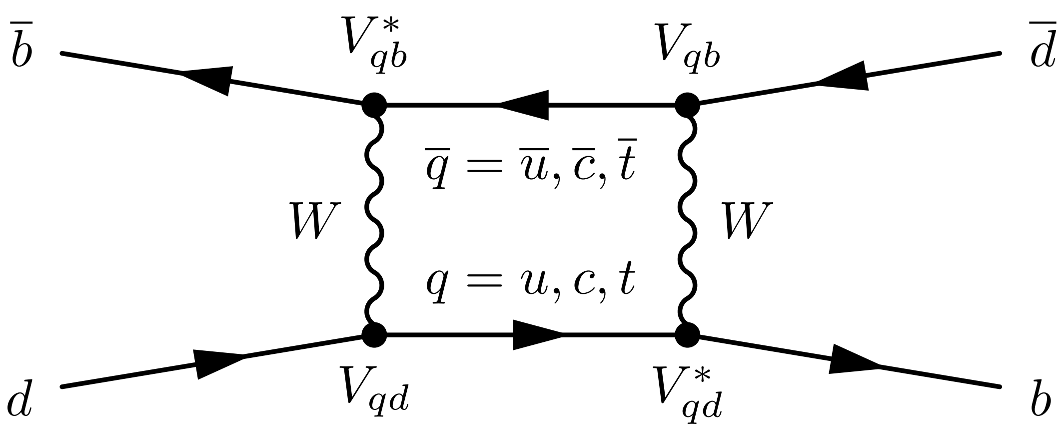
$$c - \bar{t}, \bar{c} - t: \quad \propto m_c m_t V_{tb} V_{td}^{\,*} V_{cb} V_{cd}^{\,*} \quad \propto m_c m_t \lambda^6$$

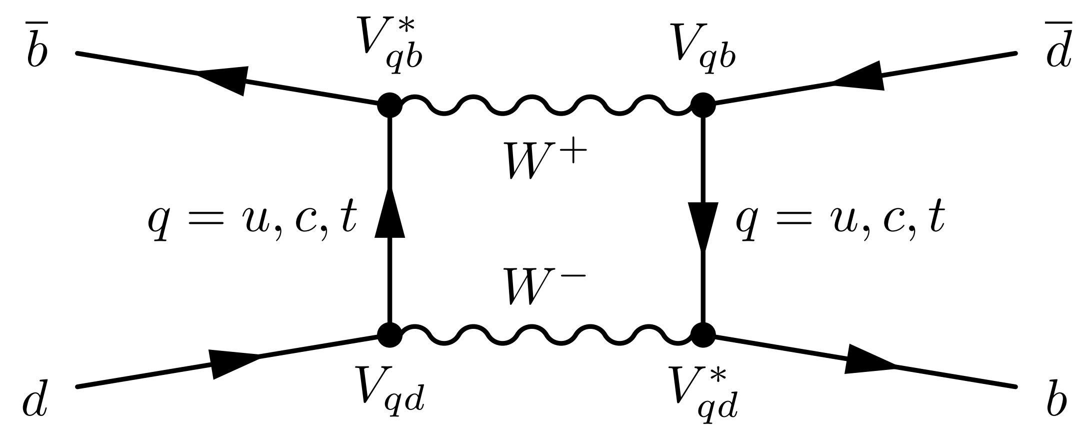
GIM (=V_{CKM} unitarity):
if u,c,t same mass, everything cancels *by construction*!

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_w^2 \eta_B S_0(m_t^2 / m_W^2) m_{B_d} |V_{td}|^2 B_{B_d} f_{B_d}^2$$

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

How do we measure $|V_{td}|$ and $|V_{ts}|$?





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

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

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

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

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_B S_0(m_t^2/m_W^2) m_{B_d} \boxed{|V_{td}|^2} B_{B_d} f_{B_d}^2$$

Dominated by top quark mass: 0.5 ps^{-1} $\approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$
(in *1987*)

The top!

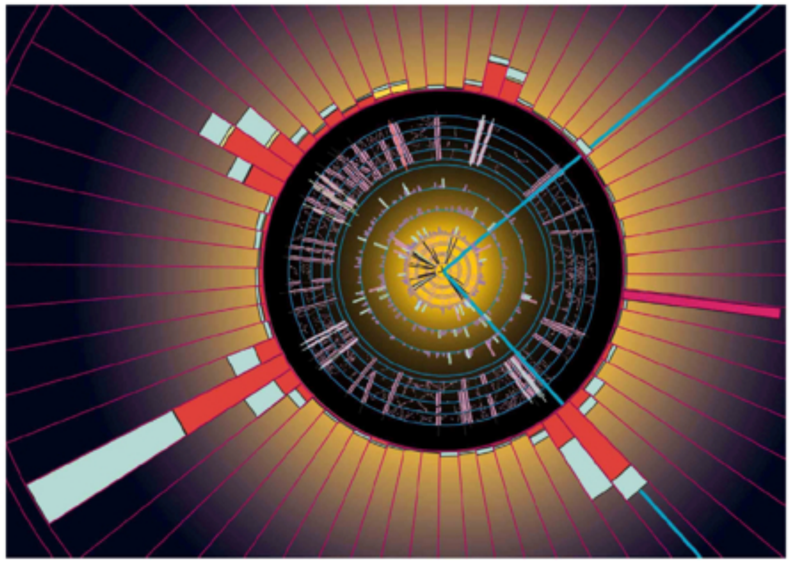
Dominated by top quark mass: 0.5 ps^{-1} $\approx 0.00002 \cdot \left(\frac{m_t}{\mathrm{GeV}/c^2} \right)^2 \mathrm{ps}^{-1}$

Mass of the top > 150 GeV

1994 top quark finally discovered by CDF and D0!

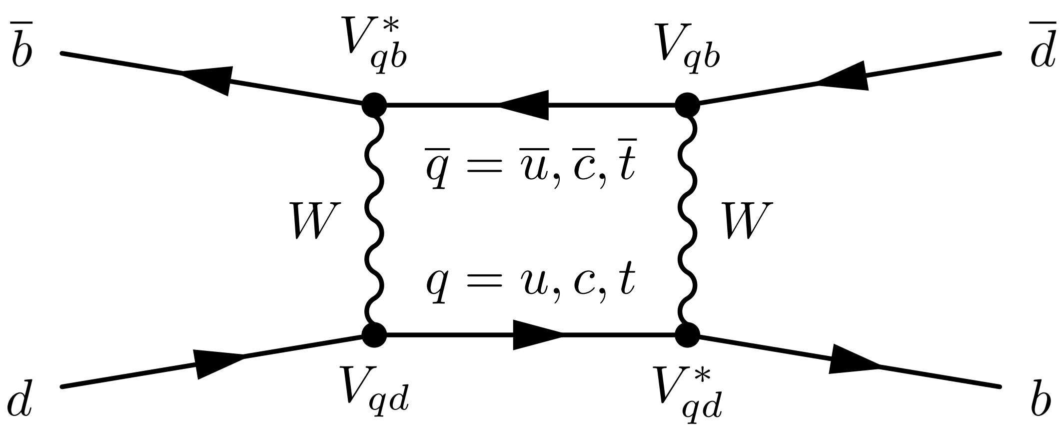
M(top)~174 GeV

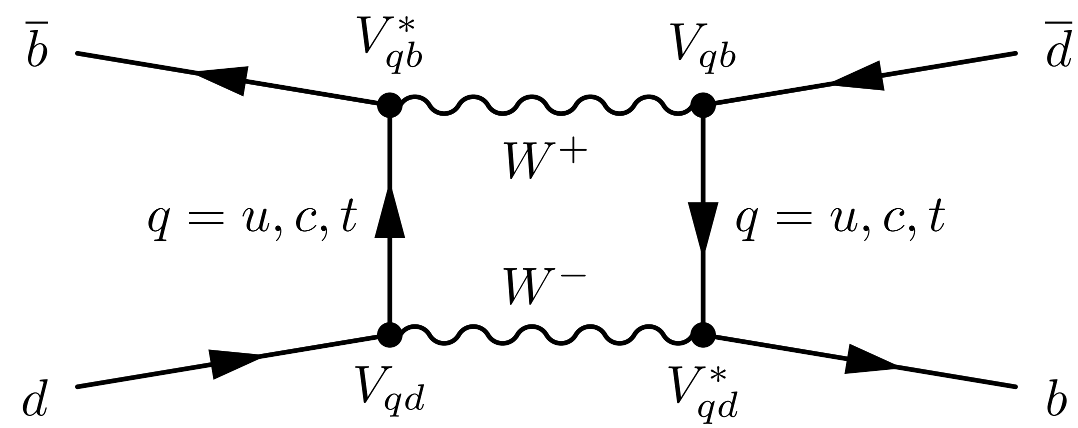
Evidence for Top Quark Production in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV



We summarize a search for the top quark with the Collider Detector at Fermilab (CDF) in a sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 19.3 pb^{-1}. We find 12 events consistent with either two W bosons, or a W boson and at least one b jet. The probability that the measured yield is consistent with the background is 0.26%. Though the statistics are too limited to establish firmly the existence of the top quark, a natural interpretation of the excess is that it is due to $t\bar{t}$ production. Under this assumption, constrained fits to individual events yield a top quark mass of $174 \pm 10^{+13}_{-12}$ GeV/c^2. The $t\bar{t}$ production cross section is measured to be $13.9^{+6.1}_{-4.8}$ pb.

How do we measure $|V_{td}|$ and $|V_{ts}|$?





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

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

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

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

Replace $|V_{td}|$ with $|V_{ts}|$

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_B S_0(m_t^2/m_W^2) m_{B_d} |V_{td}|^2 B_{B_d} f_{B_d}^2$$

$$\frac{\Delta m_d}{\Delta m_s} \approx \frac{|V_{td}|^2}{|V_{ts}|^2} \approx \frac{\lambda^6}{\lambda^4} = \lambda^2 \approx 0.04$$

$$\Delta m_d = 0.502 \pm 0.006 \text{ ps}^{-1}$$

$$\Rightarrow \Delta m_s \approx 12 \text{ ps}^{-1}$$

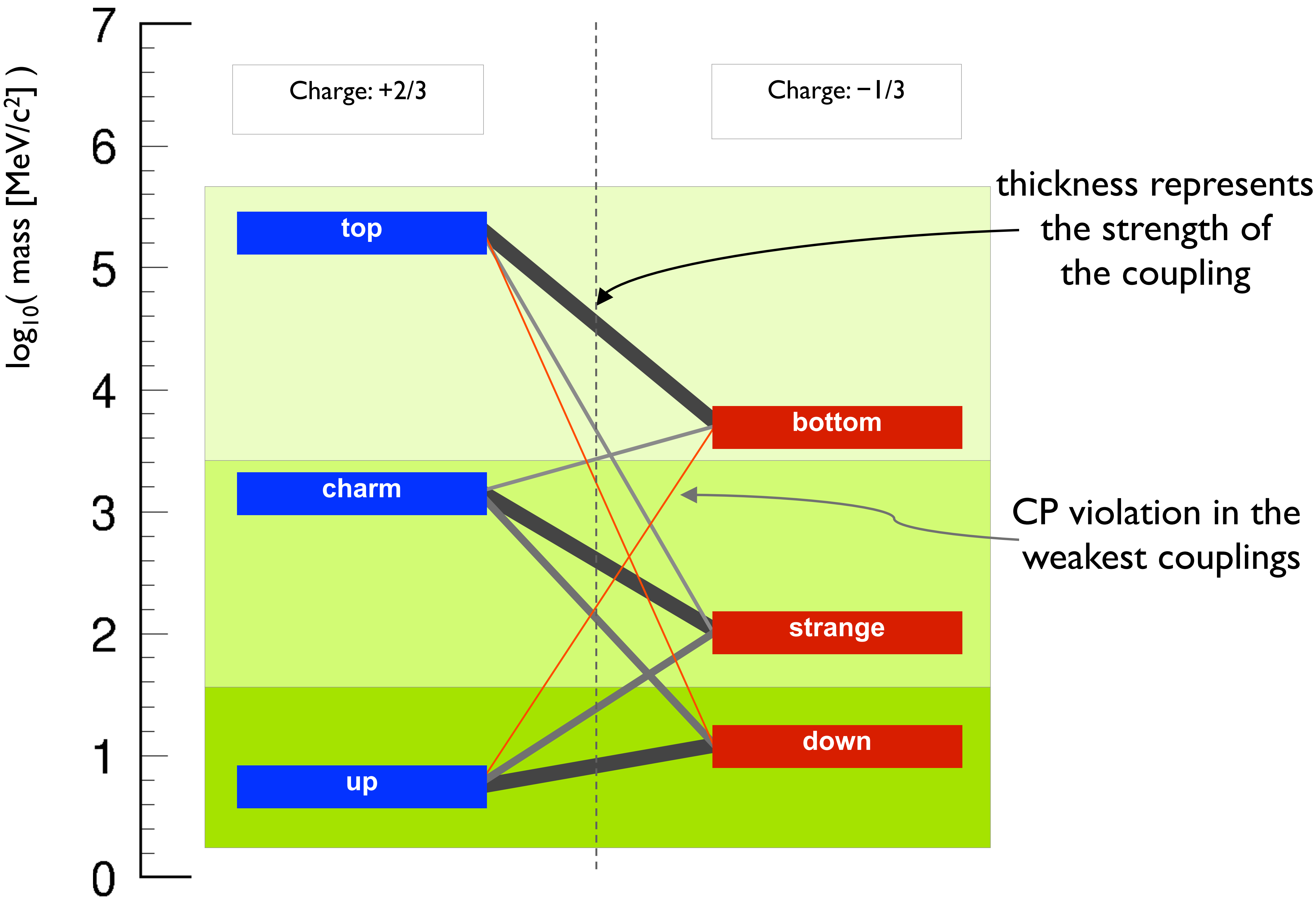
How do we measure $|V_{td}|$ and $|V_{ts}|$?

Observation of $B_s^0 - \bar{B}_s^0$ Oscillations

We report the observation of B_s^0-$\bar{B}_s^0$ oscillations from a time-dependent measurement of the B_s^0-$\bar{B}_s^0$ oscillation frequency Δm_s. Using a data sample of 1 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron, we find signals of 5600 fully reconstructed hadronic B_s decays, 3100 partially reconstructed hadronic B_s decays, and 61 500 partially reconstructed semileptonic B_s decays. We measure the probability as a function of proper decay time that the B_s decays with the same, or opposite, flavor as the flavor at production, and we find a signal for B_s^0-$\bar{B}_s^0$ oscillations. The probability that random fluctuations could produce a comparable signal is 8×10^{-8}, which exceeds 5σ significance. We measure $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ ps^{-1} and extract $|V_{\rm td}/V_{\rm ts}| = 0.2060 \pm 0.0007(\Delta m_s)^{+0.0081}_{-0.0060}(\Delta m_d + \text{theor})$.

DOI: 10.1103/PhysRevLett.97.242003 PACS numbers: 14.40.Nd, 12.15.Ff, 12.15.Hh, 13.20.He

Hierarchy



$\log_{10}$(mass [MeV/c^2])
7
6
5
4
3
2
1
0
Charge: +2/3
Charge: −1/3
top
charm
up
bottom
strange
down
thickness represents the strength of the coupling
CP violation in the weakest couplings

So far (so good?)

- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy…)
- ★ Matter-antimatter oscillations: K^0 can turn into anti-K^0;
  the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations
- ★ A very rich phenomenology of mixing of K, D, and B mesons
- ★ CP is broken!
- ★ Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).
- ★ We can measure CP violation in 3 ways: decays, mixing, interference
- ★ (time-dependent) CPV in interference allows to measure phases (difference).
  Need two interfering amplitudes with CP-violating and CP conserving phases.
- ★ Large CPV in interference for B^0 mesons
- ★ Need (at least) 6 quarks and a mixing matrix to accomodate CPV (and flavour oscillations) in the SM

The unitarity constraints

The 9 unitarity conditions of the 3×3 generations CKM matrix:

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

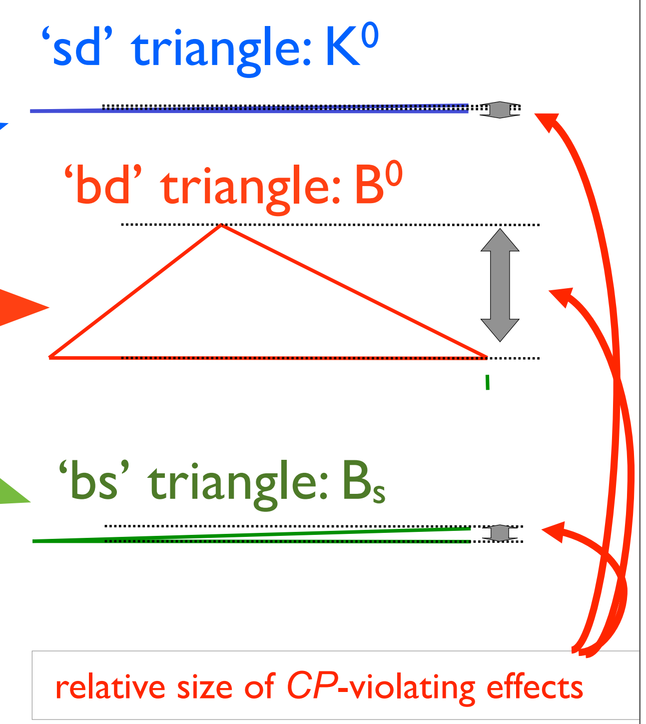
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

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

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

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



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

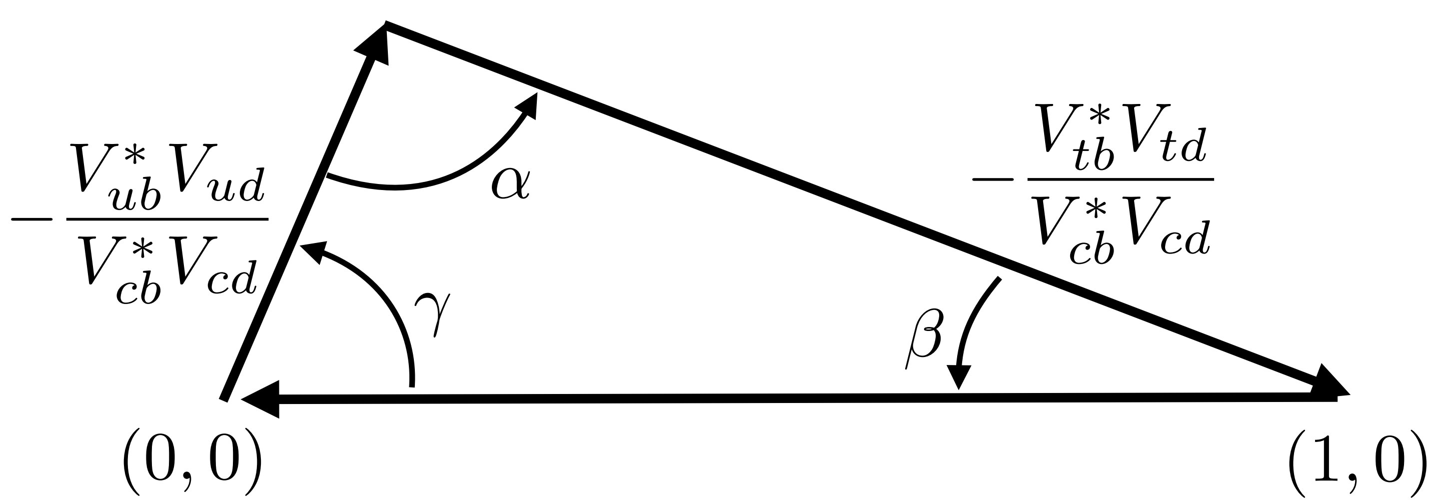
$$V_{ud} V_{td}^* + V_{us} V_{ts}^* + V_{ub} V_{tb}^* = 0$$

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

The unitarity triangle

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

- Pick a quark phase convention such that $V_{cb}^* V_{cd}$ is real
- Normalize all sides by $-V_{cb}^* V_{cd}$



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

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

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

The unitarity triangle

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

- Pick a quark phase convention such that $V_{cb}^* V_{cd}$ is real
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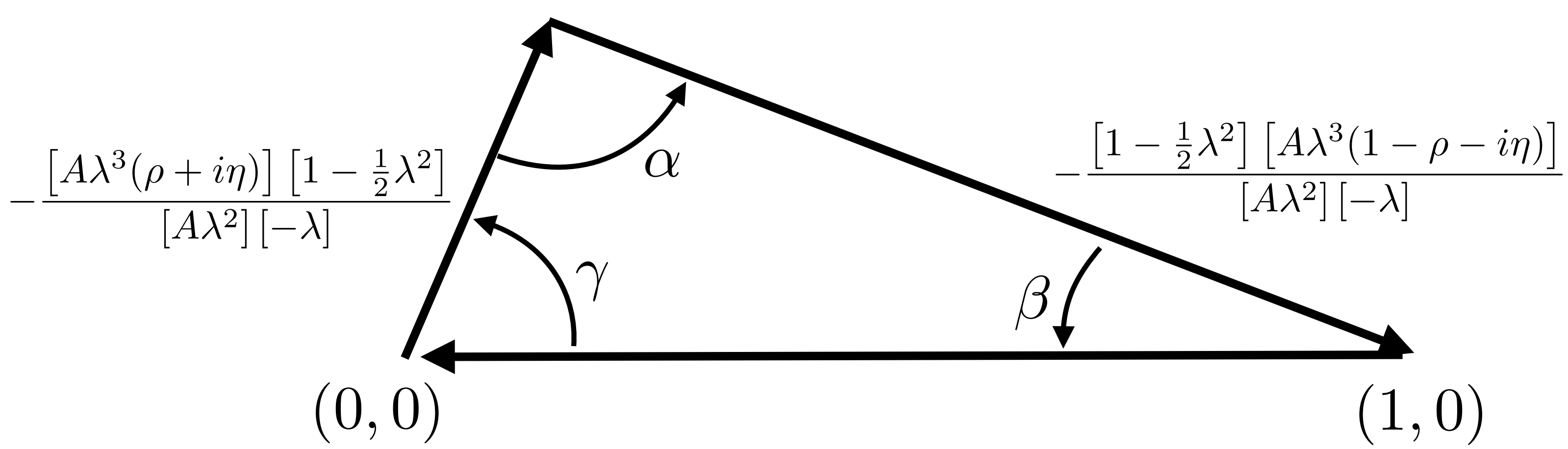


$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

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

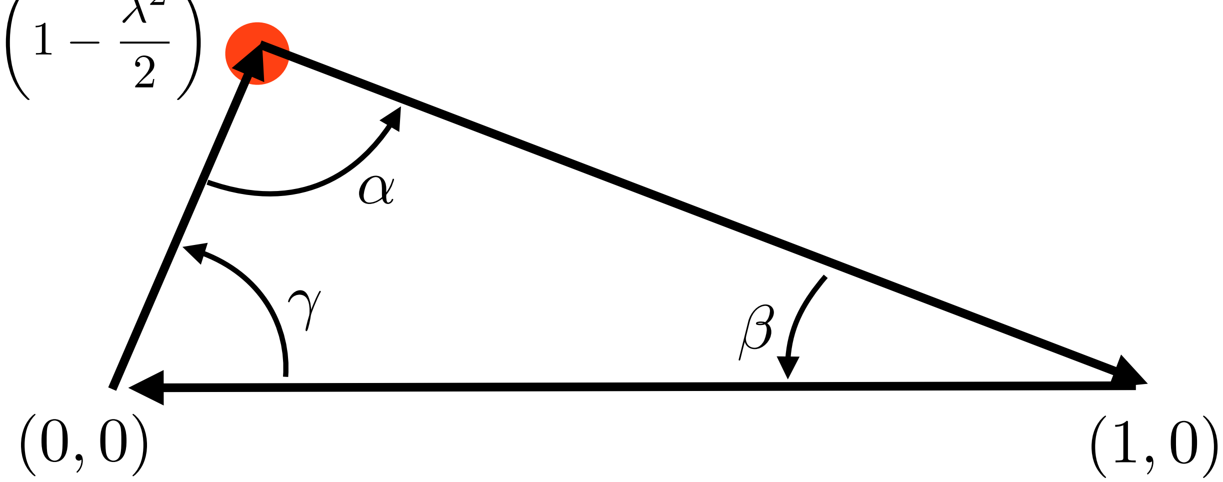
$$\beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

The unitarity triangle

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

- Pick a quark phase convention such that $V_{cb}^* V_{cd}$ is real
- Normalize all sides by $-V_{cb}^* V_{cd}$

$$\overline{\rho} + i\overline{\eta} \equiv (\rho + i\eta)\left(1 - \frac{\lambda^2}{2}\right)$$

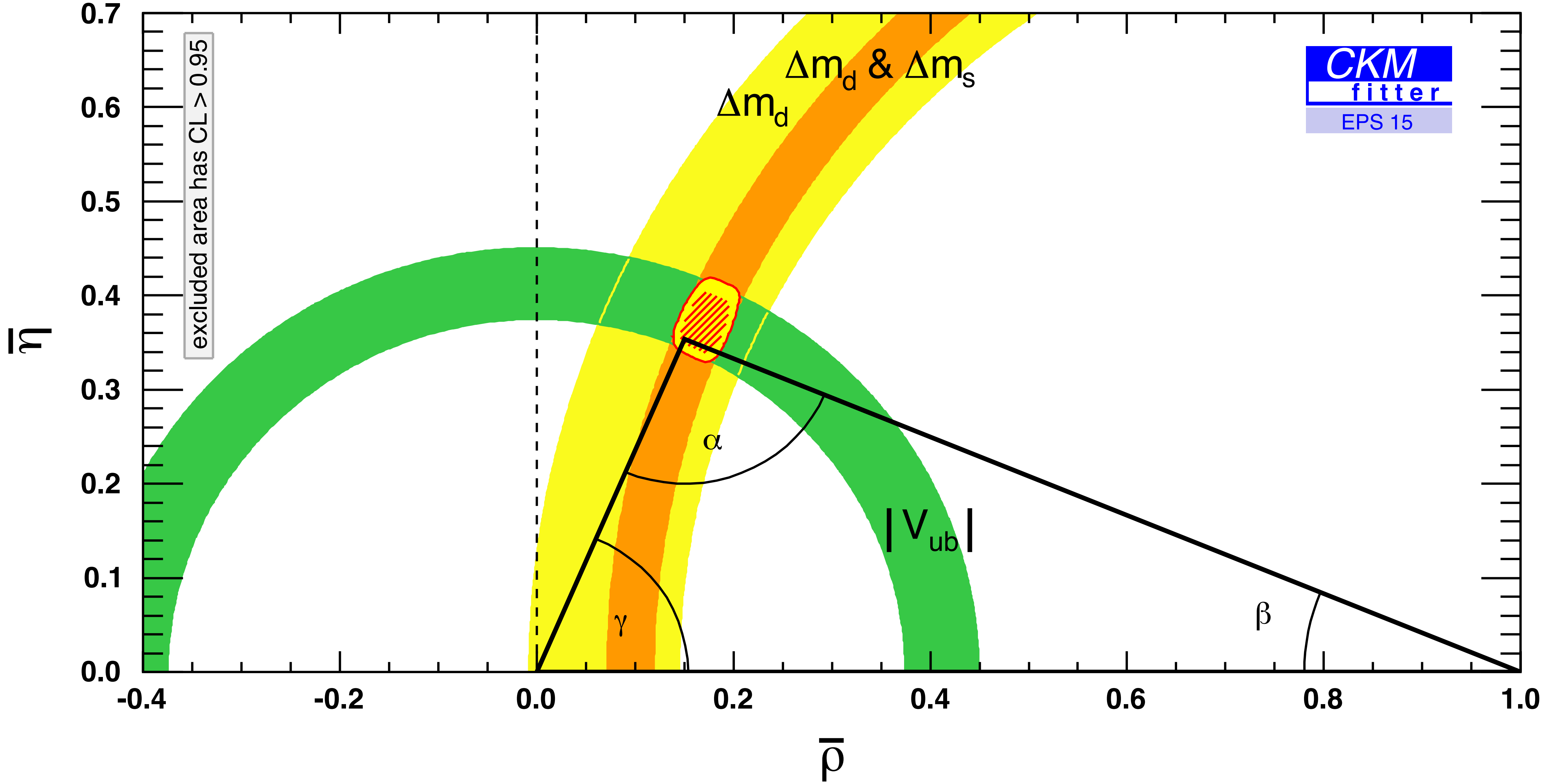


$$\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

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

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

Putting together



How to measure the angles?

Use CP violation in the interference!

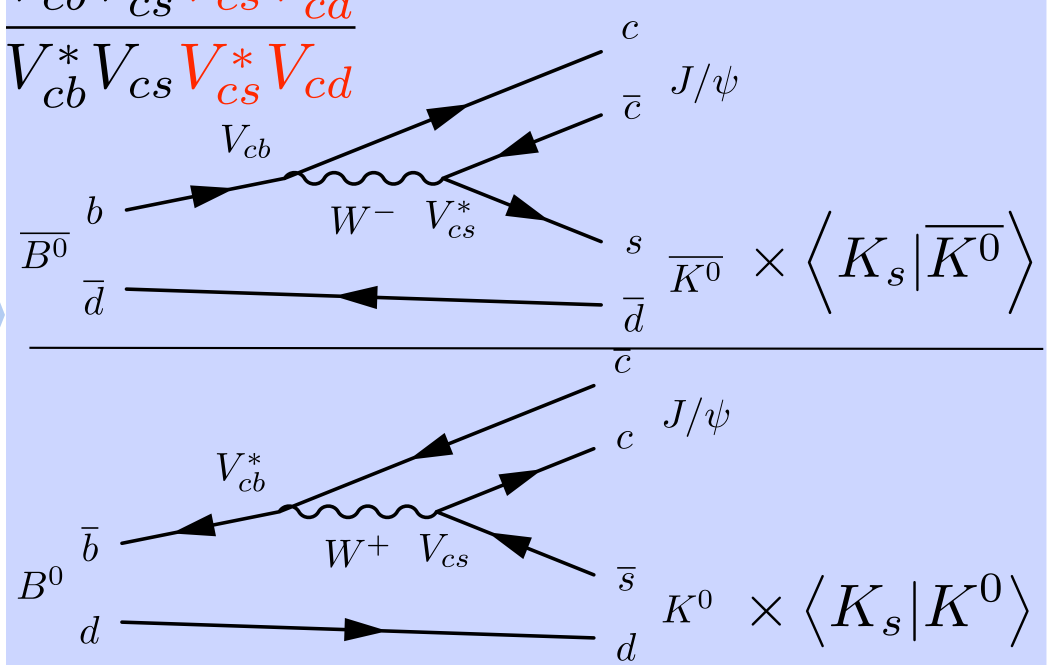
Remember $B^0 \to J/\psi(\to \mu^+\mu^-)\, K_S(\to \pi^+\pi^-)$?

$$\lambda_{J/\psi K_S} \equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}}$$

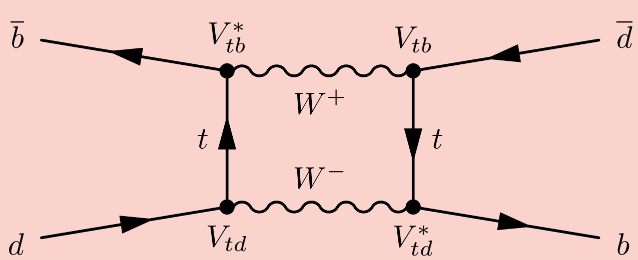
From CP parity of J/ψ and K_S

$$= \boxed{-}\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0 \to K_S}}$$

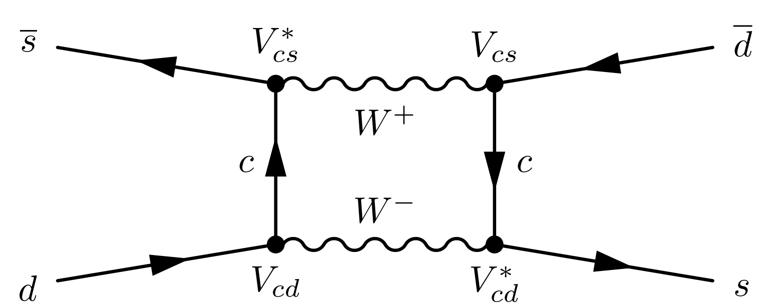
$$\frac{V_{cb}V_{cs}^{*}V_{cs}V_{cd}^{*}}{V_{cb}^{*}V_{cs}V_{cs}^{*}V_{cd}}$$



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



$$\frac{q_K}{p_K} \approx \frac{V_{cs}^{*}V_{cd}}{V_{cs}V_{cd}^{*}}$$



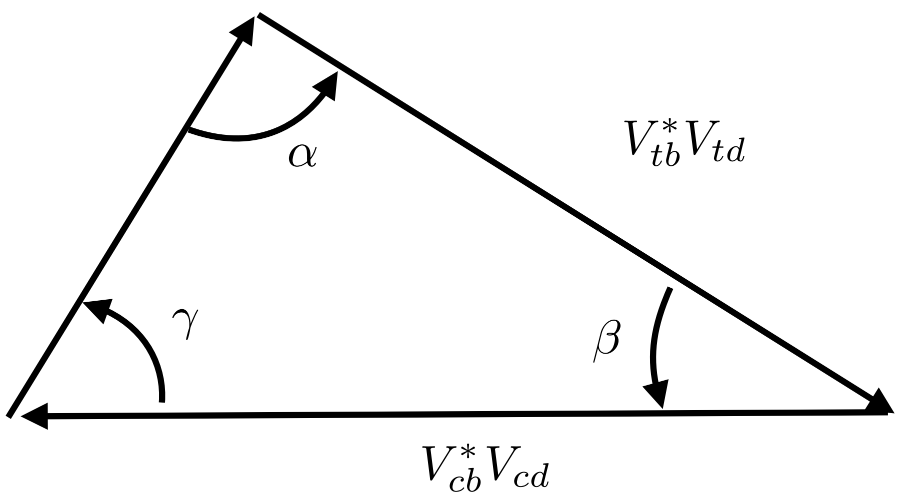
$$|K_s\rangle = p_K \left|K^0\right\rangle + q_K \left|\overline{K^0}\right\rangle$$

How to measure the angles?

Use CP violation in the interference!

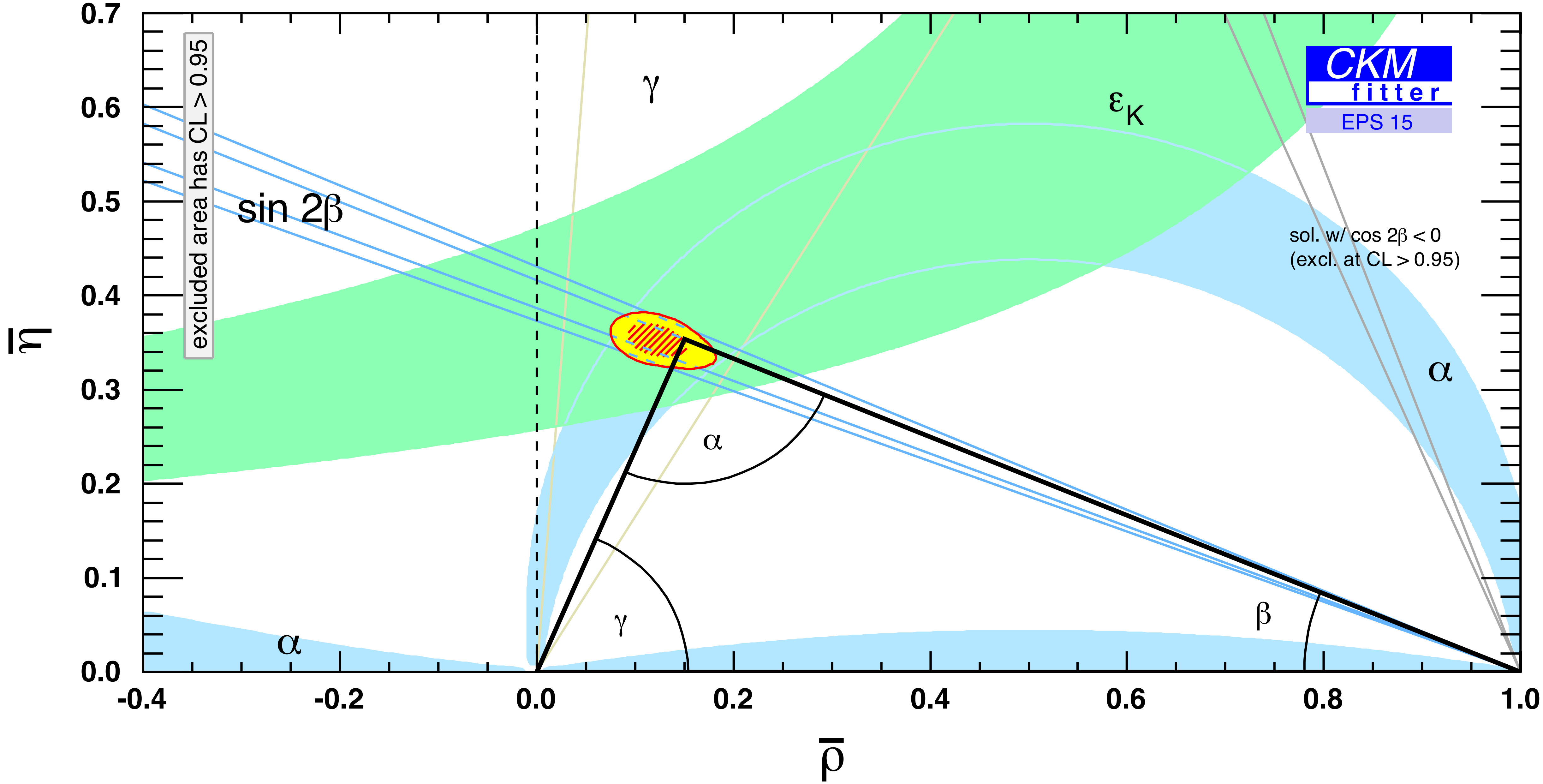
Remember $B^0 \to J/\psi(\to \mu^+\mu^-)\, K_S(\to \pi^+\pi^-)$?

$$
\begin{aligned}
\lambda_{J/\psi K_S} &\equiv \frac{q}{p}\frac{\overline{A}_{J/\psi K_S}}{A_{J/\psi K_S}} \\
&= -\frac{q}{p}\frac{\overline{A}_{J/\psi \overline{K^0}, \overline{K^0}\to K_S}}{A_{J/\psi K^0, K^0\to K_S}} \\
&= -\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*}\frac{V_{cb} V_{cd}}{V_{cb}^* V_{cd}} \\
&= -e^{-2i\beta}
\end{aligned}
$$



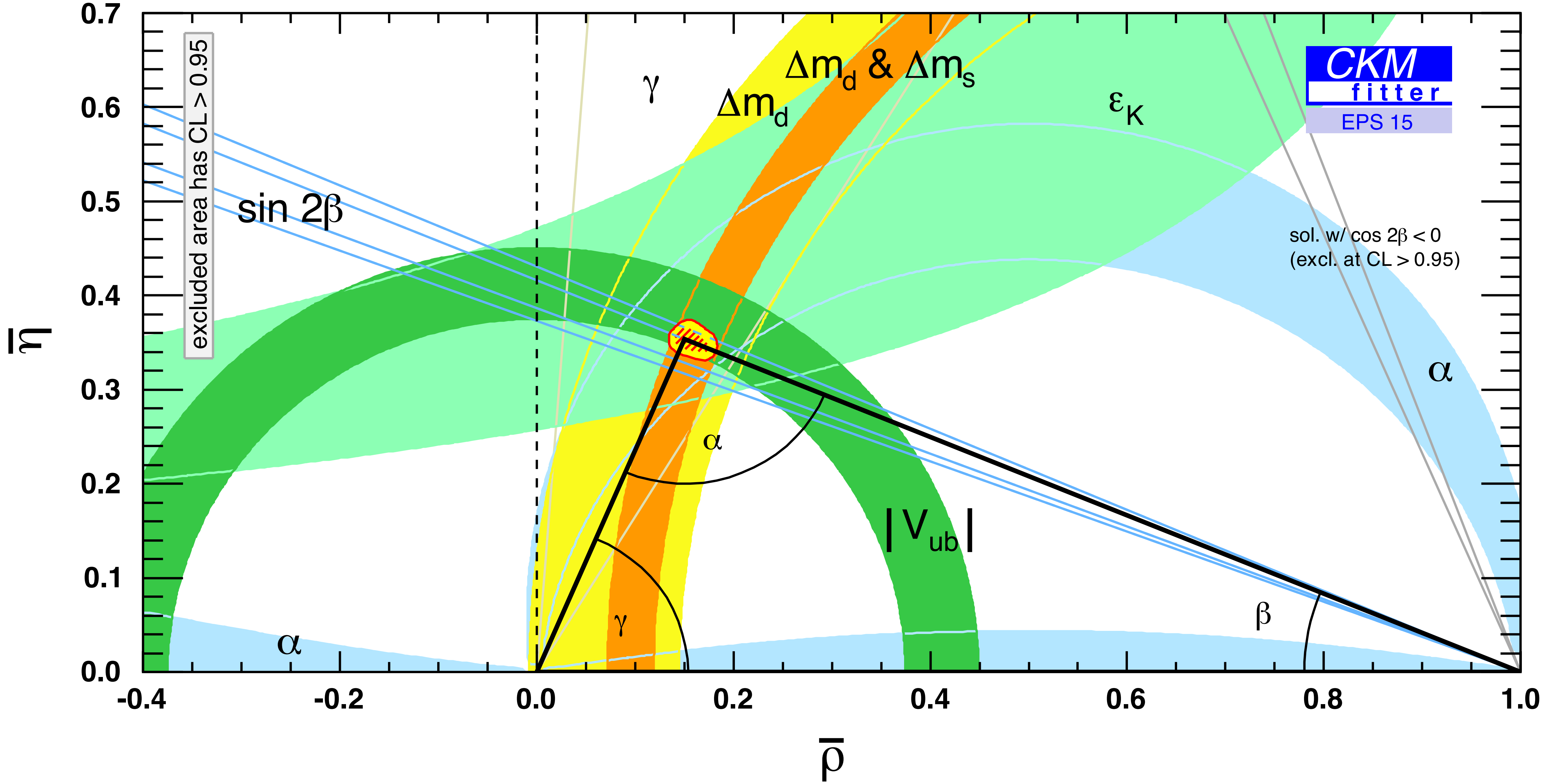
$$
\mathcal{A}_{CP} = \frac{\Gamma(\overline{B^0} \to J/\psi K_S) - \Gamma(B^0 \to J/\psi K_S)}{\Gamma(\overline{B^0} \to J/\psi K_S) + \Gamma(B^0 \to J/\psi K_S)} = \sin(2\beta)\sin(\Delta m t)
$$

CP violation



Putting all together

The CKM model of CP violation has successfully been confirmed!



No need (at current level of precision!) for physics beyond the Standard Model to explain the observed CP violation

So far (so good?)

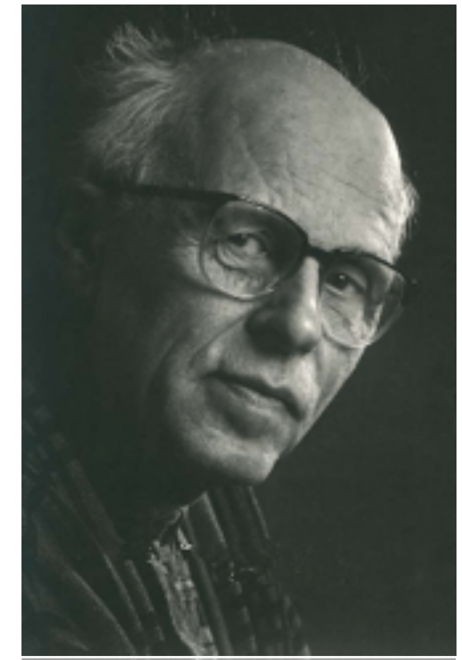
- ★ No primordial antimatter observed, universe matter dominated
- ★ Need breaking of CP symmetry to explain this
- ★ C and P are violated by weak interactions (CP looks still healthy…)
- ★ Matter-antimatter oscillations: K^0 can turn into anti-K^0; the physical states are not the flavour eigenstates.
- ★ Using flavour-specific decays we can observe the flavour oscillations
- ★ A very rich phenomenology of mixing of K, D, and B mesons
- ★ CP is broken!
- ★ Observed CP violation in K mixing; no evidence so far for B mesons (neither for D mesons).
- ★ We can measure CP violation in 3 ways: decays, mixing, interference
- ★ (time-dependent) CPV in interference allows to measure phases (difference). Need two interfering amplitudes with CP-violating and CP conserving phases.
- ★ Large CPV in interference for B^0 mesons
- ★ Need (at least) 6 quarks and a mixing matrix to accomodate CPV (and flavour oscillations) in the SM
- ★ CKM mechanism explain all CP violating phenomena observed (so far)

Sakharov's conditions

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

A. D. Sakharov
Submitted 23 September 1966
ZhETF Pis'ma 5, No. 1, 32-35, 1 January 1967

The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a non-zero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding Universe (see [1]) by making use of effects of CP invariance violation (see [2]). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.



Three requirements for a universe with a baryon asymmetry:

1. a process that violates baryon number
2. C and CP violation, i.e. breaking of the C and CP *symmetries*
3. 1&2 should occur during a phase which is NOT in thermal equilibrium

The question

VIOLATION OF CP INVARIANCE, C ASYMMETRY, AND BARYON ASYMMETRY OF THE UNIVERSE

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The theory of the expanding Universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from anti-matter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the Universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos i
out a possible explar
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we propose in addition an approximate character for the baryon conservation law.

Is this SM CP violation enough?

Three requirements for a universe with a baryon asymmetry:

1. a process that violates baryon number
2. C and CP violation, i.e. breaking of the C and CP *symmetries*
3. 1&2 should occur during a phase which is NOT in thermal equilibrium

Can estimate the magnitude of the baryon asymmetry of the Universe caused by CKM CP violation

$$\frac{n_B - n_{\overline{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \sim \frac{J \times P_u \times P_d}{M^{12}}$$

the area of every UT triangle

$$J = \cos(\theta_{12})\cos(\theta_{23})\cos^2(\theta_{13})\sin(\theta_{12})\sin(\theta_{23})\sin(\theta_{13})\sin(\delta)$$
$$P_u = (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)$$
$$P_d = (m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2)$$

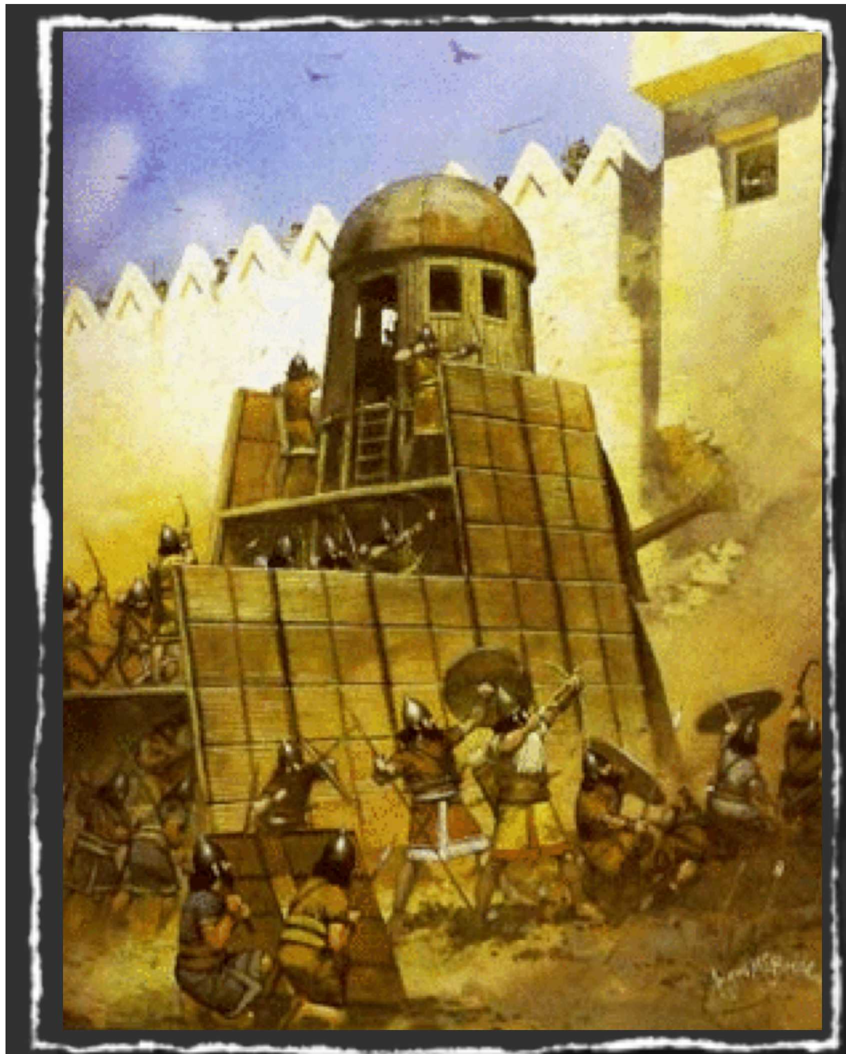
The Jarlskog parameter J is a parametrization invariant measure of CP violation in the quark sector: J ~ $O(10^{-5})$. The mass scale M can be taken to be the electroweak scale O(100 GeV).

This gives an asymmetry $O(10^{-17})$…

much much below the observed value of $O(10^{-10})$!

Still a lot to discover!

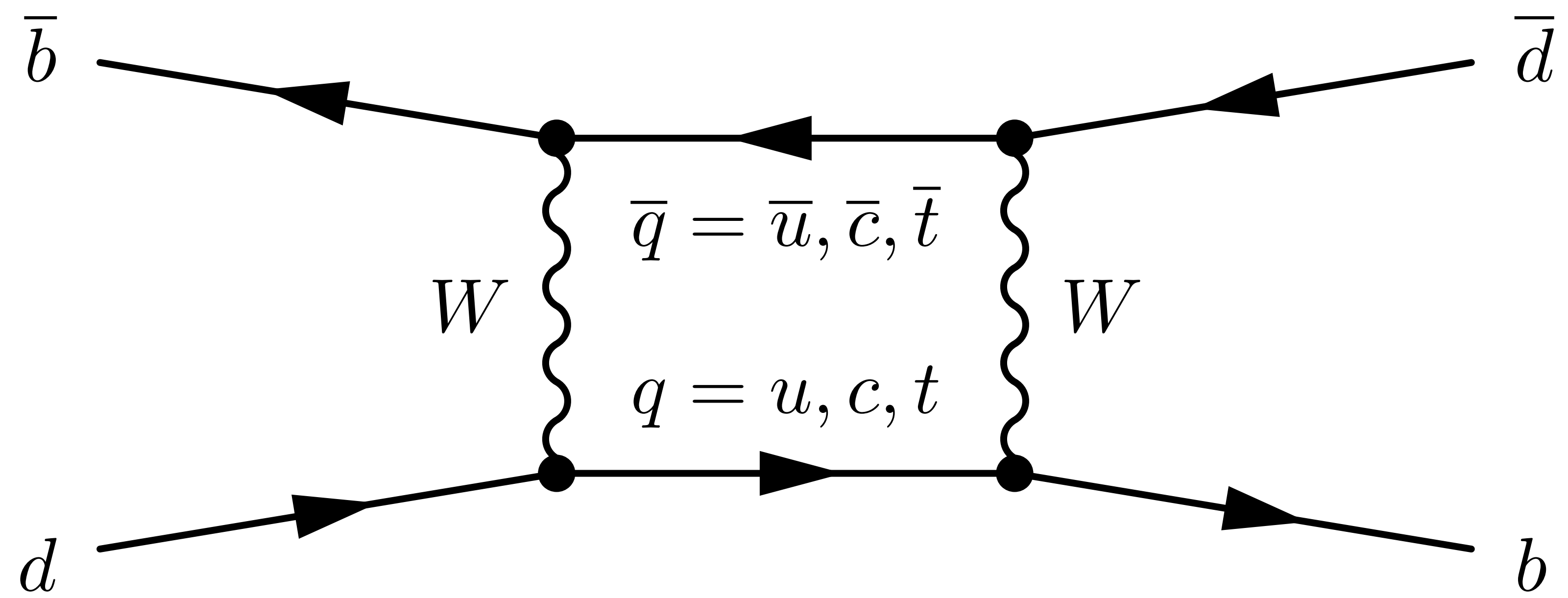
Exploring the next scale



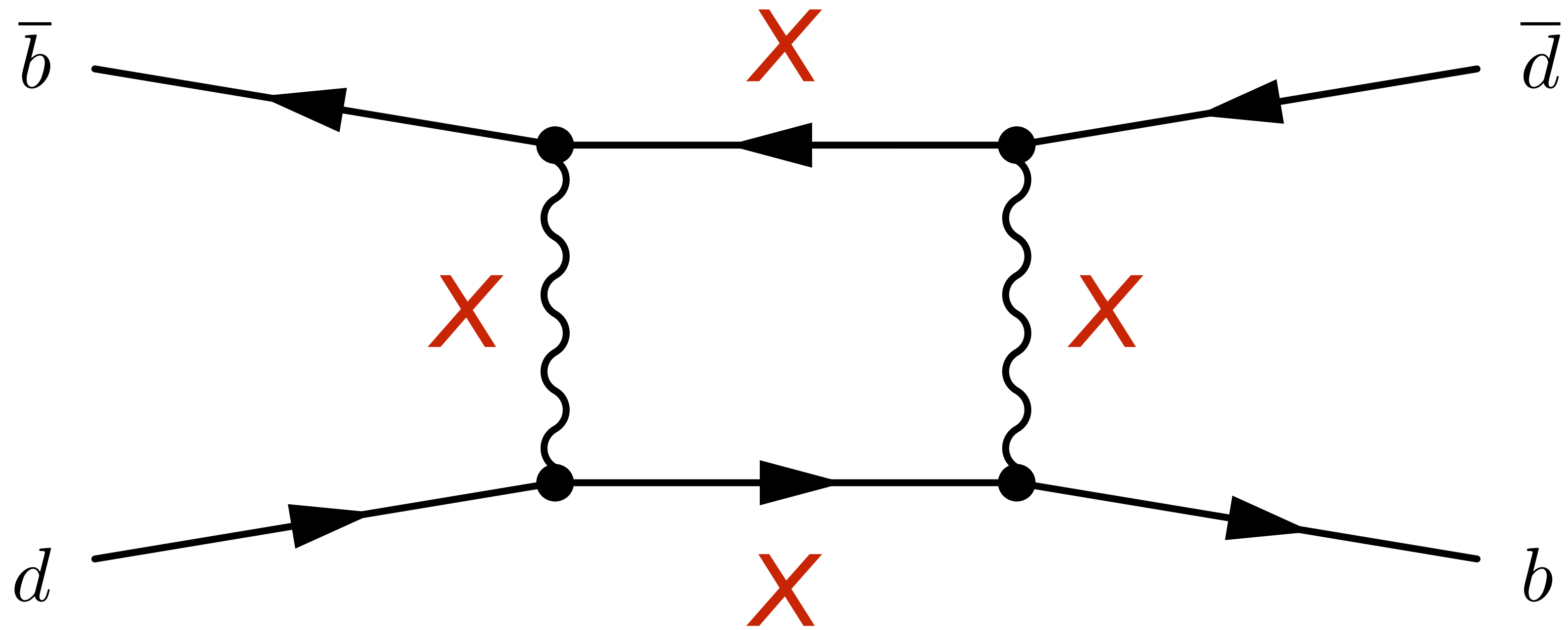
High energy
production of
new particles.

Low-energy
precision measurements.
Quantum probes of higher energy
scales than directly accessible.

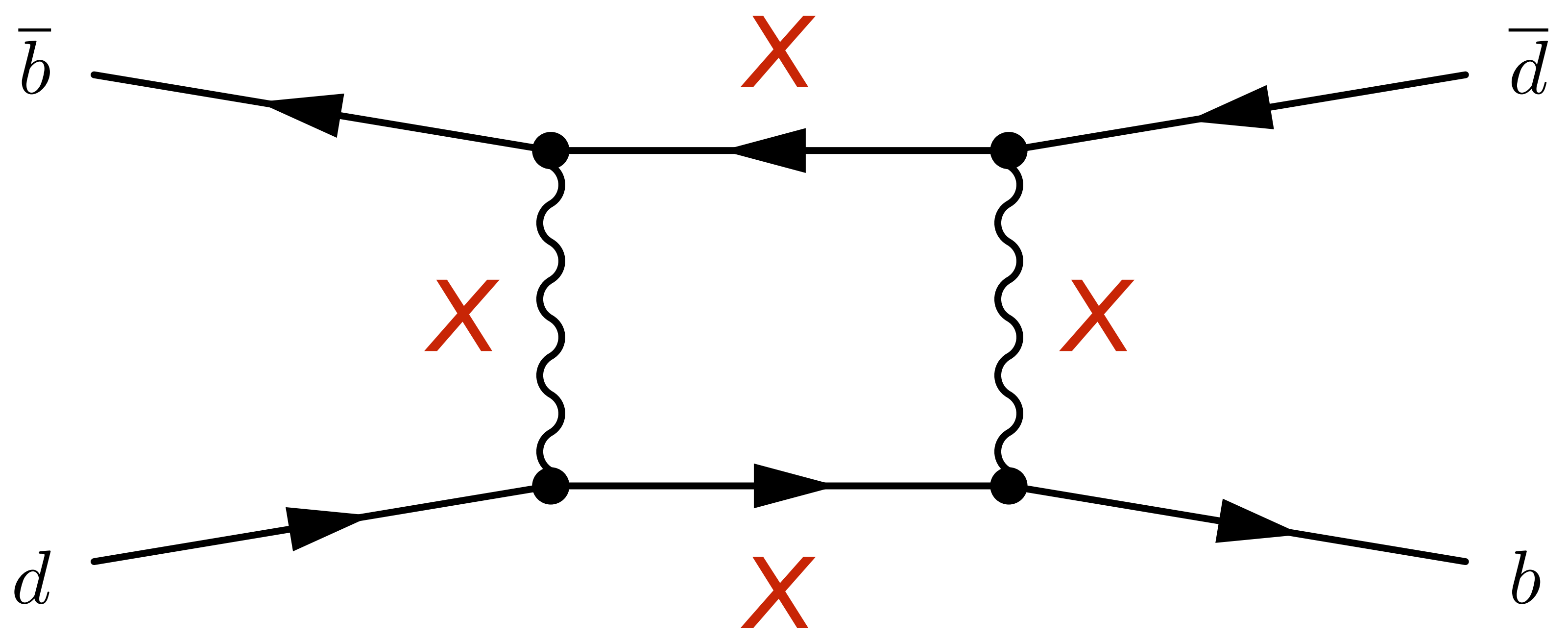
Exploring the next scale with mixing



Exploring the next scale with mixing



Exploring the next scale with flavour



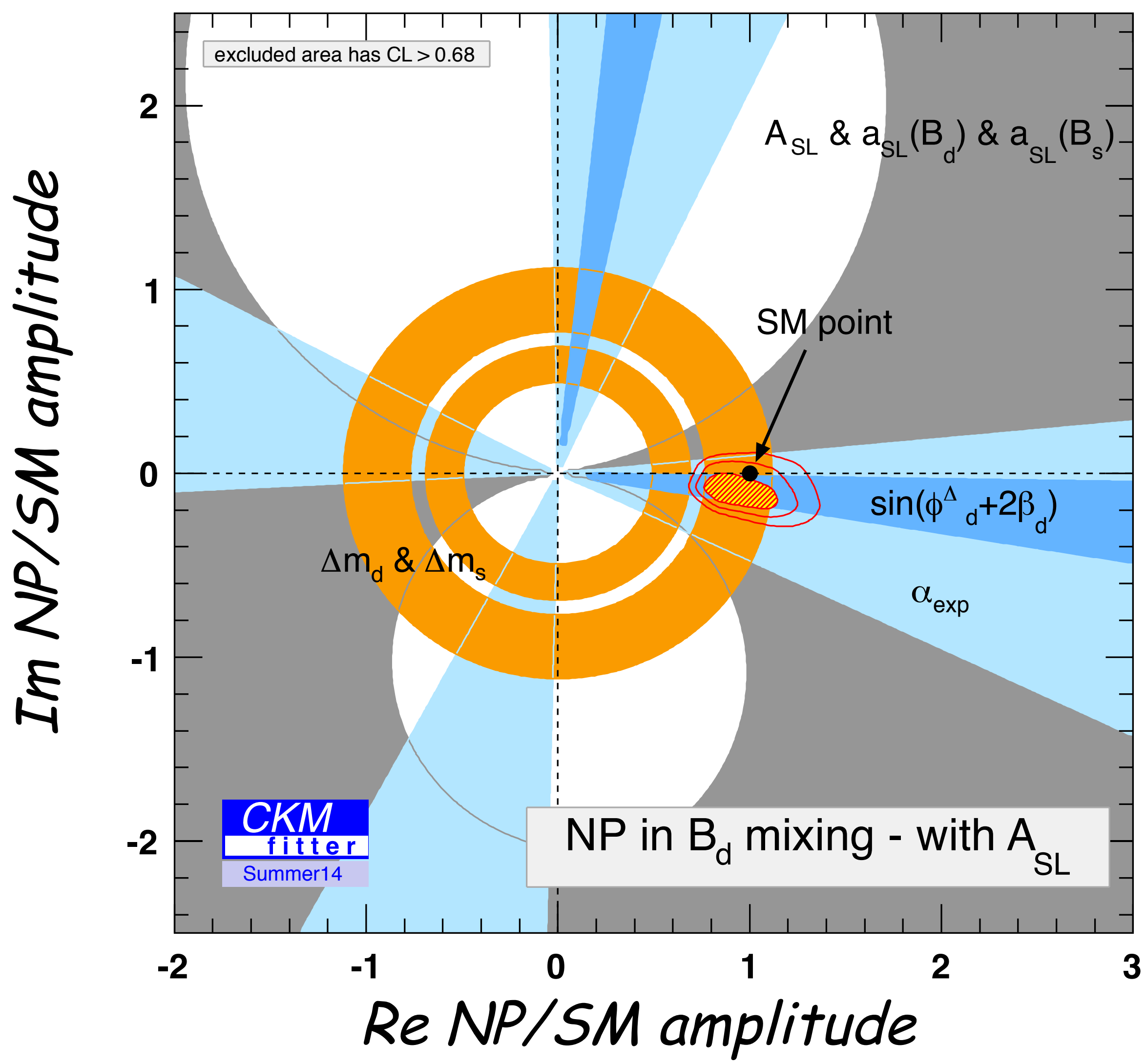
$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{c_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)}(\text{SM fields})$$

arXiv:1002.0900

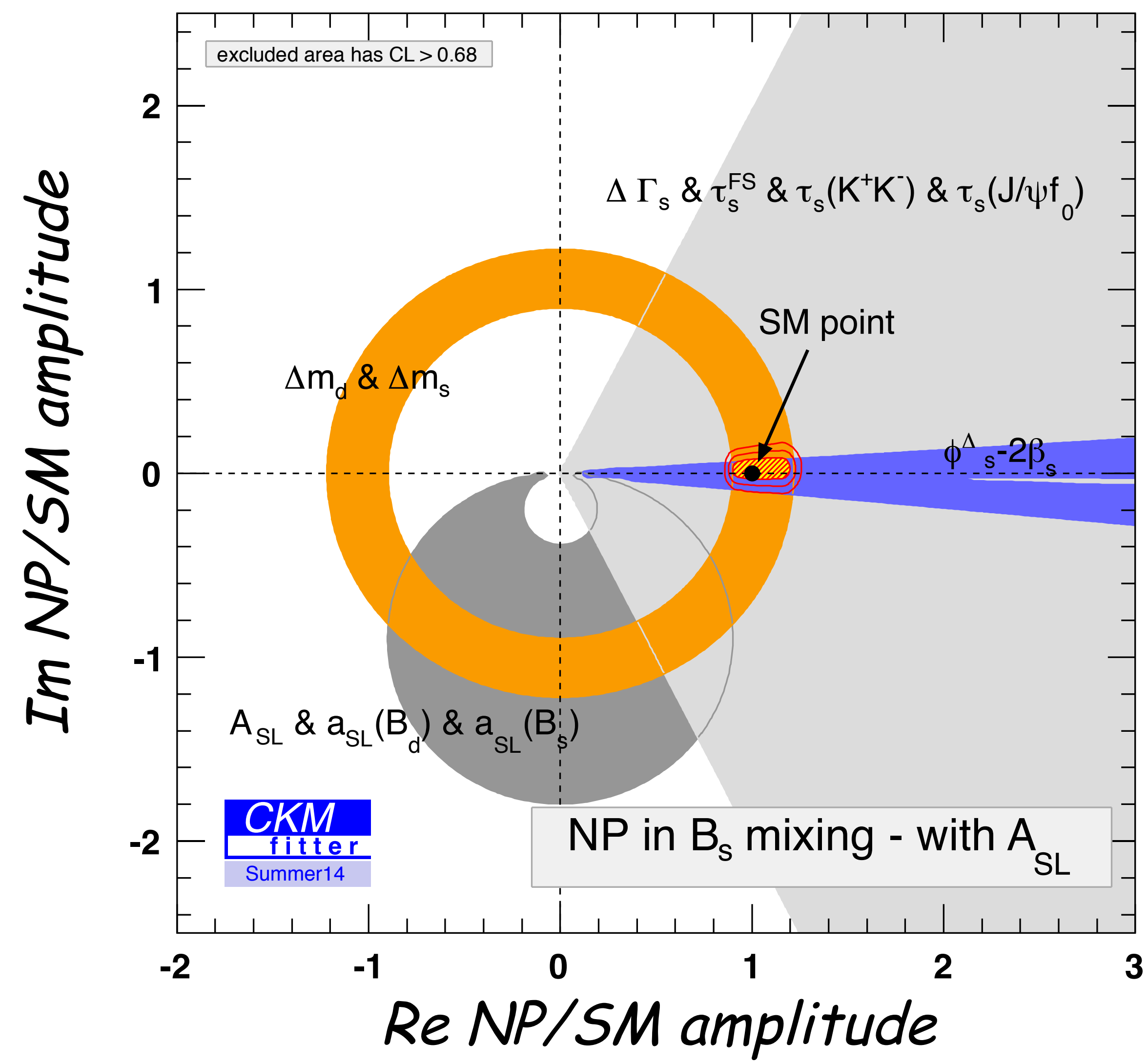
Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$; ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$; ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

Same information in a different format

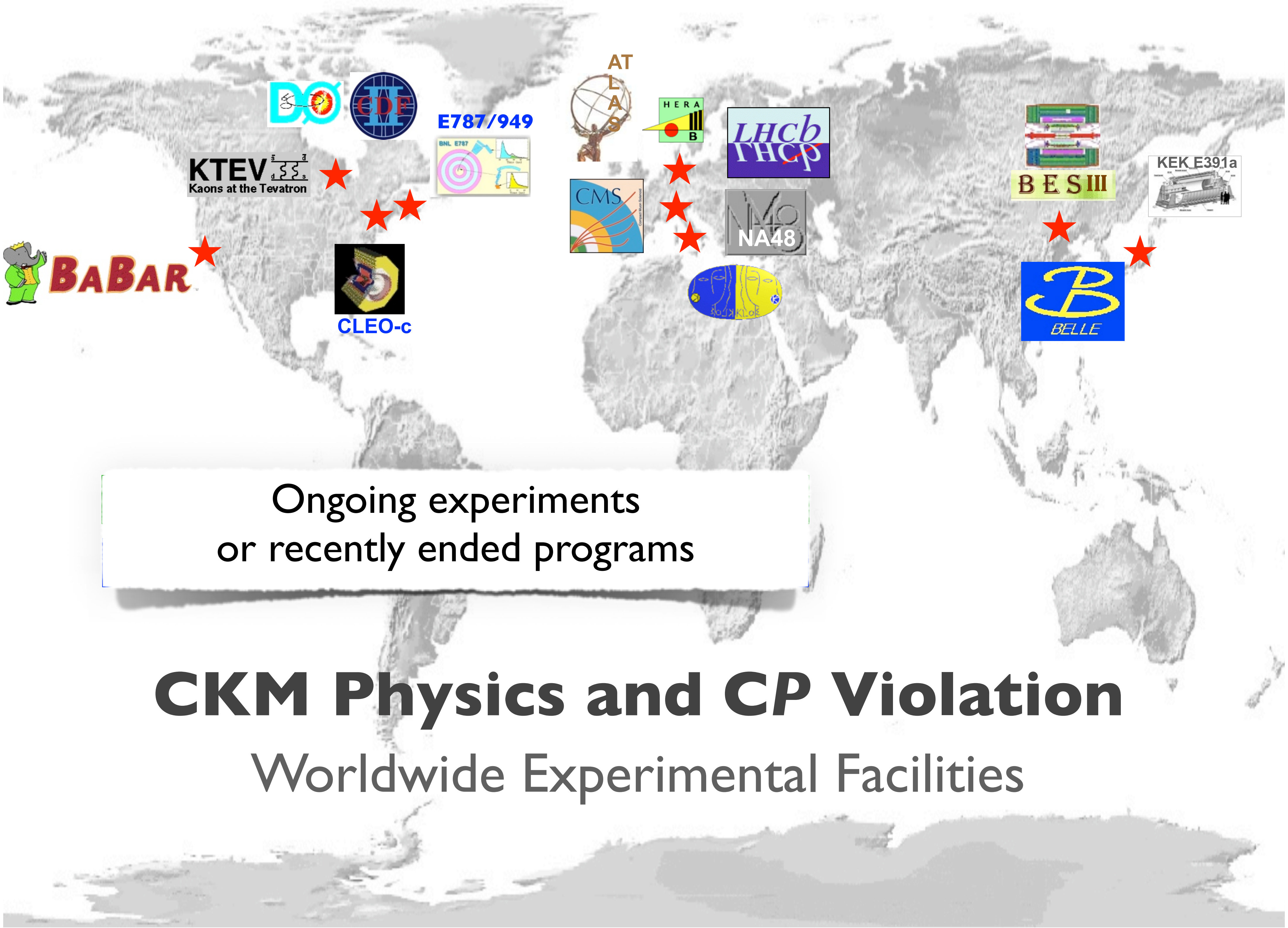
B^0



B_s^0



A huge effort



Ongoing experiments
or recently ended programs

CKM Physics and C*P* Violation

Worldwide Experimental Facilities

A huge effort

You have here in Rome!

If you want to contribute in the game,
there are plenty of opportunities in the future!

CKM Physics and *CP* Violation

Worldwide Experimental Facilities