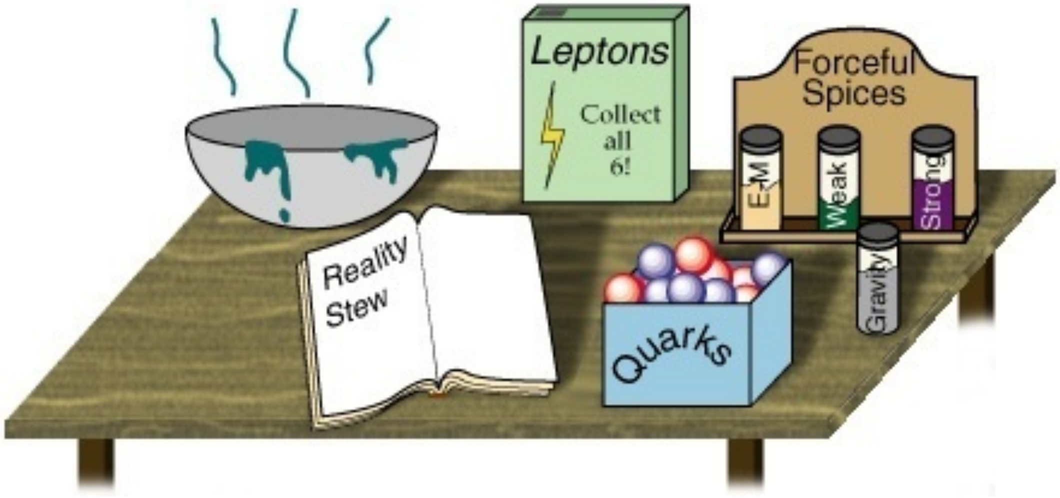
Overview of heavy flavour physics



Heavy flavour physics

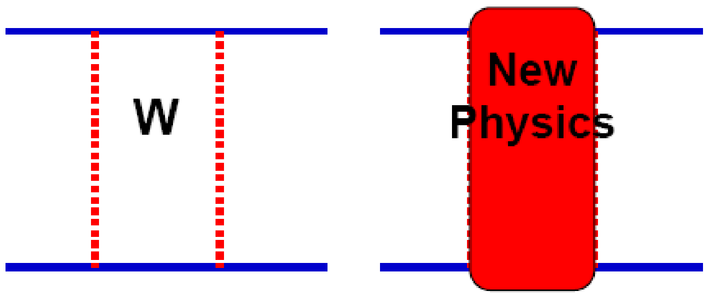
The aim of heavy flavour physics is to study B and D decays to look for anomalous effects beyond the Standard Model.

- Indirect searches have a high sensitivity to see effects from new particles.
  - Can observe new physics effects before the direct searches.
  - Indirect measurements can access higher scales.
- Possible to measure the strength and phases of the new couplings

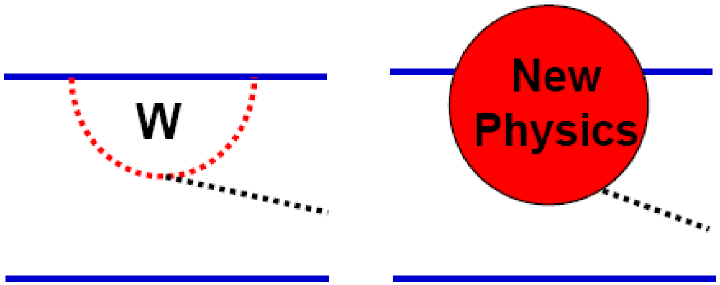
→ Complementary to direct searches at ATLAS and CMS.

Probes for New Physics

Precision B Meson Physics as Probe for New Physics in Loop-Processes:



Box Diagrams (Oscillation)



Penguin Decays

New particles can appear as virtual particles in box and penguin diagrams.

Popular New Physics Scenarios: SUSY, Little Higgs Models

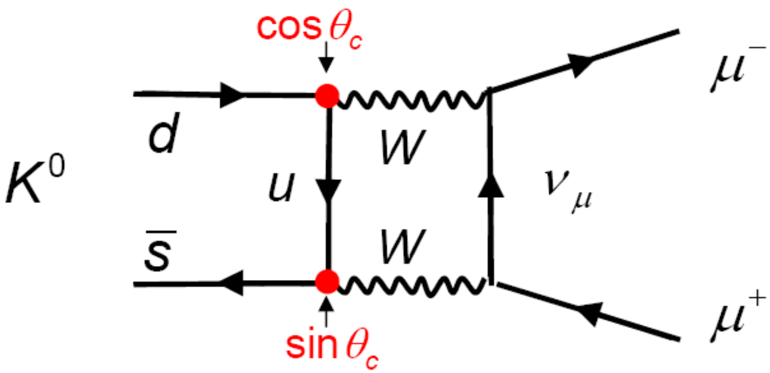
→ Deviations from Standard Model predictions

Example from the past:

GIM Mechanism

Observed branching ratio $K^0 \to \mu\mu$

$$\frac{BR(K_L \to \mu^+\mu^-)}{BR(K_L \to all)} = (7.2 \pm 0.5) \cdot 10^{-9}$$

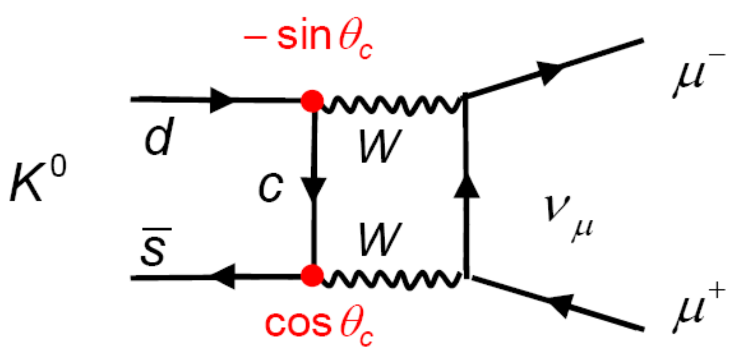


$M \sim \sin\theta_c \cos\theta_c$

In contradiction with theoretical expectation in the 3-Quark Model

Glashow, Iliopolus, Maiani (1970):

Prediction of a 2nd up-type quark, additional Feynman graph cancels the “u box graph”.



$M \sim -\sin\theta_c \cos\theta_c$

Suppresses FCNC (flavour-changing neutral currents)

Probes for New Physics searches

Requirements to look for New Physics effects:
- Should not be ruled out by existing measurements.
- Prediction from SM should be well known.

These requirements are fulfilled for these processes:
- CP violation
- Rare decays

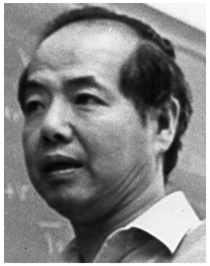
→ CP violation and rare decays of *B* and *D* hadrons are the main focus of LHCb.

Today: CP violation and mixing

Symmetries

The (probably) most important concept in physics: concept of symmetry

T.D.Lee:
"The root to all symmetry principles lies in the assumption that it is impossible to observe certain basic quantities; the non-observables"



$\Rightarrow$ If a quantity is fundamentally non-observable it is related to an exact symmetry

$\Rightarrow$ If a quantity could in principle be observed by an improved measurement; the symmetry is said to be broken

Noether Theorem: symmetry $\Longleftrightarrow$ conservation law

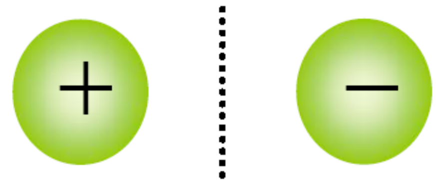
Few examples:

Non-observables	Symmetry Transformations	Conservation Laws
Absolute spatial position	Space translation $\vec{r} \rightarrow \vec{r} + \vec{\Delta}$	Momentum
Absolute time	Time translation $t \rightarrow t + \tau$	Energy
Absolute spatial direction	Rotation $\hat{r} \rightarrow \hat{r}\,'$	Angular momentum

Three discrete symmetries

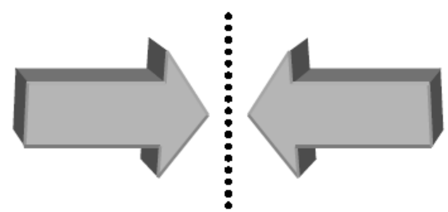
Charge conjugation C

Particle ⇔ Anti-particle



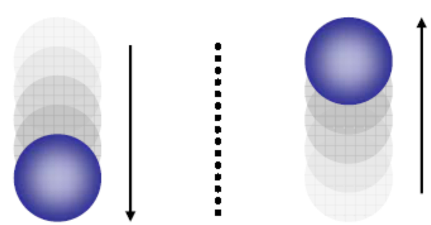
$$e^- \rightarrow e^+$$
$$\gamma \rightarrow \gamma$$

Parity P



$$\vec{r} \rightarrow -\vec{r}$$
$$\vec{p} \rightarrow -\vec{p}$$
$$\vec{L} \rightarrow \vec{L}$$

Time inversion T

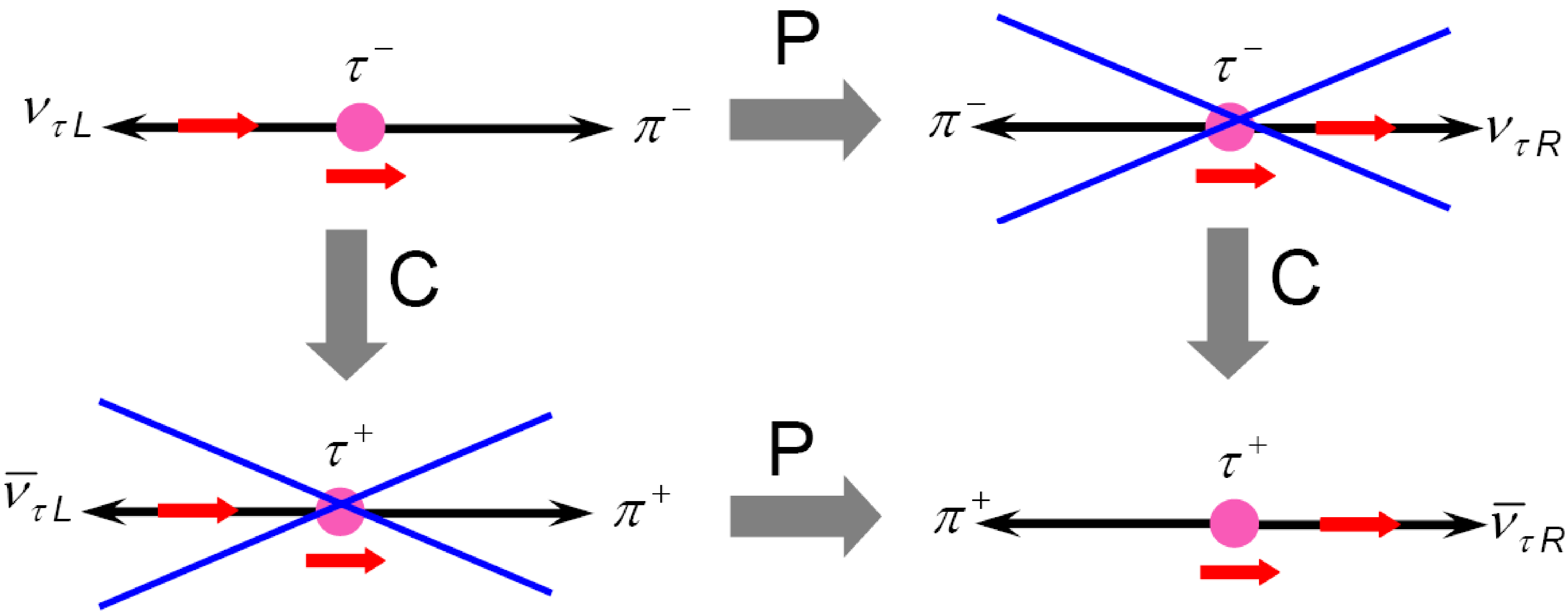


$$t \rightarrow -t$$

CPT Theorem

- All interactions are invariant under combined *C*, *P* and *T*
- Implies particle and anti-particle have equal masses and lifetimes
- One of the most important and generally valid theorems in *local* quantum field theory.

C, P and CP in weak interactions



The weak interaction violates C and P maximally.
But CP was thought to be a good symmetry, until 1964.

CP violation in Kaon system

Under CP symmetry:

K_S (CP=+1): can only decay (hadronically) to $\pi\pi$ (CP=+1)

K_L (CP=-1): can only decay (hadronically) to $\pi\pi\pi$ (CP=-1)

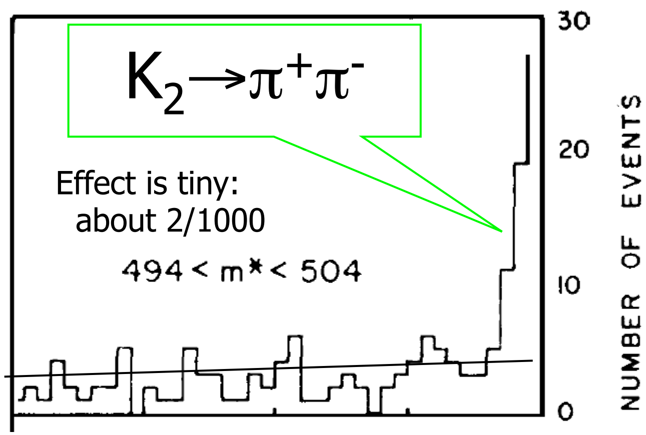
Why does the K_L live so much longer than the K_S ?

Testing CP conservation:

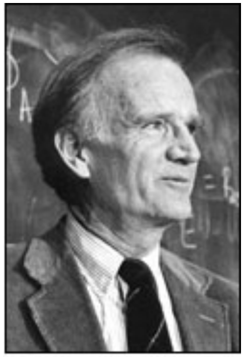
Create a pure K_L (CP=-1) beam: (Cronin & Fitch in 1964)

Easy: just "wait" until the K_s component has decayed…

If CP conserved, should *not* see the decay $K_L \rightarrow$ 2 pions



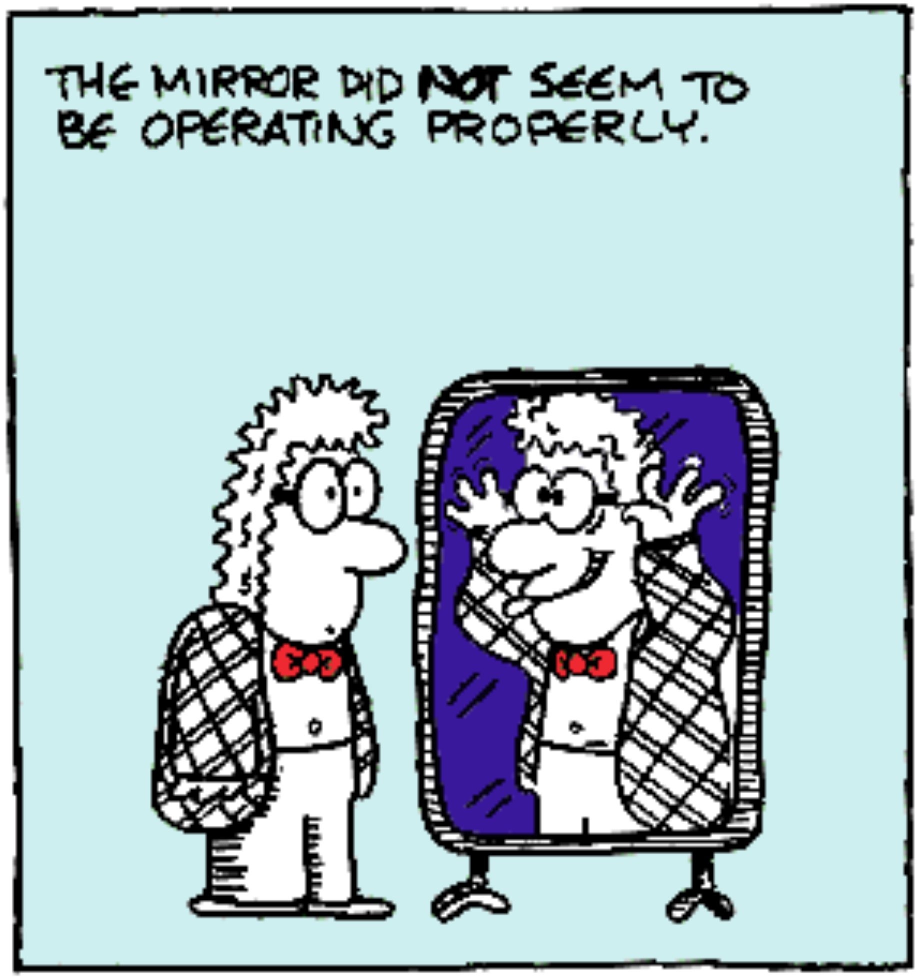

James Cronin


Val Fitch

The discovery emphasizes, once again, that even almost self evident principles in science cannot be regarded fully valid until they have been critically examined in precise experiments.

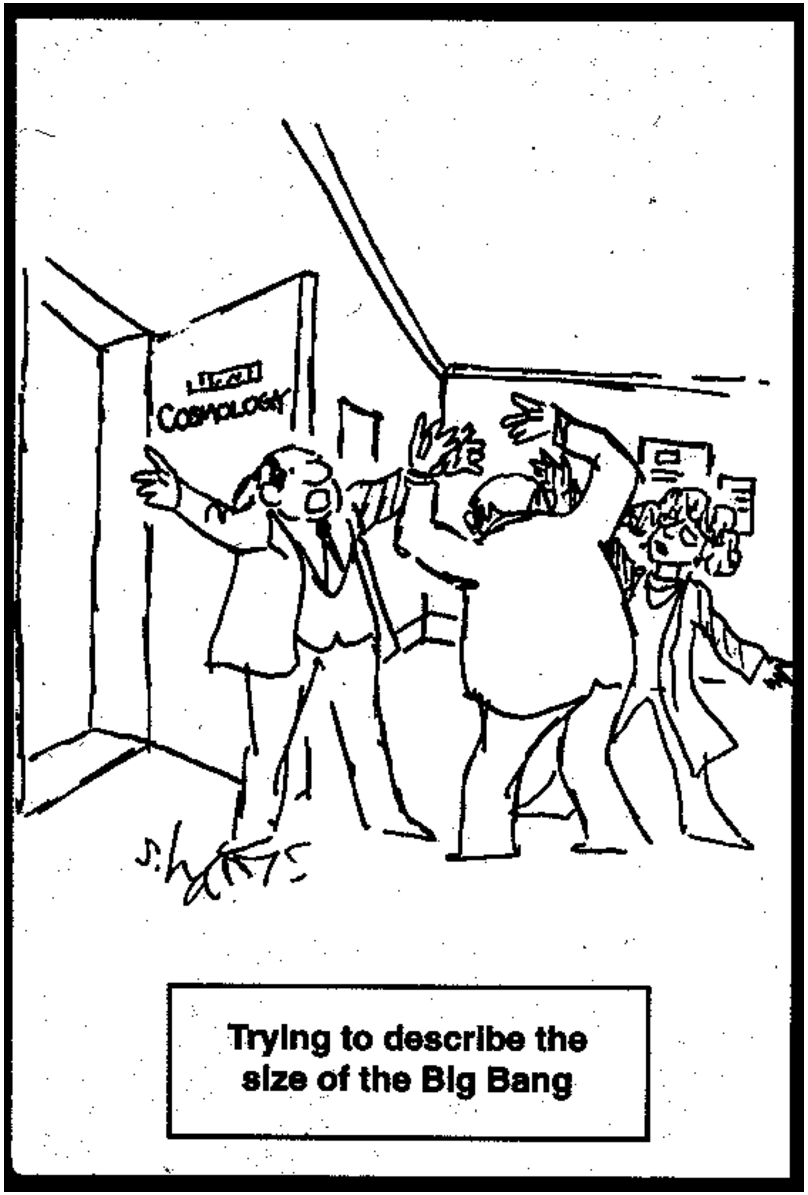
… and for this experiment they got the Nobel price in 1980…

CP symmetry is broken



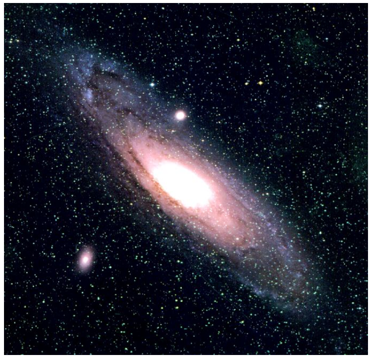
There is an absolute difference between matter and anti-matter.
Actually we could have known this already…

… because of the Big Bang



Trying to describe the size of the Big Bang

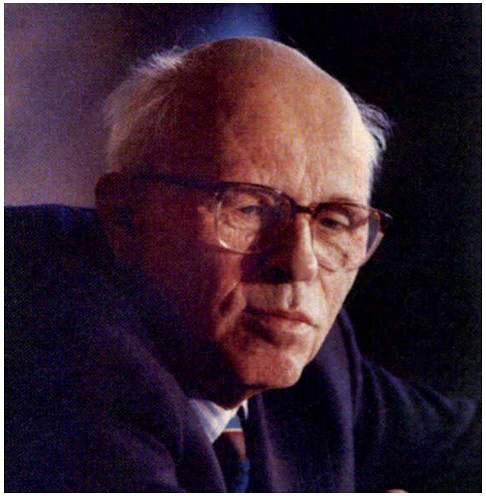
Baryon asymmetry in Universe



We know that the matter – anti-matter asymmetry in the Universe is broken: the Universe consists of matter.

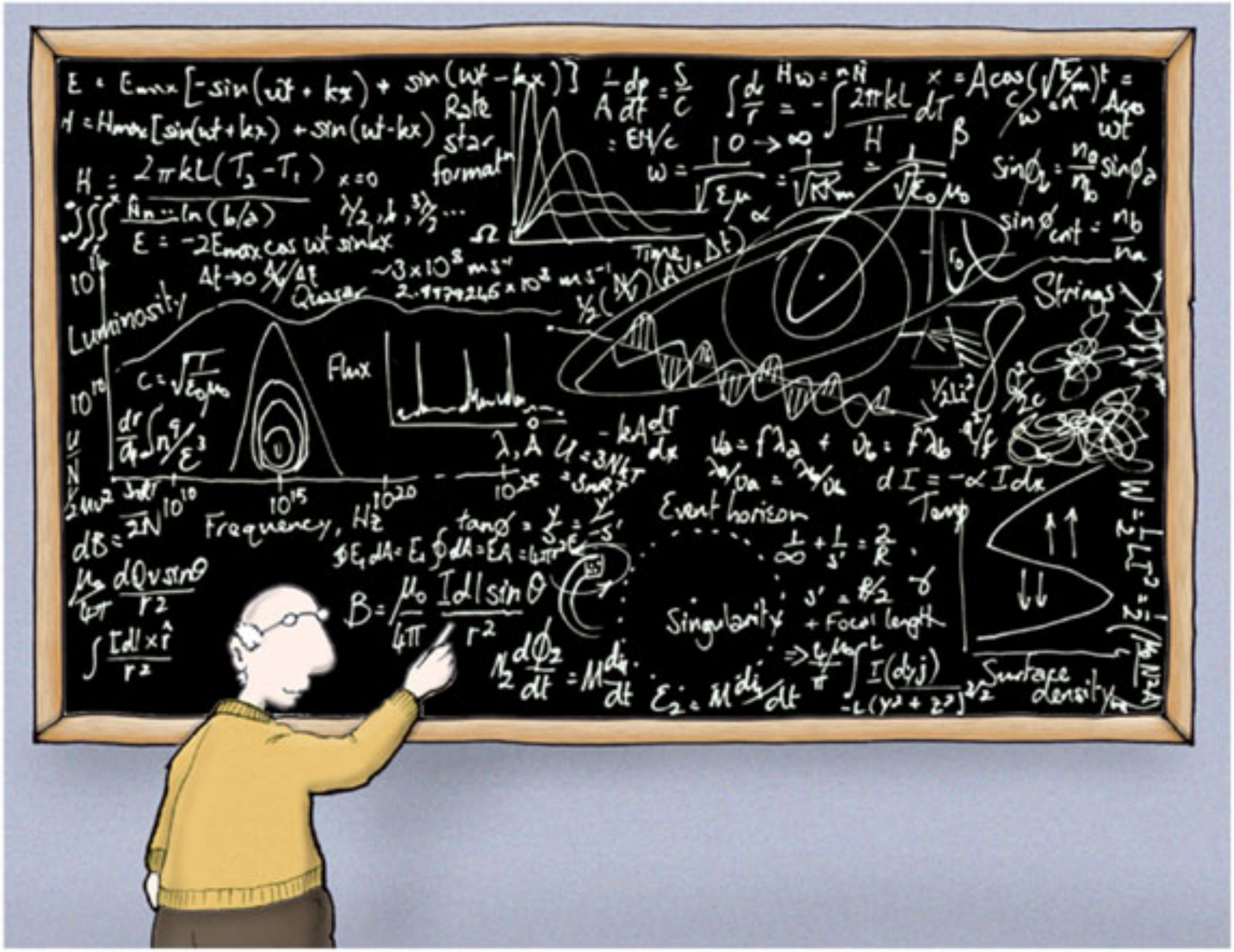
But, shortly after the Big Bang, there should have been equal amounts of matter and anti-matter
→ how did the Universe develop a preference of matter?

- In 1966, Andrei Sakharov showed that the generation of a net baryon number requires:
    1. Baryon number violating processes (*e.g.* proton decay)
    2. Non-equilibrium state during the expansion of the universe
    3. Violation of *C* and *CP* symmetry



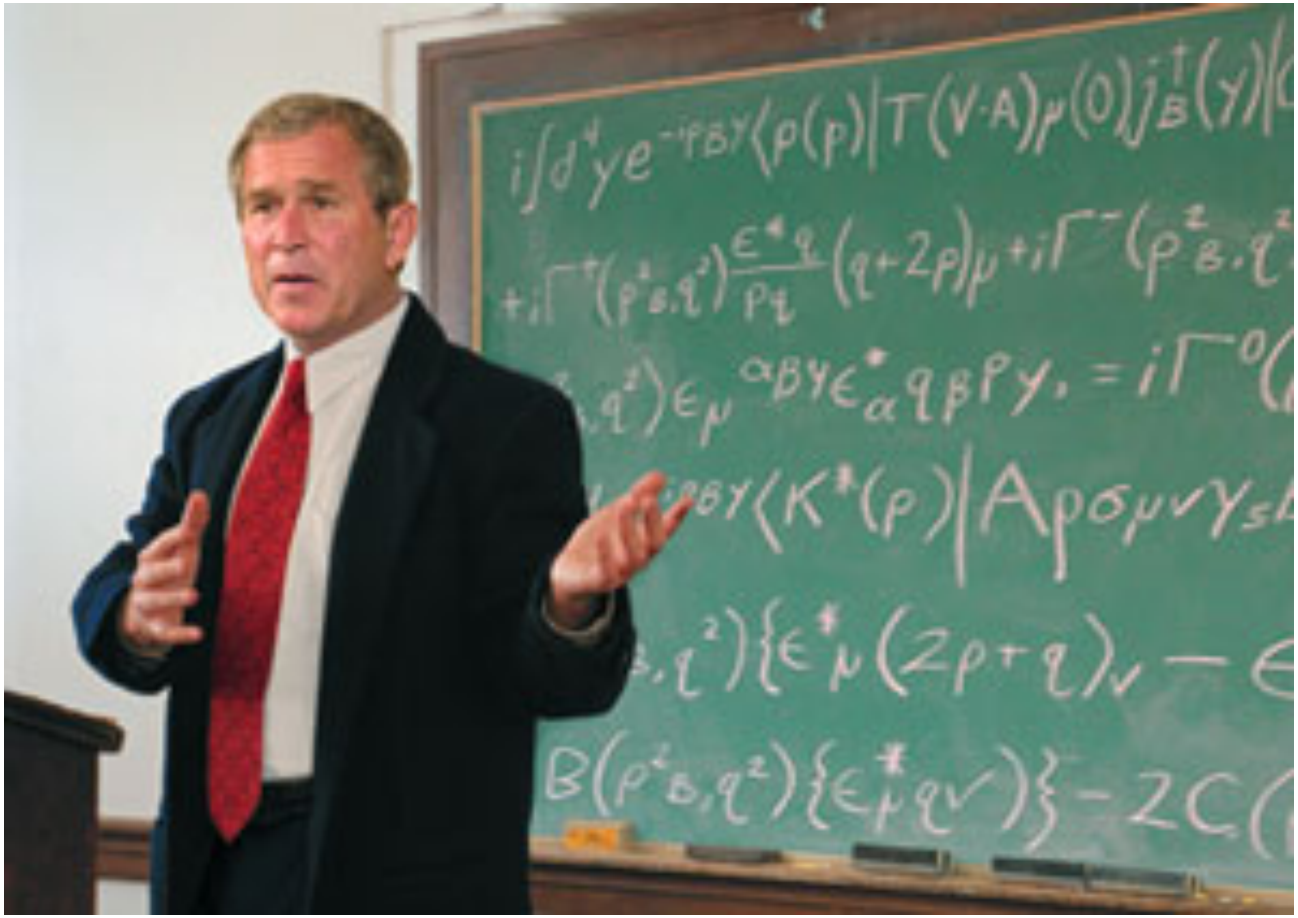
- Standard Model *CP* violation is very unlikely to be sufficient to explain matter asymmetry in the universe
    – It means there is something *beyond* the SM in *CP* violation somewhere, so a good starting place for further investigation

In more details…



Astrophysics made simple

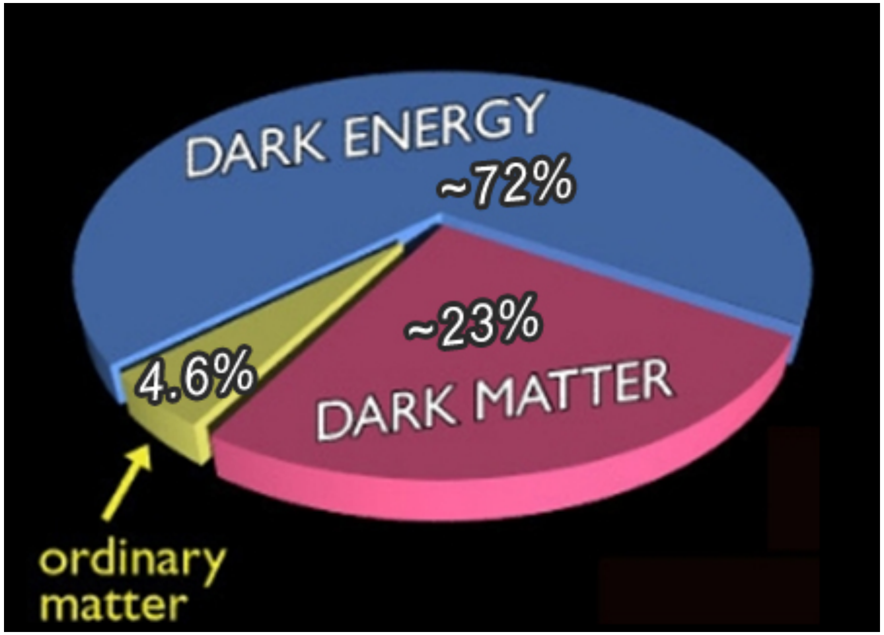
Even more details…



Particle physics made simple

Now to some simpler questions ☺ …

What is the origin of mass in the Universe?



Answers:

- Actually, we don't know (dark matter, dark energy)
- Ordinary matter: mainly QCD (mass proton=1 GeV, mass u,d quarks 10 MeV)

Higgs field explains only ~1% of your body mass!
(So don't even dream of using the Higgs field to find a way to reduce your weight.)

Flavour in Standard Model

Higgs field was introduced to give masses to W^+, W^- and Z^0 bosons (after SBB).

Since we have a Higgs field we can add (ad-hoc) interactions between the Higgs field ϕ and the fermions in a gauge invariant way (Yukawa couplings):

doublets, singlet

$$-L_{Yukawa} = Y_{ij} \left(\overline{\psi}_{Li} \, \phi \right) \psi_{Rj} + h.c.$$

The fermions are in the weak interaction basis. We can diagonalize the Y_{ij} matrices, such that we arrive in the "mass basis". However, then the Lagrangian of the charged weak current should also be rewritten:

$$-L_{W^+} = \frac{g}{\sqrt{2}} \left(\overline{u}, \overline{c}, \overline{t} \right)_L \left(V_{CKM} \right) \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L \gamma^{\mu} W_{\mu}^{+}$$

CKM matrix (rotation matrix)

Bottom line: V_{CKM} originates from the diagonalization of the Yukawa couplings.

Weak interactions in the SM

After SSB, the charged current of a W^- exchange can be written as

$$J^{\mu-} = (\overline{u}_L, \overline{c}_L, \overline{t}_L)\gamma^\mu V_{\mathrm{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

(exchange of W^+ obtained from Hermitian conjugate)

Weak interaction only couples to left-handed field: Left-handed quarks or right-handed anti-quarks. Manifestly violates parity.

The weak eigenstates are related to the mass eigenstates by the CKM matrix:

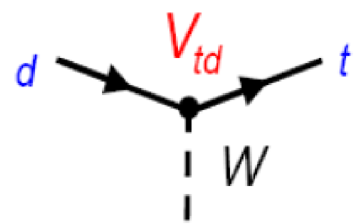
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak eigenstates — Mass eigenstates

CP transformation & the weak interaction

Quarks

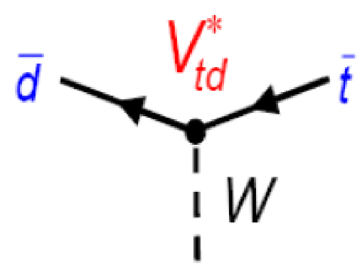
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



----- CP -----

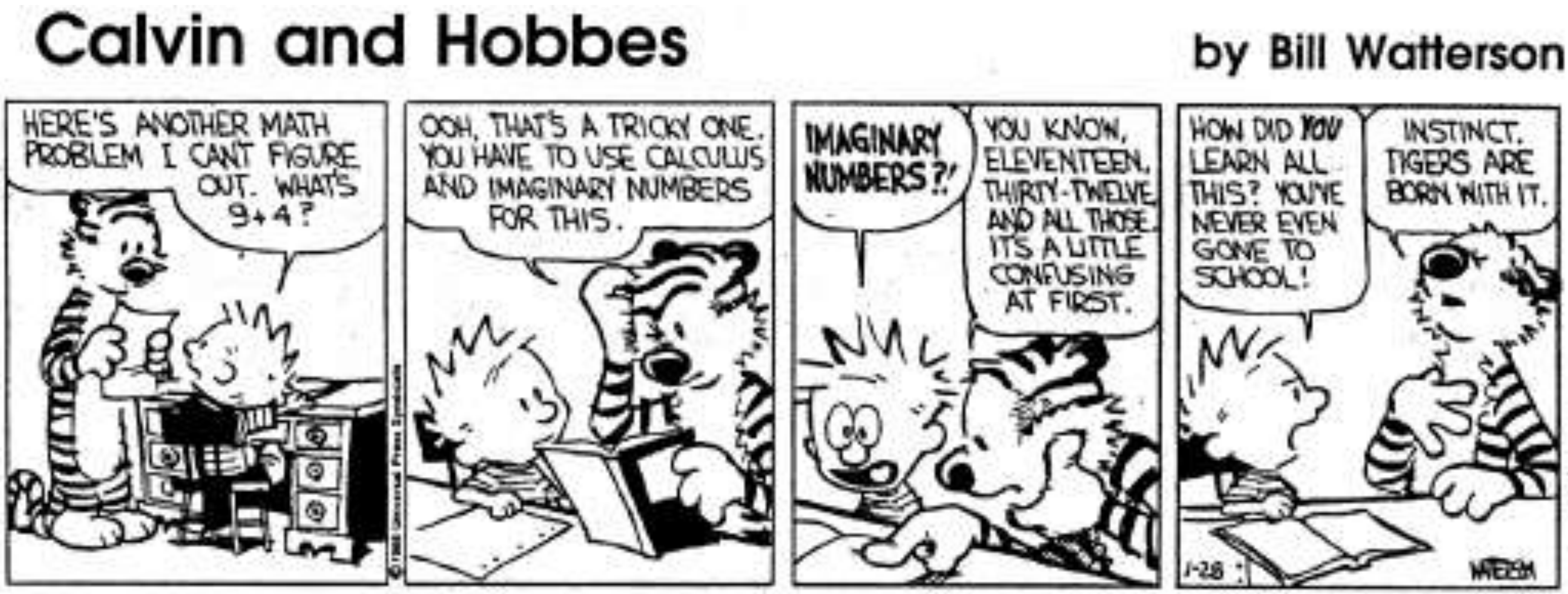
Anti-quarks:

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



CP violation requires complex matrix elements.

It's all about imaginary numbers



CKM matrix

Q: *How many parameters does the CKM matrix have?*

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

Remember:
- V_{CKM} is unitary

18 parameters (9 complex numbers)
− 9 unitary conditions: $V_{\text{CKM}} V_{\text{CKM}}^{\dagger} = 1$

9 parameters: 3 (real) Euler angles and 6 phases.

But not all phases are observable!

Relative phases

When I do a phase transformation of the (left-handed) quark fields:

$$u_{Lj} \rightarrow e^{i\phi_j} u_{Lj} \qquad\qquad d_{Lk} \rightarrow e^{i\phi_k} d_{Lk}$$

And a simultaneous transformation of the CKM matrix:

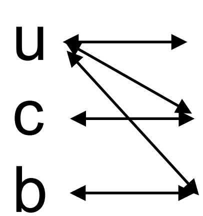
$$V \rightarrow \begin{pmatrix} e^{-i\phi_u} & & \\ & e^{-i\phi_c} & \\ & & e^{-i\phi_t} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} e^{-i\phi_d} & & \\ & e^{-i\phi_s} & \\ & & e^{-i\phi_b} \end{pmatrix}$$

or $V_{jk} \rightarrow \exp\left(-i\left(\phi_j + \phi_k\right)\right) V_{jk}$

The charged current (i.e. the physics) remains invariant:

$$J^{\mu}_{CC} = \overline{u_{Li}} \gamma^{\mu} V_{ij} d_{Lj}$$

There are only 5 relative phases (+ one overall phase)



In other words, I can always absorb the 5 relative phases by redefining the quark fields

→ These 5 phases are unobservable.

CKM matrix

Q: *How many parameters does the CKM matrix have?*

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

Remember:
- V_{CKM} is unitary
- Not all phases are observable.

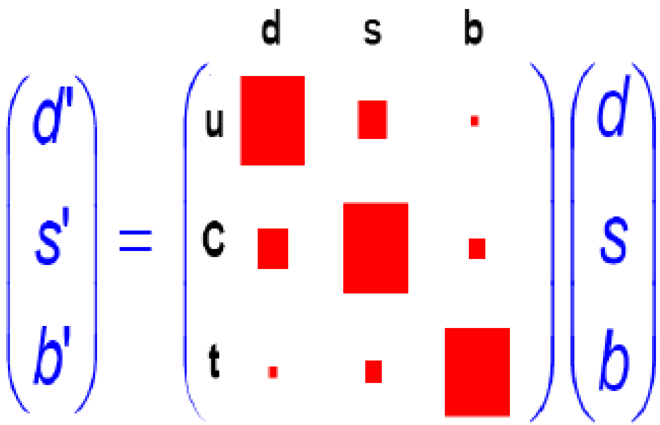
18 parameters (9 complex numbers)
− 9 unitary conditions: $V_{\text{CKM}} V_{\text{CKM}}^{\dagger} = 1$
− 5 relative phases of the quark fields
4 parameters: 3 (real) Euler angles and 1 phase.

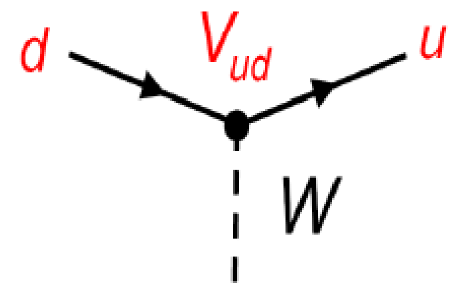
This phase is the single source of CP violation in the SM.

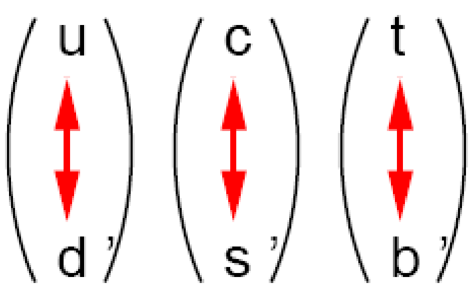
With 2 generations there is only one real (Euler) angle: the Cabbibo angle.
CP violation requires 3 generations.

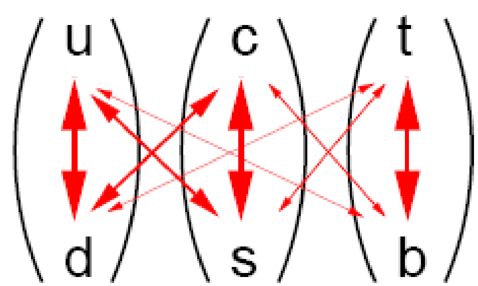
That is why Kobayashi and Maskawa proposed a third generation in 1973
(CP violation in K decay was just observed).
At the time only u,d,s were known!

Size of elements









Diagonal elements of CKM matrix are close to one.

Only small of diagonal contributions.

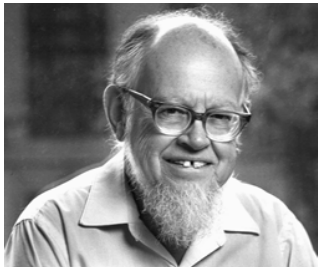
Mixing between quark families is "CKM suppressed".

Wolfenstein Parametrization

Makes use of the fact that the off-diagonal elements are small compared to the diagonal elements.

→ Expansion in $\lambda = V_{us}$, $A = V_{cb}/\lambda^2$ and ρ, η.

$$V = \begin{pmatrix} \cos\theta_C & \sin\theta_C & \\ -\sin\theta_C & \cos\theta_C & \\ & & \end{pmatrix} + O(\lambda^4)$$



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

$\lambda \sim 0.22$ (=$\sin\theta_C$, sine of Cabibbo angle)

$A \sim 1$ (actually 0.80)

$\rho \sim 0.14$

$\eta \sim 0.34$

CKM angles and unitarity triangle

Writing the complex elements explicitly:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \sim \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \sim \lambda^3 e^{-i\beta} & \sim -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix} + O(\lambda^4)$$

Definition of the angles:

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

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

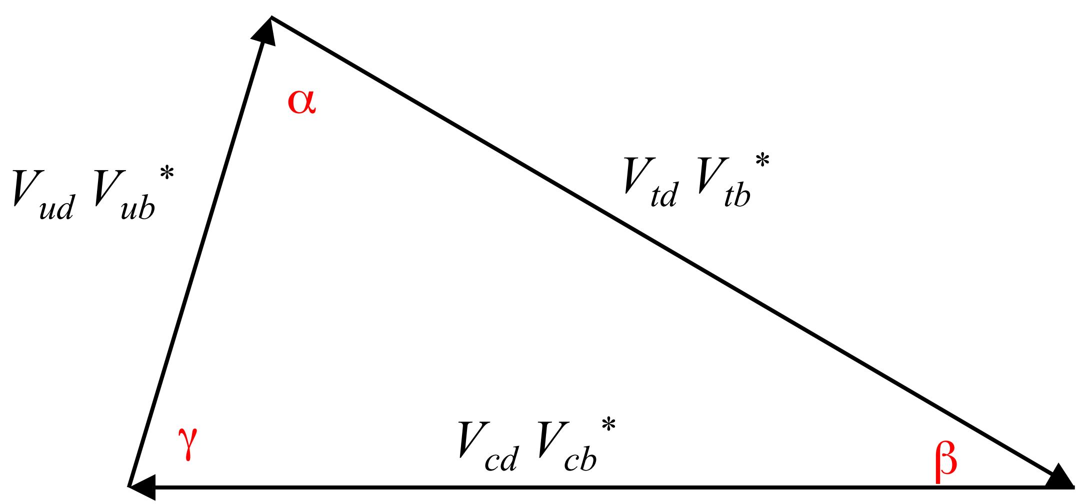
$$\gamma \equiv \arg\left(-\frac{V_{ud}V_{tb}^*}{V_{cd}V_{cb}^*}\right)$$

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

Using one of the 9 unitarity relations: $V_{\mathrm{CKM}}^\dagger V_{\mathrm{CKM}} = 1$

Multiply first “d” column with last “b” column:

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



CKM angles and unitarity triangle

Writing the complex elements explicitly:

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & \sim \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \sim \lambda^3 e^{-i\beta} & \sim -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix} + O(\lambda^4)$$

Definition of the angles:

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

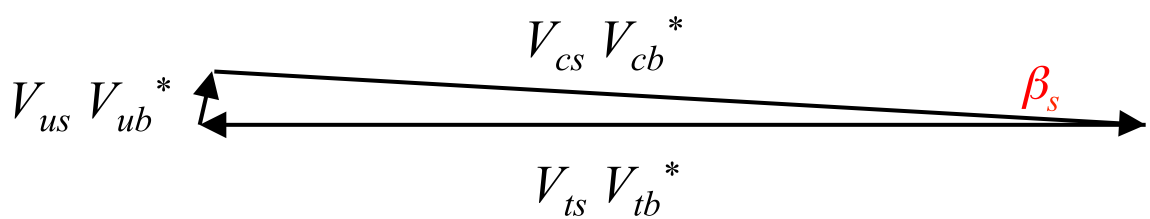
$$\beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

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

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

Using another unitarity relations: $V_{\mathrm{CKM}}^\dagger V_{\mathrm{CKM}} = 1$
Multiply second "s" column with last "b" column.

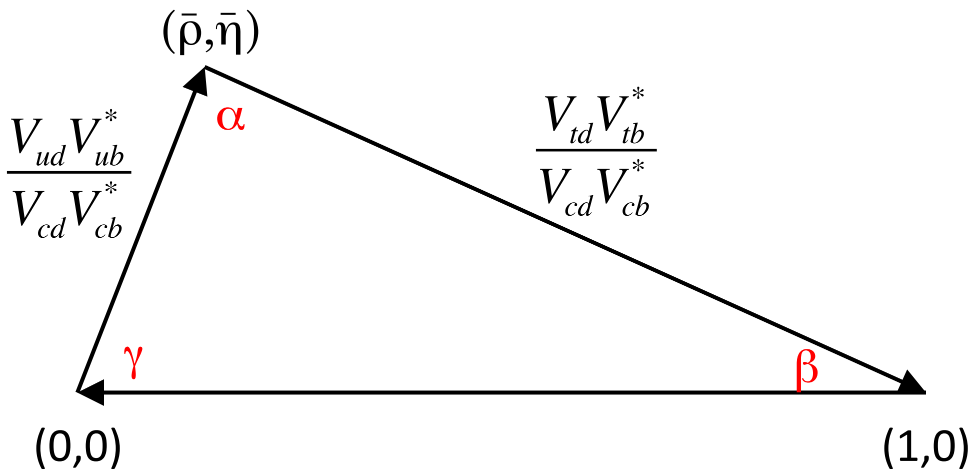
$$V_{ub}V_{us}^* + V_{cb}V_{cs}^* + V_{tb}V_{ts}^* = 0$$



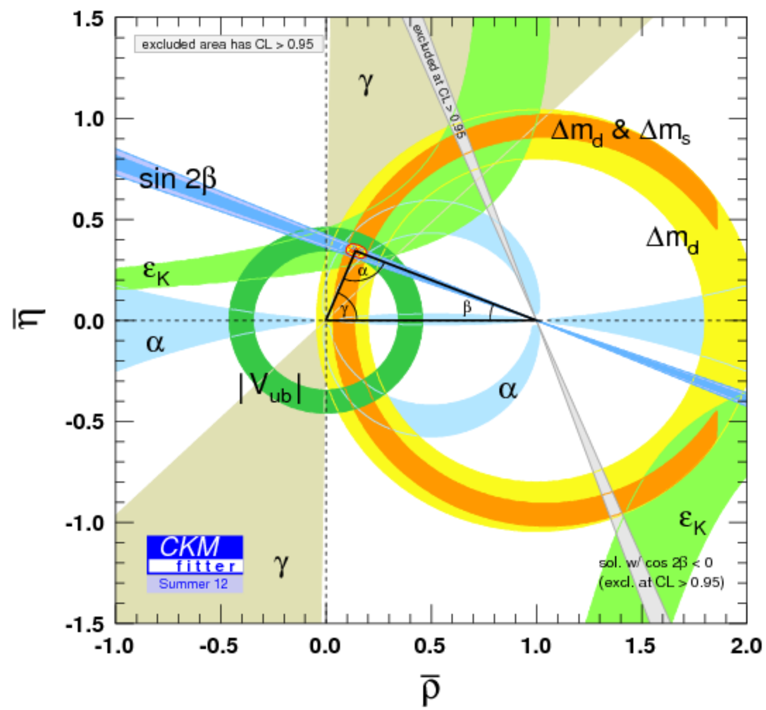
"Squashed unitarity triangle"

Back to *The* Unitarity Triangle

Normalized CKM triangle:
→ Divide each side by $V_{cd} V_{cb}^*$



Current knowledge of UT:
(from CKMFitter)



The "apex" of this triangle is then:

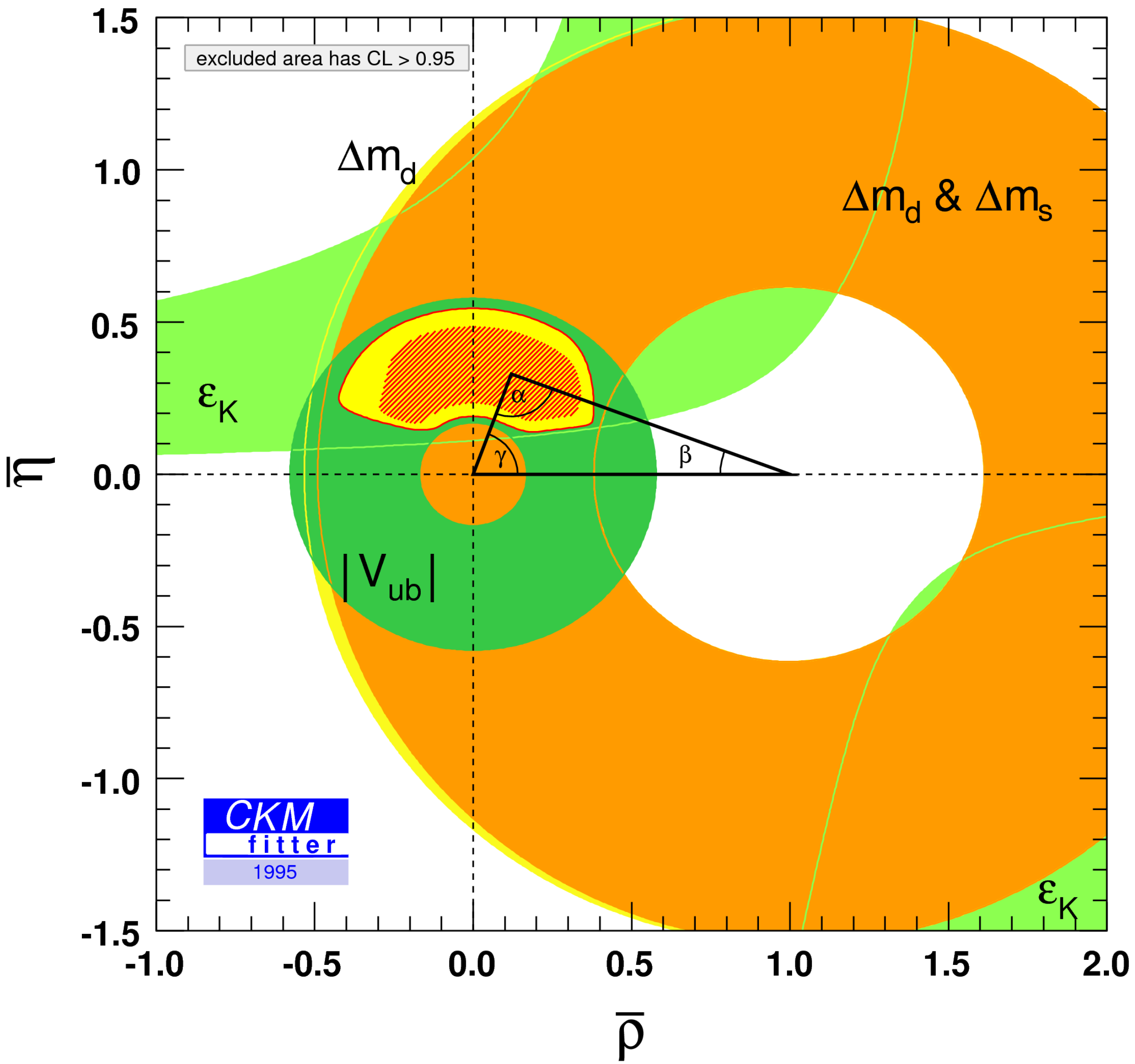
$$\bar\rho = \rho(1-\lambda^2/2)$$
$$\bar\eta = \eta(1-\lambda^2/2)$$

<u>The unitarity triangle:</u>

- Shows the size of the CP violation (no CPV means no triangle!)
- Presents our knowledge of 2 (of the 4) CKM parameters
- Shows how consistent the measurements are!

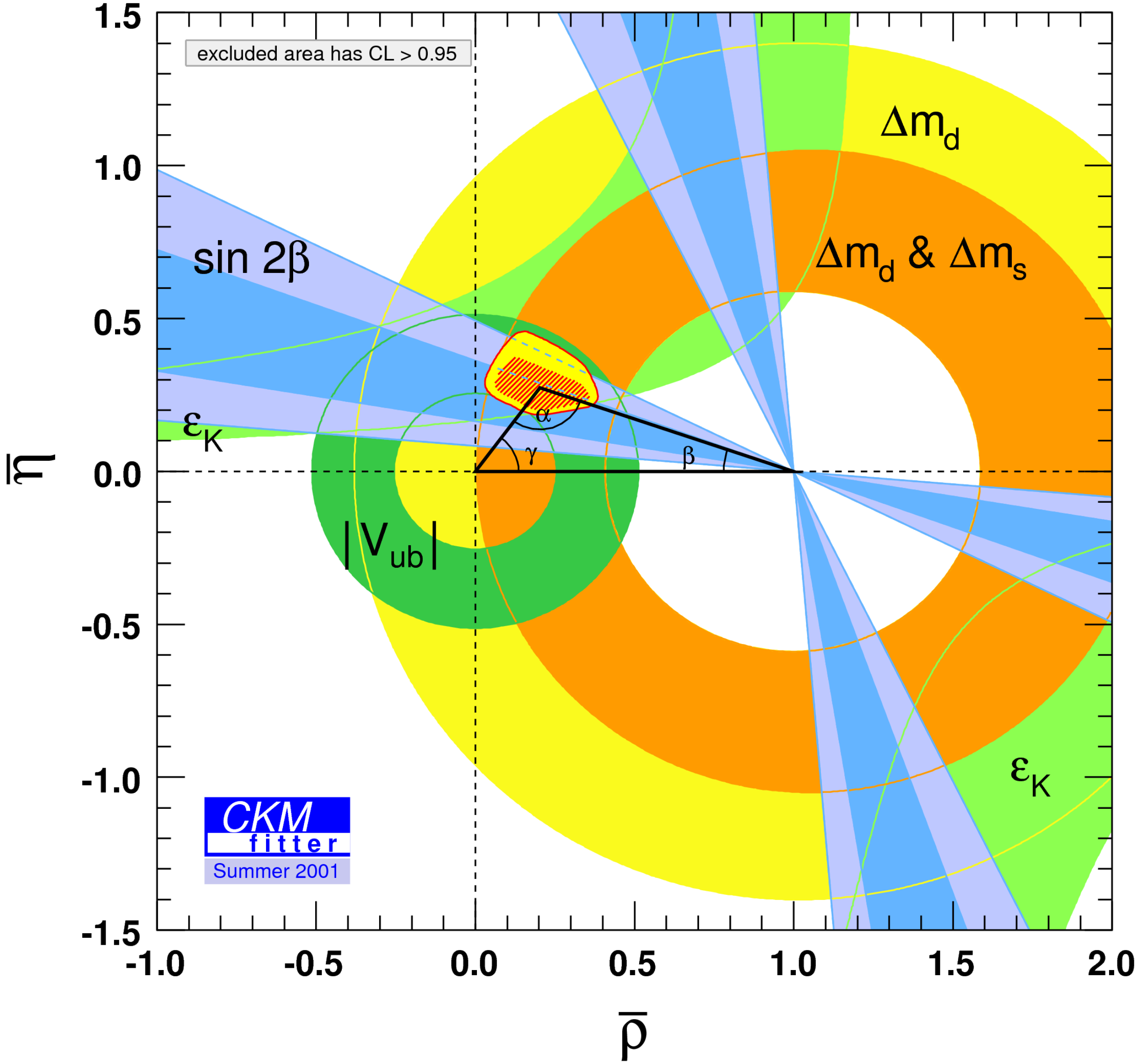
Progress in UT

1995



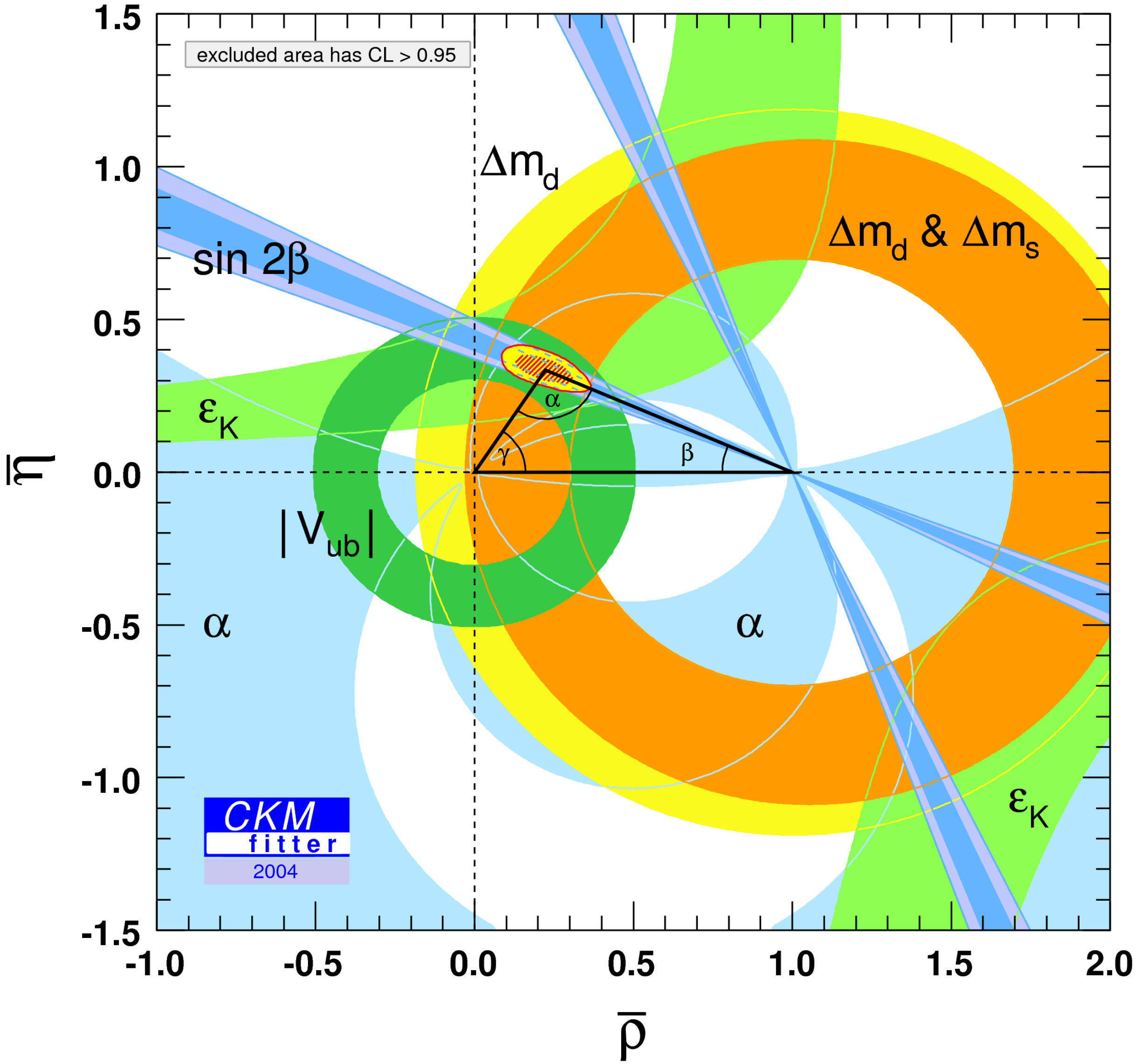
Progress in UT

2001



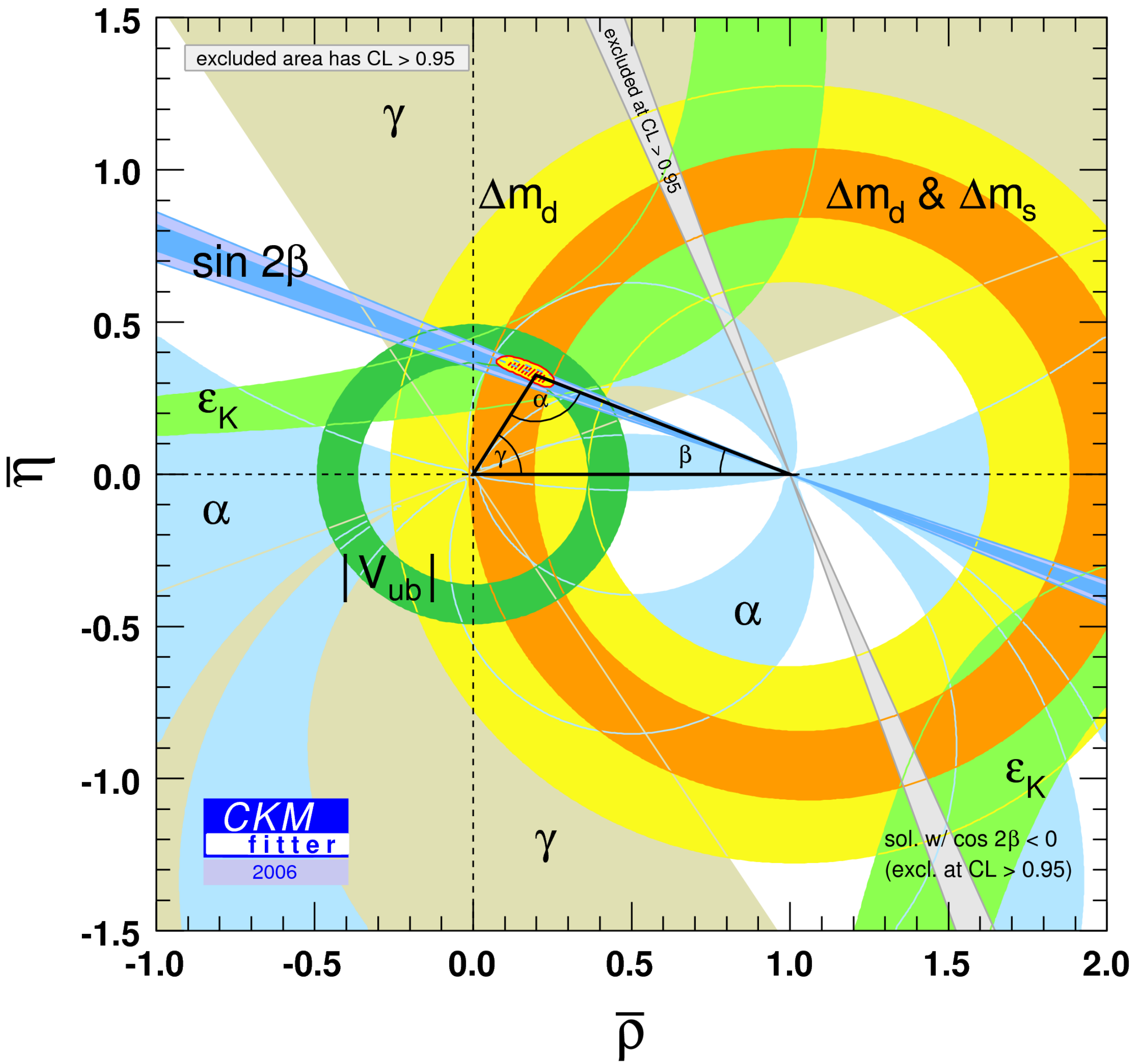
Progress in UT

2004



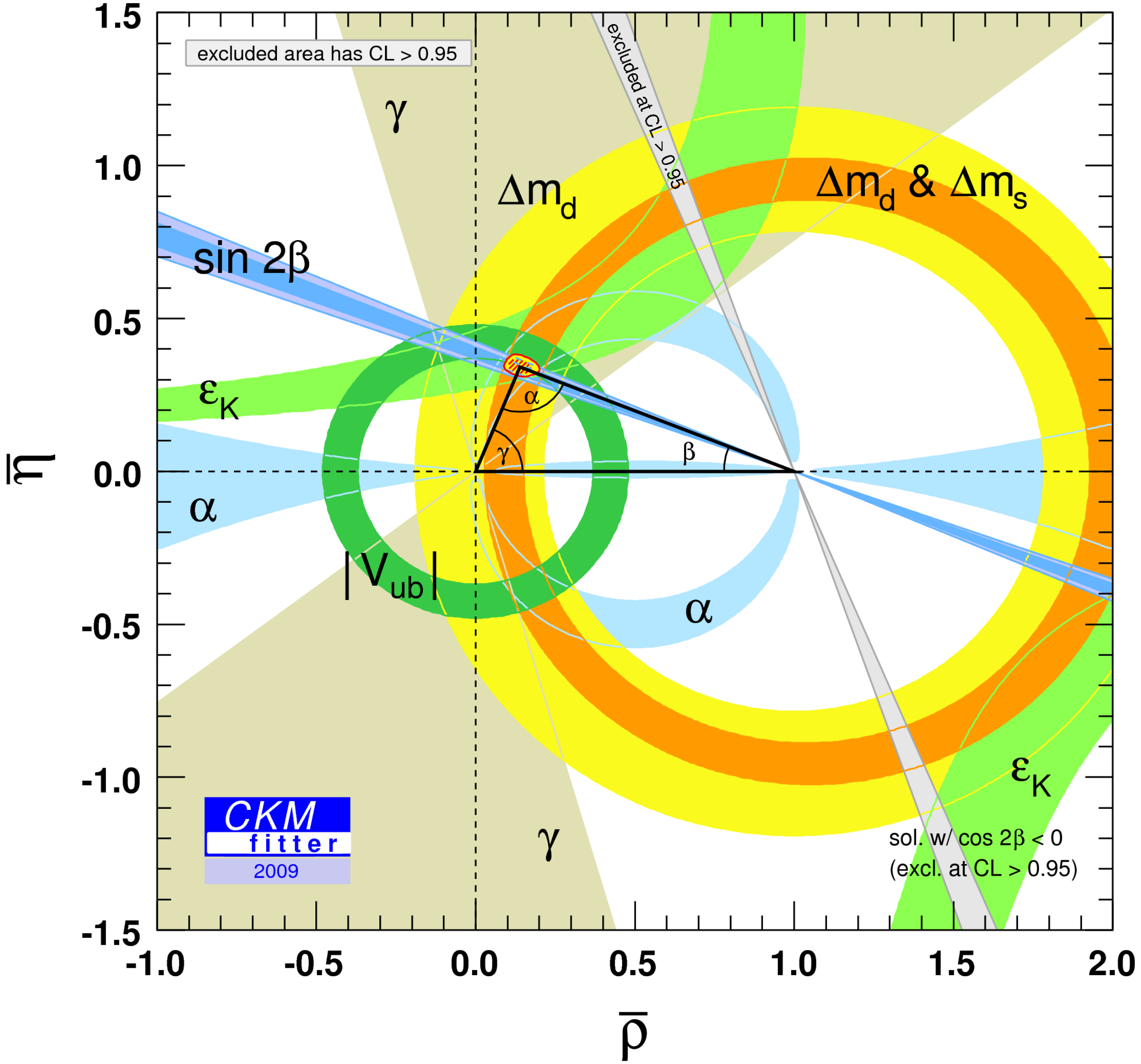
Progress in UT

2006



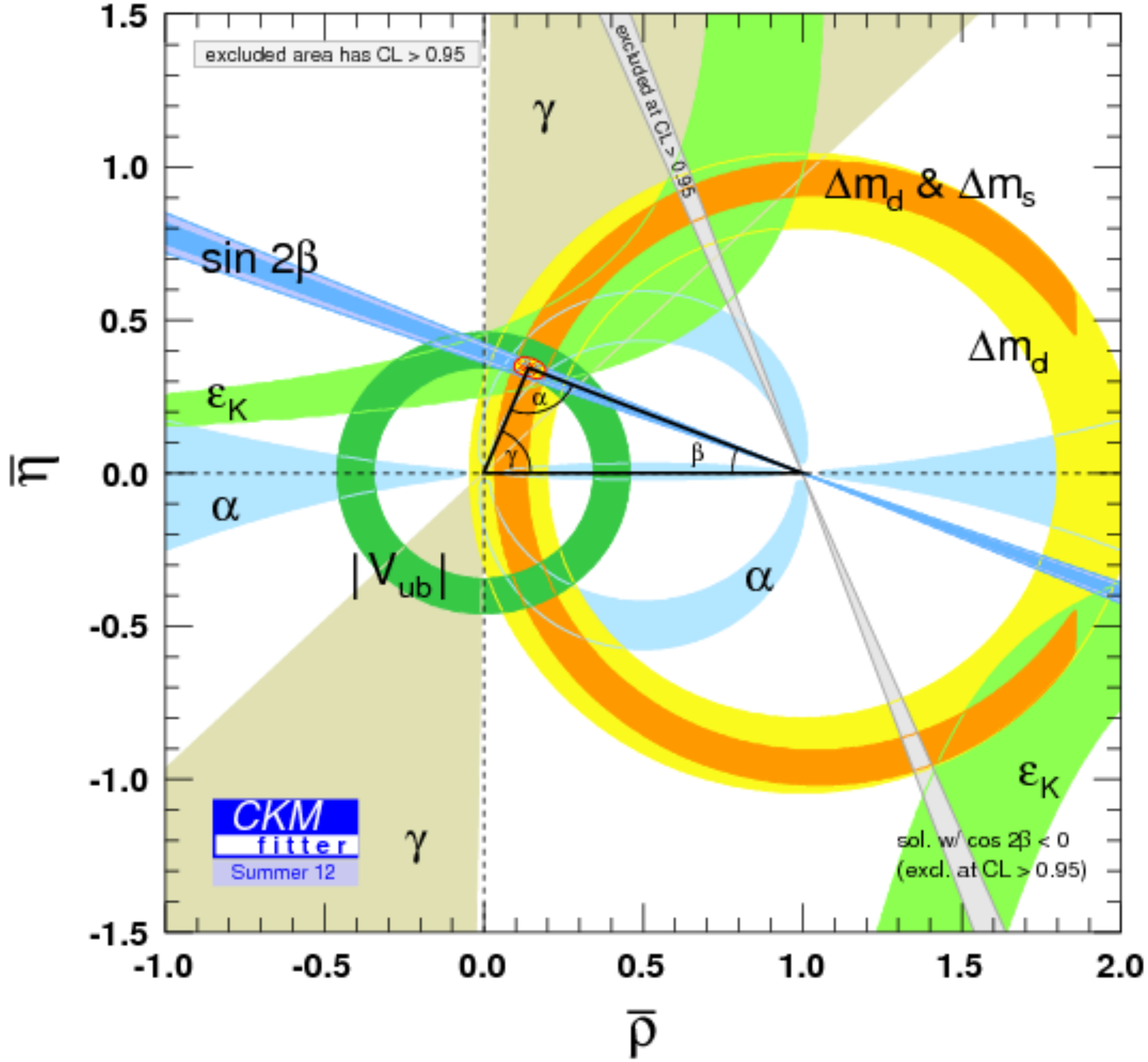
Progress in UT

2009



Progress in UT

2012



Neutral meson mixing

What are the possible neutral meson systems?

Possible neutral meson systems:

K^0-$\bar{K}^0$ system (sd): Mass eigenstates: K_S and K_L

D^0-$\bar{D}^0$ system (cu): Mass eigenstates: D_+ and D_-

B_d-$\bar{B}_d$ system (bd): Mass eigenstates: $B_{H,d}$ and $B_{L,d}$

B_s-$\bar{B}_s$ system (bs): Mass eigenstates: $B_{H,s}$ and $B_{L,s}$

Math to describe time evolution in the following slides for B_d system
Applies to all systems, nevertheless phenomenology very different.

e.g. B_d system:

$$|B^0\rangle = |\bar{b}d\rangle \quad , \quad |\overline{B}^0\rangle = |b\bar{d}\rangle$$

Beautiful example of quantum mechanics at work!

Neutral meson mixing

$$i\frac{\partial}{\partial t}\Psi = H\Psi \qquad \Psi(t) = a(t)\left|B^0\right\rangle + b(t)\left|\overline{B}^0\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Time evolution of B^0 or $\overline{B^0}$ can be described by an *effective* Hamiltonian:

$$H = \underbrace{\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix}}_{\text{hermitian}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}}_{\text{hermitian}}$$

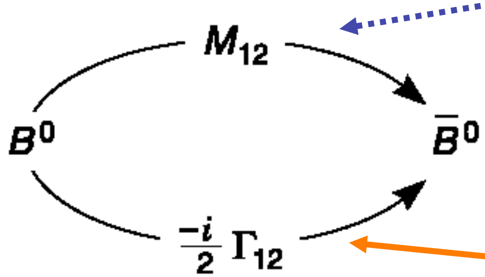
Mass term: "dispersive"

Decay term: "absorptive"

Note that H is not Hermitian!
(due to decay term; this is not the full Hamiltonian; all final state terms are missing)

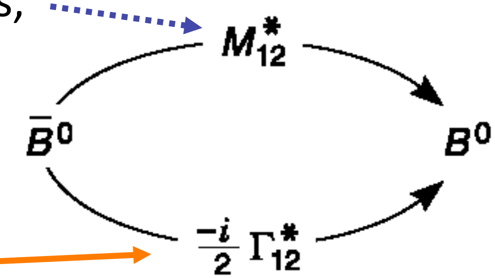
CPT symmetry: $M_{11} = M_{22} = M_B$
$\Gamma_{11} = \Gamma_{22} = 1/\tau_B$

The off-diagonal elements describe mixing – but what is the difference between M_{12} and Γ_{12}?



M_{12} describes $B^0 \leftrightarrow \overline{B^0}$ via *off-shell* states, e.g. the weak box diagram

Γ_{12} describes $B^0 \leftrightarrow f \leftrightarrow \overline{B^0}$ via *on-shell* states, e.g. $f=\pi^+\pi^-$



Solving the Schrödinger Equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = H \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

Define the mass eigenstates:

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

The heavy and light mass eigenstates have time dependence:

$$|B_{H,L}(t)\rangle = e^{-(im_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}(0)\rangle$$

The mass and decay width difference:

$$\begin{aligned}\Delta m &= m_H - m_L \\ \Delta\Gamma &= \Gamma_H - \Gamma_L\end{aligned}$$

Solving the Schrödinger equation gives:

$$\frac{q}{p} = -\sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$$

$$\Delta m = 2\,\mathrm{Re}\sqrt{\left(M_{12} - i\Gamma_{12}/2\right)\left(M_{12}^* - i\Gamma_{12}^*/2\right)}$$

$$\Delta\Gamma = 2\,\mathrm{Im}\sqrt{\left(M_{12} - i\Gamma_{12}/2\right)\left(M_{12}^* - i\Gamma_{12}^*/2\right)}$$

Time evolution of neutral meson system

Remember that strong interaction produces quarks in their flavour eigenstate.
At time t=0 the *B* meson starts either as B^0 or $\overline{B^0}$ (not as superposition).

Using

$$|B_{H,L}(t)\rangle = e^{-(im_{H,L}+\Gamma_{H,L}/2)t}|B_{H,L}(0)\rangle$$

$$|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$$

We can write the state of a particle that starts as a B^0 or $\overline{B}^0$ as

$$\begin{aligned} |B^0_{\text{phys}}(t)\rangle &= g_+(t)|B^0\rangle + \frac{q}{p}g_-(t)|\overline{B}^0\rangle \\ |\overline{B}^0_{\text{phys}}(t)\rangle &= g_+(t)|\overline{B}^0\rangle + \frac{p}{q}g_-(t)|B^0\rangle \end{aligned}$$

with

$$g_\pm(t) = \frac{1}{2}(e^{-(im_L+\Gamma_L/2)t} \pm e^{-(im_H+\Gamma_H/2)t})$$

So, the probability to observe a B^0 or $\overline{B}^0$ at after a given time t equals:

$$\begin{aligned} |\langle B^0|B^0_{\text{phys}}(t)\rangle|^2 &= |g_+(t)|^2 \quad , \\ |\langle \overline{B}^0|B^0_{\text{phys}}(t)\rangle|^2 &= \left|\frac{q}{p}\right|^2 |g_-(t)|^2 \quad , \\ |\langle B^0|\overline{B}^0_{\text{phys}}(t)\rangle|^2 &= \left|\frac{p}{q}\right|^2 |g_-(t)|^2 \quad , \\ |\langle \overline{B}^0|\overline{B}^0_{\text{phys}}(t)\rangle|^2 &= |g_+(t)|^2 \quad , \end{aligned}$$

Time evolution of neutral meson system

Probability of finding a B^0 at time t which was produced as a B^0 :

Two different decay times

$$|g_+(t)|^2 = \frac{1}{4}\left(e^{-\Gamma_H t} + e^{-\Gamma_L t} + 2e^{-\Gamma t}\cos\Delta m t\right)$$

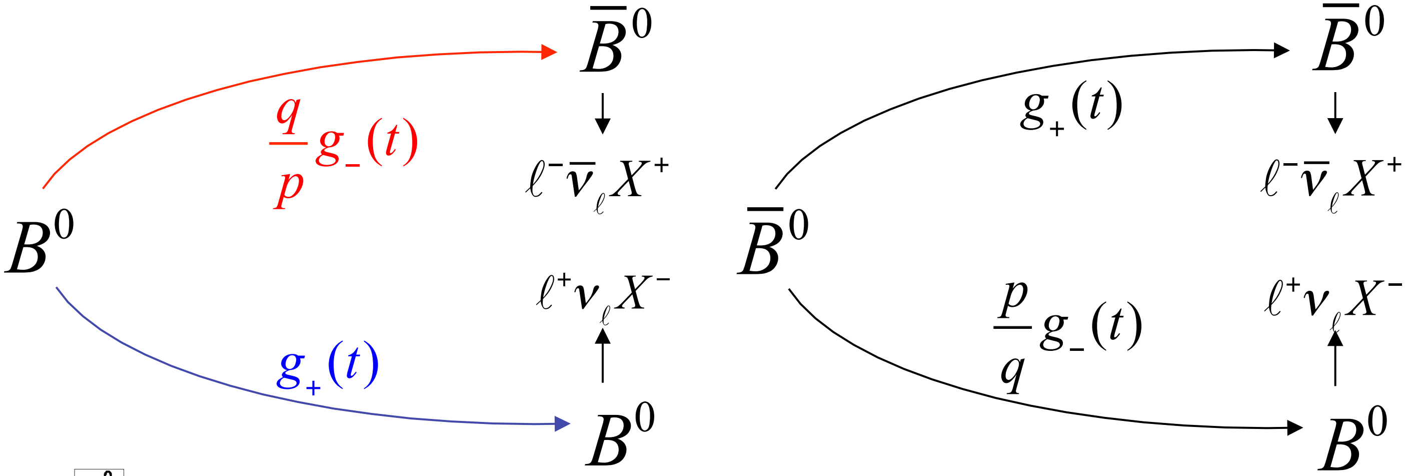
$$= \frac{1}{2}e^{-\Gamma t}\left(\cosh\Delta\Gamma t + \cos\Delta m t\right)$$

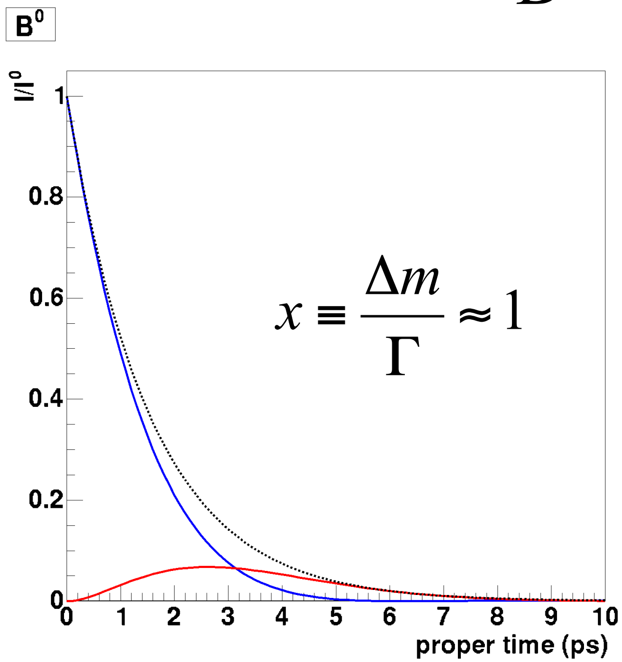
$\Delta\Gamma$ damps the oscillation
(oscillation is gone when only B_L or B_H is left)

Δm describes the oscillation

Time evolution of neutral meson system

Example: *B* decay to flavour specific final state (semileptonic decay):





Black: Double exponential decay Γ_H and Γ_L

Blue: Probability of finding a B^0 at t for an initial B^0.

Red: Probability of finding a $\overline{B}^0$ at t for an initial B^0

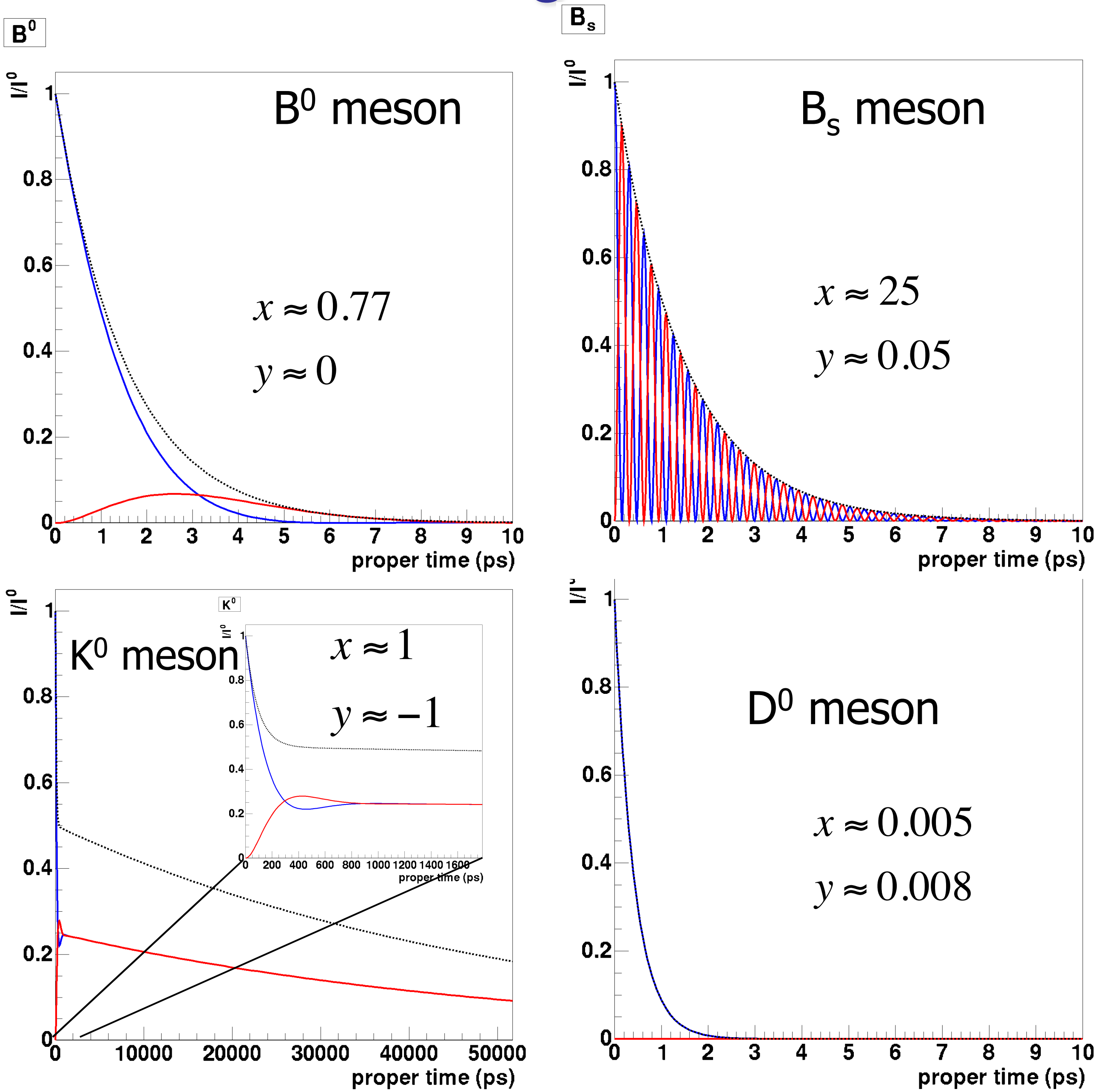
x: the average number of oscillations before decay

$$x \equiv \frac{\Delta m}{\Gamma} \approx 0.77$$

y: the relative decay width difference

$$y \equiv \frac{\Delta \Gamma}{2\Gamma} \approx 0$$

Mixing of neutral mesons



The 4 different neutral meson systems have very different mixing properties.

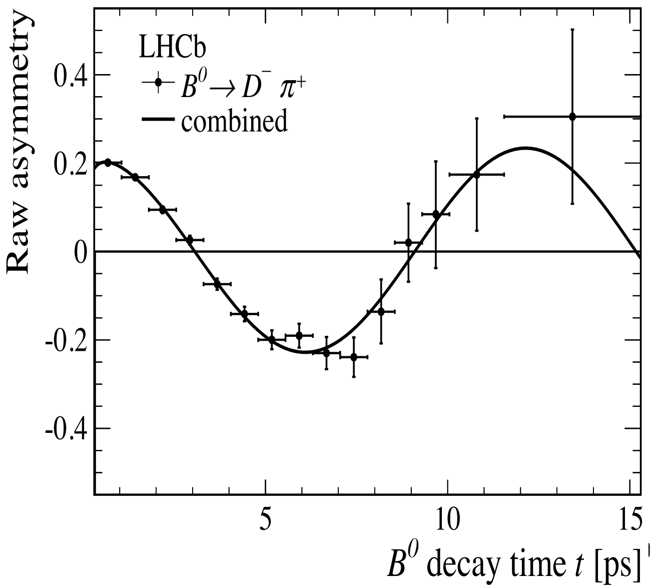
B_s system: very fast mixing

Kaon system: large decay time difference.

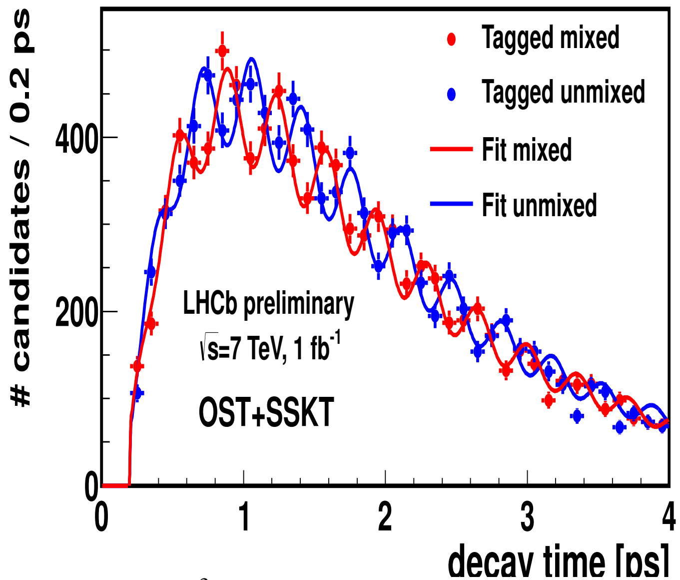
Charm system: very slow mixing

Experimental state-of-the-art

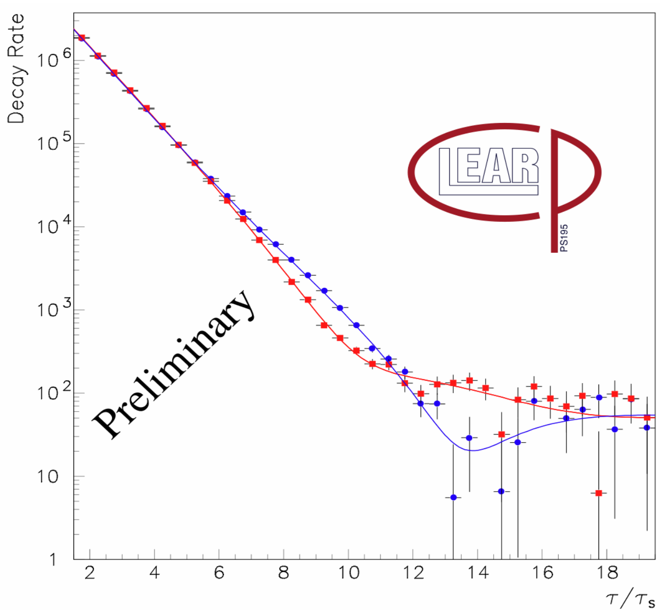
B^0

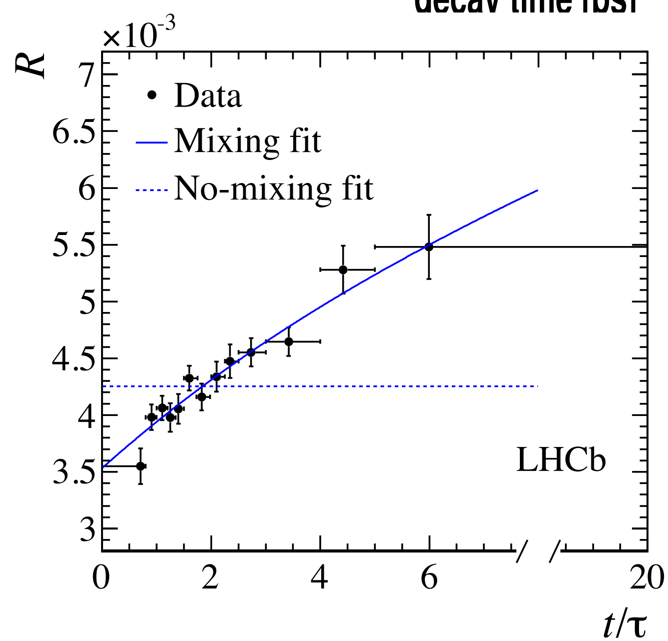


B_s



LHCb has the world's best measurements in B^0, B_s and D^0 systems!

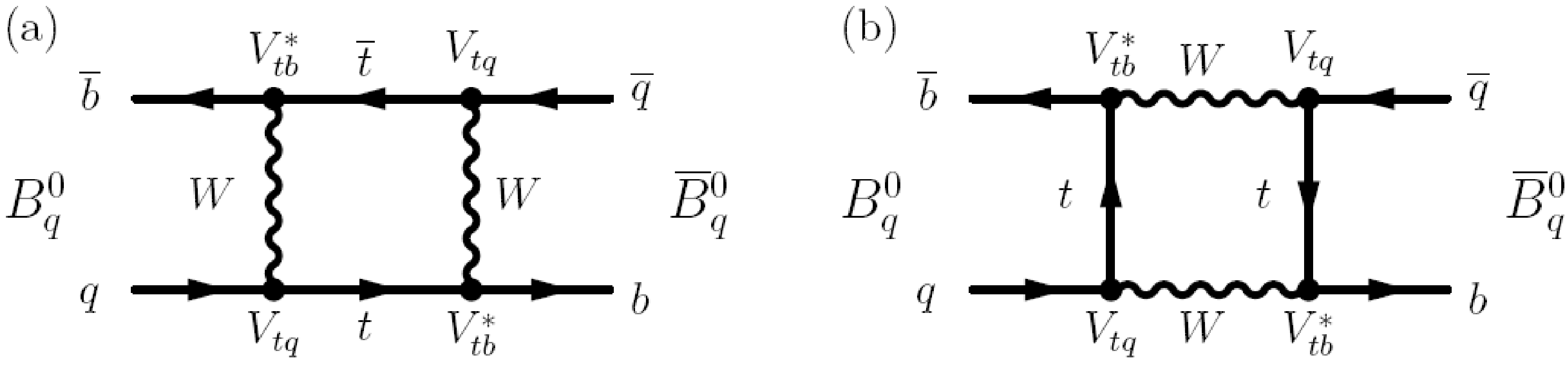




B_s and D^0 oscillations measured in this institute!

The weak box diagram

These two diagrams contribute to mixing in $B_{d,s}$ system:



The (heavy) top quark dominates the internal loop.
No GIM cancellation (if u,c,t would have the same mass these diagrams would cancel)

Why are the oscillations in the B_s system so much faster than in B_d?
Why is the mixing in the D^0 system so small?

Oscillations in B_d versus B_s system: V_{td} versus V_{ts}

Order λ^3 Order λ^2

→ Much faster oscillation in B_s system (less Cabbibo suppression).

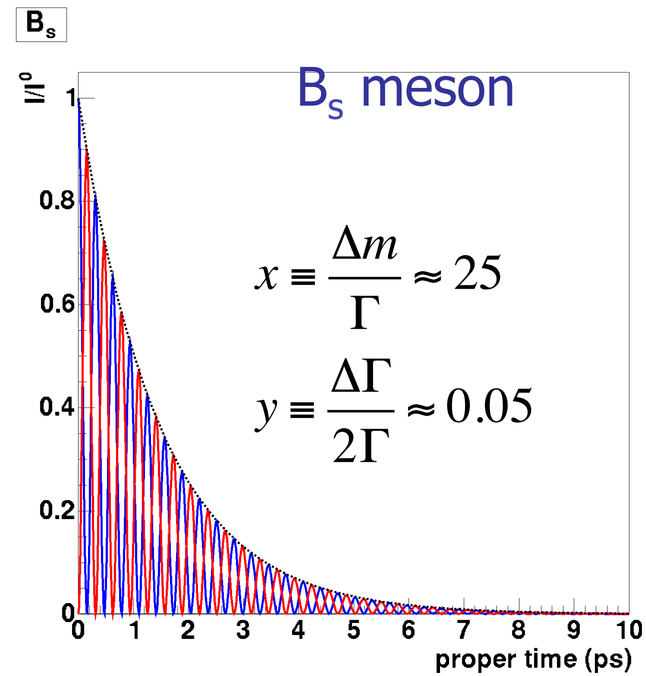
In the D^0 system, the d,s,b quarks in internal loop (no top): small mixing.

Measurement of Δm_s

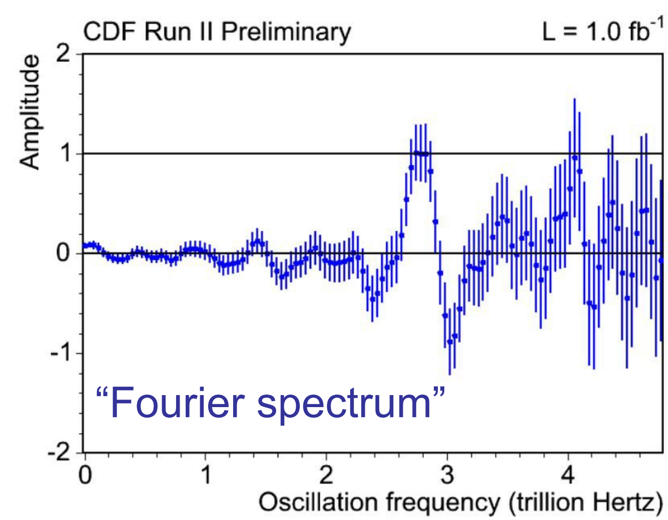
(B_s-$\overline{B}_s$ mixing frequency)

Beautiful example of oscillations.

Keep in mind this very fast oscillation in the B_s system:



This oscillation was first observed at the Tevatron in 2006 at the Tevatron:



Δm_s=17.77 ± 0.10(stat) ± 0.07 (sys) ps^{-1}

Now this measurement has been repeated with much better precision by LHCb:

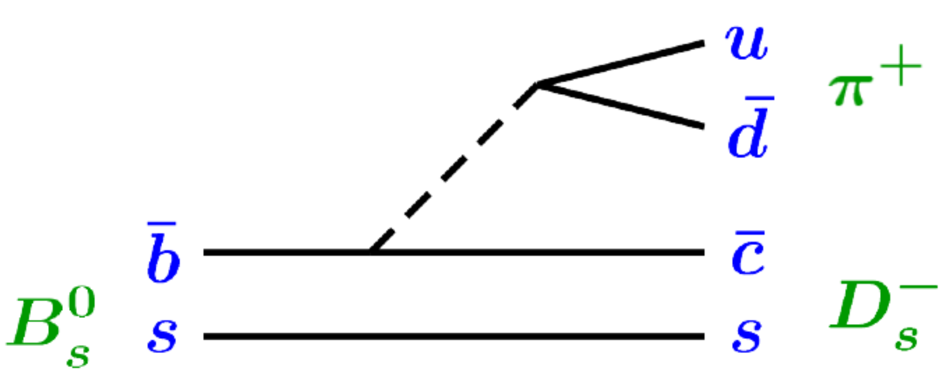
Measurement of Δm_s

(B_s-$\overline{B}_s$ mixing frequency)

What is needed to measure Δm_s ?

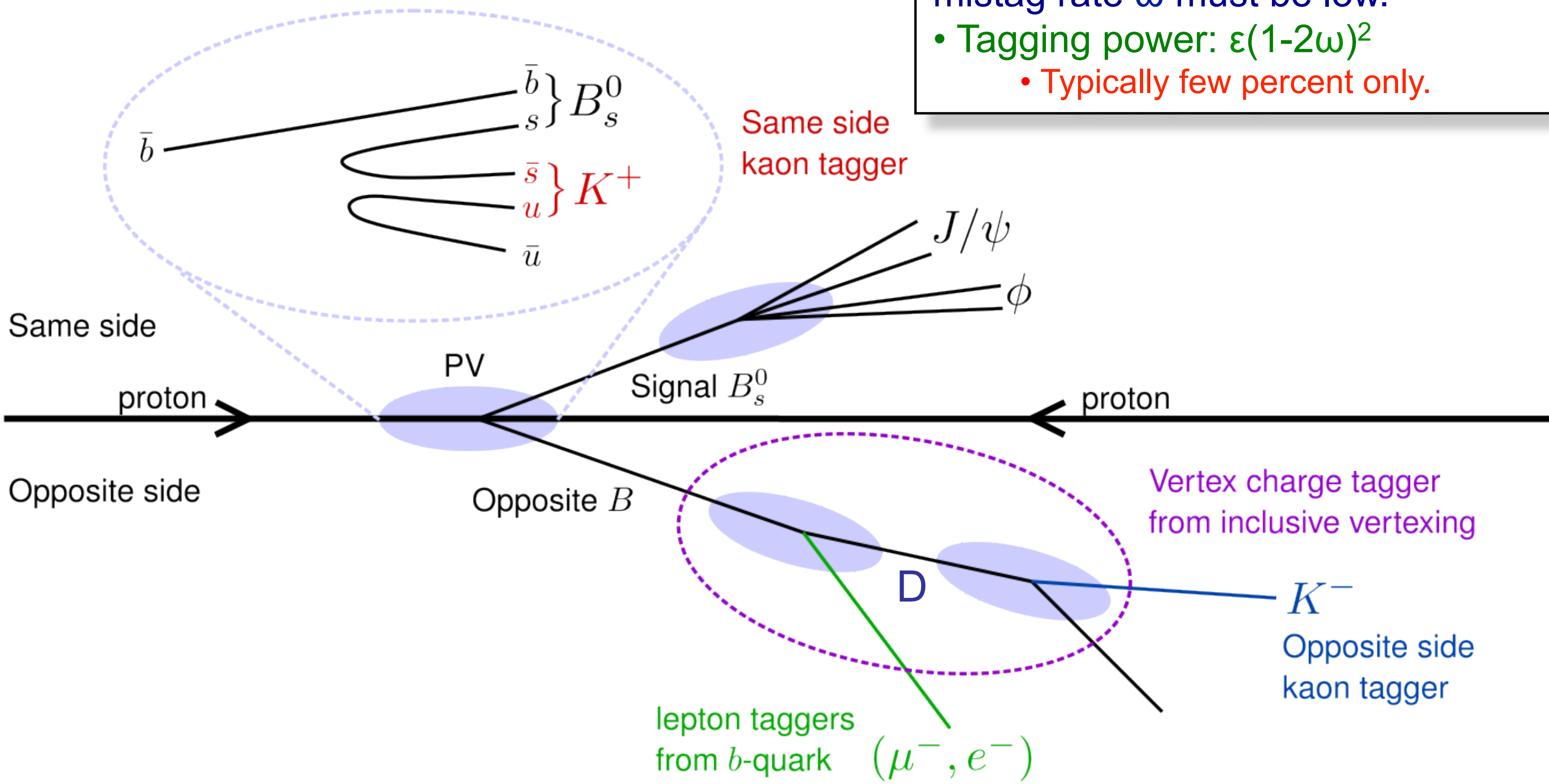
Main ingredients for measuring Δm_s:

- Resolve the fast B_s oscillations.
    - Average decay time resolution ~45 fs
- Decays into flavour specific final state: $B_s \rightarrow D_s \pi$
    - High branching ratio (~0.3%)
- Tag the B_s flavour at production.
    - High efficiency and low mistag rate.
    - Tagging power: ~5%.



Flavour tagging

<u>Flavour tagging</u>
- Tagging of production flavour (B or $\overline{\text{B}}$)
- Important for mixing & CP analyses.
- Tagging efficiency ε must be high, mistag rate ω must be low.
- Tagging power: $\varepsilon(1-2\omega)^2$
  - Typically few percent only.



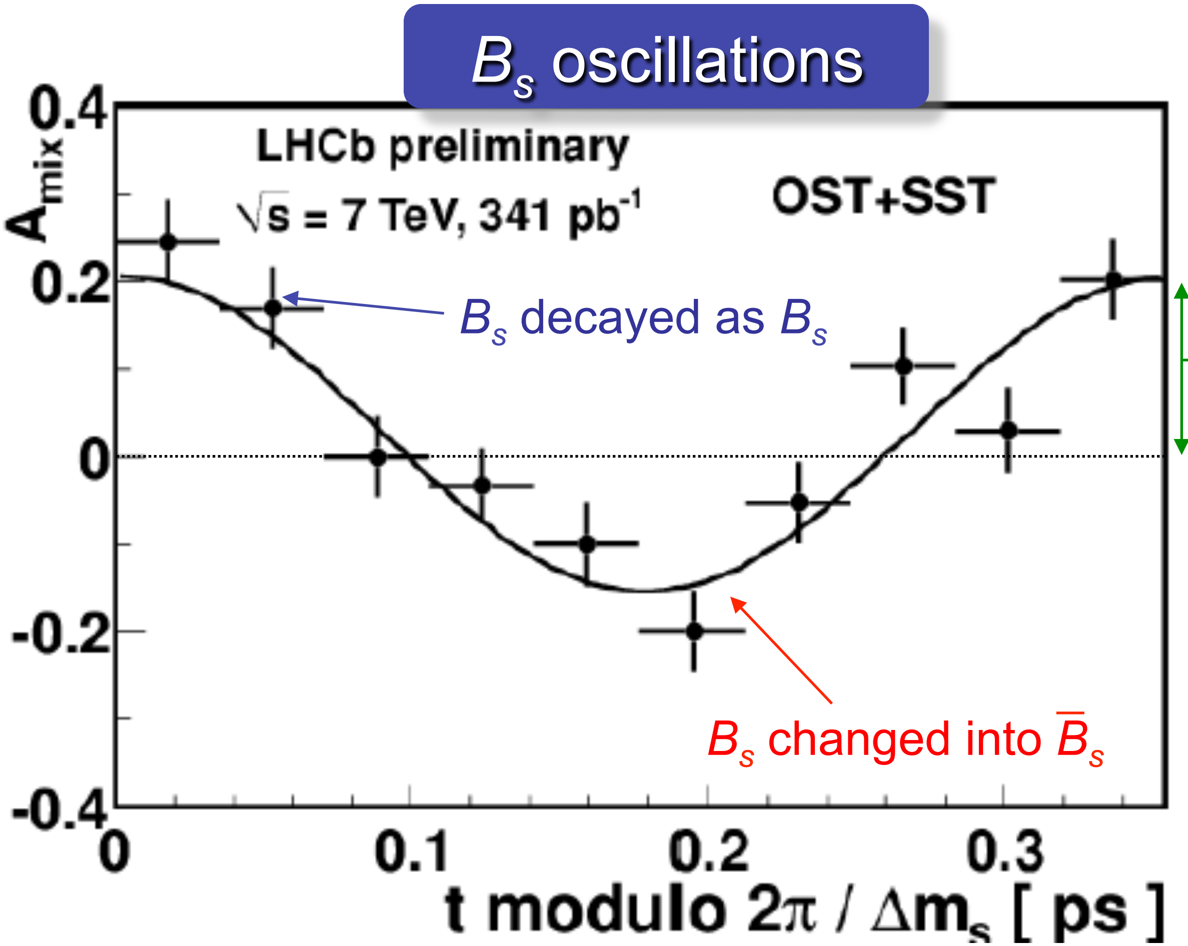
Even in a perfect detector, OS mistag rate can never be 0%. Why ?

Measurement of Δm_s

[LHCb-CONF-2011-50]

Define "mixing asymmetry":

$$A_{\text{mix}}(t) = \frac{N(B_s^0 \to D_s^- \pi^+) - N(B_s^0 \to D_s^+ \pi^-)}{N(B_s^0 \to D_s^- \pi^+) + N(B_s^0 \to D_s^+ \pi^-)}$$



Why is the amplitude not 1?

Dilution of mixing amplitude from:

- tagging and
- proper time resolution

Measurement of Δm_s

Preliminary

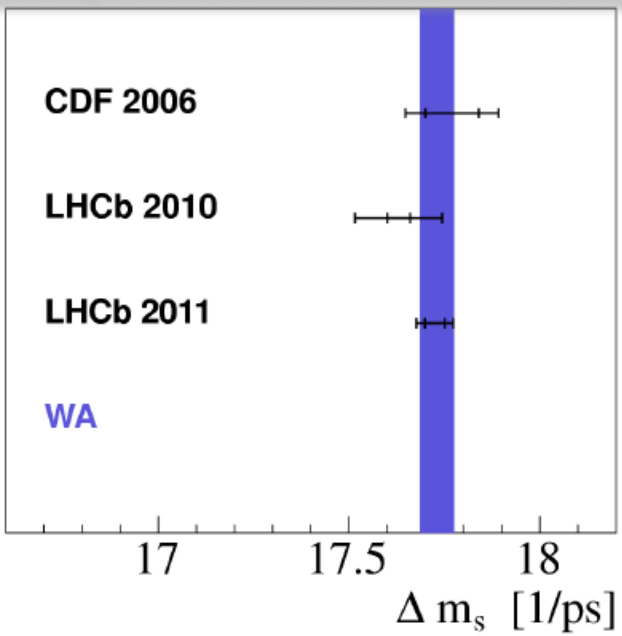
[LHCb-CONF-2011-50]

$\Delta m_s = 17.725 \pm 0.041(\text{stat}) \pm 0.025\ (\text{sys})\ \text{ps}^{-1}$

SM: $\Delta m_s = 17.3 \pm 2.6\ \text{ps}^{-1}$

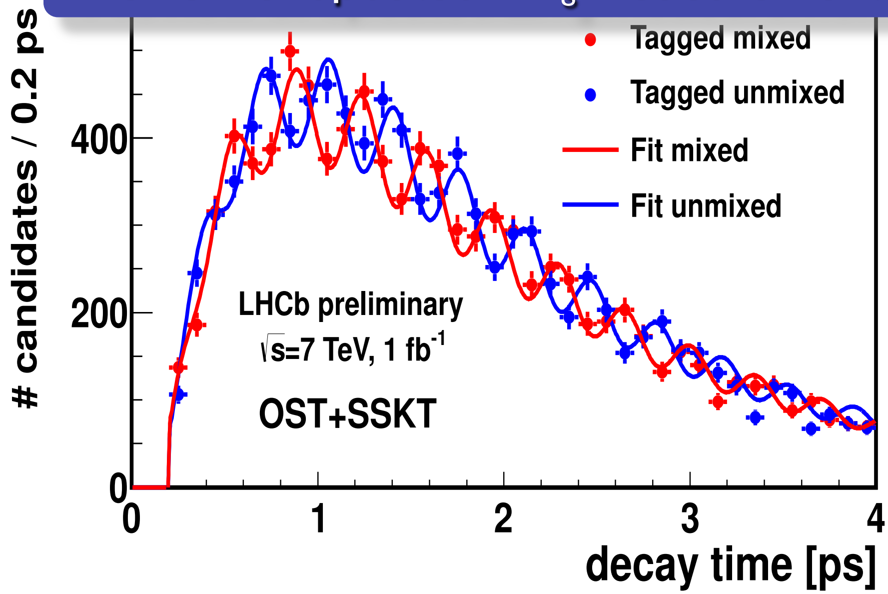
Dominant systematics uncertainty: z-scale and momentum scale

Most precise measurement of Δm_s



Analysis done with only 0.34 fb^{-1}.
(10x more data now available)

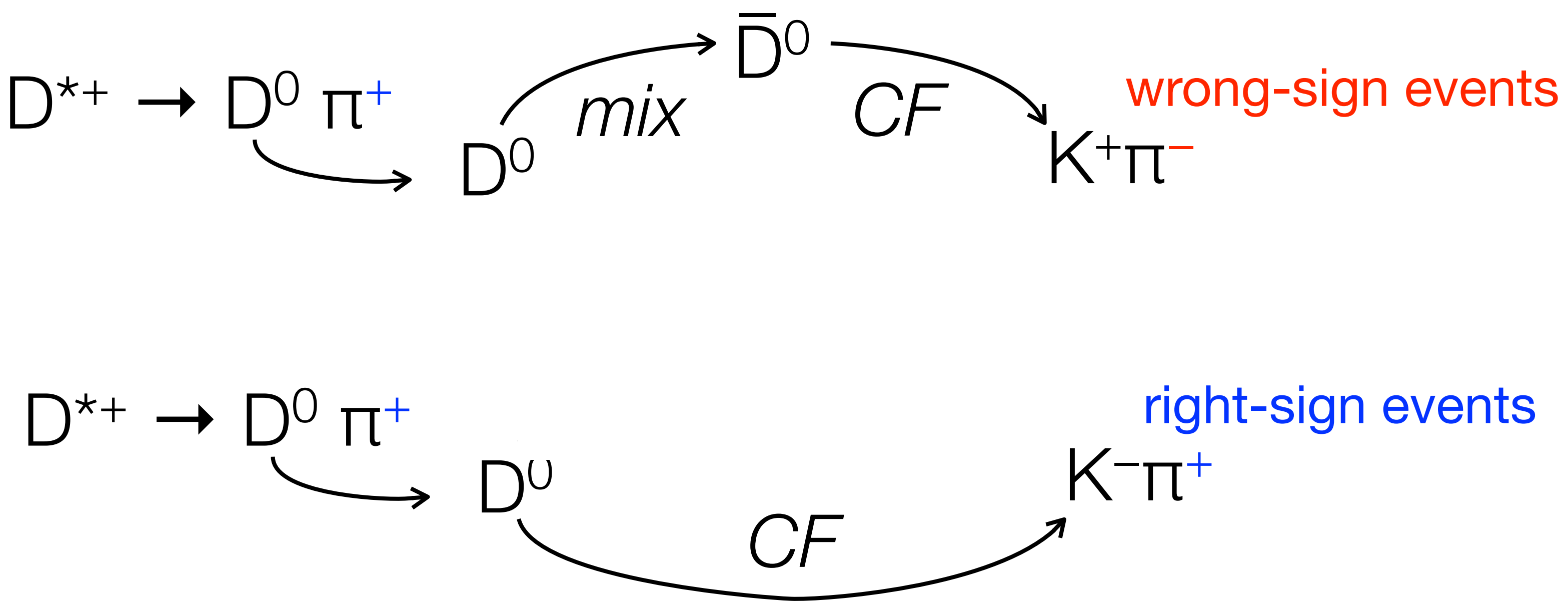
Preview of updated Δm_s measurement



Charm (D^0) mixing

Differences with B_s mixing in previous slides:

- Flavour is tagged by (slow) pion from $D^{*\pm}$ decay (SST).
- Additional path to wrong sign events: doubly-Cabibbo suppressed decays.



Since x,y << 1, can approximate ratio as:

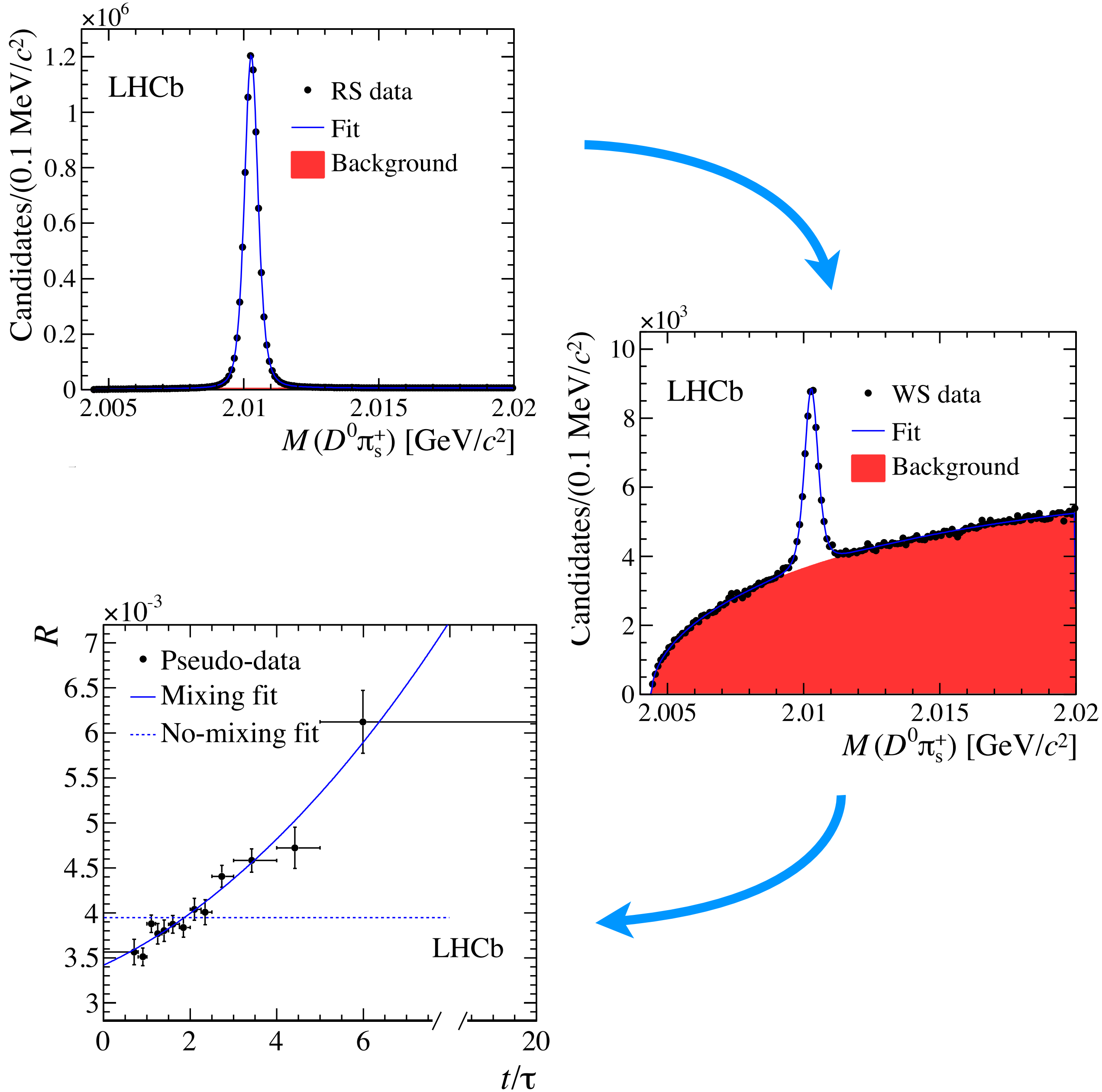
$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D}\,y' t + \frac{x'^2 + y'^2}{4} t^2 \qquad \begin{aligned} x' &= x\cos\delta + y\sin\delta \\ y' &= y\cos\delta - x\sin\delta \end{aligned}$$

We only see the start of the mixing

Time-dependent analysis

In each decay time bin

1. Fit RS sample
2. Fit WS sample
3. Calculate WS/RS ratio from yields



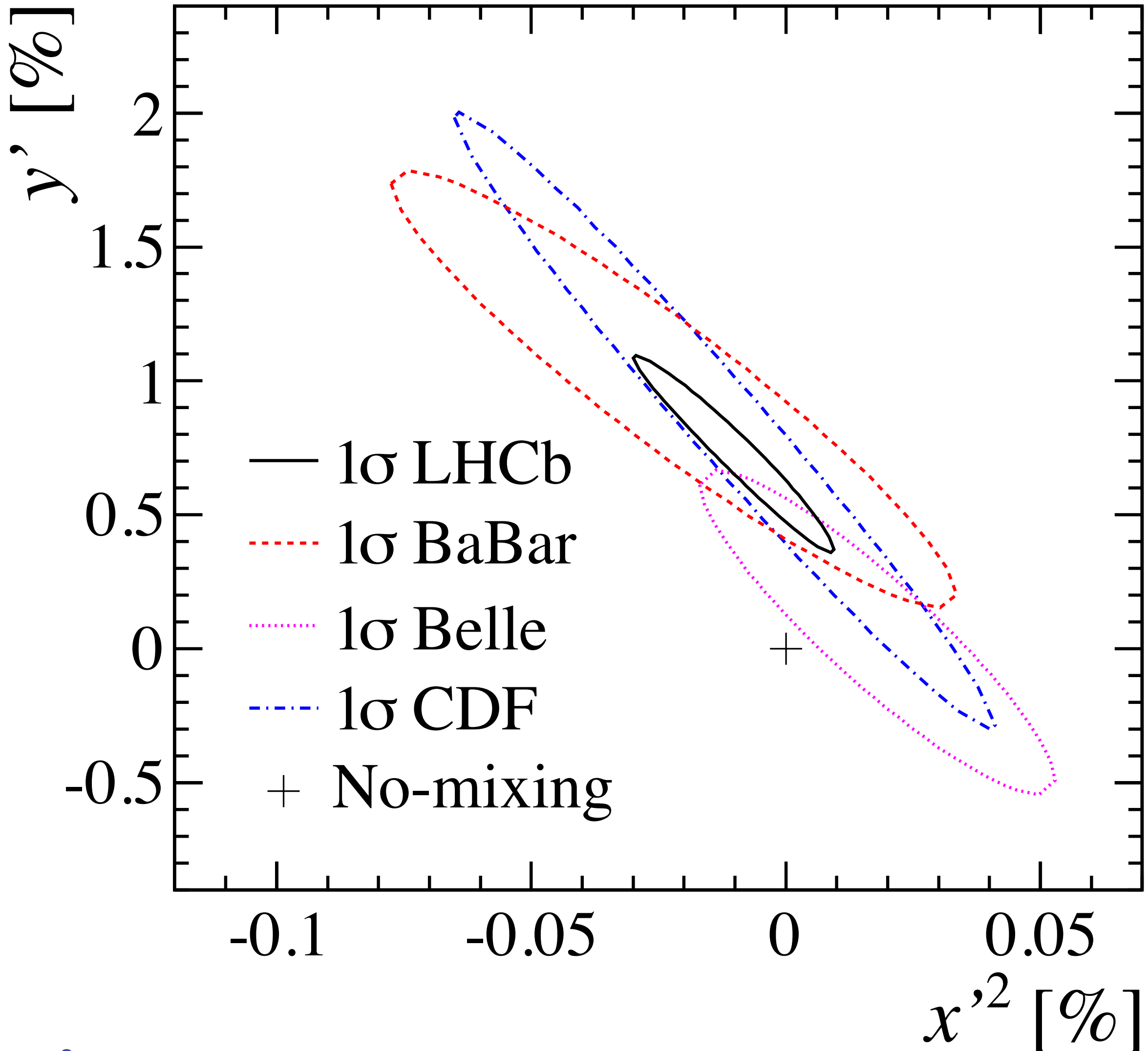
Comparison with other experiments

LHCb:

R_D	3.52 ± 0.15
y'	7.2 ± 2.4
x'^2	-0.09 ± 0.13

[arXiv:1211.1230]

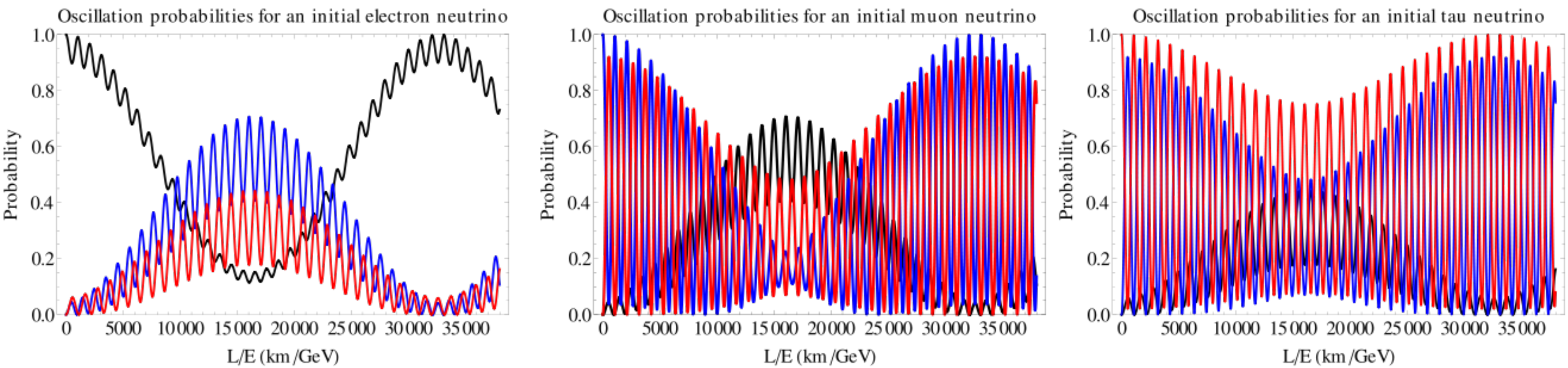
No-mixing hypothesis excluded at 9.1σ



First observation (>5σ) of D^0 mixing by a single experiment

Digression: Light flavour physics

Neutrino oscillations:



Very rich phenomenology: 3 different eigenstates !
Similarities **and** differences with quark mixing.

Why do we talk about quark **mixing** and neutrino **oscillations**?

Large differences in quark masses: decoherence too fast.

Digression: Light flavour physics

The physics of three different systems

	Quarks	**Neutrinos**	**Neutral mesons**
Matrix	CKM	PMNS	$H = M + i\Gamma$
Flavour eigenstates	d', s', b'	ν_e, ν_μ, ν_τ	B^0 and B^0
Mass eigenstates	d, s, b	ν_1, ν_2, ν_3	B_H and B_L
Detection	mass eigenstates	flavour eigenstates	flavour eigenstates
Mass difference	Large → immediate decoherence	Small → long coherence length	Small → decay long before decoherence
Phenomenology	mixing	oscillations	oscillations and mixing