Flavour Physics

LECTURE 1

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Outline of the three lectures

1
- What is flavour physics and why it is interesting
- CP Violation and baryogenesis
- Some historical remarks
- The CKM Matrix
- The rise of b physics

What we have learned from current experiments and the excitement of the field

2
- LHCb: a heavy-flavour physics detector at the LHC - experimental aspects, the LHCb upgrade
- CKM metrology and selected CP violation measurements

3
- Selected results on rare decays, tests of LFU and conclusions

A very vast subject..

- Flavour physics includes
  - neutrinos (covered by E.Akhmedov)
  - charged leptons
  - kaon physics
  - charm & beauty physics
  - some aspects of top physics

- My focus will be on charm, beauty (and kaon physics)
  - will touch on other topics when appropriate

What is flavour?

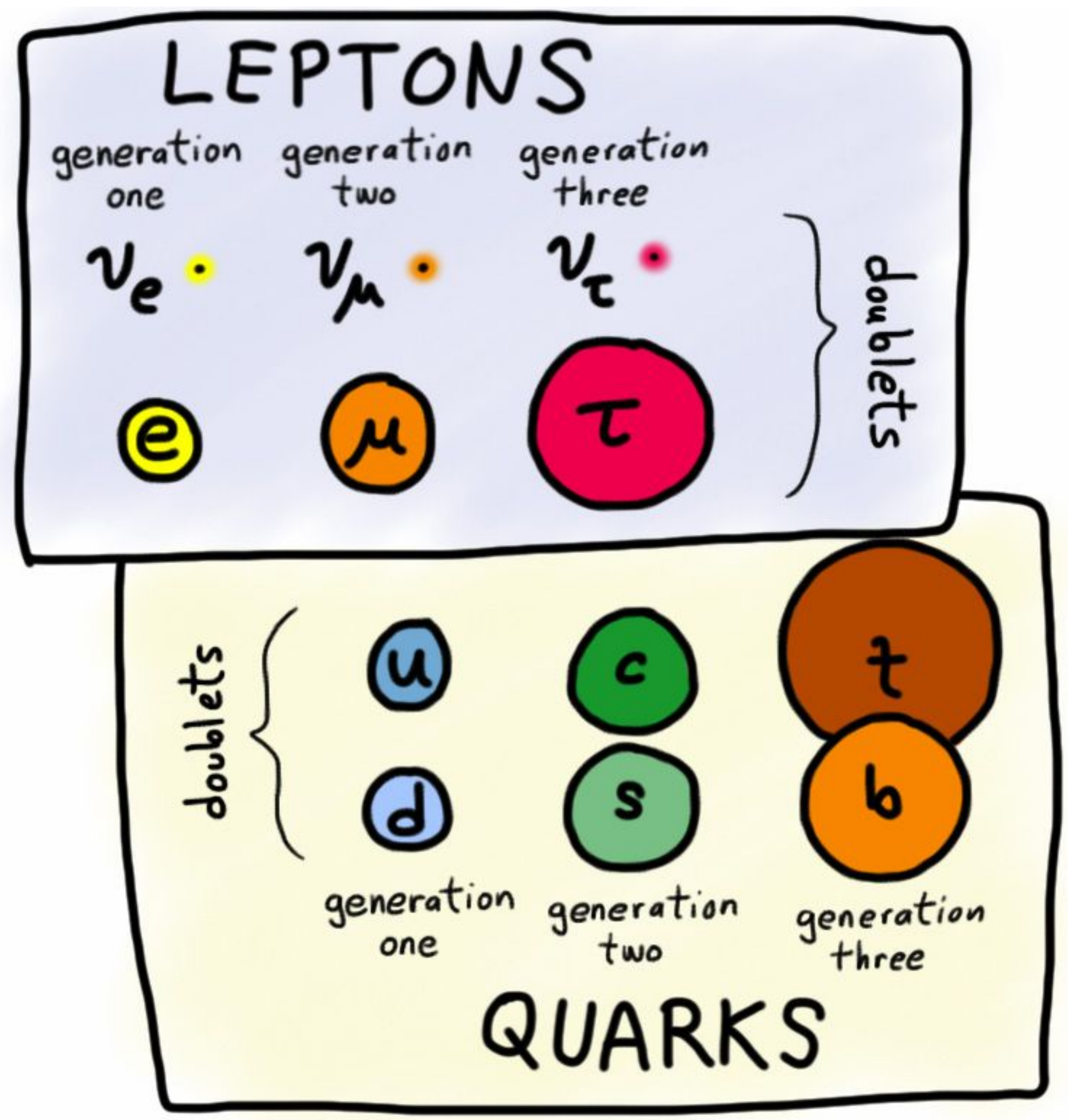
Just as ice cream has both color and flavour, so do quarks

- In 1971, at a Baskin-Robbins ice-cream store in Pasadena, Murray Gell-Mann and his student Harald Fritzsch came up with the term "flavour" to describe the different types of quarks. From the three types known at the time – up, down and strange – the list of quark flavours grew to six. A similar picture evolved for the leptons: the electron and the muon were joined by the unexpected discovery of the tau lepton at SLAC in 1975 and completed with the three corresponding neutrinos. These 12 elementary fermions are grouped into three generations of increasing mass.

Camalich & Zupan
CERN Courier

- **Flavour physics refers to the study of the interactions that distinguish between the fermion generations.**

Who ordered that?



Ordinary matter consists essentially of particles of the first generation

- … asked I.Rabi after the discovery of the μ with a mass of 207 m_e but otherwise seemingly identical properties to the electron
- $m_t/m_u \sim \mathcal{O}(10^5)$!
- Similar features arises in quark mixing!
- Even more puzzling after measurement of non-zero ν masses and mixings: no hierarchy and ν masses many orders of magnitude lighter than any other matter field!
- The Higgs mechanism does not solve the problem of why each particle has a different mass (it does not allow us to predict/compute particle masses)

Many mysteries…

- ..even if the SM is, at the current level of experimental precision and at the energies reached so far, the most successful and best tested theory of nature at a fundamental level.

  What determines the observed pattern of masses and mixing angles of quarks and leptons?

- In the SM, the only interaction distinguishing the three flavours is the Yukawa interaction (interaction of the matter fields with the Higgs boson). The complex phases present in the Yukawa couplings are also the only source of CP violation.

  Are there other sources of flavour (and CP) symmetry breaking, beside the SM Yukawa couplings?

Why flavour is interesting

- To be able to answer these questions is likely to shed light on physics beyond the SM…
- Flavour physics might provide the first indications of new physics at energy scales that are beyond the reach of direct searches
- CP (Charge-Parity) violation is connected to the matter-antimatter asymmetry of the Universe

Where did the anti-matter go?

Where did the anti-matter go?

- What led to the disappearance of antimatter assuming an initial symmetric state (or that inflation washed out any possible prior asymmetry)?
  - There are anti-protons in cosmic rays, consistent with secondaries due to the interactions of cosmic-ray protons in the Interstellar Medium
  - We can produce and study anti-matter in accelerators
  - But apparently no anti-matter around us
  - This looks really strange, given that the properties of matter and antimatter are very similar.
  - Where did it go? Why is the universe globally asymmetric?

Primordial Baryon Asymmetry

- Baryon Asymmetry of the Universe (BAU) just before antibaryons disappeared from the primordial plasma can be defined as

$$\Delta(t) = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}$$

We already know that $\Delta(10^{10}\,\text{years}) = 1$

- Since the end products of the annihilation processes are mostly photons and there are no antibaryons in the universe today, BAU can be estimated by the baryon to photon ratio η

$$\eta = \left.\frac{N_B}{N_\gamma}\right|_{T=3K} = \left.\frac{N_B - N_{\bar{B}}}{N_\gamma}\right|_{T=3K} \sim \left.\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}\right|_{T\gtrsim 1\,\mathrm{GeV}}$$

(Cosmic Microwave Background T= 2.73^0K)

Primordial Baryon Asymmetry

- From observations:
  - $N_\gamma \simeq 410$ photons/cm^3 (at T= 2.73^{0}K)
  - $N_B \simeq 0.25$ nucleons/m^3

$$\eta = \frac{N_B}{N_\gamma} \simeq 6 \times 10^{-10}$$

Small baryon-to-photon ratio in Universe today

- Conclusion is that Big Bang theory tells us that the baryon asymmetry of the early universe was a very small number , i.e., today's huge matter-antimatter asymmetry was a tiny number in the past

$$\Delta = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \sim 10^{-10}$$

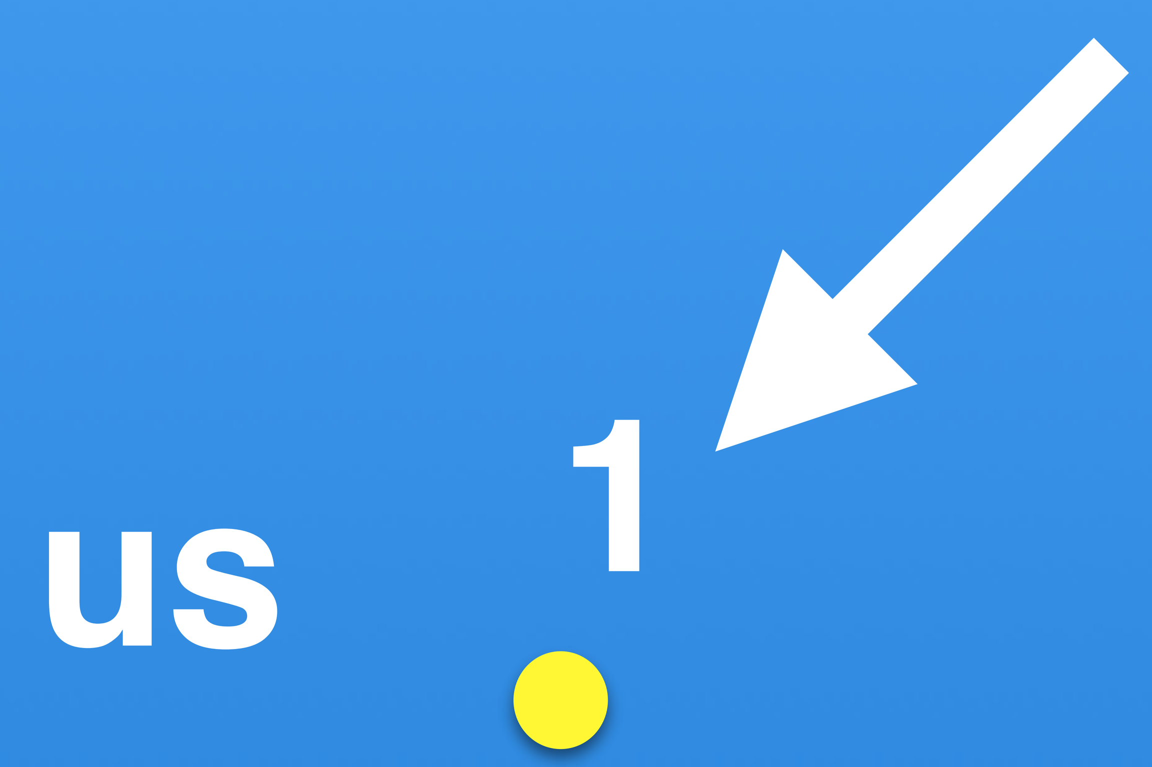
Beginning of Universe

matter	anti-matter
10,000,000,000	10,000,000,000

~10^{-6} seconds later

10,000,000,001	10,000,000,000
matter	anti-matter

Universe now



- Antimatter and matter particles annihilated massively in the early universe, but a tiny fraction of matter was left over: every 10 billion particles, a handful was not annihilated away

- We are very lucky!

Baryogenesis and Sakharov conditions

- A process called baryogenesis was hypothesized to generate this asymmetry dynamically from a matter-antimatter symmetric initial state
- In 1967 A.D. Sakharov enumerated three necessary conditions for baryogenesis (incidentally, his work went unnoticed for 11 years!)

Sakharov conditions

1. Baryon number violation

 - Otherwise there's no way to produce an excess of baryons

2. C and CP violation

 - If C and CP are exact symmetries, the total rate for any process which produces an excess of baryons is equal to the rate of the complementary process which produces an excess of antibaryons

3. Thermodynamic non equilibrium

 - Otherwise any asymmetry would be washed away by simple thermodynamics

Can the SM explain baryogenesis?

- In principle SM carries all the ingredients to satisfy the Sakharov conditions

- Relevant measure is Jarlskog determinant J (I will come back to it!), an invariant that identifies CP violation in the SM and that depends on every physical quark mixing angle $J \sim \Pi(\delta m_q^2/M_W^2)\,\Pi(\text{angles})$

- CP violation in the SM is proportional to J (a dimensionless quantity is constructed by dividing by the relevant temperature at which the BAU freezes out) $\sim 10^{-20}$

- Many orders of magnitude below the observation!

We need more CP violation!

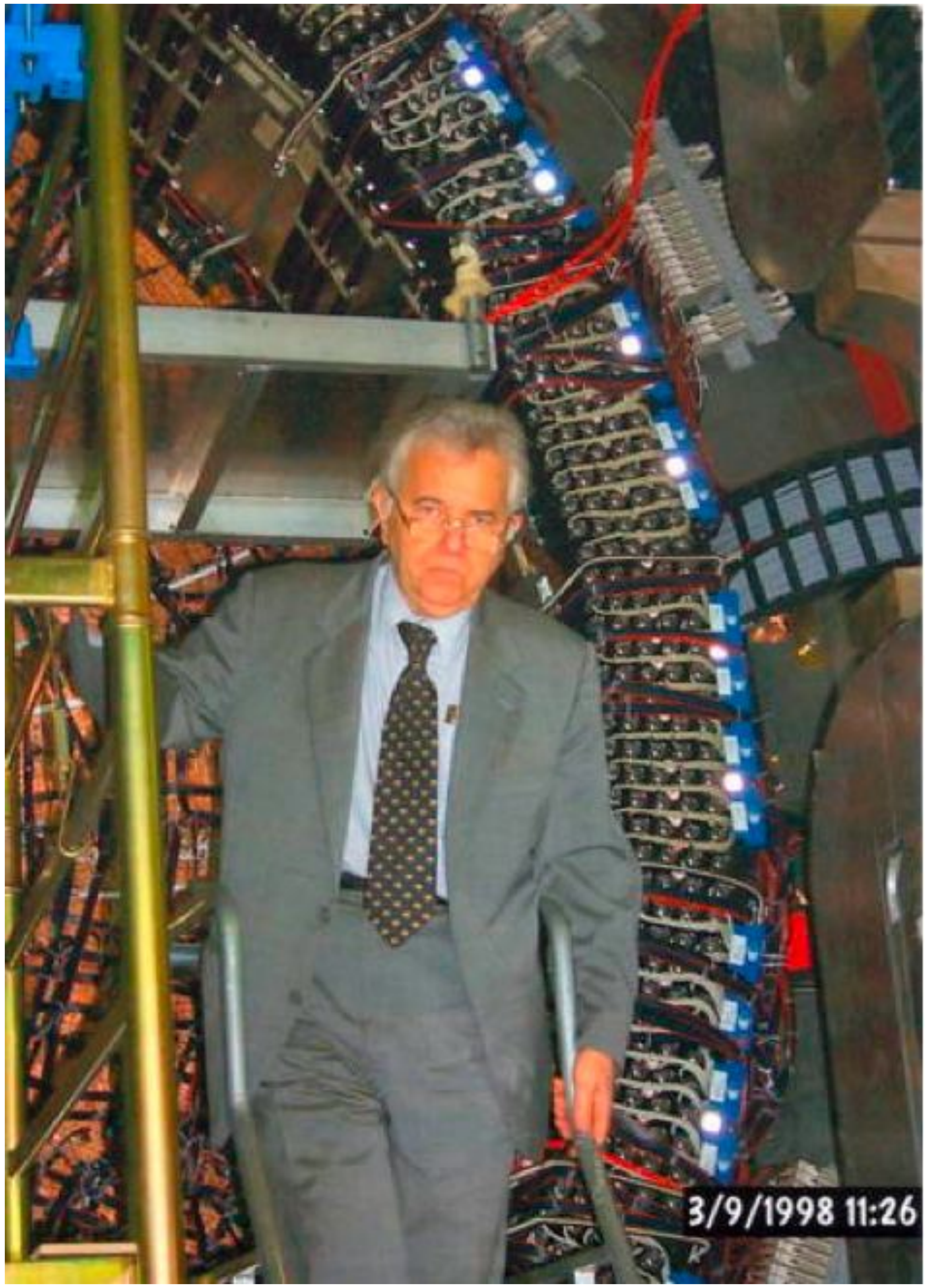
- CP violation beyond the SM must exist!
- Where might we find it?
  - **quark sector** , as deviations from CKM predictions
  - **lepton sector**, e.g. as CP violation in neutrino oscillations
  - **other new physics**: almost all TEV-scale NP contains new sources of CP violation and precision measurements of flavour observables are generically sensitive to additions to the Standard Model
  -

Some historical remarks

Cabibbo Theory

- First building block of what we now call “Flavour physics” was laid down by Nicola Cabibbo in 1963 well before many of the SM ingredients were clear

- The Cabibbo theory of semileptonic decays provided the first step towards a unified description of hadronic and leptonic weak interactions by reconciling strange-particle decays with the universality of weak interactions



The puzzling decays of strange particles

- $\Delta S = 1$ semileptonic weak decays (e.g. $K^+ \to \mu^+\nu$) are suppressed relative to those with $\Delta S = 0$ (e.g. $\pi^+ \to \mu^+\nu$)

- Cabibbo hypothesised that the weak interaction couples the up quark to an orthogonal combination of the down and strange quarks, determined by the "Cabibbo angle"

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L = \begin{pmatrix} u \\ d\cos\theta_C + s\sin\theta_C \end{pmatrix}_L$$

To determine θ, let us compare the rates for $K^+ \to \mu^+ + \nu$ and $\pi^+ \to \mu^+ + \nu$; we find

$$\Gamma(K^+ \to \mu\nu)/\Gamma(\pi^+ \to \mu\nu)$$
$$= \tan^2\theta M_K (1 - M_\mu{}^2/M_K{}^2)^2/M_\pi (1 - M_\mu{}^2/M_\pi{}^2)^2. \quad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \quad (4)$$

- The Cabibbo angle θ_c is the mixing angle expressing the weakly interacting down-quark d' in terms of fields with definite mass d, s

- Remarkable agreement of the theory with experiments, already at the time he wrote the article

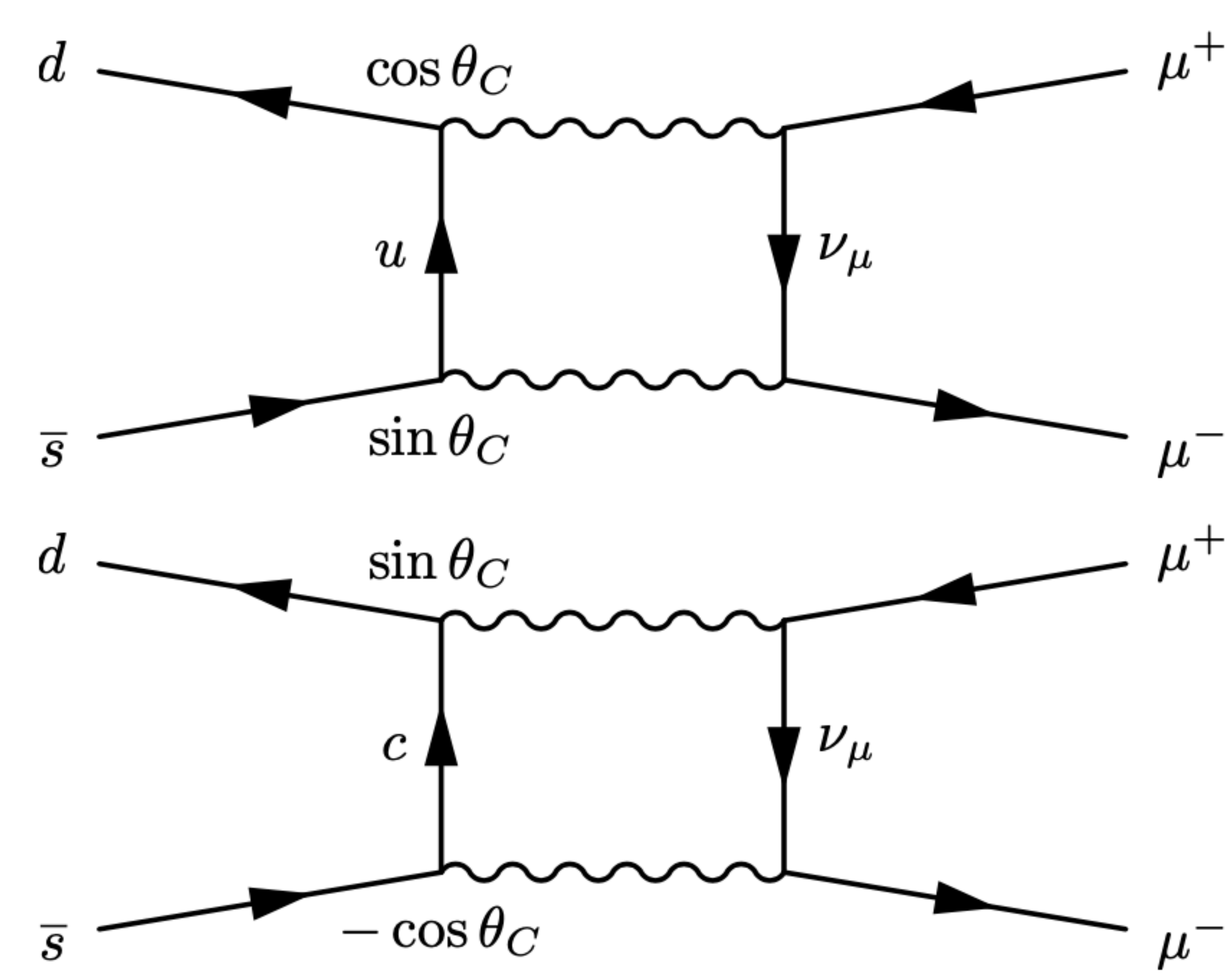
GIM mechanism and charm

- However, Cabibbo's theory could not explain the suppression of strangeness-changing neutral current processes , e.g. $\dfrac{\Gamma(K_L \to \mu^+\mu^-)}{\Gamma(K^+ \to \mu^+\bar{\nu}_\mu)} \sim 10^{-8}$

- In 1970, Glashow, Iliopoulos and Maiani brought in a new, fourth, charge 2/3 quark : "**charm**" (small detail… not yet discovered!)

- This adds an additional decay amplitude almost identical to original one, but with opposite sign $\Rightarrow$ (Almost) fully destructive interference
  (Cancellation not perfect because u, c masses not quite the same, result proportional to $m_c^2 - m_u^2$)

- At the price of adding a second doublet, the unwanted $\Delta S = 1$ neutral currents were cancelled:



weak eigenstates

mass eigenstates

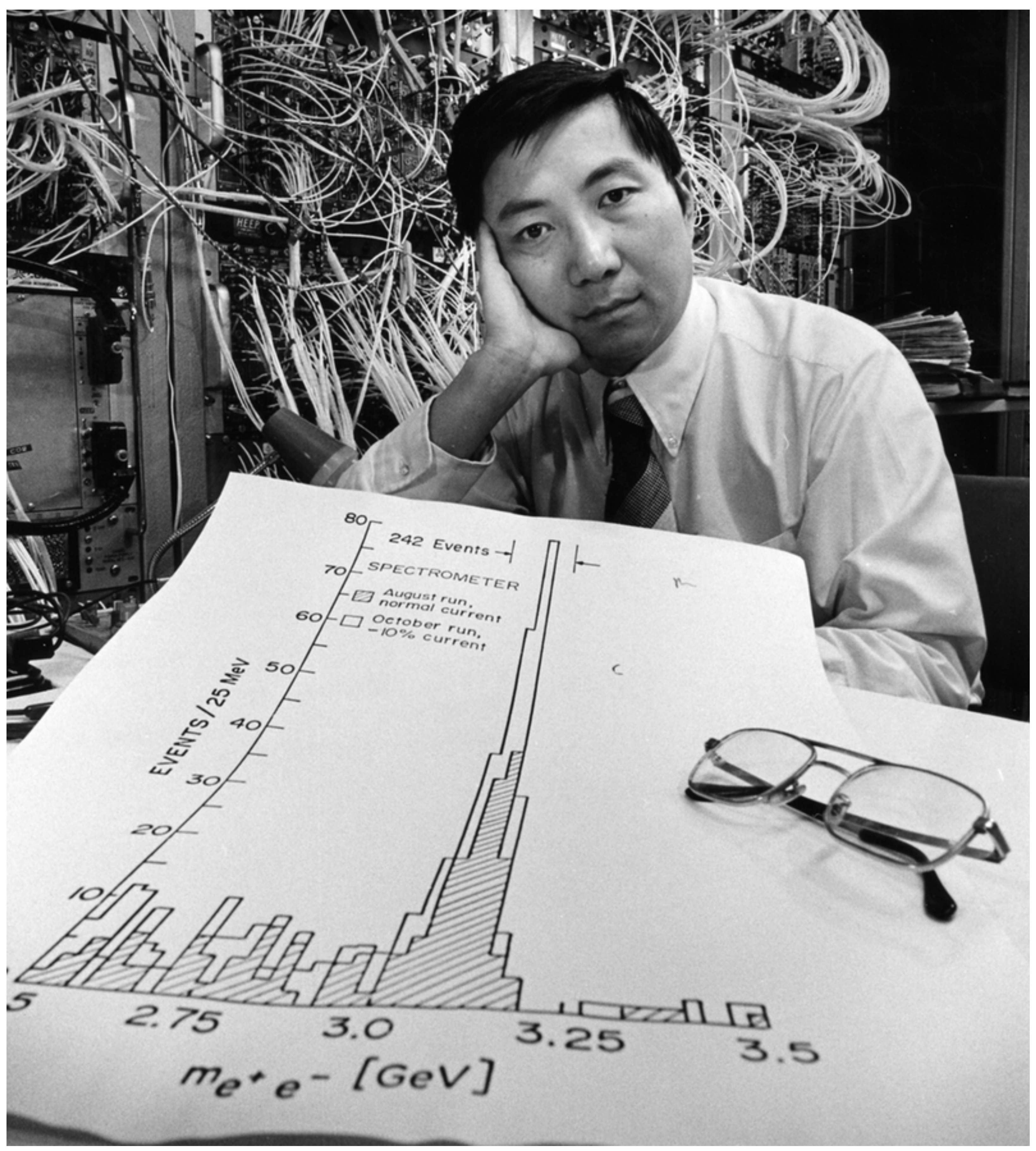
$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

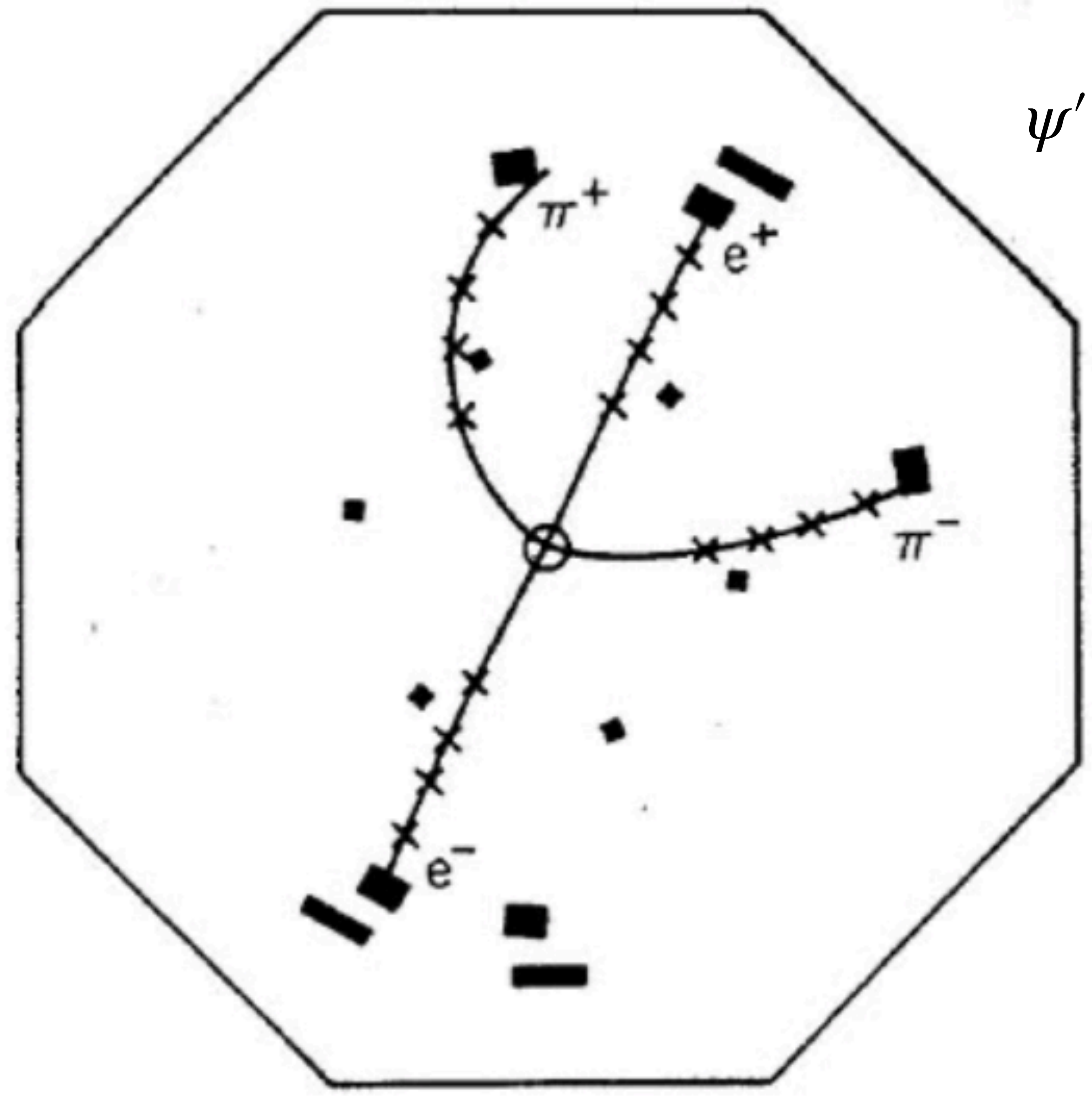
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$$
$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L$$

Remarkable symmetry between leptons and quarks!

Tremendous triumph of theory

- .. when on November 10, 1974 two groups, one at Brookhaven using a p beam on a fixed target and the other in e^+e^- at SLAC simultaneously announced the discovery of the J/Ψ resonance ($c\bar{c}$) with mass of 3.1 GeV





$\psi' \to J/\psi\,(\to e^+e^-)\,\pi^+\pi^-$

Ting&Richter, Nobel prize 1976

- The ADONE e^+e^- machine in Frascati was also pushed beyond its nominal limit of energy (2x1.5 GeV) and saw an overwhelming signal !


GIM-50
50 Years with the GIM Mechanism

Kobayashi and Maskawa

- With four quarks, matrix $V = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$, generally complex, can always be brought to a real form, thereby excluding CP violation from the weak interactions

- Three years later, in '73, Kobayashi and Maskawa showed that a complex phase does remain if the matrix is three by three (indicated as V_{CKM}, after Cabibbo, Kobayashi and Maskawa)

- It is possible to incorporate the observed CP violation in a theory with six quark flavours (remarkable conjecture when not even the second family was completed! b quark discovered in '77 by Lederman and t in '94)

- CP violation discovered in the neutral kaon system by Cronin and Fitch in 1964 (Nobel prize in 1980)

The neutral kaon system

- Neutral kaons $|K^0> = |d\bar{s}>$ and $|\bar{K}^0> = |s\bar{d}>$, generated in strong interactions and distinguished by their production mode, e.g., $\pi^- + p \to \Lambda + K^0$ or $p + \bar{p} \to K^+ + \bar{K}^0 + \pi^-$ (flavour eigenstates with definite quark content)

- They mix via the weak interactions → physical states are superpositions of $K^0, \bar{K}^0$ (states with definite mass and lifetime)

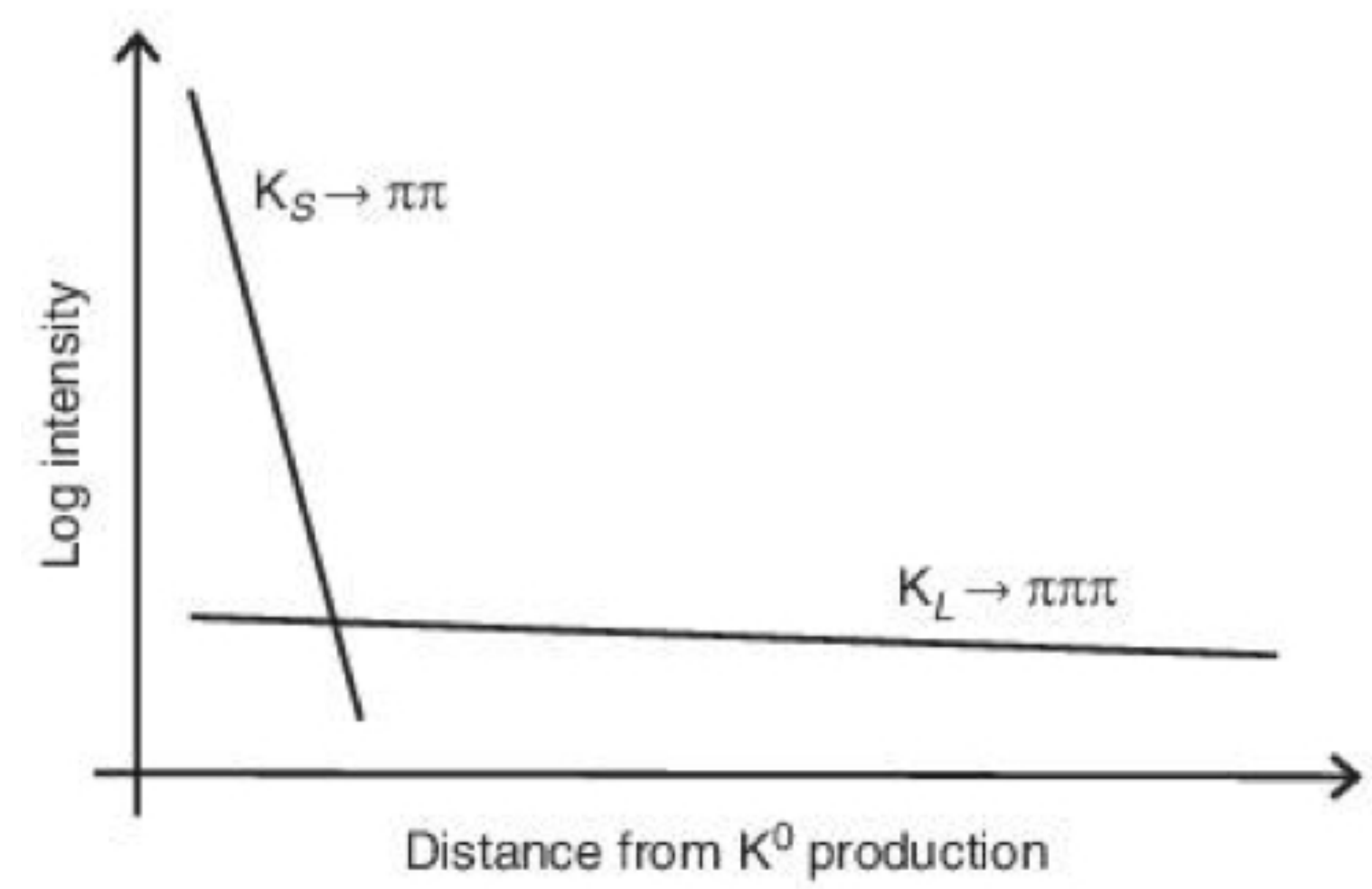
- Weak interactions thought to be invariant under CP:

CP eigenstates:
$$\begin{cases} |K_1> = \frac{1}{\sqrt{2}}(|K^0> - |\bar{K}^0>), \; CP|K_1> = +|K_1> \\ |K_2> = \frac{1}{\sqrt{2}}(|K^0> + |\bar{K}^0>), \; CP|K_2> = -|K_2> \end{cases}$$

distinguished by their mode of decay, with CP-even $K_1 \to \pi\pi$ and CP-odd $K_2 \to \pi\pi\pi$

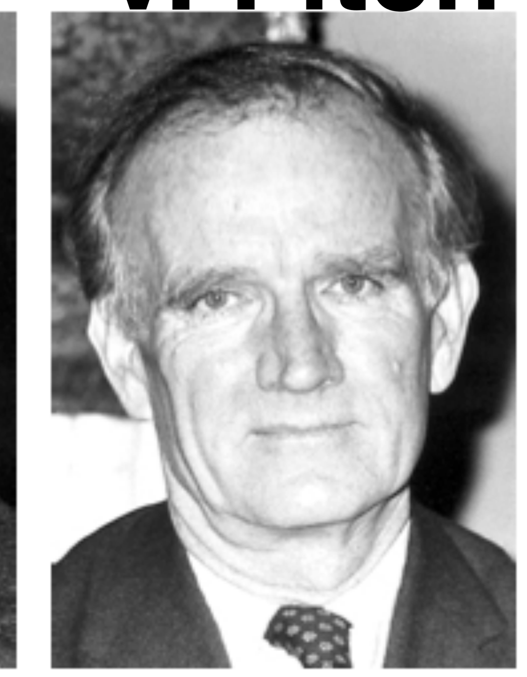
- Large difference in lifetimes:

$$m_K - 2m_\pi \sim 220\,\mathrm{MeV} \gg m_K - 3m_\pi \sim 80\,\mathrm{MeV}$$
$$\Rightarrow \tau_1 \ll \tau_2$$

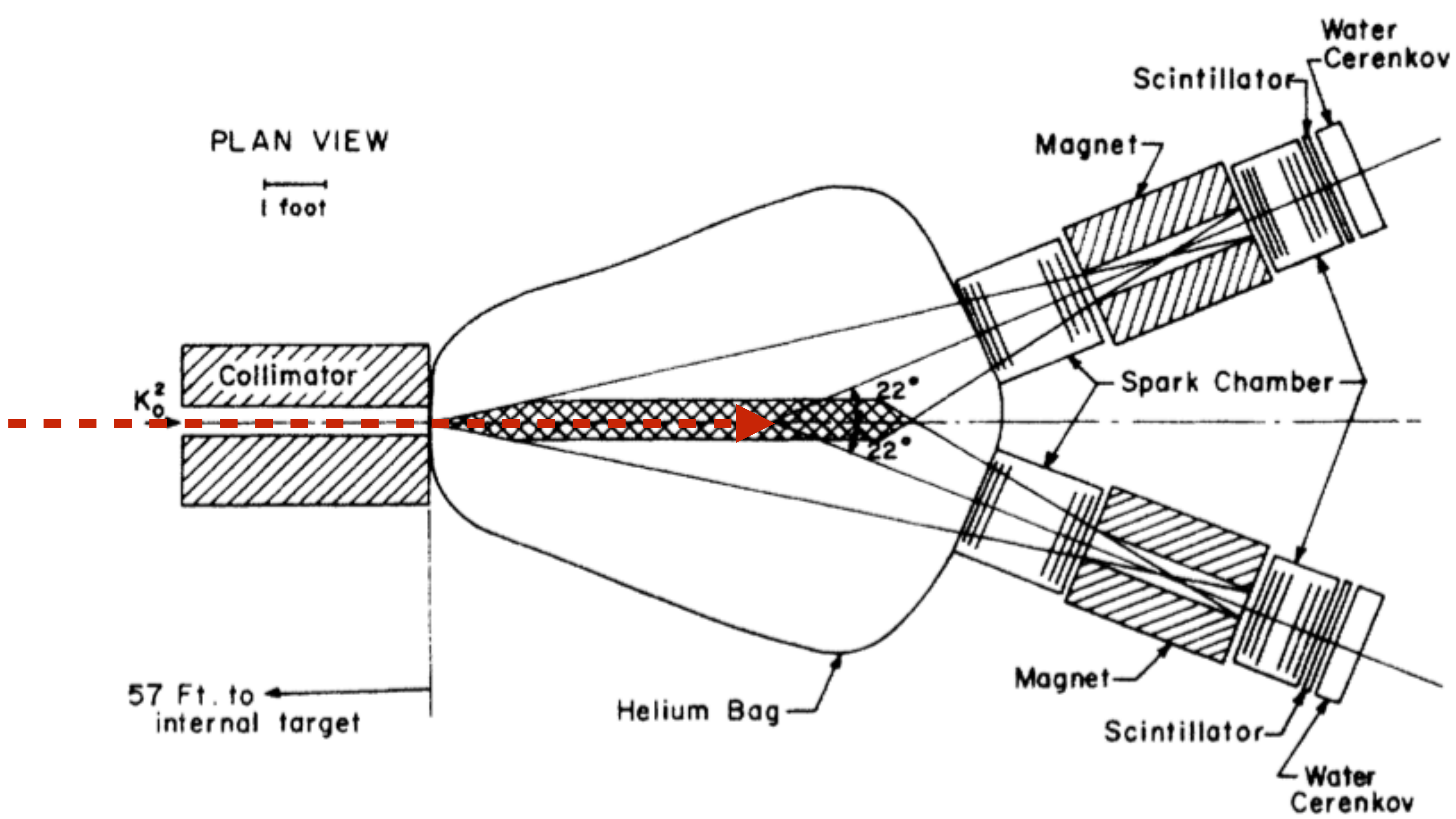


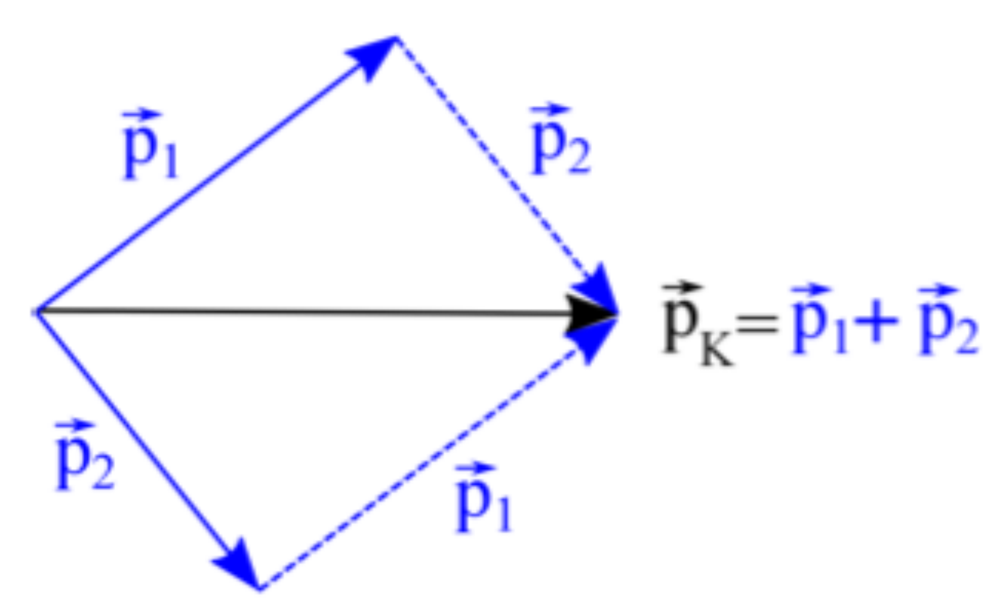
The Cronin & Fitch experiment

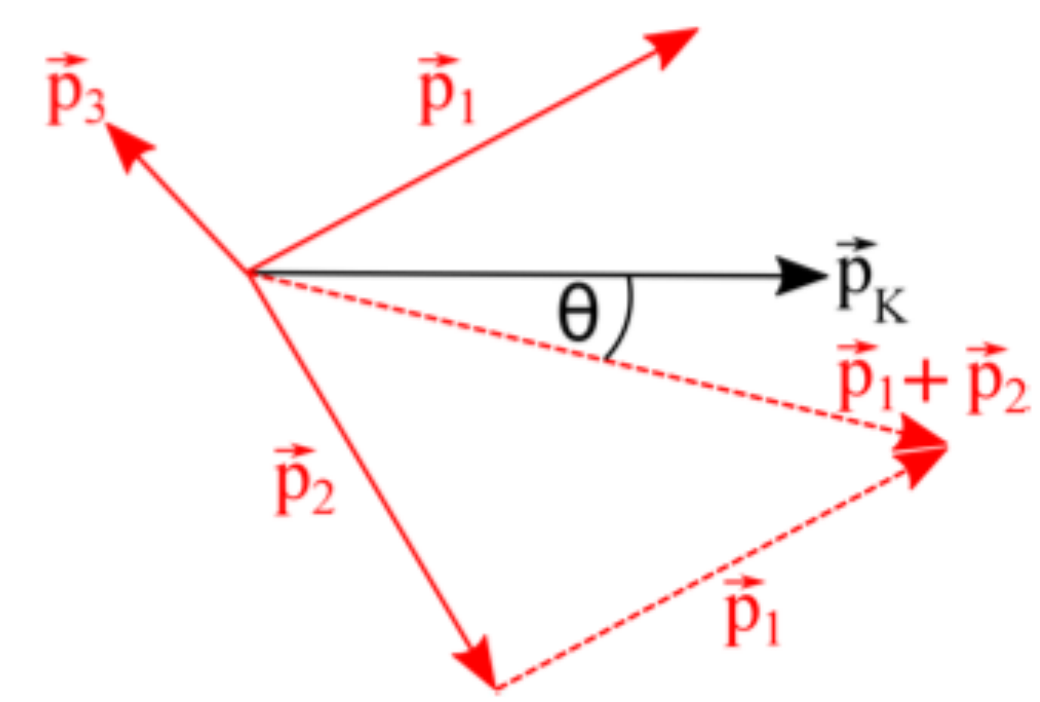
J.Cronin V. Fitch



- Investigating some anomaly reported in the “regeneration” phenomenon with 2 magnetic spectrometers ~20m away from K^0 production point (~300 K_1 lifetimes), where only K_2 are left



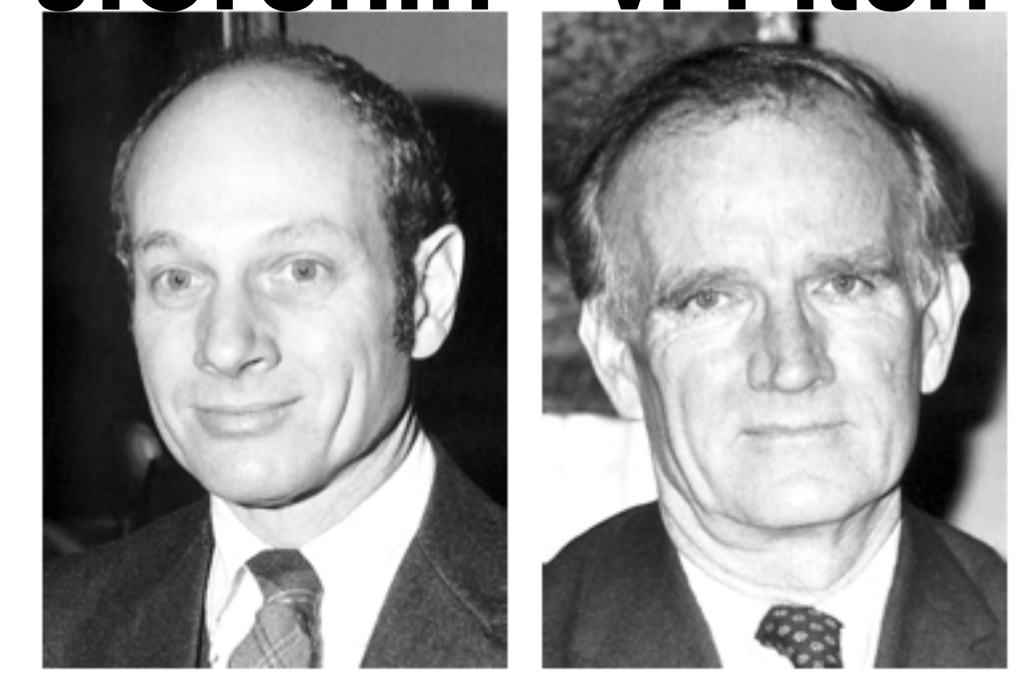




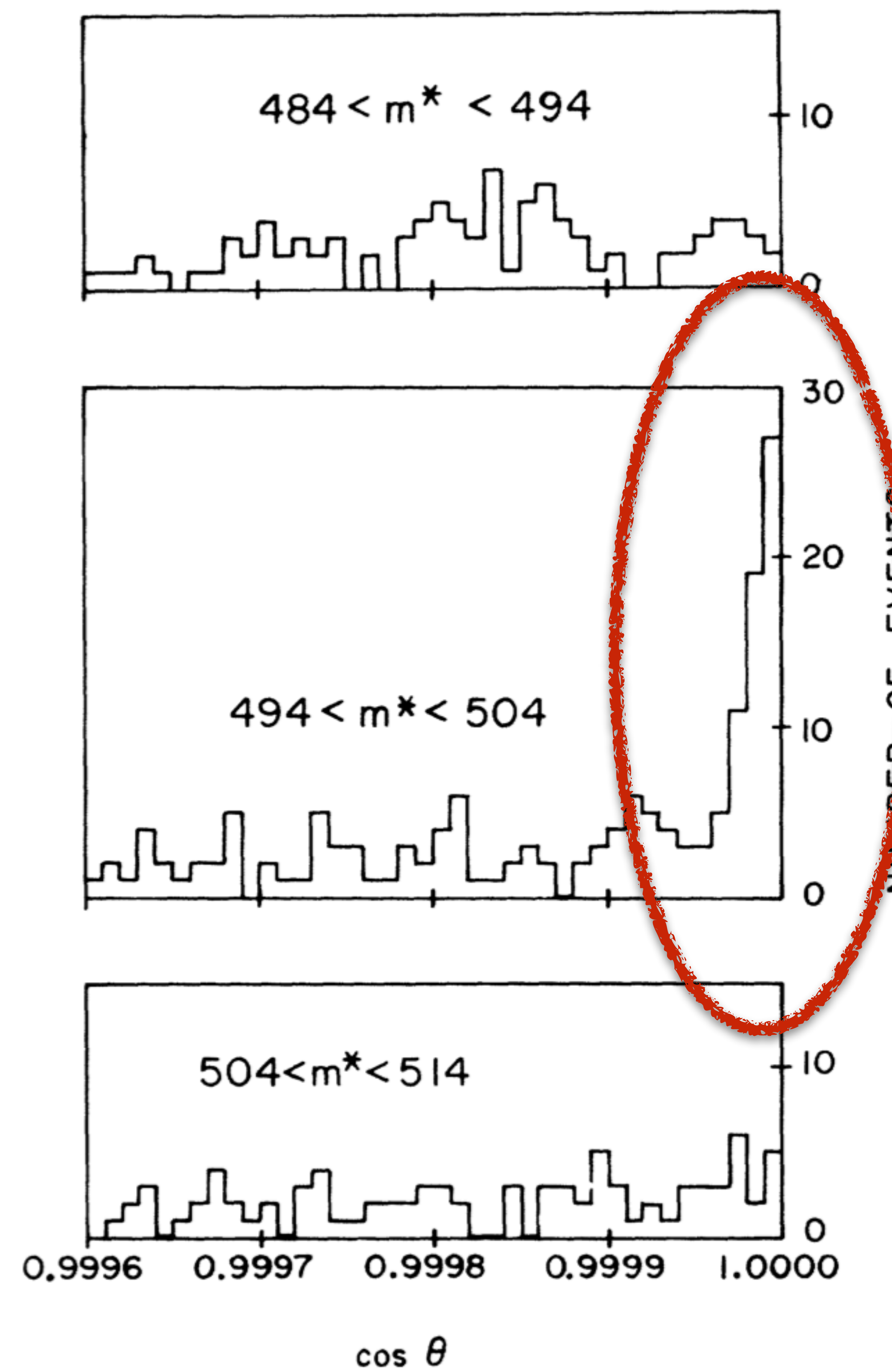
- For “wrong” CPV two-body decay $K_2 \to \pi\pi$, angle θ between vector sum of two momenta and beam direction should be $= 0$ and $\neq 0$ for three-body decays

The Cronin & Fitch experiment

J.Cronin V. Fitch



- A clear peak of ~45 events in forward direction $(cos\,\theta > 0.9999)$ at $m^* \sim m_K$
  - Background from 3-body decays $(\pi^+\pi^-\pi^0, \pi^\pm\mu^\mp\nu_\mu, \pi^\pm e^\mp\nu_e)$



- These 45 events correspond to $K_L \to \pi^+\pi^-$ decays with BF ~$2 \cdot 10^{-3}$
- Observation of $K_L \to \pi^+\pi^-$ implies that K_L is not a pure CP-eigenstate
- The actual physical states are given by

$$|K_L> \; = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_2> + \epsilon|K_1>) \sim |K_2>$$

$$|K_S> \; = \frac{1}{\sqrt{1+|\epsilon|^2}}(|K_1> + \epsilon|K_2>) \sim |K_1>$$

A more modern notation

- $|K_s^0\rangle = p|K^0\rangle + q|\overline{K}^0\rangle$
  $|K_L^0\rangle = p|K^0\rangle - q|\overline{K}^0\rangle$ with

- $p = (1+\epsilon)/\sqrt{2+|\epsilon|^2}$
  $q = (1-\epsilon)/\sqrt{2+|\epsilon|^2}$ and

- $q/p = (1-\epsilon)/(1+\epsilon)$

Cabibbo-Kobayashi-Maskawa

- Generalization to 6 quarks by Kobayashi and Maskawa (1973, 10 years after Cabibbo's theory)
- CP violation introduced in a natural way if there are at least three families of quarks

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- 2008 Nobel prize to K&M

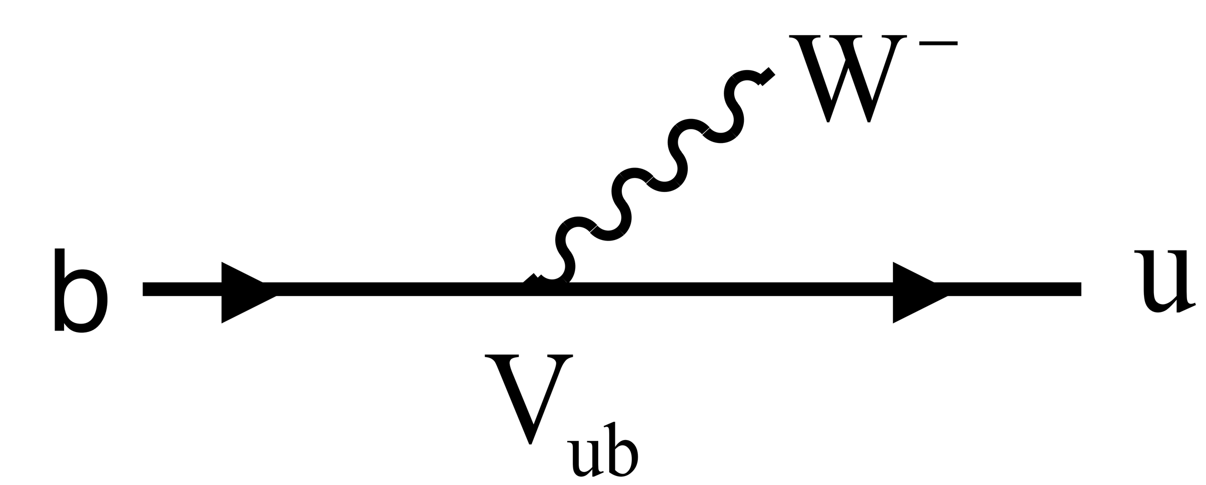
CKM matrix

- V_{CKM} describes the rotation between flavour (d', s', b') and mass (d, s, b) eigenstates

Flavour eigenstates

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

Mass eigenstates



- V_{ij} proportional to transition amplitude from quark i to quark j → V_{CKM} quark mixing matrix

- V_{CKM} induces flavour-changing transitions inside and between generations in the charged sector at tree level ($W^{\pm}$interaction). (By contrast, there are no flavour-changing transitions in the neutral sector at tree level.)

How many independent parameters are needed to determine V_{CKM}?

- $N \times N$ complex matrix (with $N = 3$)
- N^2 complex entries with N^2 unitarity constraints ($V^\dagger V = 1$)
- $2N - 1$ phases not physically meaningful → V_{CKM} depends on $N^2 - 2N + 1 = (N-1)^2$ real physical parameters
- An orthogonal matrix has $N(N-1)/2$ independent parameters (mixing angles, e.g., for $N = 3$, 3 Euler angles)
- V_{CKM} has $N(N-1)/2$ mixing angles and $(N-1)^2 - N(N-1)/2 = (N-1)(N-2)/2$ phases
- For $N = 2$, one mixing angle θ_c and no phases
- For $N = 3$, three angles $\theta_{12}, \theta_{13}, \theta_{23}$ and one complex phase δ

Important consequences

- CP violation in K decays is small, regardless of the value of the complex phase, because the dominant diagrams involve only quarks from the first two families

- If we want to see large CP-violating effects coming from the CKM matrix, we must look for processes which involve, even in leading approximation, quarks from all three generations.

- Large CP violating asymmetries are expected in b decays!

-

Are there more than three generations?

- LEP operated at CERN from 1989 to 2000, and delivered e^+e^-collisions to four experiments at $\sqrt{s} \simeq M_Z$ and above

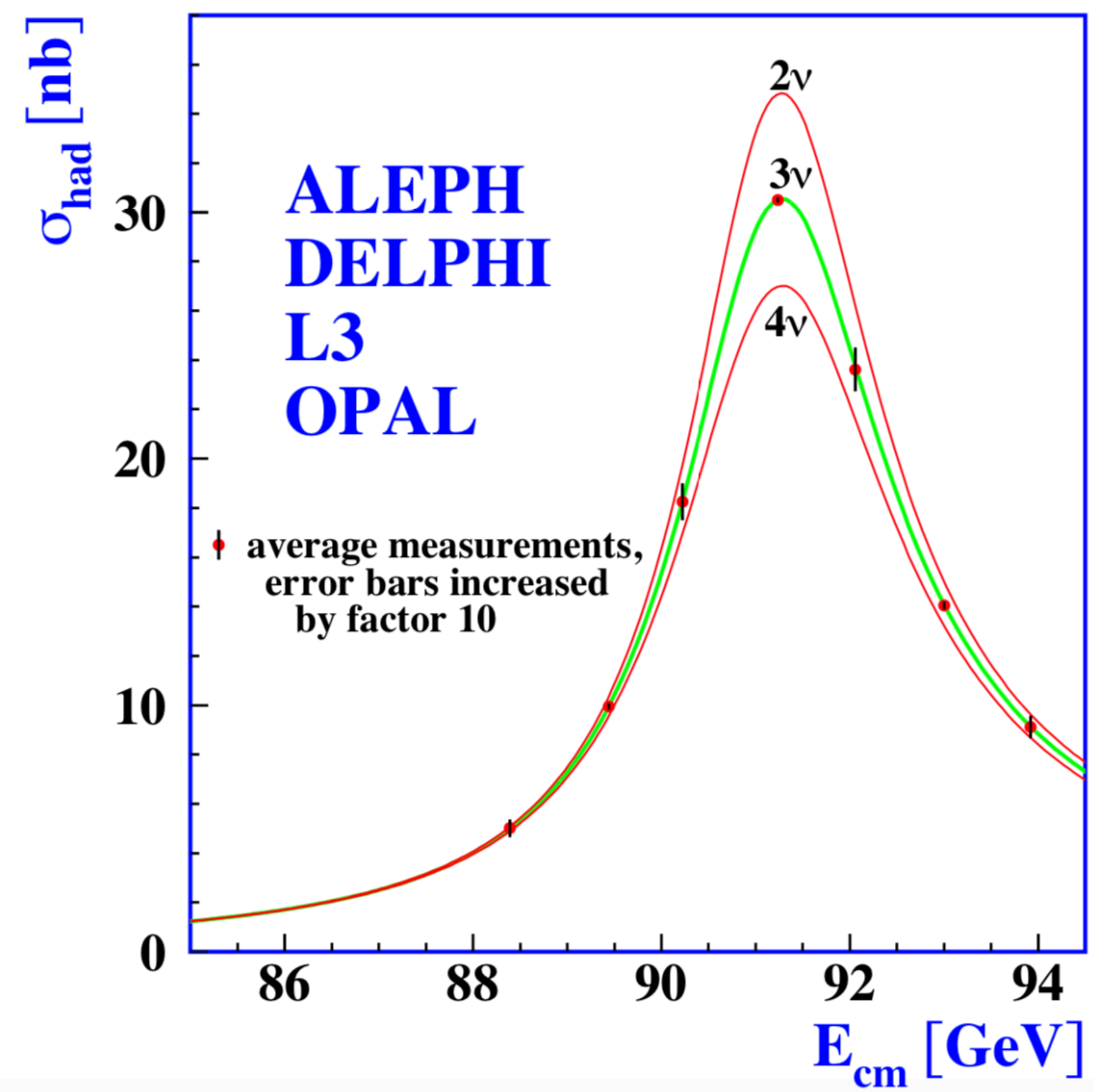
- Hadronic cross-section at the Z peak used to derive the number of light neutrino species N_ν

$$\sigma_f^0(s = M_Z^2) = 12\pi \frac{\Gamma_e \Gamma_f}{M_Z^2 \Gamma_Z^2}.$$

- Dependence on N_ν through:

$$\Gamma_Z = 3\Gamma_\ell + \Gamma_{\text{had}} + N_\nu \Gamma_\nu$$

[LEP EW WG: Phys. Rept. 427 (2006)]



$$N_\nu = 2.9840 \pm 0.0082$$

Based on 17 million Z decays

V_{CKM} parametrizations

- It can be written as product of three independent 2×2 block matrices

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

$s_{ij} = \sin\theta_{\mathrm{ij}},\ c_{ij} = \cos\theta_{\mathrm{ij}}$

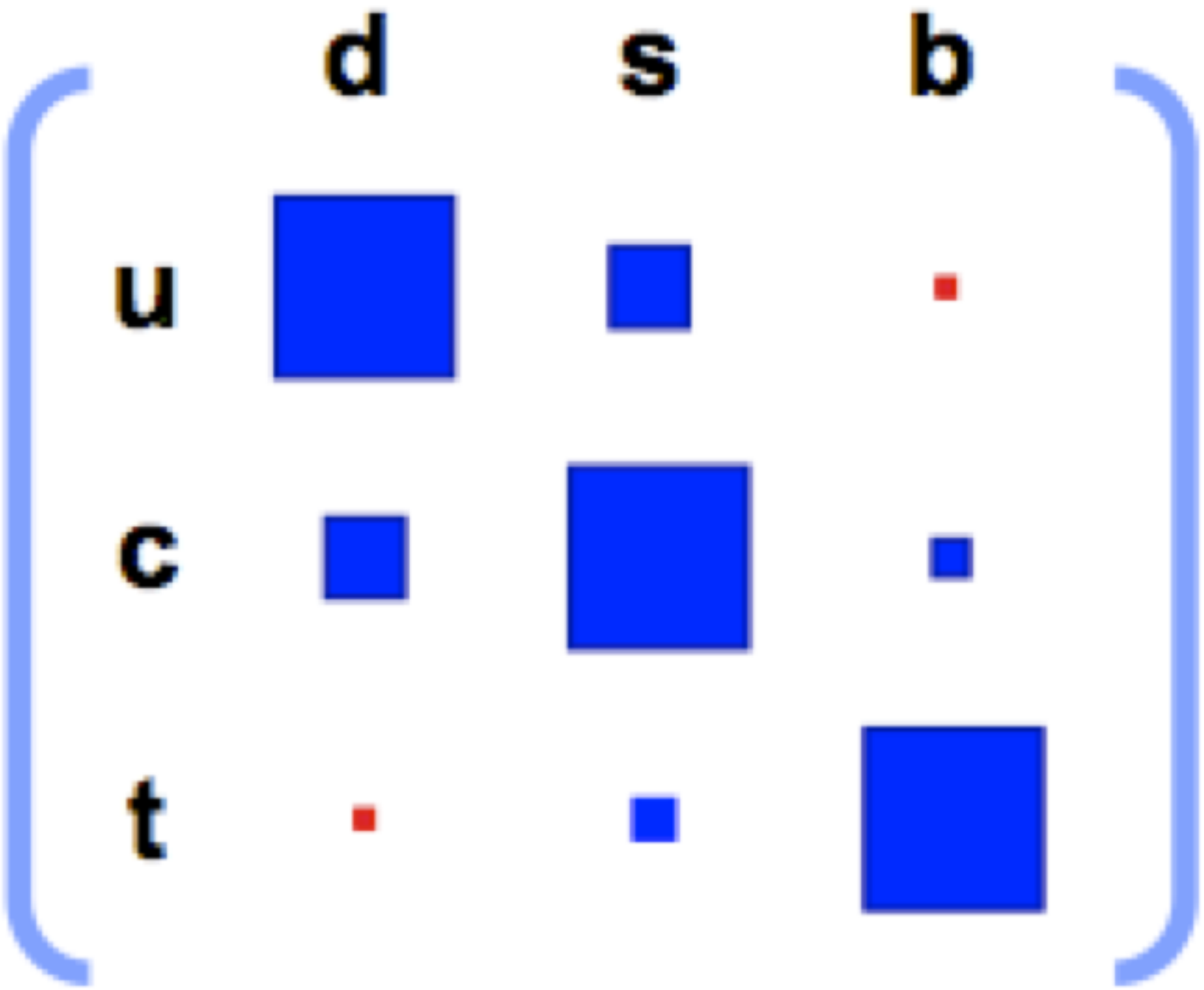
Maiani, Chau&Keung

- Advantage of this parametrization is that mixing angles are of different orders of magnitude. From experiment we know that $s_{12} \equiv \lambda,\ s_{23} \sim \mathcal{O}(\lambda^2),\ s_{13} \sim \mathcal{O}(\lambda^3)$ with $\lambda = \sin\theta_{\mathrm{c}} \approx 0.22$

- It is convenient to make this hierarchy more explicit, following Wolfenstein: $s_{12} = \lambda,\ s_{23} = A\lambda^2,\ s_{13}e^{i\delta} = A\lambda^3(\rho + i\eta)$ so that V_{CKM} can be expanded as

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

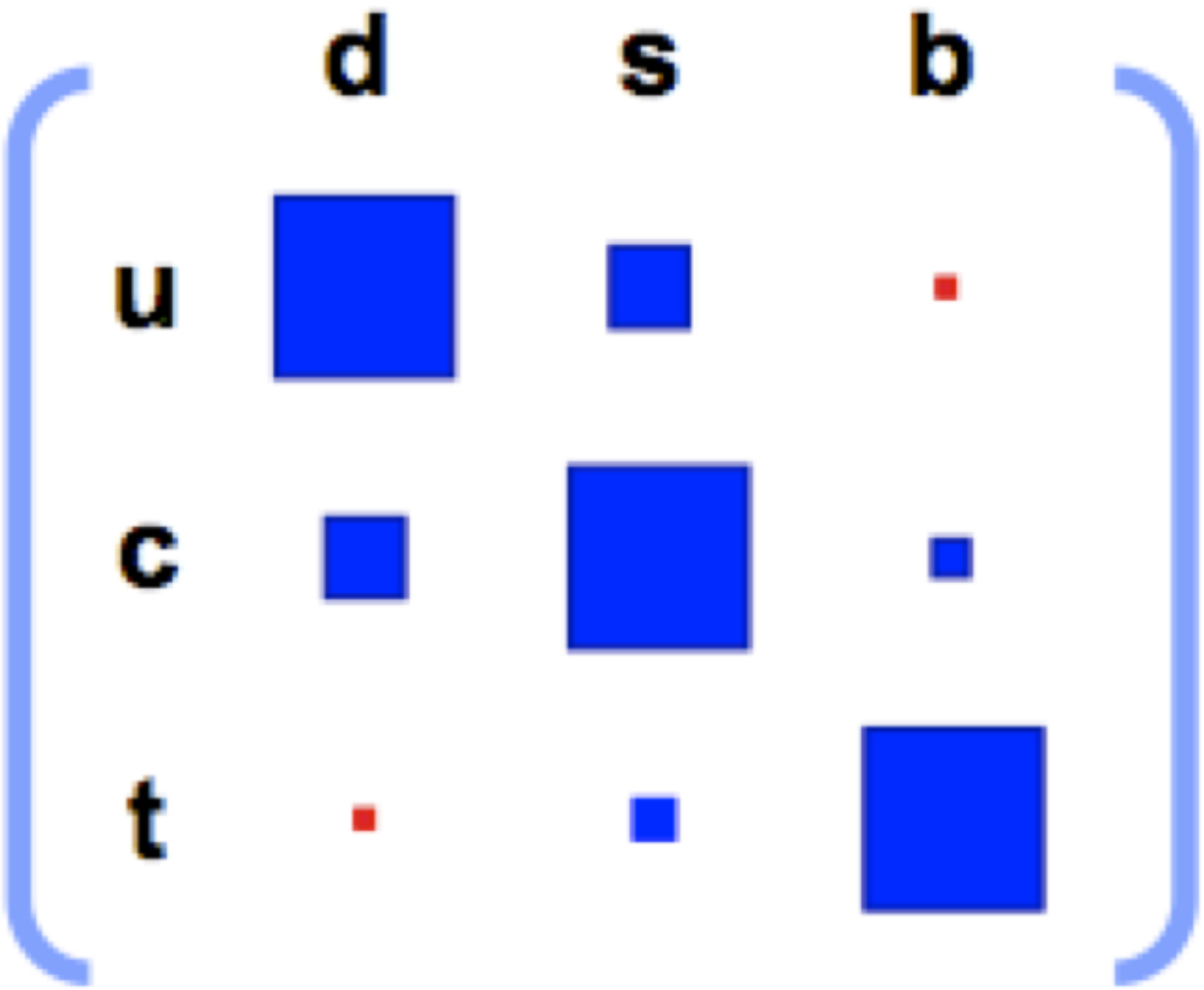
Hierarchy in quark mixing



- Each quark has a preference to transform into a quark of its own generation.
- Very suggestive pattern
- No known reasons
- Completely different in neutrino sector

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

Hierarchy in quark mixing



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$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \sim \begin{pmatrix} 0.97446 & 0.22452 & 0.00365 \\ 0.22438 & 0.97359 & 0.04214 \\ 0.00896 & 0.04133 & 0.999105 \end{pmatrix}$$

Unitarity conditions

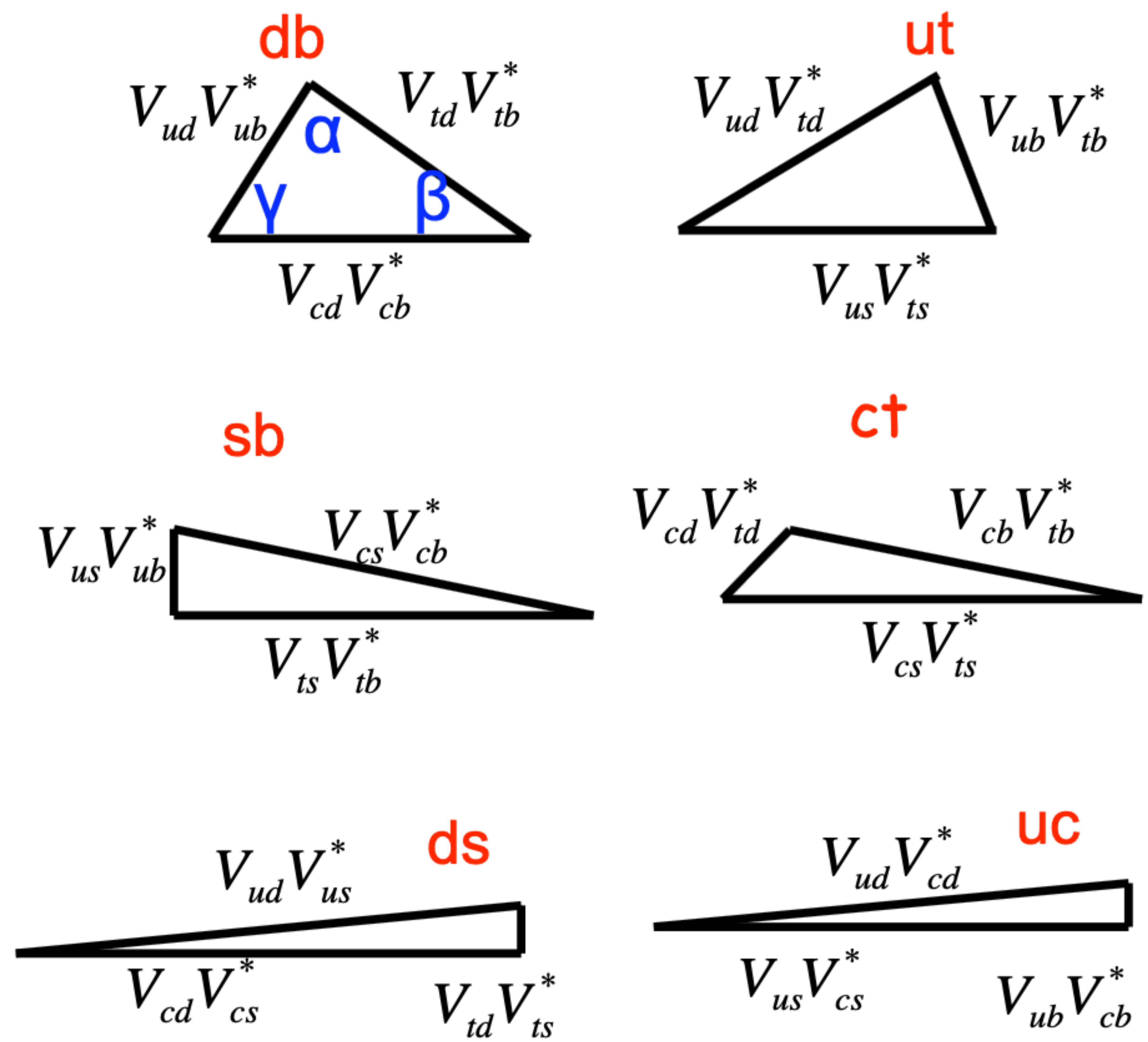
- Unitarity of CKM matrix implies relations of the form $\sum_i V_{ij}V^*_{ik} = \delta_{j,k}$, with $j \neq k$
- Each of these 6 unitarity constraints can be seen as the sum of 3 complex numbers closing a triangle in the complex plane
- All triangles have the same area a, half of the Jarlskog invariant (independent of parametrization):

$$J = 2a = c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta \simeq \lambda^6 \mathrm{A}^2\eta \simeq 10^{-5}$$

- J is a measure of CPV in the SM (we introduced J in the context of baryogenesis); J equal to zero if any one of the mixing angles or phase is zero

Unitarity conditions

- Only db and ut triangles have sides of the same order (λ^3), i.e. are not squashed
- db triangle used to define angles α, β, γ (**Unitarity Triangle**)
- ut triangle of special relevance for physics of B_s mesons



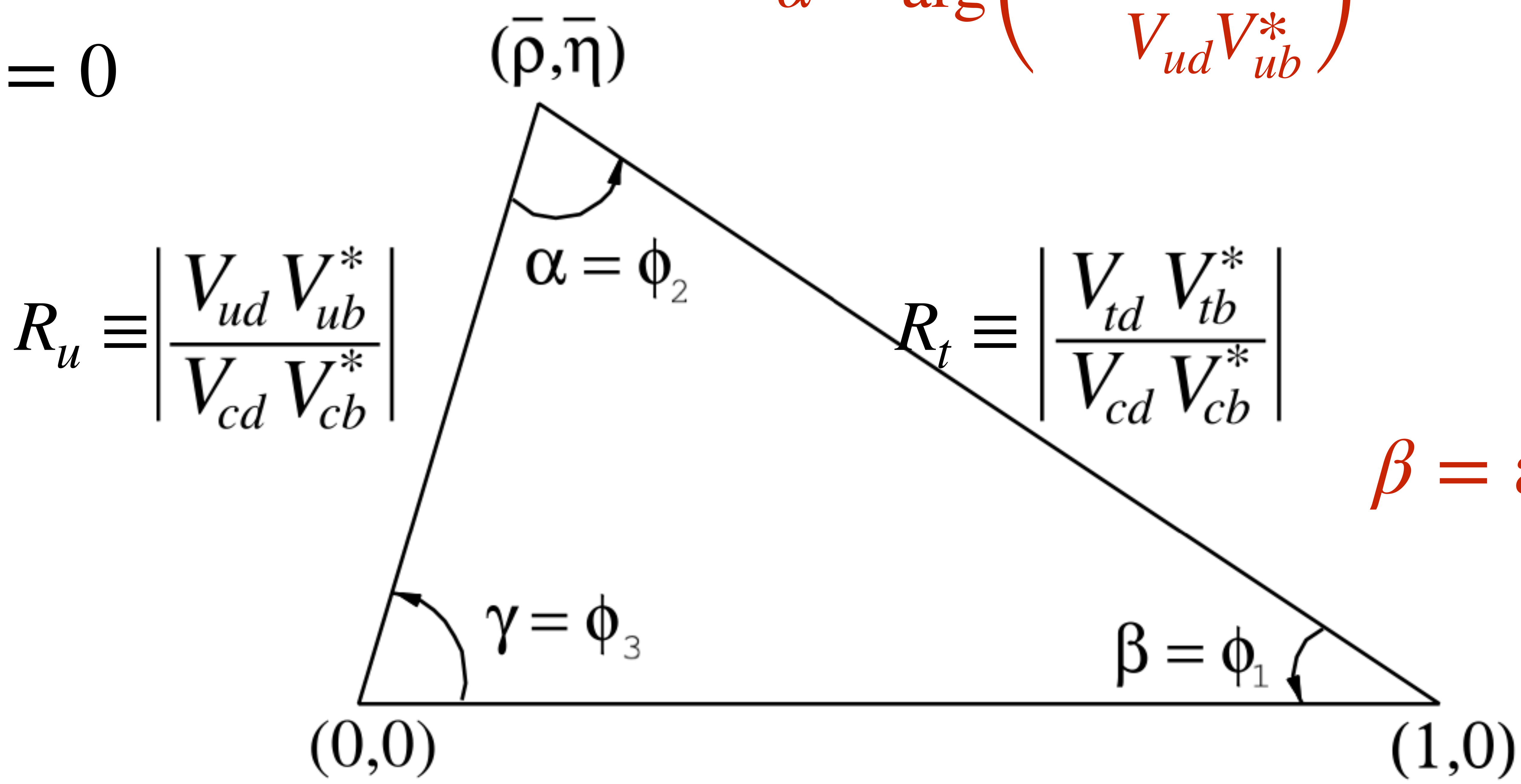
Unitarity Triangle (UT)

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

$$\mathcal{O}(\lambda^3) \qquad \mathcal{O}(\lambda^3) \qquad \mathcal{O}(\lambda^3)$$

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

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

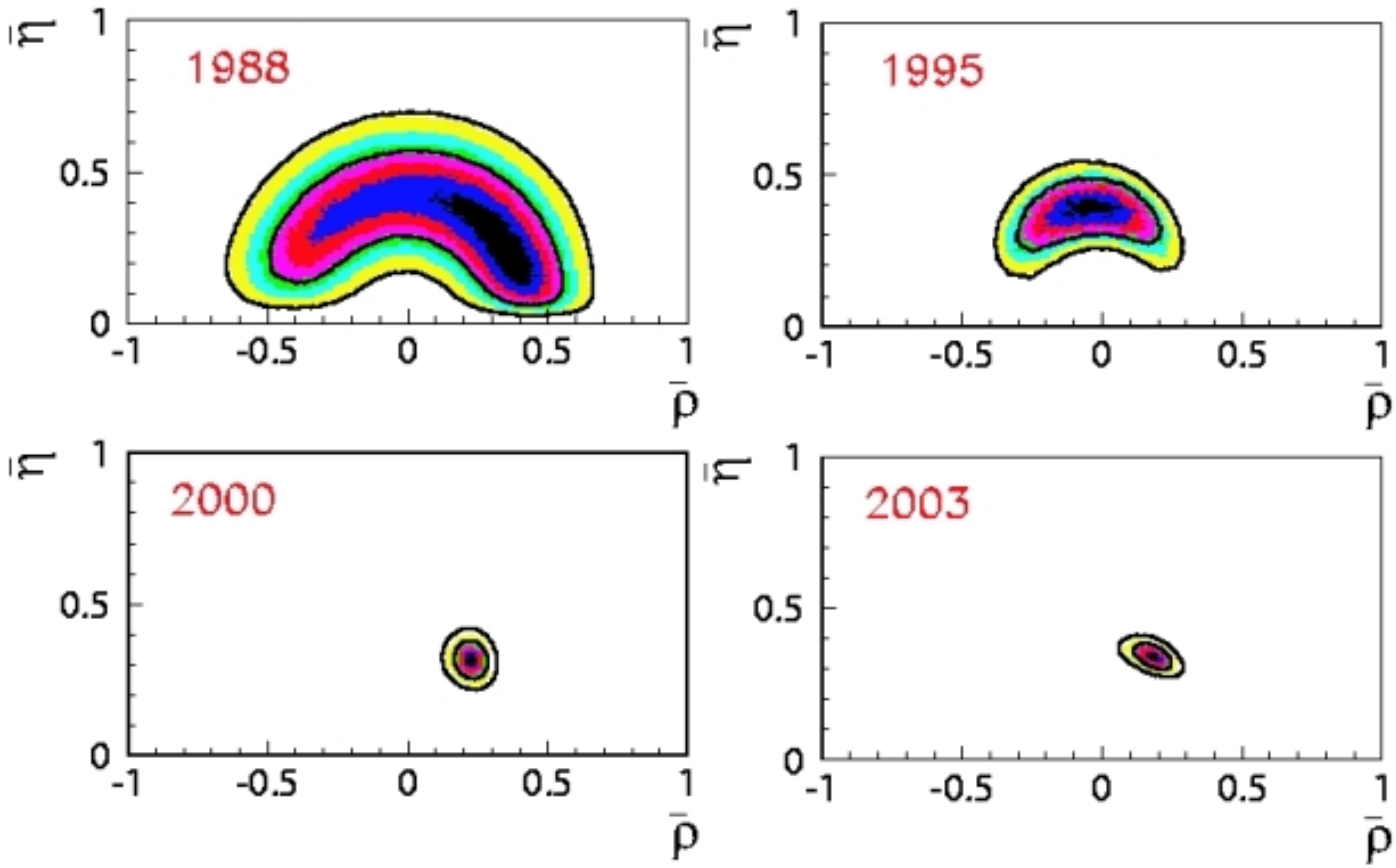


$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

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

- The triangle has vertices at $(0,0), (1,0), (\bar{\rho},\bar{\eta})$ with $\bar{\rho} \equiv \rho\left(1-\lambda^2/2\right), \bar{\eta} \equiv \eta\left(1-\lambda^2/2\right)$
- CP violation in the quark sector ($\bar{\eta} \neq 0$) is translated into a non flat UT
- Huge improvement in the knowledge of the CKM elements in the last decades!

15 years of $(\bar{\rho}, \bar{\eta})$ predictions



PDG2019

$$\bar{\rho} = 0.122^{+0.018}_{-0.017}$$

$$\bar{\eta} = 0.355^{+0.012}_{-0.011}$$

$$\lambda = 0.22453 \pm 0.00044$$

$$A = 0.836 \pm 0.015$$

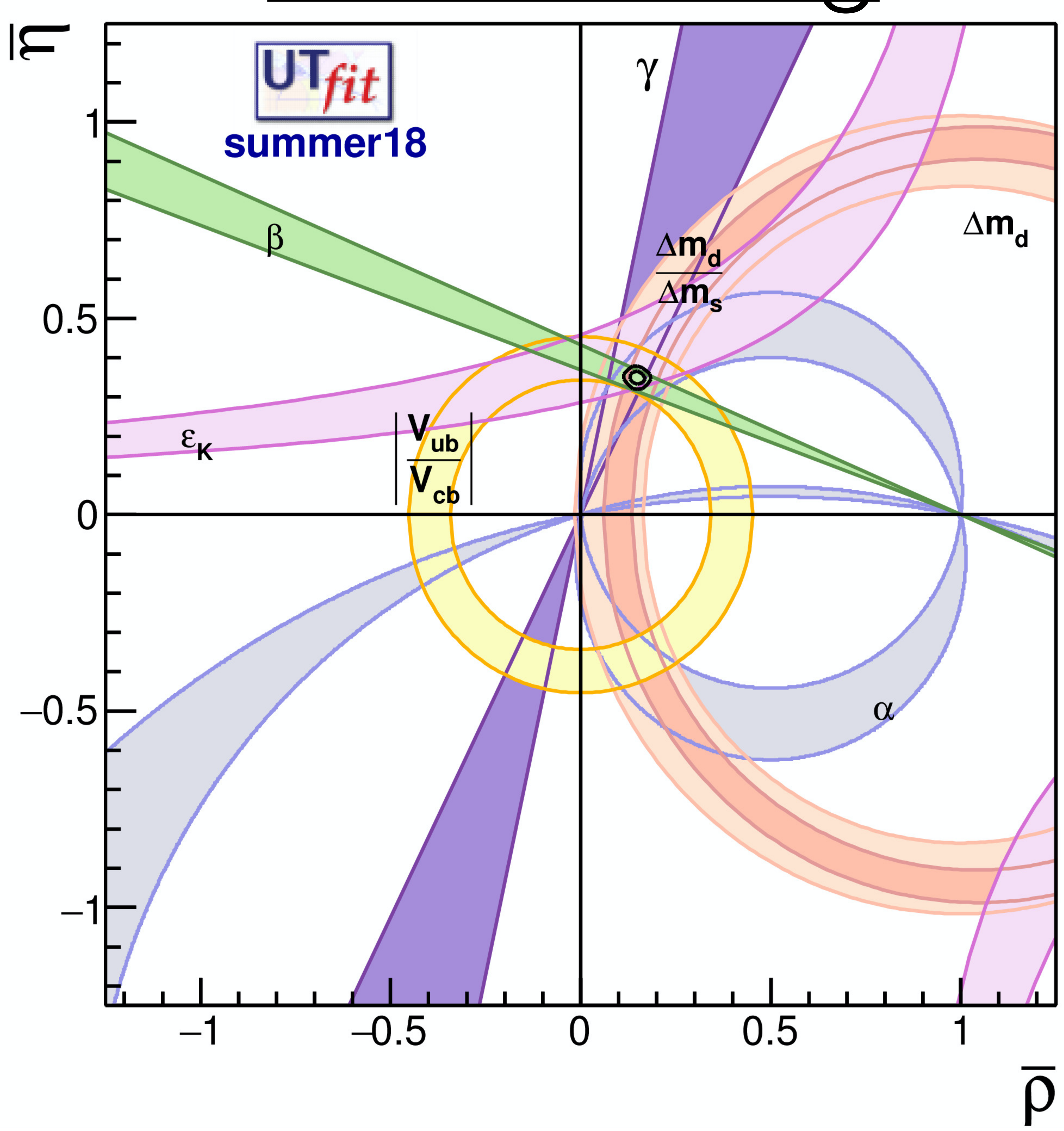
- Black curves give contours at 68% and 95% probability (from http://www.utfit.org)

Consistency of CKM fits

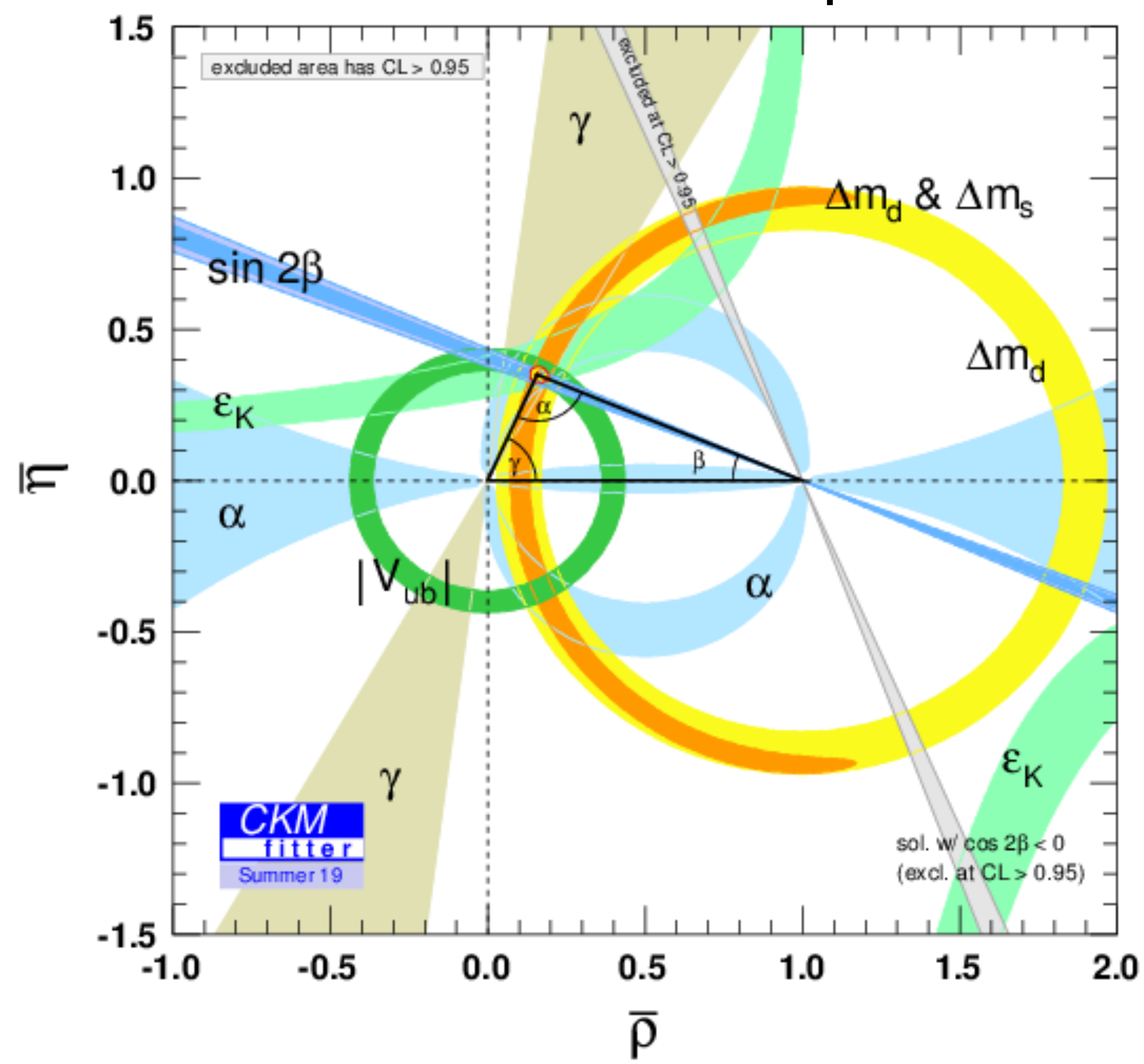
- The interesting question is not so much measuring the CKM elements, but rather testing how precisely the SM description of flavour and CP violation holds. This is done by performing “redundant" measurements, which in the SM relate to some combination of flavour parameters, testing for inconsistencies.

Consistency of CKM fits

www.utfit.org



ckmfitter.in2p3.fr



- **Impressive effort from community and tremendous success of CKM paradigm!**
- Constraints from many different quark transitions. Extensive measurements on K, D and B mesons performed at different experiments. These constraints depend also on theory input.
- At the current level of precision, all measurements are consistent and intersect in the apex of the UT
- New Physics effects (if there) are small!

A large experimental effort…

- Constraints coming from K mesons from. e.g., NA48 at CERN, KLOE at LNF, KTeV at FNAL
- Measurements of CKM parameters from D and B mesons pioneered by ARGUS at DESY, CLEO, and CLEO-c at CESR, Cornell, followed by the so-called B-factory experiments BaBar at SLAC and Belle at KEK
- Significant contributions from CDF and D0 at FNAL, especially on B_s^0 mesons
- All the above experiments have been terminated while Belle has been upgraded (Belle II)
- LHCb at the LHC is now dominating physics with b and c hadrons while the general purpose detectors ATLAS and CMS contribute in selected areas and Belle II is ramping up
- BESIII in China provides many results on c hadrons, NA62 at CERN and KOTO at J-Parc measure very rare Kaon decays

The rise of b physics

- An accurate test of the CKM paradigm requires extending the physics programme to heavy-flavoured hadrons, in particular to B-meson decays
- In the late 80s, studies indicated that the best source for such a physics programme was an e^+e^- collider operating at the $\Upsilon(4S)$ but in an asymmetric mode, i.e. with beams of unequal energy [Oddone 1987].
  - The $\Upsilon(4S)$ has a mass of 10.58 GeV and decays essentially into $B\bar{B}$ pairs (roughly equally to B^+B^- and $B^0\bar{B}^0$)
- The collider must also have unprecedented luminosity ($\mathcal{O}(\text{ few } 10^{33})$/cm²/sec), to provide enough B-mesons
- Two such asymmetric, high-luminosity e^+e^-colliders operating at the $\Upsilon(4S)$, so-called B-factories, were eventually built in the 1990s:
  - PEP-II at SLAC in the United States
  - KEK-B at KEK in Japan

Why asymmetric?

- At a symmetric B-factory, the small Q-value of the $\Upsilon(4S) \to B\overline{B}$ results in B-mesons almost at rest in the CM: $p \simeq 330$ MeV $\rightarrow$ $\beta\gamma \simeq 0.06$

- $\tau_b \sim 1.5 \cdot 10^{-12}$ sec $\rightarrow$ $d = \beta\gamma c\tau \sim 30\,\mu$m $\qquad \tau \sim 1/(m^5 |V_{cb}|^2)$
  This is a decay length too small to be resolved by vertex detectors !

- With an asymmetric B-factory, boost increases the decay length:

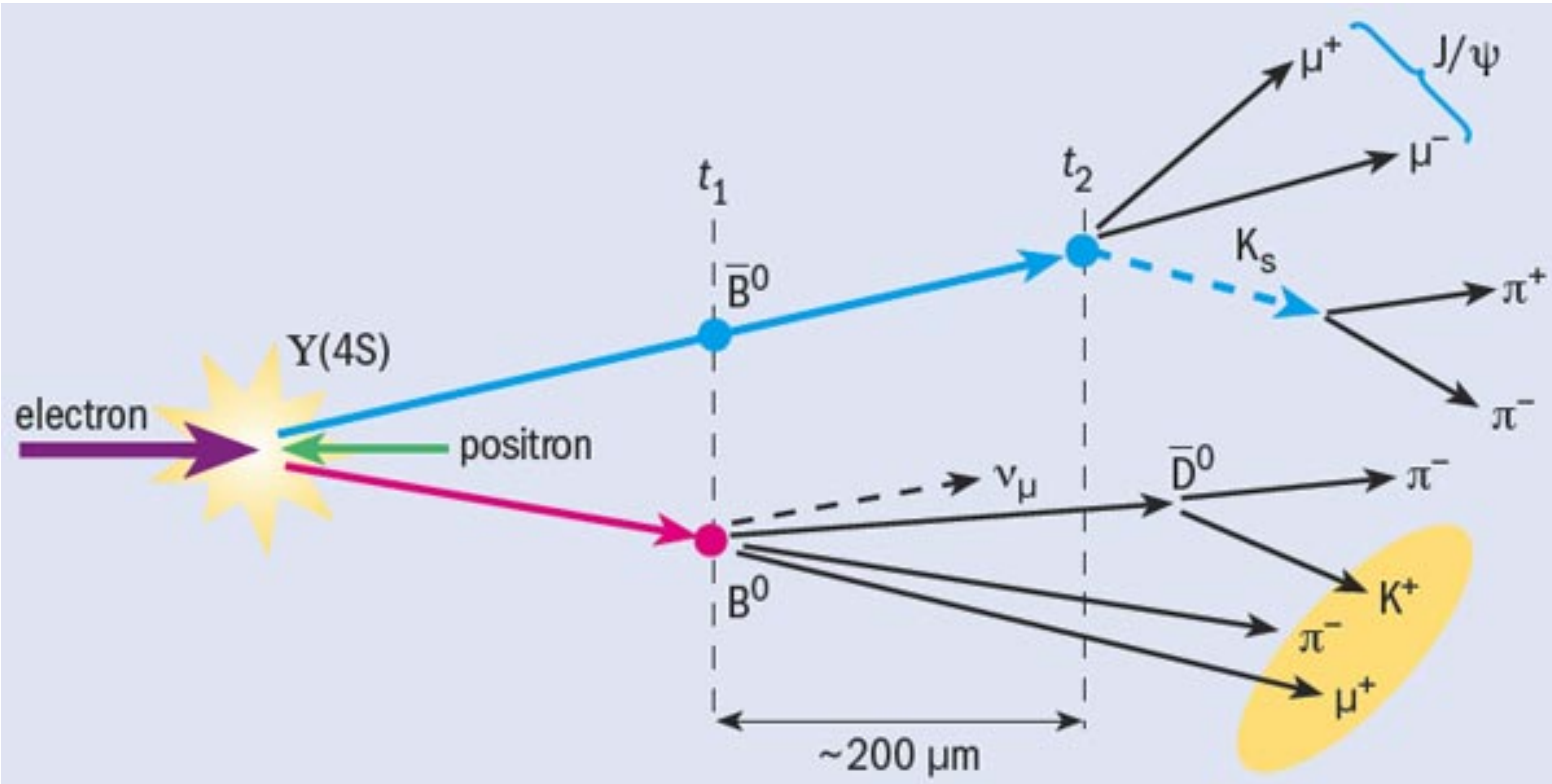
  - PEP-II collided 3.1 GeV e^+ and 9 GeV e^- head on $\rightarrow$ $\beta\gamma = 0.56$ boost of the $\Upsilon(4S)$ and an average separation between the two B vertices of $260\,\mu$s

  - KEK-B collided 3.5 GeV e^+ and 8 GeV e^-at ± 11 mrad crossing angle $\rightarrow$ $\beta\gamma = 0.43$ boost of the $\Upsilon(4S)$ and an average separation between the two B vertices of $200\,\mu$s

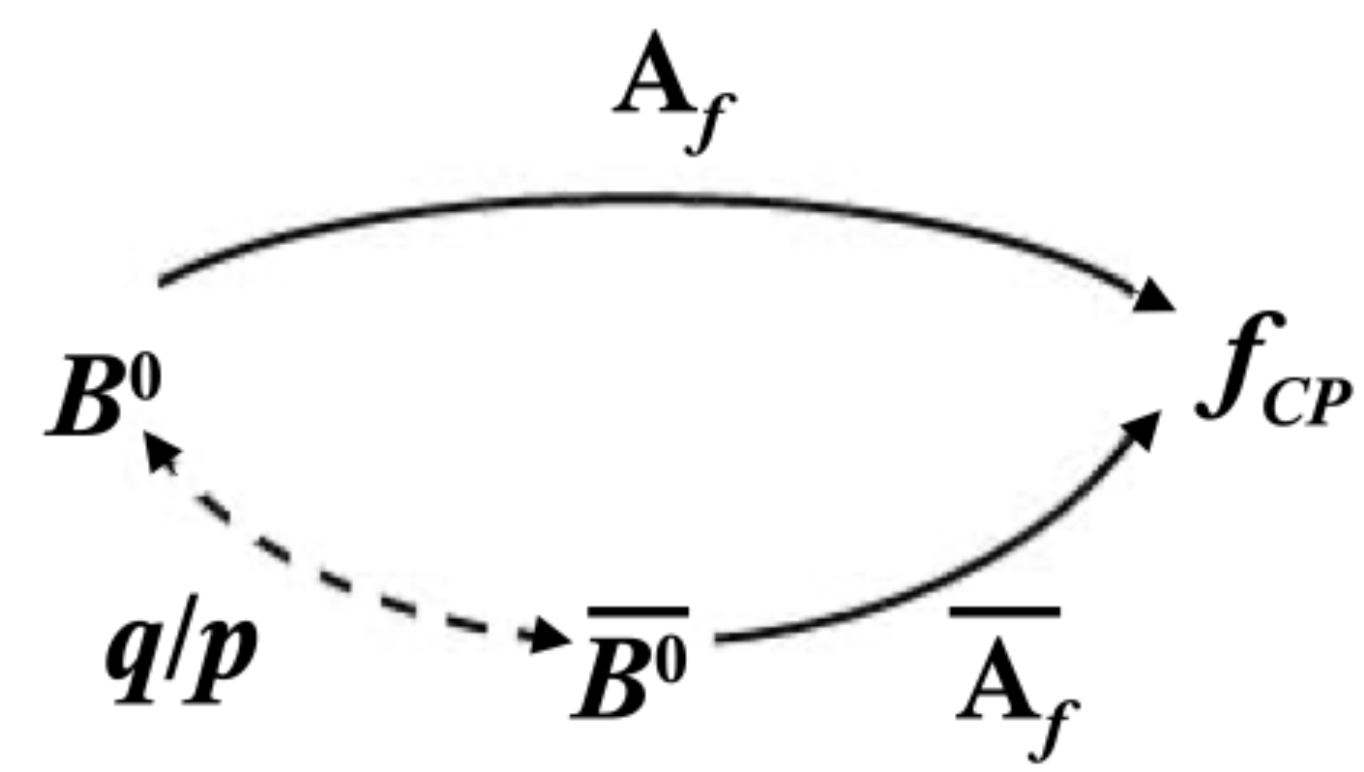
You are in business!!

- This idea [Oddone] was a radical break with tradition, as it required two separate beam pipes, each with their own magnet system and a complex interaction region

The golden mode: $B^0 \to J/\psi K_s^0$



- It allowed the first observation of CP violation in B decays at the B factories

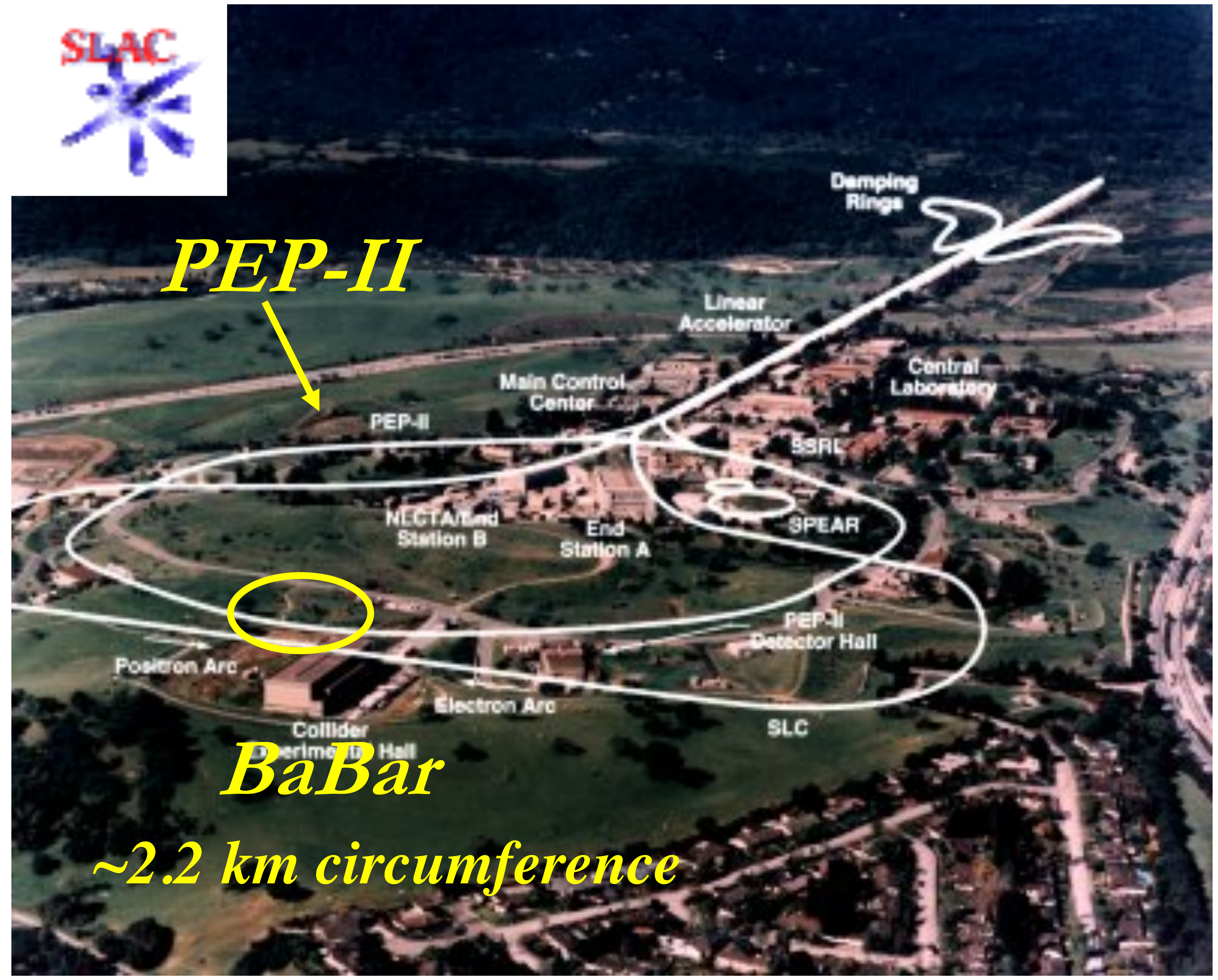


- Final state f_{CP} common to both B^0 and $\overline{B}^0$ decays: $CP\,|f_{CP}\rangle = \eta_{CP}\,|f_{CP}\rangle$ with $\eta_{CP} = \pm 1$
- Interference between the amplitudes for the direct decay and that after $B^0 - \overline{B}^0$ oscillation results in a decay-time dependent CP asymmetry :

$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0 \to J/\psi K_s) - \Gamma(B^0 \to J/\psi K_s)}{\Gamma(\overline{B}^0 \to J/\psi K_s) + \Gamma(B^0 \to J/\psi K_s)} \cong \sin(2\beta)\sin(\Delta m\,\Delta t)$$, where

$\Delta t \equiv t_{\rm rec} - t_{\rm tag}$ is the time difference between the two decays and Δm the mass difference between the heavy and light mass eigenstates of the $B^0 - \overline{B}^0$ system

KEKB and PEP-II

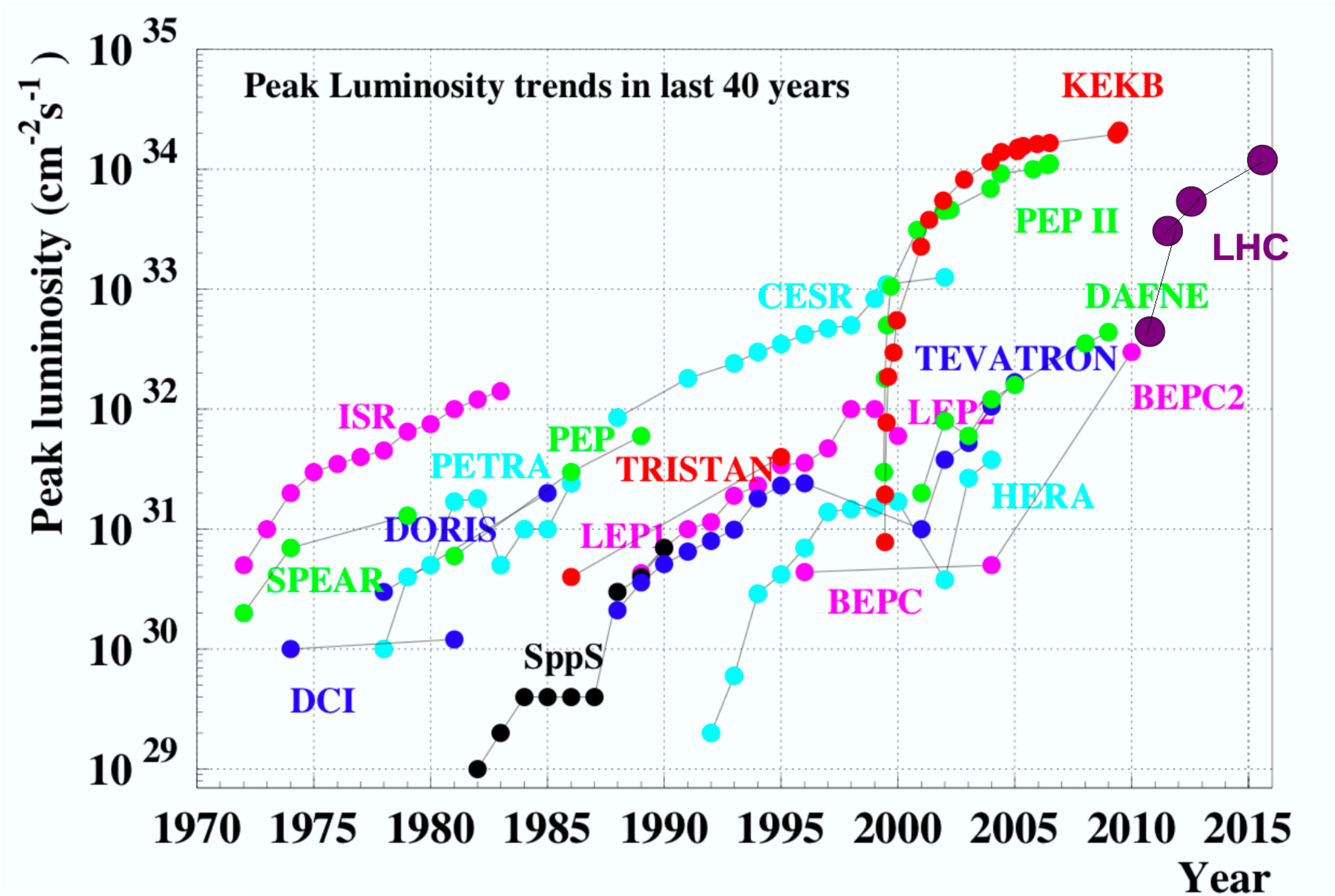


3.5 GeV e^+ 8 GeV e^- 3.1 GeV e^+ 9 GeV e^-

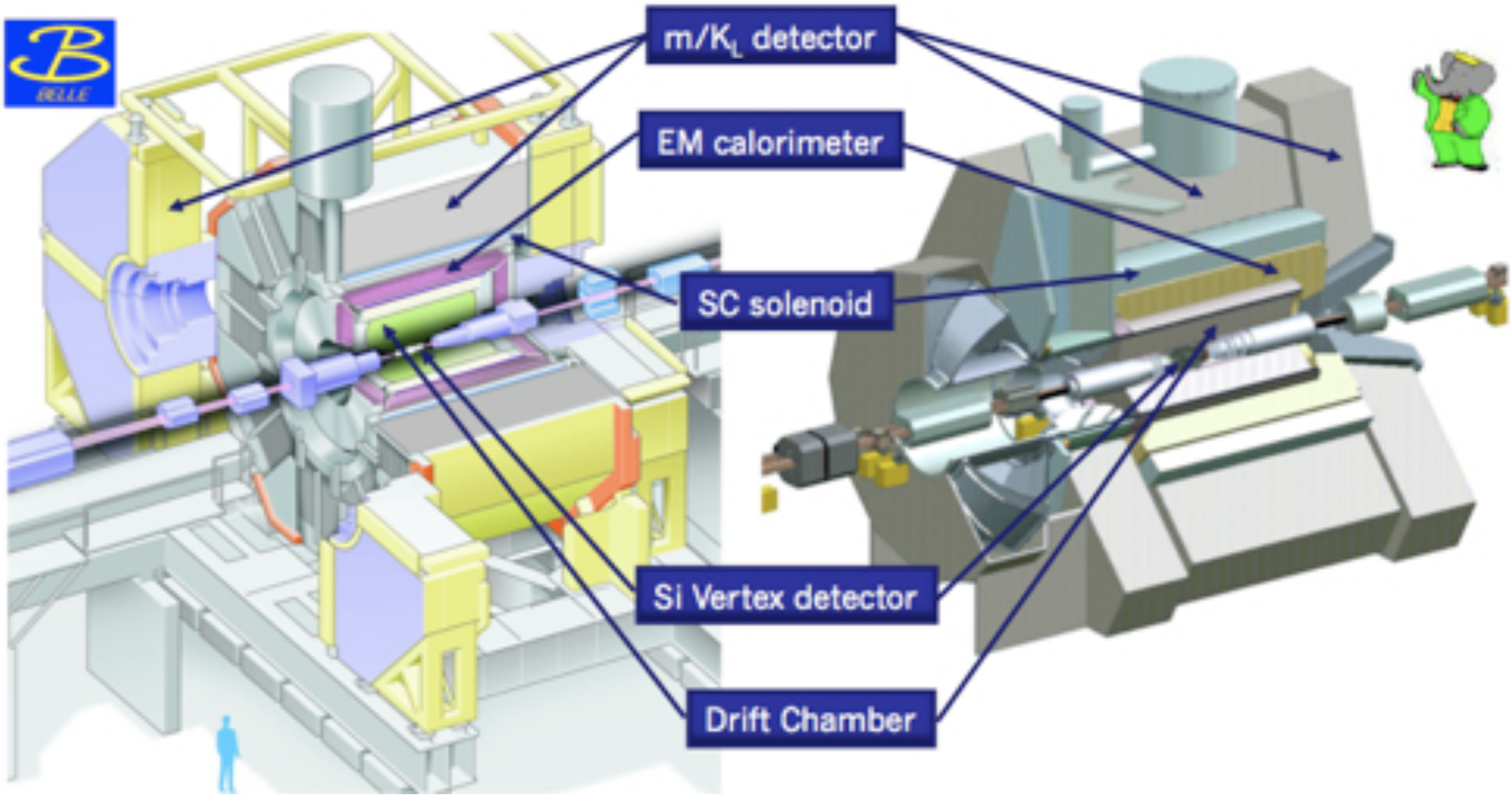
- Exceptional performance! The two machines broke any existing record of instantaneous and integrated luminosity of previous particle colliders and recorded over 10^9 $B\bar{B}$ pairs at the $\Upsilon(4S)$!

-

World record luminosities

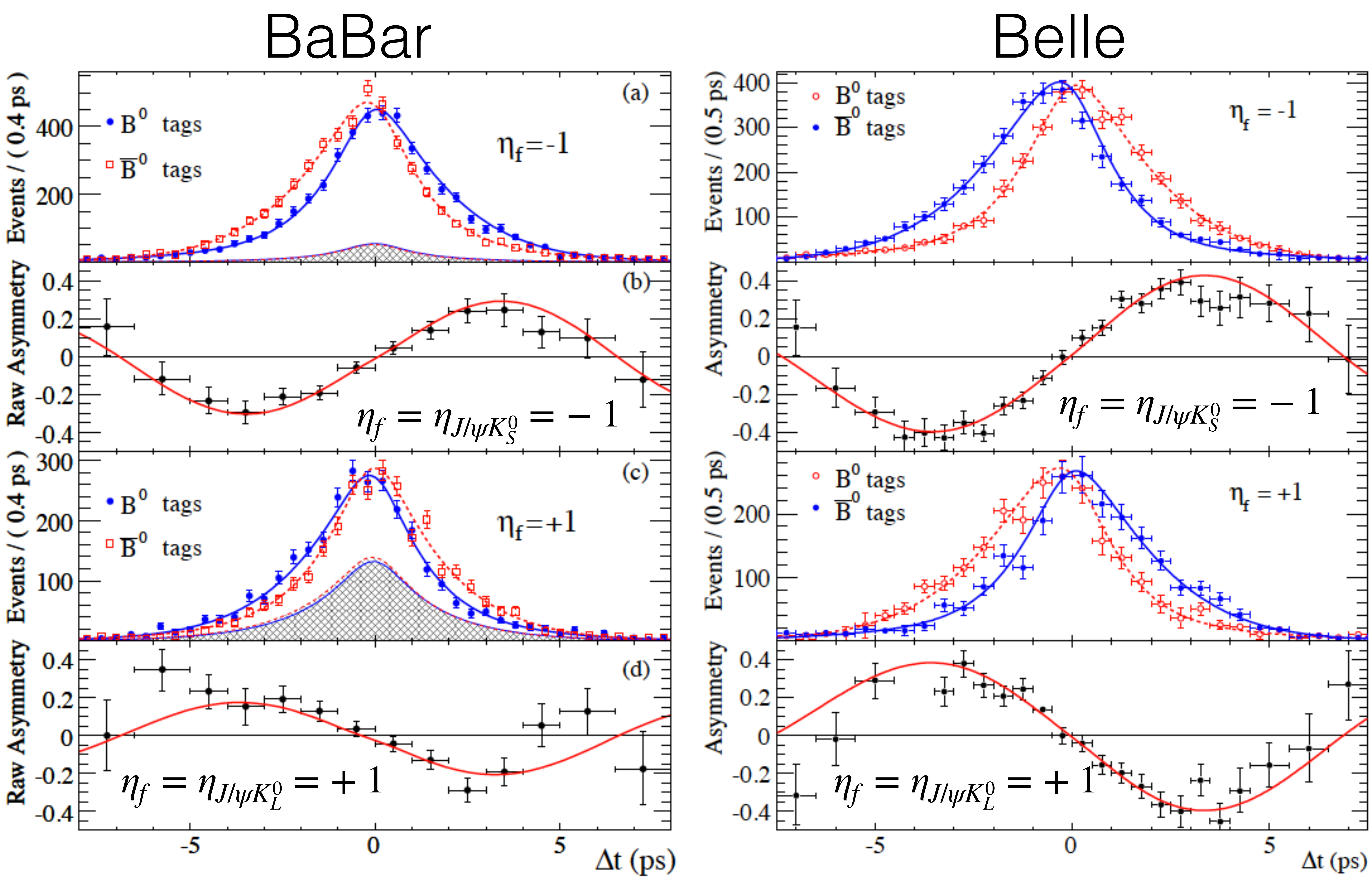


Belle and BaBar



- BaBar at PEP-II and Belle at KEKB took data from 1999 to 2008 and 2010, respectively
- Each of the two experiments did an excellent job of reconstructing charged tracks and decay vertices, detecting photons even down to low energy (~ 30 MeV) and performing particle identification to reconstruct electrons, muons, pions, kaons and protons.

$B^0 \to (c\bar{c})K^0_{S/L}$ at BaBar and Belle



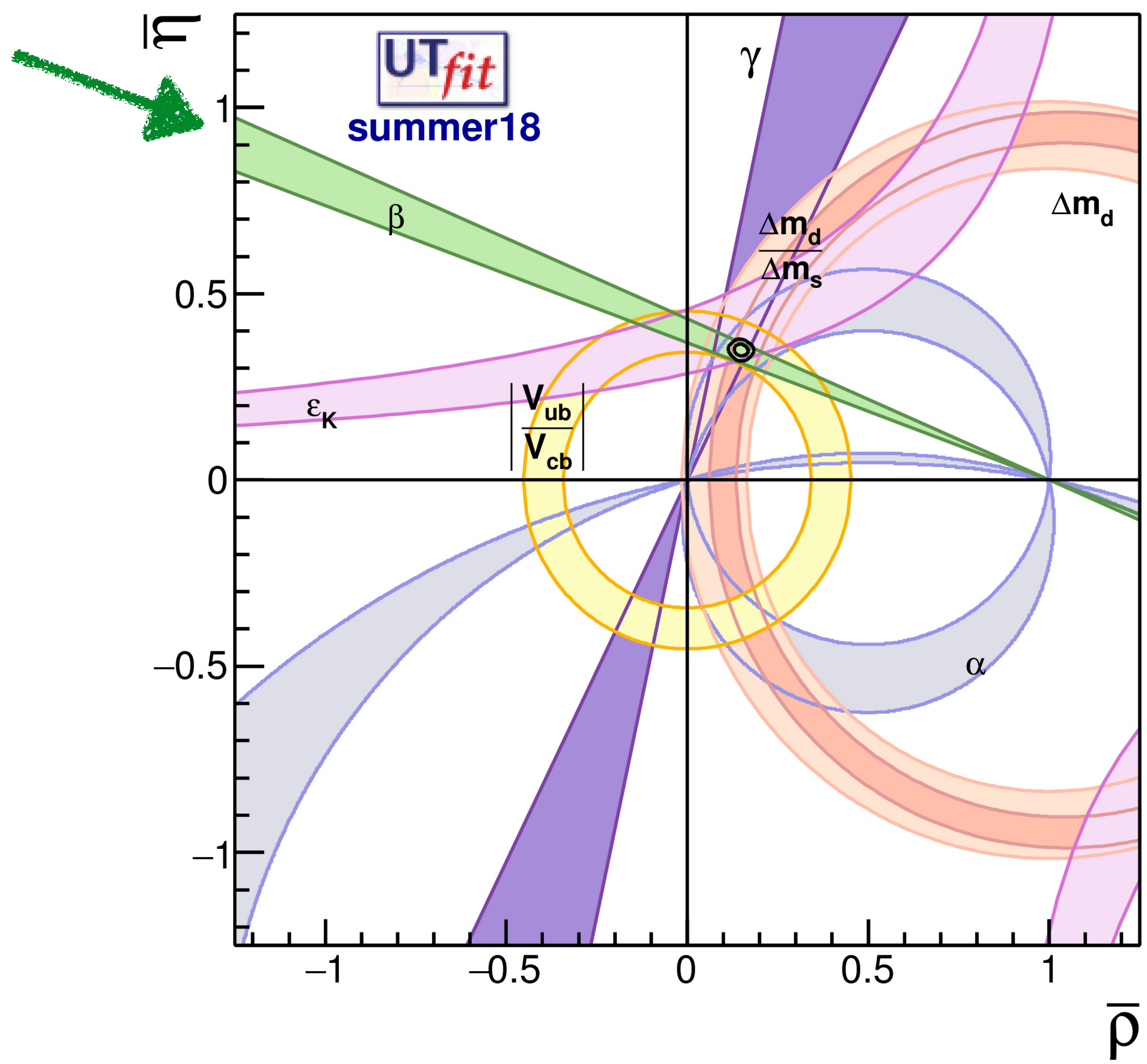
$\eta_f = +1(-1)$ is the CP eigenvalue for a CP-even (odd) finale state

$$\frac{N_{B^0} - N_{\bar{B}^0}}{N_{B^0} + N_{\bar{B}^0}}$$

$$\frac{N_{B^0} - N_{\bar{B}^0}}{N_{B^0} + N_{\bar{B}^0}}$$

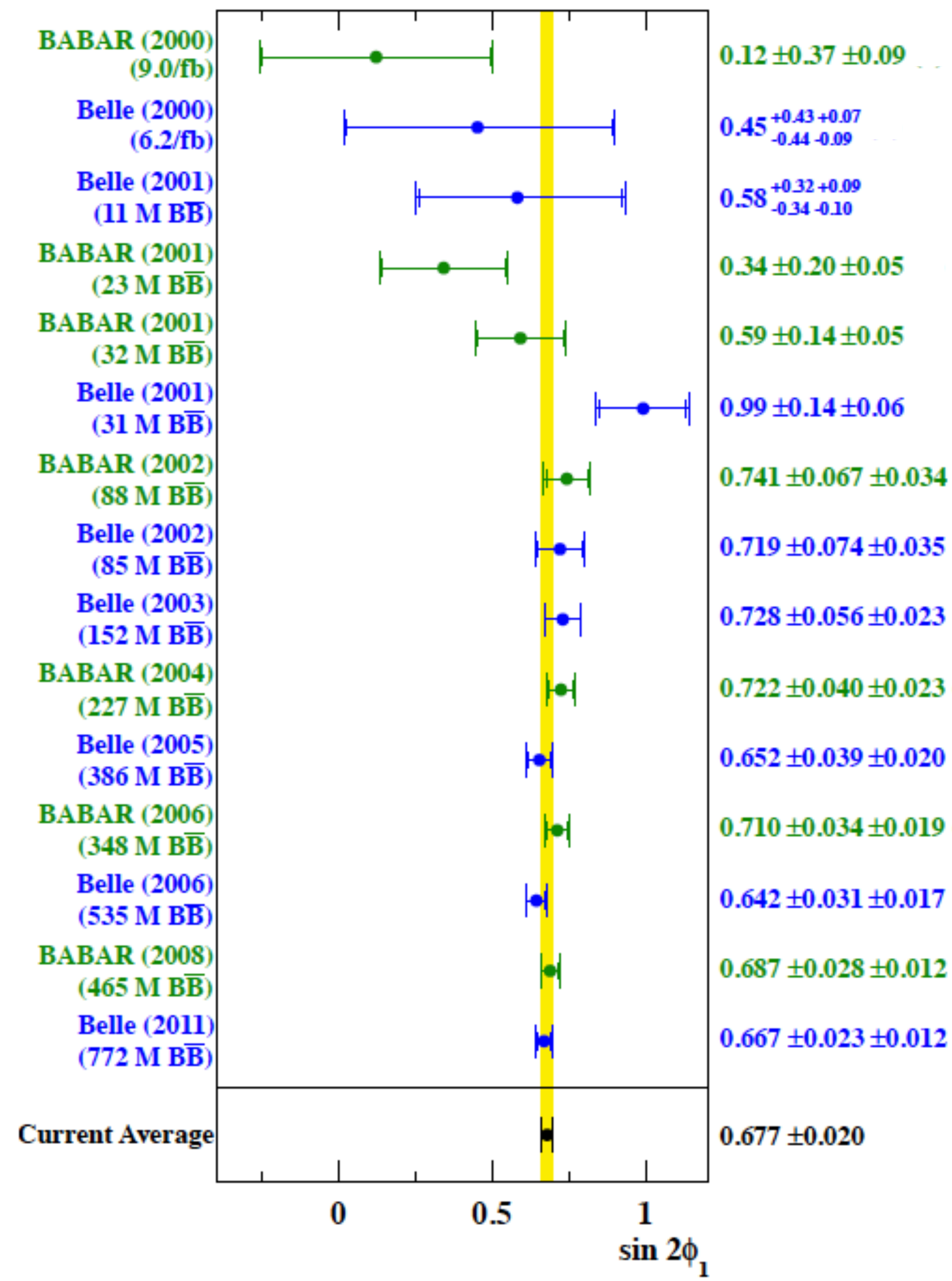
$$A_{CP}(\Delta t) = \sin(2\beta)\sin(\Delta m_d\,\Delta t)$$

$B^0 \to (c\bar{c})K^0_{S/L}$ at BaBar and Belle

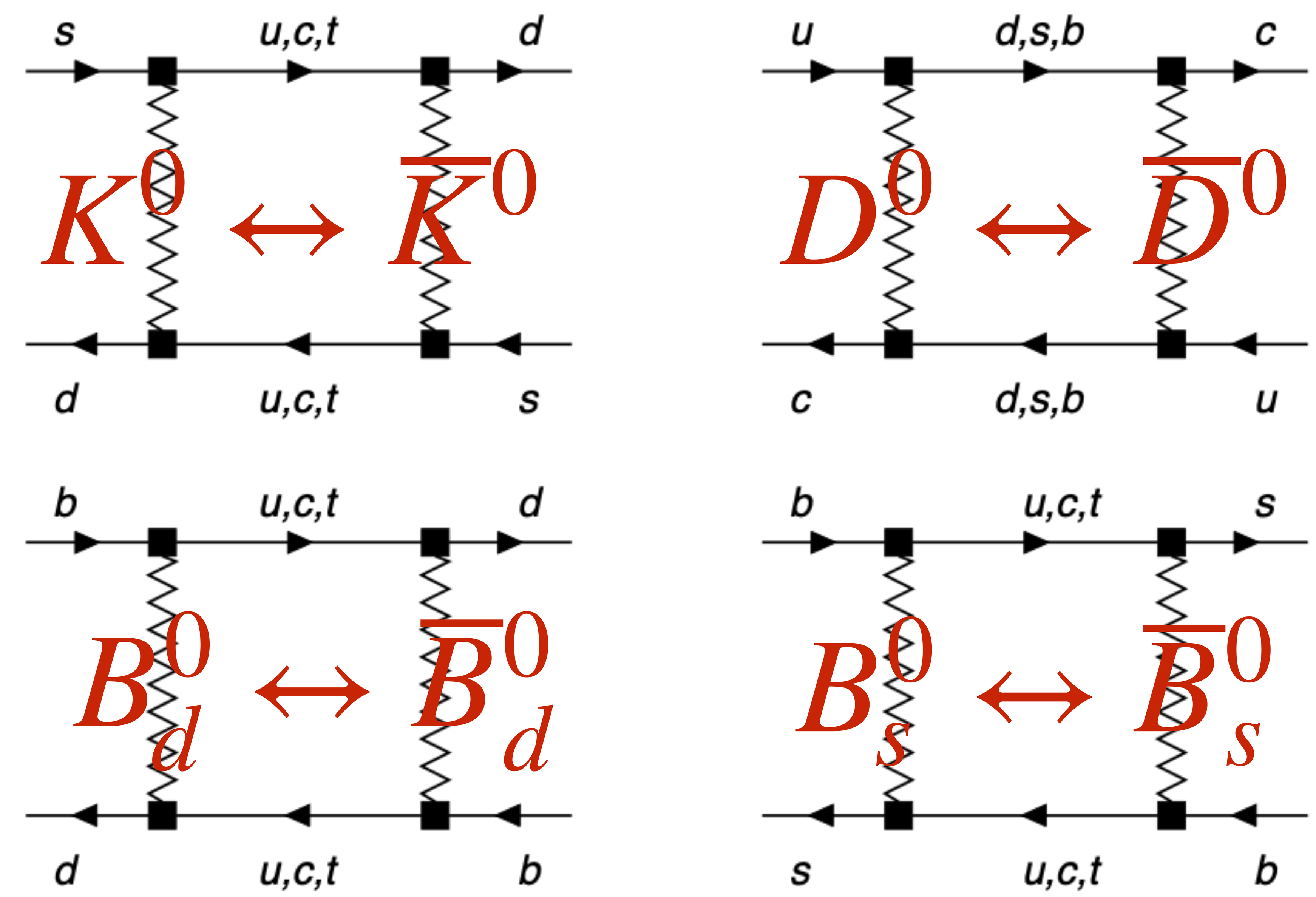


Legacy B-factories result

$\sin 2\beta = 0.677 \pm 0.020$



Neutral meson oscillations

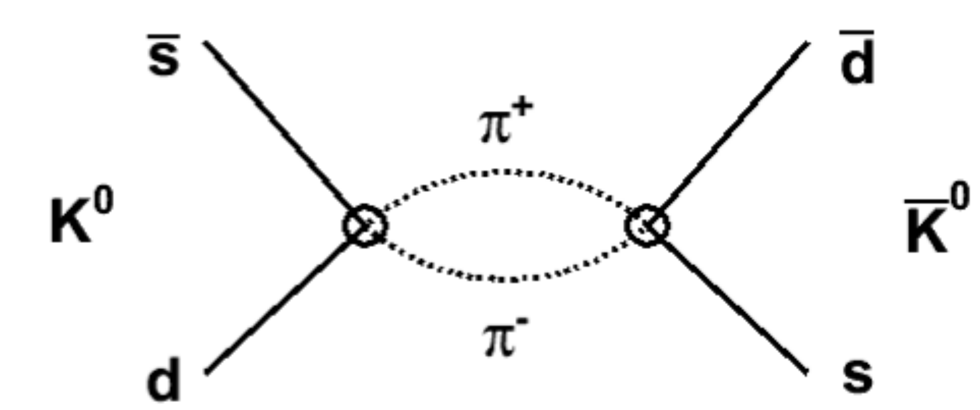


$$K^0 \leftrightarrow \overline{K}^0,\ D^0 \leftrightarrow \overline{D}^0,\ B^0 \leftrightarrow \overline{B}^0$$

- $\Delta S = 2, \quad \Delta C = 2, \quad \Delta B = 2$

  Strangeness, charm and beauty are not conserved

- Formalism is the same even if difference in mass and CKM elements results in dramatically different phenomenology
- Flavour eigenstates $M^0, \overline{M}^0$ can mix into each other
  - via short-distance (box diagrams) or long-distance processes



- Time evolution described by two-component Schrödinger equation

$$i\frac{d}{dt}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = H\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\begin{pmatrix} M^0 \\ \overline{M}^0 \end{pmatrix}$$

  - H effective hamiltonian, M mass matrix, Γ decay matrix

Solving the Schrödinger equation

- Physical states: eigenstates of effective Hamiltonian $|M_{L,H}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$ with eigenvalues $\lambda_{L,H} = m_{L,H} - \frac{i}{2}\Gamma_{L,H}$

 Labelled as either S,L (short, long-lived) or L,H (light, heavy) depending on values of Δm, $\Delta\Gamma$ (labels 1,2 usually reserved for CP eigenstates)

- They evolve as $|M_{H,L}(t)\rangle = e^{-im_{H,L}}e^{-\Gamma_{H,L}t/2}|M_{H,L}(0)\rangle$

- By inverting, starting from a pure flavour eigenstate at $t=0$, this will evolve into a superposition of $|M^0\rangle$ and $|\overline{M}^0\rangle$ (flavour oscillation):

$$|M(t)\rangle = g_+(t)|M^0\rangle + \frac{q}{p}g_-(t)|\overline{M}^0\rangle$$

$$|\overline{M}(t)\rangle = \frac{p}{q}g_-(t)|M^0\rangle + g_+(t)|\overline{M}^0\rangle$$

$$g_+(t) = \frac{1}{2}e^{-iMt}\left(e^{-i\frac{1}{2}\Delta mt-\frac{1}{2}\Gamma_H t} + e^{+i\frac{1}{2}\Delta mt-\frac{1}{2}\Gamma_L t}\right)$$

$$g_-(t) = \frac{1}{2}e^{-iMt}\left(e^{-i\frac{1}{2}\Delta mt-\frac{1}{2}\Gamma_H t} - e^{+i\frac{1}{2}\Delta mt-\frac{1}{2}\Gamma_L t}\right)$$

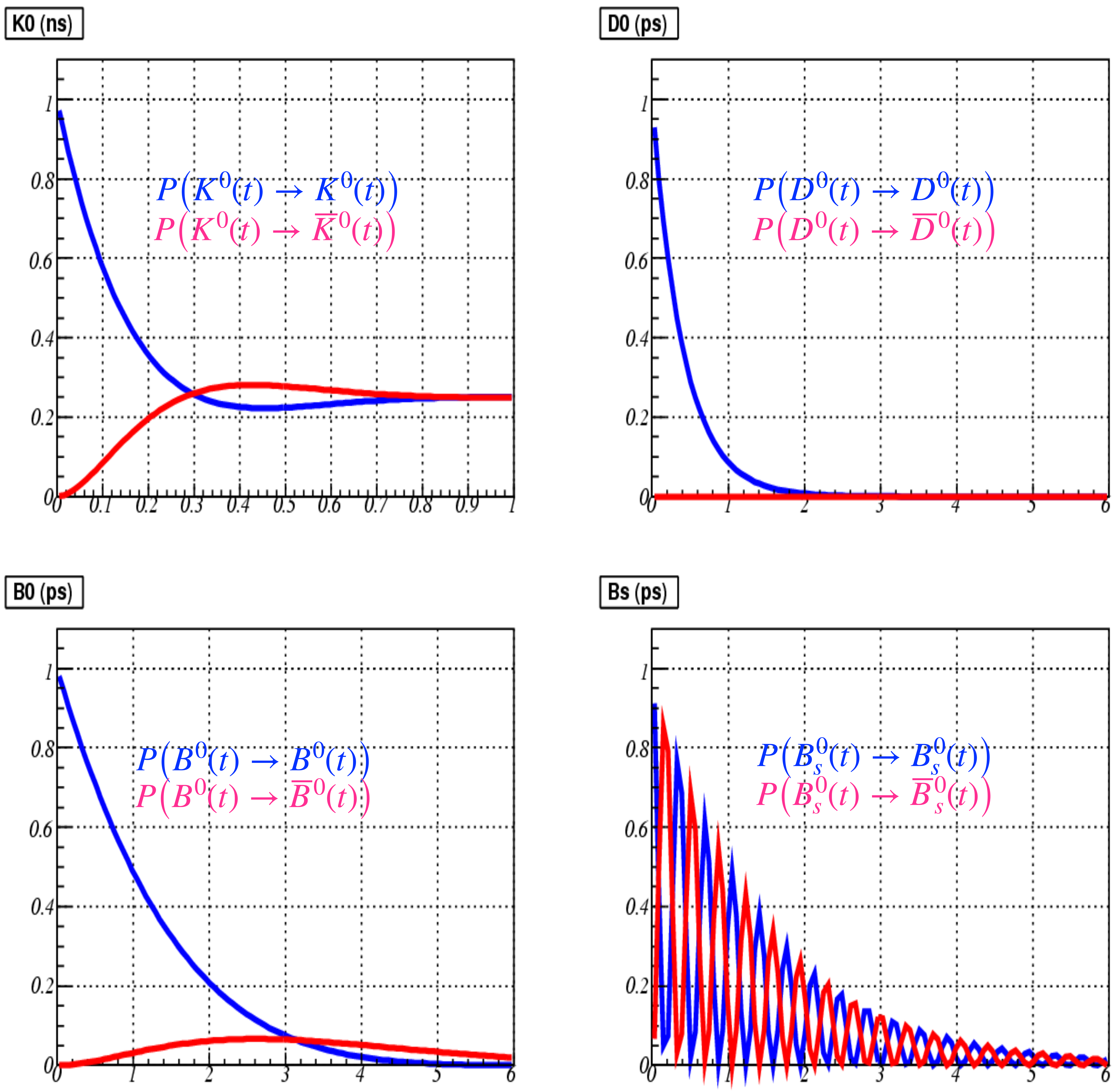
$$M = (M_H + M_L)/2,\ \Delta m = m_H - m_L$$

$$\Gamma = (\Gamma_L + \Gamma_H)/2, \Delta\Gamma = \Gamma_L - \Gamma_H$$

- Probability of measuring a state $|\overline{M}^0\rangle$ at time t starting from a pure sample of $|M^0\rangle$ particles:

$$|\langle\overline{M}^0|M^0(t)\rangle|^2 = |g_-(t)|^2\left|\frac{p}{q}\right|^2 \text{ with } |g_\pm(t)|^2 = \frac{e^{-\Gamma t}}{2}\left(\cosh\frac{\Delta\Gamma t}{2} \pm \cos\Delta mt\right)$$

Compare the mesons



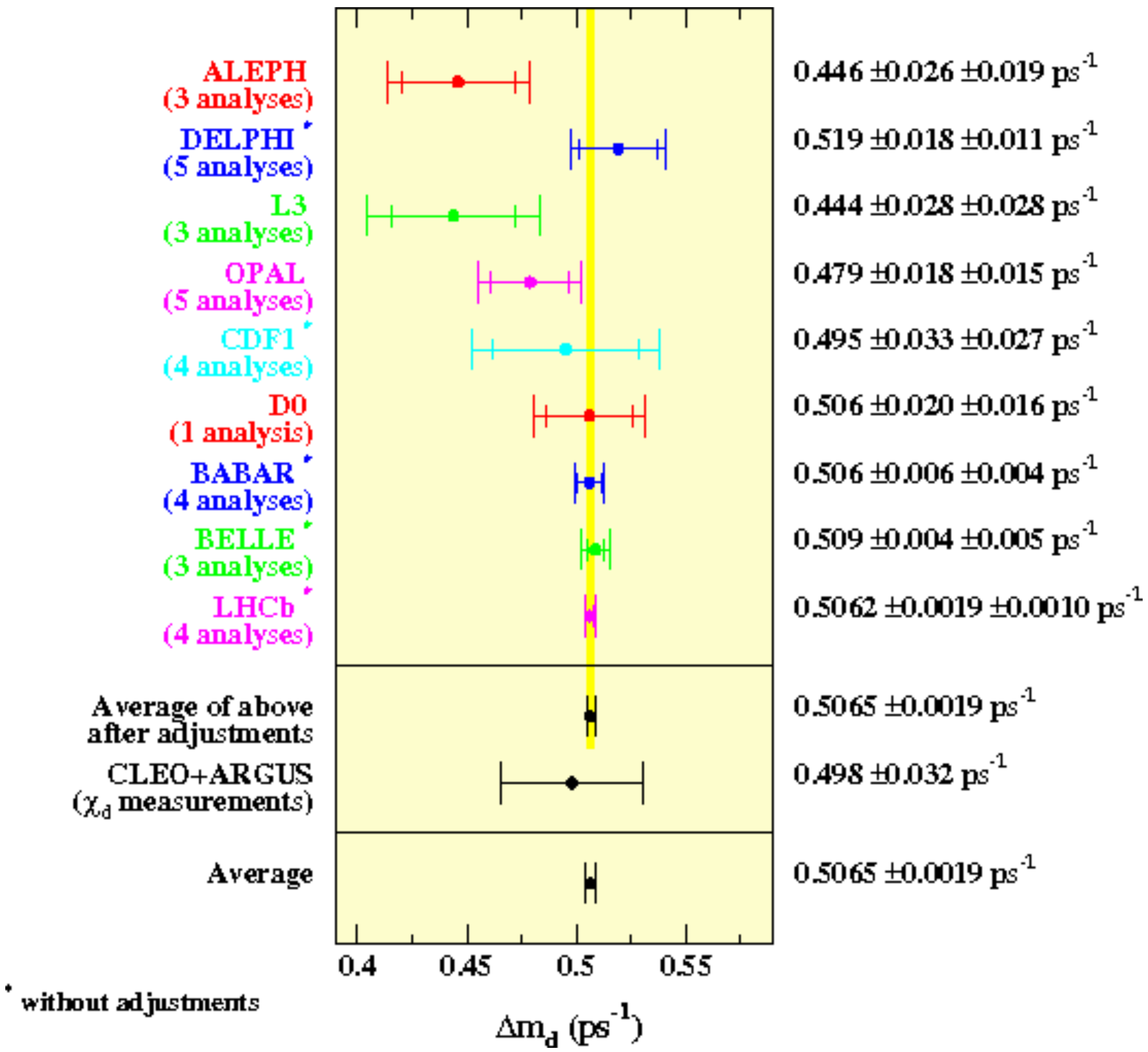
Probability to observe an M^0 or $\overline{M}^0$ at time t starting from a pure M^0 meson

- Δm depends on rate of mixing diagram, $\Delta\Gamma$ depends on widths of decays into common final states ($K^0 \to \pi^+\pi^- \to \overline{K}^0$) (large for K^0, small for D^0, B_d^0)
- $x = \Delta m/\Gamma$ gives the average number of oscillations before decay

	Δm $(x = \Delta m/\Gamma)$	$\Delta\Gamma$ $(y = \Delta\Gamma/(2\Gamma))$
K^0	large	$\sim$ maximal
	~ 500	~ 1
D^0	small	small
	$(0.63 \pm 0.19)\%$	$(0.75 \pm 0.12)\%$
B^0	medium	small
	0.770 ± 0.008	0.008 ± 0.009
B_s^0	large	medium
	26.49 ± 0.29	0.075 ± 0.010

- B^0mixing, first observed by Argus in 1987, then measured precise by B factories, ..
- B_s^0 mixing first measured by CDF in 2006 and then by LHCb

$B^0 \leftrightarrow \overline{B}^0$ mixing



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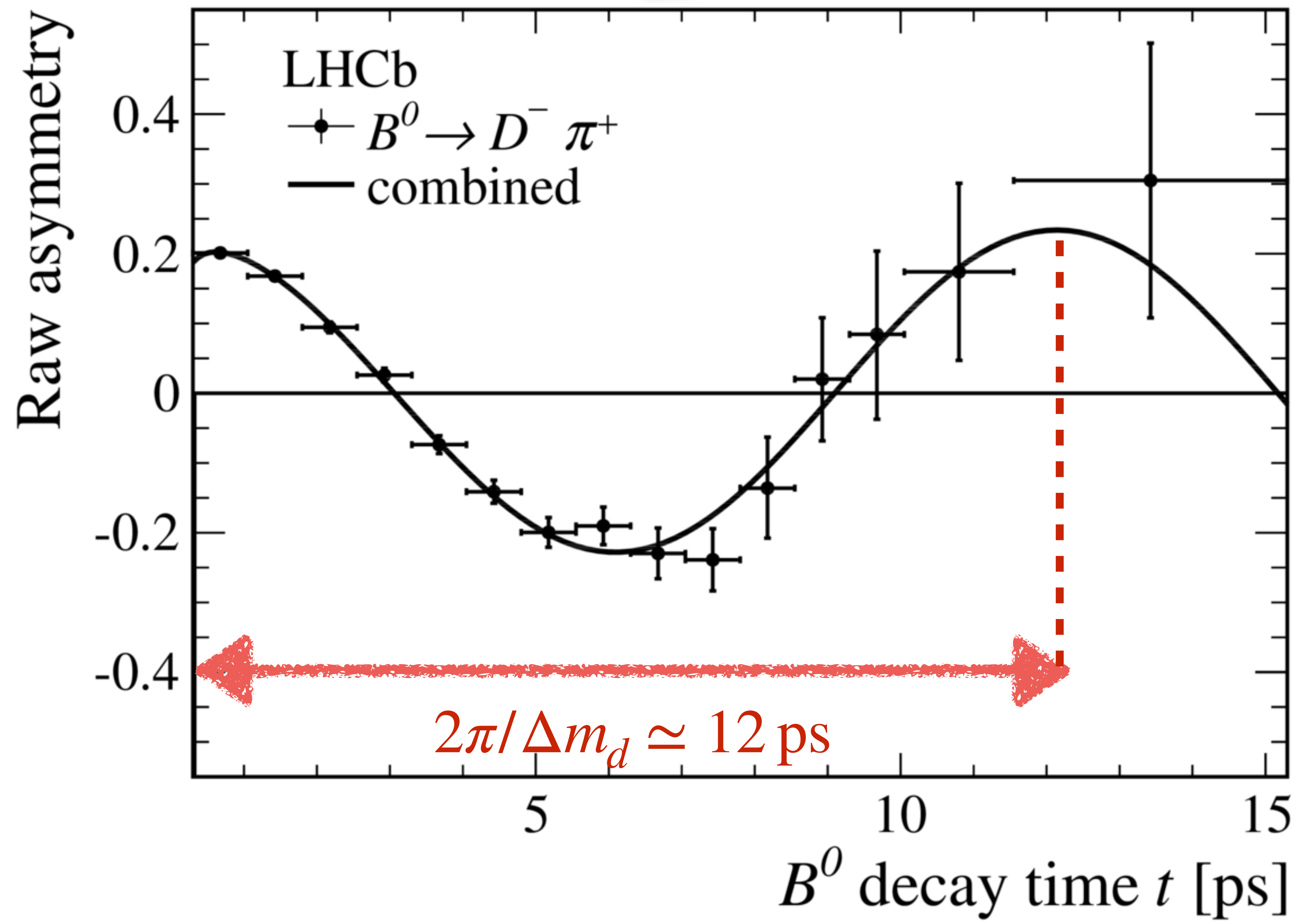
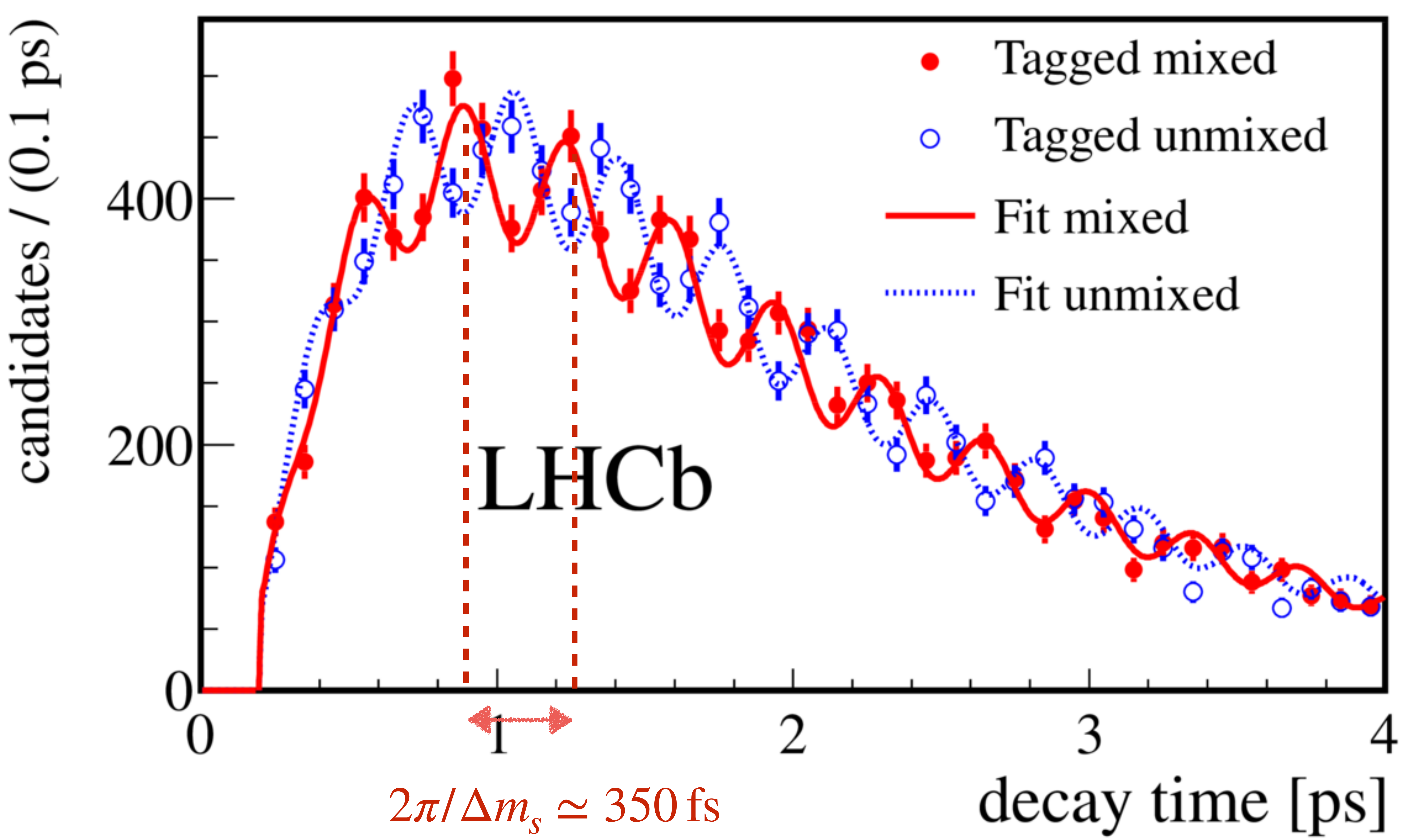


$\Delta m_d = 0.5065 \pm 0.0019$ ps^{-1}

One period of B^0oscillations $\Delta T \simeq 12\,\mathrm{ps}$ → oscillation frequency $\Delta m_d \simeq 0.5\,\mathrm{ps}^{-1}$

$B_s^0 \leftrightarrow \overline{B}_s^0$ mixing

- $\Delta m_s = 17.757 \pm 0.021\,\mathrm{ps}^{-1}$ CDF,LHCb



- Different flavour at decay and production
- Same flavour at decay and production

New J.Phys.15 (2013) 053021

One period of B_s^0 oscillations $\Delta T \simeq 350\,\mathrm{fs} \rightarrow$ oscillation frequency $\Delta m_s \simeq 17.8\,\mathrm{ps}^{-1}$