Symmetries and heavy flavours

Sergey Barsuk, IJCLab Orsay
sergey.barsuk@lal.in2p3.fr

Part II: CKM and CP symmetry

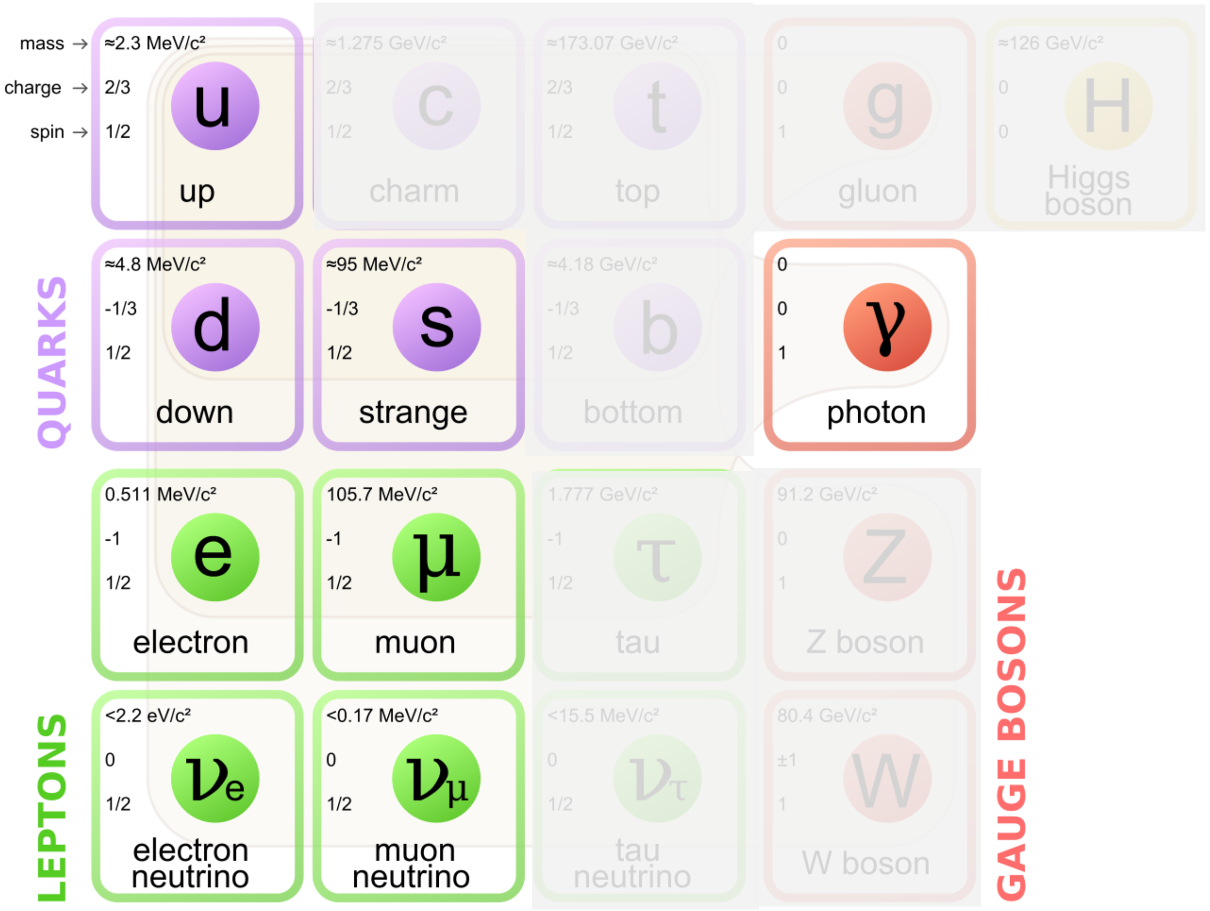
Exprimental touch

- ❑ *Selective and biased introduction by an experimental particle physicist*
- ❑ *Many simplifications, avoid formalism*
- ❑ *Slides of many colleagues used without proper references*

Дніпро 03/03/2020

Cabibbo theory, GIM mechanism and heavy flavour decays

Players by 1974



Cabibbo Theory :

θ_c : the Cabibbo angle

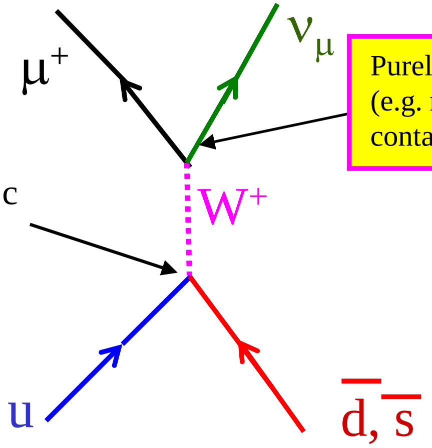
The quarks *d* and *s* involved in weak processes are « rotated » by an angle

$$\begin{pmatrix} u \\ d_c \end{pmatrix} = \begin{pmatrix} u \\ d\cos\theta_c + s\sin\theta_c \end{pmatrix}$$

Couplings : u d $G_F\cos\theta_c$ u s $G_F\sin\theta_c$

$\Delta S=1$

$\cos\theta_c$ or $\sin\theta_c$

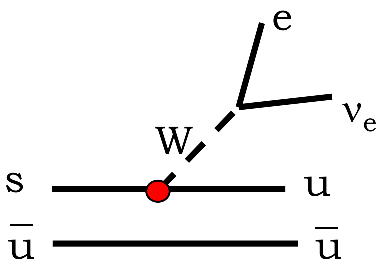


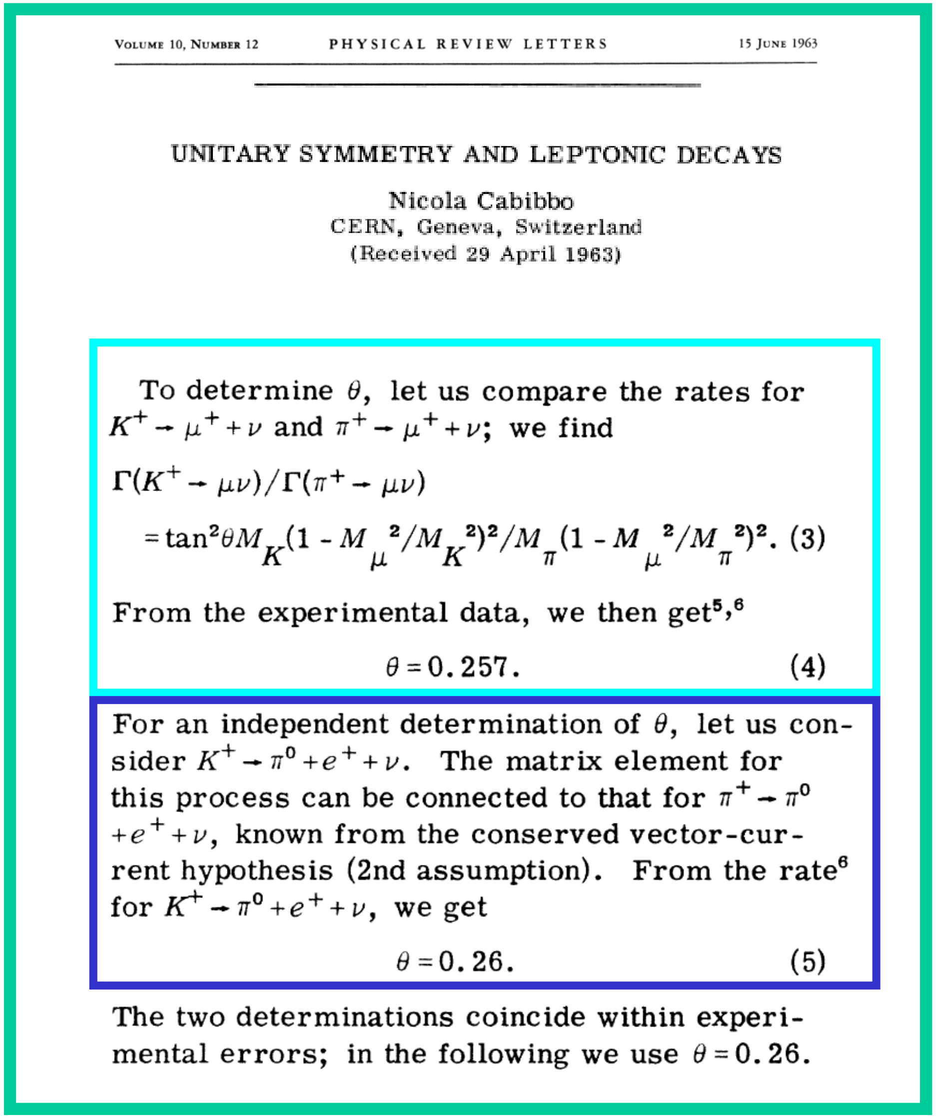
Purely leptonic decays (e.g. muon decay) do not contain the Cabibbo factor

$$\underset{2.6\,10^{-8}\,s}{\overset{1.2\,10^{-8}\,s}{\frac{\tau(K)}{\tau(\pi)}}}\;\frac{\overset{(\sim0.63)}{BR(K^+\to\mu^+\nu)}}{\underset{(\sim1)}{BR(\pi^+\to\mu^+\nu)}} = \frac{\sin^2\theta_c}{\cos^2\theta_c}\underbrace{\left[\frac{m_k}{m_\pi}\right]\left[\frac{1-(m_\mu/m_k)^2}{1-(m_\mu/m_\pi)^2}\right]^2}_{8.5}$$

$G_F^2\sin^2\theta_c$

$K^- \to \pi^0\, e^-\, \nu_e$





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UNITARY SYMMETRY AND LEPTONIC DECAYS

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

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]

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

For an independent determination of θ, let us consider $K^+\to\pi^0+e^++\nu$. The matrix element for this process can be connected to that for $\pi^+\to\pi^0+e^++\nu$, known from the conserved vector-current hypothesis (2nd assumption). From the rate[6] for $K^+\to\pi^0+e^++\nu$, we get

$$\theta=0.26. \quad (5)$$

The two determinations coincide within experimental errors; in the following we use $\theta=0.26$.

But the theory predicts **flavour changing neutral transitions (FCNC)**:

$$u\bar{u} + d\bar{d}\cos^2\theta_c + s\bar{s}\sin^2\theta_c + \left(s\bar{d} + \bar{s}d\right)\cos\theta_c \sin\theta_c$$

Strangeness changing neutral current would produce contributions larger by several order of magnitude to for instance $K_L \rightarrow \mu\mu$. Not confirmed experimentally.

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

?

1970 : Glashow, Iliopoulos et Maiani (GIM) proposed

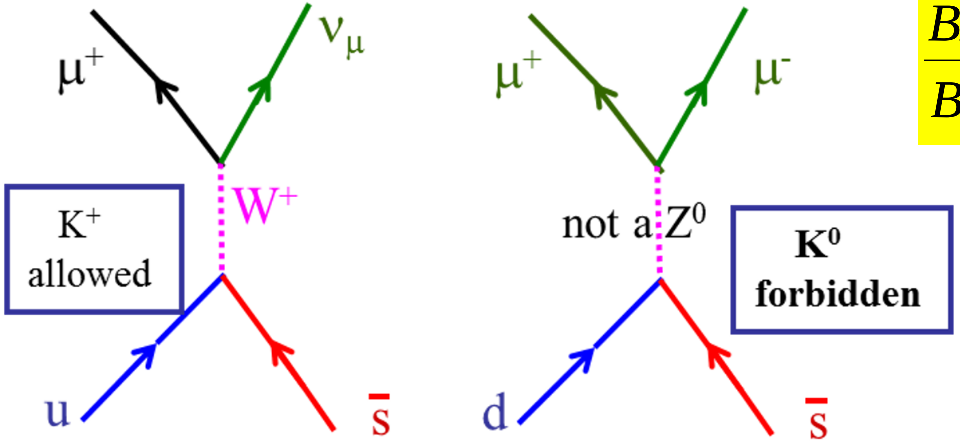
a fourth quark : the quark *c* (of charge 2/3)

➔ explanation of the absence of FCNC :

$$u\bar{u}+d\bar{d}\cos^2\theta_c+s\bar{s}\sin^2\theta_c+\boxed{\left(s\bar{d}+\bar{s}d\right)}\cos\theta_c\sin\theta_c$$

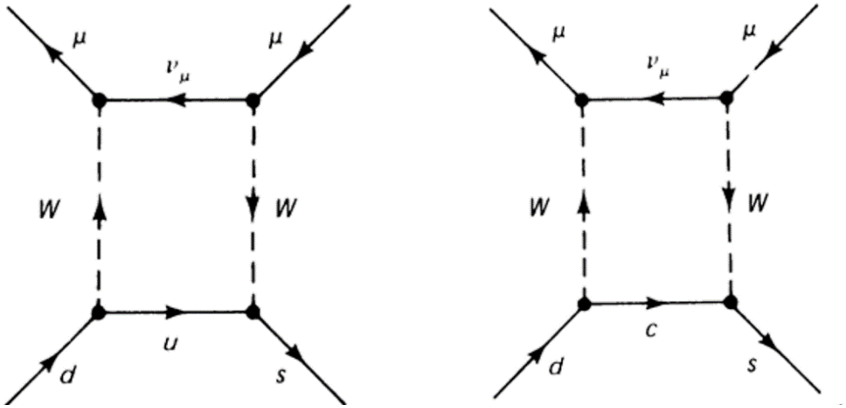
$$u\bar{u}+c\bar{c}+\left(d\bar{d}+s\bar{s}\right)\cos^2\theta_c+\left(d\bar{d}+s\bar{s}\right)\sin^2\theta_c=u\bar{u}+c\bar{c}+d\bar{d}+s\bar{s}$$

1st order



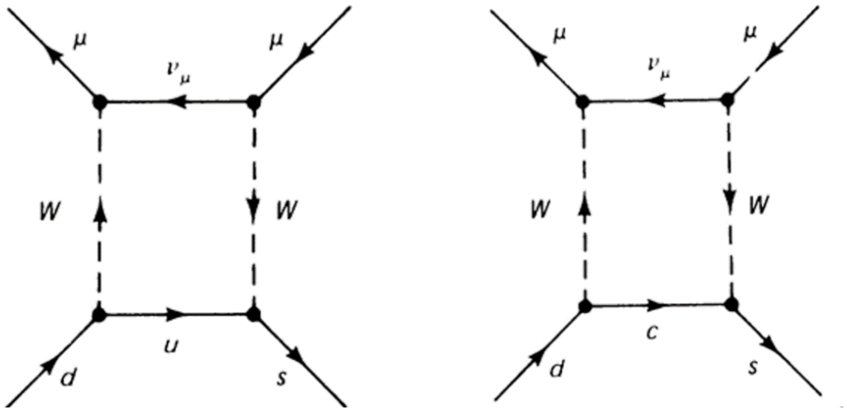
$$\frac{BR(K^0\to\mu^+\mu^-)}{BR(K^+\to\mu^+\nu_\mu)}=\frac{7\times10^{-9}}{0.64}\approx10^{-8}$$

2nd order



only u-quark → ultraviolate divergence

2nd order



only u-quark → ultraviolate divergence

$$\frac{BR(K^0 \to \mu^+\mu^-)}{BR(K^+ \to \mu^+\nu_\mu)} = \frac{7\times10^{-9}}{0.64} \approx 10^{-8}$$

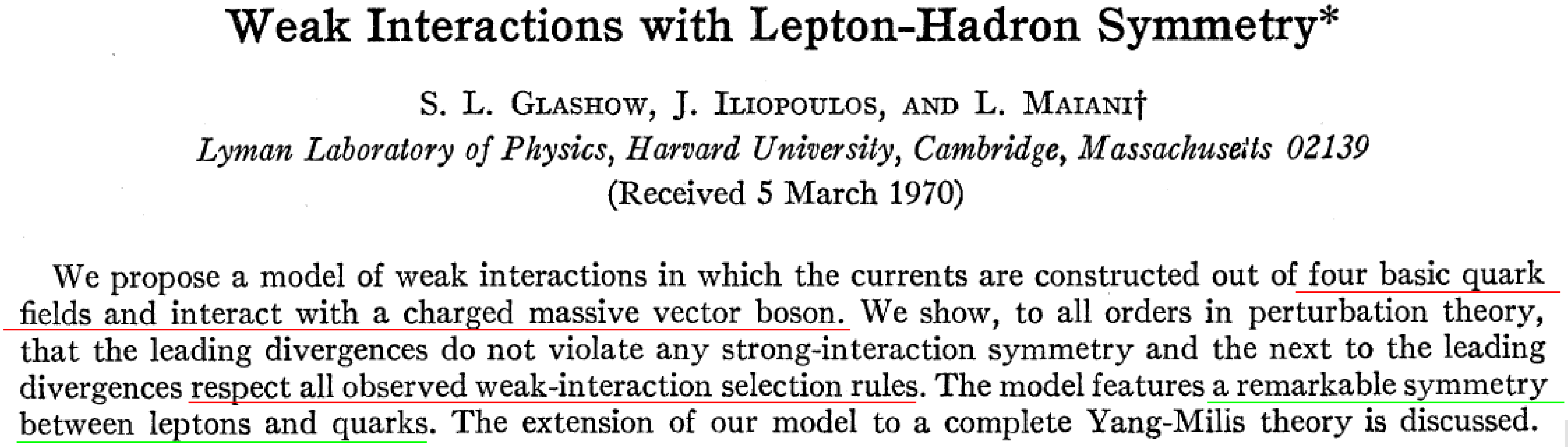
$\sim (m_c^2 - m_u^2) \cos^2\theta_c \sin^2\theta_c$

These two diagrams cancel out the divergence

It remains a non zero contribution (which is infrared divergent) for momentum lower than the mc, which does not cancel out. The amount of cancellation depends on the mass of the new quark

- ☐ Prediction of the charm quark with m~1.5 GeV

For $m_c = m_u$ it would be $BR(K^0 \to \mu^+\mu^-) = 0$



Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139

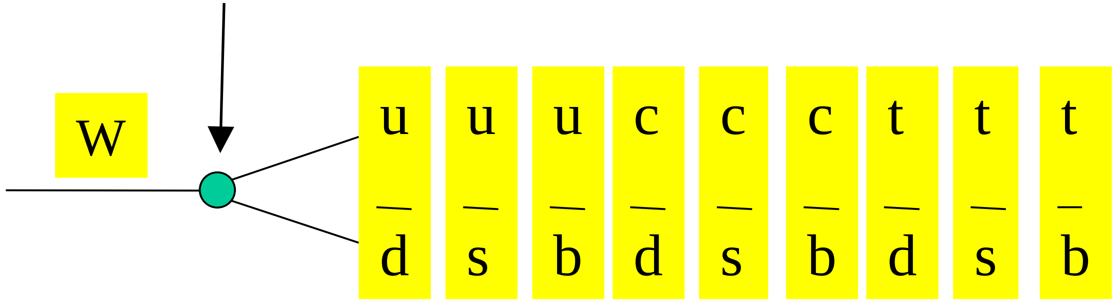
(Received 5 March 1970)

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.

… and yet another conclusion …

The coupling is not anymore universal

and this is codified in the CKM matrix.

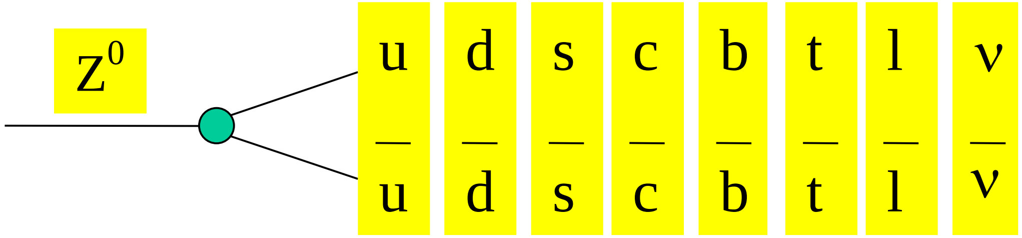


W

$u\bar{d}$ $u\bar{s}$ $u\bar{b}$ $c\bar{d}$ $c\bar{s}$ $c\bar{b}$ $t\bar{d}$ $t\bar{s}$ $t\bar{b}$

The neutral currents stay universal, in the mass basis :

we do not need extra parameters for their complete description



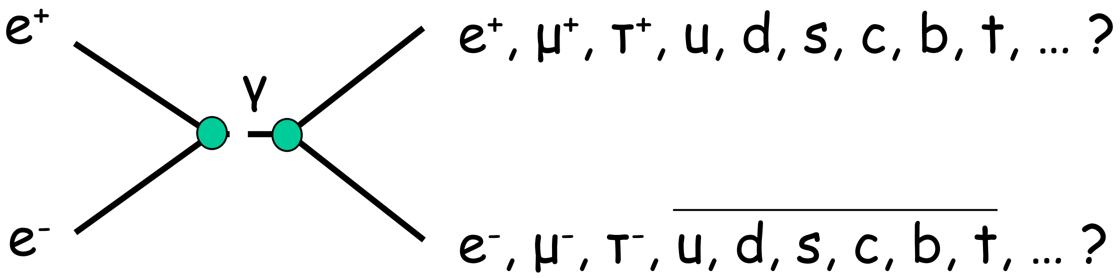
Z^0

$u\bar{u}$ $d\bar{d}$ $s\bar{s}$ $c\bar{c}$ $b\bar{b}$ $t\bar{t}$ $l\bar{l}$ $\nu\bar{\nu}$

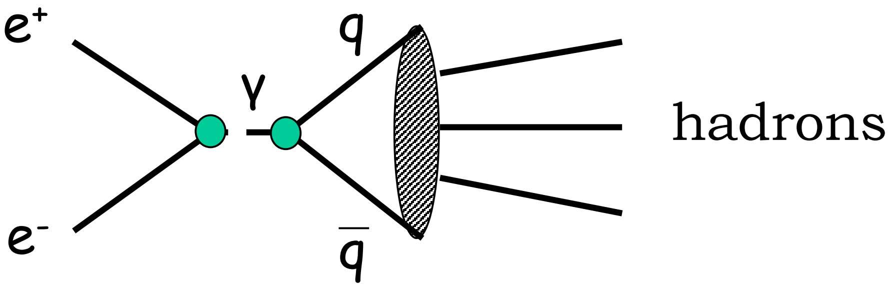
… and this is completly included and comes out « naturally » from the Standard Model.

Discovery of c-quark, heavy quarkonia : J/ψ

Studying number of players
via e^+e^- cross-section

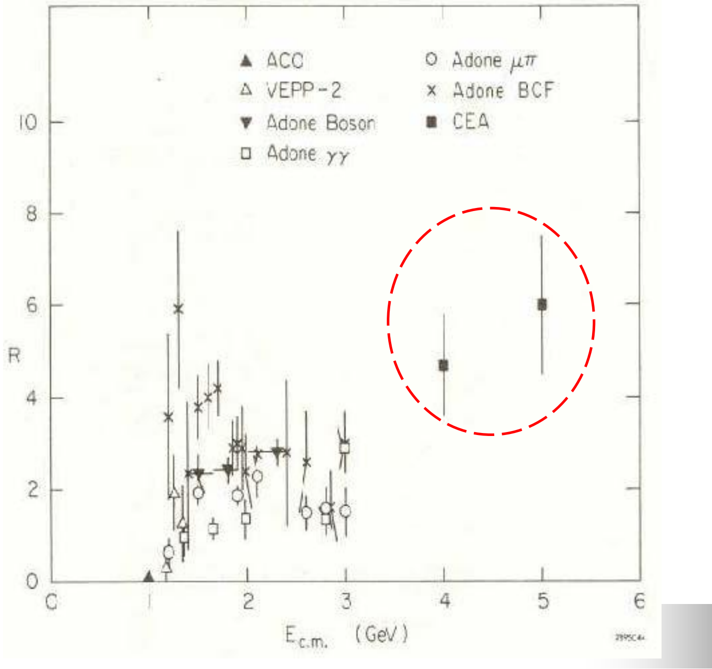


The $e^+e^- \to q\bar{q}$ detected via decays
to stables hadrons.



$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2$$

The R ratio (July 1974), from J. Otwinowski

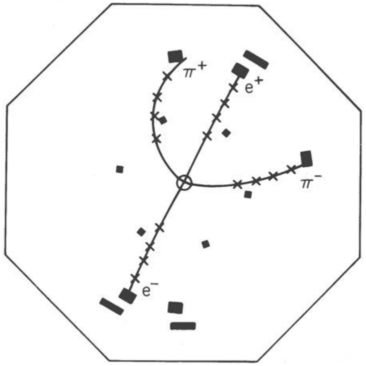


- Guess on the mass
- Guess on the charge
  - With u,d,s R = Nc x [6/9]
  - With u,d,s,c R = Nc x [6/9 + q_c^2]

    Nc = 3 – number of QCD colours
- Inspiration for the charm quark discovery scan at SLAC

Discovery of c-quark, heavy quarkonia : J/ψ

- ψ at SLAC: scan particle yields (cross-section) over the center of mass energy of the e+e- colliding beams



Computer reconstruction of a psi-prime decay in the SLAC Mark I detector

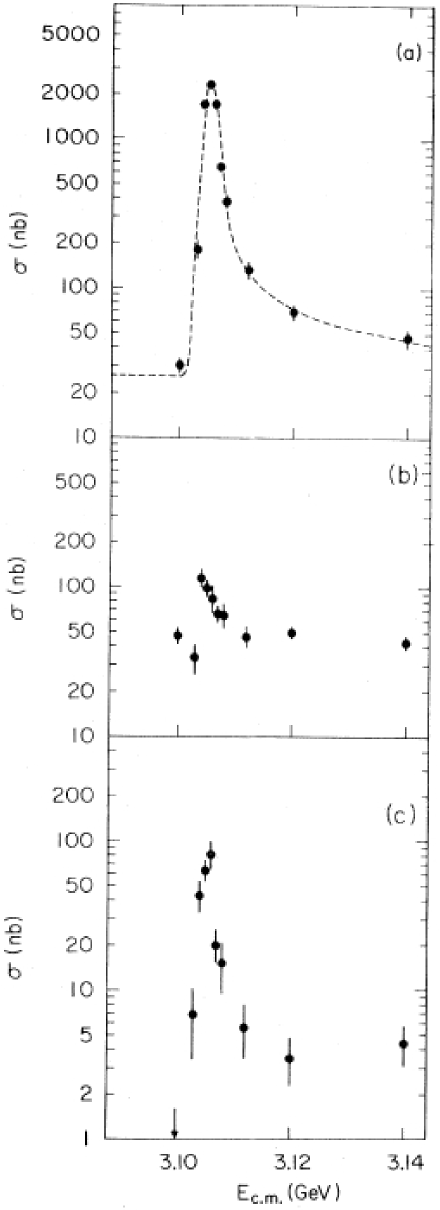


FIG. 1. Cross section versus energy for (a) multihadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

- J at BNL: proton beam on target, look at invariant mass of the e+e- pairs

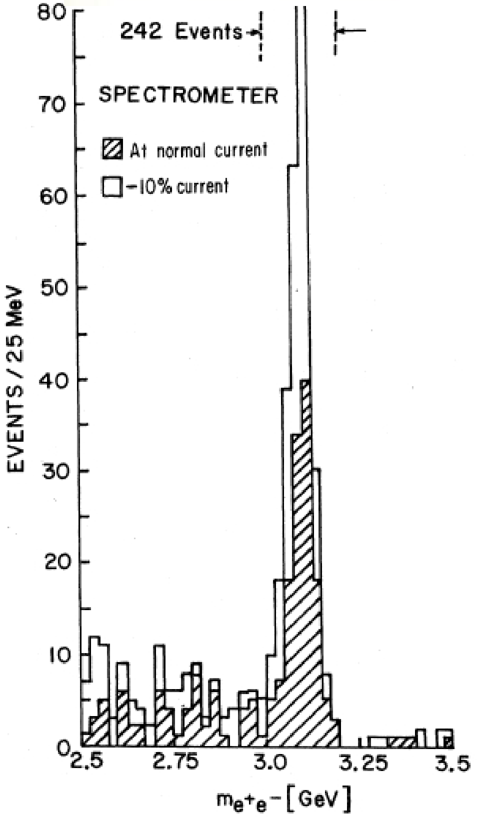
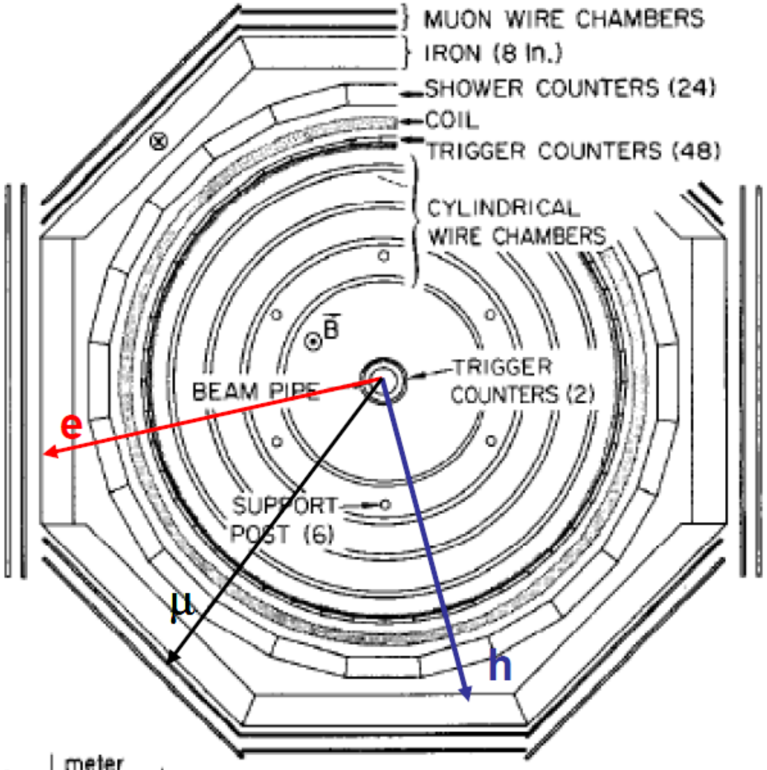


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

Discovery of c-quark, heavy quarkonia : J/ψ

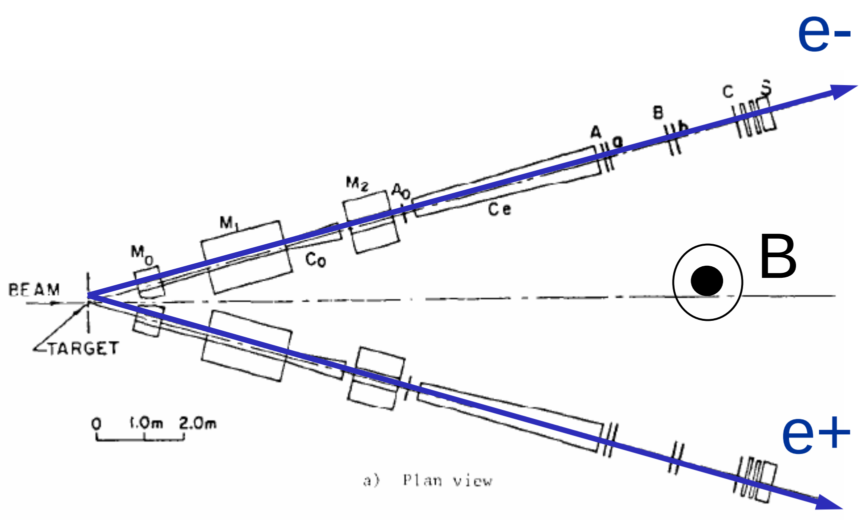
- ψ at SLAC: scan particle yields (cross-section) over the center of mass energy of the e+e- colliding beams



Ann. Rev. Nucl. Sci. 26 (1976) 89

Mark I detector at SLAC :
Tracking (cylindrical magnet + cylindrical wire chambers
PID detectors:
Trigger chambers (TOF)
Shower counters (e identification)
Muon wire chambers

- J at BNL: proton beam on target, look at invariant mass of the e+e- pairs

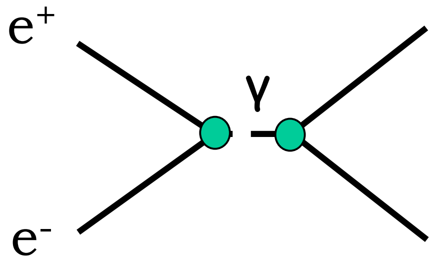


Two arms e+e- spectrometer :

Tracking (dipole magnets + MWPCs)
PID detectors: Hodoscopes (TOF)
EM shower counters
Ĉerenkov counters (charged hadron ID)

Discovery of c-quark, heavy quarkonia : J/ψ

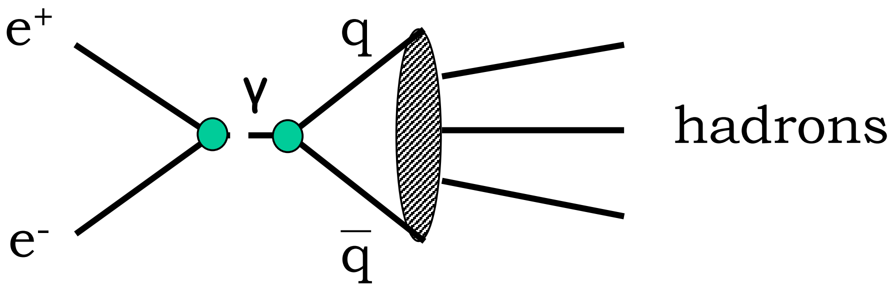
Studying number of players
via e^+e^- cross-section



e^+, μ^+, τ^+, u, d, s, c, b, t, … ?

e^-, μ^-, τ^-, $\overline{u, d, s, c, b, t}$, … ?

The e^+e^- → qq detected via decays
to stables hadrons.



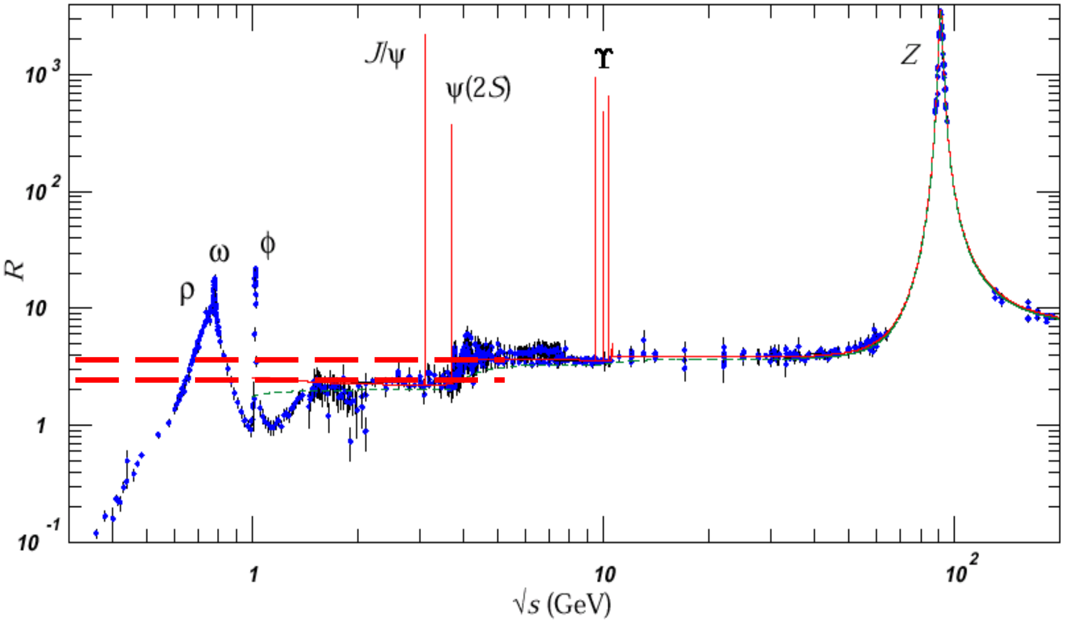
$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_C \sum_i q_i^2$$

☐ With u,d,s R = Nc x [6/9]

☐ With u,d,s,c R = Nc x [6/9 + q_c^2]

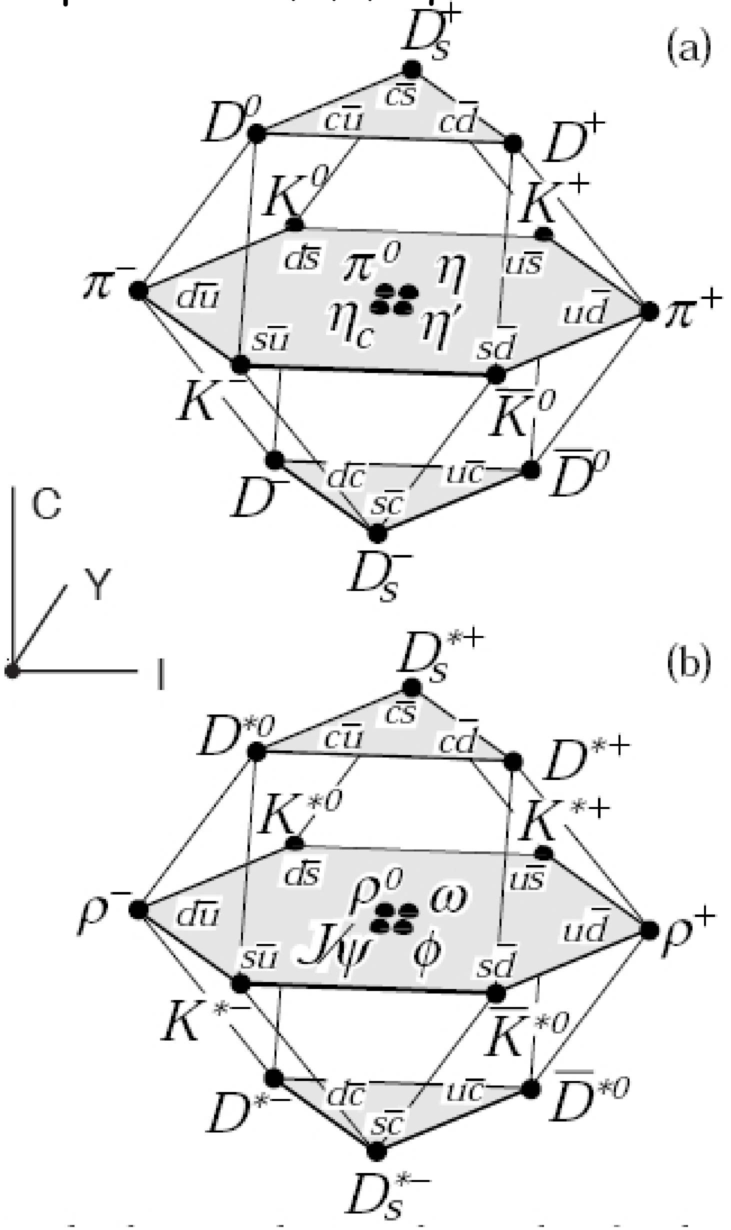
Nc = 3 – number of QCD colours

q_c = + 2/3 ; ($c\bar{c}$) state "J/ψ" of ~3.1 GeV

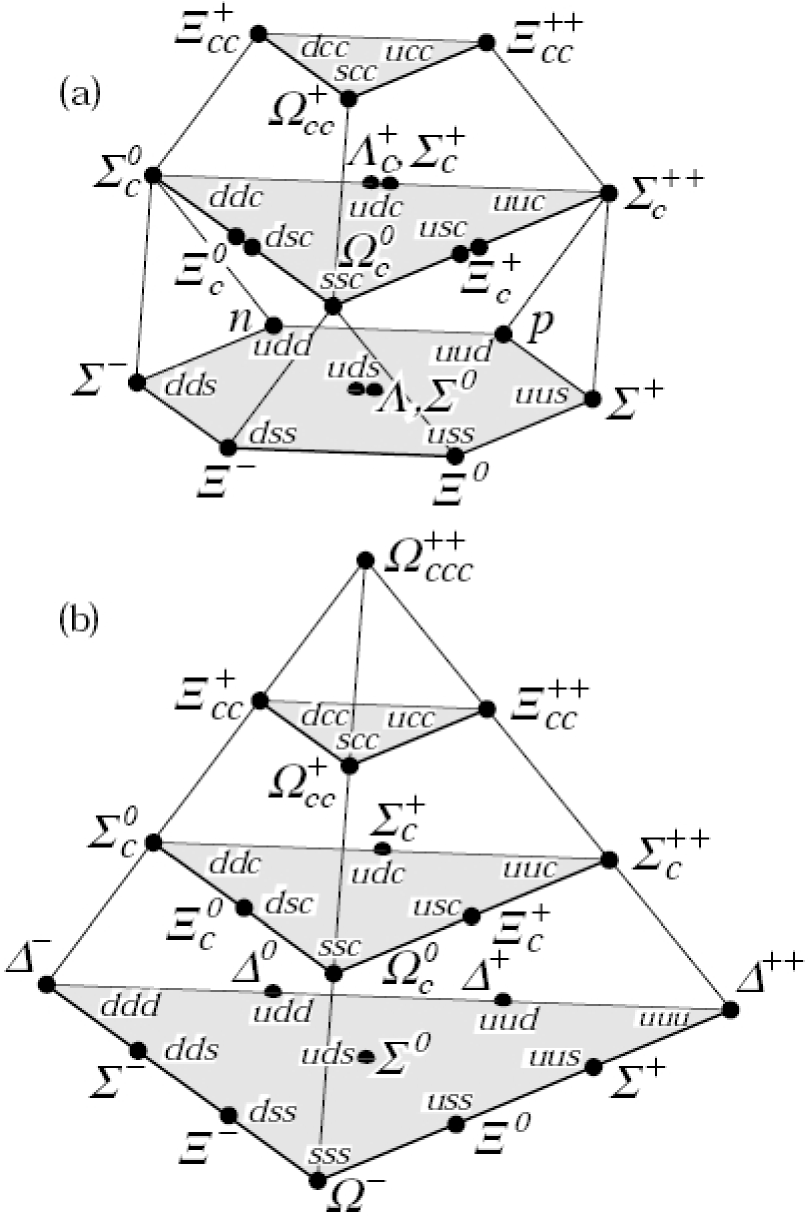


Charmed hadrons

SU(4) weight diagrams for mesons composed of u,d,s,c quarks

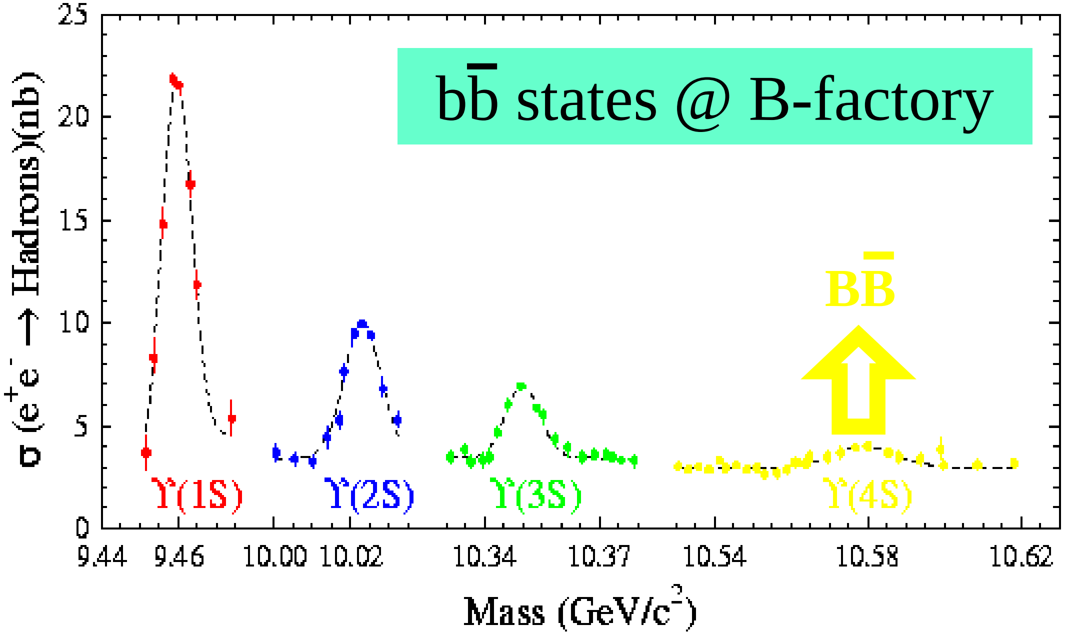


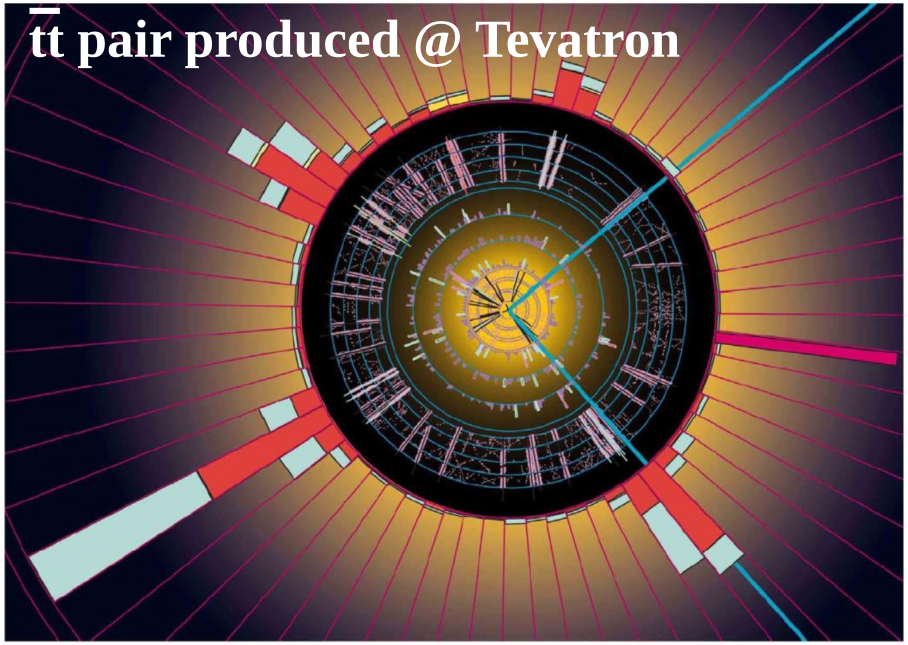
SU(4) multiplets of baryons composed of u,d,s,c quarks



Hyper-charge Y = S + C + B + T + B', Gell-Mann&Nishijima: Y = 2(Q – I3)

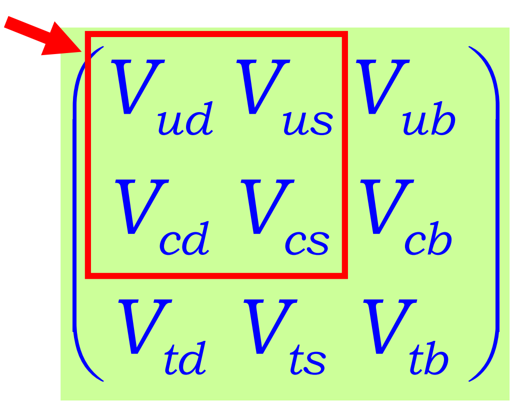
Then discovery of the b, t quarks …




tt̄ pair produced @ Tevatron

Discovery of c quark (1974) : 4 years after GIM mechanism (1 year after KM paper)
Discovery of b quark (1977) : 4 years after KM paper
Discovery of t quark (1994) : 21 years after KM paper

… Cabibbo Kobayashi Maskawa 3 x 3 matrix :



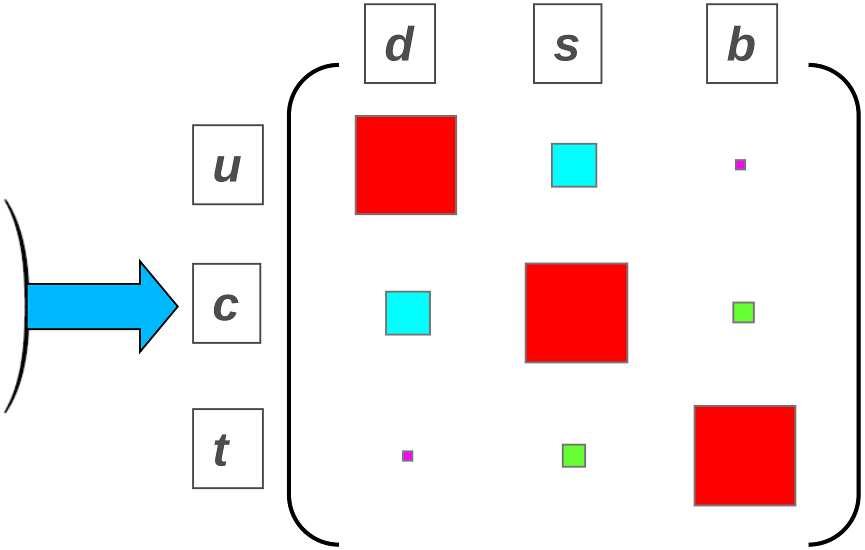
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Weak interaction eigenstates ≠ Mass eigenstates (≡ flavour or strong interaction eigenstates)

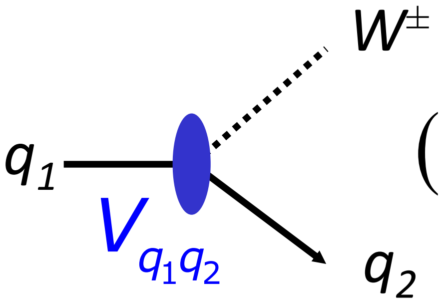
$$\boxed{\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \boxed{\begin{pmatrix} d \\ s \\ b \end{pmatrix}}$$

V_{CKM} 3X3 unitary (complex) matrix describing the **quarks mixing**: the **CKM matrix**

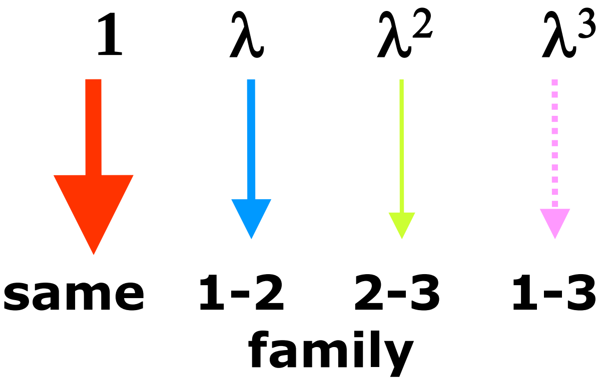
$$\begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$



As a consequence, the charged currents couplings are given through :

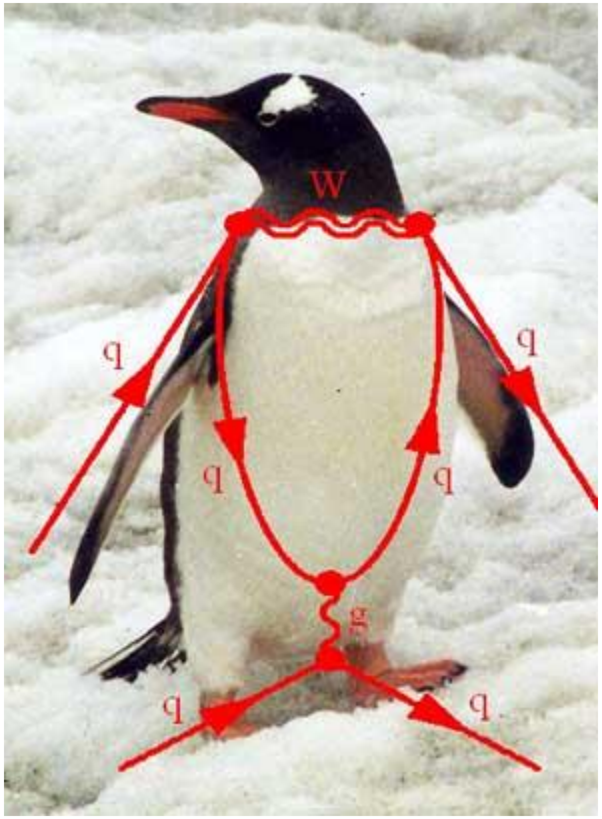


$$\begin{pmatrix} u & c & t \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



$$\boxed{\lambda = \sin\theta_c \sim 0.22}$$

onic B-decays

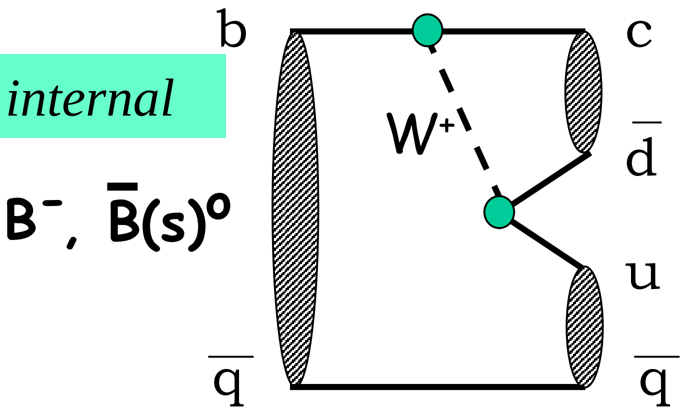


:-

;

,π, ...

internal



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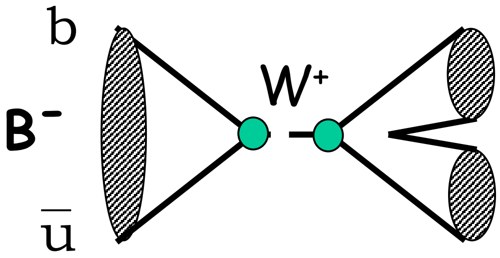
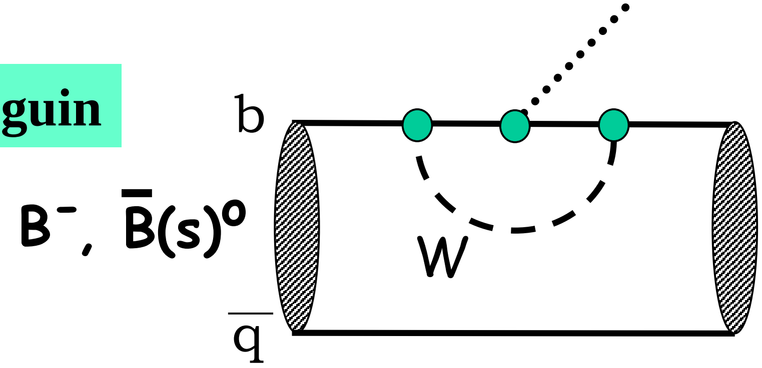


Penguin



- ❑ ***Every line, vertex and <u>loop</u> can contain NP contribution***

Who is heavy (enough) ?

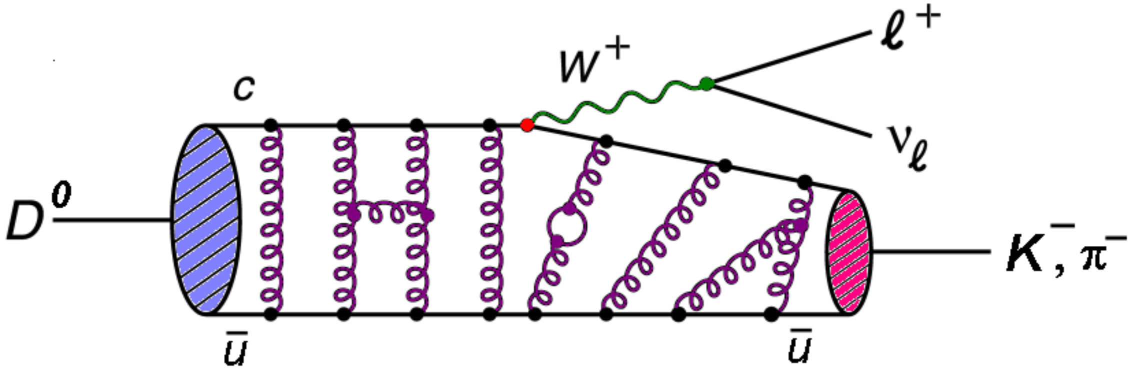
“Heavy” quarks :	**s**	**c**	**b**	**t**
“Nude” mass :	**~100 MeV**	**~1.3 GeV**	**~4.2 GeV**	**~171 GeV**

CKM mechanism :

description of the charged weak couplings

But .. We don’t work at the quark level :

strong interaction



Top is so heavy that it decays before hadronization

$$\Gamma_t = \frac{G_F^2 m_t^5}{192\pi^3}$$

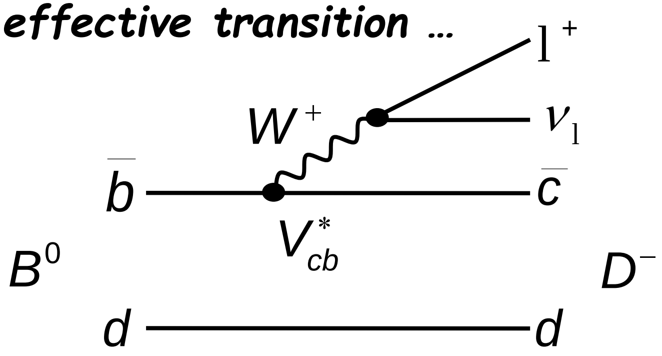
$$\tau(t) = m^5(\mu)/m^5(t)\ \tau(\mu)$$
$$\sim 2 \times 10^{-23}\ \text{sec}$$

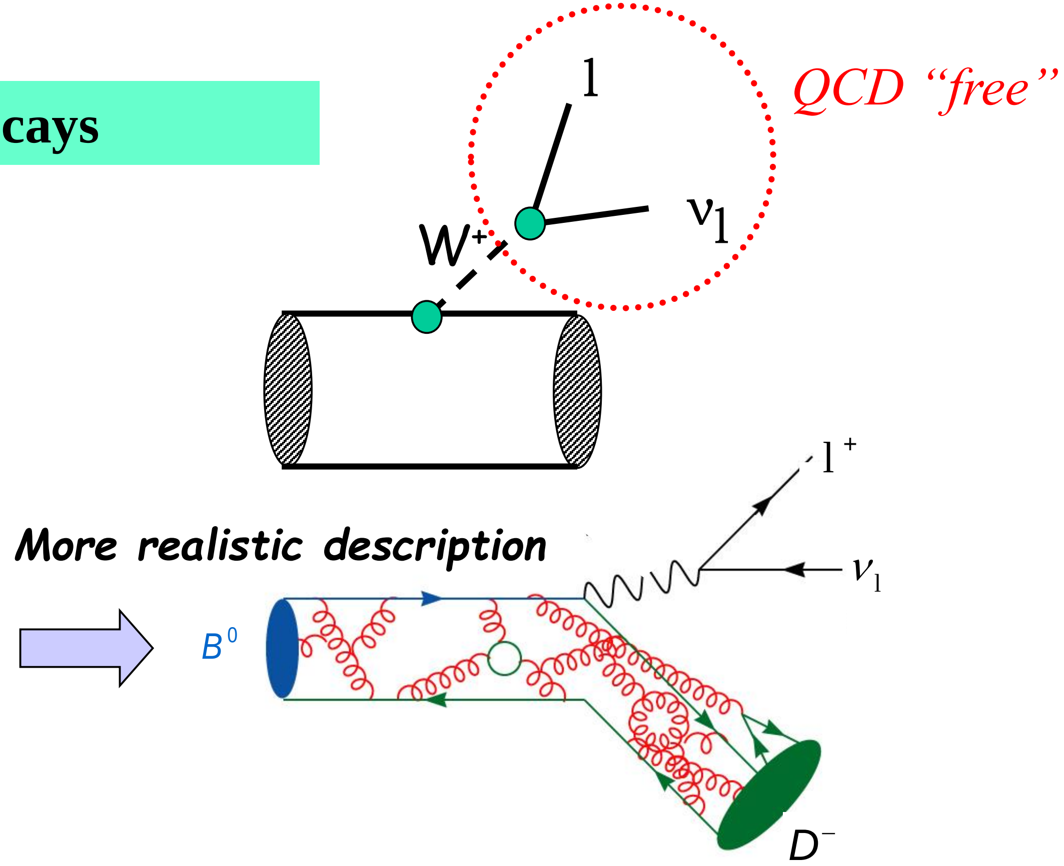
QCD complications

Less QCD: leptonic and semi-leptonic decays

W emission: SemiLeptonic decays

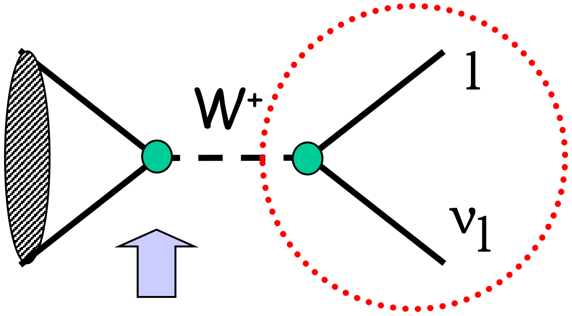
Still QCD
in B → D effective transition …





More realistic description

Weak annihilation: decay constant determination



$\sim f_H V_{ij}$

$|V_{ij}| \sim \lambda$ or 1 for D-decays

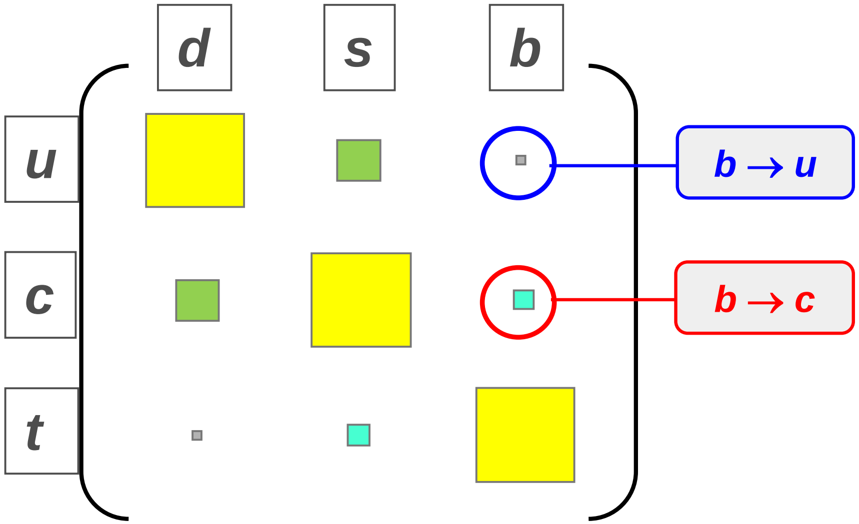
$|V_{ij}| \sim \lambda^3$ or λ^2 for B-decays

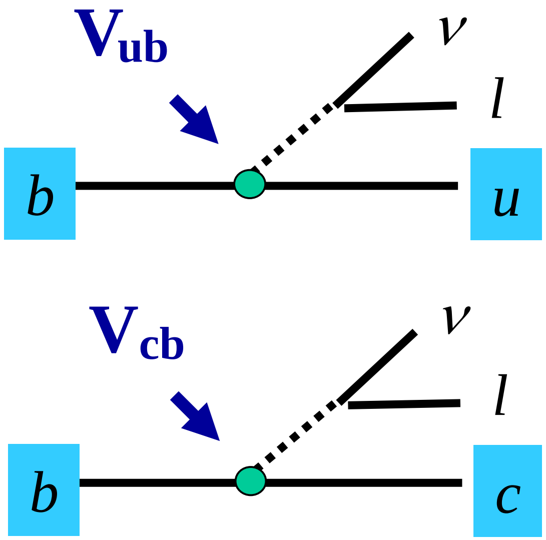
Helicity suppressed

CKM matrix elements

V_{ub}, V_{cb}

➔ Determined from semileptonic B decays



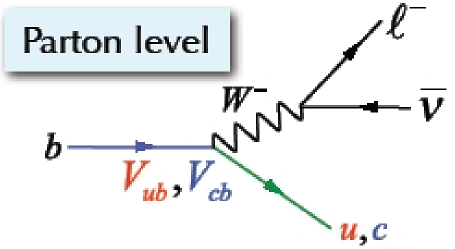


$$\Gamma(b \rightarrow u) \ll \Gamma(b \rightarrow c)$$

Measurement of |Vub| and |Vcb|

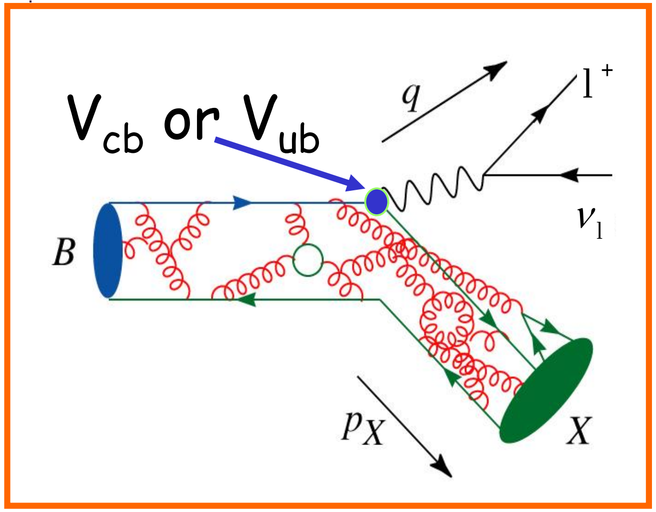
Weak decay of a free quark :

$$G_0 \equiv \Gamma\left(b \to c[u] l \bar{\nu}\right) = \frac{G_F^2 \left|V_{c[u]b}\right|^2}{192\pi^3} m_b^5$$



At the hadron level :

$$\frac{\partial^3\Gamma}{\partial E_l \partial q^2 \partial m_X} = \underbrace{\Gamma_0}_{\text{free quark decay}} \times f(E_l, q^2, m_X) \times \underbrace{\left(1 + \sum_n C_n \left(\frac{\Lambda_{QCD}}{m_b}\right)^n\right)}_{\text{Perturbative +non-perturbative corrections}}$$

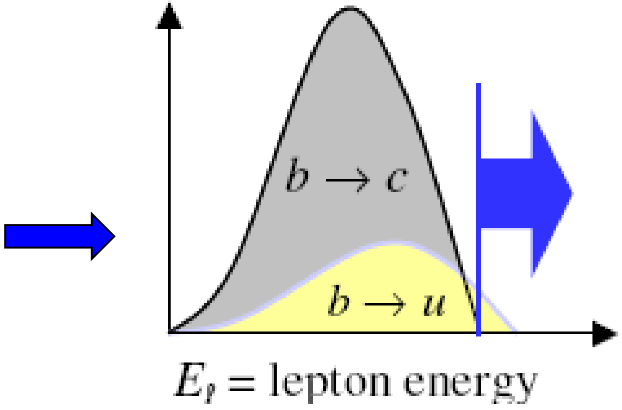


- ☐ OPE+HQE → decay rate known to ~ 3%

exclusive	inclusive
$B \to \pi \ell\nu$	$B \to X_u \ell\nu$
QCD form factors	*Heavy Quark symmetry+ OPE*
$B \to D^* \ell\nu$	$B \to X_c \ell\nu$

$\Gamma(B\to X_c l\nu) = 50 \times \Gamma(B\to X_u l\nu)$

$B\to X_c \ell\nu$ & $B\to X_u \ell\nu$



|Vub| and |Vcb|: inclusive measurement

V_{ub} inclusive determination :

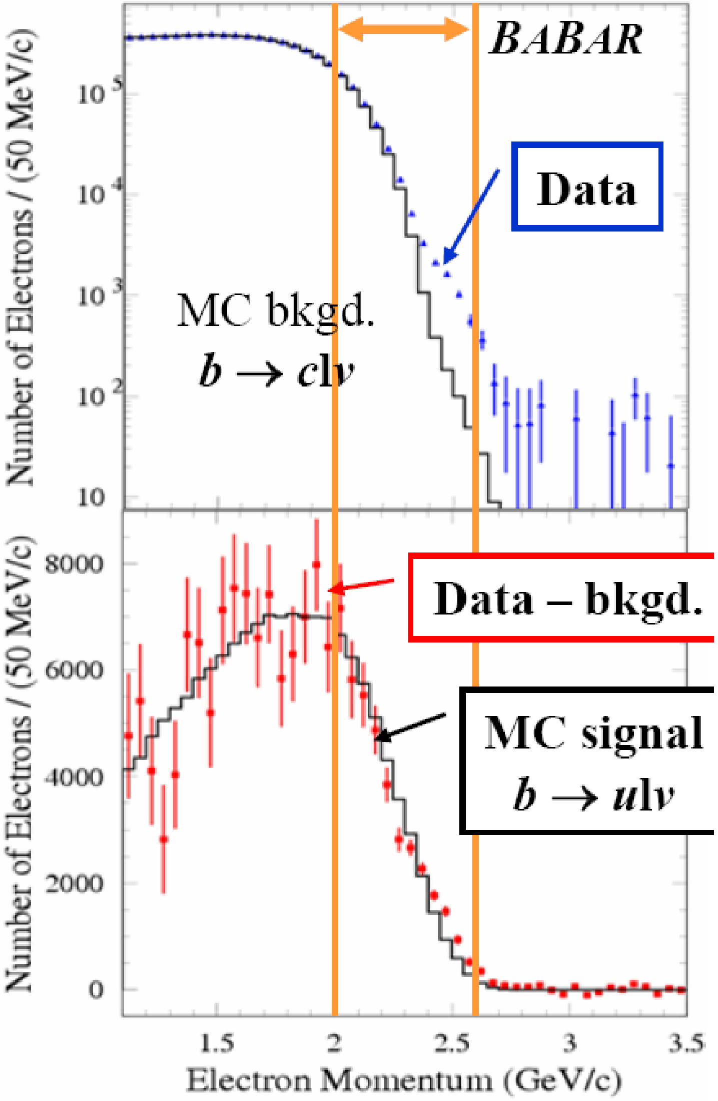
example of the lepton end-point

Electrons 2.0 < E_l < 2.6 GeV

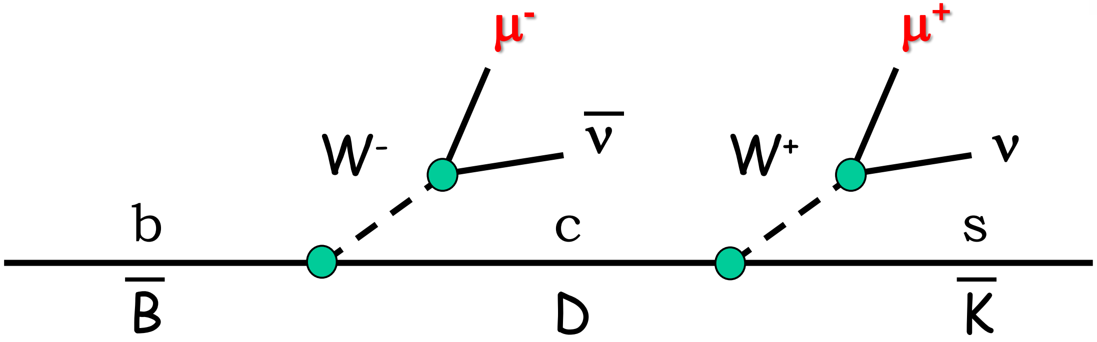
- accept some $B \to X_c l \nu$ events

- precise subtraction of the background is crucial

off peak data, fit the various backgrounds from $B \to X_c l \nu$



Leptons from cascade decays



Summary of |Vub| and |Vcb| results

$|V_{cb}|$: 1.5–2% precision

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad \text{(inclusive)}$$

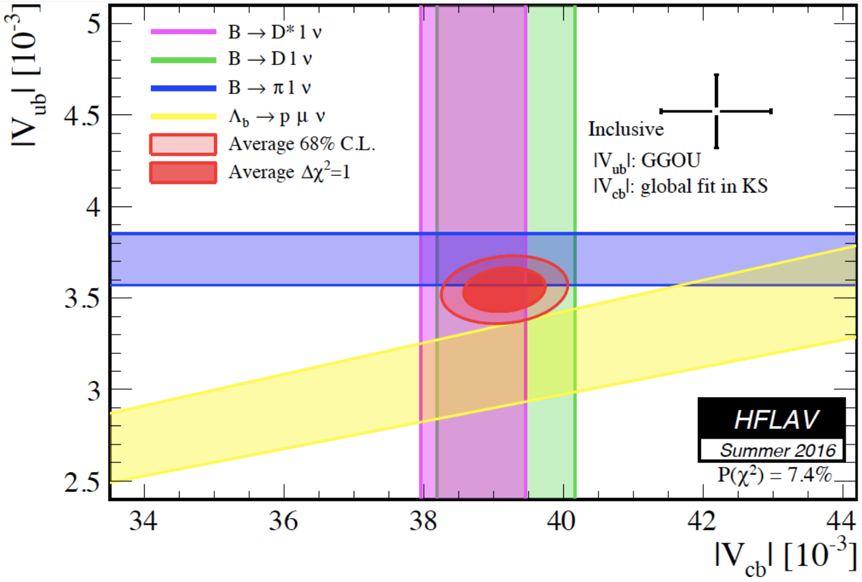
$$|V_{cb}| = (39.2 \pm 0.7) \times 10^{-3} \quad \text{(exclusive)}$$

$|V_{ub}|$: SM prediction : $|V_{ub}| = (3.67 \pm 0.15) \times 10^{-3}$

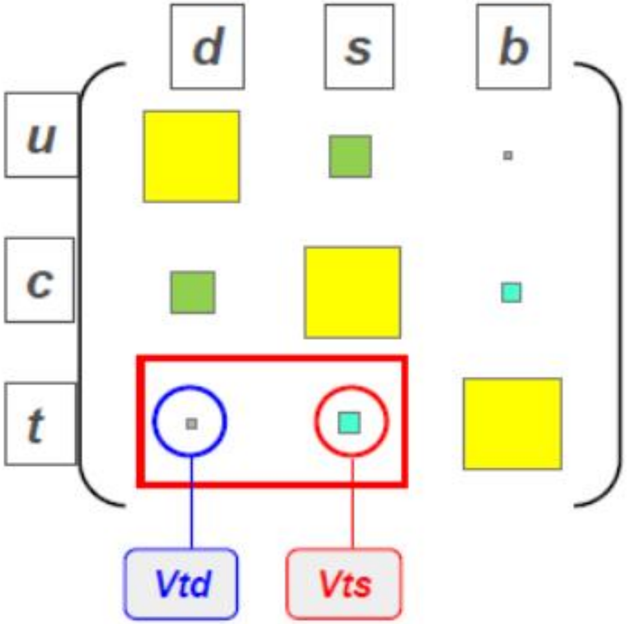
$$|V_{ub}| = (4.49 \pm 0.16 \, {}^{+\,0.16}_{-\,0.18}) \times 10^{-3} \quad \text{(inclusive)}$$

$$|V_{ub}| = (3.72 \pm 0.19) \times 10^{-3} \quad \text{(exclusive)}$$

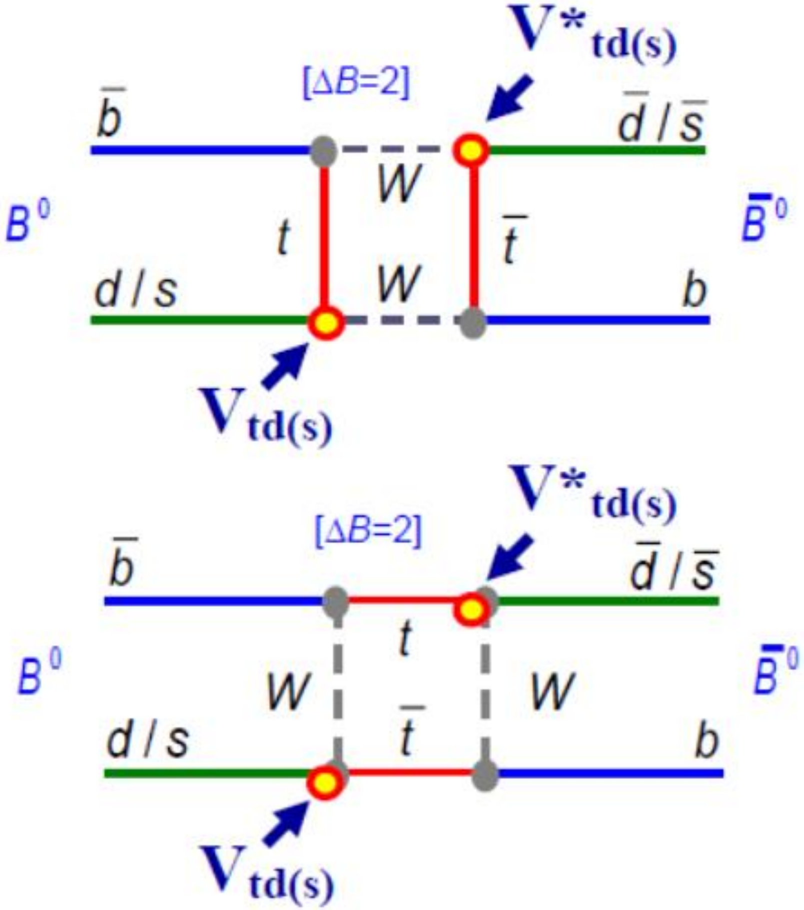
- Marginal agreement between inclusive and exclusive techniques may indicate some fundamental question in the decay description
- Intense research fields both in experiments and theory



V_{td}, V_{ts} from $B\bar{B}$ mixing



Box diagram : ΔB = 2 process



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

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

$|B_L\rangle$, $|B_H\rangle$: mass eigenstates

$|B^0\rangle$, $|\bar{B}^0\rangle$: flavour eigenstates

$|B^0(t)\rangle$ ($|\bar{B}^0(t)\rangle$) : the flavour state of a B meson that was a B^0 ($\bar{B}^0$) at $t=0$.

Schrödinger equation governs time evolution of the B^0-$\bar{B}^0$ System:

$$\boxed{i\frac{d}{dt}\begin{pmatrix}|B^0(t)\rangle \\ |\bar{B}^0(t)\rangle\end{pmatrix} = \underbrace{\left(M - \tfrac{i}{2}\Gamma\right)}\begin{pmatrix}|B^0(t)\rangle \\ |\bar{B}^0(t)\rangle\end{pmatrix}}$$

≡ ***H*** (effective Hamiltonian)

$$\left(\frac{q}{p}\right)^2 = \frac{\mathrm{M}_{12}^* - (i/2)\Gamma_{12}^*}{\mathrm{M}_{12} - (i/2)\Gamma_{12}}$$

$$\Delta m_B \equiv M_H - M_L$$
$$\Delta\Gamma_B \equiv \Gamma_H - \Gamma_L$$
$$m_B \equiv \frac{M_H + M_L}{2}$$
$$\Gamma_B \equiv \frac{\Gamma_H + \Gamma_L}{2}$$
$$\frac{q}{p} = \frac{\Delta m + i\Delta\Gamma/2}{2M_{12} - i\Gamma_{12}}$$

Neglect CPV : q/p=1; assume $\Delta\Gamma=0$

Time evolution of the physical states $|B^0(t)\rangle$ ($|\bar{B}^0(t)\rangle$)

Starting from a B^0
(produced by strong interaction)

$$\boxed{\left|\langle B^0|H|B^0(t)\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1+\cos\Delta m t)}$$

Starting from a $\bar{B}^0$

$$\boxed{\left|\langle \bar{B}^0|H|B^0(t)\rangle\right|^2 = \frac{e^{-\Gamma t}}{2}(1-\cos\Delta m t)}$$

If one does not neglect $\Delta\Gamma$ (useful for charm) :

$$\frac{e^{-\Gamma t}}{4}(\underbrace{e^{\frac{\Delta\Gamma}{2}t}+e^{-\frac{\Delta\Gamma}{2}t}}_{\cosh\left(\frac{\Delta\Gamma}{2}t\right)} \pm 2\cos\Delta m t)$$

So for the time dependent mixing asymmetry:

$$A_{mix}(t) \equiv \frac{N(unmixed)-N(mixed)}{N(unmixed)+N(mixed)}(t) = \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}$$

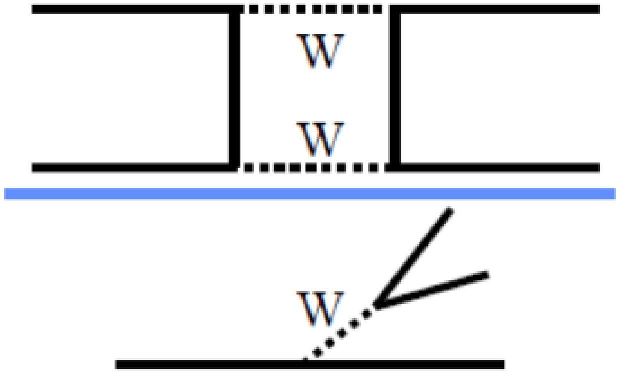
Mixed : $\bar{B}^0 \rightarrow B^0$ or $B^0 \rightarrow \bar{B}^0$

Unmixed : $\bar{B}^0 \rightarrow \bar{B}^0$ or $B^0 \rightarrow B^0$

$\cosh(\Delta\Gamma t/2) \rightarrow 1$ when $\Delta\Gamma \rightarrow 0$

$$\cos\Delta m t = \cos\left(\frac{\Delta m}{\Gamma}\right)\left(\frac{t}{\tau}\right)$$

Mixing parameters: $x=\Delta m/\Gamma$; $y=\Delta\Gamma/2\Gamma$ x,y ~



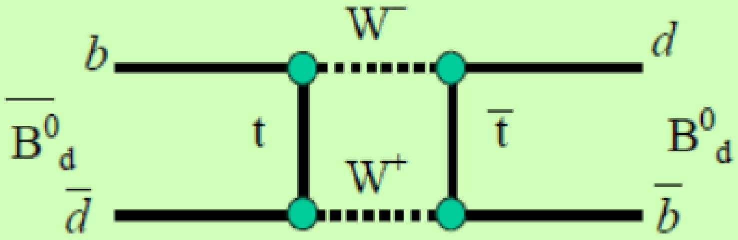
x : the mixing frequency in units of lifetime

x>>1 rapid oscillation
x<<1 slow oscillation

x values for $B_{d,s}$:

Δm Γ

B_d



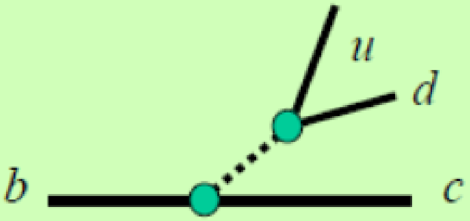
$f(m_t)[V_{td}^*V_{tb}]^2 \sim m_t^2\lambda^6$

$f(m_c)[V_{cd}^*V_{cb}]^2 \sim m_c^2\lambda^6$ totally negligible

Slow oscillations $\Delta m_d \sim 0.50 ps^{-1}$

$1/\Gamma_d \sim 1.50 ps$

$x = \Delta m_d / \Gamma_d \sim 0.75$



$[V_{ud}^*V_{cb}]^2 \sim \lambda^4$

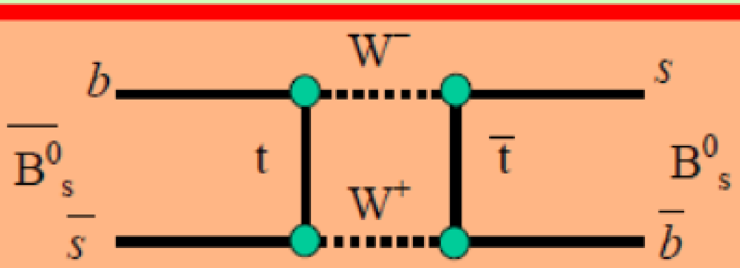
$$\boxed{x_d = \Delta m_d / \Gamma_d \sim m_t^2\lambda^2}$$

First hint of a *really large* m_{top}!

$B^0\overline{B}^0$ mixing: ARGUS, 1987

Phys.Lett.B192:245,1987

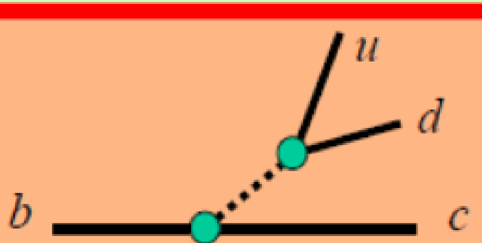
B_s



$f(m_t)[V_{ts}^*V_{tb}]^2 \sim f(m_t)\lambda^4$

$$\boxed{x_s = \Delta m_s / \Gamma_s \sim m_t^2}$$

~ very large $x_s >> 1$

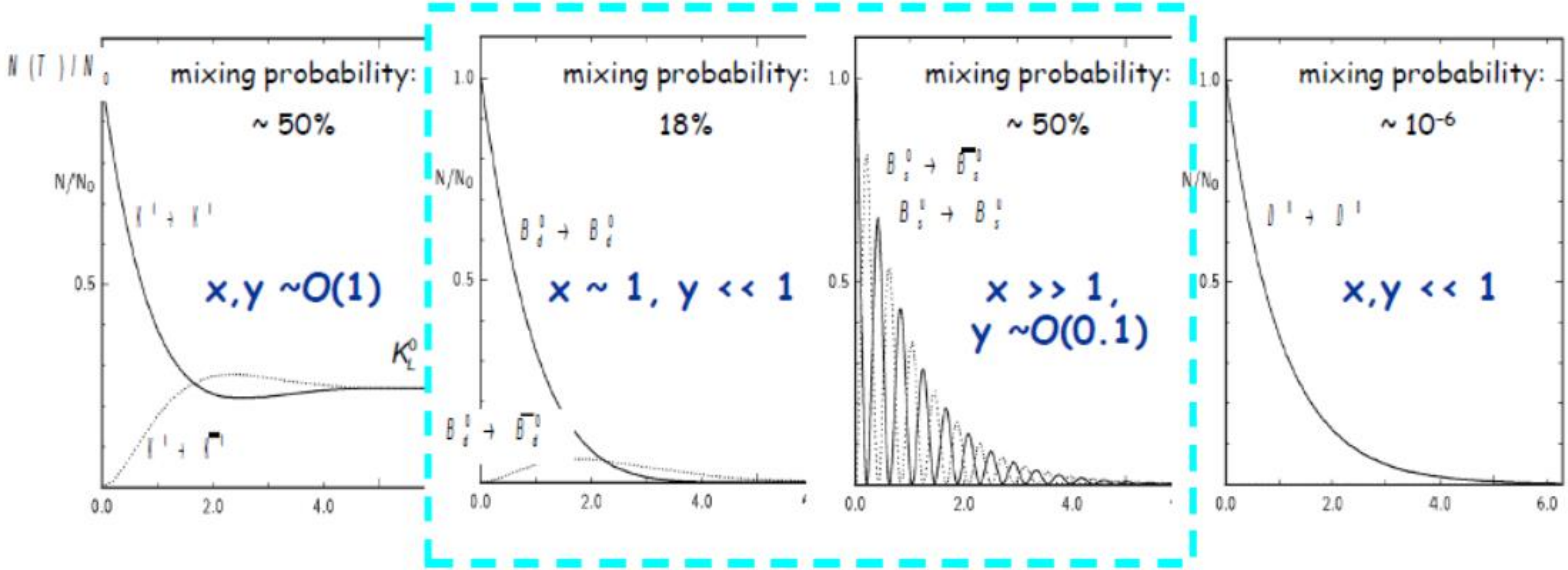


$[V_{ud}^*V_{cb}]^2 \sim \lambda^4$

$\Delta m_s \sim 17 ps^{-1}$

$1/\Gamma_s \sim 1.50 ps$ Rapid oscillations

$x = \Delta m_s / \Gamma_s \sim 25$



Perturbative QCD

CKM Matrix Elements

$$\Delta m_q = \frac{G_F^2}{6\pi^2} m_{B_q} m_W^2 \; \eta_B \; S(x_t) \; f_{B_q}^2 B_q \; \left|V_{tq}V_{tb}^*\right|^2 \quad (\text{for } q = d,s)$$

Loop integral
(top loop dominates)

Non-perturbative QCD :
dominant theoretical
uncertainty

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_{B_d} m_W^2 \;\; \eta_B \;\; S(x_t) \;\; f_{B_d}^2 B_d \;\; \left|V_{td}V_{tb}^*\right|^2$$

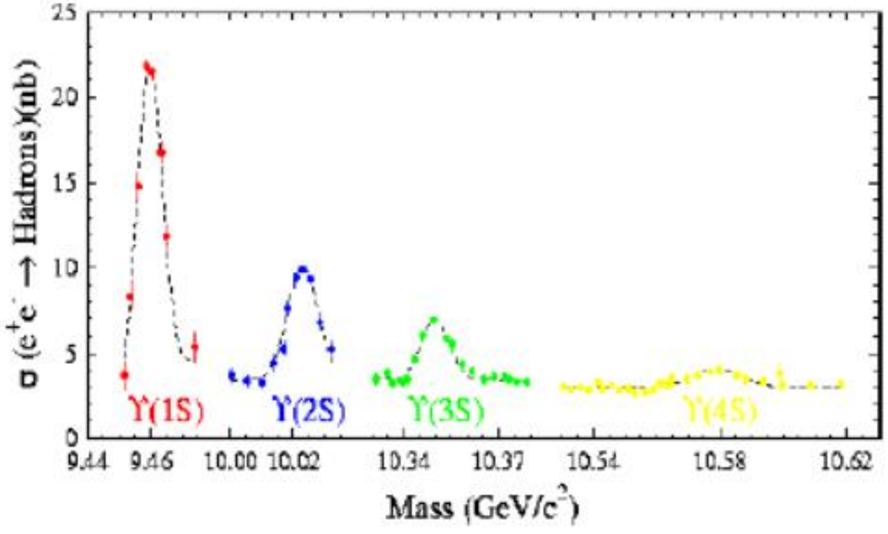
$$\Delta m_s = \frac{G_F^2}{6\pi^2} m_{B_s} m_W^2 \;\; \eta_B \;\; S(x_t) \;\; f_{B_s}^2 B_s \;\; \left|V_{ts}V_{tb}^*\right|^2$$

$$\frac{\left|V_{td}V_{tb}^*\right|^2}{\left|V_{ts}V_{tb}^*\right|^2} \longleftarrow \sim\lambda^2$$

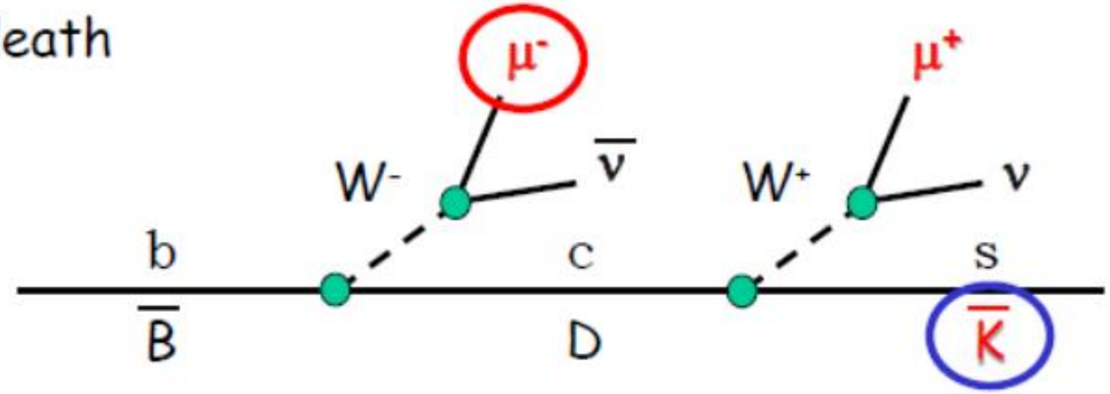
$\Delta m_s \approx \;\; 20\,\Delta m_d$
Excellent time
resolution required

$B_d\bar{B}_d$ mixing : slow oscillations

- Correlated $B\bar{B}$-production



- **Tag** B-flavour (or **fully reconstruct** B) at production/birth AND at decay/death



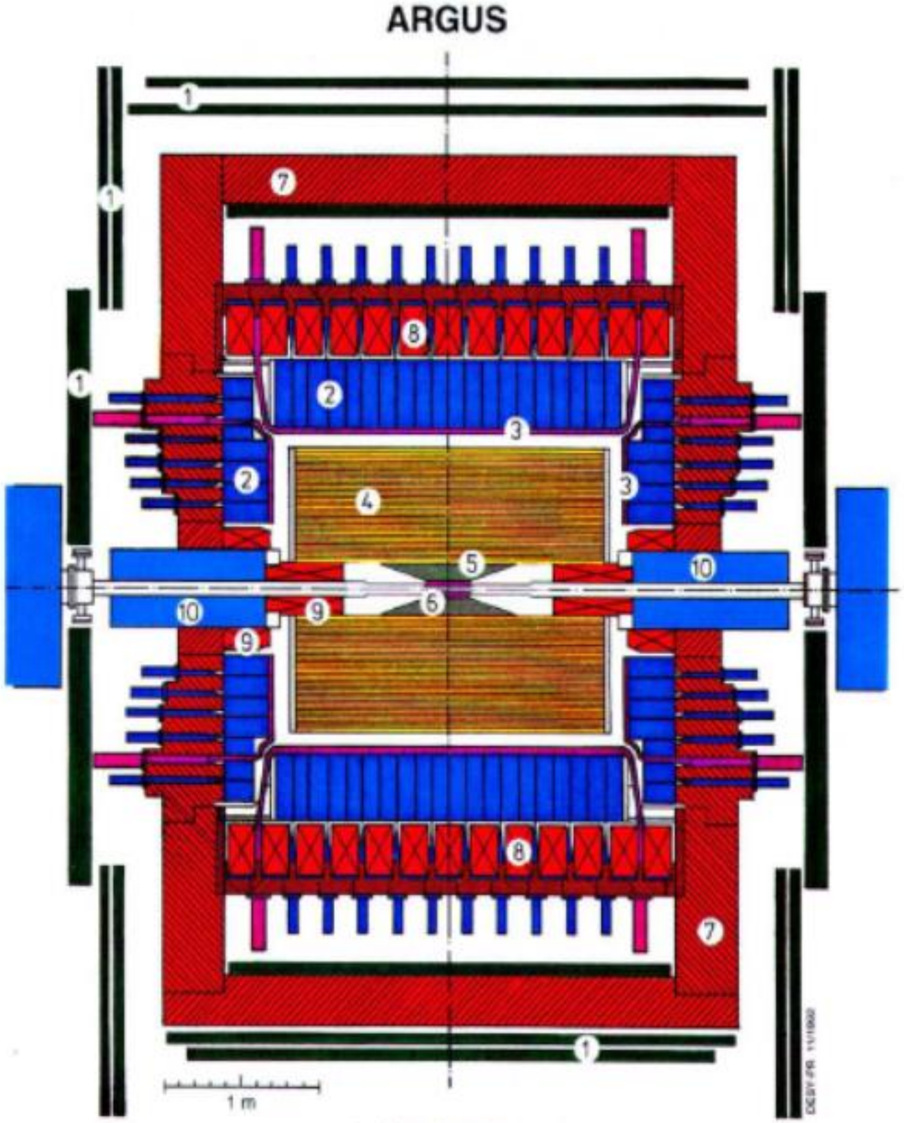
- Compare tags if more than one
- Aim at high efficiency
- Deal with dilutions

→ Track (and vertex) reconstruction

→ Identify leptons (e, μ) and charged hadrons

→ Measure kinematics : B-masses and/or missing energy/momentum

1987: discovery of $B\bar{B}$-mixing, ARGUS detector at e+e- machine DORIS@DESY



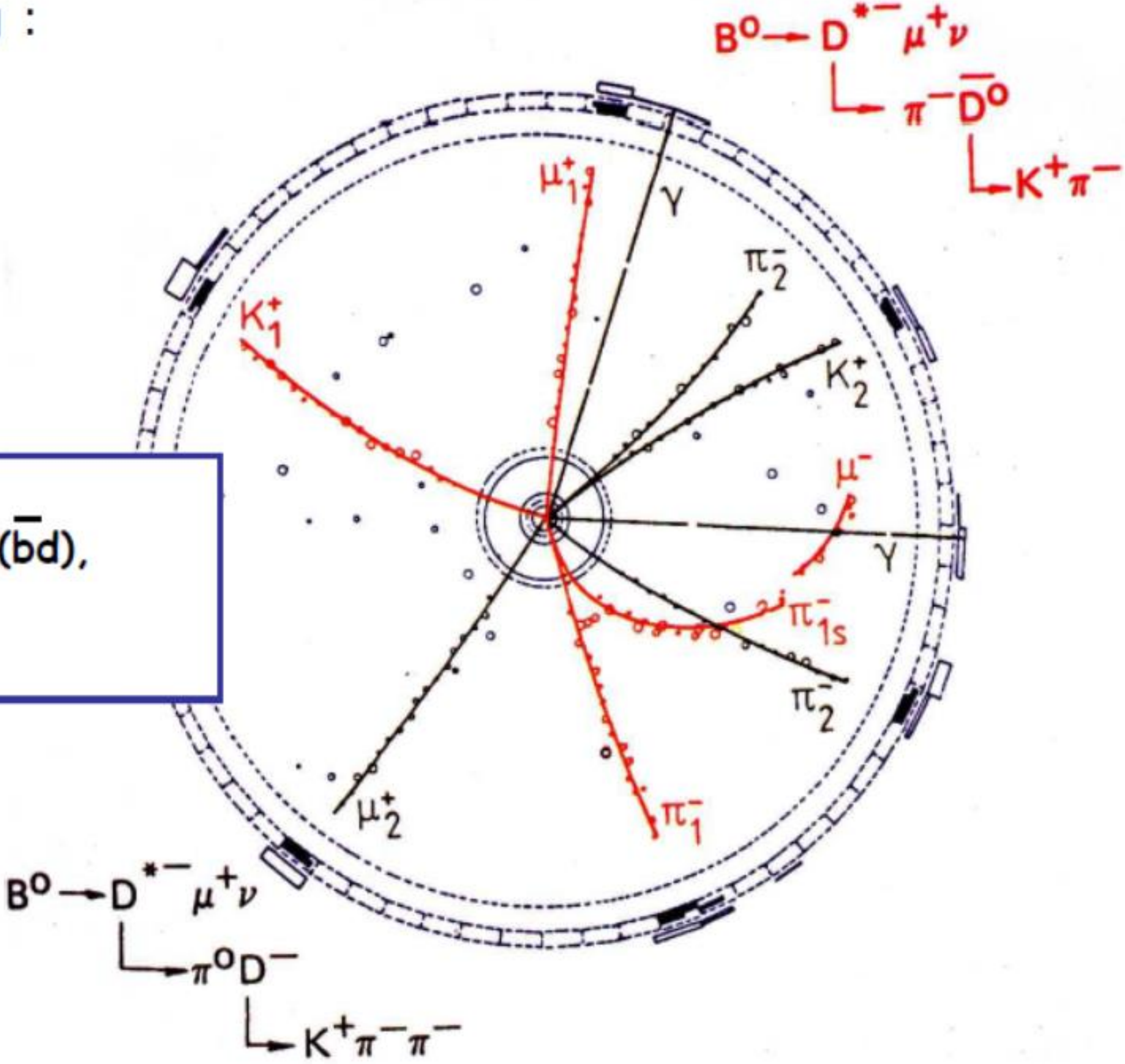
1 Muon chambers
2 Shower counters
3 Time of flight counters
4 Drift chamber
5 Vertex chamber
6 Silicon counter
7 Iron yoke
8 Solenoid coils
9 Compensation coils
10 Mini beta quadrupole

Fully reconstructed event with $B\bar{B}$ mixing at ARGUS experiment

Signature of the $B\bar{B}$ mixing :

$e^+e^- \rightarrow Y(4S) \rightarrow$
$\rightarrow B^0\bar{B}^0 \rightarrow B^0B^0$

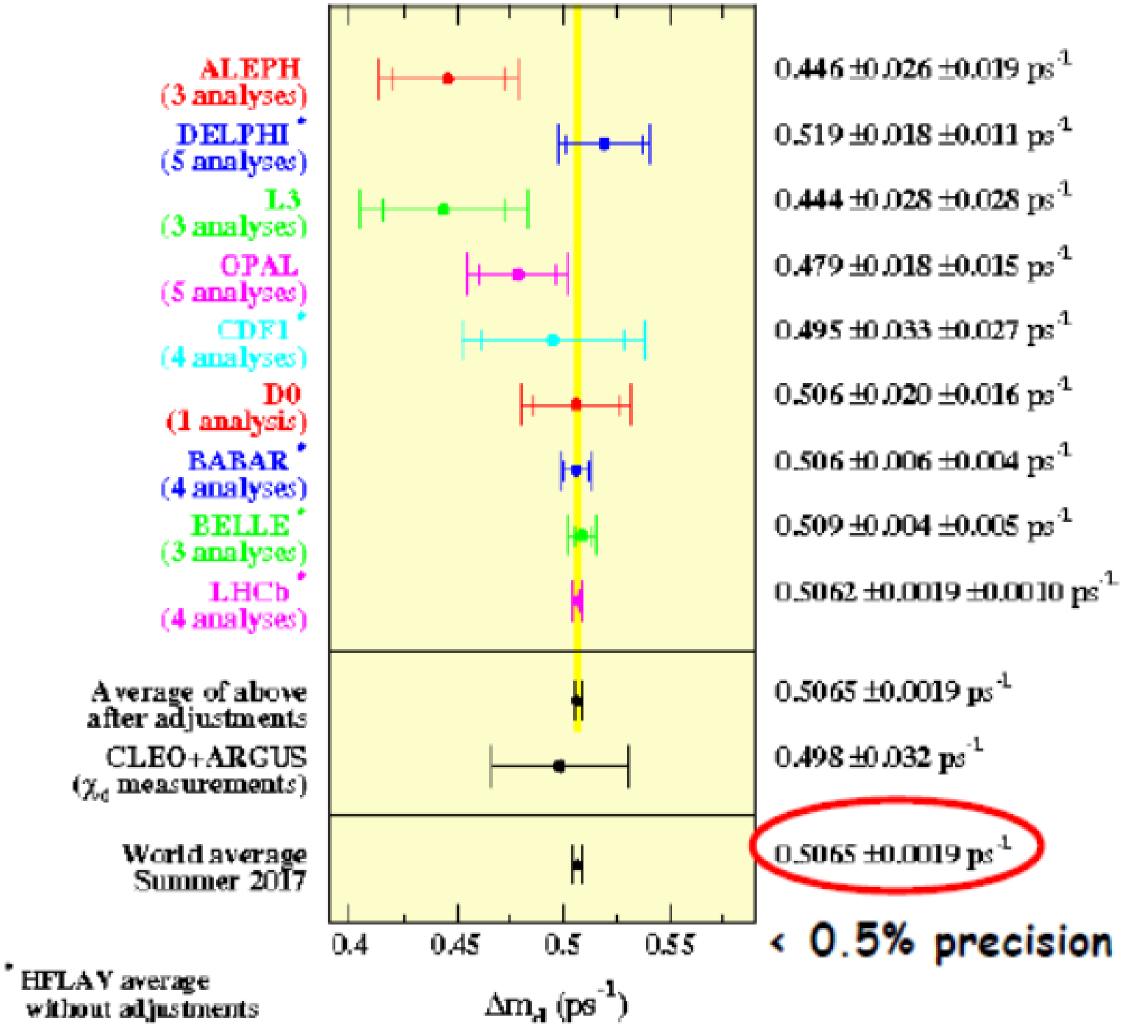
at birth (at production): $b\bar{b}$
at death (at decay): $B^0(\bar{b}d)B^0(\bar{b}d)$,
i.e. $\bar{b}\bar{b}$
→ process $b \rightarrow \bar{b}$ occured



$B_d\bar{B}_d$ mixing : slow oscillations

- ☐ Important: tag B-flavour at production AND at decay
- ☐ Time dependent measurements $A_{mix}(t) \equiv \frac{N(unmixed) - N(mixed)}{N(unmixed) + N(mixed)}(t) = \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}$

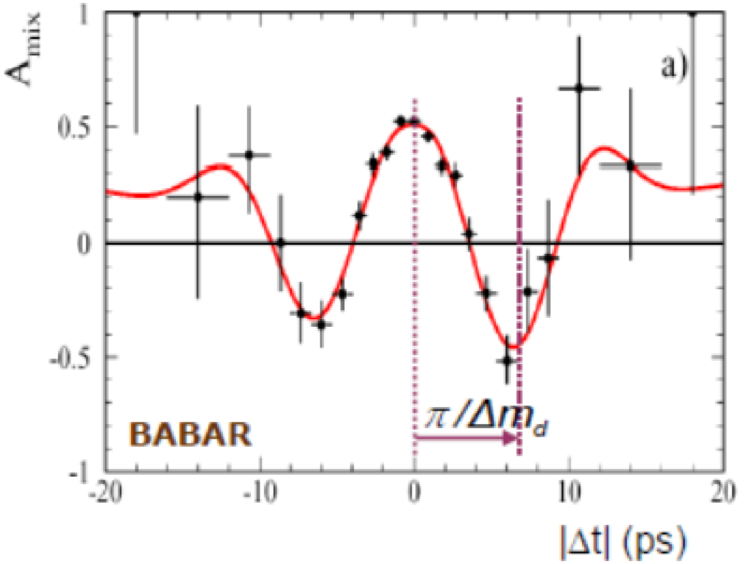
Intense field since the 1990's



< 0.5% precision !

BaBar/Belle : boost Υ(4S)

Measured asymetry∝cos(Δm_dt)



$$\Delta m_d = 0.510 \pm 0.003 \text{ ps}^{-1}$$

$$x_d = 0.775 \pm 0.006$$

$B_s\bar{B}_s$ mixing : fast oscillations

In addition :

❑ Large boost

❑ Precision decay time measurement (reconstruction of production and decay vertices) !

❑ Tag flavour

Fast oscillations are experimentally difficult to reconstruct (time resolution → vertex reconstruction)

Example: BsBs oscillations at the LHCb experiment

- ☐ Reconstruct the decay

  over the background

- ☐ Tag initial B flavour

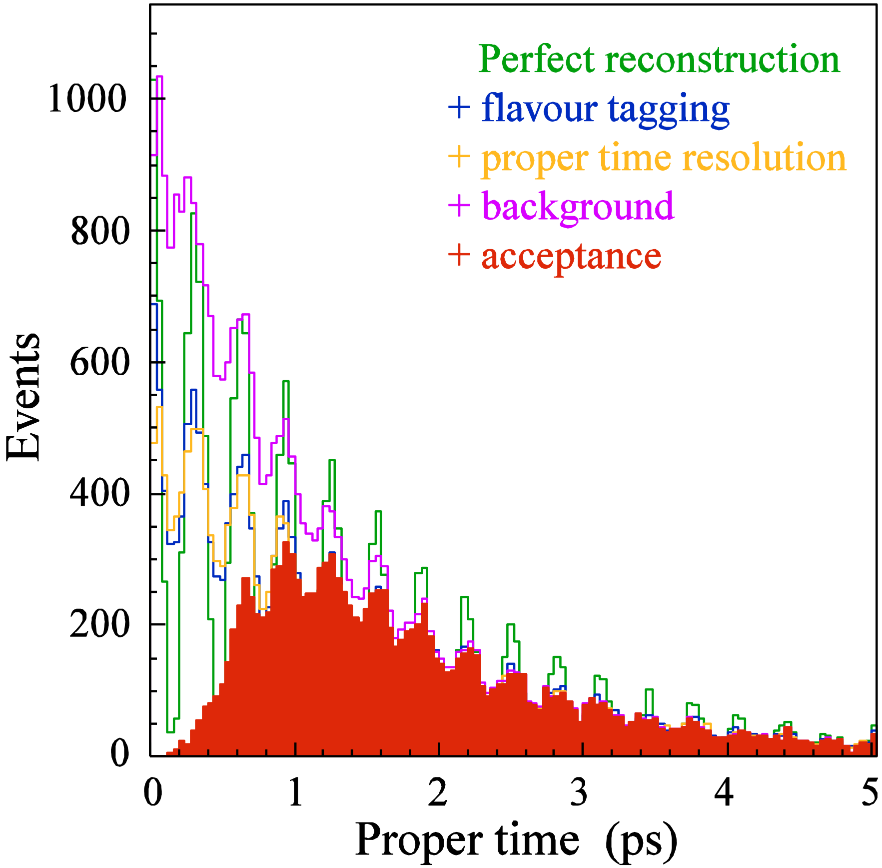
  over the background

- ☐ Measure B flavour at the decay

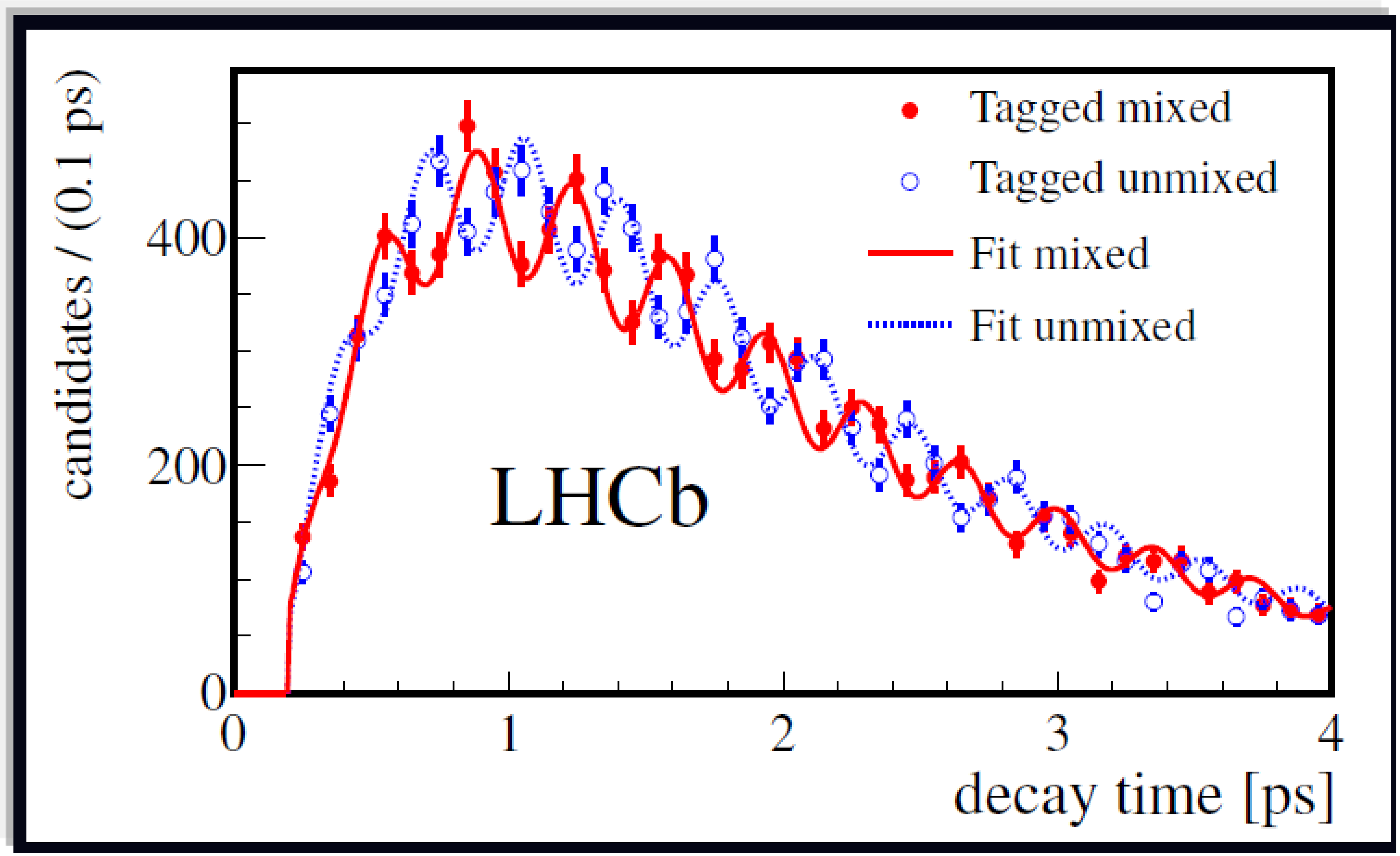
  over the background

- ☐ Measure proper time (=vertices) to be more precise

  over the background



$B_s\bar{B}_s$ mixing : fast oscillations



- ☐ A clear oscillation pattern
- ☐ On average Bs changes flavour 9 times
- ☐ x~27

$$\Delta m_s = 17.757 \pm 0.021\ \mathrm{ps}^{-1}$$
$$x_s = 26.80 \pm 0.08$$

CKM

(More on) V_{CKM} the Cabibbo-Kobayashi-Maskawa matrix

Matrix parameterization

Idea : current translating n α-quarks to n κ-quarks requires n x n matrix

In general n x n matrix : n^2 complex numbers or $2n^2$ real parameters

Unitarity condition $V^+V = 1$:

diagonal : n conditions like $V_{1k}\, V_{k1}{}^+ = V_{1k}\, V_{1k}{}^* = 1$

off-diagonal : $V_{1k}\, V_{k2}{}^+ = V_{1k}\, V_{2k}{}^* = V_{2k}\, V_{1k}{}^* = V_{2k}\, V_{k1}{}^+ = 0$

➔ ½ n/(n-1) conditions like Re $V_{1k}\, V_{2k}{}^* = 0$

➔ ½ n/(n-1) conditions like Im $V_{1k}\, V_{2k}{}^* = 0$

➔ it rests n^2 real parameters

Rotating matrix elements redefine (remove) 2n-1 non-physical phases :

n-1 for α-quarks and n for κ-quarks

$$\begin{array}{c} \begin{array}{cccccc} / & / & / & / & / & X \end{array} \\ \left(\begin{array}{cccccc} o & o & o & o & o & \backslash \\ o & o & o & o & o & \backslash \\ o & o & o & o & o & \backslash \\ o & o & o & o & o & \backslash \end{array}\right) \end{array}$$

➔ it rests $n^2 - (2n - 1) = (n - 1)^2$ parameters (orthogonal rotation angles and phases)

In n-dimensional space : $n_o = ½\, n\, (n - 1)$ independent rotations

Physical phases : $n_\delta = (n - 1)^2 - ½\, n/(n - 1) = ½\, (n - 1)\, (n - 2)$

Number of generations = 3

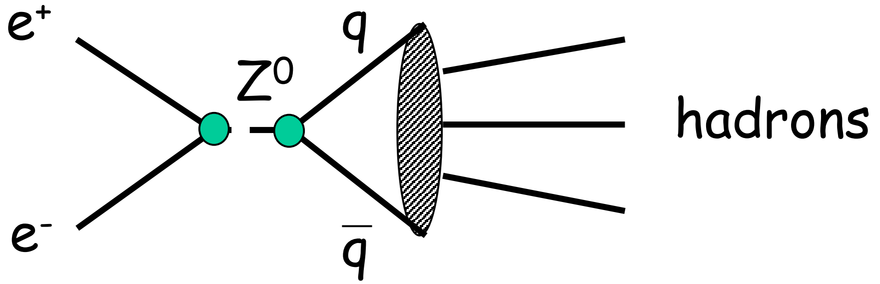
LEP : ALEPH, DELPHI, OPAL, L3

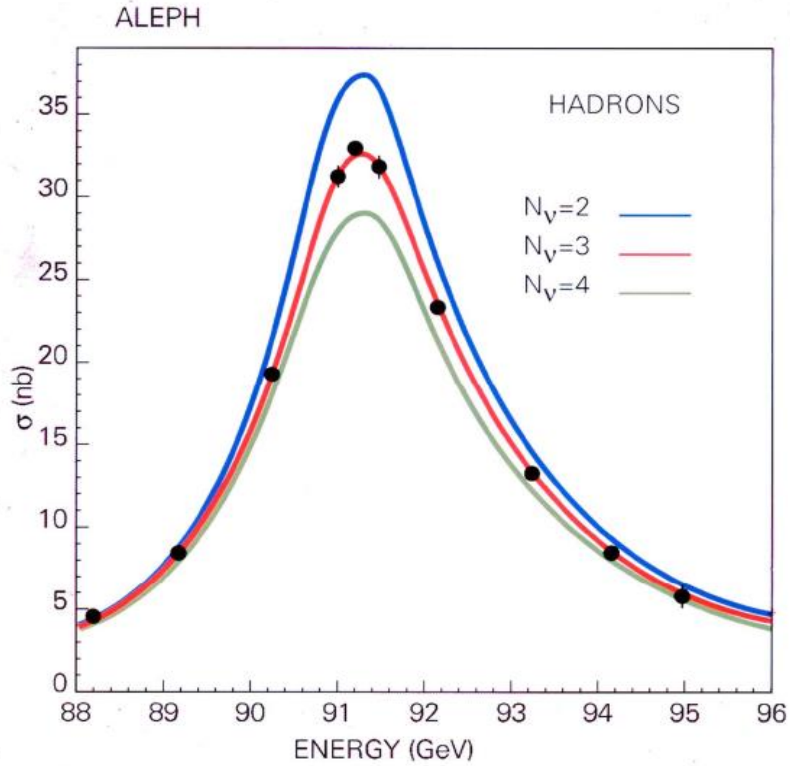
- ☐ Compare full Z^o width from $\sigma(e^+e^- \rightarrow Z^o \rightarrow \text{hadrons})$

  and

  partial width of $Z^o \rightarrow$ ee, μμ, ττ, uu, dd, ss, cc, bb

- ☐ Then divide the difference by the $\Gamma(Z^o \rightarrow \nu\nu)$, where ν – low mass neutrinos.

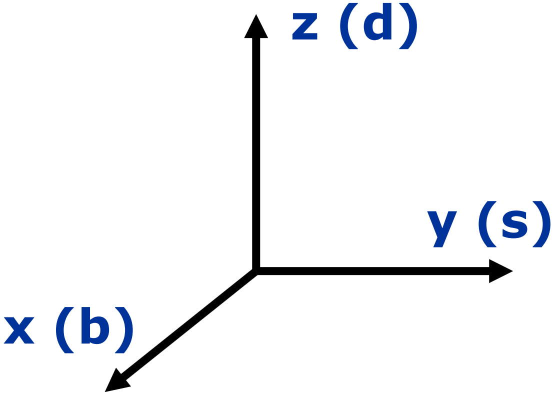




➔ 3 (neutrino, left-handed, active, m<M(Z)/2) generations.

# families	# angles	# reducible phases	# irreducible phases
n	n(n-1)/2	2n-1	n(n+1)/2 –(2n-1)=(n-1)(n-2)/2
2	1	1	0
3	3	5	1
4	6	7	3

For n = 3, i.e. u,c,t,d,s,b quarks :



do 3 sequential rotations of (z y x) …

$c_i = \cos\theta_i$, $s_i = \sin\theta_i$, θ_i - Euler angles, $i = 1..3$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c2 & s2 \\ 0 & -s2 & c2 \end{pmatrix}\begin{pmatrix} c1 & s1 & 0 \\ -s1 & c1 & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c3 & s3 \\ 0 & -s3 & c3 \end{pmatrix}$$

… insert the phase …

$$(\bar{u}\ \ \bar{c}\ \ \bar{b})\begin{pmatrix} 1 & 0 & 0 \\ 0 & c2 & s2 \\ 0 & -s2 & c2 \end{pmatrix}\begin{pmatrix} c1 & s1 & 0 \\ -s1 & c1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}\begin{pmatrix} 1 & 0 & 0 \\ 0 & c3 & s3 \\ 0 & -s3 & c3 \end{pmatrix}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

… and multiply …

KM parametrization

$$(\bar{u}\ \ \bar{c}\ \ \bar{b})\boxed{\begin{pmatrix} c1 & s1\,c3 & s1\,s3 \\ -s1\,c2 & c1\,c2\,c3 - e^{i\delta}\,s2\,s3 & c1\,c2\,s3 + e^{i\delta}\,s2\,c3 \\ s1\,s2 & -\,c1\,s2\,c3 - e^{i\delta}\,c2\,s3 & -\,c1\,s2\,s3 + e^{i\delta}\,c2\,c3 \end{pmatrix}}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Chau, Keung: 3 angles (θ_{ij}) and one phase (δ)

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

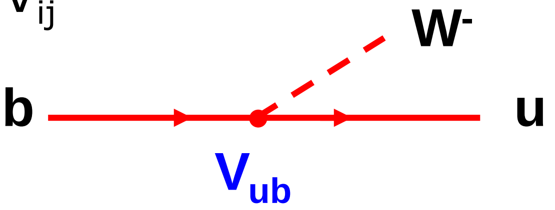
$c_{ij} = \cos\theta_{ij}$

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

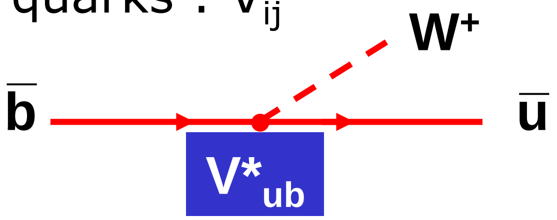
“12” – Cabibbo angle

$\delta \Rightarrow$ CP violation :

Transition amplitude between i and j quarks : V_{ij}



Transition amplitude between i and j anti-quarks : V_{ij}^{*}



Irreducible phase

➔ $V^{*}_{ub} \neq V_{ub}$

➔ matter behaves differently from anti-matter

i.e. **CP symmetry violation**

however, not visible when considering $|V_{ub}|^2$

Original idea in: M.Kobayashi and T.Maskawa, Prog. Theor. Phys 49, 652 (1973)

3 family flavour mixing in quark sector needed for CP violation.

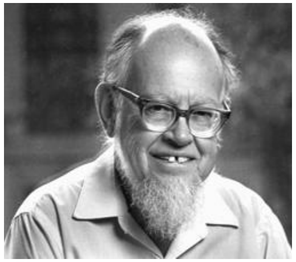
Before the discovery of the charm quark !

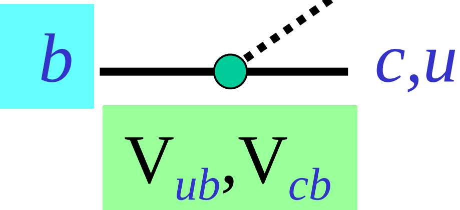
CKM Matrix in Wolfenstein parametrization

- ☐ 4 parameters (3 real parameters and 1 complex phase): λ, A, ρ, $\boxed{\eta}$

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \left(\begin{array}{ccc} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ \underbrace{A\lambda^3(1-\rho-i\eta) \quad -A\lambda^2}_{\text{B Oscillations}} & & 1 \end{array} \right) \end{array}$$

V_{tb}





B decays

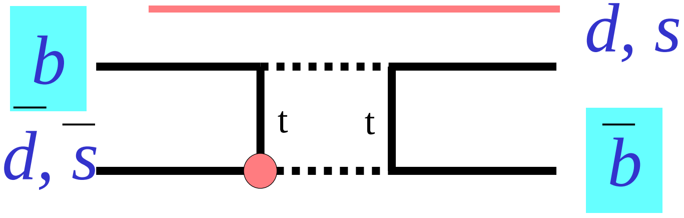
$$\lambda = 0.2257^{+0.0009}_{-0.0010}$$

$$\bar{\rho} = 0.135^{+0.031}_{-0.016}$$

$$\bar{\eta} = 0.349^{+0.015}_{-0.017}$$

$$A = 0.814^{+0.021}_{-0.022}$$

B Oscillations



V_{td}, V_{ts}

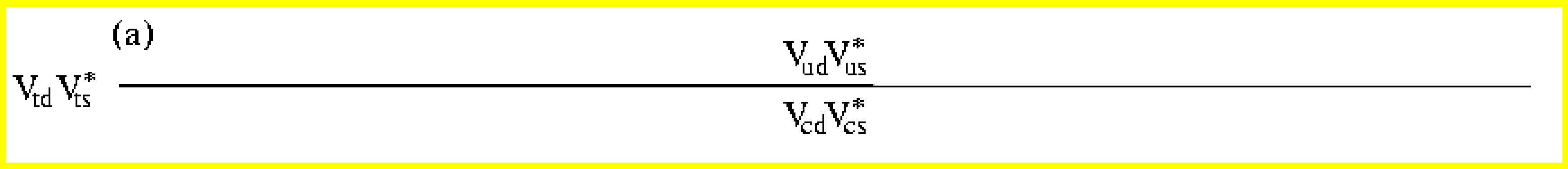
- ☐ **Single complex parameter** in the CKM matrix **responsible for CPV**
  → strong predictive power !
- ☐ **B-physics** solely capable to determine **CKM mixing parameters of 3rd quark generation** and **for CPV up to** λ^3

Unitarity triangles

- Unitarity of the CKM matrix : $VV^{\dagger} = V^{\dagger}V = 1 \Rightarrow$ 9 relations

$$\sum_{k=1}^{n} V_{ik}V^{*}_{jk} = \delta_{ij},$$

- The non-diagonal elements of the matrix products correspond to 6 triangle equations :



$$V^*_{ud}V_{us} + V^*_{cd}V_{cs} + V^*_{td}V_{ts} = 0 \quad \lambda\ \lambda\ \lambda^5$$

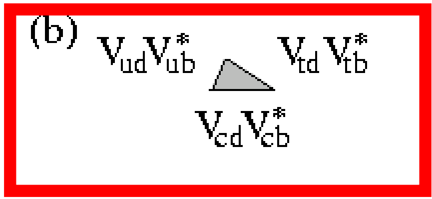
$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0 \quad \lambda^3\ \lambda^3\ \lambda^3$$

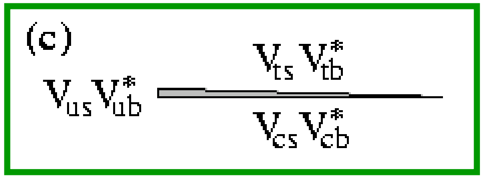
$$V^*_{us}V_{ub} + V^*_{cs}V_{cb} + V^*_{ts}V_{tb} = 0 \quad \lambda^4\ \lambda^2\ \lambda^2$$

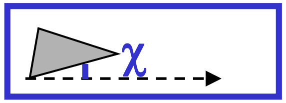
$$V^*_{ud}V_{td} + V^*_{us}V_{ts} + V^*_{ub}V_{tb} = 0 \quad \lambda^3\ \lambda^3\ \lambda^3$$

$$V^*_{td}V_{cd} + V^*_{ts}V_{cs} + V^*_{tb}V_{cb} = 0 \quad \lambda^4\ \lambda^2\ \lambda^2$$

$$V^*_{ud}V_{cd} + V^*_{us}V_{cs} + V^*_{ub}V_{cb} = 0 \quad \lambda\ \lambda\ \lambda^5$$







The Unitarity triangle

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

$$V_{ud}\,V_{ub}^{*} = A\lambda^{3}(\overline{\rho} + i\overline{\eta})$$

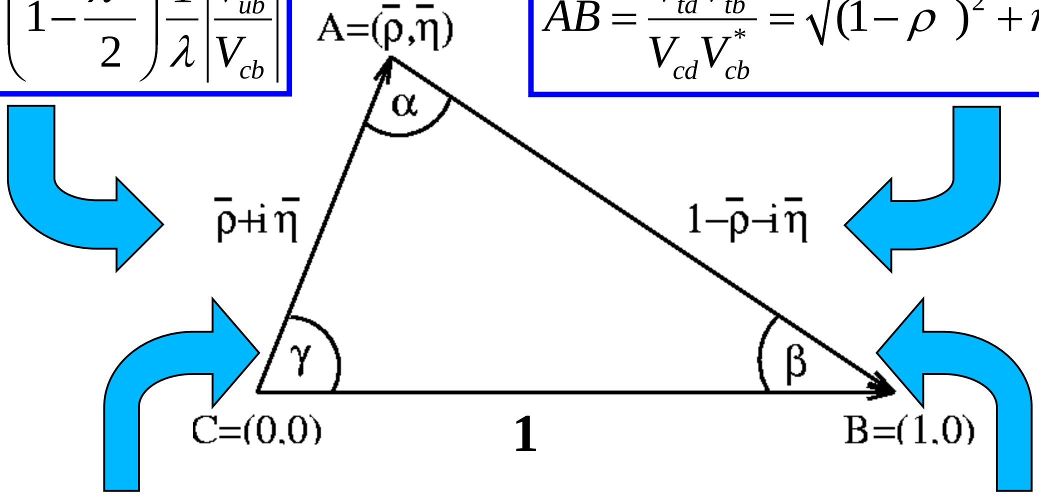
$$V_{cd}\,V_{cb}^{*} = -A\lambda^{3}$$

$$V_{td}\,V_{tb}^{*} = A\lambda^{3}(1-\overline{\rho} - i\overline{\eta})$$

$$\overline{AC} = \frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} = \sqrt{\overline{\rho}^{2} + \overline{\eta}^{2}} = \left(1-\frac{\lambda^{2}}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

$$\overline{AB} = \frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}} = \sqrt{(1-\overline{\rho}\ )^{2} + \overline{\eta}^{2}} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right| \sim \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$

(b→u transitions)



(B mixing)

$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right) = \text{atan}\left(\frac{\overline{\eta}}{\overline{\rho}}\right)$$

$$\beta = \arg\left(\frac{V_{td}V_{tb}^{*}}{V_{cd}V_{cb}^{*}}\right) = \text{atan}\left(\frac{\overline{\eta}}{(1-\overline{\rho})}\right)$$

(b→u phase)

$$\alpha + \beta + \gamma = \pi$$

(B mixing phase)

Amount of CP violation

Using Standard Parametrization of CKM:

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

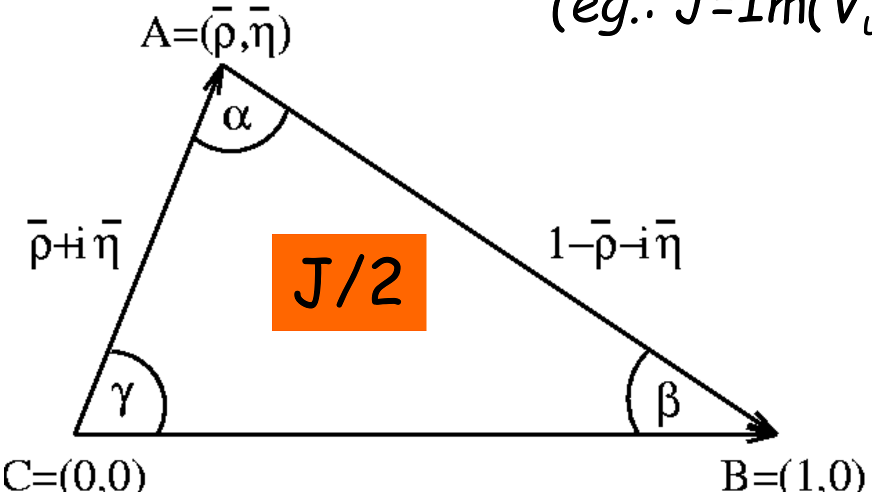
$$c_{ij} \equiv \cos\theta_{ij}$$
$$s_{ij} \equiv \sin\theta_{ij}$$

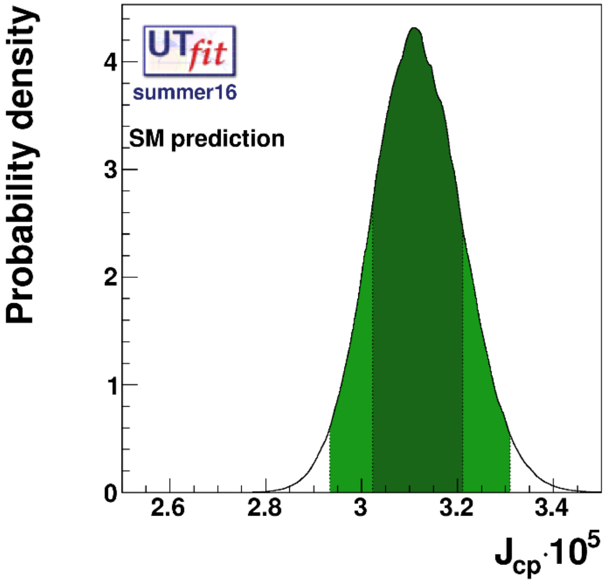
Area of each UT = |J|/2

Jarlskog invariant:

$J \equiv c_{12}c_{23}c_{13}^2 s_{12}s_{23}s_{13}\sin\delta = (3.115 \pm 0.093) \times 10^{-5}$

(eg.: $J = Im(V_{us} V_{cb} V_{ub}^* V_{cs}^*)$)

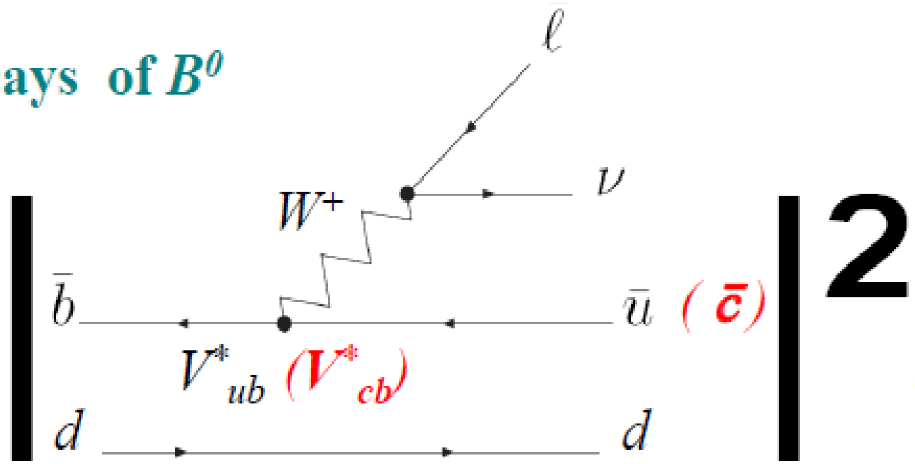




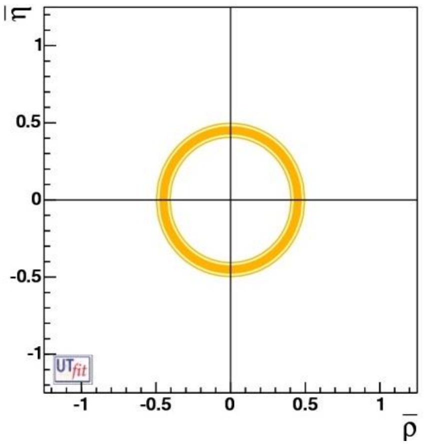
UT from Vub

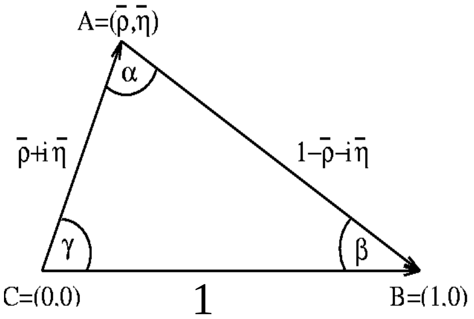
- Rates of semileptonic decays of B^0

Provide information on V_{ub} (V_{cb})



$\propto |V_{ub}|^2$ ($|V_{cb}|^2$)



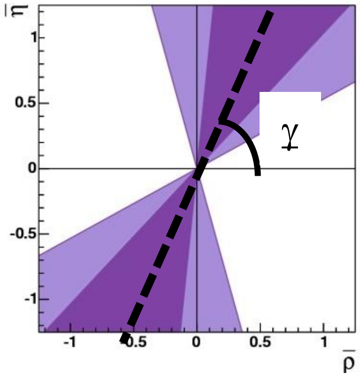


$$\overline{AC} = \frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \sqrt{\bar{\rho}^2 + \bar{\eta}^2} = \left(1 - \frac{\lambda^2}{2}\right)\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|$$

Circle around (0,0) in the $\bar{\rho}$–$\bar{\eta}$ plane

If we can access to the imaginary part of the ampliutude involving V_{ub} → access to γ angle

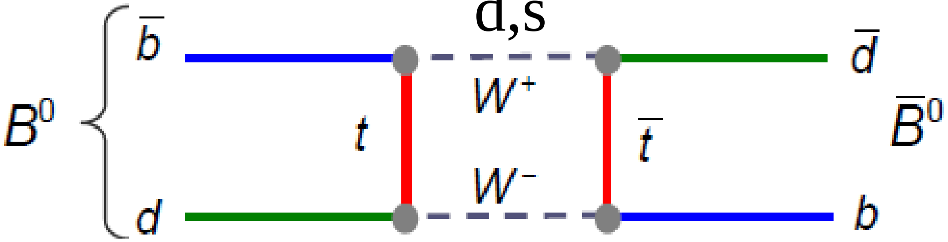
$$\gamma = \arg\left(\frac{V_{ud}\boxed{V_{ub}^*}}{V_{cd}V_{cb}^*}\right) = \operatorname{atan}\left(\frac{\bar{\eta}}{\bar{\rho}}\right)$$

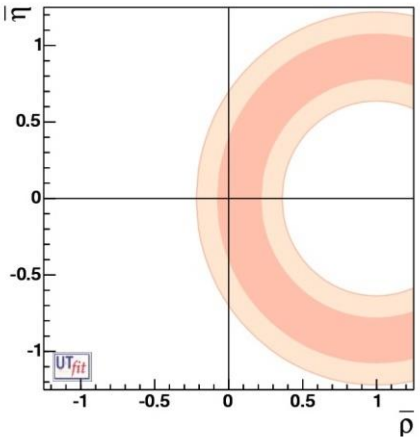


UT from Vtd

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

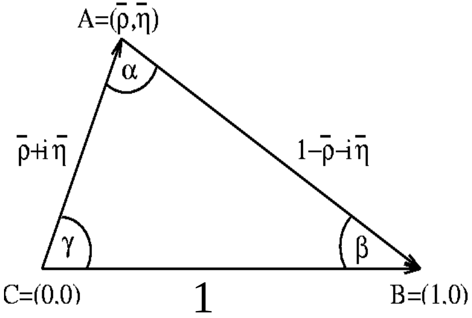
~ $(V_{td}\, V^*_{tb})^2$





Oscillation frequency of B_d ~ $|V_{td}|^2$

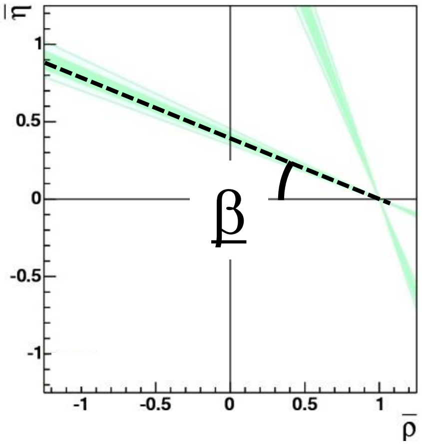
$$\overline{AB} = \frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}} = \sqrt{(1-\bar\rho)^2+\bar\eta^{2}} = \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right| \sim \frac{1}{\lambda}\left|\frac{V_{td}}{V_{ts}}\right|$$



Circle around (1,0) in the $\bar\rho$–$\bar\eta$ plane

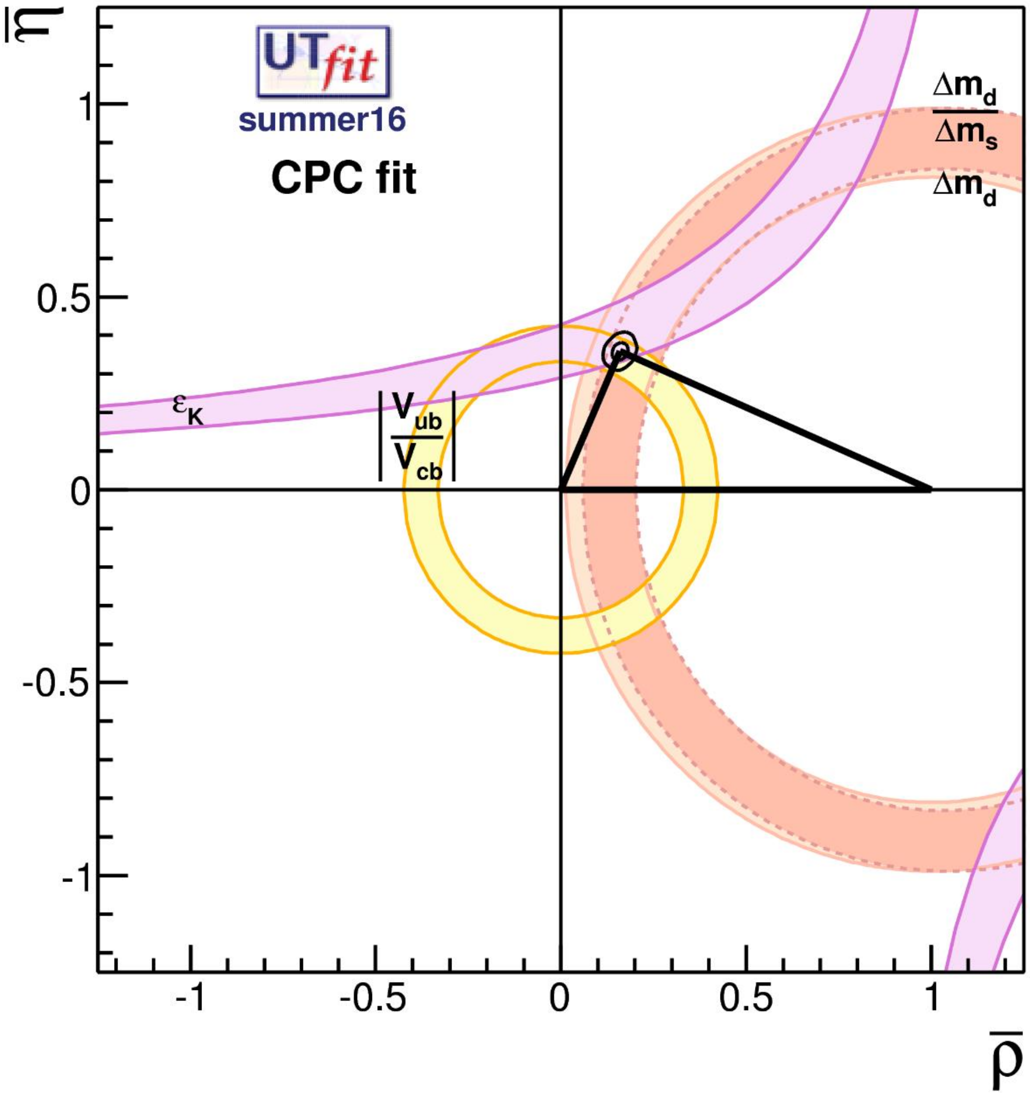
If we can access to the imaginary part of the amplitude involving V_{td} → access to β angle

$$\beta = \arg\left(\frac{V_{td}V^*_{tb}}{V_{cd}V^*_{cb}}\right) = \mathrm{atan}\left(\frac{\bar\eta}{(1-\bar\rho)}\right)$$



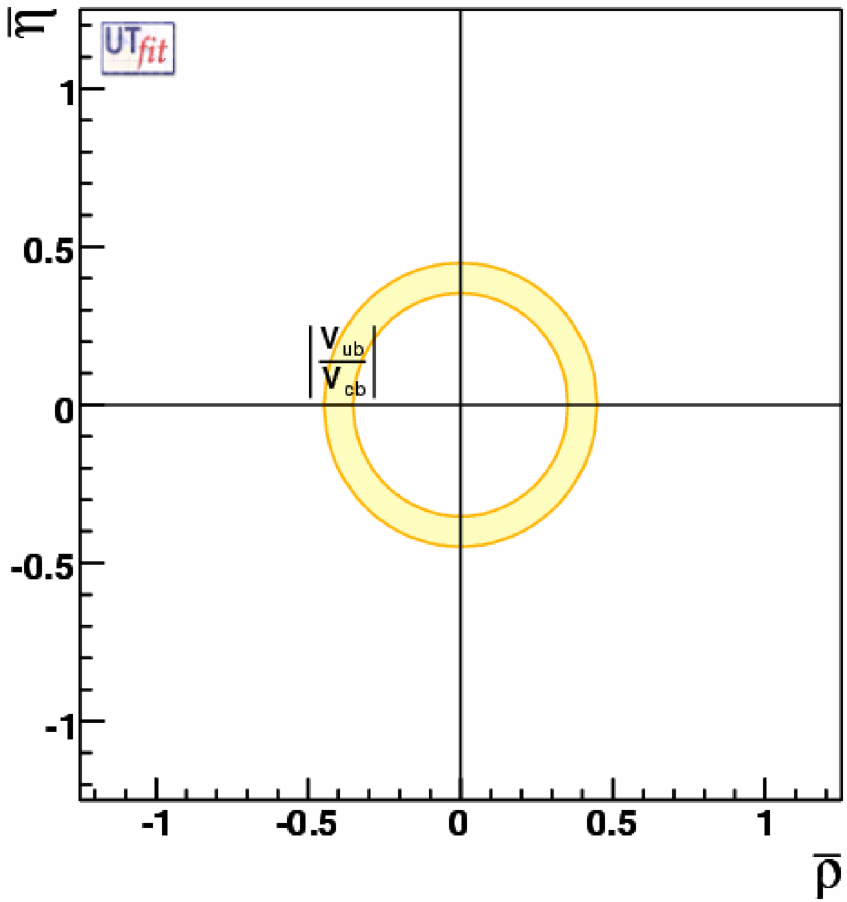
Building UT from b-decays and BB mixing …

… and kaon CPV …



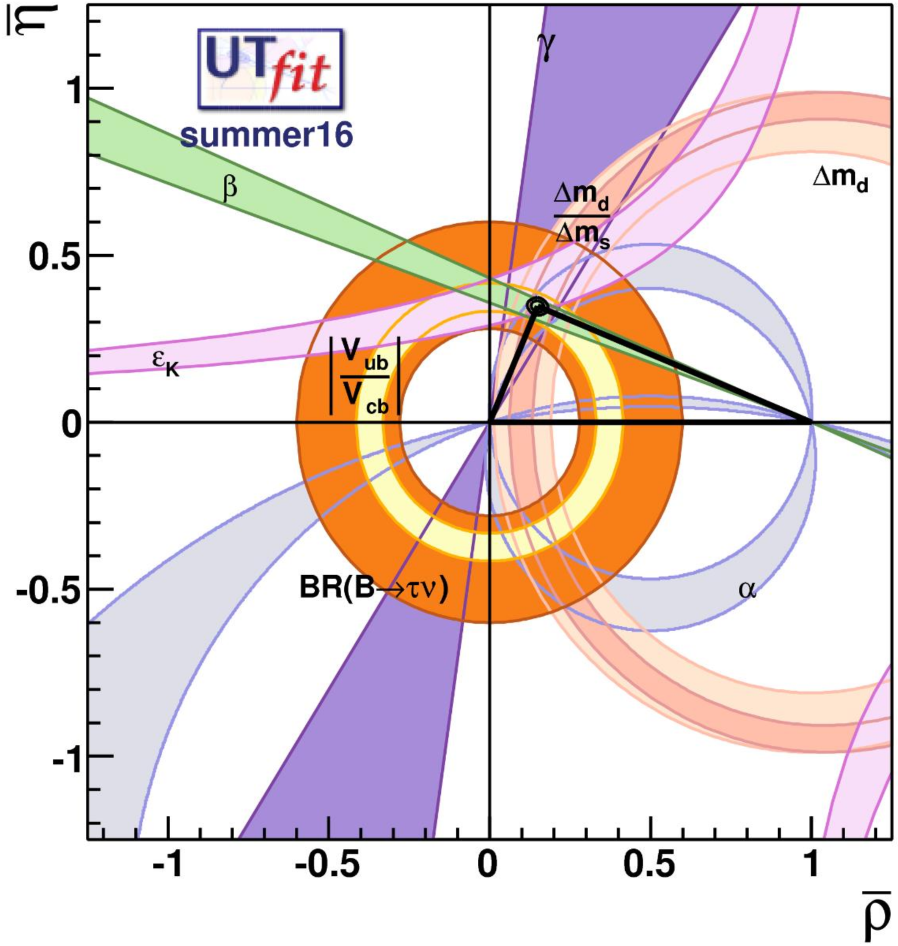
… non-degenerated triangle → CPV !

Combining measurements



Measurements of:

$\Delta m_d, \Delta m_s, V_{ub}, V_{cb}, \varepsilon_k$ + $\cos 2\beta$ + β + α + γ + $2\beta+\gamma$



$\rho = 0.153 \pm 0.013$
$\eta = 0.343 \pm 0.011$

- ☐ ALL the measurements are (so far) consistent …

… but progress further :

- ☐ Over-constrain UT, check that UT closes
- ☐ Compare measurements involving CPV (angles) to decay-probability measurements (sides)
- ☐ Compare CPV in tree-mediated processes to CPV in processes involving loops

Experimental touch

CPV in the interference between decay and mixing

Starting from the time evolution of the B^0 and $\bar{B}^0$ mesons

time-dependent rates of an initially pure flavor state :

$$\left|\langle f|H|B^0(t)\rangle\right|^2 = |A_f|^2\cdot|g_+(t)+\lambda_f g_-(t)|^2 \quad \text{and} \quad \left|\langle f|H|\bar{B}^0(t)\rangle\right|^2 = \left|\frac{p}{q}\right|^2\cdot|A_f|^2\cdot|g_-(t)+\lambda_f g_+(t)|^2$$

$$\begin{aligned} g_+(t) &= e^{-i(m_B-i\frac{\Gamma_B}{2})t}\left[\cosh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} - i\,\sinh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right], \\ g_-(t) &= e^{-i(m_B-i\frac{\Gamma_B}{2})t}\left[-\sinh\frac{\Delta\Gamma_B t}{4}\cos\frac{\Delta m_B t}{2} + i\,\cosh\frac{\Delta\Gamma_B t}{4}\sin\frac{\Delta m_B t}{2}\right] \end{aligned}$$

$$\lambda_f = \frac{q}{p}\frac{<f\,|\,H\,|\,\bar{B}^0>}{<f\,|\,H\,|\,B^0>} \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

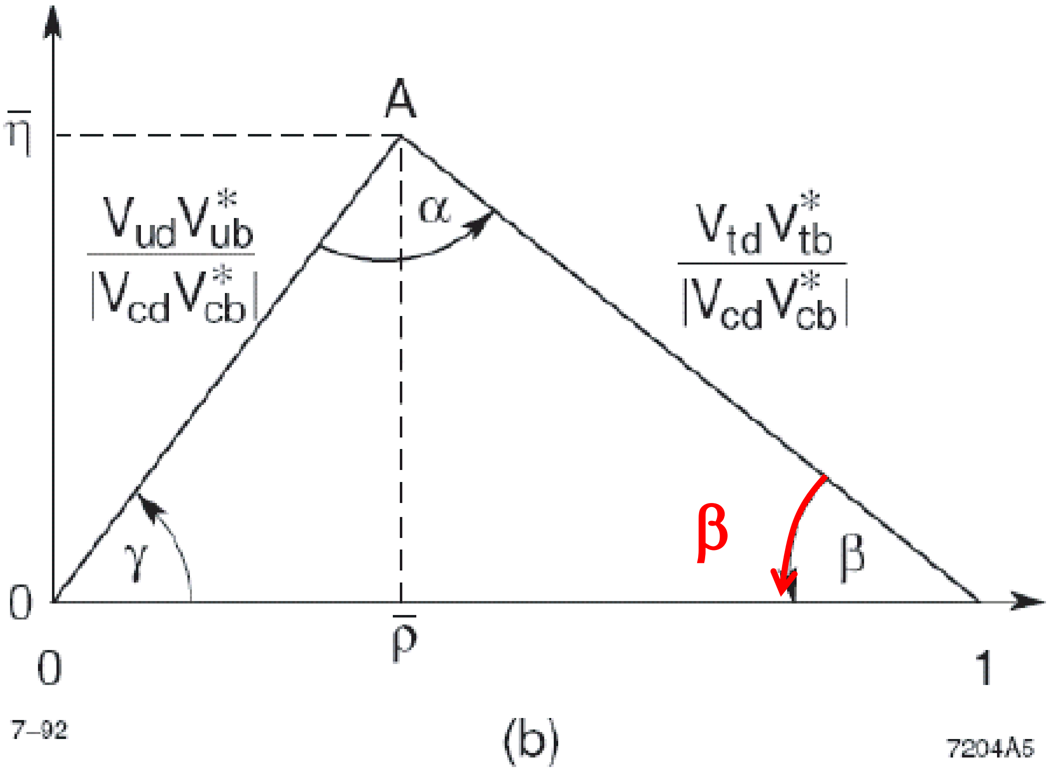
and after some trigonometry and assuming no CPV in mixing ($|q\,/\,p| = 1$)

$$\left|\langle f|H|B^0(t)\rangle\right|^2 = e^{-t/\tau_B}\cdot|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\left[1+C_f\cos(\Delta m_d t)-S_f\sin(\Delta m_d t)\right] \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

$$\left|\langle f|H|\bar{B}^0(t)\rangle\right|^2 = e^{-t/\tau_B}\cdot|A_f|^2\,\frac{1+|\lambda_f|^2}{2}\left[1-C_f\cos(\Delta m_d t)+S_f\sin(\Delta m_d t)\right] \qquad S_f = \frac{2\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}$$

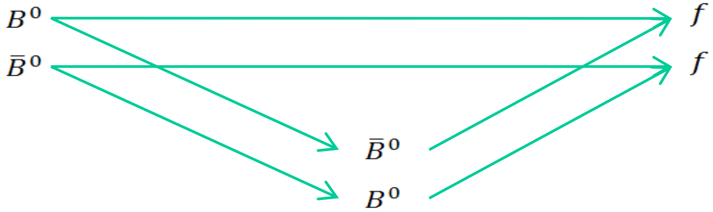
- ☐ $|\lambda_f|^2 \neq 1$: direct CP
- ☐ $\mathrm{Im}[\lambda_f] \neq 0$: CP in the interference

Measurement of the angle β



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

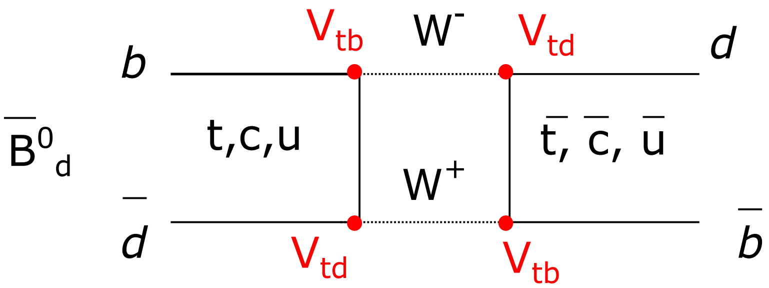
CP violation in the interference between mixing and decay :



$$\lambda = \frac{q}{p}\frac{< f \mid H \mid \overline{B}^0 >}{< f \mid H \mid B^0 >} \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

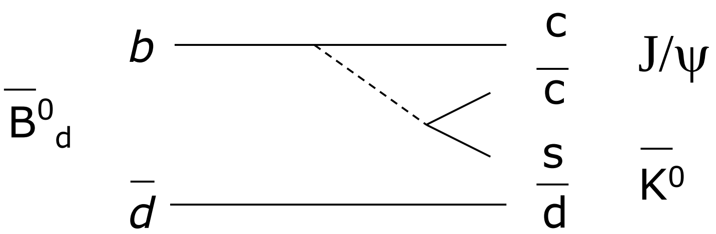
Example: the angle β from B → J/ψ Ks

$$\frac{q}{p} = -\frac{M_{12}^*}{|M_{12}|} = -\sqrt{\frac{M_{12}^*}{M_{12}}}$$



$$= \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} e^{-2i\xi_K}$$

$$\frac{< J/\psi K_S^0 \mid H \mid \overline{B}^0 >}{< J/\psi K_S^0 \mid H \mid B^0 >}$$



$$= \eta_{CP}^{J/\psi K_S^0} \underbrace{\left(\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}}\right)}_{\text{B decay}} \underbrace{\left(\frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right)}_{\text{K mixing}} e^{-2i\xi_B}$$

$$< (J/\psi K_S^0) \mid H \mid B^0 > = < (J/\psi K_S^0) \mid (CP)^\dagger HCP \mid B^0 > =$$

$$\eta_{CP}^{J/\psi K_S^0} < (J/\psi K_S^0) \mid H \mid B^0 > e^{2i\xi_B}$$

$$\operatorname{Im} \lambda^{CP}(J/\psi K_S^0) = \eta_{CP}^{J/\psi K_S^0} \operatorname{Im}\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right) = \eta_{CP}^{J/\psi K_S^0} \sin 2\beta \qquad \beta = \arg\left(\frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*}\right)$$

$$\text{because } \operatorname{Im}\left(\frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} \frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} \frac{V_{cs} V_{cd}^*}{V_{cs}^* V_{cd}}\right) = \operatorname{Im}\left(\frac{V_{cd}^* V_{cb}}{V_{td}^* V_{tb}} \frac{V_{tb}^* V_{td}}{V_{cd} V_{cb}^*} \cancel{\frac{V_{cs}^* V_{cs}}{V_{cs} V_{cs}^*}}\right) \qquad \operatorname{Im}\left(z \times \frac{1}{z^*}\right) = \sin(2\operatorname{Arg}(z))$$

$$a_{f_{CP}}(t) = \frac{\mathrm{Prob}(B^0(t) \to f_{CP}) - \mathrm{Prob}(\overline{B^0}(t) \to f_{CP})}{\mathrm{Prob}(\overline{B^0}(t) \to f_{CP}) + \mathrm{Prob}(B^0(t) \to f_{CP})} =$$

$$= C_f \cos \Delta m_d t + S_f \sin \Delta m_d t$$

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$$

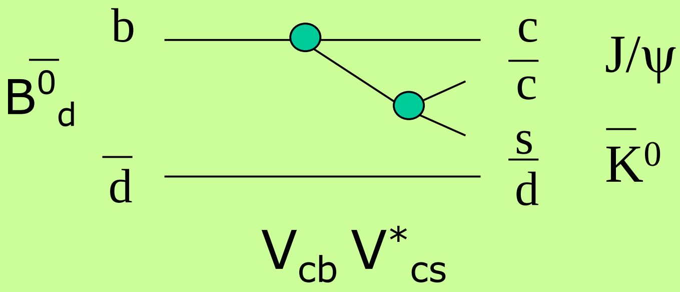
For J/ψ,K⁰ $|\lambda_f| = 1$

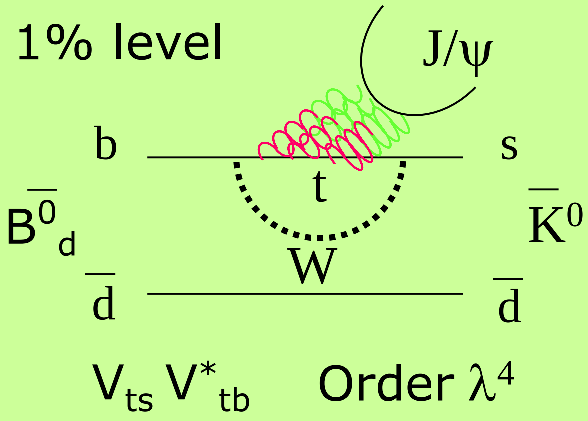
$$S_f = \frac{2\mathrm{Im}[\lambda_f]}{1+|\lambda_f|^2}$$

$$\Rightarrow \begin{cases} C_f = 0 & \text{~only one amplitude} \\ S_f = -\eta_{CP} \sin 2\beta \end{cases}$$

$$\boxed{a_{f_{CP}}(t) = -\eta_{CP} \sin \Delta m_d t \sin 2\beta}$$

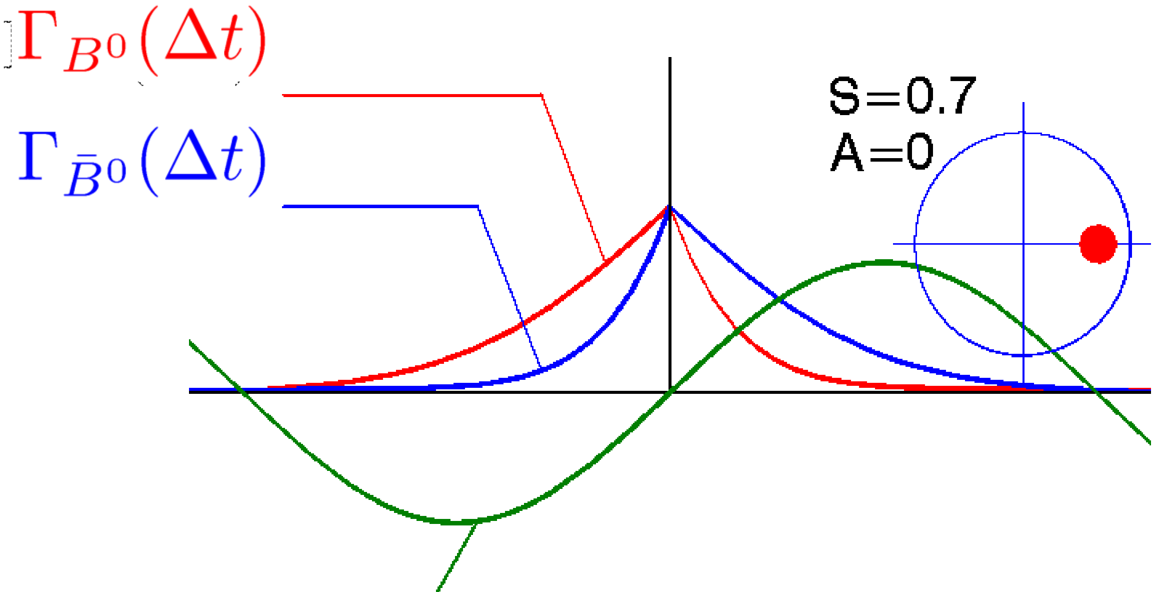
Extraction of sin2β from J/ψ K⁰ theoretically clean at 1% level





1. The diagram at tree level is dominant
2. The penguin diagram has the same phase at order λ^2 since V_{ts} is complex and differs from V_{cb} at order λ^4

tCPV in B^0 decays



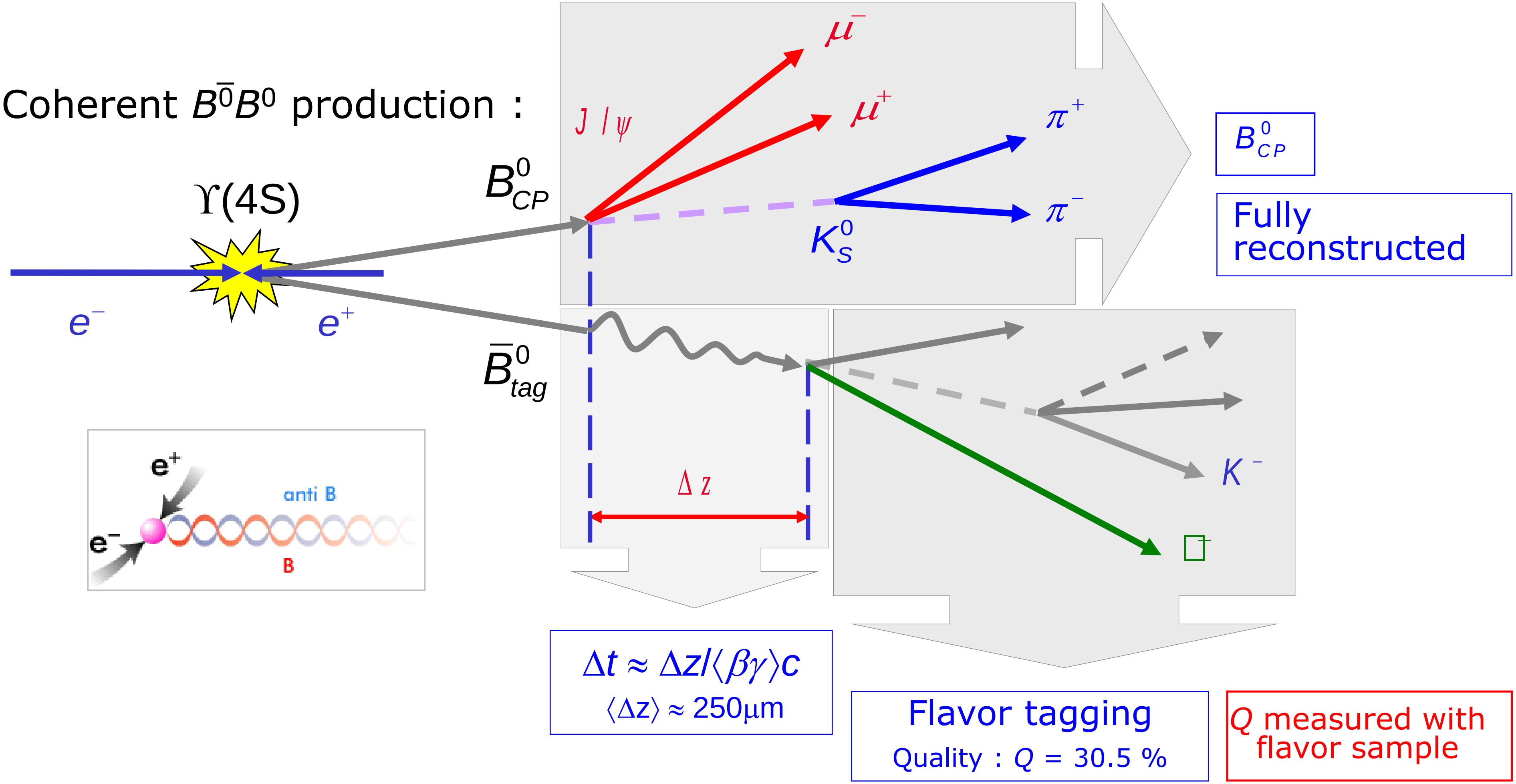
$$A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)} = \mathcal{S} \sin \Delta m \Delta t + \mathcal{A} \cos \Delta m \Delta t$$

Mixing-induced CPV

Direct CPV

Experimental Technique

Coherent $B^{\overline{0}}B^0$ production :



Fully reconstructed

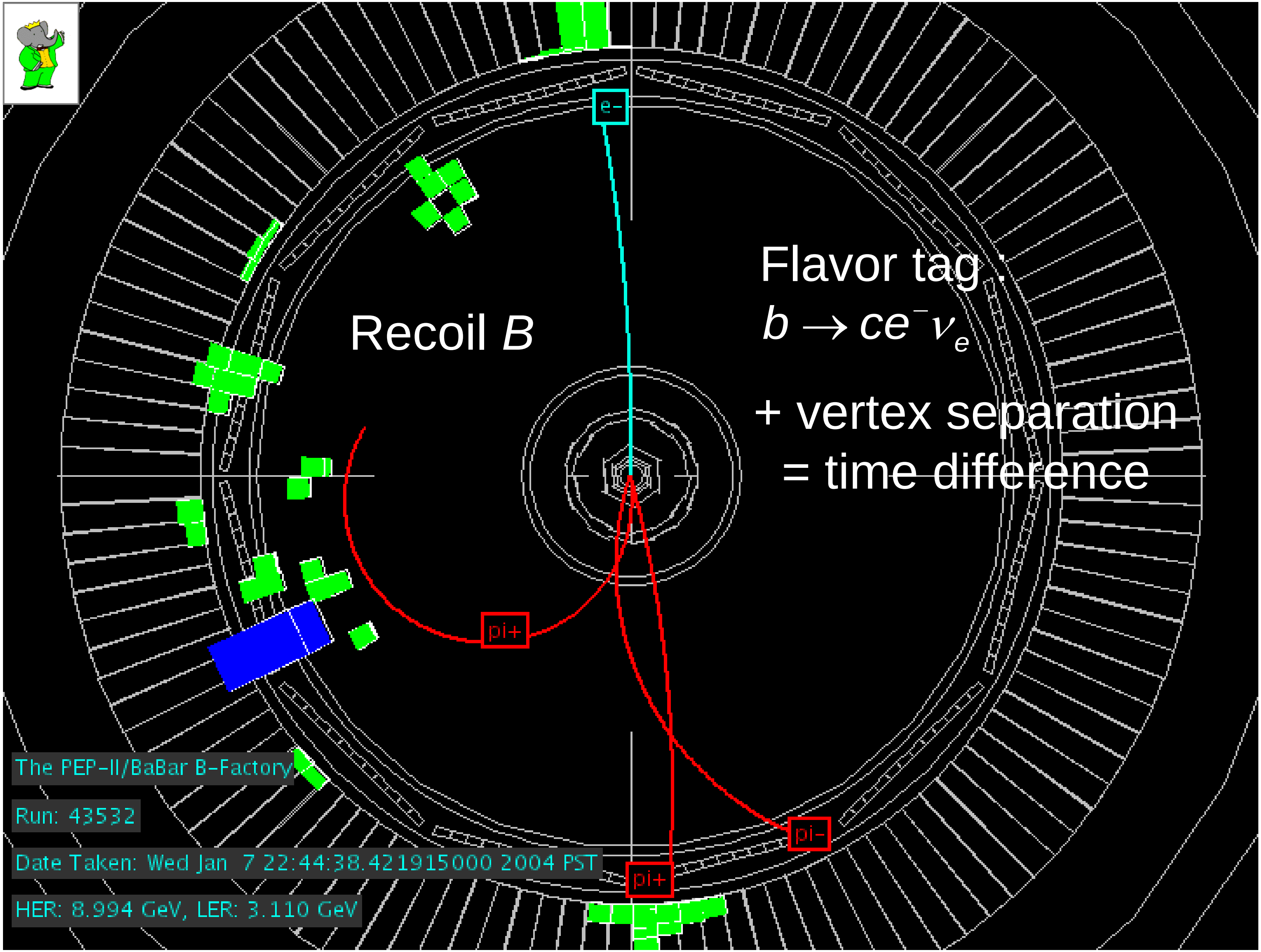
$\Delta t \approx \Delta z / \langle \beta\gamma \rangle c$

$\langle \Delta z \rangle \approx 250 \mu m$

Flavor tagging

Quality : Q = 30.5 %

Q measured with flavor sample



Recoil *B*

Flavor tag :

$b \to c e^- \nu_e$

+ vertex separation

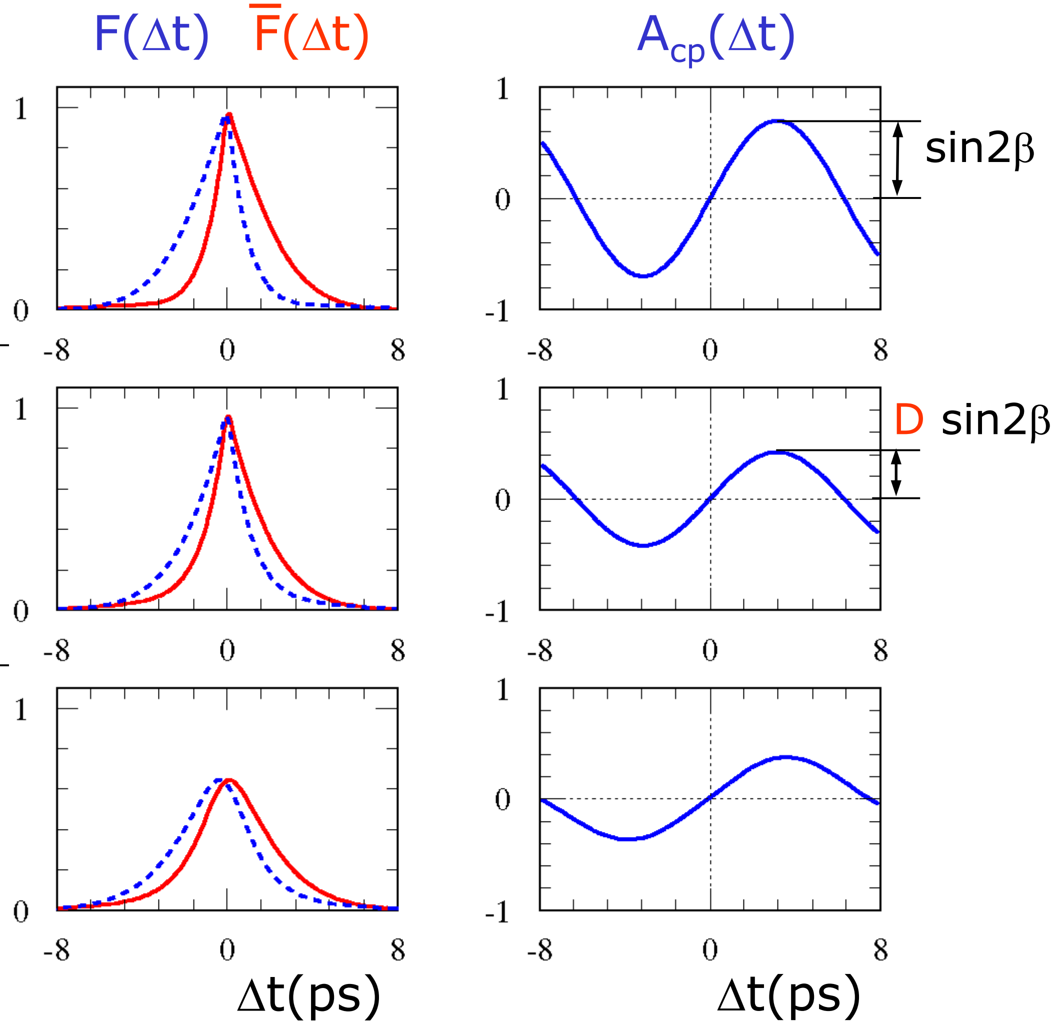
= time difference

Experimental aspects of the sin2β measurement

Everything perfect →

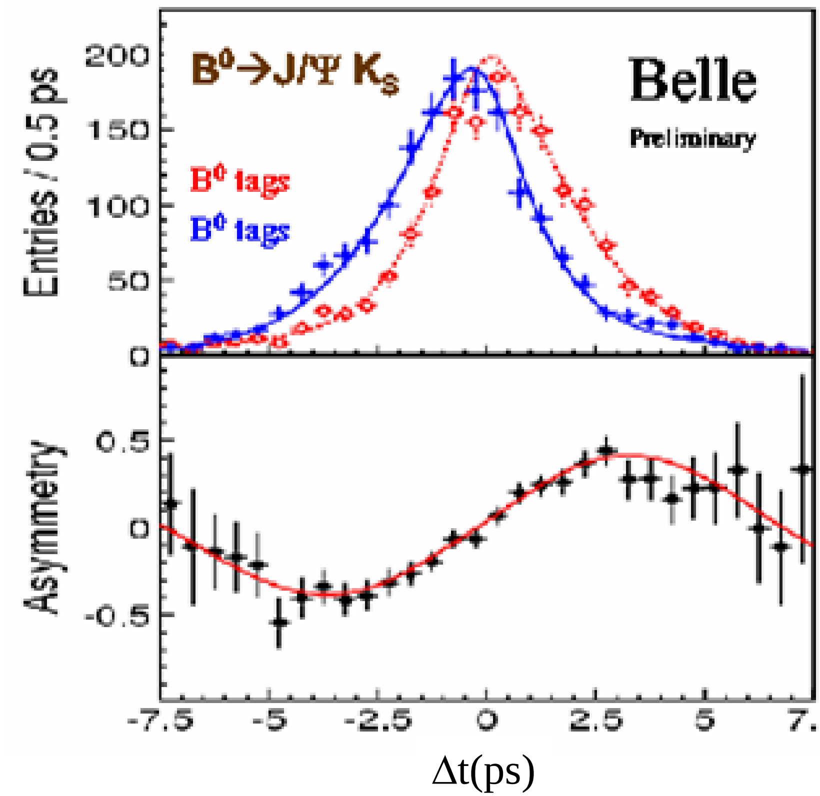
Add tag mistakes →
Dilution: D=1-2w

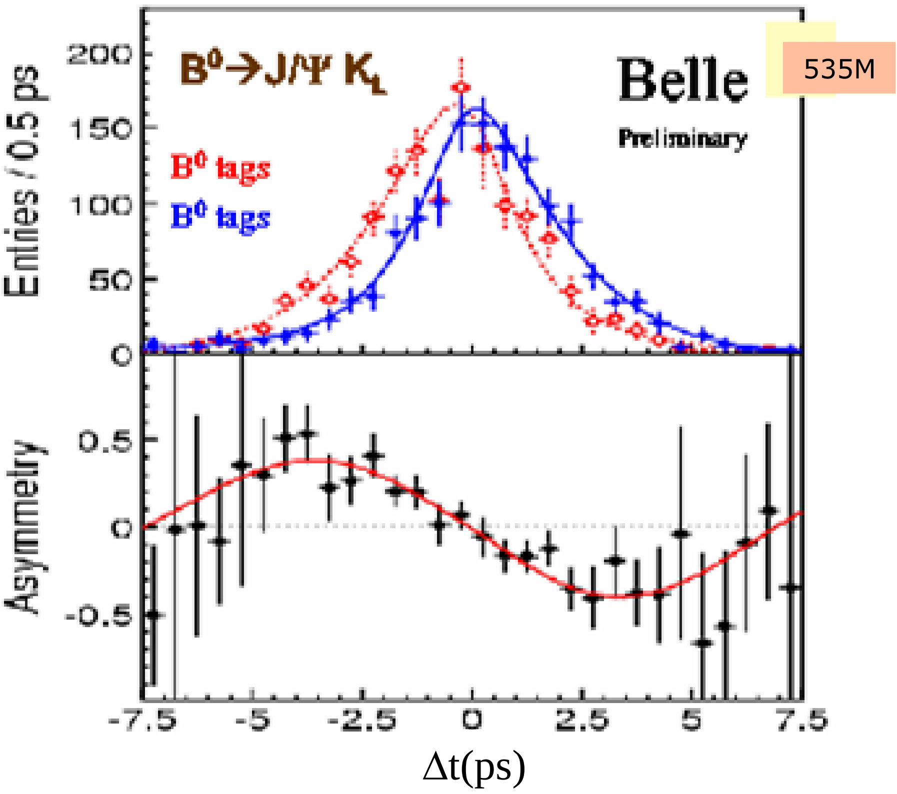
Add imperfect
Δt resolution →

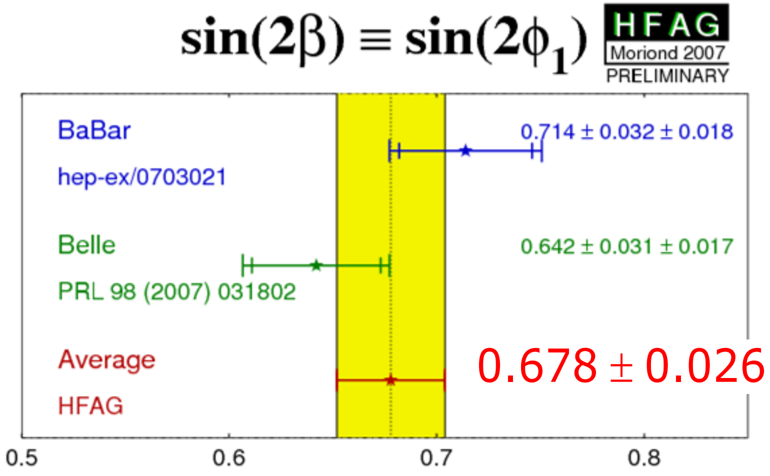


- ☐ Time resolution and tagging knowledge is crucial. Obtained directly from data using the known B^0 mixing frequency (Δm_d)

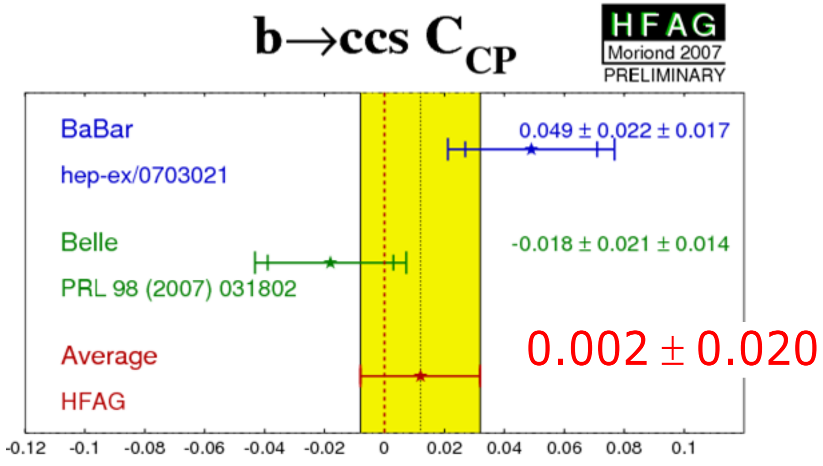
Adding K_Ls :





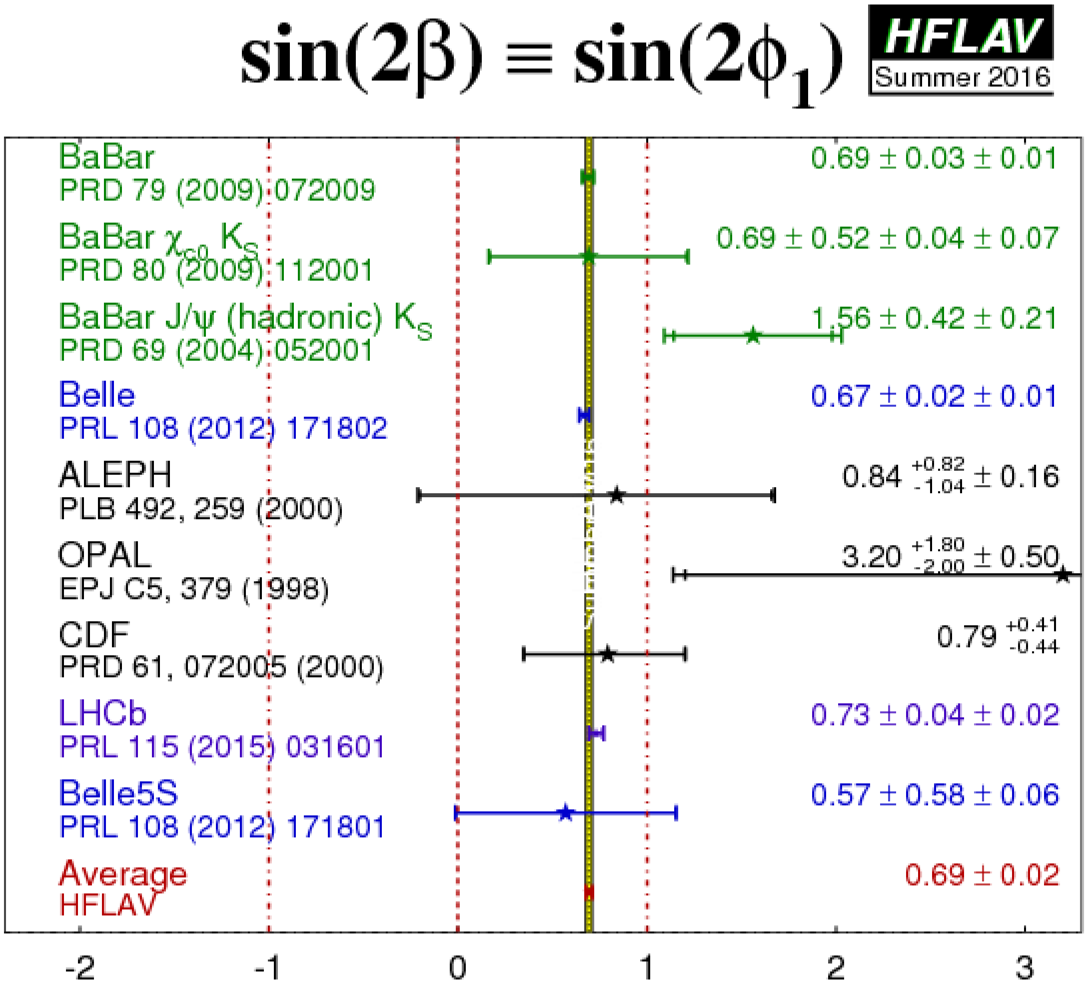


0.678 ± 0.026



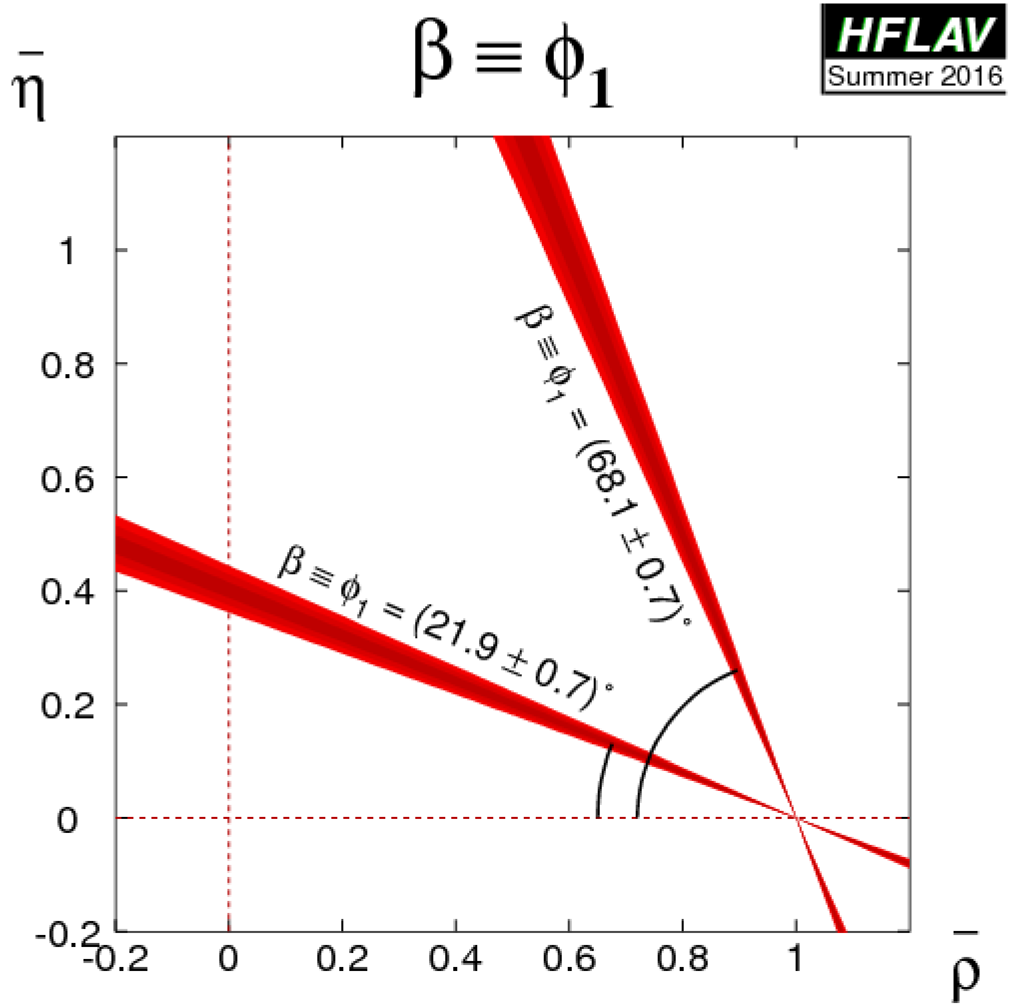
0.002 ± 0.020

sin2β measurement



sin2β measurement

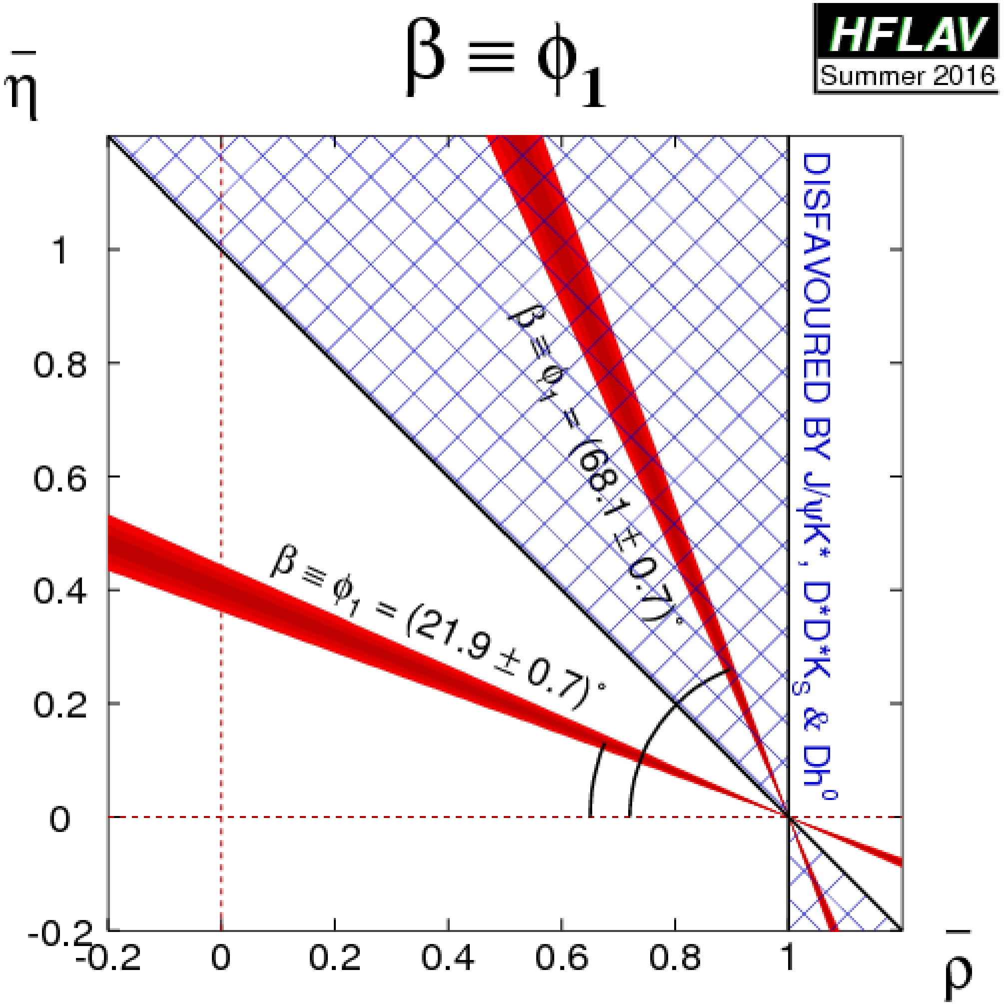
- ☐ HFAG average of the sin2β measurements



- ☐ Two solutions, measurement of other parameters needed

sin2β measurement

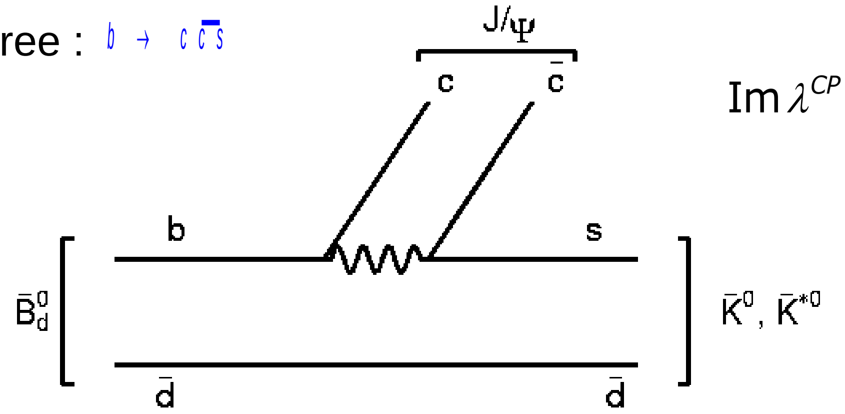
- ❑ HFAG average of the sin2β measurements



- ❑ Two solutions, measurement of other parameters needed

Comparison of sin(2β) measurements from tree and penguin diagrams

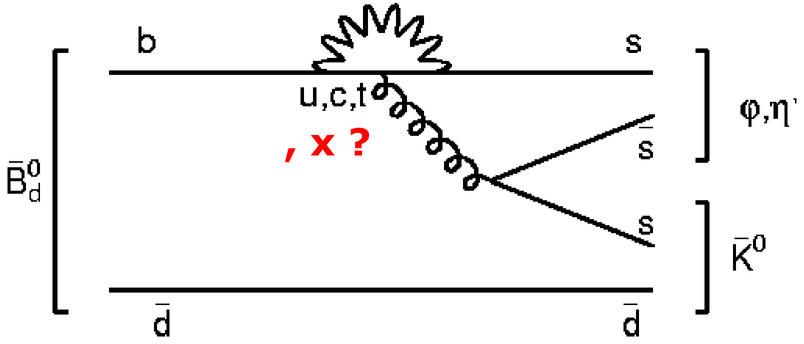
Tree : $b \to c\bar{c}s$



$$\mathrm{Im}\,\lambda^{CP}(J/\psi K^0_S) = \eta_{CP}^{J/\psi K^0_S}\,\mathrm{Im}\left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\,\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}\,\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) = \eta_{CP}^{J/\psi K^0_S}\sin 2\beta$$

B^0 mixing **K^0 mixing**

Penguin : $b \to s\bar{s}s$



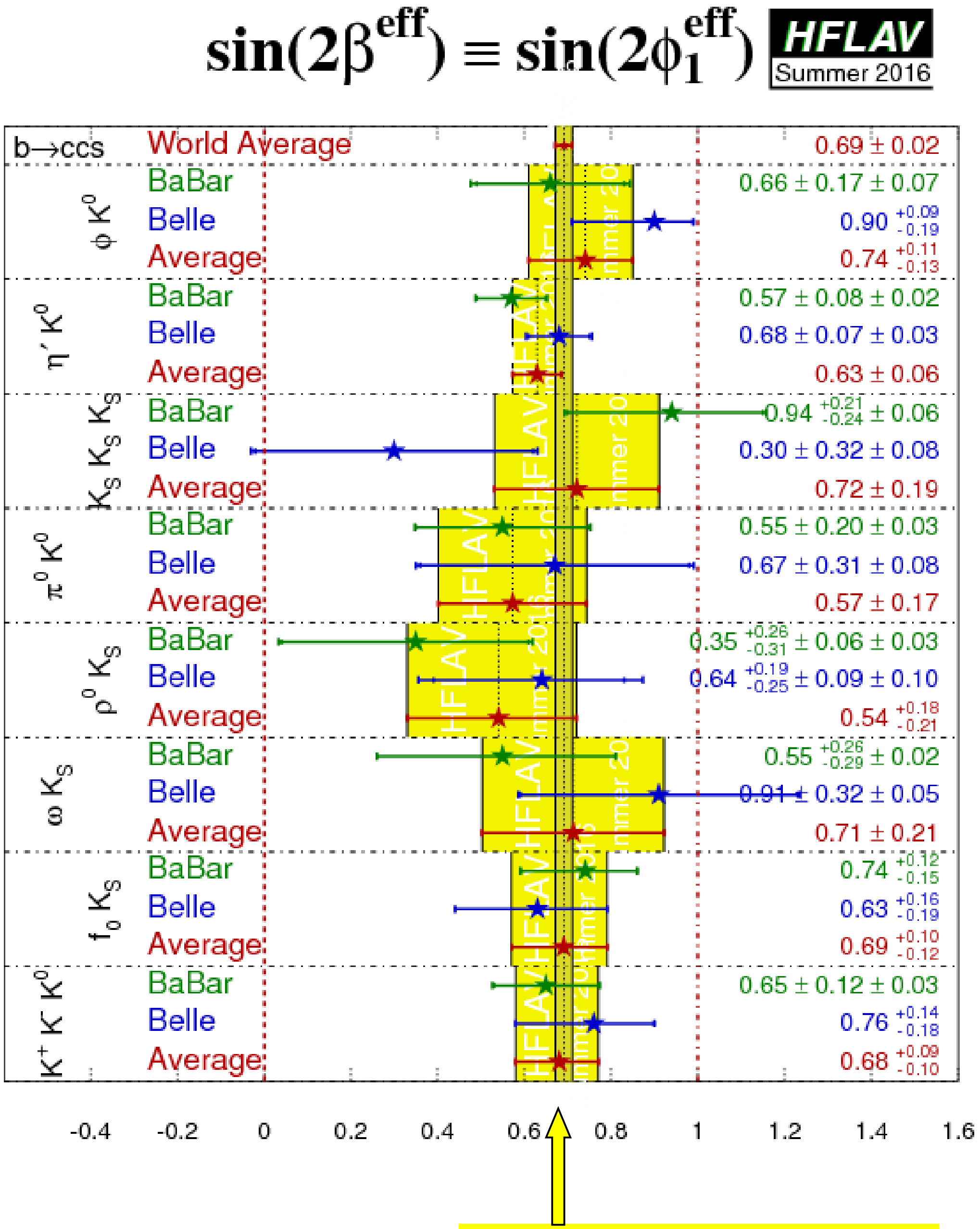
$$\mathrm{Im}\,\lambda^{CP}(\phi K^0_S) = \eta_{CP}^{\phi K^0_S}\,\mathrm{Im}\left(\frac{V_{tb}^*V_{td}}{V_{tb}V_{td}^*}\,\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}\,\frac{V_{cs}V_{cd}^*}{V_{cs}^*V_{cd}}\right) \sim \eta_{CP}^{\phi K^0_S}\sin 2\beta$$

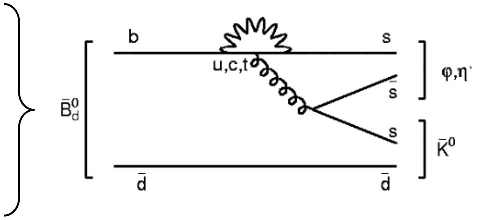
Unitarity : $\underset{\lambda^4}{V_{us}^*\,V_{ub}} + V_{cs}^*\,V_{cb} + V_{ts}^*\,V_{tb} = 0$

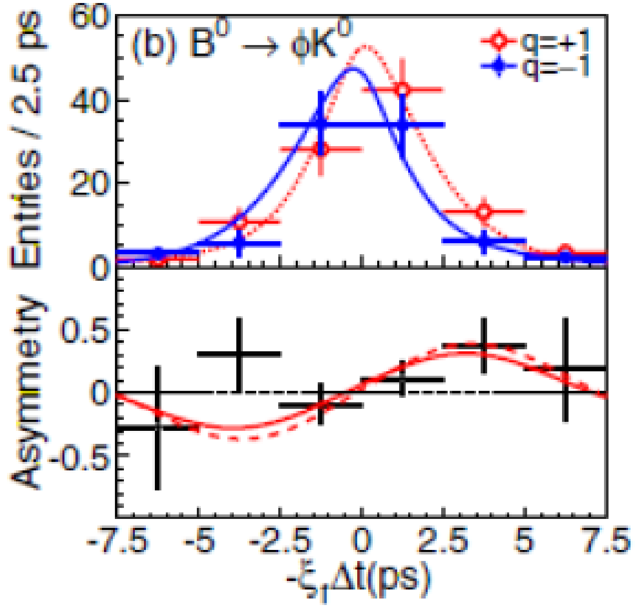
$\Rightarrow V_{cs}^*\,V_{cb} + V_{ts}^*\,V_{tb} = 0$

$\sin 2\beta$ [charmonium] $\overset{?}{=}$ $\sin 2\beta$ [s-pingouin]

Comparison of sin(2β) measurements from tree and penguin diagrams







No contradiction between sin2β from b→ccs and b→qqs

Sin(2β) from Charmonium (J/Ψ)K0

CP violation in the decay

CP-conjugated amplitudes :

$$\begin{cases} A_f = A(B \to f) \\ \bar{A}_f = A(\bar{B} \to \bar{f}) \end{cases}$$

$$A_f = \sum_j a_j \cdot e^{i\theta_j} e^{i\phi_j}$$

$$\bar{A}_{\bar{f}} = \sum_j a_j \cdot e^{i\theta_j} e^{-i\phi_j}$$

ϕ_j alters sign under *CP* (weak phase)

θ_j *CP* invariant (strong phase)

$$A_{CP} \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} = \frac{|\bar{A}_f|^2 - |A_f|^2}{|\bar{A}_f|^2 + |A_f|^2}$$

$$A_{CP} = \frac{\sum_{ij} a_i a_j \cdot \sin(\theta_i - \theta_j) \cdot \sin(\phi_i - \phi_j)}{\sum_{ij} a_i a_j \cdot \cos(\theta_i - \theta_j) \cdot \cos(\phi_i - \phi_j)}$$

- ☐ Direct *CPV* requires at least two amplitudes with **different weak *and* strong phases**
- ☐ Large A_{CP} requires amplitudes of similar order

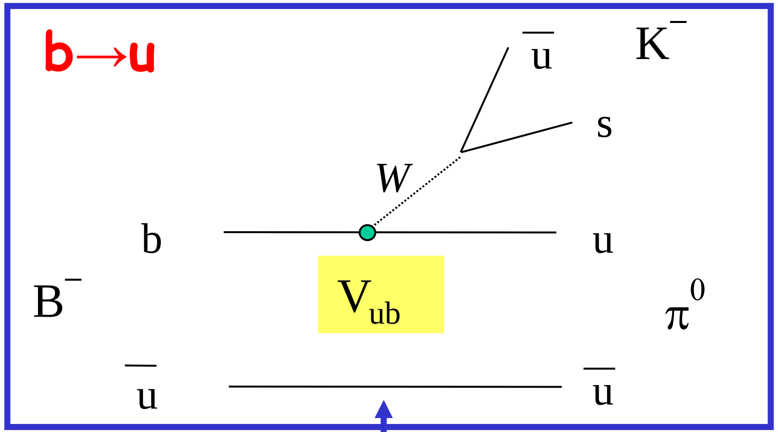
CP violation in decay (« direct CP») :

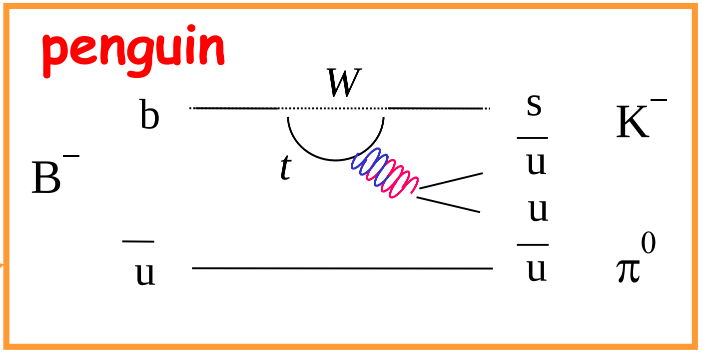
$$B \xrightarrow{A} f$$

$$\bar{B} \xrightarrow[\bar{A}]{} \bar{f}$$

Only one existing for charged B

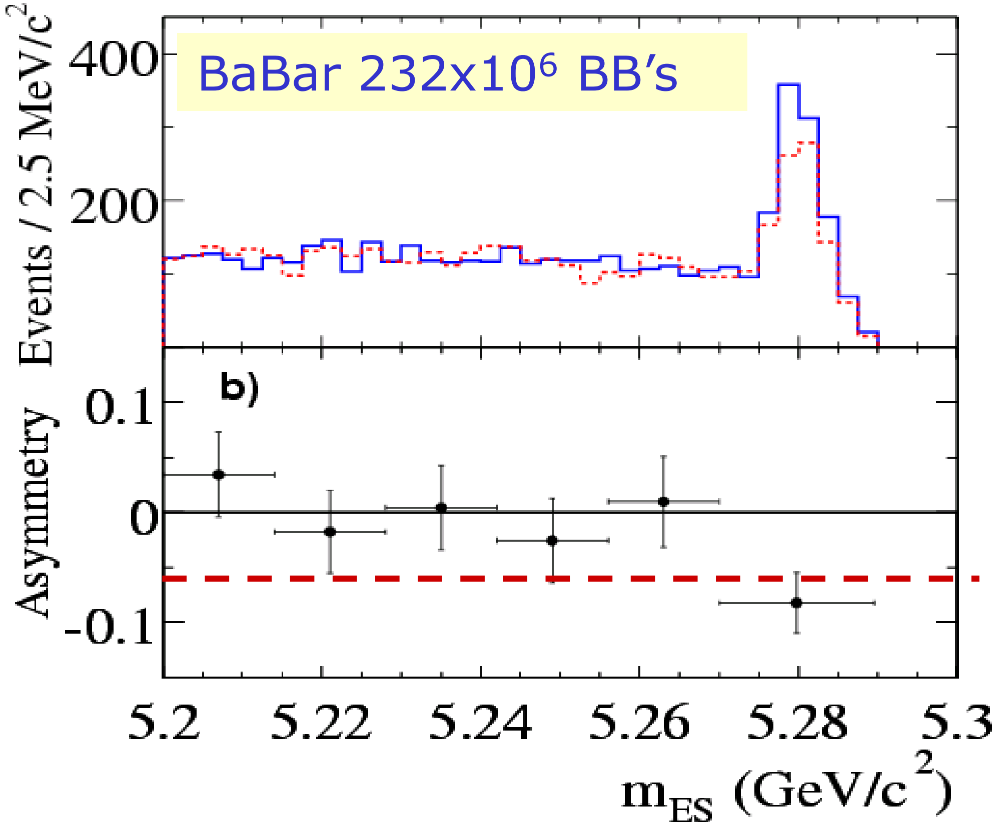
Direct CPV: B →Kπ





$$A_-(B^- \to f) = a_1 e^{i\theta_1} e^{i\phi_1} + a_2 e^{i\theta_2} e^{i\phi_2}$$

$$A_+(B^+ \to \bar{f}) = a_1 e^{i\theta_1} e^{-i\phi_1} + a_2 e^{i\theta_2} e^{-i\phi_2}$$

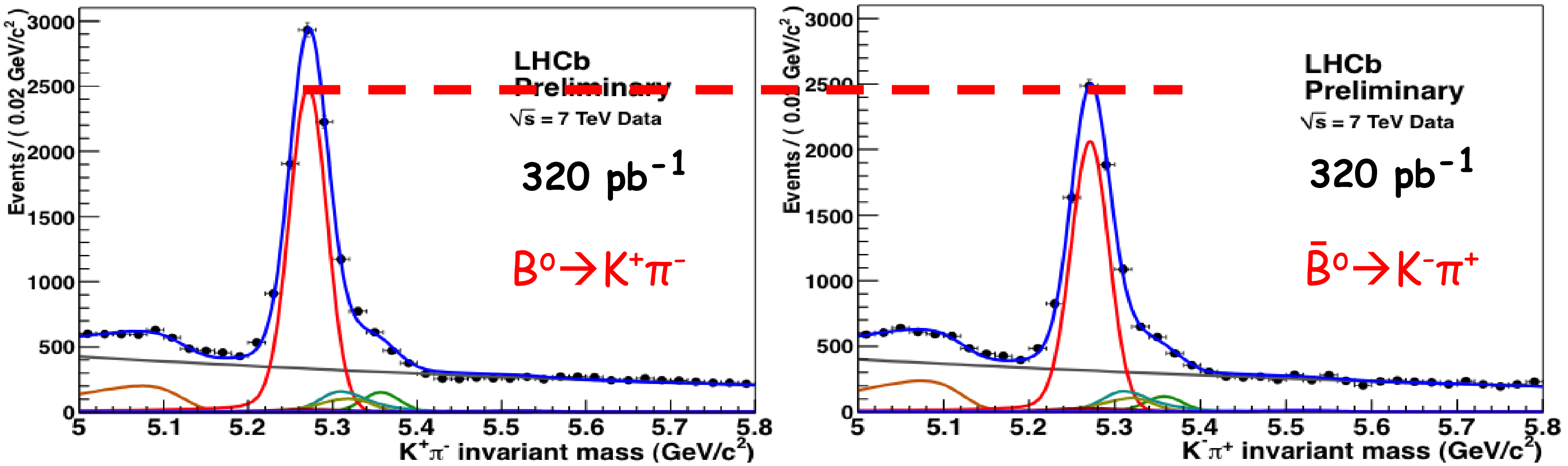


- In this case weak phase difference : γ

$A_{cp}(B^0 \to K^+\pi^o)$= -0.097+/- 0.012

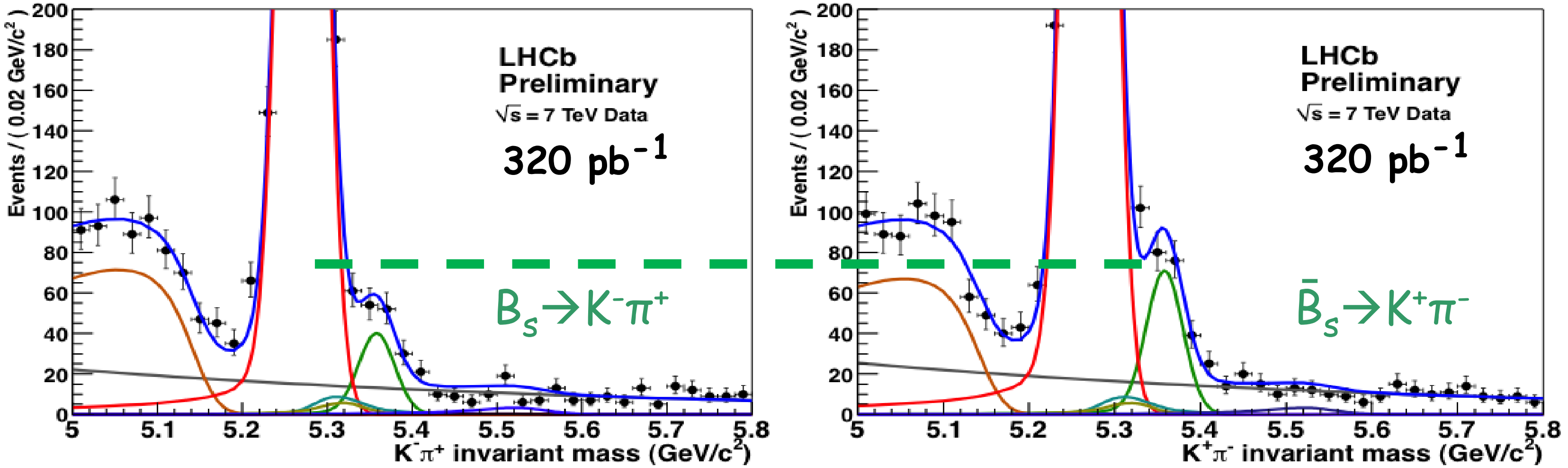
- ***Angle γ cannot be extracted from it, since it depends upon weak phase and strong amplitude and phase***

Direct CPV: $B_{d,s}$→Kπ



Most precise single measurement and first 5σ observation of CPV at hadron machine:

$$\boxed{A_{CP}(B^0 \to K^+\pi^-) = -0.088 \pm 0.011(\mathrm{stat}) \pm 0.008(\mathrm{syst})}$$



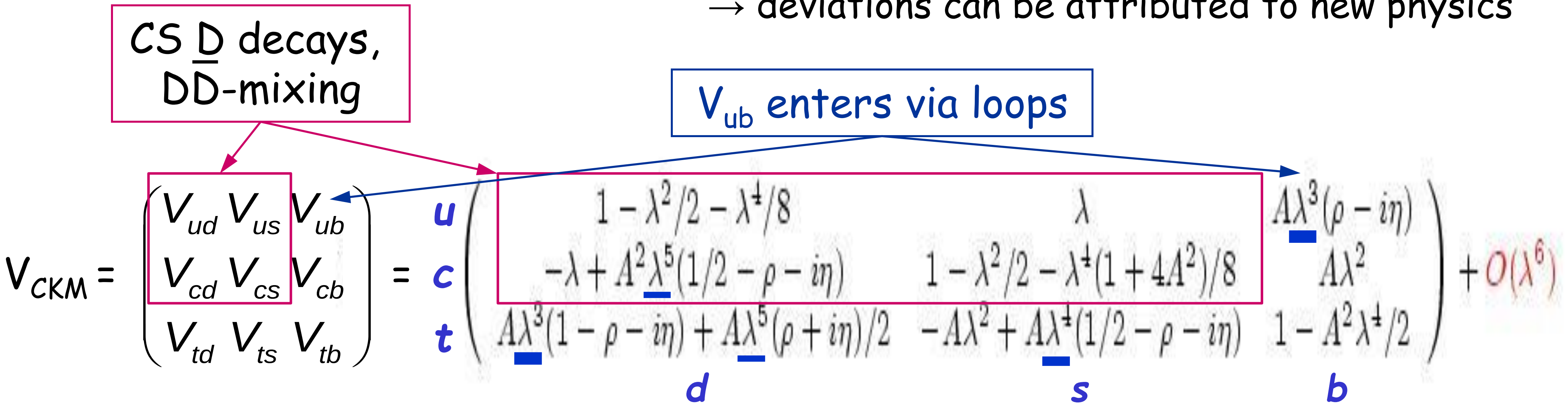
First evidence of CPV in Bs decays:

$$\boxed{A_{CP}(B_s^0 \to \pi^+K^-) = 0.27 \pm 0.08(\mathrm{stat}) \pm 0.02(\mathrm{syst})}$$

CP-parity violation in charm

- ❑ SM predicts small effects in mixing and **CP violation** due to suppression by GIM mechanism (d,s) and CKM matrix (b)

→ deviations can be attributed to new physics



CS $\underline{D}$ decays, $D\bar{D}$-mixing

V_{ub} enters via loops

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{array}{cc} & \begin{array}{ccc} \quad d & \quad s & \quad b \end{array} \\ \begin{array}{c} u \\ c \\ t \end{array} & \begin{pmatrix} 1-\lambda^2/2-\lambda^4/8 & \lambda & A\underline{\lambda}^3(\rho-i\eta) \\ -\lambda+A^2\underline{\lambda}^5(1/2-\rho-i\eta) & 1-\lambda^2/2-\lambda^4(1+4A^2)/8 & A\lambda^2 \\ A\underline{\lambda}^3(1-\rho-i\eta)+A\underline{\lambda}^5(\rho+i\eta)/2 & -A\lambda^2+A\underline{\lambda}^4(1/2-\rho-i\eta) & 1-A^2\lambda^4/2 \end{pmatrix} \end{array} + O(\lambda^6)$$

η - CP-violating phase

CP-parity violation in charm

- Access CP violation through asymmetry measurements

PRL 122 (2019) 2113803

$\sqrt{s}$ = 13 TeV, $\int Ldt \sim 5.9\ \mathrm{fb}^{-1}$

$$A_{CP}(f) \equiv \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)} \approx \underbrace{a^{dir}_{CP}(f)}_{\text{CPV in decay}} + \underbrace{\frac{\langle t(f) \rangle}{\tau(D^0)} A_\Gamma(f)}_{\text{CPV in mixing + interfer.}}$$

CP eigenstate

Measure time integrated A_{CP} difference for $f = K^+K^-$ and $f = \pi^+\pi^-$

$$\Delta A_{CP} = A^{raw}_{CP}(K^+K^-) - A^{raw}_{CP}(\pi^+\pi^-)$$

$$\approx [a^{dir}_{CP}(K^+K^-) - a^{dir}_{CP}(\pi^+\pi^-)] - \frac{< t >_{K^+K^-} - < t >_{\pi^+\pi^-}}{\tau_{D^0}} A_\Gamma$$

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$$A^{h^+h^-}_{meas} = A^{h^+h^-}_{CP} + A_D + A_P$$

CP asymmetry of h^+ h^-

Production asymmetry between D^{*+} and D^{*-} / B and $\bar{B}$

Detection asymmetry of the positive and negative tagging π / μ

Small and independent of the final state

- Difference $\Delta A_{CP} = A^{KK}_{meas} - A^{\pi\pi}_{meas} = A^{KK}_{CP} - A^{\pi\pi}_{CP}$ cancels detection and production asymmetries and is largely insensitive to systematic effects

- Tag D-flavour

$$B \to D^0 \mu^- \nu_\mu X$$

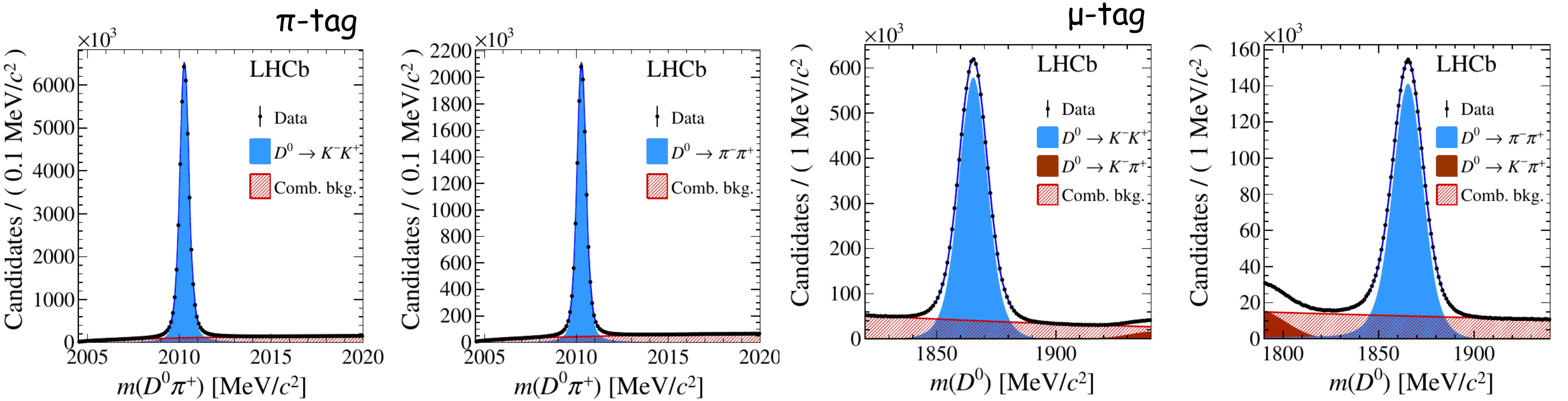
$$D^{*+} \to D^0 \pi^+$$

CP-parity violation in charm

PRL 122 (2019) 2113803

$\sqrt{s}$ = 13 TeV, $\int L dt \sim 5.9$ fb^{-1}

- ❑ Asymmetry determined from invariant mass fits

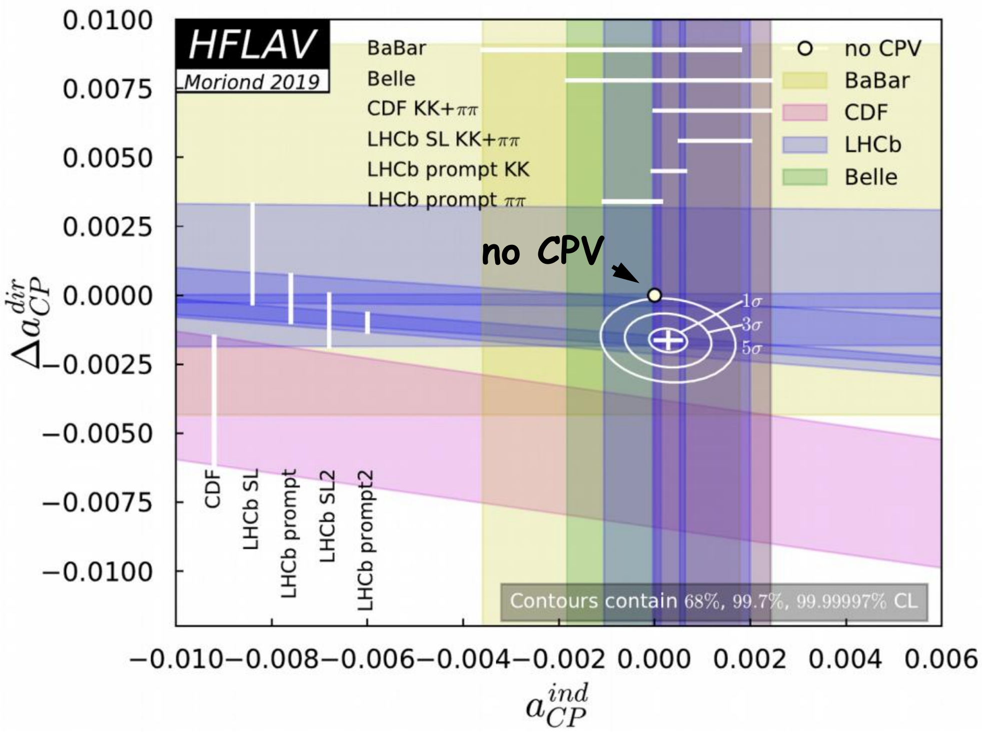


$$\Delta A_{CP} = (-15.4 \pm 2.9) \cdot 10^{-4}$$

- ❑ **First observation of CP-violation in charm decays** at 5.3σ, essentially **direct CP-violation**

$$\Delta a_{CP}^{dir} = (-15.7 \pm 2.9) \cdot 10^{-4}$$

- ❑ **No CP-violation excluded at 5.4σ**



What we learned: reminder

- Flavour physics players and rules of the game
- How interactions respect C, P, T symmetries
- Kaon system
- Two more quarks: c and b
- Charged currents and more quark diagrams
- Measure two elements of the CKM matrix V_{ub}, V_{cb}
- $B\bar{B}$ mixing and two more elements of the CKM matrix V_{td}, V_{ts}
- CKM matrix: size and parametrization
- CP symmetry violation from the complex phase
- Unitarity triangles
- Measuring CKM parameters