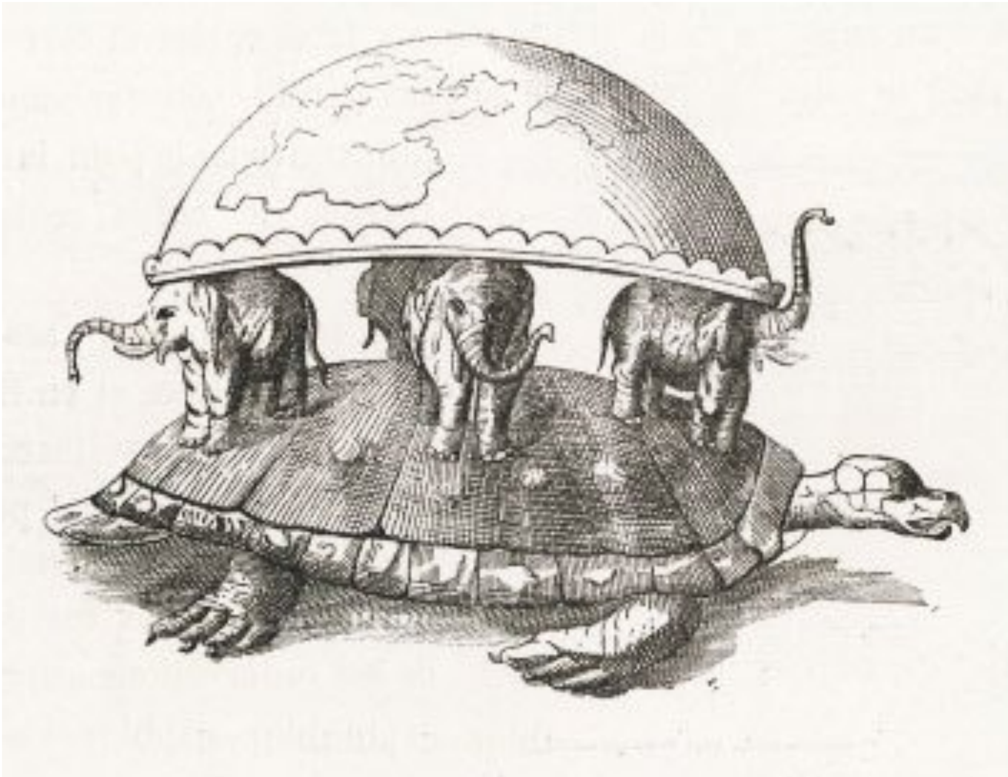
CP violation and baryogenesis



The baryon asymmetry

- The universe appears to be made of matter, with little/no antimatter content.
- Almost no antimatter in cosmic rays.
- Lack of X-ray spectrum from annihilation processes in local cluster of galaxies -> no antimatter within 20 Mpc.
- No excess flux of red-shifted diffuse X-rays from larger distances -> appears to rule out Universe with large bubbles of antimatter.

- Baryon content specified by ratio to photons:

$$\eta = \frac{n_B + n_{\overline{B}}}{n_\gamma} \approx \frac{n_B}{n_\gamma} \approx 10^{-10}$$

- Would expect BB to create all possible particle states in proportion to their degrees of freedom. High number of photons because matter-antimatter annihilation converted (almost) everything to radiation.
- Calculation for equal initial numbers of baryons and antibaryons leads to almost total annihilation with $\eta \approx 10^{-20}$
- Conclude: either there was always more matter, or some dynamic process created difference.

Sakharov conditions

Dynamic baryogenesis requires

- Departure from thermal equilibrium

  -> otherwise any reaction creating baryons will be in equilibrium with the inverse reaction. Natural in BB cosmologies

- Baryon number violating processes

  -> obviously! (Allowed in SM)

- C and CP violating processes

  -> since both change baryon <-> antibaryon

  Observed in SM.

C and P symmetries

- P violated in weak interaction couplings:

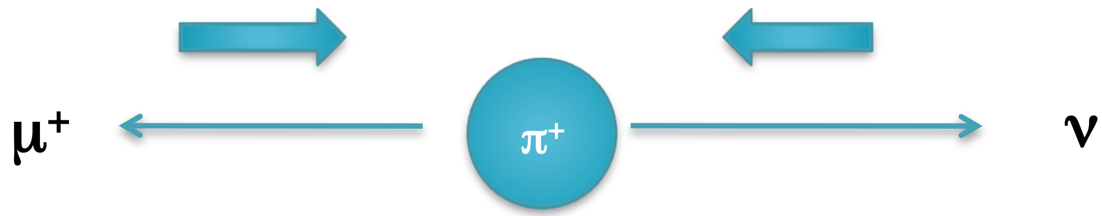
$$(A_{RH\ particle} = A_{LH\ antipaticle}) \neq (A_{LH\ particle} = A_{RH\ antiparticle})$$

but C changes particle <-> antiparticle

Maybe CP is good quantum number?

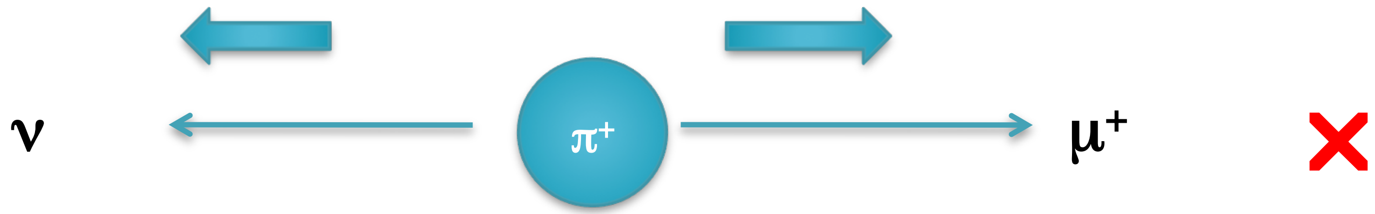
If so, particle interactions will look the same before and after a CP transformation and CP is "conserved"

Pion decay

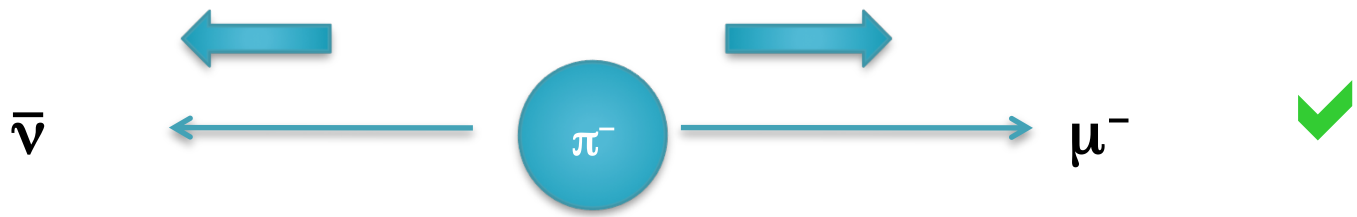


Operate with P

$$\vec{L} = \vec{r} \times \vec{p}$$



Operate with C



Looks good for CP conservation....

The CKM matrix

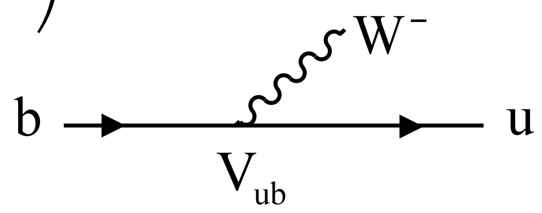
V_{CKM} describes rotation between the weak eigenstates (d',s',b') and mass eigenstates (d,s,b)

weak states | CKM matrix | mass states

Quarks

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

V_{ij} proportional to transition amplitude from quark j to quark i



CPV due to complex phases of CKM matrix elements

Unitary matrix so only 4 free parameters in total: 3 angles and one phase.

The Kaon system

$$K^0 = d\bar{s} \quad (s = +1) \qquad \bar{K}^0 = \bar{d}s \quad (s = -1)$$

strangeness eigenstates of strong interaction

$$C\left|K^0\right\rangle = -\left|\bar{K}^0\right\rangle \qquad C\left|\bar{K}^0\right\rangle = -\left|K^0\right\rangle$$

$$P\left|K^0\right\rangle = -\left|K^0\right\rangle \qquad P\left|\bar{K}^0\right\rangle = -\left|\bar{K}^0\right\rangle$$

hence

$$CP\left|K^0\right\rangle = +\left|\bar{K}^0\right\rangle \qquad CP\left|\bar{K}^0\right\rangle = +\left|K^0\right\rangle$$

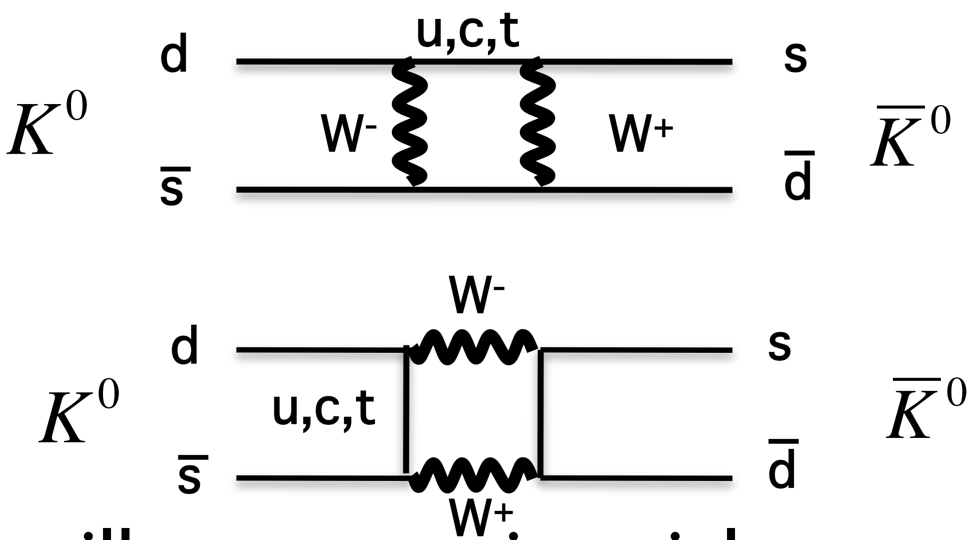
K^0 and $\bar{K}^0$ are not CP eigenstates but

$$\left|\mathrm{K}_1\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right) \quad \left|K_2\right\rangle = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)$$

give $\quad CP\left|\mathrm{K}_1\right\rangle = +\left|\mathrm{K}_1\right\rangle \quad CP\left|\mathrm{K}_2\right\rangle = -\left|\mathrm{K}_2\right\rangle$

Mass eigenstates

- State propagating through free space must be mass eigenstate.



- K^0 oscillates to antiparticle, so cannot be mass eigenstate. Perhaps K_1 and K_2 are?
- Produce K beam, measure CP when Ks decay

Measuring CP in Kaon decays

$$K^0 \to \pi^0 \pi^0$$

- Pions are identical bosons, so wavefunction unchanged if swapped: P=+1
- π^0 is its own antiparticle: C=+1
- Hence two-pion decays are CP=+1

- (same for pair of charged pions)

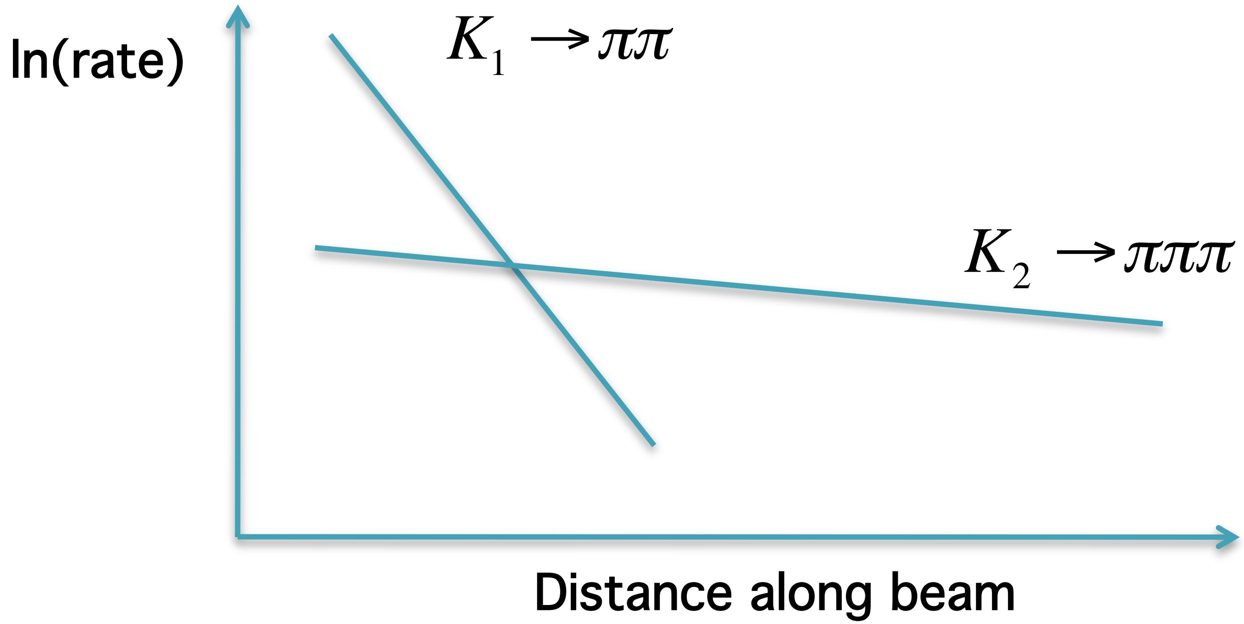
Measuring CP in Kaon decays

$$K^0 \rightarrow \pi^0 \pi^0 \pi^0$$

- For any pair of pions, L must be even (identical particles): $P_{\pi\pi}$=+1
- Intrinsic P_π=-1so $P_{\pi\pi\pi}$=-1
- Pion is its own antiparticle: C=+1
- Hence three-pion decays are CP=-1

- (same for $\pi^0\pi^+\pi^-$)

- Observe 2 and 3 pions decays: these come from CP eigenstates K_1 and K_2
- 2 pion mode has more free energy -> shorter lifetime. Predict decays in a beam of kaons:



- Expect only 3-pion decays at large distance

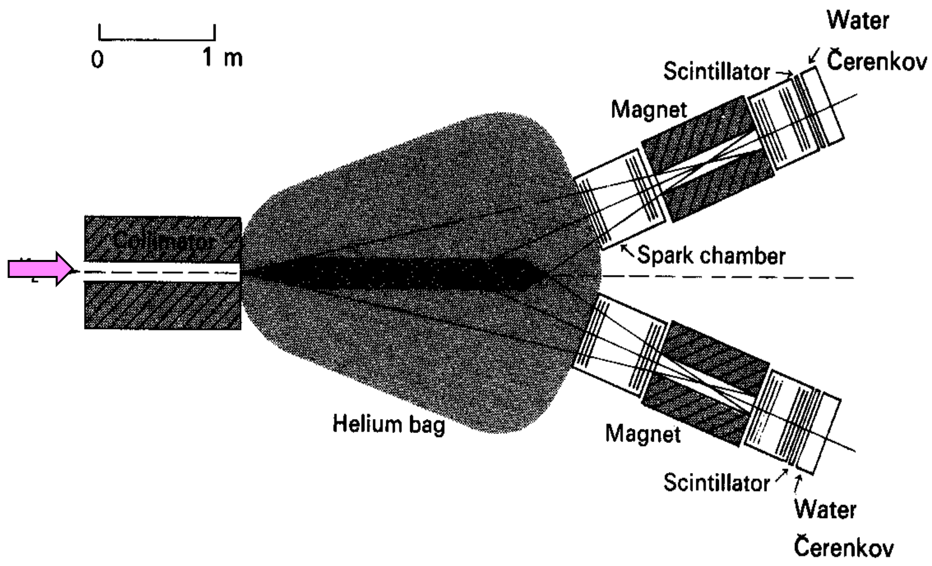
Kaon data

- 1956 Lande et al (PR 103(1956)1901 observed 26 3-body decays 6m from target (after 100 “short” lifetimes)
- 1964 Christenson et al (PRL 13(1964)138 observed 22700 decays. 45+-9 2-pion decays over 30m from target.
- Proof that long and short lifetime states both contain CP-even – and hence it is not the mass eigenstate. CP is not conserved!

[Christenson, Cronin, Fitch and Turlay (1964)]

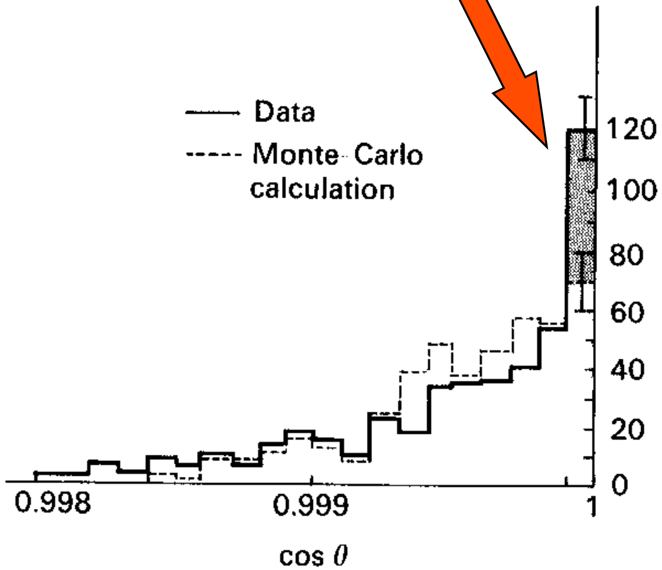
First observation of

$$K_L \to \pi^+\pi^-$$



(a)

$$\frac{K_L \to \pi^+\pi^-}{K_S \to \pi^+\pi^-} \approx \frac{1}{500}$$



- Observed rate of CP violation in the kaon system is of order 2×10^{-3}
- But kaon tightly bound meson – decay amplitudes enhanced by non-perturbative corrections.
- Cannot expect such large effects in early Universe from SM CP violation.
- CPT theorem says any Lorentz invariant field theory must conserve CPT. Hence CPV implies T violation, which is also observed.

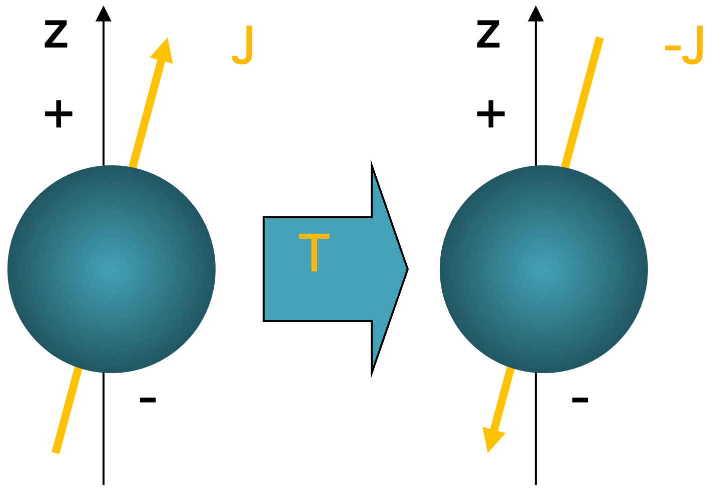
T violation

Electric dipole moment of neutron $<6\times10^{-26}$ e cm

-strong limit on CP and T non-conservation (CPT Theorem)

-strong constraints on Supersymmetry models (which predict extra CP violating terms).

Any neutron EDM must be along z axis defined by its spin



Time reversal flips J=rxp => -J=rx(-p), but doesn't alter EDM. Hence EDM=0 if T conserved (but T should be not conserved).

Calculation of SM CP violation

- Consider decay of X to final state f

$$A_f = \langle f | H | X \rangle \quad \text{and} \quad \overline{A}_{\bar{f}} = \langle \bar{f} | H | \overline{X} \rangle$$

For CP violation need

$$|\mathrm{A_f}|^2 - |\overline{A}_{\bar{f}}|^2 \neq 0$$

Can only happen if two or more processes interfere :

$$\mathrm{A_f} = A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}$$

$$\overline{\mathrm{A}}_{\bar{\mathrm{f}}} = A_1 e^{+i\phi_1} e^{i\delta_1} + A_2 e^{+i\phi_2} e^{i\delta_2}$$

- Strong phase δ has same sign but weak phase φ changes sign. $A_{1,2}$ are real.

$$A_f^* A_f = \left(A_1 e^{+i\phi_1} e^{-i\delta_1} + A_2 e^{+i\phi_2} e^{-i\delta_2}\right)\left(A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2}\right)$$

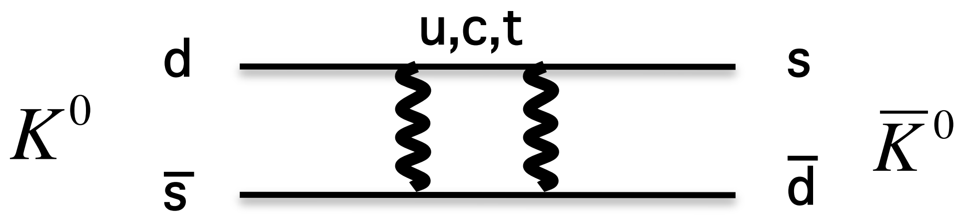
$$= A_1^2 + A_2^2 + 2A_1A_2 \begin{bmatrix} \cos(\phi_1 - \phi_2)\cos(\delta_1 - \delta_2) \\ +\sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2) \end{bmatrix}$$

$$\overline{A}_{\bar{f}}^* \overline{A}_{\bar{f}} = A_1^2 + A_2^2 + 2A_1A_2 \begin{bmatrix} \cos(\phi_1 - \phi_2)\cos(\delta_1 - \delta_2) \\ -\sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2) \end{bmatrix}$$

since $\sin(-\phi) = -\sin(\phi)$

$$A_f^* A_f - \overline{A}_{\bar{f}}^* \overline{A}_{\bar{f}} = 2A_1A_2 \sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$$

CP violation requires more than one amplitude to interfere, with different strong and weak phases. In SM this occurs in quark loops due to quark mixing.



For K system, three amplitudes are involved, for u, c, and t in loop. Strong phases differ because quark masses different.

3x3 CKM matrix allows a relative weak phase to occur which cannot be defined to zero.

If there were only two quark families, there would be no CP violation in the SM.

Effect in K is relatively small because V_{td}, V_{ts} small: larger effects in B meson system.

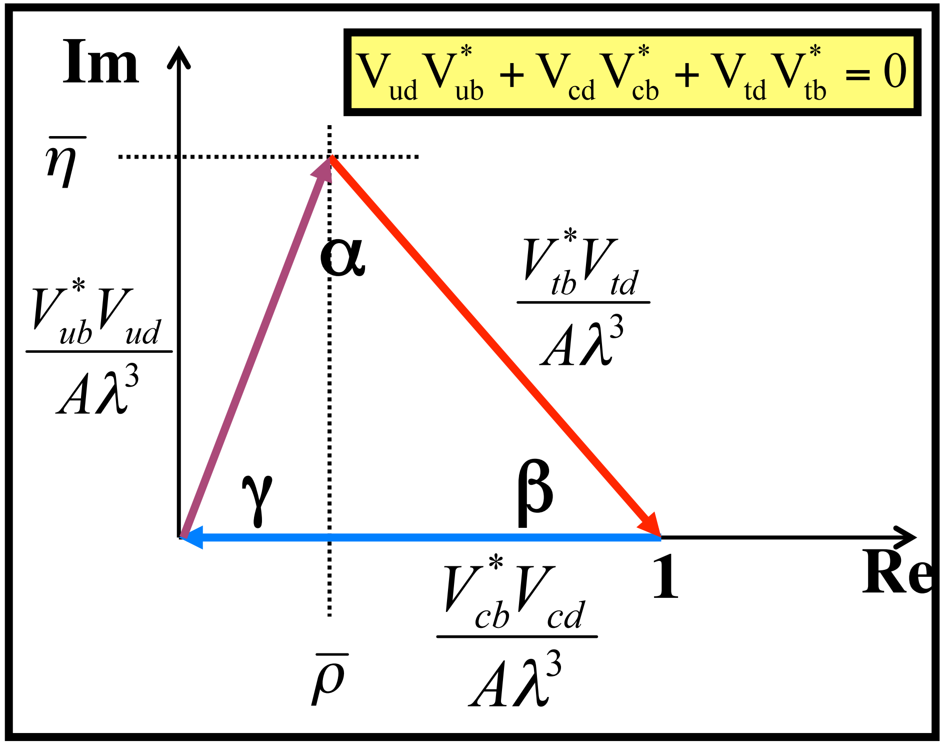
Semileptonic Kaon decays

- Look at other kaon decays:

$$\frac{\Gamma(K_L^0 \rightarrow e^+ \pi^- \upsilon)}{\Gamma(K_L^0 \rightarrow e^- \pi^+ \overline{\upsilon})} = 1.00662 \pm 0.00012$$

- Can define electron vs positron without ambiguity.
- This shows an absolute difference between matter and antimatter!

Unitarity triangle



V_{CKM} is Unitary, $V^*V=1$
Can create six conditions for off-diagonal elements. If SM correct, triangle is closed.

$$\alpha \equiv \pi - \beta - \gamma$$

$$\gamma \equiv \arg\left[-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right] = \tan^{-1}\frac{\eta}{\rho} \sim 70^{\circ}$$

$$\beta \equiv \arg\left[-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right] = \tan^{-1}\frac{\bar{\eta}}{1-\bar{\rho}} \sim 21^{\circ}$$

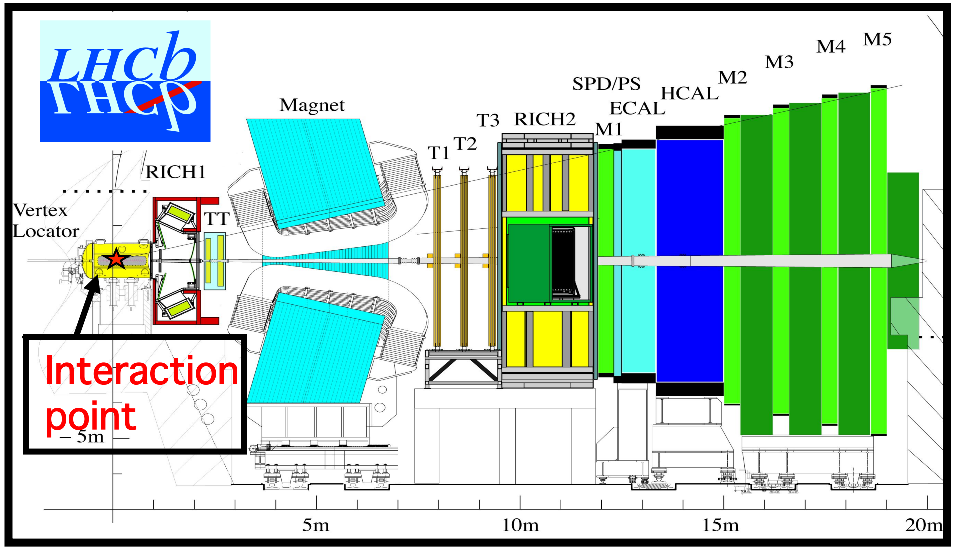
LHCb

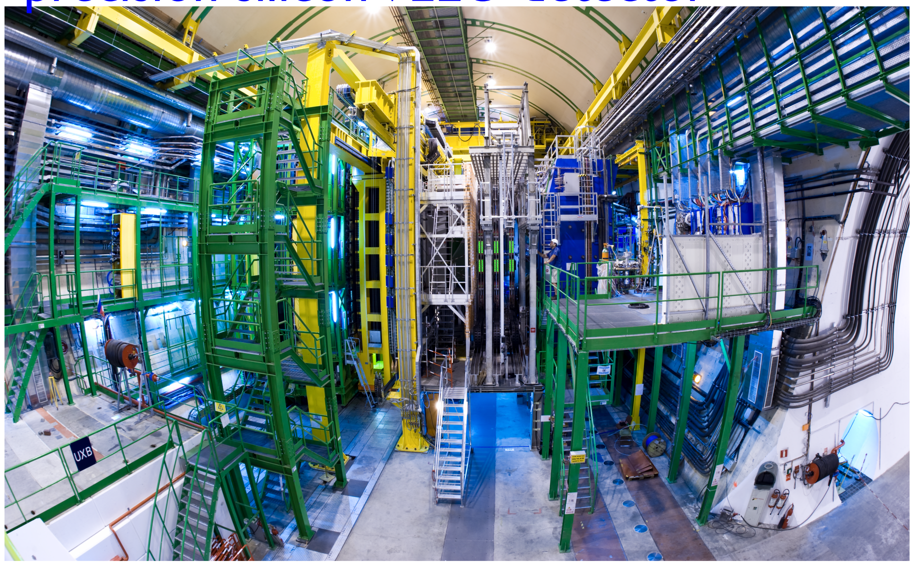
An experiment dedicated to the search for New Physics in heavy flavours: need high statistics and good particle ID

Forward single arm spectrometer

Excellent tracking

precision silicon VELO detector





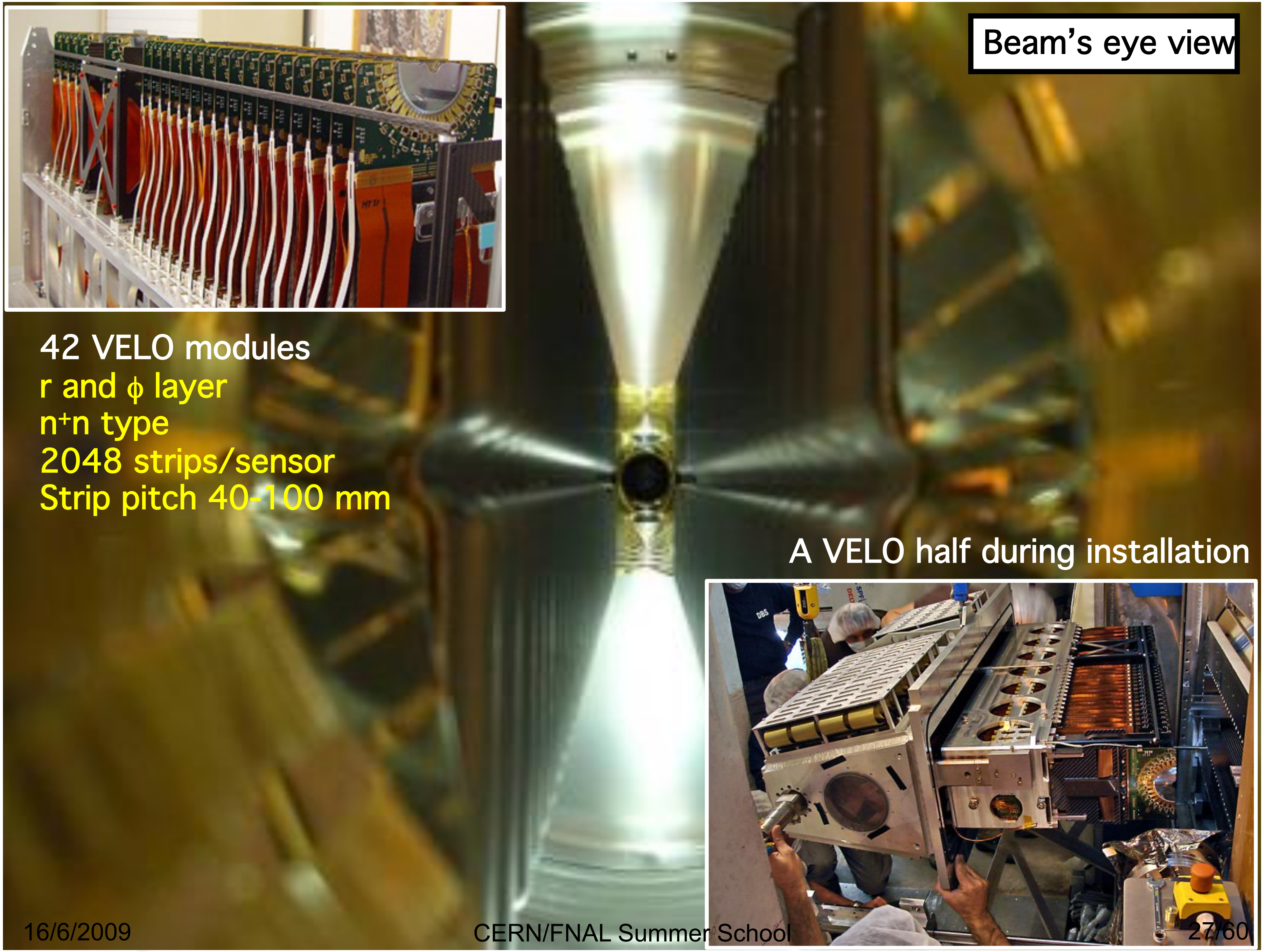
Excellent particle identification

2 RICH detectors

π/K separation over p ~2−100 GeV

Efficient Trigger

Low p_T lepton, γ/π^0 & hadron thresholds



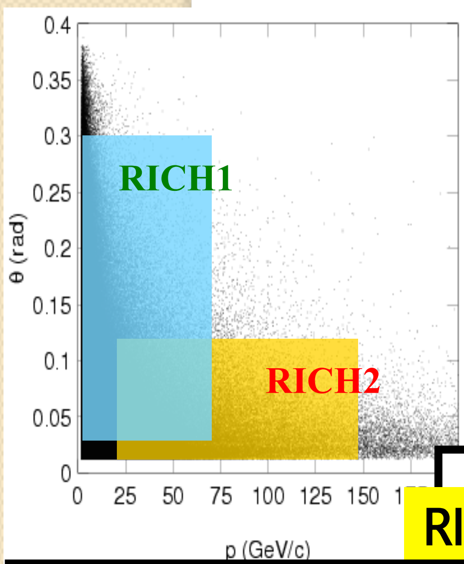
Beam’s eye view

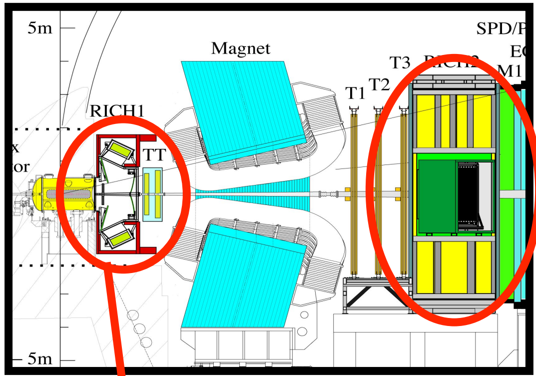
42 VELO modules
r and ϕ layer
$n^{+}n$ type
2048 strips/sensor
Strip pitch 40-100 mm

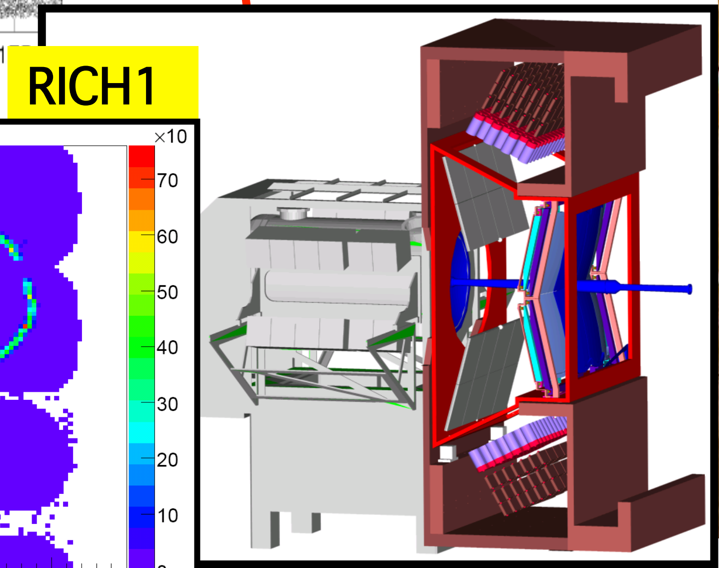
A VELO half during installation

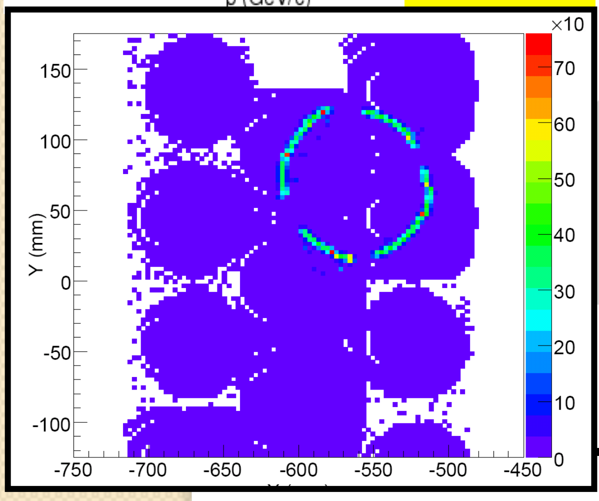
LHCb RICH Detectors

Particle ID: p~2-100 GeV provided by 2 RICH detectors





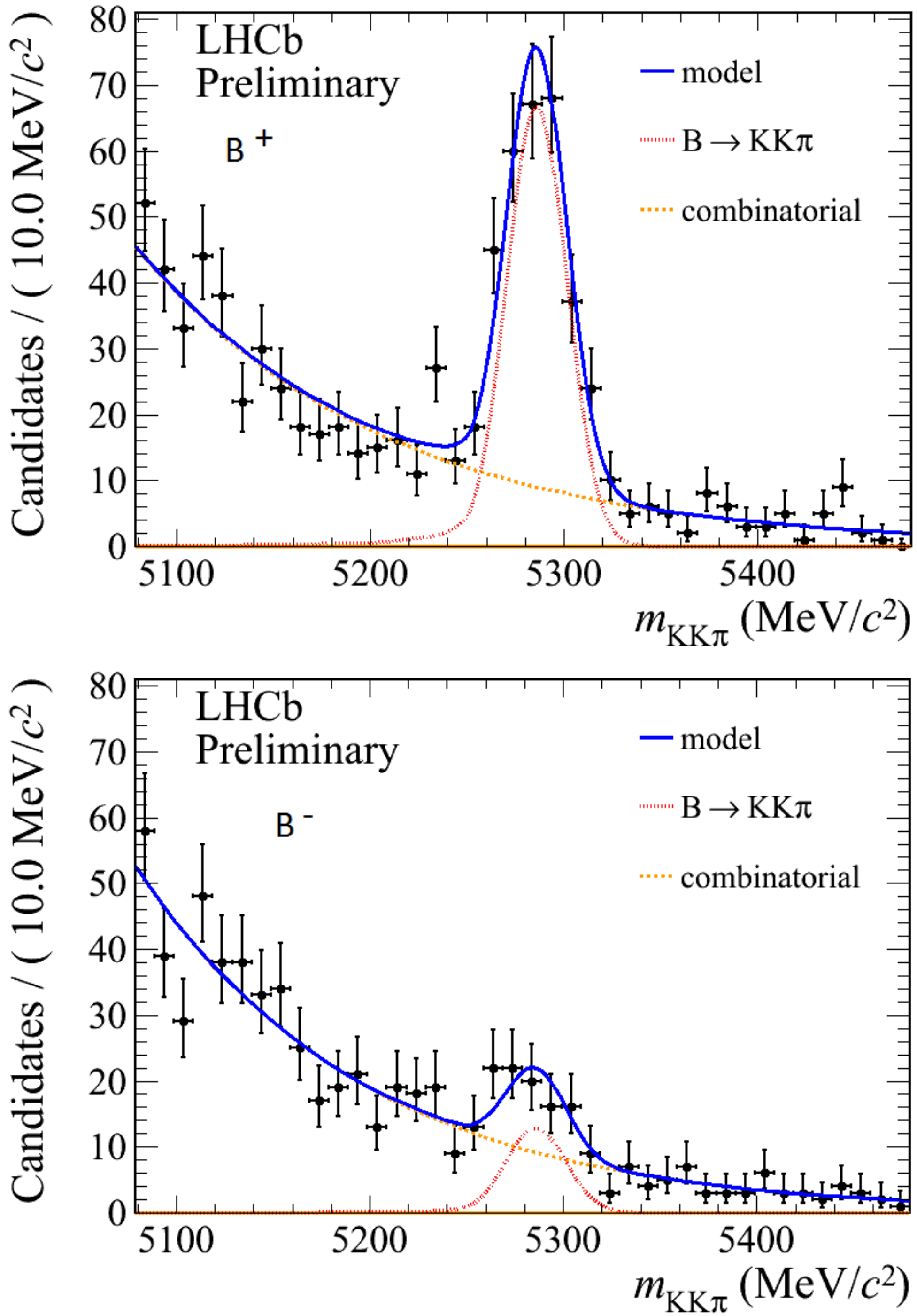




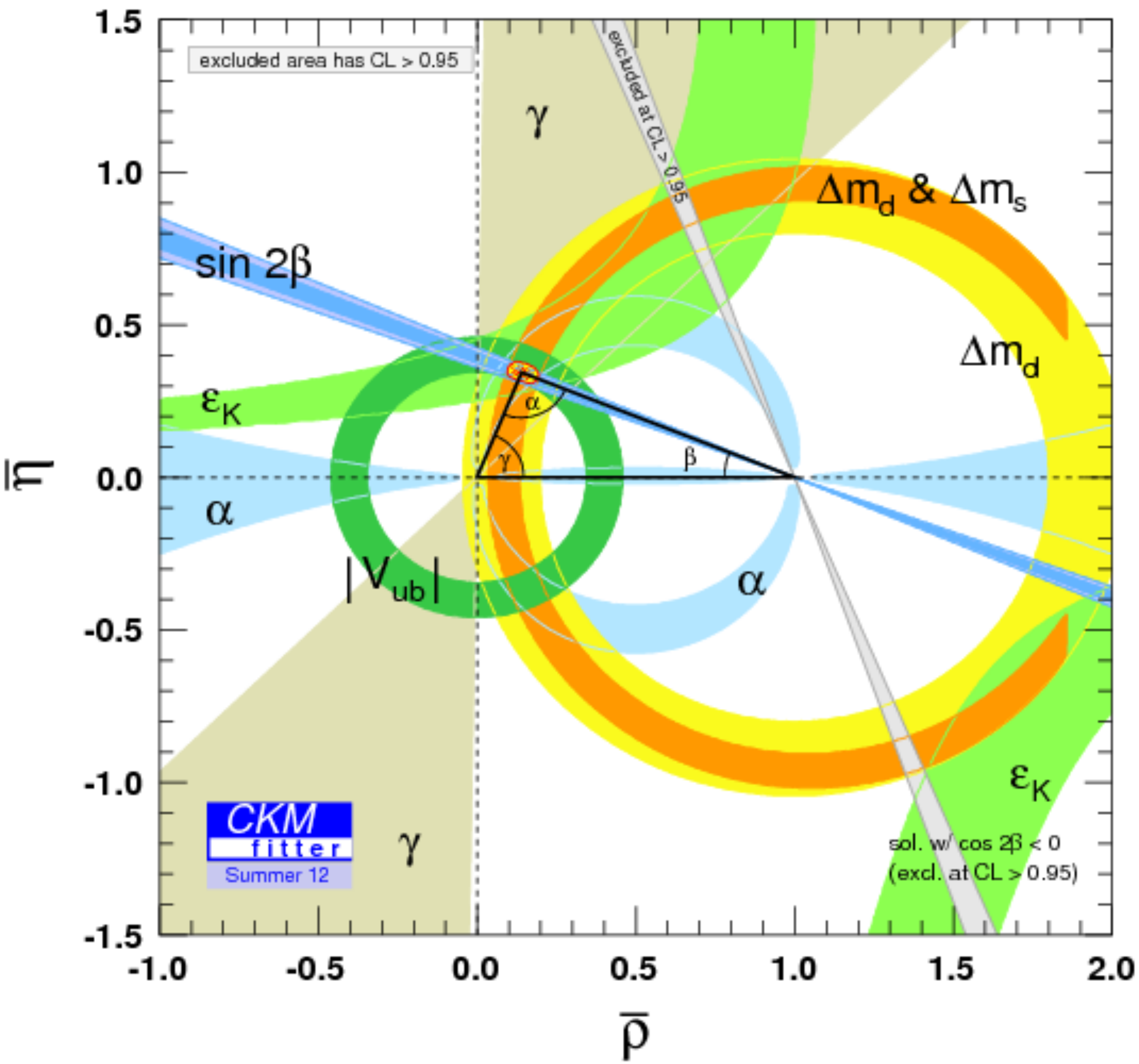
LHCb sees large CP violation effects in B meson decays

B+ decays to KKp much more often than its antiparticle B-

(Note: no charm quark in this final state)



State of the art – CPV in SM



$$\alpha = \left(90.5^{+4.3}_{-4.1}\right)^{o}$$

$$\beta = \left(21.7 \pm 0.8\right)^{o}$$

$$\gamma = \left(67.7^{+4.1}_{-4.3}\right)^{\circ}$$

Everything consistent with SM CKM mechanism: need new physics in early universe!

SM CPV in early Universe

- At high T can use perturbative estimate:
- Need interference involving all 3 families and at least 8 weak vertices:

PRD 20(1979)2494

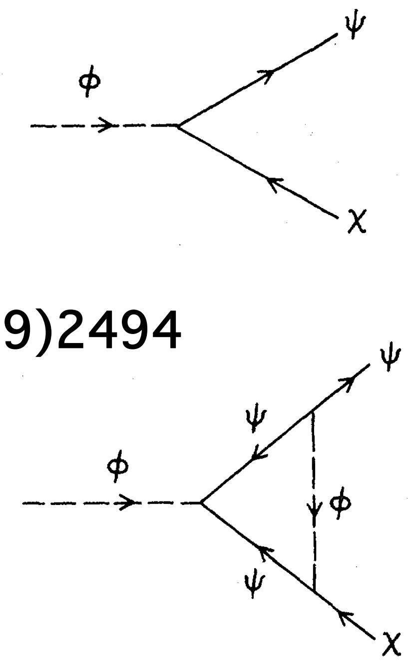


FIG. 1. A tree and one-loop diagram whose interference fails to give a ΔB in the KM model.

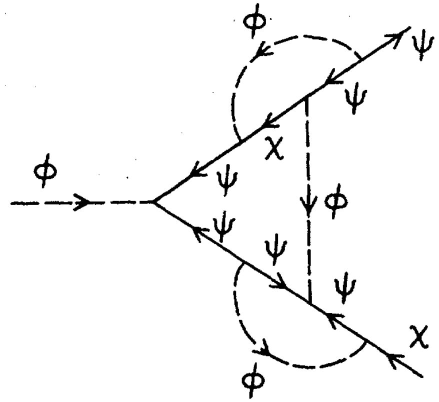


FIG. 2. A typical contribution to ΔB from ϕ decay in the KM model.

Leads to $\eta << 10^{-18}$: far too small – new physics needed!

Out of equilibrium decay

- Consider BSM model with

$$X \rightarrow qq \text{ (at rate } r) \text{ , } \bar{q}\bar{l} \text{ (at rate } 1 - r)$$

$$\bar{X} \rightarrow \bar{q}\bar{q} \; (\bar{r}) \quad , \; ql \; (1 - \bar{r})$$

from CPT $M_X = M_{\bar{X}}$ but with CPV $r \neq \bar{r}$

Start with $n_x = n_{\bar{x}}$

Decays cause baryon asymmetry :

$$n_B - n_{\bar{B}} = n_X \left[r\frac{2}{3} + (1-r)\left(-\frac{1}{3}\right) \right] + n_{\bar{X}} \left[\bar{r}\left(-\frac{2}{3}\right) + (1-\bar{r})\left(\frac{1}{3}\right) \right]$$

$$= n_X (r - \bar{r})$$

But if universe was in thermal equilibrium, $n \propto \exp(-M/T)$

so would expect $n_B = n_{\bar{B}}$ always!

- In equilibrium, decay (and annihilation) processes balanced by their inverse creation processes: no asymmetry possible
- But if expansion rate H>reaction rate, can get excess n_X , larger than equilibrium value.
- When age of Universe exceeds decay lifetime, excess will decay away leaving asymmetry.
- -> Requires weakly coupled X in order to give slow reaction rates.
- -> Process happens at early time.

GUTS and BSM models

- In GUTS and BSM models, quarks and leptons occur in same multiplets, and such processes are natural

eg SU(5) contains 5-plet with

$$\psi_L = (\underbrace{d_R, d_G, d_B}_{\text{gluons}} \overset{X}{,} \underbrace{e^-, -\upsilon_e}_{W})_L$$

X and Y bosons create transitions between the leptons and the (red/green/blue) d-quark components.

- Many BSM models use supersymmetry, giving partners to every SM particle with spin changed by ½ unit.
- Leads to many free phases between fields, and hence large CPV effects
- Normally implemented in a GUT framework with baryon-violating transitions.

Summary

- Baryon asymmetry in Universe must involve CP and B violating processes
- These occur in the SM but at much too low a level to explain observations
- Extensions to SM predict larger CPV sources
- B-physics experiments will clarify data