FYST17 Lecture 2

Left-overs &

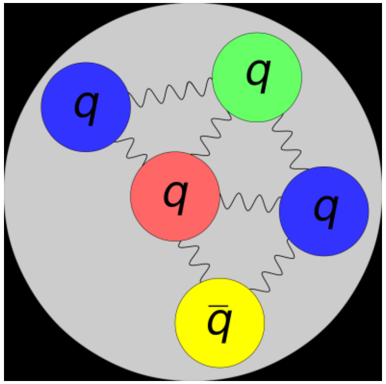
Symmetries and CP violation

Thanks to A. Hocker, C. Parkes

Today’s topics

- Hadrons that do not fit into the Standard Model: Pentaquarks!
- Symmetries
  - Broken symmetries
- Neutral kaon mixing
- CP violation
  - Matter / anti-matter asymmetry
- The CKM matrix

Pentaquarks!



- The ”old” story:
- Proposed states with 5quarks (or 4q, 1$\bar{q}$)
- Discovered (?) 2003 by LEPS experiment:
  - Θ+ ($uudd\bar{s}$) , mass = 1,54 GeV.
  - Not very significant, little statistics

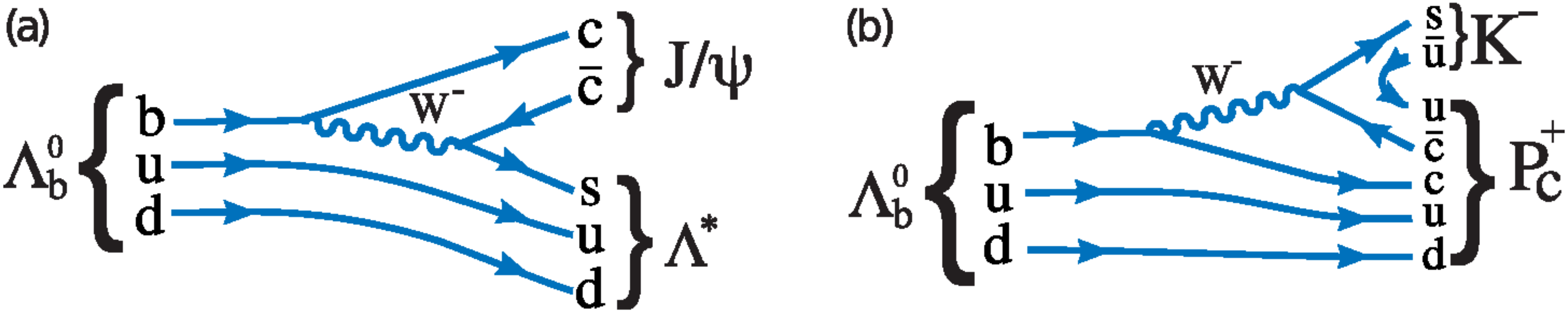
Over the next few years several other low statistics experiments report that they also see it!

By 2006: High statistics collider searches for pentaquarks at LEP & Belle. These experiments see NOTHING

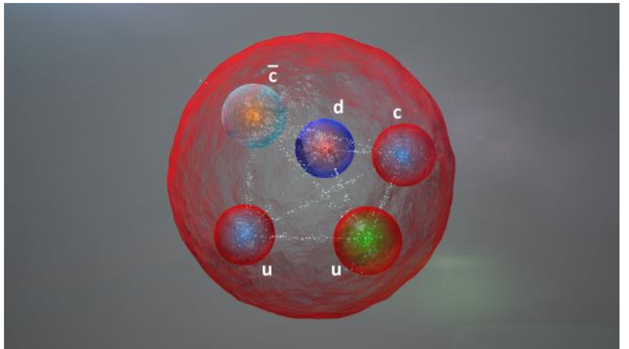
→ the pentaquark is dead ?

The 2015 pentaquark ”accident”

- LHCb collaboration publishes in Phys.Rev.Letters (arXiv:1507:03414) July 2015: ”Observation of J/psi p resonances consistent with pentaquarks”

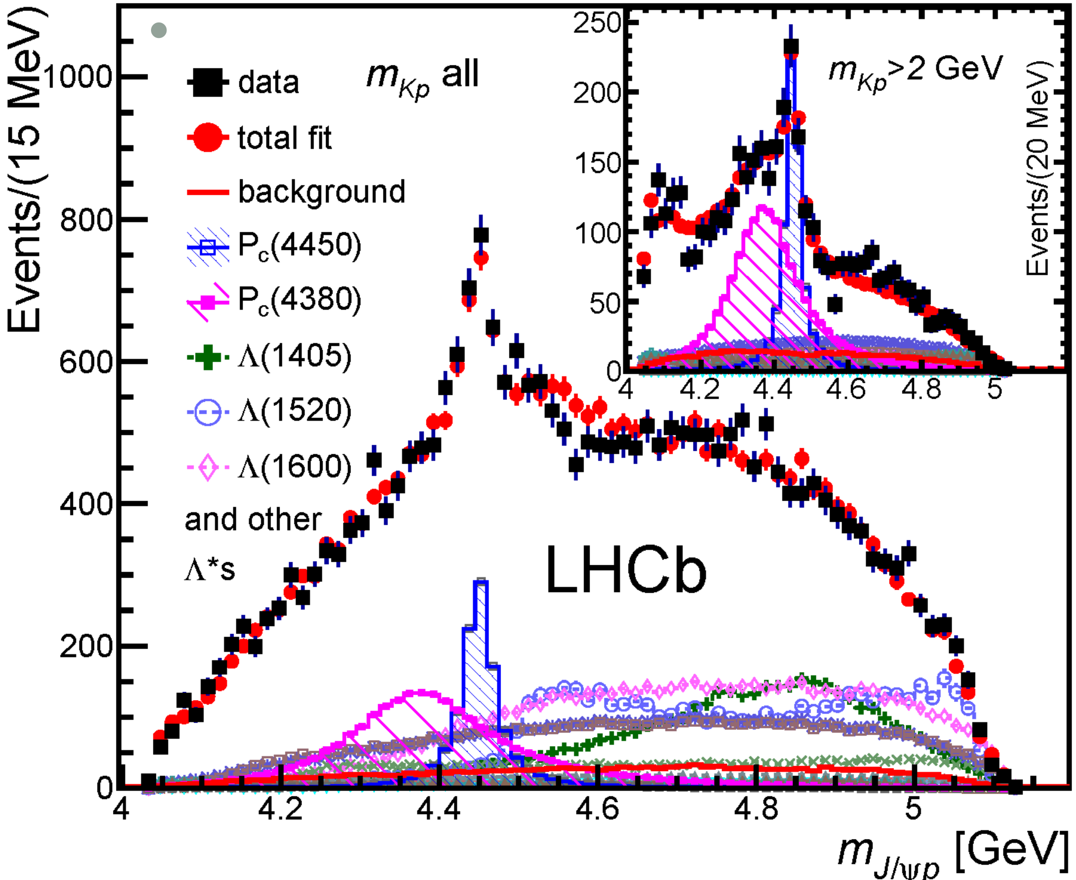


- Proposed state would be $\mathrm{uudc\bar{c}}$



Best fit to data involves two new states with masses

- P_c+(4050) mass = 4449.8 ± 1.7 ± 2.5 MeV
- P_c+(4380) mass = 4380 ± 8 ± 29 MeV



Systematical uncertainty

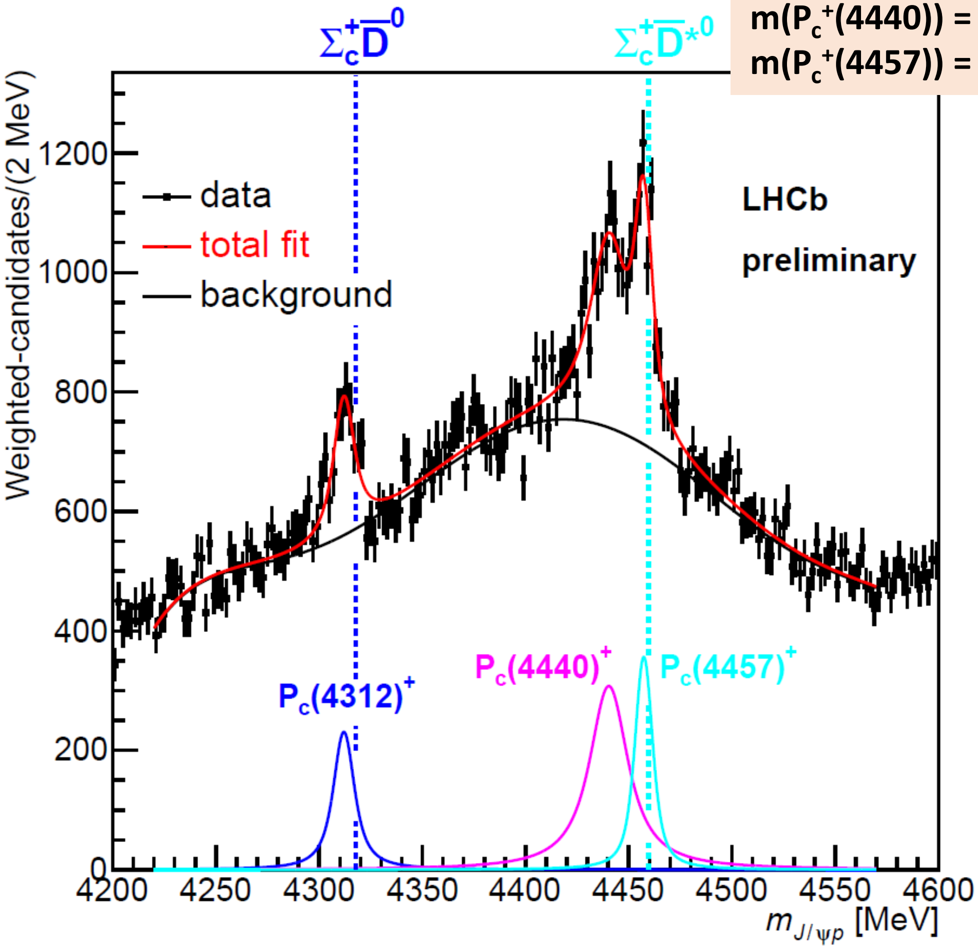
Statistical uncertainty

Significances 9-15 σ

2016 analysis confirms this

And more new pentaquarks in 2019!

m(P_c^+(4312)) = 4311.9±0.7+6.8/-0.6 MeV, Γ = 9.8±2.7+3.7/-4.5 MeV
m(P_c^+(4440)) = 4440.3±1.3+4.1/-4.7 MeV, Γ = 20.6±4.9+8.7/-10.1 MeV
m(P_c^+(4457)) = 4457.3±0.6+4.1/-1.7 MeV, Γ = 6.4±2.0+5.7/-1.9 MeV



Discovery of a new narrow pentaquark particle, $P_c(4312)^+$, decaying to a J//ψ and a proton, with a statistical significance of 7.3 σ!!

The $P_c(4450)^+$ pentaquark structure previously reported by LHCb is also confirmed, but a more complex structure consisting of two narrow overlapping peaks, $P_c(4440)^+$ and $P_c(4457)^+$
(The two-peak structure has statistical significance of 5.4 σ compared to a single-peak hypothesis).

https://arxiv.org/abs/1904.03947

Now we move on to symmetries!

Continuous Symmetries and Conservation Laws

- In classical mechanics we have learned that to each continuous symmetry transformation, which leaves the scalar Lagrange density invariant, can be attributed a conservation law and a constant of movement (E. Noether, 1915)

- Continuous symmetry transformations lead to additive conservation laws

Symmetry	Invariance under movement in time	Homogeneity of space	Isotropy of space
Transformation	Translation in time	Translation in space	Rotation in space
Conserved quantity	Energy	Linear momentum	Angular momentum

No evidence for violation of these symmetries seen so far

Continuous Symmetries and Conservation Laws

In general, if *U* is a symmetry of the Hamiltonian *H*, one has: $[H,U]=0 \;\Rightarrow\; H=U^{\dagger}HU$

$$\boxed{\langle f'|H|i'\rangle=\langle Uf|H|Ui\rangle=\langle f|U^{\dagger}HU|i\rangle=\langle f|H|i\rangle}$$

- Accordingly, the Standard Model Lagrangian satisfies local gauge symmetries (the physics must not depend on local (and global) phases that cannot be observed):

U(1) gauge transformation	→	**Electromagnetic interaction**
SU(2) gauge transformation	→	**Weak interaction**
$SU(3)_C$ gauge transformation	→	**Strong interaction (QCD)**

- Conserved additive quantum numbers:
  - Electric charge (processes can move charge between quantum fields, but the sum of all charges is constant)
  - Similar: color charge of quarks and gluons, and the weak charge
  - Quark (baryon) and lepton numbers *(however, no theory for these, therefore believed to be only approximate asymmetries)* → evidence for lepton flavor violation in “neutrino oscillation”

Discrete Symmetries

Discrete symmetry transformations lead to multiplicative conservation laws

The following discrete transformations are fundamental in particle physics:

- Parity ***P*** (“handedness”):

  Reflection of space around an arbitrary center;
  P invariance → cannot know whether we live in *this* world, or in *its mirror* world

- Particle-antiparticle transformation ***C*** :

  Change of all additive quantum numbers (for example the electrical charge) in its opposite (“charge conjugation”)

- Time reversal ***T*** :

  The time arrow is reversed in the equations;
  T invariance → if a movement is allowed by a the physics law, the movement in the opposite direction is also allowed

In particle physics:

$$P\left|e_L^-\right\rangle = \left|e_R^-\right\rangle$$

$$P\left|\pi^0\right\rangle = -\left|\pi^0\right\rangle$$

$$P\left|n\right\rangle = +\left|n\right\rangle$$

$$C\left|e_L^-\right\rangle = \left|e_L^+\right\rangle$$

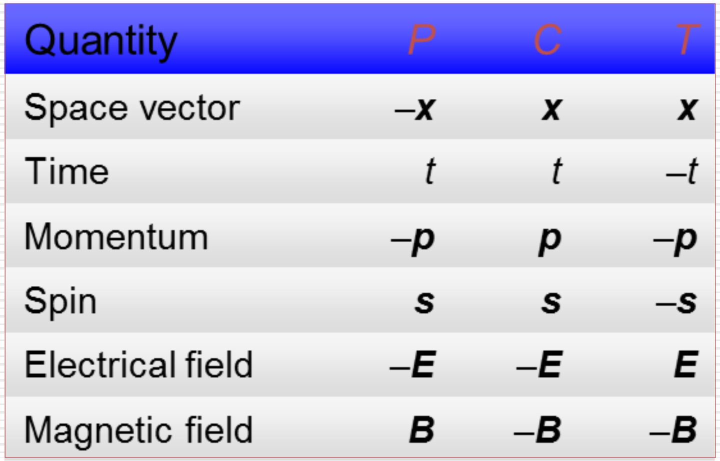
$$C\left|u\right\rangle = \left|\bar{u}\right\rangle$$

$$C\left|d\right\rangle = \left|\bar{d}\right\rangle$$

$$C\left|\pi^0\right\rangle = +\left|\pi^0\right\rangle$$

Time reversal symmetry (invariance under change of time direction) does certainly not correspond to our daily experience. The macroscopic violation of *T* symmetry follows from maximising thermodynamic entropy (leaving a parking spot has a larger solution space than entering it). In the microscopic world of single particle reactions thermodynamic effects can be neglected, and *T* invariance is realised.

C, *P*, *T* Transformations and the *CPT* Theorem



Quantity	*P*	*C*	*T*
Space vector	$-\boldsymbol{x}$	$\boldsymbol{x}$	$\boldsymbol{x}$
Time	t	t	$-t$
Momentum	$-\boldsymbol{p}$	$\boldsymbol{p}$	$-\boldsymbol{p}$
Spin	$\boldsymbol{s}$	$\boldsymbol{s}$	$-\boldsymbol{s}$
Electrical field	$-\boldsymbol{E}$	$-\boldsymbol{E}$	$\boldsymbol{E}$
Magnetic field	$\boldsymbol{B}$	$-\boldsymbol{B}$	$-\boldsymbol{B}$

The *CPT* theorem (1954): **"Any Lorentz-invariant local quantum field theory is invariant under the successive application of *C*, *P* and *T*"**

proofs: G. Lüders, W. Pauli; J. Schwinger

- Fundamental consequences:
  - Relation between spin and statistics: fields with integer spin ("bosons") commute and fields with half-numbered spin ("fermions") anticommute → Pauli exclusion principle
  - Particles and antiparticles have **equal mass and lifetime**, equal magnetic moments with opposite sign, and **opposite quantum numbers**

- Best experimental test: $\left|\left(m_{K^0} - m_{\bar{K}^0}\right)/m_{K^0}\right| < 10^{-18}$

EM and strong interactions are (so far) C, P, and T invariant

Example: $\pi^0 \rightarrow \gamma\gamma$ but **not** $\pi^0 \rightarrow \gamma\gamma\gamma$

$$\pi^0 = \frac{1}{\sqrt{2}}\left[u\bar{u} \; - d\bar{d}\right]_{L=0,S=0} \Rightarrow C|\pi^0\rangle = +|\pi^0\rangle$$

$$C \cdot \bar{B}, \bar{E} = -\bar{B}, \bar{E} \;\; \Rightarrow C|\gamma\rangle = -|\gamma\rangle$$

Thus initial and final states are C even, *C is conserved*

In general:

$$P|q\bar{q}\rangle = (-1)^{L+1}|q\bar{q}\rangle, C|q\bar{q}\rangle = (-1)^{L+S}|q\bar{q}\rangle$$

Experimental tests of P and C invariance of the EM interaction:

C invariance: BR($\pi^0 \rightarrow 3\gamma$) < 3.1 x 10^{-8}

P invariance: BR($\eta \rightarrow 4\pi^0$) < 6.9 x 10^{-7}

Experimental tests of C invariance of strong interaction: Compare rates of positive and negative particles, like $p\bar{p} \rightarrow \pi^+\pi^-$X, K^+K^-X, …

And … the Surprise in Weak Interaction !

T.D. Lee and C.N. Yang pointed out in 1956 (to explain the observation of the decays *K* → 2π *and* 3π - the cosmic-ray θ/τ puzzle) that *P* invariance had not been tested in weak interaction → C.S. Wu performed in 1957 the experiment they suggested and observed parity violation

- Angular distribution of electron intensity:

$$I(\theta) = 1 + \alpha\frac{\vec{\sigma}\cdot\vec{P}_e}{E_e} = 1 + \boxed{\alpha\frac{v}{c}}\cos\theta$$

helicity

where: $\vec{\sigma}$ - spin vector of electron

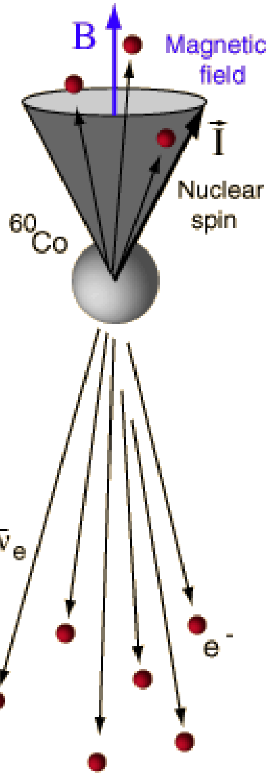
$\vec{P}_e$ - electron momentum

E_e - electron energy

$$\alpha = \begin{cases} -1 & \text{for electron} \\ +1 & \text{for positron} \end{cases}$$

Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957



$^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^- + \bar{\nu}_e$

T_{CO} ~ 0.01 K polarized in magnetic field

It was found that parity is even *maximally* violated in weak interactions !

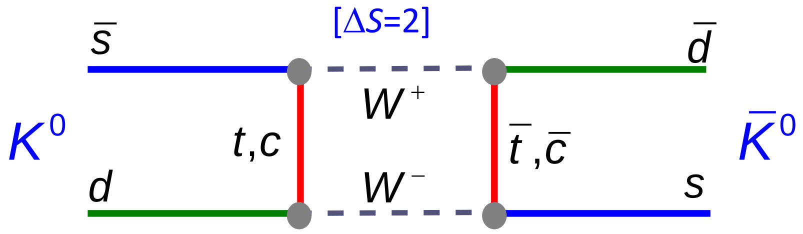
Neutral Kaon Mixing

Full details in chapter 10

- Neutral kaons can “mix” through the charged weak current, which does not conserve strangeness, and neither *P* nor *C*. Weak interaction *cannot* distinguish K^0 from $\bar{K}^0$
- Simple picture: they mix through common virtual states:

$$\begin{tikzcd}
 & (\pi\pi)^0 \arrow[dl, <->] \arrow[dr, <->] & \\
K^0 & & \bar{K}^0 \\
 & (\pi\pi\pi)^0 \arrow[ul, <->] \arrow[ur, <->] &
\end{tikzcd}$$

- Because $\Delta m(K) = m(K_L) - m(K_S) = 3.5 \times 10^{-12}$ MeV > 0, a K^0 will change with time into a $\bar{K}^0$ and vice versa
- These oscillations are described in QCD by $\Delta S = 2$ Feynman “box” diagrams:



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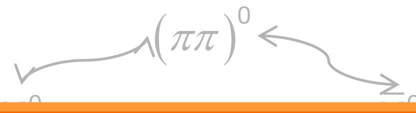
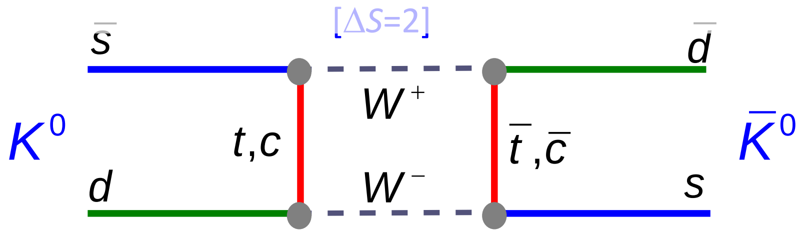


Neutral kaons with fixed strangeness quantum number do not exist in nature !
Note: *A priori*, mixing has nothing to do with *CP* violation !

- Because $\Delta m(K)$ = … with time into a $\bar{K}^0$ and vice ve…
- These oscillations are described in QCD by ΔS = 2 Feynman “box” diagrams:



Neutral Kaon Mixing

- An initially pure K^0 state, will evolve into a superposition of states:

$$|K(t)\rangle = g(t)|K^0\rangle + h(t)|\bar{K}^0\rangle$$

- The time dependence is obtained by solving the time-dependent Schrödinger equation:

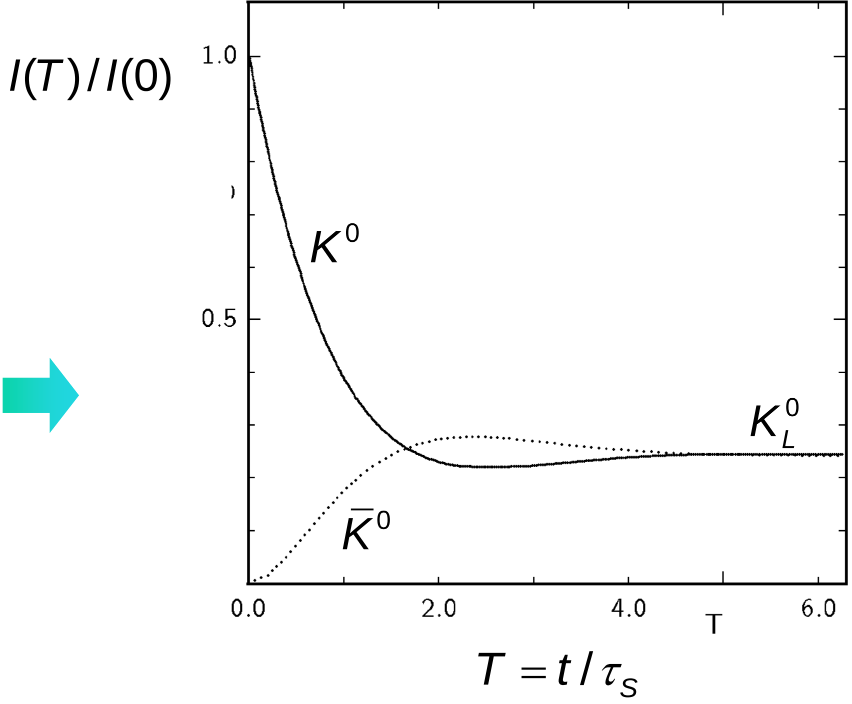
$$i\frac{d}{dt}\begin{pmatrix} |K^0(t)\rangle \\ |\overline{K}^0(t)\rangle \end{pmatrix} = \left(M - \tfrac{i}{2}\Gamma\right)\begin{pmatrix} |K^0(t)\rangle \\ |\overline{K}^0(t)\rangle \end{pmatrix}$$

with 2x2 matrices *M (mass matrix)*, Γ (decay matrix), of which the off-diagonals proportional to Δm, $\Delta\Gamma$ govern the mixing

- The respective time-dependent intensities are found to be (neglecting *CP* violation):

$$I_{K^0}(t) \propto e^{-\Gamma_L t} + 2e^{-\Gamma_L t/2}\cos(\Delta m \cdot t)$$

$$I_{\bar{K}^0}(t) \propto e^{-\Gamma_L t} - 2e^{-\Gamma_L t/2}\cos(\Delta m \cdot t)$$



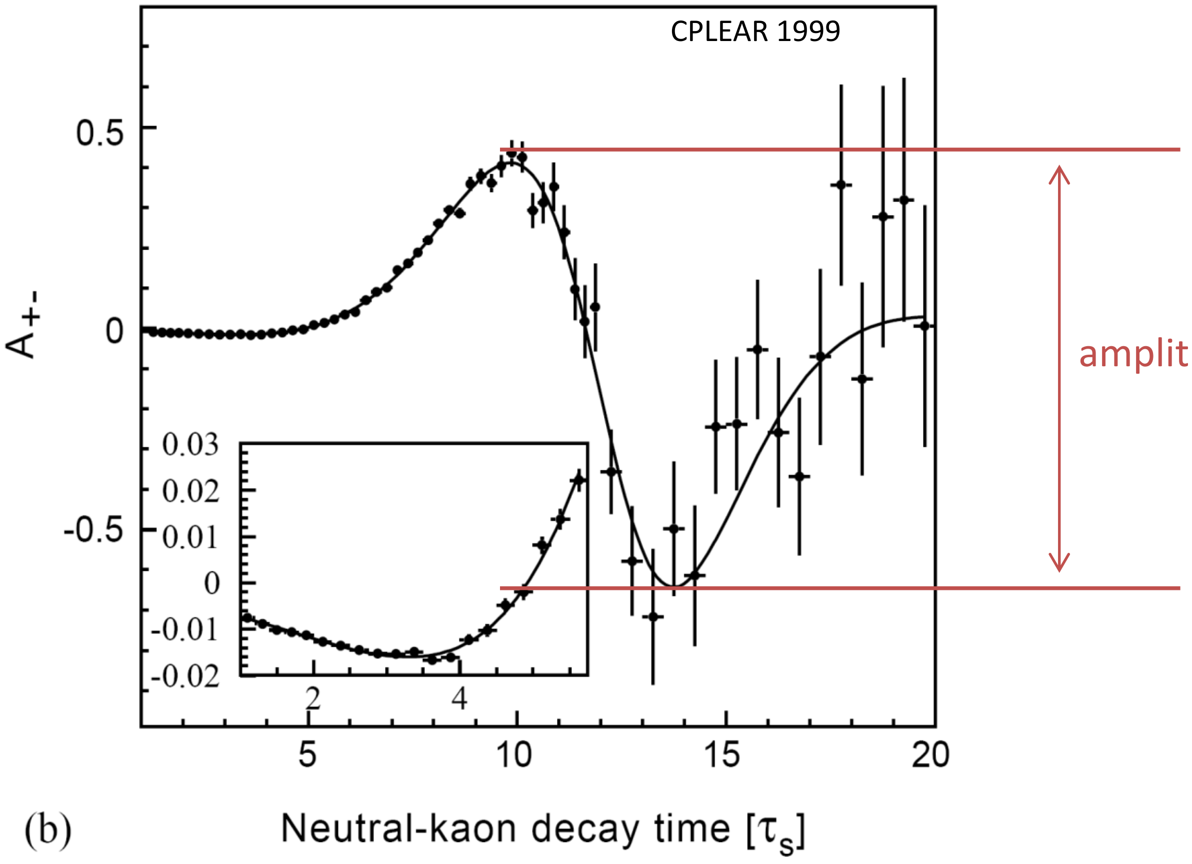
- After several K_S lifetimes, only K_L are left

Neutral Kaon Mixing and *CP* Violation

- Since K_S and K_L are not *CP* eigenstates, the time dependence has to be slightly modified by the size of ε, giving rise to an additional term.

Asymmetry: $$A_{\pi\pi} = \frac{\Gamma\left(\bar{K}^0 \to \pi^+\pi^-\right) - \Gamma\left(K^0 \to \pi^+\pi^-\right)}{\Gamma\left(\bar{K}^0 \to \pi^+\pi^-\right) + \Gamma\left(K^0 \to \pi^+\pi^-\right)} \propto |\varepsilon| \cos\left(\Delta m \cdot t - \varphi\right)$$

Neglecting other sources of *CP* violation & assuming arg(ε) = π/4.



amplitude ∝ |ε|

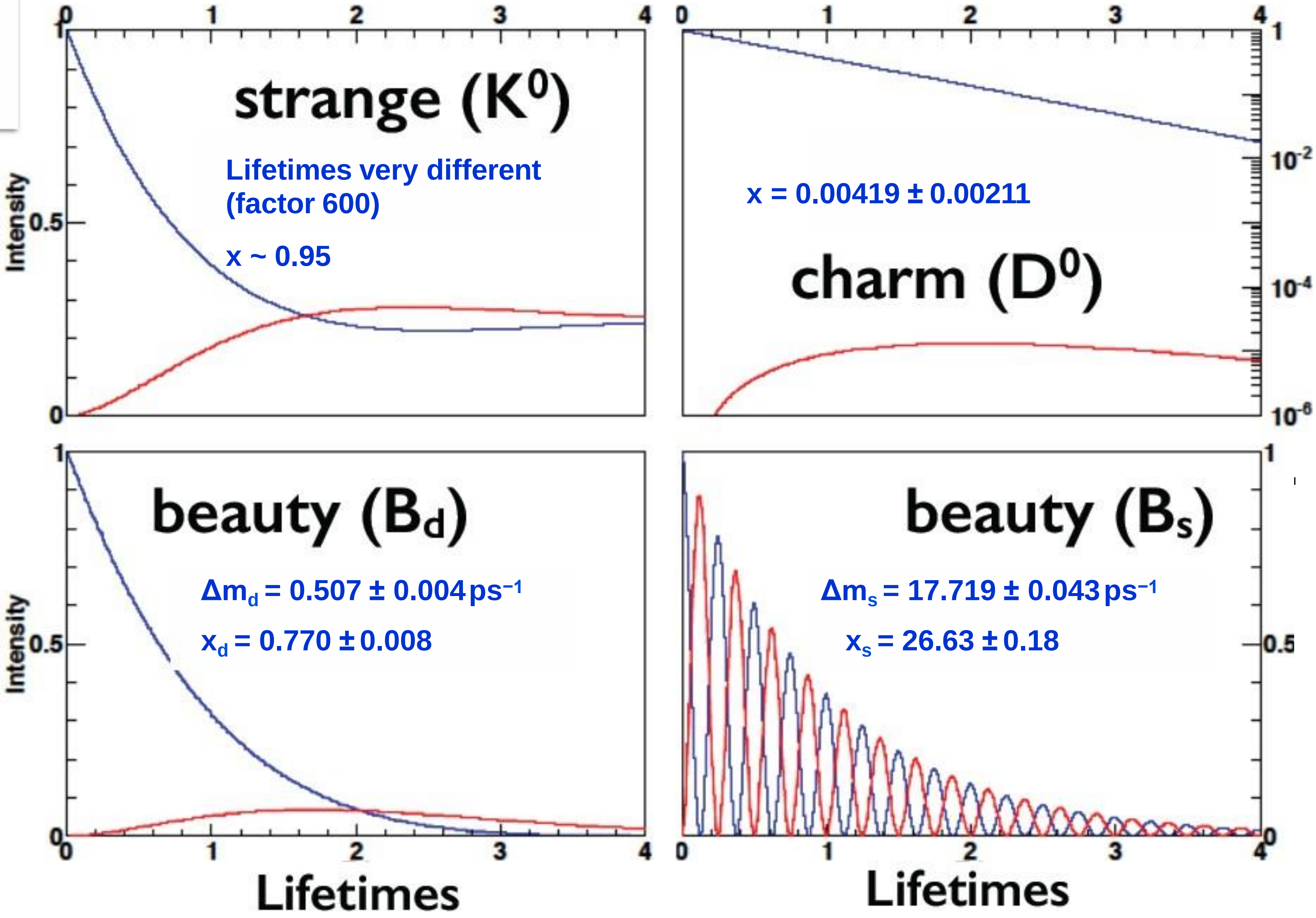
There are in fact 4 meson systems with Mixing!

- Pairs of self-conjugate mesons that can be transformed to each other via flavor changing weak interaction transitions are:

$$\left|K^0\right\rangle = \left|\bar{s}d\right\rangle \qquad \left|D^0\right\rangle = \left|c\bar{u}\right\rangle \qquad \left|B_d^0\right\rangle = \left|\bar{b}d\right\rangle \qquad \left|B_s^0\right\rangle = \left|\bar{b}s\right\rangle$$

- They have very different oscillation properties that can be understood from the “CKM couplings” (see later in this lecture) occurring in the box diagrams

Neutral meson mixing: summary



Lifetimes very different (factor 600)

$x \sim 0.95$

$x = 0.00419 \pm 0.00211$

$\Delta m_d = 0.507 \pm 0.004\,\mathrm{ps}^{-1}$

$x_d = 0.770 \pm 0.008$

$\Delta m_s = 17.719 \pm 0.043\,\mathrm{ps}^{-1}$

$x_s = 26.63 \pm 0.18$

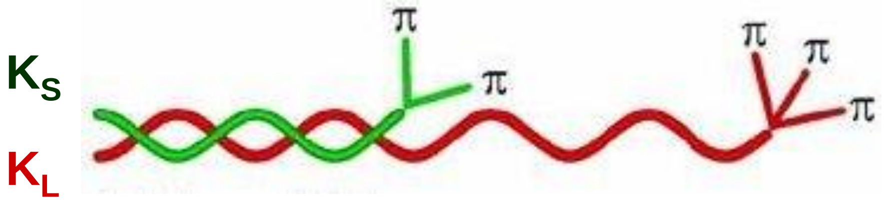
Blue:
given a P^0, at t=0,
the probability of
finding a P^0 at t.

Red:
given a P^0, at t=0,
the probability of
finding a P^0bar at t.

CP violation

From Schrödinger eqn:

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



3 types of CP violation:

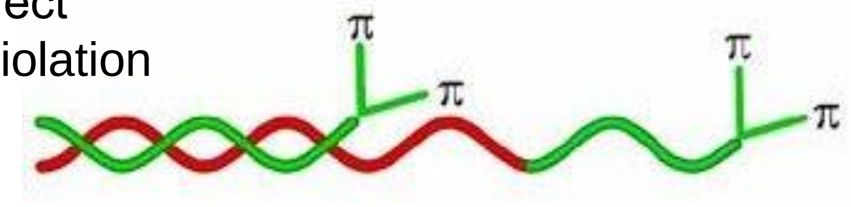
violation in mixing

$$\text{Prob}(K^0 \to \bar{K}^0) \neq \text{Prob}(\bar{K}^0 \to K^0)$$

violation in interference

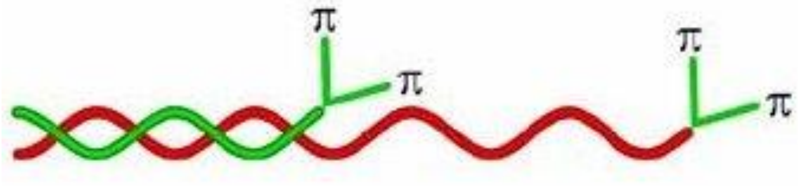
$$\text{Prob}(K^0(t) \to \pi^+\pi^-) \neq \text{Prob}(\bar{K}^0(t) \to \pi^+\pi^-)$$

Parameter ε
"indirect"
CP violation



violation in decays

$$\text{Prob}(K \to f) \neq \text{Prob}(\bar{K} \to \bar{f})$$



"direct"
CP violation

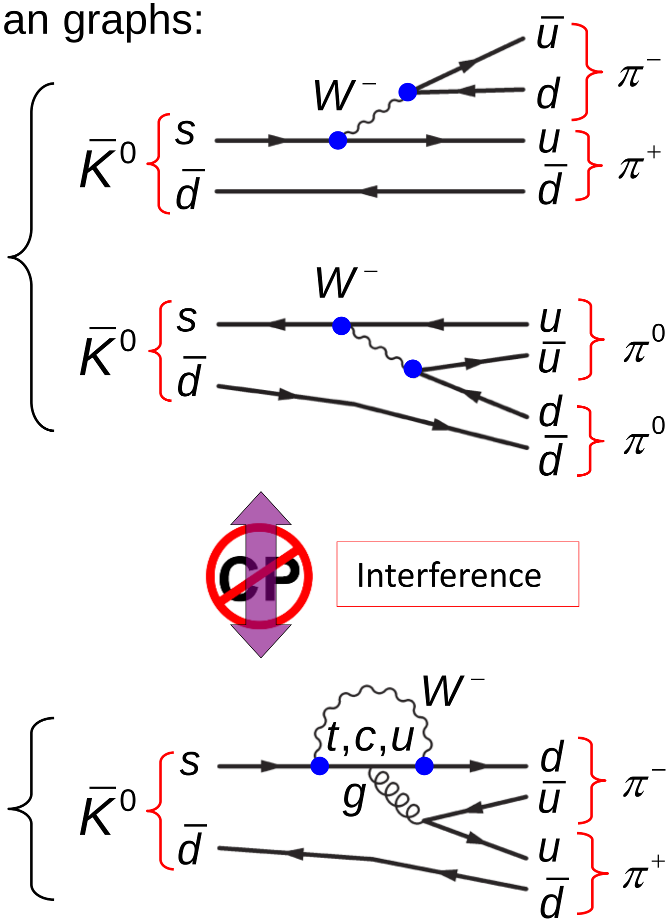
Parameter ε'

The Discovery of *CP* Violation in decays = “Direct” *CP* violation

- Due to the smallness of the effect, it took several experiments and over 30 years of effort to establish the existence of direct CPV

- Feynman graphs:

“Tree”
(born-level)
amplitudes

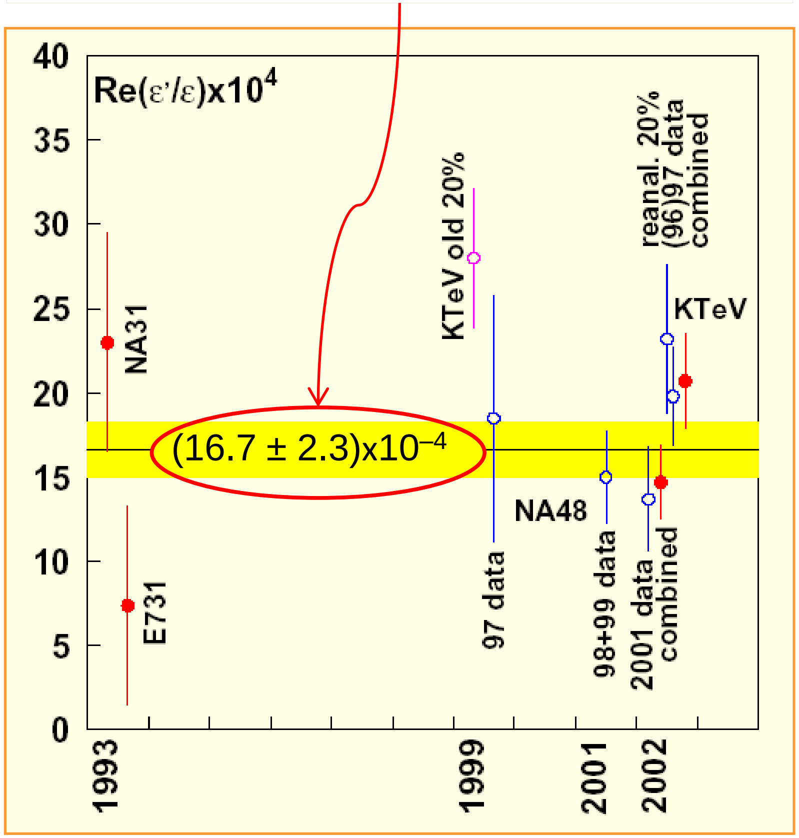


Interference

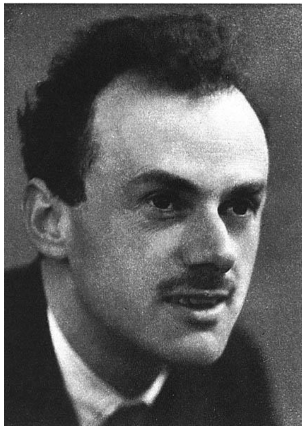
“Penguin”
(loop-level)
amplitude

Experimental average

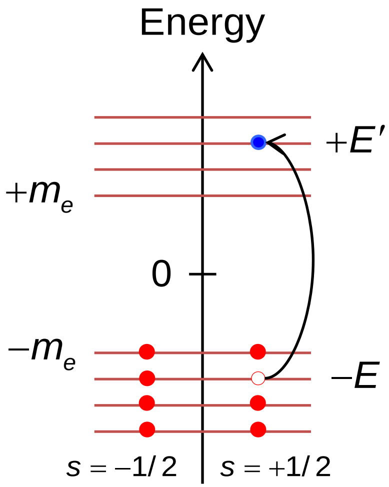
Indeed, a *very* small CPV effect !



Anti-particles



Dirac, imagining holes and seas in 1928



This picture fails for bosons !

- Combining quantum mechanics with special relativity, and the wish to linearize δ/δ*t,* leads Dirac to the equation

$$i\gamma^{\mu}\partial_{\mu}\psi(x,t)-m\psi(x,t)=0$$

(1928)

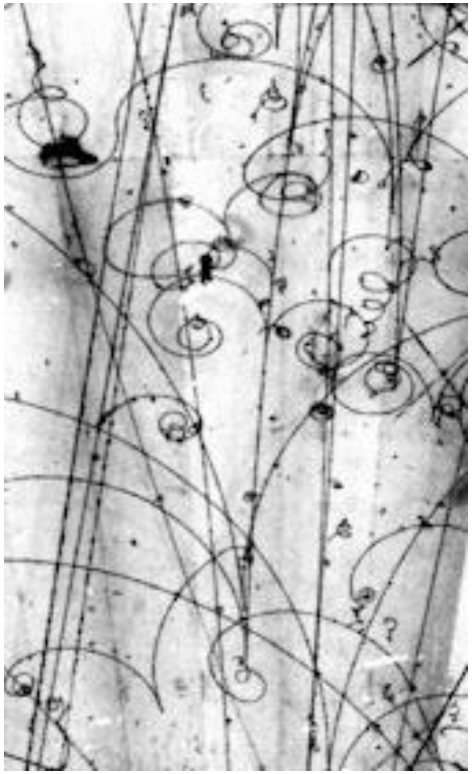
for which **solutions with negative energy** appear

- Vacuum represents a “sea” of such negative-energy particles (fully filled according to Pauli’s principle)
- Dirac identified holes in this sea as “antiparticles” with opposite charge to particles … (however, he conjectured that these holes were protons, despite their large difference in mass, because he thought “positrons” would have been discovered already)
- An electron with energy *E* can fill this hole, emitting an energy 2*E* and leaving the vacuum (hence, the hole has effectively the charge +*e* and positive energy).

Particles and Antiparticles Annihilate

What happens if we bring particles and antiparticles together ?

- A particle can annihilate with its antiparticle to form gamma rays
- An example whereby matter is converted into pure energy by Einstein’s formula $E = mc^2$
- Conversely, gamma rays with sufficiently high energy can turn into a particle-antiparticle pair

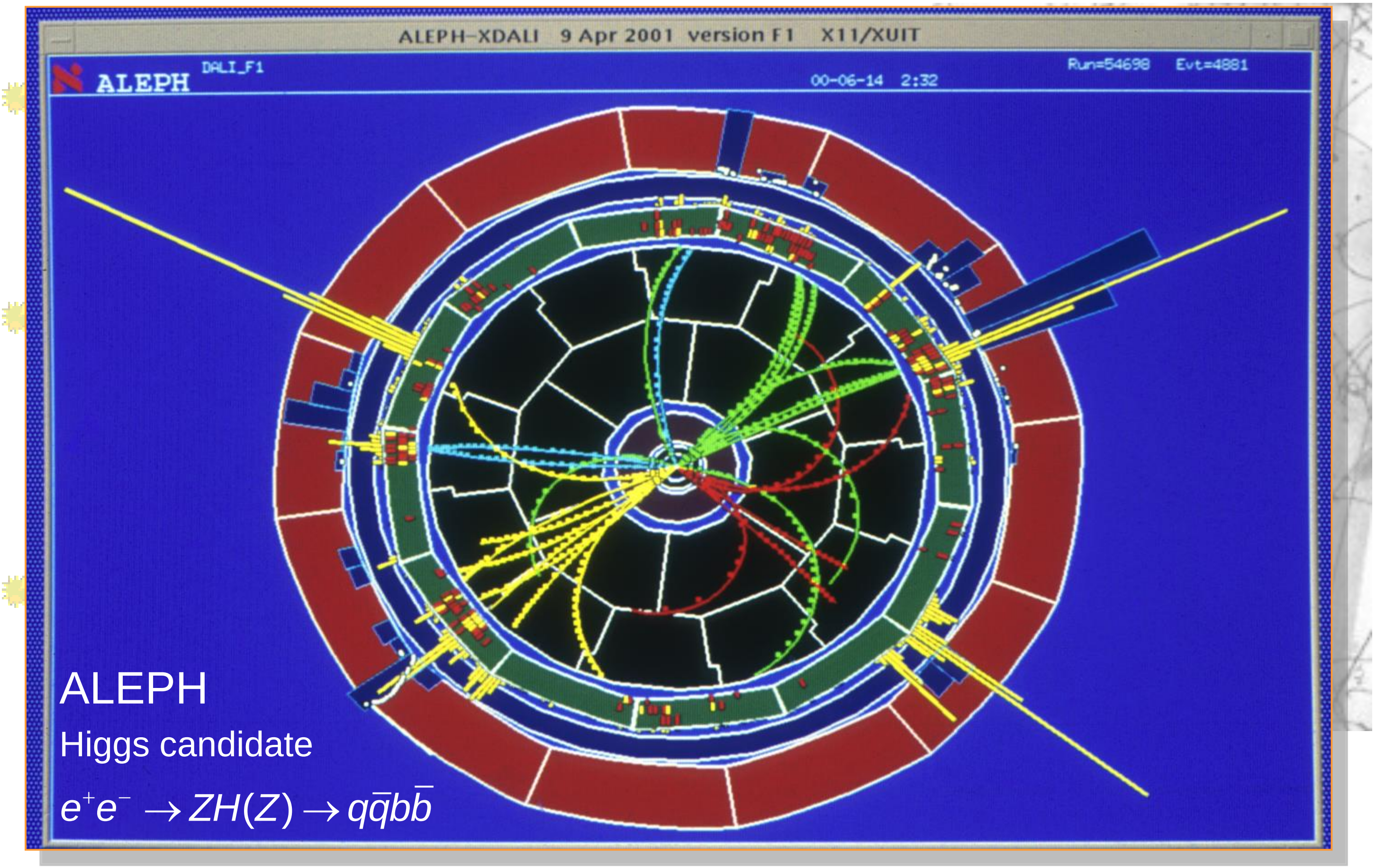


Fermilab

Particle-antiparticle tracks in a bubble chamber

Particles and Antiparticles Annihilate

What happens if we bring particles and antiparticles together ?



ALEPH

Higgs candidate

$e^+e^- \to ZH(Z) \to q\bar{q}b\bar{b}$

Fermilab

So the Standard Model can handle both particles and anti-particles

in most cases with the same couplings

What about anti-matter in our Universe?

Antimatter in the Universe ?

Balloon-borne Superconducting Solenoidal (BESS) spectrometer

- Does stable antimatter exist in the universe ?
  - No antinuclei (e.g., Antihelium) seen in cosmic rays (relative limit from BESS: $< 10^{-6}$)
  - No significant (diffuse) cosmic γ rays from nucleon-antinucleon annihilation in the boundary between matter & antimatter regions

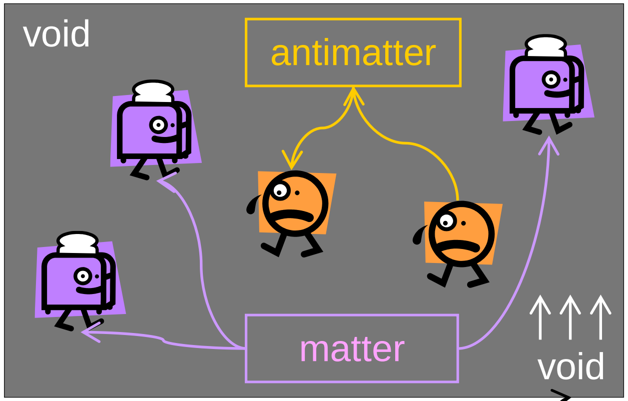
➡ No evidence of antimatter in our domain of the universe (~20 Mpc = 0.6×10^8 light years)

- Could our universe be like inverse Swiss cheese, with distant matter or antimatter regions(*) ?

➡ Difficult within the current limits

- Likely: no antimatter in our universe

  (apart from the antimatter created dynamically in particle collisions)



The *voids* would create anisotropy in CMB spectrum, which is not seen

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(*) “If we accept the view of complete symmetry between positive and negative electric charge so far as concerns the fundamental laws of nature,we must regard it rather as an accident that the Earth (and presumably the whole solar system), contains a preponderance of negative electrons and positive protons. In fact there may be half the stars of each kind. The two kinds of stars would both show exactly the same spectra, and there would be no way of distinguishing them from present astronomical methods." P. A. M. Dirac, Nobel Lecture (1933)

CP violation can give us asymmetry!

- Unfortunately not enough to explain observations …
- But perhaps there are new sources of CP violation waiting to be discovered?
  - High energy?
  - Lepton sector? We'll talk about neutrinos later
  - Quark sector? We'll talk about the CKM matrix next
  - Gauge sector? Or in new exotic particle decays

CP violation and flavor asymmetries in the SM

Parameters of the Standard Model

- 3 gauge couplings
- 2 Higgs parameters
- 6 quark masses
- 3 quark mixing angles + 1 phase
- 3 (+3) lepton masses
- (3 lepton mixing angles + 1 phase)

flavour parameters

Cabibbo–Kobayashi–Maskawa

CKM matrix

PMNS matrix

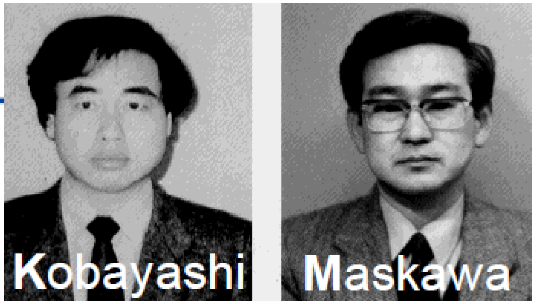
Pontecorvo–Maki–Nakagawa–Sakata

( ) = with Dirac neutrino masses

What breaks the flavour symmetries?

- In the Standard Model, the vacuum expectation value of the Higgs field breaks the electroweak symmetry
- Fermion masses arise from the Yukawa couplings of the quarks and charged leptons to the Higgs field (taking $m_\nu=0$)
- The CKM matrix arises from the relative misalignment of the Yukawa matrices for the up- and down-type quarks
- Consequently, the only flavour-changing interactions are the charged current weak interactions
  - no flavour-changing neutral currents (GIM mechanism)
  - not generically true in most extensions of the SM
  - flavour-changing processes provide sensitive tests

The CKM matrix (1/2)



Brilliant idea from Kobayashi and Maskawa

(Prog. Theor. Phys. 49, 652(1973))

- ☐ Try and extend number of families (based on GIM ideas). e.g. with 3:

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

Imagine a new doublet of quarks

2D rotation matrix

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

3D rotation matrix

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

… as mass and flavour eigenstates need not be the same (→rotated)

- ☐ **This matrix relates the weak states to the mass states**

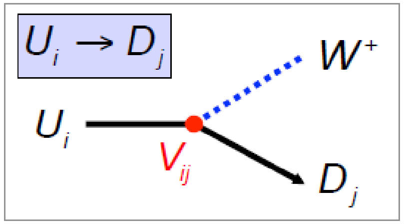
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

The CKM matrix (2/2)

- **Standard Model weak charged current**

Feynman diagram amplitude proportional to $V_{ij} U_i D_j$

  - U (D) are up (down) type quark vectors



$$U = \begin{pmatrix} u \\ c \\ t \end{pmatrix} \qquad D = \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- **V_{ij} is the quark mixing matrix, the CKM matrix**
  - for 3 families this is a 3x3 matrix

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

Can estimate relative probabilities of transitions from factors of $|V_{ij}|^2$

"PDG" parametrization (exact, fully general)

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

$s_{ij} \equiv \sin\Theta_{ij}$, $c_{ij} \equiv \cos\Theta_{ij}$. δ is the CP violating phase.

Numerical values:

$$\begin{pmatrix} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ 0.004 & -0.04 & \sim 1 \end{pmatrix}$$

Notice: very weak coupling of b quarks to lighter flavors
→ "long" lifetime

If the CKM matrix describes all possible states, it should be unitary!

Wolfenstein parametrization

$$V_{CKM} \approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda - iA^2\lambda^5\eta & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\hat{\rho}-i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1 \end{pmatrix}$$

where A~1, λ~0.22 and
V_{ub}^*= Aλ^3($\rho + i\eta$)

Using $\hat{\rho},\hat{\eta}$ rather than ρ,η

adds higher order correction terms

$$\hat{\rho} = \rho\left(1-\frac{\lambda^2}{2}\right), \hat{\eta} = \eta\left(1-\frac{\lambda^2}{2}\right)$$

Note:
smallest couplings are
complex (⇒ *CP*-violation)

Unitarity conditions and triangles

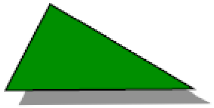
$$\sum_{i=1}^{3} \left|V_{ij}\right|^2 = 1 \ , \ \ j = 1,2,3$$: no phase info.

$$\boxed{\sum_j V_{ij} V^*_{jk} = \delta_{ik}}$$

$$\sum_{i=1}^{3} V_{ij} V^*_{ik} = 0 \ , \ \ j,k = 1,2,3 \ , \ \ j \neq k$$

6 triangles in complex plane

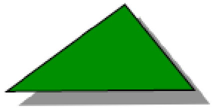
db: $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$



sb: $V_{us}V^*_{ub} + V_{cs}V^*_{cb} + V_{ts}V^*_{tb} = 0$

ds: $V_{ud}V^*_{us} + V_{cd}V^*_{cs} + V_{td}V^*_{ts} = 0$

ut: $V_{ud}V^*_{td} + V_{us}V^*_{ts} + V_{ub}V^*_{tb} = 0$



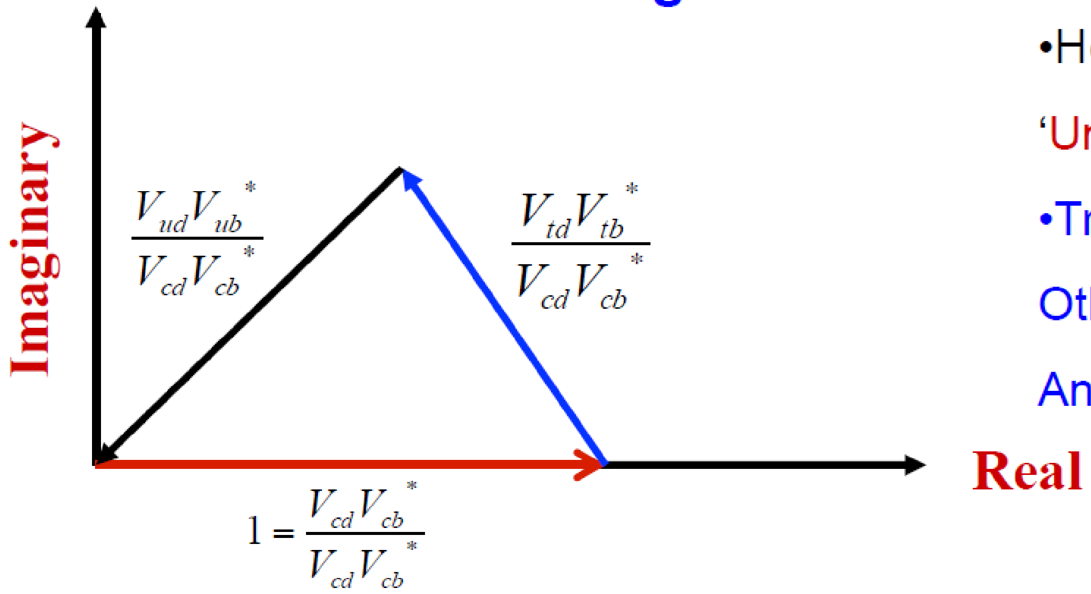
ct: $V_{cd}V^*_{td} + V_{cs}V^*_{ts} + V_{cb}V^*_{tb} = 0$

uc: $V_{ud}V^*_{cd} + V_{us}V^*_{cs} + V_{ub}V^*_{cb} = 0$

CKM – Unitarity Triangle

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

- **Three complex numbers, which sum to zero**
- **Divide by $V_{cd}V_{cb}^*$ so that the middle element is 1 (and real)**
- **Plot as vectors**
- **If all numbers real – triangle has no area – No CP violation**



- Hence, get a triangle

'Unitarity' or 'CKM triangle'

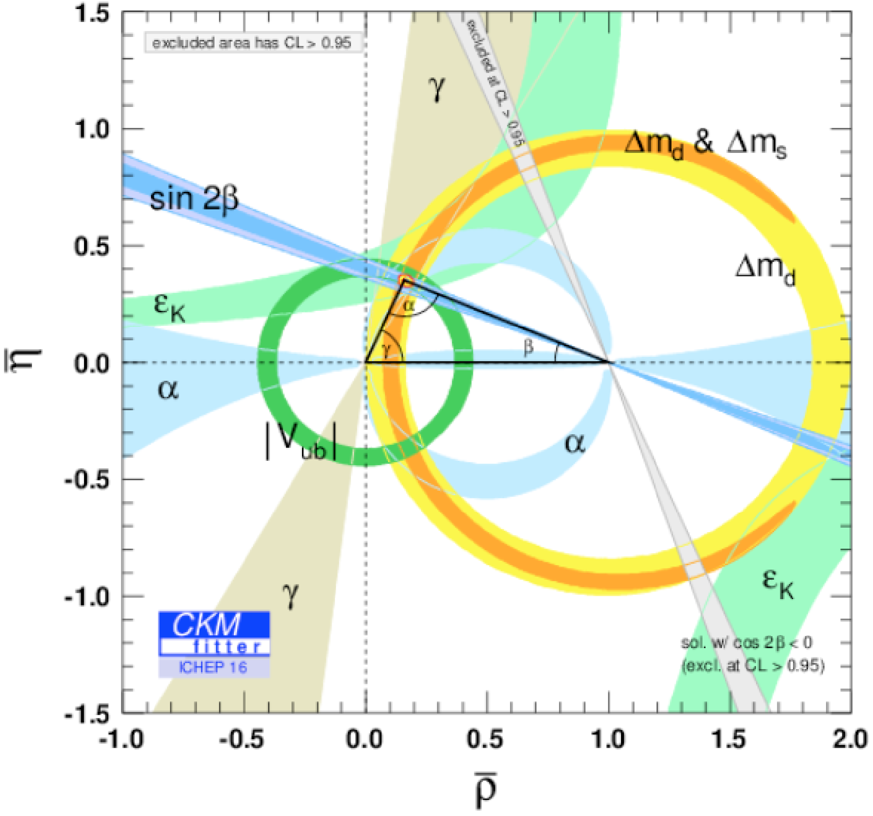
- Triangle if SM is correct.

Otherwise triangle will not close,

Angles won't add to 180°

CKM Triangle - Experiment

- **Find particle decays that are sensitive to measuring the angles (phase difference) and sides (probabilities) of the triangles**



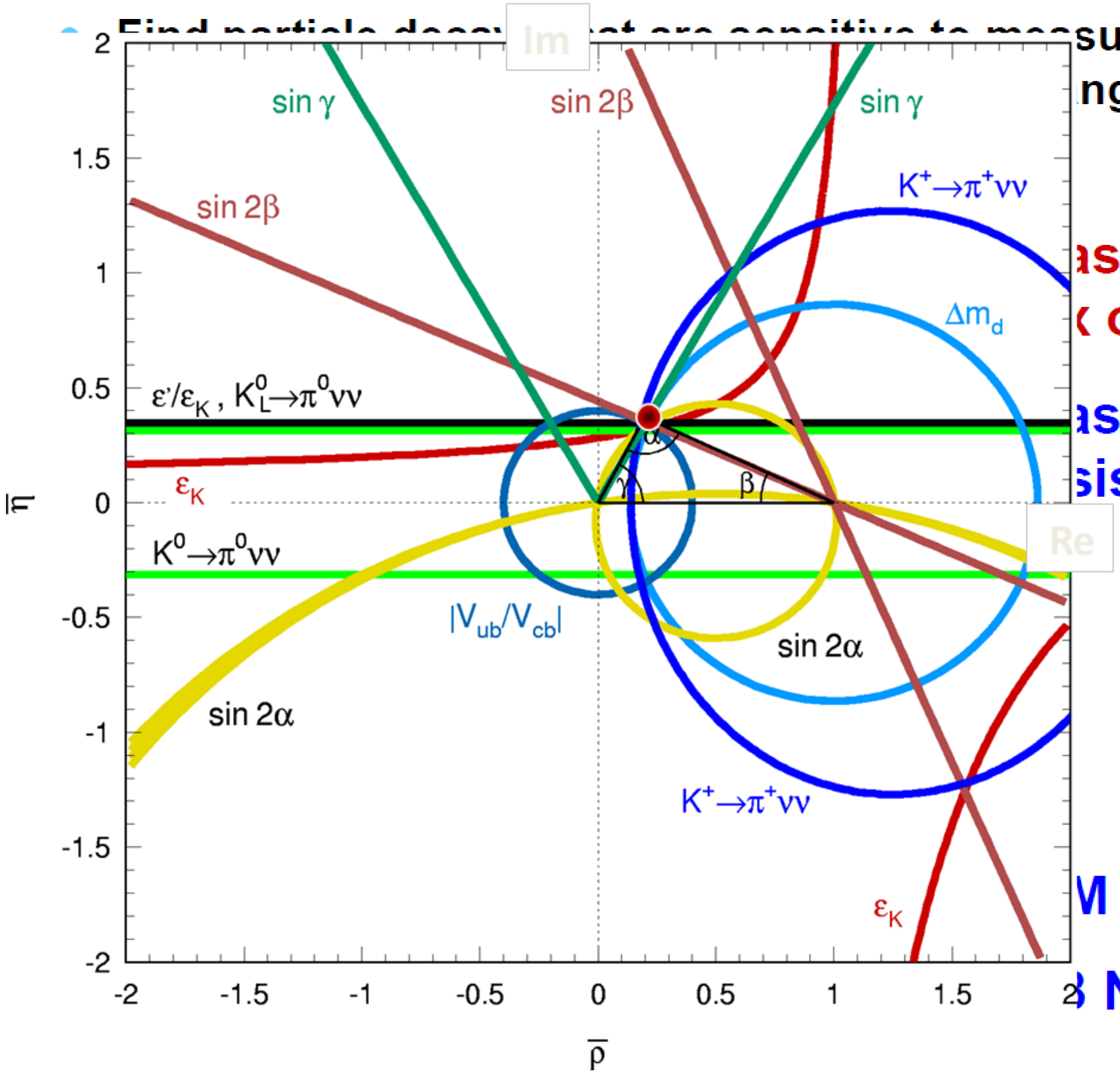
•Measurements constrain the apex of the triangle

•Measurements are consistent

•CKM model works,

2008 Nobel prize

CKM Triangle - Experiment



- Find particle decay at are sensitive to measuring the angles (phase ngles

asurements constrain the of the triangle

asurements are sistent

M model works,

Nobel prize

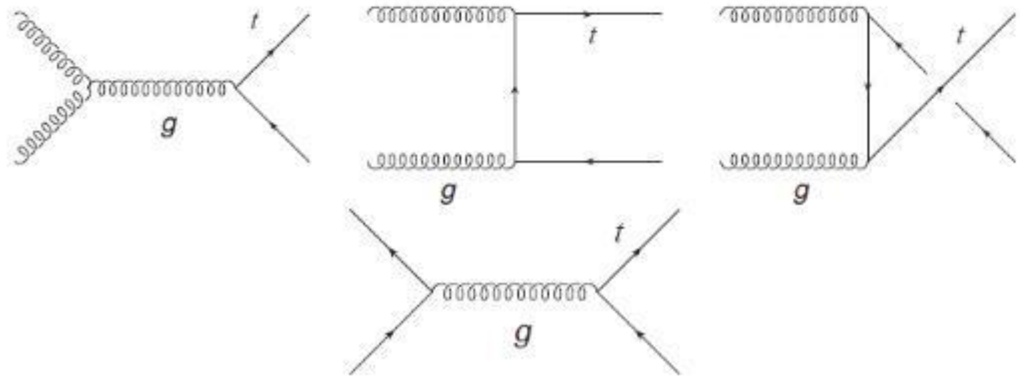
Summary

- The study of CP violation is a fundamental part of particle physics and cosmology!
- It might explain the matter / anti-matter asymmetry
- We don’t fully understand it – we probably need BSM physics and new particles
- Flavor physics and CP violation seem to be closely connected
- Precision measurements from a plethora of experiments to constrain the CKM triangle
- LHCb has some nice new results on new sources of CP violation – to be discussed during LHC physics lectures

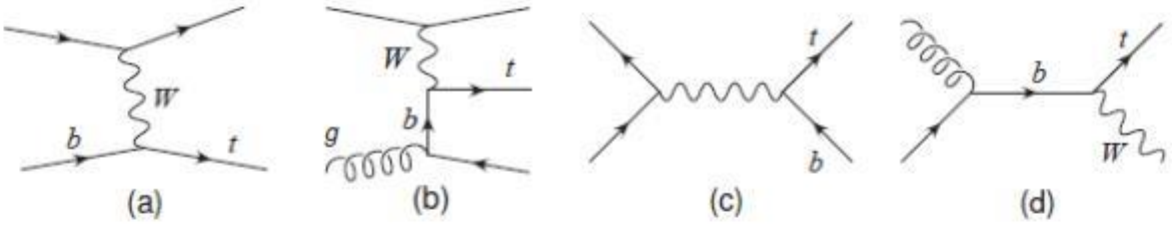
Top quarks

Only seen in hadron collisions so far

Pair production: qq and gg fusion

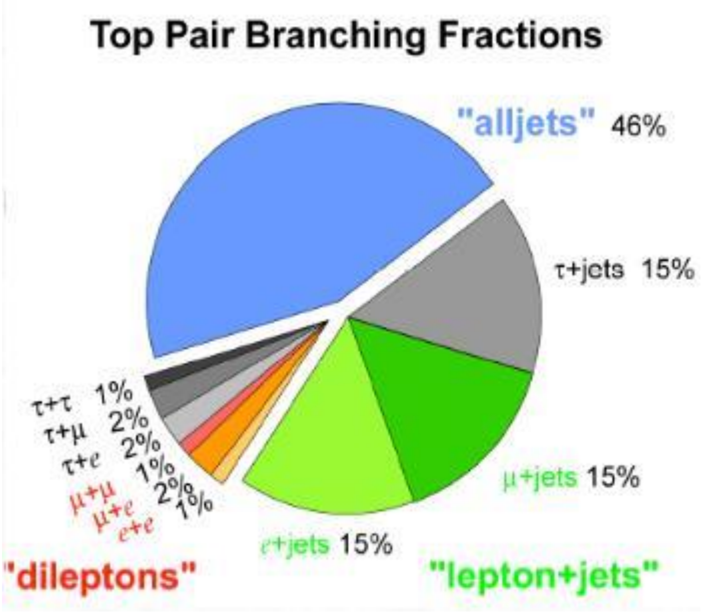


Single production: Drell-Yan and Wg fusion

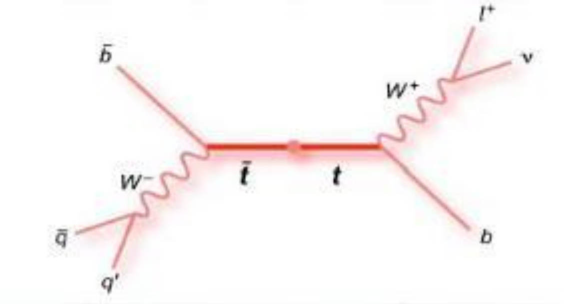


(a) (b) (c) (d)

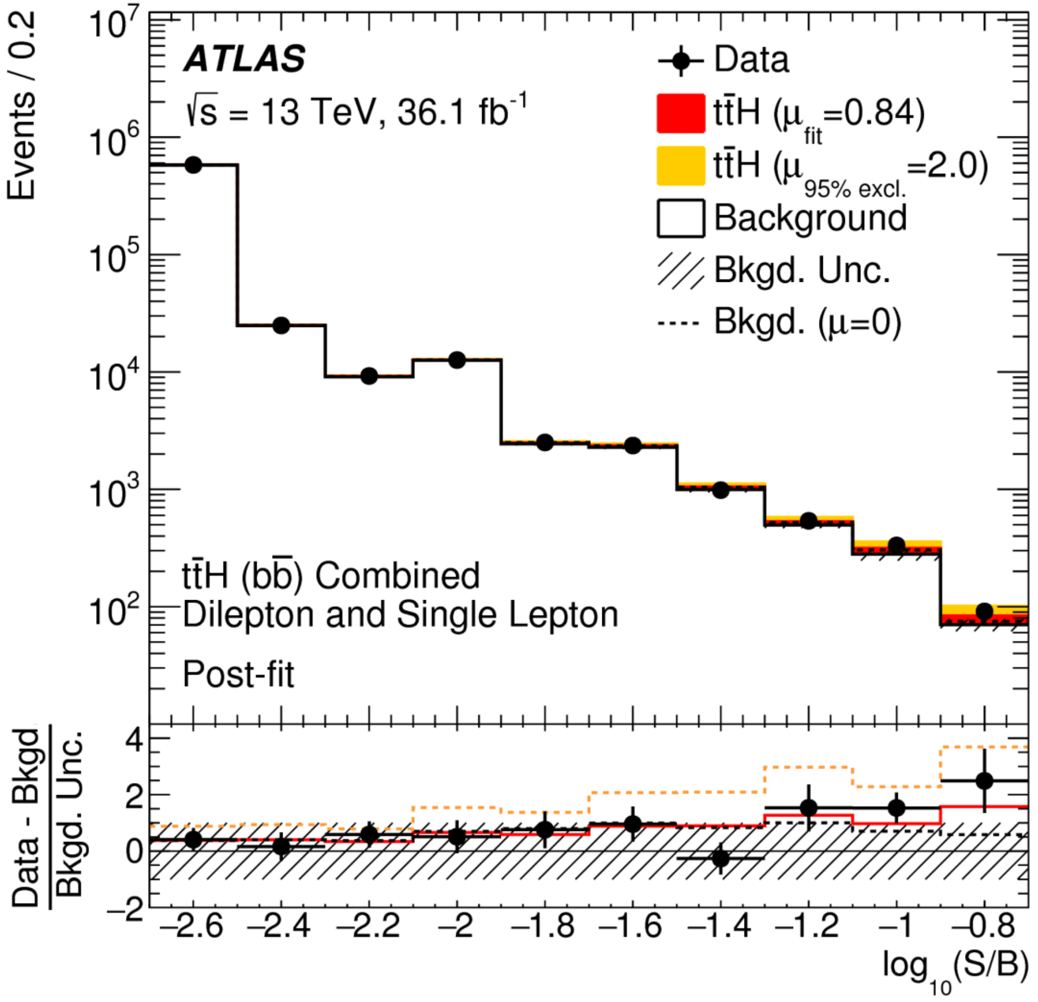
Top quark decays



Top Pair Branching Fractions



Top quark properties

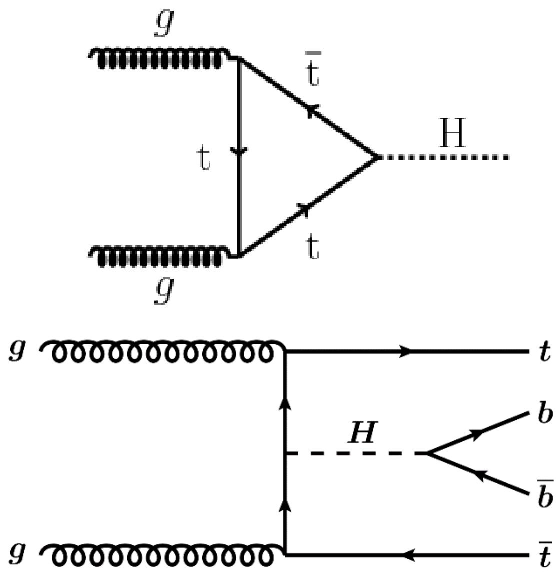


The LHC is a top factory:

Precision measurements of the mass and other properties

M_{top} = 173.34 ± 0.36 ± 0.67 GeV

Investigating the $Ht\bar{t}$ vertex:



Unitarity relations

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

multiply with its conjugate transpose

$VV^{\dagger} = V^{\dagger}V = 1$

$\Sigma_i V_{ij} V^*_{ik} = \delta_{jk}$ column orthogonality

$\Sigma_j V_{ij} V^*_{kj} = \delta_{ik}$ row orthogonality

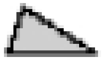
Unitarity relations

column orthogonality

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

Areas have to be the same
→ Jarlskog parameter

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

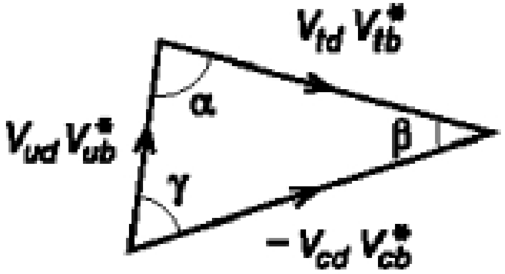


$$V_{ud}V_{ub}^{*}+V_{cd}V_{cb}^{*}+V_{td}V_{tb}^{*}\simeq\mathcal{O}(\lambda^{3})+\mathcal{O}(\lambda^{3})+\mathcal{O}(\lambda^{3})=0$$

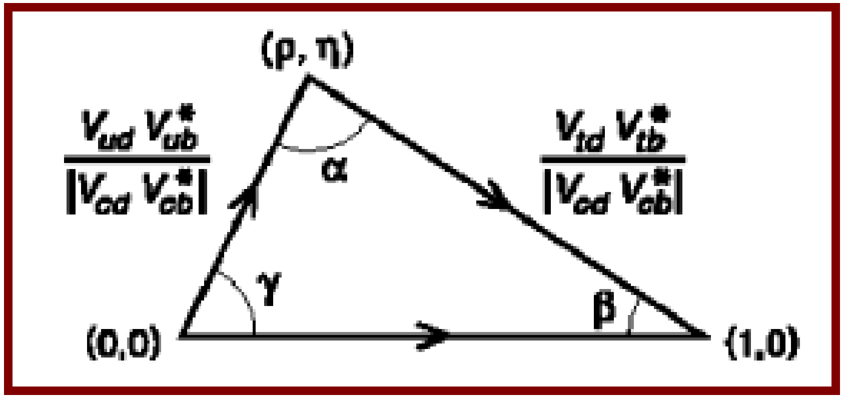
Third unitarity relation

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

$V_{id}V^*_{ib} = 0$ represents the orthogonality condition between the first and the third column of the CKM matrix (the orientation depends on the phase convention)



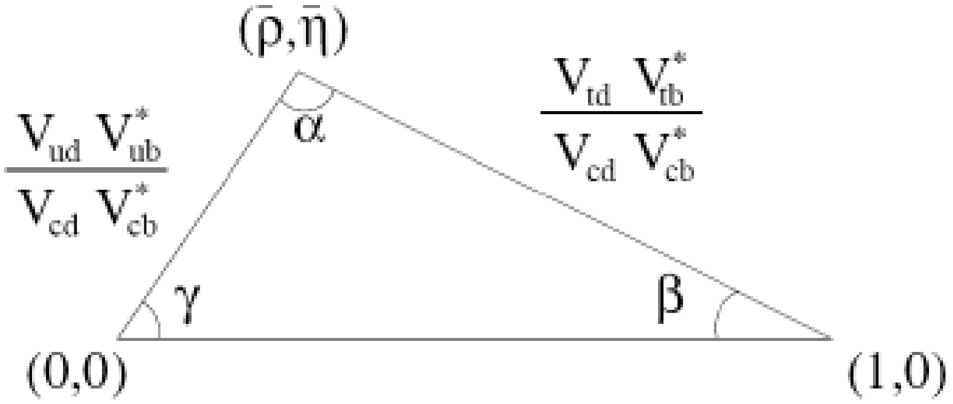
re-scaled version where sides have been divided by $|V_{cd}V^*_{cb}|$



In terms of the Wolfenstein parameterization, the coordinates of this triangle are (0, 0), (1, 0) and (ρ, η):
the two sides are ($\rho - i\eta$) and ($1 - \rho + i\eta$).

Probing the structure of the CKM mechanism

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



The angles can be written in terms of CKM matrix elements as:

$$\alpha \equiv \arg[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}]$$

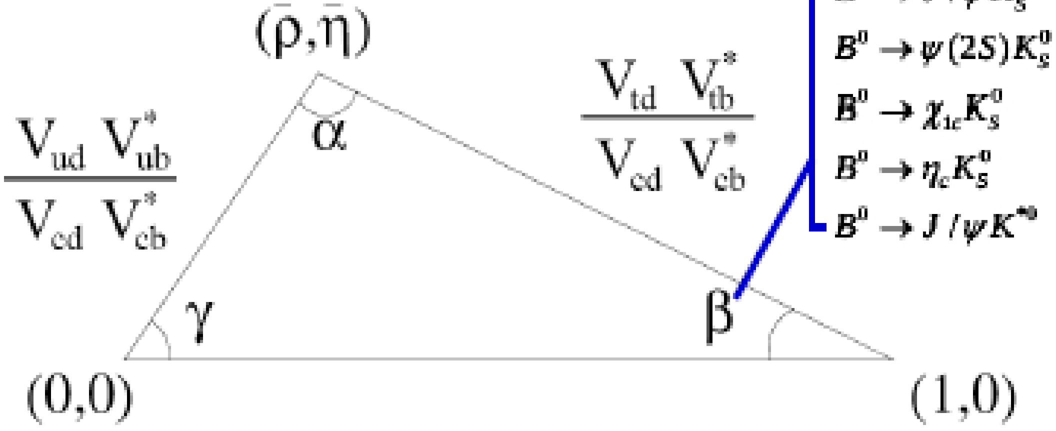
$$\beta \equiv \arg[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}]$$

$$\gamma \equiv \arg[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}]$$

- We need to measure the angles and sides to over-constrain this triangle, and test that it closes.
- Need experiments to measure these quantities

Constraining the angles

Theoretically clean (SM uncertainties ~10^{-2} to 10^{-3}) tree dominated decays to Charmonium + K^0 final states.



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

$B^0 \to J/\psi K_L^0$

$B^0 \to J/\psi K_S^0$

$B^0 \to \psi(2S) K_S^0$

$B^0 \to \chi_{1c} K_S^0$

$B^0 \to \eta_c K_S^0$

$B^0 \to J/\psi K^{*0}$

$B \to J/\psi \pi^0$

$B \to D^{(*)+} D^{(*)-}$

$B \to \eta' K^0$

$B \to \rho K^0$

$B \to \omega K^0$

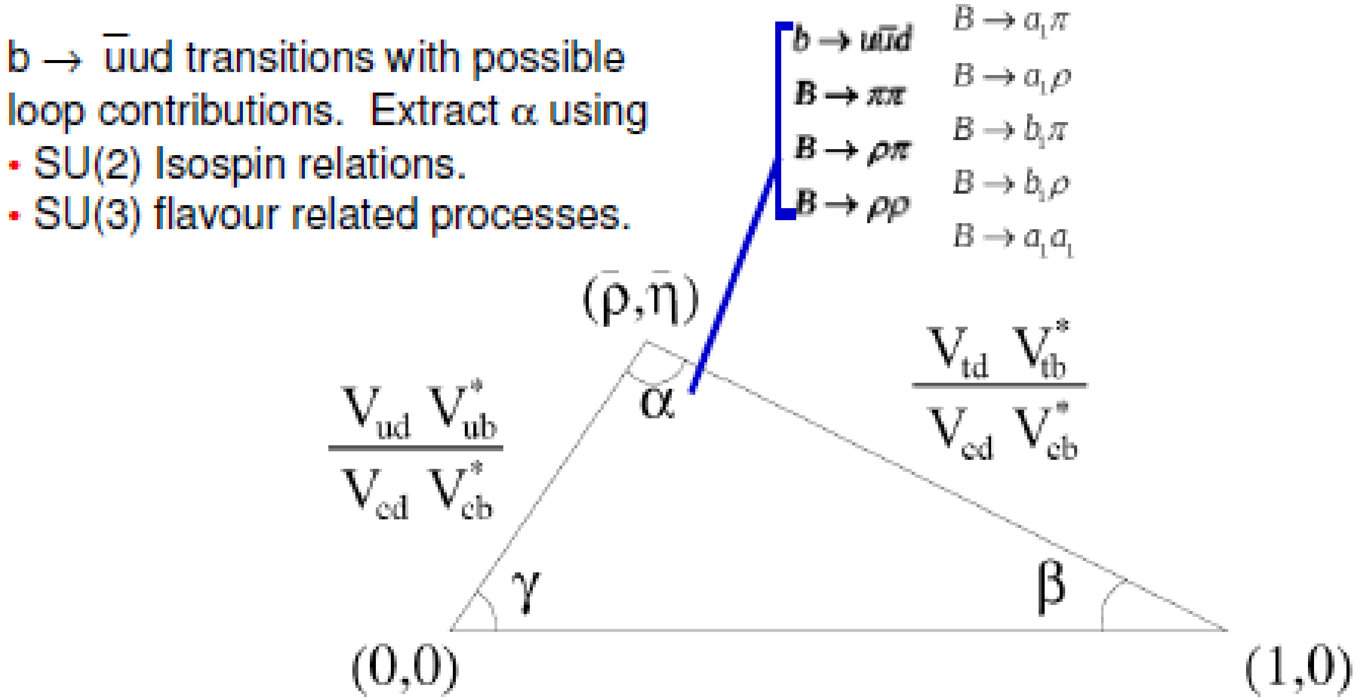
$B \to \pi^0 K^0$

$B \to \phi K^{(*)0}$

$B \to KKK^0$

$B \to f^0(980) K^0$

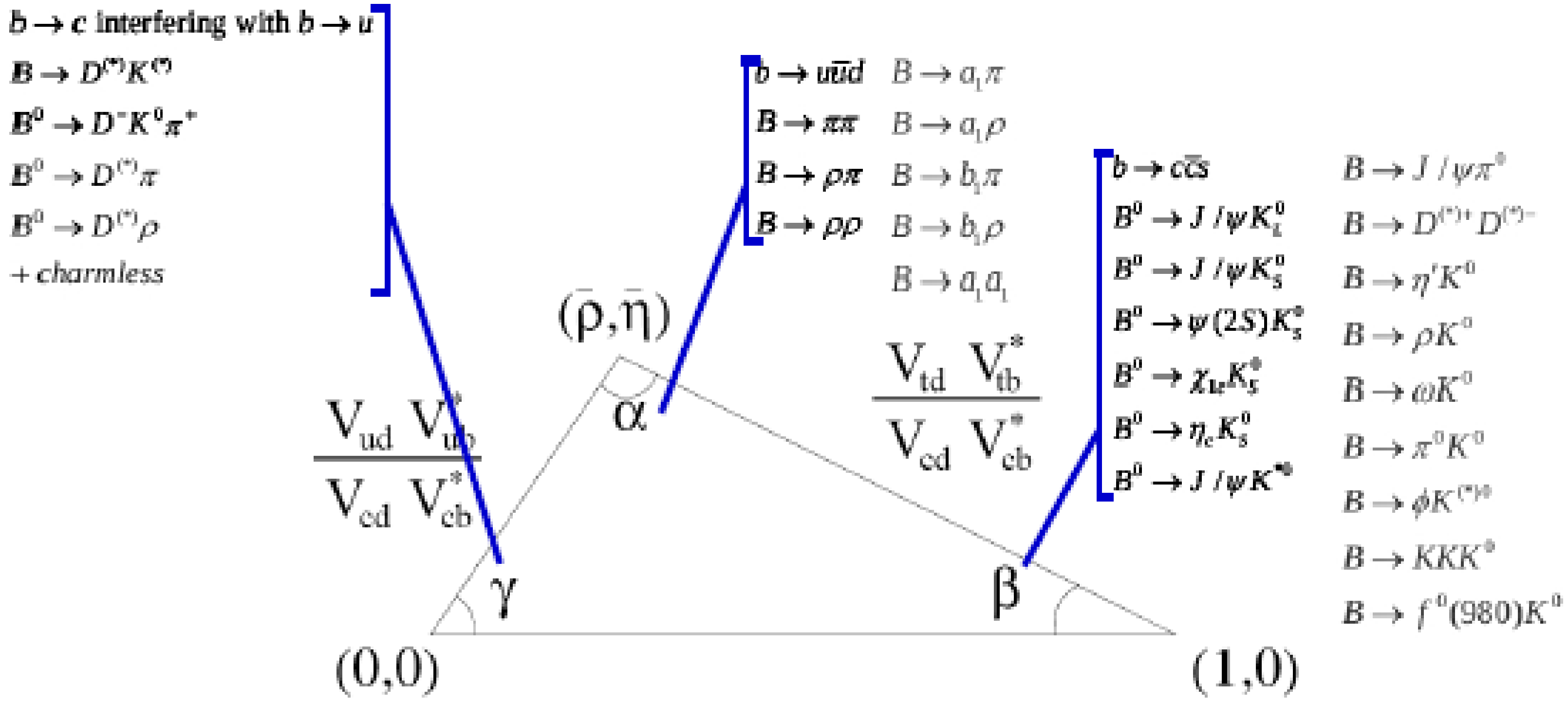
Constraining the angles



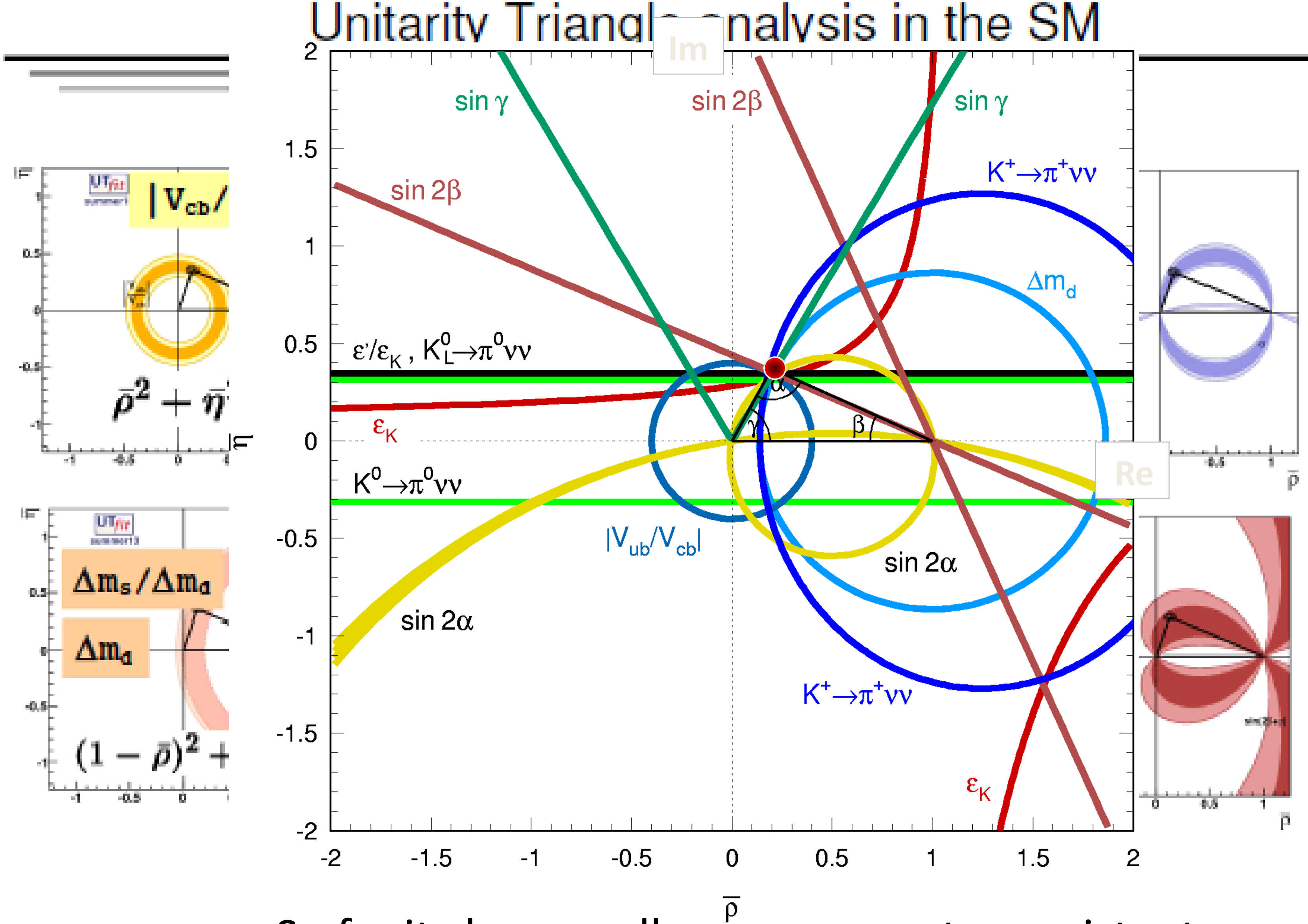
b → $\bar{u}$ud transitions with possible loop contributions. Extract α using

- SU(2) Isospin relations.
- SU(3) flavour related processes.

Constraining the angles



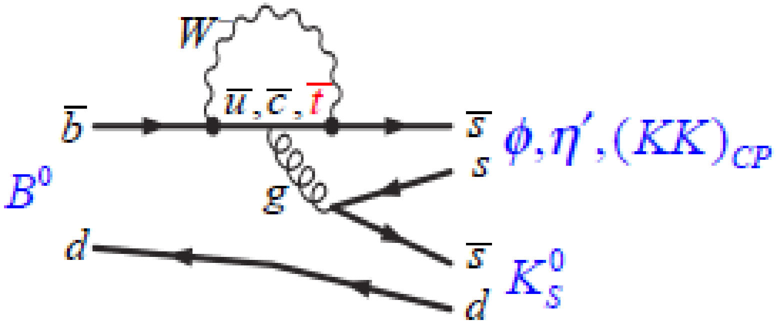
Unitarity Triangl nalysis in the SM



So far it closes – all measurements consistent

CP violation: Searching for new physics

- sin2β has been measured to O(1°) accuracy in $b \to \bar{c}cs$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to sin2β (loop dominated process).
  - Measure S precisely in that mode (S_{eff}).
  - Control the theoretical uncertainty on the Standard Model 'pollution' (ΔS_{SM}).
  - Compute $\Delta S_{\rm NP} = S_{eff} - S_{c\bar{c}s} - \Delta S_{\rm SM}$
- In the presence of NP: $\Delta S_{NP} \neq 0$



- Many tests have been performed in:
  - B→d processes.
  - B→s processes.

► Unknown heavy particles can introduce new amplitudes that can affect physical observables of loop dominated processes.

► Observables that might be affected include branching fractions, CP asymmetries, forward backward asymmetries … and so on.

► A successful search requires that we understand Standard Model contributions well!