Swiss Institute of Particle Physics

PhD Winter School 2013
Grindelwald, Switzerland
January 21-25, 2013

Flavour Physics

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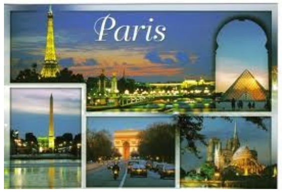
Your Lecturer

- **born in Bremen, Germany**

- **studied physics in Bonn**
- **PhD work at CERN**
  - on a small experiment you will never have heard of
- **1st PostDoc at Saclay**
  - working on the construction of the NA48 detector
  - observation of direct CP violation in neutral kaon decays



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  - (failed) attempt to search for CP violation in the $B^0\bar{B}^0$ system

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  - working on the LHCb experiment
  - indirect search for "New Physics" (= physics beyond the Standard Model) via precision measurements of CP violation and rare heavy quark decays

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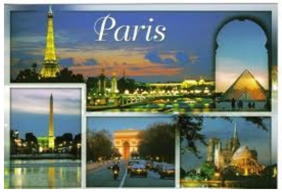

Outline

- **Part I: Introduction**
  - what is (quark) flavour physics and why is it so exciting?
  - how we got here: brief history of flavour physics in the 20th century

- **Part II: Particle-Antiparticle Mixing**
  - a short summary of the formalism (don't worry, I'm an experimentalist …)
  - introduce experimental facilities and techniques

- **Part III: Precision tests of the Standard Model**
  - CP violating observables: sin 2β, CKM angle γ, $B^0_s\overline{B}^0_s$ mixing phase ϕ_s
  - rare decays: search for $B^0_{(s)} \rightarrow \mu^+ \mu^-$, angular observables in $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

[selected topics, no attempt at giving a comprehensive overview of the field !]

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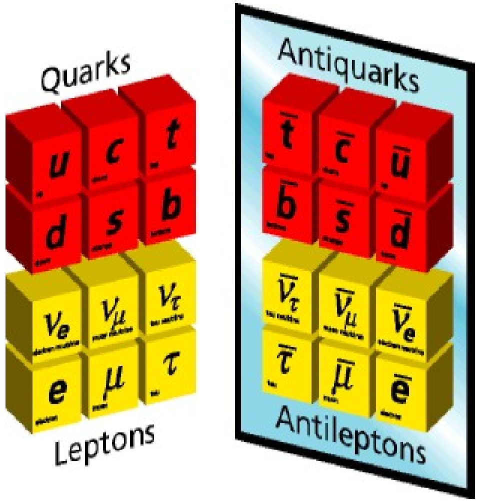
Flavour Physics

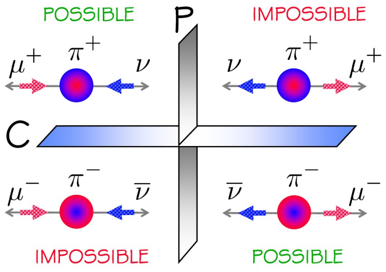
- **study properties of the three lepton families and their interactions**
  - masses, lifetimes, spins, …
  - couplings, amplitudes, phases, …



- **it's all about the weak interaction**
  - flavour conserved in strong and electromagnetic interactions
- **three distinct sectors** (theoretical questions and experimental approaches)
  - **quarks:** measure mixing parameters, test Standard Model predictions
  - **charged leptons:** test lepton number conservation
  - **neutrinos:** measure oscillation parameters, masses, Dirac ↔ Majorana ?

this course

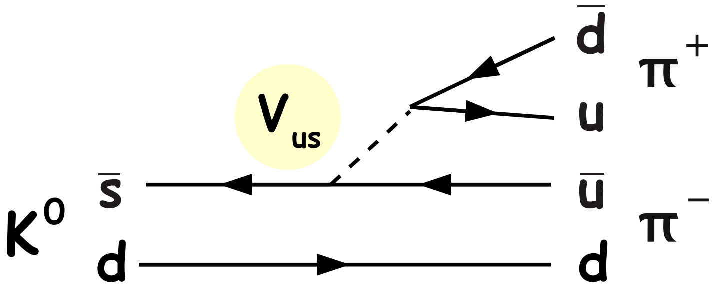
- **guiding principle: symmetries and their violation**
  - Parity (P), Charge Conjugation (C), Time reversal (T), combined CP symmetry, all violated in weak interactions



CKM Matrix

Observe mixing between quark families in charged-current interactions

- e.g. kaons and B mesons would otherwise be stable particles



- described by quark mixing matrix V_{ij} (Cabibbo-Kobayashi-Maskawa = CKM) in the charged current Lagrangian

$$-L_{CC} = \frac{g}{\sqrt{2}} \bar{u}_i \gamma^\mu (1-\gamma_5) \boxed{V_{ij}} d_j W^+_\mu + h.c.$$

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

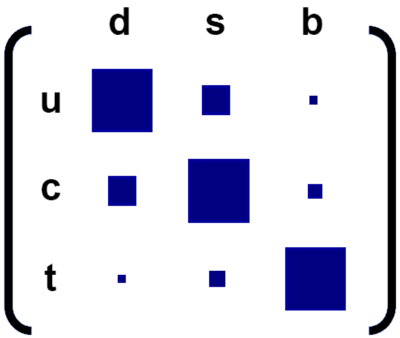
- studying the parameters of the CKM matrix is one of the main goals of quark flavour physics
- 3 quark families: 4 free parameters = 3 rotation angles + complex phase
- this complex phase is the only source of CP violation in the Standard Model

Wolfenstein Parametrization

Values of the CKM matrix elements not predicted by theory

- measured magnitudes show clear hierarchy (PDG 2012)

$$V_{CKM} = \begin{pmatrix} 0.97425 \pm 0.00022 & 0.2252 \pm 0.0009 & 0.00389 \pm 0.00044 \\ 0.2230 \pm 0.0011 & 1.023 \pm 0.036 & 0.0406 \pm 0.0013 \\ 0.0084 \pm 0.0006 & 0.0387 \pm 0.0021 & 0.88 \pm 0.07 \end{pmatrix}$$



- is there some deeper meaning hidden in this?

This hierarchy reflected in Wolfenstein parametrisation

- expand all CKM elements in terms of $\lambda = \sin\theta_C \approx 0.23$
- approximate to order λ^3
- assign the complex phase to the smallest elements, V_{td} and V_{ub}

$$V_{CKM} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\cdot\lambda^3 \boxed{(\rho - i\eta)} \\ -\lambda & 1-\lambda^2/2 & A\cdot\lambda^2 \\ A\cdot\lambda^3 \boxed{(1-\rho-i\eta)} & -A\cdot\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Unitarity Triangles

Unitarity of CKM matrix → 6 orthogonality relations

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0 \quad (\lambda , \lambda , \lambda^5)$$

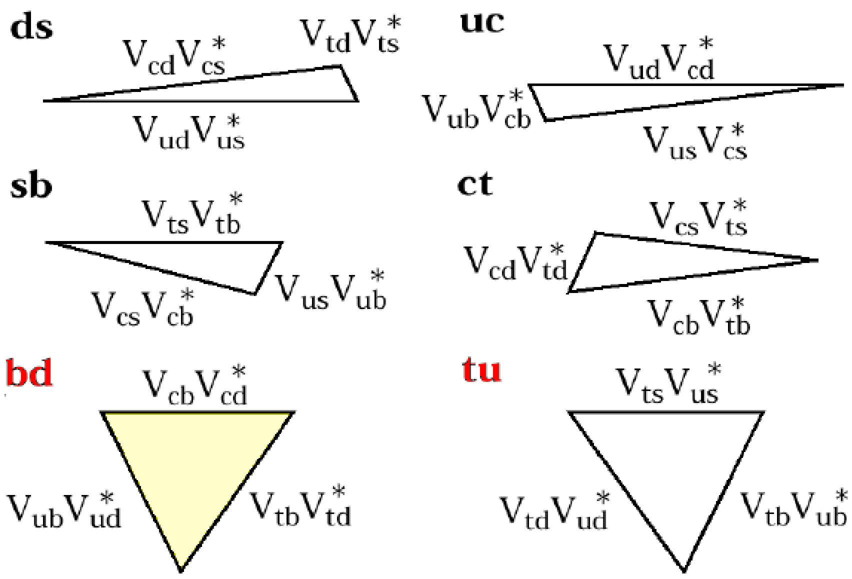
$$\boxed{V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)}$$

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

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

$$\boxed{V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)}$$

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

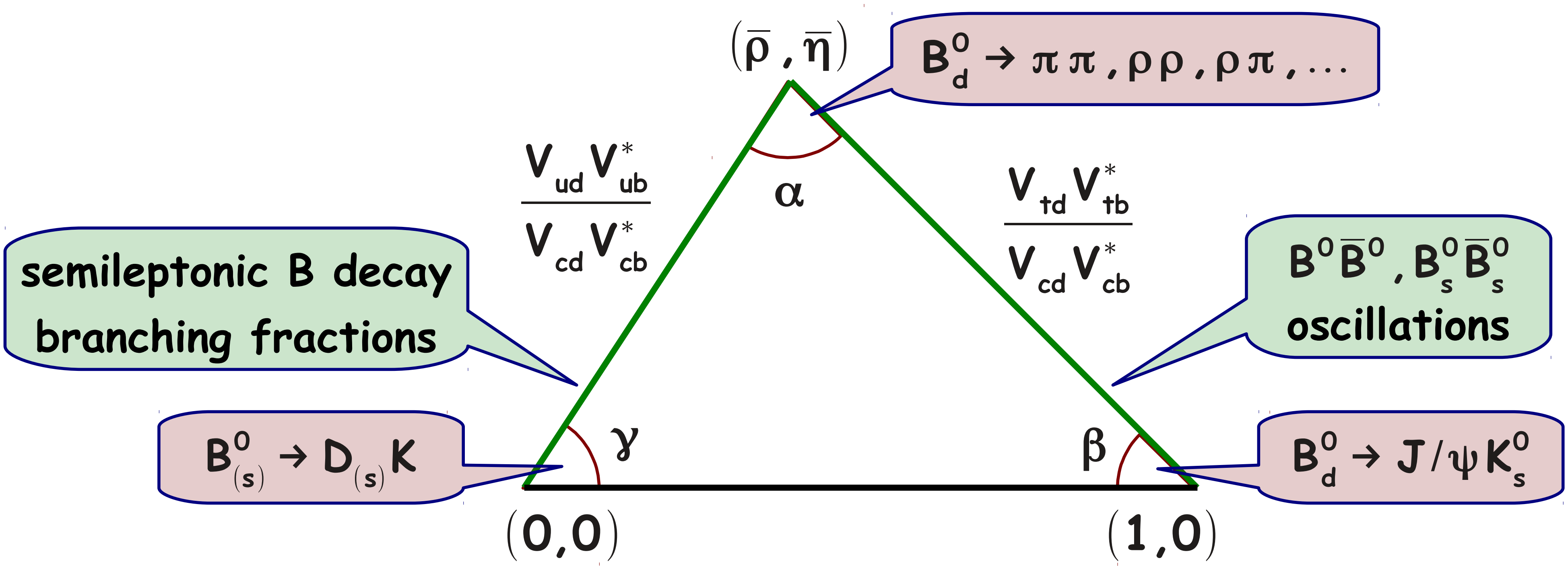


- **can be visualized as triangles in the complex plane**
  - all six triangles have the same surface area ∝ CP violation
  - but four of them are “squashed”
- **the two non-squashed triangles are identical in Wolfenstein approximation**
  - differences appear at higher orders of λ → become relevant at LHCb

angles and sides of these triangles are related to measurable quantities

“The” Unitarity Triangle

Use $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ and normalize to $V_{cd}V_{cb}^*$



$B_d^0 \to \pi\pi, \rho\rho, \rho\pi, \ldots$

semileptonic B decay branching fractions

$B^0\bar{B}^0, B_s^0\bar{B}_s^0$ oscillations

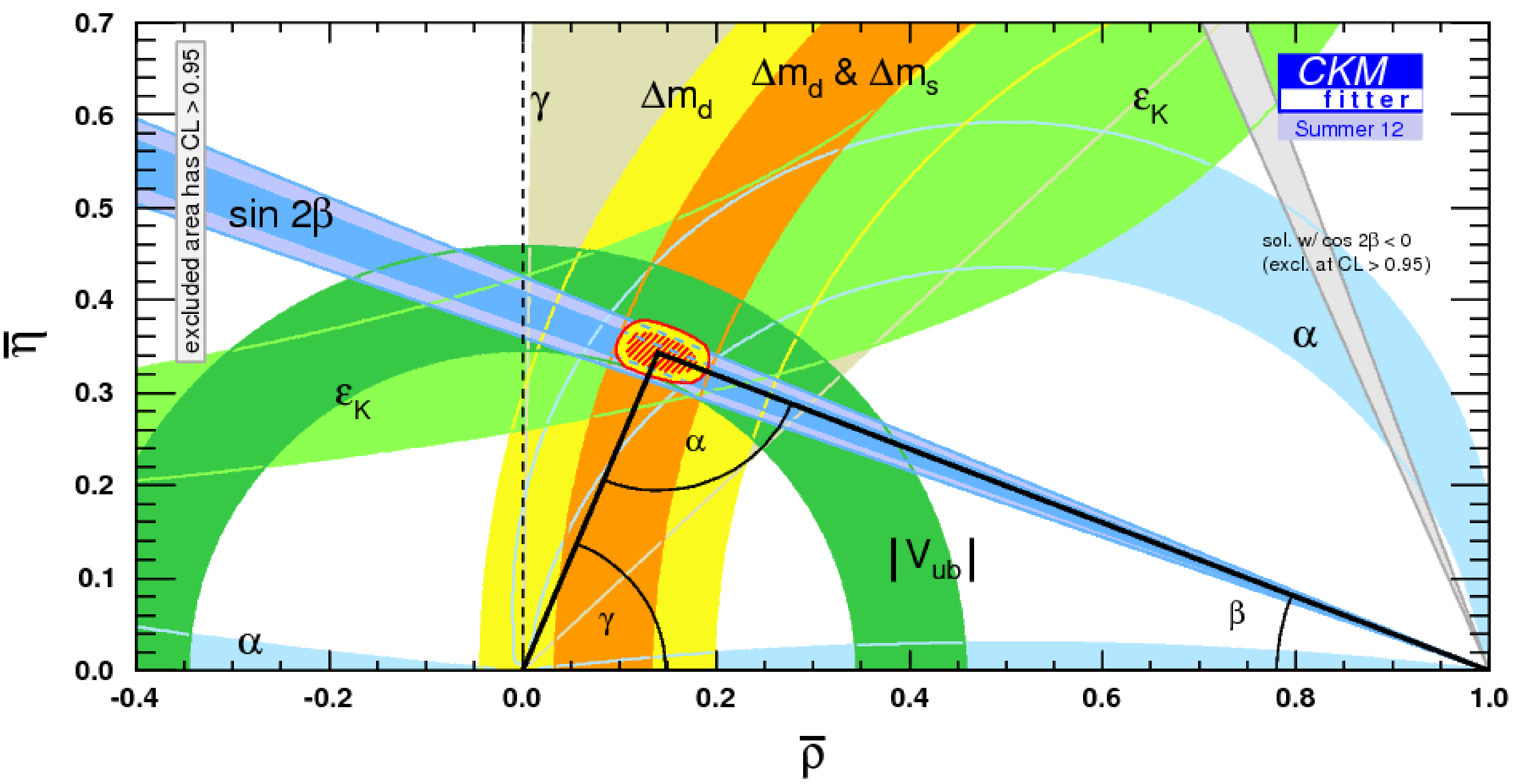
$B_{(s)}^0 \to D_{(s)}K$

$B_d^0 \to J/\psi K_s^0$

- measure the lengths of the two sides: CP conserving quantities
- measure all three angles: CP violating quantities (angles = phases !)
- many observables → overconstraint determination of triangle

consistency check of Standard Model !

“The” Unitarity Triangle 2012



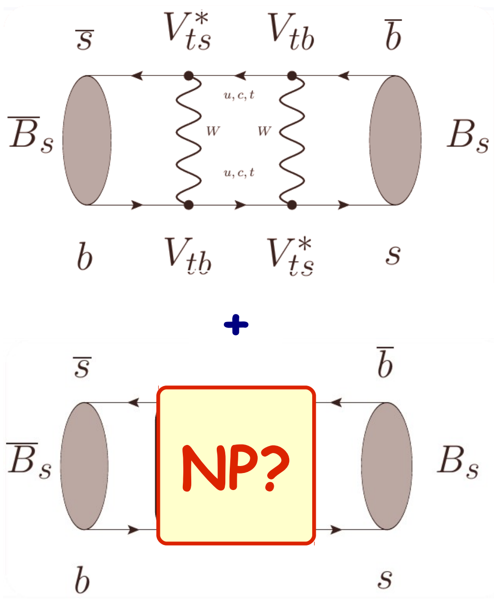
- so far a huge success story for the Standard Model
- current measurement precision permits ~20% contribution from New Physics

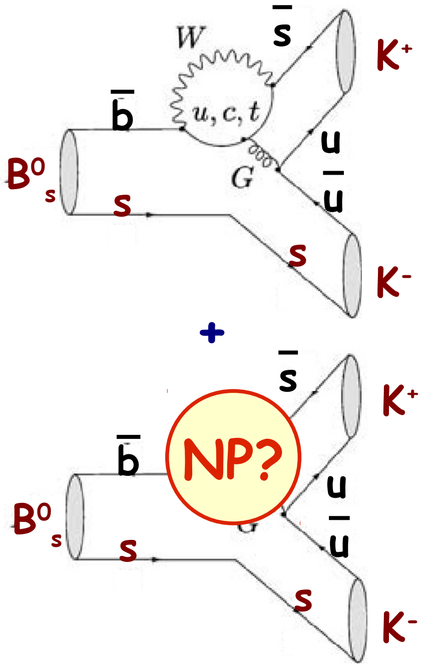
need more precise measurements: this is the goal of LHCb !

Loops !

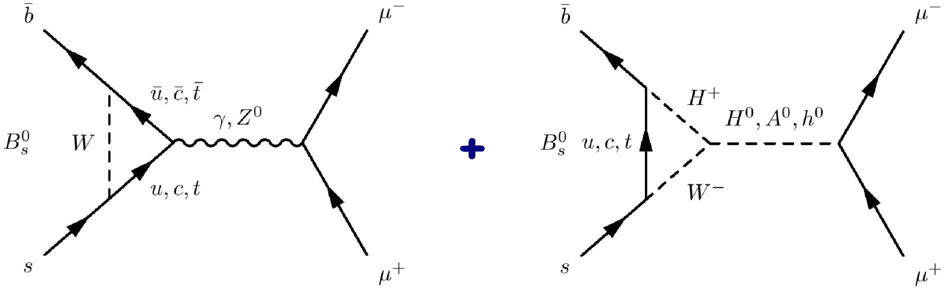
Why do we expect New Physics to show up in these observables?

- many processes involve loop diagrams:
  - box diagrams (mixing)
  - Penguin diagrams (decays)





- New Physics models usually predict new, heavy particles (e.g. SUSY)
- these particles can appear in the loops and affect magnitudes and phases
- searches are sensitive to the appearance of <u>virtual</u> particles in loops
  - test much higher mass scales than direct searches for new particles (limited by center-of-mass energy)
- another promising hunting ground: rare heavy quark decays



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Isospin

Observe similar behaviour of proton/neutron and of $\pi^+/\pi^0/\pi^-$

- different charge but similar masses, same couplings in nuclear interactions

Heisenberg (1932): Isospin multiplets

- p/n form an Isospin doublet

$$p \; : \; (I, I_z) = (1/2, +1/2)$$
$$n \; : \; (I, I_z) = (1/2, -1/2)$$

- $\pi^+/\pi^0/\pi^-$ form an Isospin triplet

$$\pi^+ \; : \; (I, I_z) = (1, +1)$$
$$\pi^0 \; : \; (I, I_z) = (1, \; 0)$$
$$\pi^- \; : \; (I, I_z) = (1, -1)$$

- Hamiltonian of strong interaction is invariant under global SU(2) rotation in Isospin space → strong interaction identical for the members of a multiplet

In today's language: $I_z = +1/2 \rightarrow$ u quark, $I_z = -1/2 \rightarrow$ d quark

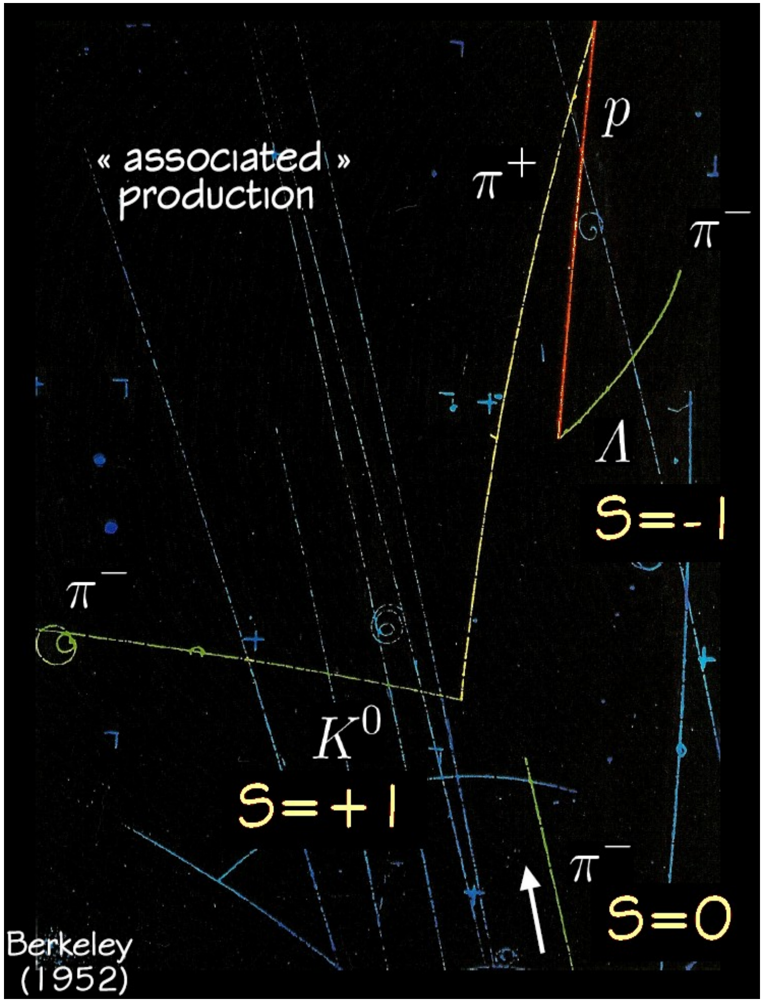
$$p = (uud) \, , \;\; n = (udd) \qquad \pi^+ = (u\bar{d}) \, , \;\; \pi^0 = 1/\sqrt{2}\,(u\bar{u} + d\bar{d}) \, , \;\; \pi^- = (\bar{u}d)$$

- Isospin is not an exact symmetry but rather successful as a concept
  - works so well because $m_u \sim m_d$ and $m_u, m_d \ll \Lambda_{QCD} \approx 200$ MeV

Strangeness

Observe "strangely behaved" particles

- large production cross sections
  - typical for strong interaction
- but long lifetimes of order 10^{-10}s
  - typical for weak decays
- always produced in pairs: "associated production"



Pais (1947): "strangeness" quantum number

- conserved in strong interactions (production)
- not conserved in weak interactions (decay)

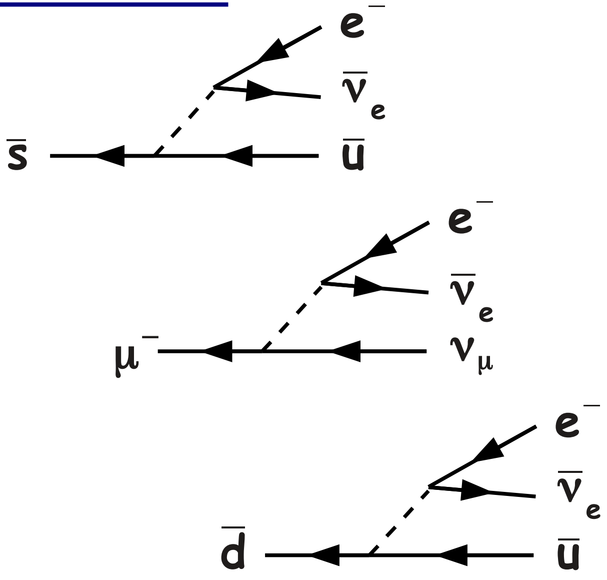
In today's language: strangeness → s quark

- associated production: creation of an $s\bar{s}$-pair in strong interaction

Cabibbo Angle

Observe different coupling strengths of weak interaction

- weak coupling constant should be universal if weak interactions are a fundamental force, but:
  - coupling in decays of strange particles seems about a factor 20 smaller than in muon decay
  - coupling in neutron decay about 4% smaller than in muon decay



Cabibbo (1963): weak interaction couples to a linear combination

[PRL 10 (1963) 531]

$$d' = \cos\theta_c \cdot d + \sin\theta_c \cdot s \quad \text{with} \quad \lambda = \sin\theta_c \approx 0.22$$

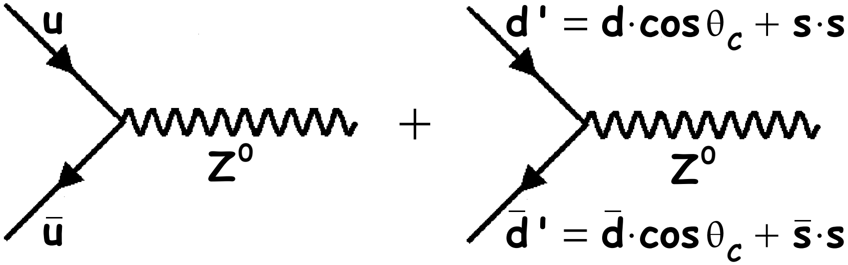
- coupling strengths in hadronic decays are then (using today's language)

$$\frac{d \to u\,W^-}{\mu^- \to \nu_\mu W^-} = \cos^2\theta_c \approx 0.96 \qquad \frac{s \to u\,W^-}{d \to u\,W^-} = \frac{\sin^2\theta_c}{\cos^2\theta_c} \approx \frac{1}{20}$$

GIM Mechanism

Observe strong suppression of Flavour-Changing Neutral Currents

- for example: BF $(K^+ \to \mu^+ \nu_\mu) \approx 63.5\%$ but BF $(K^0_L \to \mu^+ \mu^-) \approx 7 \times 10^{-9}$
- but would expect sizeable amplitude if weak interaction couples to u and d'



$$d' = d \cdot \cos\theta_C + s \cdot \sin\theta_C$$

$$\bar{d}' = \bar{d} \cdot \cos\theta_C + \bar{s} \cdot \sin\theta_C$$

$$\Rightarrow \quad u\bar{u} + d\bar{d}\cos^2\theta_C + s\bar{s}\sin^2\theta_C \quad \ldots + (d\bar{s} + \bar{d}s)\cos\theta_C \sin\theta_C$$

Glashow, Ilioupolis, Maiani (1970): quark doublets

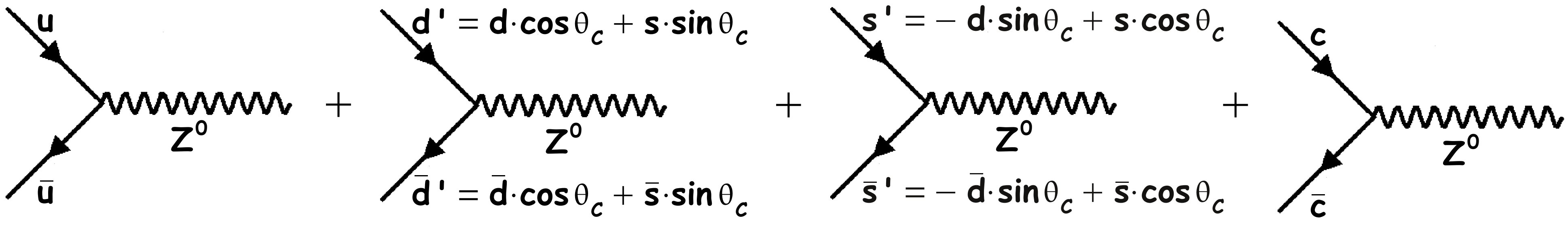
`[PRD 2 (1970) 1285]`

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \cdot \begin{pmatrix} d \\ s \end{pmatrix}$$

- leads to cancellation of FCNC amplitudes at tree level (→ next slide)
- requires an additional, not yet observed quark (c quark discovered in 1974)

GIM Mechanism

Quark doublets → suppression of FCNC at tree level



$$u\bar{u} \;+\; c\bar{c} \;+\; (d\bar{d} + s\bar{s}) \cdot \cos^2\theta_c \;+\; (d\bar{d} + s\bar{s}) \cdot \sin^2\theta_c$$

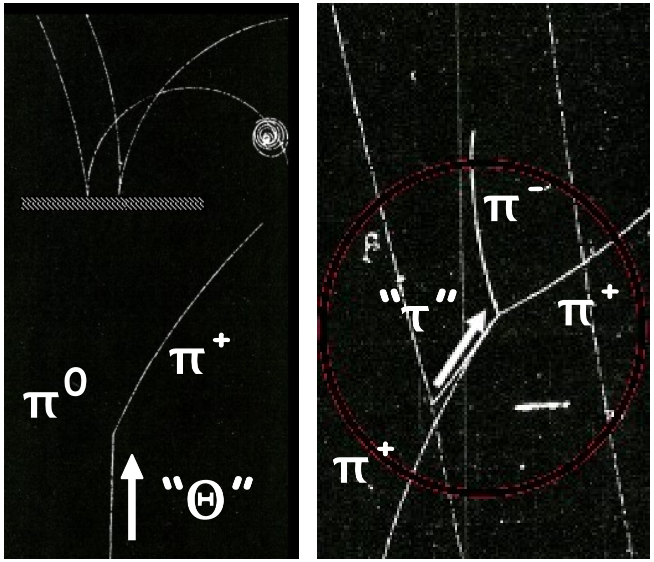
$$\ldots \;+\; (d\bar{s} + \bar{d}s) \cdot \cos\theta_c \sin\theta_c \;-\; (d\bar{s} + \bar{d}s) \cdot \sin\theta_c \cos\theta_c \;=\; u\bar{u} + c\bar{c} + d\bar{d} + s\bar{s}$$

- **cancellation only exact if all quark masses are the same**
  - valid to very good approximation, because quark masses « Z^0 mass
- **FCNC can proceed through 2nd order processes (e.g. double W-exchange)**
  - but strongly suppressed because of smallness of weak coupling constant

Parity Violation

"Θ/τ-puzzle": observe two charged, strange, spin-0 mesons

- same mass (~ 500 MeV) and same lifetime, but:
- one ("Θ") decays into $\pi^+\pi^0$ (even parity)
- the other ("τ") decays into $\pi^+\pi^+\pi^-$ (odd parity)



Yang,Lee (1956): V-A theory of weak interactions

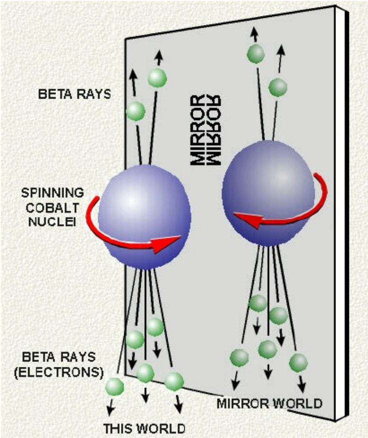
[PR 104 (1956) 254]

- parity is not conserved in weak interactions
- "Θ" and "τ" are in fact the same particle (K^+)

Wu et al. (1957): experimental proof of parity violation

[PR 105 (1957) 1413]

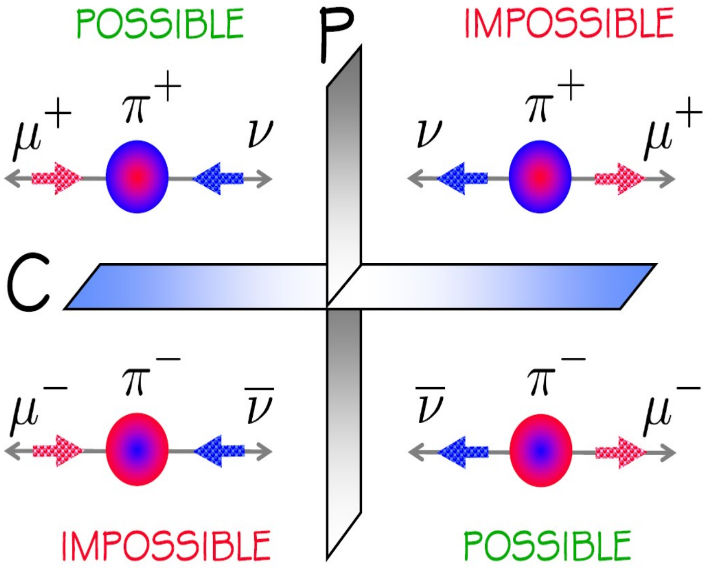
- measure angular distribution of electrons from β-decay of polarized ^{60}Co (spin=5^+) to ^{60}Ni* (spin=4^+)
- must be up-down symmetric if parity is conserved
- observation: electrons are emitted predominantly opposite to ^{60}Co-spin → parity is maximally violated !



CP Symmetry

Parity violation in semi-leptonic pion decays

- **muons from $\pi^\pm$ decays are polarized:**
  - μ^- from π^--decays are left-handed
  - μ^+ from π^+-decays are right-handed
- **parity is maximally violated, as expected**
- **charge conjugation is also maximally violated**
- **but: decay rates for π^- to left-handed μ^- and for π^+ to right-handed μ^+ are the same !**



Landau, Okun (1957): relevant symmetry in weak interactions is CP

[Nucl Phys 3 (1957) 127]
[Zh Eksp Teor Fiz 32 (1957) 1587]

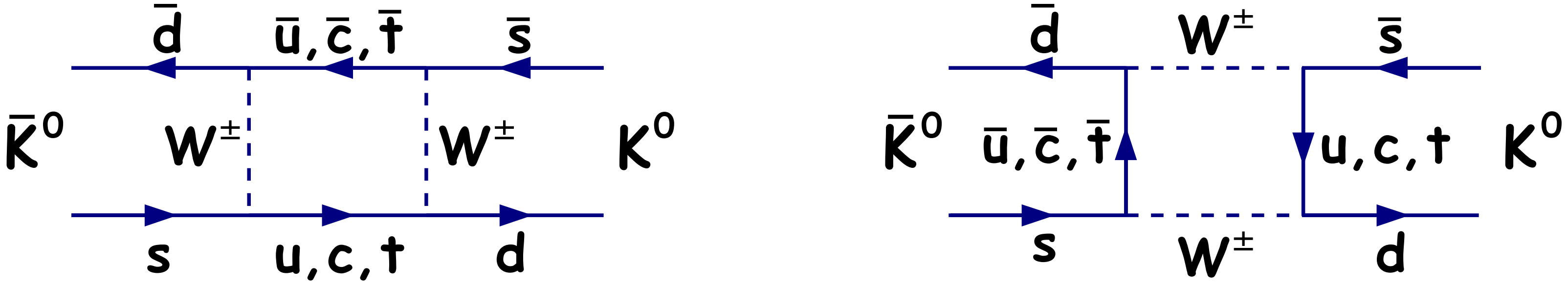
- CP = Charge conjugation × Parity
- Richard Feynman in *Symmetries in Physical Laws*, 1963:

> "it is really true that right and left symmetry is still maintained … the right-handed matter behaves the same way as the left-handed antimatter"

Two K^0 States

Short excursion: $K^0\bar{K}^0$ mixing

- **strangeness is the only quantum number that distinguishes K^0 from $\bar{K}^0$**
- **strangeness is not conserved in weak interactions: transitions $K^0 \leftrightarrow \bar{K}^0$**
  - in today's language: transitions via double W exchange (“box diagrams”)



- **pure state $|K^0>$ produced at time t=0 will evolve into a mixed state at t>0**

$$|\psi(t)\rangle = a(t)\cdot|K^0\rangle + b(t)\cdot|\bar{K}^0\rangle$$

- **define Eigenstates of CP operator:**

$$|K_1\rangle = \frac{1}{\sqrt{2}}\cdot\left\{|K^0\rangle + |\bar{K}^0\rangle\right\} \quad \Rightarrow \quad CP\,|K_1\rangle = +\,|K_1\rangle$$

$$|K_2\rangle = \frac{1}{\sqrt{2}}\cdot\left\{|K^0\rangle - |\bar{K}^0\rangle\right\} \quad \Rightarrow \quad CP\,|K_2\rangle = -\,|K_2\rangle$$

Two K^0 States

Gell-Mann,Pais (1957): two K^0 states with different lifetimes

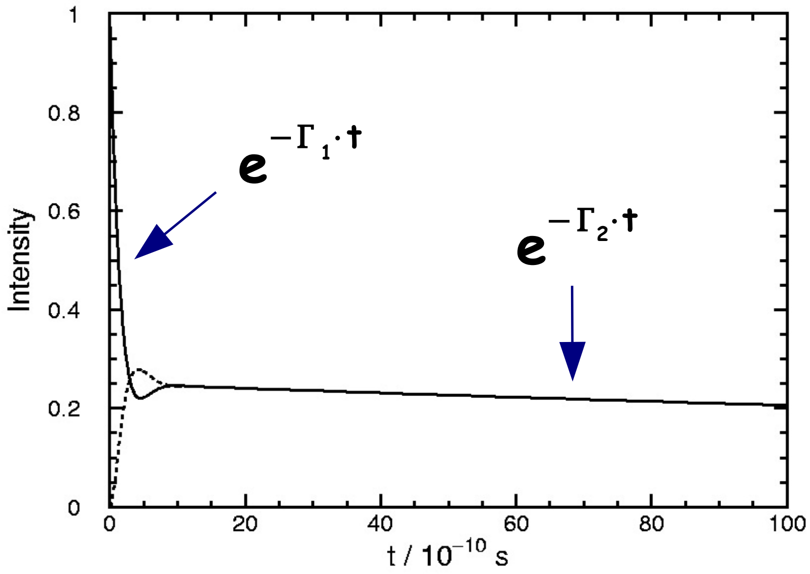
- if CP conserved in weak interactions, then
  - K_1 and K_2 are also eigenstates of weak interaction
  - K_1 can decay into 2 pions
  - K_2 cannot decay into 2 pions

$$J_K = J_\pi = 0 \;\Rightarrow\; L_{\pi\pi} = 0$$

$$\Rightarrow\; CP_{\pi\pi} = -1^{L_{\pi\pi}} = +1$$

- all possible decay channels for K_2 suppressed:
  - decays to 3 pions by phase space
  - semi-leptonic decays by parity violation
- K_2 must have much longer lifetime than K_1
  - measured lifetimes:

$$\tau(K_2) \approx 500 \times \tau(K_1)$$

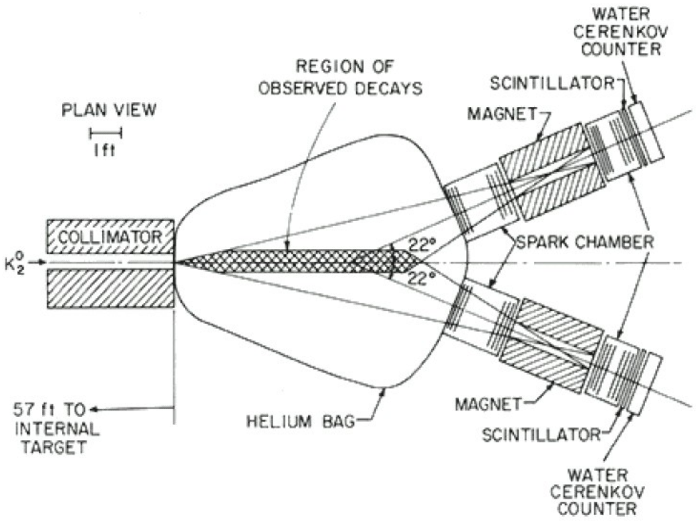


CP Violation

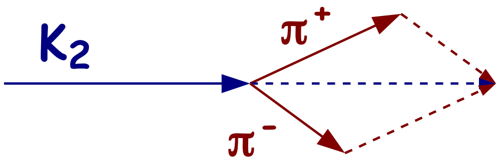
Christenson, Cronin, Fitch, Turlay (1964): observation of $K_2 \to \pi^+\pi^-$

[PRL 13 (1964) 138]

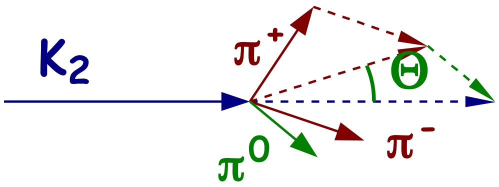
- **shoot protons into fixed target, produce K^0 and $\bar{K}^0$**
  - let them propagate in a vacuum tube
  - K_1 component decays away → obtain pure K_2 beam
- **search for $\pi^+\pi^-$ decays in this K_2 beam**
  - energy conservation: invariant mass of $\pi^+\pi^-$ pair
  - momentum conservation: momentum balance

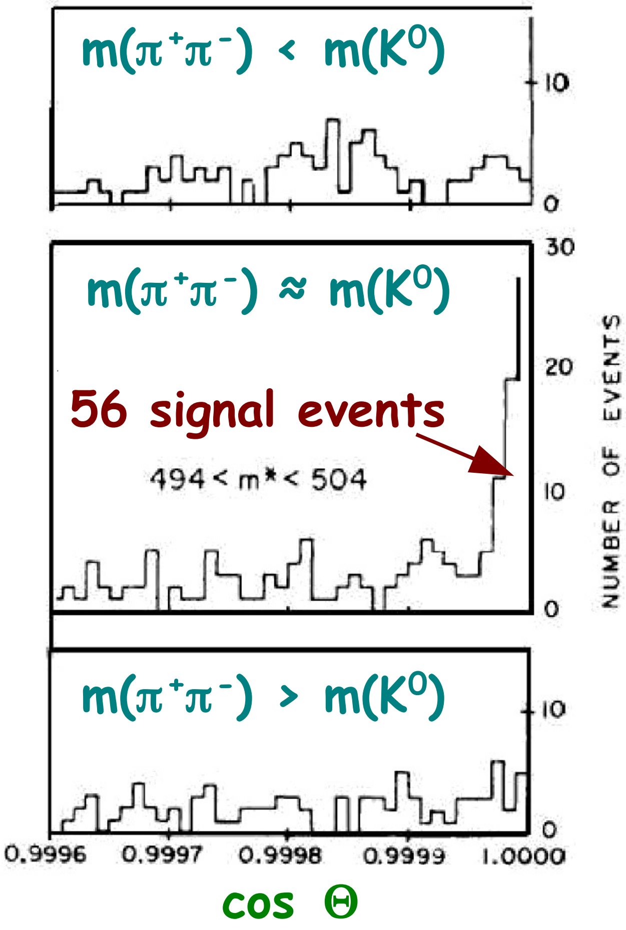


2-body decays:



3-body decays:





- **observe excess of 56 events in signal region ⇒**

$\boxed{BR(K_2 \to \pi^+\pi^-) \approx 2 \times 10^{-3}}$

Sakharov Conditions

Sakharov (1967): CP violation required to create a matter/antimatter asymmetry in the Universe

[JETP Lett 5 (1967) 24]

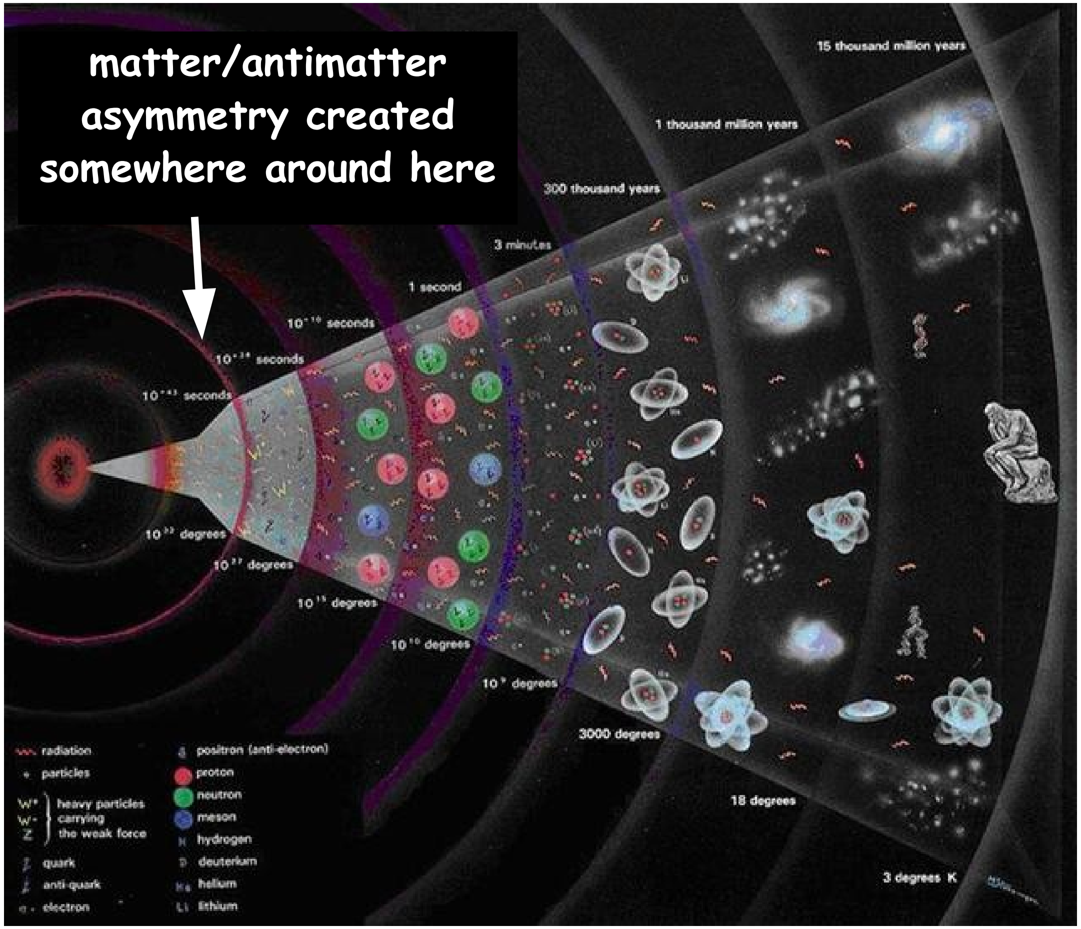
- **Sakharov's three conditions:**
  - Baryon-number violation
  - C violation and CP violation
  - thermal non-equilibrium

- **but: baryon asymmetry observed in the universe is**

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6\times10^{-10}$$

- **CKM-induced CP violation gives**

$$\eta \approx 10^{-18}$$


matter/antimatter asymmetry created somewhere around here

- **need additional sources of CP violation**

CKM Mechanism

Kobayashi, Maskawa (1972): CP violation if three quark doublets

[PTP 49 (1973) 652]

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- 9 complex numbers = 18 parameters
  - 9 unitarity constraints ($V^\dagger V = VV^\dagger = 1$)
  - 5 arbitrary ("unphysical") phases
  - = 4 free parameters: 3 rotation angles + 1 complex phase

$$\left.\begin{array}{l} u_i \rightarrow e^{i\phi_i} u_i \\ d_j \rightarrow e^{i\phi_j} d_j \end{array}\right\} \Leftrightarrow V_{ij} \rightarrow e^{i(\phi_j - \phi_i)} V_{ij}$$

- CP violation due to interference if diagrams with different weak phase contribute to the same process
- "prediction" of third quark family before even charm quark was discovered

Various other models proposed at the time to explain CP violation

- most prominent: new "superweak" force that acts only in kaon mixing

Charm Quark

"November revolution" (1974)

[PRL 33 (1974) 1404]
[PRL 33 (1974) 1406]

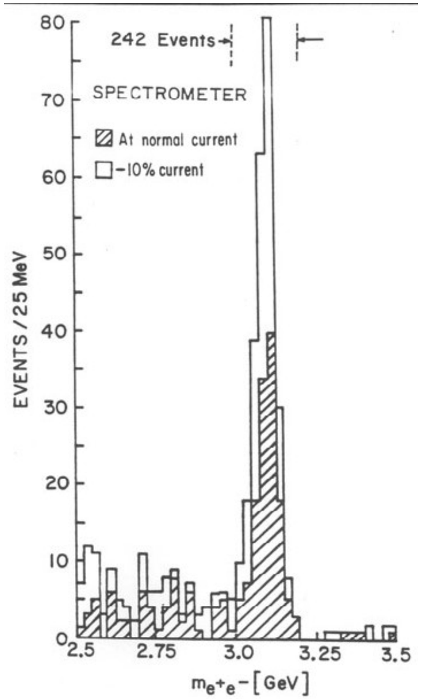
- observation of a narrow resonance at a mass of 3.1 GeV, simultaneously
  - in $p + Be \rightarrow e^+ e^- + X$ at BNL (Ting et al.) → "J"
  - in $e^+ e^- \rightarrow e^+ e^-$, $\mu^+ \mu^-$, hadrons at SLAC (Richter et al.) → "Ψ"

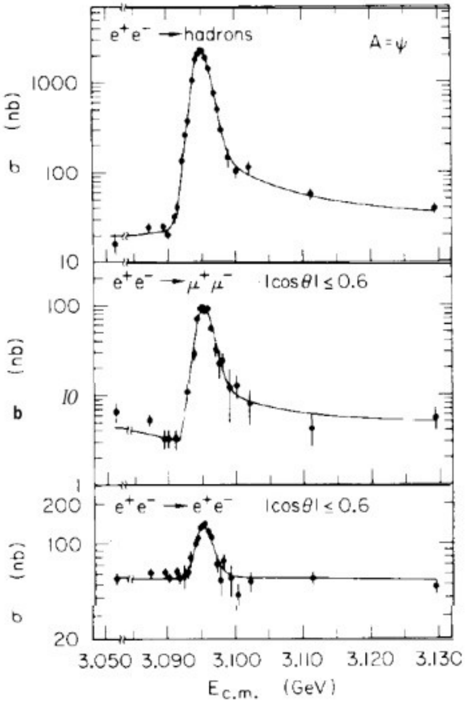
  $\Big\}$ J/Ψ
  - in both cases, measured width dominated by the detector resolution
- narrow width → long lifetime

  → cannot be an excited u,d,s state
- interpretation: bound $c\bar{c}$ state

$$\boxed{m(c) \sim 1.5 \text{ GeV}}$$

- soon confirmed by observation of other $c\bar{c}$ states and of open charm (D mesons)



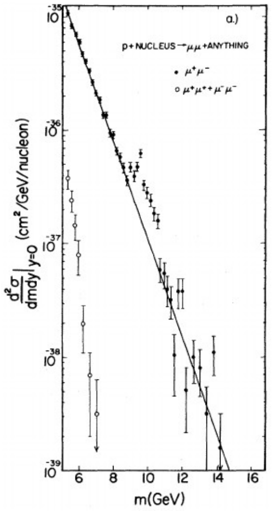


Bottom and Top Quarks

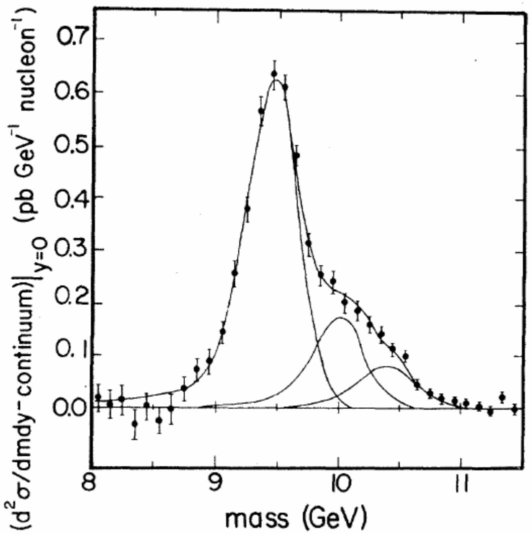
Lederman et al. (1977): search for $b\bar{b}$ resonances in $p + Cu \to \mu^+\mu^- + X$

- observe excess of $\mu^+\mu^-$ pairs around an invariant mass of 9.4-10.4 GeV
- resolved into three resonances, interpreted as bound $b\bar{b}$ states

m(b) ~ 4.5 GeV



[PRL 39 (1977) 252]



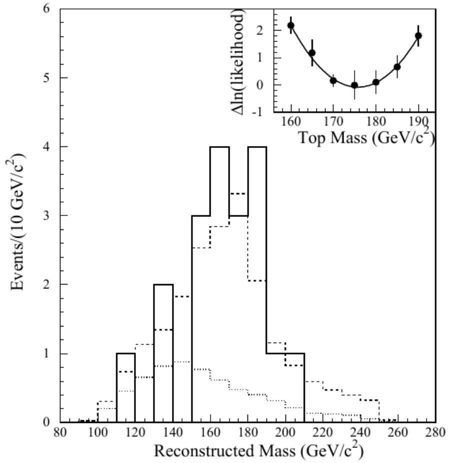
[PRL 42 (1979) 486]

CDF/D0 (1995): first observation of top quark

[PRL 74 (1995) 2626]
[PRL 74 (1995) 2632]

- existence of top quark taken for granted after discovery of b quark
- mass around 170 GeV predicted from fits to electroweak precision measurements at LEP and SLC
- production in 1.8 TeV $p\bar{p}$ collisions at Tevatron
- detection in $t \to W\,b$ decays

m(t) ~ 176 GeV



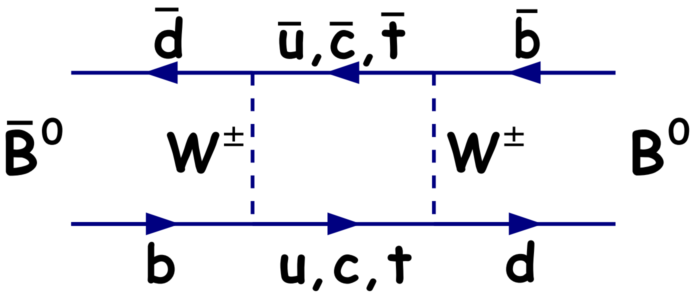
$B^0\bar{B}^0$ Mixing

Argus experiment at DESY (1987)

[PLB192 (1987) 245]

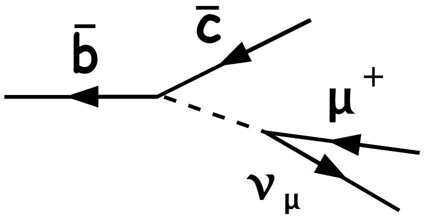
- e^+e^- collider operating at $\Upsilon(4s)$ resonance
- produce $B^0\bar{B}^0$ pairs through

$$e^+e^- \rightarrow \Upsilon(4s) \rightarrow B^0\bar{B}^0$$

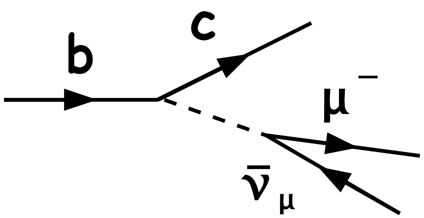


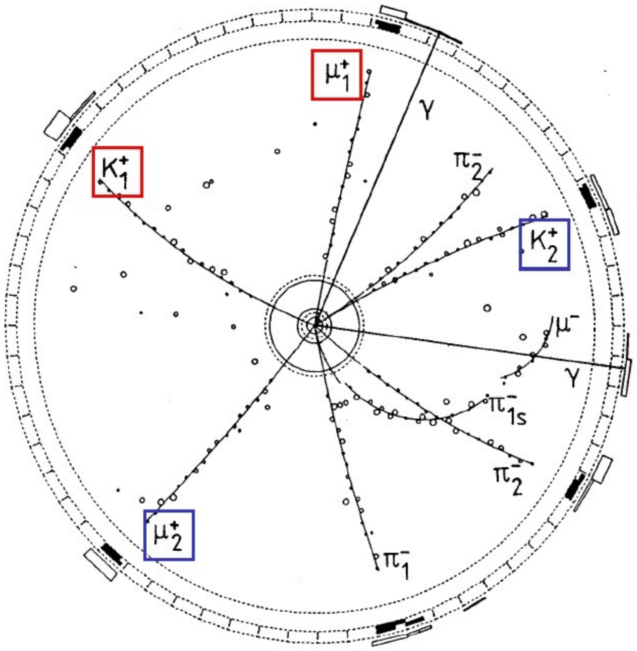
- $B^0\bar{B}^0$ mixing through box diagrams
- can be observed in semi-leptonic decays

$B^0 \rightarrow D^{*-}\mu^+\nu_\mu$



$\bar{B}^0 \rightarrow D^{*+}\mu^-\bar{\nu}_\mu$



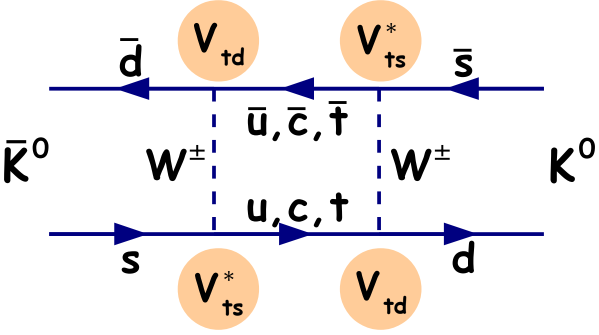


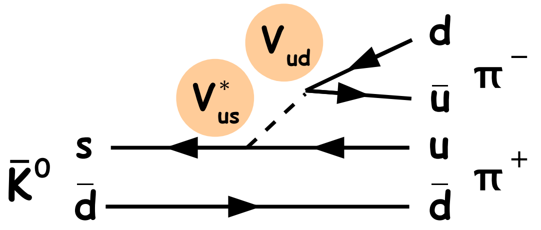
- observe "like-sign event" with two μ^- or two μ^+
  → B^0 or $\bar{B}^0$ must have mixed
- strong mixing observed → predict large top quark mass

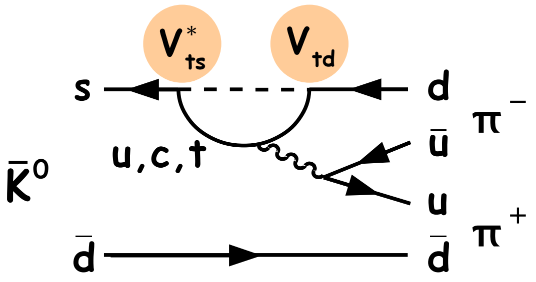
Direct CP Violation

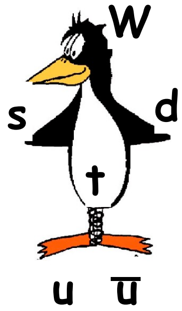
CKM: CP violation from interference of diagrams with different phase

- interference of box diagrams with different internal quarks: “indirect” CP violation in K mixing
- interference of tree and penguin decay diagrams with different phases: “direct” CP violation in decay









- can be tested by comparing CP violation in $\pi^+\pi^-$ and $\pi^0\pi^0$ decays: different decay diagrams → expect CP violation to be slightly different

$$\eta_{+-} = \frac{\Gamma\left(K_L \to \pi^+\pi^-\right)}{\Gamma\left(K_S \to \pi^+\pi^-\right)} = \varepsilon + \varepsilon' \quad ; \quad \eta_{00} = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right)}{\Gamma\left(K_S \to \pi^0\pi^0\right)} = \varepsilon - 2\,\varepsilon'$$

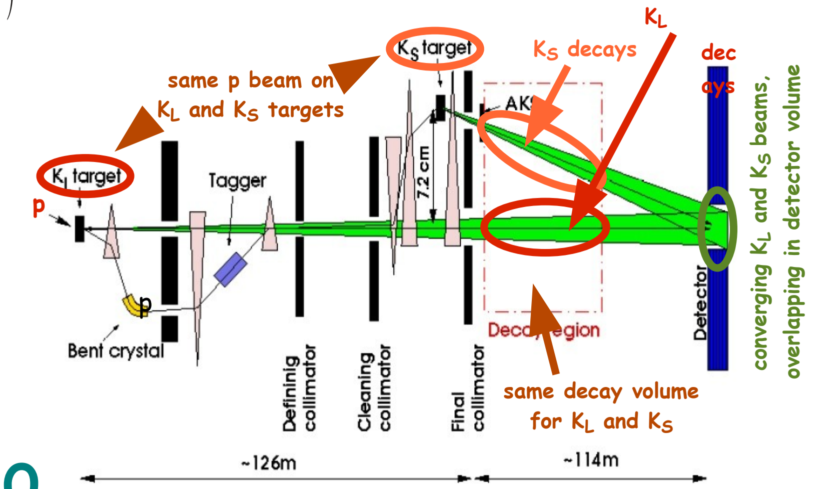
- in Standard Model expect $\varepsilon'/\varepsilon \approx 10^{-3}$
- if CP violation only in K mixing (superweak interaction): $\eta_{+-} = \eta_{00}$, $\varepsilon' = 0$

Direct CP Violation

Experimental approach: measure the "double ratio"

$$R = \left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 = \frac{\Gamma\left(K_L \to \pi^0\pi^0\right) / \Gamma\left(K_S \to \pi^0\pi^0\right)}{\Gamma\left(K_L \to \pi^+\pi^-\right) / \Gamma\left(K_S \to \pi^+\pi^-\right)} \approx 1 - 6 \cdot \mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

- challenge: control systematics to $O(10^{-4})$
- many systematic effects cancel to first order if all four decay rates are measured simultaneously (same beam, same detector)



NA48 simultaneous K_L and K_S beams

NA48/KTeV (2001): observation of $\varepsilon'/\varepsilon \neq 0$

- end of a decades long competition CERN ↔ FNAL

NA48@CERN: $\mathrm{Re}\left(\varepsilon'/\varepsilon\right) = \left(14.7 \pm 2.2\right) \times 10^{-4}$ [PLB 544 (2002) 97]

KTeV@FNAL: $\mathrm{Re}\left(\varepsilon'/\varepsilon\right) = \left(19.2 \pm 2.1\right) \times 10^{-4}$ [PRD 83 (2011) 092001]

- vindication of CKM model of CP violation
- but large hadronic uncertainties, do not learn much about CKM parameters

CP Violation in The $B^0\bar{B}^0$ System

Many advantages over $K^0\bar{K}^0$ system

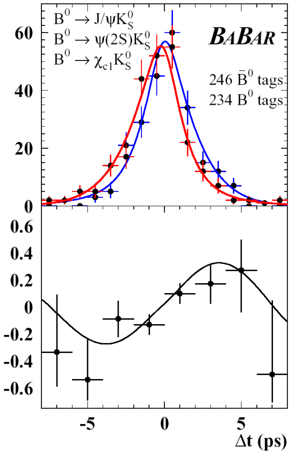
- many decay channels and observables, large CP asymmetries, theoretically "clean" predictions, …

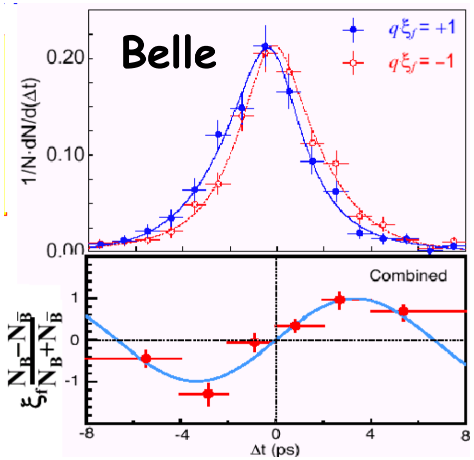
But experimental challenges

- B mesons heavy → small production cross section
- many decay channels → small branching ratios
- short lifetime and fast oscillation frequency

} need high-luminosity accelerators and very precise detectors

- dedicated "B factories" constructed especially for CP measurement: BaBar at PEP-II, Belle at KEKB
- 2001: both observe CP asymmetry in "golden decay channel" $B^0 \rightarrow J/\psi\, K^0_S$
  - measured values in good agreement with CKM prediction





2001 ++

Many more and much more precise results

- BaBar/Belle, CDF/D0 at Tevatron, now LHCb
- results so far in very good agreement with CKM predictions (2-3σ deviations came and went)

} remainder of this lecture

- Babar and Belle stopped data taking, Belle collected ~ 1 ab^{-1}
- Tevatron stopped in autumn 2011 → CDF/D0 collected ~ 9 fb^{-1}
- LHCb collected ~1 fb^{-1} at 7 TeV in 2011 and ~2 fb^{-1} at 8 TeV in 2012
  - $b\bar{b}$ production cross section ~ 5 x Tevatron, ~ 500'000 x Babar/Belle
  - many analyses ongoing, already ~ 80 papers published
- LHC shutdown in 2013/2014, resume at ≥ 13 TeV in 2015
  - another factor two in $b\bar{b}$ production cross section
- "Belle II" under construction; goal: collect ~ 50 x Belle luminosity by 2022