Karlsruhe Institute of Technology

Particle Physics 1
Lecture 13: Flavour Physics

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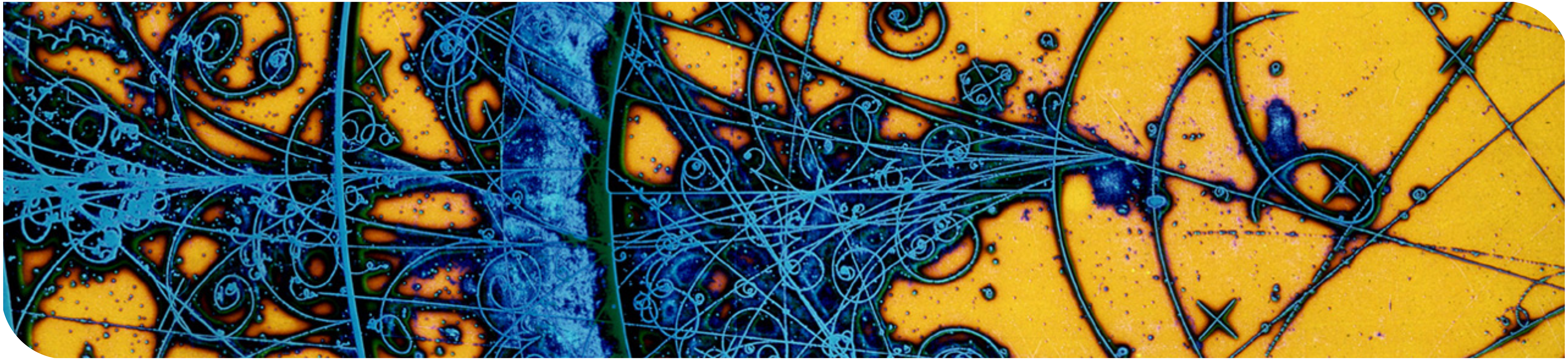
Wintersemester 2023/2024



Credit: CERN

Questions from past lectures

Lecture evaluation

https://onlineumfrage.kit.edu/evasys/online.php?p=J99EY

Learning goals

- Be able to define flavour physics
- Understand the GIM mechanism
- Understanding of Cabibbo mechanism, the CKM matrix and how to measure its parameters
- Understand Meson-Antimeson Mixing: Kaons and B-mesons

Flavour physics

- What is flavor physics?
  - Experimentally: **three fermion families** (generations)
    → six different quark and lepton flavors
  - Flavor quantum numbers (weak isospin, strangeness, charm, beauty, truth) **conserved** in electromagnetic and strong interactions
- Only charged current (CC) weak interactions change quark flavours:
  - Up to now: Universal W-boson coupling to left handed fermions $\mathscr{L} \sim \bar{f}\gamma^{\mu}\frac{1}{2}(1-\gamma_5)f'$
  - Transitions within the same $SU(2)_L$ doublet occurs in particle decays

Flavour physics

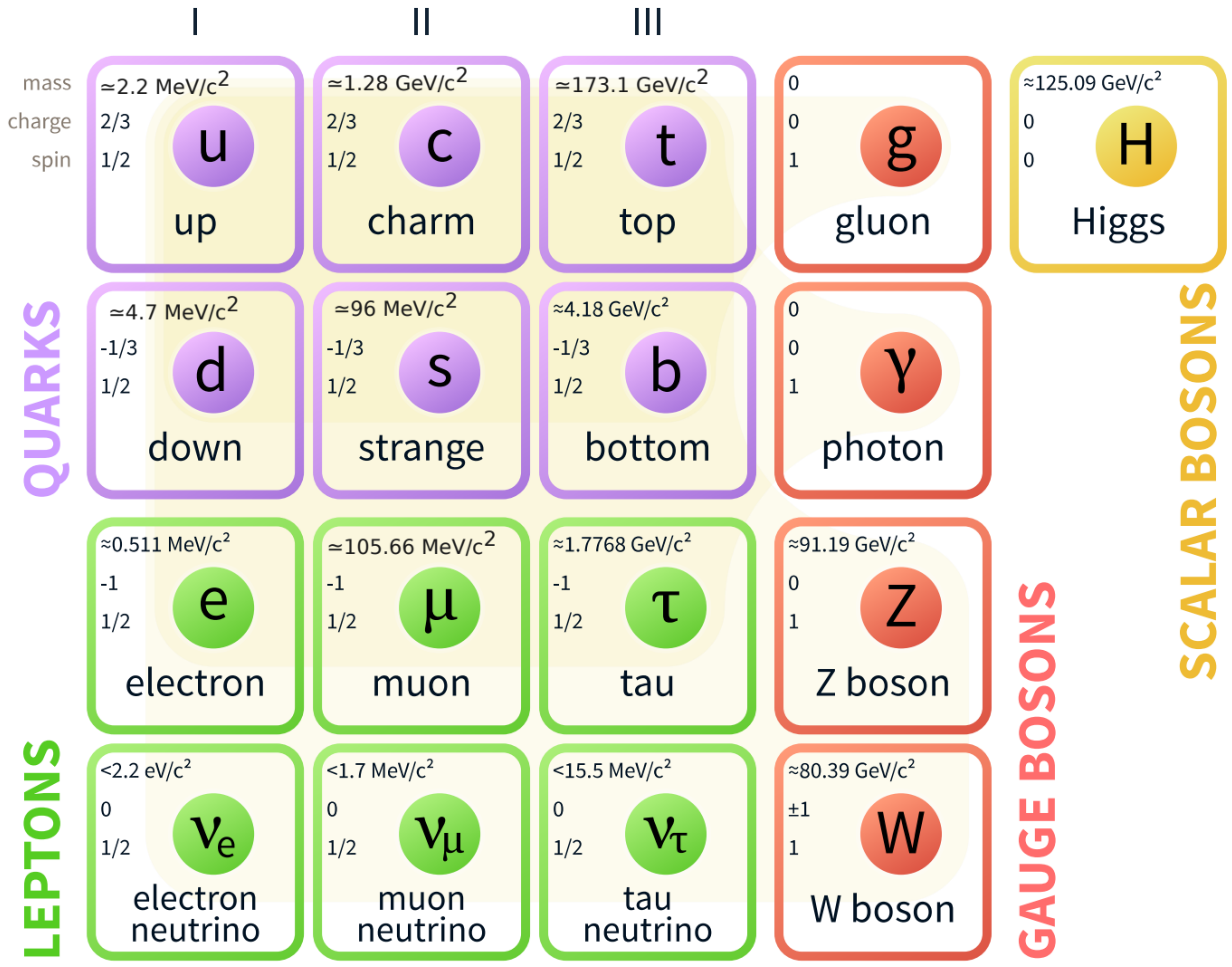
DEFINITION: **Flavour**
is a quantum number used to distinguish particles/fields that have the same gauge quantum numbers

In the SM: quarks and leptons come in three copies with the same colour representation and electric charge

DEFINITION: **Flavour physics**
deals with interactions that distinguishes between flavours

In the SM: QED and QCD interactions do not distinguish between flavours, while the weak interactions (and the couplings to the Higgs field) do

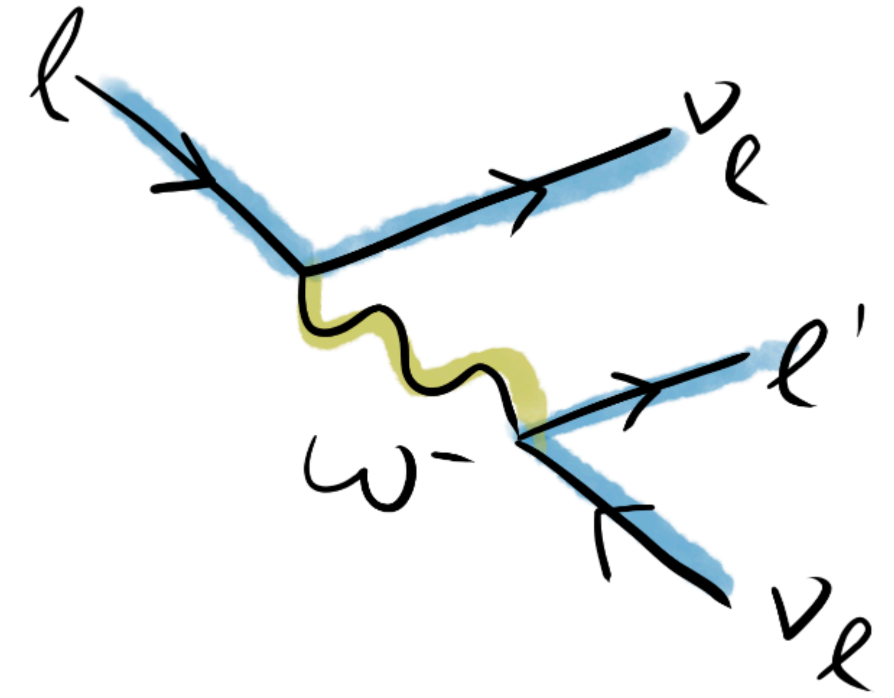
Flavour physics



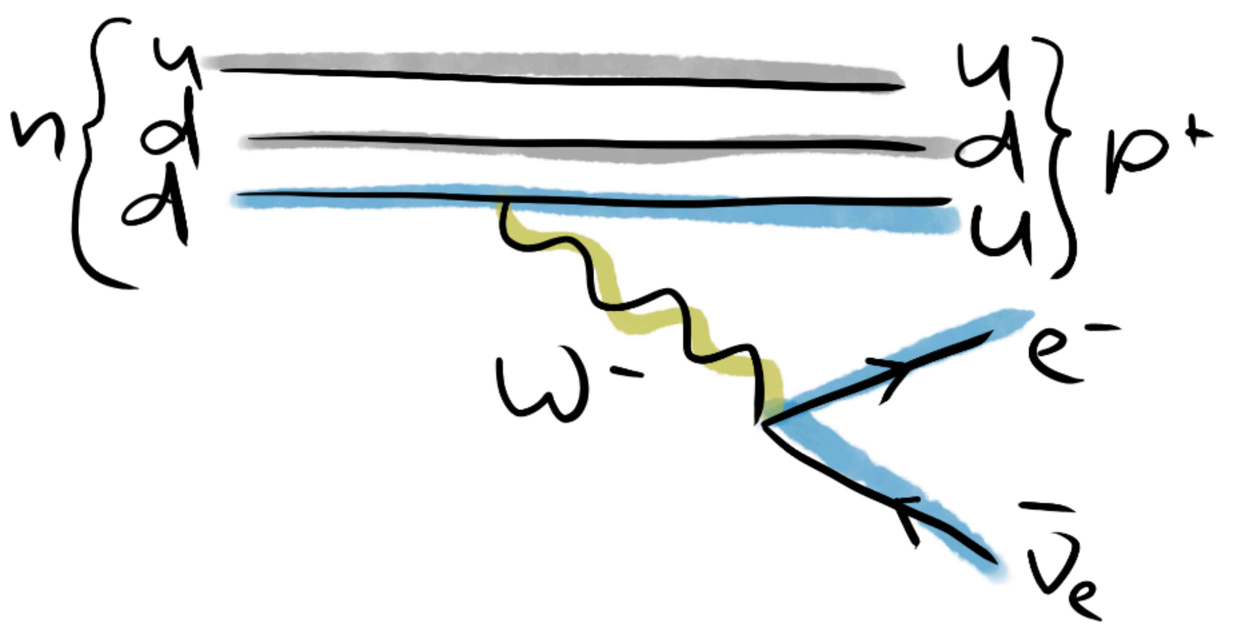
Columns: Families or generations
Rows: Type
Cell: Flavour

Decay classification

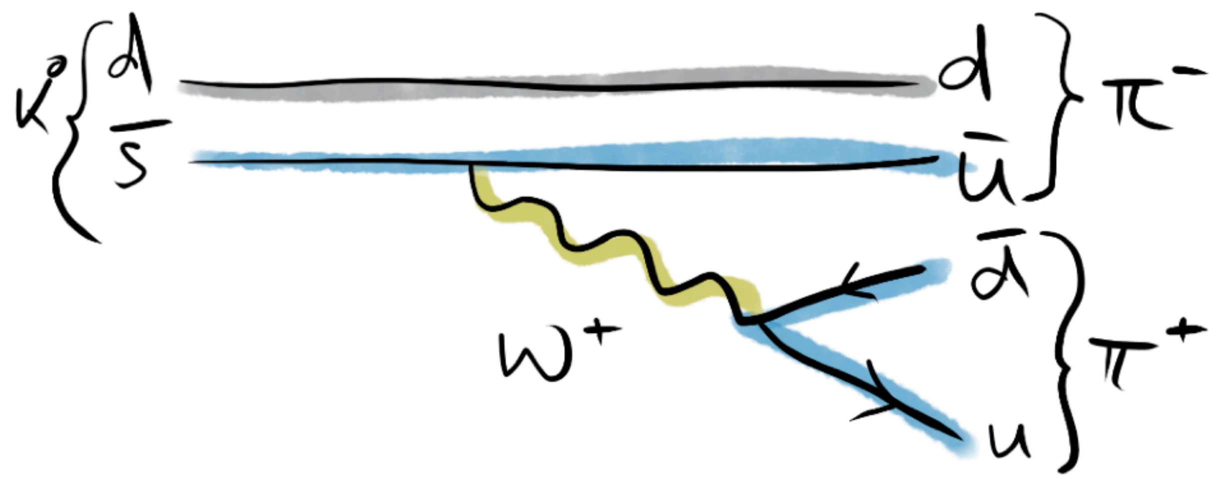
- Leptonic decays
  - Final state does only contain leptons
  - Example: Muon decay $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



- Semileptonic decays
  - Final state contains leptons and hadrons
  - Example: β-decay $n \to p^+ e^- \bar{\nu}_e$

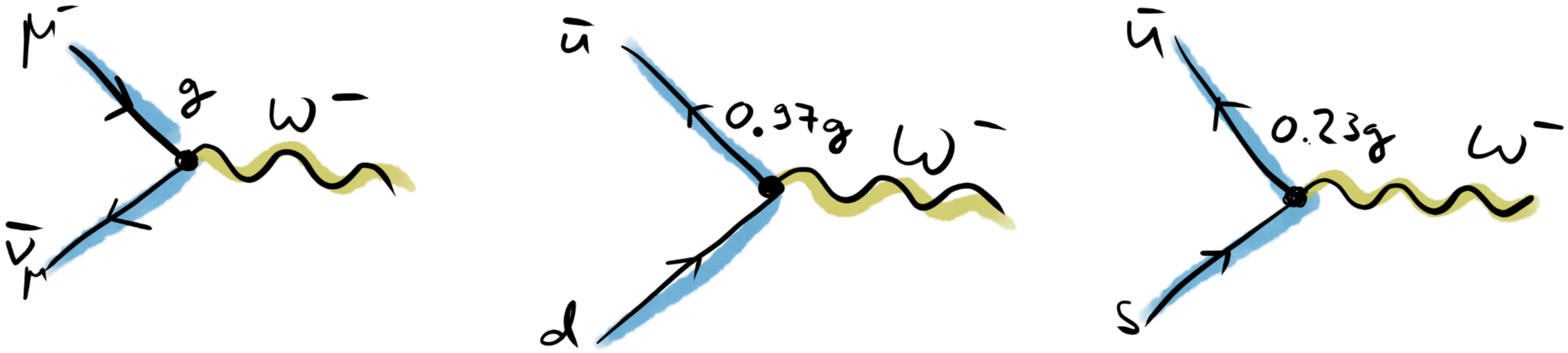


- Hadronic decays
  - Final state contains only hadrons
  - Example: $K^0 \to \pi^+ \pi^-$



Challenge 1: Semi-leptonic vs leptonic decays, and Kaon decays

- Two experimental observations challenge the electroweak theory:
  - Coupling strength in (semileptonic) neutron decays is 3% smaller than in (leptonic) muon decays
  - Kaon decays $K^- \to \ell^- \nu$ are significantly rarer than pion decays $\pi^- \to \ell^- \nu$:



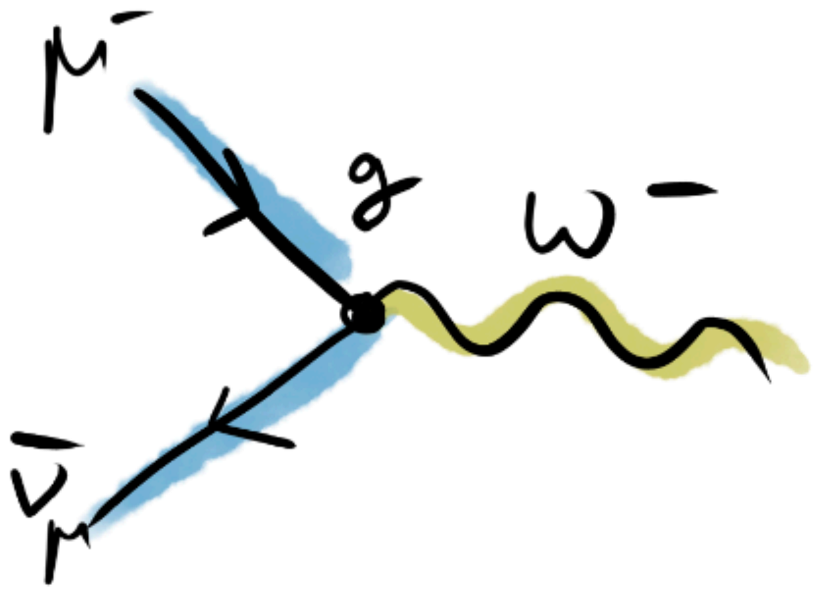
Cabibbo theory (1963)

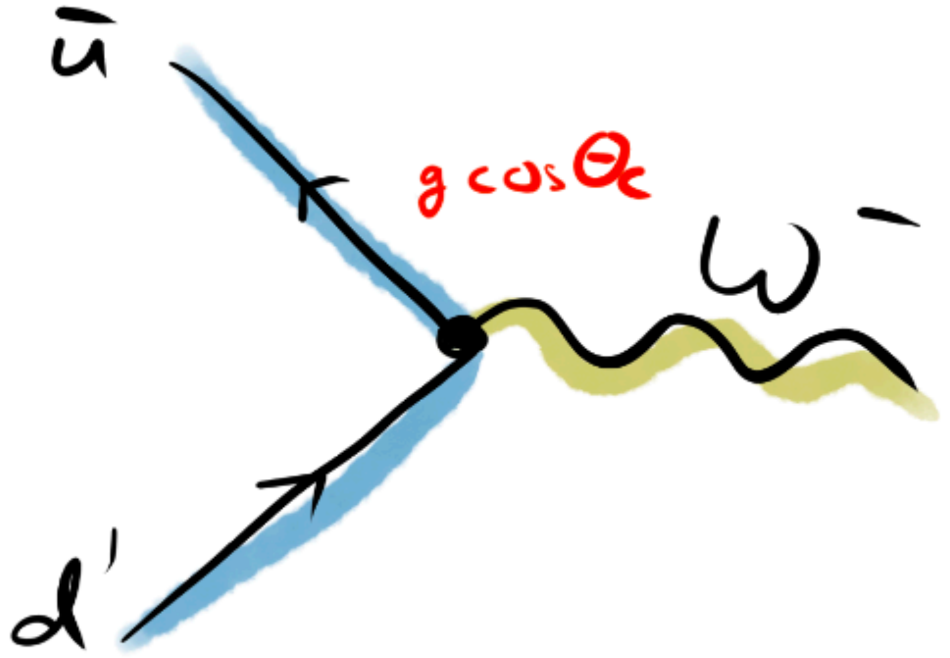
- Quark eigenstates of the weak interactions are not the mass eigenstates *(the actual reason behind this: the Yukawa coupling in the Higgs sector is not flavour diagonal)*

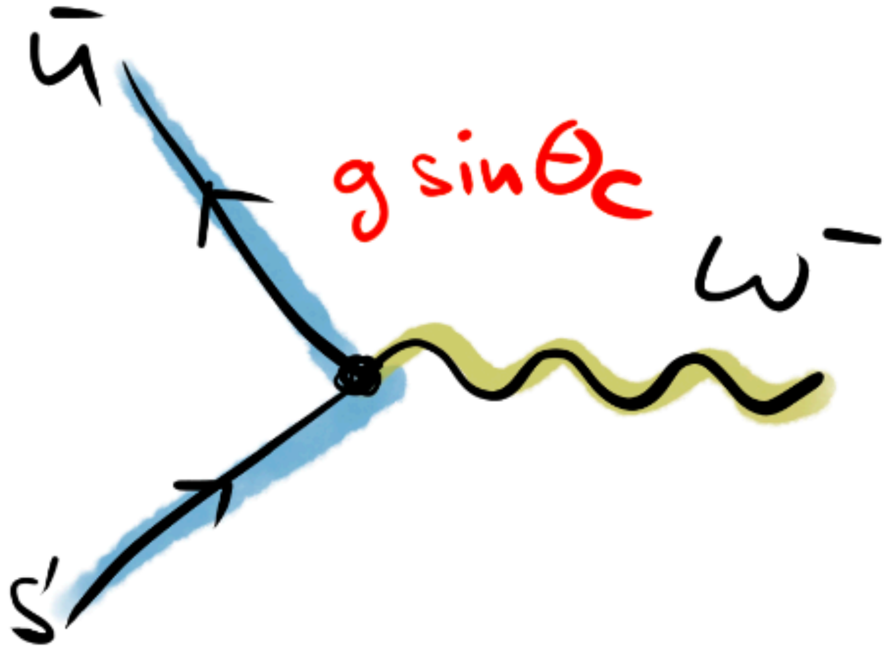
- Quark states are rotated by the Cabibbo angle θ_C (for 2 generations):

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

- W bosons couple to the rotated down-type and the up-type states
  - Why rotate the down-type and not the up-type states? As usual: Convention.

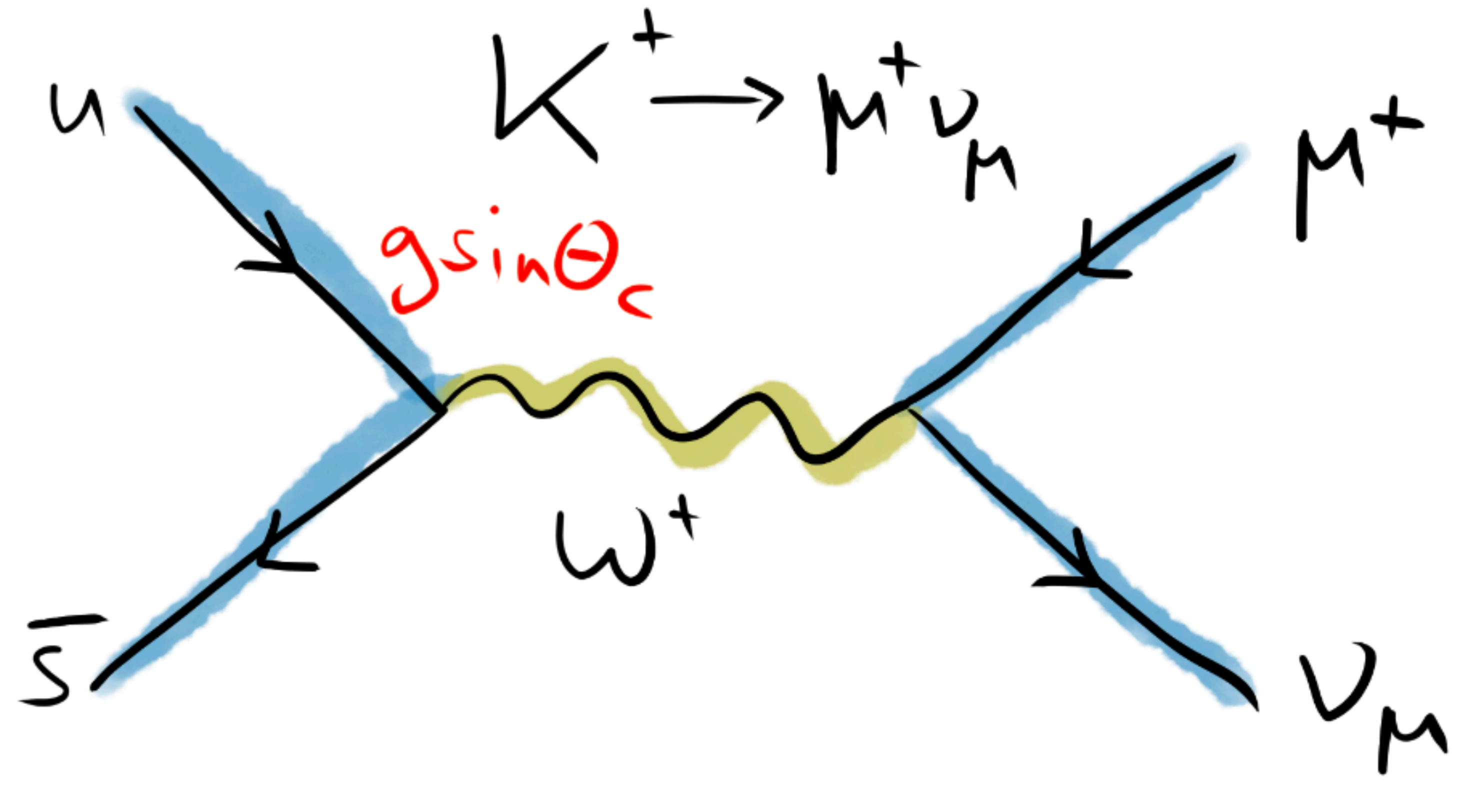






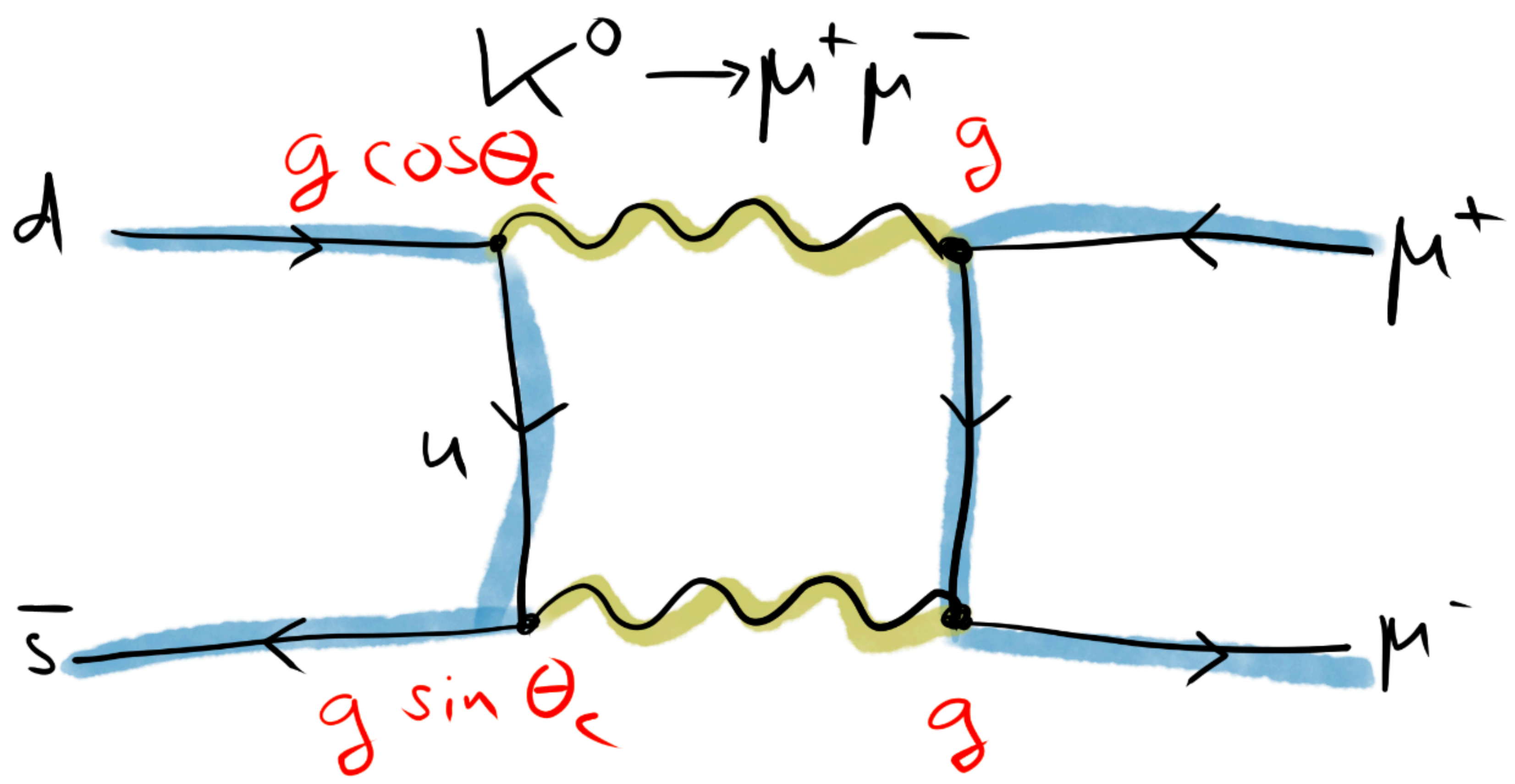
Challenge 2: “Forbidden” Kaon decays

- Compare branching fractions of two kaon decays:
  - $K^+ \to \mu^+\nu_\mu$: flavour changing charged current current with Δs = 1 (strangeness violated)
  - $K^0 \to \mu^+\mu^-$: flavour changing current neutral current (FCNC) with Δs = 1 (strangeness violated)
    → forbidden at tree level in the SM



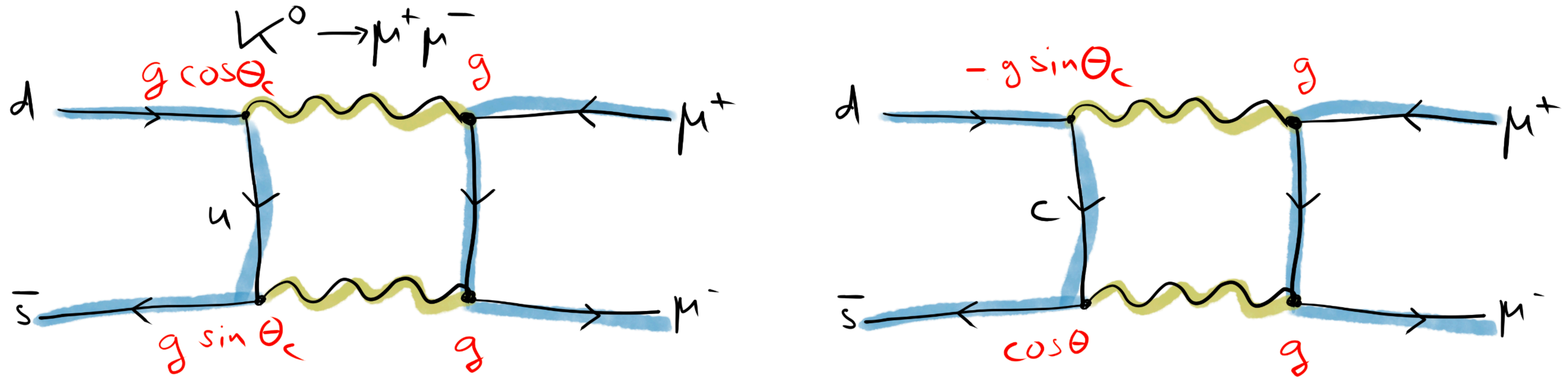
- Experimentally today: $\dfrac{\mathscr{B}(K^0 \to \mu\mu)}{\mathscr{B}(K^+ \to \mu\nu)} \approx 6 \times 10^{-9}$,
  in the 1960s the decay $K^0 \to \mu^+\mu^-$ had not been observed

- While the Box diagram with two W-bosons is suppressed compared to a single W-boson exchange, it does not explain such a tiny branching fraction…



GIM mechanism

- S. Glashow, J. Iliopoulos and L. Maiani postulated* the existence of a fourth quark



- Destructive interference (there is a minus sign!) leads to tiny branching fraction
- If mass of charm quark and mass of up quark were identical: Exact cancellation: Limits on $\mathscr{B}(K^0 \to \mu\mu)$ can be translated on limits on charm quark mass
- In 1974: Direct discovery of the charm quark bound state J/ψ

*PRD 2 (1970) 1285

Challenge 3: CP violation in Kaon decays

- In other news, 1964: Discovery on CP violation (discrete symmetries C and P violated simultaneously) discovered in neutral Kaon decays…
  - The GIM mechanism does not provide an answer for that
- M. Kobayashi, T. Maskawa and postulated the existence of a third quark generation in 1973:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{\mathrm{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \rightarrow J^{\mu,+}_{\mathrm{CC}} = (\overline{u}, \overline{c}, \overline{t}) \left(\gamma^{\mu} \frac{1}{2}(1 - \gamma_5) V_{\mathrm{CKM}} \right) \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- This is todays description using the so-called CKM matrix
- Provides a mechanism to explain CP violation (later)

*Prog. Theor. Phys. 49 (1973) 634)

Nobel prize 2008

Prize motivation: “for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature”

Source: https://www.nobelprize.org/prizes/physics/2008/maskawa/facts/

Toshihide Maskawa

Born: 7 February 1940, Nagoya, Japan

Died: 23 July 2021, Kyoto, Japan

Makoto Kobayashi

Born: 7 April 1944, Nagoya, Japan

Source: https://www.nobelprize.org/prizes/physics/2008/kobayashi/facts/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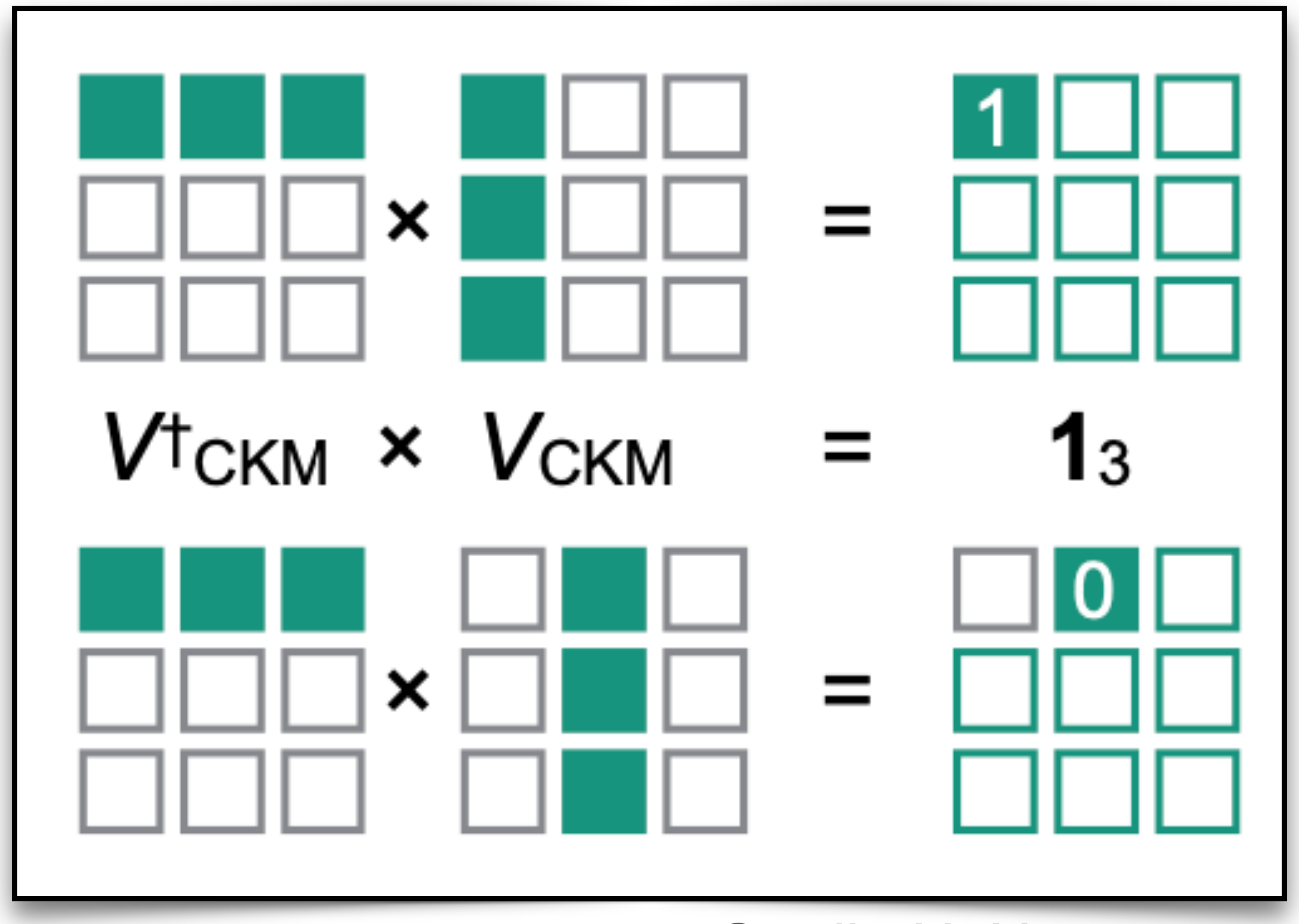
Properties of the CKM matrix

- Unitary, complex 3×3 matrix (3 generations, 6 flavours): 18 parameters
  - Unitarity: $V^{\dagger}_{CKM} V_{CKM} = V_{CKM} V^{\dagger}_{CKM} = 1_3$
- Quark fields can absorb one parameter ("phase") each (6), but overall offset ("global phase") is unknown (1): parameters reduced by 6-1=5 (next slide)
- CKM Unitarity reduces parameters by another 3+6=9:
  - $\sum_{i=1}^{3} V_{ij} V^*_{ij} = 1$ for $j = 1..3$
  - $\sum_{i=1}^{3} V_{ij} V^*_{ij} = 0$ for $j, k = 1..3, k > j$
- **4 free parameters (experimental input)**



Credit: U. Husemann

Properties of the CKM matrix: Unobservables phases

Phases of left-handed fields in J^{cc} are unobservable: possible redefinition

$$u_L \to e^{i\phi(u)} u_L \qquad c_L \to e^{i\phi(c)} c_L \qquad t_L \to e^{i\phi(t)} t_L$$

$$d_L \to e^{i\phi(d)} d_L \qquad s_L \to e^{i\phi(s)} s_L \qquad b_L \to e^{i\phi(b)} b_L$$

Real numbers

Under phase transformation:

$$V \to \begin{pmatrix} e^{-i\phi(u)} & 0 & 0 \\ 0 & e^{-i\phi(c)} & 0 \\ 0 & 0 & e^{-i\phi(t)} \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} e^{i\phi(d)} & 0 & 0 \\ 0 & e^{i\phi(s)} & 0 \\ 0 & 0 & e^{i\phi(b)} \end{pmatrix}$$

$$\boxed{V\alpha j \to \exp[i(\phi(j) - \phi(\alpha))] V\alpha j}$$

5 unobservable phase differences !

Unitarity constraints of the CKM matrix

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1$$

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$$

$$V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb} = 0$$

$$V_{ud}^* V_{td} + V_{us}^* V_{ts} + V_{ub}^* V_{tb} = 0$$

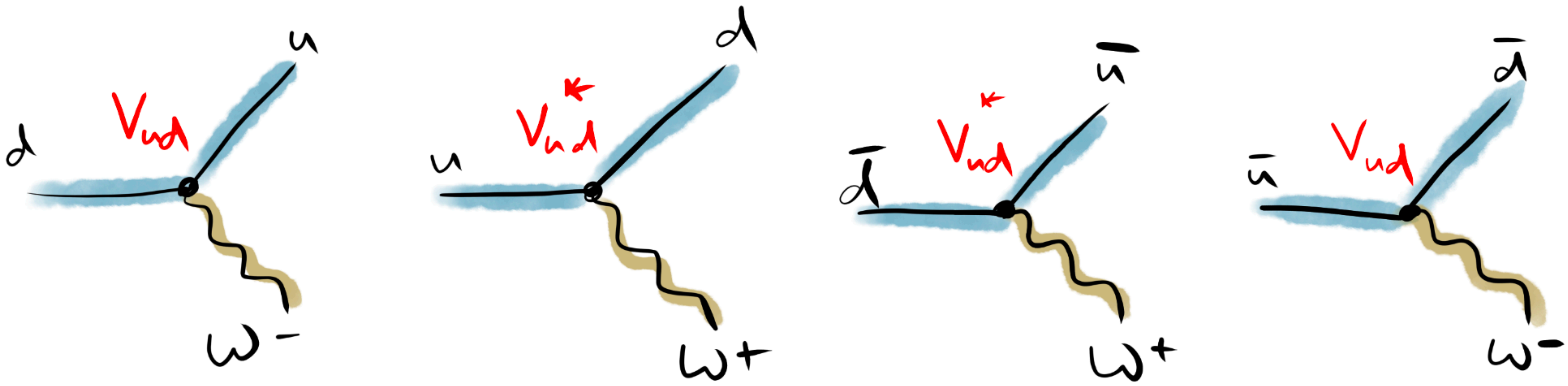
$$V_{cd}^* V_{td} + V_{cs}^* V_{ts} + V_{cb}^* V_{tb} = 0$$

$$V_{ud} V_{us}^* + V_{cd} V_{cs}^* + V_{td} V_{ts}^* = 0$$

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

$$V_{us} V_{ub}^* + V_{cs} V_{cb}^* + V_{ts} V_{tb}^* = 0$$

CKM Matrix



CKM Matrix: Parametrizations

- Standard parametrization*: Three Euler angles θ_{ij} and one phase δ:

$$V_{CKM} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{s\text{-}b \text{ mixing}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{d\text{-}b \text{ mixing + phase}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{d\text{-}s \text{ mixing}}$$

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

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

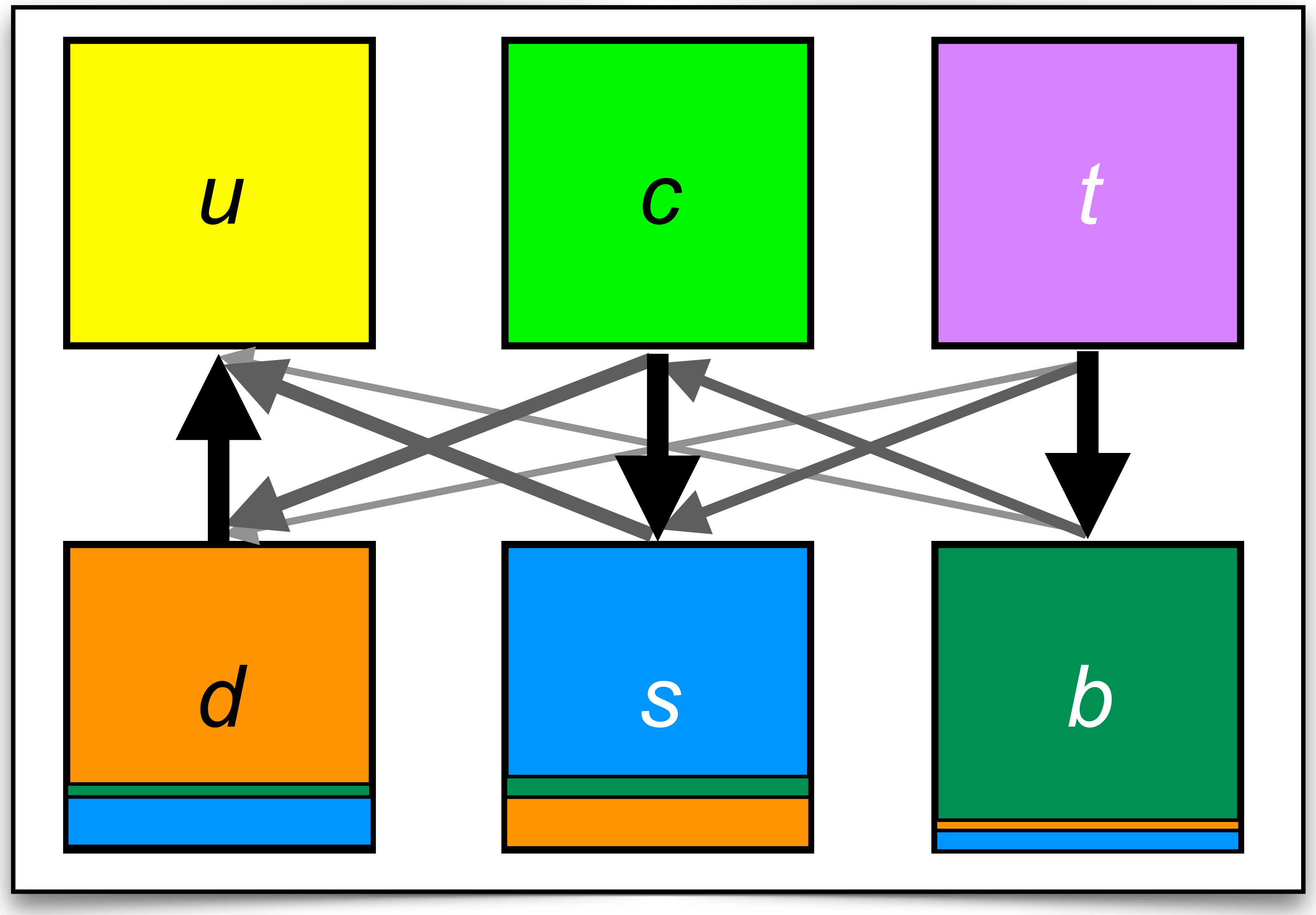
*Almost never used for the CKM Matrix.

CKM Matrix: Parametrizations

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{pmatrix}$$

Source: PDG 2022

- Clear hierarchy of matrix elements:
  - diagonal elements all ~1 → transitions within one generation are most likely
  - $1 \gg s_{12} \gg s_{23} \gg s_{13}$



Credit: U. Husemann

CKM Matrix: Wolfenstein Parametrizations

- Use hierarchy and expand in Cabibbo angle $s_{12} = \sin\theta_C$

$$s_{12} = \lambda = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}\,, \qquad s_{23} = A\lambda^2 = \lambda\left|\frac{V_{cb}}{V_{us}}\right|,$$

$$s_{13}e^{i\delta} = V_{ub}^* = A\lambda^3(\rho + i\eta) = \frac{A\lambda^3(\bar{\rho} + i\bar{\eta})\sqrt{1 - A^2\lambda^4}}{\sqrt{1-\lambda^2}\left[1 - A^2\lambda^4(\bar{\rho} + i\bar{\eta})\right]}$$

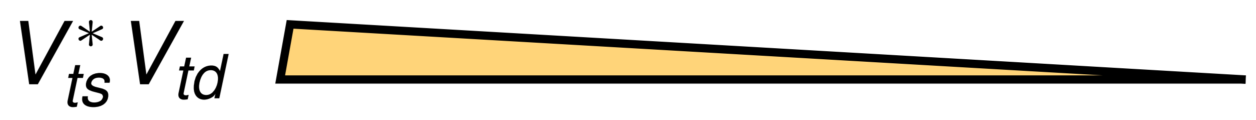
$$V_{\text{CKM}} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

CKM Matrix: Experimental

- Experimentally: four physical CKM parameters can be over-constrained with >4 measurements
- **Unitarity** dictates relations among CKM matrix elements, consider six complex equations (columns 12*, 13*, 23*, 1*2, 1*3, 2*3)
- Sum of three complex numbers = 0: triangle in complex plane → **unitarity triangles**
- Base length normalized to 1

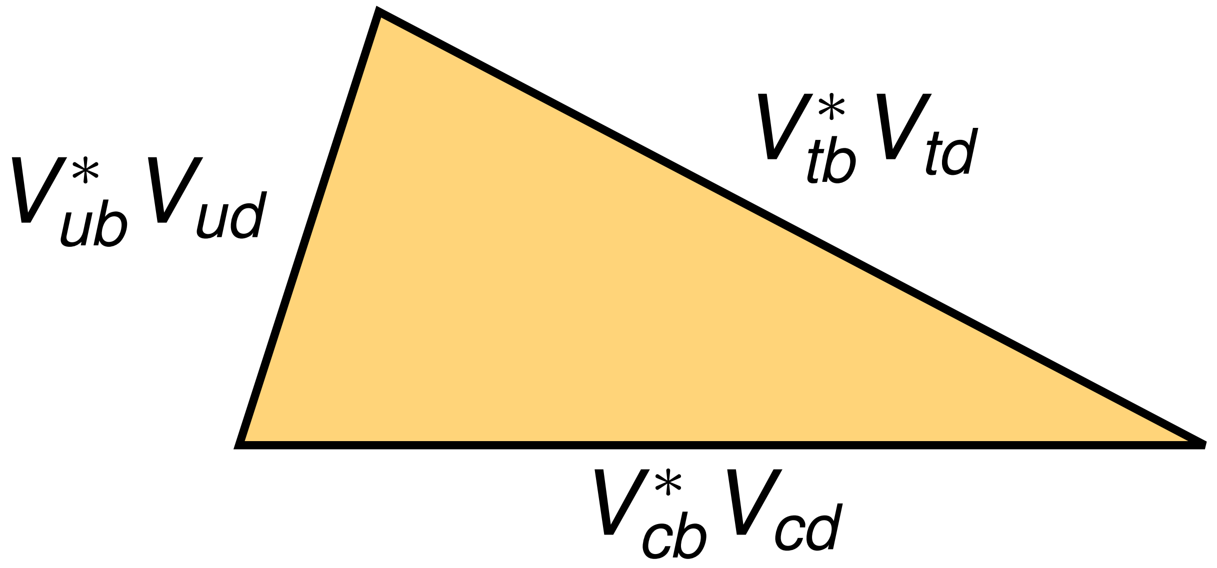
First and second* column:

$$V_{us}^* V_{ud} + V_{cs}^* V_{cd} + V_{ts}^* V_{td} = 0$$



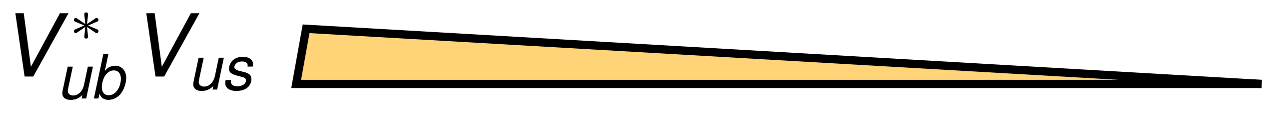
First and third* column:

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



Second and third* column

$$V_{ub}^* V_{us} + V_{cb}^* V_{cs} + V_{tb}^* V_{ts} = 0$$



(not to scale)

Credit: U. Husemann

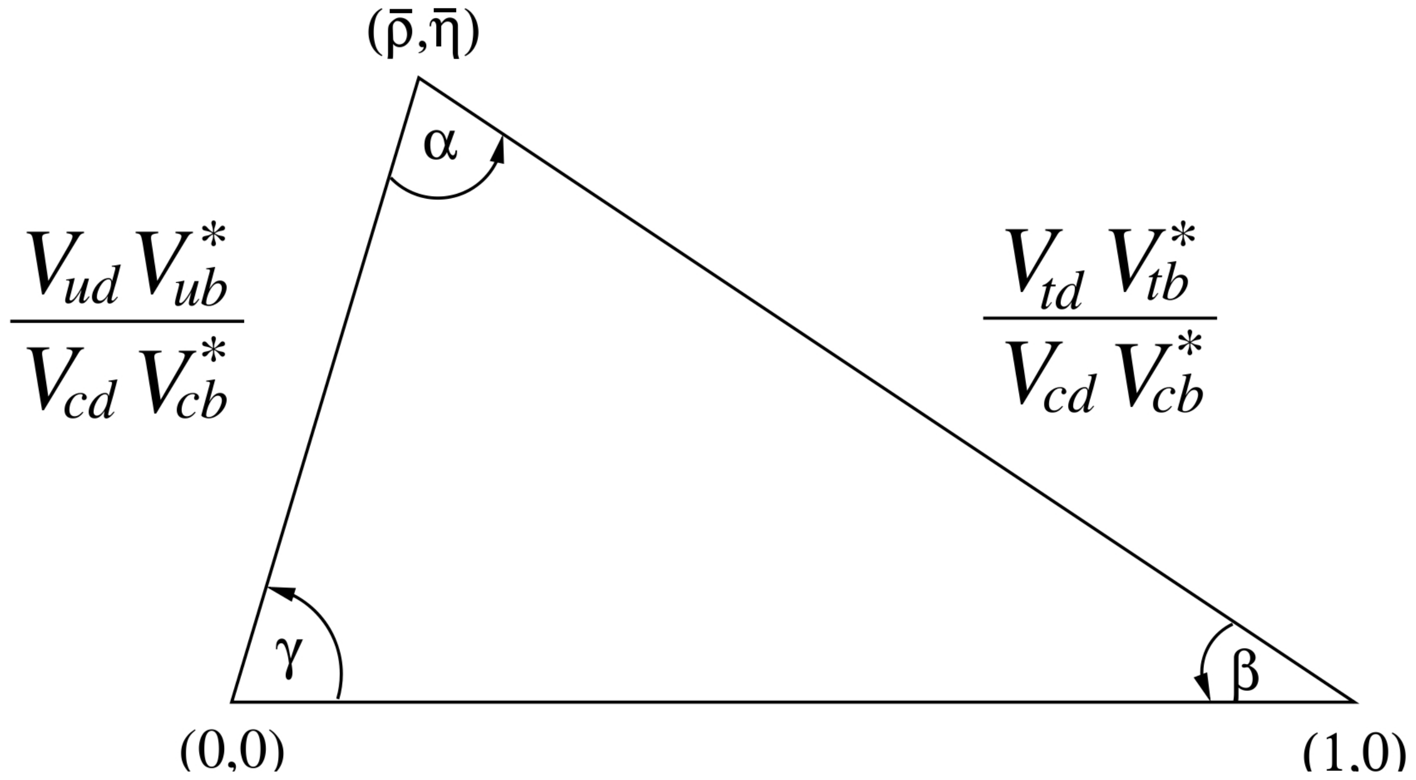
CKM Matrix: Experimental

$$B_d \text{ meson (bd)}: \quad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \quad (\lambda^3, \lambda^3, \lambda^3)$$

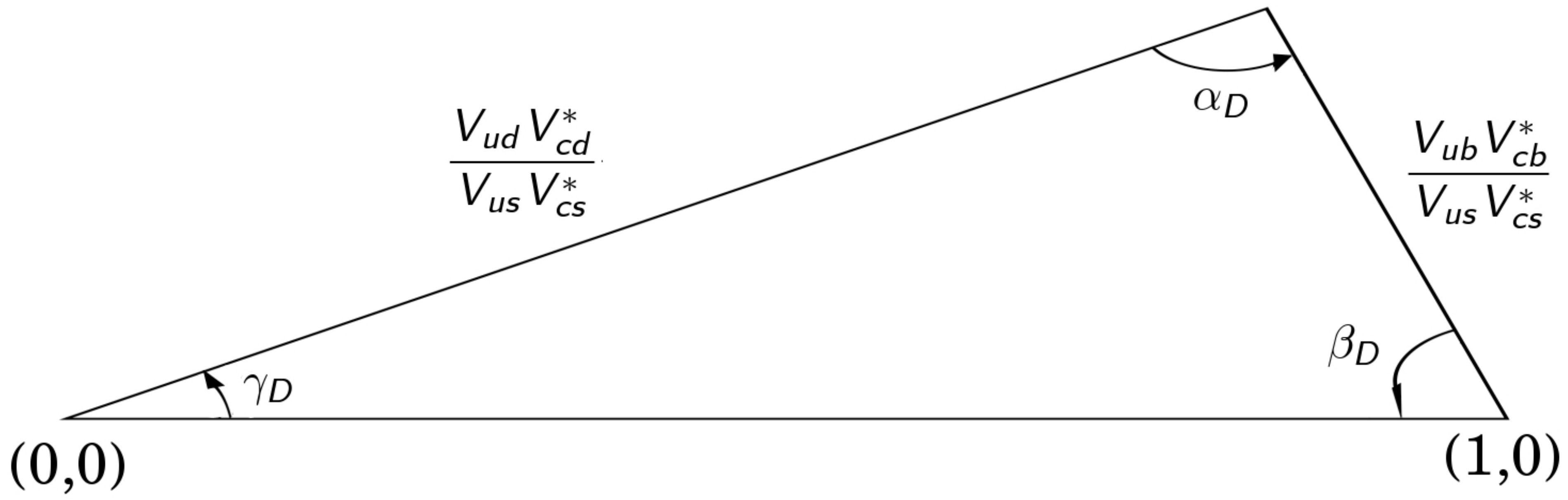
$$B_s \text{ meson (bs)}: \quad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0 \quad (\lambda^4, \lambda^2, \lambda^2)$$

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

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



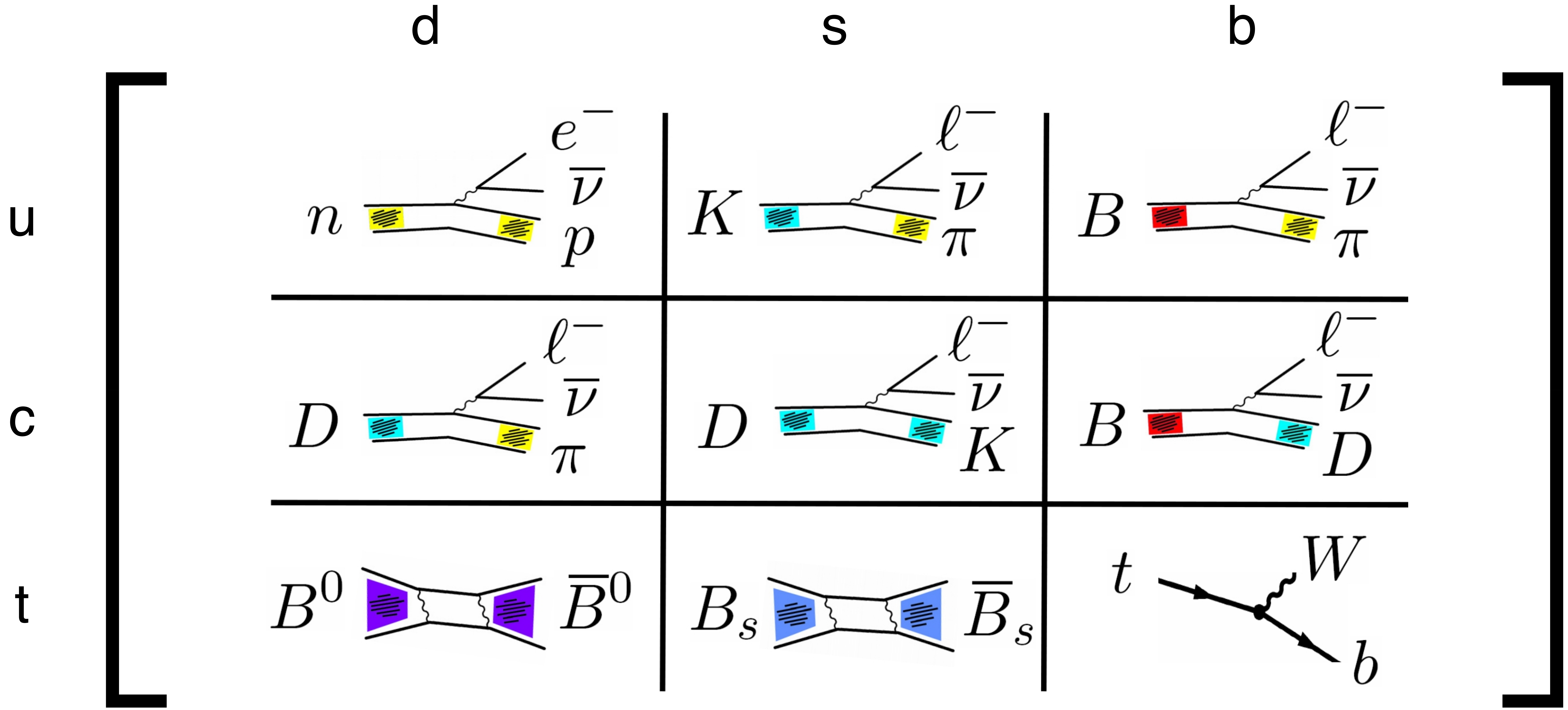
(small but non squashed)
B_D-meson triangle (bd)



(large but squashed)
D-meson triangle (cu)

In reality, people ~always talk about the (bd) triangle when talking about the CKM triangle.

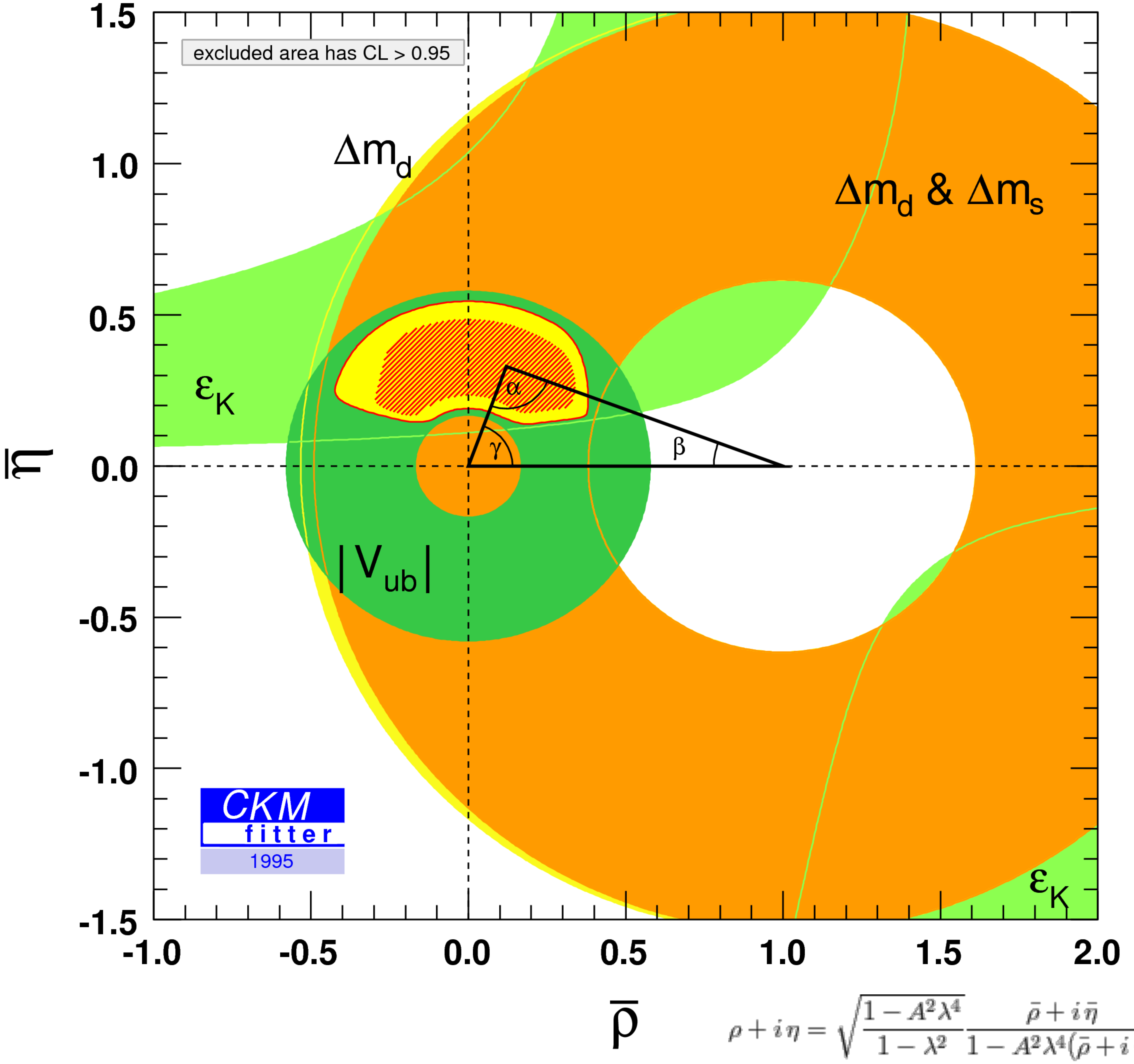
CKM Matrix: Measurements

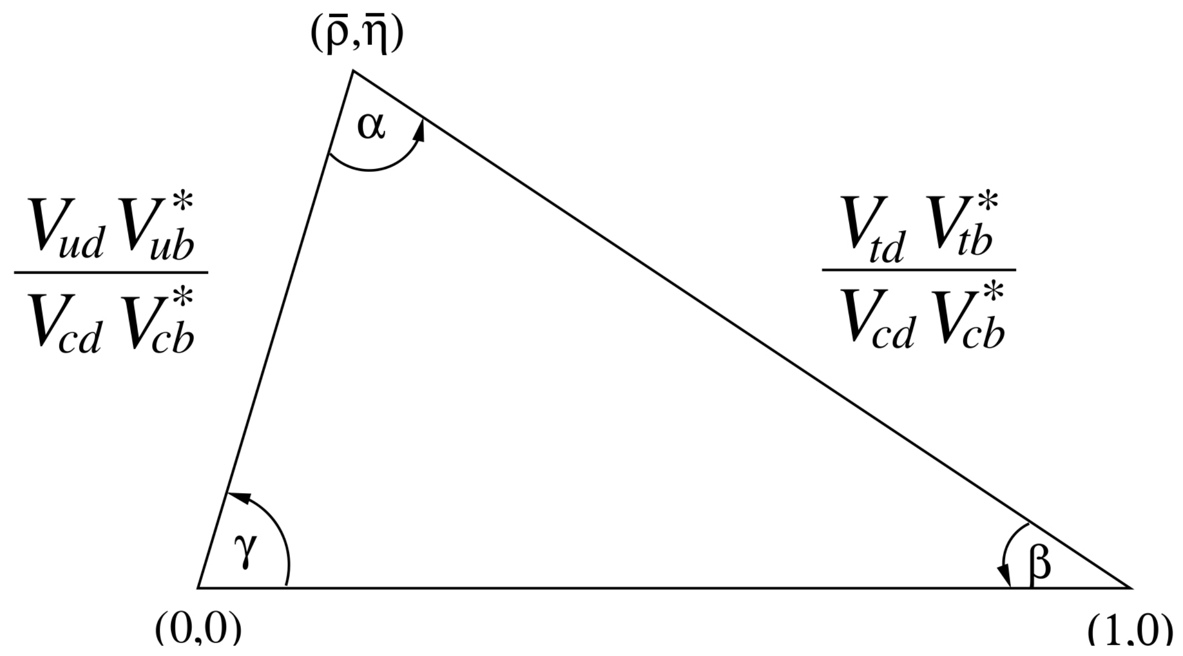


$d \to u$: Nuclear physics (superallowed β decays)
$s \to u$: Kaon physics (KLOE, KTeV, NA62)
$c \to d, s$: Charm physics (CLEO-c, Babar, Belle, BESIII)
$b \to u, c$ and $t \to d, s$: B physics (Babar, Belle, CDF, DØ, LHCb)
$t \to b$: Top physics (CDF/DØ, ATLAS, CMS)

CKM Matrix 1995

β,α,γ = Φ_1, Φ_2, Φ_3

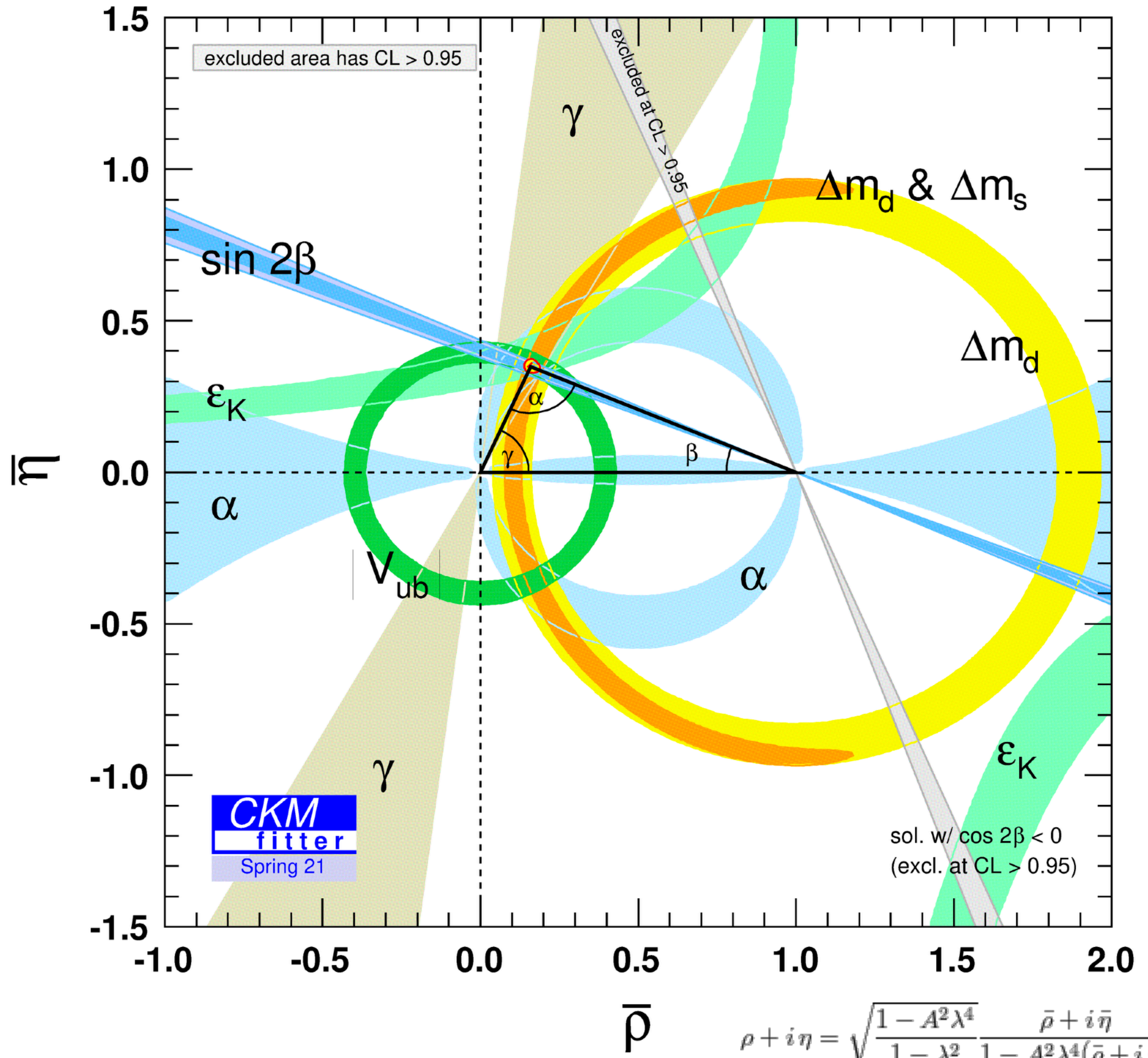


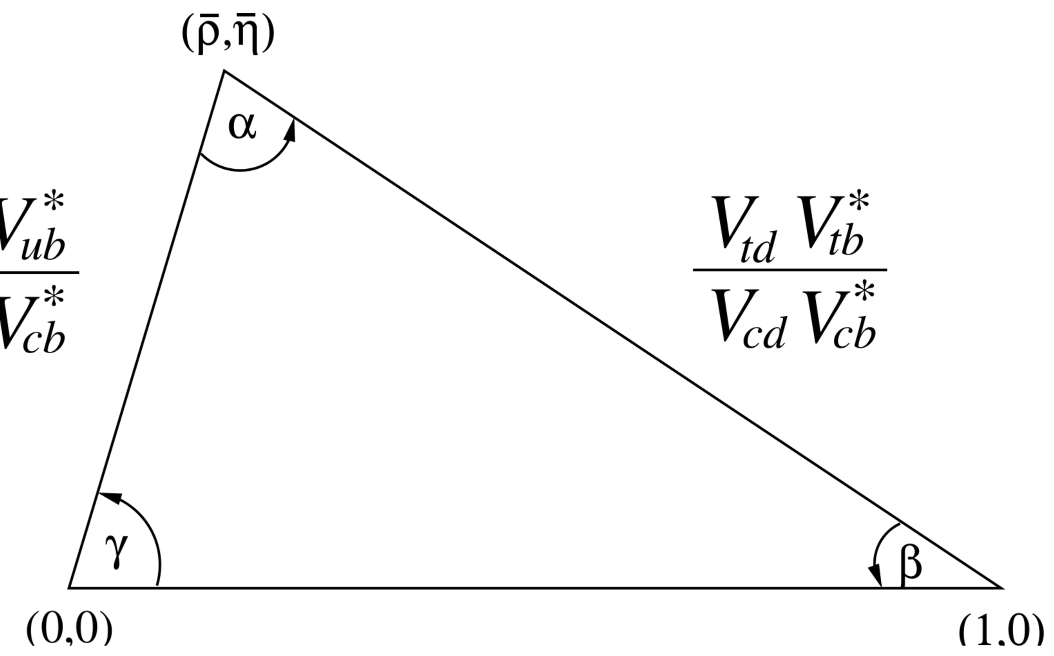


$$\rho + i\eta = \sqrt{\frac{1-A^2\lambda^4}{1-\lambda^2}}\frac{\bar\rho + i\bar\eta}{1-A^2\lambda^4(\bar\rho + i\bar\eta)} \simeq \left(1+\frac{\lambda^2}{2}\right)(\bar\rho + i\bar\eta) + \mathcal{O}(\lambda^4).$$

CKM Matrix 2021

$\beta, \alpha, \gamma = \Phi_1, \Phi_2, \Phi_3$



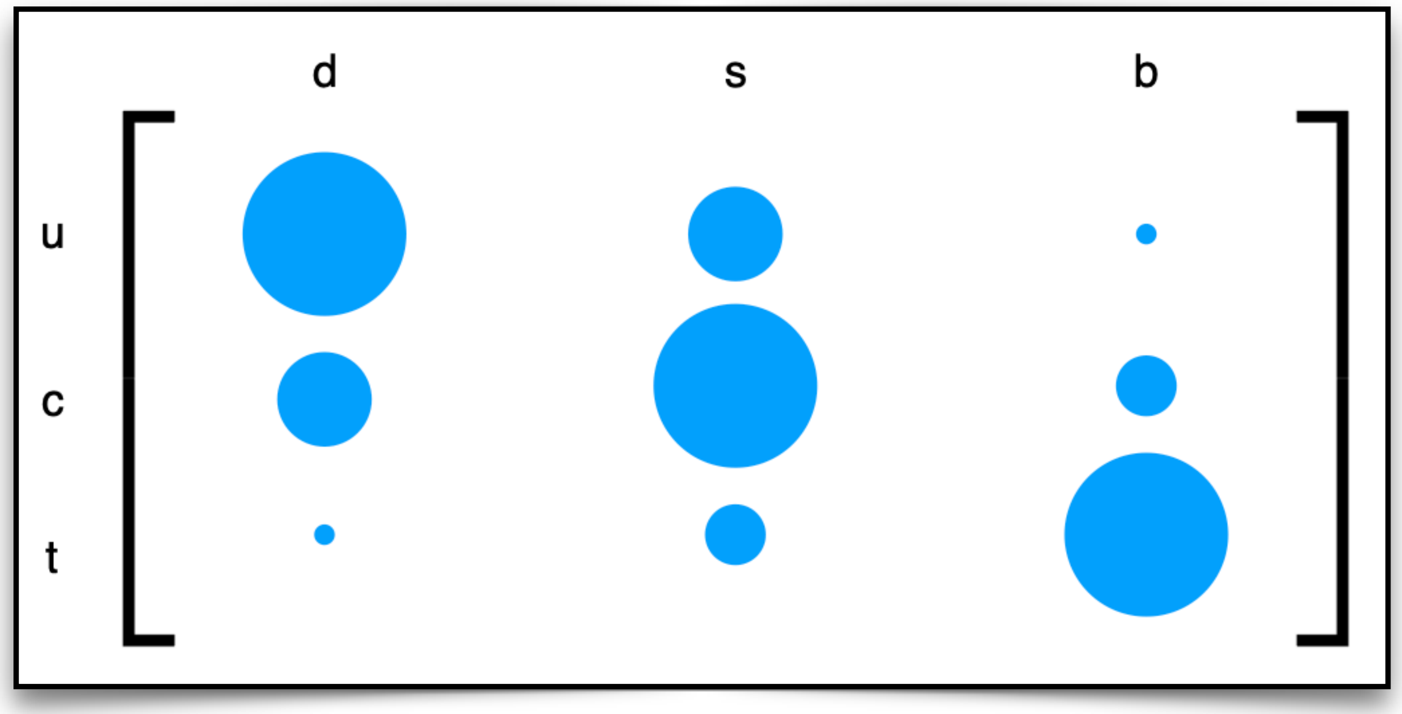


$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$ $\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}$

$$\rho + i\eta = \sqrt{\frac{1-A^2\lambda^4}{1-\lambda^2}}\frac{\bar\rho + i\bar\eta}{1-A^2\lambda^4(\bar\rho+i\bar\eta)} \simeq \left(1+\frac{\lambda^2}{2}\right)(\bar\rho+i\bar\eta)+\mathcal{O}(\lambda^4).$$

Interim Summary

- Concept of quark mixing:
  - **Cabibbo**: charged-current couplings smaller for quarks than for leptons
    →*u* quark couples to linear combination of *d* and *s* quark
  - **GIM**: flavor-changing neutral currents suppressed
    → 2×2 mixing matrix, charm quark predicted
  - **KM**: CP violation requires ≥3 quark families
    → 3×3 mixing matrix: CKM matrix, third quark family predicted, CP violation explained (later)
- CKM Matrix: Must be determined experimentally!
  - Unitary 3×3 matrix
  - 4 free parameters (3 angles and one phase)
  - Strong hierarchy, experimentally overconstrained

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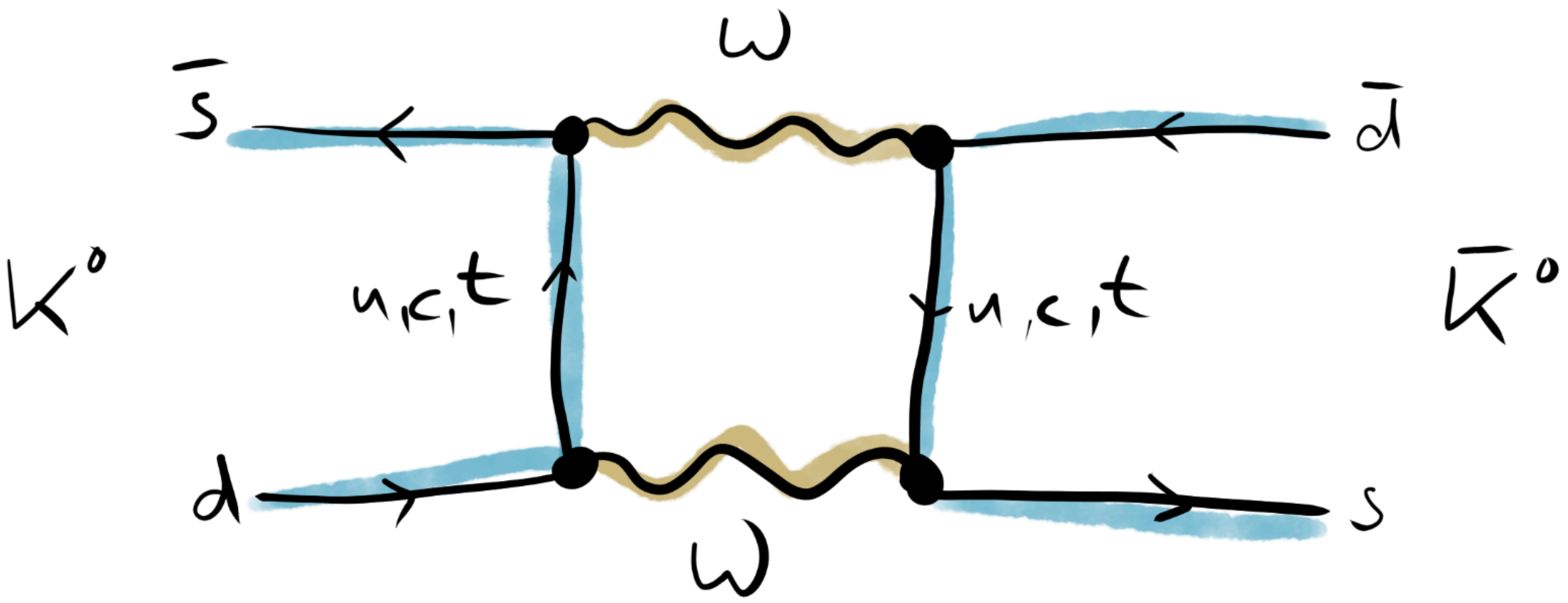
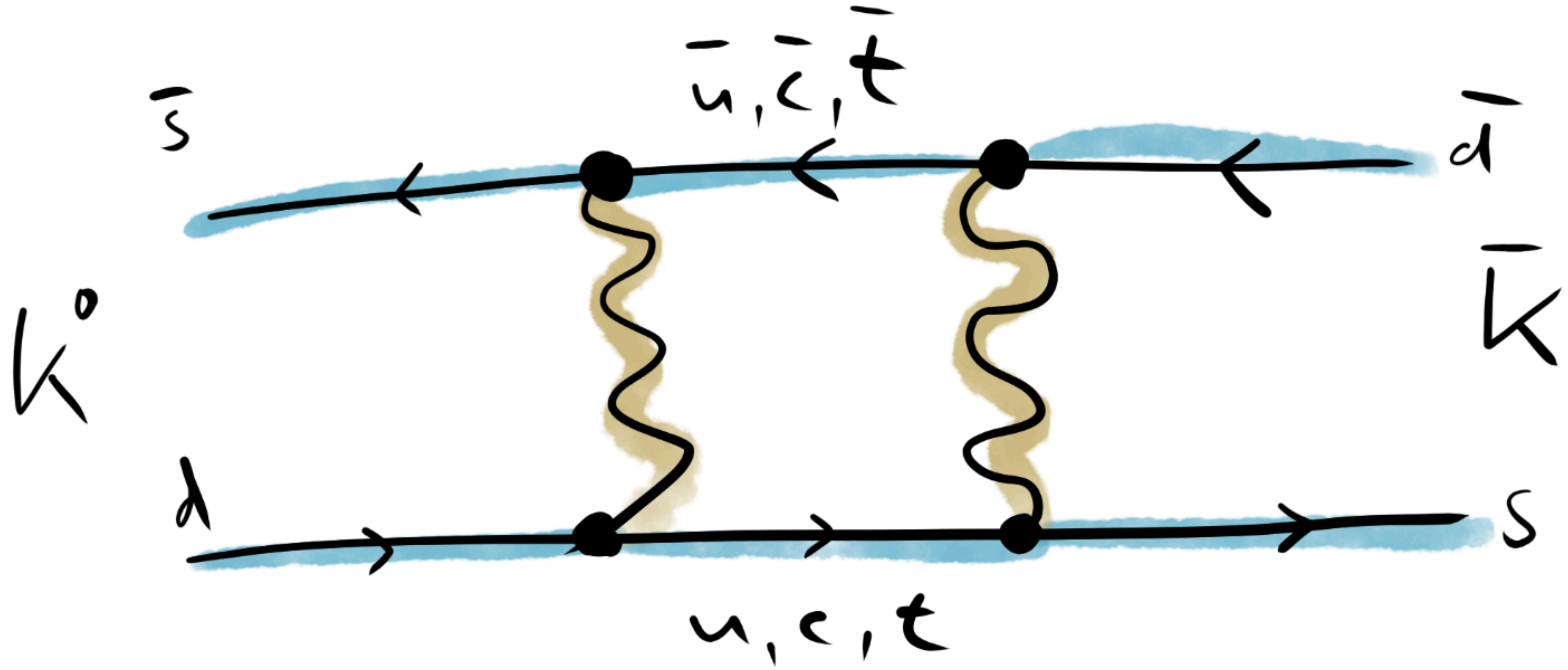
Meson-Antimeson-Mixing

- Hadrons are produced as **strong eigenstates** in strong interactions (reminder: all quantum numbers are conserved in QCD)
- Hadrons (and all particles) propagate as **mass eigenstates**
- Hadrons can decay via the **weak interaction**

  → In general, those eigenstates can be different (and nature choose this solution)
- This produces a strange phenomenon, known as **meson-antimeson mixing** (observed for neutral mesons K^0, D^0, B_d^0, B_s^0)
  - The physical idea is always the same, the resulting experimental observables are different
- Note that no Baryon oscillations (e.g. $n \leftrightarrow \bar{n}$) have been observed yet (Baryon number violation)

Meson-Antimeson-Mixing





Meson-Antimeson-Mixing

- Now the weirdness starts! (this is quantum mechanics at its best)
  - Starting point is a hadron produced as $|P\rangle$ or $|\bar{P}\rangle$ in a strong interaction
  - After a time Δt: Mixture of $|P\rangle$ or $|\bar{P}\rangle$, superimposed with (potential) particle decays (different lifetimes for different particles)
  - Description of the time evolution of such a system via the Schrödinger equation with an effective Hamiltonian

Meson-Antimeson-Mixing

- Time evolution

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|P(t)\rangle \\ |\bar{P}(t)\rangle\end{pmatrix} = \Sigma \begin{pmatrix}|P(t)\rangle \\ |\bar{P}(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|P(t)\rangle \\ |\bar{P}(t)\rangle\end{pmatrix} \text{ with } M^\dagger = M,\ \Gamma^\dagger = \Gamma$$

Mass matrix

Decay width matrix

- Components of the effective Hamiltonian:

$$\Sigma = M - i\frac{\Gamma}{2} = \begin{pmatrix} M_{11} - i\Gamma_{11}/2 & M_{12} - i\Gamma_{12}/2 \\ M_{12}^* - i\Gamma_{12}^*/2 & M_{22} - i\Gamma_{22}/2 \end{pmatrix}$$

- M_{11}, M_{22}: Quark masses and binding energies given by strong interaction
- $\Gamma_{11}, \Gamma_{22}, \Gamma_{12}, M_{12}$: Oscillations and decay through weak processes
- CPT symmetry: $M_{11} = M_{22} = m$, $\Gamma_{11}, \Gamma_{22} = \Gamma, \Gamma_{12} = \Gamma_{12}^*, M_{12} = M_{12}^*$

Meson-Antimeson-Mixing: Diagonalize

- Diagonalize the effective Hamiltonian operator to get physical masses and widths
  - Try linear combinations of $|P\rangle$ and $|\bar{P}\rangle$: $|P_L\rangle = p|P\rangle + q|\bar{P}\rangle$ and $|P_H\rangle = p|P\rangle - q|\bar{P}\rangle$ with complex p and q and $|p|^2 + |q|^2 = 1$. “L” and “H” stand for “light” and “heavy”.
- Time evolution of physical particles $|P_L\rangle$ and $|P_H\rangle$:
  - $$|P_{L,H}(t)\rangle = \exp\left(-iM_{L,H}t - \frac{\Gamma_{L,H}}{2}t\right)|P_{L,H}\rangle$$
- Time evolution of flavour eigenstates $|P\rangle$ and $|P\rangle$:
  - $$\begin{pmatrix}|P(t)\rangle\\ |\overline{P}(t)\rangle\end{pmatrix} = \begin{pmatrix}p & p\\ q & -q\end{pmatrix}\begin{pmatrix}\exp\left[-iM_Lt - \frac{\Gamma_L}{2}t\right] & 0\\ 0 & \exp\left[-iM_Ht - \frac{\Gamma_H}{2}t\right]\end{pmatrix}\begin{pmatrix}p & p\\ q & -q\end{pmatrix}^{-1}\begin{pmatrix}|P\rangle\\ |\overline{P}\rangle\end{pmatrix}$$

Meson-Antimeson-Mixing: Result

- Result of the (rather short) calculation:

$$\begin{pmatrix} |P(t)\rangle \\ |\overline{P}(t)\rangle \end{pmatrix} = \begin{pmatrix} g_+(t) & \frac{p}{q} g_-(t) \\ \frac{q}{p} g_-(t) & g_+(t) \end{pmatrix} \begin{pmatrix} |P\rangle \\ |\overline{P}\rangle \end{pmatrix}$$

$$\text{with } g_\pm(t) = \frac{1}{2}\left(\exp\left[-iM_L t - \frac{\Gamma_L}{2} t\right] \pm \exp\left[-iM_H t - \frac{\Gamma_H}{2} t\right]\right)$$

- Interpretation as transition probabilities:

$|g_+(t)|^2$: probability for $|\mathrm{P}\rangle$ ($|\overline{\mathrm{P}}\rangle$) to remain in the same state

$|q/p|^2 |g_-(t)|^2$: probability for $|\mathrm{P}\rangle$ to oscillate to $|\overline{\mathrm{P}}\rangle$ after time interval t

$|p/q|^2 |g_-(t)|^2$: probability for $|\overline{\mathrm{P}}\rangle$ to oscillate to $|\mathrm{P}\rangle$ after time interval t

Meson-Antimeson-Mixing

- As usual (you should be used to this by now) it is convention to express the light and heavy mass eigenstates by their averages:

$$m = M_{11} = M_{22} = \frac{1}{2}(M_H + M_L) \qquad \Gamma = \Gamma_{11} = \Gamma_{22} = \frac{1}{2}(\Gamma_L + \Gamma_H)$$

$$\Delta m = M_H - M_L \qquad \Delta\Gamma = \Gamma_L - \Gamma_H$$

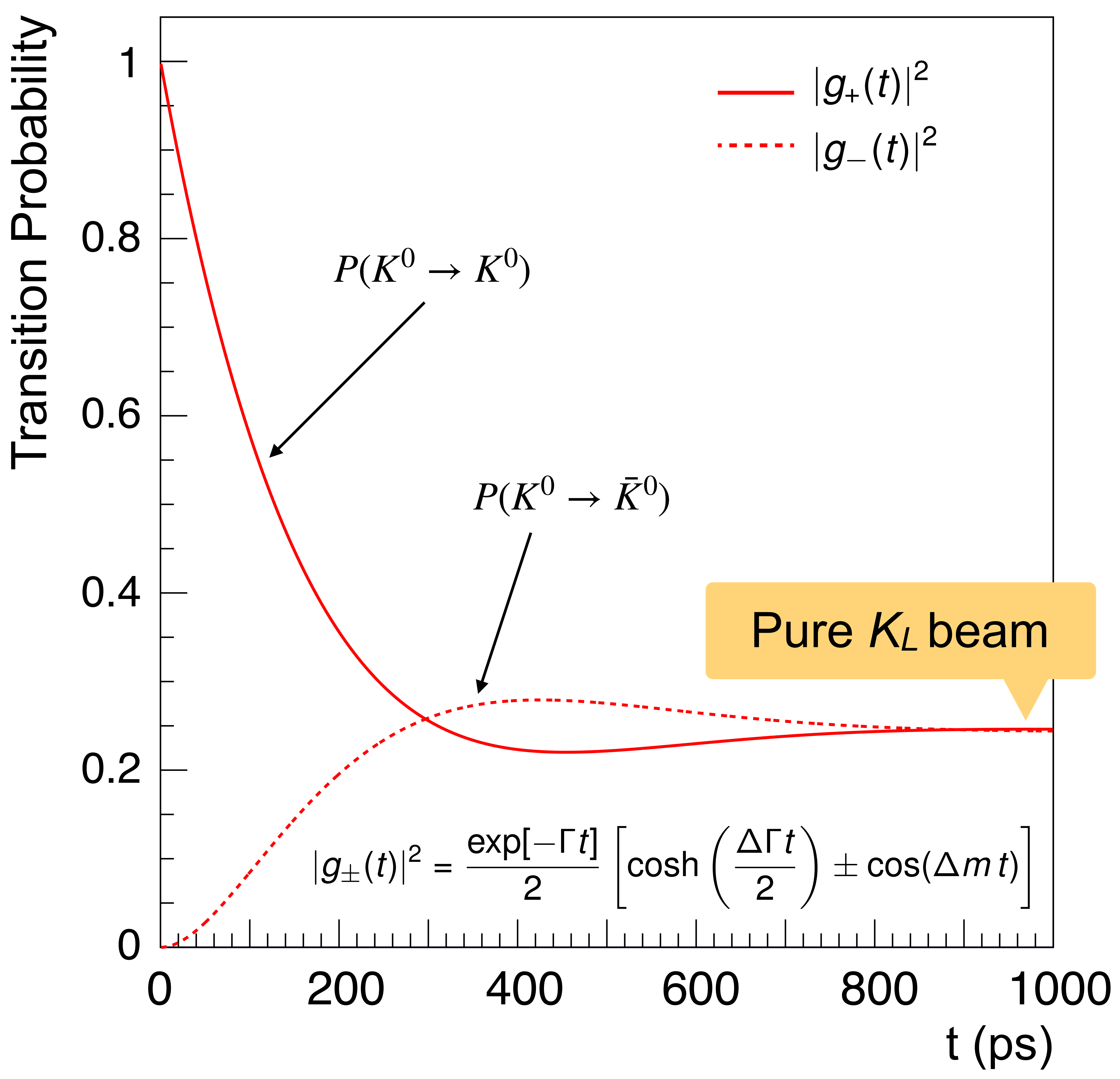
sometimes also: $x = \dfrac{\Delta m}{\Gamma}$

- Express the transition probabilities as function of these variables:

$$|g_\pm(t)|^2 = \underbrace{\frac{\exp[-\Gamma t]}{2}}_{\text{Decay}} \left[\underbrace{\cosh\left(\frac{\Delta\Gamma t}{2}\right)}_{\text{Oscillation due to decay width difference}} \pm \underbrace{\cos(\Delta m\, t)}_{\text{Oscillation due to mass difference}}\right]$$

Neutral kaons

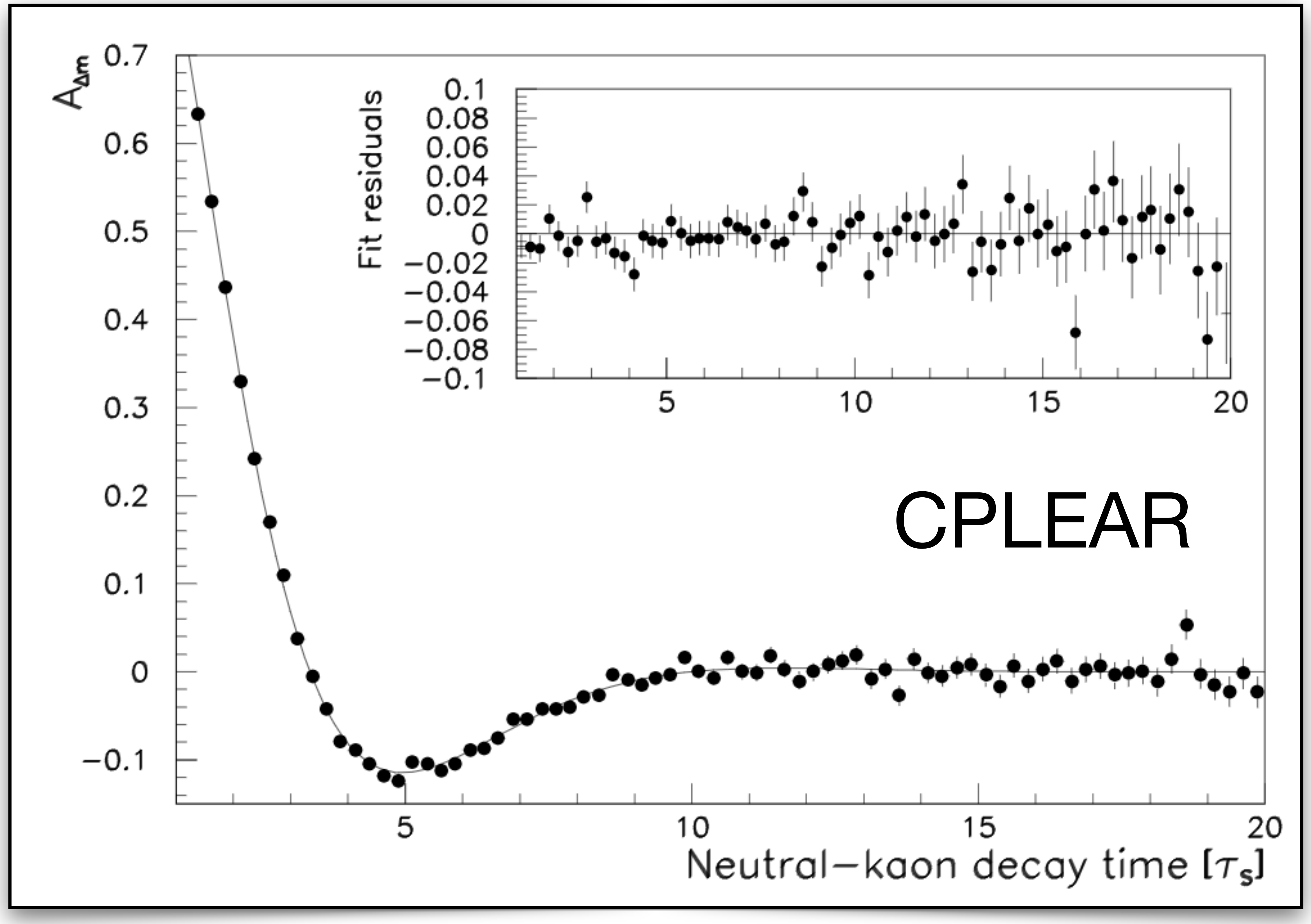
- Historically: Mass eigenstates identified by their lifetimes ("K short" and "K long"), $|P_L\rangle = |K_S^0\rangle$ and $|P_H\rangle = |K_L^0\rangle$
  - $\Gamma = 1/178.8$ ps
  - $\Delta\Gamma_d \approx \Gamma$ ($|P_L\rangle$ decays very fast)
  - $\Delta M_d = 0.507$ ps^{-1}
- → practically no oscillation since one component decays very fast



Kaon mixing

$$A_{\Delta m}(\tau) = \frac{[R_+(\tau) + \overline{R}_-(\tau)] - [\overline{R}_+(\tau) + R_-(\tau)]}{[R_+(\tau) + \overline{R}_-(\tau)] + [\overline{R}_+(\tau) + R_-(\tau)]}$$

$$R_+(\tau) \equiv R(\mathrm{K^0}_{t=0} \to \mathrm{e}^+\pi^-\nu_{t=\tau})$$
$$R_-(\tau) \equiv R(\mathrm{K^0}_{t=0} \to \mathrm{e}^-\pi^+\overline{\nu}_{t=\tau})$$
$$\overline{R}_-(\tau) \equiv R(\overline{\mathrm{K}}^0{}_{t=0} \to \mathrm{e}^-\pi^+\overline{\nu}_{t=\tau})$$
$$\overline{R}_+(\tau) \equiv R(\overline{\mathrm{K}}^0{}_{t=0} \to \mathrm{e}^+\pi^-\nu_{t=\tau})$$

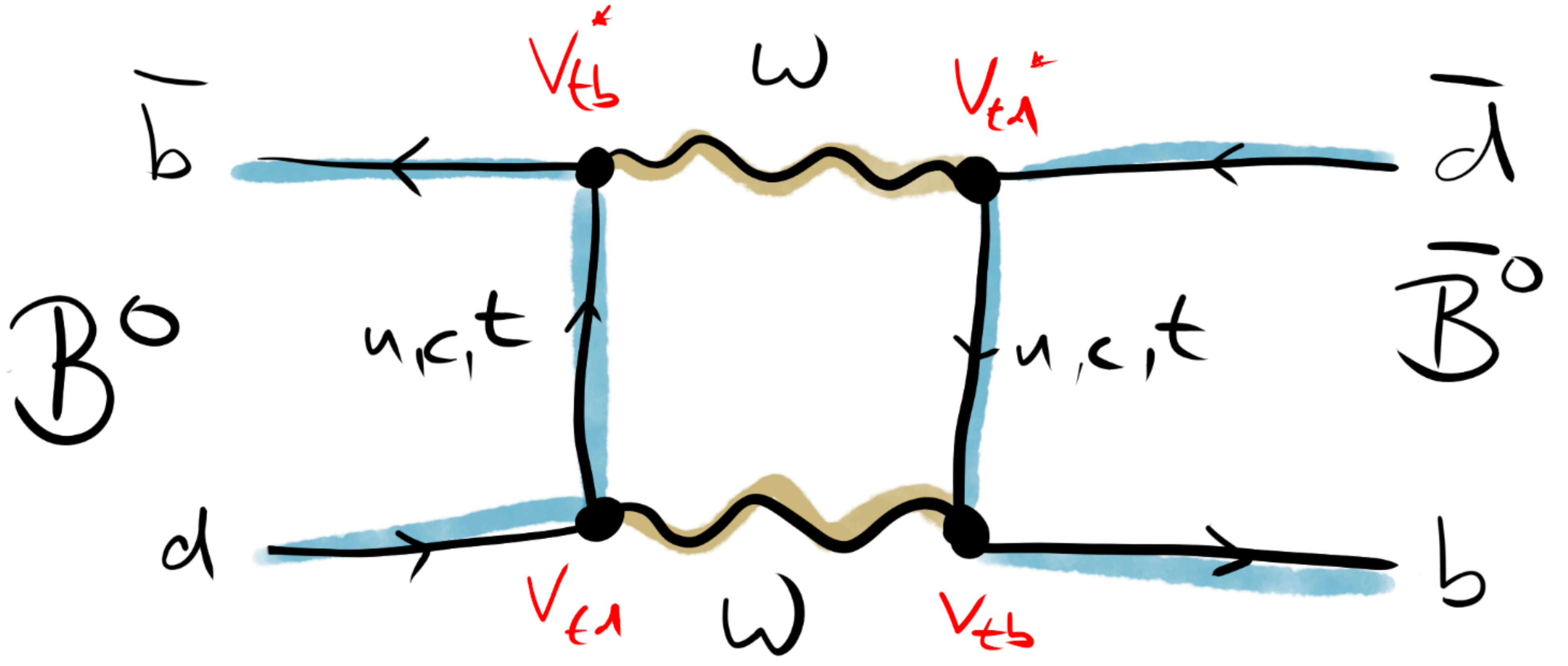


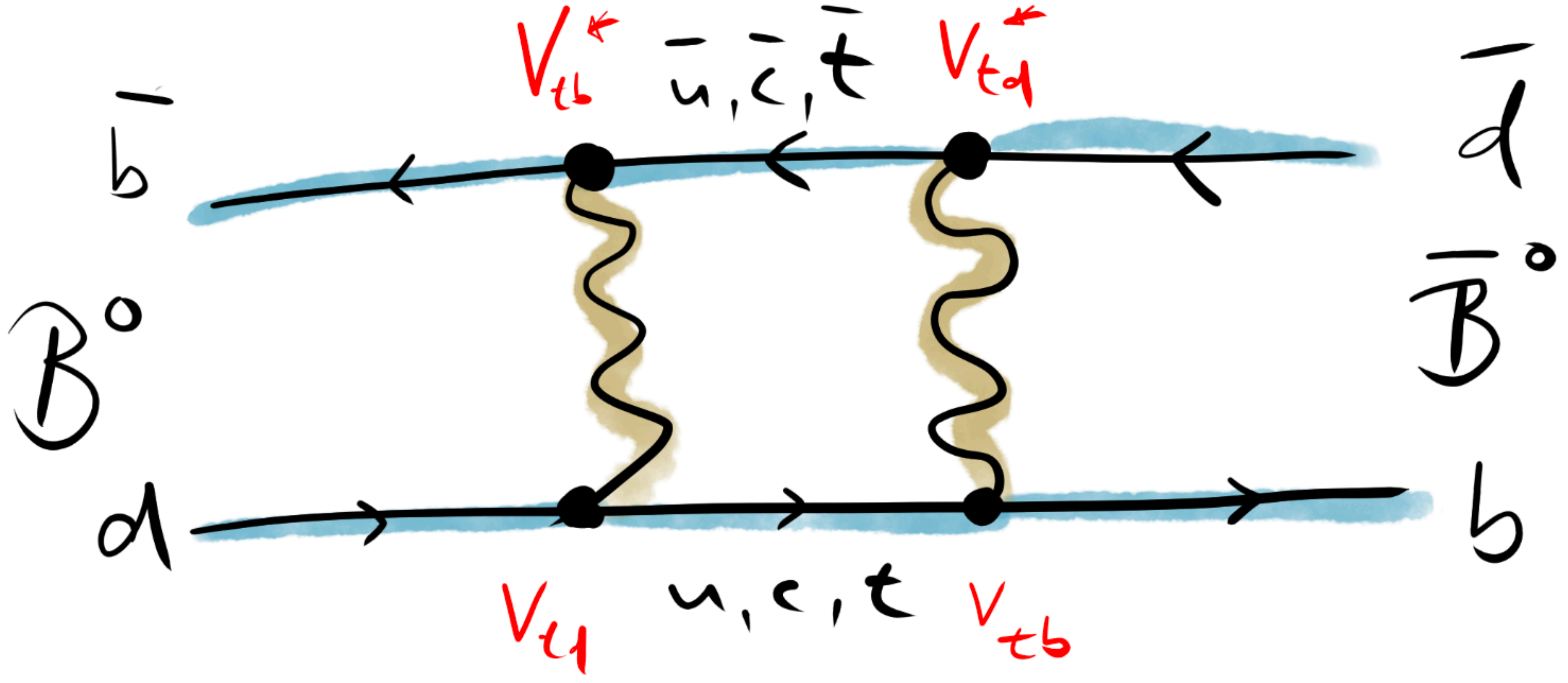
Source: Phys. Lett. B 444 (1998) 38-42

Neutral B-mesons: B_d^0

- Since $|V_{td}| \approx 0$, the top quark is the (by far) most relevant contribution here

- Large top (large mass predicted $m_t > 50$ GeV) predicted already long before LEP global fits or the actual discovery of the top

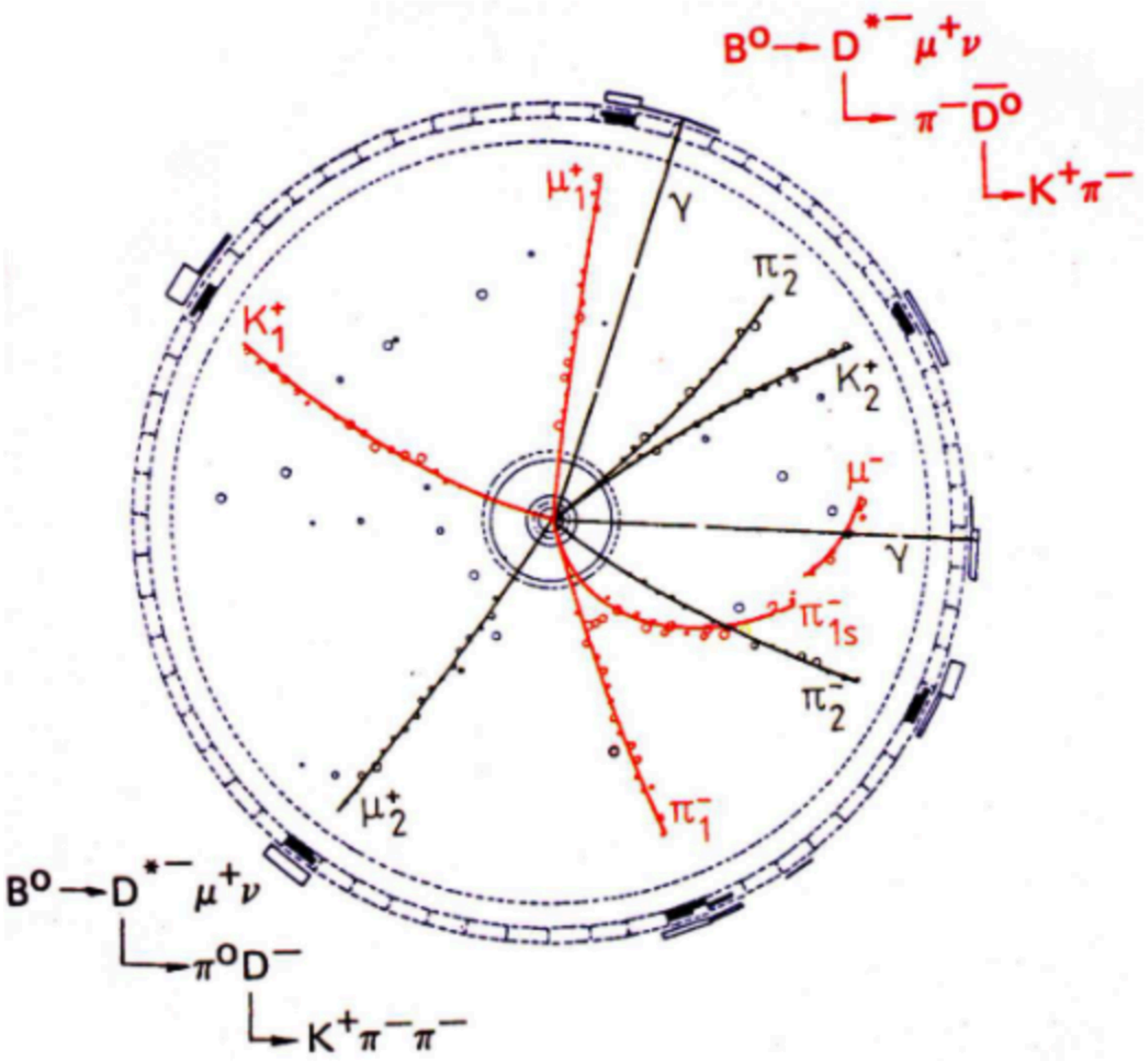




Neutral B-mesons oscillation at ARGUS

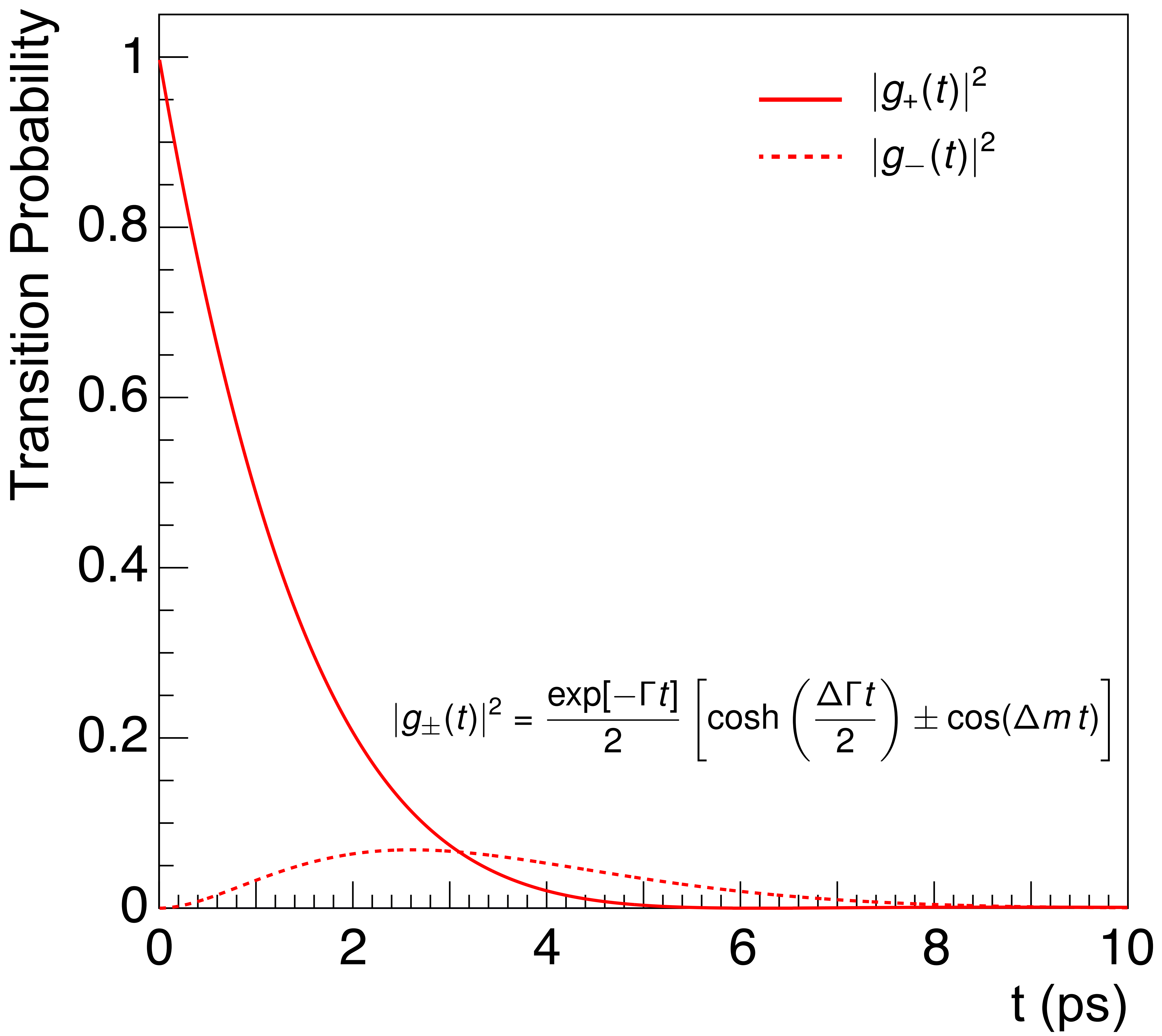
Credit: Aleksander Mielczarek

Discovery of B-meson mixing



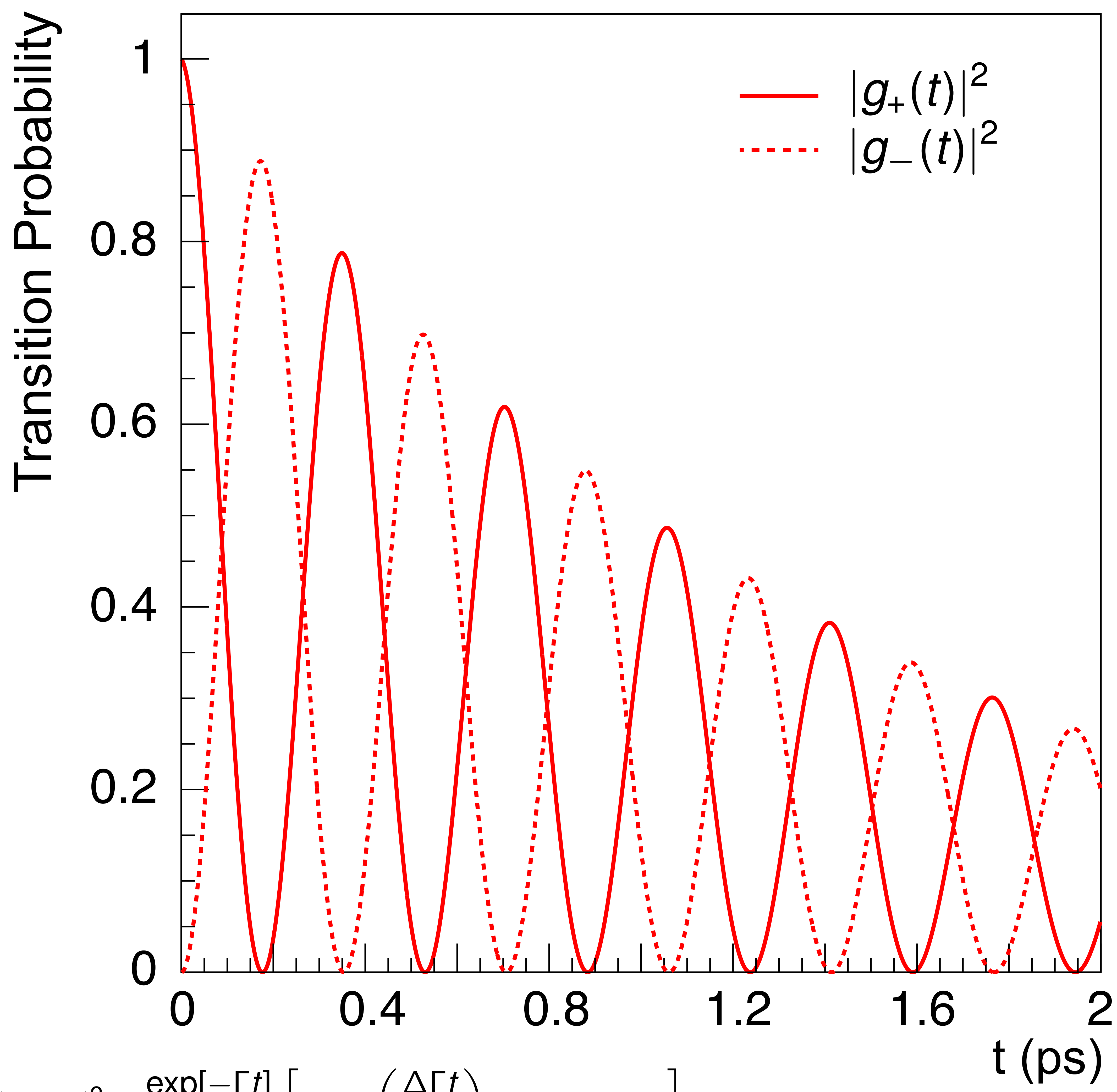
Neutral B-mesons: B_d^0

- Oscillation parameters
  - $\Gamma_d = 1/1.53$ ps
  - $\Delta\Gamma_d \approx 0$
  - $\Delta M_d = 0.53$ ps^{-1}
- Lifetime approximately one oscillation period before decay
- Oscillation dominated by mass difference ΔM_d



Neutral B-mesons: B_s^0

- Oscillation parameters
  - $\Gamma_s = 1/1.47$ ps
  - $\Delta\Gamma_s \approx 0$
  - $\Delta M_s = 17.77$ ps^{-1}
- Very fast oscillations, many periods before decay
- Oscillation dominated by mass difference ΔM_s



$$|g_\pm(t)|^2 = \frac{\exp[-\Gamma t]}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) \pm \cos(\Delta m t)\right]$$

What questions do you have?