QFT with Hadrons

Introduction to B Physics

1. Leptonic Decays of Hadrons: from $\pi \to \ell\nu$ to $B \to \ell\nu$

QFT in Hadron Decays. Decay Constants. Helicity Suppression in the SM.

2. On the Structure and Unitarity of the CKM Matrix

The CKM Matrix. The GIM Mechanism. The Unitarity Triangle.

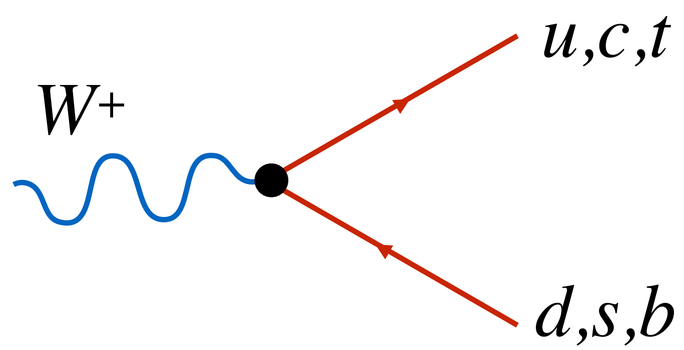
3. Semi-Leptonic Decays and the "Flavour Anomalies"

$B \to D^{(*)} \ell \nu$. The Spectator Model. Form Factors. Heavy Quark Symmetry.

$B \to K^{(*)} \ell^+ \ell^-$. FCNC. Aspects beyond tree level. Penguins. The OPE.

Peter Skands
Monash University

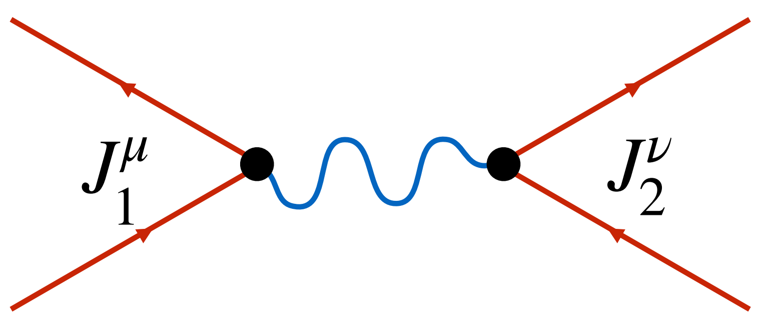
Consider *W* interactions with quarks *("charged current")*



For now, assume free quarks, for simplicity

(will reintroduce effects of confinement later.)

Generic amplitude for *W* exchange between two **fermion currents**, J_1, J_2:



$$\mathscr{M} = \frac{4G_F}{\sqrt{2}} J_1^\mu J_{2\mu}^\dagger$$

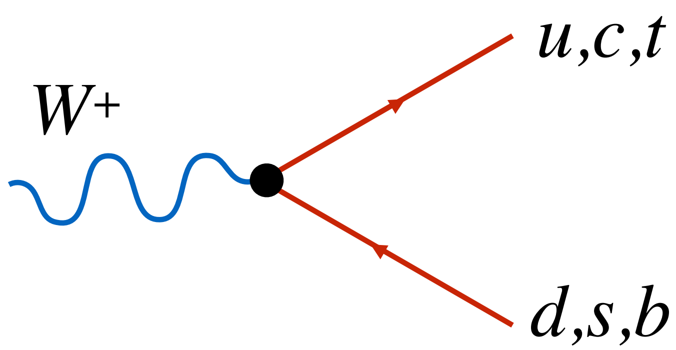
Question: What assumption has been made about q_W^2 here?

$$\text{with} \quad J^\mu_{\text{quark}} = (\bar{u}, \bar{c}, \bar{t})\, \gamma^\mu \tfrac{1}{2}(1-\gamma_5)\, U \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitary matrix

Recap: Charged-Current Processes at Low Energies

Consider *W* interactions with quarks *("charged current")*



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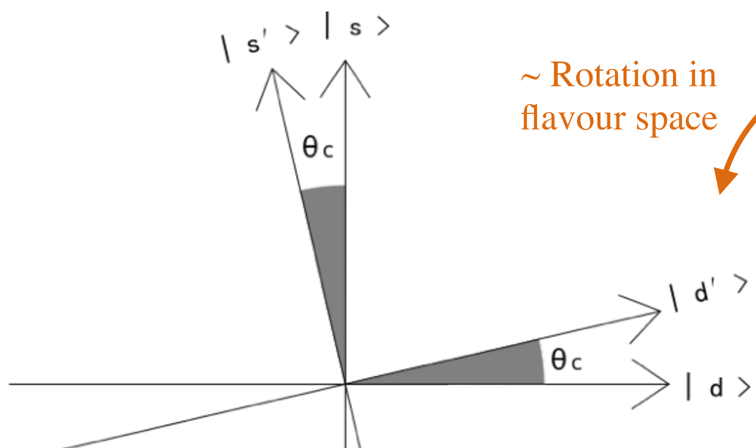
Unitary matrix

~ Rotation in flavour space



SU(2)$_L$ Weak-interaction ("current") eigenstates slightly **rotated** relative to Hamiltonian ("mass") eigenstates

$$\sum_i \bar{d}'_i d'_i = \sum_j \bar{d}_j d_j \qquad \text{(due to unitarity)}$$

(same for leptons*, with U = 1)

*Note I use the word **lepton** to refer collectively to charged leptons + neutrinos

Historical example: first two generations:

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

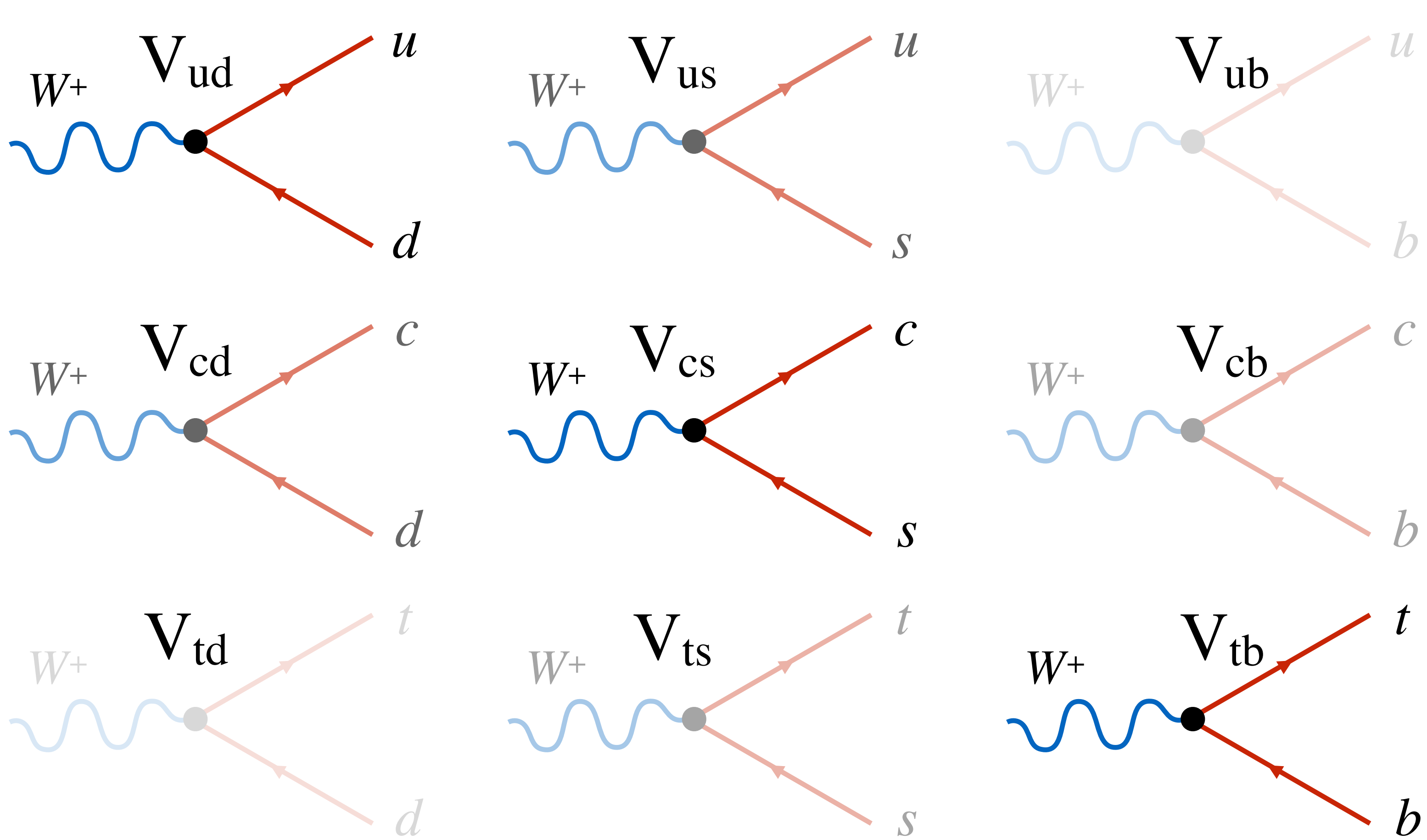
with "**Cabibbo Angle**" $\theta_C \sim 13°$

➤ $\sin\theta_C \sim 0.23$

Recap: The CKM Matrix

"**Wolfenstein** parametrisation", to O(λ^2)

$$U = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} \boxed{1-\frac{1}{2}\lambda^2} & \boxed{\lambda} & \mathcal{O}(\lambda^3) \\ \boxed{-\lambda} & \boxed{1-\frac{1}{2}\lambda^2} & \boxed{A\lambda^2} \\ \mathcal{O}(\lambda^3) & \boxed{-A\lambda^2} & \boxed{1} \end{pmatrix} + \mathcal{O}(\lambda^4)$$



$$\lambda \sim \sin\theta_C$$
$$\sim 0.23$$

$$A \sim 0.81$$

+ two more parameters (ρ, η),
to specify complex V_{ub}, V_{td}

Note: there *are* other parametrisations, such as the "PDG" parametrisation: same numerical values of V_{ij}, cast in terms of a 3 rotation angles and a phase instead of (λ, A, ρ, η)

The CKM elements in Physical Processes

(Note that most of these processes are charged-current **semileptonic** decays)

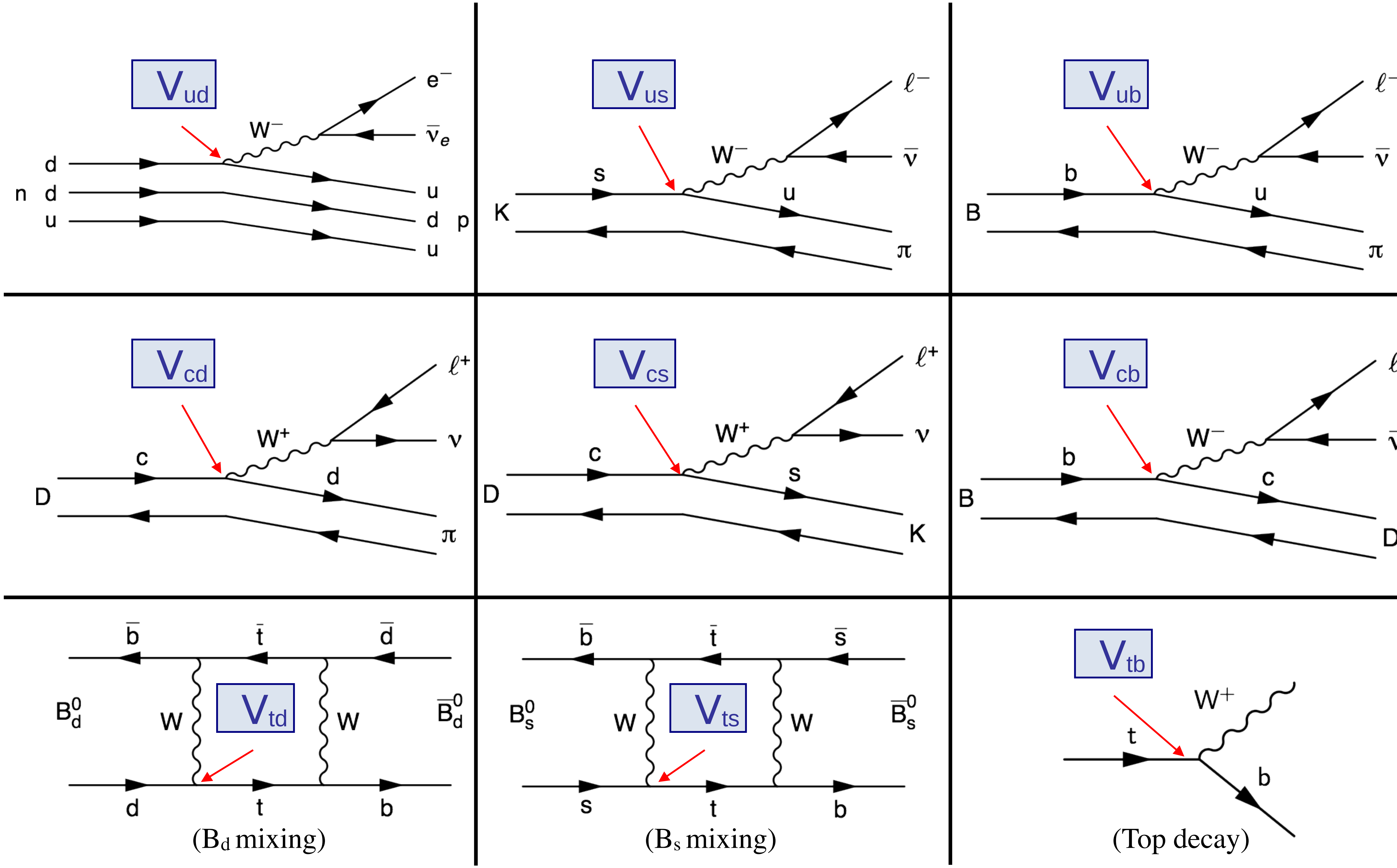


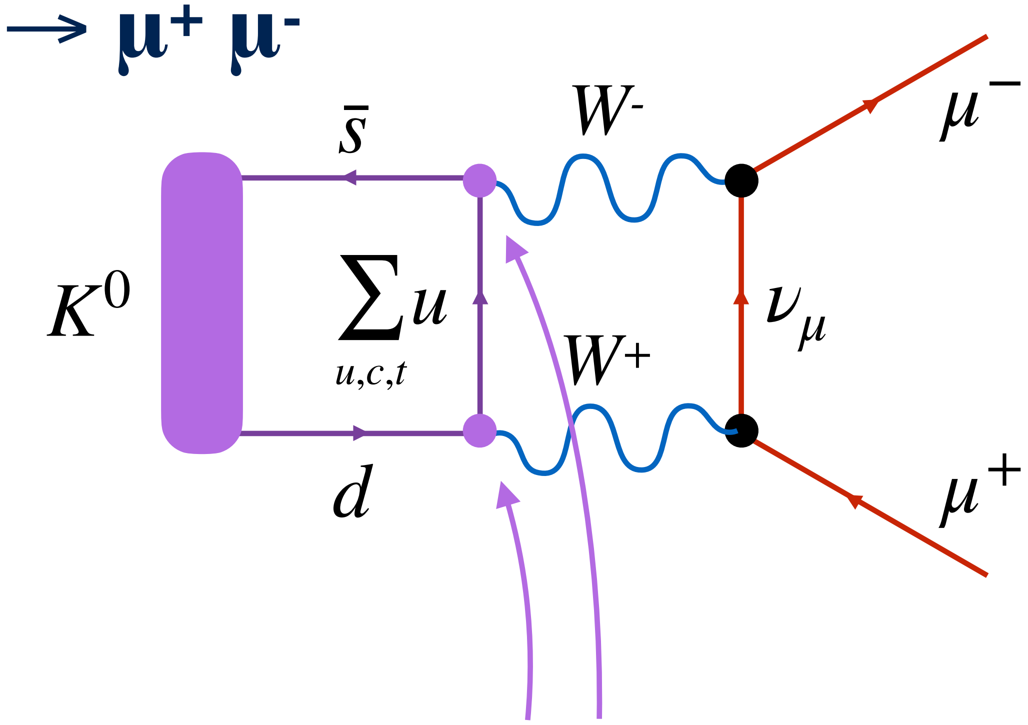
Illustration by M. Bona

Consequences of CKM Unitarity 1: The GIM Mechanism

S.L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285.

Off-diagonal CKM terms imply amplitudes for processes like:

$\boldsymbol{K^0 \to \mu^+ \mu^-}$



Expect $M \propto G_F V_{us} \sim G_F \sin\theta_C$

Observed to be much more strongly suppressed (BR~10^{-8})

Historical Note: *the absence of the processes discussed on this slide led GIM to* ***predict*** *the existence of the charm quark!*

Unitarity: $\sum_j V_{ij} V^\dagger_{jk} = \delta_{jk}$

(Summed amplitude small but non-zero because $m_c \neq m_u$)

E.g.,: $V_{ud}V^*_{us} + V_{cd}V^*_{cs} \sim \cos\theta_C \sin\theta_C - \sin\theta_C \cos\theta_C = 0$

Also: $\begin{cases} K^+(u\bar{s}) \to \pi^+ e^+ e^- \\ K^+(u\bar{s}) \to \pi^+ \nu\bar{\nu} \end{cases}$

Exercise problem E4: draw diagrams analogous to the one above for these two processes and show how the GIM mechanism is at work in them.
Hint: One of the incoming quarks is a "spectator"

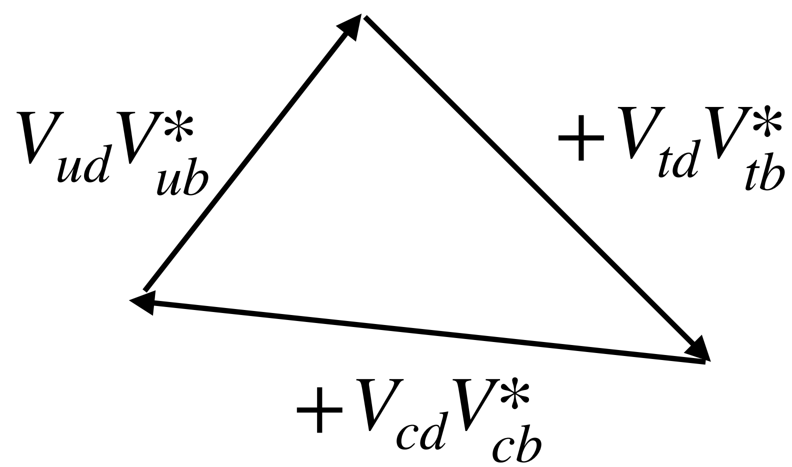
Write the unitarity constraints explicitly:

$$\sum_j V_{ij} V^\dagger_{jk} = \delta_{ik}$$

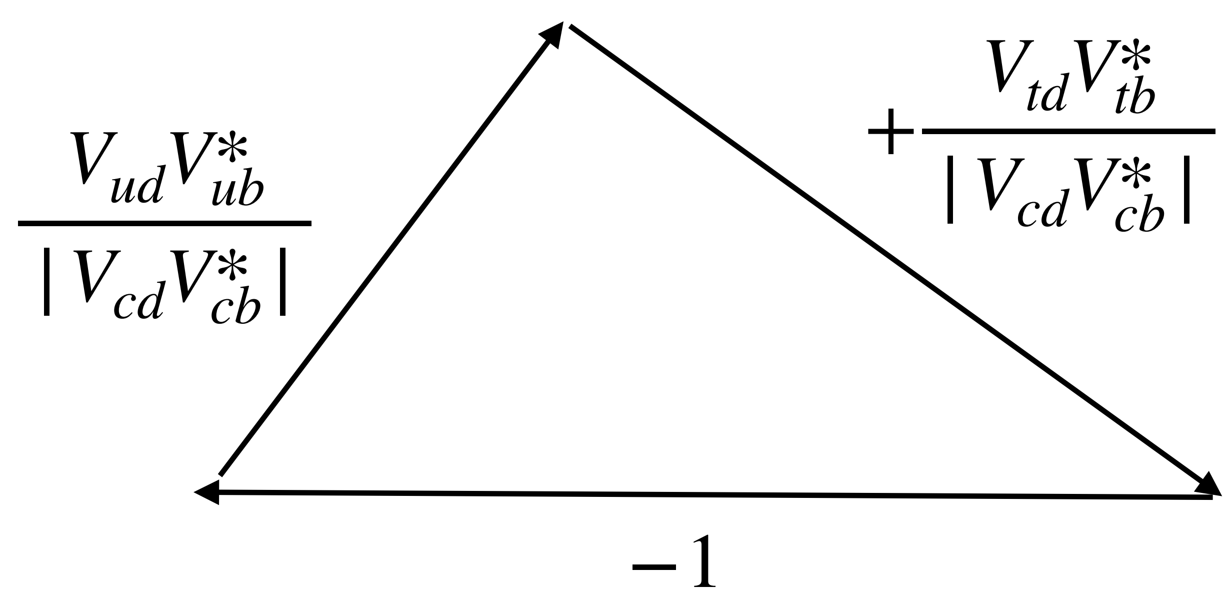
e.g.

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

Sum of three complex numbers = 0

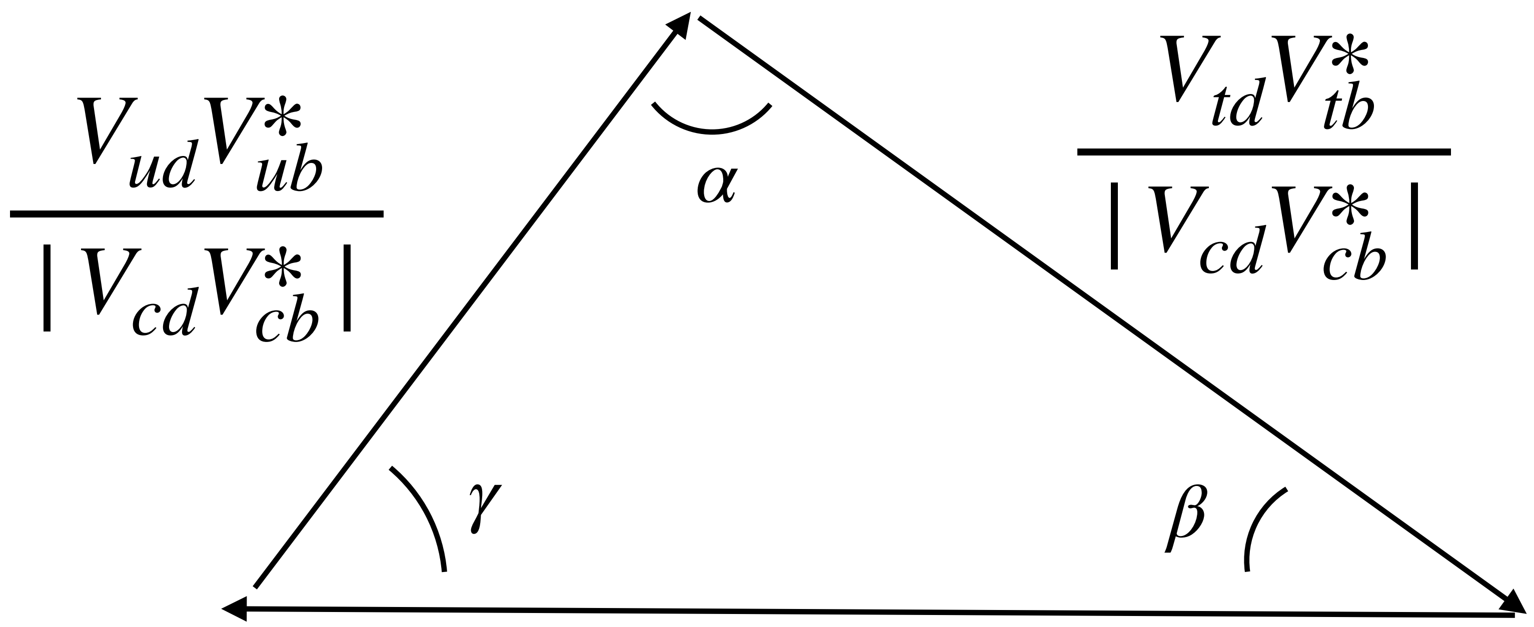


Normalise by $|V_{cd}V_{cb}^*|$:



Recap: The Unitarity Triangle*

This is called "the unitarity triangle"



Exercise problem E5: show mathematically why CPV is only observable in processes with at least two interfering amplitudes with different relative CKM phases.

Note: complex phases $\Rightarrow$ **CP Violation** (Note: requires **interfering** amplitudes)

➤ Measurements of CPV processes constrain relative phases.

$$\alpha = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*] = \phi_2$$

$$\beta = \arg[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*] = \phi_1$$

$$\gamma = \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*] = \phi_3$$

Different **weak processes** probe different combinations of the CKM elements ➜ constrain different sides or angles in the triangle.

Measure many processes

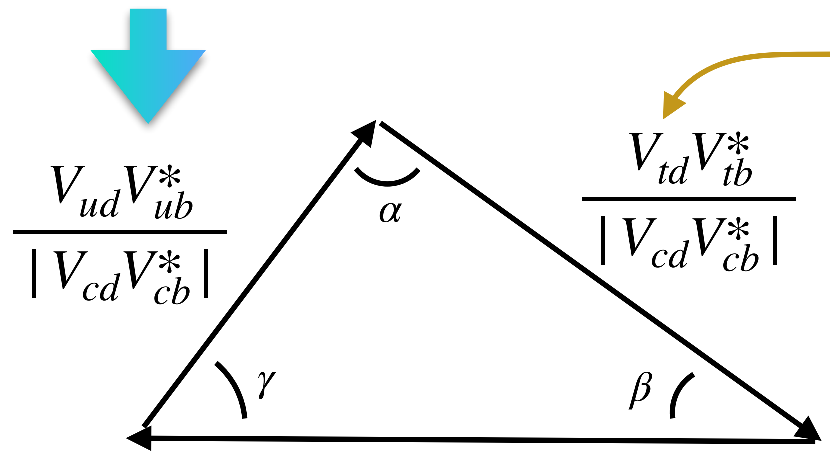
➜ Overconstrain the triangle = Test SM

(*In principle, each unitarity constraint has its own "triangle" - this is the standard one.)

Example: "Our" process, $B \to \tau\nu$, is proportional to $|V_{ub}|^2$:

First measured by Belle in 2012

https://arxiv.org/abs/1208.4678

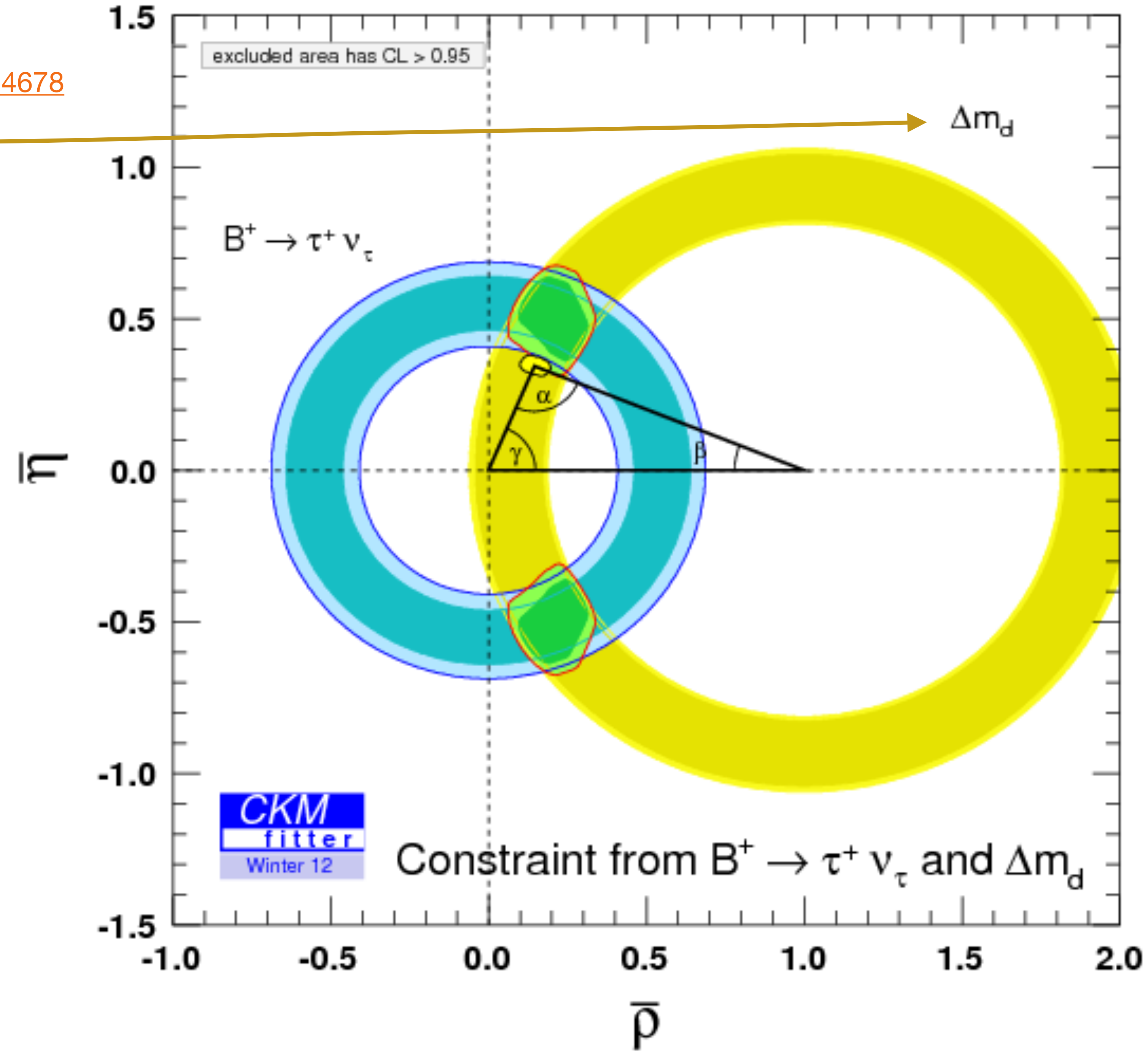


The first determination of V_{ub} from $B \to \tau\nu$ (combined with V_{td} from Δm_d)

➤ Green area(s)

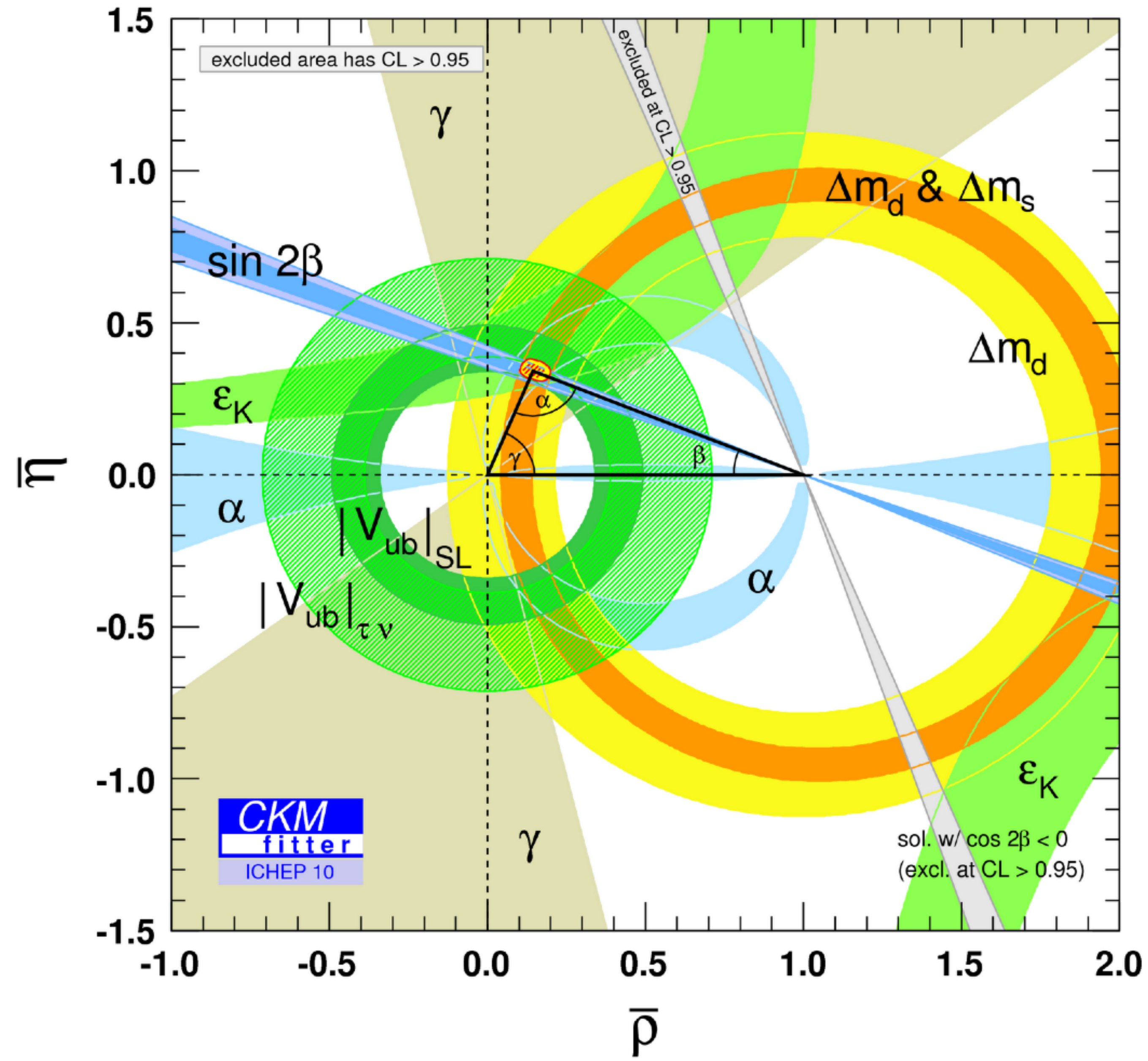
Seemed to be in slight tension with other existing constraints

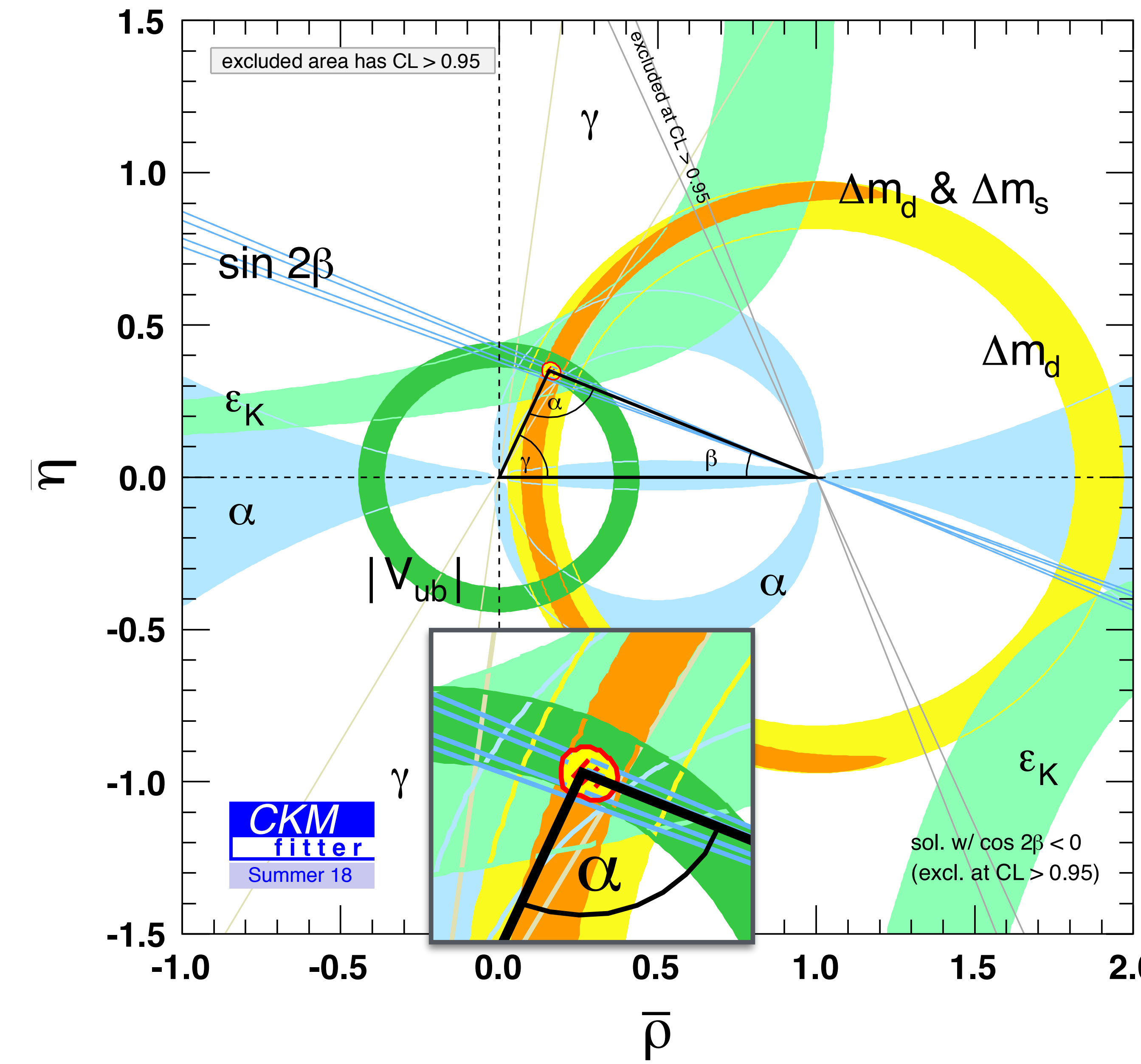
➤ (the little yellow area)



The Current Picture

Before (2010) → **Now (2018)**





Conclusion (for now):

All determinations of coordinates of top corner $(\bar{\rho},\bar{\eta})$ self-consistent at this level.

Why keep going?

The triangle *has to* break, at some point…

For 2023, explain the Sakharov conditions

+ maybe general considerations: new physics easily introduces new phase(s)

Summary of Problems and Exercises for Self Study

E4. Draw diagrams for processes on <u>p.6</u>; explain their GIM suppression

E5. Show why CPV is only physically observable in processes with at least two interfering amplitudes with different CKM phases.

E6. Draw LO Feynman diagrams for (1) $D^0 \to K^+\pi^-$ and (2) $D^0 \to K^-\pi^+$, and explain the observation that $\Gamma_{(1)} / \Gamma_{(2)} \sim 4 \times 10^{-3}$.

You will present your progress on these in the next lesson and we will discuss any questions / issues you encounter.

Assignment Problems 1&2 : the B physics research problems

Discrepancies between inclusive and exclusive determinations of V_{cb} and V_{ub}

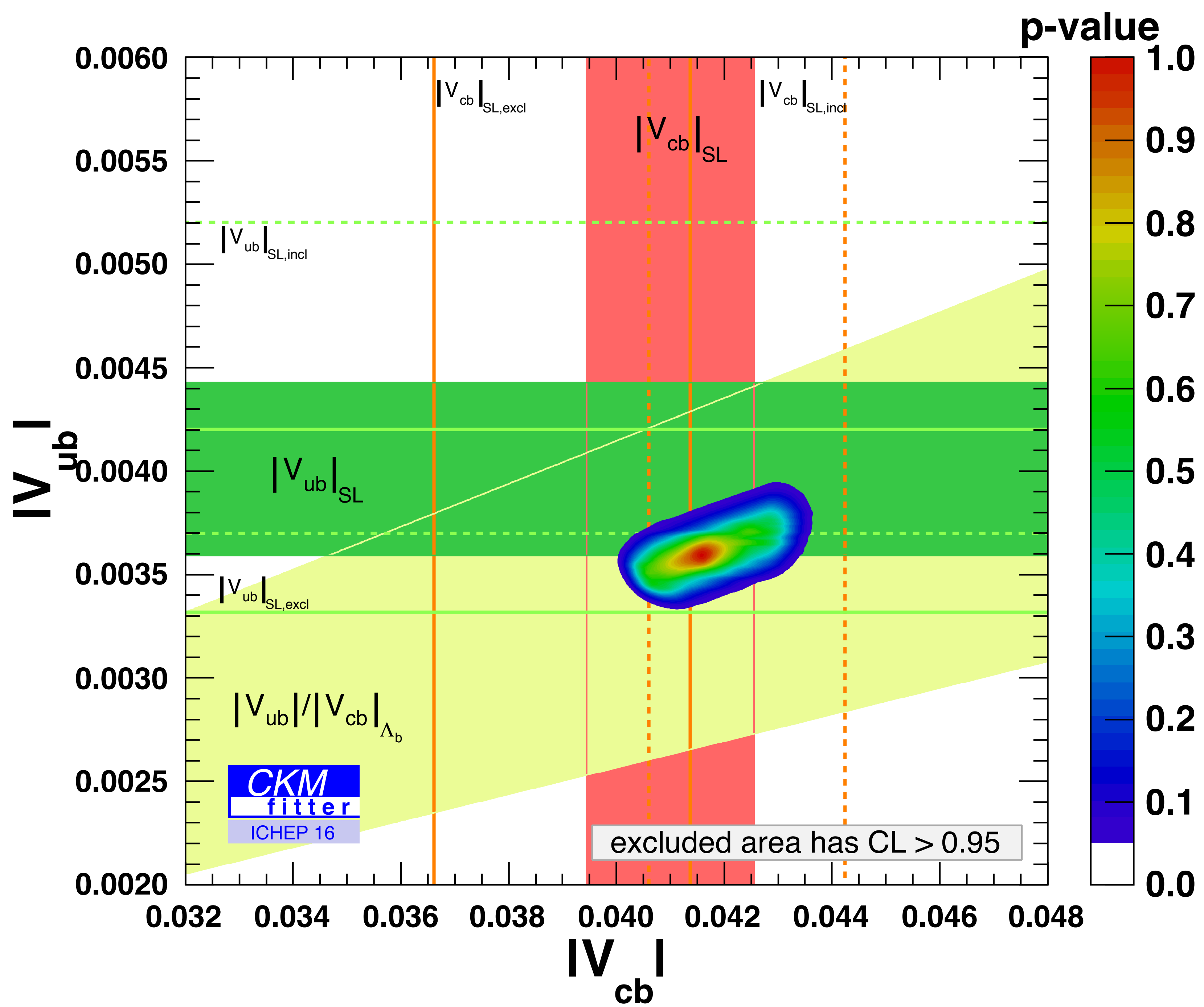
Examples:

Exclusive: $B \to \pi \ell \nu$

Exclusive means one specific decay mode

Inclusive: $B \to X_u \ell \nu$

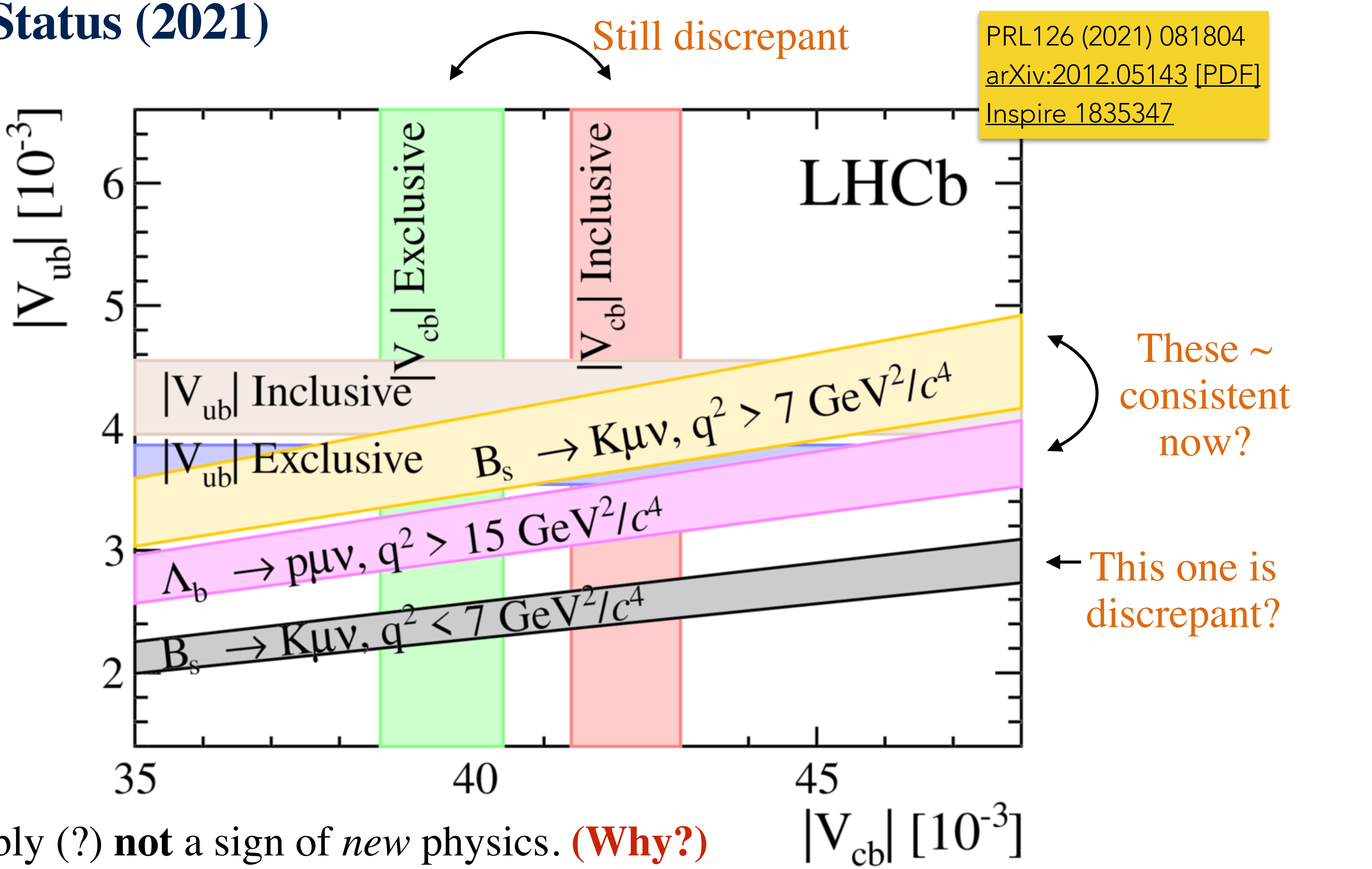
Inclusive means sum over any and all modes that involve a $b \to u$ transition



An example of a recent conundrum

Current Status (2021)

PRL126 (2021) 081804
arXiv:2012.05143 [PDF]
Inspire 1835347



Probably (?) **not** a sign of *new* physics. **(Why?)**

Still important to understand what is going on (since otherwise ➤ large uncertainties!)