Experimental flavour physics: an introduction

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Outline

- What is flavour physics ?
- Why studying it ?
- Selected topics

What is Flavour physics ?

- Hard to define in a fully comprehensive way. A personal attempt:

«The research program in particle physics which exploits the existence of different generations of quarks (and leptons) to explore the Standard Model and its possible extensions»

- With this definition many results in particle physics are in the domain of flavour physics: CKM structure, universality and CP violation, hadron spectroscopy…(and neutrino physics, too !)

- Historically, the term is related to the **quark sector**. I will focus on that in this lecture. With the above definition «Flavor physics» in the lepton sector is strictly related to neutrino (oscillation) physics, which has an experimental approach of its own given the peculiar nature of these elusive particles (However in SM extensions the distinction between quarks and leptons may become less relevant…)

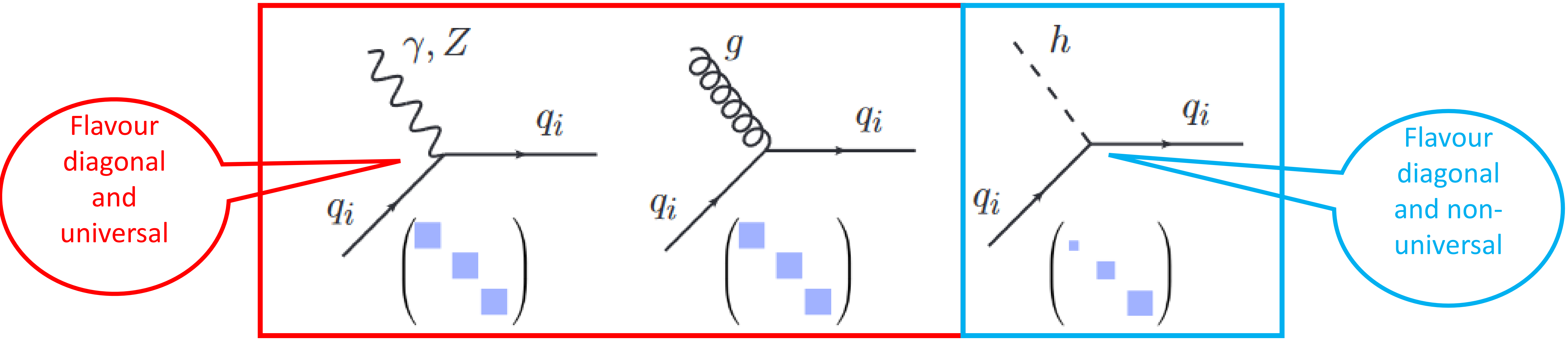
These lectures

- A collection of selected topics based mainly on personal prejudice could be easily called…

A taste of flavour physics…

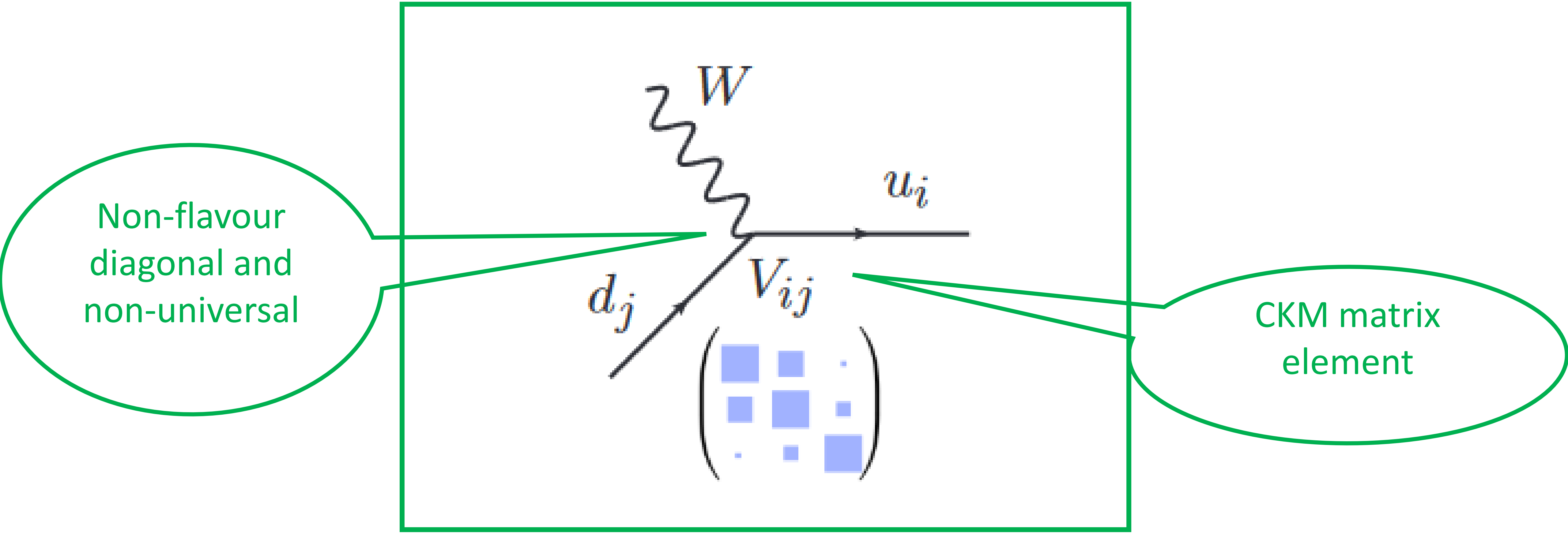
The flavour physics basic block (1)

- Most of SM fundamental vertices are *flavour diagonal :* they do not couple different generations. Coupling to photons, Z boson and gluons are also *universal*, i.e. they are identical for the three generations.
- As such, while they are of course needed to evaluate the observables to be compared to the experiment, they are *not essential* to the flavour physics program.



The flavour physics basic block (2)

- The basic block of any SM flavour physics observable is the qq'W charged weak vertex. It is both *non-diagonal* and *non-universal*.



Masses and couplings

- The presence of the non-diagonal CKM matrix in the SM is just a consequence of the Higgs-fermion Yukawa coupling(s). (*See previous lecture!*)

$$\mathcal{L}_Y = -Y^d_{ij}\,\overline{Q^I_{Li}}\,\phi\,d^I_{Rj} - Y^u_{ij}\,\overline{Q^I_{Li}}\,\epsilon\,\phi^* u^I_{Rj} + \text{h.c.}$$

$$M^f_{\text{diag}} = V^f_L\,Y^f\,V^{f\dagger}_R(v/\sqrt{2}) \qquad V_{\text{CKM}} \equiv V^u_L V^{d\dagger}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\mathcal{L}_{\text{SM}} \supset (\bar{q}_i \not{D}_{\text{NC}} q_i) + \frac{g}{\sqrt{2}}\bar{u}^i_L \not{W}^+ V^{ij}_{\text{CKM}} d^j_L + m_{u_i}\bar{u}^i_L u^i_R\left(1+\frac{h}{v}\right) + m_{d_i}\bar{d}^i_L d^i_R\left(1+\frac{h}{v}\right) + \text{h.c.}$$

- In the massless limit for quarks: no mixing→ **no flavour physics** ! This is indeed what happens in the lepton sector in the limit of massless neutrinos.
- This is somewhat trivial, but the important point here is that SM with three non massless generations includes naturally the unitary, complex CKM mixing matrix.

Why bothering about flavour anyway ?

- In the context of the SM:

Out of the **19** (26) parameters of the SM (of the SM extension including neutrino masses) **4** (8) are only measurable through flavour physics observables: they are the 4 CKM mixing parameters (+ 4 additional lepton mixing matrix PMNS parameters). CP violation (apart from strong θ_{CP}) is uniquely related to flavour physics.

- New Physics searches beyond SM:

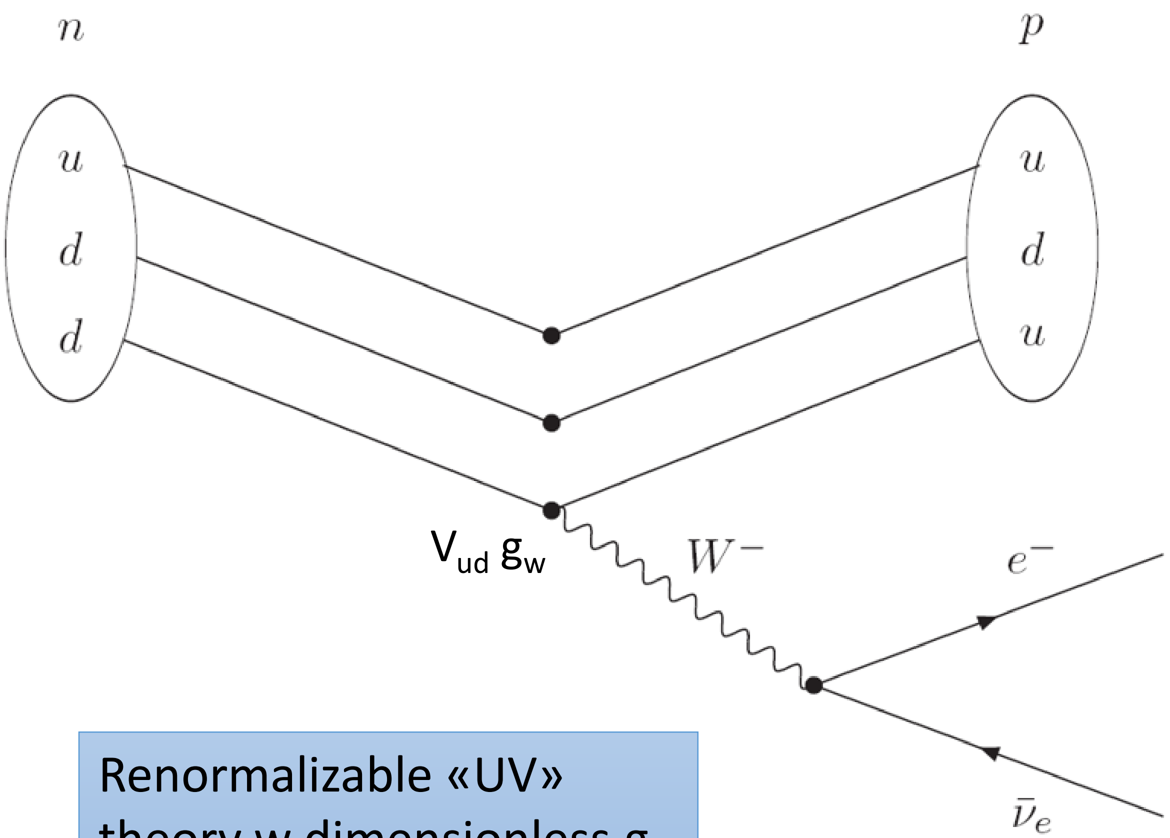
The flavour structure of NP may exhibit a different structure, which can bring to its discovery even if direct production of new degrees of freedom is not yet available in current accelerators.

A lesson from the past (1)

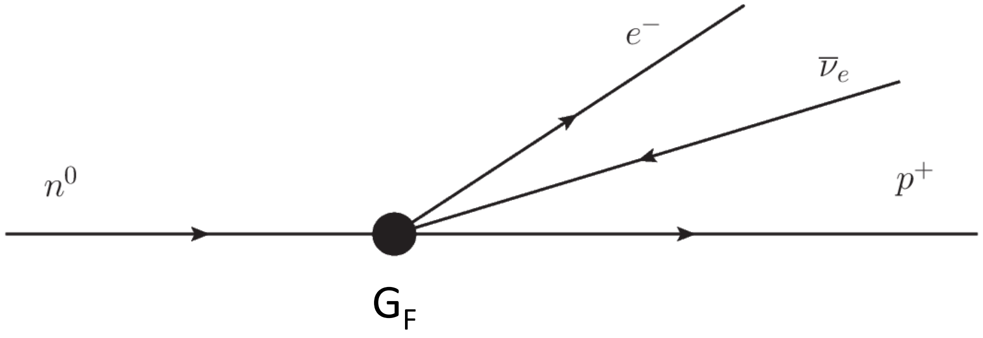
- Imagine a hypothetical «esSM» of only e.m and strong interactions with two «pseudoflavours» up and down: it has a purely diagonal pseudoflavour structure.
- In other words, the number of protons and neutrons are separately conserved in any pure strong or e.m. reaction/decay.
- However the «full» SM has also an additional («New Physics») weak interaction which has a different and non diagonal pseudoflavour structure. This allows for beta decays and electron capture to happen, where only overall barion number is conserved !

- **These processes are studied at very low energies, but they imply the exchange of a virtual W whose mass is 80 GeV !!! Even if direct access to the scale of this EW «New Physics» is not possible, the peculiar EW «signature» is enough to spot the existence of a different kind of interaction and falsify the «esSM»!**

A lesson from the past (2)



Renormalizable «UV» theory w dimensionless g_w coupling constant and propagator $1/M^2_W$



Non-renormalizable «effective» theory with $[E]^{-2}$ dimensional coupling constant G_F

A lesson from the past (3)

- The effect of high mass mediator is to *suppress* the probability of the process at low energies with a M^{-4} dependence.

$$\Gamma(n \to p e \bar{\nu}_e) \propto \frac{(m_p - m_n)^5}{m_W^4} \sim 10^{-20}(m_p - m_n)$$

- The weak («NP») process would have been a tiny correction to the «esSM» if the beta decay were not forbidden by strong and e.m. interaction, and it would have needed an **extremely precise comparison between experiment and theory** to sort it out.

Rare & forbidden processes

- NP may only be spotted by falsifying a SM prediction.
- **Rare** (and *a fortiori* **forbidden**) processes in SM are the ideal test ground, since a NP effect which is small on an absolute scale represents a sizeable correction to the SM expectations and can lead to a discovery.
- Interplay with **theory** is **essential** as more and more refined theoretical predictions are crucial to the program. These predictions in turn rely also on the experimental determination of SM parameters such as the CKM matrix elements !

The flavour physicist shopping list

- CKM parameters (overconstraining)
- CP violation

Today

- Flavour Changing Neutral Current processes
- Universality tests
- Charged lepton flavor/number violations
- …

Tomorrow

CKM and the Unitary Triangle(s) (1)

- CKM matrix has 4 free parameters (3 Euler angles + 1 phase) and exhibits a hierarchical structure.
- In Wolfenstein's parametrization the hierarchy is evident, with $\lambda = |V_{us}|$ as order parameter:

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

$A = 0.8132\ (12)$, $\lambda = 0.2250\ (2)$, $\bar{\rho} \simeq \rho\left(1 - \frac{\lambda^2}{2}\right) = 0.157(9)$, $\bar{\eta} \simeq \eta\left(1 - \frac{\lambda^2}{2}\right) = 0.348(12)$

CKMfitter Group (J. Charles *et al.*), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184],
updated results and plots available at: http://ckmfitter.in2p3.fr

CKM and the Unitary Triangle(s) (2)

- Unitarity implies any scalar product of a row and a column of the matrix with different indices must be zero. Three complex numbers adding up to zero may be seen as a triangle in the complex plane.
- The only triangle which has all sides of same order of magnitude is the one which stems from scalar product of the first row for the third column. This is called the **standard unitarity triangle**.

$V_{ud}^*V_{cd}+V_{us}^*V_{cs}+V_{ub}^*V_{cb}=0$	$\lambda, \lambda, \lambda^5$
$V_{ud}^*V_{td}+V_{us}^*V_{ts}+V_{ub}^*V_{tb}=0$	$\lambda^3, \lambda^3, \lambda^3$
$V_{cd}^*V_{td}+V_{cs}^*V_{ts}+V_{cb}^*V_{tb}=0$	$\lambda^4, \lambda^2, \lambda^2$
$V_{ud}V_{us}^*+V_{cd}V_{cs}^*+V_{td}V_{ts}^*=0$	$\lambda, \lambda, \lambda^5$
$V_{ud}V_{ub}^*+V_{cd}V_{cb}^*+V_{td}V_{tb}^*=0$	$\lambda^3, \lambda^3, \lambda^3$
$V_{us}V_{ub}^*+V_{cs}V_{cb}^*+V_{ts}V_{tb}^*=0$	$\lambda^4, \lambda^2, \lambda^2$

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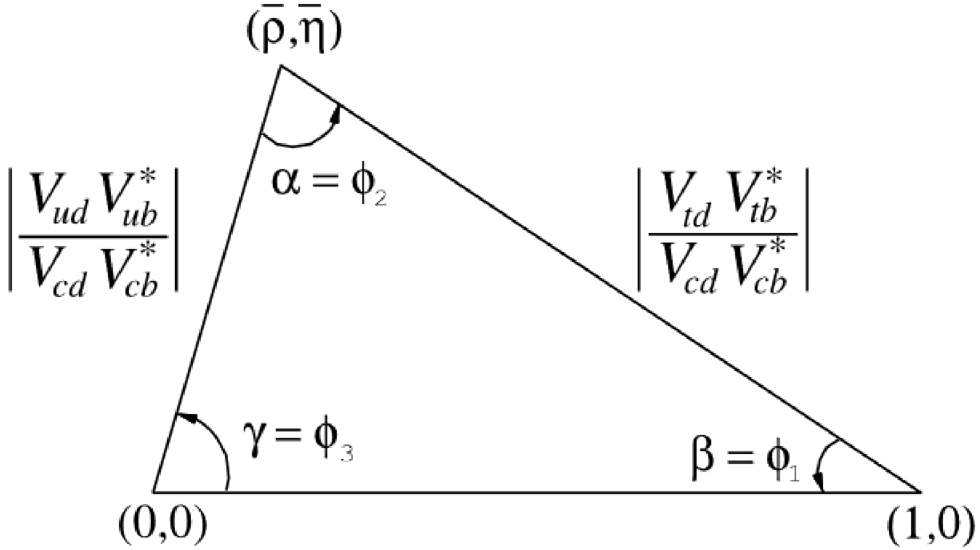
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

$$-\left(\bar{\rho} + i\bar{\eta}\right) + 1 + \left(-1 + \bar{\rho} + i\bar{\eta}\right) = 0$$

CKM and the Unitary Triangle(s) (3)



$$\beta=\phi_1=\arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right),$$

$$\alpha=\phi_2=\arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right),$$

$$\gamma=\phi_3=\arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

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

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}+1+\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}=0$$

$$-\left(\bar\rho+i\bar\eta\right)+1+\left(-1+\bar\rho+i\bar\eta\right)=0$$

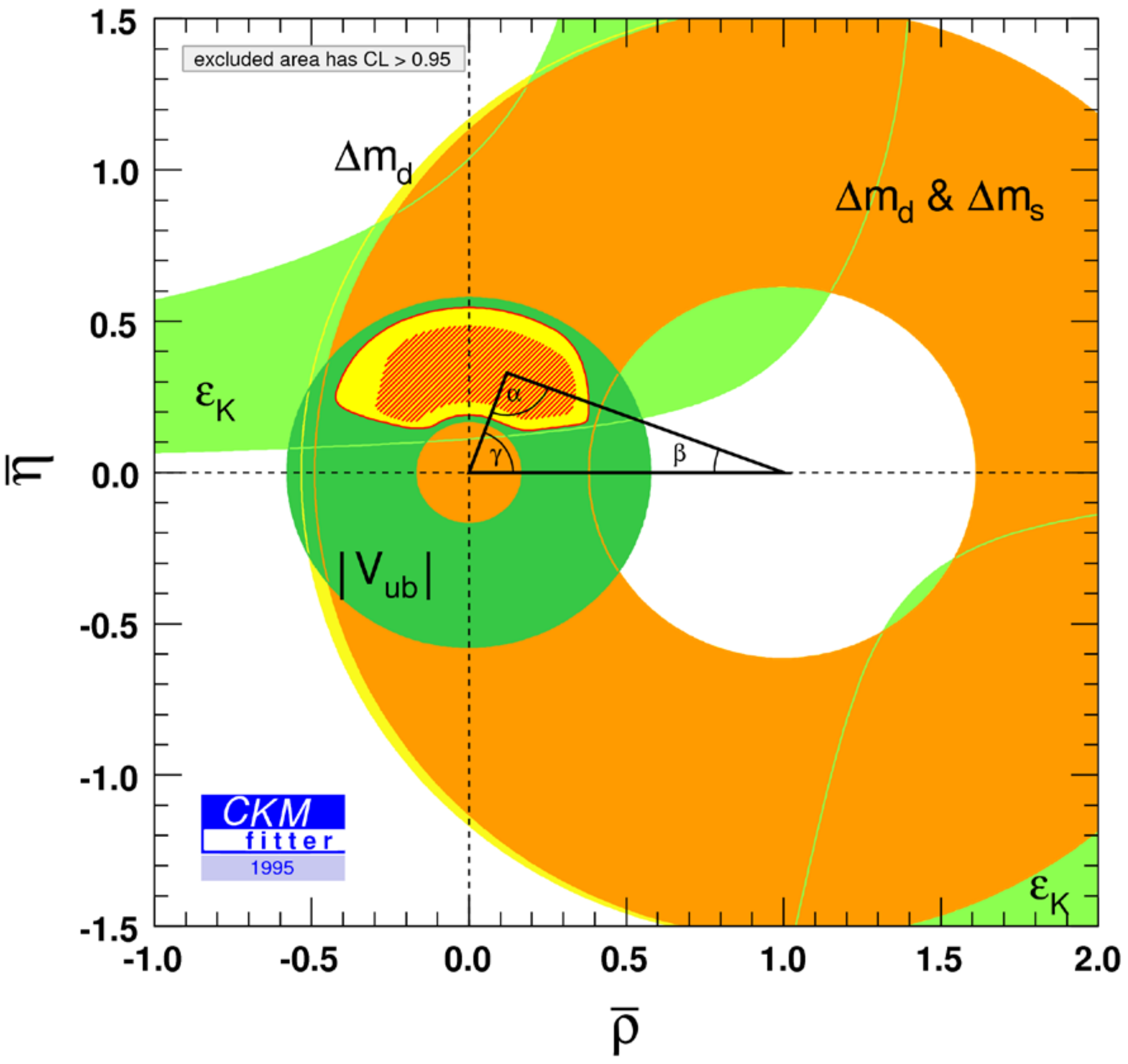
Overconstraining the UT

- In the SM, once the flavour structure is fixed, processes which depend on different CKM matrix elements may be used to measure sizes and angles of the UT.
- All (combinations of) extracted parameters must point to the same result for the triangle vertices, disregarding the particular channel and or process used to extract them. This helps pinning down uncertainty on SM parameters.

- **This is NOT necessarily true for general extensions of the SM which may exhibit a different flavour structure**. NP contributions may show up e.g. as inconsitencies on the positions of UT vertices as obtained from processes involving different generations.

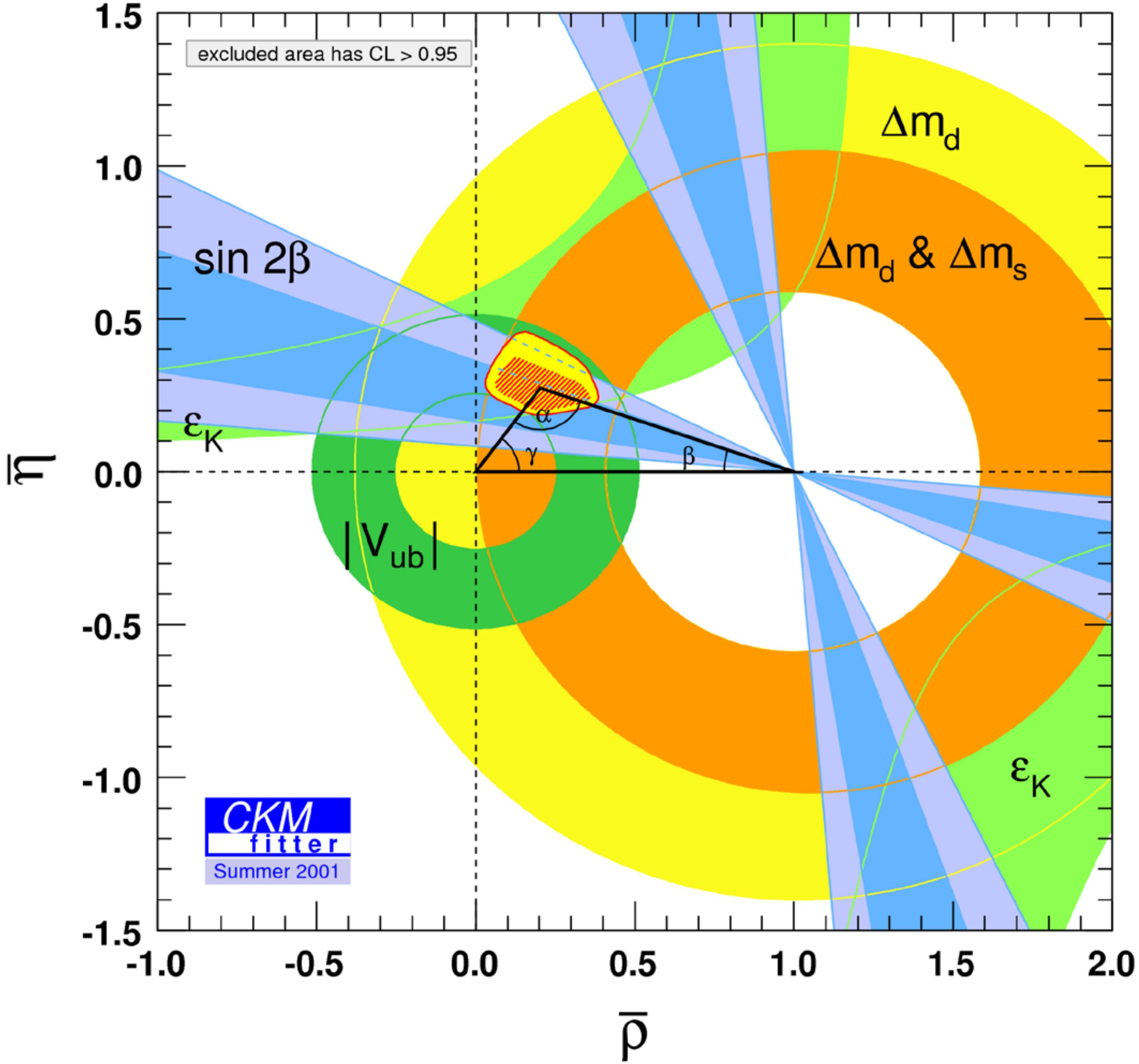
UT , circa 1997

- In 1997, when I was attending the X edition of this same school, the situation for the UT was rather poor…
- B factories had yet to start their work…



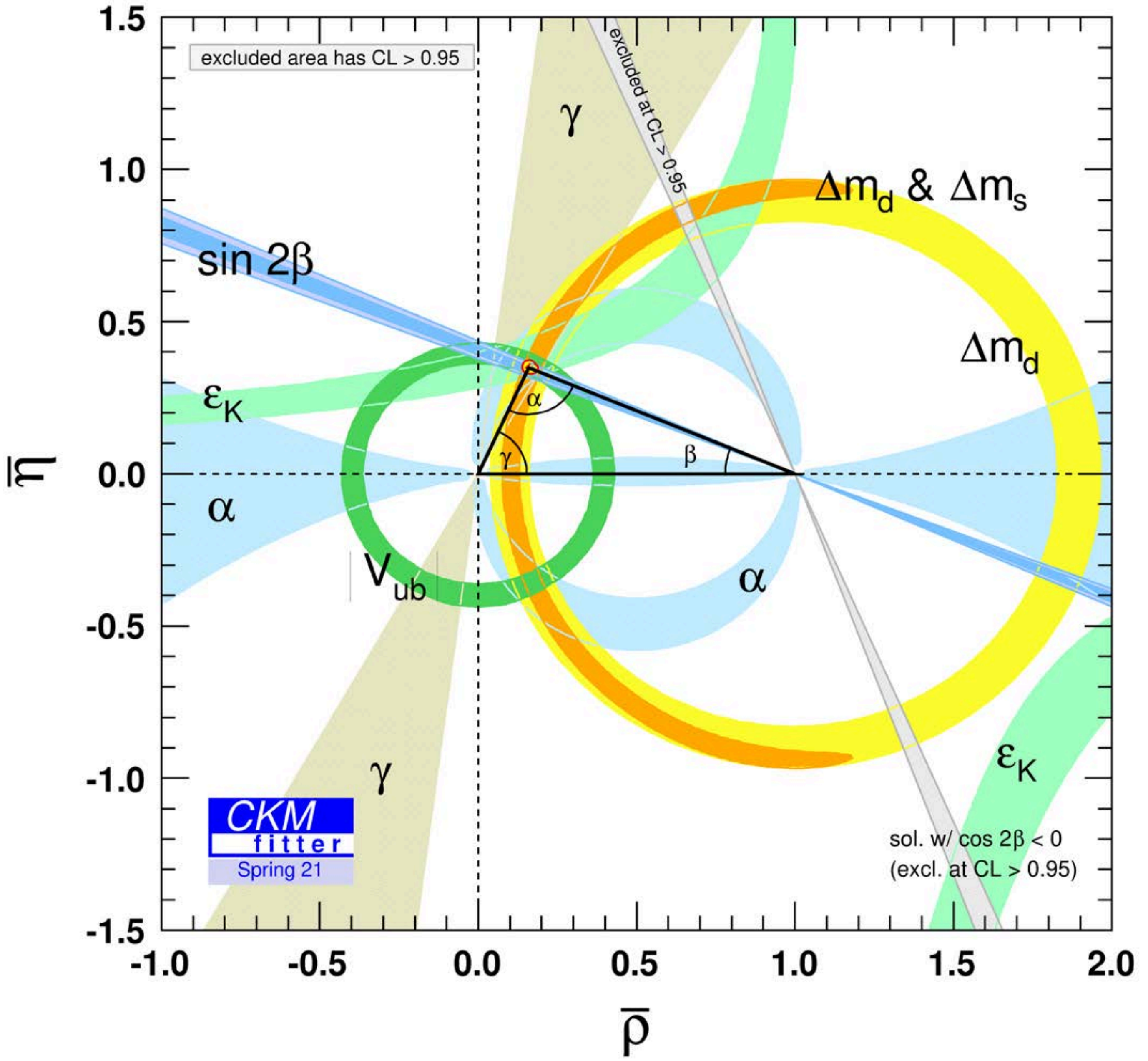
UT , circa 2001

- At the exciting Lepton Photon 2001 conference the first results on $\sin 2\beta = \sin 2\phi_1$ from BaBar and Belle came out and started changing the game.



UT , circa 2021

- Final results from BaBar and Belle, plus several other experimental inputs (most notably, but not only, LHCb !) as well as theoretical progresses (lattice and more) pins down the uncertainty and the constraints on the UT.
- This allows to put more stringent constraints on NP, both from the UT itself and thanks to the accuracy in CKM parameters which contribute to other flavour observables.



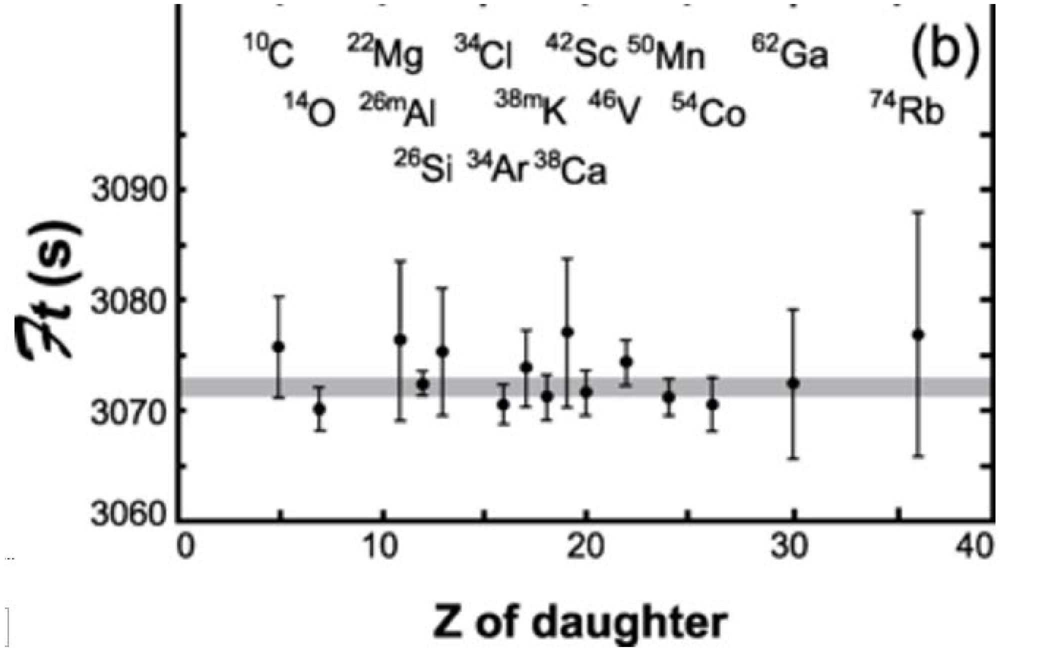
UT & CPV: some experimental inputs

- $|V_{ud}|$ and superallowed Fermi nuclear decays
- $|V_{us}|$ and kaons (semi)leptonic decays
- $|V_{cb}|$ and B semileptonic decays
- $|V_{tb}|$ and single top production cross section
- $|V_{td}/V_{ts}|$ and B meson mass differences

- ϵ_K and neutral kaon mixing
- $\sin 2\beta$ and B_0 oscillations
- Direct CPV and ε'

$|V_{ud}|$ and superallowed Fermi decays

- $0^+ \rightarrow 0^+$ nuclear beta decays allow for a clean extraction of $G_F|V_{ud}|$ by measuring lifetimes and Q values of the reactions.
- However extraction depends on a overall ew radiative correction (RC) factor and a nuclear structure (NS) correction, which introduce further uncertainty.



$$V_{ud} = 0.97373(11)_{\text{exp.,nucl.}}(9)_{\text{RC}}(27)_{\text{NS}} \text{ (superallowed)}$$

J. C. Hardy and I. S. Towner, Phys. Rev. C 102, 4, 045501 (2020)

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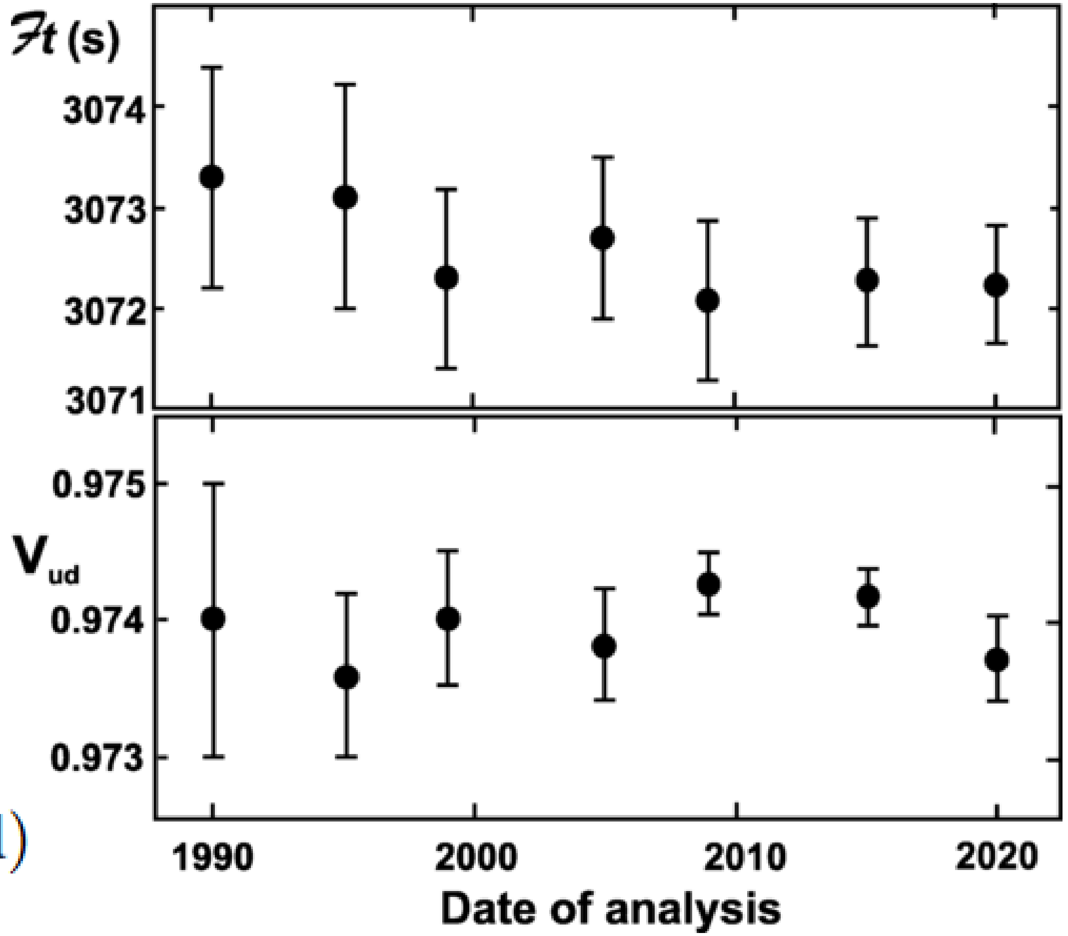

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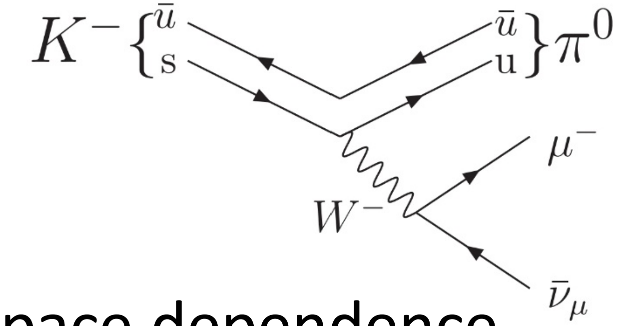
$|V_{us}|$ and kaon (semi)leptonic decays (1)



- The width of semi-leptonic kaon decays is related to $|V_{us}|$

$$\Gamma_{K\ell3} = \frac{G_F^2 M_K^5}{192\pi^3} S_{EW}(1+\delta_K^\ell+\delta_{SU2})C^2\,|V_{us}|^2\, f_+^2(0) I_K^\ell$$

- Require to measure Branching fraction, lifetimes and phase space dependence of the form factor (to evaluate the integral I_K^ℓ)
- Theory inputs: EW corrections and form factor at zero momentum transfer $f^+(0)$ (from lattice calculations).
- KLOE, NA48, KTeV, ISTRA+ put forward a big effort to measure all relevant channels for charged and neutral kaons and for both e, μ leptons.

T. Alexopoulos *et al.* (KTeV), Phys. Rev. Lett. **93**, 181802 (2004), [hep-ex/0406001].

T. Alexopoulos *et al.* (KTeV), Phys. Rev. D **70**, 092006 (2004), [hep-ex/0406002].

F. Ambrosino *et al.* (KLOE), Phys. Lett. B **632**, 43 (2006), [hep-ex/0508027].

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F. Ambrosino *et al.* (KLOE), Phys. Lett. B **636**, 173 (2006), [hep-ex/0601026].

B. Sciascia (KLOE), PoS **HEP2005**, 287 (2006), [hep-ex/0510028].

A. Lai *et al.* (NA48), Phys. Lett. B **602**, 41 (2004), [hep-ex/0410059].

A. Lai *et al.* (NA48), Phys. Lett. B **645**, 26 (2007), [hep-ex/0611052].

J. Batley *et al.* (NA48/2), Eur. Phys. J. C **50**, 329 (2007), [Erratum: Eur.Phys.J.C 52, 1021-1023 (2007)], [hep-ex/0702015].

V. Romanovsky *et al.* (2007), [arXiv:0704.2052].

$|V_{us}|$ and kaon (semi)leptonic decays (2)

			Approx contrib to % err			
Mode	$V_{us} f_+(0)$	% err	BR	τ	Δ	I
K_{Le3}	0.2163(6)	0.25	0.09	0.20	0.11	0.05
$K_{L\mu3}$	0.2166(6)	0.28	0.15	0.18	0.11	0.06
K_{Se3}	0.2155(13)	0.61	0.60	0.02	0.11	0.05
$K^{\pm}_{e3}$	0.2171(8)	0.36	0.27	0.06	0.22	0.05
$K^{\pm}_{\mu3}$	0.2170(11)	0.51	0.45	0.06	0.22	0.06

M. Moulson, PoS CKM2016, 033 (2017), [arXiv:1704.04104].

$$V_{us} f_+(0) = 0.21654(41)$$

$|V_{us}|$ and kaon (   )leptonic decays (3)

- Can use also purely leptonic decays !
- But in order for hadronic uncertainties to cancel out compare pion and kaon decay mode.

$$\frac{\Gamma(K \to \mu\nu(\gamma))}{\Gamma(\pi \to \mu\nu(\gamma))} = \frac{|V_{us}|^2}{|V_{ud}|^2} \times \frac{f_K}{f_\pi} \times \frac{m_K (1 - m_\mu^2 / m_K^2)^2}{m_\pi (1 - m_\mu^2 / m_\pi^2)^2} \times \left[1 + \alpha(C_K - C_\pi)\right]$$

$$\frac{|V_{us}| f_{K^+}}{|V_{ud}| f_{\pi^+}} = 0.27600(37)$$

$|V_{us}|$: putting thing together

- Using FLAG lattice averages:

$$f_+(0) = 0.9677(27) \quad N_f = 2+1$$
$$f_+(0) = 0.9698(17) \quad N_f = 2+1+1$$

$$\frac{f_{K^+}}{f_{\pi^+}} = 1.1917(37) \qquad N_f = 2+1$$
$$= 1.1932(21) \quad N_f = 2+1+1$$

- And using both leptonic and semileptomi modes, one gets:

$$\boxed{\begin{array}{l} |V_{us}| = 0.2244(5) \quad N_f = 2+1 \\ |V_{us}| = 0.2243(4) \quad N_f = 2+1+1. \end{array}}$$

First row unitarity = universality

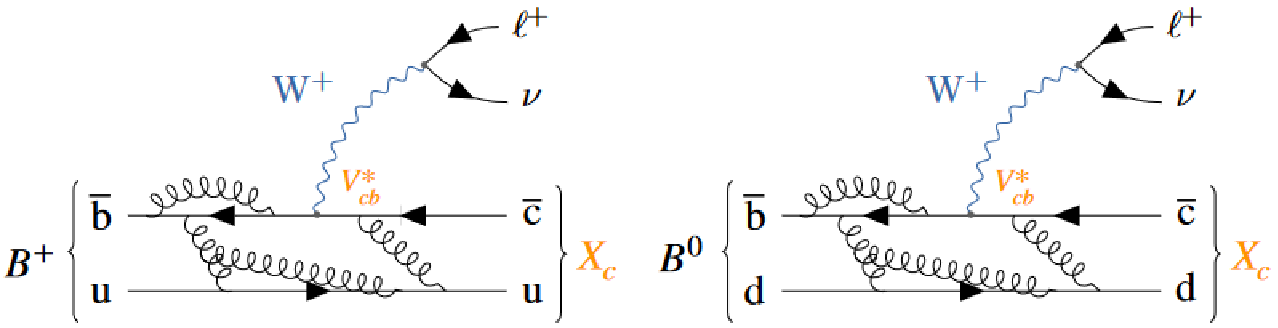
- Unitarity for first row of CKM implies the scalar product of the first row by itself must be 1
- Since $|V_{ud}|$ and $|V_{us}|$ are currently the best measured parameters and $|V_{ub}|$ is small, this is currently the most stringent unitarity test of the CKM
- The result show a 2 sigma «tension» wrt to unitarity/SM

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(6)(4).$$

Uncertainty on $|V_{us}|^2$

Uncertainty on $|V_{ud}|^2$

$|V_{cb}|$ and semileptonic B decays (1)



- **Inclusive decays techniques**: measure both **total width** of semileptonic transitions including $b \to c$ and **moments** of the lepton energy/hadronic invariant mass spectra distribution, and, more recently, on the momentum transfer squared q^2. Extraction of $|V_{cb}|$ requires essential theoretical input using Operator Product Expansion techniques, and has a strong dependence on the quark mass m_b (and more loosely on charm quark mass). This dependence is used to fit simultaneously the quark mass and $|V_{cb}|$

Electron Energy moment of order n

$$\langle E_e^n \rangle_{E_e > E_{\rm cut}} = \int_{E_{\rm cut}}^{E_{\rm max}} \frac{d\Gamma}{dE_e} E_e^n dE_e \bigg/ \int_{E_{\rm cut}}^{E_{\rm max}} \frac{d\Gamma}{dE_e} dE_e$$

$|V_{cb}|$ and semileptonic B decays (2)

- **Exclusive decays techniques**: measure the processes $B \to D(D^*)l^+\nu_l$ and more recently its «heavier» brother $B_s \to D_s(D_s^*)l^+\nu_l$.
- To extract |Vcb| need to know several independent form factors as a function of the variable $w = v \cdot v'$ (the scalar product of the four velocities of the B and D hadron).

$$\frac{d\Gamma}{dw}(\bar{B} \to D^*\ell\bar{\nu}_\ell) = \frac{G_F^2 m_B^5}{48\pi^3}|V_{cb}|^2|\eta_{\rm EW}|^2(w^2-1)^{1/2}P(w)|\mathcal{F}(w)|^2$$

Form factors here !

$$\frac{d\Gamma}{dw}(\bar{B} \to D\ell\bar{\nu}_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2(m_B+m_D)^2 m_D^3(w^2-1)^{3/2}(\eta_{\rm EW}\mathcal{G}(w))^2$$

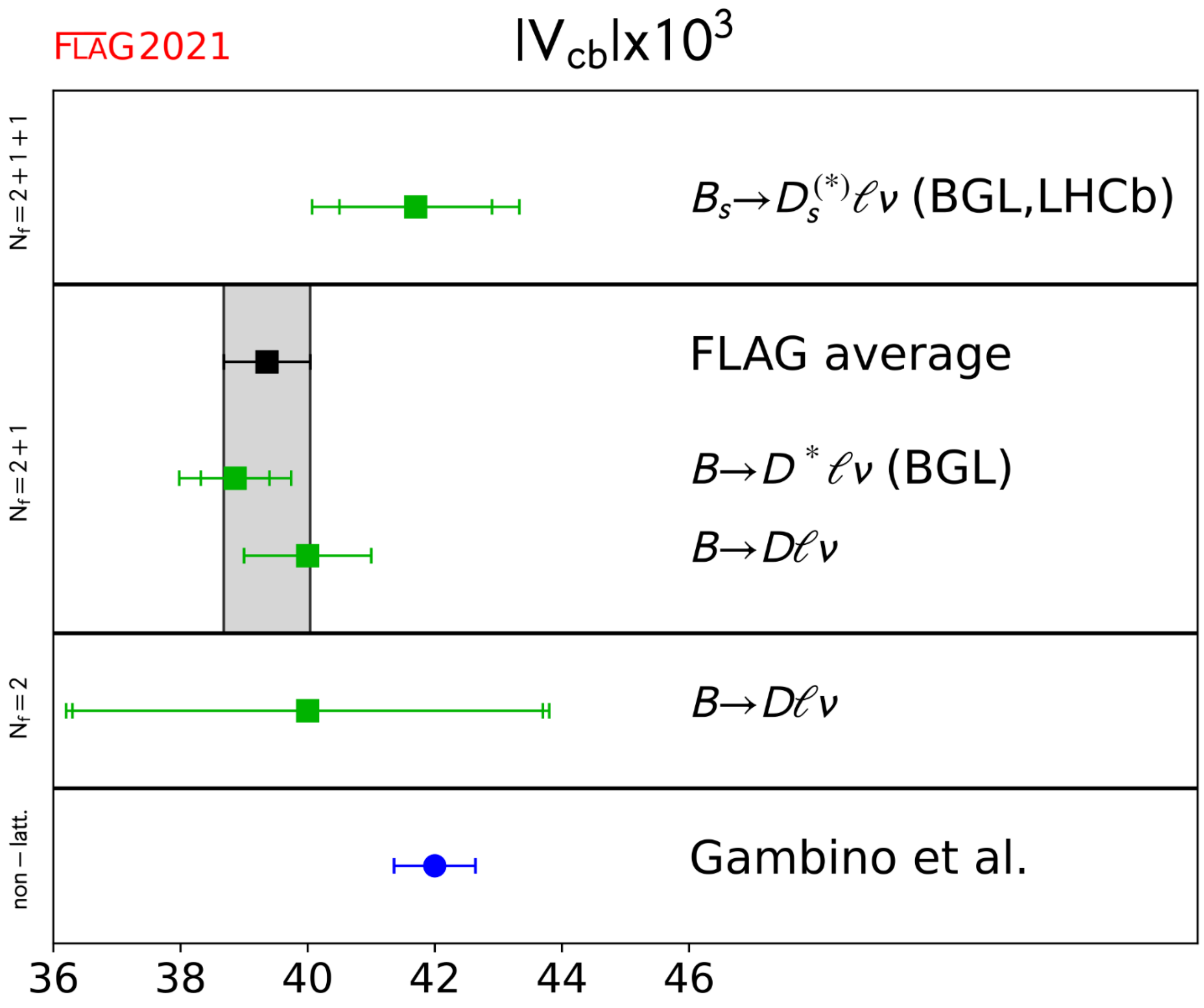
The |Vcb| tension

- Most recent PDG average quotes:

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \quad \text{(inclusive)}$$
$$|V_{cb}| = (39.4 \pm 0.8) \times 10^{-3} \quad \text{(exclusive)}.$$

- This is a more than 2 sigma effect, which should be further investigated by the upcoming measurements.
- Recent q^2 based measurements in better agreement w inclusive.
- Improvements in theoretical uncertainties may shed light on this longstanding puzzle.

(For recent developments see e.g.G. Martinelli et al. https://arxiv.org/abs/2209.15413)



$|V_{tb}|$ and top physics

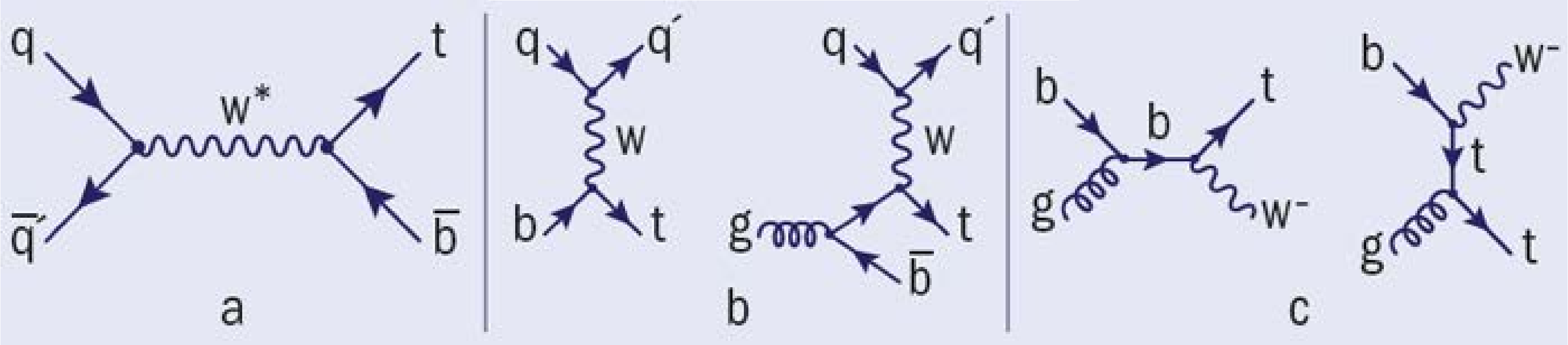
- Using unitarity one can compare:

$$\frac{Br(t \to Wb)}{Br(t \to Wq)} = |Vtb|^2 / \sum_q |V_{tq}|^2$$

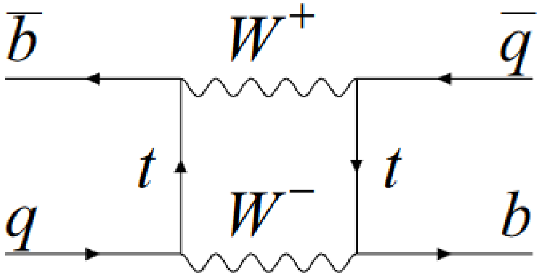
this has been used at Tevatron and LHC to set lower limits on $|V_{tb}|$.

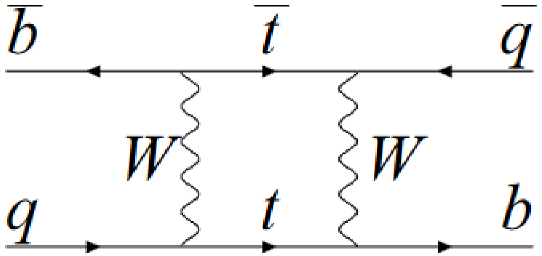
- A direct determination with no unitarity assumption is possible if one measures single top production cross sections. This has been done in s-channel, t-channel, and in association with a W boson. Combination of Tevatron and LHC results gives

$$|V_{tb}| = 1.014 \pm 0.029$$



$|V_{td}/V_{ts}|$, Δm_d and Δm_s





- Measurements of tree level top quark coupling to light quarks are very difficult, so determination of these parameters must rely on processes with **virtual exchange of top quarks in loops.**
- This can be done by measuring oscillations of B and B_s mesons and extracting their mass difference, which in turn is related to CKM parameters.
- Uncertainties from lattice QCD calculations reduce significantly using the ratio of mass differences and yield a precise determination of $|V_{td}/V_{ts}|$

$$|V_{td}/V_{ts}| = 0.207 \pm 0.001 \pm 0.003$$

Flavour oscillation and Δm

- Step 1: **tag** the flavour of the neutral meson at t=0.

  In the recent LHCb Δm_s analysis it is done using both Opposite Side tagging (identifying the other side meson via $b \to c \to s$ transitions) and Same Side tagging (kaon charge $\to s$ or $\bar{s}$ quark identification.)

- Step 2: Detect the **meson decay** in some «filtering» final state at some t > 0 . This usually exploits ΔF=ΔQ rule (or equivalently the flavor conservation at tree level in neutral currents) in SM.

  In the LHCb analysis the charge of D meson e.g. in $B_s \to D_s^- \pi^+$ does the trick
  ($\Delta B = \Delta Q = -1 \Rightarrow B = +1 \Rightarrow$ a B_s state, and not a $\bar{B}_s$ is decaying at instant t.
  And vice versa for D_s^+)

- Step 3: **Measure** as a function of time the probability $P(t)$ to decay as a $B_s(t)$ or $\bar{B}_s(t)$ for both states which were tagged as $B_s(t=0)$ and $\bar{B}_s(t=0)$. Frequency of oscillation in natural units is $1/(\Delta m)$.

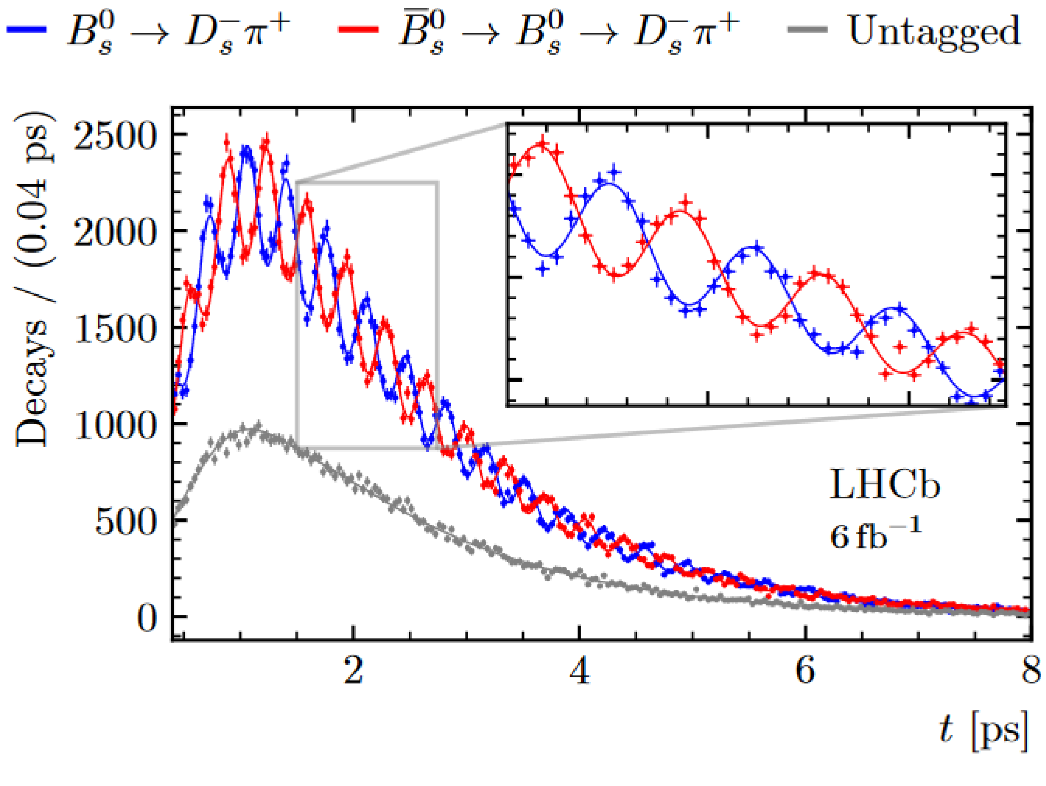
R. Aaij et al. (LHCb), Nature Phys. 18, 1, 1 (2022), [arXiv:2104.04421

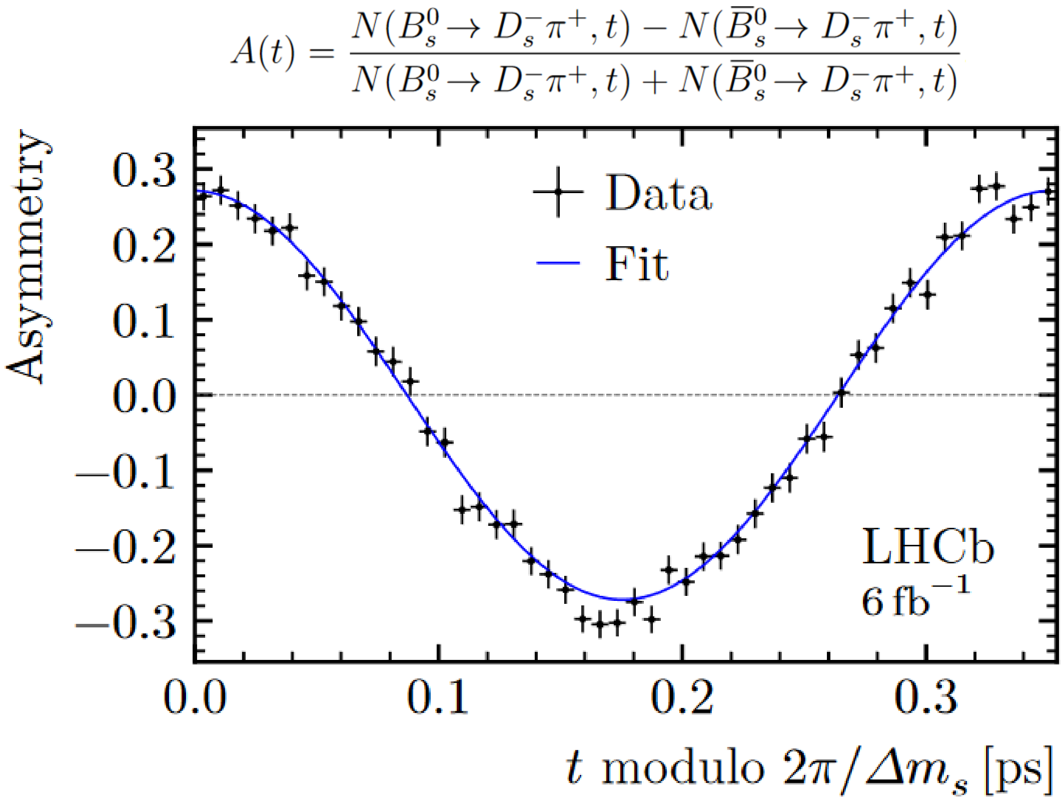
Flavour oscillation and Δm

- Ideal behavior:

$$P(t) \sim e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) + C \cdot \cos(\Delta m_s t)\right]$$

- But need to take into account mistagging, acceptance, resolution, backgrounds…





CPV parameters: $|\varepsilon|$

- This parameter is historically related to the discovery of CP violation in 1964 by Cronin and Fitch.

- It is essentially related to $K^0 - \overline{K^0}$ mixing and is the dominant factor setting the scale for the rate of $K_L \rightarrow 2\pi$ decays. Can be extracted from several K_L observables, including fits to Kaon oscillations (CPLEAR). A recent fit to kaon data yields:

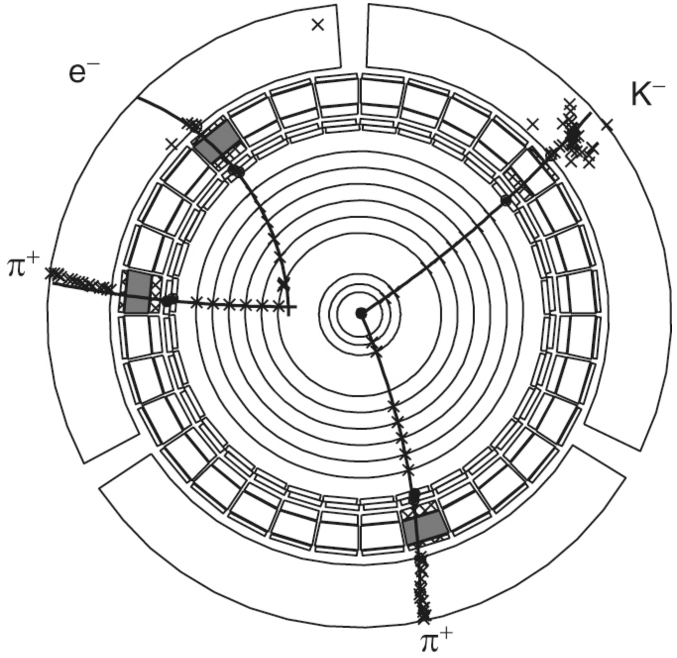
$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$$

- It is interesting to note that in terms of fundamental CKM parameters one has: $|\varepsilon| \propto \bar{\eta}(1 - \bar{\rho})$ so that bounds on this parameters show a peculiar hyperbolic shape on the UT plane.

CPLEAR and kaon oscillations (1)

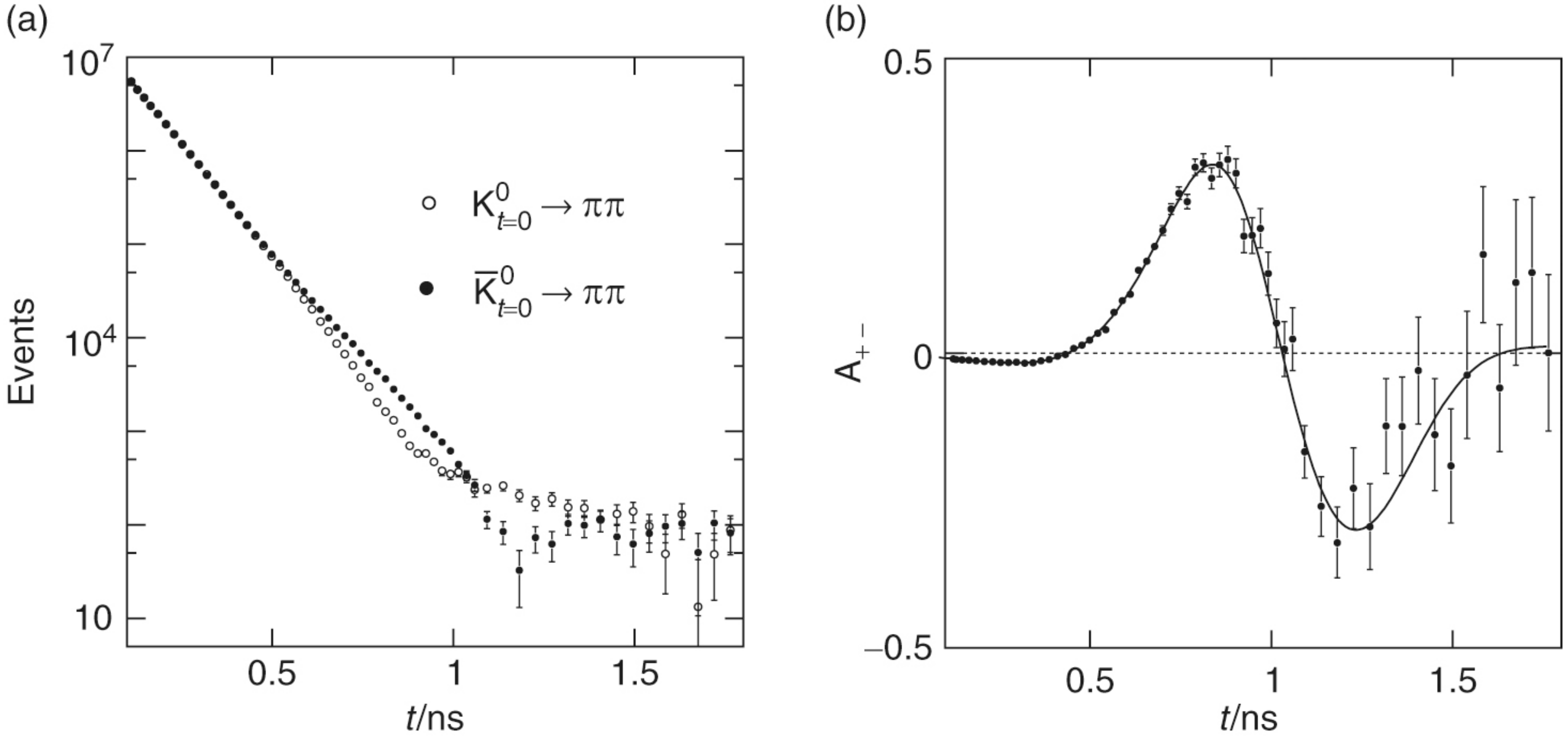
- Measurement of kaon oscillations (as for Δm) but with the same final state ($\pi^+\pi^-$). Tagging at t=0 using associated charged kaon production.
- Exploits the fact that a K^0 (or a $\overline{K^0}$) tagged at t=0 evolves in time oscillating between the two CP eigenstates K_L and K_S due to mixing governed by the complex parameter $\varepsilon = |\varepsilon| e^{i\phi}$
- Time asymmetry in the oscillation is sensitive to both $|\varepsilon|$ and ϕ

$$p\overline{p} \rightarrow K^-\pi^+K^0 \qquad p\overline{p} \rightarrow K^+\pi^-\overline{K}^0$$



$$A_{+-} \equiv \frac{\Gamma(\overline{K}^0_{t=0} \rightarrow \pi^+\pi^-) - \Gamma(K^0_{t=0} \rightarrow \pi^+\pi^-)}{\Gamma(\overline{K}^0_{t=0} \rightarrow \pi^+\pi^-) + \Gamma(K^0_{t=0} \rightarrow \pi^+\pi^-)} \approx 2\,\Re e\,(\varepsilon) - \frac{2|\varepsilon| e^{(\Gamma_S-\Gamma_L)\,t/2} \cos(\Delta m\, t - \phi)}{1+|\varepsilon|^2 e^{(\Gamma_S-\Gamma_L)\,t}}$$

CPLEAR and kaon oscillations (2)



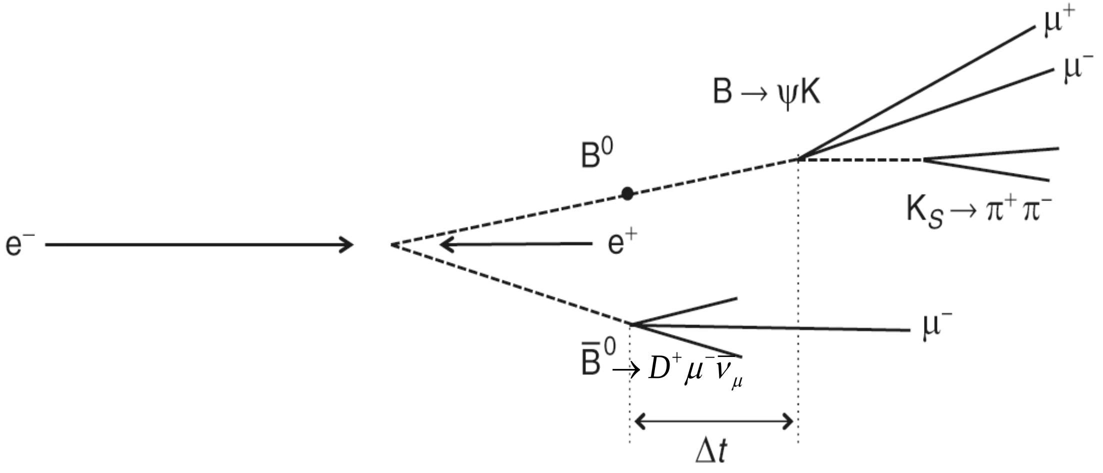
$$|\varepsilon| = (2.264 \pm 0.035)\times 10^{-3} \qquad \phi = (43.19 \pm 0.73)^o$$

CPV observables: $\sin 2\beta$ (1)

- A triumph of B factories, measurement of this parameter has become textbook since.
- Unlike kaon system, CP violation in B meson mixing is small, and the CPLEAR technique to extract both CPV parameters from pure mixing is not viable.
- However it may rather be observed in the interference between decays to a common final state f with and without mixing, i.e. $B^0 \to f$ and $B^0 \to \overline{B^0} \to f$
- Historically the final state $f = J/\Psi\, K_S$ is of great importance, and it is still one of the modes used to extract this CPV parameter.

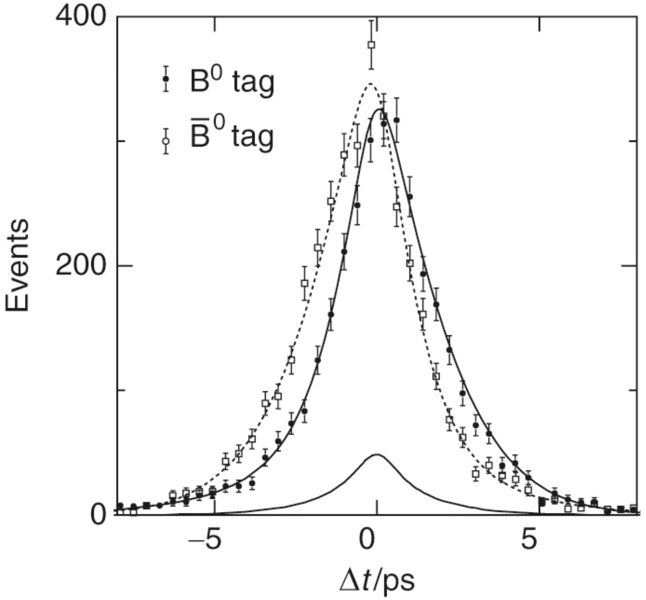
CPV observables: $\sin 2\beta$ (2)

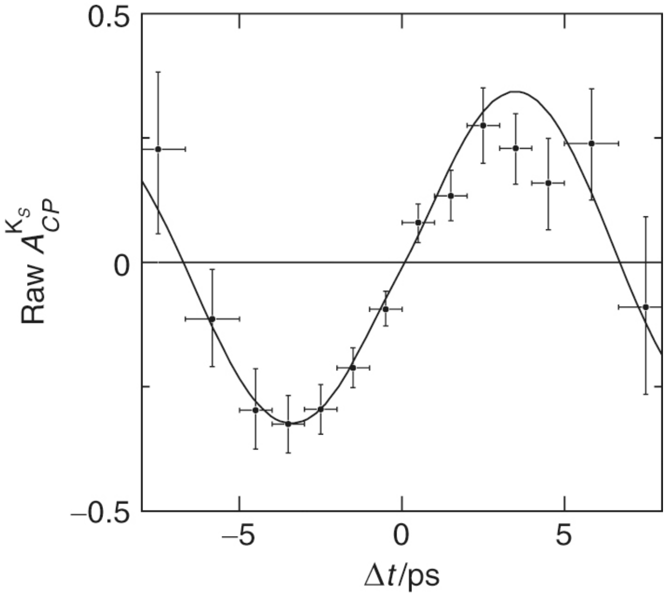
- Intrinsic CP of the final state J/Ψ K_S is (+1)(+1) = 1
- However for conservation of angular momentum they must be created in a state with $\ell = 1$ since the transition is Pseudoscalar → Vector + Pseudoscalar. So overall CP = -1.
- A tagged B (or $\bar{B}$) at t=0 may decay directly to J/Ψ K_S final state or do it after oscillating into an opposite flavour B meson.
- A time dependent asymmetry may be defined:

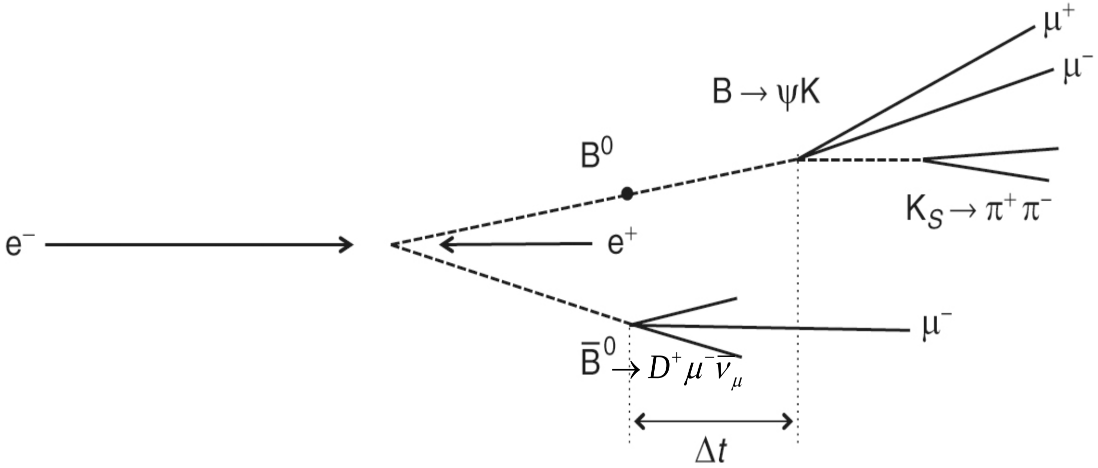


$$A_{CP}^{K_S} \equiv \frac{\Gamma(\bar{B}^0_{t=0} \to J/\psi\ K_S) - \Gamma(B^0_{t=0} \to J/\psi\ K_S)}{\Gamma(\bar{B}^0_{t=0} \to J/\psi\ K_S) + \Gamma(B^0_{t=0} \to J/\psi\ K_S)} = sen(\Delta m_d t)\ sen(2\beta)$$

CPV observables: $\sin 2\beta$ (3)







$$A_{CP}^{K_S} \equiv \frac{\Gamma(\overline{B}^0_{t=0} \to J/\psi\ K_S) - \Gamma(B^0_{t=0} \to J/\psi\ K_S)}{\Gamma(\overline{B}^0_{t=0} \to J/\psi\ K_S) + \Gamma(B^0_{t=0} \to J/\psi\ K_S)} = sen(\Delta m_d t)\ sen(2\beta)$$

Direct CPV and ε'

- We have seen CPV in mixing and in the interference between mixing and decay.
- In the SM a third CPV mechanism, the so-called direct CPV is possible. It manifest itself when the amplitudes of two CP conjugates meson states into two CP conjugates final state are different. This is the only possible CPV mechanism for charged mesons, but has first been observed in the neutral meson system, parametrized by the non zero value of ε'

$$\mathcal{R}e(\epsilon') = \frac{1}{6}\left(\left|\frac{\overline{A}_{\pi^0\pi^0}}{A_{\pi^0\pi^0}}\right| - \left|\frac{\overline{A}_{\pi^+\pi^-}}{A_{\pi^+\pi^-}}\right|\right) = (2.5 \pm 0.4) \times 10^{-6}$$

- It has been established also in the B sector, in B and B_s to $K^{\pm}\pi^{\mp}$ final states.

Take home messages

- Flavour physics is a physics program which exploits the existence of the 3 families of fermions in the SM to test its consistency and search for NP. If sufficient precision is reached it can explore energy ranges of virtual mediators higher than that directly accessible to accelerators.

- A tremendous progress in the last 25 years has been obtained with the determination of the CKM parameters and overconstraining the Unitarity Triangle, passing from «CKM conjecture» to precision physics. Key observables come from very different experiments, including nuclear physics experiments, Kaon and B meson factories, Tevatron and the LHC.

- Interplay with theory is crucial, and is a «continuous feedback» process.