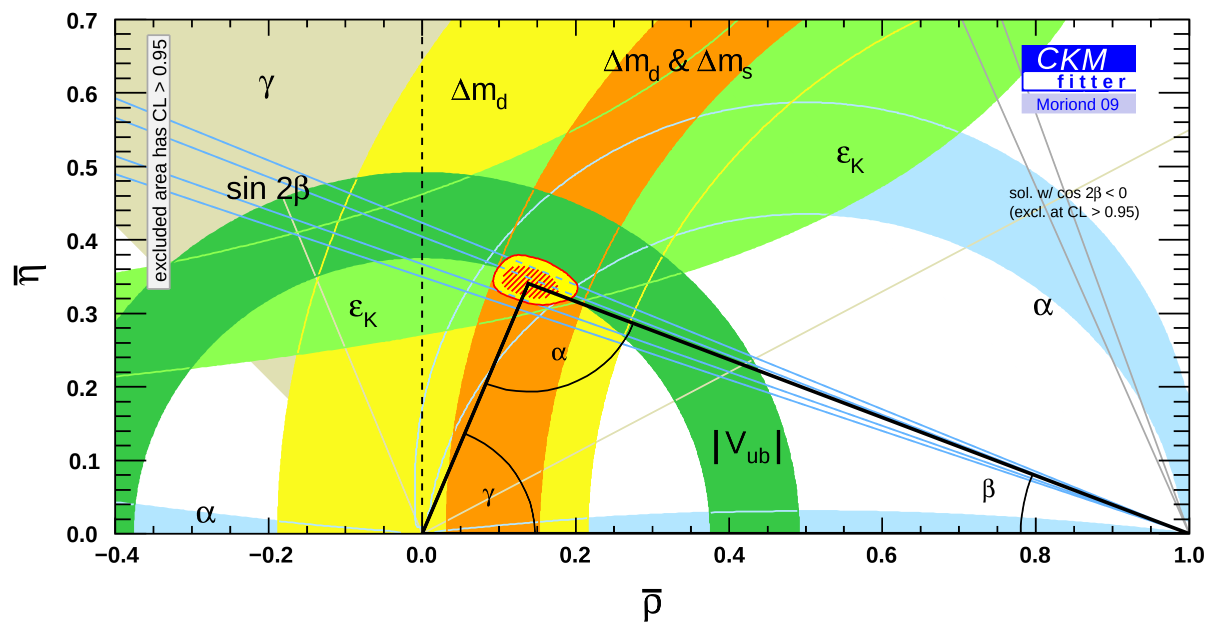
BaBar Symposium 2009: theory overview

Einan Gardi (Edinburgh)



- Experimental confirmation of the SM picture of flavour physics
- Beginning of a new era: precision flavour physics

BaBar Symposium 2009: theory overview

Outline:

- The Standard Model picture of flavour:
  flavour $\longleftrightarrow$ CP violation: confirmed!
- Flavour as a window into physics beyond the Standard Model
  Flavour is complementary to searches at colliders, having
  - sensitivity to symmetries
  - a far reach in energy, slow decoupling
- Specific measurements and the status of the Unitarity Triangle:
  - Time–dependent CP asymmetries: measuring the phases
  - Semileptonic decays: $|V_{\rm ub}/V_{\rm cb}|$ and the role of QCD

richness: a major asset of flavour physics.

- Conclusions

The Standard Model

gauge interaction (bosons):

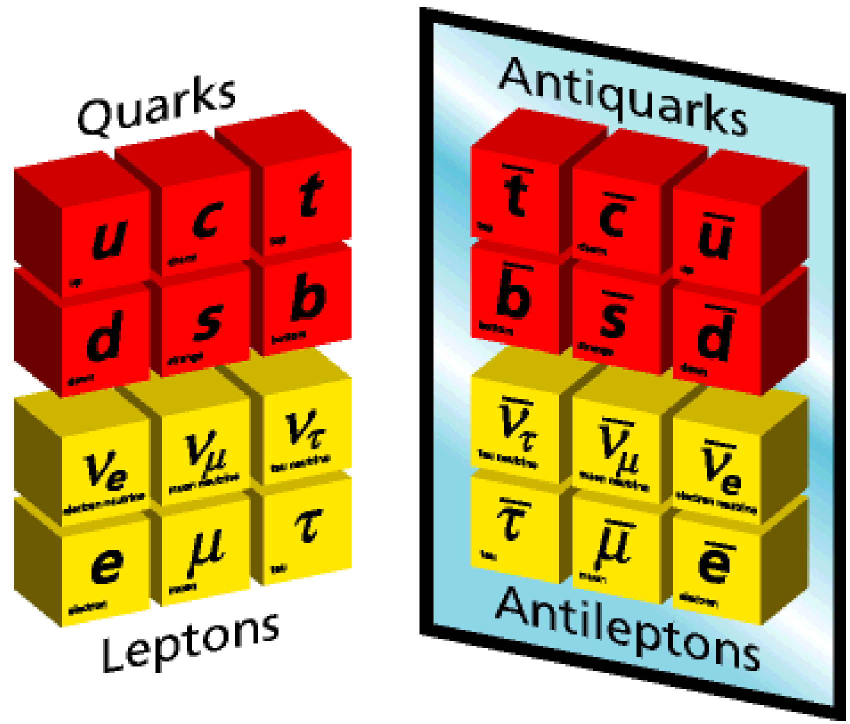
$$\underbrace{\mathrm{SU(3)}_{\mathrm{color}}}_{\mathrm{QCD}} \times \underbrace{\mathrm{SU(2)}_{\mathrm{L}} \times U(1)_Y}_{\mathrm{electroweak}}$$

gluons $\qquad W^{\pm},\ Z^0,\ \gamma$

CPT invariance

(Charge–Parity–Time reversal)

3 generations of matter:



Broken symmetries:

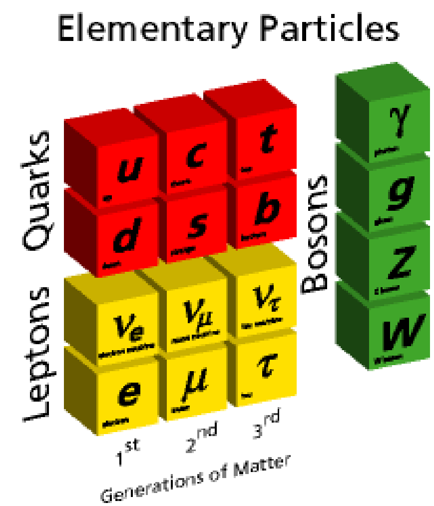
- electroweak symmetry: Higgs

  Massive vector bosons: $M_W = 80$ GeV, $M_Z = 91$ GeV

- flavour symmetry: Yukawa interaction
  - quarks have different masses and couplings to Higgs
  - flavour–changing currents $\Longrightarrow$ CP violation

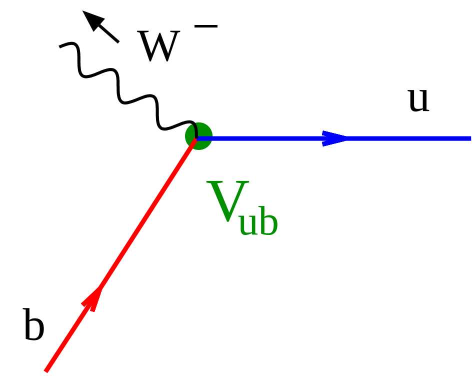
The Cabibbo-Kobayashi-Maskawa (CKM) matrix

- SM flavour symmetry: 3 identical copies of the first generation; within each: $u \to W^+ d$.
- The symmetry is broken by masses $\Longrightarrow u \to W^+ d'$



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

Weak eigenstates — Mass eigenstates



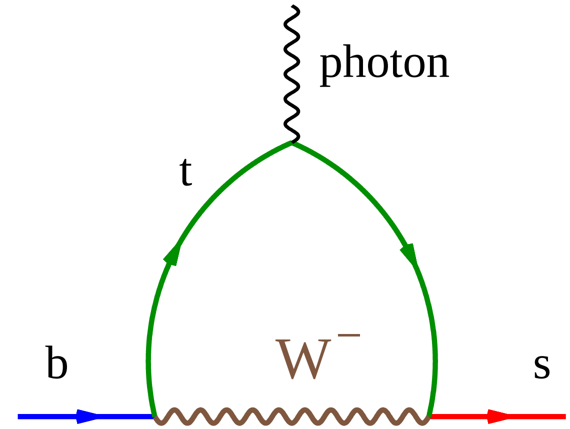
- Unitarity: $V_{\rm CKM} V_{\rm CKM}^\dagger = I$
- CP violation! $\Longleftrightarrow V_{\rm CKM}$ complex, at least 3 generations (KM 1973)
- Higgs and neutral electroweak currents do not modify flavour: no Flavour Changing Neutral Currents (FCNC).

Flavour changing neutral current: $b \to s\gamma$

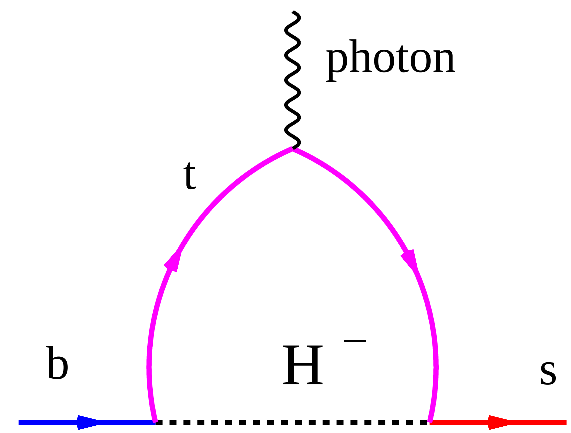
- Standard Model (SM): at tree level
  no *flavour–changing neutral currents*.
  $b \to s$ transition is suppressed, occurring through loops.

- Beyond the SM the width is modified:
  $b \to s\gamma$ provides a strong constraint.

- Currently: good agreement with SM.
  Uncertainties: $\sim 10\%$.



Standard Model



models with charged Higgs

The small non-diagonal elements of CKM

CKM is *nearly diagonal* — Wolfenstein parametrization:

$$V_{\mathrm{CKM}} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \simeq \begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

key point: off-diagonal elements are small,

$$\lambda = 0.2258 \pm 0.0014 \qquad A \simeq 0.82,$$

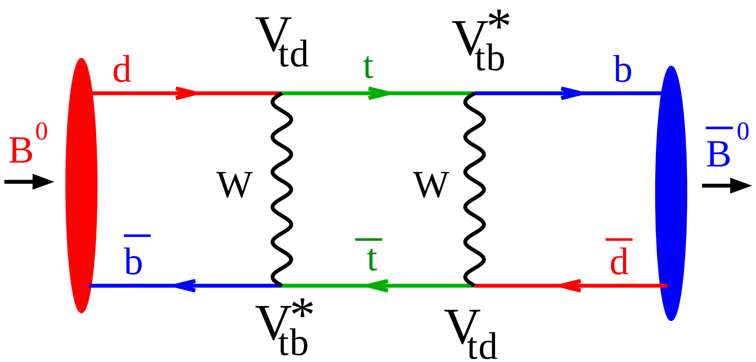
$$|V_{\mathrm{ub}}| \simeq 4 \cdot 10^{-3} \qquad |V_{\mathrm{td}}| \simeq 8.5 \cdot 10^{-3}$$

so in the SM flavour and CP–violating transitions are suppressed.
Most extensions of the SM (e.g. SUSY) introduce additional d.o.f. that would propagate in loops and change the amplitudes!
$\Longrightarrow$ flavour–changing processes are sensitive to new physics!

$B^0 \leftrightarrow \bar{B}^0$ mixing and the New Physics "flavour problem"

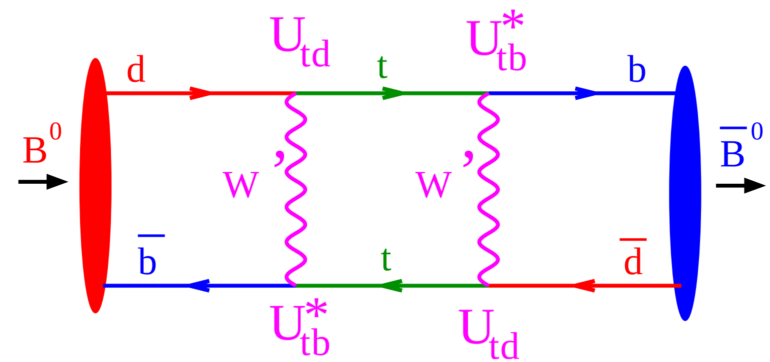
Beyond the SM: new particles that induce flavour changing interactions.

Example: new W' interaction with mixing parameters $\mathrm{U_{ud}}$:



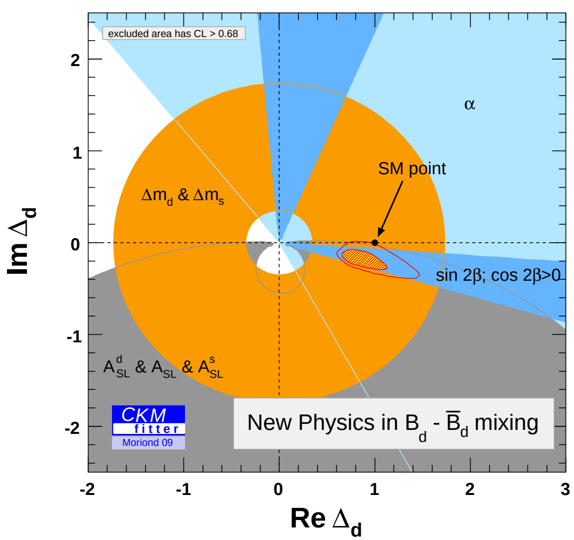
SM mixing $M_{12}^{\rm SM}$

+



mixing beyond the SM

$$M_{12}^{\rm data}/M_{12}^{\rm SM} = \Delta_d$$



- Potentially large effect: the SM off-diagonal terms are small $|V_{\rm td}| \simeq 8.5 \cdot 10^{-3}$
- W' with generic flavour structure $U^*_{\rm tb} U_{\rm td} \sim \mathcal{O}(1)$ is already excluded at LHC energies.

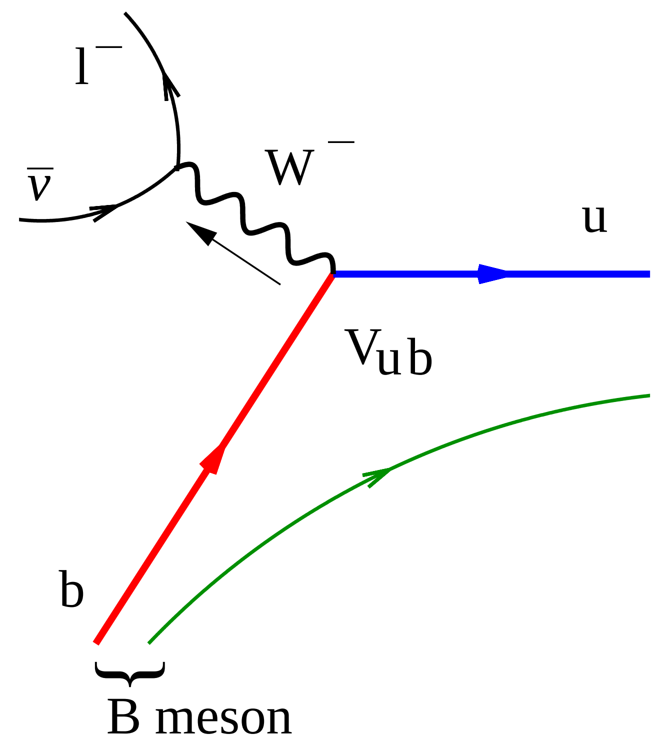
$$M_{W'} \gtrsim \frac{U^*_{\rm tb} U_{\rm td}}{V^*_{\rm tb} V_{\rm td}} M_W \simeq 10\,\mathrm{TeV}$$

Measuring the CKM parameters

$$\begin{bmatrix} V_{\rm ud} & V_{\rm us} & V_{\rm ub} \\ V_{\rm cd} & V_{\rm cs} & V_{\rm cb} \\ V_{\rm td} & V_{\rm ts} & V_{\rm tb} \end{bmatrix} \simeq \begin{bmatrix} \text{nuclear } \beta \text{ decay} & K \to \pi l \nu & b \to u l \nu \\ c \to d l \nu & c \to s l \nu & b \to c l \nu \\ \text{loops } b \to d & \text{loops } b \to s & t \to b l \nu \end{bmatrix}$$

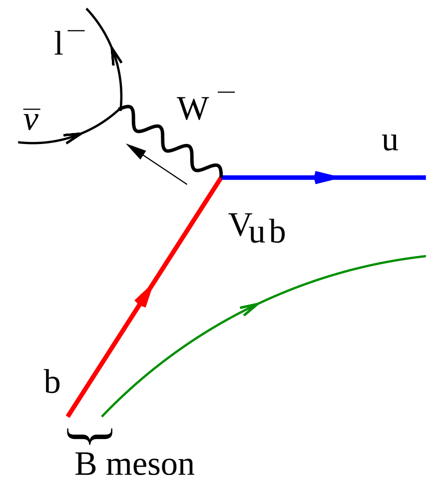
Many measurements from b decays:

- $V_{\rm cb}$ and $V_{\rm ub}$: SM tree–level decays



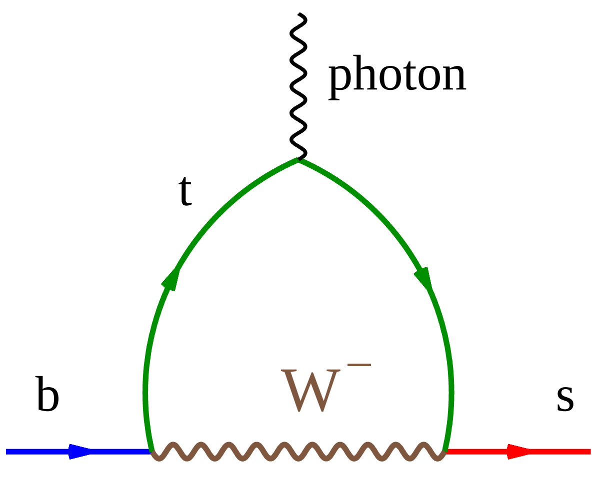
Measuring the CKM parameters

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \simeq \begin{bmatrix} \text{nuclear } \beta \text{ decay} & K \to \pi l \nu & b \to u l \nu \\ c \to d l \nu & c \to s l \nu & b \to c l \nu \\ \text{loops } b \to d & \text{loops } b \to s & t \to b l \nu \end{bmatrix}$$

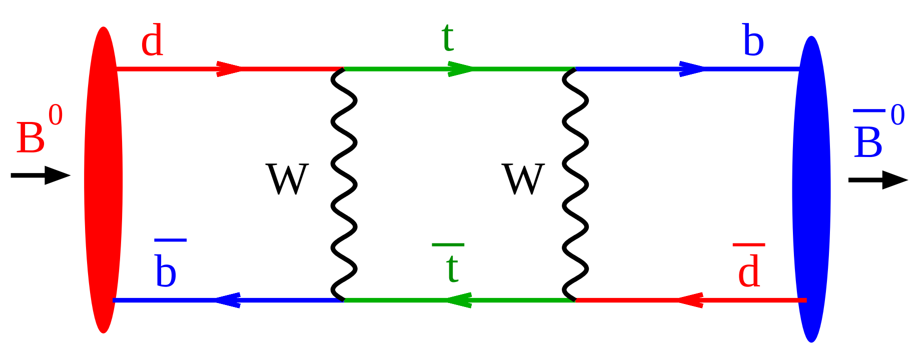


Many measurements from b decays:

- V_{cb} and V_{ub}: SM tree–level decays
- V_{td} and V_{ts} involve loops
  $\Longrightarrow$ sensitive to new physics!



FCNC

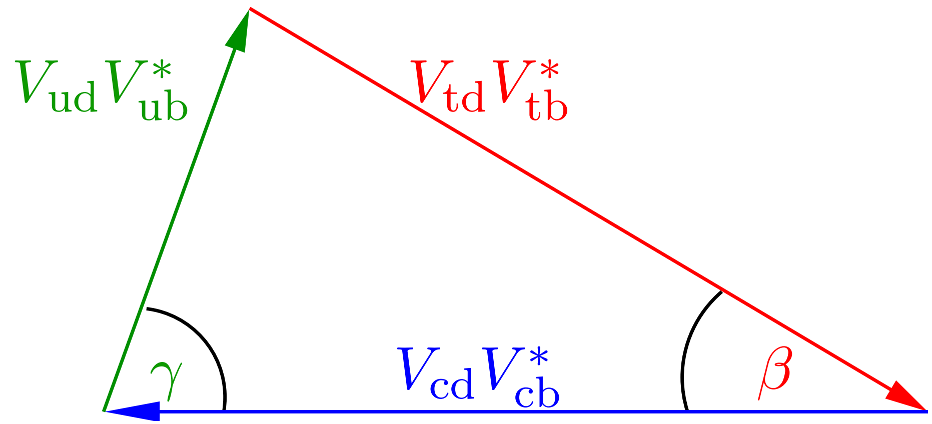


mixing

CKM and the Unitarity Triangle

$$V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = I \quad \Longrightarrow \quad V_{\mathrm{ud}} V_{\mathrm{ub}}^{*} + V_{\mathrm{cd}} V_{\mathrm{cb}}^{*} + V_{\mathrm{td}} V_{\mathrm{tb}}^{*} = 0$$

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



The goal: over-constraining the triangle

CKM and the Unitarity Triangle

$$V_{\mathrm{CKM}} V_{\mathrm{CKM}}^{\dagger} = I \quad \Longrightarrow \quad V_{\mathrm{ud}} V_{\mathrm{ub}}^{*} + V_{\mathrm{cd}} V_{\mathrm{cb}}^{*} + V_{\mathrm{td}} V_{\mathrm{tb}}^{*} = 0$$

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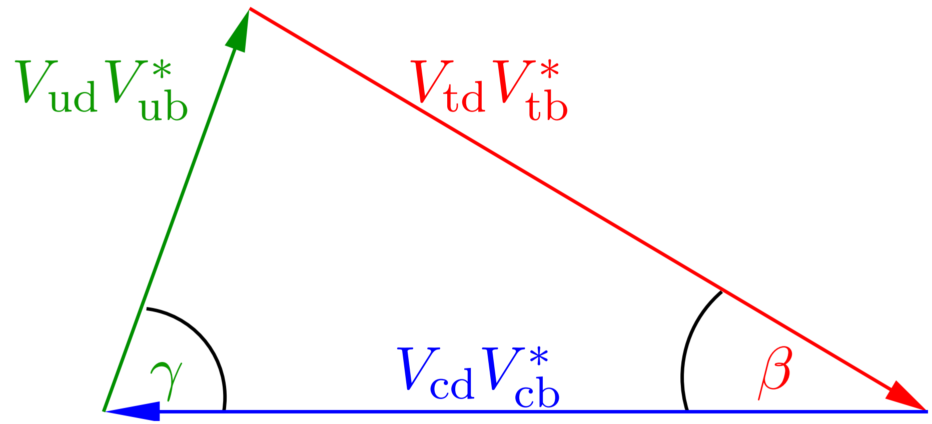
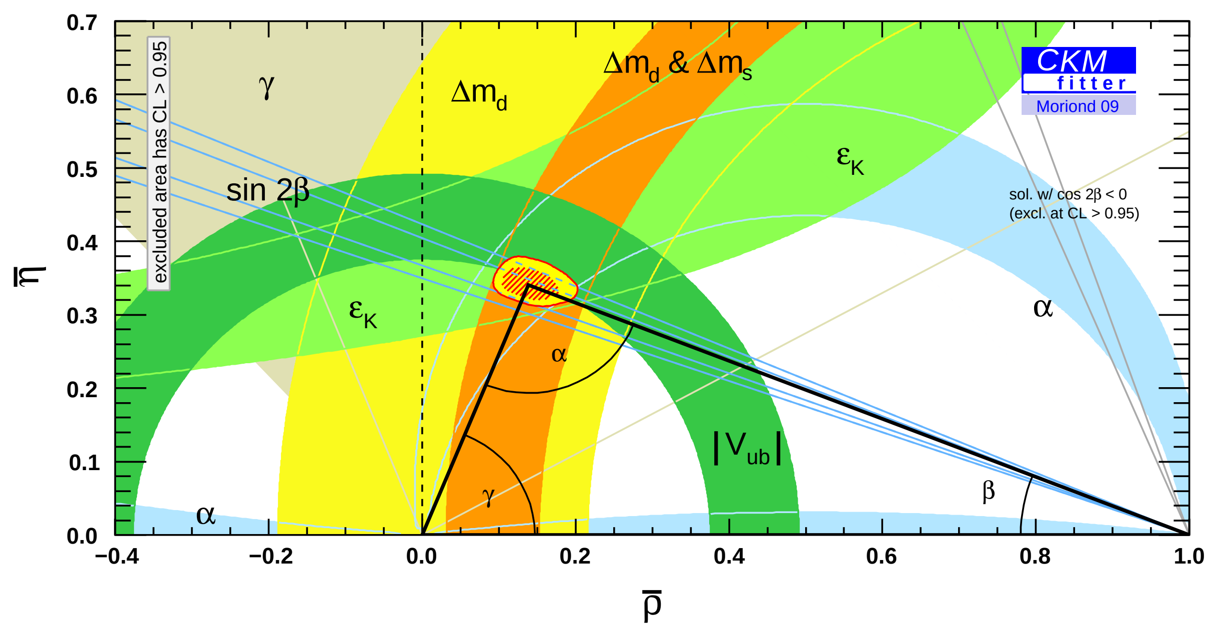
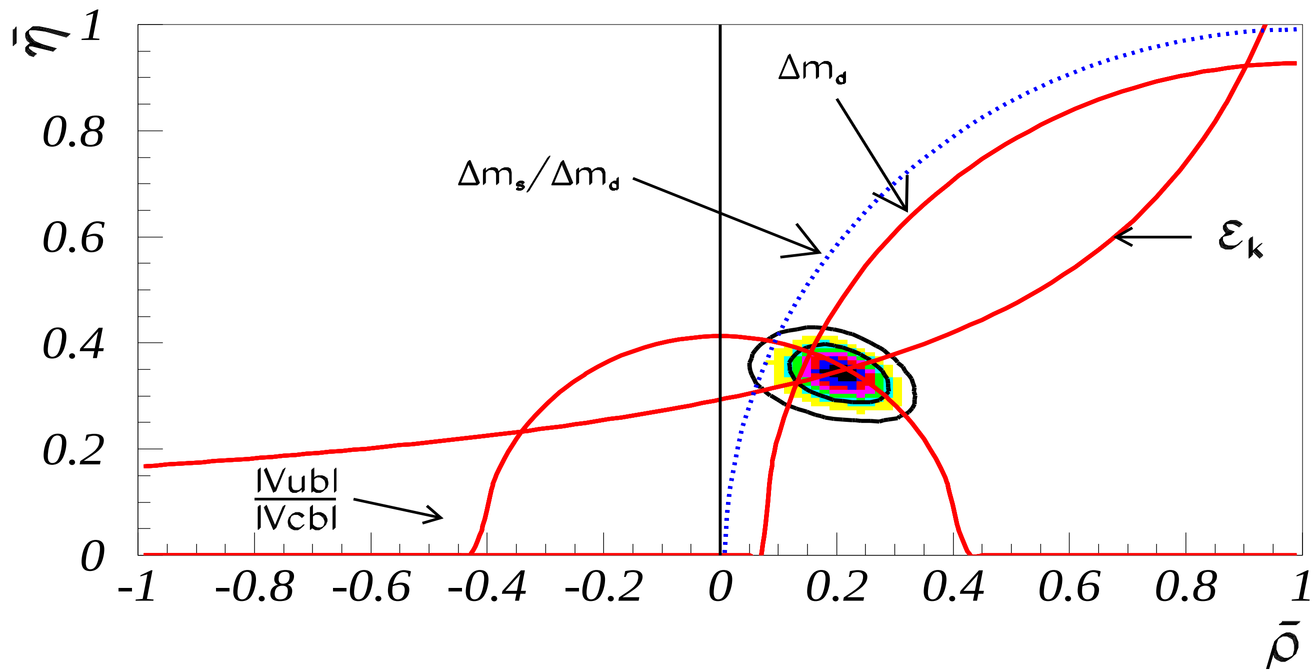




Constraining the unitarity triangle



10 years ago:

sides: $\sim \pm 20\%$

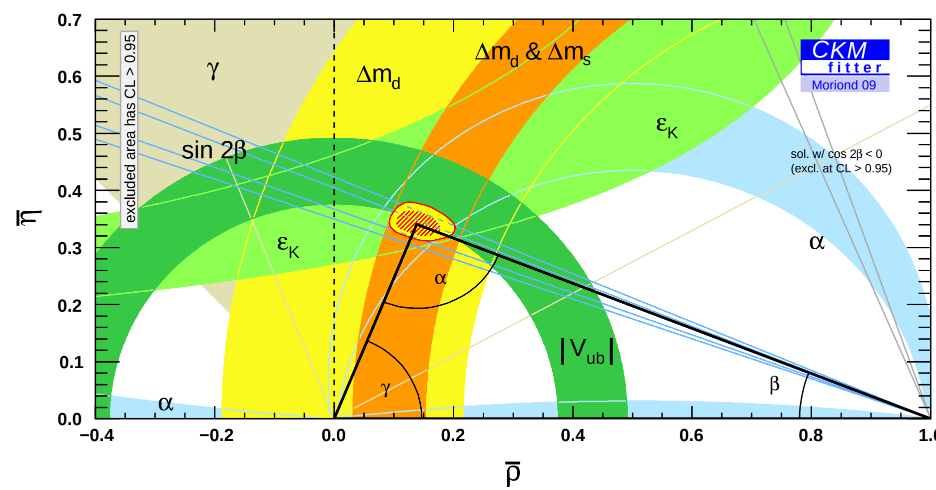
No angles!

Now:

many precise contraints

Especially angles!

KM mechanism confirmed.



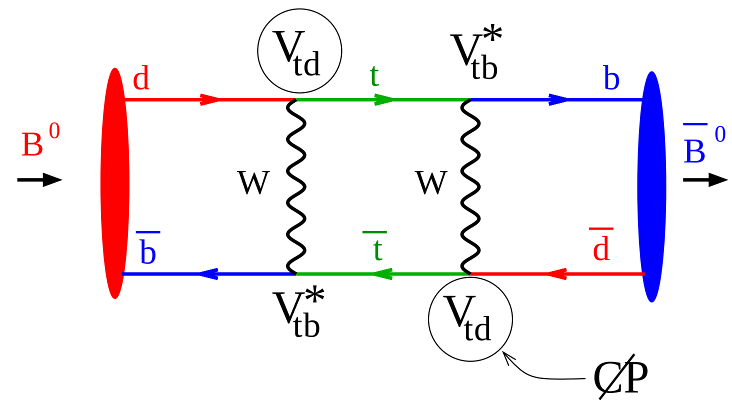
$B^0 \leftrightarrow \bar{B}^0$ mixing

Meson mass matrix is non-diagonal in the flavour basis due to $O^{(6)} = \left(\bar{b}\gamma^\mu(1-\gamma_5)d\right)^2$.

Mass eigenstates: $|B_{L,H}\rangle = p\,|B^0\rangle \mp q\,|\bar{B}^0\rangle$; $q/p \simeq \mathrm{e}^{-2i\beta}$.

$\Longrightarrow$ B^0 and $\bar{B}^0$ oscillate into each other with a frequency $\Delta m \equiv m_H - m_L = 2|\mathcal{M}_{12}|$.

$$\mathcal{M}_{12} \sim \frac{g^4}{(8\pi M_W)^2} \underbrace{(V_{\rm tb}^* V_{\rm td})^2}_{\text{phase } e^{-2i\beta}} \underbrace{\left\langle B^0 | O^{(6)} | \bar{B}^0 \right\rangle}_{\text{confinement}}$$

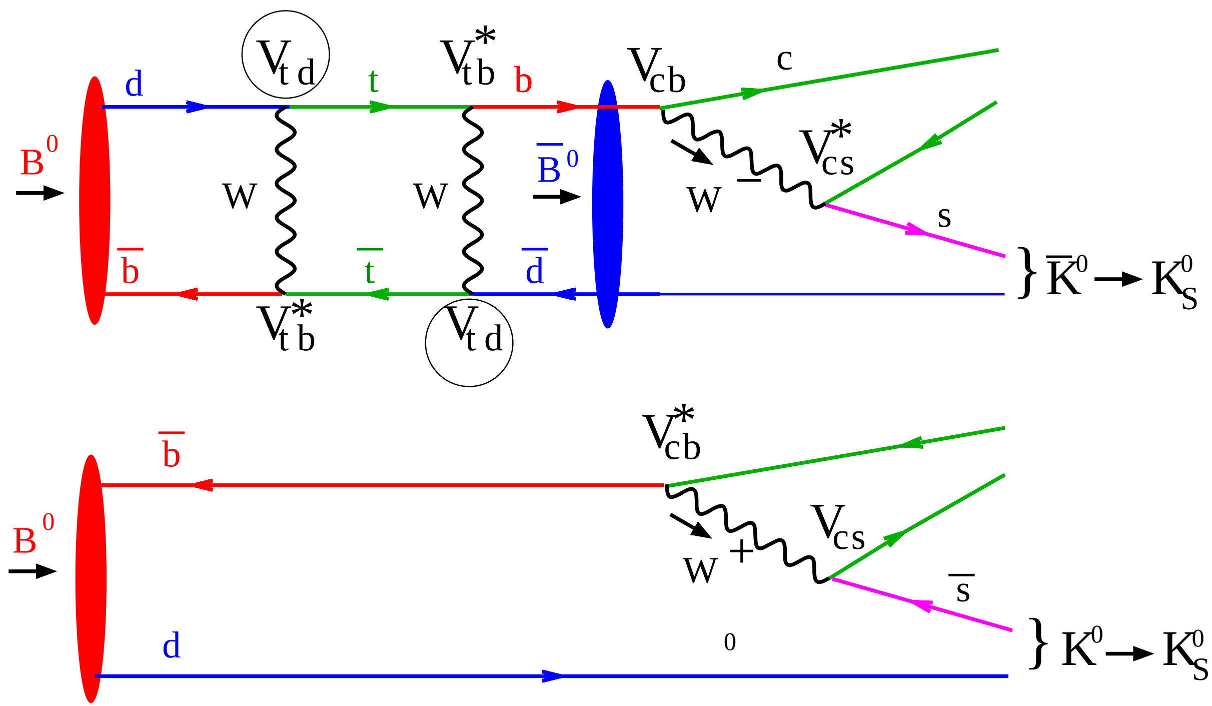


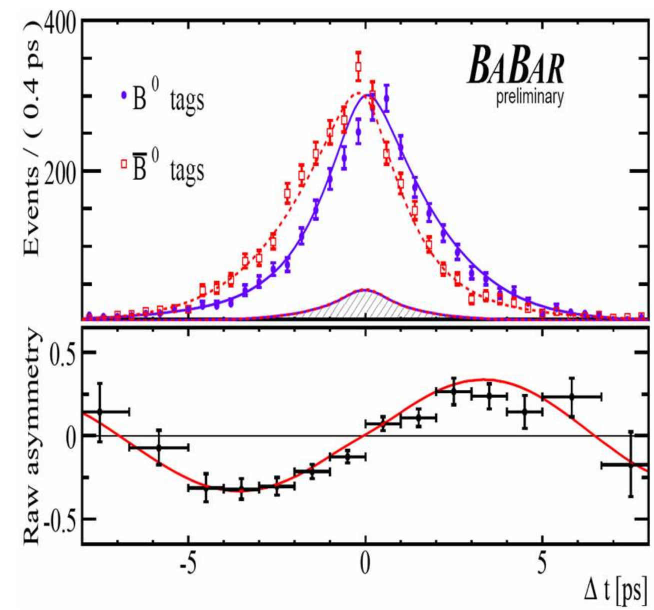
- The oscillation frequency:
  $\Delta m_{B_d} = 0.507 \pm 0.005\,\text{ps}^{-1}$,
  $\Delta m_{B_s} = 17.77 \pm 0.12\,\text{ps}^{-1}$,
  Lattice QCD needed to extract $|V_{\rm td}|$! — talk by Christine Davies
- $P(B^0 \to \bar{B}^0)$ depends on $|q/p|^2$— how can we measure β? time-dependent CP asymmetry in interference between mixing and decay Bigi & Sanda (1981)

CP violation: interference between mixing and decay

Consider a final state f_{CP} that can be reaches from both B_0 and $\bar{B}_0$:

$$\Gamma\left(B^0 \to f_{\mathrm{CP}}\right) = \left| A\left(B^0(0) \to B^0(t)\right) A\left(B^0 \to f_{\mathrm{CP}}\right) + \underbrace{A\left(B^0(0) \to \bar{B}^0(t)\right)}_{\text{phase: } e^{-2i\beta}} A\left(\bar{B}^0 \to f_{\mathrm{CP}}\right) \right|^2$$

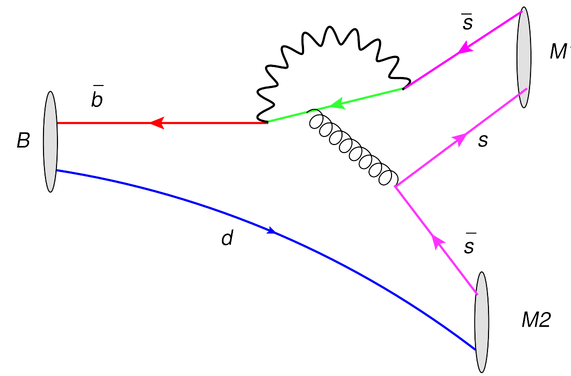




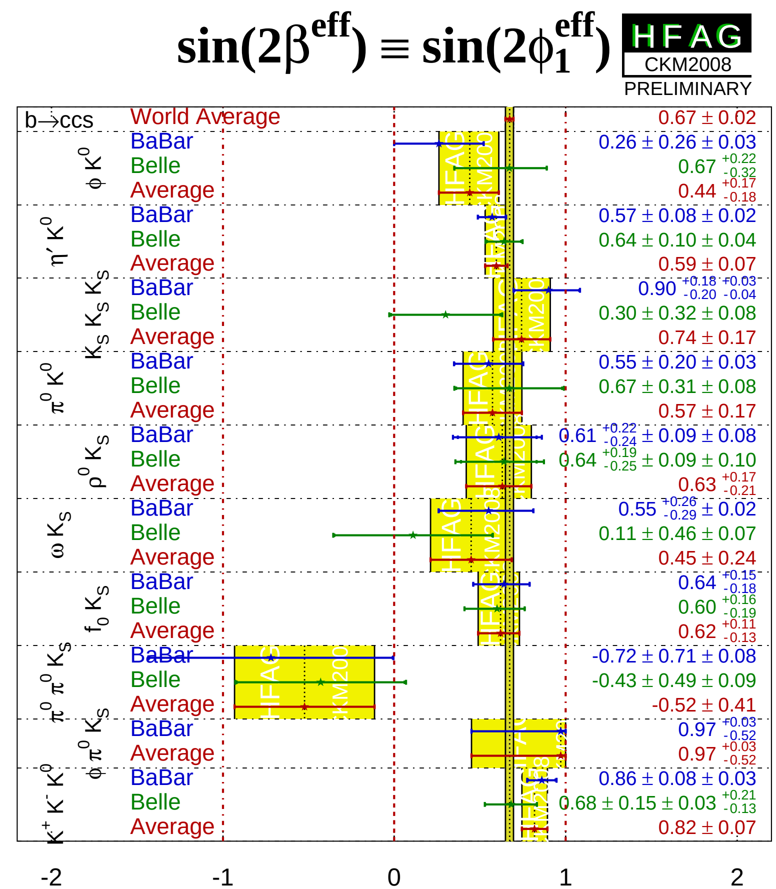
Time–dependent CP asymmetry in $B_d^0 \to c\bar{c}\,K_S^0$:

$$a_{c\bar{c}K_S}(t) \equiv \frac{\Gamma\left(\bar{B}^0(t) \to c\bar{c}K_S\right) - \Gamma\left(B^0(t) \to c\bar{c}K_S\right)}{\Gamma\left(\bar{B}^0(t) \to c\bar{c}K_S\right) + \Gamma\left(B^0(t) \to c\bar{c}K_S\right)} = \sin(2\beta)\sin(\Delta m t)$$

β from Penguin decays

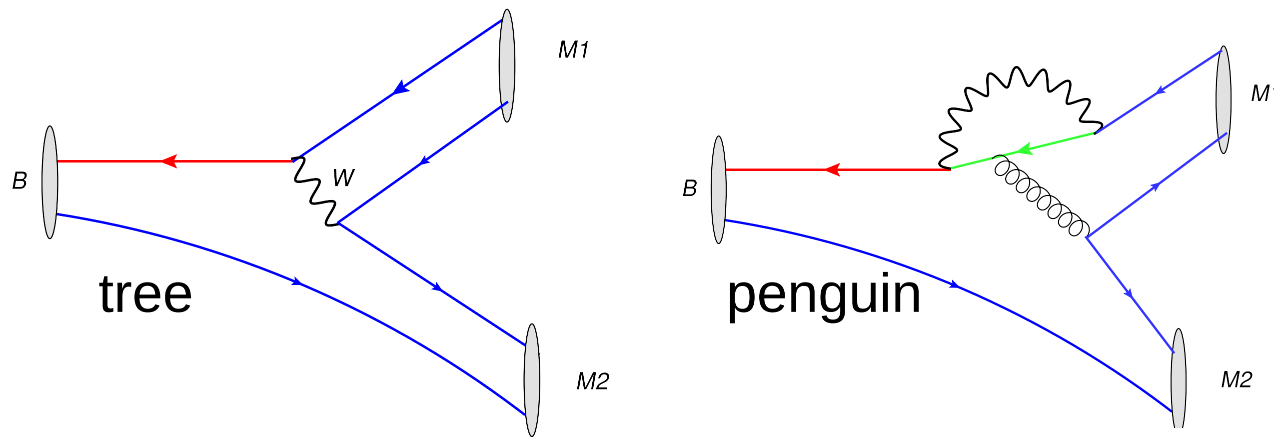


- $B^0 \to J/\Psi K_S$ is a tree decay — new physics in the mixing only.
- Penguin modes $b \to s s \bar{s}$, e.g. $B^0 \to \phi K^0$ are sensitive to new physics also through the decay.
- $B^0 \to J/\Psi K_S$ and $B^0 \to \phi K^0$ are theoretically clean: single decay diagram. QCD effects drop out in the asymmetry.
- In many cases different contributions from tree and penguin involving weak phases are weighted by different factors. $\Longrightarrow$ QCD is necessary.



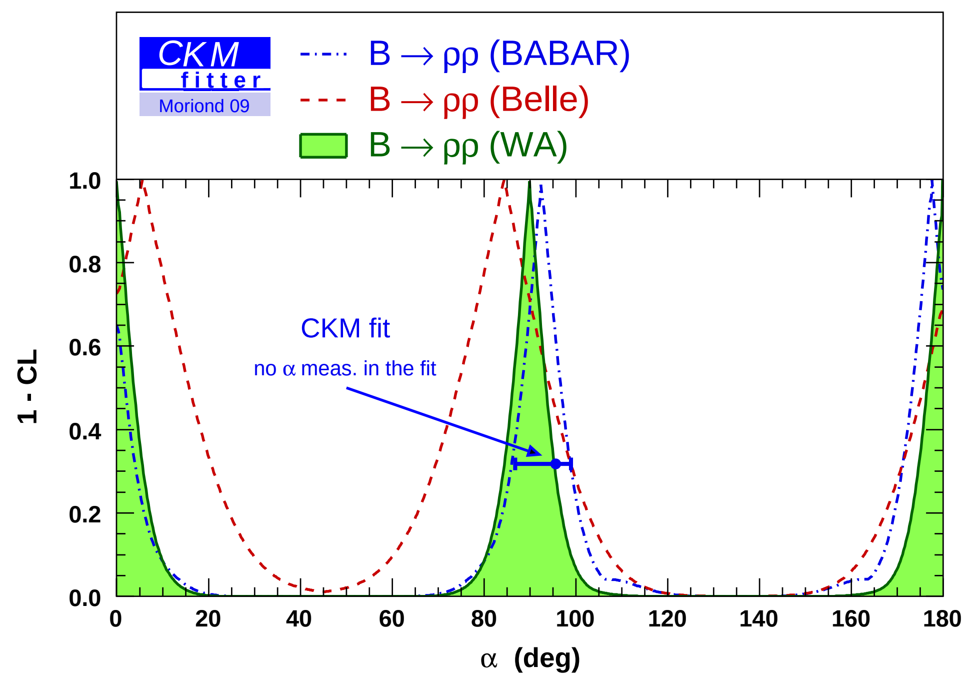
Measuring the weak angle α: $B \to \pi\pi, \rho\rho$

Measuring $\alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ud} V_{ub}^*}\right)$: both Tree and Penguin decays



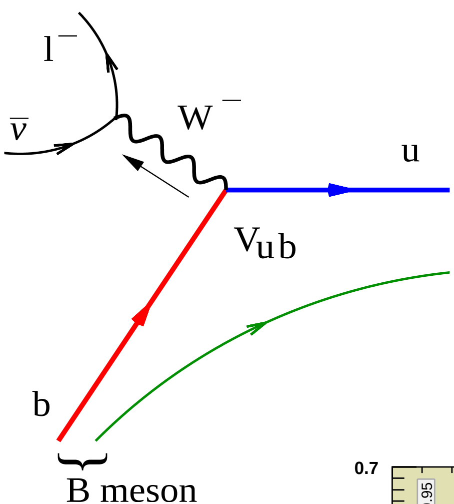
new results!

- using several modes and isospin symmetry
- precision: $\pm 5\%$!



The crucial role of semileptonic B decays

- $|V_{\rm ub}/V_{\rm cb}|$ (Unitarity Triangle side) is determined by tree–level Weak decays, $b \to u l \bar{\nu}$ and $b \to c l \bar{\nu}$, free of physics BSM
- Confronted with constraints involving loops — sensitive to physics beyond the SM, e.g. $\sin(2\beta)$ from $B^0 \leftrightarrow \bar{B}^0$.



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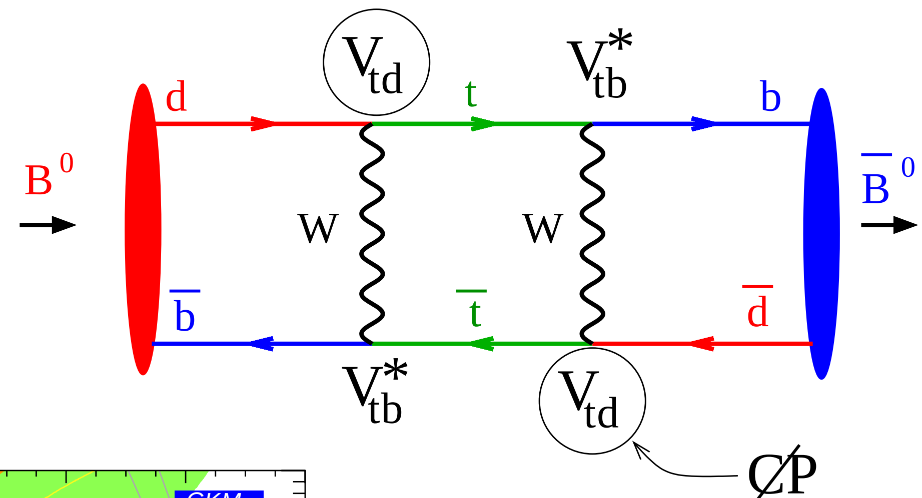
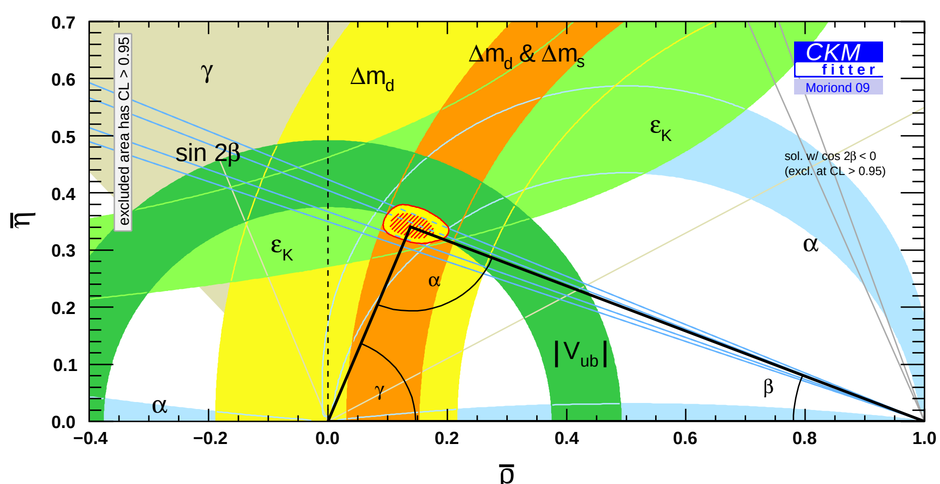
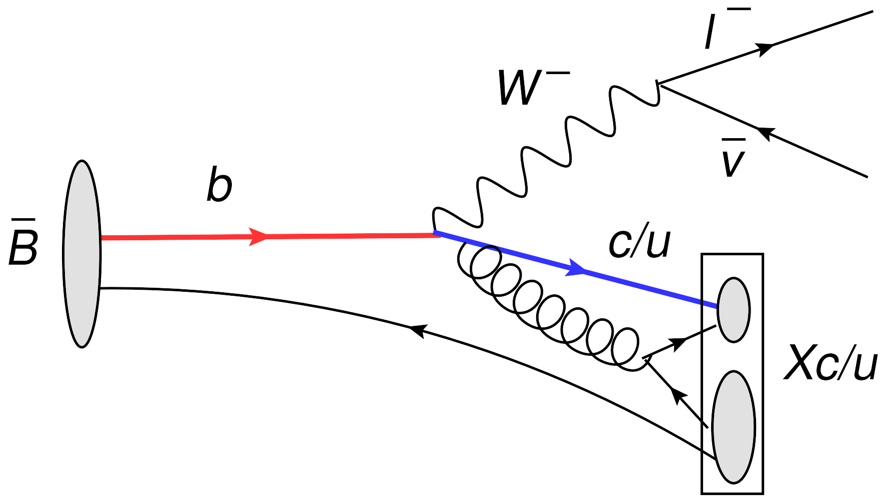




Inclusive vs. Exclusive semileptonic B decays

Inclusive final state



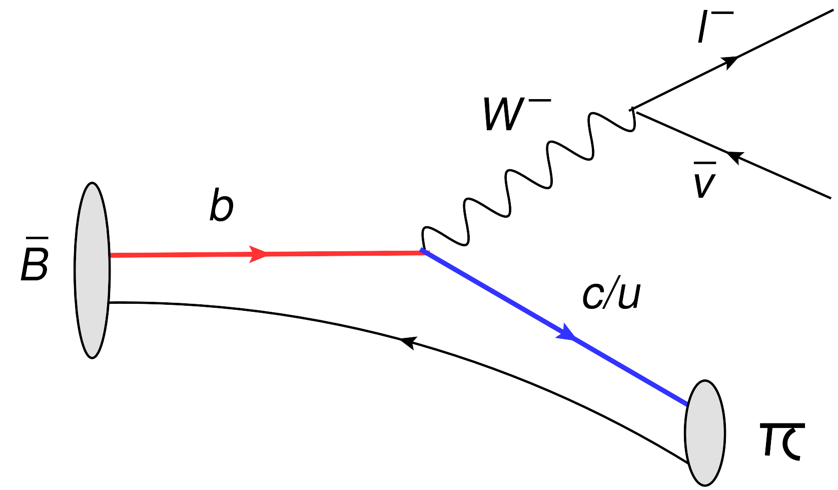
$$\Gamma = \frac{G_F^2 |V_{\rm qb}|^2}{192\pi^3} m_b^5 (1 + \cdots)$$

Total width easy to compute:

confinement is $\mathcal{O}(\Lambda^2/m_b^2)$

but — in $b \to u$ kinematic cuts are essential to reduce $b \to c$ background

Exclusive final state



$$d\Gamma/dq^2 = \frac{G_F^2 |V_{\rm qb}|^2}{192\pi^3} \left| f_+(q^2) \right|^2$$

Experimentally: Good S/B

but — proportional to form factor:

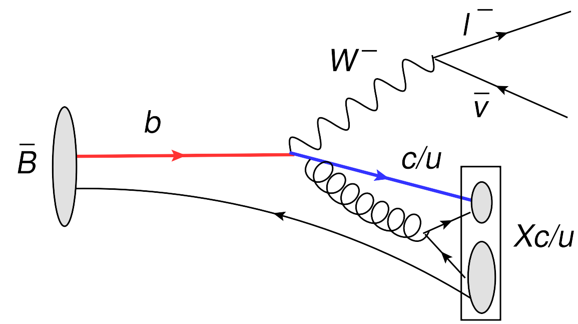
confinement is $\mathcal{O}(1)$ — need Lattice — talk by Christine Davies

Inclusive and Exclusive have different strengths — complementarity!

Inclusive semileptonic $b \to u$ decays

- Inclusive $b \to u$ has *an overwhelming* charm background:

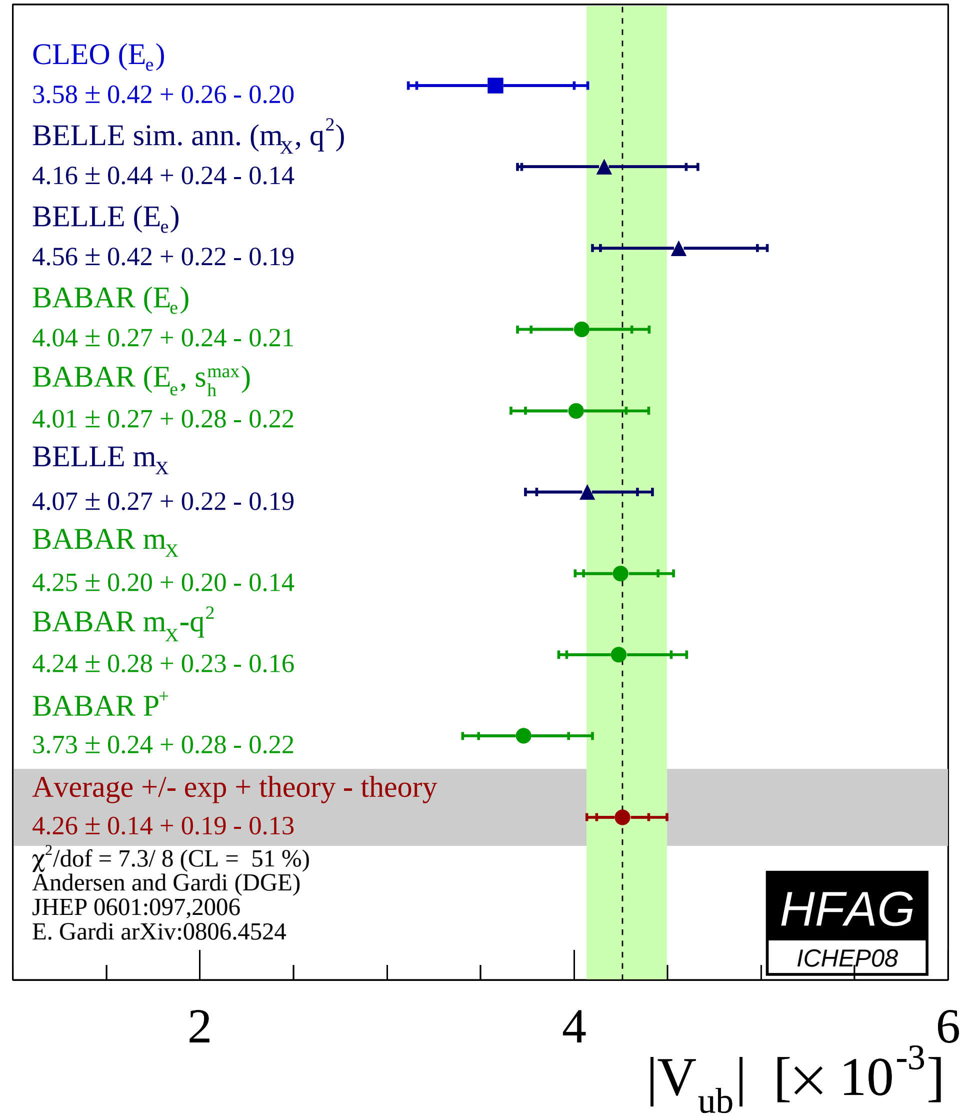
$$\frac{\Gamma(b \to u l^- \bar{\nu})}{\Gamma(b \to c l^- \bar{\nu})} = \frac{|V_{\rm ub}|^2}{|V_{\rm cb}|^2} \simeq \frac{1}{50}$$



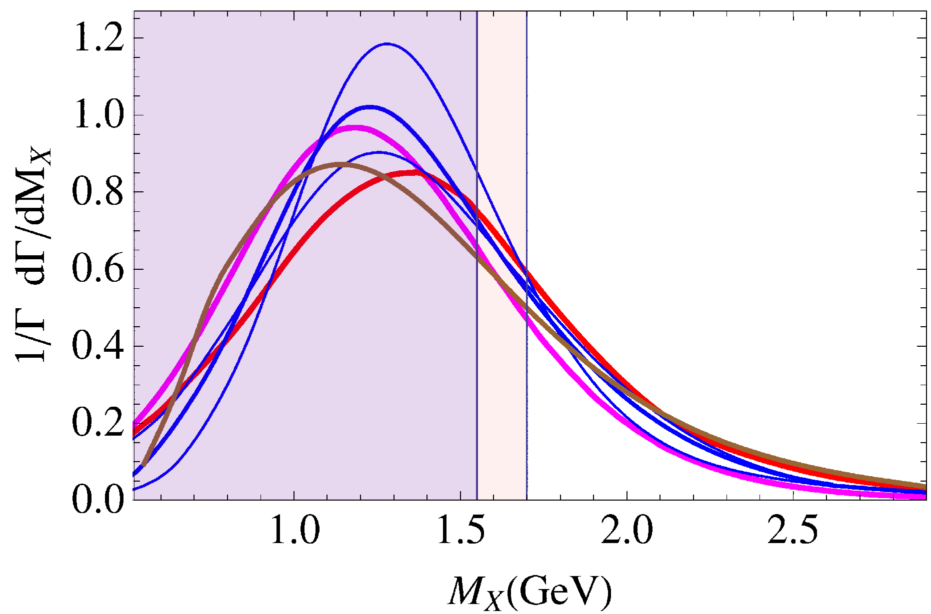
- $b \to c$ events always have $M_X > 1.7$ GeV — cuts distinguish them!
- Many experimental analyses; measured branching fraction varies: 20%– 70% of the total.
  $\Longrightarrow$ To extract $|V_{\rm ub}|$ we need to compute the spectrum.
- OPE does not apply in a restricted kinematic region. For small M_X there are large corrections...
- Major progress on the theory side. Different approaches:
  - Expansion in shape functions, matched with OPE (BLNP)
  - Resummed perturbation theory $+$ power corrections (DGE)
  - OPE–based structure–function parametrization (GGOU)

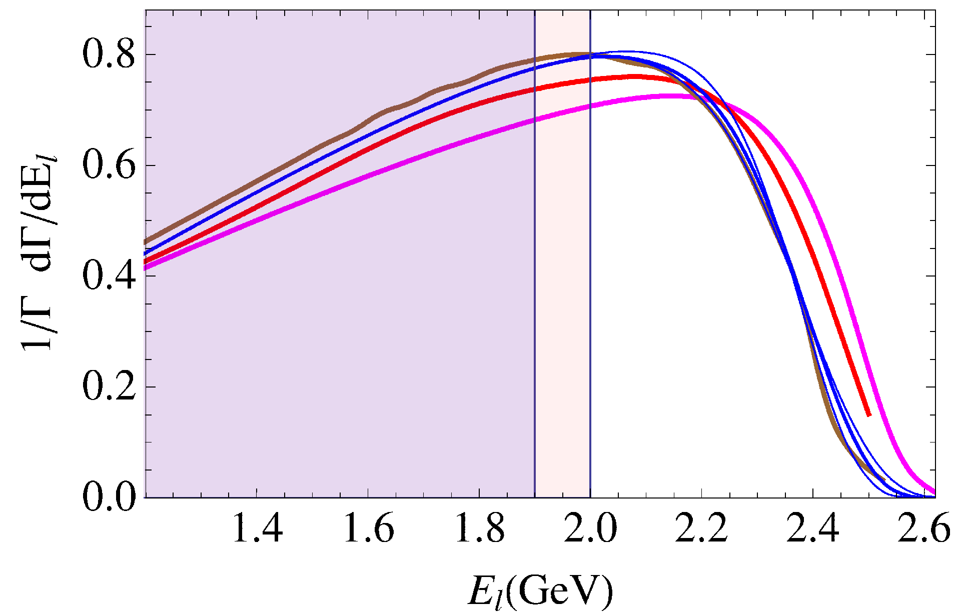
World Average $|V_{\rm ub}|$ from inclusive decays (using DGE)

- CLEO, Belle & BaBar performed several inclusive measurements of the partial $b \to u$ width with different kinematic cuts on E_l, q^2, M_X, etc.
- Each measurement is translated by HFAG into a value for $|V_{\rm ub}|$
- The results are all consistent.

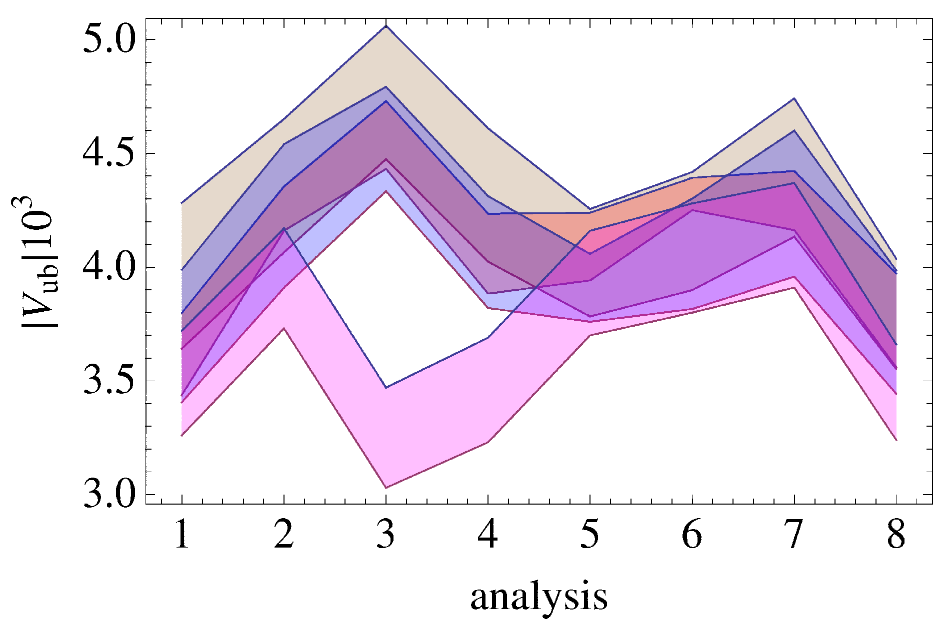


Comparing the different theoretical approaches





- DGE-BLNP-GGOU: consistent spectra
- Consistent $|V_{\rm ub}|$ from each analysis within non-parametric theory uncertainty



Semileptonic decays: up-to-date results, tensions

Tension I: $|V_{\rm cb}|$ Inclusive *vs.* Exclusive

$|V_{\rm cb}|_{\rm incl.} = (41.5 \pm 0.5 \pm 0.6) \cdot 10^{-3}$ Gambino et al.

$|V_{\rm cb}|_{\rm excl.} = (38.2 \pm 0.5 \pm 1.1) \cdot 10^{-3}$ Laiho et al.

Tension II: $|V_{\rm ub}|$ Inclusive *vs.* Exclusive

$|V_{\rm ub}|_{\rm incl.} = (4.2 \pm 0.2 \pm 0.2) \cdot 10^{-3}$ DGE, BLNP, GGOU

theory uncertainty dominated by b-quark mass $m_b = 4.24 \pm 0.04$ GeV

$|V_{\rm ub}|_{\rm excl.} = (3.4 \pm 0.1 \pm 0.4) \cdot 10^{-3}$ HPQCD, Fermilab/MILC, LCSR

Inclusive *vs.* Exclusive is perplexing: new physics at tree level?

Right-handed currents are not excluded... [Chen& Nam 2008]

Tension III: Inclusive semileptonic $|V_{\rm ub}|$ *vs.* $\sin(2\beta)$:

$|V_{\rm ub}|_{\sin(2\beta)} = 3.5 \pm 0.2$ Global fits (UTfit, CKMfitter)

New physics in $\sin(2\beta)$? — not conclusive

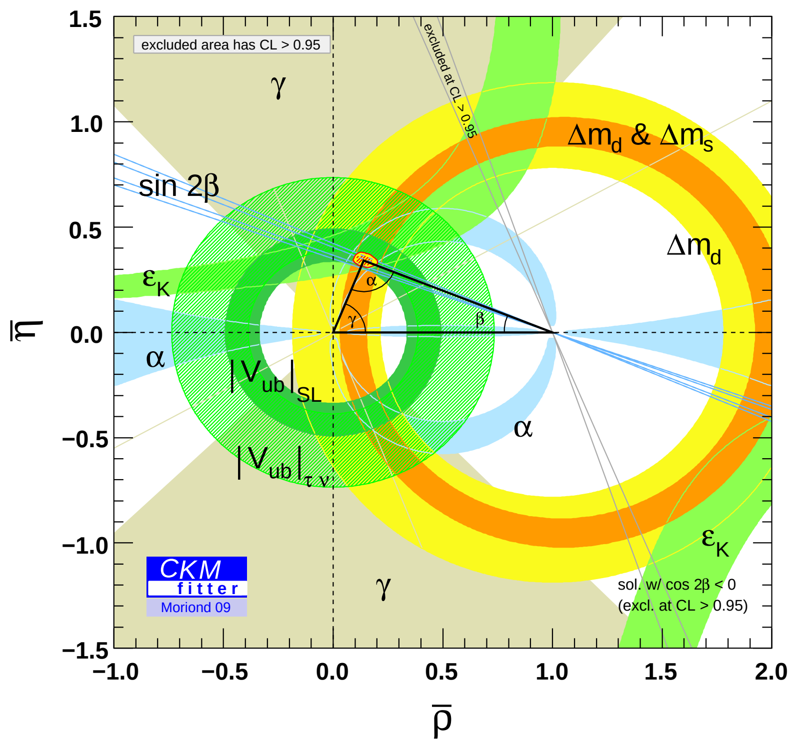
Leptonic decays: more tension

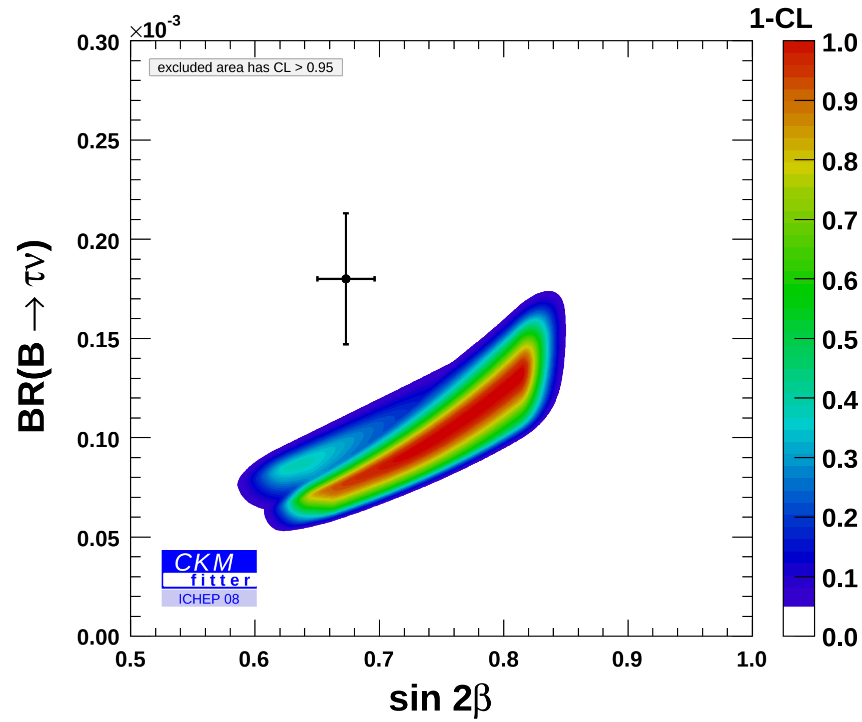
Tension IV: $|V_{\rm ub}|$ from leptonic $B \to \tau\nu$ vs. $\sin(2\beta)$:

Standard Model: $$\mathcal{B}(B \to \tau\nu_\tau) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right) f_B^2 |V_{\rm ub}|^2 \tau_B$$

decay constant: $f_B = 0.216 \pm 0.022$ GeV [HPQCD 2005]

$\mathcal{B}(B \to \tau\nu_\tau) = (1.73 \pm 0.35) \cdot 10^{-4}$ CKMfitter based on BaBar 08, Belle 09





- Right-handed current can enhance $\mathcal{B}(B \to \tau\nu_\tau)$, Chen & Nam 08
- New physics in $\sin(2\beta)$? — still not conclusive.

Conclusions

- The B factories (and Tevatron) confirmed the CKM picture!
- Severe constraints on new physics: extra particles in the TeV range generate very little $\Delta F = 1$ and $\Delta F = 2$ transitions.
  $\Longrightarrow$ Either not there, or have a special flavour structure
- Complementarity: high–energy frontier and precision measurements in the flavour sector (energy reach, properties)
- We do not yet have a theory of flavour. If we are lucky hints may come from investigating the EW symmetry breaking.
- Good control of QCD is essential for precision flavour physics. A lot of progress. The experiments gave the proper boost.
- Experimental effort in B physics continues: LHCb, super B factories, promising a lot of interesting physics.

LHC and (super) B factories: B physics program

Highly complementary program in (super) B factories and LHCb:

B factories

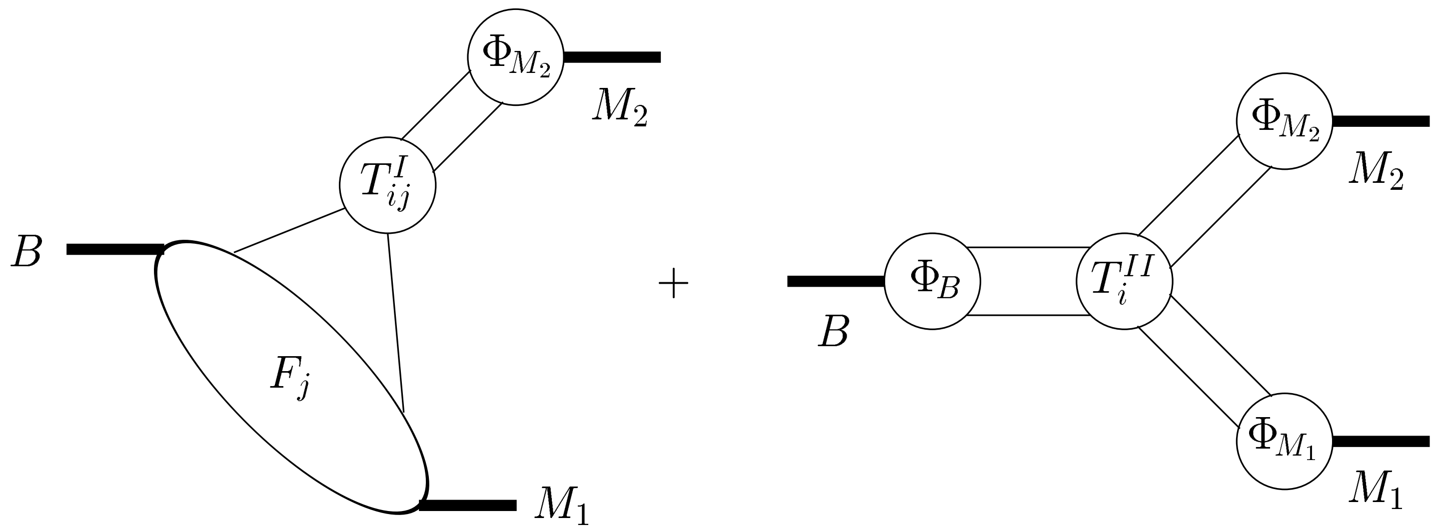
- semileptonic decays: $|V_{\rm ub}|$
- mixing in B_d^0, tree & penguin modes
- rare FCNC decays, e.g. $B \to X_{s/d}\gamma$, $B \to \tau\nu$

LHC

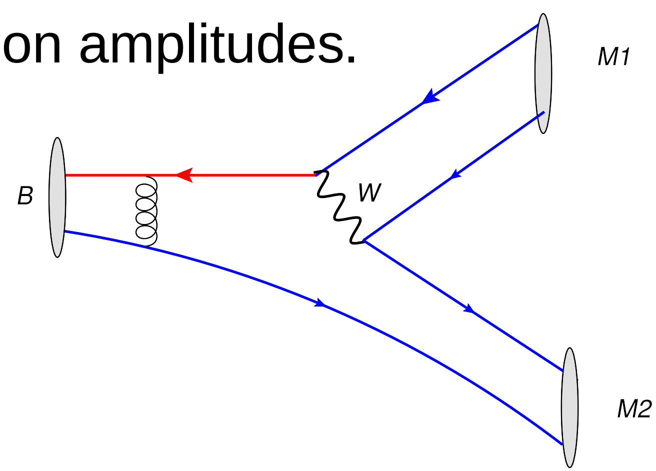
- $B \to DK$: measure γ
- mixing in B_s^0: $B_s \to \psi\,\phi$ (tree) & penguin modes
- rare FCNC decays, e.g. $B \to K^*\mu^+\mu^-$, $B_s \to \mu^+\mu^-$

Measuring the weak angle α: theory

QCD Factorization: separating computable short–distance effects from universal long-distance effects to leading order in Λ/m_b, all orders in α_s: [BBNS (2000)]



Form factor is not sufficient — there are HARD spectator interactions:
⟹ Need to quantify distribution amplitudes.



Ways beyond the Standard Model

Two complementary elements:

- high–energy frontier: search for new heavy particles
- flavour physics: precision measurements at low energy that are sensitive to symmetry properties.

  SM flavour- and CP-violating interactions are *highly constrained*

  $\Longrightarrow$ a variety of rare transitions (with well–predicted SM rates)

  $\Longrightarrow$ sensitivity to new physics!

  - lepton sector (ν oscillations, LFV $\mu \to e\gamma$, e EDM, $\ldots$)
  - quark sector (B physics, K physics, $\ldots$)

Theoretical tool box

- Effective weak Hamiltonian: integrating out W and t.
- $m_b \gg \Lambda_{QCD}$:
  - factorization: form factors, distribution amplitudes,...
  - heavy quark expansion in powers of Λ_{QCD}/m_b
  - perturbation theory: expansion in $\alpha_s(m_b)$
- $\Lambda_{\text{QCD}} \gg m_s, m_d, m_u$: $SU(2)$ or $SU(3)$ global symmetries
- QCD sum rules on the lightcone — suitable for decay into light energetic partons. Unfortunately, not precise.
- Lattice gauge theory — systematic regularization of QCD! Difficult to deal with light energetic particles.