Flavour Physics

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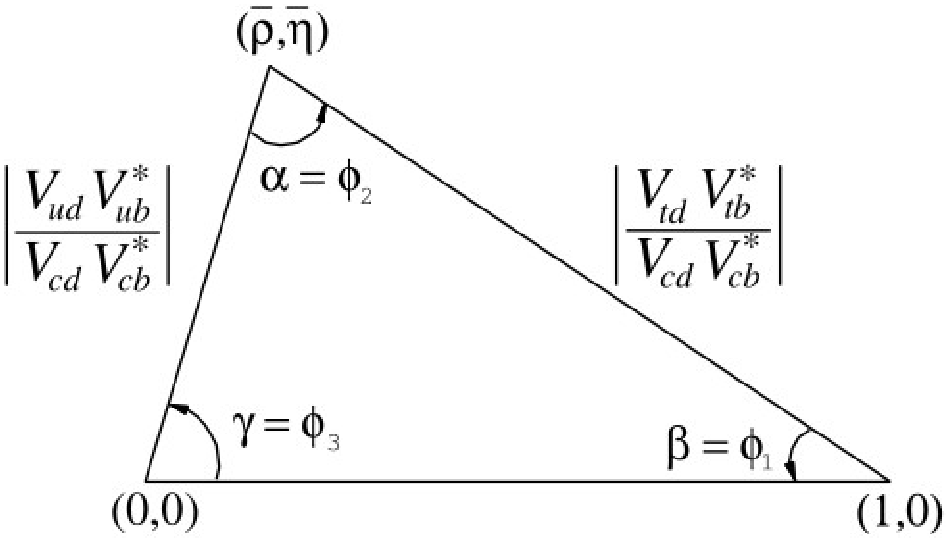
13th NExT Ph.D. Workshop
QMUL, London

Lecture 2

Outline

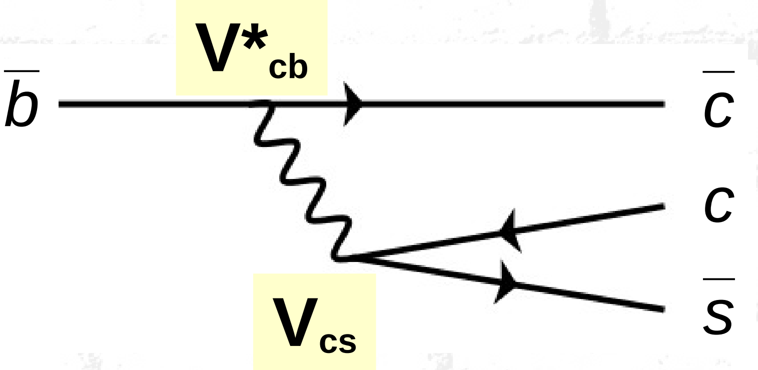
- Short recap
- Angles of the unitarity triangle
- Inputs to the Unitarity Triangle fit
- Global fit results in and beyond the SM
- New physics Scale analysis
- b to sll FCNC: ongoing work



sin2β in golden $b \to c\bar{c}s$ modes

$B^0 \to J/\psi K_{S,L}$

Leading-order tree decays to $c\bar{c}s$ final states



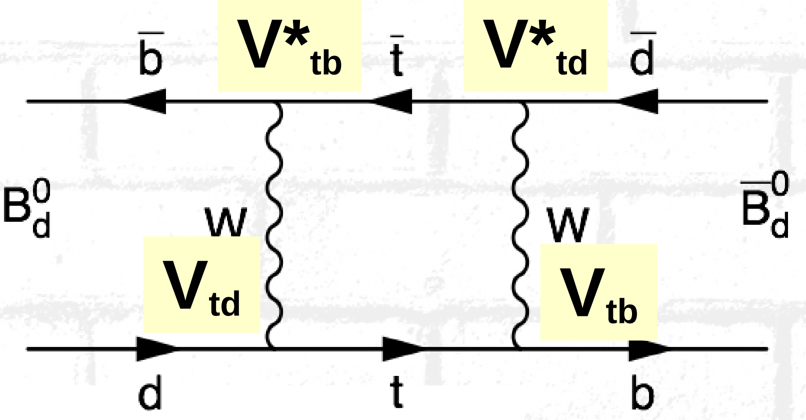
+d $K^0 \to K_{S,L}$

tree diagram

$$\frac{\bar{A}}{A} = \frac{V_{cb}V^*_{cs}}{V^*_{cb}V_{cs}} \; \frac{V_{cs}V^*_{cd}}{V^*_{cs}V_{cd}}$$

K mixing

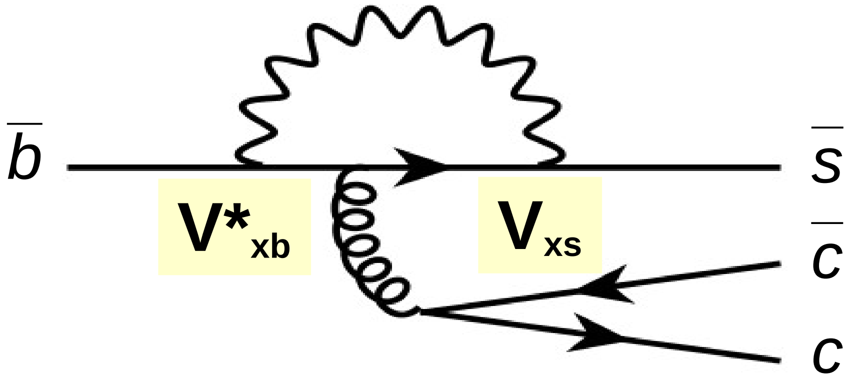
because both B and $\bar{B}$ can decay in this common final state, this can interfere with the oscillation diagram:



$$\lambda = \frac{q}{p}\frac{A(\bar{B} \to f)}{A(B \to f)} = \frac{V^*_{td}V_{tb}}{V_{td}V^*_{tb}}\frac{\bar{A}}{A} \sim e^{-i2\beta}\frac{\bar{A}}{A}$$

$\sin 2\beta$ in golden $b \to c\bar{c}s$ modes

$B^0 \to J/\psi K_{S,L}$



$$\begin{cases} x=u \to P^u \sim V_{ub}V^*_{us} \\ x=c \to P^c \sim V_{cb}V^*_{cs} \\ x=t \to P^t \sim V_{tb}V^*_{ts} \end{cases}$$

using this unitary condition ($2^{nd} \rightleftarrows 3^{rd}$ family), we eliminate $V_{tb}V^*_{ts}$

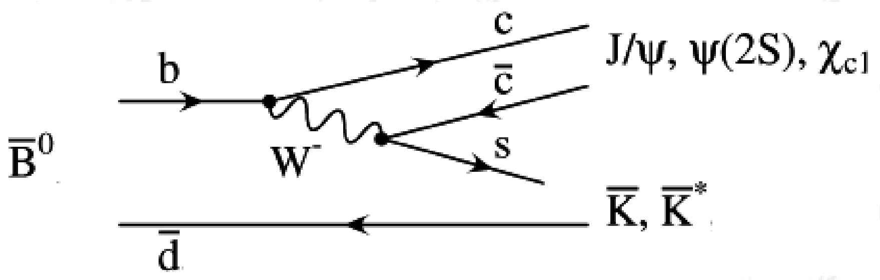
$$V_{ub}V^*_{us} + V_{cb}V^*_{cs} + V_{tb}V^*_{ts} = 0 \quad \to \quad V_{tb}V^*_{ts} = -V_{ub}V^*_{us} - V_{cb}V^*_{cs}$$

thus the amplitude is:

$$A_{ccs} \sim \underbrace{V_{cb}V^*_{cs}}_{\mathcal{O}(\lambda^2)}(T + P^c - P^t) + \underbrace{V_{ub}V^*_{us}}_{\mathcal{O}(\lambda^4)}(P^u - P^t)$$

CKM-suppressed pollution by penguins

$\sin 2\beta$ in golden $b \to c\bar{c}s$ modes



- ◎ branching fraction: $O(10^{-3})$
  the colour-suppressed tree dominates
  and the penguin pollution has
  the same weak phase of the tree or is CKM suppressed
- ◉ $$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

S ~ sin2β
C ~ 0

- ◎ theoretical uncertainty:
  - ◉ model-independent data-driven estimation from $J/\psi\pi^0$ data:
    $$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta = -0.01 \pm 0.01$$
  - ◉ model-dependent estimates of the u- and c- penguin biases
    $$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta \sim O(10^{-3})$$
    $$\Delta S_{J/\psi K0} = S_{J/\psi K0} - \sin 2\beta \sim O(10^{-4})$$

M.Ciuchini et al.
arXiv:1102.0392 [hep-ph].

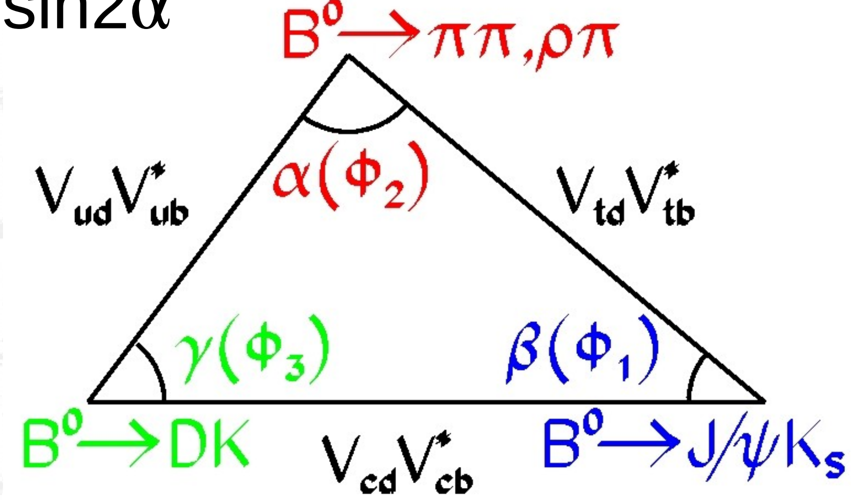
H.Li, S.Mishima
JHEP 0703:009 (2007)

H.Boos et al.
Phys. Rev. D73, 036006 (2006)

CP Violation in the B Meson System

Time-dependent analysis
CP violation in interference
Less clean channel due to big penguin contributions

$S_{f_{CP}} \propto \sin 2\alpha$



Time-dependent analysis:
CP violation in interference

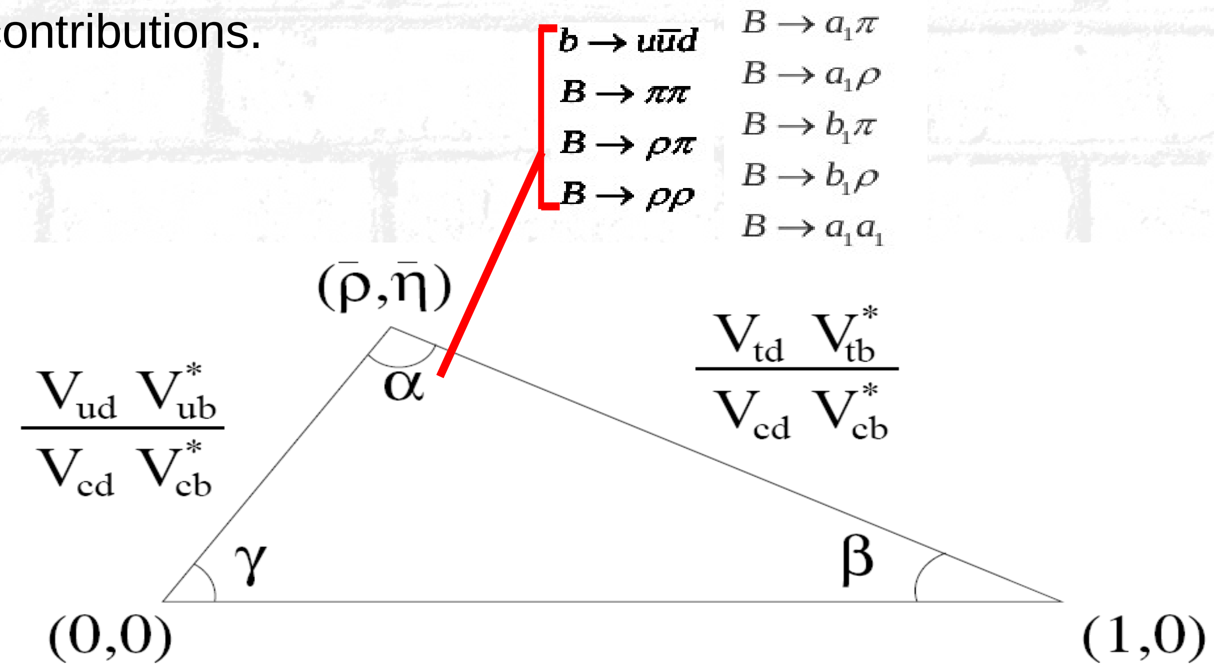
$S_{f_{CP}} = -\eta_{CP}\sin 2\beta$

Direct CP violation
Interference of two tree diagrams

α/ϕ_2 angle

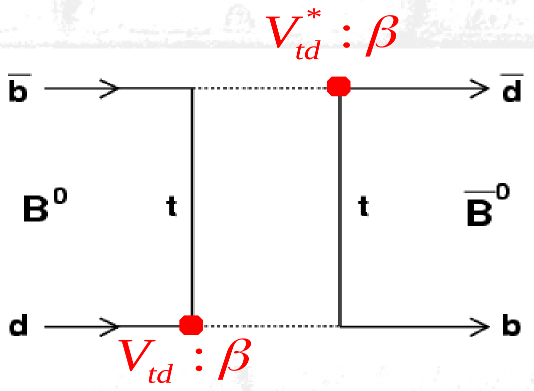
$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

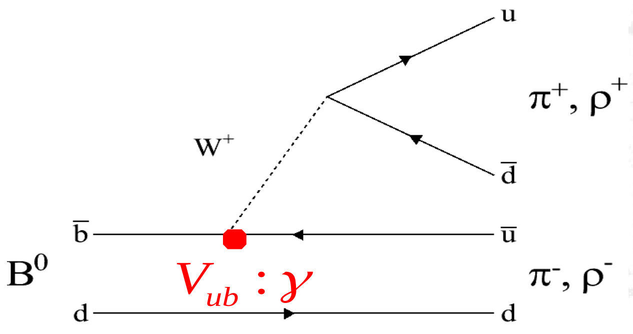
$B \rightarrow u\bar{u}d$ transitions
with possible loop contributions.



α/ϕ_2 angle

◎ Interference between box and tree results in an asymmetry that is sensitive to α in $B \to hh$ decays: $h = \pi, \rho, \ldots$



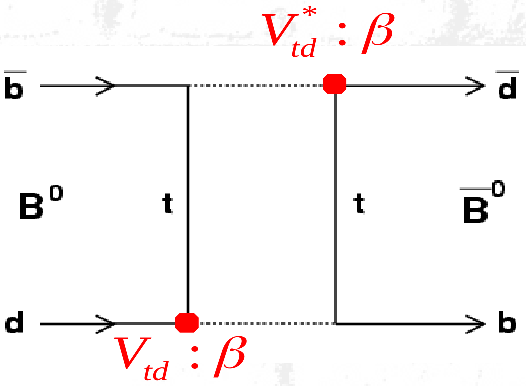


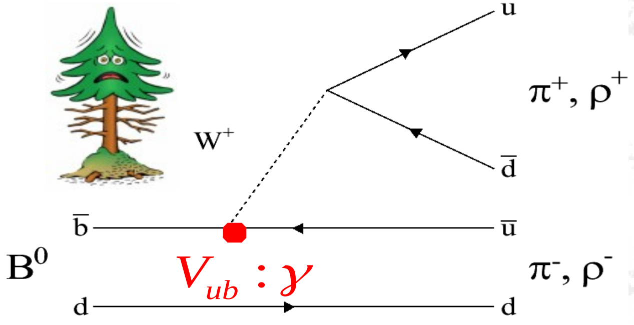
$$C_{hh} = 0$$
$$S_{hh} = \sin(2\alpha)$$

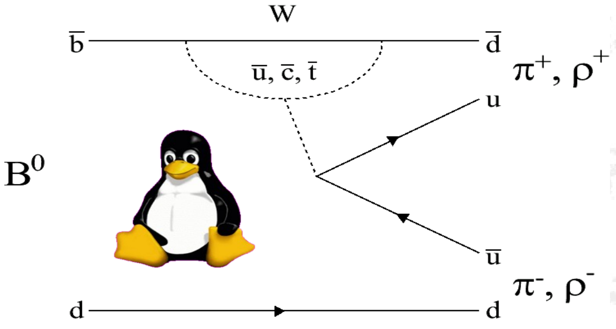
This is again a case of interference between mixing and decay.
This scenario is equivalent to the measurement of sin2β in Charmonium decays … but in this case it is more complicated..

α/ϕ_2 angle

◎ Interference between box and tree results in an asymmetry that is sensitive to α in $B \to hh$ decays: h = π, ρ, …







$\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$

In this case the penguin diagram is not CKM suppressed so it spoils the clean measurement of the CP violation effect

α (ϕ_2) from $\pi\pi$, $\rho\rho$, $\pi\rho$ decays with Isospin analysis

Interference between box mixing and tree diagrams results in an asymmetry that is sensitive to α in $B \rightarrow hh$ decays: $h = \pi, \rho$

Unlike for β, loop (penguin diagrams) corrections are not negligible for α

Need Isospin analysis including all modes (B of all charges and flavours) to obtain the α estimate

- Considering the tree (T) only:

  $\lambda_{\pi\pi} = e^{2i\alpha}$

  $C_{\pi\pi} = 0$

  $S_{\pi\pi} = \sin(2\alpha)$

- adding the penguins (P):

$$\lambda_{\pi\pi} = e^{2i\alpha}\frac{1+|P/T|e^{i\delta}e^{i\gamma}}{1+|P/T|e^{i\delta}e^{-i\gamma}}$$

$$C_{\pi\pi} \propto \sin(\delta)$$

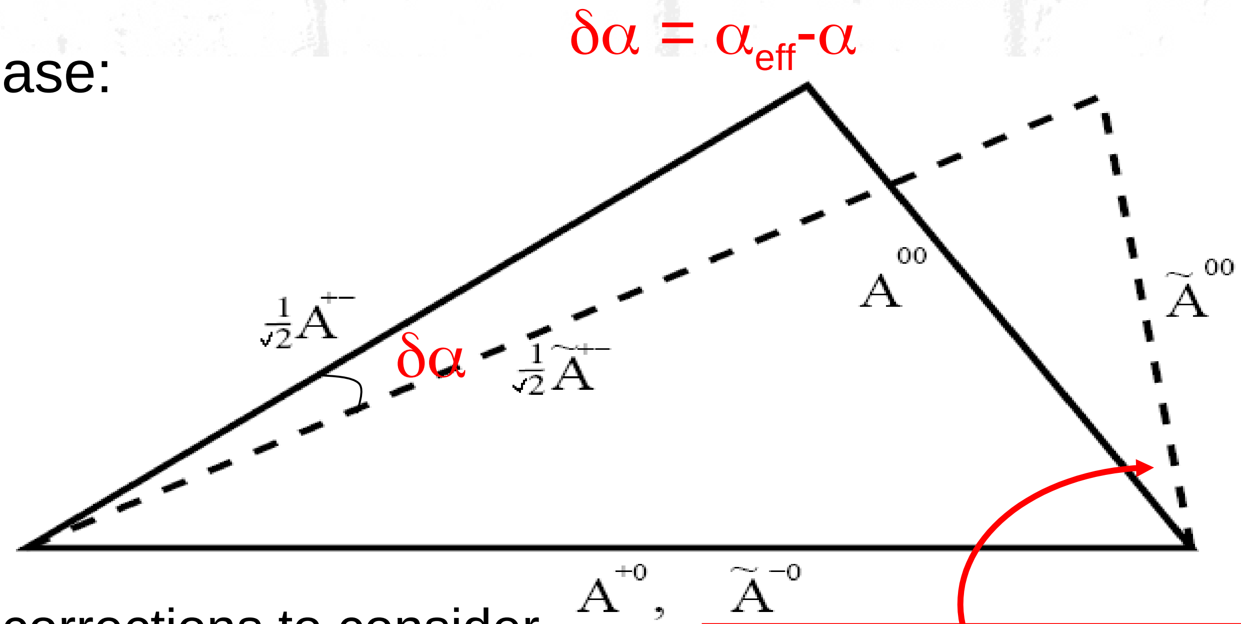
$$S_{\pi\pi} = \sqrt{1-C^2_{\pi\pi}}\sin(2\alpha_{eff})$$

Isospin analysis

- Consider the simplest case:
  $B \to \pi\pi$ / $\rho\rho$ decays.

$$\frac{1}{\sqrt{2}} A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}} \bar{A}^{+-} + \bar{A}^{00} = \bar{A}^{+0}$$

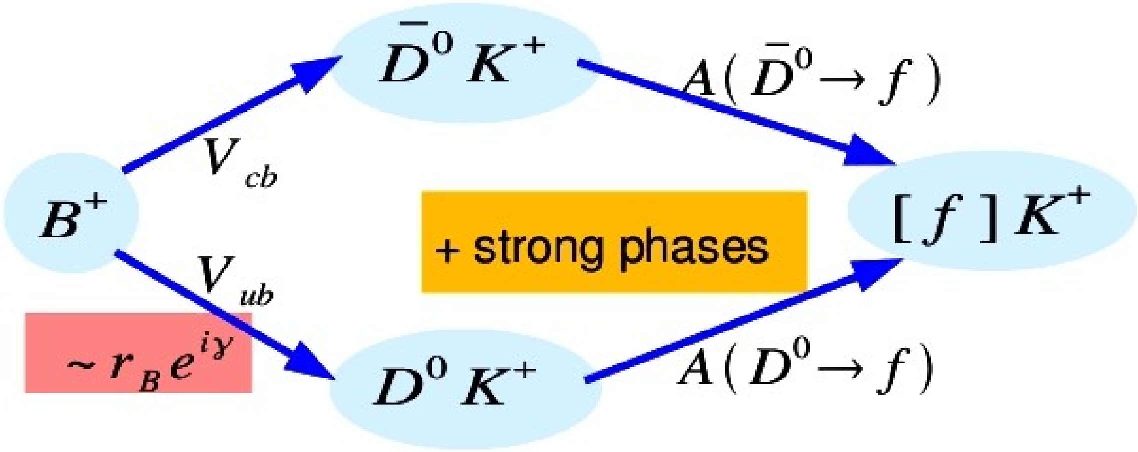


- There are SU(2) violating corrections to consider, for example electroweak penguins (~5%), but these are much smaller than current experimental accuracy and eventually they can be incorporated into the Isospin analysis.

Measuring S in h^0h^0 provides an additional constraint on this angle.

γ (ϕ_3) from B decays in DK

B to $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates.



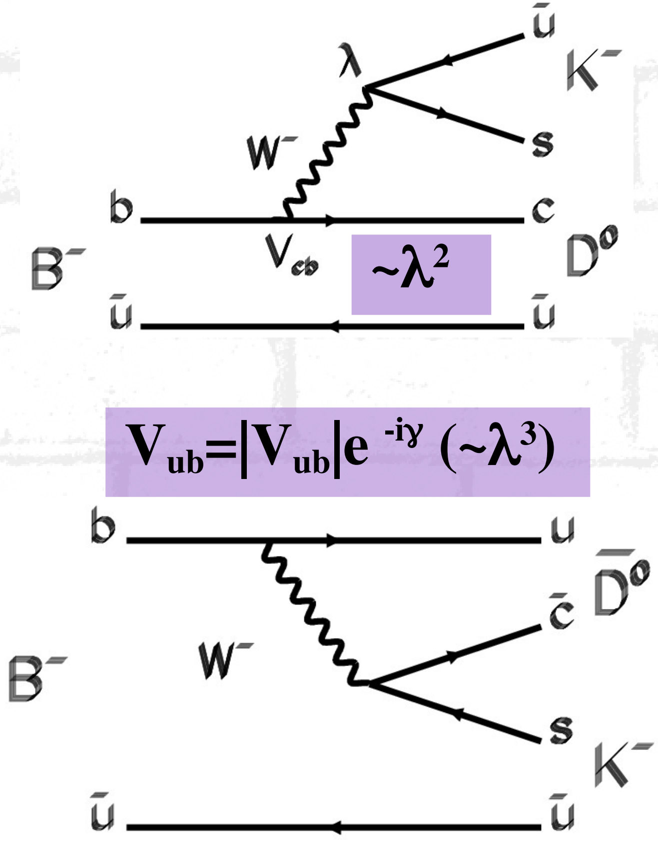
$B \to D^{(*)0}(\bar{D}^{(*)0})K^{(*)}$ decays can proceed both through V_{cb} and V_{ub} amplitudes

γ (ϕ_3) from B decays in DK

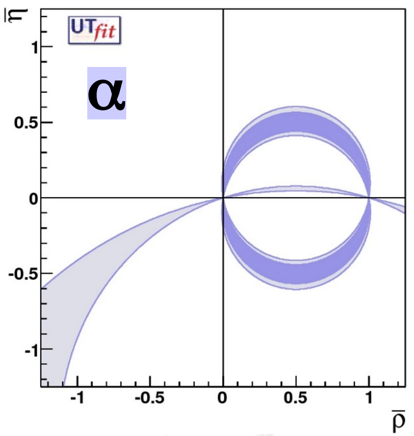
B to $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates.

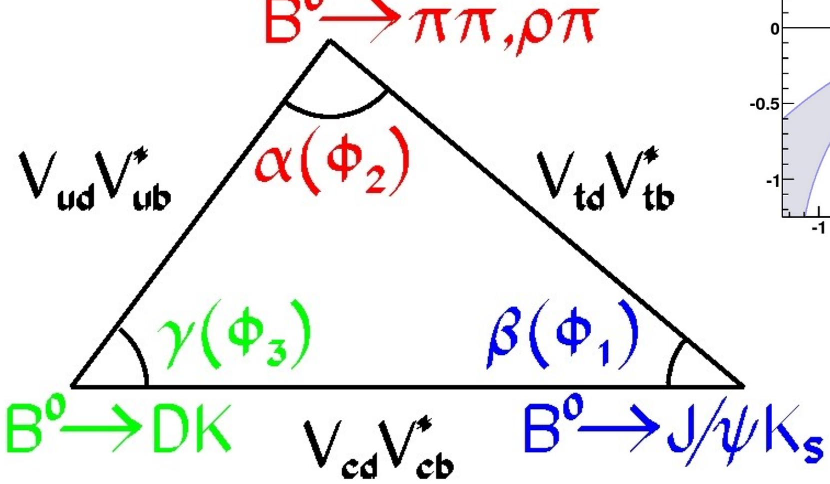
The phase γ is measured exploiting interferences between b $\rightarrow$ c and b $\rightarrow$ u transitions: two amplitudes leading to the same final states

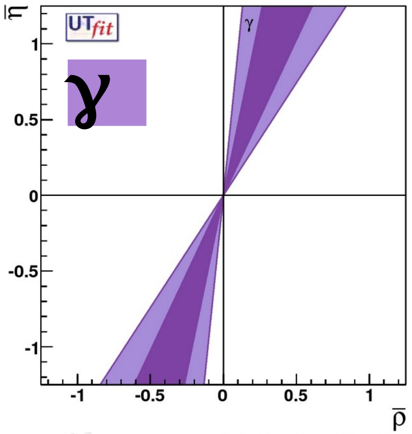
Some rates can be really small: ~ 10^{-7}
need to combine all the possible modes and analysis methods.

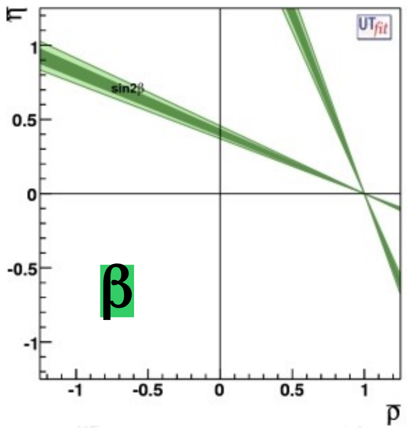


CP Violation in the B Meson System

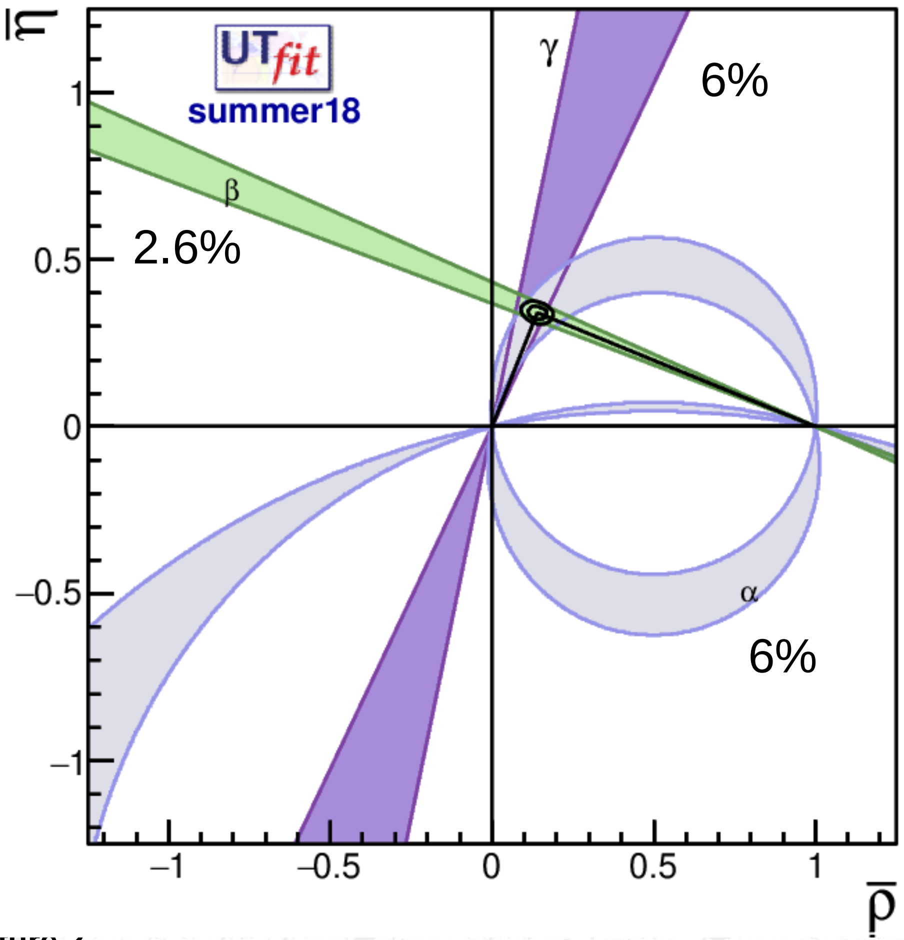








CP Violation in the B Meson System as Unitary Triangle



More inputs to determine the Unitary Triangle

Tree-level diagrams: $|V_{ub}|$, $|V_{cb}|$, γ

Loop diagrams from neutral meson mixing: Δm_d, Δm_s, ε_K

CP-conserving: $|V_{xb}|$, Δm_d, Δm_s

CP-violating: $\sin(2\beta)$, α, γ, ε_K

CKM parameter extraction

example of observables

$(b \to u)/(b \to c)$	$\bar{\rho}^2 + \bar{\eta}^2$	$\bar{\Lambda}, \lambda_1, F(1), \ldots$
ϵ_K	$\bar{\eta}[(1-\bar{\rho}) + P]$	B_K
Δm_d	$(1-\bar{\rho})^2 + \bar{\eta}^2$	$f_B^2 B_B$
$\Delta m_d / \Delta m_s$	$(1-\bar{\rho})^2 + \bar{\eta}^2$	ξ
$A_{CP}(J/\psi K_S)$	$\sin 2\beta$	—

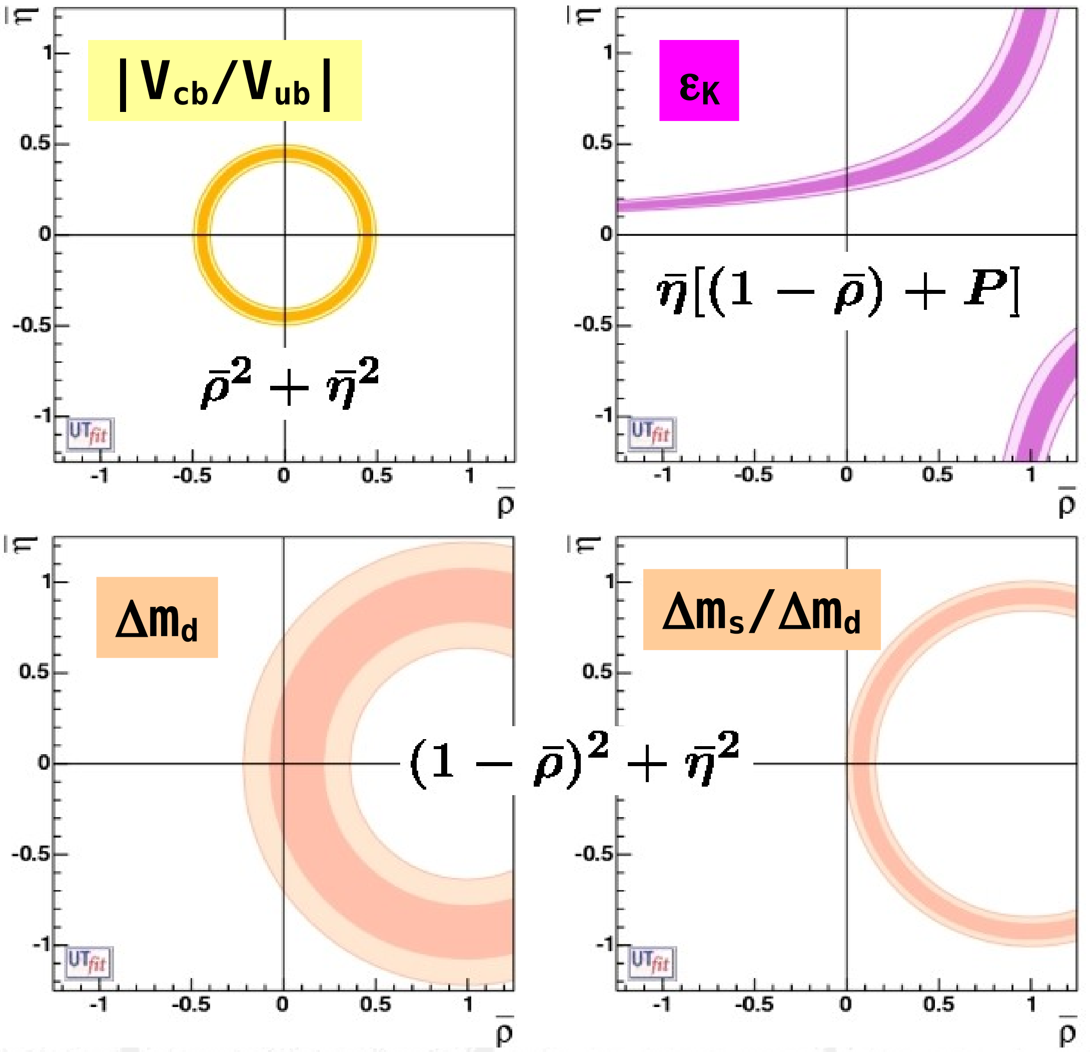
m_t

Standard Model +
OPE/HQET/
Lattice QCD
to go
from quarks
to hadrons

M. Bona *et al*. (UTfit Collaboration)
JHEP 0507:028,2005 hep-ph/0501199
M. Bona *et al*. (UTfit Collaboration)
JHEP 0603:080,2006 hep-ph/0509219

More inputs

In addition to the angles we already discusses, there are the mixing parameters (Δm), the CP violation in the kaon system and tree-level semileptonic B decays



CPV in the Kaon system

The physical states K_S and K_L are not pure CP eigenstates, with the deviation described by complex parameter ε (or ε_K).

Linking formalism:

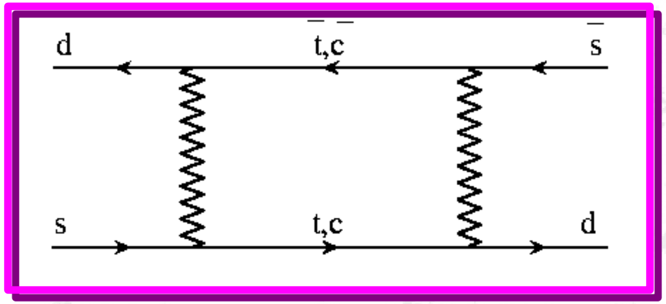
$$p/q = (1+\varepsilon)/(1-\varepsilon)$$

Direct CP violation can occur in kaon decays to two pions [K_L (CP=-1) is seen to decay in two pions (CP=+1)]. This is described by complex parameter ε′.

1. CP Violation in K-$\bar{K}$ mixing (Indirect CPV): Re(ε)
2. in the decay amplitudes (Direct CPV): Re(ε')
3. in the interference between decays with and without mixing: Im(ε) and Im(ε')

CPV in the Kaon system

ε_K from K-$\overline{K}$ mixing



$\varepsilon_K = (2.228 \pm 0.011) \cdot 10^{-3}$

PDG

$$B_K = \frac{<K|J_\mu J^\mu|\overline{K}>}{<K|J_\mu|0><0|J^\mu|\overline{K}>}$$

$$\mathbf{B_K = 0.731 \pm 0.036}$$

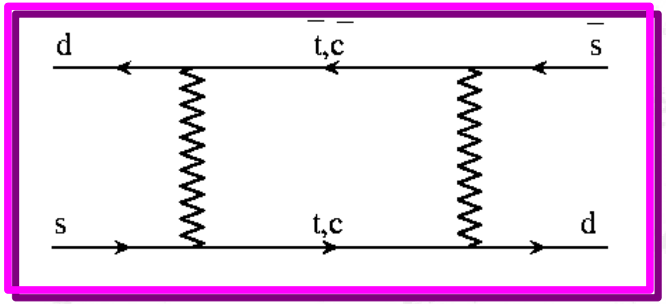
from lattice QCD

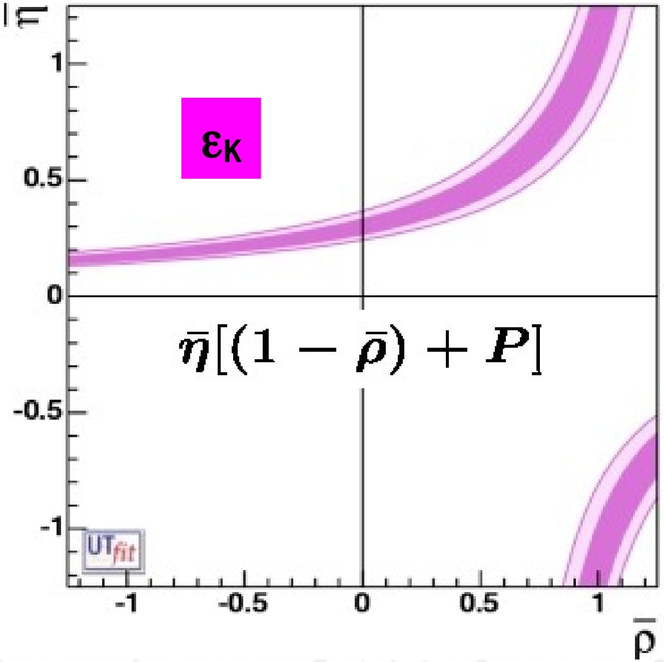
$$|\varepsilon_K| = C_\varepsilon B_K A^2 \lambda^6 \bar{\eta}\{-\eta_1 S_0(x_c)(1-\lambda^2/2) + \eta_3 S_0(x_c, x_t) + \eta_2 S_0(x_t) A^2 \lambda^4 (1-\bar{\rho})\}$$

S_0 = Inami-Lim functions for c-c, c-t, e t-t contributions
(from perturbative calculations)

CPV in the Kaon system

ε_K from $K\text{-}\bar{K}$ mixing





from lattice QCD

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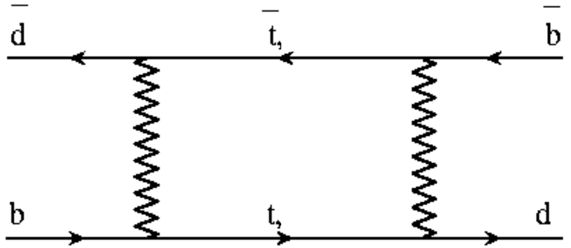
B meson mixing parameter Δm_q

q=d.s



$\Delta m_d = 0.507 \pm 0.005\ ps^{-1}$ WA

$\Delta m_s = 17.70 \pm 0.08\ ps^{-1}$ CDF +LHCb

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2 =$$
$$= \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{cb}|^2 \lambda^2 ((1-\bar{\rho})^2 + \bar{\eta}^2)$$

$$\Delta m_d \approx [(1-\rho)^2 + \eta^2] \frac{f_{B_s}^2 B_{B_s}}{\xi^2}$$

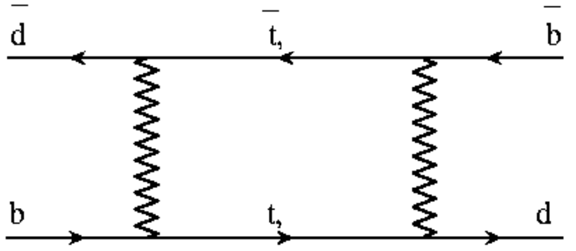
$$\Delta m_s \approx f_{B_s}^2 B_{B_s}$$

S = Inami-Lim function
for the t-t contribution
(from perturbative calculations)

B_{B_q} and f_{B_q} from lattice QCD

B meson mixing parameter Δm_q

q=d.s



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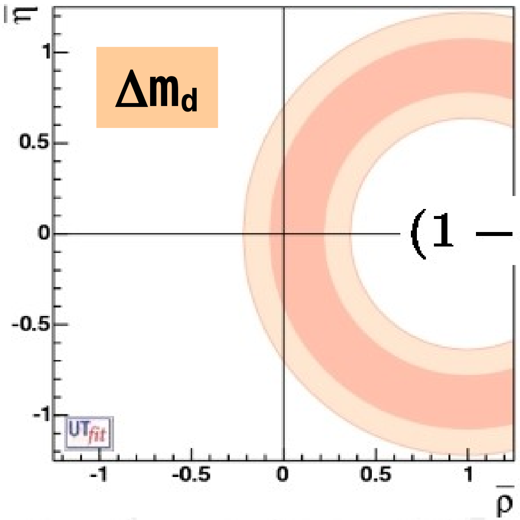
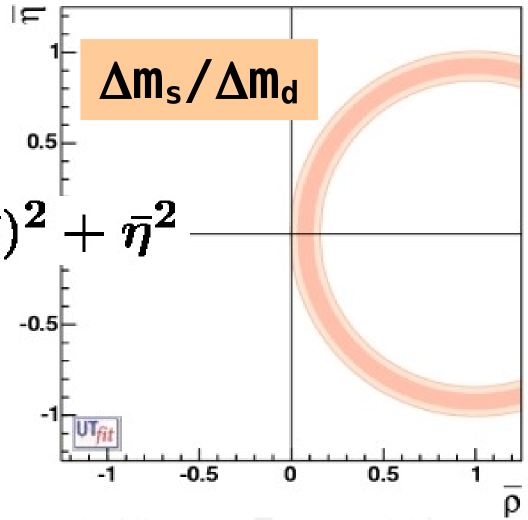


$$(1-\bar{\rho})^2 + \bar{\eta}^2$$



$$\Delta m_d \approx [(1-\rho)^2 + \eta^2] \frac{f_{B_s}^2 B_{B_s}}{\xi^2}$$

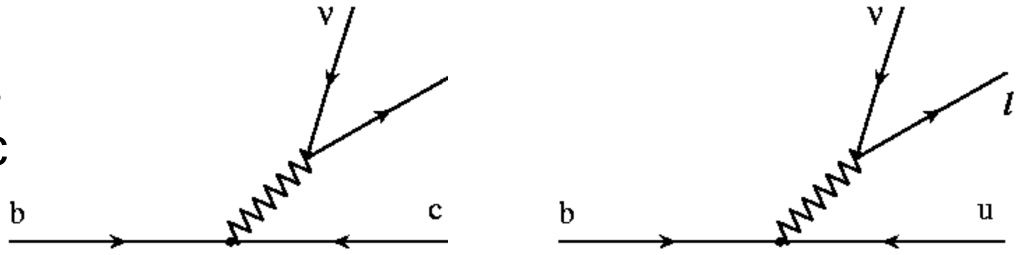
$$\Delta m_s \approx f_{B_s}^2 B_{B_s}$$

Semileptonic decays for $|V_{ub}/V_{cb}|$

tree diagrams

$b \to c$ and $b \to u$ transition

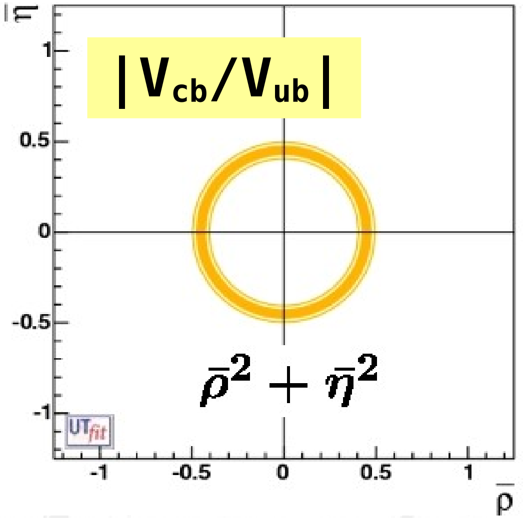
- o negligible new physics contributions
- o inclusive and exclusive semileptonic B decay branching ratios



QCD corrections to be included

- o inclusive measurements: OPE
- o exclusive measurements: form factors from lattice QCD

$$\left|\frac{V_{ub}}{V_{cb}}\right| = \frac{\lambda}{1-\frac{\lambda^2}{2}}\sqrt{\bar{\rho}^2+\bar{\eta}^2}$$

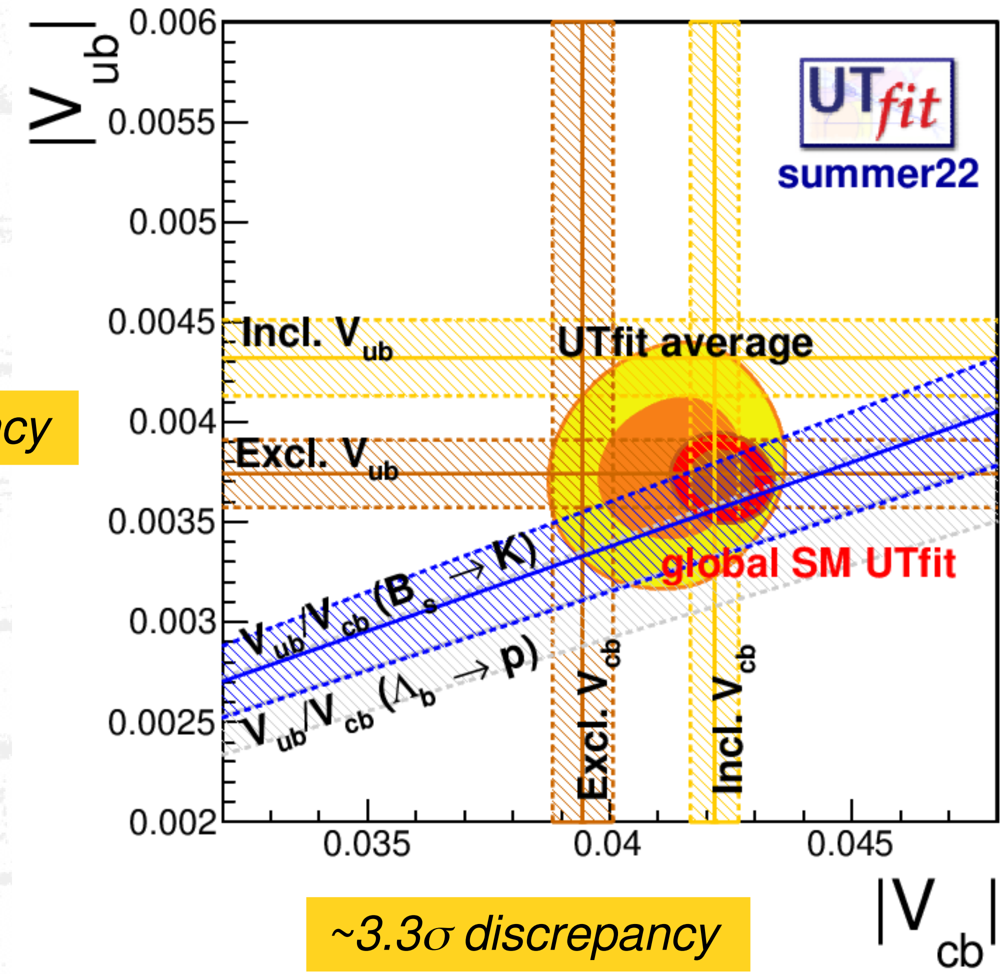


Semileptonic decays for $|V_{ub}/V_{cb}|$

- Inclusive and exclusive Measurements affected by different uncertainties both theoretical and experimental

~1.7σ discrepancy

- Long standing discrepancy between the two sets of measurements and the global fit does not help



~3.3σ discrepancy

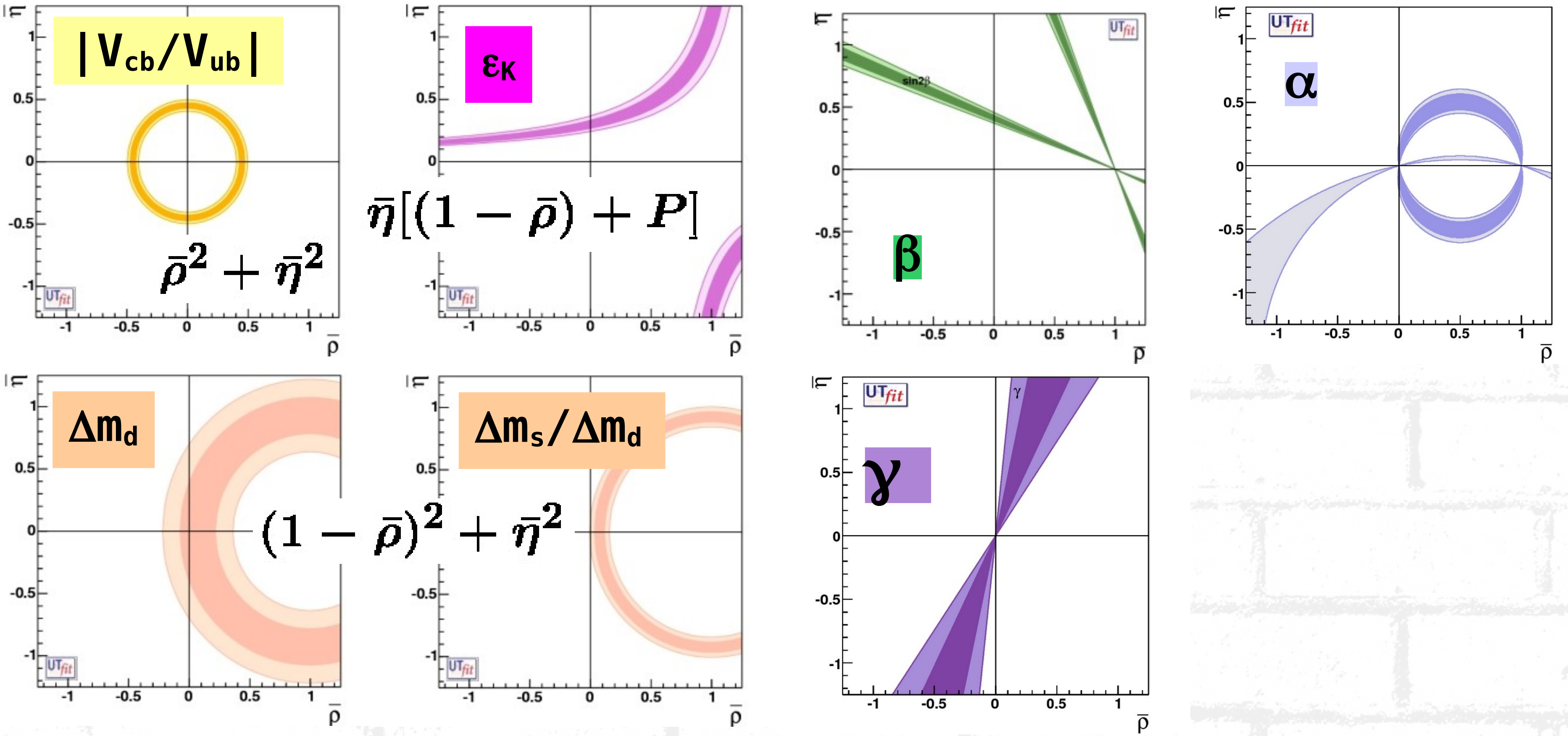
Lattice QCD

lattice inputs updated in Summer 2022

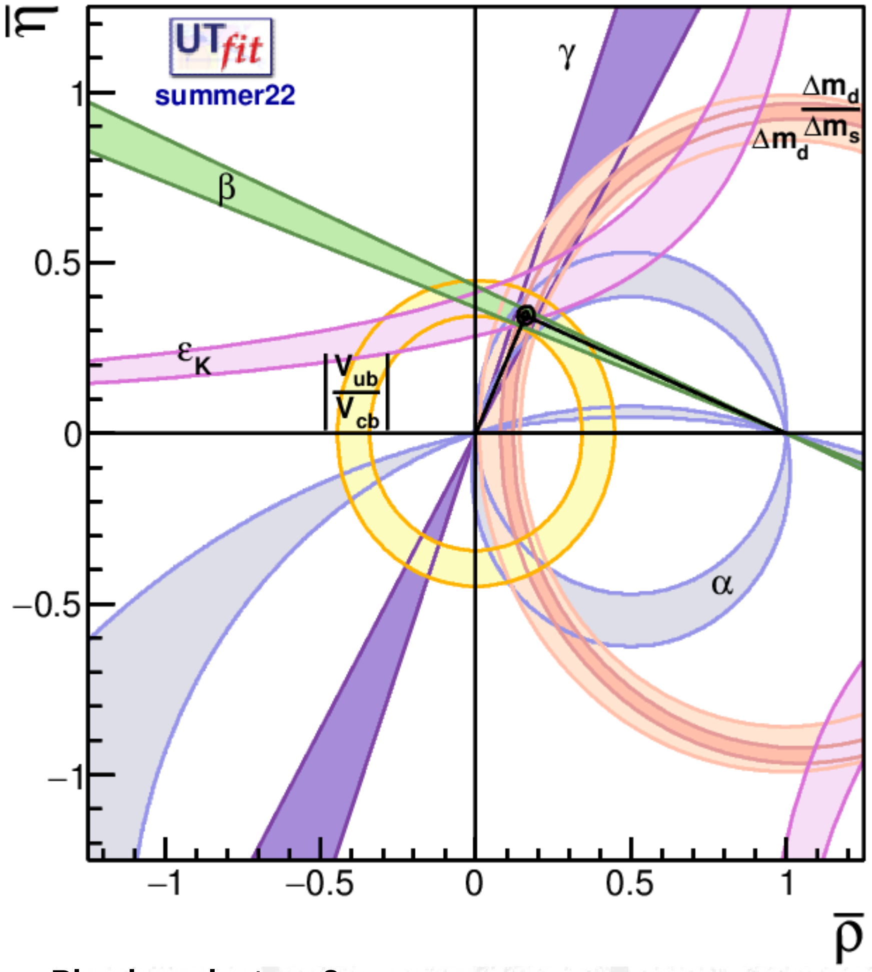
Observables	Measurement
B_K	0.756 ± 0.016
f_{Bs}	0.2301 ± 0.0012
f_{Bs}/f_{Bd}	1.208 ± 0.005
$\mathbf{B_{Bs}/B_{Bd}}$	**1.015 ± 0.021**
B_{Bs}	**1.284 ± 0.059**

We quote, instead, the weighted average of the N_f=2+1+1 and N_f=2+1 results with the error rescaled when chi2/dof > 1, as done by FLAG for the N_f=2+1+1 and N_f=2+1 averages separately [new HPQCD (2+1+1) result 1907.01025]

Unitarity Triangle analysis in the SM:



Unitarity Triangle analysis in the SM:



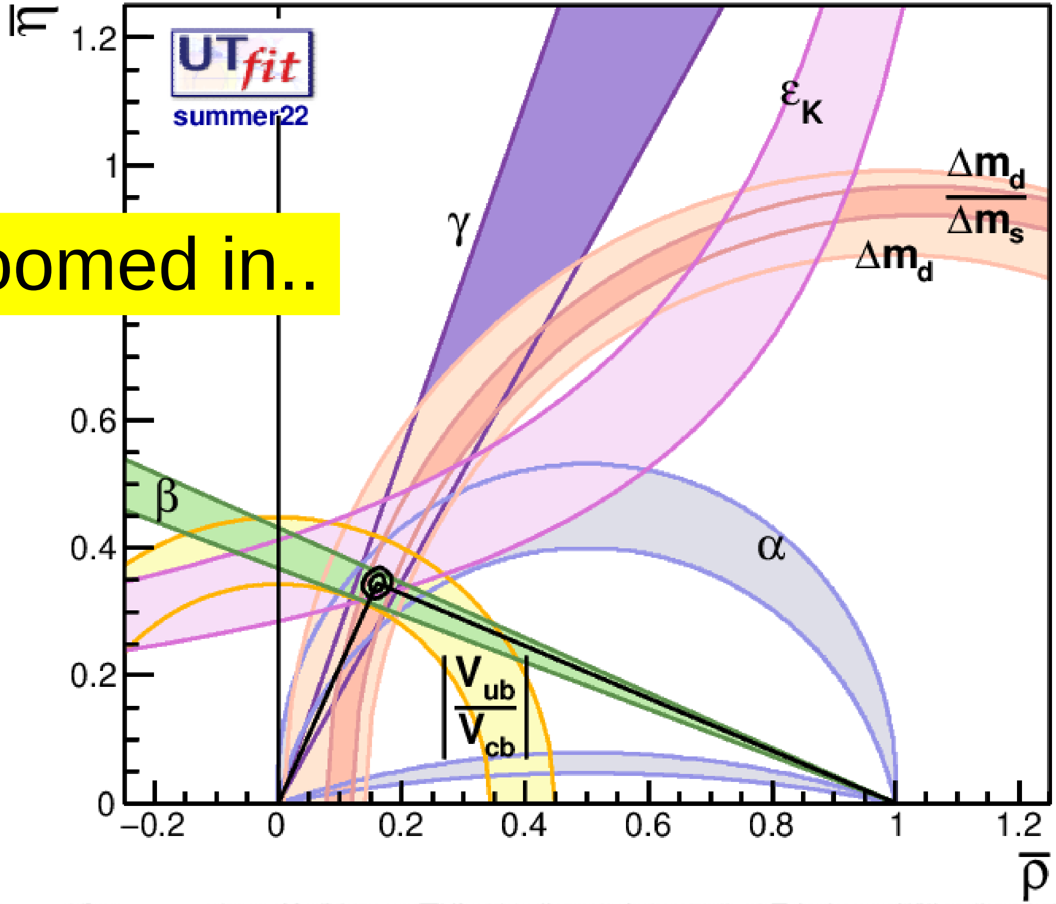
levels @
95% Prob

~6%

$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.345 \pm 0.009$

~3%

Unitarity Triangle analysis in the SM:



zoomed in..

levels @
95% Prob

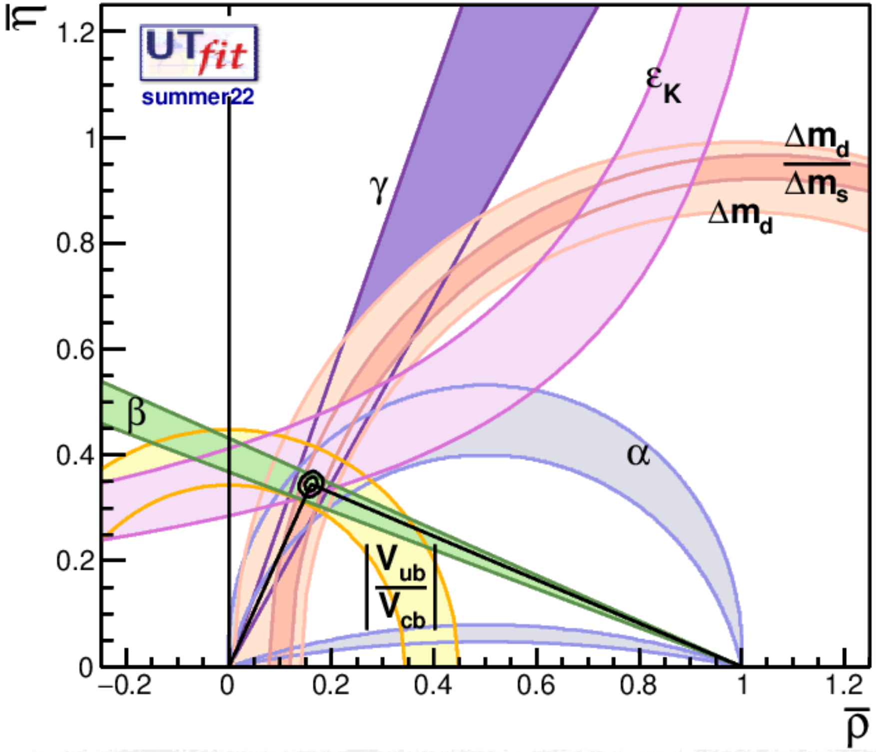
~6%

$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.345 \pm 0.009$

~3%

Unitarity Triangle analysis in the SM:

2022



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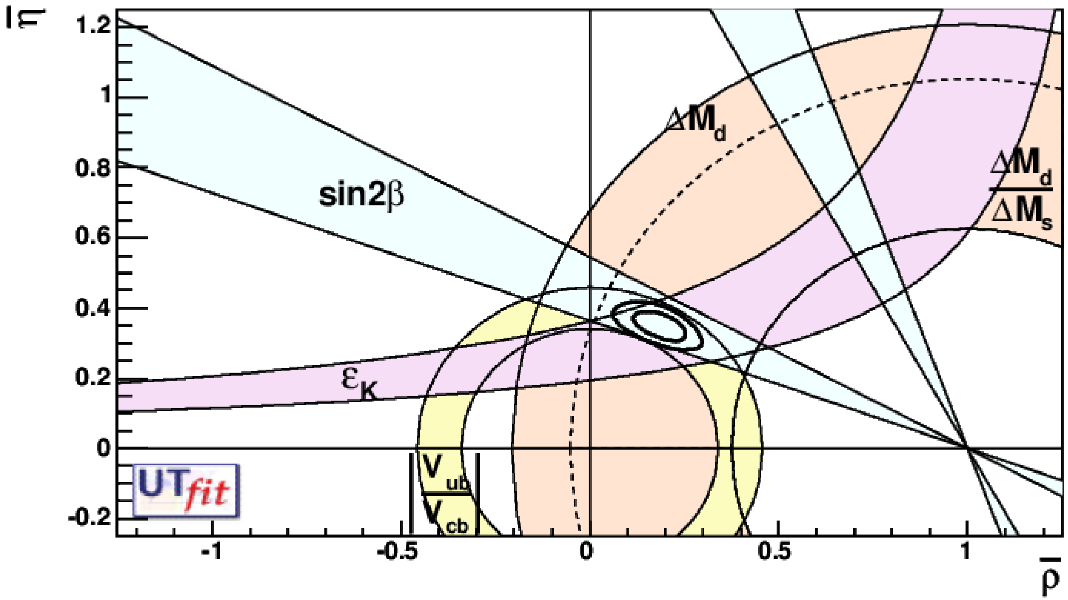
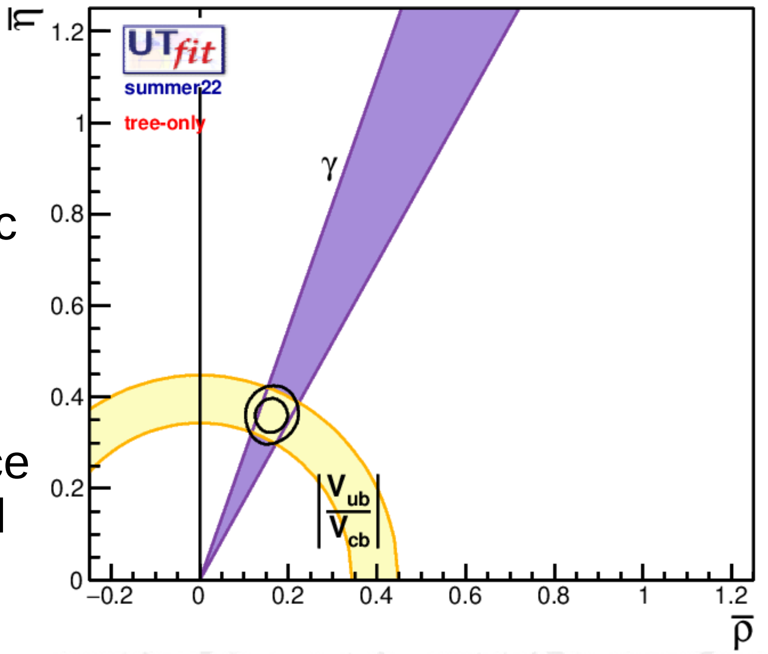


Some interesting configurations

Tree-level processes: Semileptonic and DK B decays

→ reference for model building

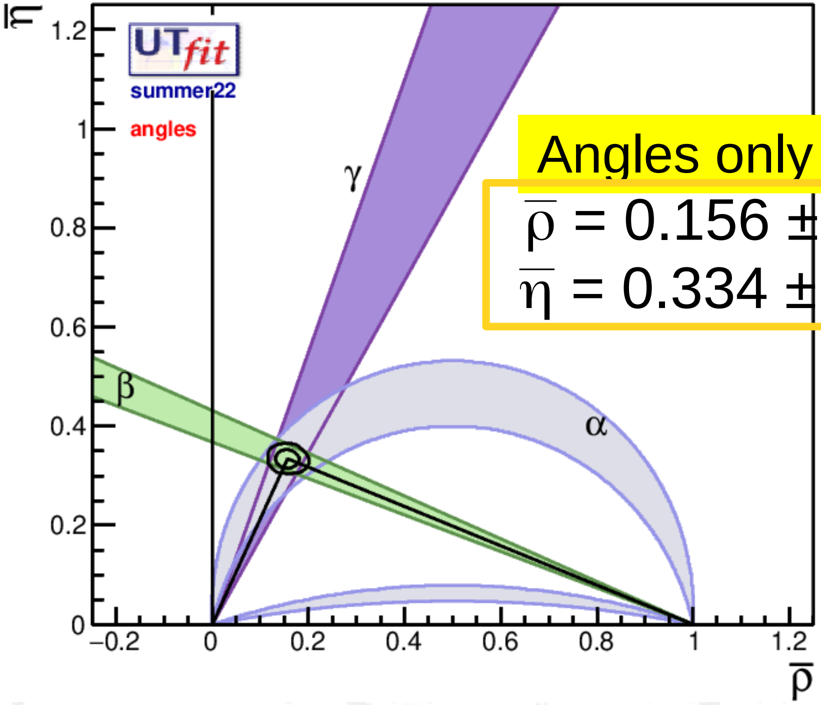


"Tree-only" ~15%

$\bar{\rho} = \pm 0.162 \pm 0.024$
$\bar{\eta} = \pm 0.361 \pm 0.025$

~7%

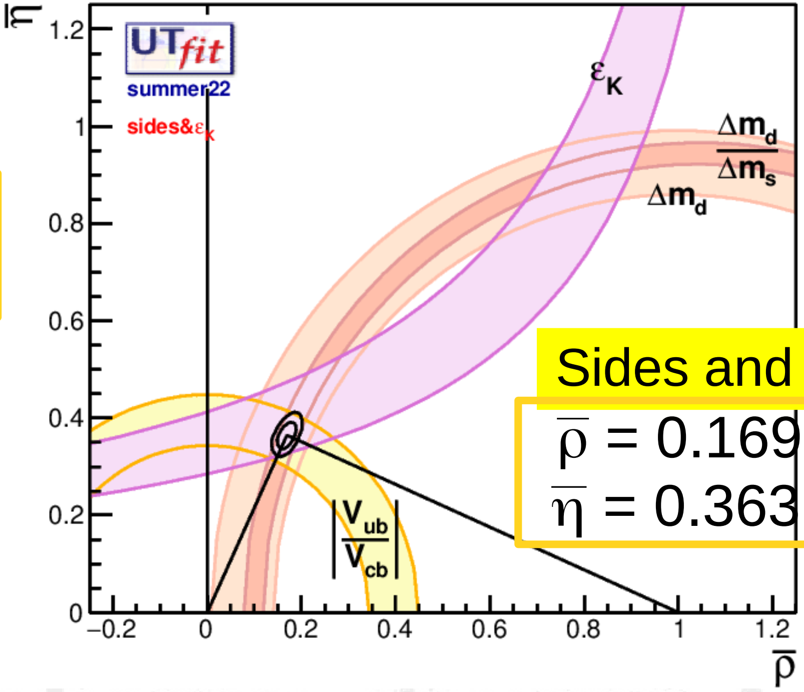
Some interesting configurations



Angles only ~11%

$\bar{\rho} = 0.156 \pm 0.017$
$\bar{\eta} = 0.334 \pm 0.012$

~4%



Sides and ε_K ~8%

$\bar{\rho} = 0.169 \pm 0.013$
$\bar{\eta} = 0.363 \pm 0.019$

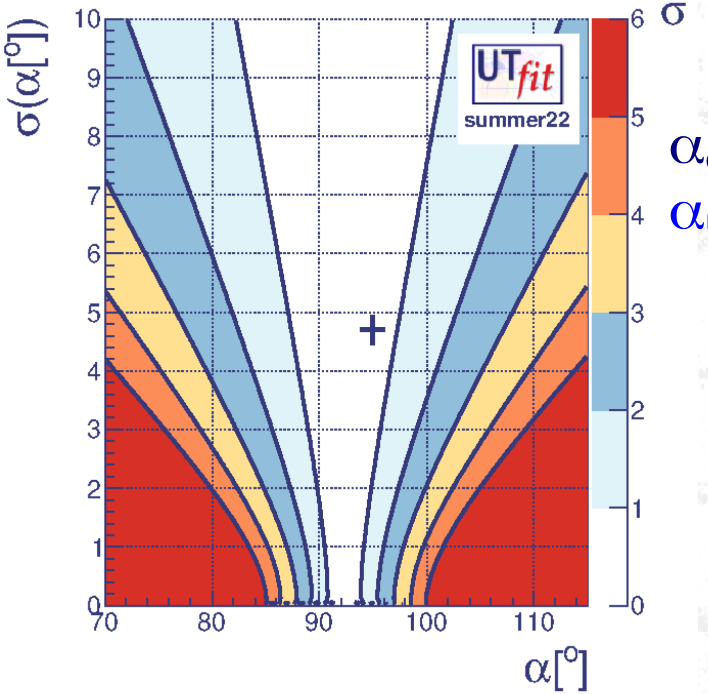
~5%

compatibility plots

To “measure” the agreement of a single measurement with the indirect determination from the fit using all the other inputs:

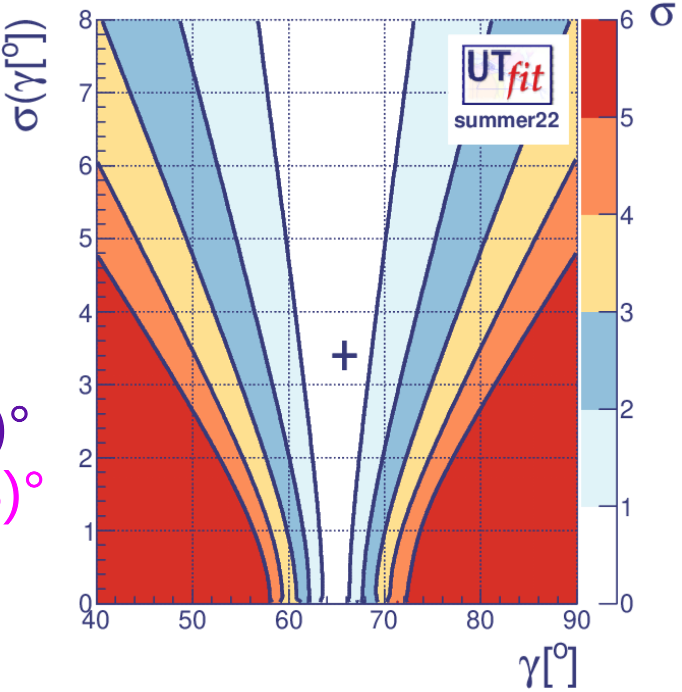
Color code: agreement between the predicted values and the measurements at better than 1, 2, ...nσ

The cross has the coordinates (x,y)=(central value, error) of the direct measurement

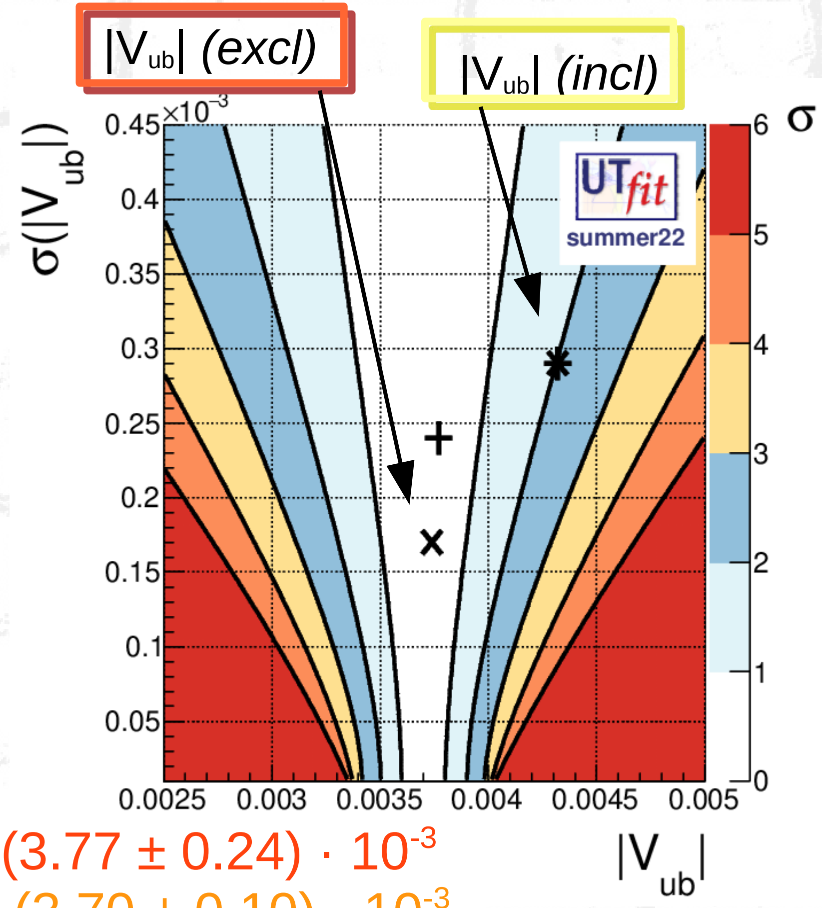


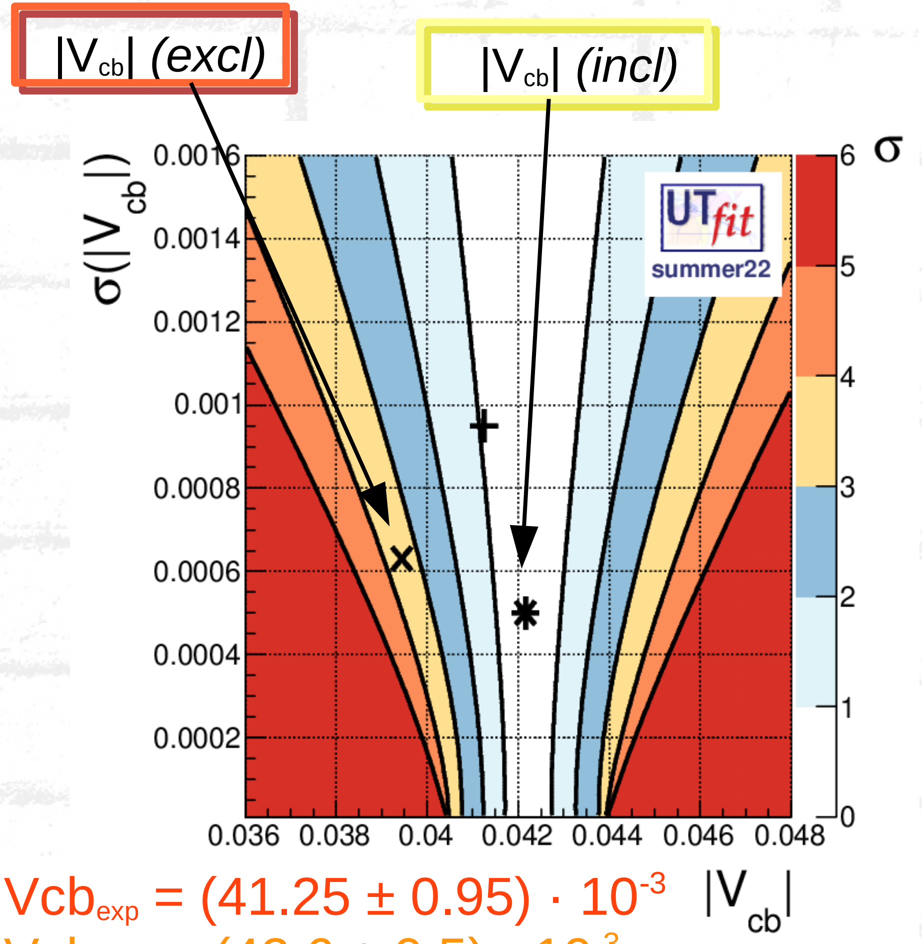
α_{exp} = (95.0 ± 4.7)°
α_{UTfit} = (92.3 ± 1.5)°

γ_{exp} = (65.8 ± 3.4)°
γ_{UTfit} = (64.9 ± 1.3)°



Checking the usual *tensions..*





$Vub_{exp} = (3.77 \pm 0.24) \cdot 10^{-3}$

$Vub_{UTfit} = (3.70 \pm 0.10) \cdot 10^{-3}$

$Vcb_{exp} = (41.25 \pm 0.95) \cdot 10^{-3}$

$Vcb_{UTfit} = (42.6 \pm 0.5) \cdot 10^{-3}$

Unitarity Triangle analysis in the SM:

obtained excluding the given constraint from the fit

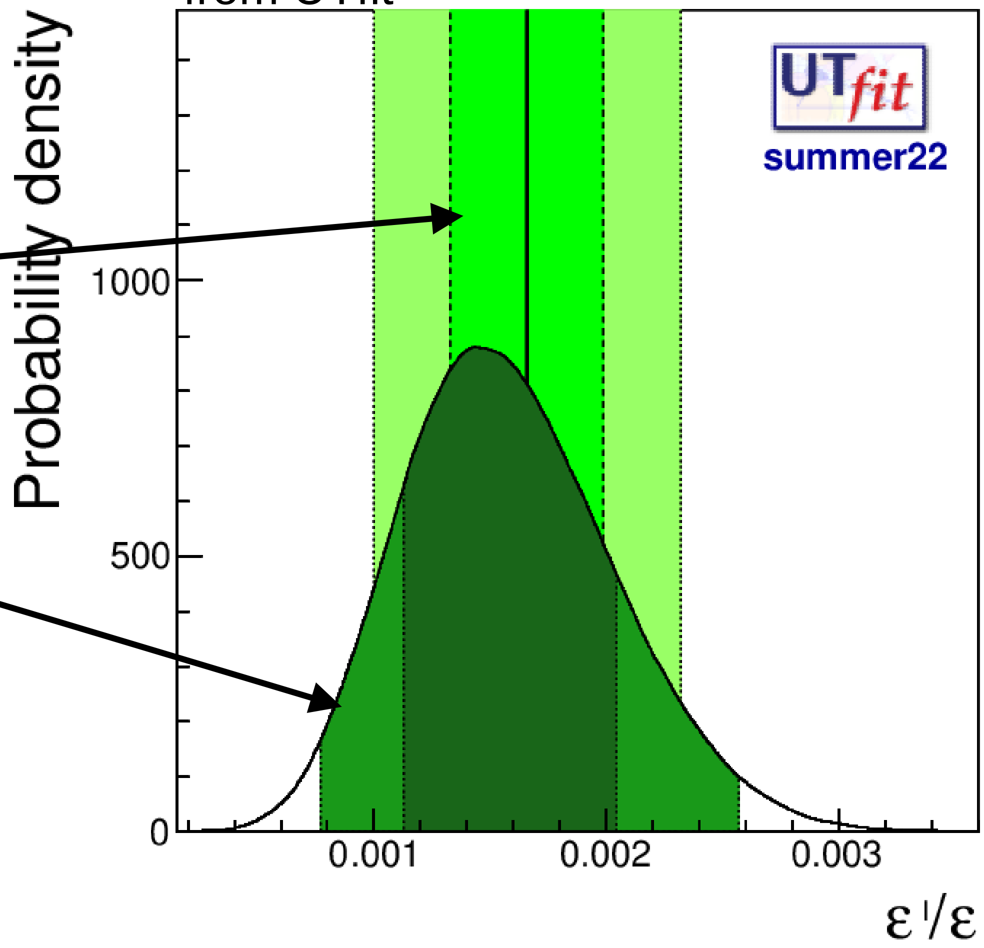
Observables	Measurement	Prediction	Pull (#σ)
$\sin 2\beta$	0.688 ± 0.020	0.732 ± 0.027	~ 1.3
γ	65.8 ± 3.4	64.9 ± 1.3	< 1
α	95.0 ± 4.7	92.3 ± 1.5	< 1
$\varepsilon_K \cdot 10^3$	2.228 ± 0.001	2.04 ± 0.14	< 1
$\|V_{cb}\| \cdot 10^3$	41.25 ± 0.95	42.6 ± 0.5	< 1
$\|V_{cb}\| \cdot 10^3$ (incl)	42.16 0.50		< 1
$\|V_{cb}\| \cdot 10^3$ (excl)	39.44 0.63		~ 4.0
$\|V_{ub}\| \cdot 10^3$	3.77 ± 0.24	3.70 ± 0.10	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.32 ± 0.29	-	~ 2.0
$\|V_{ub}\| \cdot 10^3$ (excl)	3.74 ± 0.17	-	< 1

New ε'/ε prediction from the Unitarity Triangle fit

Experimental value
$\varepsilon'/\varepsilon = (16.6 \pm 3.3) \cdot 10^{-4}$

New UTfit work:
$\varepsilon'/\varepsilon = (15.2 \pm 4.7) \cdot 10^{-4}$

from UTfit



UT analysis including new physics

fit simultaneously for the CKM and
the NP parameters (generalized UT fit)

- add most general loop NP to all sectors
- use all available experimental info
- find out NP contributions to ΔF=2 transitions

B_d and B_s mixing amplitudes
(2+2 real parameters):

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

UT analysis including new physics

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_s} = \sin 2(\beta + \phi_{B_d})$$

$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right)$$

$$\varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$\Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

new-physics-specific constraints

$$A_{SL}^s \equiv \frac{\Gamma(\bar{B}_s \to \ell^+ X) - \Gamma(B_s \to \ell^- X)}{\Gamma(\bar{B}_s \to \ell^+ X) + \Gamma(B_s \to \ell^- X)} = \mathrm{Im}\left(\frac{\Gamma_{12}^s}{A_s^{\mathrm{full}}}\right)$$

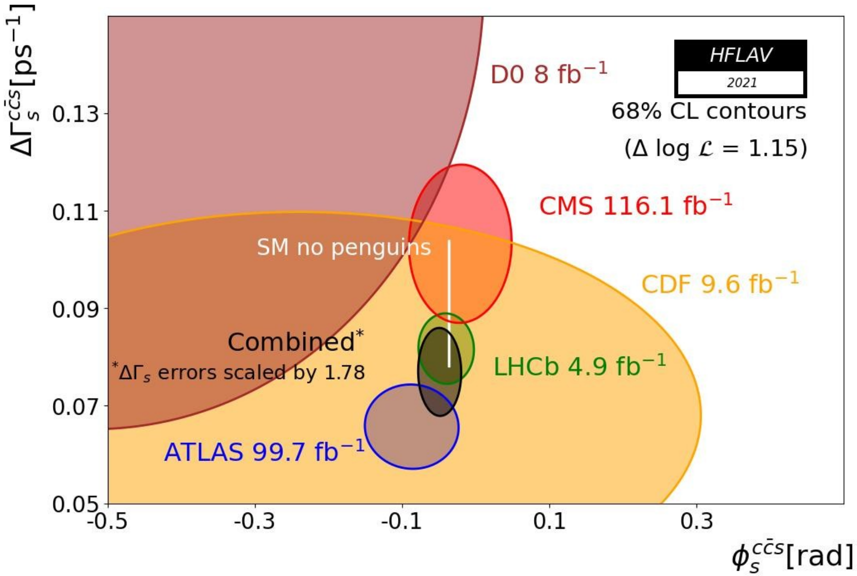
semileptonic asymmetries in B^0 and B_s: sensitive to NP effects in both size and phase. Taken from the latest HFLAV.

lifetime τ^{FS} in flavour-specific final states: average lifetime is a function to the width and the width difference

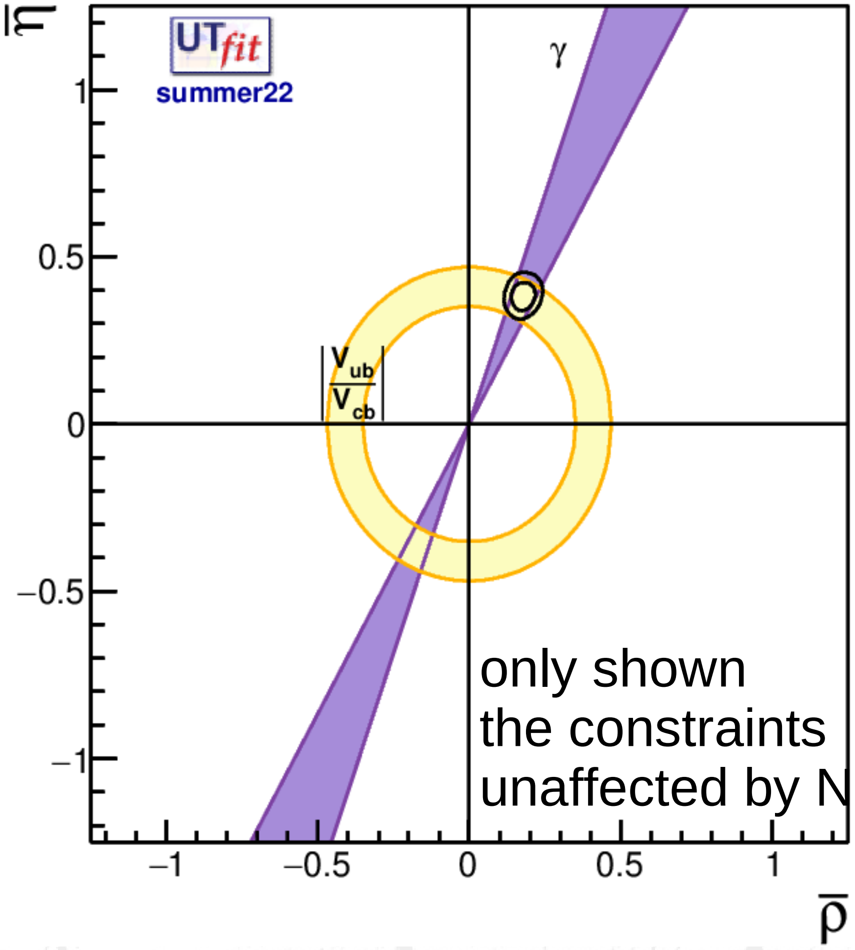
$$\tau^{FS}(B_s) = 1.527 \pm 0.011 \text{ ps}$$

$\phi_s = 2\beta_s$ vs $\Delta\Gamma_s$ from $B_s \to J/\psi\phi$

angular analysis as a function of proper time and b-tagging



NP analysis results



only shown the constraints unaffected by NP

levels @ 95% Prob

$\bar{\rho} = 0.169 \pm 0.025$
$\bar{\eta} = 0.365 \pm 0.026$

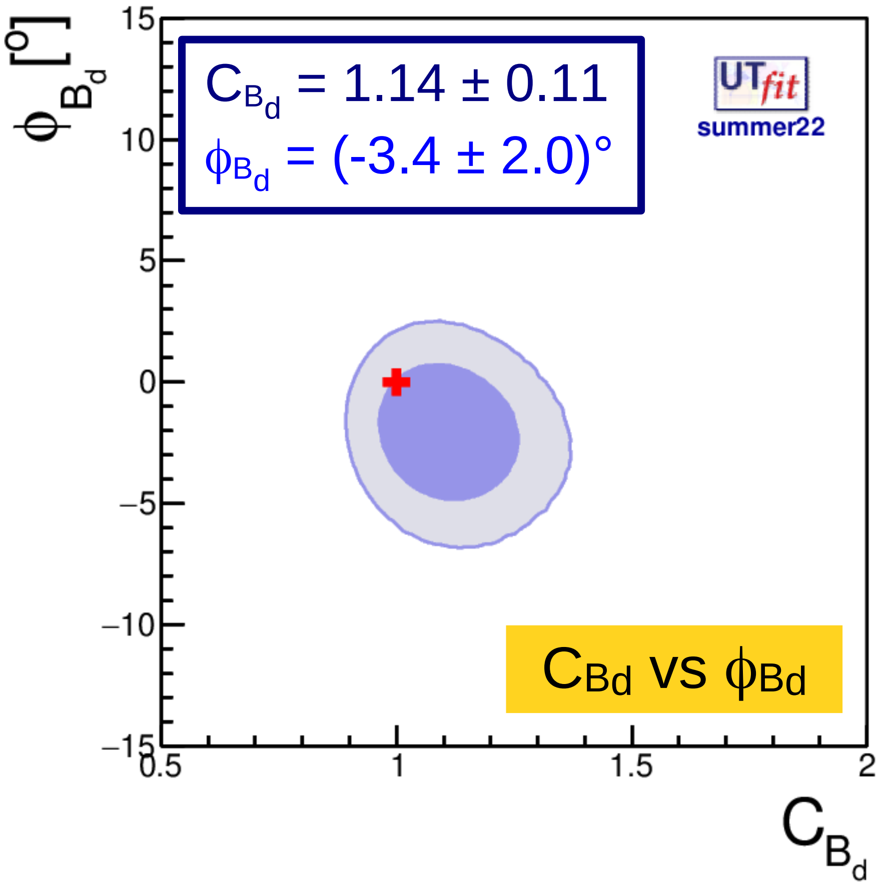
SM is

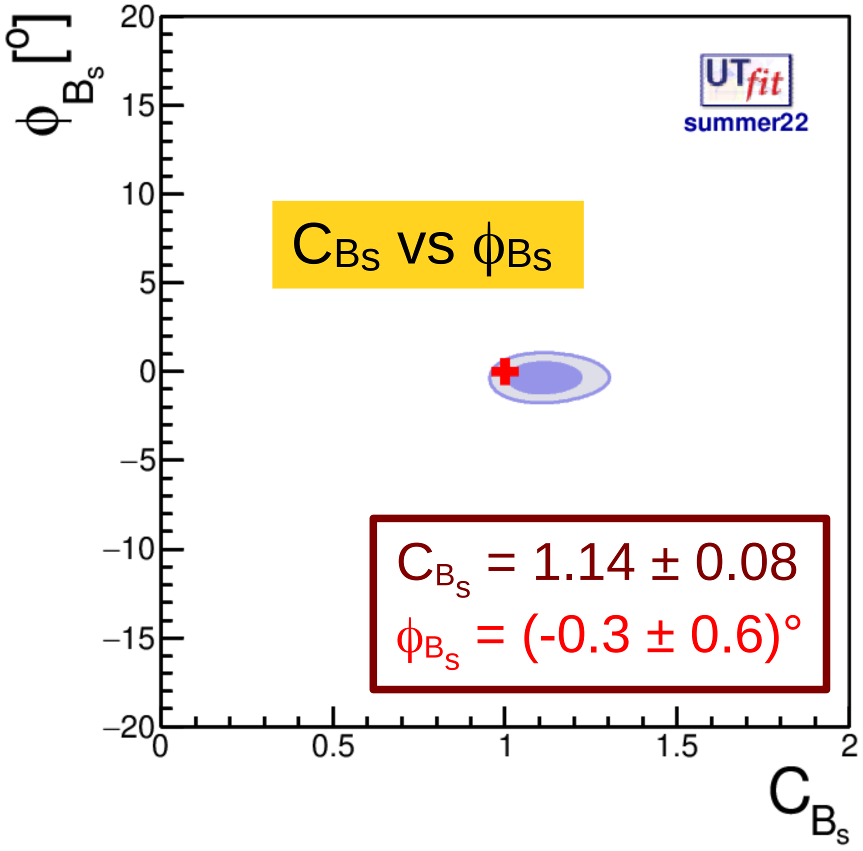
$\bar{\rho} = 0.160 \pm 0.009$
$\bar{\eta} = 0.345 \pm 0.009$

NP analysis results

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

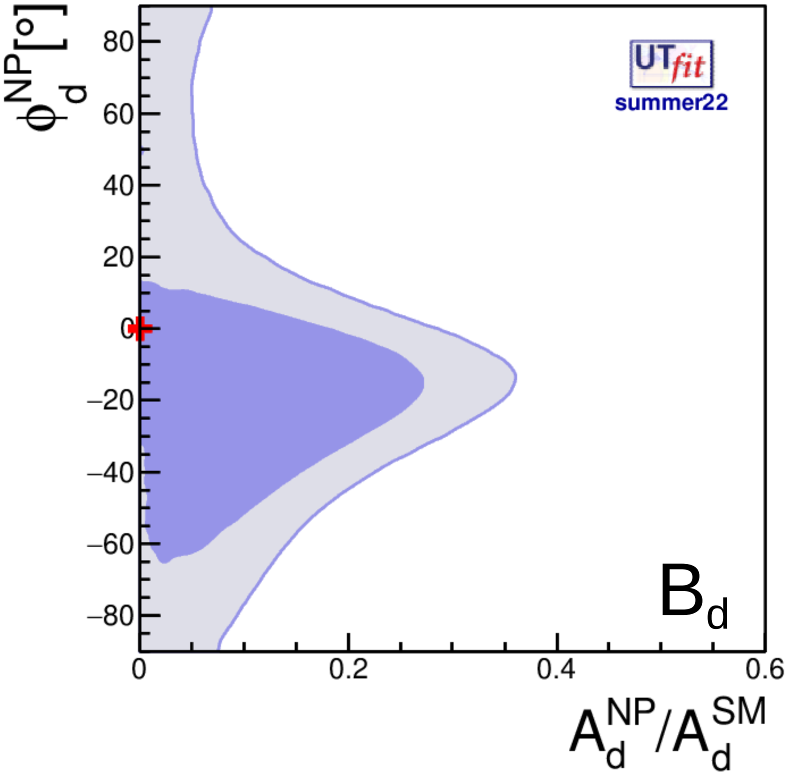
dark: 68%
light: 95%
SM: red cross

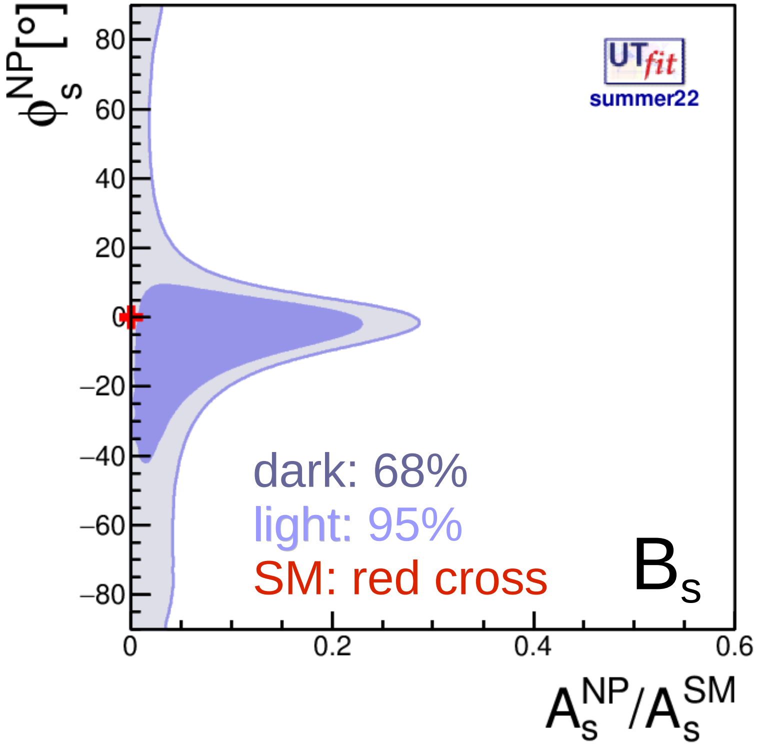




NP analysis results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$





The ratio of NP/SM amplitudes is:

< 25% @68% prob. (35% @95%) in B_d mixing

< 25% @68% prob. (30% @95%) in B_s mixing

testing the new-physics scale

M. Bona *et al.* (UTfit)
JHEP 0803:049,2008
arXiv:0707.0636

R G E

At the high scale
new physics enters according to its specific features

At the low scale
use OPE to write the most general effective Hamiltonian.
the operators have different chiralities than the SM
NP effects are in the Wilson Coefficients C

$$C_i(\Lambda) = \frac{F_i L_i}{\Lambda^2}$$

$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} \, , \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} \, , \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} \, , \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} \, , \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} \, .
\end{aligned}$$

testing the new-physics scale

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

F_i: function of the NP flavour couplings

L_i: loop factor (in NP models with no tree-level FCNC)

Λ: NP scale (typical mass of new particles mediating $\Delta F=2$ processes)

testing the new-physics scale

The dependence of C on Λ changes depending on the flavour structure.
We can consider different flavour scenarios:

- ◉ Generic: $C(\Lambda) = \alpha/\Lambda^2$ — $F_i \sim 1$, arbitrary phase
- ◉ NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_i \sim |F_{SM}|$, arbitrary phase
- ◉ MFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ — $F_1 \sim |F_{SM}|$, $F_{i\neq 1} \sim 0$, SM phase

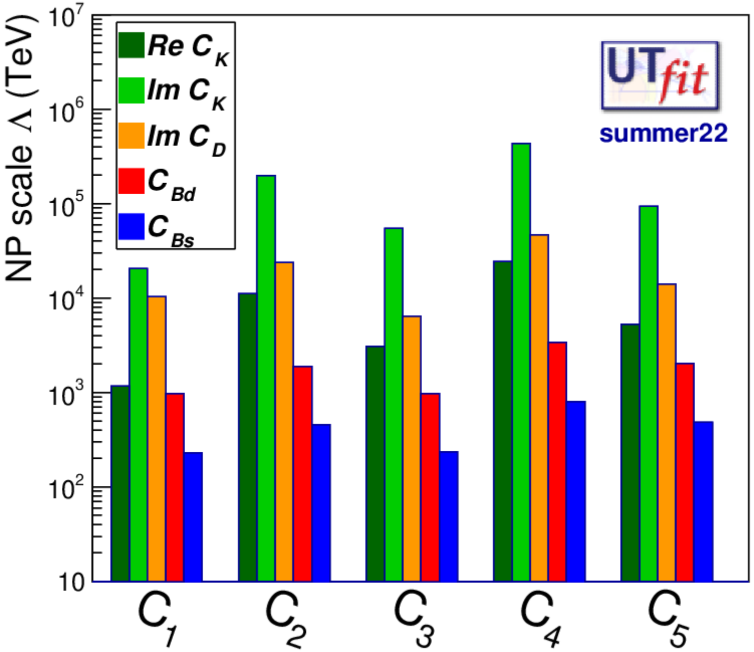
α (L_i) is the coupling among NP and SM
- ◎ $\alpha \sim 1$ for strongly coupled NP
- ◎ $\alpha \sim \alpha_W$ (α_S) in case of loop coupling through weak (strong) interactions

If no NP effect is seen lower bound on NP scale Λ

F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

results from the Wilson coefficients

Generic: $C(\Lambda) = \alpha/\Lambda^2$,
F_i~1, arbitrary phase
α ~ 1 for strongly coupled NP



Lower bounds on NP scale (at 95% prob.)

$\Lambda > 4.4\ 10^5$ TeV

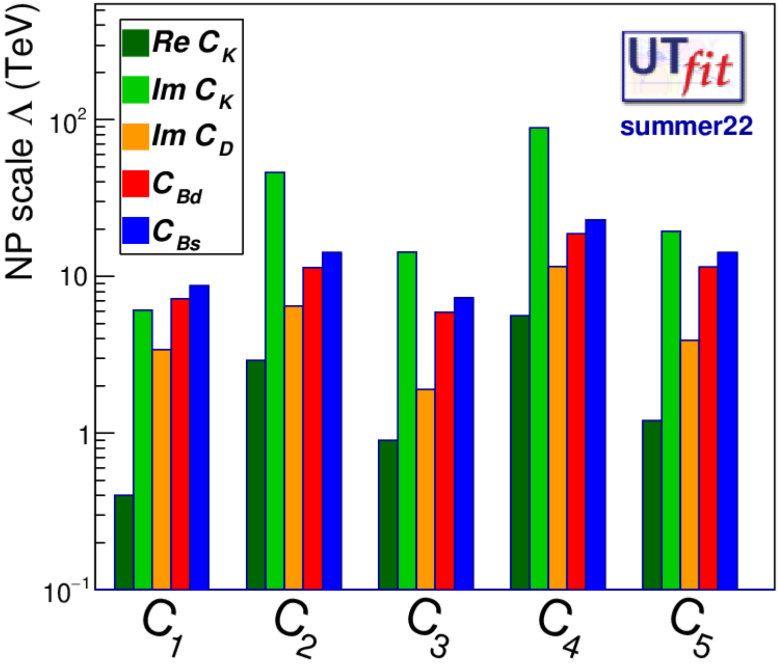
$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 1.3\ 10^4$ TeV

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

results from the Wilson coefficients

NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$,
$F_i \sim |F_{SM}|$, arbitrary phase
$\alpha \sim 1$ for strongly coupled NP



Lower bounds on NP scale (at 95% prob.)

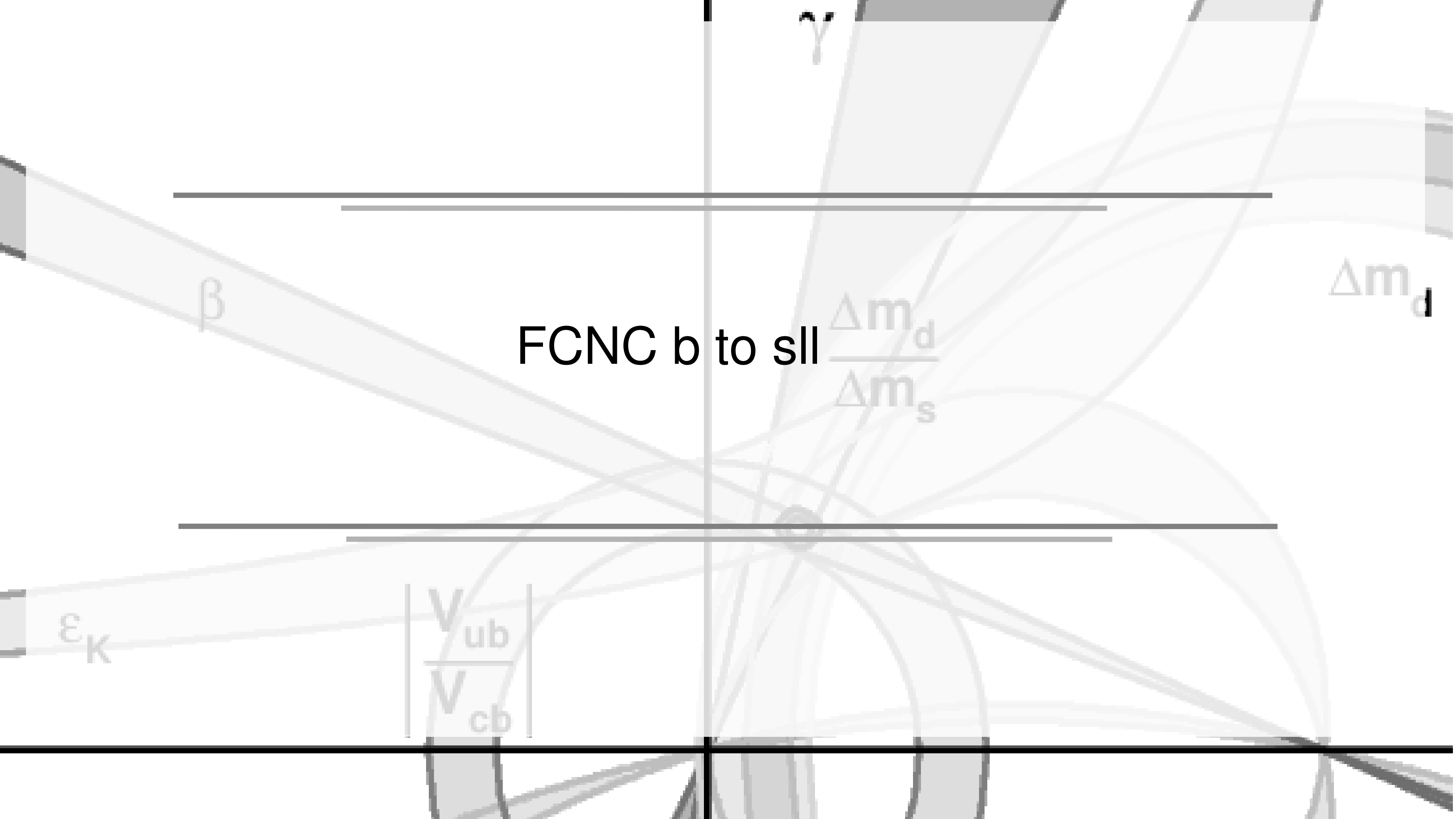
$\Lambda > 95$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 2.9$ TeV

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

FCNC b to sll

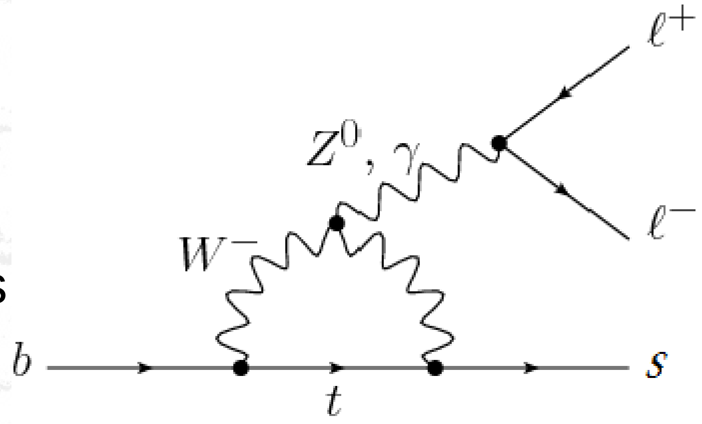


Flavour changing neural current b to sℓℓ

There are a lot of measurements
that can test b to sℓℓ transitions:

Branching ratios,
Angular analyses
SM symmetry tests

$B_s \to \ell^+\ell^-, B \to K\ell^+\ell^-,$
$B \to K^*\ell^+\ell^-, B_s \to \phi\ell^+\ell^-,$
$\Lambda_b \to pK^-\ell^+\ell^-, \ldots$

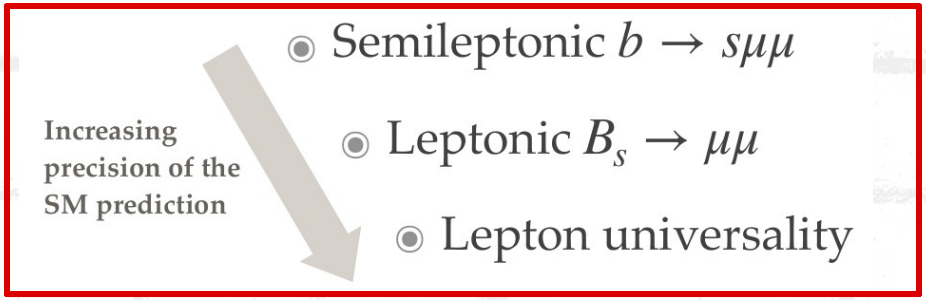


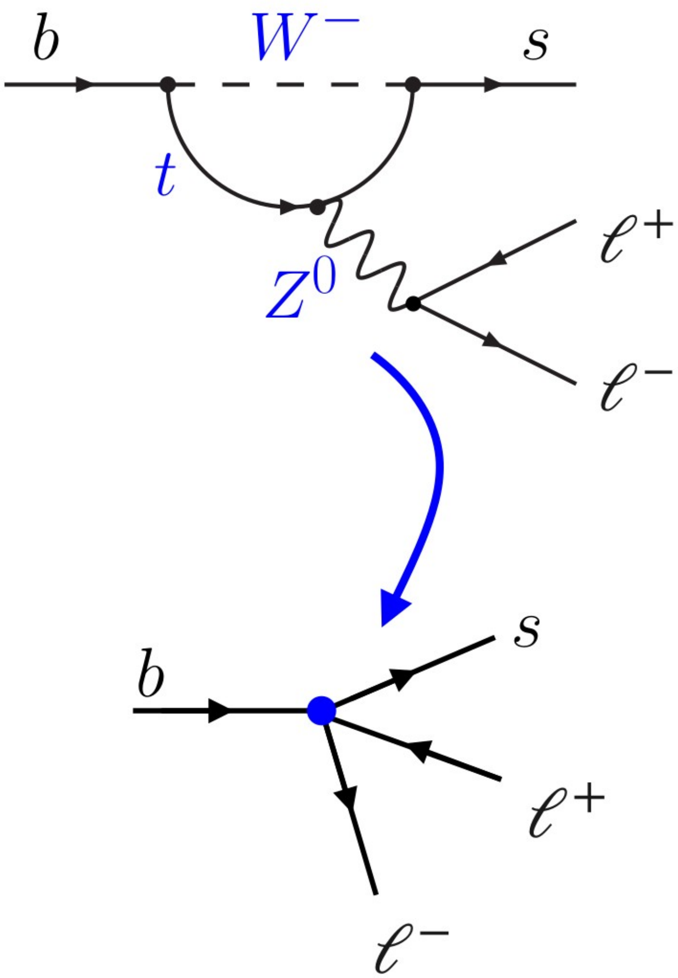
Suppressed: with branching ratios from 10^{-6} down
hence new physics effects can enhance their rates
Clean: varying levels of cleaness

Increasing precision of the SM prediction

- Semileptonic $b \to s\mu\mu$
- Leptonic $B_s \to \mu\mu$
- Lepton universality

Flavour changing neural current b to sℓℓ





Weak effective theory:

four-fermion interaction with effective couplings:

Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$

Main SM contributions:

Vector (C_9) and Axial-vector (C_{10}) leptonic currents

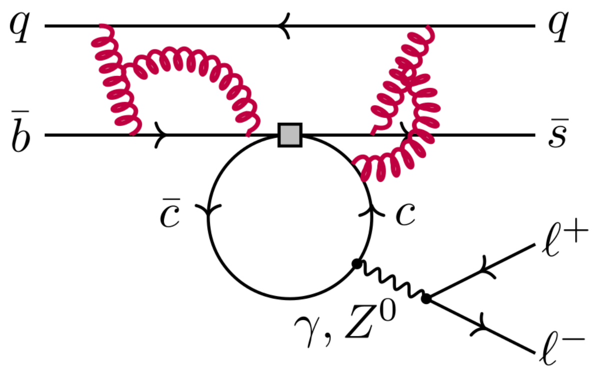
$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

Flavour changing neural current b to $s\ell\ell$

Increasing precision of the SM prediction

- Semileptonic $b \to s\mu\mu$
- Leptonic $B_s \to \mu\mu$
- Lepton universality

	Wilson coeff.	Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$\sim (\bar{s}\sigma_{\mu\nu}P_{R(L)}b)\ F^{\mu\nu}$
EW-penguins (V)	$\mathcal{C}_9^{(\prime)}$	$\sim (\bar{s}\gamma_{\mu}P_{L(R)}b)\ (\ell\gamma^{\mu}\bar{\ell})$
(A)	$\mathcal{C}_{10}^{(\prime)}$	$\sim (\bar{s}\gamma^{\mu}P_{L(R)}b)\ (\ell\gamma_{\mu}\gamma_5\bar{\ell})$
Scalar	$\mathcal{C}_S^{(\prime)}$	$\sim (\bar{s}P_{R(L)}b)\ (\ell\bar{\ell})$
Pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\sim (\bar{s}P_{L(R)}b)\ (\ell\gamma_5\bar{\ell})$

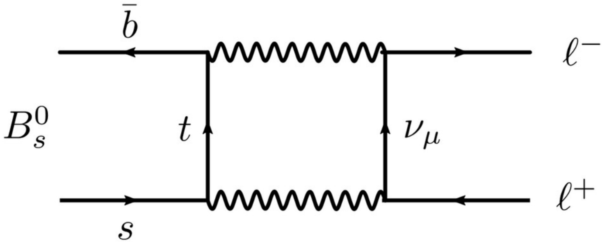


QCD complications

- Quarks are bound in hadrons $\to$ local form factors.
- Insertion of $q\bar{q}$ loop $\to$ non-local form factors + non-factorisable soft gluon corrections.

Flavour changing neural current b to sℓℓ

Fully leptonic

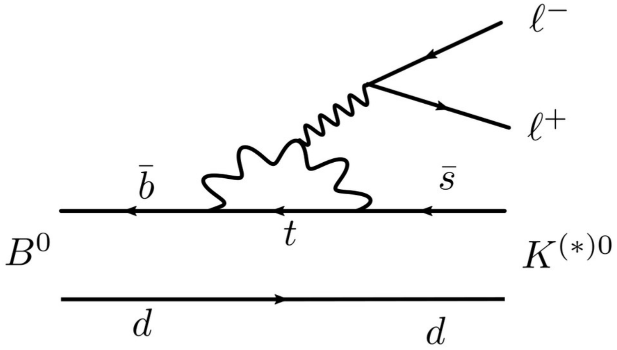


Very rare! $\mathcal{B} \lesssim 10^{-9}$

- Theoretically clean
- Mostly clean to reconstruct

Sensitive mainly to $\mathcal{C}_{10}^{(\prime)}$**.**

Semi-leptonic

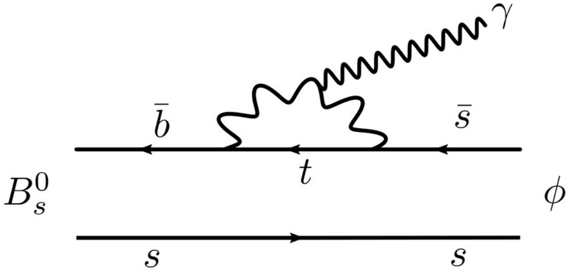


Quite rare, $\mathcal{B} \sim 10^{-6}$

- Hadronic pollution.
- Mostly clean to reconstruct.
- Electron reconstruction very challenging.

Sensitive to $\mathcal{C}_7^{(\prime)}$, $\mathcal{C}_9^{(\prime)}$ **and** $\mathcal{C}_{10}^{(\prime)}$ depending on $q^2 \equiv m^2_{\ell^+\ell^-}$ region.

Radiative



Fairly rare, $\mathcal{B} \sim 10^{-5}$

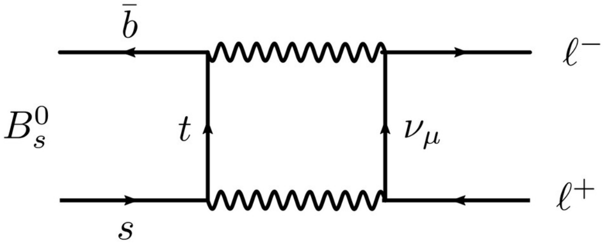
- Similar to semi-leptonic.
- Experimental resolution not great.

Sensitive to $\mathcal{C}_7^{(\prime)}$**.**

Slide from R.Henderson

Flavour changing neural current b to sℓℓ

Fully leptonic

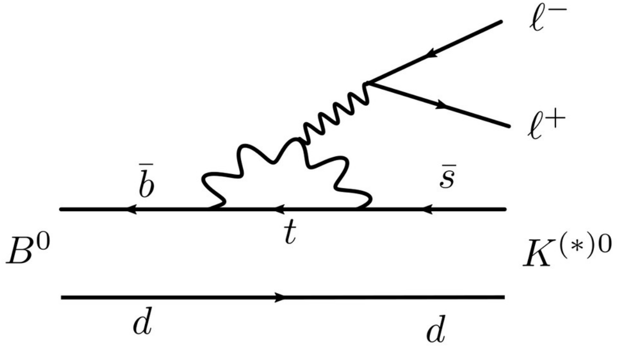


Very rare! $\mathcal{B} \lesssim 10^{-9}$

- Theoretically clean
- Mostly clean to reconstruct

Sensitive mainly to $\mathcal{C}_{10}^{(\prime)}$**.**

Semi-leptonic



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- Hadronic pollution.
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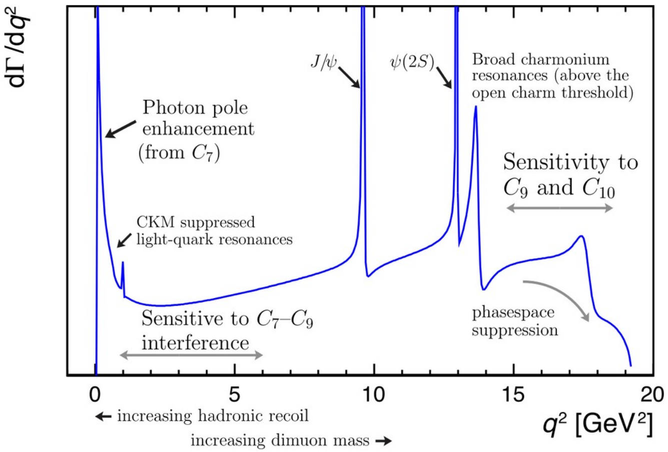


Slide from R.Henderson

Flavour changing neural current b to sℓℓ

Cleanest measurement: lepton universality tests via ratios

- $b \to s\ell^+\ell^-$ is lepton universal in the SM
  $\to$ can identify LU violating NP contribution

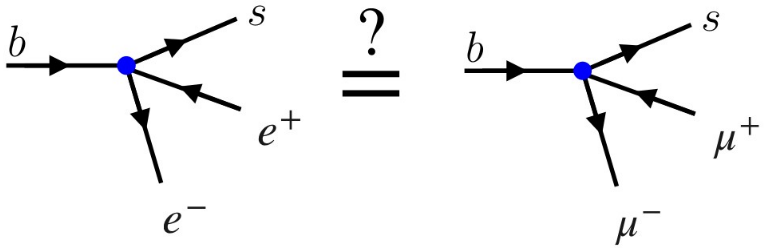
  Hiller & Kruger arXiv:hep-ph/0310219

- $b \to s\tau\tau$ not observed yet $\to$ compare μ and e

- Predictions are extremely precise
  - QCD uncertainty cancels to 10^{-4}
  - Up to ~1% QED corrections

  Bordone et al arXiv:1605.07633

- Main challenge at LHCb is e/μ differences in the detector response



$$R_H = \frac{\int_{q^2_{\rm min}}^{q_{\rm max}} \frac{{\rm d}\mathcal{B}(B \to H\mu^+\mu^-)}{{\rm d}q^2}\,{\rm d}q^2}{\int_{q^2_{\rm min}}^{q_{\rm max}} \frac{{\rm d}\mathcal{B}(B \to He^+e^-)}{{\rm d}q^2}\,{\rm d}q^2} \cong 1$$

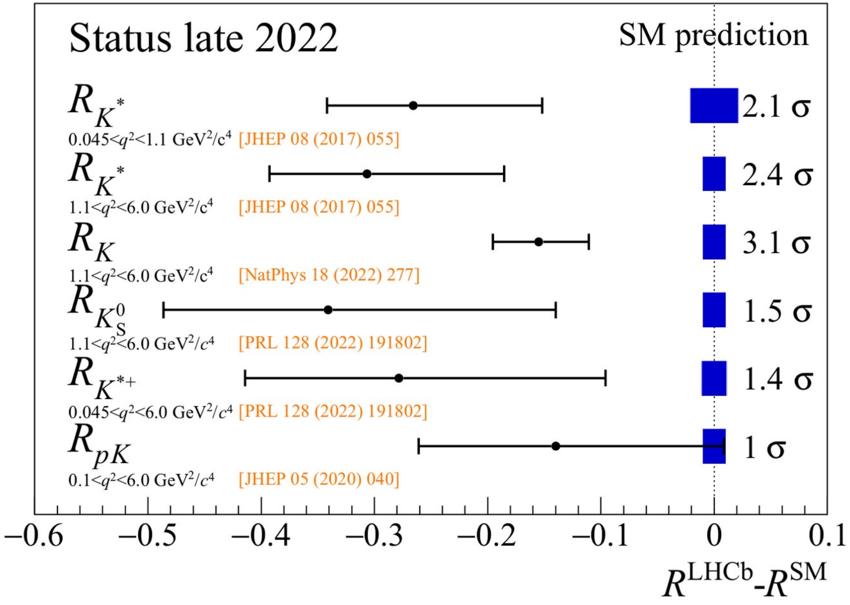
SM

Slide from M.Borsato

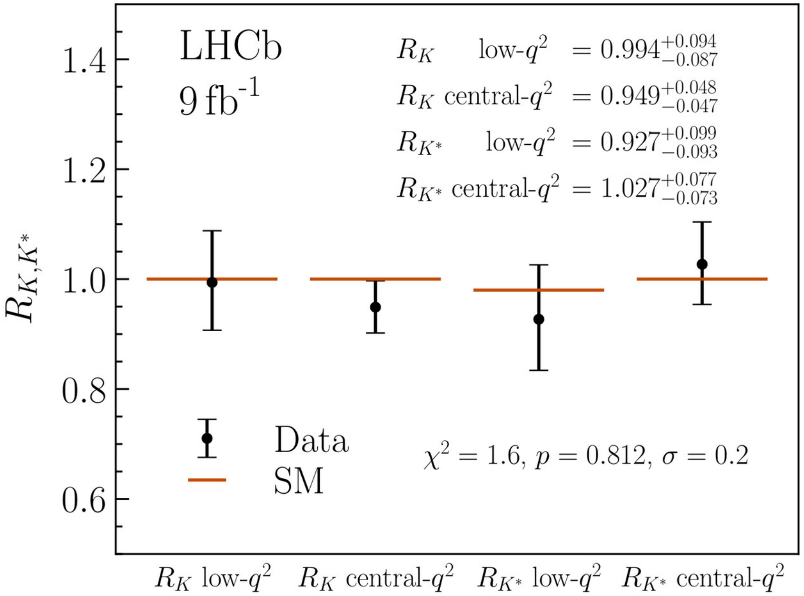
Flavour changing neural current b to sℓℓ

Cleanest measurement: lepton universality tests via (double) ratios

$$R_X = \frac{\mathcal{B}(B \to X\mu^+\mu^-)}{\mathcal{B}(B \to Xe^+e^-)} \Bigg/ \frac{\mathcal{B}(B \to XJ/\psi(\to \mu^+\mu^-))}{\mathcal{B}(B \to XJ/\psi(\to e^+e^-))}$$

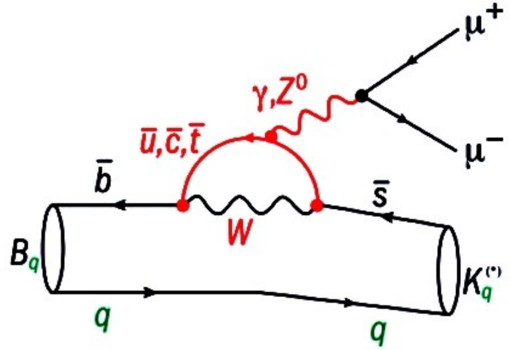


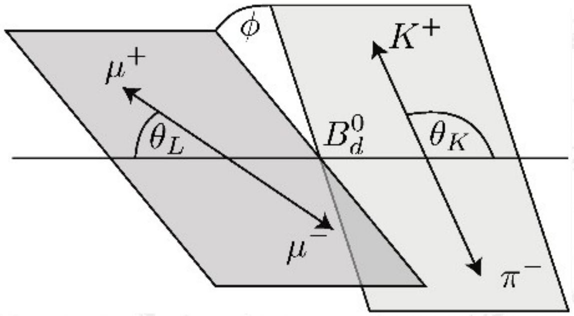
[arXiv:2212.09153] [arXiv:2212.09152]



Flavour changing neural current b to sℓℓ

- another way to look at FCNC: $b \to s$ transition with a BR ~ $1.1\ 10^{-6}$
- angular distribution of the 4 particles in the final state sensitive to new physics for the interference of NP and SM diagrams
  - allows measuring a large set of angular parameters sensitive to Wilson coefficients $C^{(\prime)}_{7}$, $C^{(\prime)}_{9}$, $C^{(\prime)}_{10}$, $C^{(\prime)}_{S,P}$



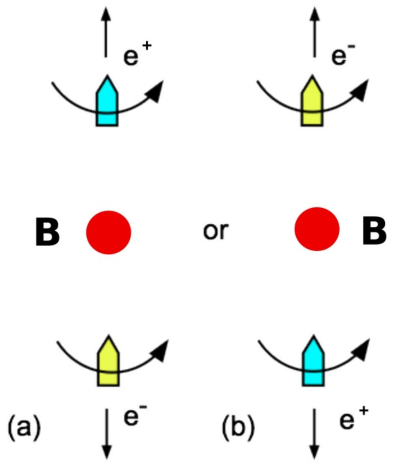


- decay described by three angles (θ_L, θ_K, ϕ) and the di-muon mass squared q^2 → the angular distribution is analysed in finite bins of q^2 as a function of θ_L, θ_K and ϕ.
- Hadronic uncertainties (form factors) difficult to evaluate

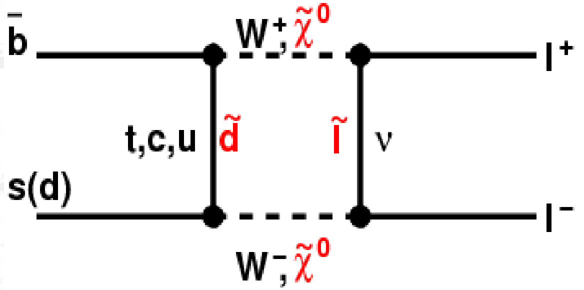
Fully leptonic decays

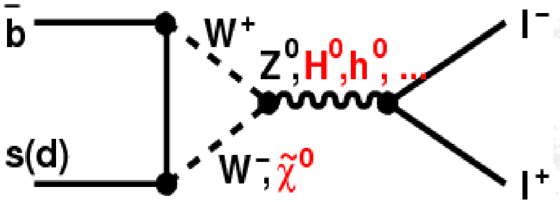
- Flavour Changing Neutral Currents (FCNC)
- In addition, they are CKM and helicity suppressed.
- Within the SM, they can be calculated with small theoretical uncertainties of order 6-8%

meson type	Lepton type e	μ	τ
B^0	$(2.48 \pm 0.21)10^{-15}$	$(1.06 \pm 0.09)10^{-10}$	$(2.22 \pm 0.19)10^{-8}$
B_s^0	$(8.54 \pm 0.55)10^{-14}$	$(3.65 \pm 0.23)10^{-9}$	$(7.73 \pm 0.49)10^{-7}$

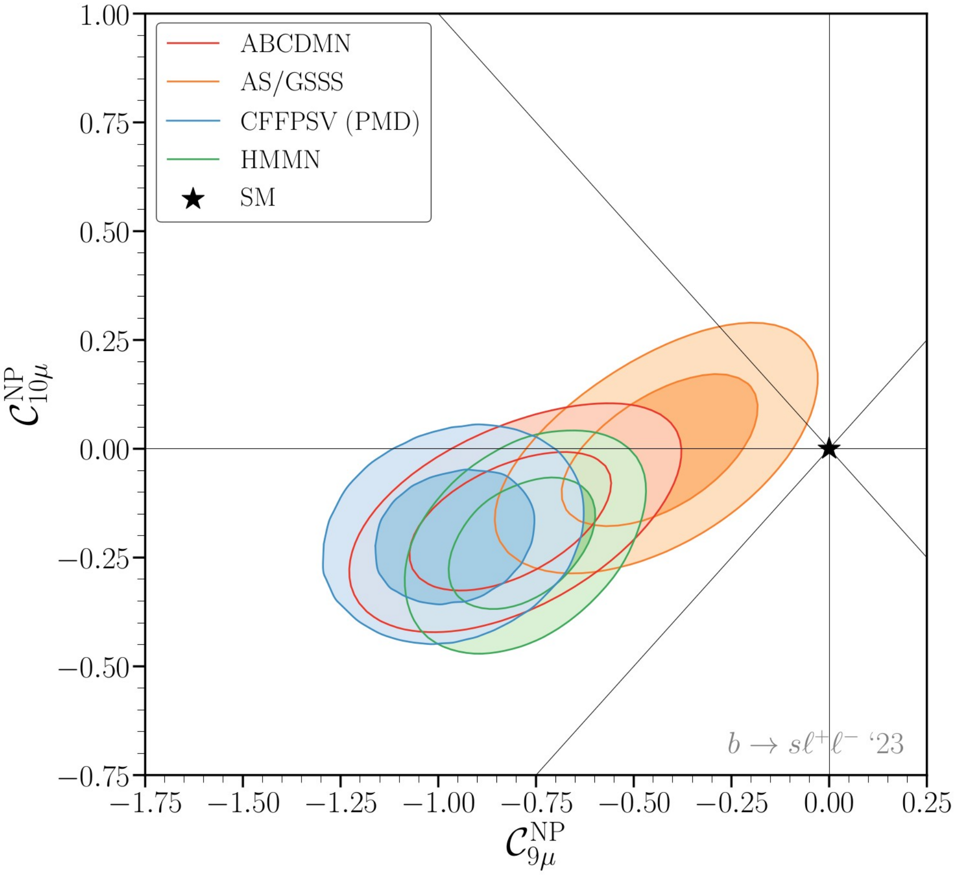


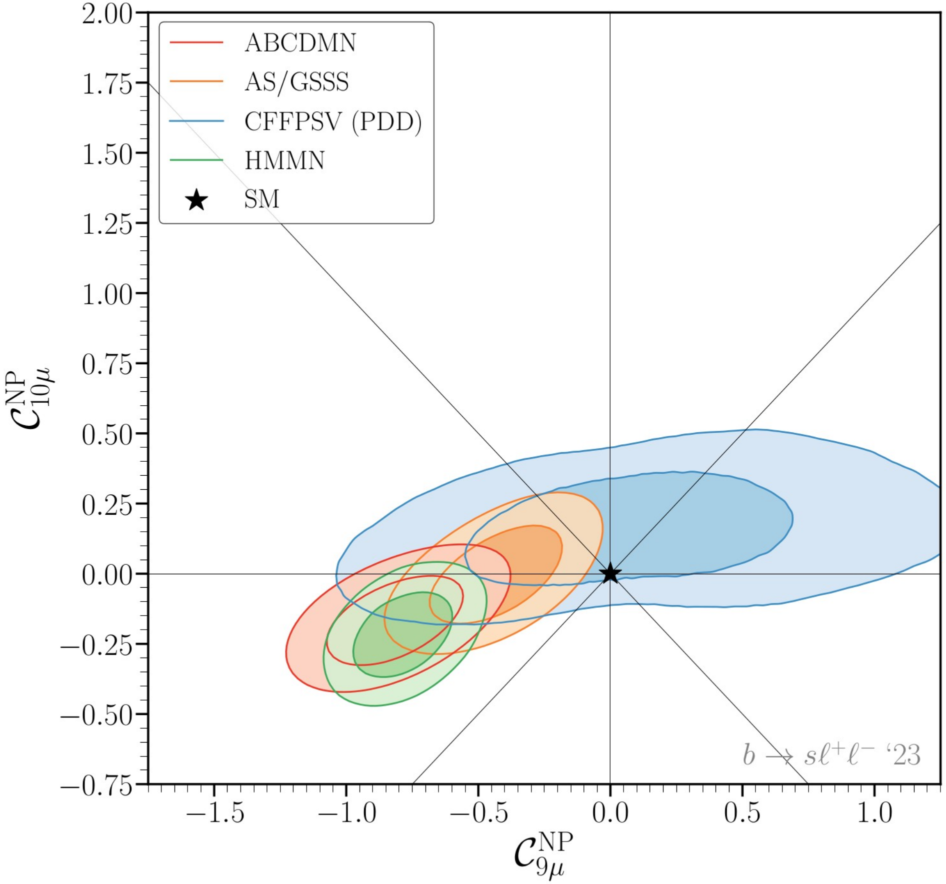
- Perfect ground for indirect new physics searches:
  - virtual new particles can contribute to the loop
  - both enhancement and suppression effects are possible





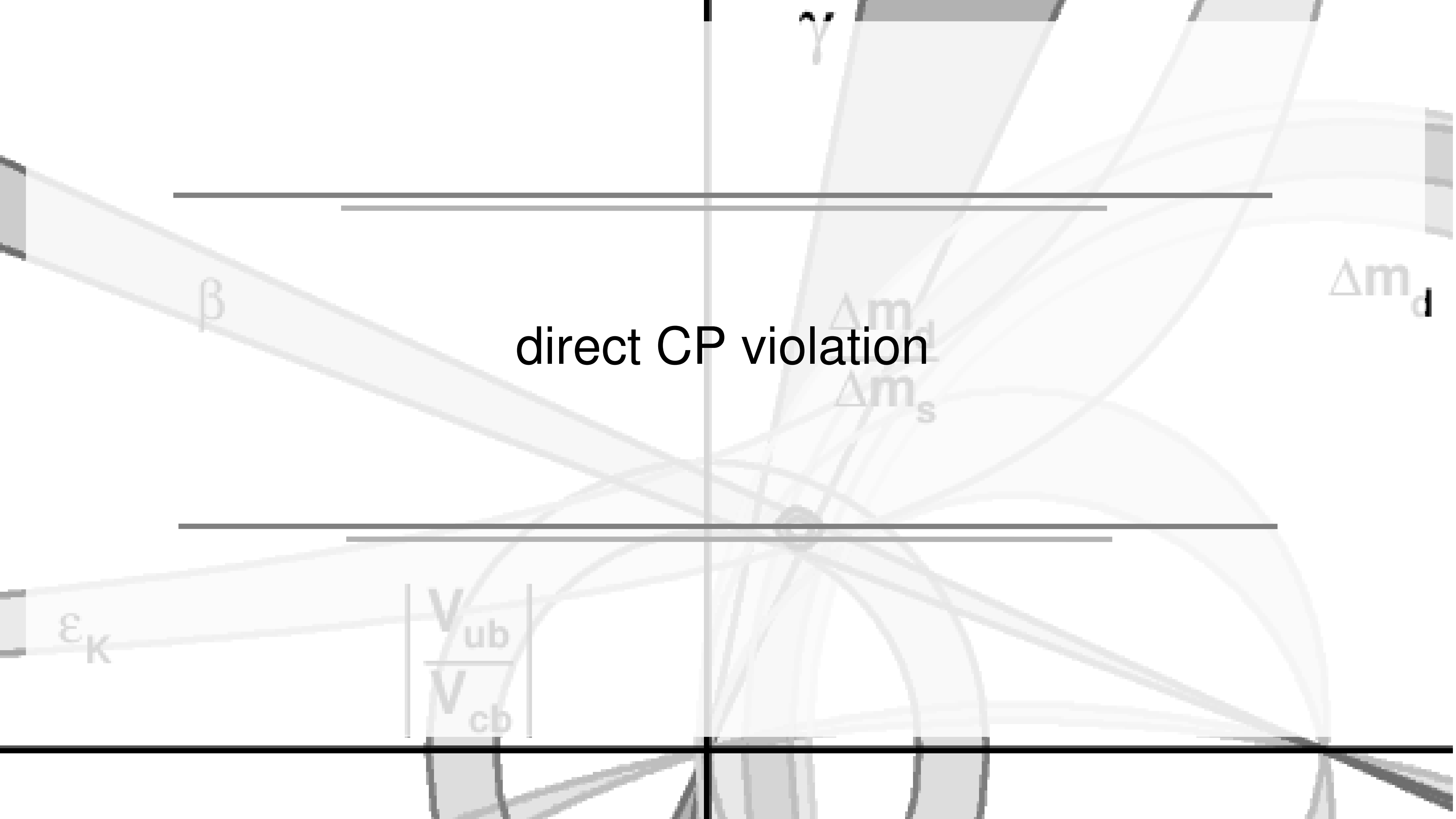
Global fits to b to sll processes





Conclusions

- Flavour physics is an essential tool in the current circumstances
  - Could point us in the direction of the new physics
  - A lot of measurements and experiments can look at this from a number of points of view
  - Theory is also improving in calculations and testing more closely the Standard Model



direct CP violation
γ
β
Δm_d
Δm_d
Δm_s
ε_K
|V_ub/V_cb|

Time-integrated direct CP asymmetries

- can be measured in decays of both neutral and charged mesons
- measure a direct CP asymmetry by comparing amplitudes of decay
- Event counting exercise: when studying neutral B mesons we can select a self-tagging final state.
- need an interference between (*at least*) two amplitudes contributing to the same final state

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

$$A_1 = a_1 e^{i(\phi_1+\delta_1)}$$
$$A_2 = a_2 e^{i(\phi_2+\delta_2)}$$

$$A_f = a_1 \exp\left[i(\delta_1 + \phi_1)\right] + a_2 \exp\left[i(\delta_2 + \phi_2)\right]$$
$$\bar{A}_{\bar{f}} = a_1 \exp\left[i(\delta_1 - \phi_1)\right] + a_2 \exp\left[i(\delta_2 - \phi_2)\right]$$

δ_i: strong phases CP even

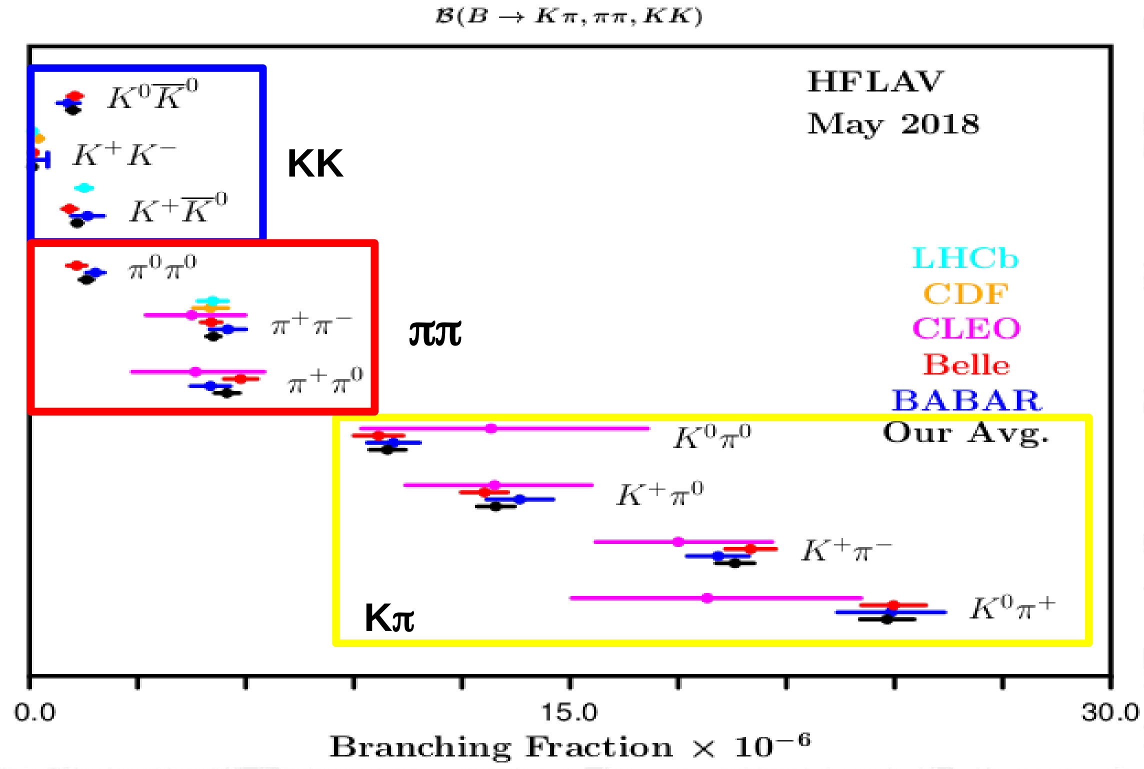
ϕ_i: weak phases CP odd

- the measured asymmetry becomes:

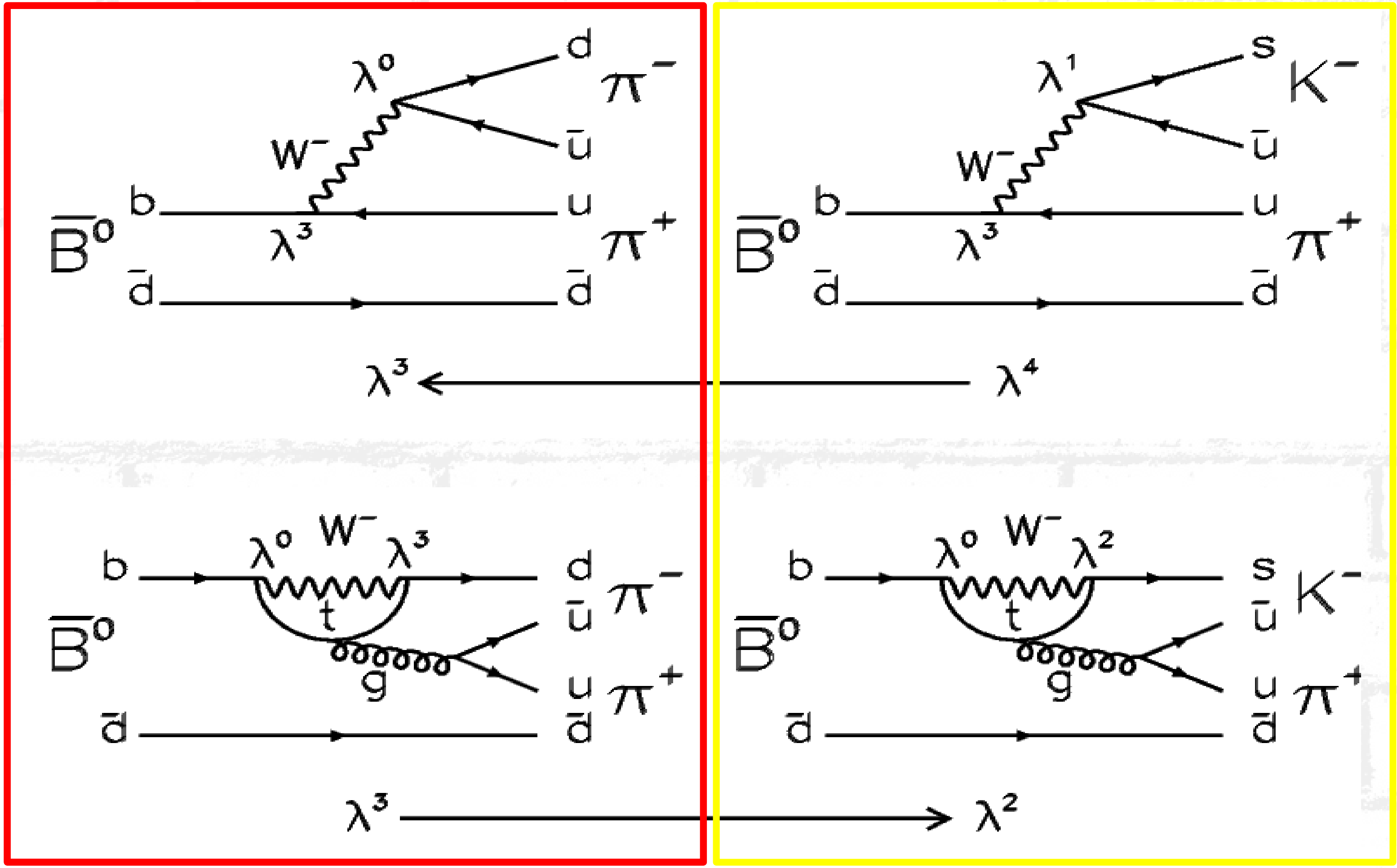
$$A_{CP} \equiv \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \sim \sum_{i,j} a_i\, a_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j)$$

- limited by our knowledge of weak and strong phase differences.
  - ▻ But there are many possible measurements that we can compare!

Charmless two-body B decays



Charmless two-body B decays



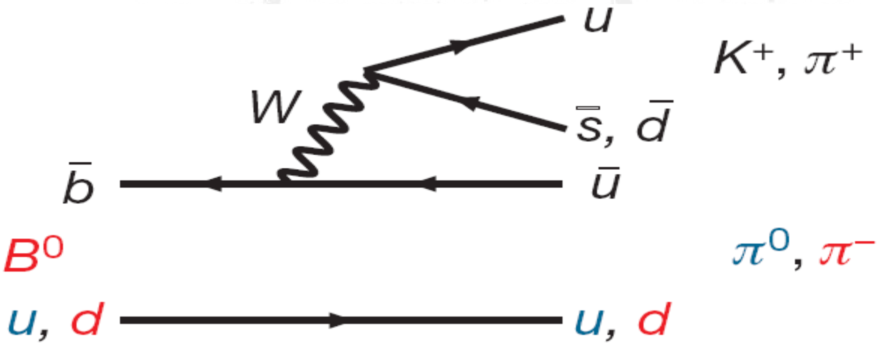
Direct CP violation in charmless two-body B decays

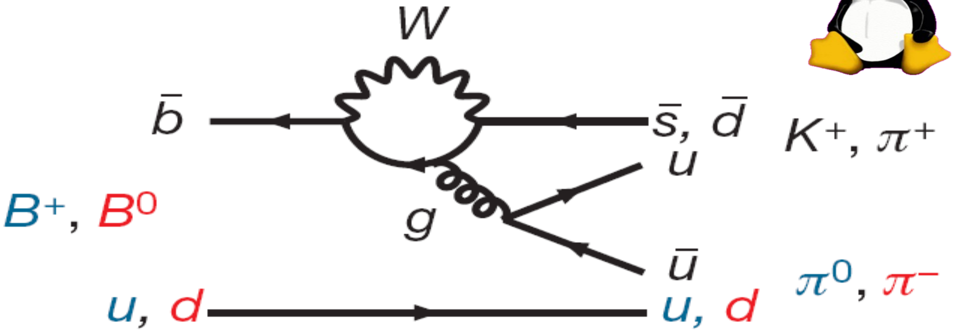
$$A_{CP} \equiv \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \sim \sum_{i,j} a_i \, a_j \sin(\phi_i - \phi_j) \sin(\delta_i - \delta_j)$$

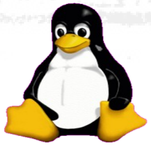
δ_i: strong phase
CP even

ϕ_i: weak phase
CP odd

interesting modes:
- $K^+\pi^-$: penguin+tree
- $K^+\pi^0$: penguin+tree
- $K^0\pi^+$: pure penguin







The kπ amplitudes

CKM enhanced | CKM suppressed

$$A(B^0 \to K^+\pi^-) = V_{ts} V_{tb}^* \times P_1(c) - V_{us} V_{ub}^* \times \{E_1 - P_1^{GIM}(u-c)\}$$

$$A(B^+ \to K^0\pi^+) = -V_{ts} V_{tb}^* \times P_1(c) + V_{us} V_{ub}^* \times \{A_1 - P_1^{GIM}(u-c)\}$$

$$\sqrt{2} \cdot A(B^+ \to K^+\pi^0) = V_{ts} V_{tb}^* \times P_1(c) - V_{us} V_{ub}^* \times \{E_1 + E_2 + A_1 - P_1^{GIM}(u-c)\}$$

$$\sqrt{2} \cdot A(B^0 \to K^0\pi^0) = -V_{ts} V_{tb}^* \times P_1(c) - V_{us} V_{ub}^* \times \{E_2 + P_1^{GIM}(u-c)\}$$

Charming Penguin ~ λ^2 | $V_{us} V_{ub}^* \sim \lambda^4$

The ingredients:

⇨ The elements of the CKM matrix (from the UT analysis)

⇨ Color Allowed (E_1) and Color suppressed (E_2) tree-level emissions

⇨ Charming (P_1) and GIM (P_1^{GIM}) penguins

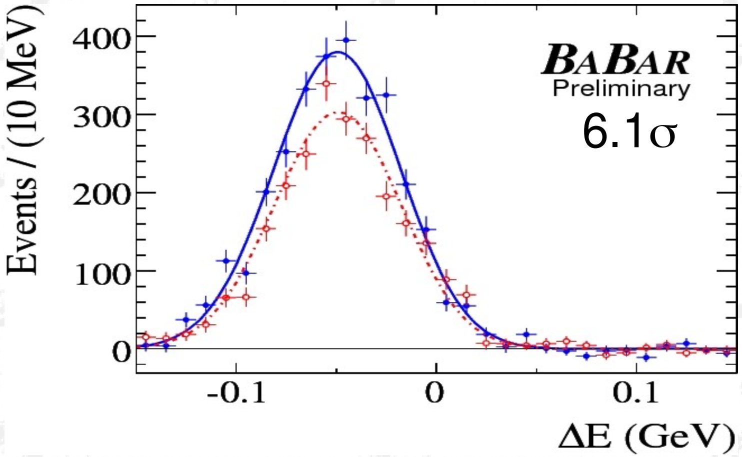
⇨ Annihilation (A_1)

Direct CP violation in charmless two-body B decays

- $B^0 \to K^{\pm}\pi^{\mp}$: tree and gluonic penguin contributions
- Compute time integrated asymmetry

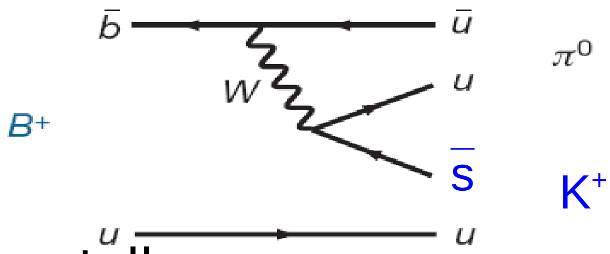
$$\mathcal{A}_{K^{\pm}\pi^{\mp}} \equiv \frac{N(\bar{B}^0 \to K^-\pi^+) - N(B^0 - K^+\pi^-)}{N(\bar{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)} = -0.084 \pm 0.004$$

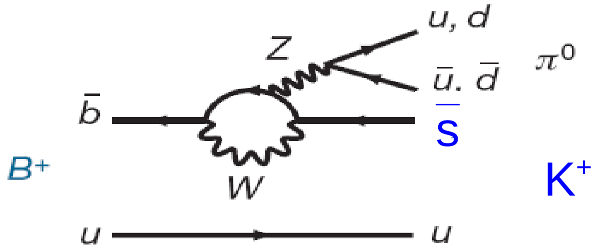
- Experimental results from Belle, BaBar, and now also LHCb have significant weight in the world average of this CP violation parameter.
- First measurement of direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we cannot use this to measure weak phases



Direct CP violation in charmless two-body B decays

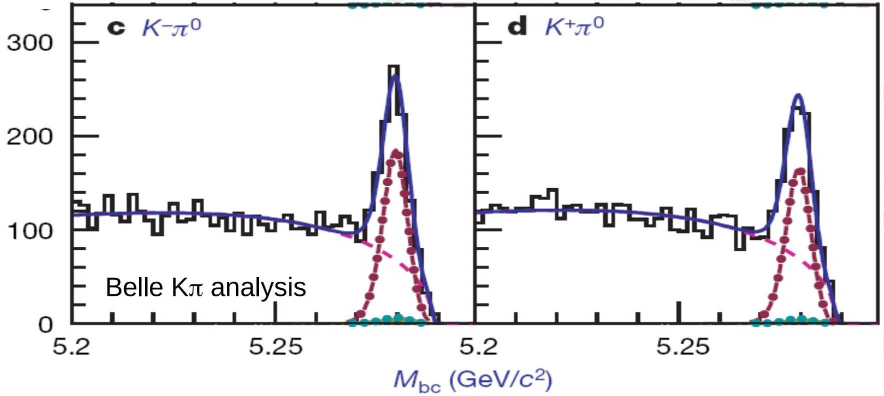
- $B^+ \to K^+\pi^0$: colour suppressed tree (in addition to the colour allowed one) and gluonic penguin contributions





- Experimentally measure:

$$A(K^+\pi^0) = 0.040 \pm 0.021$$



- Difference between B^+ and B^0 asymmetries:

$$A(K^+\pi^-) = -0.084 \pm 0.004$$

- Difference claimed to be an indication of new physics, however:
  - Theory calculations assume that only T+P contribute to $K^+\pi^-$, and C+P contribute to $K^+\pi^0$.
  - The C contribution is larger than originally expected in $K^+\pi^0$.

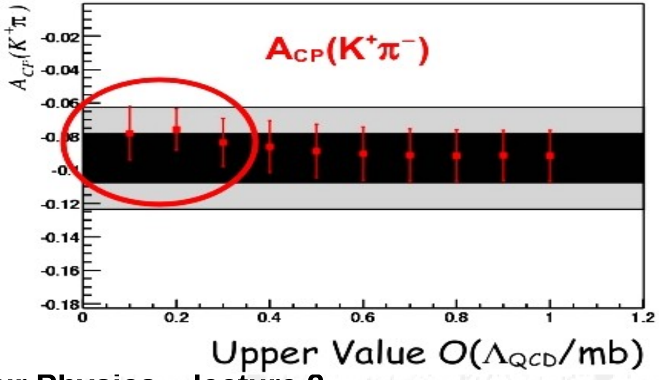
For example, see Gedlou arXiv:0808.1932 and references therein

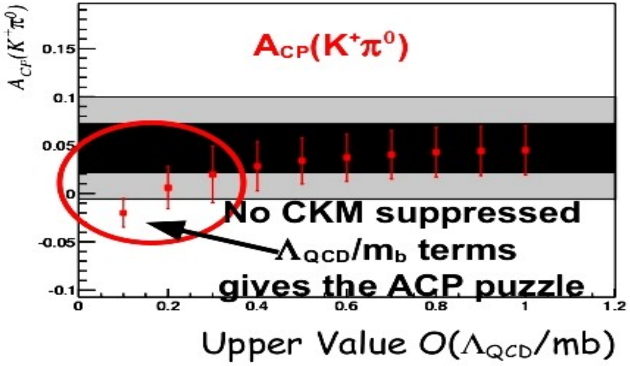
Is there a kπ puzzle?

caveat: quite old

Only SCET includes a non-factorizable $O(\Lambda_{QCD}/m_b)$ charming penguin.
All these approaches neglect the CKM-suppressed $O(\Lambda_{QCD}/m_b)$ corrections

	QCDF [50]	PQCD [54, 55]	SCET [58]	exp
$BR(\pi^-\bar{K}^0)$	$19.3^{+1.9+11.3+1.9+13.2}_{-1.9-7.8-2.1-5.6}$	$24.5^{+13.6}_{-8.1}$	$20.8 \pm 7.9 \pm 0.6 \pm 0.7$	23.1 ± 1.0
$A_{CP}(\pi^-\bar{K}^0)$	$0.9^{+0.2+0.3+0.1+0.6}_{-0.3-0.3-0.1-0.5}$	0 ± 0	< 5	0.9 ± 2.5
$BR(\pi^0 K^-)$	$11.1^{+1.8+5.8+0.9+6.9}_{-1.7-4.0-1.0-3.0}$	$13.9^{+10.0}_{-5.6}$	$11.3 \pm 4.1 \pm 1.0 \pm 0.3$	12.8 ± 0.6
$A_{CP}(\pi^0 K^-)$	$7.1^{+1.7+2.0+0.8+9.0}_{-1.8-2.0-0.6-9.7}$	-1^{+3}_{-5}	$-11 \pm 9 \pm 11 \pm 2$	4.7 ± 2.6
$BR(\pi^+ K^-)$	$16.3^{+2.6+9.6+1.4+11.4}_{-2.3-6.5-1.4-4.8}$	$20.9^{+15.6}_{-8.3}$	$20.1 \pm 7.4 \pm 1.3 \pm 0.6$	19.4 ± 0.6
$A_{CP}(\pi^+ K^-)$	$4.5^{+1.1+2.2+0.5+8.7}_{-1.1-2.5-0.6-9.5}$	-9^{+6}_{-8}	$-6 \pm 5 \pm 6 \pm 2$	-9.5 ± 1.3
$BR(\pi^0\bar{K}^0)$	$7.0^{+0.7+4.7+0.7+5.4}_{-0.7-3.2-0.7-2.3}$	$9.1^{+5.6}_{-3.3}$	$9.4 \pm 3.6 \pm 0.2 \pm 0.3$	10.0 ± 0.6
$A_{CP}(\pi^0\bar{K}^0)$	$-3.3^{+1.0+1.3+0.5+3.4}_{-0.8-1.6-1.0-3.3}$	-7^{+3}_{-3}	$5 \pm 4 \pm 4 \pm 1$	-12 ± 11





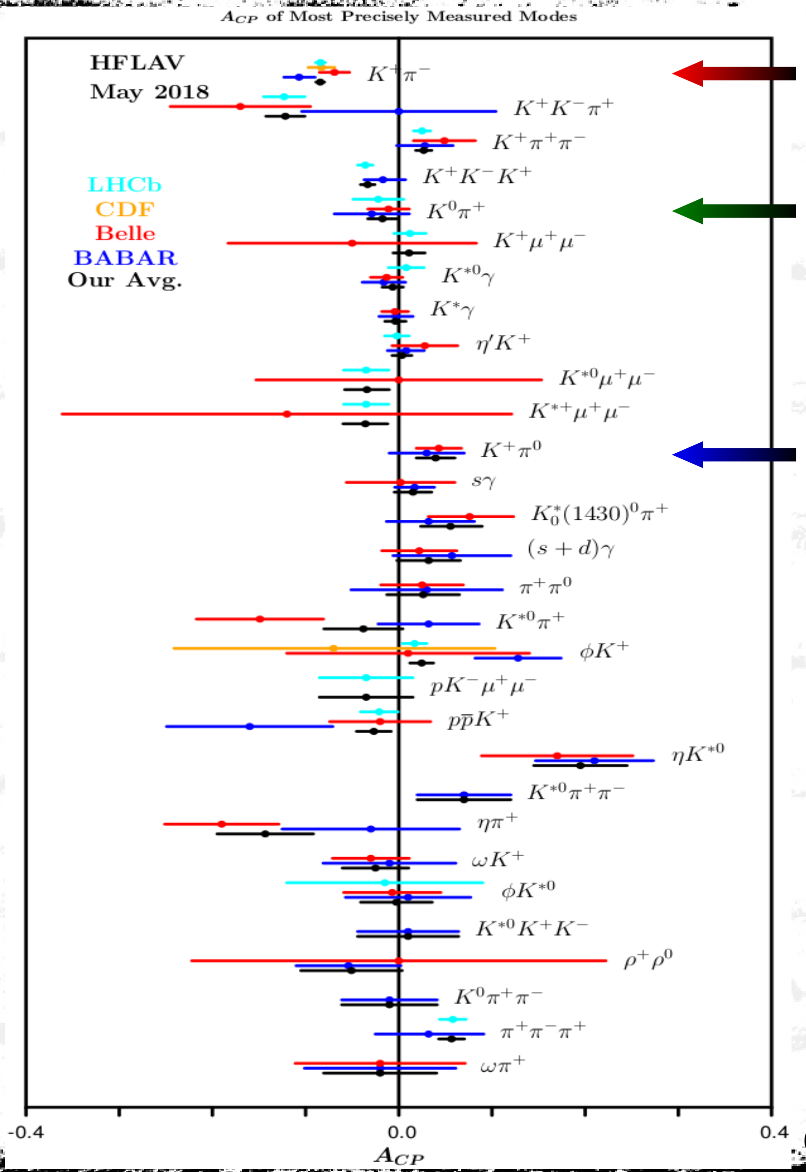
Direct CP violation searches

$$A_{CP} = \frac{\overline{N} - N}{\overline{N} + N}$$

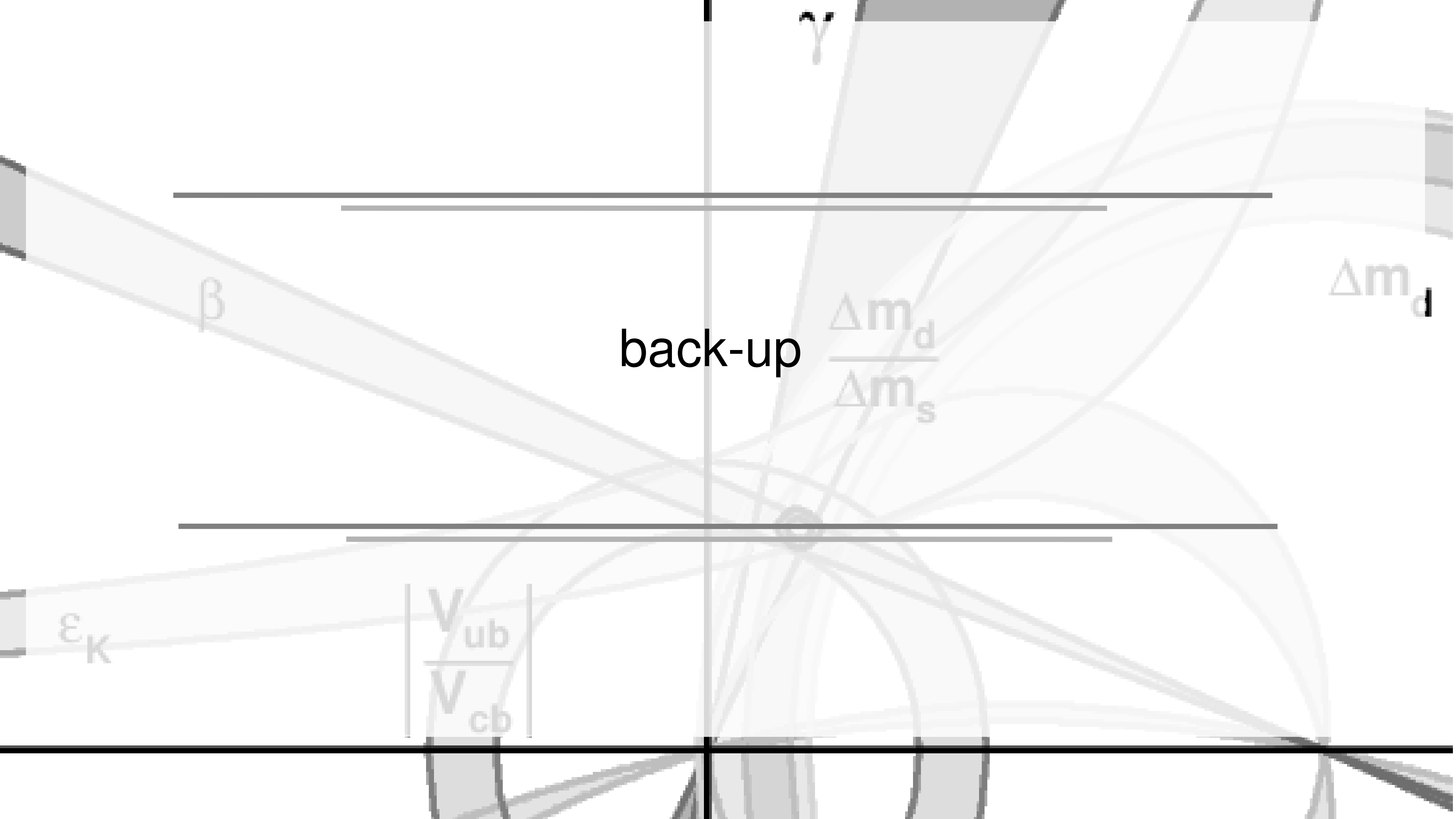
$A_{CP} = 0$

$= \text{no CP violation}$

- We have searched for direct CP violation now in a huge number of channels.
- This is a selection of the modes more precisely measured.



back-up

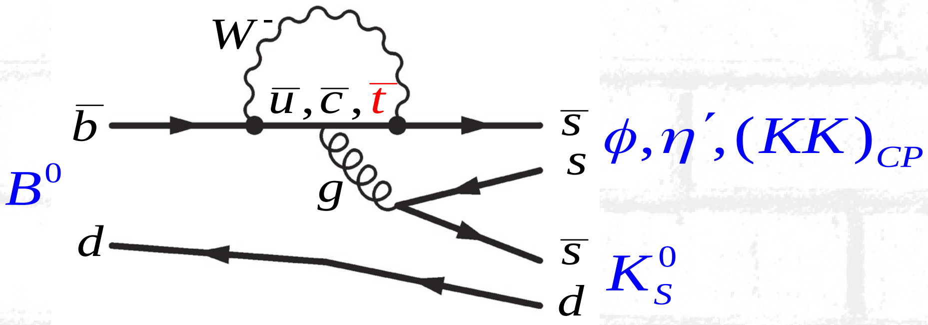


Searching for new physics via other $b \to c\bar{c}s$ modes

- $\sin 2\beta$ has been measured to O(1°) accuracy in $b \to c\bar{c}s$ decays.
- Can use this to search for signs of New Physics (NP) if:
  - Identify a rare decay sensitive to $\sin 2\beta$ (loop dominated process).
  - Measure S precisely in that mode (S_{eff}).
  - Control the theoretical uncertainty on the Standard Model 'pollution' (ΔS_{SM}).
  - Compute

$$\Delta S_{\mathrm{NP}} = S_{eff} - S_{c\bar{c}s} - \Delta S_{\mathrm{SM}}$$

- In the presence of NP: $\Delta S_{NP} \neq 0$



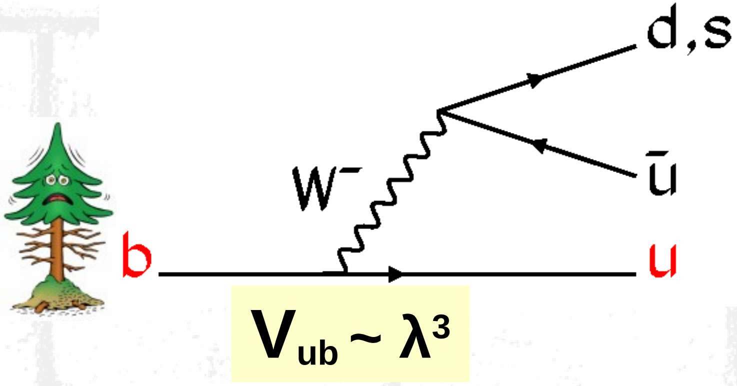
► New heavy particles can introduce new amplitudes affecting physical observables of loop dominated processes.
► Observables affected include branching fractions, CP asymmetries, forward backward asymmetries.. etc..
► The Standard Model contributions need to be understood

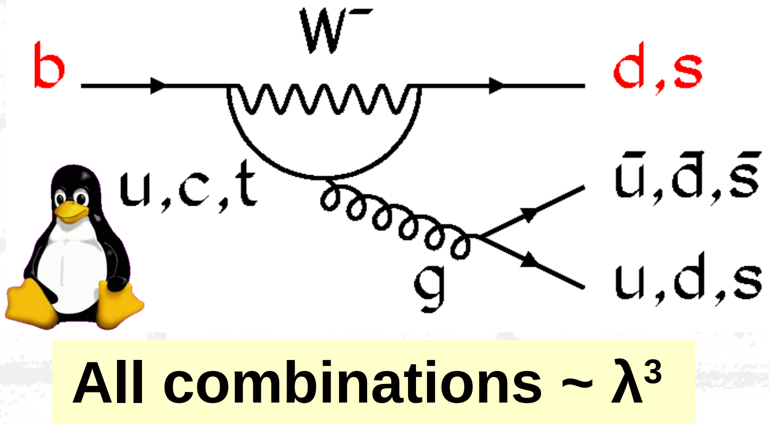
α (ϕ_2) from $\pi\pi$, $\rho\rho$, $\pi\rho$ decays with Isospin analysis

Interference between box mixing and tree diagrams results in an asymmetry that is sensitive to α in $B \rightarrow hh$ decays: $h = \pi, \rho$

Unlike for β, loop (penguin diagrams) corrections are not negligible for α

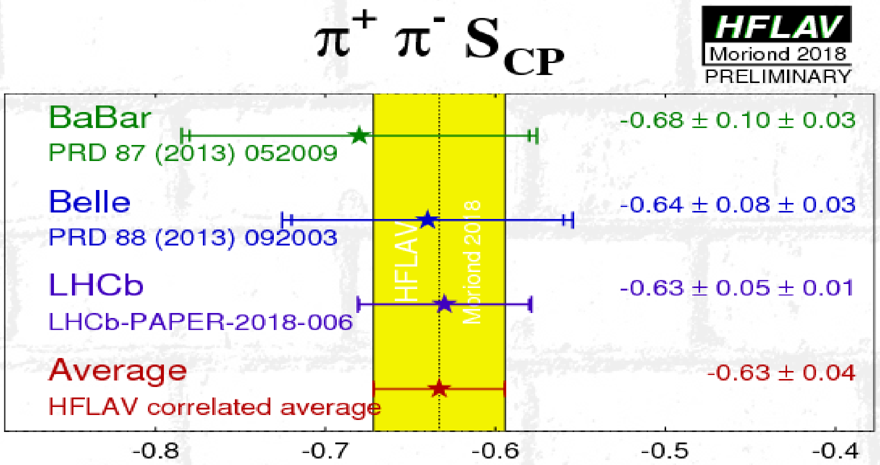
Need Isospin analysis including all modes (B of all charges and flavours) to obtain the α estimate

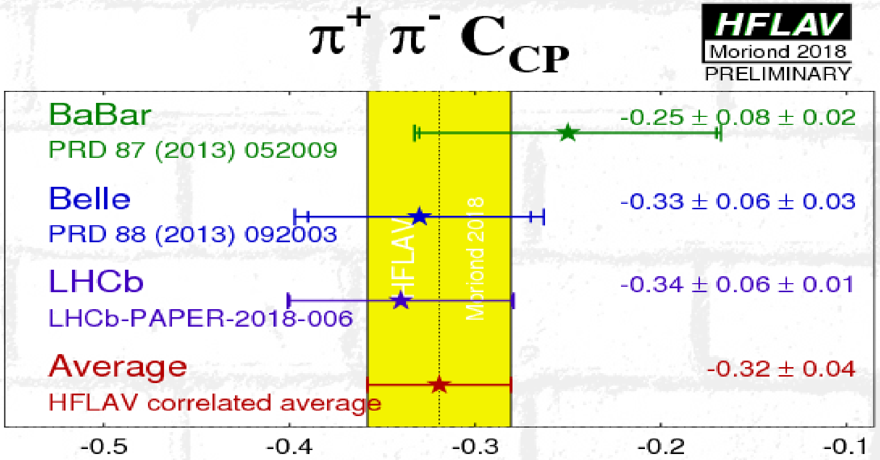


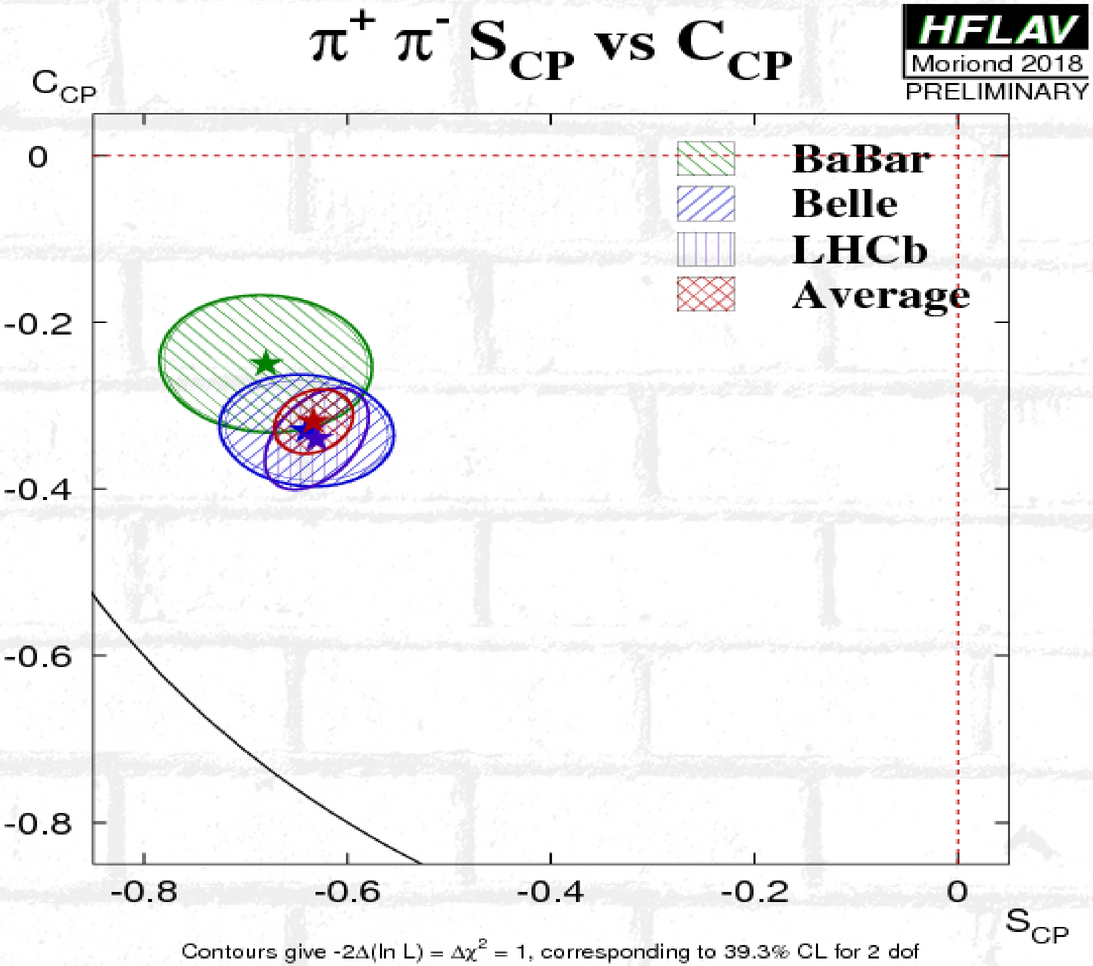


$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

$B \rightarrow \pi\pi$



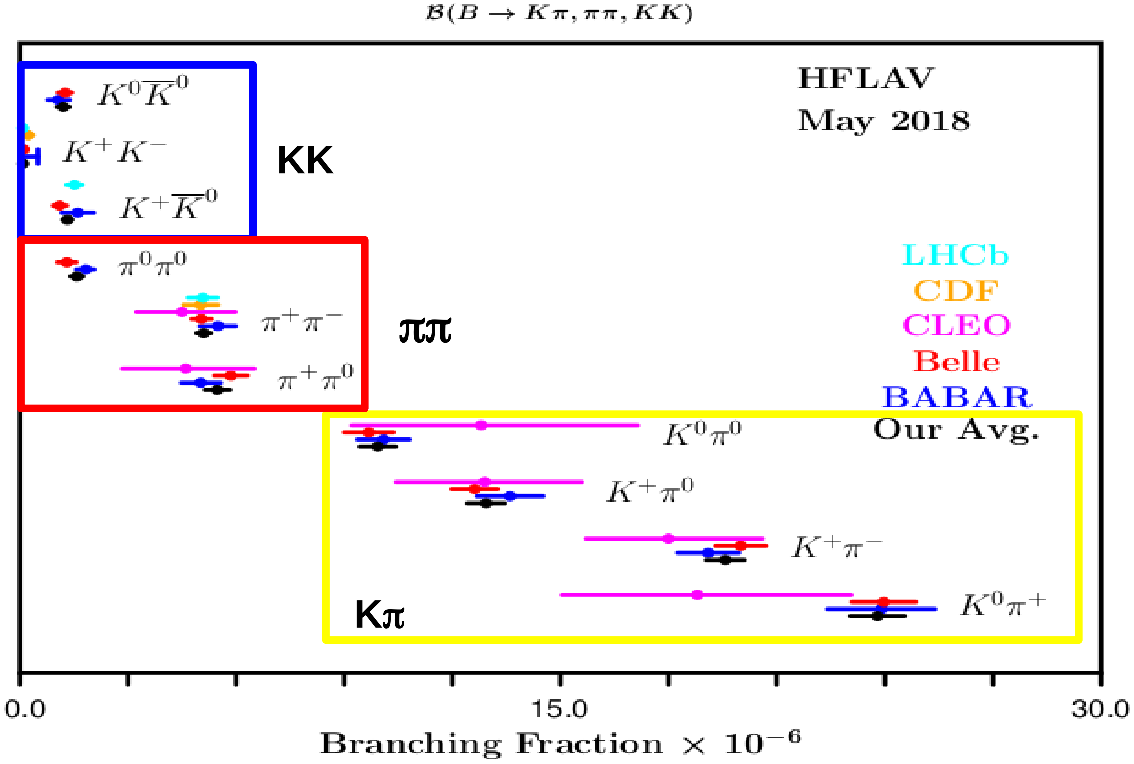




$\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$

Isospin-related ππ decays

- simultaneous ML fit to all hh modes with h being π or K:
  - $B^+ \to \pi^+\pi^-$, $K^+\pi^-$, K^+K^- (and cc)
  - $B^+ \to \pi^+\pi^0$, $K^+\pi^0$ (and cc)



$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

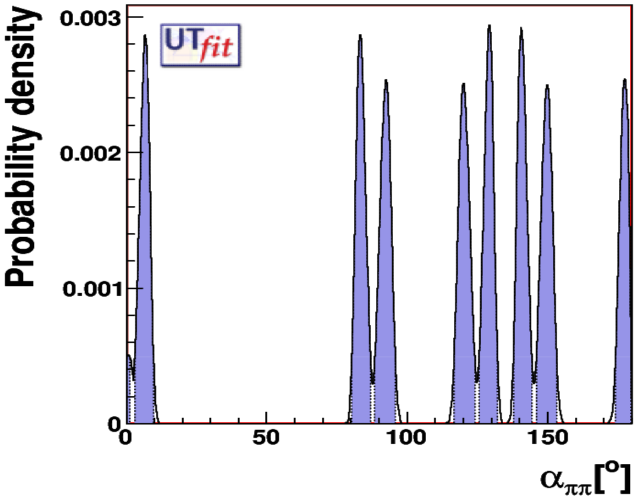
$B \rightarrow \pi\pi$

- Inputs from: $B^0 \rightarrow \pi^+\pi^-$

  $B^+ \rightarrow \pi^+\pi^0$

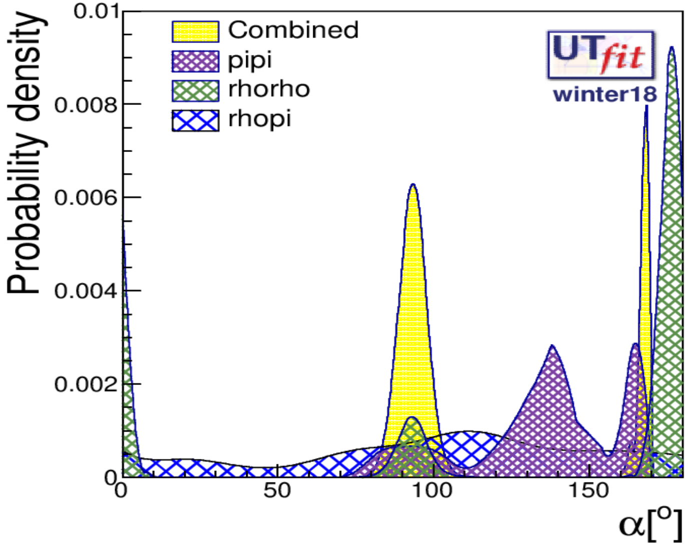
  $B^0 \rightarrow \pi^0\pi^0$

eight solutions to the isospin system: shown here a case with uncertainties reduced of a factor 10



additional information can be used: to reduce the degeneracy of the solutions and also to keep the amplitudes to go to infinity (unphysical)

for example Bs to KK (assuming SU(3) and a big uncertainty on that) can put an upper limit on the penguin amplitude



from ππ, ρρ, πρ combined SM:

α=(93.3 ± 5.6)°

UTfit prediction:

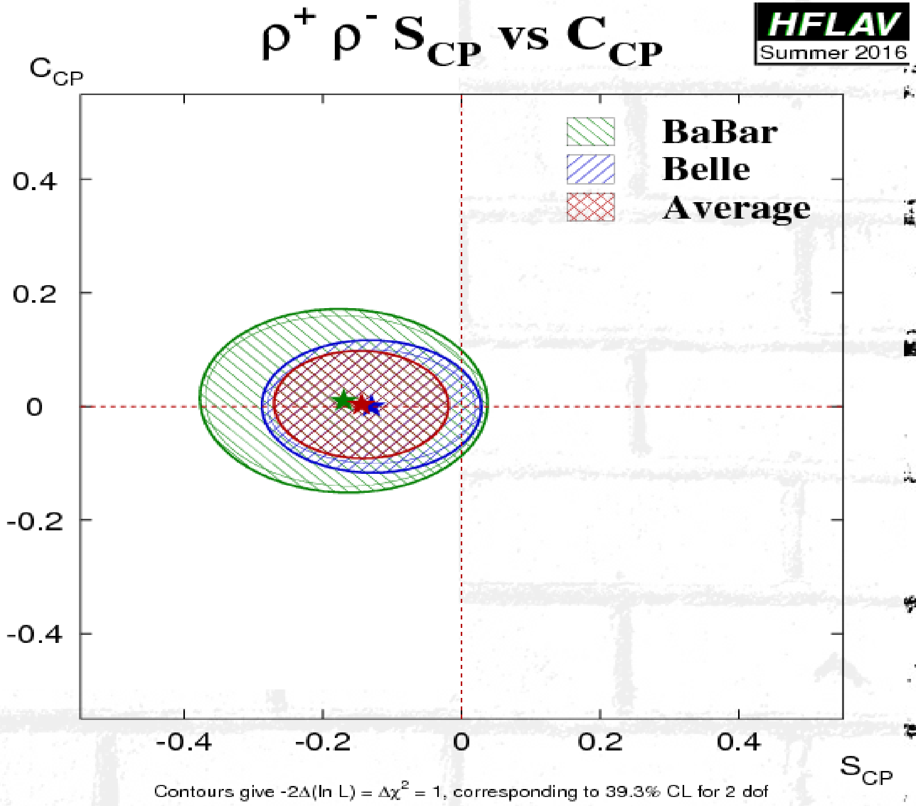
α=(90.1 ± 2.2)°

$B \to \rho\rho$

- Vector-Vector modes: angular analysis required to determine the CP content. L=0,1,2 partial waves:
  - longitudinal: CP-even state
  - transverse: mixed CP states
- +-: two π^0 in the final state
- wide ρ resonance

but

- BR 5 times larger with respect to $\pi\pi$
- penguin pollution smaller than in $\pi\pi$
- ρ are almost 100% polarized:
  - almost a pure CP-even state

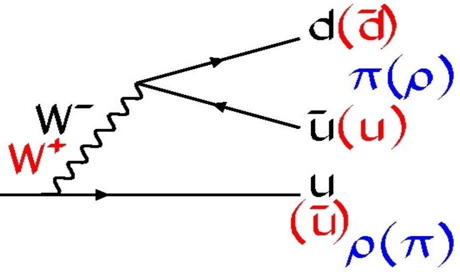


$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$

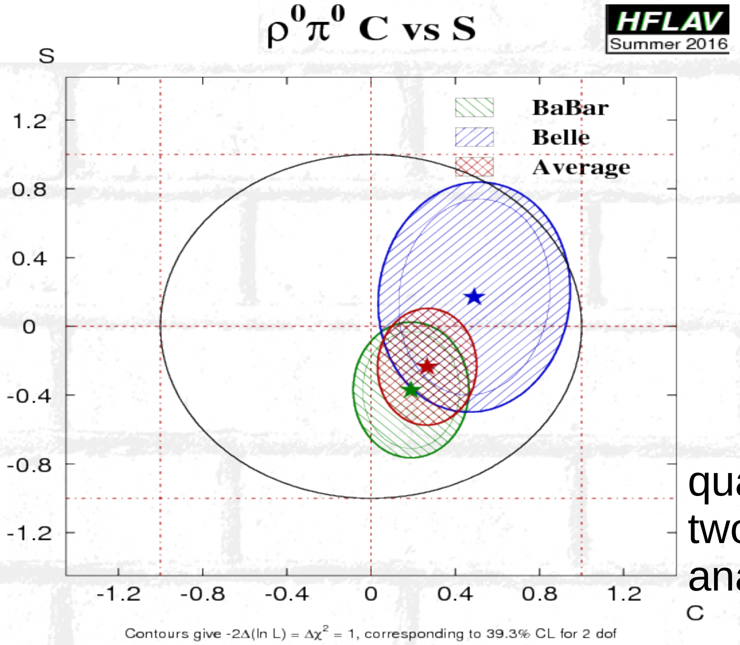
B → ρπ ($\pi^+\pi^-\pi^0$ Dalitz Plot)

◉ dominant decay ρπ is not a CP eigenstate

◉ 5 amplitudes need to be considered:
- ◎ $B^0 \rightarrow \rho^+\pi^-$, $\rho^-\pi^+$, $\rho^0\pi^0$ and $B^+ \rightarrow \rho^+\pi^0$, $\rho^0\pi^+$
- ◎ Isospin pentagon



◉ or time-dependent dalitz analysis: α extraction together with the strong phases exploiting the amplitude interference:
- ◎ interference at equal masses-squared give information on the strong phases between resonances



quasi-two-body analysis

γ/ϕ_3 angle

$$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$$

$b \rightarrow c$ interfering with $b \rightarrow u$

$B \rightarrow D^{(*)}K^{(*)}$

$B^0 \rightarrow D^- K^0 \pi^+$

$B^0 \rightarrow D^{(*)}\pi$

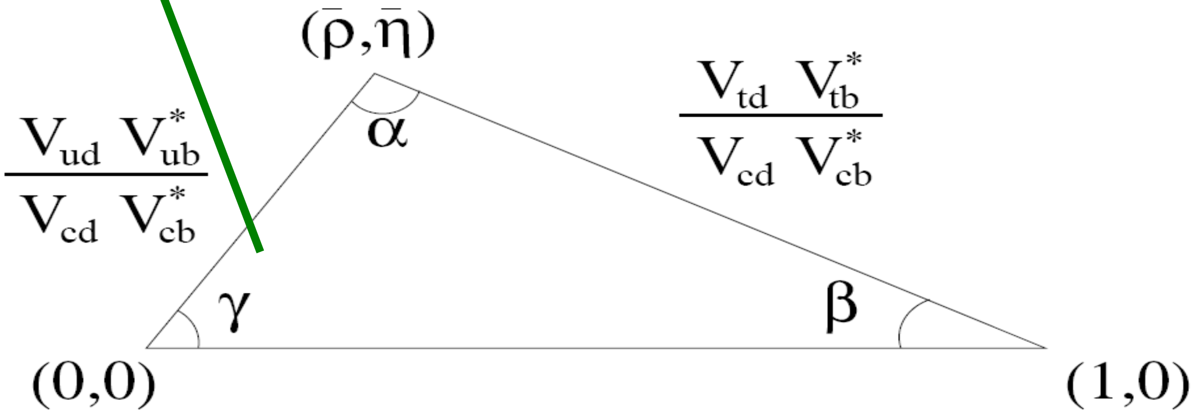
$B^0 \rightarrow D^{(*)}\rho$

$+$ *charmless*

Extract γ using $B \rightarrow D^{(*)}K^{(*)}$ final states using:

- GLW: Use CP eigenstates of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D \rightarrow K_s h^+ h^-$ decays.

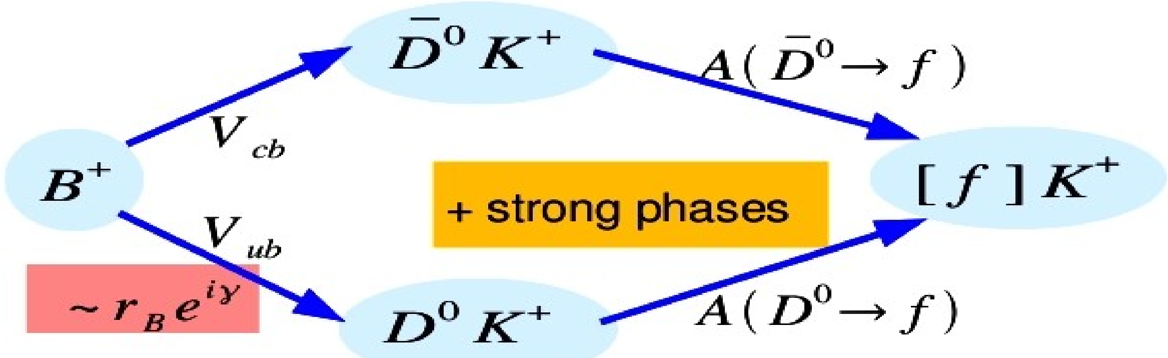
Measurements using neutral D mesons ignore D mixing.



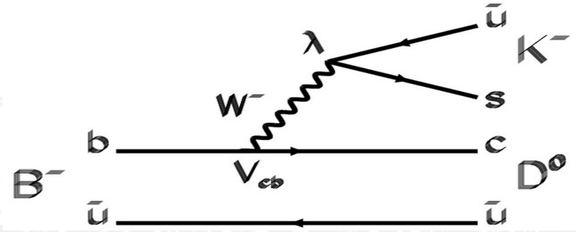
$\gamma \equiv \arg[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*]$

γ and DK trees

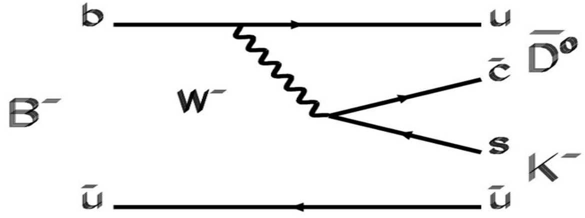
- ◎ $D^{(*)}K^{(*)}$ decays: from BRs and BR ratios, no time-dependent analysis, just rates
- ◎ the phase γ is measured exploiting interferences: two amplitudes leading to the same final states
- ◎ some rates can be really small: ~ 10^{-7}



Theoretically clean (no penguins *neglecting the D^0 mixing*)



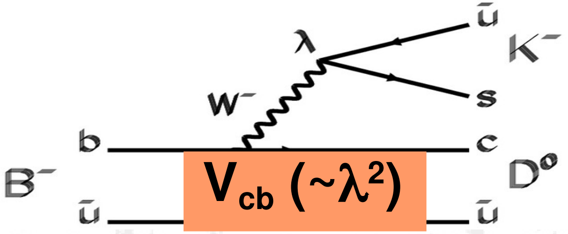
V_{cb} $(\sim\lambda^2)$

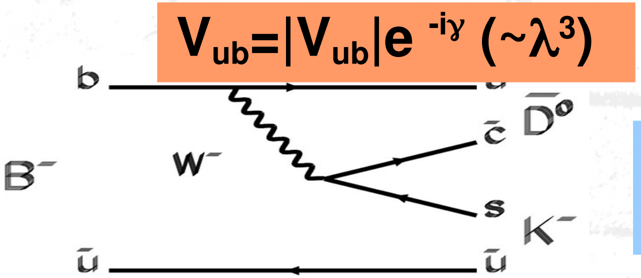


$V_{ub}=|V_{ub}|e^{-i\gamma}$ $(\sim\lambda^3)$

$\gamma \equiv \arg[-V_{ud}V^*_{ub}/V_{cd}V^*_{cb}]$

Sensitivity to γ: the ratio r_B





δ_B = strong phase diff.

$$A(B^- \to D^0K^-) = A_B$$
$$A(B^+ \to \bar{D}^0K^+) = A_B$$

$$A(B^- \to \bar{D}^0K^-) = A_B r_B e^{i(\delta_B - \gamma)}$$
$$A(B^+ \to D^0K^+) = A_B r_B e^{i(\delta_B + \gamma)}$$

r_B = amplitude ratio

$$r_B = \left|\frac{B^- \to \bar{D}^0K^-}{B^- \to D^0K^-}\right| = \sqrt{\bar{\eta}^2 + \bar{\rho}^2} \times F_{CS}$$

~0.36

hadronic contribution
channel-dependent

- in $B^+ \to D^{(*)0}K^+$: r_B is ~0.1
- to be measured: $r_B(DK)$, $r^*_B(D^*K)$ and $r^s_B(DK^*)$

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$

Three ways to make DK interfere

GLW(*Gronau, London, Wyler*) method: uses the CP eigenstates $D^{(*)0}_{CP}$ with final states: K^+K^-, $\pi^+\pi^-$ (CP-even), $K_s\pi^0$ (ω,ϕ) (CP-odd)

more sensitive to r_B

$$R_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B \qquad A_{CP\pm} = \frac{\pm 2r_B \sin\gamma \sin\delta_B}{1 + r_B^2 \pm 2r_B \cos\gamma \cos\delta_B}$$

ADS(*Atwood, Dunietz, Soni*) method: B^0 and $\bar{B}^0$ in the same final state with $D^0 \rightarrow K^+\pi^-$ (suppr.) and $\bar{D}^0 \rightarrow K^+\pi^-$ (fav.)

$$R_{ADS} = r_B^2 + r_{DCS}^2 + 2 r_B r_{DCS} \cos\gamma \cos(\delta_B + \delta_D)$$

the most sensitive way to γ ecays $B^- \rightarrow D^{(*)0}[K_S\pi^+\pi^-]\,K^-$

three free parameters to extract: γ , r_B and δ_B

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*}\right]$

γ: GLW Method

- GLW Method: Study $B^+ \to D_{CP}^0 X^+$ and $B^+ \to \bar{D} X^+$ + cc ($\bar{D}^0 \to K^+\pi^-$)
- X^+ is a strangeness one meson e.g. a K^+ or K^{*+}.
- D_{CP}^0 is a CP eigenstate (use these to extract γ):

$$D^0_{CP=+1} = K^+K^-, \pi^-\pi^+$$

$$D^0_{CP=-1} = K^0_S\pi^0, K^0_S\omega, K^0_S\phi$$

- 4 observables
- 3 unknowns: r_B, γ and δ

$$R_{CP\pm} = \frac{BF(B^- \to D^0_\pm K^-) + BF(B^+ \to D^0_\pm K^+)}{BF(B^- \to D^0 K^-) + BF(B^+ \to D^0 K^+)} = 1 + r_B^2 \pm 2 r_B \cos\delta \cos\gamma$$

$$A_{CP\pm} = \frac{BF(B^- \to D^0_\pm K^-) - BF(B^+ \to D^0_\pm K^+)}{BF(B^- \to D^0_\pm K^-) + BF(B^+ \to D^0_\pm K^+)} = \pm 2 r_B \sin\delta \sin\gamma / R_{CP\pm}$$

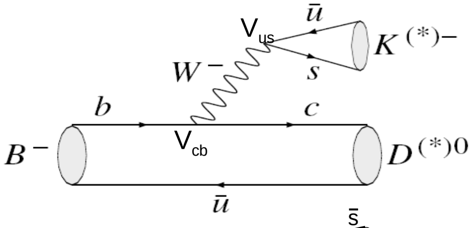
- The pr… n the value of r_B.
  - r_B~0.1 as this is a ratio of Cabibbo suppressed to Cabibbo allowed decays and also includes a colour suppression factor for $B^+ \to D^{(*)}K^{(*)}$ b→u decays.
- Measurement has an 8-fold ambiguity on γ.

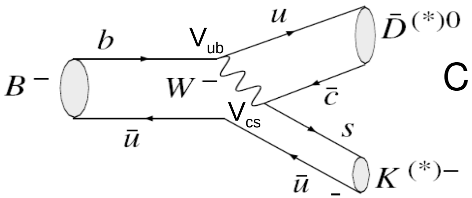
Gronau, London, Wyler, PLB253 p483 (1991).

γ: ADS Method

- ADS Method: Study $B^{\pm,0} \rightarrow D^{(*)0} K^{(*)\pm}$ — Attwood, Dunietz, Soni, PRL **78** 3257 (1997)
- Reconstruct doubly suppressed decays with common final states and extract γ through interference between these amplitudes:

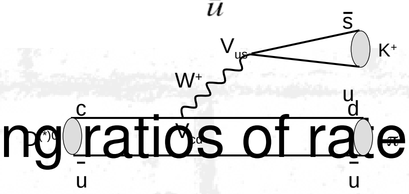
$B^- \rightarrow D^{(*)0} K^{(*)-}$
CKM Favoured

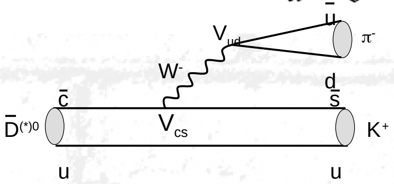




$B^- \rightarrow \bar{D}^{(*)0} K^{(*)-}$
CKM and Color Suppressed

$D^{(*)0} \rightarrow K^+\pi^-$
Doubly CKM Suppressed





$\bar{D}^{(*)0} \rightarrow K^+\pi^-$
CKM Favoured

- γ extracted using ratios of rates:

$$r_B^{(*)} = \left| \frac{A(B^- \rightarrow \bar{D}^{(*)0} K^-)}{A(B^- \rightarrow D^{(*)0} K^-)} \right|$$

$$r_D = \left| \frac{A(D^0 \rightarrow K^+\pi^-)}{A(D^0 \rightarrow K^-\pi^+)} \right|$$

- $\delta^{(*)} = \delta^{(*)}_B + \delta_D$
- $\delta^{(*)}$ is the sum of strong phase differences between the two B and D decay amplitudes.
- r_D and r_B are measured in B and charm factories.
- δ_D is measured by CLEO-c

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$

γ: GGSZ Method

- GGSZ ("Dalitz") Method: Study $D^{(*)0}K^{(*)}$ using the $D^{(*)0} \to K_s h^+ h^-$ Dalitz structure to constrain γ. (h = π, K)
  - Self tagging: use charge for $B^\pm$ decays or $K^{(*)}$ flavour for B^0 mesons.

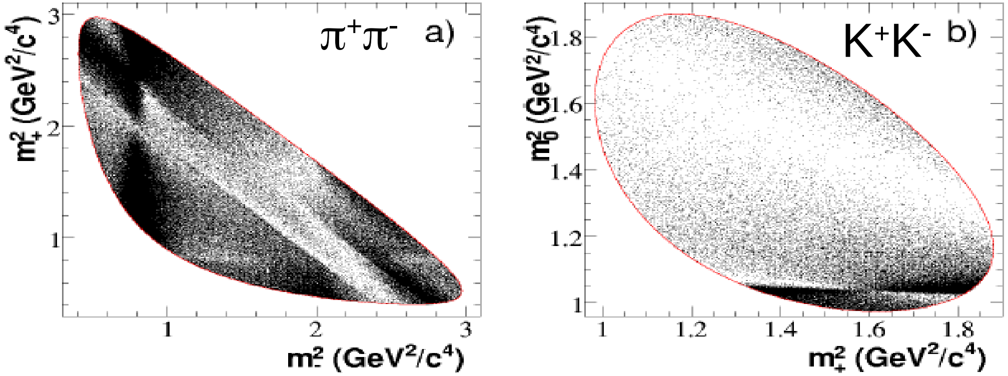
$$A(B^\pm \to (K^0_S h^+ h^-)_D K^\pm) \propto f(m_+^2, m_-^2) + f(m_-^2, m_+^2) r_B e^{i(\delta_B \pm \gamma)}$$

where

$$m_\pm = m_{K^0_S h^\pm}$$

  - Need detailed model of the amplitudes in the D meson Dalitz plot.
    - Use a control sample (CLEO-c data or $D^{*+} \to D^0\pi^+$) to measure the Dalitz plot.

$$D^{*+} \to D^0 \pi^-$$
$$\hookrightarrow D^0 \to K^0_S h^+ h^-$$

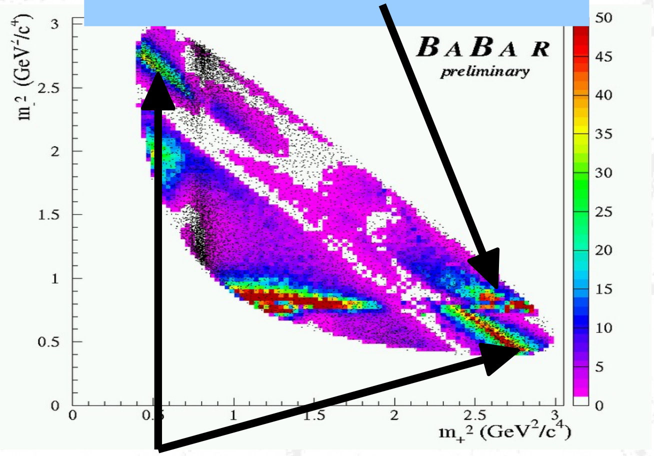


Control sample plots from BaBar GGSZ paper

γ: GGSZ Method

- ◎ neutral D mesons reconstructed in three-body CP-eigenstate final states (typically $D^0 \rightarrow K_S\pi^-\pi^+$)
- ◎ the complete structure (amplitude and strong phases) of the D^0 decay in the phase space is obtained on independent data sets and used as input to the analysis
- ◎ use of the cartesian coordinate:
  - ◉ $x_\pm = r_B \cos(\delta \pm \gamma)$
  - ◉ $y_\pm = r_B \sin(\delta \pm \gamma)$
- ◎ γ , r_B and δ_B are obtained from a simultaneous fit of the $K_S\pi^+\pi^-$ Dalitz plot density for B^+ and B^-
- ◎ need a model for the Dalitz amplitudes
- ◎ 2-fold ambiguity on γ

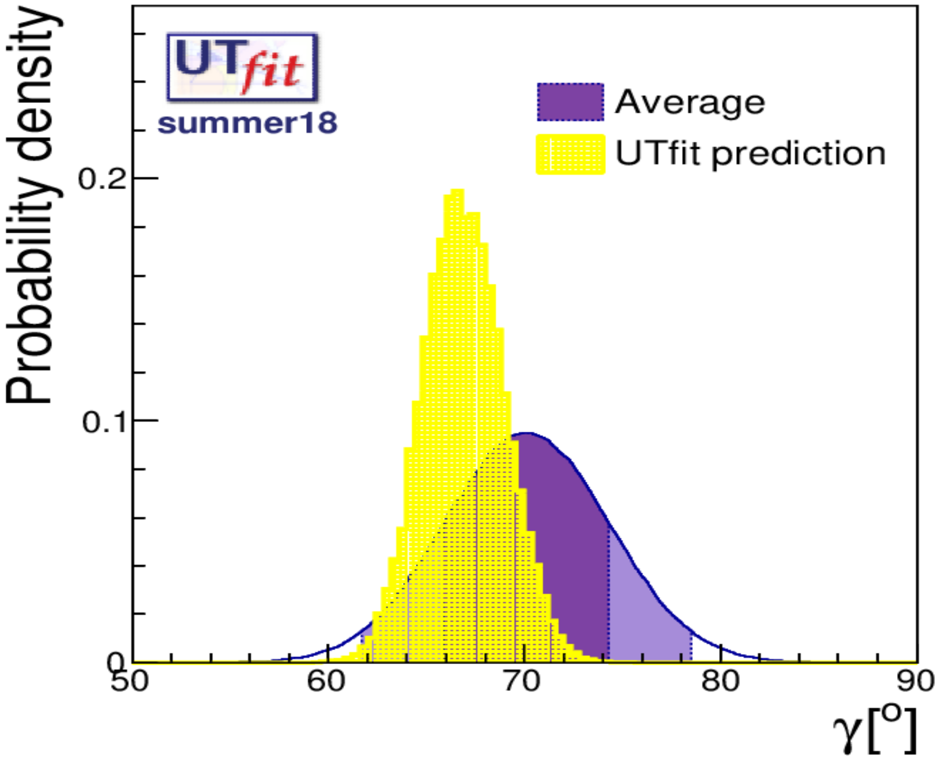
Interference of
$B^- \rightarrow D^0K^-$, $D^0 \rightarrow K^{*+}\pi^-$ (suppressed) with
$B^- \rightarrow D^0K^-$, $D^0 \rightarrow K^{*+}\pi^-$
~ ADS like



Interference of
$B^- \rightarrow D^0K^-$, $D^0 \rightarrow K^0_S\rho^0$ with
$B^- \rightarrow D^0K^-$, $D^0 \rightarrow K^0_S\rho^0$
~ GLW like

$\gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$

CP violation: γ



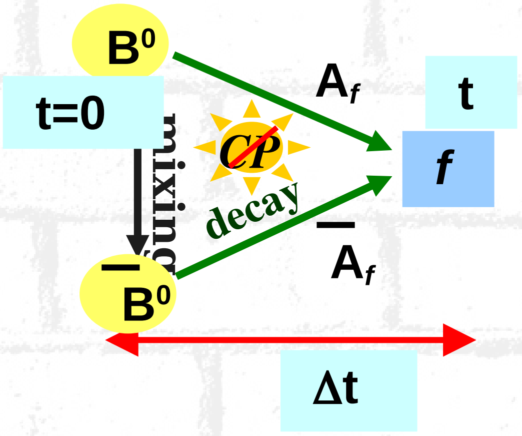
γ from B into DK decays:

combined: (73.4 ± 4.4)°

UTfit prediction: (65.8 ± 2.2)°

CP violation in interference between mixing and decay:

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$



◎ decays in final state *f* accessible to both a B or a $\bar{B}$ (*f* is not necessarily a CP eigenstate)

◎ if Im$\lambda \neq 0$ then → CP violation

$$\lambda = \frac{q}{p}\frac{A(\bar{B} \to f)}{A(B \to f)} = \frac{V_{td}^* V_{tb}}{V_{td} V_{tb}^*}\frac{\bar{A}}{A} \sim e^{-i2\beta}\frac{\bar{A}}{A}$$

β is the mixing phase

examples

	f	Arg($\frac{\bar{A}}{A}$)	$\lvert\lambda\rvert$	parameter
mixing	$B^0 \to l\nu X, D^{(*)}\pi(\rho, a_1)$	0	~ 0	ΔM_{B^0}
"sin 2β"	$B^0 \to J/\psi K^0, \ldots$	0	1	$\sin 2\beta$
"sin 2α"	$B^0 \to \pi\pi, \rho\pi, \pi\pi\pi$	$\sim(-2\gamma)$	~ 1	$\sin 2\alpha$
"sin(2β + γ)"	$B^0 \to D^{(*)}\pi$	$\sim(-\gamma)$	~ 0.02	$\sin(2\beta + \gamma)$

$B\bar{B}$ pair coherent production

◎ The B^0 and $\bar{B}^0$ mesons from the $\Upsilon(4S)$ are in a coherent L = 1 state:

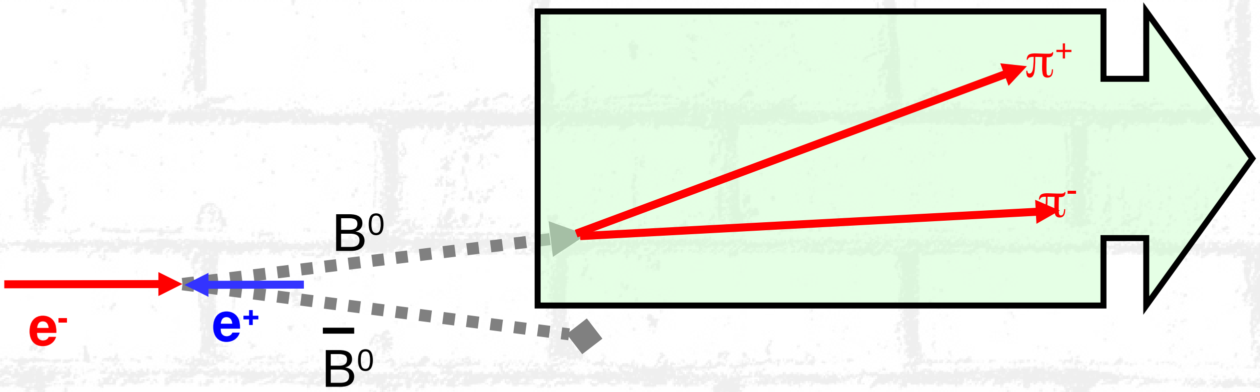
- ◉ The $\Upsilon(4S)$ is a $b\bar{b}$ state with **$J^{PC} = 1^{--}$**.
- ◉ B mesons are scalars (**$J^P = 0^-$**)
  - ⇨ total angular momentum conservation
  - ⇨ the $B\bar{B}$ pair has to be produced in a **L = 1 state**.

◎ The $\Upsilon(4S)$ decays strongly so B mesons are produced in the two flavour eigenstates B^0 and $\bar{B}^0$:

- ◉ After production, each B evolves in time, but **in phase** so that at any time there is always exactly one B^0 and one $\bar{B}^0$ present, at least until one particle decays:
  - ⇨ If at a given time t one B could oscillate independently from the other, they could become a state made up of two identical mesons: but the L = 1 state is anti-symmetric, while a system of **two identical mesons (bosons!)** must be completely symmetric for the two particle exchange.

◎ Once one B decays the other continues to evolve, and so it is possible to have events with **two B or two $\bar{B}$ decays.**

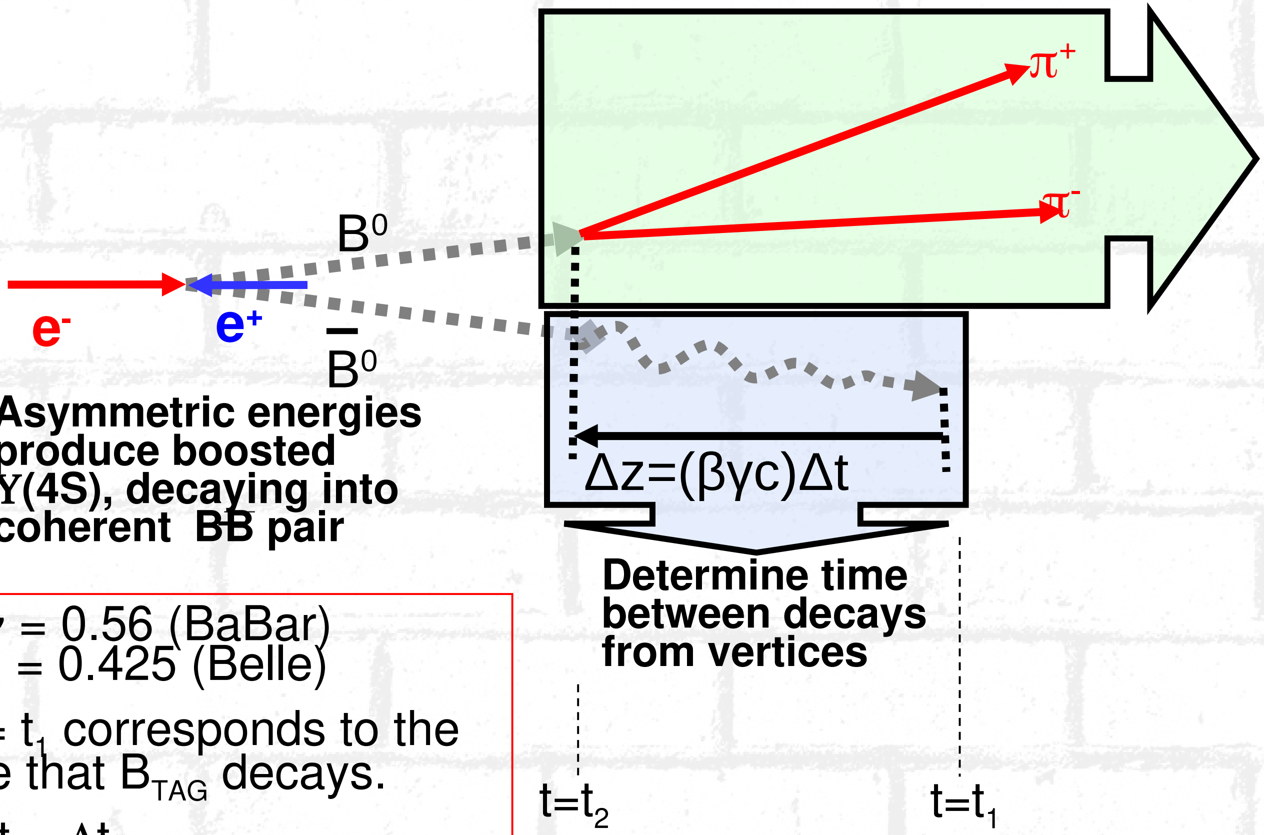
Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

Measuring Δt



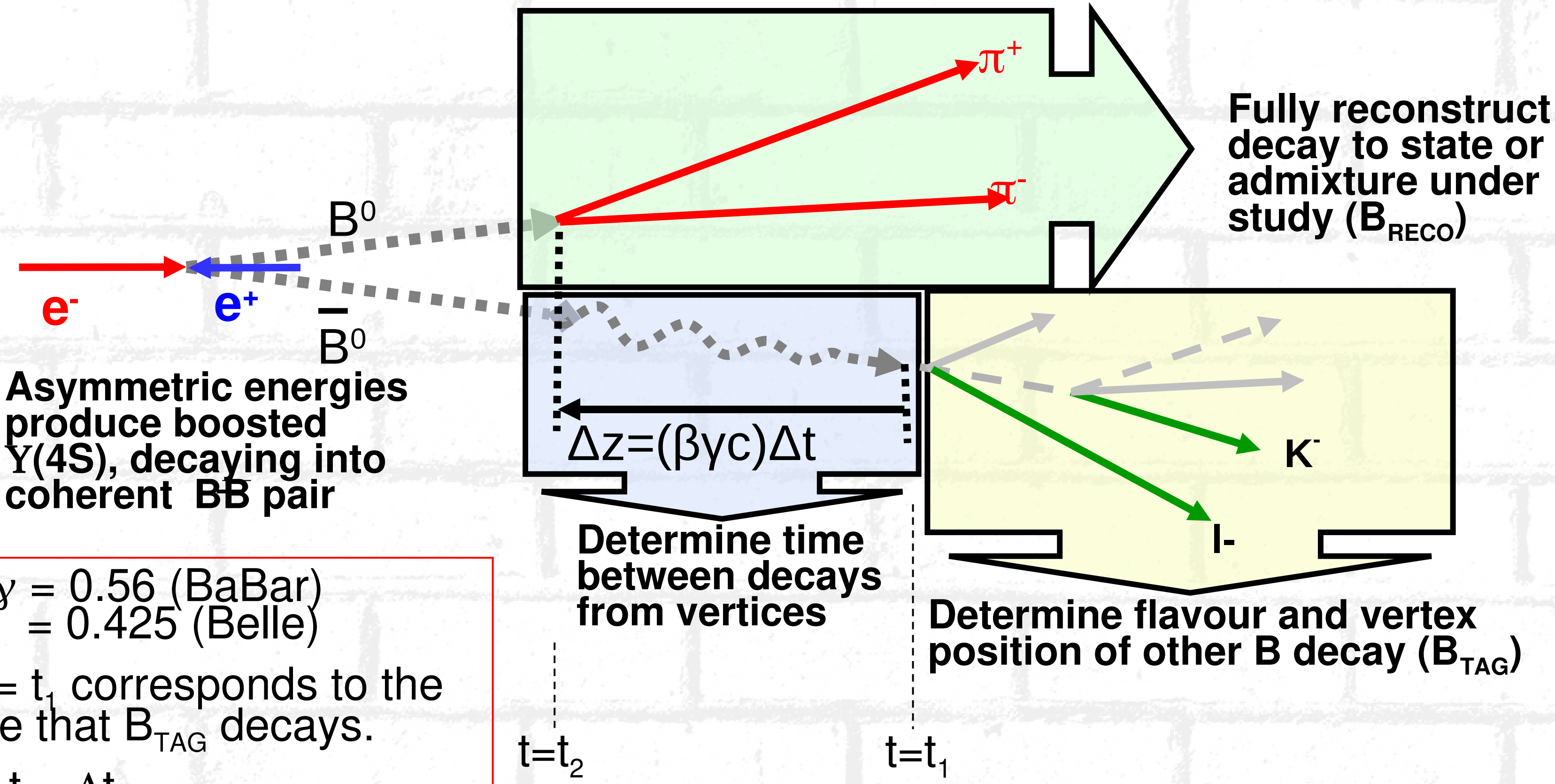
Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- t = t_1 corresponds to the time that B_{TAG} decays.
- t_2-t_1= Δt

Measuring Δt



- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

⇨ Then fit the Δt distribution to obtain the amplitude of sine and cosine terms.

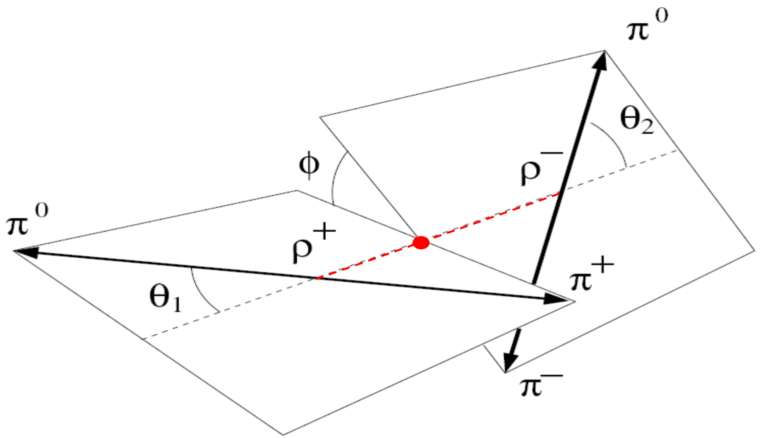
B → ρρ

- (simplified) angular analysis
- Inputs from:

$B^0 \rightarrow \rho^+\rho^-$

$B^+ \rightarrow \rho^+\rho^0$

$B^0 \rightarrow \rho^0\rho^0$



θ_i are the helicity angles: angles between the π^0 momentum and the direction opposite to that of the B^0 in the vector rest frame.

ϕ is the angle between the vector meson decay planes.

- We define the fraction of longitudinally polarised events as:

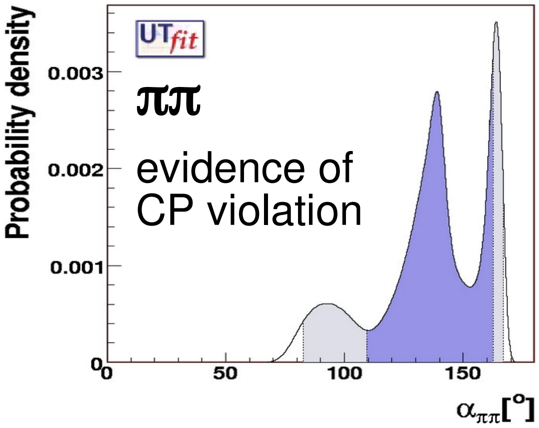
$$\frac{\Gamma_L}{\Gamma} = \frac{|H_0|^2}{|H_0|^2 + |H_{+1}|^2 + |H_{-1}|^2}, = f_L.$$

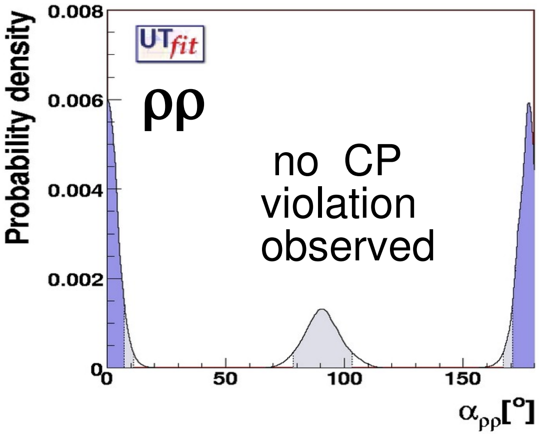
- $$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4}(1-f_L)\sin^2\theta_1 \sin^2\theta_2\right]$$
- Can measure S^{00} as well as C^{00} to help resolve ambiguities.
- Finite width of the ρ is ignored in the α determination

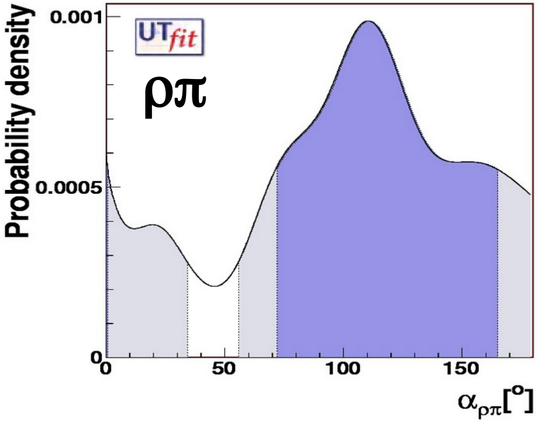
$\alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$

CP violation: α

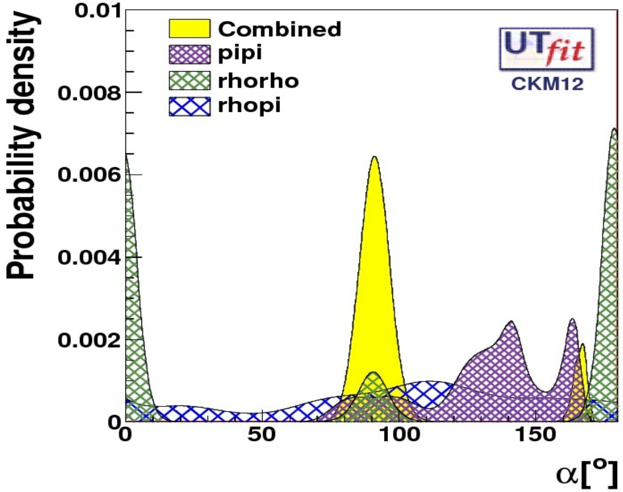
◎ Combining all the modes to maximize our knowledge of α..







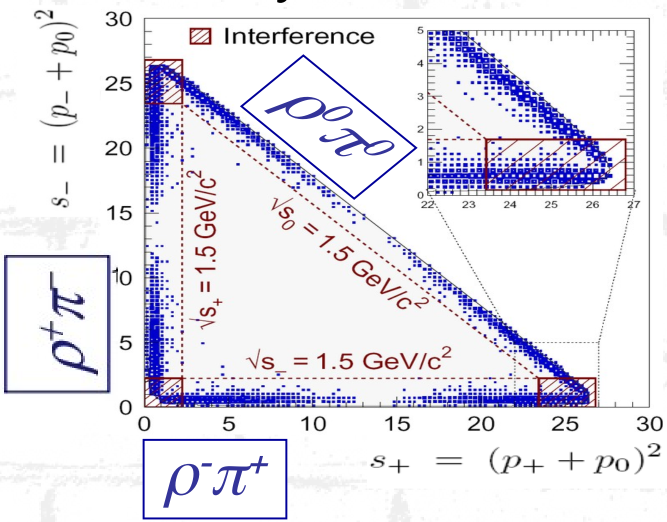
bayesian analysis:
the quantity plotted is now the Probability Density Function (PDF)

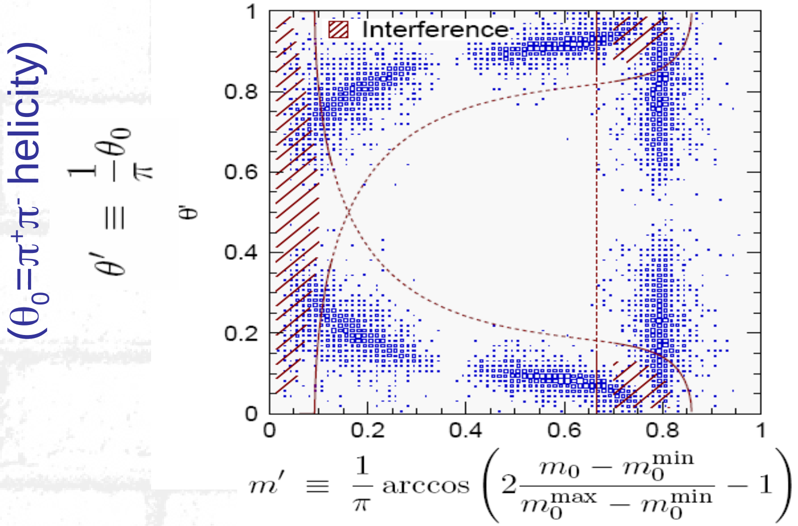


α_{SM} = (92 ± 7)°

B → ρπ ($\pi^+\pi^-\pi^0$ Dalitz Plot)

◎ Analyse a transformed Dalitz Plot to extract parameters related to α.
◎ Use the Snyder-Quinn method.





◎ Fit the time-dependence of the amplitudes in the Dalitz plot:

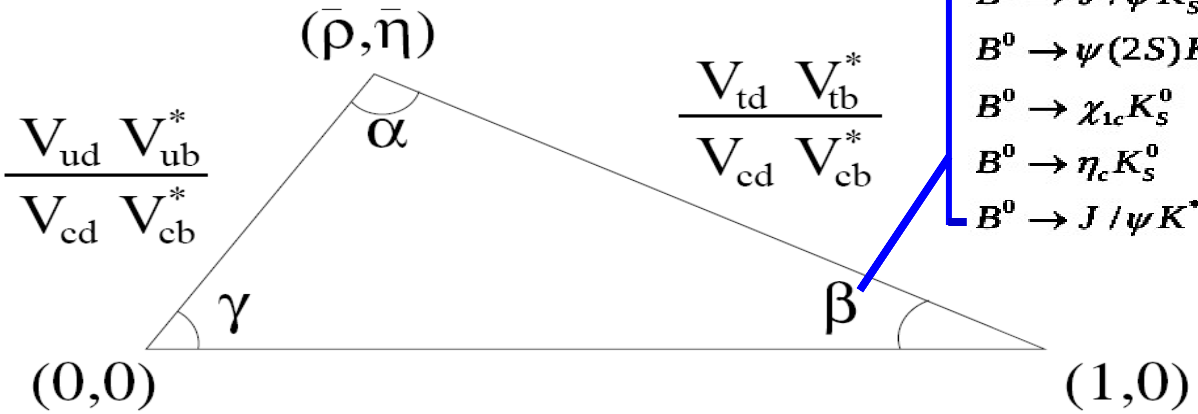
$$|\mathcal{A}_{3\pi}^{\pm}(\Delta t)|^2 = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[|\mathcal{A}_{3\pi}|^2 + |\overline{\mathcal{A}}_{3\pi}|^2 \mp \left(|\mathcal{A}_{3\pi}|^2 - |\overline{\mathcal{A}}_{3\pi}|^2\right)\cos(\Delta m_d \Delta t) \pm 2\mathrm{Im}\left[\overline{\mathcal{A}}_{3\pi}\mathcal{A}_{3\pi}^{*}\right]\sin(\Delta m_d \Delta t)\right],$$

β/ϕ_1 angle [recap]

Theoretically cleaner (SM uncertainties ~10^{-2} to 10^{-3})

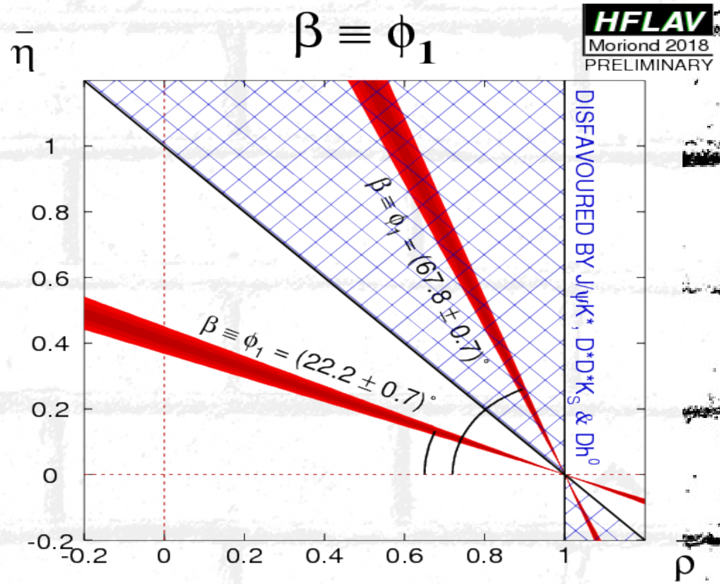
→ tree dominated decays to Charmonium + K^0 final states.

$$\beta \equiv \arg\left[-V_{cd}V_{cb}^{*}/V_{td}V_{tb}^{*}\right]$$



$b \to c\bar{c}s$

- $B^0 \to J/\psi K_L^0$
- $B^0 \to J/\psi K_S^0$
- $B^0 \to \psi(2S) K_S^0$
- $B^0 \to \chi_{1c} K_S^0$
- $B^0 \to \eta_c K_S^0$
- $B^0 \to J/\psi K^{*0}$



$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

α/ϕ_2 angle [recap]

$$\alpha \equiv \arg\left[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}\right]$$

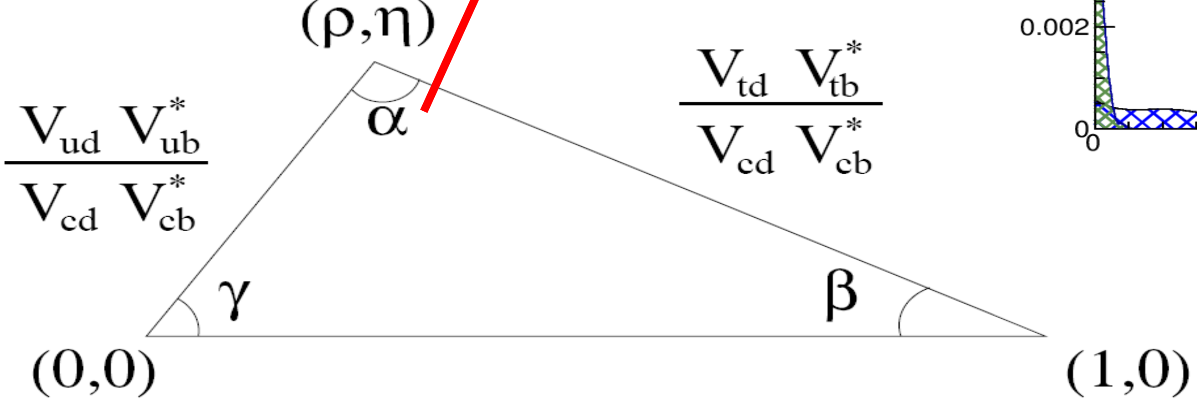
b → uūd transitions with possible loop contributions. Extract α using
- SU(2) Isospin relations.
- SU(3) flavour related processes.

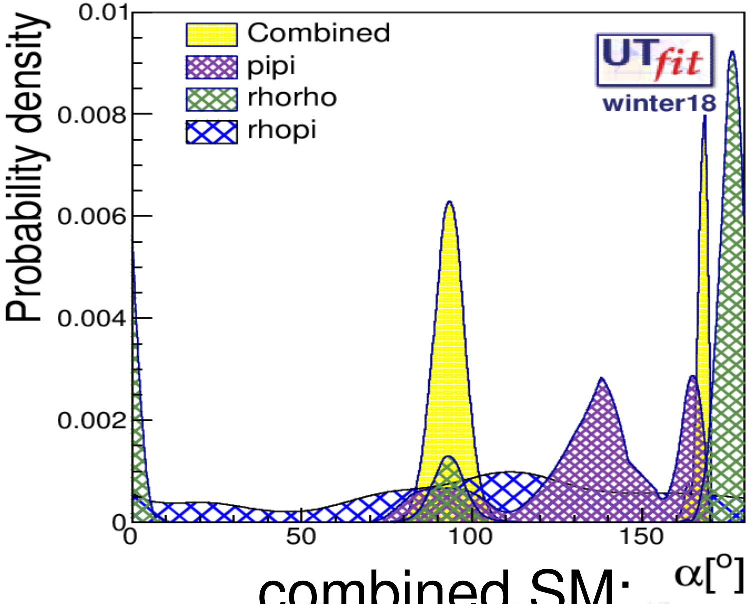
$b \to u\bar{u}d$

$B \to \pi\pi$

$B \to \rho\pi$

$B \to \rho\rho$





combined SM:

$\alpha = (93.3 \pm 5.6)^\circ$

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f_{CP}) - \Gamma(B^0(t) \to f_{CP})}{\Gamma(\bar{B}^0(t) \to f_{CP}) + \Gamma(B^0(t) \to f_{CP})}$$

γ/ϕ_3 angle

$$\gamma \equiv \arg\left[-V_{ud}V^*_{ub}/V_{cd}V^*_{cb}\right]$$

$b \to c$ interfering with $b \to u$

$B \to D^{(*)}K^{(*)}$

$B^0 \to D^- K^0 \pi^+$

$B^0 \to D^{(*)}\pi$

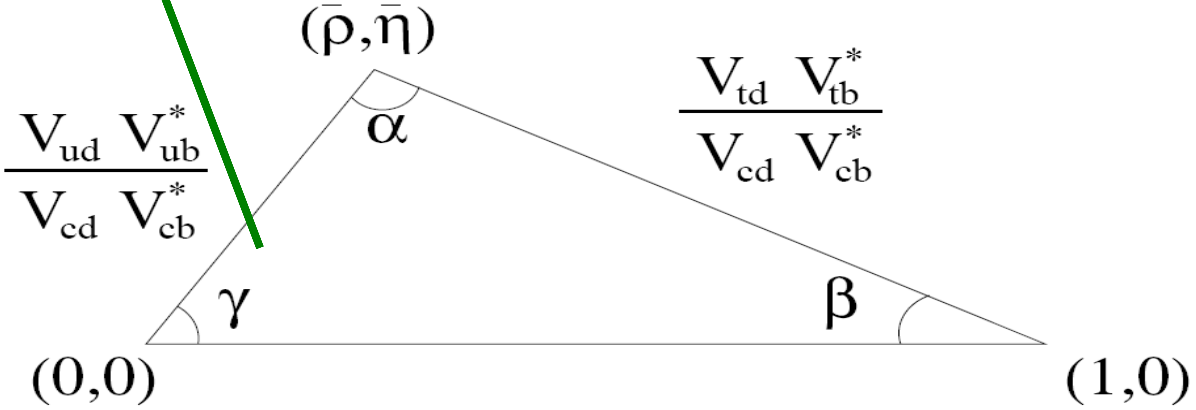
$B^0 \to D^{(*)}\rho$

+ *charmless*

Extract γ using $B \to D^{(*)}K^{(*)}$ final states using:

- GLW: Use CP eigenstates of D^0.
- ADS: Interference between doubly suppressed decays.
- GGSZ: Use the Dalitz structure of $D \to K_s h^+ h^-$ decays.

Measurements using neutral D mesons ignore D mixing.



Sides of the Unitarity Triangle

Sides of the Unitarity Triangle

$b \to ul\nu$

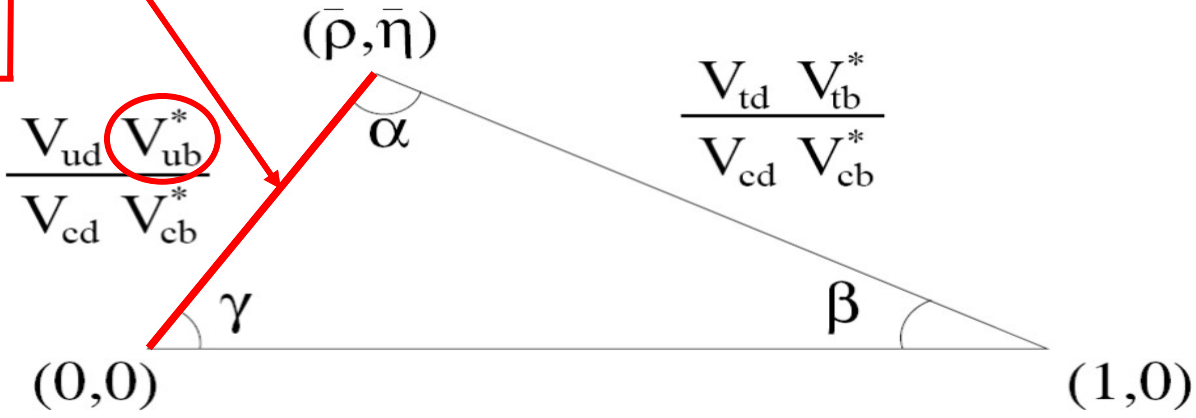
$B \to \pi l\nu$

$B \to X_u l\nu$

$B \to \rho l\nu$

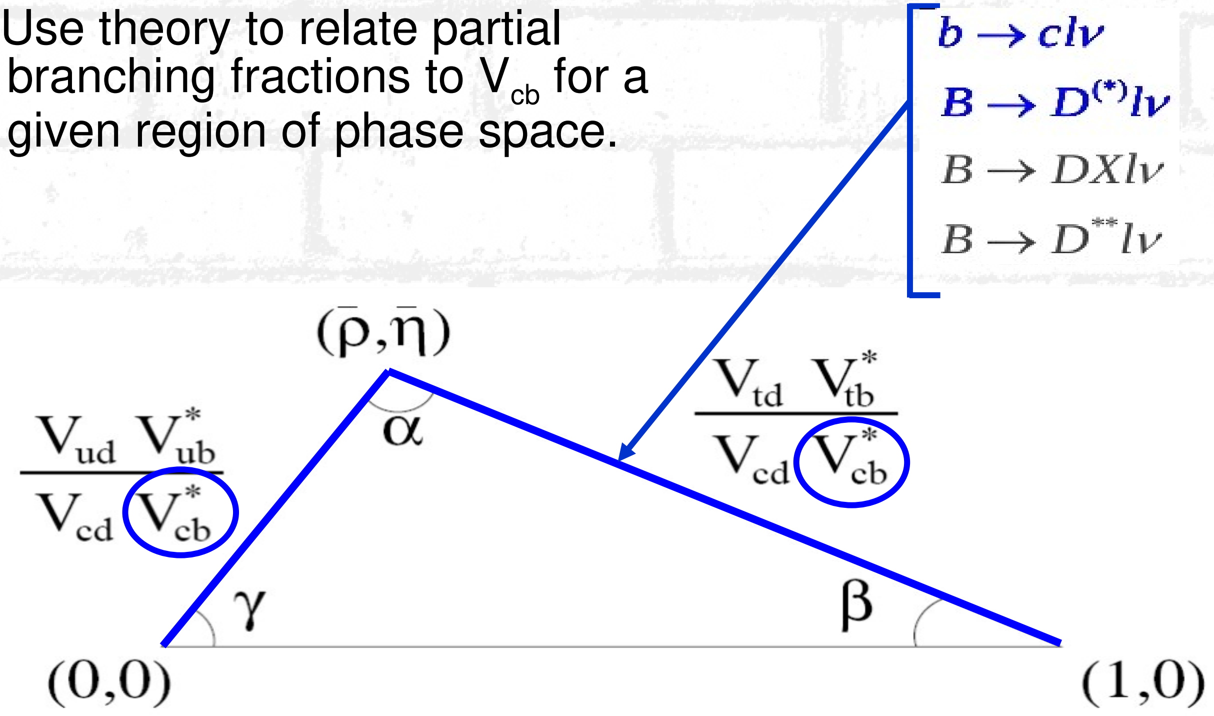
$B \to \omega l\nu$

- Use theory to relate partial branching fractions to V_{ub} for a given region of phase space.
- Several theoretical schemes available.



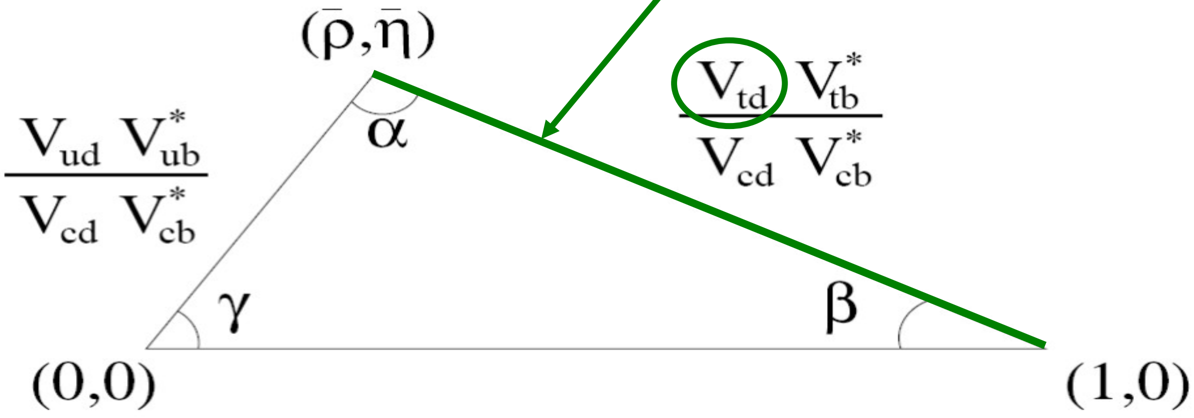
Sides of the Unitarity Triangle

- Use theory to relate partial branching fractions to V_{cb} for a given region of phase space.



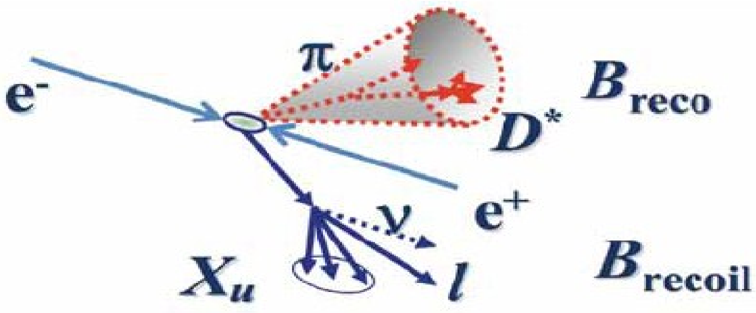
Sides of the Unitarity Triangle

V_{td} is linked to the B^0 mixing (box) diagram so to the B^0 oscillation parameter Δm_d



Side measurement: V_{ub}

- $|V_{ub}| \propto BR(B \to X_u l\nu)$ in a limited region of phase space.



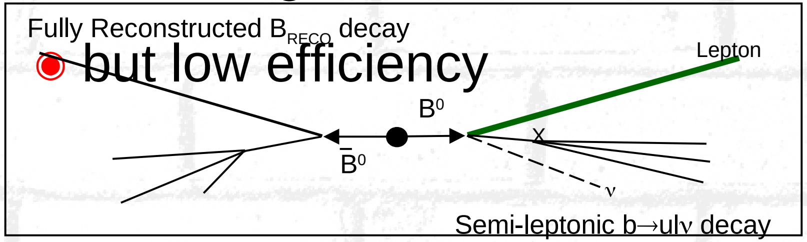
- Reconstruct both B mesons in an event.
  - Study the B_{recoil} to measure V_{ub}.
  - Measure BR as a function of

    $$q^2_{l\nu},\ m_X,\ m_{MISS} \text{ or } E_l$$

    and use theory to convert these results into $|V_{ub}|$.
- Can study modes exclusively or inclusively.
- Several models available to estimate $|V_{ub}|$
  - The resulting values have a significant model uncertainty.

Exclusively reconstructed $b \to u l \nu$

- If we fully reconstruct one B meson in an event, then …
- … with a single ν in the event, we can infer P^{ν} and 'reconstruct' the ν
- Clean signals
- but low efficiency



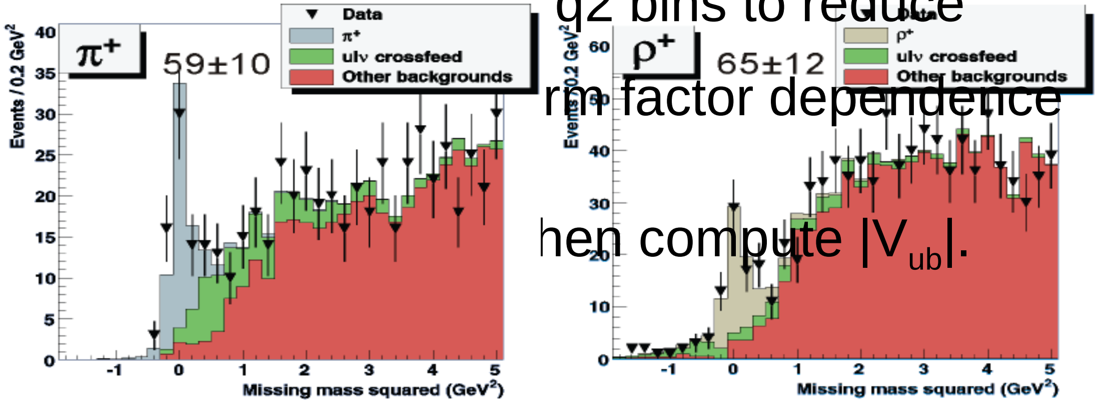
Use the beam energy to constrain P^{ν} to effectively 'reconstruct' the ν from the missing energy-momentum: $m_{MISS} = m_{\nu} = 0$.

- Study B decays to:

$$B^0 \to \pi^- l^+ \nu$$
$$B^0 \to \rho^- l^+ \nu$$
$$B^+ \to \pi^0 l^+ \nu$$
$$B^+ \to \rho^0 l^+ \nu$$
$$B^+ \to \omega l^+ \nu$$

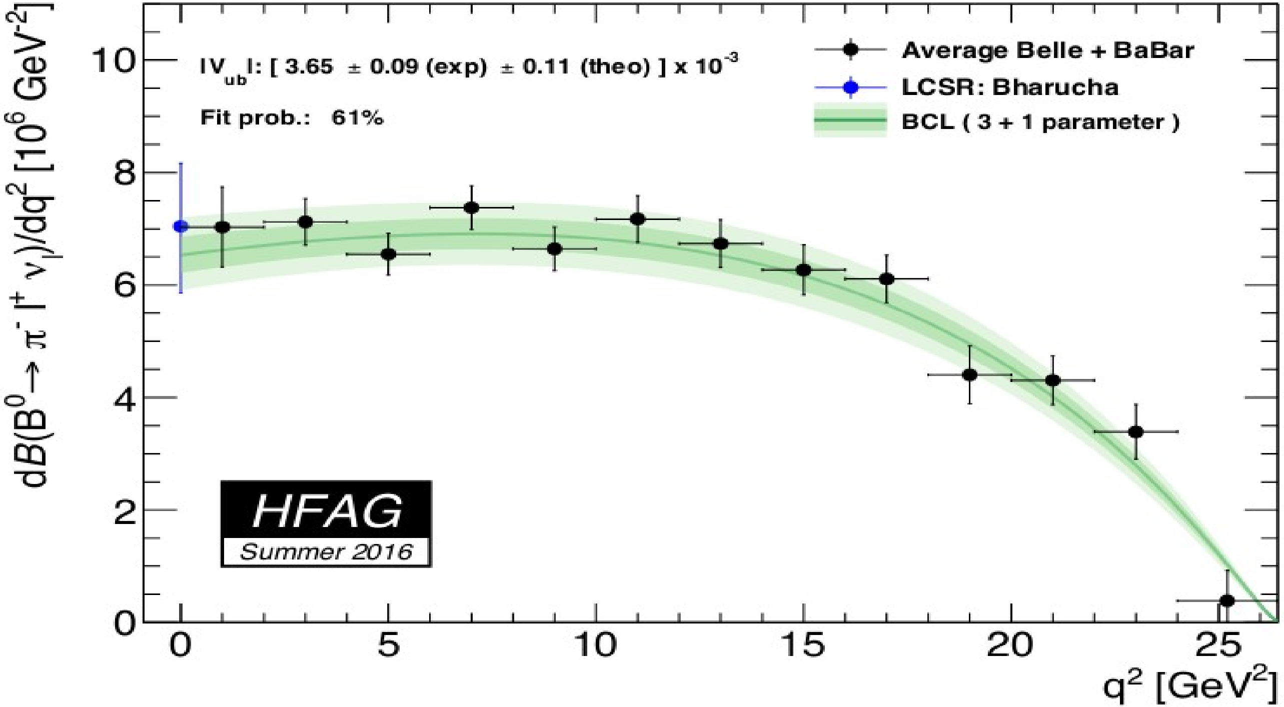
- Fully reconstruct B_{RECO}
- tagged or untagged for the second B
- Extract yields from m^2_{MISS} in q2 bins to reduce rm factor dependence

hen compute $|V_{ub}|$.



V_{ub}: Using q^2 distribution

$$\frac{d\Gamma(B \to \pi l \nu)}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ub}|^2 \; p_\pi^3 \; |f(q^2)|^2$$



$|V_{ub}|$ is determined from a combined fit of a B → π form factor parameterization to theory predictions and the average q^2 spectrum in data.

Form factor input:

- Low q^2 region (< 6-7 GeV^2): Light cone sum rules, unperturbative, at $q^2 = 0$
- Intermediate to high q^2 region (>14 GeV^2): LQCD, unquenched.

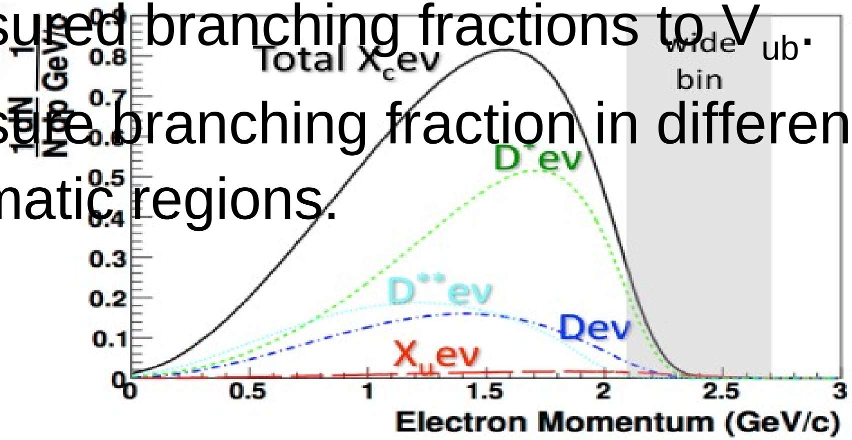
From the fit (in 10^{-3}):

$|V_{ub}| = (3.65 \pm 0.09 \pm 0.11)$

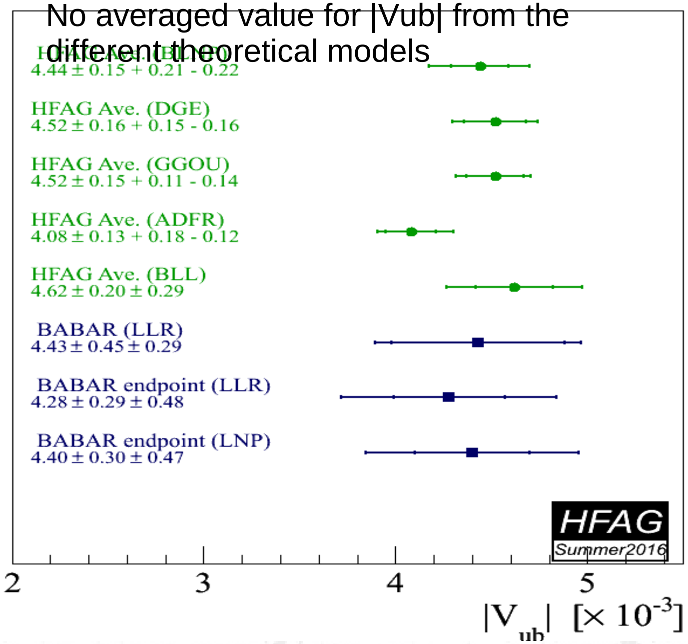
uncertainty 14%

V_{ub}: inclusive analysis

- Treat B meson decay like a free b quark (+corrections)
- High background from clν decays.
  - Kinematic cuts are used to suppress background.
- Use Operator Product Expansions to translate measured branching fractions to V_{ub}.
- Measure branching fraction in different kinematic regions.



The following theoretical calculations are used to extract |Vub|:
BLNP [arXiv:hep-ph/0504071v3]
DGE [arXiv:hep-ph/0509360v2].
Recent update: [arXiv:0806.4524]
GGOU [arXiv:0707.2493].
ADFR [arXiv:0711.0860]
BLL [arXiv:hep-ph/0107074v1]
No averaged value for |Vub| from the different theoretical models



Side measurements: V_{cb}

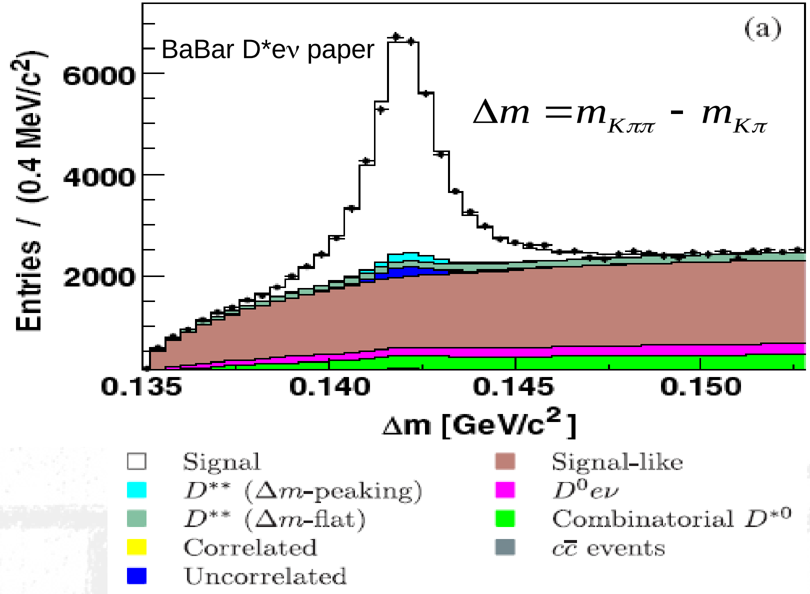
◎ Use the differential decay rates of $B \to D^* l\nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \to D^* l^- \bar{\nu})}{d\omega\, d\cos\theta_l\, d\cos\theta_V\, d\chi} \propto F^2(\omega, \theta_l, \theta_V, \chi)\,|V_{cb}|^2$$

- F is a form factor.
- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.

- Reconstruct

$$B^- \to D^{*0} e^- \bar{\nu}_e$$
$$D^{*0} \to D\pi$$
$$D \to K^+\pi^-$$



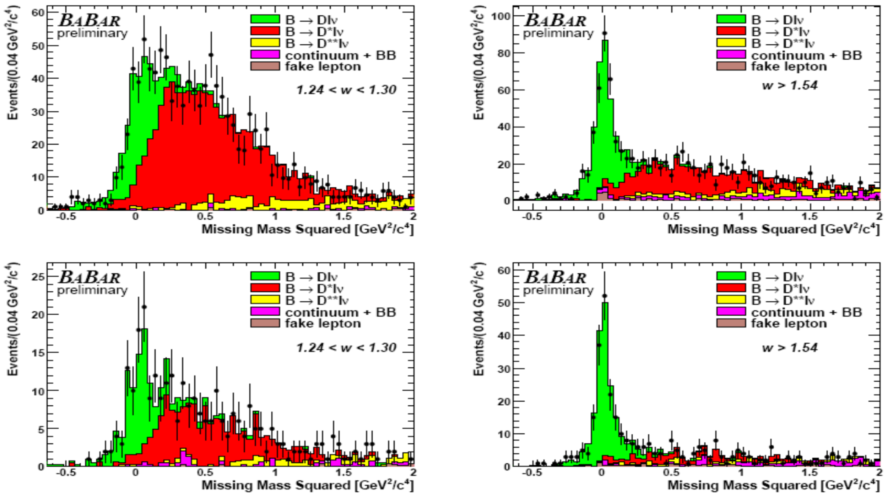
- Measurement is not statistically limited, so use clean signal mode for $D \to K\pi$ decay only.
- Extract signal yield, $F(1)|V_{cb}|$ and ρ from 3D binned fit to data.

Side measurements: V_{cb}

◎ Use the differential decay rates of $B \to Dl\nu$ to determine $|V_{cb}|$:

$$\frac{d\Gamma(\bar{B} \to D l^- \bar{\nu})}{d\omega \, d\cos\theta_l \, d\cos\theta_V \, d\chi} \propto G^2(\omega) |V_{cb}|^2$$

- Use a sample of fully reconstructed tag B mesons, then look for the signal.
- Improves background rejection, at the cost of signal efficiency.

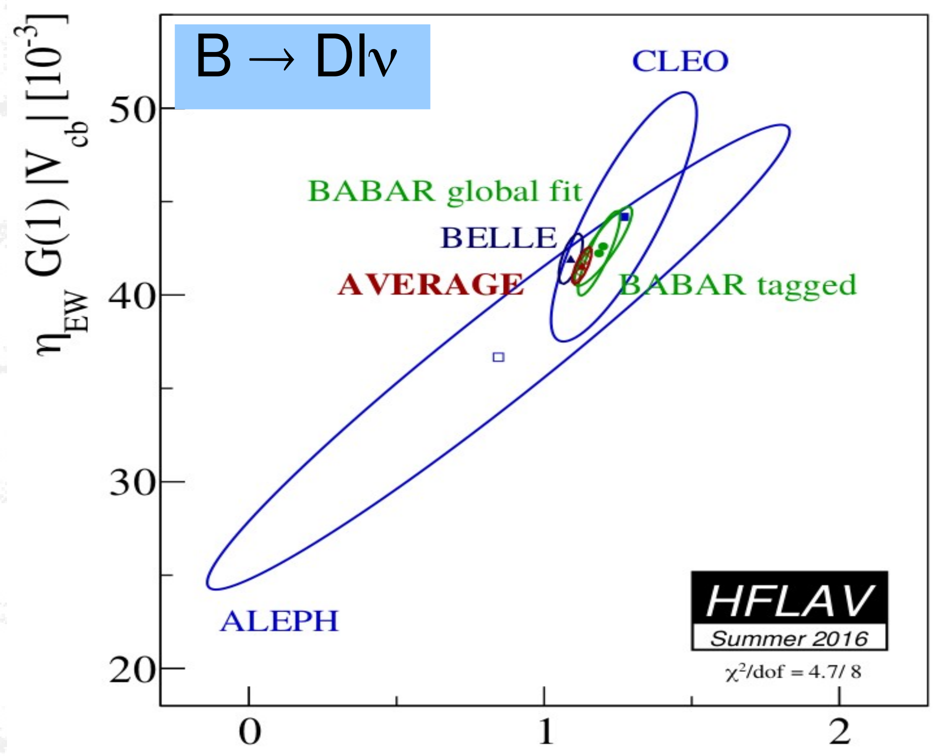


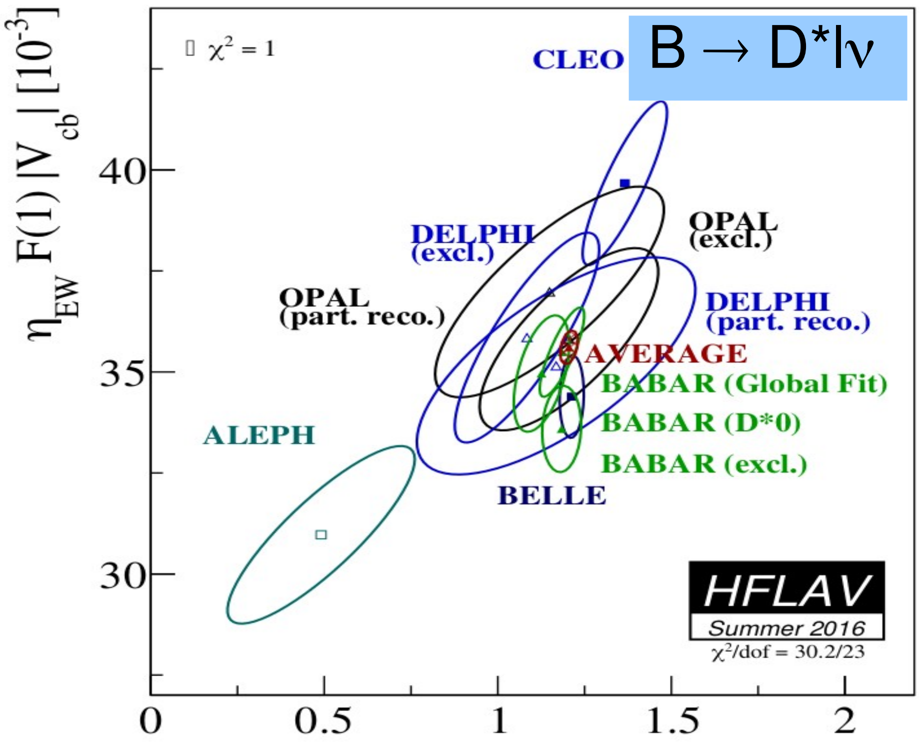
ω is related to q^2 of the B meson to the D

- G is a form factor.
- Need theoretical input to relate the differential rate measurement to $|V_{cb}|$.
- Reconstruct the following D decay channels:

$D^0 \to K^-\pi^+$	$D^+ \to K^-\pi^+\pi^+$
$K^-\pi^+\pi^0$	$K^-\pi^+\pi^+\pi^0$
$K^-\pi^+\pi^-\pi^+$	$K^0_S\pi^+$
$K^0_S\pi^+\pi^-$	$K^0_S\pi^+\pi^0$
$K^0_S\pi^+\pi^-\pi^0$	$K^+K^-\pi^+$
$K^0_S\pi^0$	$K^0_S K^+$
K^+K^-	$K^0_S\pi^+\pi^+\pi^-$
$\pi^+\pi^-$	
$K^0_S K^0_S$	

Exclusive $|V_{cb}|$





$G(1)|V_{cb}| = (42.3 \pm 1.5)\ 10^{-3}$ ρ^2

$|V_{cb}| = (39.4 \pm 1.7)\ 10^{-3}$

$F(1)|V_{cb}| = (36.0 \pm 0.5)\ 10^{-3}$ ρ^2

$|V_{cb}| = (39.0 \pm 1.1)\ 10^{-3}$

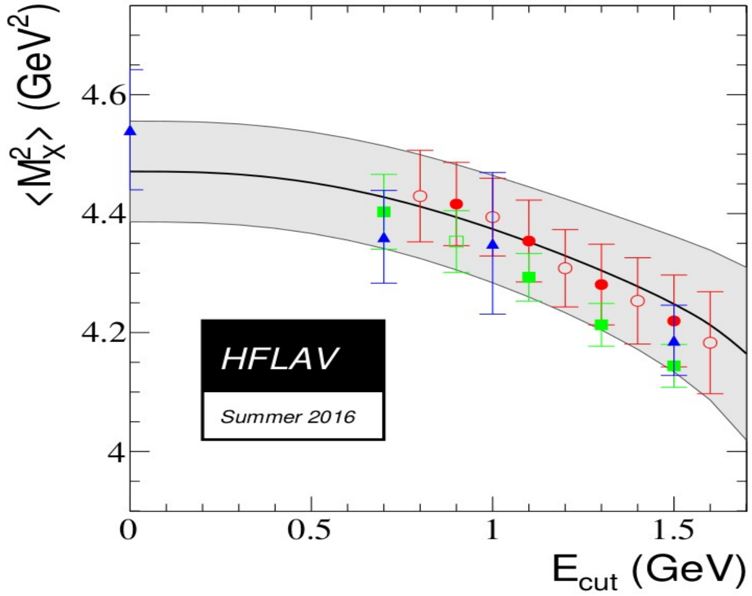
Inclusive $|V_{cb}|$

At parton level, the decay rate for $b \to c l \nu$ can be calculated accurately and is proportional to $|V_{cb}|^2$

To relate measurements of semileptonic B-meson decays to $|V_{cb}|^2$ the parton-level expressions have to be corrected for the effects of non-perturbative effects.

Heavy-Quark-Expansions (HQE) successful tool to incorporate perturbative and nonperturbative QCD corrections.

$$\Gamma_{sl} = \Gamma_0 \Big[1 + a^{(1)} \frac{\alpha_s(m_b)}{\pi} + a^{(2,\beta_0)} \beta_0 \left(\frac{\alpha_s}{\pi}\right)^2 + a^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \left(-\frac{1}{2} + p^{(1)} \frac{\alpha_s}{\pi}\right) \frac{\mu_\pi^2}{m_b^2} + \left(g^{(0)} + g^{(1)} \frac{\alpha_s}{\pi}\right) \frac{\mu_G^2(m_b)}{m_b^2} + d^{(0)} \frac{\rho_D^3}{m_b^3} - g^{(0)} \frac{\rho_{LS}^3}{m_b^3} + \text{higher orders} \Big]$$



E.g. total decay rate expanded in the kinetic scheme

Determine the five parameters + $|V_{cb}|$ from a simultaneous fit to moments

From the fit (in 10^{-3}):

$|V_{cb}| = (42.19 \pm 0.78)$

uncertainty 2%

$|V_{cb}|$ and $|V_{ub}|$ in 2018

$|V_{cb}|$ *(excl)* = $(38.9 \pm 0.6)\ 10^{-3}$

$|V_{cb}|$ *(incl)* = $(42.19 \pm 0.78)\ 10^{-3}$

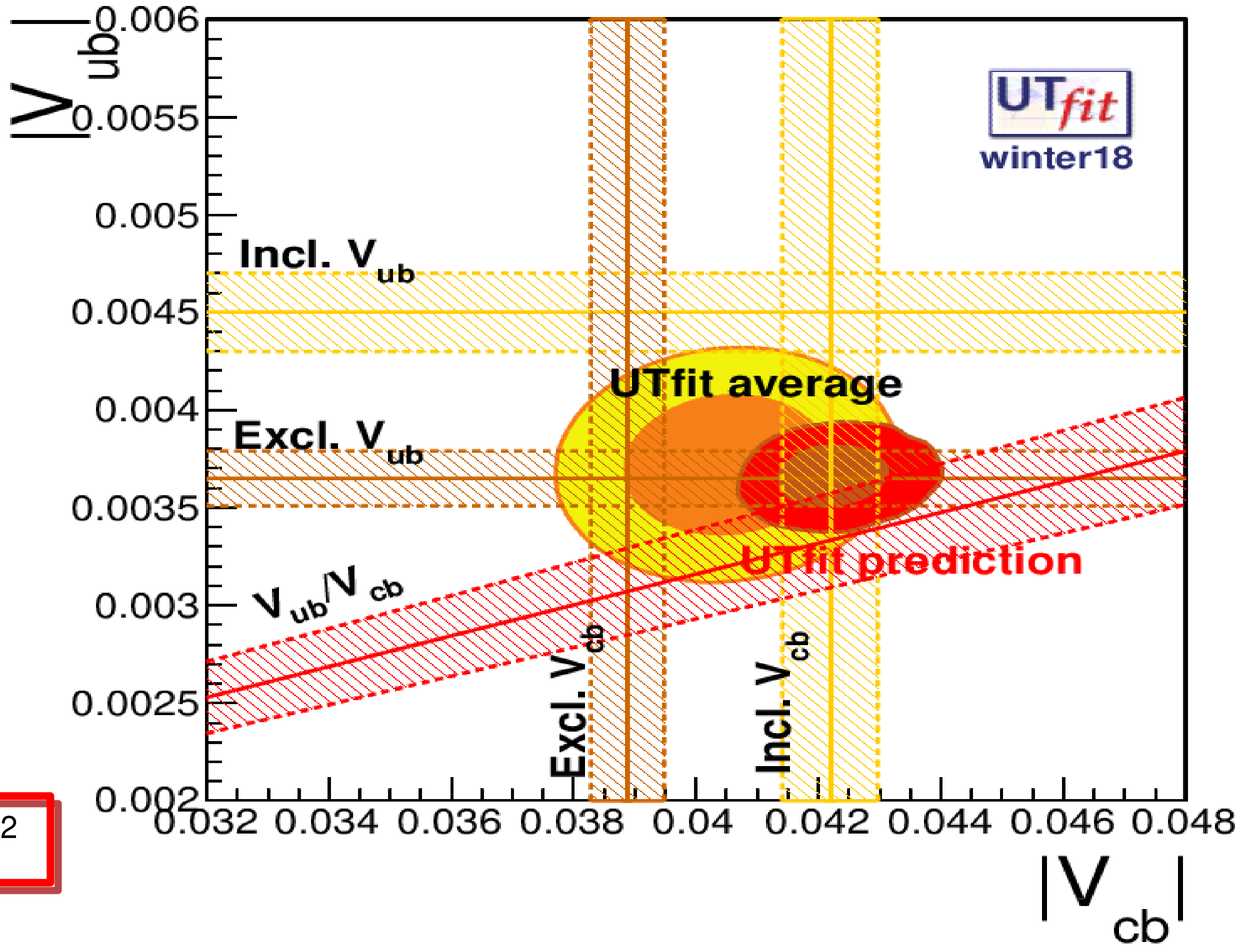
~3.3σ discrepancy

$|V_{ub}|$ *(excl)* = $(3.65 \pm 0.14)\ 10^{-3}$

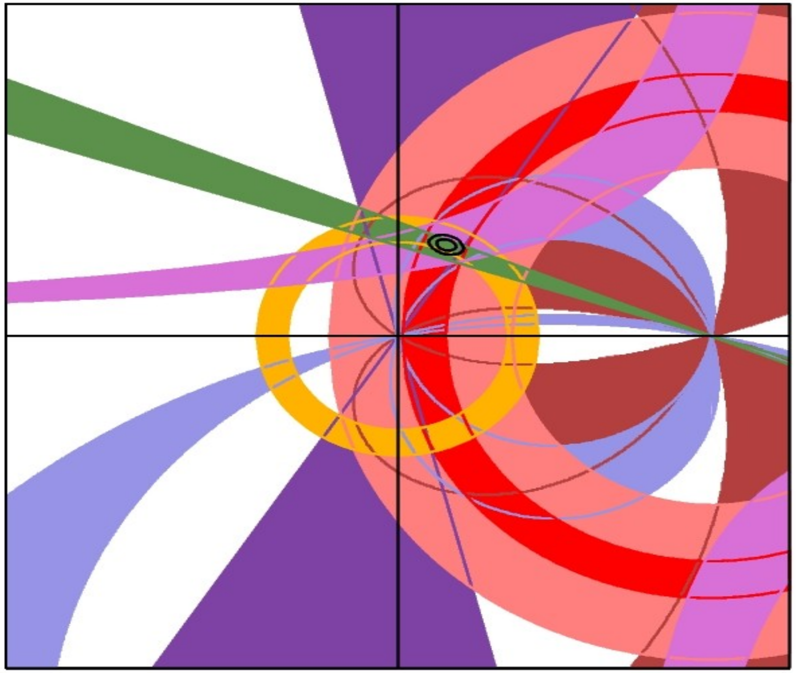
$|V_{ub}|$ *(incl)* = $(4.50 \pm 0.20)\ 10^{-3}$

~3.4σ discrepancy

$|V_{ub} / V_{cb}|$ *(LHCb)* = $(7.9 \pm 0.6)\ 10^{-2}$



Unitarity Triangle analysis



Unitarity Triangle analysis in the SM

- SM UT analysis:
  - provide the best determination of CKM parameters
  - test the consistency of the SM ("direct" vs "indirect" determinations)
  - provide predictions for future experiments (ex. $\sin 2\beta$, Δm_s, ...)

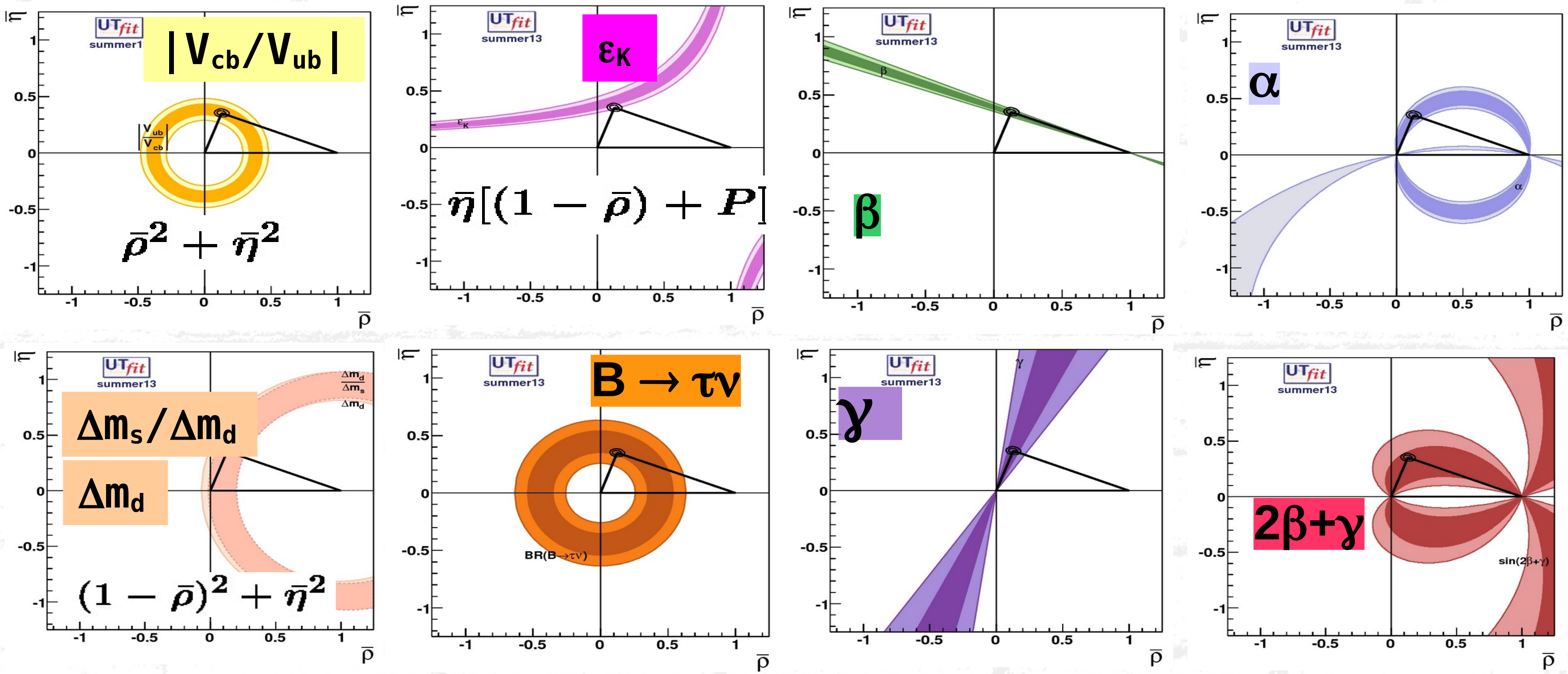
analysis from

UTfit

M. Bona *et al.* (UTfit)
JHEP0507:028, 2005

www.utfit.org

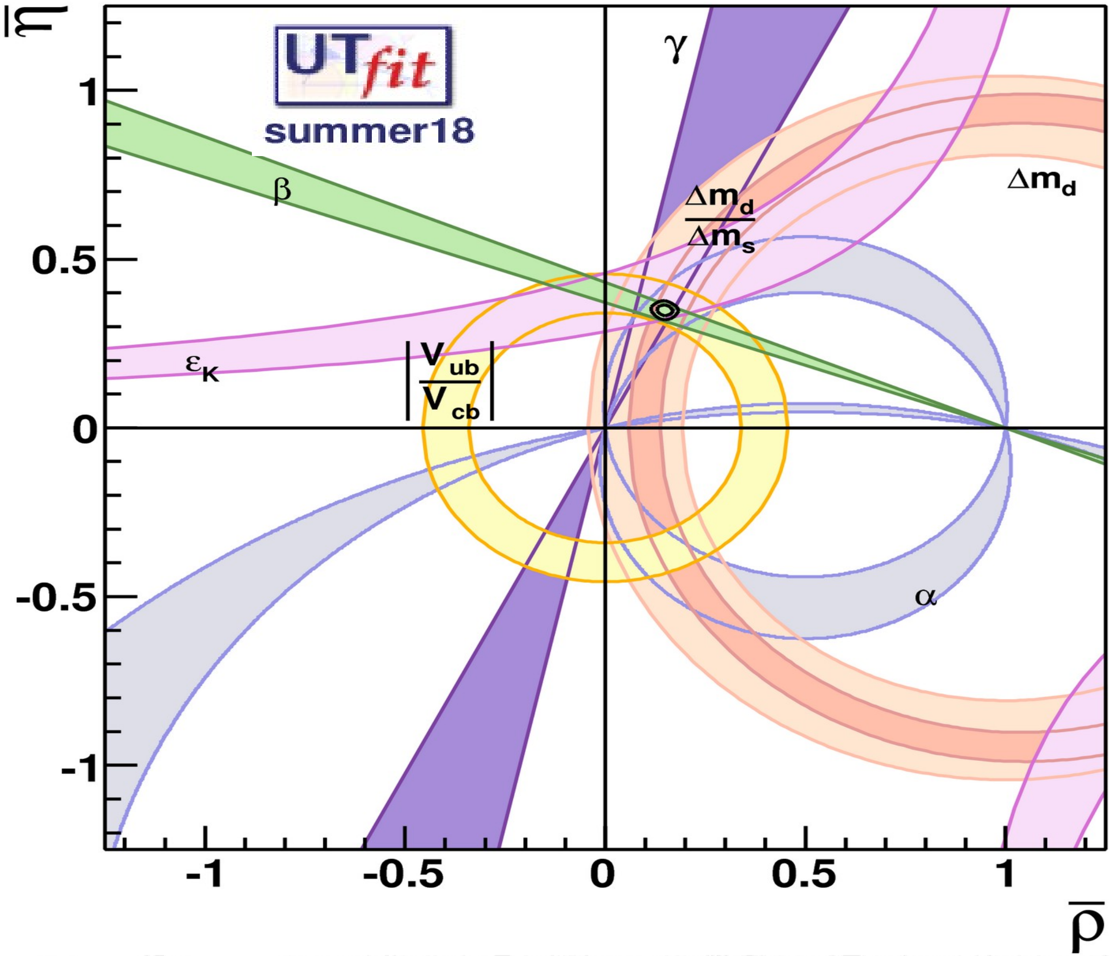
Unitarity Triangle analysis in the SM



Unitarity Triangle analysis in the SM

Observables	Accuracy
$\|V_{ub}/V_{cb}\|$	~ 7%
ε_K	~ 0.5%
Δm_d	~ 1%
$\|\Delta m_d/\Delta m_s\|$	~ 1%
$\sin 2\beta$	~ 3%
$\cos 2\beta$	~ 13%
α	~ 6%
γ	~ 6%

Unitarity Triangle analysis in the SM



levels @
95% Prob

~9%

$$\bar{\rho} = 0.148 \pm 0.013$$
$$\bar{\eta} = 0.348 \pm 0.010$$

~3%

analysis from
www.utfit.org

M. Bona *et al.* (UTfit)
JHEP0507:028, 2005

Unitarity Triangle analysis in the SM

obtained excluding the given constraint

Observables	Measurement	Prediction	Pull (#σ)
sin2β	0.689 ± 0.018	0.738 ± 0.033	~ 1.2
γ	73.4 ± 4.4	65.8 ± 2.2	< 1
α	93.3 ± 5.6	90.1 ± 2.2	< 1
$\|V_{ub}\| \cdot 10^3$	3.72 ± 0.23	3.66 ± 0.11	< 1
$\|V_{ub}\| \cdot 10^3$ (incl)	4.50 ± 0.20	-	~ 3.8
$\|V_{ub}\| \cdot 10^3$ (excl)	3.65 ± 0.14	-	< 1
$\|V_{cb}\| \cdot 10^3$	40.5 ± 1.1	42.4 ± 0.7	~ 1.4
BR($B \rightarrow \tau\nu$)[10^{-4}]	1.09 ± 0.24	0.81 ± 0.05	~ 1.2
$A_{SL}^d \cdot 10^3$	-2.1 ± 1.7	-0.292 ± 0.026	~ 1

Unitarity triangle fit beyond the SM

1. fit simultaneously for the CKM and the NP parameters (generalized UT fit)
   - add most general loop NP to all sectors
   - use all available experimental info
   - find out NP contributions to $\Delta F=2$ transitions

2. perform a $\Delta F=2$ EFT analysis to put bounds on the NP scale
   - consider different choices of the FV and CPV couplings

generic NP parameterization:

B_d and B_s mixing amplitudes
(2+2 real parameters):

$$C_{B_s} e^{-2i\phi_{B_s}} = \frac{\langle \overline{B}_s | H_{eff}^{SM} + H_{eff}^{NP} | B_s \rangle}{\langle \overline{B}_s | H_{eff}^{SM} | B_s \rangle} = 1 + \frac{A_{NP} e^{-2i\phi_{NP}}}{A_{SM} e^{-2i\beta_s}}$$

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}} = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$

Observables:

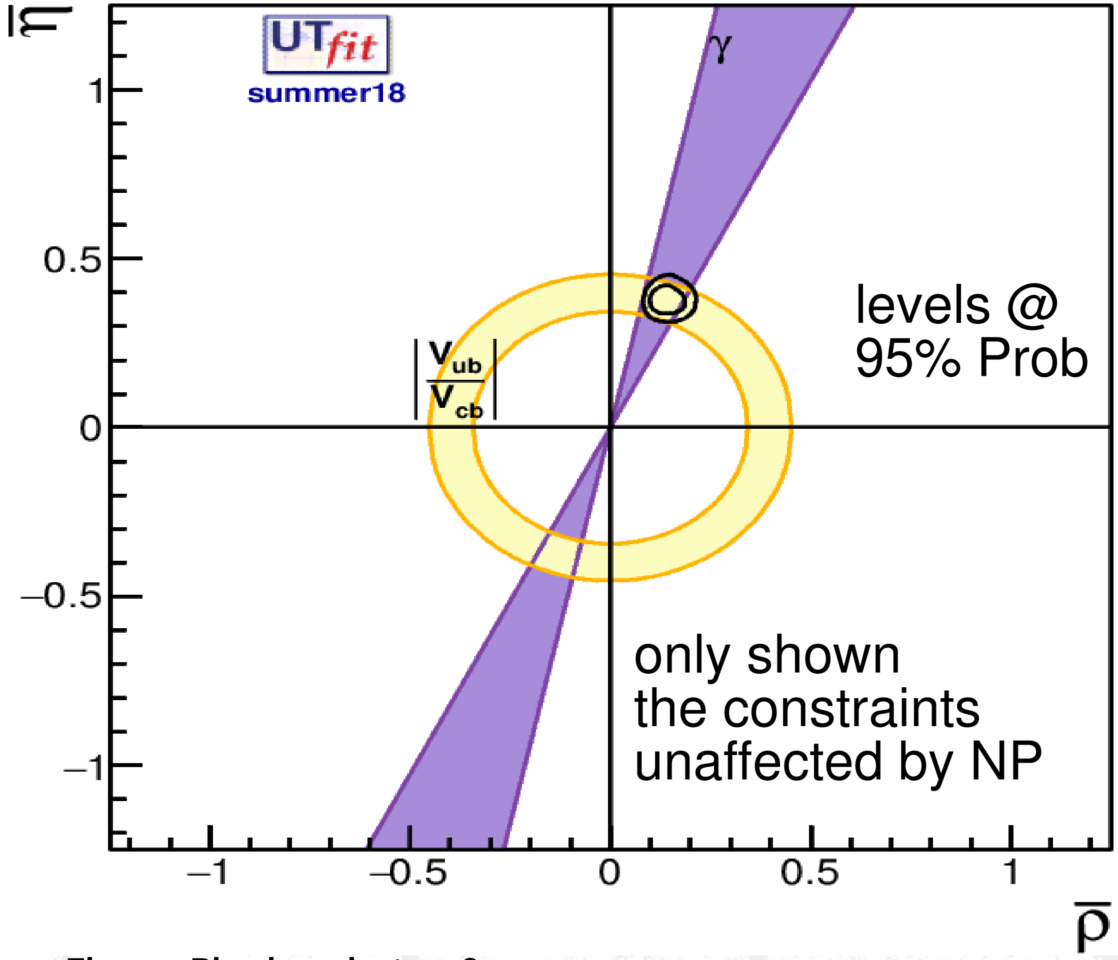
assume NP only in loop

$$\Delta m_{q/K} = C_{B_q/\Delta m_K} (\Delta m_{q/K})^{SM} \qquad \varepsilon_K = C_\varepsilon \varepsilon_K^{SM}$$

$$A_{CP}^{B_d \to J/\psi K_S} = \sin 2(\beta + \phi_{B_d}) \qquad A_{CP}^{B_s \to J/\psi \phi} \sim \sin 2(-\beta_s + \phi_{B_s})$$

$$A_{SL}^q = \mathrm{Im}\left(\Gamma_{12}^q / A_q\right) \qquad \Delta\Gamma^q / \Delta m_q = \mathrm{Re}\left(\Gamma_{12}^q / A_q\right)$$

NP analysis results



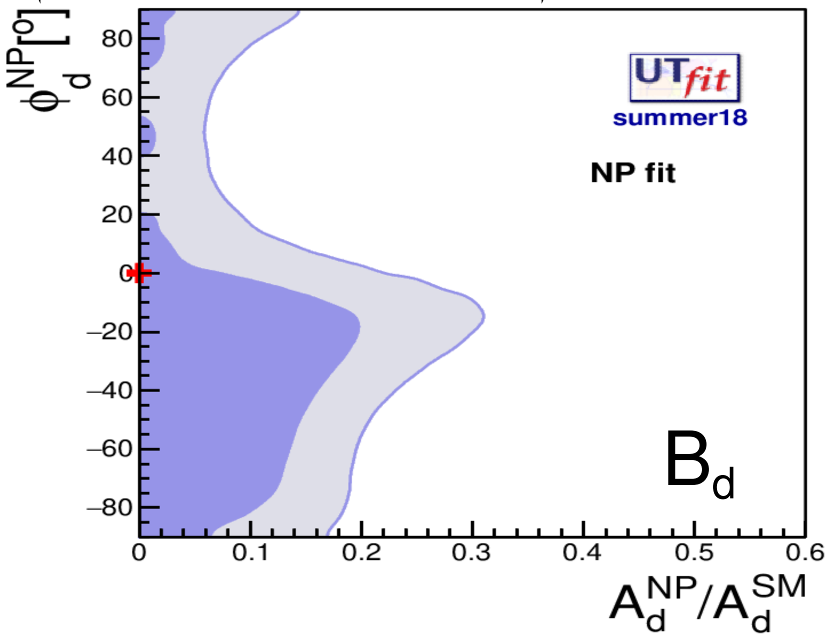
$\bar{\rho} = 0.144 \pm 0.028$
$\bar{\eta} = 0.378 \pm 0.027$

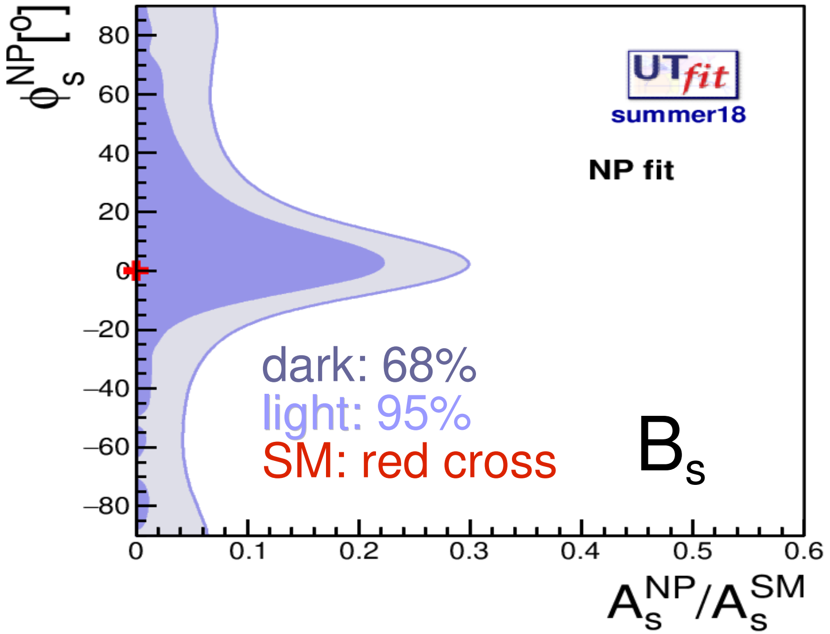
SM is

$\bar{\rho} = 0.148 \pm 0.013$
$\bar{\eta} = 0.348 \pm 0.010$

NP parameter results

$$A_q = \left(1 + \frac{A_q^{NP}}{A_q^{SM}} e^{2i(\phi_q^{NP} - \phi_q^{SM})}\right) A_q^{SM} e^{2i\phi_q^{SM}}$$





The ratio of NP/SM amplitudes is:

< 18% @68% prob. (30% @95%) in B_d mixing

< 20% @68% prob. (30% @95%) in B_s mixing

Testing the new-physics scale

M. Bona *et al.* (UTfit)
JHEP 0803:049,2008
arXiv:0707.0636

At the high scale
new physics enters according to its specific features

At the low scale
use OPE to write the most general effective Hamiltonian.
the operators have different chiralities than the SM
NP effects are in the Wilson Coefficients C

$$\mathcal{H}_{\rm eff}^{\Delta B=2} = \sum_{i=1}^{5} C_i Q_i^{bq} + \sum_{i=1}^{3} \tilde{C}_i \tilde{Q}_i^{bq}$$

$$\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}_{jL}^{\alpha} \gamma_\mu q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} \gamma^\mu q_{iL}^{\beta} , \\
Q_2^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jR}^{\beta} q_{iL}^{\beta} , \\
Q_3^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jR}^{\beta} q_{iL}^{\alpha} , \\
Q_4^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\alpha} \bar{q}_{jL}^{\beta} q_{iR}^{\beta} , \\
Q_5^{q_i q_j} &= \bar{q}_{jR}^{\alpha} q_{iL}^{\beta} \bar{q}_{jL}^{\beta} q_{iR}^{\alpha} .
\end{aligned}$$

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

F_i: function of the NP flavour couplings
L_i: loop factor (in NP models with no tree-level FCNC)
Λ: NP scale (typical mass of new particles mediating ΔF=2 processes)

Effective BSM Hamiltonian for ΔF=2 transitions

The dependence of C on Λ changes depending on the flavour structure.
We can consider different flavour scenarios:

$$C_i(\Lambda) = F_i \frac{L_i}{\Lambda^2}$$

- Generic: $C(\Lambda) = \alpha/\Lambda^2$ $F_i \sim 1$, arbitrary phase
- NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_i \sim |F_{SM}|$, arbitrary phase
- MFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$ $F_1 \sim |F_{SM}|$, $F_{i\neq 1} \sim 0$, SM phase

α (L_i) is the coupling among NP and SM
- $\alpha \sim 1$ for strongly coupled NP
- $\alpha \sim \alpha_W$ (α_S) in case of loop coupling through weak (strong) interactions

If no NP effect is seen lower bound on NP scale Λ

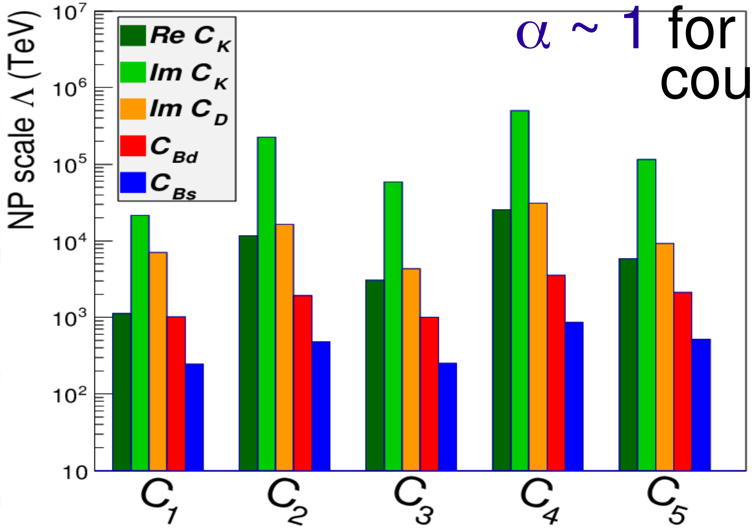
F is the flavour coupling and so
F_{SM} is the combination of CKM factors for the considered process

results from the Wilson coefficients

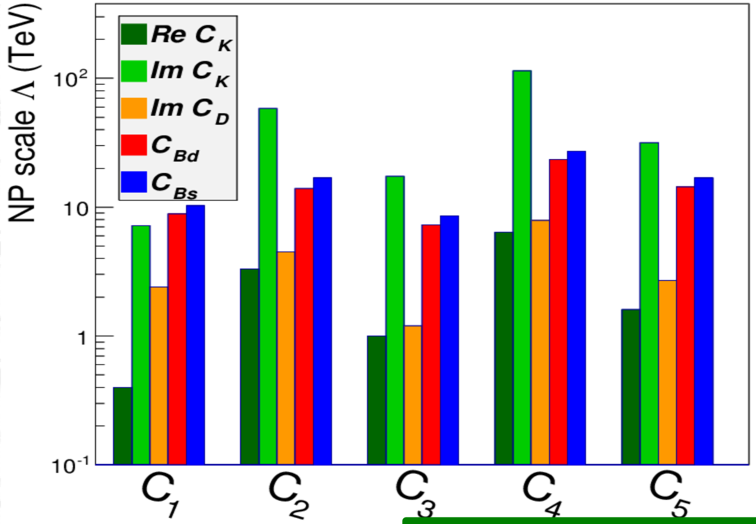
EPS17

Generic: $C(\Lambda) = \alpha/\Lambda^2$, F_i~1, arbitrary phase

α ~ 1 for strongly coupled NP



NMFV: $C(\Lambda) = \alpha \times |F_{SM}|/\Lambda^2$, F_i~$|F_{SM}|$, arbitrary phase



Lower bounds on NP scale

$\Lambda > 5.0\ 10^5$ TeV

$\Lambda > 114$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

$\Lambda > 1.5\ 10^4$ TeV

$\alpha \sim \alpha_W$ in case of loop coupling through weak interactions

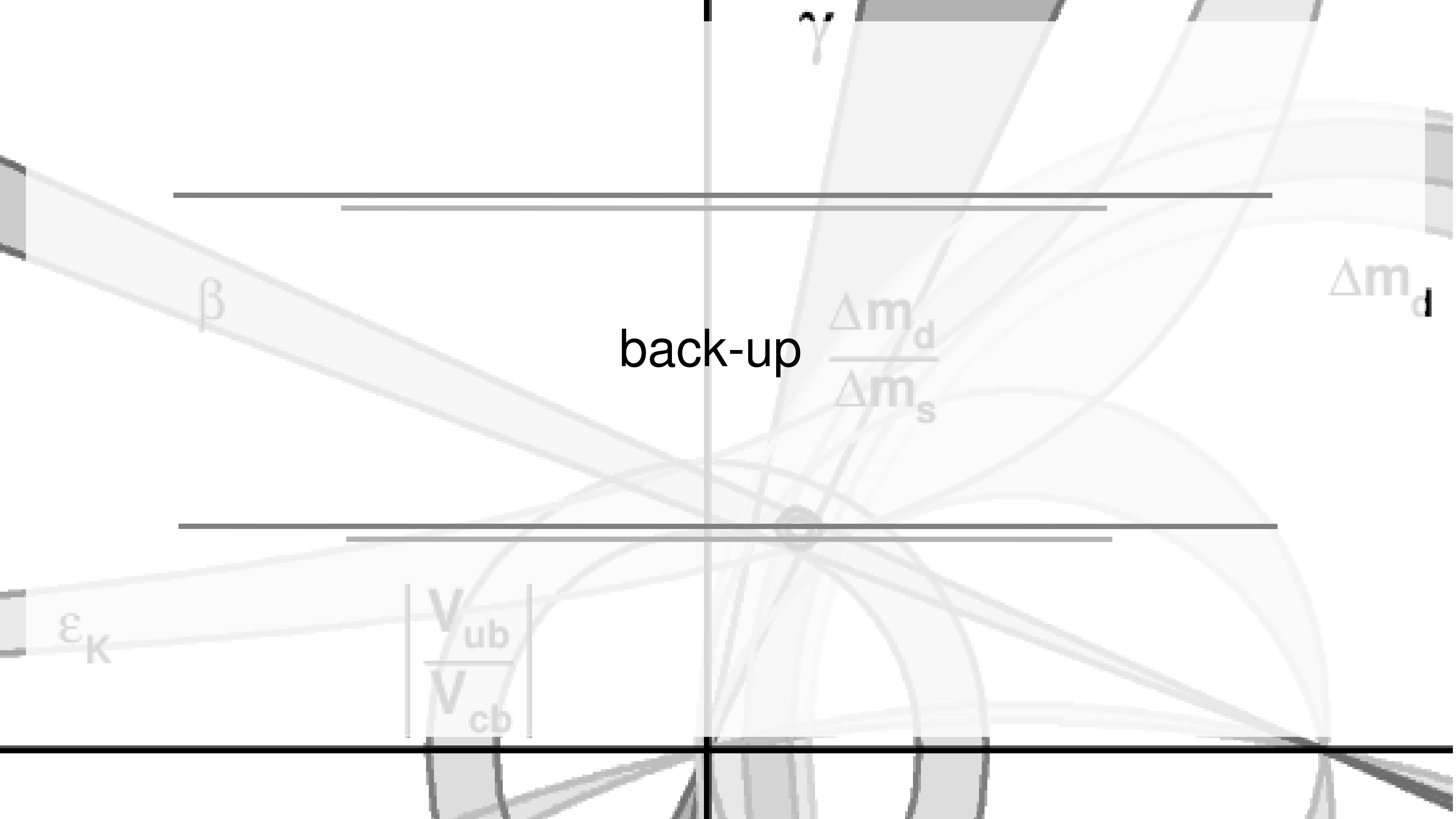
$\Lambda > 3.4$ TeV

for lower bound for loop-mediated contributions, simply multiply by α_s (~ 0.1) or by α_W (~ 0.03).

Summary

- Very partial, shallow and simplified vision of flavour physics
- Points to consider to measure a CP violating asymmetry.
  - Need more than one amplitude (more than one Feynman diagram) to have a non-zero CP violation signal.
    - Neutral mesons to measure the weak phase cleanly (usually).
    - Charged mesons to measure direct CP violation. Knowledge of strong phases limits how you can interpret these measurements in terms of the weak phases.
      - Need a model, and many measurements to say anything sensible.
      - Even then you will have a large theoretical uncertainty.
      - The right parameterisation for the experimental fit can be different from the theoretical framework. Keep an open mind.

Flavour physics has the fundamental role to carry on precise measurements and indirect searches that could be more powerful than the direct one in finding our way towards new physics back-up

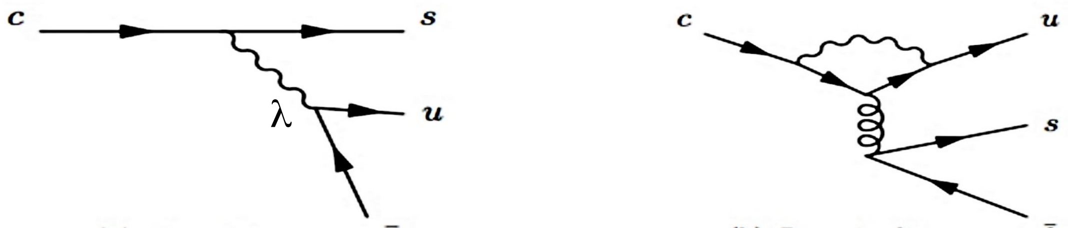


CP violation in the D system

- B factories have measured the D mixing (2007)
- The time-integrated CP asymmetry have contributions from both direct CP violation (in the decays) and indirect CP violation (in the mixing or in interference)
- In the SM, indirect CP violation in charm is expected to be very small and universal between CP eigenstates:
  $\Rightarrow$ predictions of about $O(10^{-3})$ for CPV parameters
- Direct CP violation can be larger in SM: it depends on final state (on the specific amplitudes contributing)
  $\Rightarrow$ negligible in Cabibbo-favoured modes (SM tree dominates everything)
  $\Rightarrow$ In singly-Cabibbo-suppressed modes: up to $O(10^{-4} - 10^{-3})$ plausible
- Both can be enhanced by NP, in principle up to O(%)

Where to look for direct CP violation

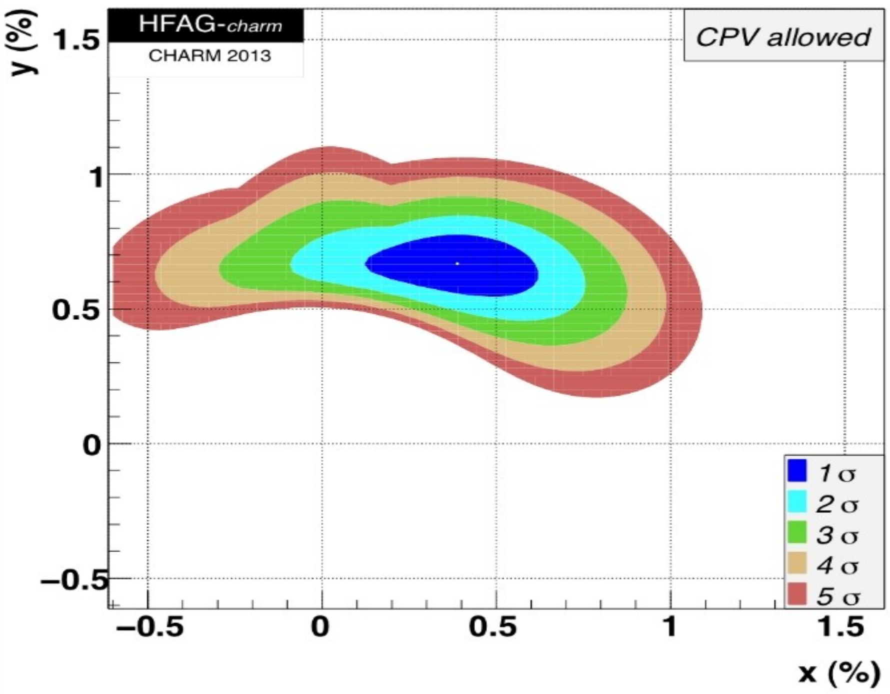
- Remember: need (at least) two contributing amplitudes with different strong and weak phases to get CPV.
- **$D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays:**
  - Singly-Cabibbo-suppressed modes with gluonic penguin diagrams
  - Several classes of NP can contribute ... but also non-negligible SM contribution

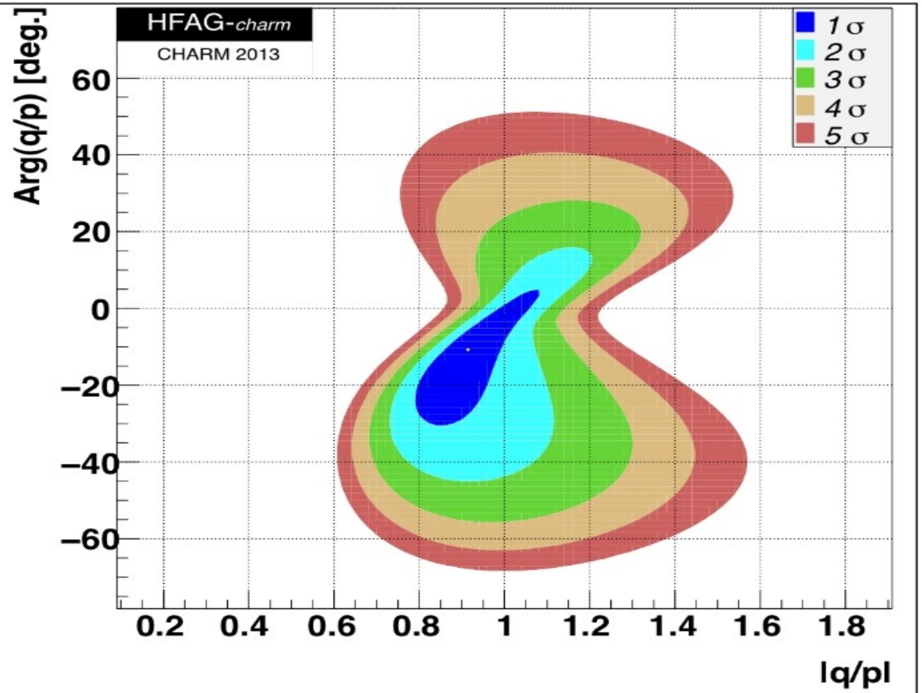


(a) *Tree diagram.* (b) *Penguin diagram.*

No CP violation measured so far

$$\Gamma = \frac{\Gamma_2 + \Gamma_1}{2} \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$





CPV-allowed plot, no mixing (x,y) = (0,0) point: $\Delta\chi^2 > 300$

No CPV (|q/p|, φ*) = (1,0) point:* $\Delta\chi^2 = 1.479$, *CL = 0.48 , consistent with no CPV*

$\Delta\Gamma_s$ and ϕ_s measurement from $B_s \rightarrow J/\psi\phi$

- The time evolution of the meson B_S and $\bar{B}_S$ is described by the superposition of B_H and B_L states, with masses $m_S \pm \Delta m_S/2$ and lifetimes $\Gamma_S \pm \Delta\Gamma_S/2$.

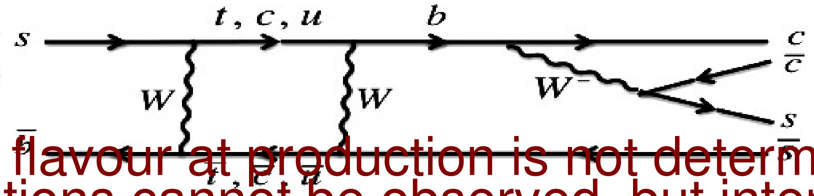
  These states deviate from defined values CP = ± 1, as described in the SM by the mixing phase ϕ_S ($\phi_S = -2\beta_S$),

  SM prediction (fit): $\phi_S = -0.0368 \pm 0.0018$ *rad*

  $\Delta\Gamma_S = 0.082 \pm 0.021\ ps^{-1}$

  New Physics can contribute to ϕ_S, and change the ratio $\Delta\Gamma_S/\Delta m_S$.

- In general, the decay to a final state that is coupled to B_S and/or $\bar{B}_S$, exhibits fast oscillations driven by Δm_S. Interference between amplitudes for both states generates CP violation, and conveys information on ϕ_S .



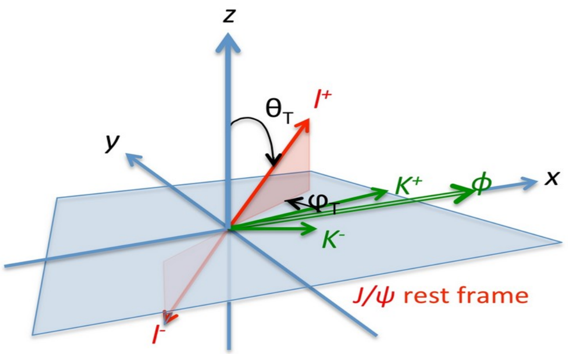
Decay amplitude with mixing (ϕ_s)

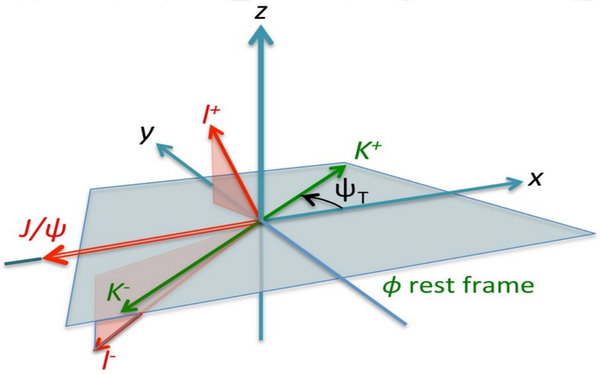
Amplitude with direct decay

If $\bar{B}$/B flavour at production is not determined (not tagged), the fast oscillations cannot be observed, but interference terms remain if the final state is described by a superposition of amplitudes of different CP values.

angular analysis in $B_s \to J/\psi\phi$

- In the decay $\bar{B}_S(B_S) \to J/\psi\phi \to l^+l^- K^+K^-$ different components in the angular-distributions amplitudes correspond to CP = +1 or –1
- The “transversity angles” are used to describe the angular distributions





angular analysis in $B_s \to J/\psi\phi$

- Angular analysis as a function of proper time and b-tagging
- Similar to B_d measurement in $B_d \to J/\psi K^*$
- Additional sensitivity from the $\Delta\Gamma_s$ terms (negligible for B_d)

$$\frac{d^4P(t,w)}{dtdw} \propto |A_0|^2\, T_+ f_1(\vec{w}) + |A_{||}|^2\, T_+ f_2(\vec{w}) + |A_\perp|^2\, T_- f_3(w) + |A_{||}||A_\perp|\, U_+ f_4(w) + |A_0||A_{||}|\cos(\delta_{||}) T_+ f_5(w) + |A_0||A_\perp|\, V_+ f_6(w)$$

$$T_\pm = e^{-\Gamma t} \times [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \mp \eta \sin(2\beta_s)\sin(\Delta m_s t)],\ \eta = +1(-1) \text{ for } P(\bar{P})$$

$$U_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp - \delta_{||})\cos(\Delta m_s t) - \cos(\delta_\perp - \delta_{||})\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp - \delta_{||})\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

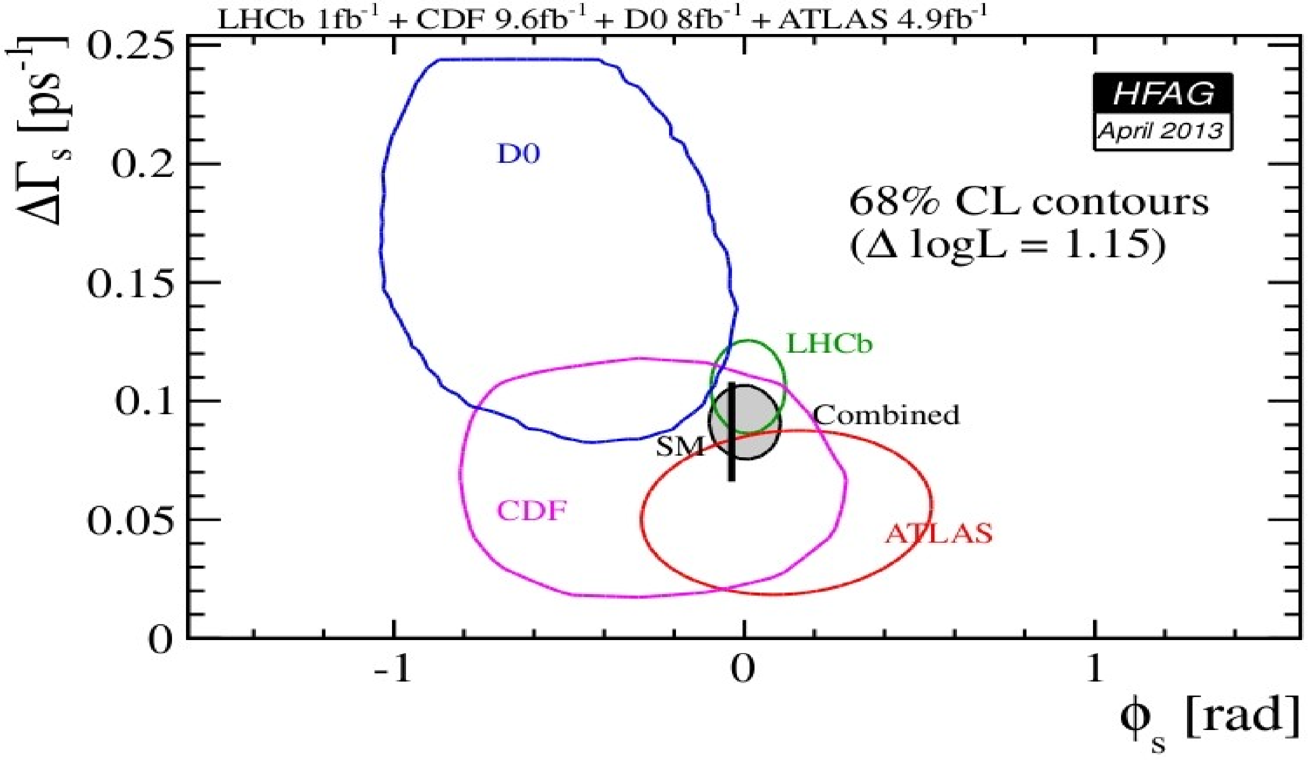
$$V_\pm = \pm e^{-\Gamma t} \times [\sin(\delta_\perp)\cos(\Delta m_s t) - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)]$$

Dunietz et al.
Phys.Rev.D63:114015,2001

Ambiguities for
$\phi_s \to \pi - \phi_s$,
$\Delta\Gamma_s \to -\Delta\Gamma_s$,
$\cos(\delta_\perp - \delta_\parallel) \to -\cos(\delta_\perp - \delta_\parallel)$

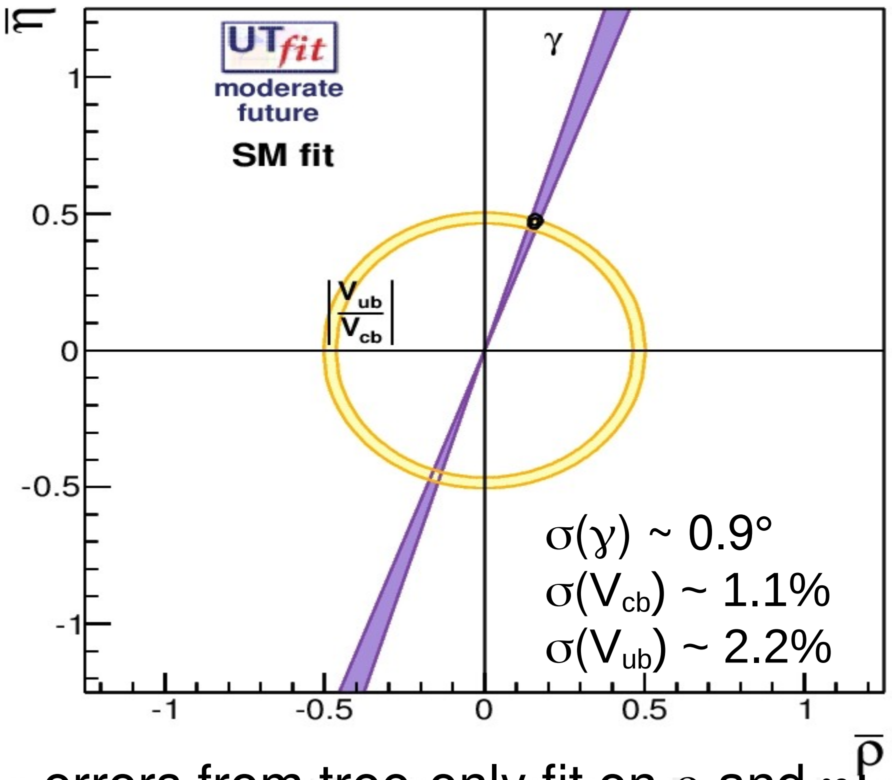
- transversity basis: $W(\theta, \varphi, \psi)$
- θ and φ: direction of the μ^+ from J/ψ decay
- ψ: between the decay planes of J/ψ and ϕ

angular analysis in $B_s \to J/\psi\phi$

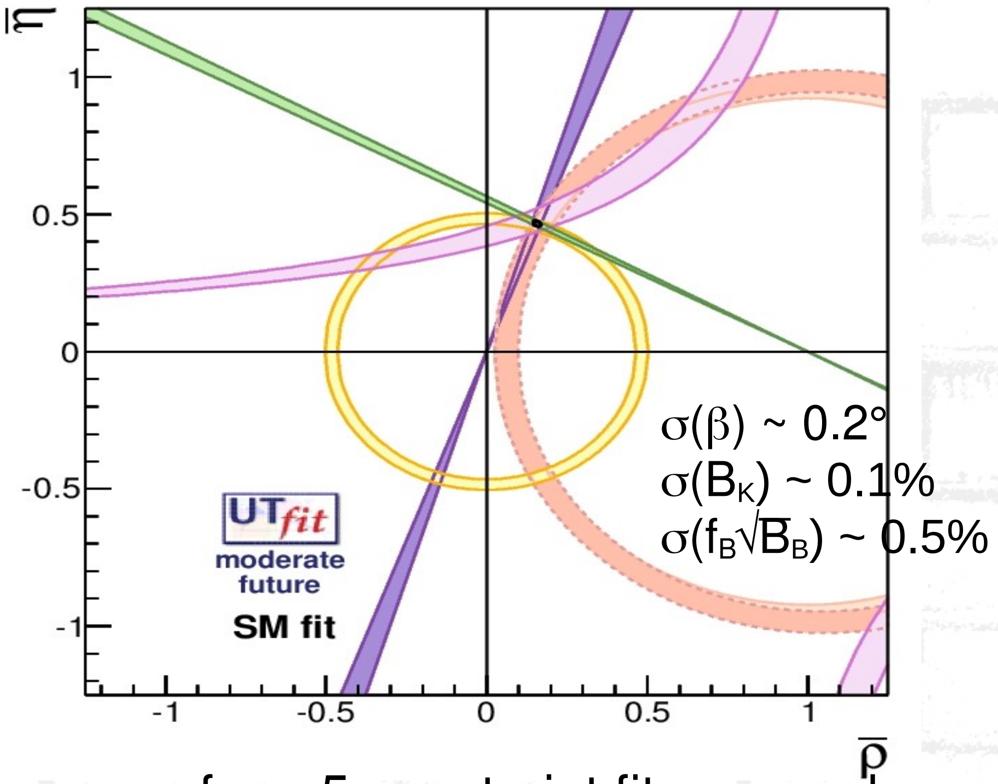


Look at the future

errors predicted from
Belle II + LHCb upgrade



errors from tree-only fit on ρ and η:
$\sigma(\rho) = 0.008$ *[currently 0.051]*
$\sigma(\eta) = 0.010$ *[currently 0.050]*



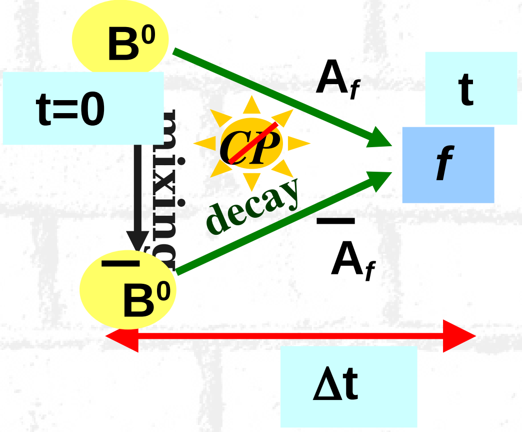
errors from 5-constraint fit on ρ and η:
$\sigma(\rho) = 0.005$ *[currently 0.034]*
$\sigma(\eta) = 0.004$ *[currently 0.015]*

Summary

- Points to consider to measure a CP violating asymmetry.
  - Need more than one amplitude (more than one Feynman diagram) to have a non-zero CP violation signal.
    - Neutral mesons can be used to measure the weak phase cleanly (usually).
    - Charged mesons can be used to measure direct CP violation. Knowledge of strong phases limits how you can interpret these measurements in terms of the weak phases.
      - Need a model, and many measurements to say anything sensible.
      - Even then you will have a large theoretical uncertainty.
  - You can count the CKM vertex factors in the Feynman diagrams to tell you relative sizes of decays that you expect (This works for tree level processes. You need to consider colour / Zweig supression for more detailed guesses).

CP violation in interference between mixing and decay:

$$\lambda_{f_{CP}} = \frac{q}{p} \cdot \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$



- decays in final state *f* accessible to both a B or a $\bar{B}$ (*f* is not necessarily a CP eigenstate)
- if Im$\lambda \neq 0$ then → CP violation

$$\lambda = \frac{q}{p}\frac{A(\bar{B} \to f)}{A(B \to f)} = \frac{V_{td}^* V_{tb}}{V_{td} V_{tb}^*}\frac{\bar{A}}{A} \sim e^{-i2\beta}\frac{\bar{A}}{A}$$

β is the mixing phase

examples

	f	$\mathrm{Arg}(\frac{\bar{A}}{A})$	$\lvert\lambda\rvert$	parameter
mixing	$B^0 \to l\nu X, D^{(*)}\pi(\rho, a_1)$	0	~ 0	ΔM_{B^0}
"sin 2β"	$B^0 \to J/\psi K^0, \ldots$	0	1	$\sin 2\beta$
"sin 2α"	$B^0 \to \pi\pi, \rho\pi, \pi\pi\pi$	$\sim(-2\gamma)$	~ 1	$\sin 2\alpha$
"sin(2β + γ)"	$B^0 \to D^{(*)}\pi$	$\sim(-\gamma)$	~ 0.02	$\sin(2\beta + \gamma)$

$B\bar{B}$ pair coherent production

◎ The B^0 and $\bar{B}^0$ mesons from the $\Upsilon(4S)$ are in a coherent L = 1 state:

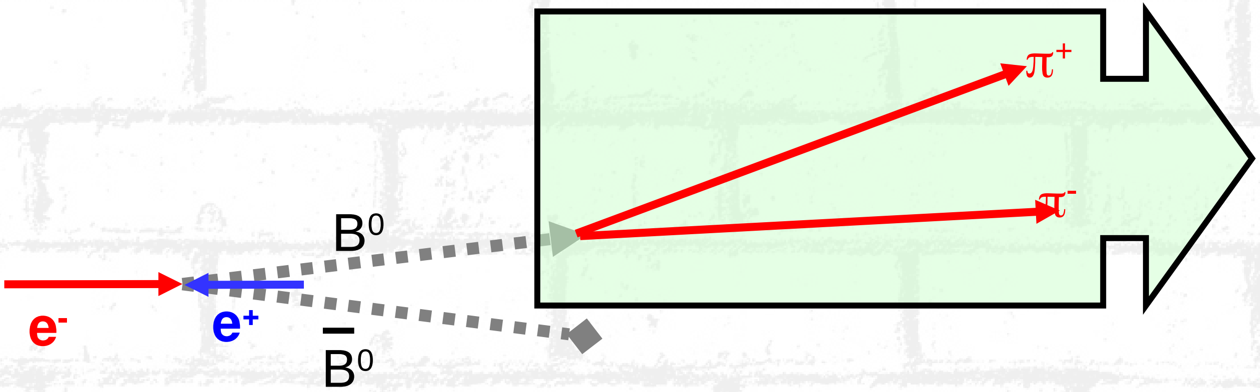
- ◉ The $\Upsilon(4S)$ is a $b\bar{b}$ state with **$J^{PC} = 1^{--}$**.
- ◉ B mesons are scalars (**$J^P = 0^-$**)
  - ⇨ total angular momentum conservation
  - ⇨ the $B\bar{B}$ pair has to be produced in a **L = 1 state**.

◎ The $\Upsilon(4S)$ decays strongly so B mesons are produced in the two flavour eigenstates B^0 and $\bar{B}^0$:

- ◉ After production, each B evolves in time, but **in phase** so that at any time there is always exactly one B^0 and one $\bar{B}^0$ present, at least until one particle decays:
  - ⇨ If at a given time t one B could oscillate independently from the other, they could become a state made up of two identical mesons: but the L = 1 state is anti-symmetric, while a system of **two identical mesons (bosons!)** must be completely symmetric for the two particle exchange.

◎ Once one B decays the other continues to evolve, and so it is possible to have events with **two B or two $\bar{B}$ decays**.

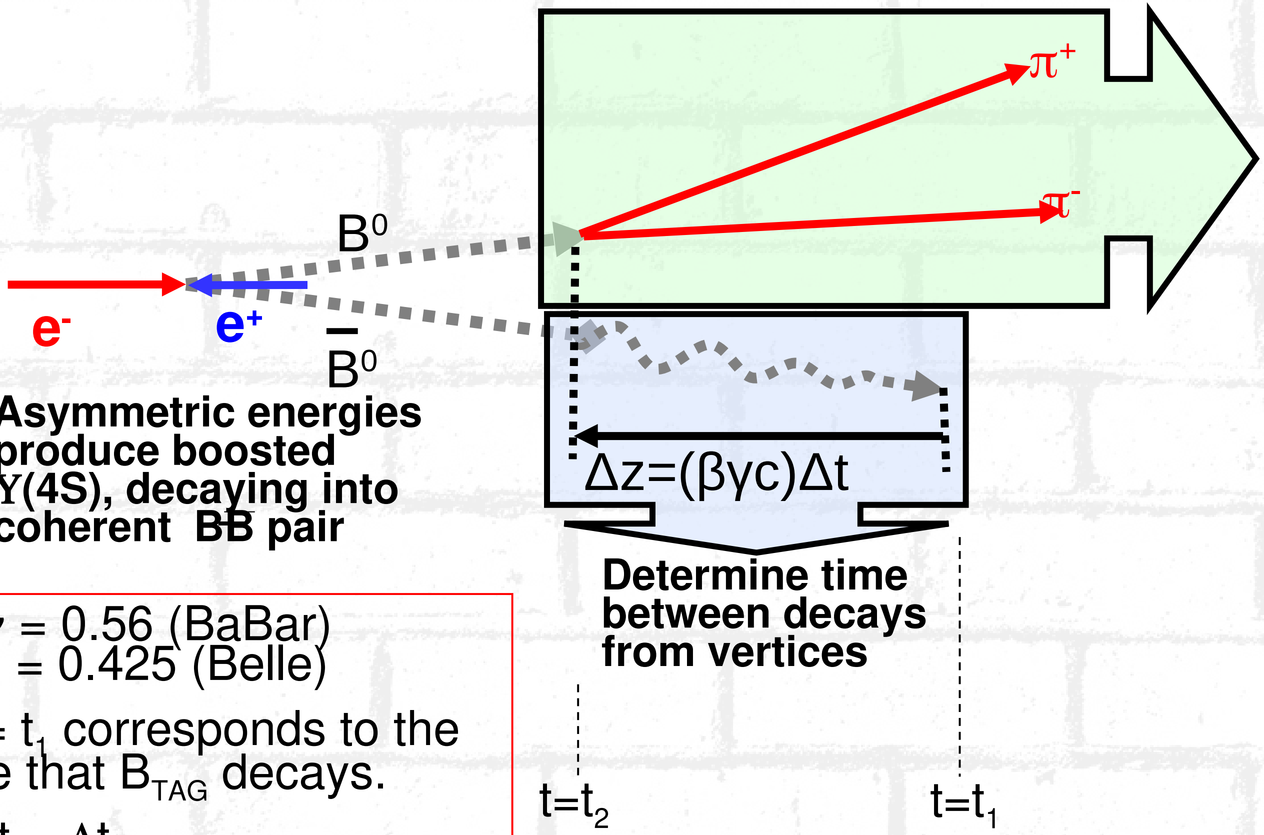
Measuring Δt



Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted ϒ(4S), decaying into coherent $B\bar{B}$ pair

Measuring Δt



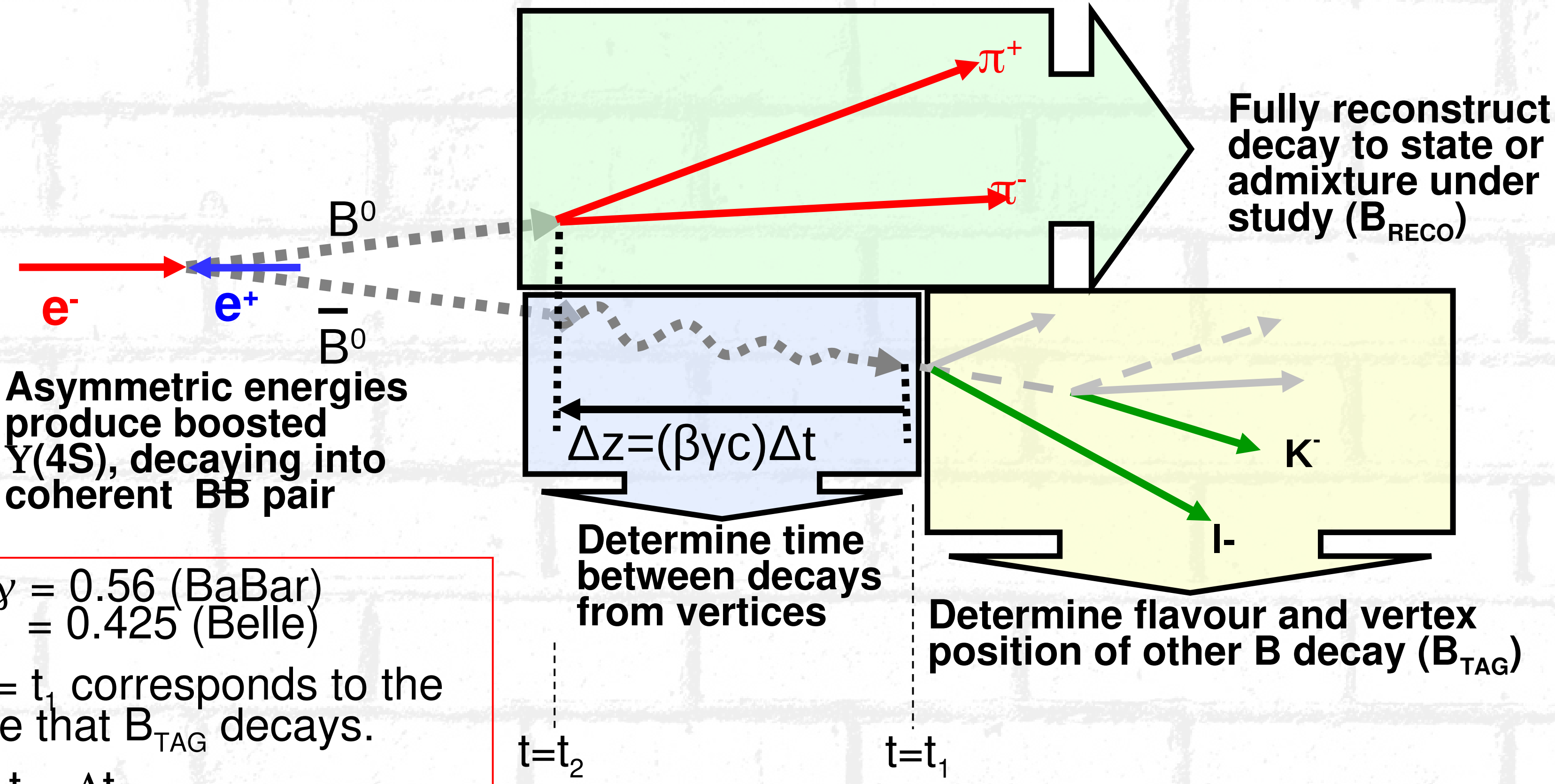
Fully reconstruct decay to state or admixture under study (B_{RECO})

Asymmetric energies produce boosted Υ(4S), decaying into coherent $B\bar{B}$ pair

Determine time between decays from vertices

- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- t = t_1 corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

Measuring Δt



- $\beta\gamma$ = 0.56 (BaBar)
  = 0.425 (Belle)
- $t = t_1$ corresponds to the time that B_{TAG} decays.
- $t_2 - t_1 = \Delta t$

⇨ Then fit the Δt distribution to obtain the amplitude of sine and cosine terms.