Imperial College
London

Recent developments in *B* physics

YETI '05, Durham
7 January 2005

Ulrik Egede

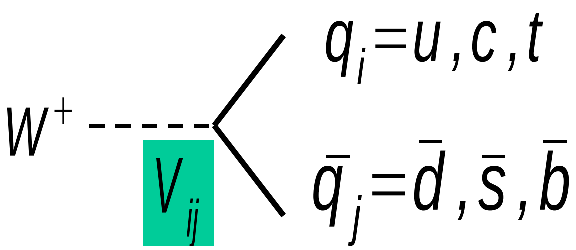
What is B physics and why do we do it

- The discovery of New Physics that will provide an insight into why the Standard Model works so well is the ultimate goal!
- I will focus on *CP* violation in *B* decays but there are many other areas in Heavy Flavour physics:
  - Rare decays
  - Radiative decays
  - Branching fractions
  - Dalitz analysis
  - *CP* violation and oscillations in *D* meson decays
  - Search for new excited charm and beauty states
- As will be seen B physics has a great past and certainly a great future for many years to come.

The CKM matrix

We use the CKM **unitary** matrix to describe the relation between the weak eigenstates and the mass eigenstates of the down type quarks.

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



A **single complex phase** describes **all** *CP* violation in the quark sector within the Standard Model.

The CKM matrix

We nearly always use the Wolfenstein parametrisation.

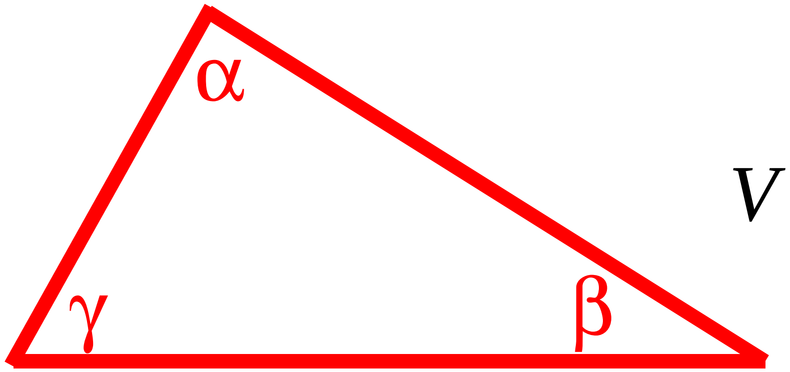
$$-|V_{ub}|e^{-i\gamma}$$

$$V_{CKM}=\begin{pmatrix} 1-\frac{\lambda^2}{2}+\frac{\lambda^4}{4} & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{A^4\lambda^4}{2}-A^2\lambda^5(\rho+i\eta) & 1-\frac{\lambda^2}{2}+\frac{\lambda^4(1-2A^2)}{4} & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+A\lambda^4(\frac{1}{2}-\rho-i\eta) & 1-\frac{A^2\lambda^4}{2} \end{pmatrix}+O(\lambda^6)$$

$$-|V_{td}|e^{-i\beta} \qquad |V_{ts}|e^{i\chi}$$

Notice: Only one independent phase even if we here represent it as 3 phases.

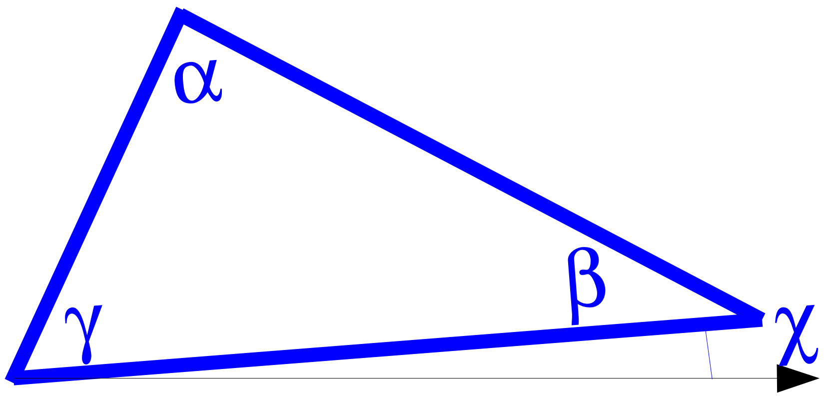
Unitarity triangles



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & -|V_{ub}|e^{-i\gamma} \\ V_{cd} & V_{cs} & V_{cb} \\ -|V_{td}|e^{-i\beta} & |V_{ts}|e^{i\chi} & V_{tb} \end{pmatrix}$$

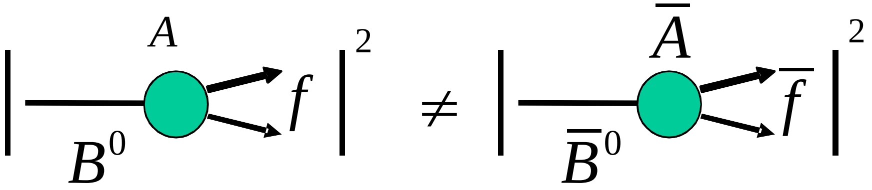
Unitarity states that $VV^{\dagger}=V^{\dagger}V=I$.

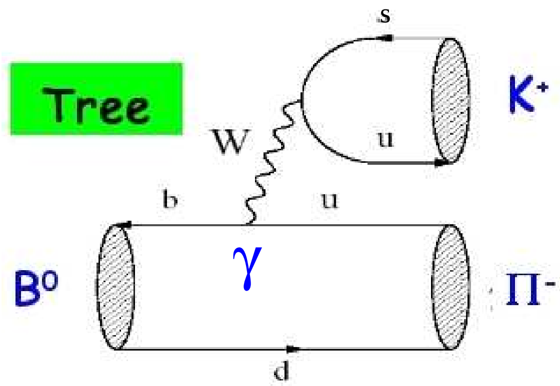
- 6 conditions normalising columns and rows.
  - Built into parametrisation
- 6 conditions expressing columns and rows are orthogonal.
  - Can be depicted as a triangle with 3 vectors adding up to zero.
- 4 very flat triangles
- 2 almost identical triangles.



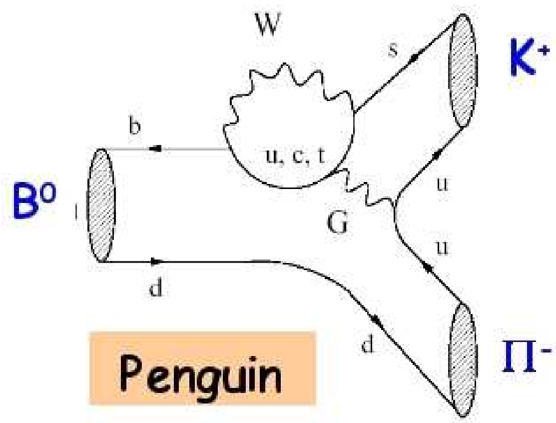
3 types of *CP* violation – Direct

Direct *CP* violation is when the probability for of a decay and *CP* conjugated decay are not the same.

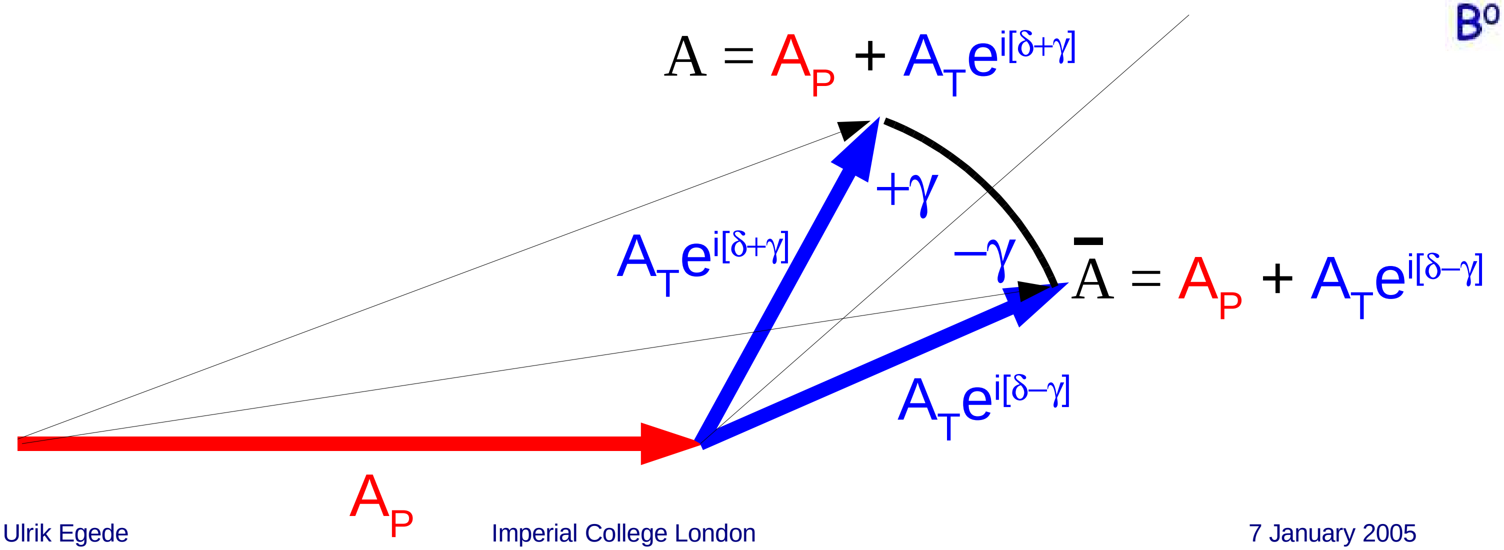




Requires two decay paths and a difference in strong and weak phase between them.



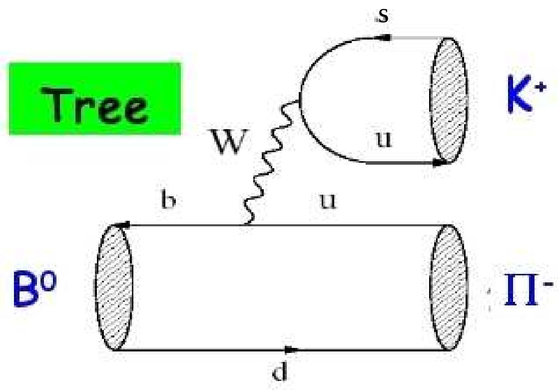
Take $B^0 \to K^+ \pi^-$ as an example:

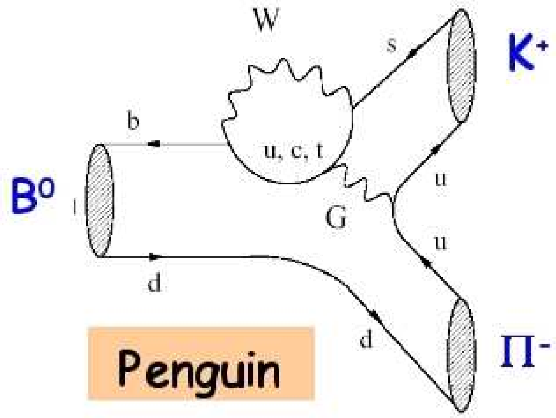


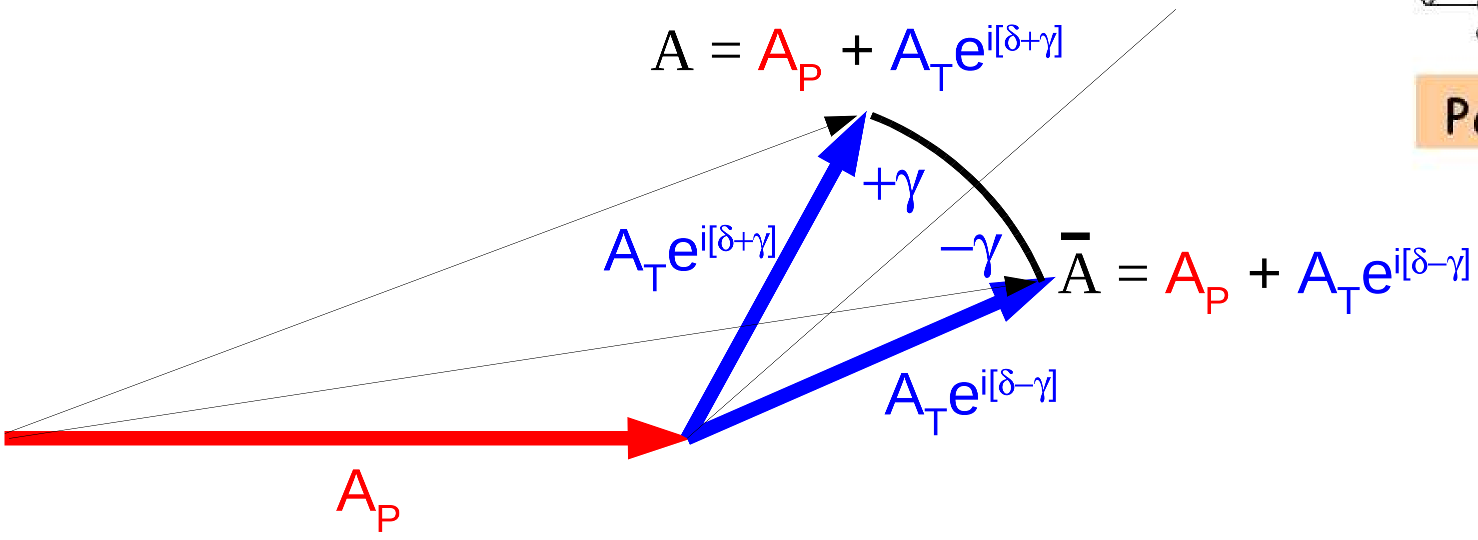
3 types of *CP* violation – Direct

Assume relative amplitude $|A_T|/|A_P|$ and the strong phase difference $\delta = \delta_T - \delta_P$ were known.

- Ratio of B^+ and B^- branching ratios would then measure γ.
- Unfortunate large theoretical uncertainty gives limited value of method.

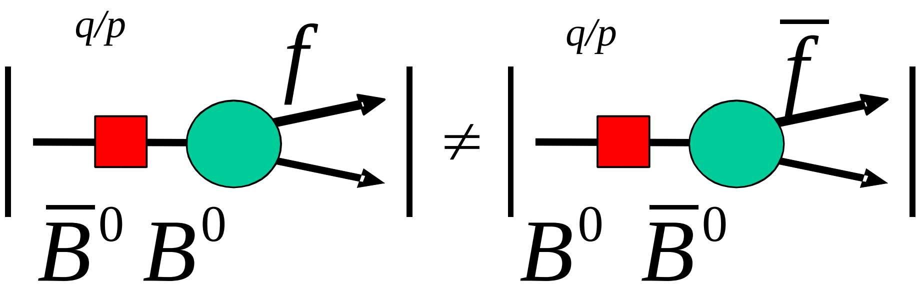






3 types of *CP* violation – In oscillations

Happens if probability of $B^0 \rightarrow \bar{B}^0$ oscillations is different to $\bar{B}^0 \rightarrow B^0$ oscillations.



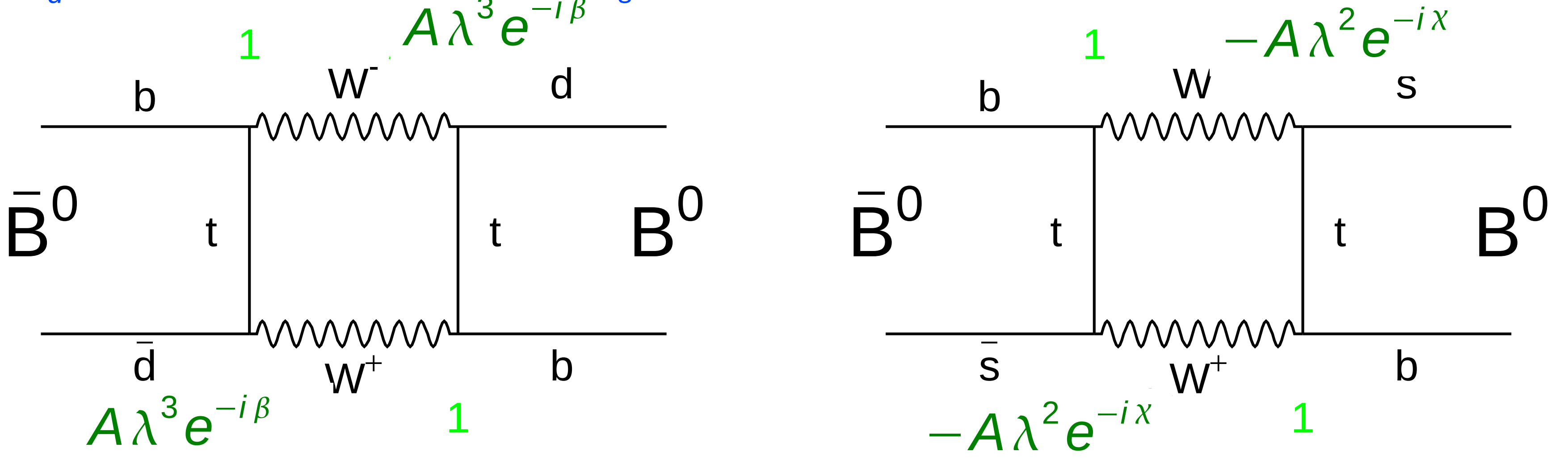
Not relevant for *B* physics as $\frac{\Delta \Gamma}{\Delta m} \ll 1$.

Important for Kaon (and maybe charm) physics.

3 types of *CP* violation – Interference

The interference between *B* oscillations and the decay to a final state shared by B^0 and $\bar{B}^0$ can also give rise to *CP* violation.

B_d mixing has a phase 2β, B_s mixing has 2χ.



Leads to time dependent asymmetry in a measurement:

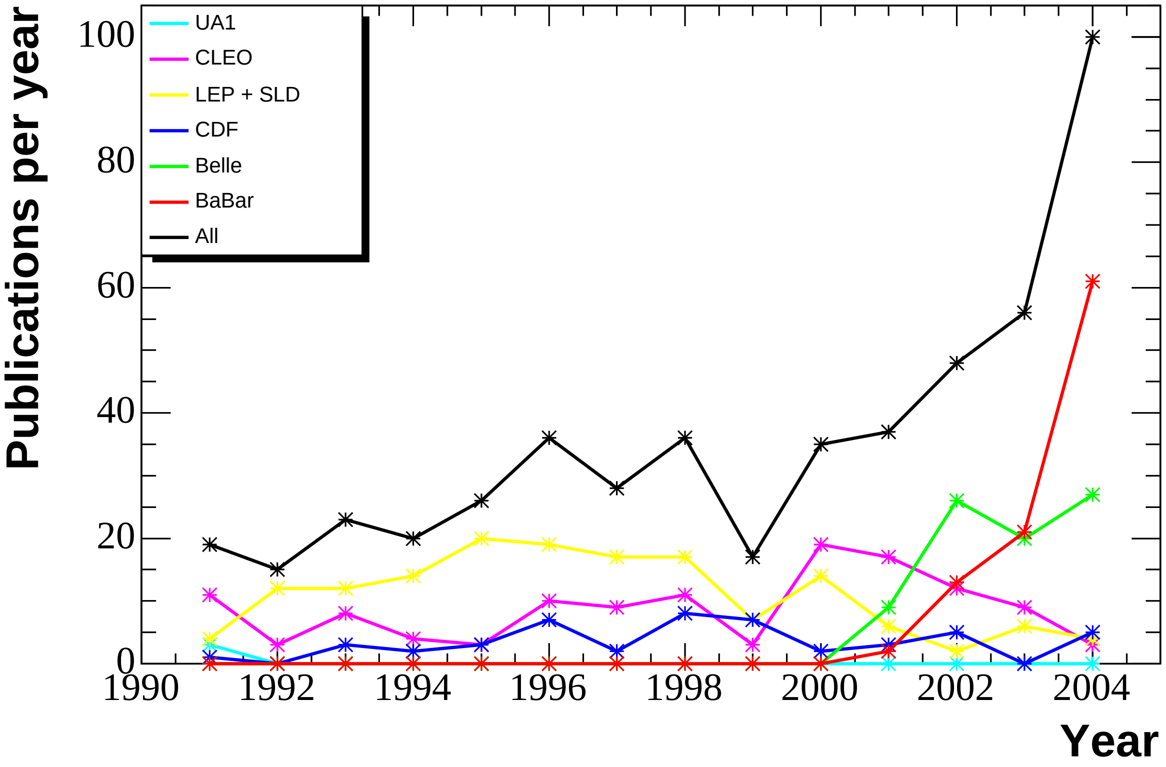
$$A_f(t) = \frac{\mathrm{BF}(B \to f) - \mathrm{BF}(\bar{B} \to f)}{\mathrm{BF}(B \to f) + \mathrm{BF}(\bar{B} \to f)} = \mathcal{A}^{\mathrm{C}} \cos(\Delta m t) + \mathcal{A}^{\mathrm{S}} \sin(\Delta m t)$$

Best known example is the $B_d \to J/\Psi K^0_s$ decay.

$\boxed{\sin(2\beta) \;\text{ or }\; \sin(2\chi)}$

Is *B* physics an active field?

Number of publications in the last 15 years.



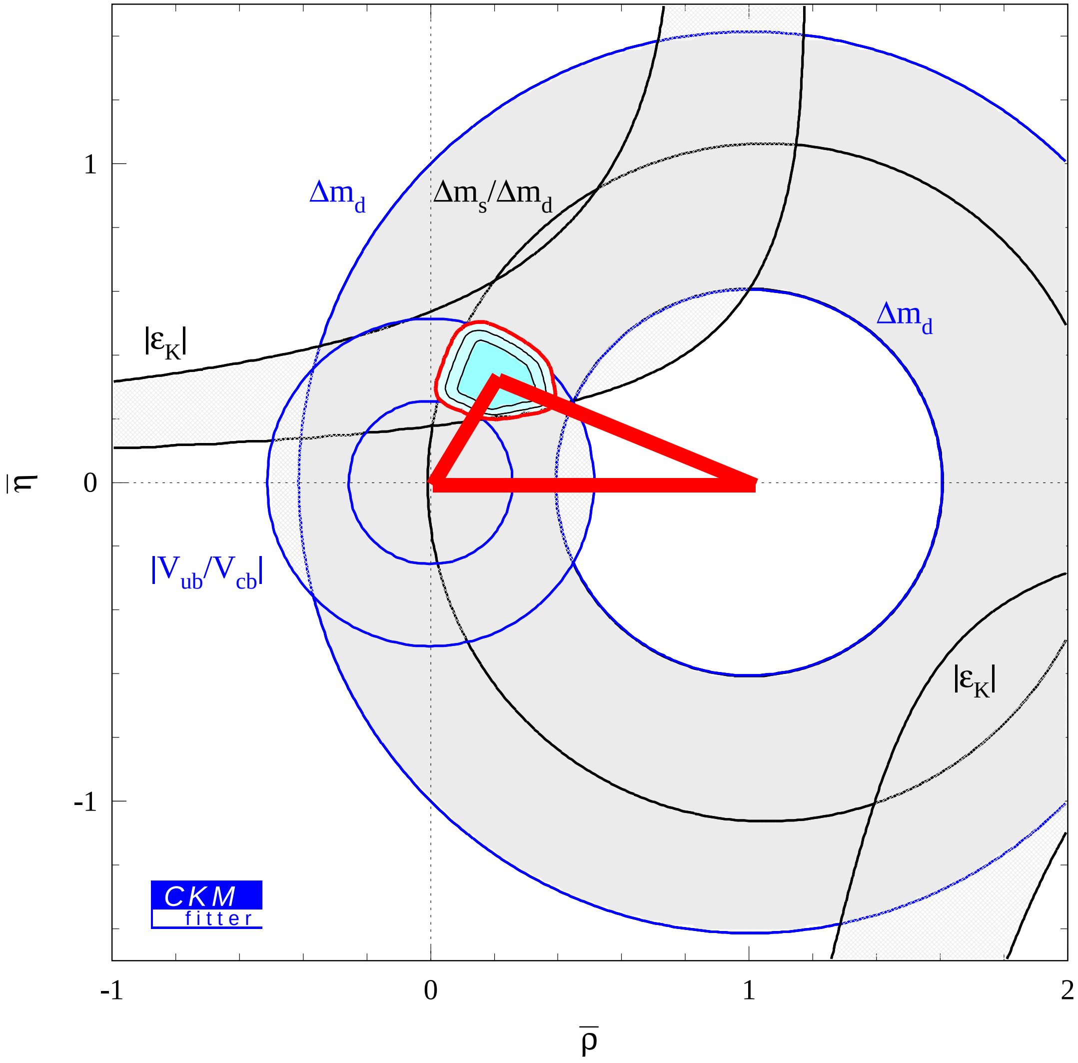
Numbers are my own and has uncertainties – articles wrongly categorised, some proceedings included etc.

The field is indeed very active.

Lots more to come – here I demonstrate just a single aspect.

Evolution of field: 2000

- Before the first results from BaBar and Belle
- Plot illustrates knowledge about apex of unitarity triangle.
  - Each type of measurement gives a contraint.
- In 2000 only constraints on length of sides – no angles.
  - Left side from charmless BFs giving V_{ub}.
  - Top side from B_d oscillations giving V_{td}.

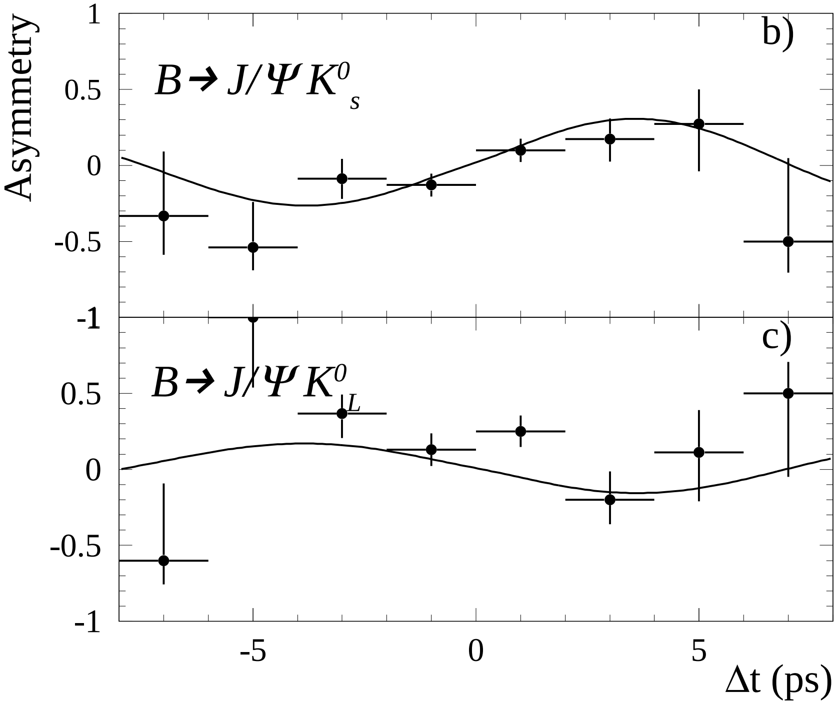


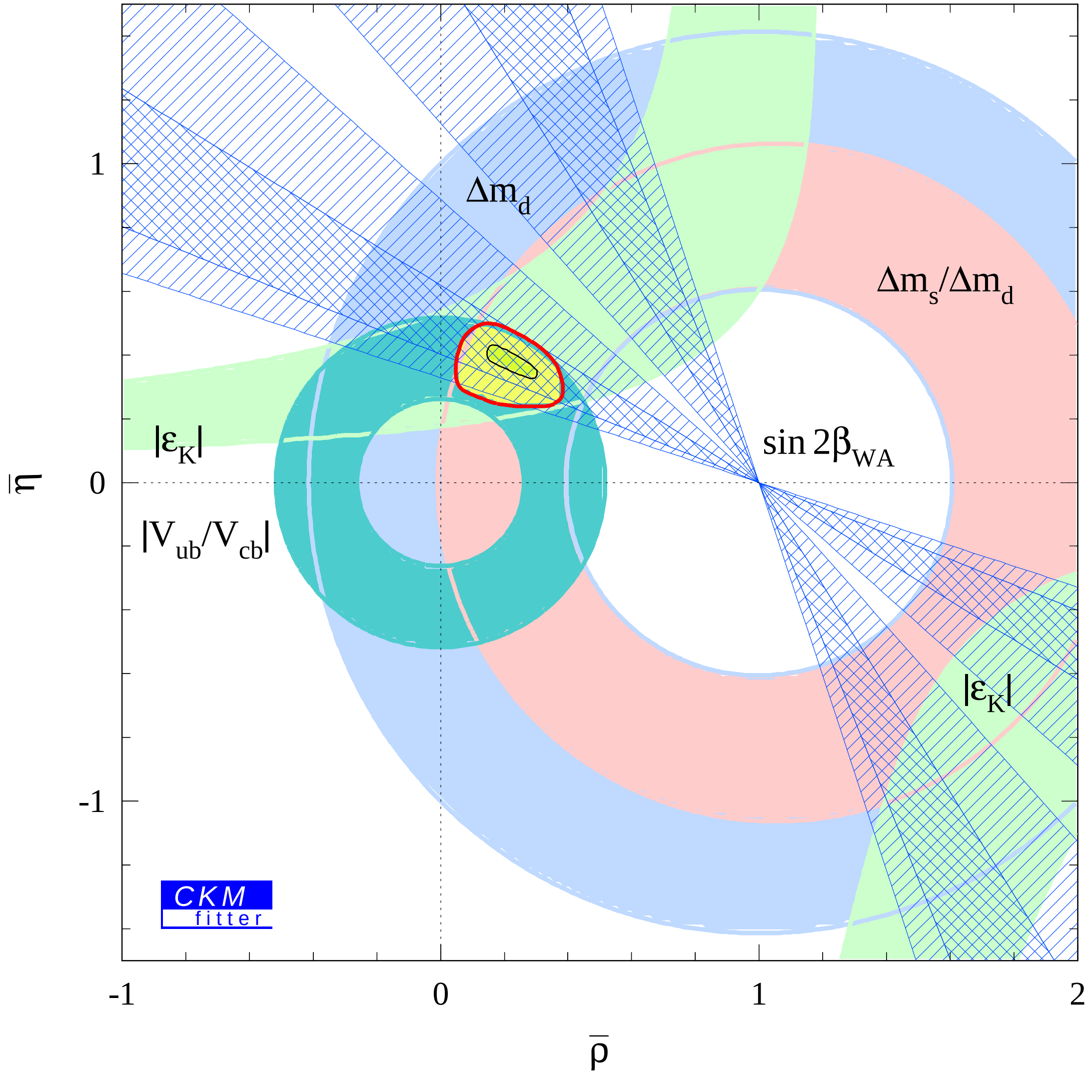
Evolution of field: 2001

Both BaBar and Belle measure *CP* violation in the *B* system.

The agreement within the SM holds yet again.

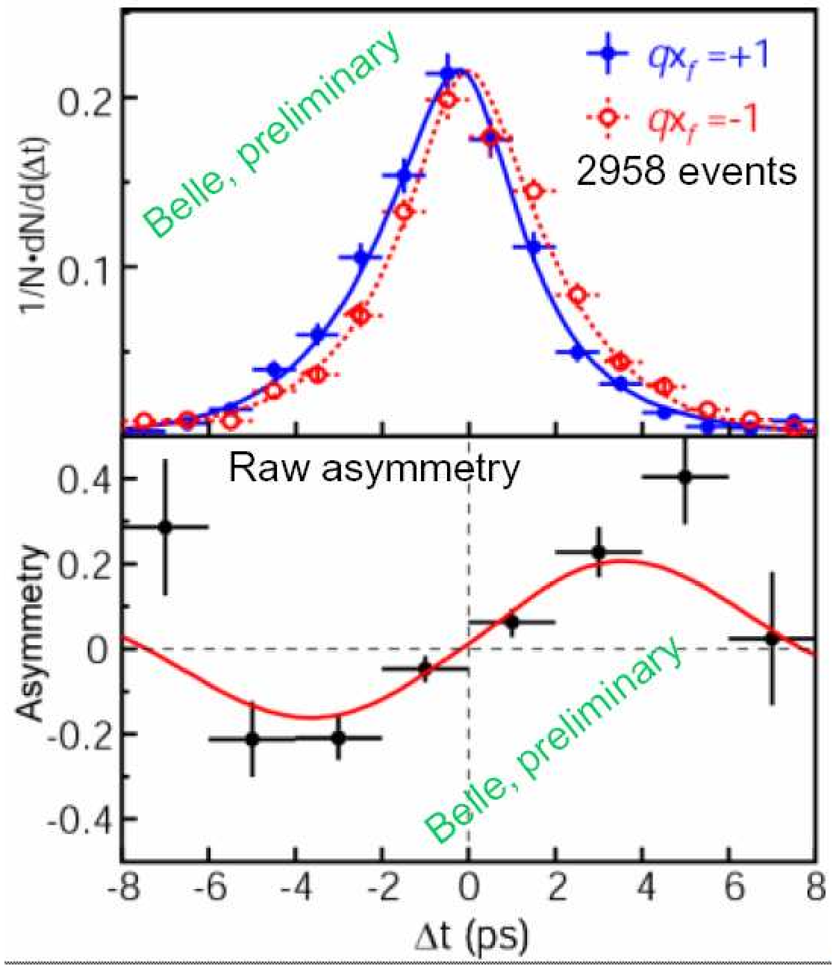
BaBar 2001 result for sin(2β)

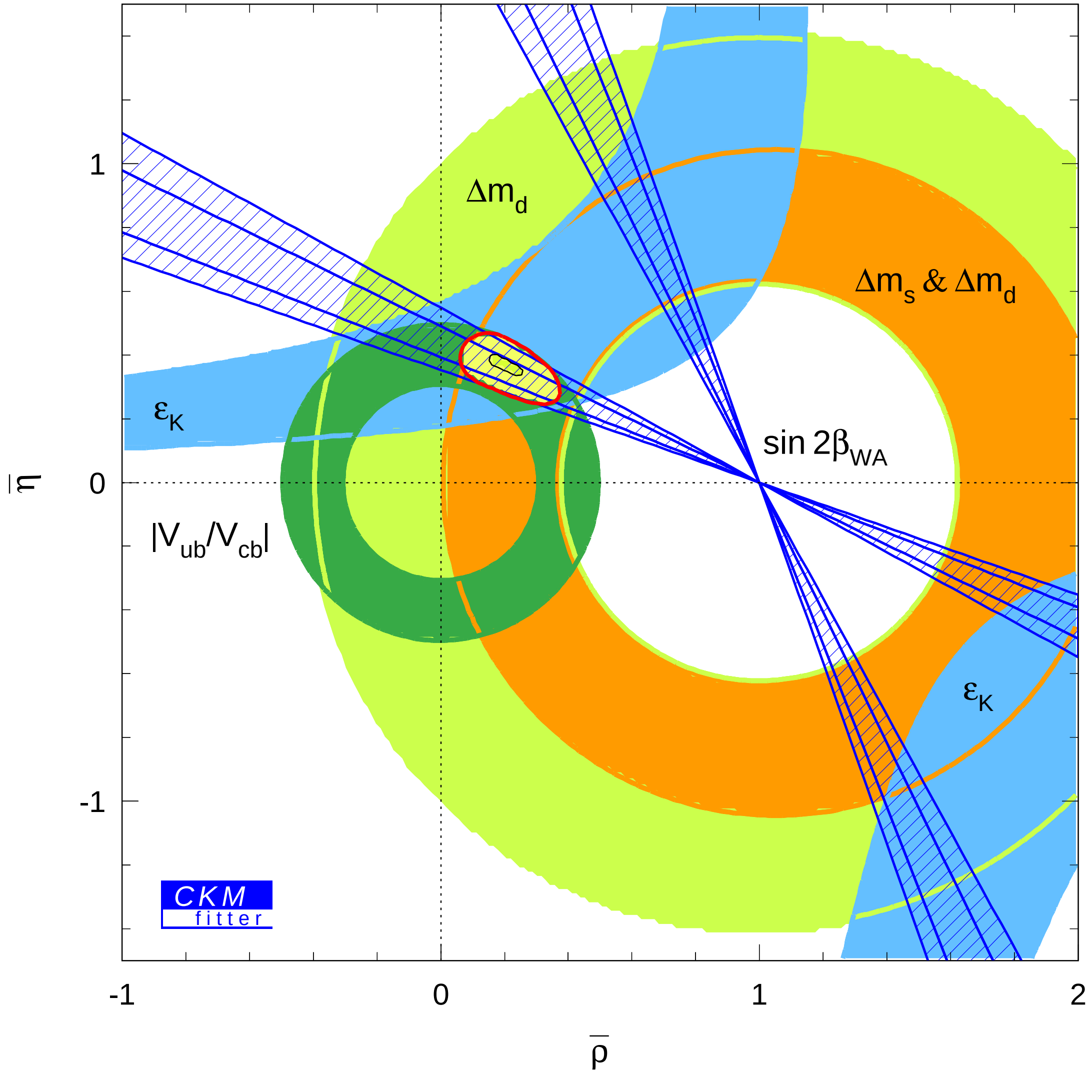




Evolution of field: 2002

Measurement of sin(2β) improves dramatically

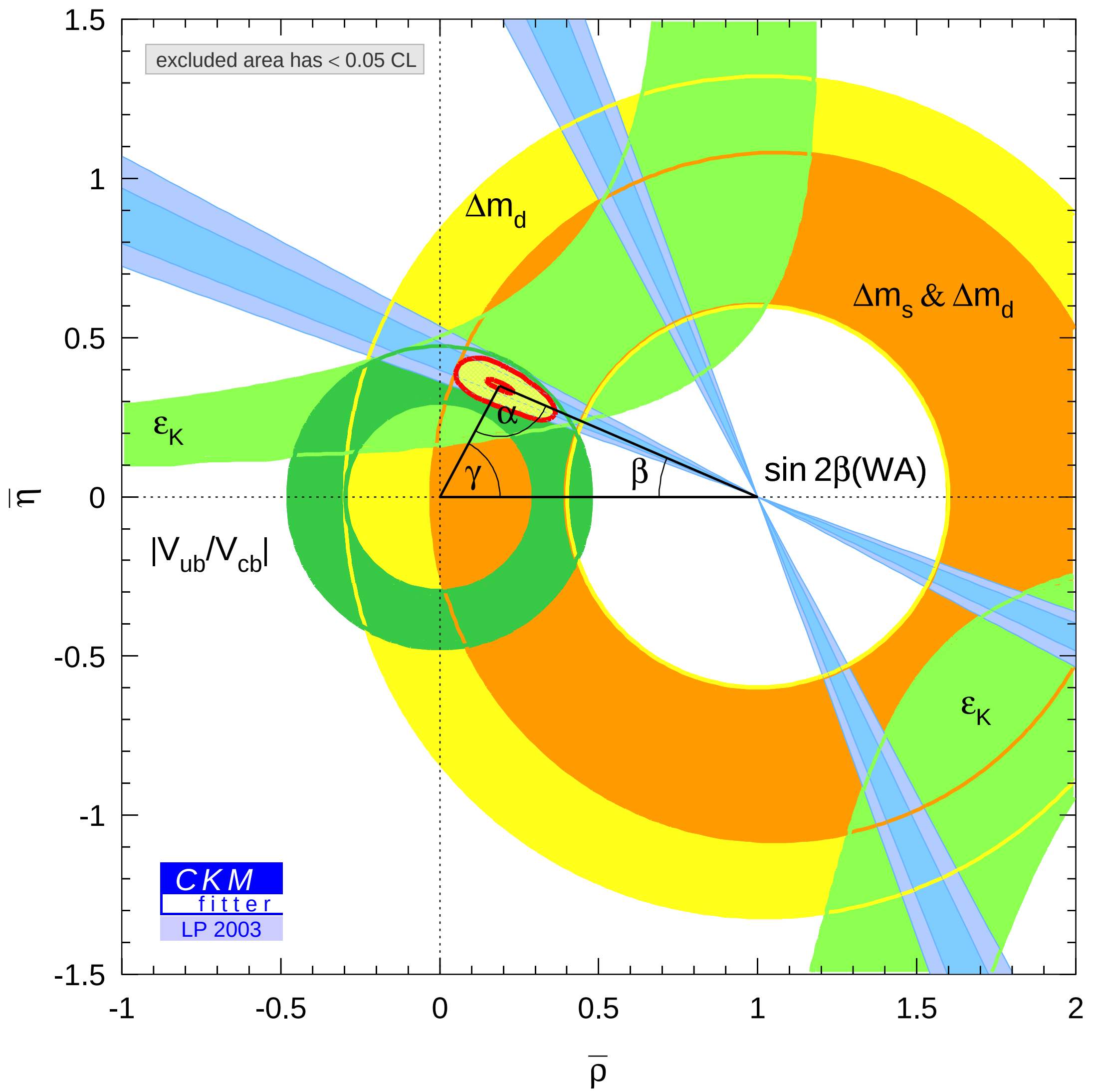




Evolution of field: 2003

Measurement of β in $b \rightarrow s$ penguin channels disagree with measurement from golden $B \rightarrow J/\Psi K^0_s$ channel.

See later ...

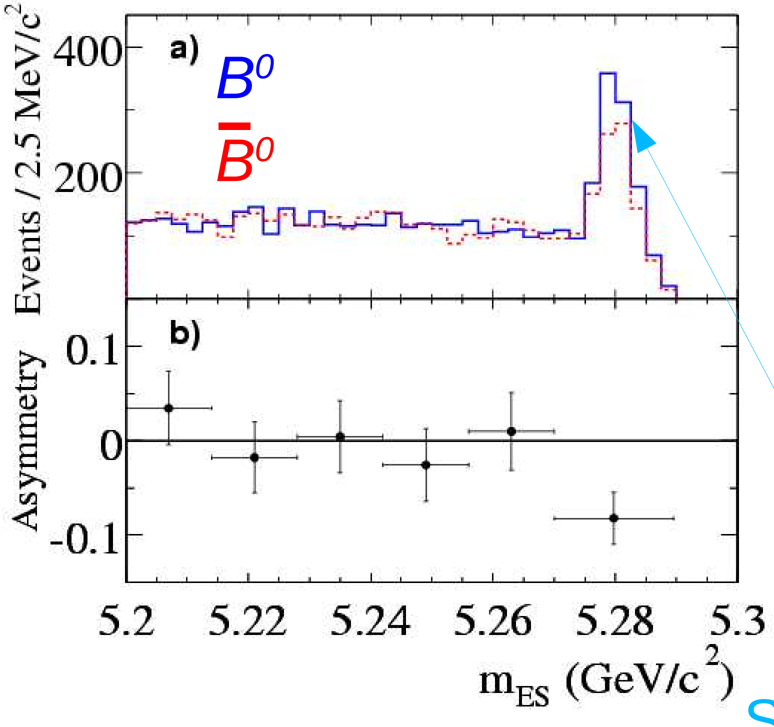


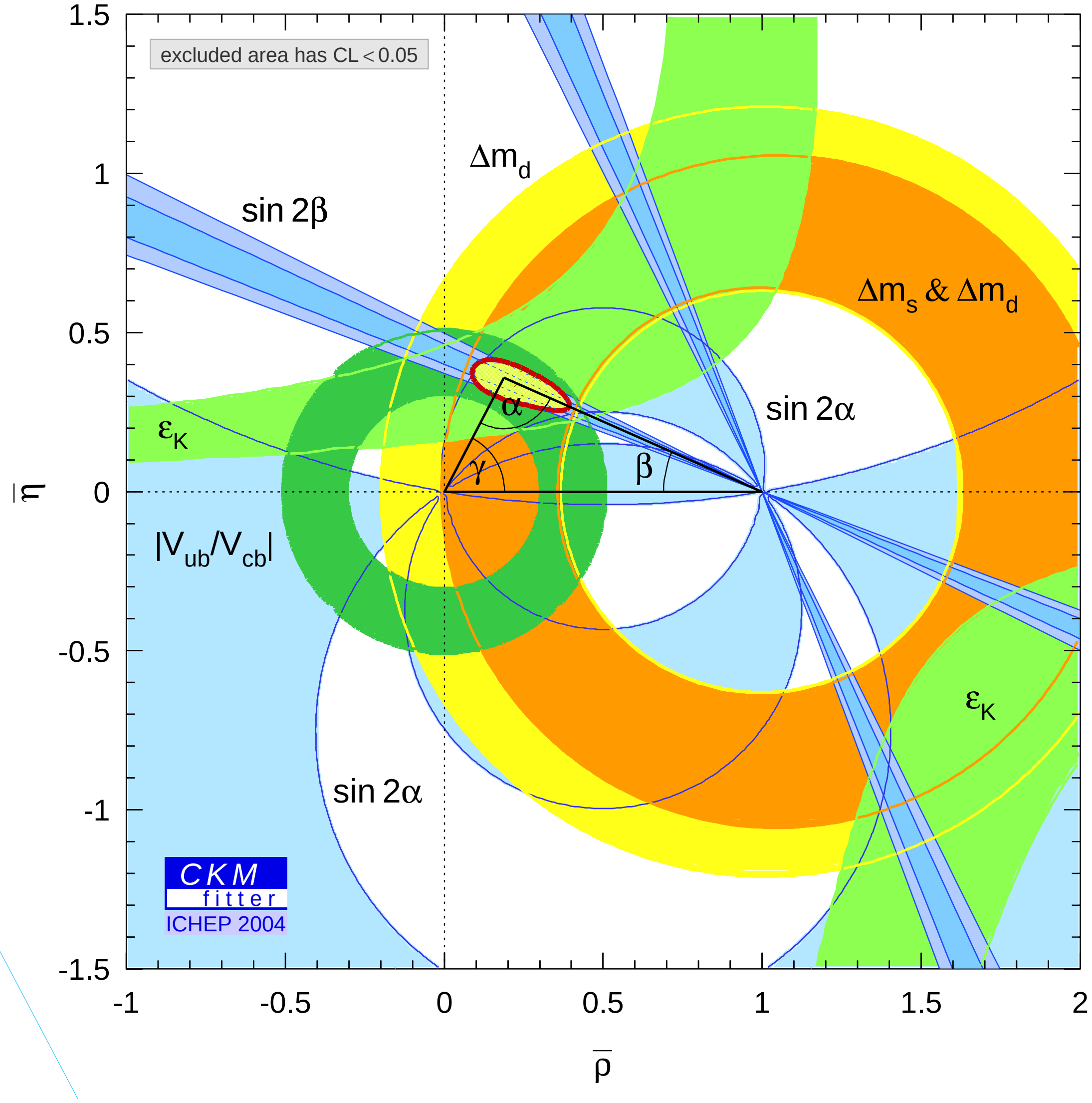
Evolution of field 2004

First measurements of α that sets any real constraints.

Constraint on $\cos(2\beta)$.

Direct *CP* violation in $B^0 \rightarrow K^+ \pi^-$.





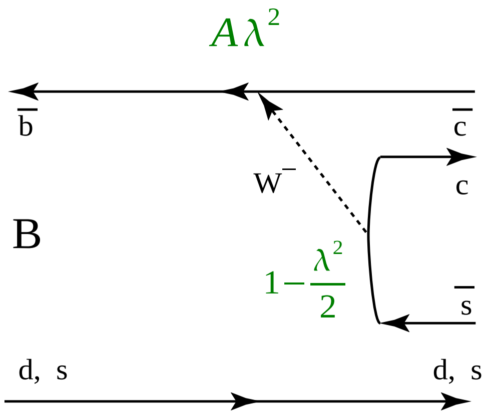
Significant difference in signal peak

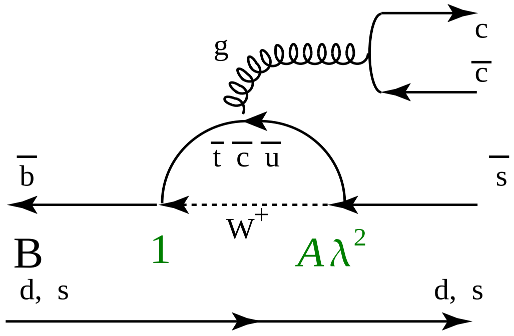
CKM angle β – the basic measurement

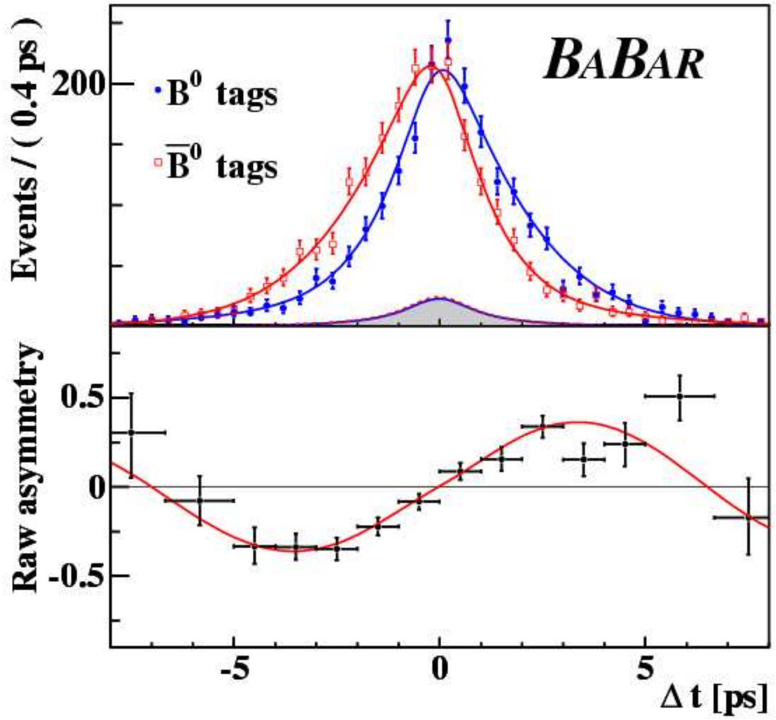
From $B \rightarrow J/\Psi K^0_s$.

Both tree and penguin diagram has no weak phase to leading order.

Only phase is from oscillation.







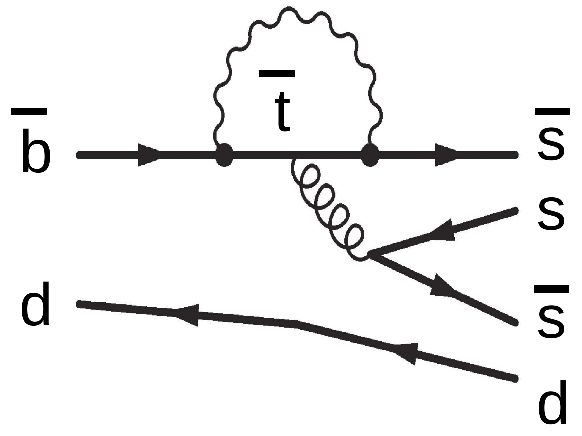
All $(c\bar{c})K^0_s$ modes can be combined.

Summer 2004 result for BaBar

$\sin(2\beta) = 0.722 \pm 0.040(\text{stat}) \pm 0.023(\text{syst})$

CKM angle β – recent developments

- In principle β can also be measured from $b \rightarrow s\bar{s}s$ penguin processes.
  - Again the only weak phases involved are from B_d mixing so sin(2β) is the expected amplitude in an asymmetry measurement.
  - No tree level diagram that has similar magnitude to penguin.



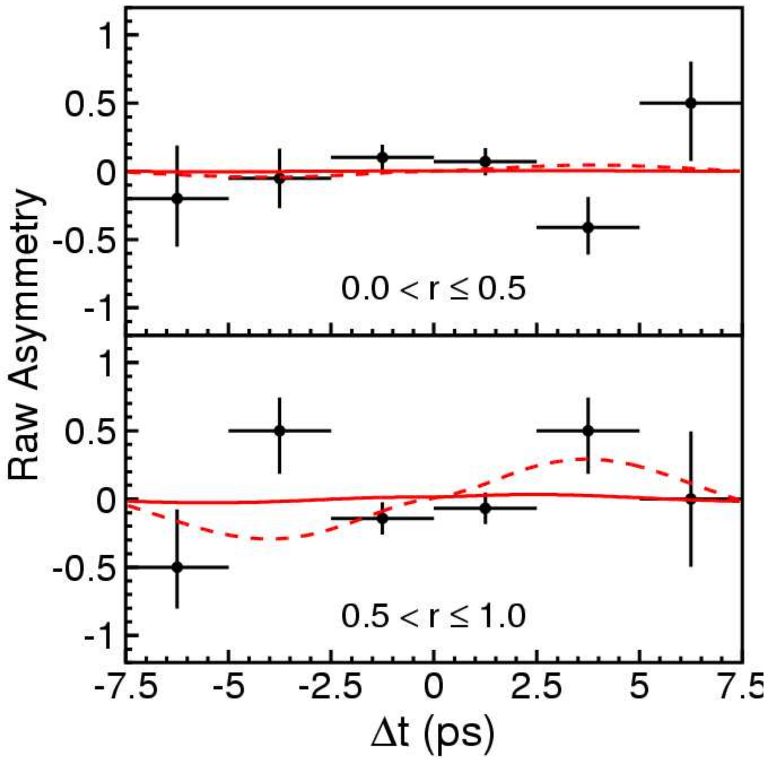
CKM angle β – recent developments

Belle results for $B^0 \to \phi K^0_S$ and $B^0 \to \phi K^0_L$.

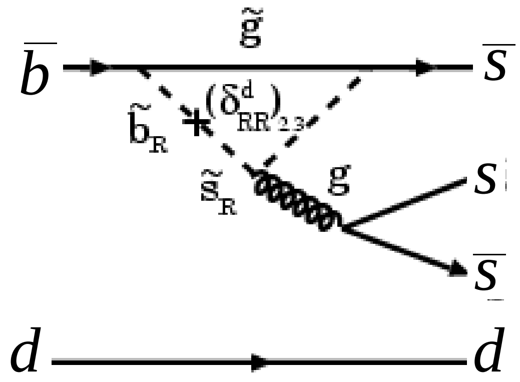
$S(\phi K^0) = +0.06 \pm 0.33 \pm 0.09$.

Around 2σ away from Standard Model (naïve expectation).

Other $b \to s$ penguin results point in same direction.

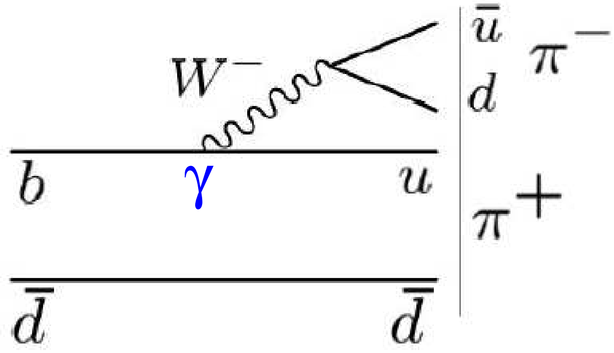


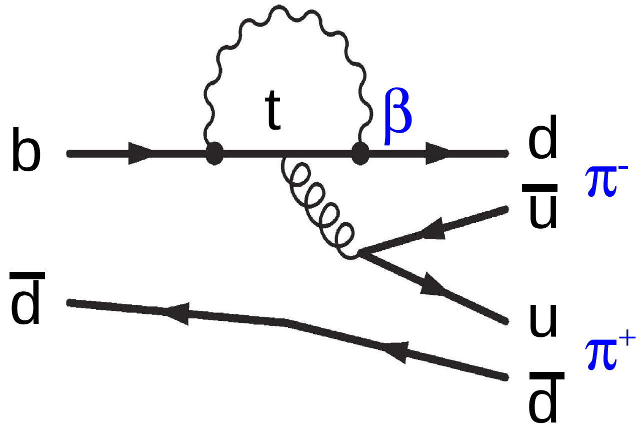
Could this be a sign of New Particles giving non-CKM phases in Penguin?



CKM angle α

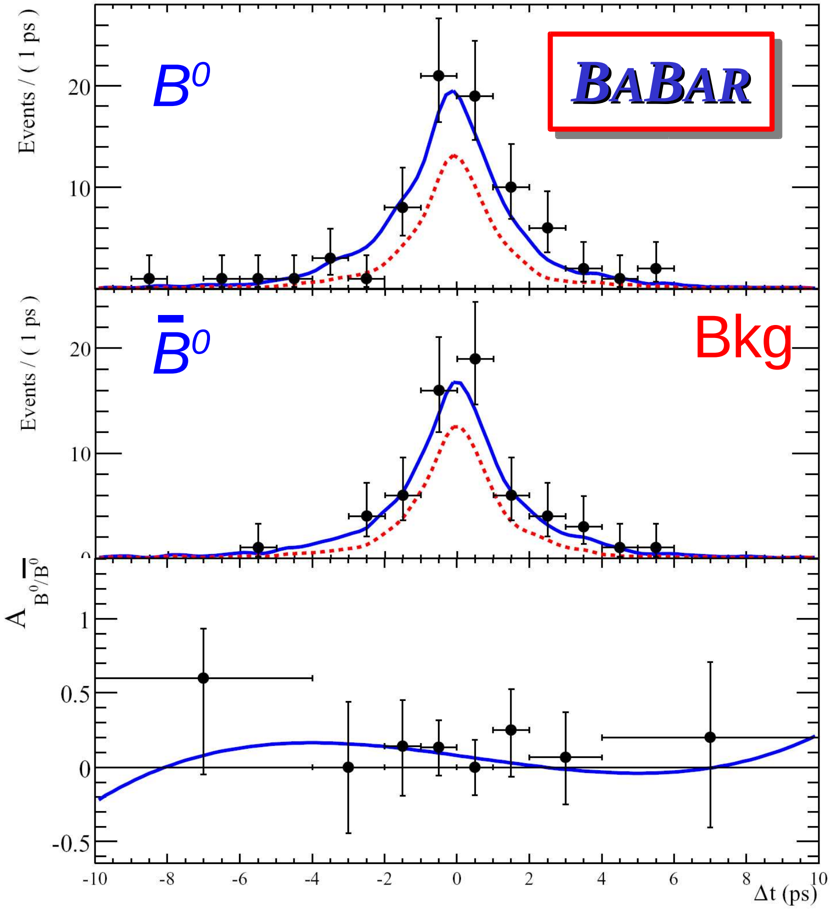
- In principle in should be very easy to get the CKM angle α from $B^0 \to \pi^+\pi^-$ decays.
  - Interference will be of amplitude $2\beta+2\gamma$ ($= 2\alpha$)
    - $B^0 \to \pi^+\pi^-$ gives phase γ
    - $B^0 \to \bar{B}^0 \to \pi^+\pi^-$ gives phase $-2\beta-\gamma$
  - Problem is that penguin is not suppressed and has different phase.
  - Measurement of the BFs of **all** $B \to \pi\pi$ modes can set upper limit on model dependent error.





CKM angle α – the $B \rightarrow \rho\rho$ channel

- New addition this year is to look at $B \rightarrow \rho\rho$ decays.
- Branching fractions more favourable for getting a small model dependent error.
- BaBar $B \rightarrow \rho^+\rho^-$ result based on 122M BB pairs:
  - S = -0.19 ± 0.33 ± 0.11
  - C = -0.23 ± 0.24 ± 0.14

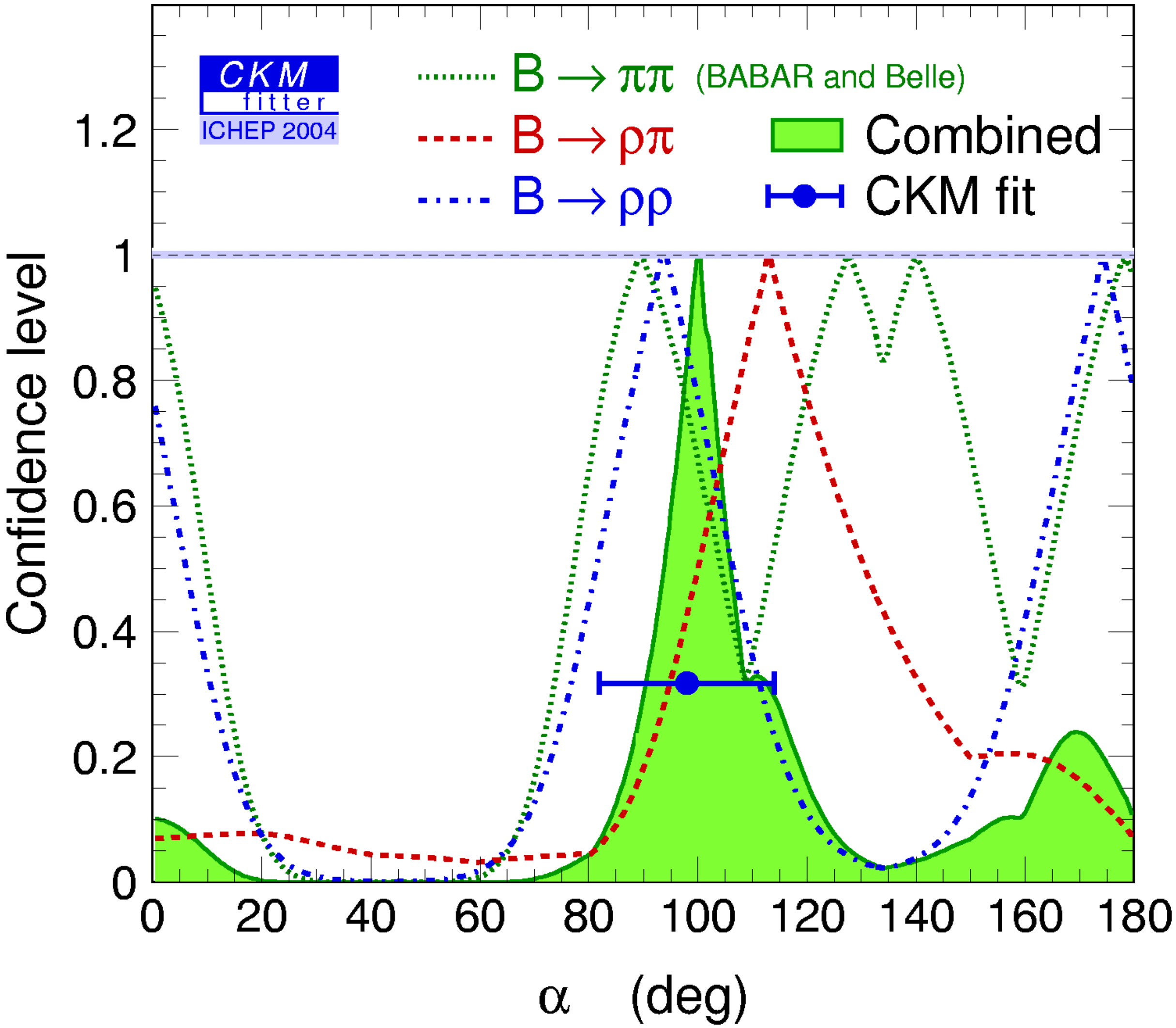


CKM angle α – the overall result

Combining all the a results

$\alpha = 100° \pm 12°$

Some effects neglected that will ultimately limit precision.



Current state of angles and sides

β

- Measurements much better than for any other angle. Will within a few years hit theoretical limit.

α

- Some further progress can be made at current experiments. Will still suffer from large theoretical uncertainty though.

γ

- The first tentative measurements are made. Will really need to wait for hadron machine experiments though.

χ

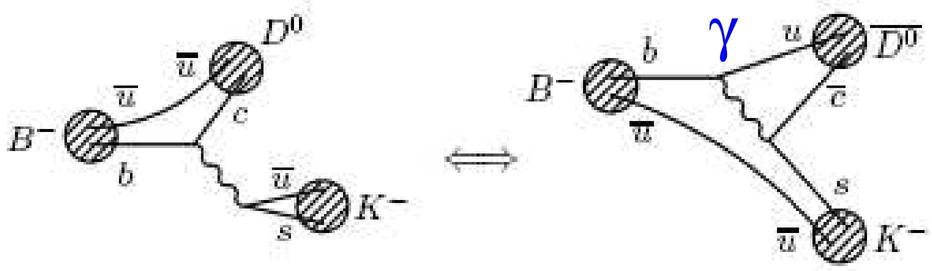
- Requires large amount of B_s decays so will have to wait for LHC.

Towards the future

- TeVatron ($p\bar{p}$ collisions at $\sqrt{s}$=2 TeV)
  - CDF and D0 record large samples of *B*-mesons
  - Should be able to observe SM B_s oscillations soon
    - If not this is a strong hint of New Physics.
- LHC (pp collisions at $\sqrt{s}$=14 TeV)
  - LHC*b* is the dedicated *B* experiment at LHC.
  - 10^{12} *B*'s will be produced in interaction region per year.
  - From 2007 this will be the next generation *B* experiment.
    - Will here only look at extraction of γ.
- Why do indirect searches for New Physics when we have ATLAS and CMS to discover SUSY particles.
  - The short answer is that the methods are very complimentary.

γ from $B^- \to (K_s\pi^-\pi^+)K^-$ decays

Nearly all methods for extracting γ relies on the interference between the $b \to c$ and $b \to u$ amplitude.



BR($B^+ \to D^0/\bar{D}^0 K^+$) = 4×10^{-4}.

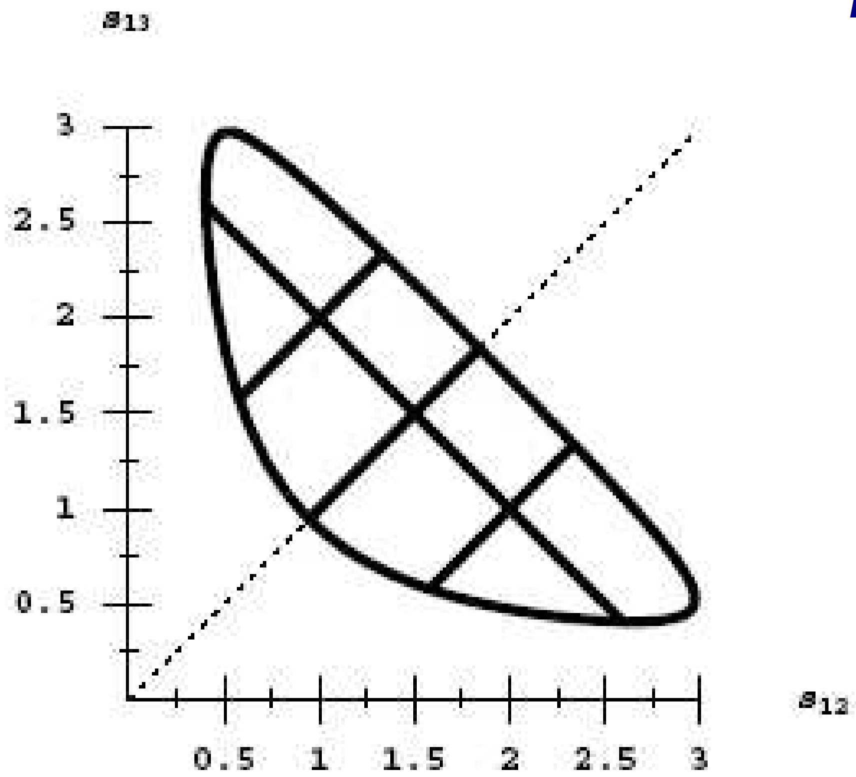
Method is **not** sensitive to New Physics as only tree level diagrams involved.

For this to work we need to look at common decay modes between D^0 and $\bar{D}^0$.

- With 2-body decays this forces us to look at Cabibbo suppressed and doubly Cabibbo suppressed modes.
- I will look at a single example here of a 3-body decay mode

γ from $B^- \rightarrow (K_s\pi^-\pi^+)K^-$ decays

[Zupan, Giri, Grossman, Soffer]

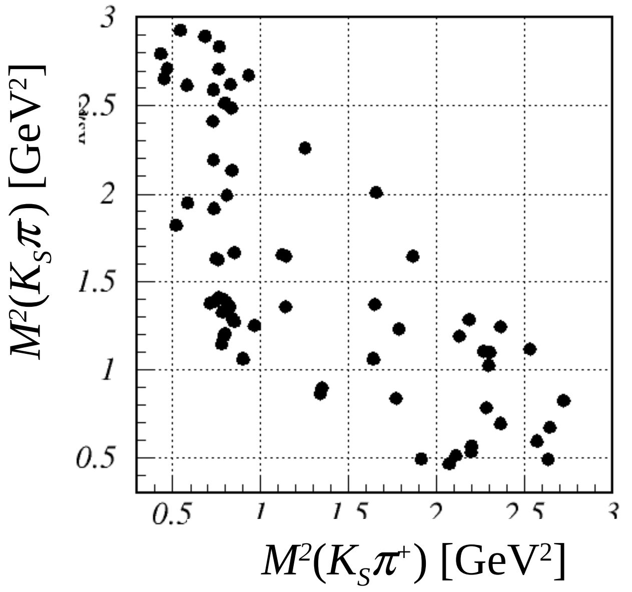


- Method to extract γ from 3-body decays of $B \rightarrow DK$ decays.
  - Extract γ without theoretical uncertainty from $B^+ \rightarrow D^0K^+$, $D^0 \rightarrow K^0_s\pi^+\pi^-$.
  - Only binning to Dalitz plot required (ie no full Dalitz fit).
- The idea is to divide Dalitz plot into 2n bins
  - Simple counting in each bin gives
    - 4n equations (2n for B^+, 2n for B^-)
    - $2n + r_B + \gamma + \delta$ unknowns.
  - Can be solved for γ if $n \geq 2$.

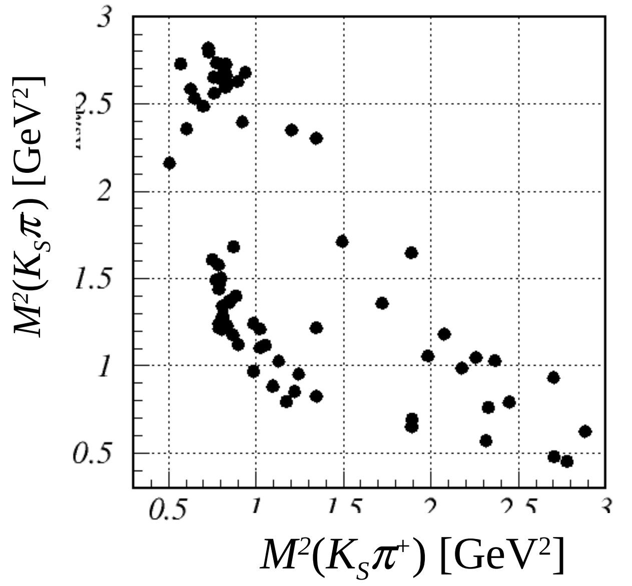
γ from $B^- \rightarrow (K_s\pi^-\pi^+)K^-$ decays – Belle

- The concept of this method has already been proved by Belle.
  - But model dependence from Dalitz plot parametrisation
  - Necessary due to statistics too low for binned method.
- Asymmetry visible by eye.
  - $26° < \gamma < 126°$ [95% CL]

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



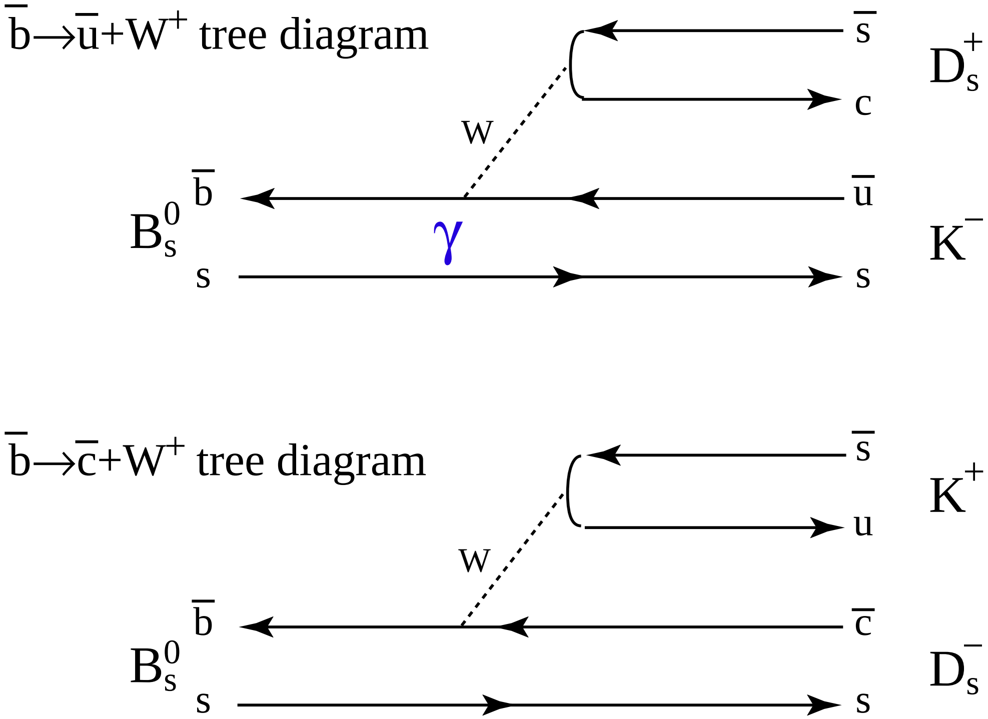
$B^- \rightarrow D^0 K^-$



γ from $B_s \to D_s^{\pm} K^{\mp}$, $B_d \to D^{*\pm} \pi^{\mp}$

[Alexan, Dunietz, Kayser]

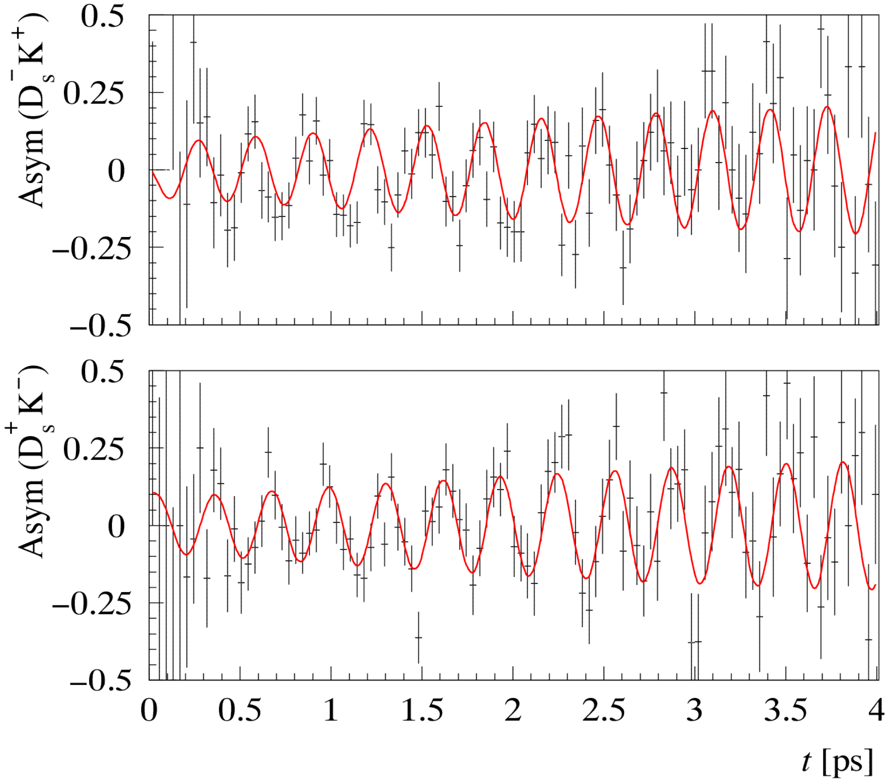
- Asymmetry $A_f(t)$ for decay into non-*CP* eigenstate *f*.
  - Both *B* and $\overline{B}$ can decay into *f*.
- Interference between two tree diagrams so we measure γ unaffected by new physics.
- Method only works if we have flavour tagging fully under control.
  - We need to distinguish $B \to f$ from $\overline{B} \to f$.



γ from $B_s \to D_s^{\pm} K^{\mp}$, $B_d \to D^{*\pm} \pi^{\mp}$

- $B_s \to D_s^{\pm} K^{\mp}$ (small statistics)
  - Mistag rate from $B_s \to D_s^{-} \pi^{+}$.
  - $\sigma(\gamma) \approx 14^{o}$ in one year at LHC*b* with no theoretical uncertainty.
- For $B_d \to D^{*\pm} \pi^{\mp}$ (large statistics)
  - Some theoretical uncertainty introduced as we can't measure $\Delta\Gamma_d$.
- Both methods have 8-fold ambiguity in measurement.

$B_s \to D_s^{\pm} K^{\mp}$ asymmetries after 5 years



γ from $B_d \to \pi^+\pi^-$ / $B_s \to K^+K^-$

[Fleischer]

The transition amplitude for $B_d \to \pi^+\pi^-$ is $A(B_d^0 \to \pi^+\pi^-) \propto [e^{i\gamma} - d\,e^{i\theta}]$

If no penguin contributions this leads to the familiar (but inaccurate) prediction $\mathcal{A}_{CP}^{dir}(B_d \to \pi^+\pi^-) = 0$ and $\mathcal{A}_{CP}^{mix}(B_d \to \pi^+\pi^-) = \sin(\phi_d + 2\gamma)$.

An elegant approach to avoid the uncertainty from penguin contributions is to add the $B_s \to K^+K^-$ decay with transition amplitude

$$A(B_s^0 \to K^+K^-) \propto \left[e^{i\gamma} - \left(\frac{1-\lambda^2}{\lambda^2} \right) d'\,e^{i\theta'} \right]$$

In the limit of U-spin ($d \leftrightarrow s$ quark interchange) symmetry we have $d = d'$ and $\theta = \theta'$ which gives us 4 measurables with γ, θ and δ as unknown parameters:

$$\mathcal{A}_{CP}^{dir}(B_d \to \pi^+\pi^-) = f_1(\phi_d, \gamma, \theta, \delta) \qquad \mathcal{A}_{CP}^{dir}(B_s \to K^+K^-) = f_2(\phi_s, \gamma, \theta, \delta)$$

$$\mathcal{A}_{CP}^{mix}(B_d \to \pi^+\pi^-) = f_3(\phi_d, \gamma, \theta, \delta) \qquad \mathcal{A}_{CP}^{mix}(B_s \to K^+K^-) = f_4(\phi_s, \gamma, \theta, \delta)$$

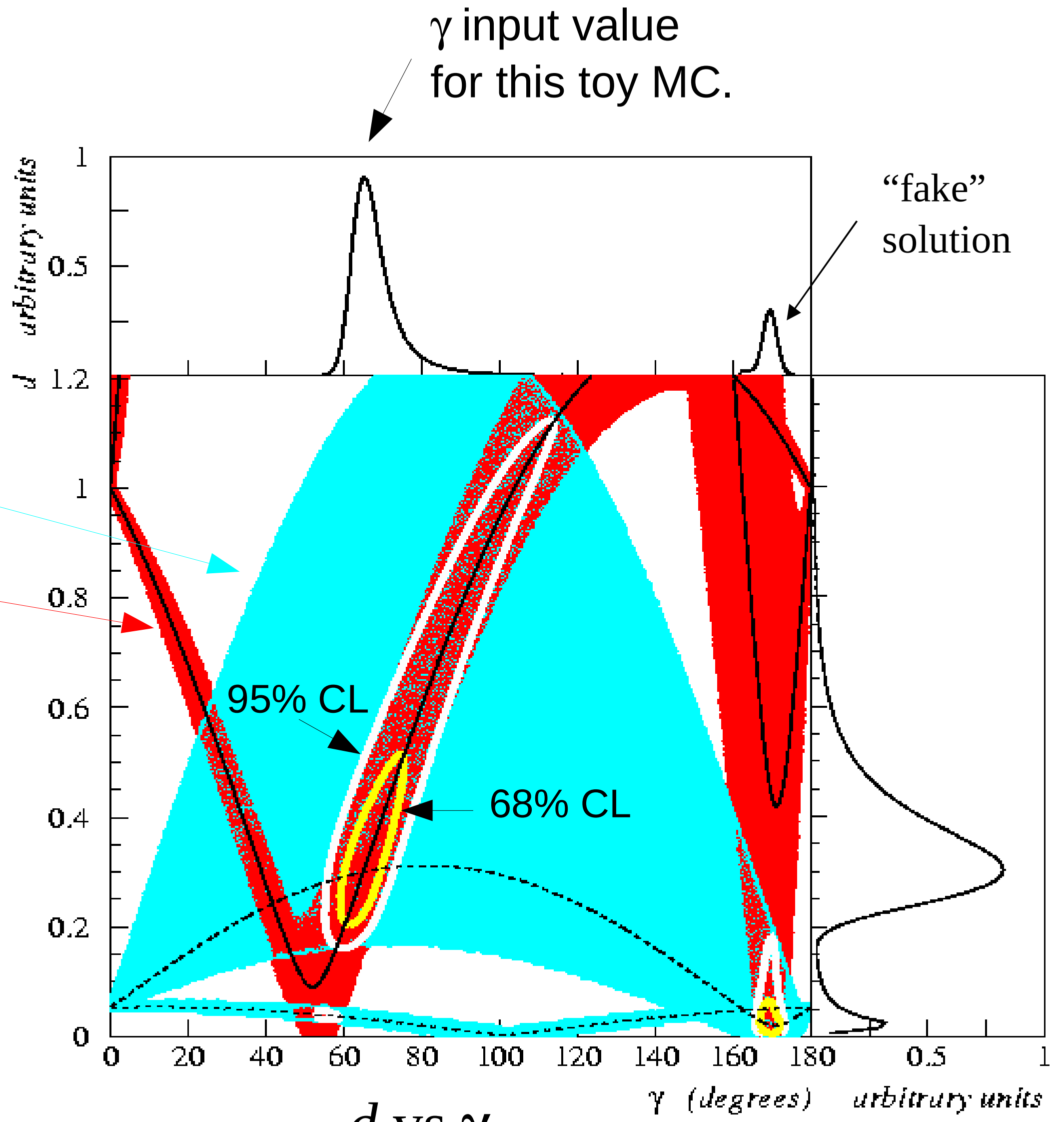
γ from $B_d \rightarrow \pi^+\pi^-$ / $B_s \rightarrow K^+K^-$

A Toy Monte Carlo study shows LHCb resolution after one year.

Theoretical input on penguin contribution not required.

- $B_s \rightarrow K^+K^-$ (95%CL).
- $B_d \rightarrow \pi^+\pi^-$ (95%CL).

Resolution in one year is 4°–6°.



d vs γ

Do we really measure what we think we do?

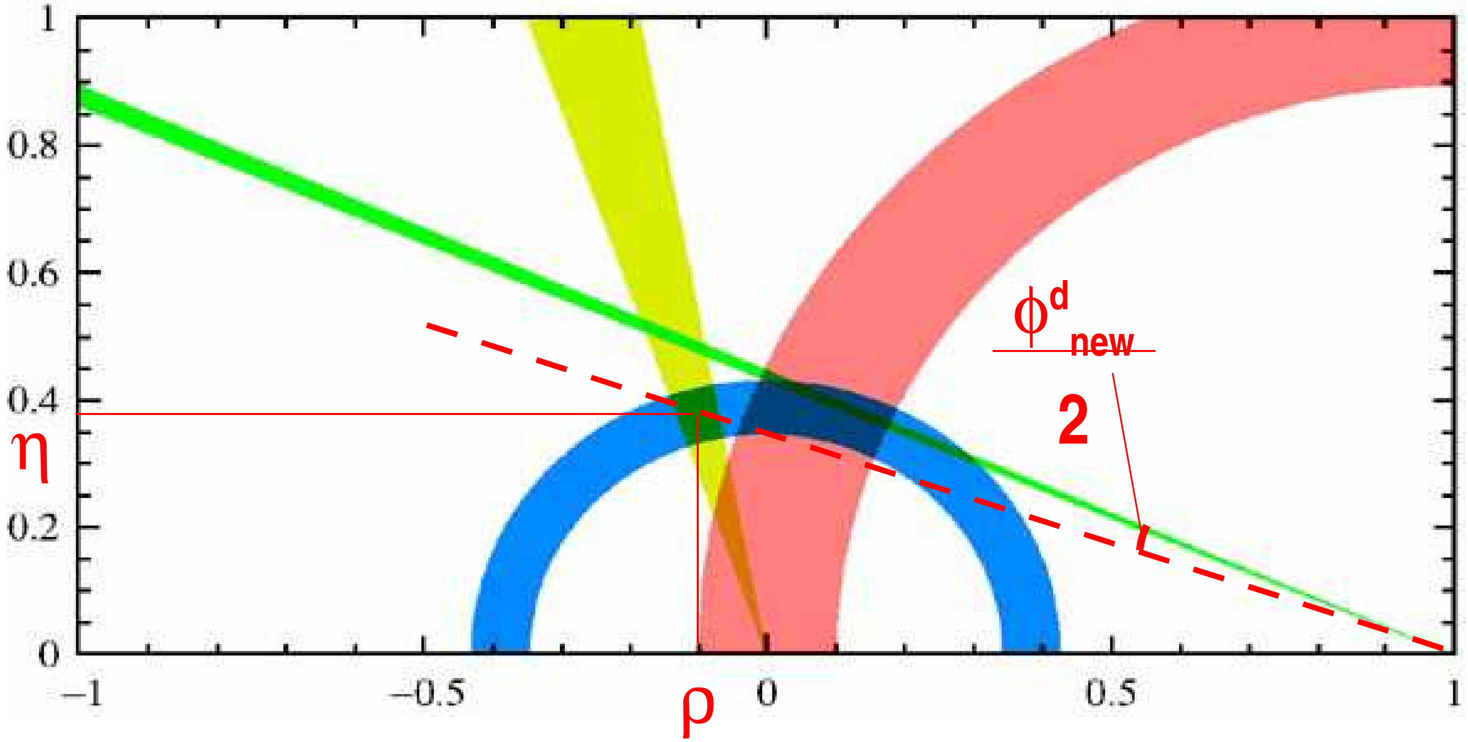
- The *CP* violating phase in the CKM matrix is a free parameter of the Standard Model.
  - To be able to see New Physics as a deviation from the Standard Model we need first to know the SM value.
  - Reference measurements where we know New Physics doesn't enter are required.
    - Channels with only tree level diagrams.
    - None of the current *B*-factory results acts as this reference.
  - New γ measurements are the most obvious place for this.
- Several smoking guns required before we will believe in non SM effects.
  - Single results like the $\sin(2\beta)$ penguins can always be explained away.

Channels sensitive to SM and to New Physics

Look at hypothetical case with two different triangles.

- One from $B_d \rightarrow J/\Psi\, K_s^0$ and B_d mixing affected by New Physics
- One from $B_s^0/\overline{B_s^0} \rightarrow D_s^{\pm}\pi^{\mp}$ and $|V_{ub}|/|V_{cb}|$ showing the SM value.

If triangles do not match we have New Physics!



Conclusion

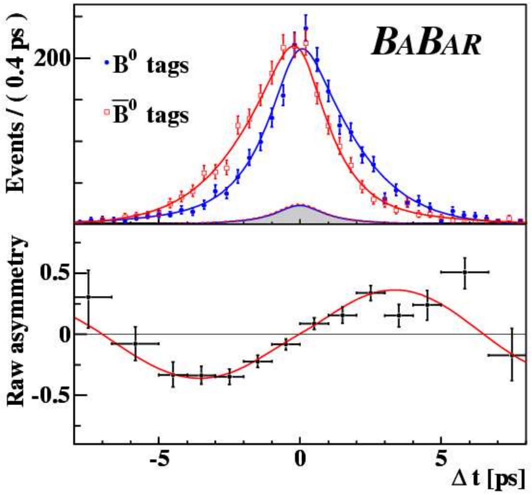
Large improvements have been made in our understanding of Heavy Flavour physics over the last 4 years:

- *CP* violation in *B* sector discovered
- Flavour physics in now the area of precision testing of the Standard Model.

Much exciting work ahead with next generation *B* experiment.

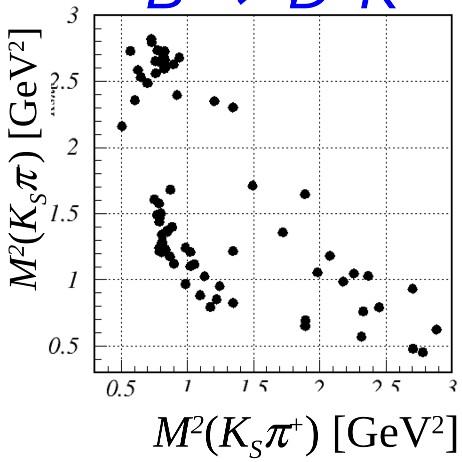
- A great time to join a *B* experiment.

Precision

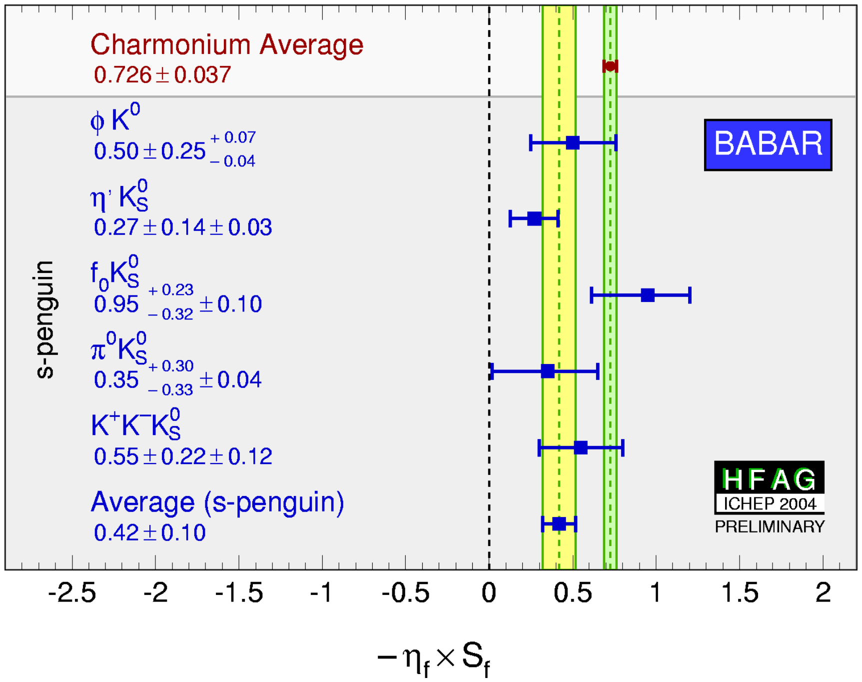


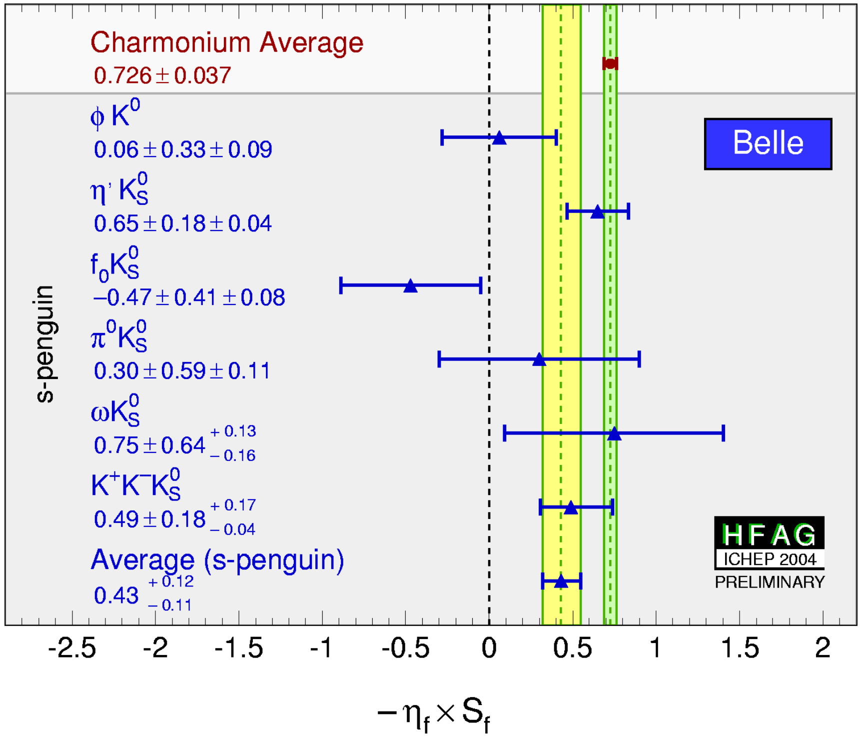
Towards γ

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



Backup: All "sin(2β)" measurements





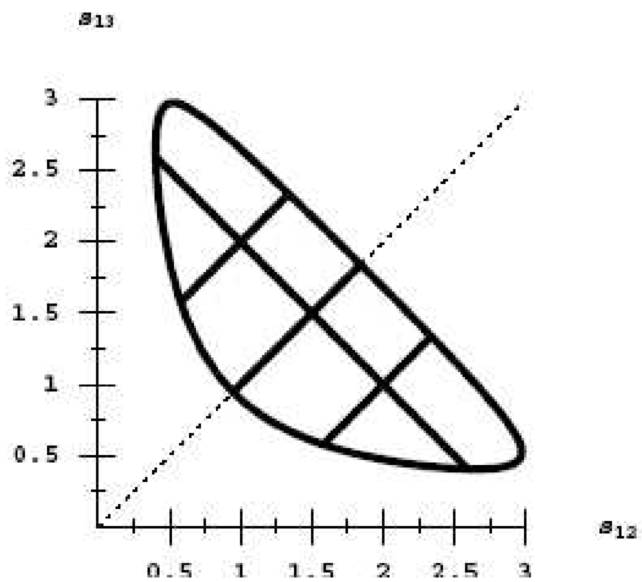
γ from $B^- \to (K_s \pi^- \pi^+) K^-$ decays

$$\Gamma^{-}_{i} \equiv \int_i d\Gamma(B^- \to (K_S\, \pi^-\, \pi^+)_D K^-) = T_i + r_B^2 T_i + 2r_B[c_i \cos(\delta_B - \gamma) + s_i \sin(\delta_B - \gamma)]$$

$$\Gamma^{-}_{i} \equiv \int_i d\Gamma(B^- \to (K_S\, \pi^-\, \pi^+)_D K^-) = T_i + r_B^2 T_i + 2r_B[c_i \cos(\delta_B - \gamma) - s_i \sin(\delta_B - \gamma)]$$

$$\Gamma^{+}_{i} \equiv \int_i d\Gamma(B^+ \to (K_S\, \pi^-\, \pi^+)_D K^+) = T_i + r_B^2 T_i + 2r_B[c_i \cos(\delta_B + \gamma) - s_i \sin(\delta_B + \gamma)]$$

$$\Gamma^{+}_{i} \equiv \int_i d\Gamma(B^+ \to (K_S\, \pi^-\, \pi^+)_D K^+) = T_i + r_B^2 T_i + 2r_B[c_i \cos(\delta_B + \gamma) + s_i \sin(\delta_B + \gamma)]$$



T terms can be determined from flavour tagged Dalitz plot, ie where we know if it was a D^0 or $\bar{D}^0$ that decayed.

The c and s terms are unknown as are r_B, δ_b and γ.

With statistics for enough bins (more than 2 on each side) we can solve for all unknowns.

If r_B is smaller than expectation (~0.1) method is less sensitive.

γ from $B_s \to D_s^{\pm} K^{\mp}$, $B_d \to D^{*\pm} \pi^{\mp}$

[Alexan, Dunietz, Kayser]

Asymmetry $A_f(t)$ for decay into non-*CP* eigenstate *f*.

Both *B* and $\overline{B}$ can decay into *f*.

$|\eta|^2$ from here

$$\mathcal{A}^{dir} = \frac{1-|\eta|^2}{1+|\eta|^2}$$

$|\eta|\sin(\delta+(\phi+\gamma))$ from here

$$\mathcal{A}^{mix} = \frac{2\,\Im(\eta)}{1+|\eta|^2}$$

$$A_f(t) = \frac{\mathcal{A}^{dir}\cos(\Delta m t) + \mathcal{A}^{mix}\sin(\Delta m t)}{\cosh(\Delta\Gamma t/2) + \mathcal{A}^{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}$$

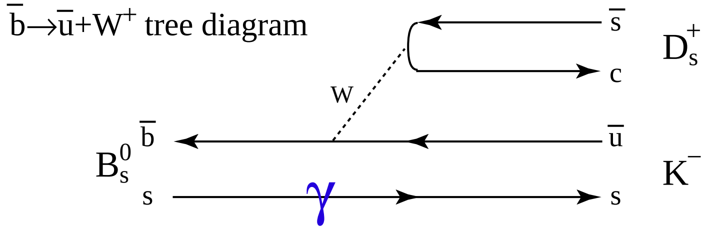
($\Delta\Gamma$ from here)

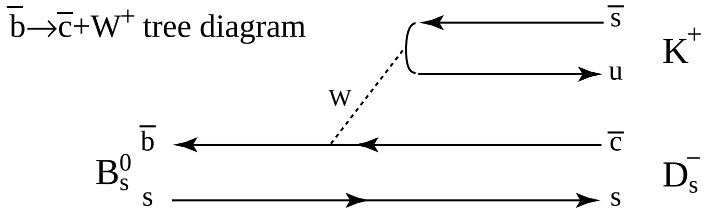
$$\mathcal{A}^{\Delta\Gamma} = \frac{2\,\Re(\eta)}{1+|\eta|^2}$$

$|\eta|\cos(\delta+(\phi+\gamma))$ from here

ϕ is the B_d/B_s oscillation phase.

[We get $\delta-(\phi+\gamma)$ from *CP* conjugate of *f*]





Interference between two tree diagrams so we measure γ unaffected by new physics.