Standard Model and CKM Physics at the B Factories: Legacy for LHC

SLAC Summer Institute
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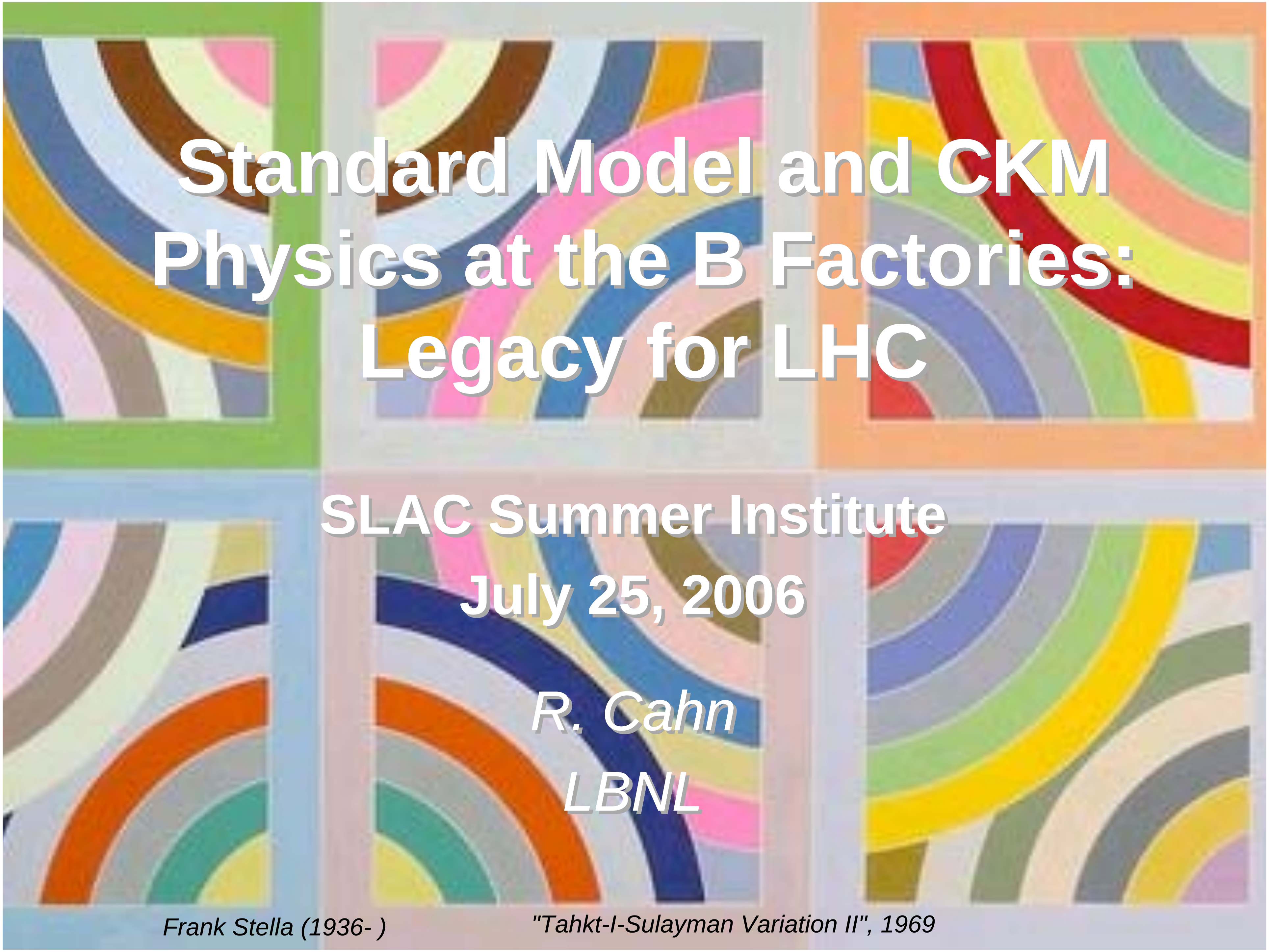
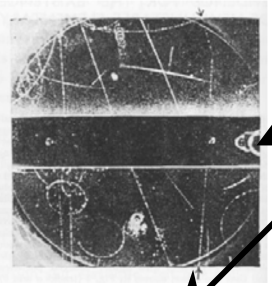
LBNL



Frank Stella (1936-) *"Tahkt-I-Sulayman Variation II", 1969*

The Kaon Taught Us Most of 20th Century Particle Physics

- Strangeness
- Oscillations
- Parity Violation
- CP Violation
- Quarks
- No flavor-changing neutral currents



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Scanned at the American Institute of Physics

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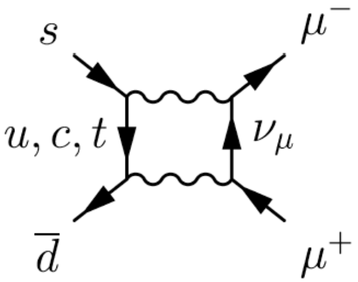
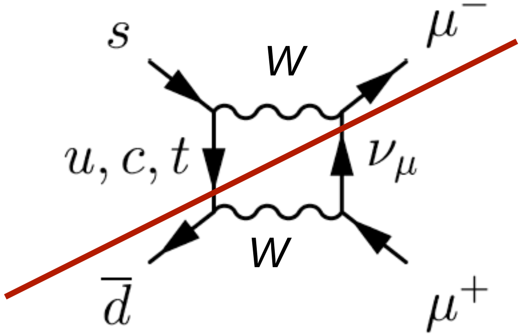
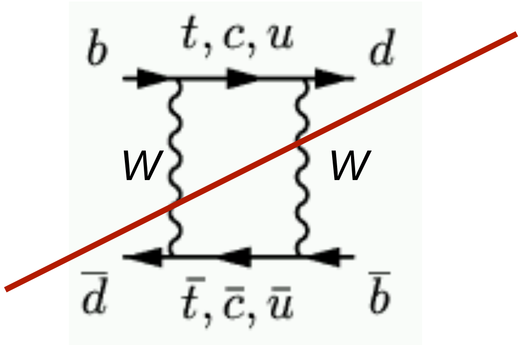


$K_L \to \mu^+\mu^-$

No Flavor-Changing Neutral Currents

BF=7 x 10^{-9}





If quarks were degenerate we could define away CKM angles. Only d→u, s→c, b→t transitions.

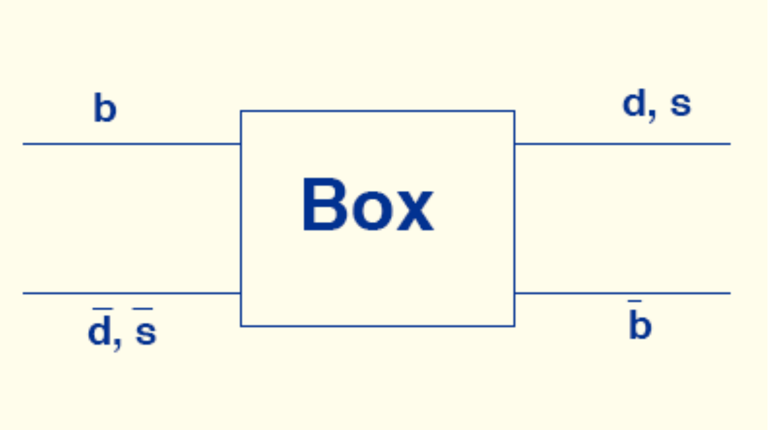
FCNC Effects $\propto \Delta m_q^2 / M_W^2$

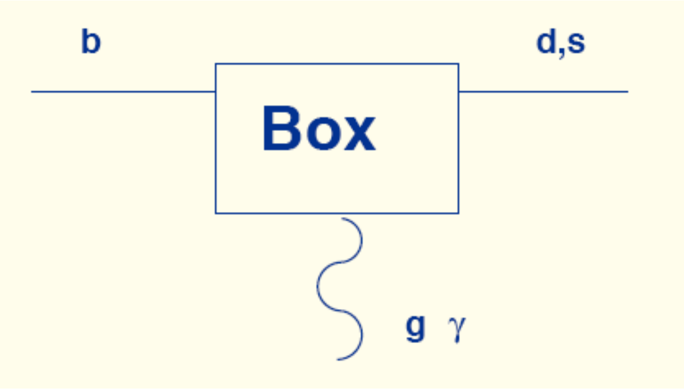
New physics must not upset delicate balance suppressing FCNC.

FCNC come from loops (boxes).

Will B Mesons be the K Mesons of the 21st Century?

The New Physics is hidden in the boxes of mixing and penguins, together with the old physics due to unequal quark masses.





Two Approaches

B physics:

shake the Box, listen

Some pieces might be heard without being seen.

The sound you hear is flavor-changing neutral currents!

LHC: open the Box

Even LHC scissors might not be strong enough.

$$b \to s\gamma$$

$$b \to sg$$

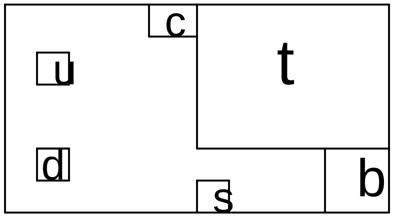
$$b\bar{d} \to \bar{b}d$$

Listening for Flavor-Changing Neutral Currents

If all quarks had the same mass we could pack them perfectly and not a sound would be heard.

u	c	t
d	s	b

Because the *t* is heavy, they rattle around.



How B Physics Could Play Decisive Role in LHC Era

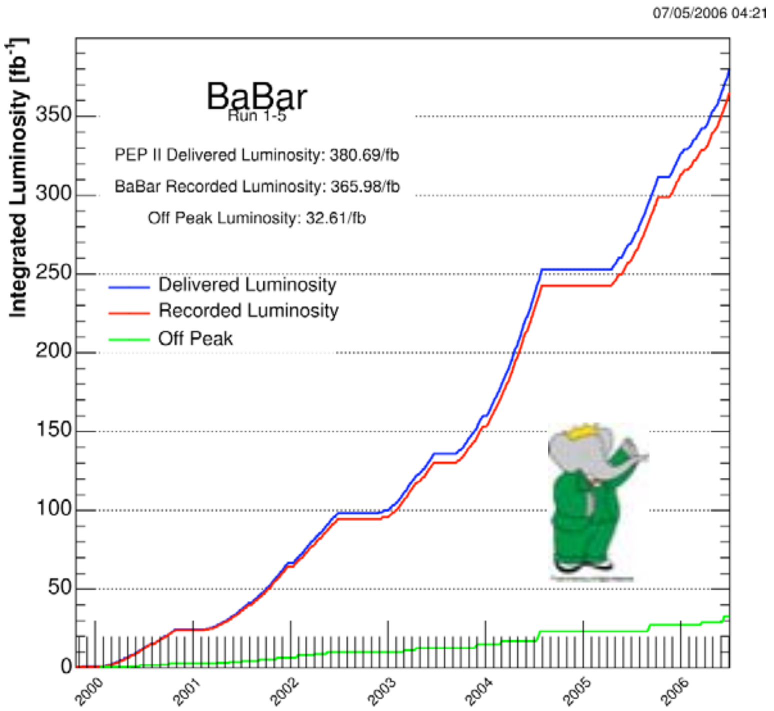
- Challenge at LHC likely to be relationships among the new particles and between old and new particles:
  - Do the new particles fit snugly together because they are degenerate in mass?
  - Are the new particles aligned in just the same way the quarks are aligned, so we hear the same sounds?

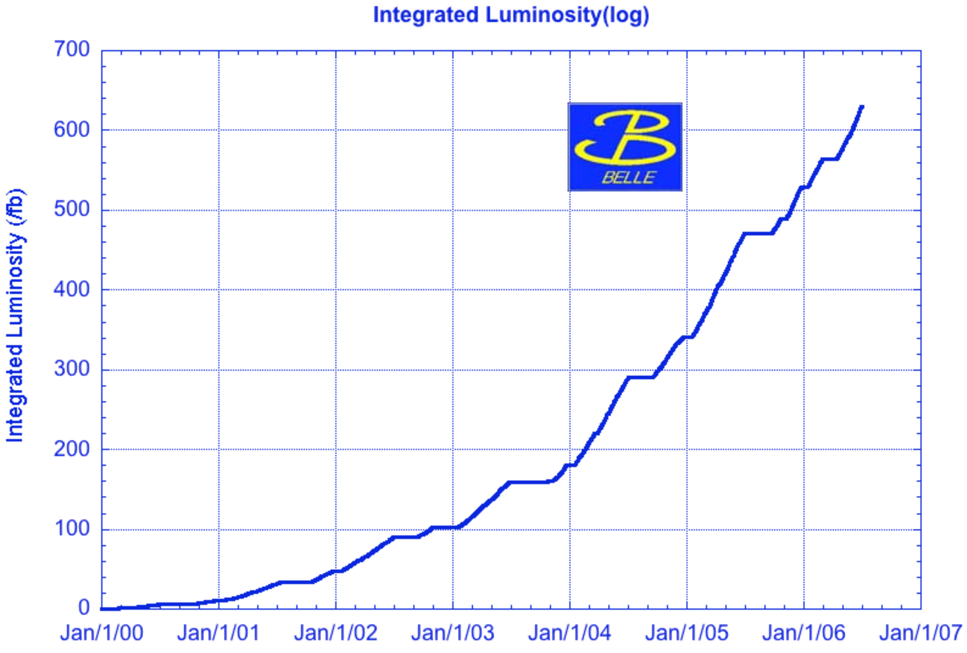
- High precision data, *either agreeing with or contradicting Standard Model*, likely be essential in revealing the structure of new physics.

Real Power of B Factories Comes in the Long Term

- To demonstrate *on their own* a failure of the Standard Model Belle/BaBar need a 5-σ effect.
- An isolated effect would be hard to interpret, with myriad models to choose from.
- LHC results should lead to restricted set of models.
- Results from B factories, *patterns of 3-σ deviations or even precisely confirmed agreement with the Standard Model*, would powerfullly constrain the interpretation of LHC results.

Outperforming Expectations





1 ab^{-1} achieved. On the way to 2.5 ab^{-1}.

Overall Strategy

- New physics involves heavy particles that cannot be produced and thus appear only in loops. (K. Kinoshita's talk)
  - Mixing is intrinsically a loop process.
  - "Penguin" process also are loops.
- Comparison between "tree" (non-loop) and loop processes is key.
- Focus here is "tree" decays and mixing.

Unitarity Triangle

Weak decay: $d \to V_{ud}u + V_{cd}c + V_{td}t$

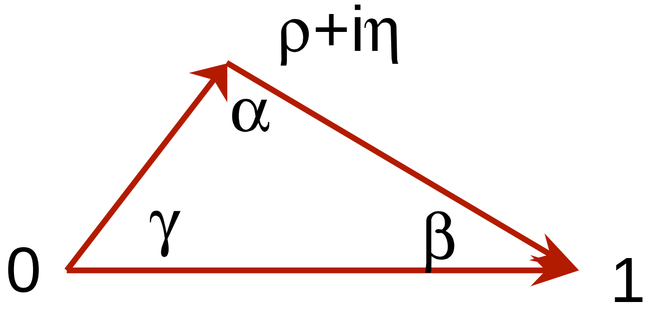
$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein convention:

Expand in $\lambda \approx 0.22$.

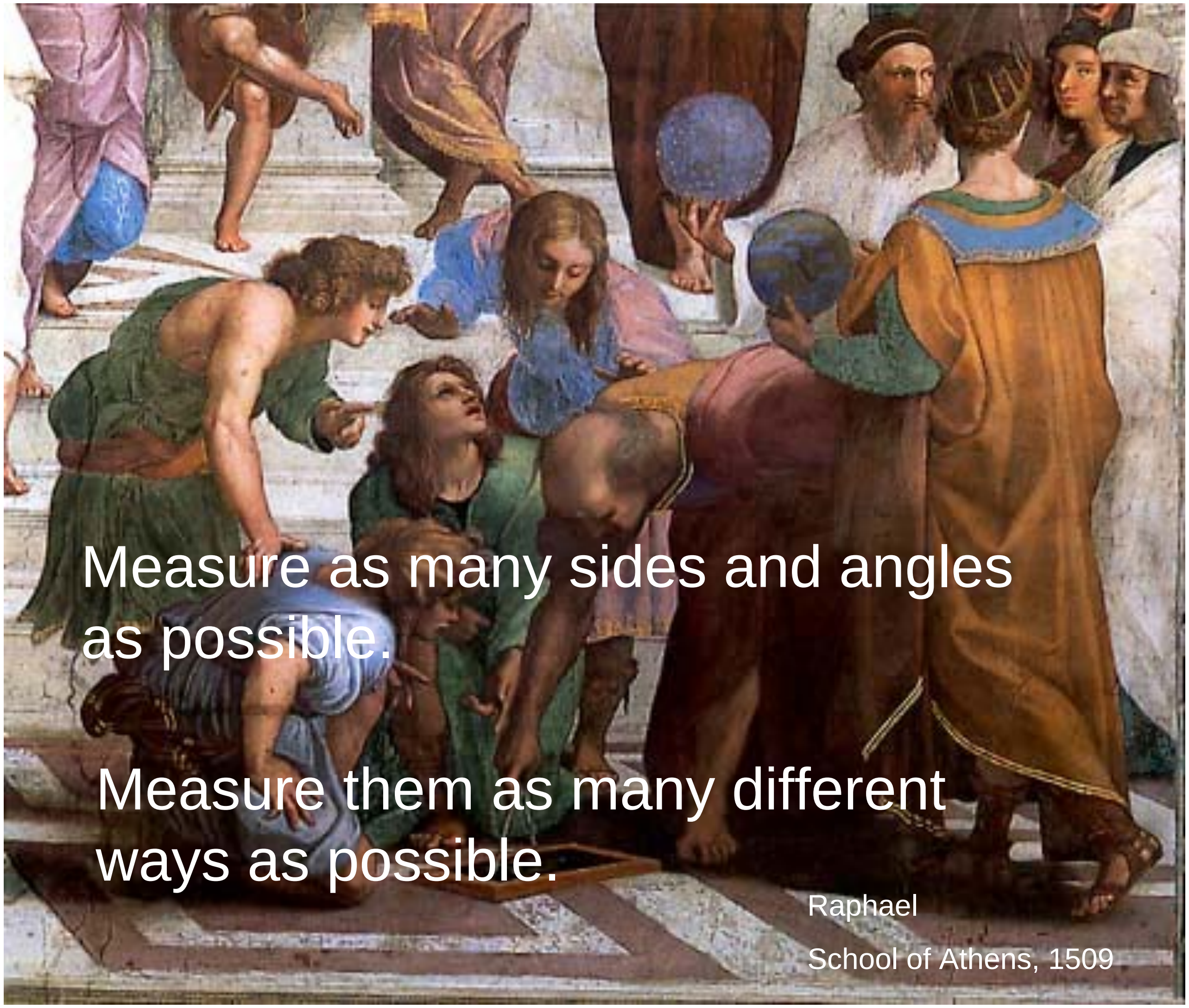
A unitary transformation so

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



CKM matrix elements convention-dependent, but angles aren’t.

Basic Strategy



Measure as many sides and angles as possible.

Measure them as many different ways as possible.

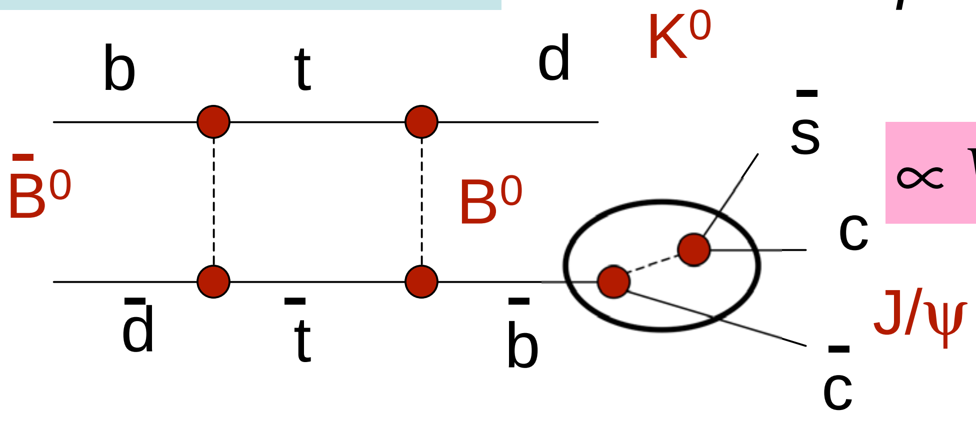
Raphael

School of Athens, 1509

CP Violation in $B \to J/\psi\ K_S$

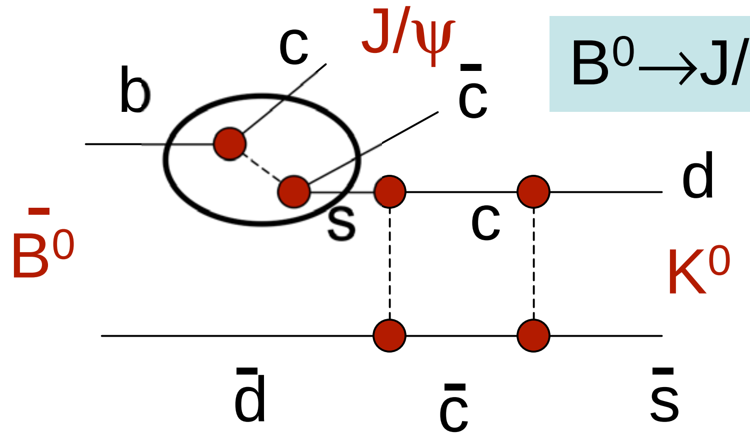
Dynamics cancels: relative amplitude depends just on phases.

$\bar{B}^0 \to B^0 \to J/\psi\ K^0$



$$\propto V_{tb}^{2} V_{td}^{*2} V_{cb}^{*} V_{cs}$$

$B^0 \to J/\psi\ \bar{K}^0 \to J/\psi\ K^0$



$$\propto V_{cb} V_{cs}^{*} V_{cs}^{2} V_{cd}^{*2}$$

Relative phase:

$$\frac{V_{cb} V_{cd}^{*}}{V_{cb}^{*} V_{cd}} \frac{V_{tb}^{*} V_{td}}{V_{tb} V_{td}^{*}} = e^{-2i\beta}$$

All observables are independent of phase convention.

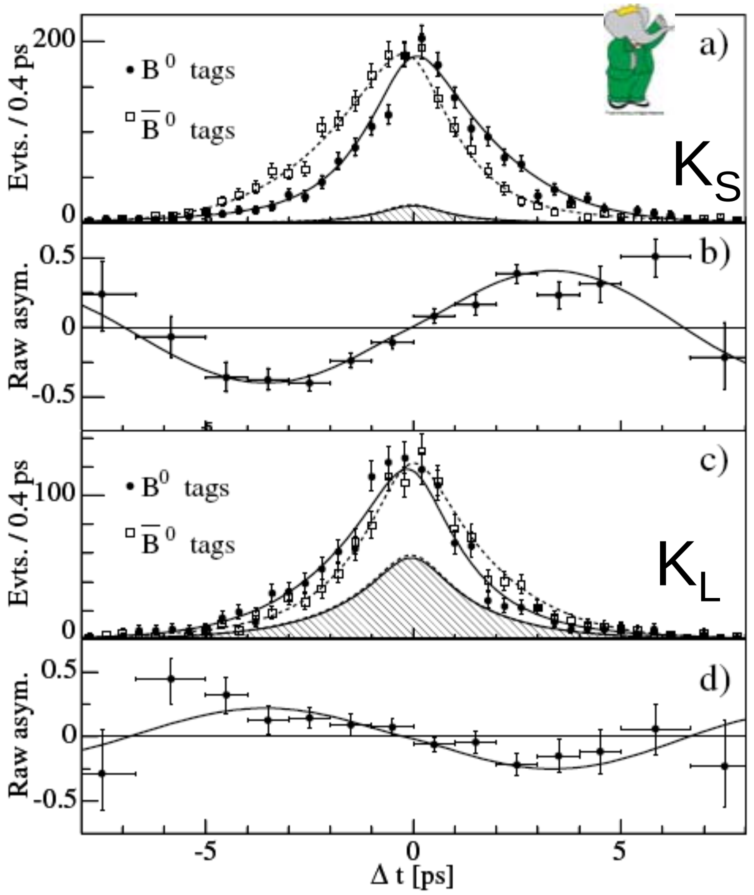
Measurement of sin 2β

Generally, because of oscillations of neutral B mesons, their decay rates are not exponential, but rather

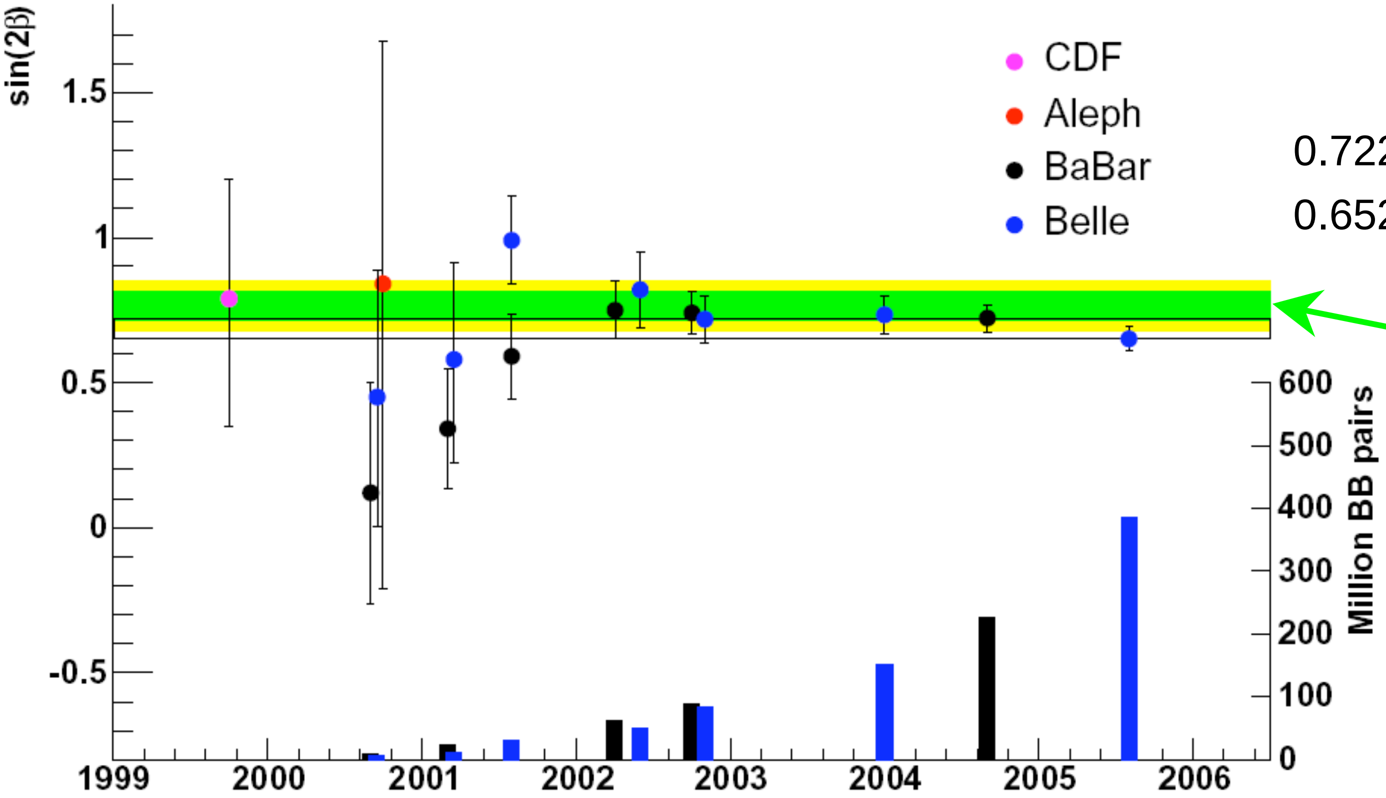
$$\Gamma(\overline{B}^0 \to f) \propto (1 + S\sin\Delta mt - C\cos\Delta mt)e^{-\Gamma|t|}$$

$$\Gamma(B^0 \to f) \propto (1 - S\sin\Delta mt + C\cos\Delta mt)e^{-\Gamma|t|}$$

If one decay mechanism,e.g. $B \to J/\psi\ K_s$: S=sin 2β, C=0



Sin 2β from J/ψ $K_{S,L}$: Progress and Surprise



PRL 94, 161803 (2005)

0.722 ± 0.040 ± 0.023

0.652 ± 0.039 ± 0.020

hep-ex/0507037

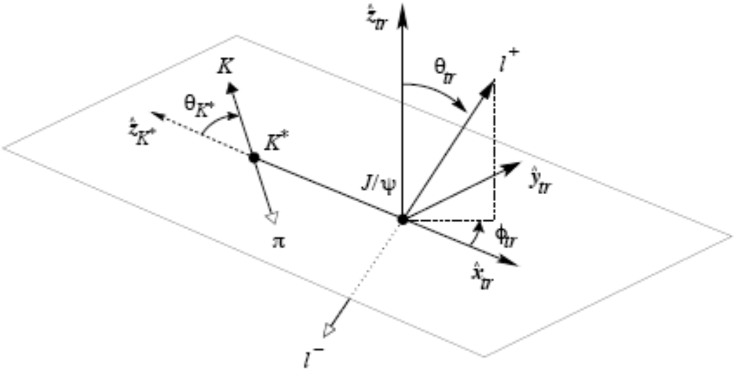
Present CKM fit

Resolving the 2β vs $\pi-2\beta$ Ambiguity

$B \to J/\psi K^*$

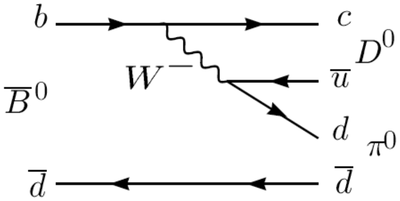
Angular, time-dependent analysis

$\cos 2\beta > 0$ at 86% CL



$B \to D^{(*)}[K_s\pi^+\pi^-]\pi^0,\eta^0,\omega^0$

Time-dependent Dalitz plot

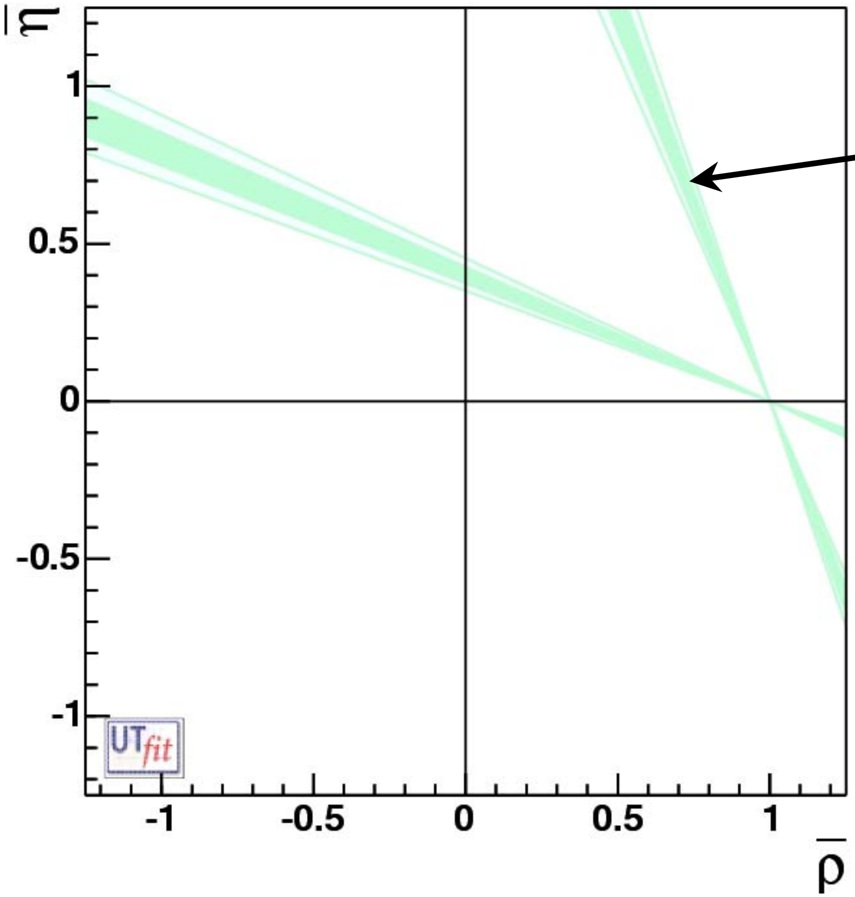


$$\cos 2\beta = 1.87^{+0.40+0.22}_{-0.53-0.32}$$

98.3% exclusion of "wrong" value.

hep-ex/0605023

β Constraint



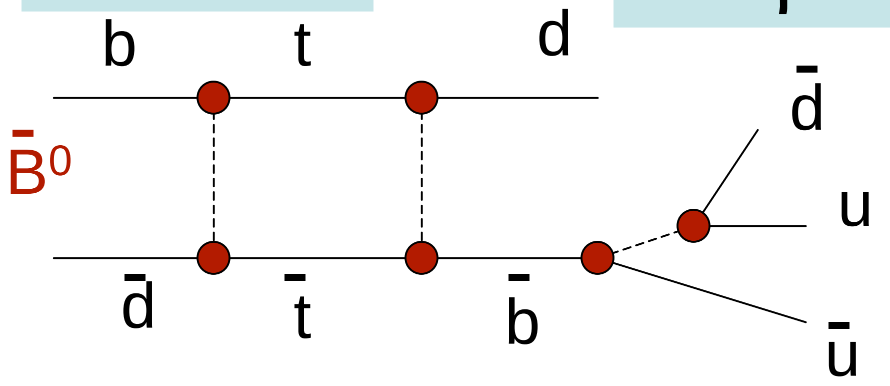
Excluded

Measuring α

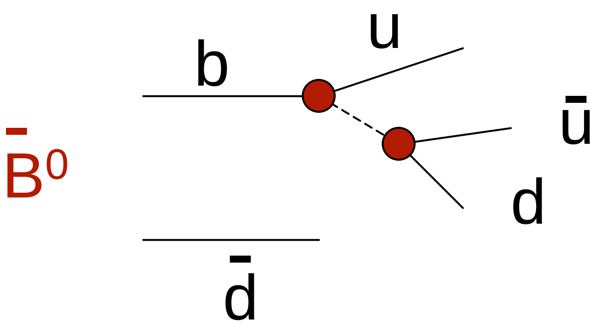
B→ππ

B→ρπ

B→ρρ



$$\propto \left(V_{td}^* V_{tb}\right)^2 V_{ub}^* V_{ud} \propto \frac{\left(V_{td}^* V_{tb}\right) V_{ub}^* V_{ud}}{V_{td} V_{tb}^*}$$



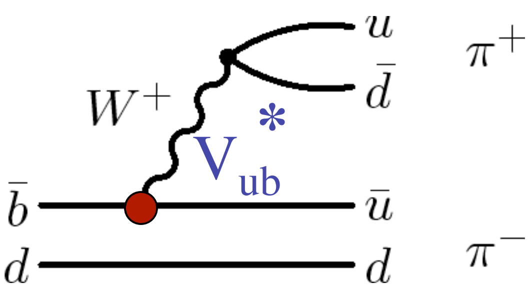
$$\propto V_{ub} V_{ud}^*$$

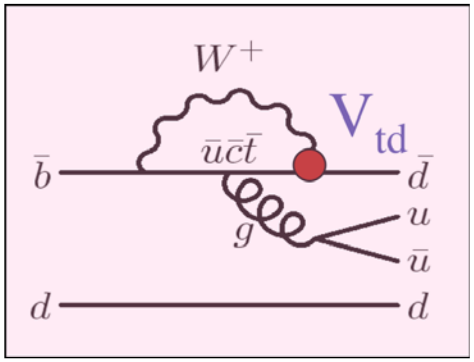
Relative phase:

$$\frac{V_{ub} V_{ud}^*}{V_{ub}^* V_{ud}} \frac{V_{td} V_{tb}^*}{V_{td}^* V_{tb}} = e^{-2i\alpha}$$

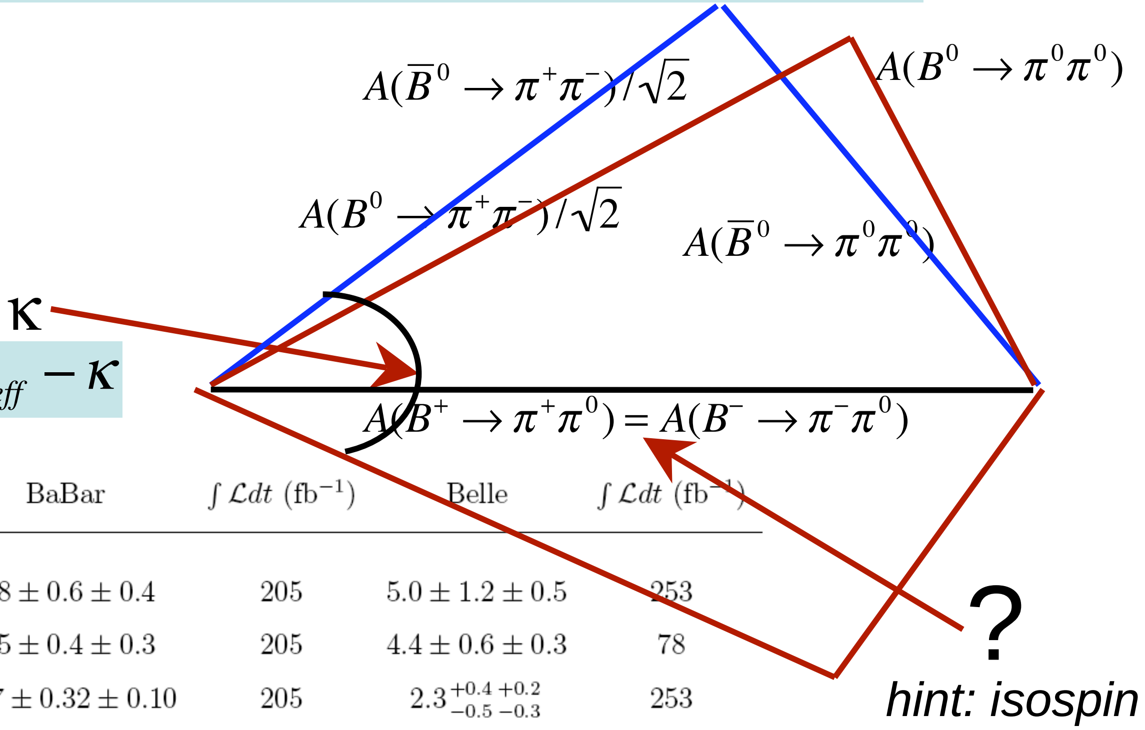
Penguins and sin 2α

Two weak mechanisms to final state, more complicated.
Isospin triangle provides correction.





$$2\alpha = 2\alpha_{eff} - \kappa$$



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hint: isospin

(10^{-6})	BaBar	$\int \mathcal{L}dt$ (fb^{-1})	Belle	$\int \mathcal{L}dt$ (fb^{-1})
BF$(\pi^+\pi^0)$	$5.8 \pm 0.6 \pm 0.4$	205	$5.0 \pm 1.2 \pm 0.5$	253
BF$(\pi^+\pi^-)$	$5.5 \pm 0.4 \pm 0.3$	205	$4.4 \pm 0.6 \pm 0.3$	78
BF$(\pi^0\pi^0)$	$1.17 \pm 0.32 \pm 0.10$	205	$2.3^{+0.4}_{-0.5}{}^{+0.2}_{-0.3}$	253

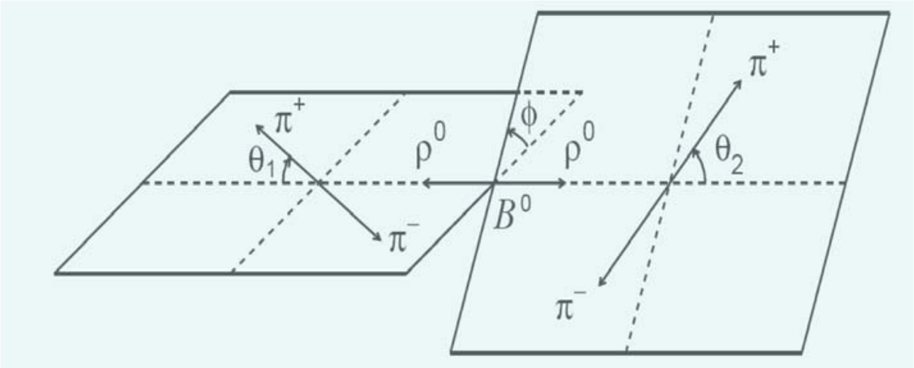
If the branching fractions to $\pi^0\pi^0$ were small as expected, the triangles would be flat and κ would be small. Instead $|\alpha - \alpha_{\text{eff}}| < 35^\circ$ @ 90% C.L.

ρρ Rescues α, For Now.

- ρρ longitudinally polarized. No spin problem.
- $\rho^0\rho^0$ much smaller than other channels. Triangle flat, so small κ correction.

$$\frac{d^2N}{d\cos\theta_1 d\cos\theta_2} \propto f_L \cos^2\theta_1 \cos^2\theta_2 + \tfrac{1}{4}(1-f_L)\sin^2\theta_1 \sin^2\theta_2$$

$$f_L = 0.978 \pm 0.014^{+0.021}_{-0.019}$$



Current Status of α from ρρ

$$S_{\rho^+\rho^-} = -0.08 \pm 0.41 \pm 0.09$$

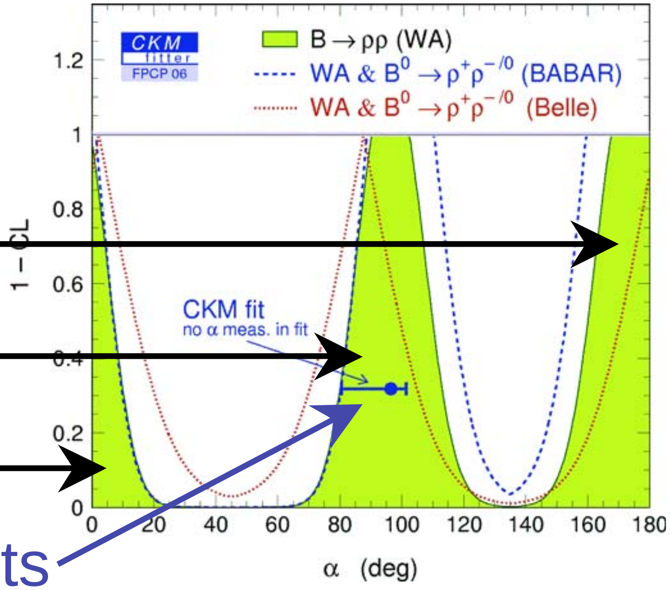
$$C_{\rho^+\rho^-} = -0.00 \pm 0.30 \pm 0.09$$

BELLE

$$S_{\rho^+\rho^-} = -0.33 \pm 0.24^{+0.08}_{-0.14}$$

$$C_{\rho^+\rho^-} = -0.03 \pm 0.18 \pm 0.09$$

(10^{-6})	BaBar	$\int \mathcal{L}dt\ (\text{fb}^{-1})$	Belle	$\int \mathcal{L}dt\ (\text{fb}^{-1})$
$\text{BF}(\rho^+\rho^0)$	$17.2 \pm 2.5 \pm 2.8$	210	$31.7 \pm 7.1^{+3.8}_{-6.7}$	78
$\text{BF}(\rho^+\rho^-)$	$30 \pm 4 \pm 5$	82	$22.8 \pm 3.8^{+2.3}_{-2.6}$	253
$\text{BF}(\rho^0\rho^0)$	< 1.1	205		



preferred regions

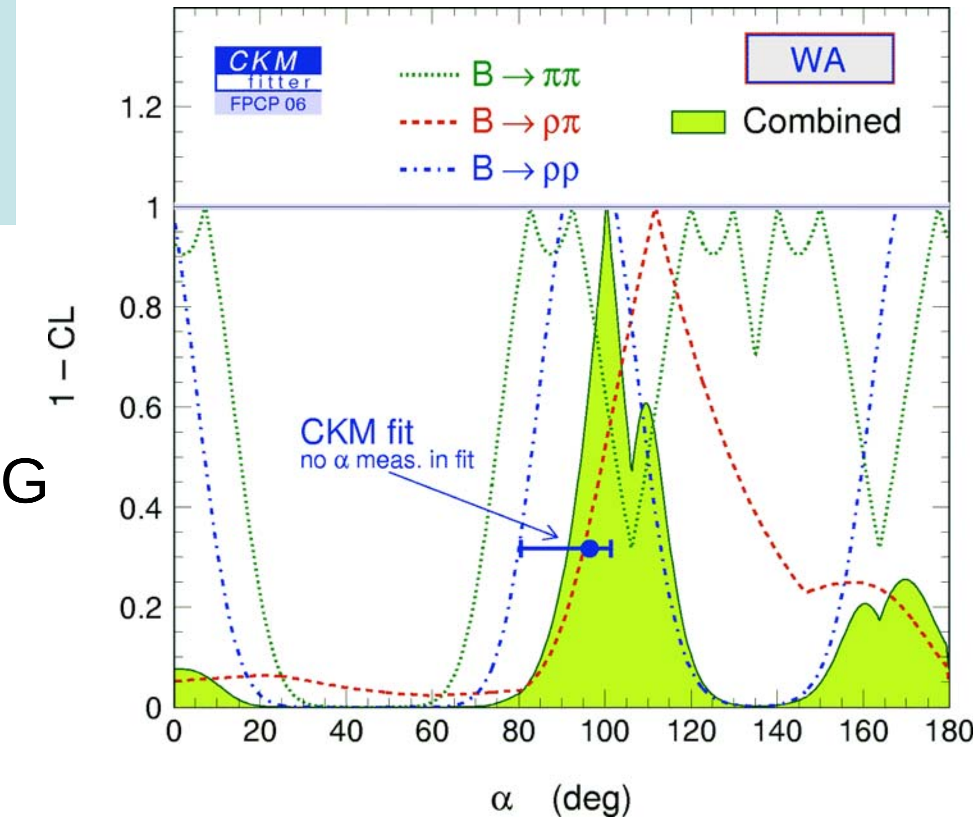
expectation from other measurements

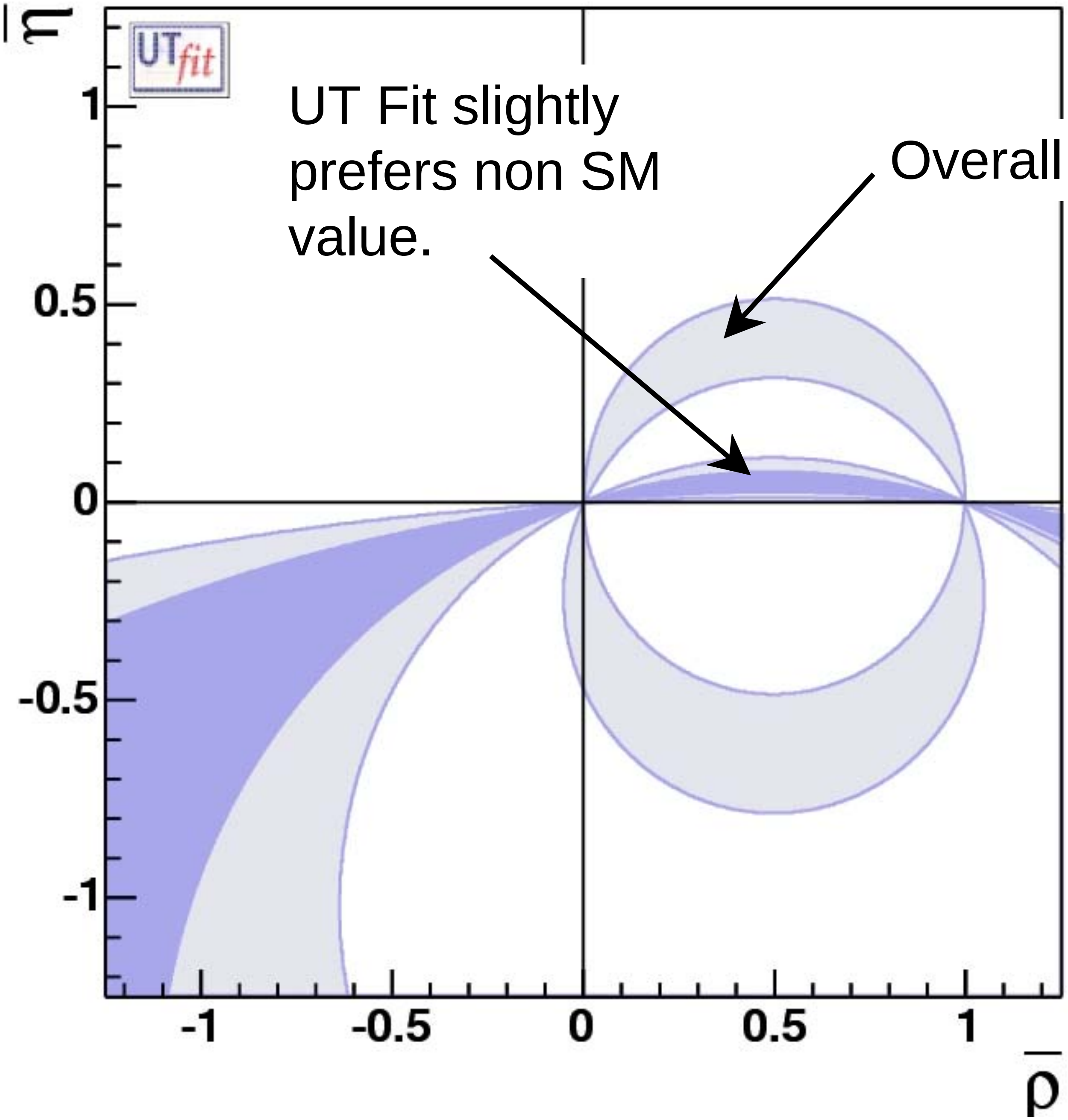
Status of α Combination of $\pi\pi, \rho\rho, \rho\pi$.

Precision depends on smallness of $\rho^0\rho^0$ mode.

$$\alpha = (99^{+12}_{-9})^0$$

HFAG

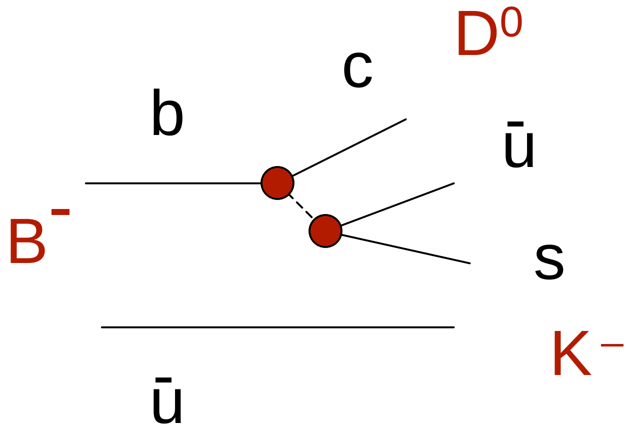




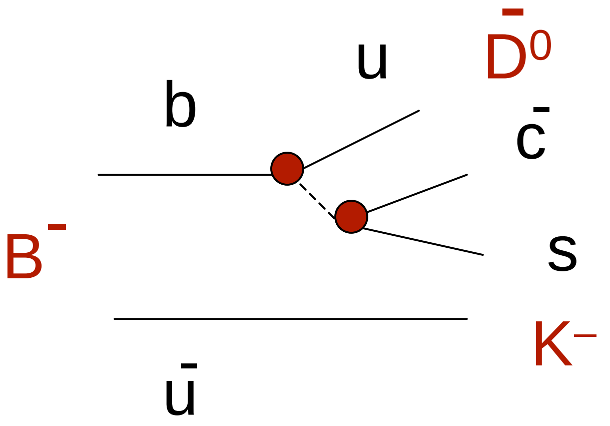
UT Fit slightly prefers non SM value.

Overall fit

Measuring γ



$\propto V_{cb} V_{ud}^*$



$\propto V_{ub} V_{cd}^*$

suppression

strong

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

weak

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

Need common final state for D^0 and $\overline{D}^0$:
K^+K^-, $\pi^+\pi^-$, $K_S\, \pi^+\pi^-$

Dalitz Plot Analysis for $K_S\pi\pi$

$D^0 \to \overline{K}^0\pi^-\pi^+$ has K^{*-} resonance

$\overline{D}^0 \to K^0\pi^-\pi^+$ has K^{*+} resonance

The relative strong phase between these channels is "known" from the ordinary Dalitz plot with $D^{*+}\to D^0\pi^+$.

The relative strength $r_B \approx |A(b\to u)/A(b\to c)|$ isn't.

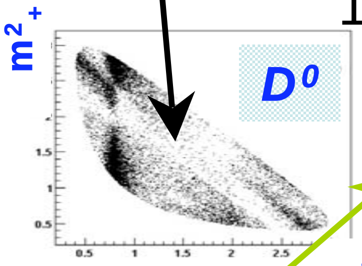
Nor are the relative weak phase, γ, and strong phase, δ.

A. Bondar (2002); Giri et al. (2003).

Interference in Dalitz Plot

Amplitude analysis from D^0 events

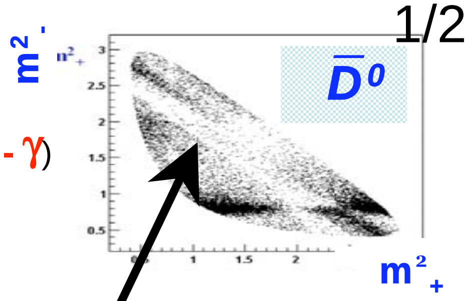
$A(B^-) = |A(D^0K^-)| \times$



$^{1/2}$

$\times\ f(m^2_-, m^2_+)$

$+\, r_B e^{i(\delta_B - \gamma)}$



$^{1/2}$

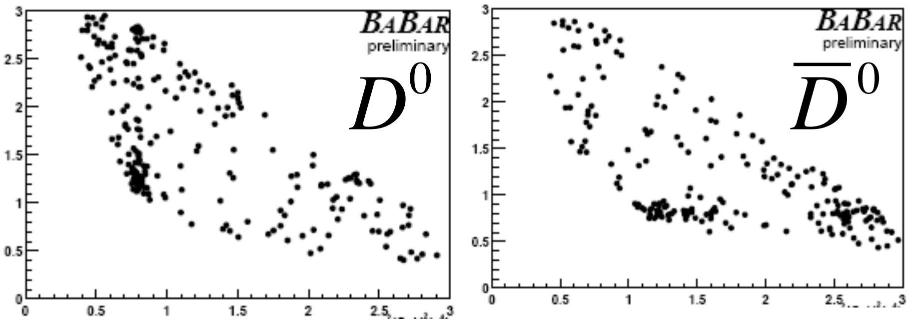
$\times\ f(m^2_+, m^2_-)$

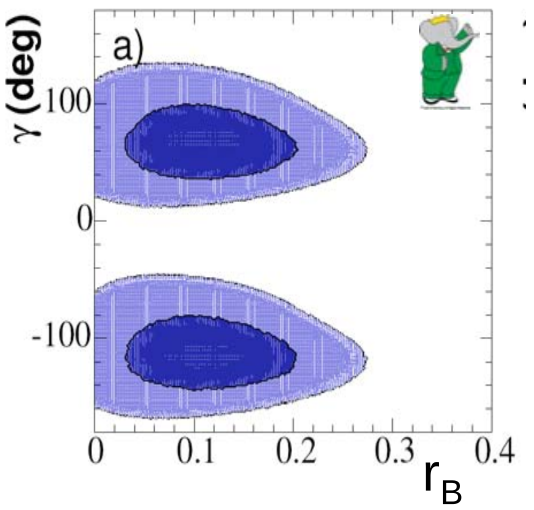
Amplitude for $D^0 \to \overline{K}^0\pi^+\pi^-$

$$r_B \equiv \left| \frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)} \right|$$

Model $D^0 \to \overline{K}^0\pi\pi$ has combination of many resonances.

Current Status of γ from Dalitz Plot Analysis





BaBar (205/fb):

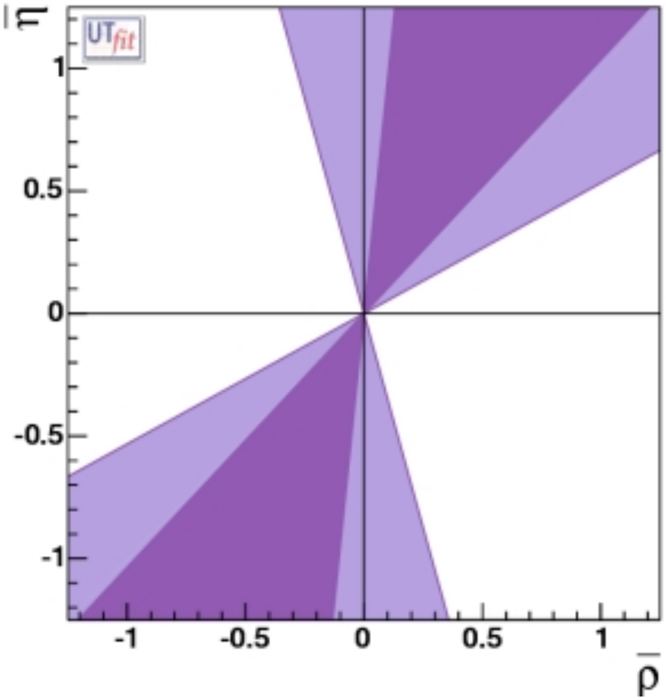
$$\gamma = 70 \pm 31\ (\text{stat})^{+12}_{-10}\ (\text{syst})\ ^{+14}_{-11}\ (\text{model})$$

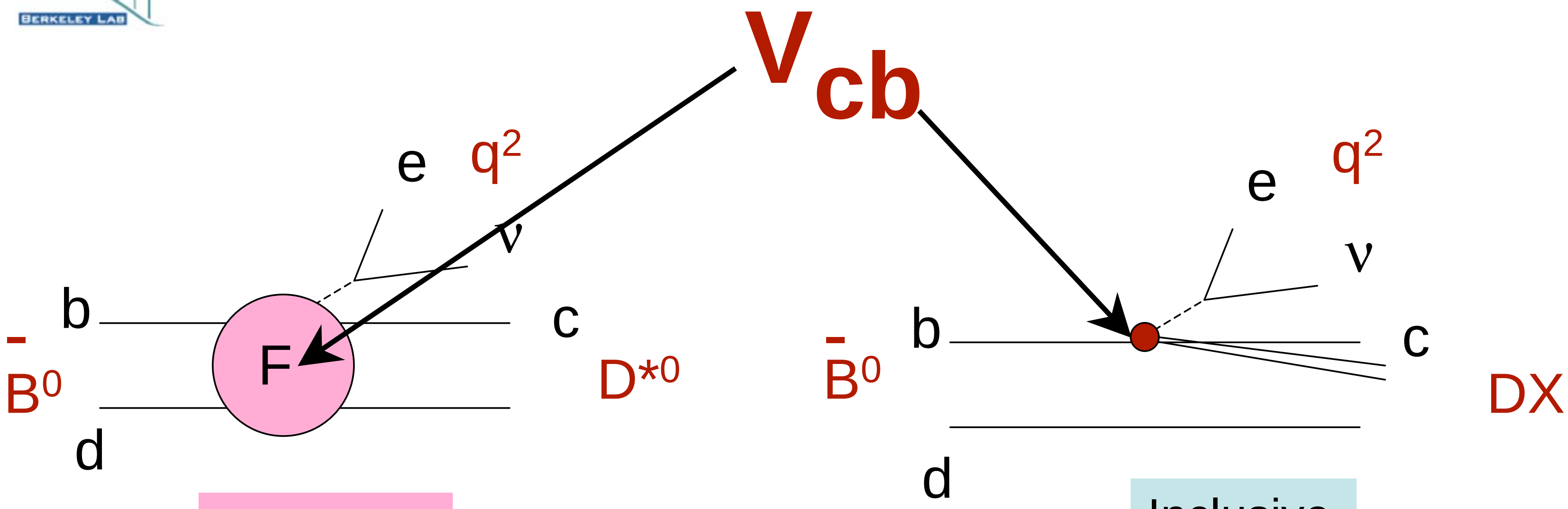
Error on γ depends on value of r_B

Belle (357/fb):

$$\gamma = 53\ ^{+15}_{-18}\ (\text{stat}) \pm 3\ (\text{syst}) \pm 9\ (\text{model})$$

γ Constraint





Exclusive

Three form factors:

Two ratios.

One coefficient for q^2 dependence.

Extrapolate to find $F(q^2_{max})V_{cb}$.

Need theory for $F(q^2_{max})$.

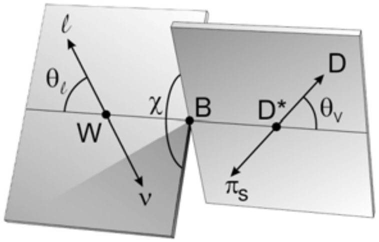
Inclusive

Analog of deep inelastic scattering.

Theory relates moments of lepton energy, etc. to total rate and thus to Vcb. Expand in α_s and $1/m_b$.

Determine simultaneously a few non-perturbative parameters, which reflect properties of B mesons.

Exclusive Measurement of V_{cb}



Measure q^2 and angles.

Determine form factors.

Extrapolate to $q^2_{max.}$

Get $F(q^2_{max})V_{cb}$.

$$B \to D^* \ell \nu$$

$$B \to D \ell \nu$$

BaBar: 0.0355±0.0003±0.0016

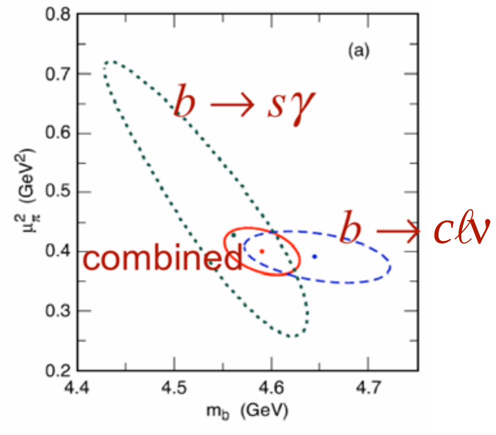
Belle: 0.036±0.0019±0.0018

$F(q^2_{max})$=0.91± 0.04 (theory)

Vcb=0.039±0.002 (unofficial average)

V_{cb} from Inclusive Analysis

Buchmuller & Flacher, PRD 73,073008(2006)



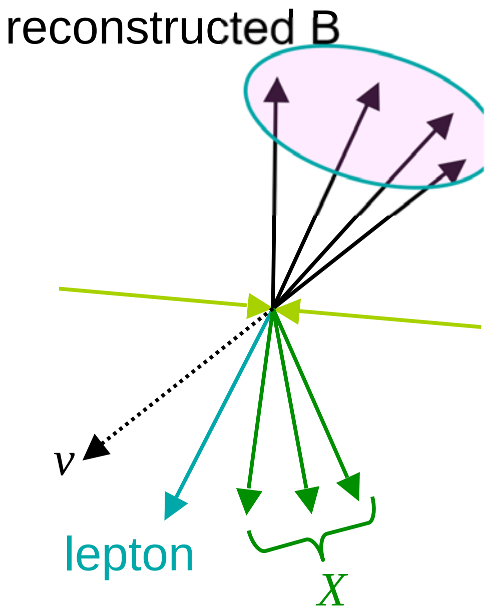
$$|V_{cb}| = (41.96 \pm 0.23_{\exp} \pm 0.35_{OPE} \pm 0.59_{\Gamma sl}) \times 10^{-3}$$

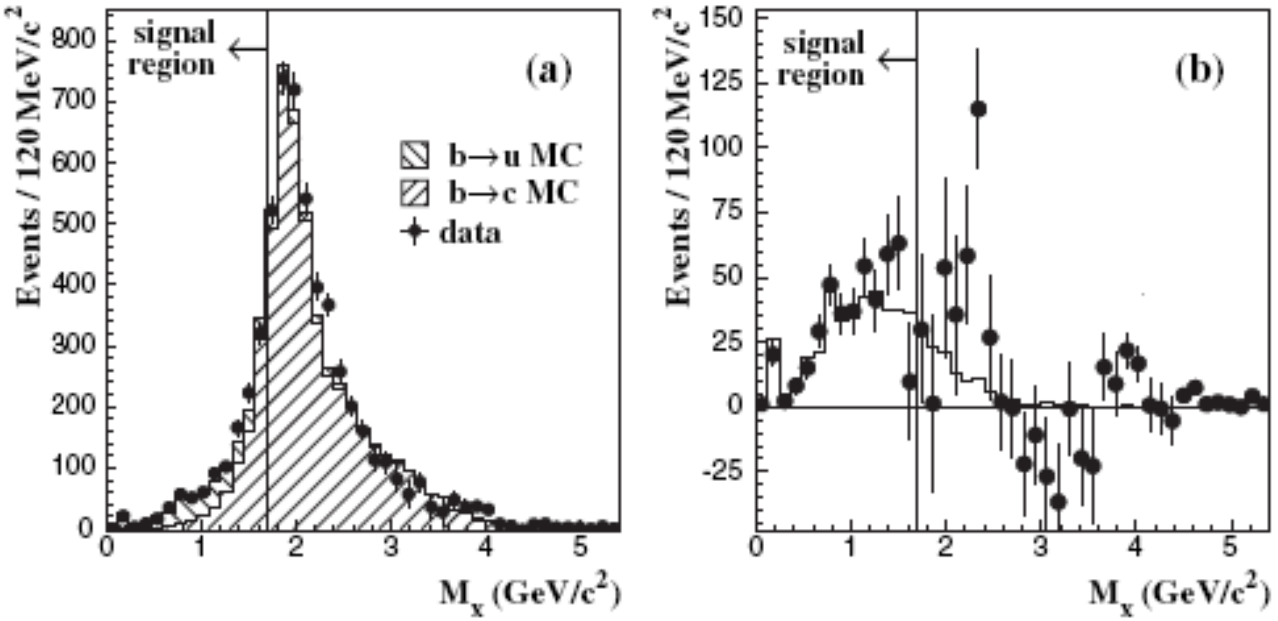
Vcb known to ±1.5%.

Bauer et al, PRD 70, 094017 (2004)

$$|V_{cb}| = (41.4 \pm 0.6 \ \pm 0.1_{\tau_B}) \times 10^{-3}$$

V_{ub} Much Harder: Reconstruct Other B

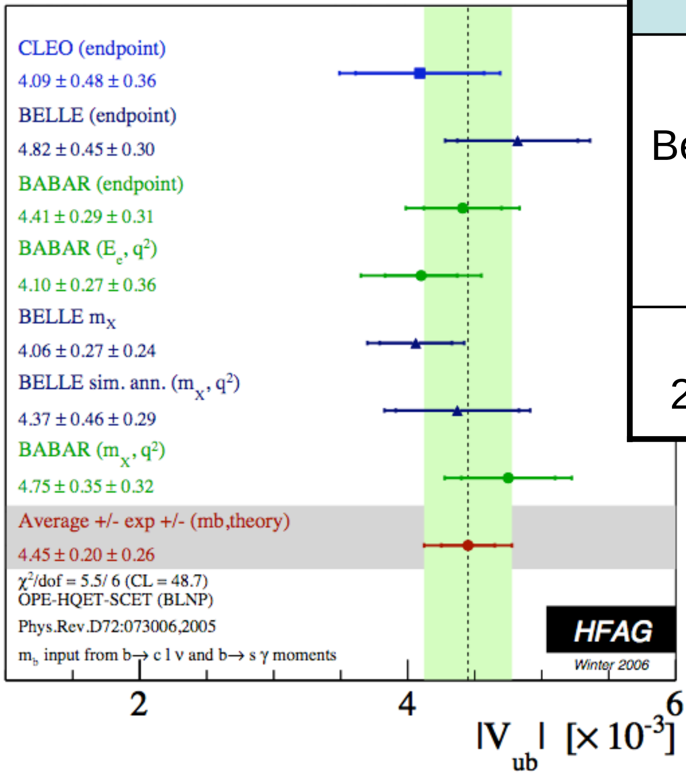




Momentum of semileptonically decaying B known!

Low M_X excludes b→c.

V_{ub} Inclusive Summary



	Region	$\lvert V_{ub}\rvert$ (10^{-3})
Belle 253M *BB*	$m_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$4.70 \pm 0.37_{\text{exp}} \pm 0.31_{\text{SF+theo}}$
	$m_X < 1.7$ GeV	$4.09 \pm 0.28_{\text{exp}} \pm 0.24_{\text{SF+theo}}$
	$P_+ > 0.66$ GeV	$4.19 \pm 0.36_{\text{exp}} \pm 0.28_{\text{SF+theo}}$
BABAR 210M *BB*	$m_X < 1.7$ GeV, $q^2 > 8$ GeV^2	$4.75 \pm 0.35_{\text{exp}} \pm 0.32_{\text{SF+theo}}$

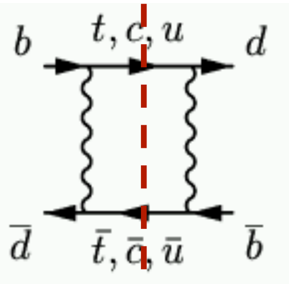
M. Morii, APS Dallas 2006

Vub known to 8 - 10%.

A_{SL}

$$A_{SL} = \frac{\Gamma(\Upsilon(4S) \to \ell^+\ell^+X) - \Gamma(\Upsilon(4S) \to \ell^-\ell^-X)}{\Gamma(\Upsilon(4S) \to \ell^+\ell^+X) + \Gamma(\Upsilon(4S) \to \ell^-\ell^-X)}$$

CP violation in mixing alone: $\left|\left\langle B^0 \middle| \overline{B}^0 \right\rangle\right| \neq \left|\left\langle \overline{B}^0 \middle| B^0 \right\rangle\right|$



$$A_{SL} \propto \mathrm{Im}\frac{\Gamma_{12}}{M_{12}} \propto \mathrm{Im}\frac{(V_{cb}V_{cd}^* + V_{ub}V_{ud}^*)^2}{(V_{tb}V_{td}^*)^2} \approx 0$$

physical

virtual: new physics?

Suppressed by (m_c^2/m_b^2) in Standard Model.

Theory: -(5.5±1.3)x10^{-4}

Belle: -(1.1±7.9±7.0) x10^{-3}

BaBar: (1.6±5.4±3.8)x10^{-3}

$B \to J/\psi K$

$B \to J/\psi K^*; B \to D^0\pi^0$

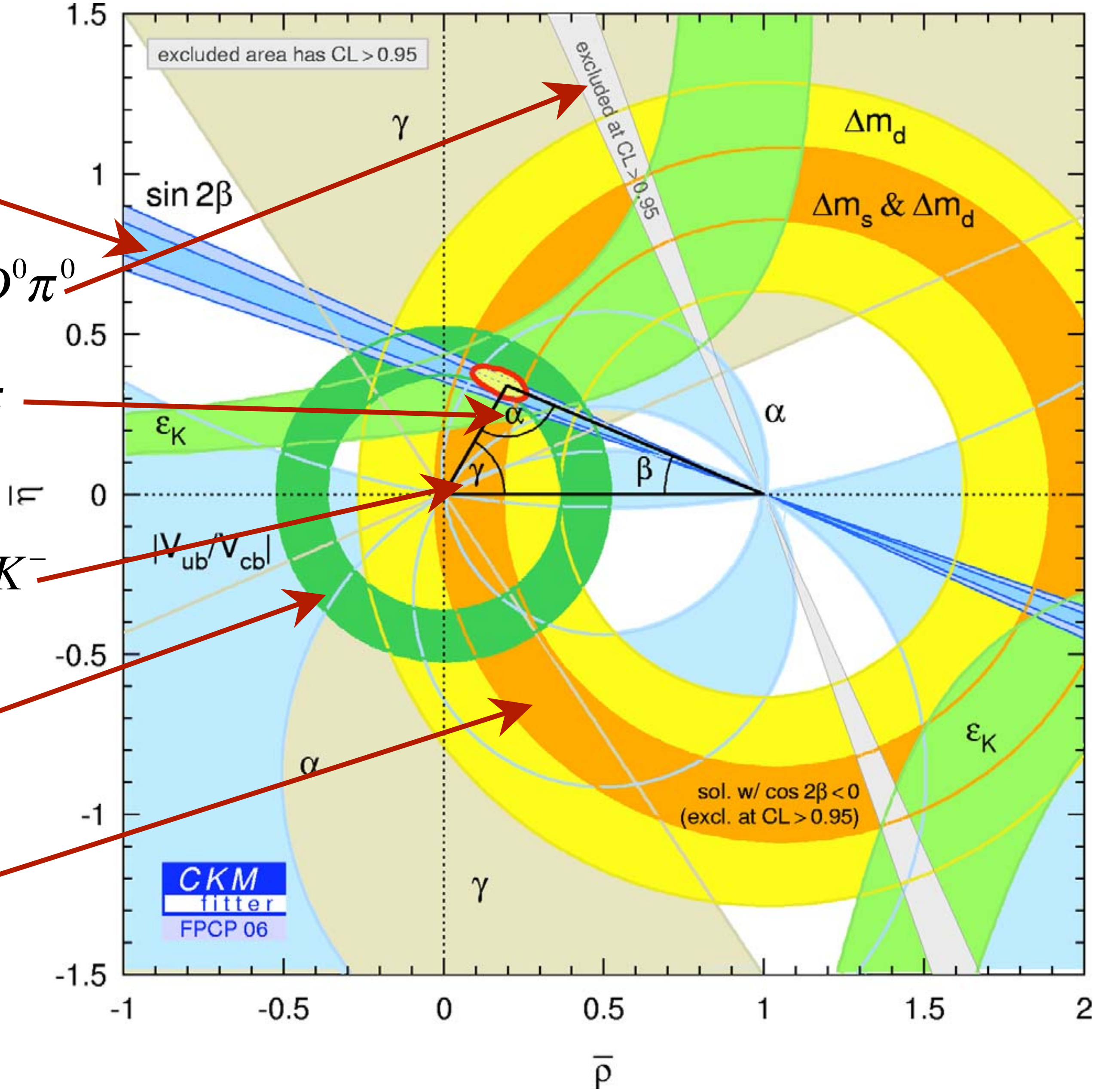
$B \to \rho\rho, \pi\pi, \rho\pi$

$B^- \to D(K_S\pi^+\pi^-)K^-$

$B \to D^*\ell\nu$

$B \to X_s\ell\nu$

$\Delta m_s / \Delta m_d$



Listen Carefully

- If we “listen” carefully, we may still find New Physics.
- But not hearing it, could be just as important:

Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"

Holmes: "To the curious incident of the dog in the night-time."

Gregory: "The dog did nothing in the night-time."

Holmes: "That was the curious incident."

“Silver Blaze,” Arthur Conan Doyle