Results from the B-factories

(Lecture 2)

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$b \to c$ 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*

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

$B \to \pi\pi$

$B \to \rho\pi$

$B \to \rho\rho$

$B \to a_1 \pi$

$B \to a_1 \rho$

$B \to b_1 \pi$

$B \to b_1 \rho$

$B \to a_1 a_1$

$\vdots$

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

$B^0 \to J/\psi K^0_L$

$B^0 \to J/\psi K^0_S$

$B^0 \to \psi(2S) K^0_S$

$B^0 \to \chi_{1c} K^0_S$

$B^0 \to \eta_c K^0_S$

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

$B \to J/\psi \pi^0$

$B \to D^{(*)+} D^{(*)-}$

$B \to \eta' K^0$

$B \to \rho K^0$

$B \to \omega K^0$

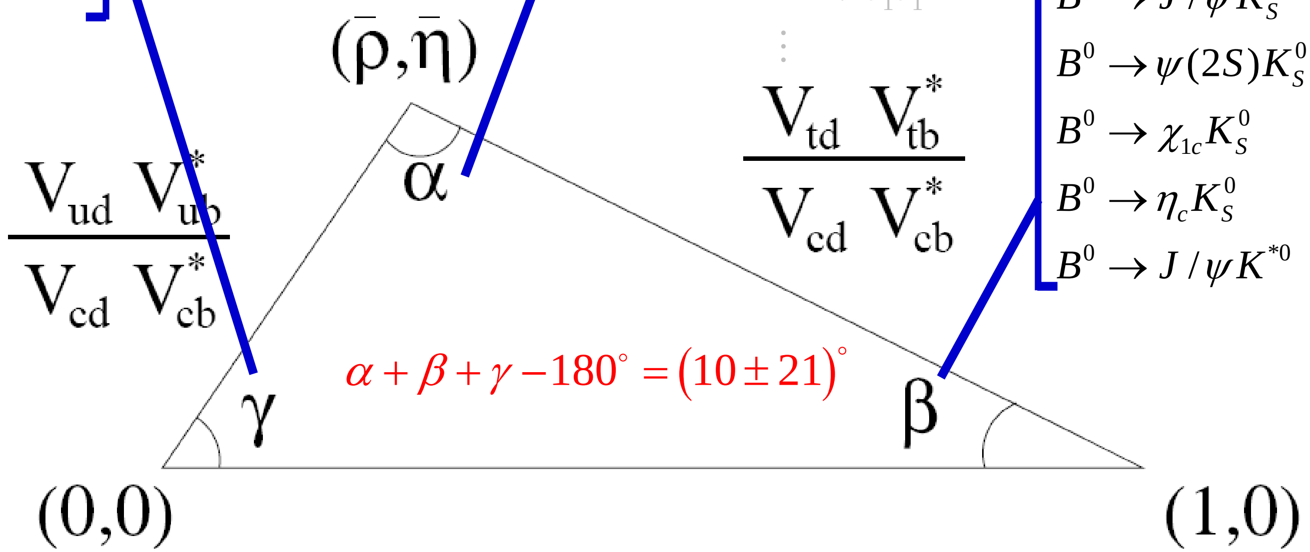
$B \to \pi^0 K^0$

$B \to \phi K^{(*)0}$

$B \to KKK^0$

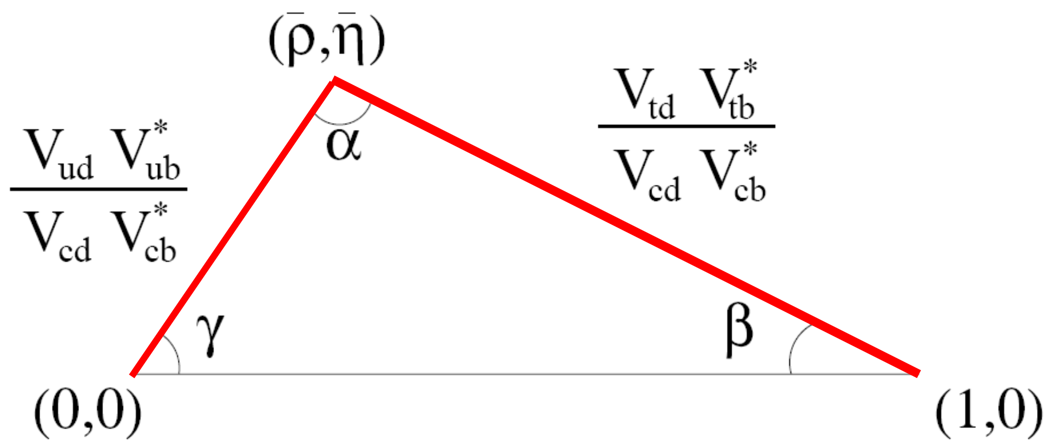
$B \to f^0(980) K^0$

$\vdots$



This lecture

- Direct CP violation
- Searching for New Physics
  - Alternate measurements of angles: ΔS
  - Sides of the Unitarity Triangle: Over-constraining the SM



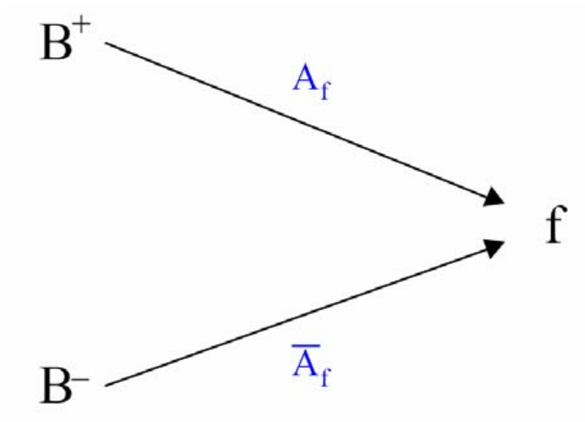
- CPT Tests
- B→VV decays (and related channels)

CP violation: Direct CP violation

- Recap from Lecture 1:
  - Number counting exercise: $A_{CP} = \dfrac{\overline{N} - N}{\overline{N} + N}$
  - Requires at least two amplitudes to interfere.
  - Amplitudes have to have different weak and strong phases.

$$A_{CP} \propto a_1 a_2 \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2)$$

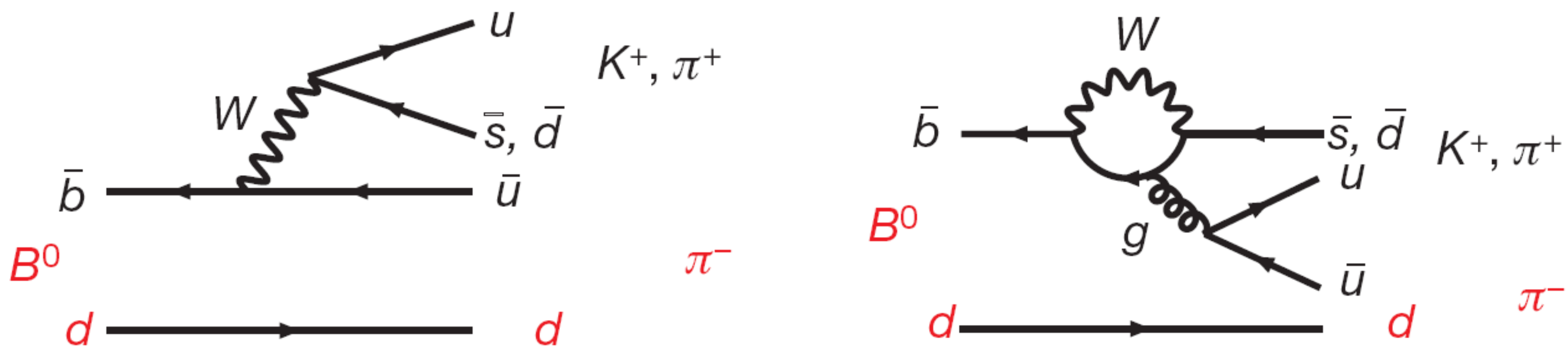
  - We are comparing A_f with $\overline{A}_f$.



  - Predictive power will be limited by our knowledge of weak phases and of the strong phase differences.
    - But there are many possible measurements that we can compare!

CP violation: Direct CP violation

- $B^0 \to K^{\pm}\pi^{\mp}$: Tree and gluonic penguin contributions

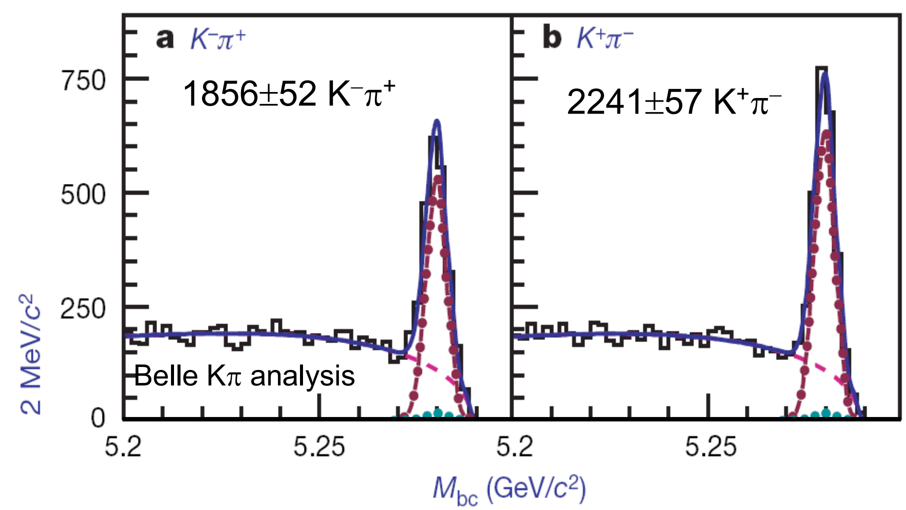


- Compute time integrated asymmetry

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

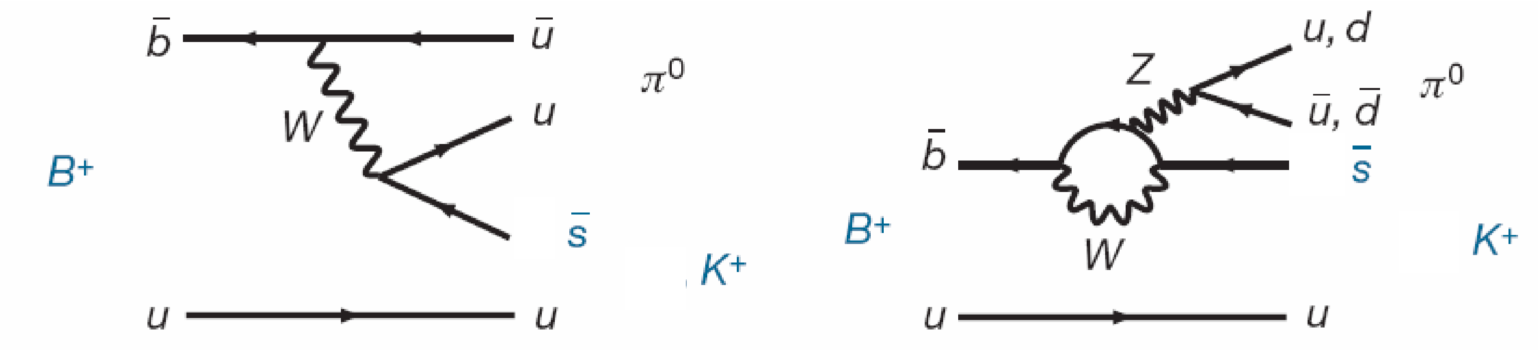
$$A_{K^{\pm}\pi^{\mp}} = -0.097 \pm 0.012$$

- Experimental results from Belle, BaBar, and CDF have significant weight in the world average of this CP violation parameter.
- Direct CP violation present in B decays.
- Unknown strong phase differences between amplitudes, means we can't use this to measure weak phases!



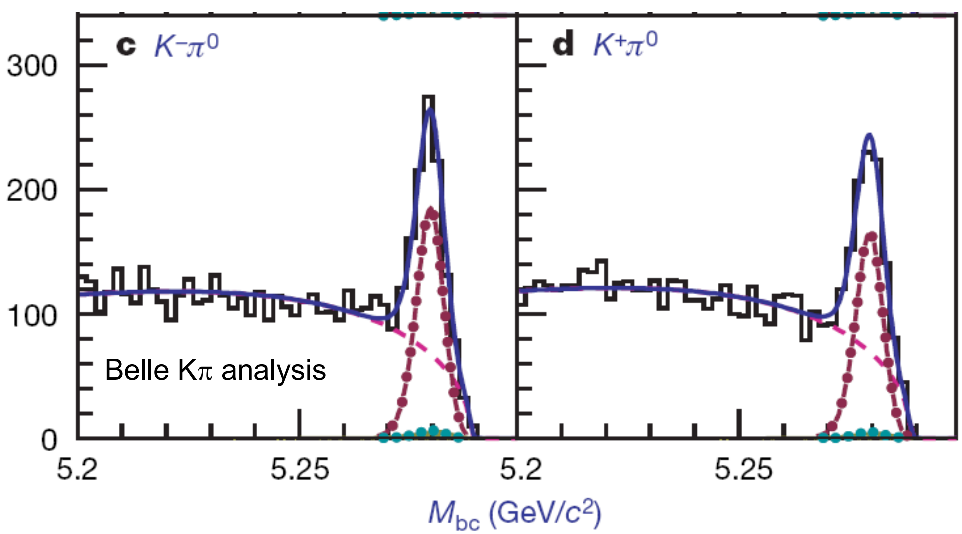
CP violation: Direct CP violation

- $B^+ \to K^+\pi^0$: Color suppressed tree and gluonic penguin contributions



- Many theory calculations indicate that $A_{K^+\pi^-} \geq A_{K^+\pi^0}$.
- Experimentally measure:

$$A_{K^+\pi^0} = 0.050 \pm 0.025$$



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

$$\Delta A_{K\pi} = 0.147 \pm 0.028 \quad \text{(>5}\sigma\text{ from zero)}$$

- Difference could 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 G. Hou arXiv:0808.1932 and references therein.

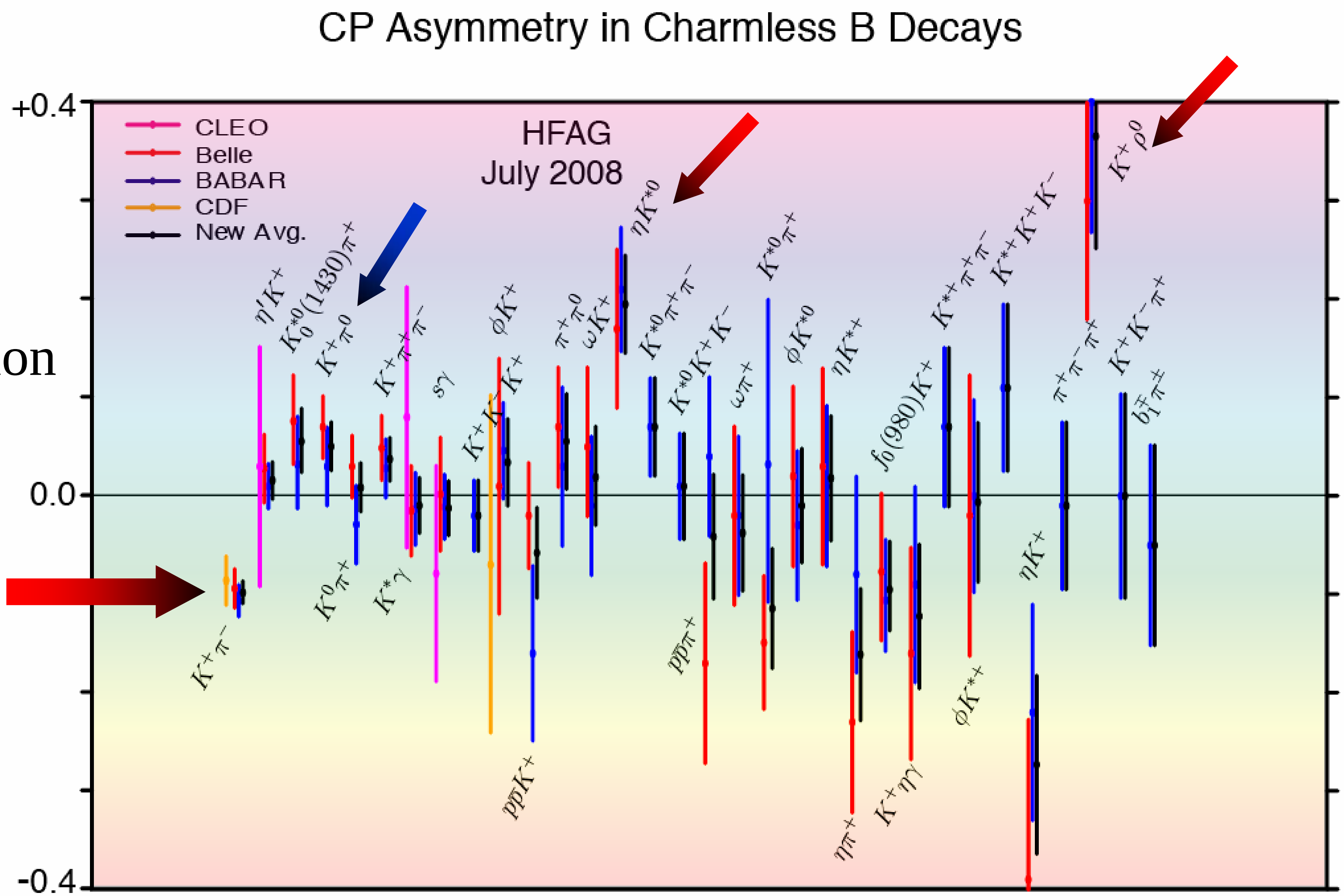
Direct CP violation searches

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

$A_{CP} = 0$

$= \text{no CP violation}$

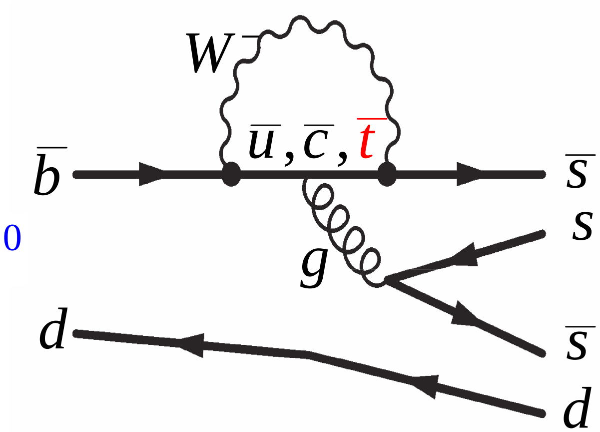
- Observed signal of direct CP violation in B meson decay



- This is a small sub-set of decays where we have searched for direct CP violation.
- 2 observed signals (> 5σ): $K^+\pi^-$ and $\pi^+\pi^-$; five possible effects (> 3σ): ρ^0K^+, ηK^{*0}, $\rho^+\pi^-$ $D^{(*)0}K^{(*)}$, and $D^0_{CP}K$.

CP violation: Searching for new physics

- $\sin 2\beta$ 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 $\Delta S_{\rm NP} = S_{eff} - S_{c\bar{c}s} - \Delta S_{\rm SM}$
- In the presence of NP: $\Delta S_{NP} \neq 0$



B^0 $\phi, \eta', (KK)_{CP}$ K_S^0

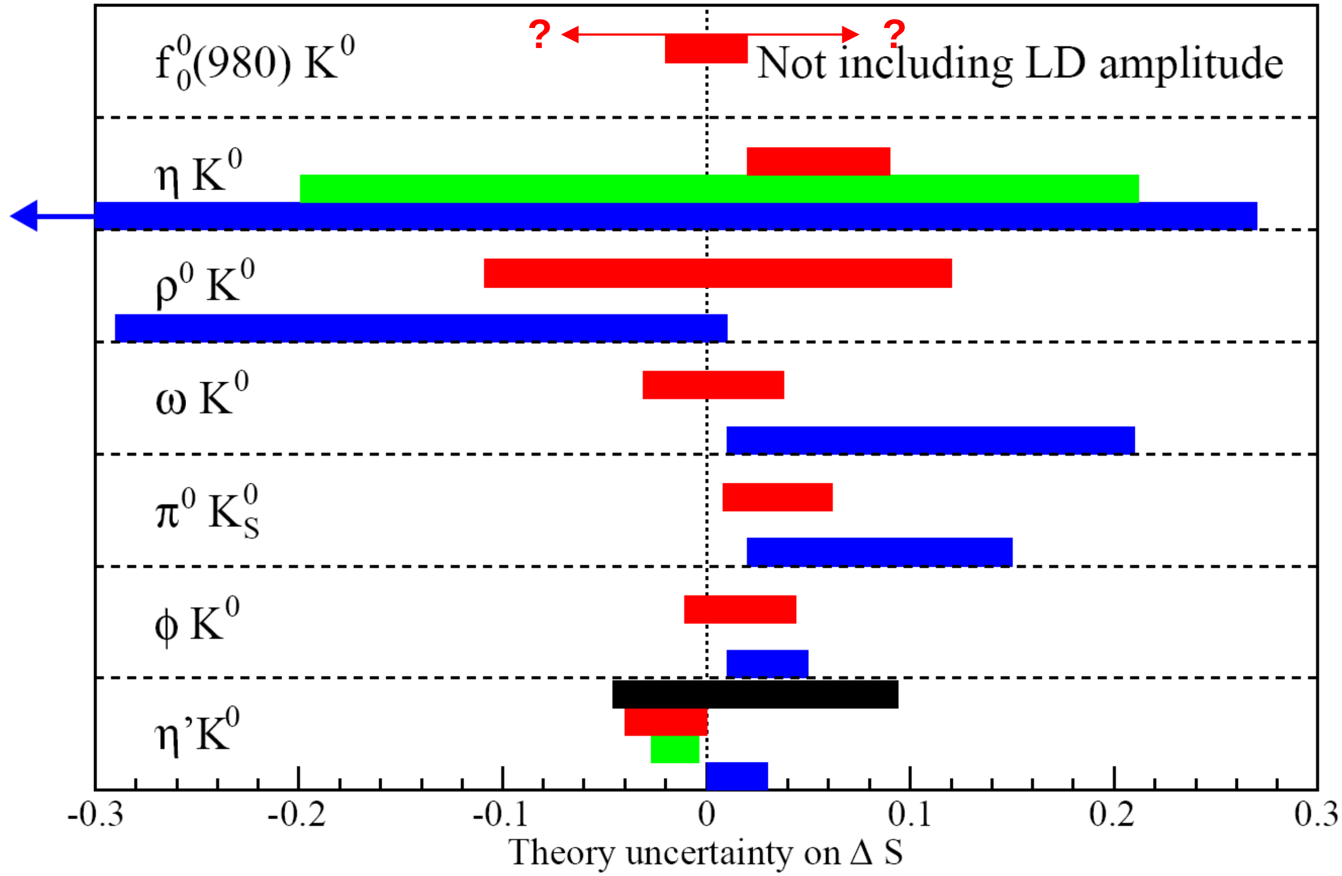
- Many tests have been performed in:
  - $B \to d$ processes.
  - $B \to s$ processes.

- Unknown heavy particles can introduce new amplitudes that can affect physical observables of loop dominated processes.
- Observables that might be affected include branching fractions, CP asymmetries, forward backward asymmetries … and so on.
- A successful search requires that we understand Standard Model contributions well!

SM uncertainties on ΔS

- To find NP we need to understand the SM contributions to a process.
  - Leading order term is expected to be the same as a SM weak phase.
  - Higher order terms including re-scattering, suppressed amplitudes, final state radiation and so on can modify our expectations.

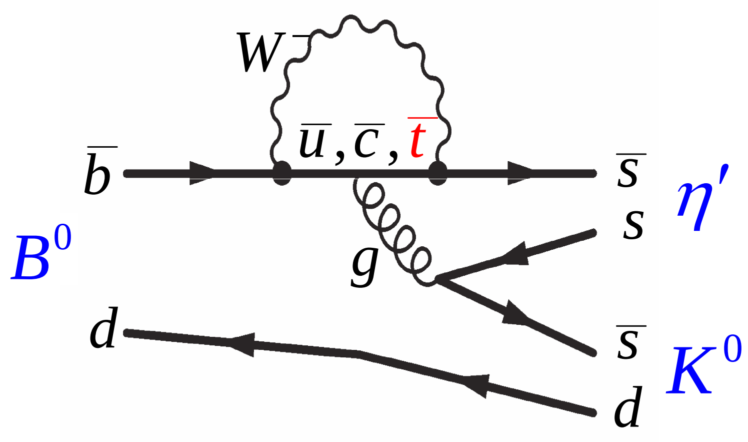
- Some channels are better understood than others.
- Sign of ΔS correction is mode dependent.
- Most precise ΔS correction is for $B^0 \rightarrow \eta' K^0$, where $\Delta S_{theory} \sim \pm 0.01$.
- Concentrate efforts on well understood channels.



QCDF Beneke, PLB**620**, 143 (2005)
SCET/QCDF, Williamson and Zupan, PRD**74**, 014003 (2006)
QCDF Cheng, Chua and Soni, PRD**72**, 014006 (2005)
SU(3) Gronau, Rosner and Zupan, PRD**74**, 093003 (2006)

$B \to \eta' K^0$

- Loop dominated b→s decay.



$$S_{\eta' K^0} = 0.60 \pm 0.07$$

$$C_{\eta' K^0} = -0.04 \pm 0.05$$

$$\Delta S_{\eta' K^0} = 0.07 \pm 0.07_{\text{exp}} \pm 0.01_{\text{theory}}$$

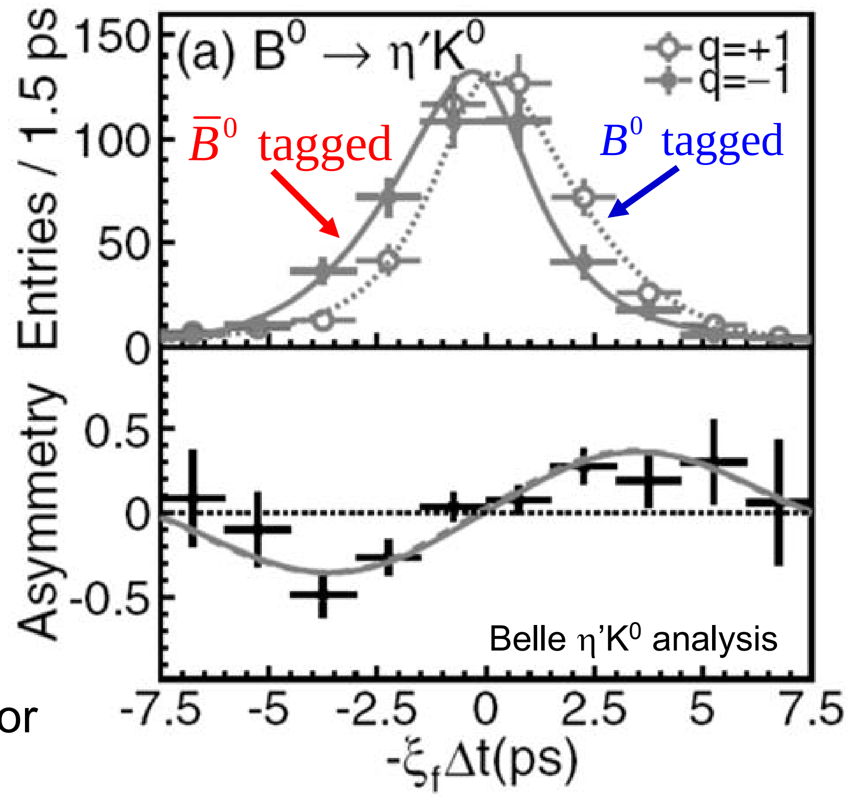
- CP violation has been established in this decay channel by the B factories.
- Need at least 50 ab^{-1} of data to do a precision search for NP at the level of current theoretical uncertainties.

- Possible to measure S and C for both

$$B^0 \to \eta' K^0_S \quad \text{(CP odd)}$$

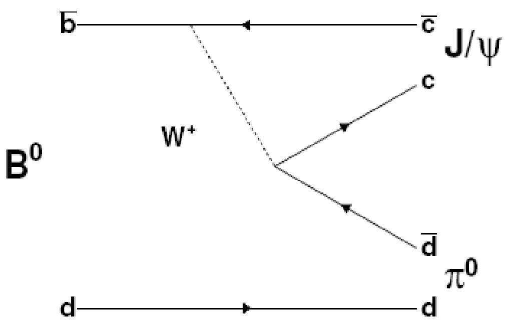
$$B^0 \to \eta' K^0_L \quad \text{(CP even)}$$

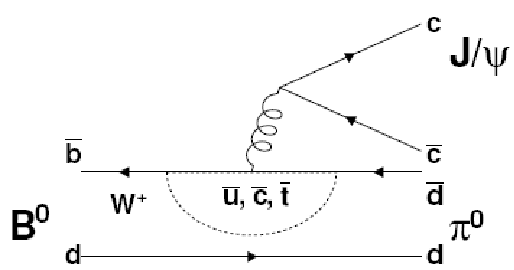
- These asymmetries can be compared with the Charmonium reference measurement to calculate ΔS.



$B^0 \to J/\psi\pi^0$

- Tree and penguin contributions: can be sensitive to NP.
- Alternatively, can be used to constrain SM uncertainties in the Charmonium β measurement. M. Ciuchini, M. Pierini, L. Silvestrini, **95**, 221804 (2005).





- CP even final state:

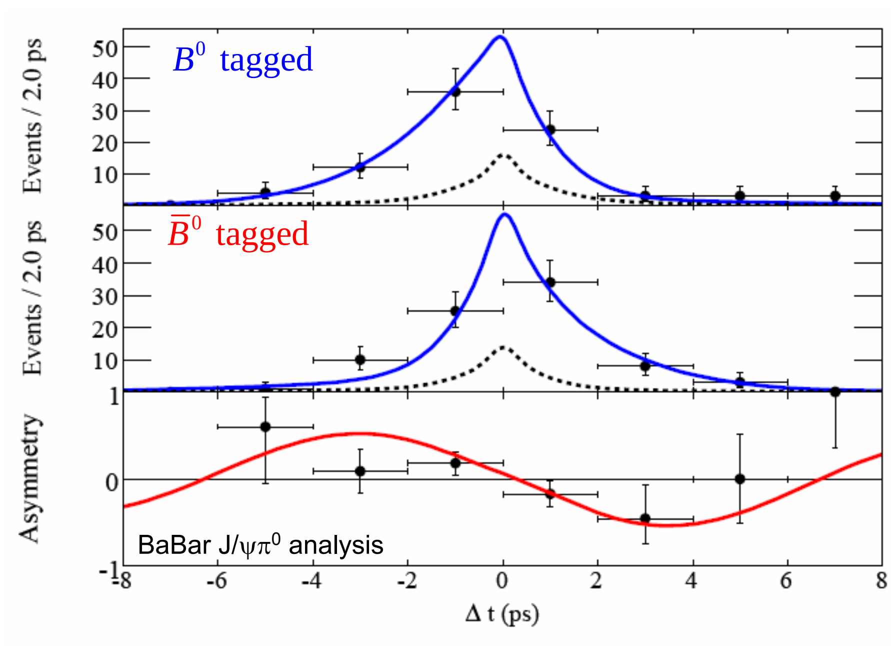
$$S^{Tree}_{J/\psi\pi^0} = -S_{c\bar{c}s}$$

- CP violation observed in this decay.

$$S_{J/\psi\pi^0} = -0.93 \pm 0.15$$

$$C_{J/\psi\pi^0} = -0.10 \pm 0.13$$

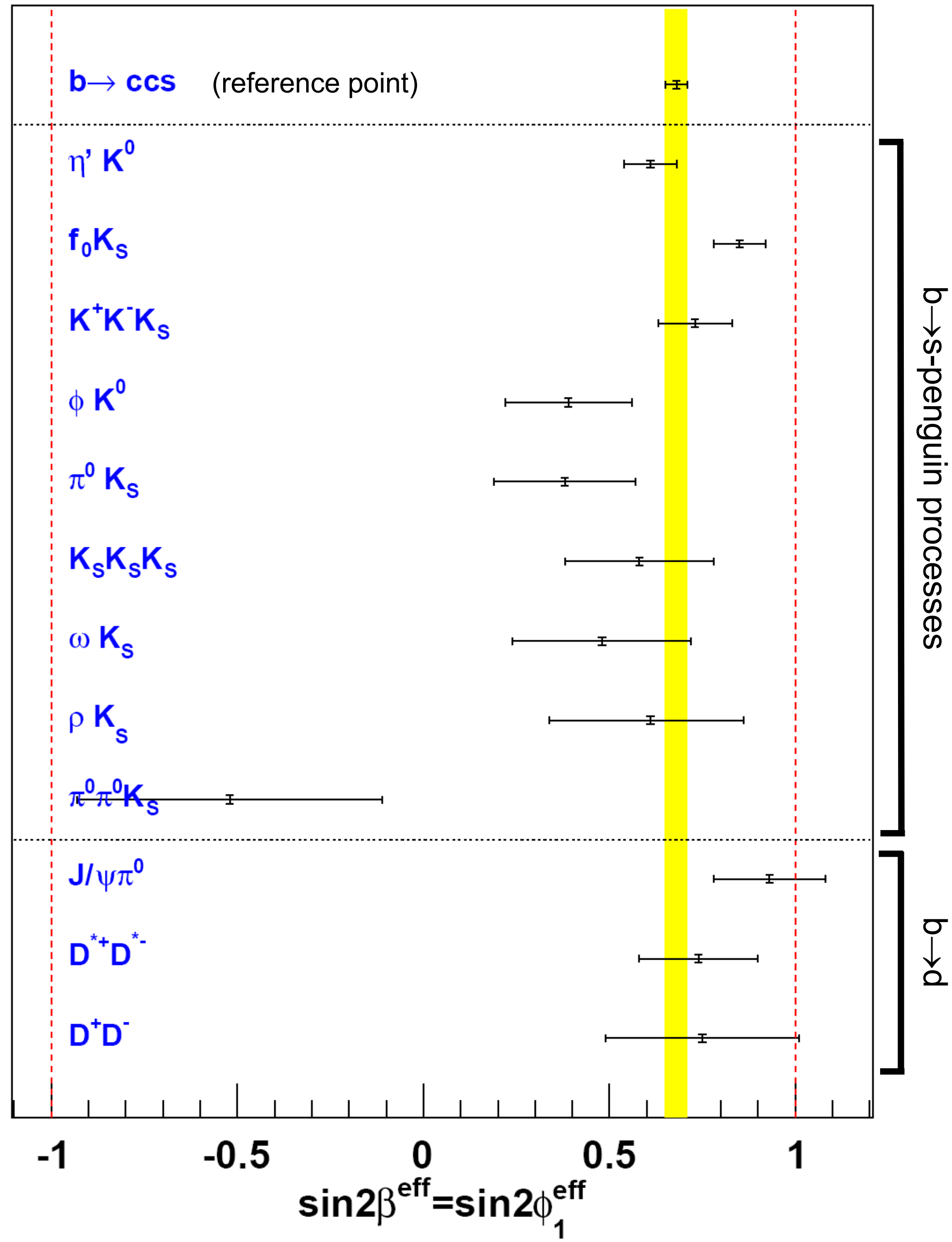
$$\Delta S_{J/\psi\pi^0} = 0.23 \pm 0.15_{exp}$$



- Require a dataset of ~220ab^{-1} to make a 1% ΔS measurement in this channel.

Overview of ΔS measurements

- Comparing $\sin 2\beta$ in different physical processes, we see good agreement with the $b \to ccs$ reference point.
- Most of the $b \to s$ penguin channels have $\sin 2\beta_{eff} < \sin 2\beta$.
  - Could this be an indication of NP?
    - Insufficient statistics to tell.
  - Need to perform a mode-by-mode precision measurement in order to properly decouple Standard Model uncertainties from possible signals of NP.
- We need at least $50ab^{-1}$ to start performing measurements that will have comparable experimental and theoretical uncertainties in $b \to s$ penguin processes.
- Need $\sim 220ab^{-1}$ to do the same for $b \to d$.
- Can start to do the same with α and γ once we have a precision measurement from one mode.



Summary of CP violation signals found

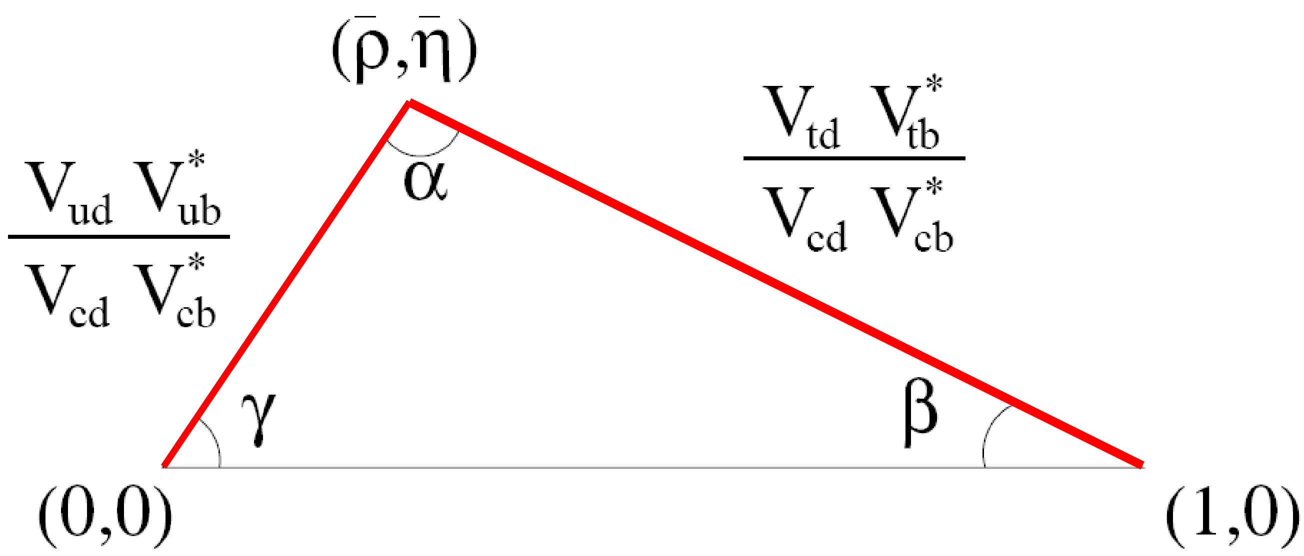
- We have discovered CP violation in the following channels:
  - $B^0 \to J/\psi K^0$ (S)
  - $B^0 \to J/\psi \pi^0$ (S)
  - $B^0 \to \psi(2S) K^0_S$ (S)
  - $B^0 \to \eta_{1c} K^0_S$ (S)
  - $B^0 \to \eta' K^0$ (S)
  - $B^0 \to f^0_0(980) K^0_S$ (S)
  - $B^0 \to K^+ K^- K^0$ (S)
  - $B^0 \to D^{*+} D^{*-}$ (S)
  - $B^0 \to \pi^+\pi^-$ $(S \text{ and } C)$
  - $B^0 \to \eta K^{*0}$ (A_{CP})
  - $B^0 \to \rho^\pm \pi^\mp$ $(\mathcal{A}_{+-})$
  - $B^0 \to K^\pm \pi^\mp$ (A_{CP})
  - $B^\pm \to \rho^0 K^\mp$ (A_{CP})
  - $B \to D^0_{\mathrm{CP}+} K$ (A_{CP})
  - $B \to D^{(*)0} K^*$ (A_{CP})

- Indirect CP violation measurement:
  - related to a weak phase in the Standard Model.
  - These modes measure either β or α.

- Direct CP violation measurement:
  - related to weak phase differences and strong phase differences in the Standard Model.
  - Can be used to constrain weak phases using model dependent analysis of charmless rare B meson decays.

- All of our measurements have been consistent with the SM (so far).

Sides of the Unitarity Triangle



Sides of the Unitarity Triangle

$b \to u l \nu$

$B \to \pi l \nu$

$B \to X_u l \nu$

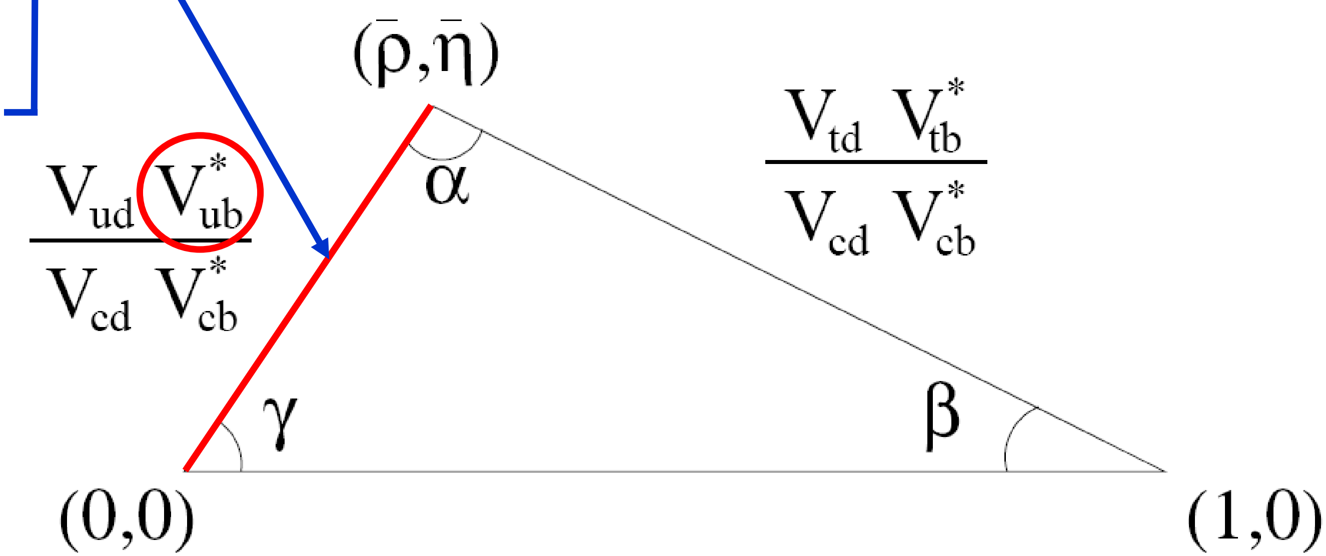
$B \to \rho l \nu$

$B \to \omega l \nu$

⋮

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

- Several theoretical schemes available.

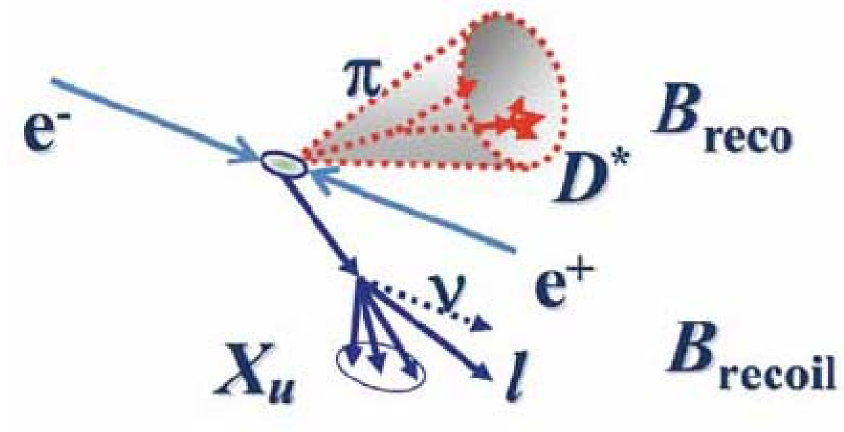


Side measurements: V_{ub}

- $|V_{ub}| \propto \mathcal{B}(B \rightarrow X_u l \nu)$ in a limited region of phase space.
- Reconstruct both B mesons in an event.
  - Study the B_{recoil} to measure V_{ub}.
  - Measure $\mathcal{B}$ 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 of V_{ub} have a significant model uncertainty.

Exclusively reconstructed b→ulν

- If we fully reconstruct one B meson in an event, then …
- … with a single ν in the event, we can infer P^μ and 'recontruct' the ν.
- Clean signals!
- Low efficiency!

- Study B decays to:

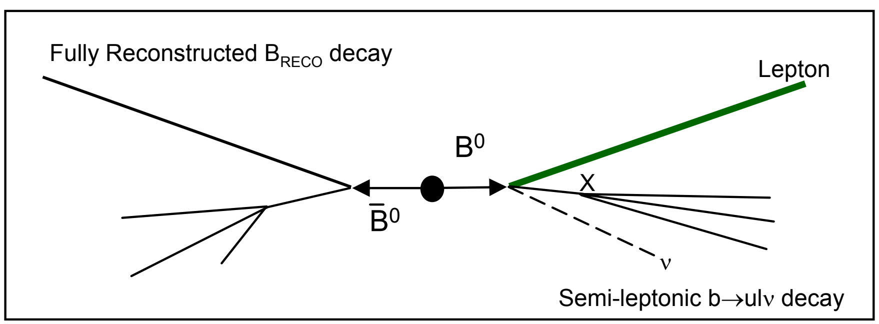
$$B^0 \to \pi^- l^+ \nu$$
$$B^0 \to \rho^- l^+ \nu$$
$$B^+ \to \pi^0 l^+ \nu$$
$$B^+ \to \rho^0 l^+ \nu$$
$$B^+ \to \omega l^+ \nu$$

- Fully reconstruct B_{RECO}
- Extract yields from m^2_{MISS}

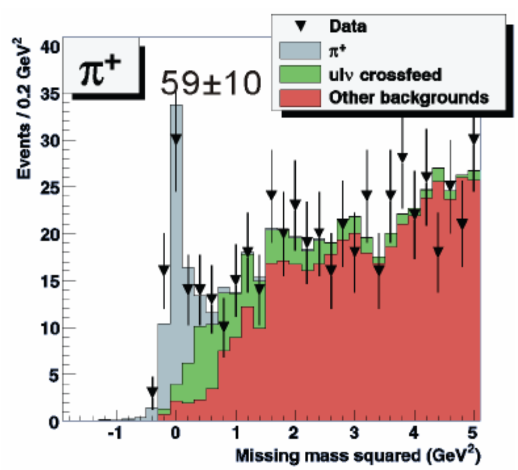
$$q^2 < 8 (GeV)^2$$
$$8 < q^2 < 16 (GeV)^2$$
$$q^2 > 16 (GeV)^2$$

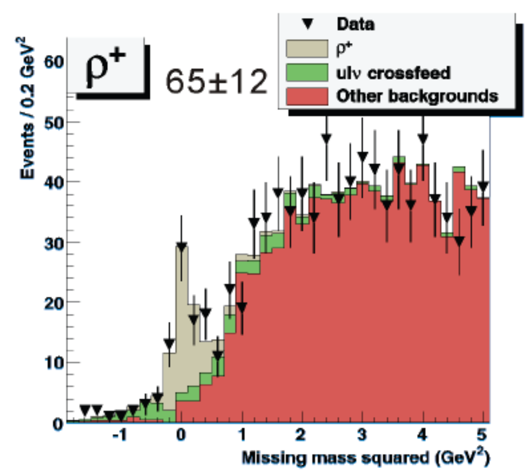
(reduces form factor dependence)

- Then compute $|V_{ub}|$.



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





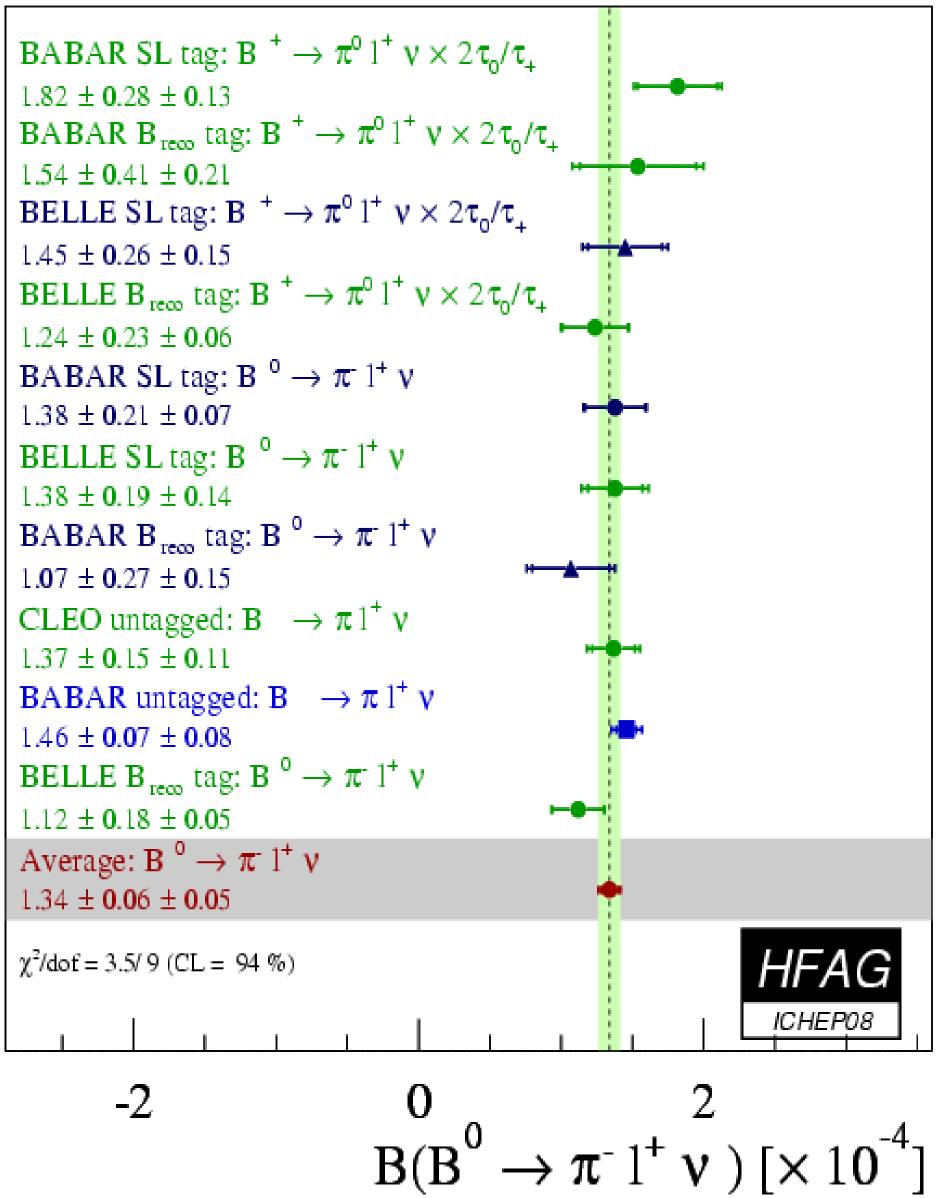
Belle: See W. Dungel, ICHEP 08 for more details

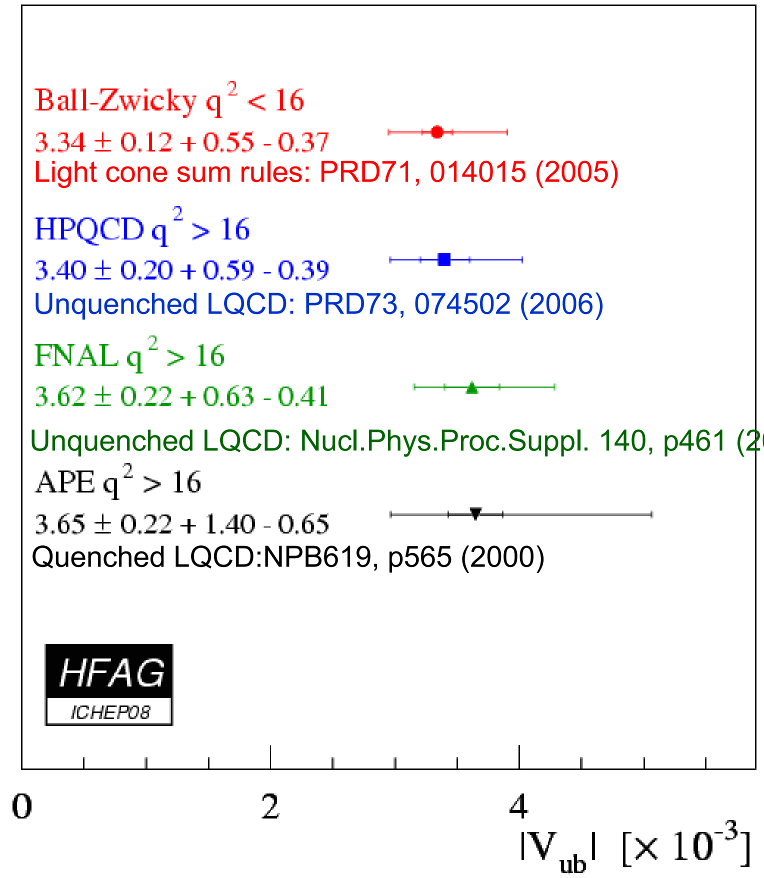
V_{ub}: Using q^2 distribution

- Use $B \to \pi l \nu$ decays

$$\mathcal{B}(B^0 \to \pi^+ l^- \nu) = (1.34 \pm 0.06 \pm 0.05) \times 10^{-4}$$

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





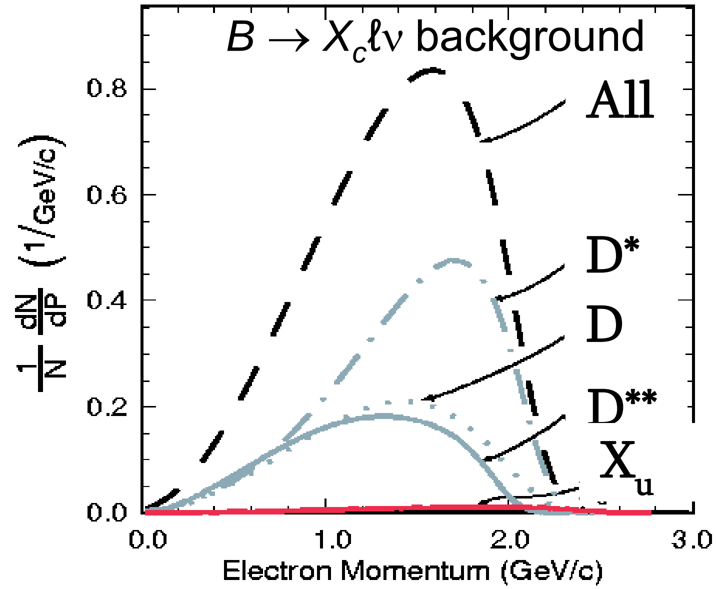
$\sigma(V_{ub})_{EXPT}$ ~ 5%

$\sigma(V_{ub})_{THEORY}$ ~ 11 to 17%

Experiments have also studied higher mass meson $l\,\nu$ decays

V_{ub}: Using M_X distribution

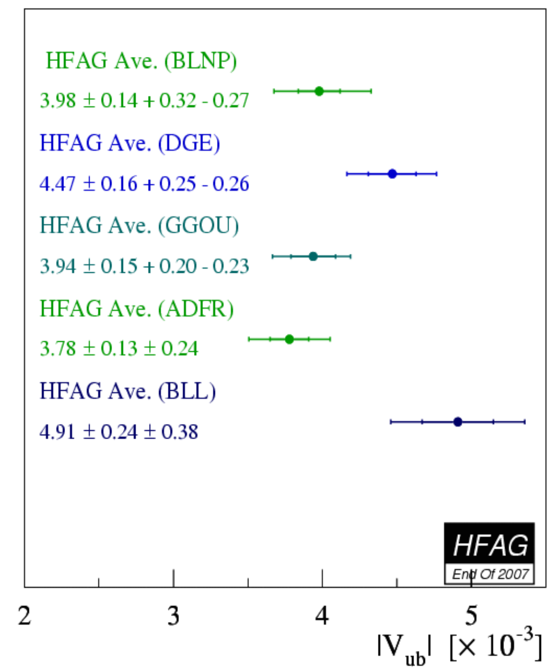
- High background from $c \to l\nu$ decays.
  - Kinematic cuts are used to suppress background.



- Use Operator Product Expansions to translate measured branching fractions to V_{ub}.

- Measure branching fraction in different kinematic regions.

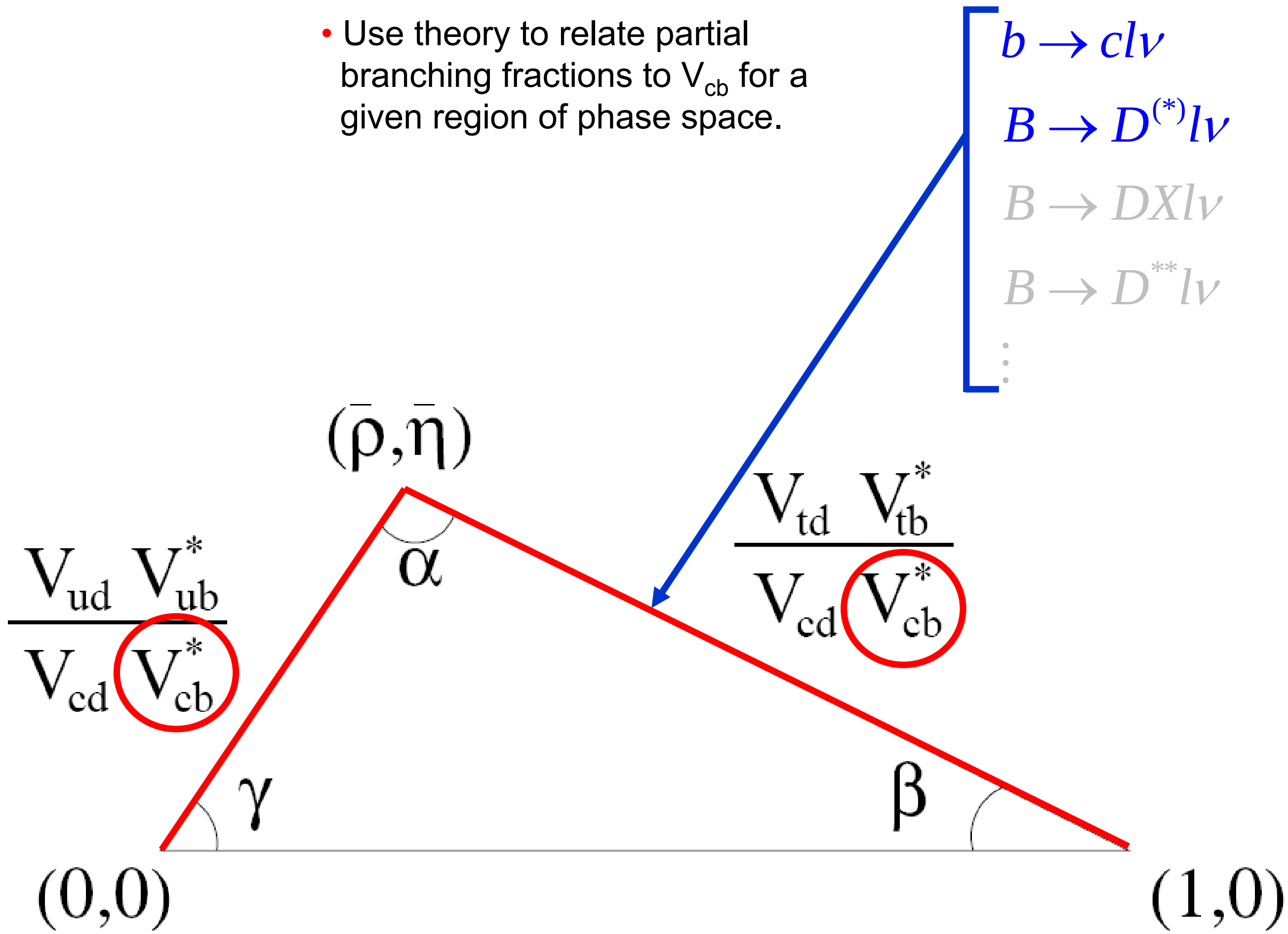
Experiment [Accepted region]	$\Delta\mathcal{B}[10^{-4}]$
CLEO $[E_e > 2.1\,\text{GeV}]$	$3.3 \pm 0.2 \pm 0.7$
BABAR $[E_e > 2.0\,\text{GeV}]$ $s_h^{max} < 3.5\,\text{GeV}^2$	$4.4 \pm 0.4 \pm 0.4$
BABAR $[E_e > 2.0\,\text{GeV}]$	$5.7 \pm 0.4 \pm 0.5$
BELLE $[E_e > 1.9\,\text{GeV}]$	$8.5 \pm 0.4 \pm 1.5$
BABAR $[M_X < 1.7\,\text{GeV}/c^2, q^2 > 8\,\text{GeV}^2/c^2]$	$8.1 \pm 0.8 \pm 0.7$
BELLE $[M_X < 1.7\,\text{GeV}/c^2, q^2 > 8\,\text{GeV}^2/c^2]$	$7.4 \pm 0.9 \pm 1.3$
BELLE $[M_X < 1.7\,\text{GeV}/c^2, q^2 > 8\,\text{GeV}^2/c^2]$	$8.4 \pm 0.8 \pm 0.4$
BABAR $[P_+ < 0.66\,\text{GeV}]$	$9.4 \pm 1.0 \pm 0.8$
BELLE $[P_+ < 0.66\,\text{GeV}]$	$11.0 \pm 1.0 \pm 1.6$
BABAR $[M_X < 1.55\,\text{GeV}/c^2]$	$11.7 \pm 0.9 \pm 0.7$
BELLE $[M_X < 1.7\,\text{GeV}/c^2]$	$12.3 \pm 1.1 \pm 1.2$



BLNP: PRD**72**, 073006 (2005)
DGE: JHEP 0601:097 (2006)
GGOU: JHEP 0710:058 (2007)
ADFR: arXiv:0711.0860
BLL: PRD**64**, 113004 (2001)

Sides of the Unitarity Triangle

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

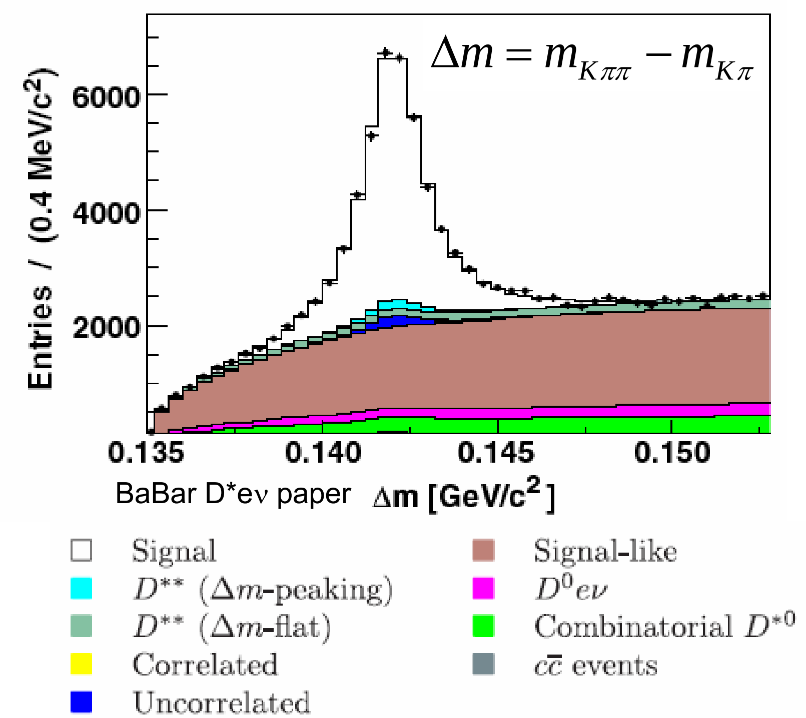


Side measurements: V_{cb}

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

$$D^{*0} \to D\pi$$

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

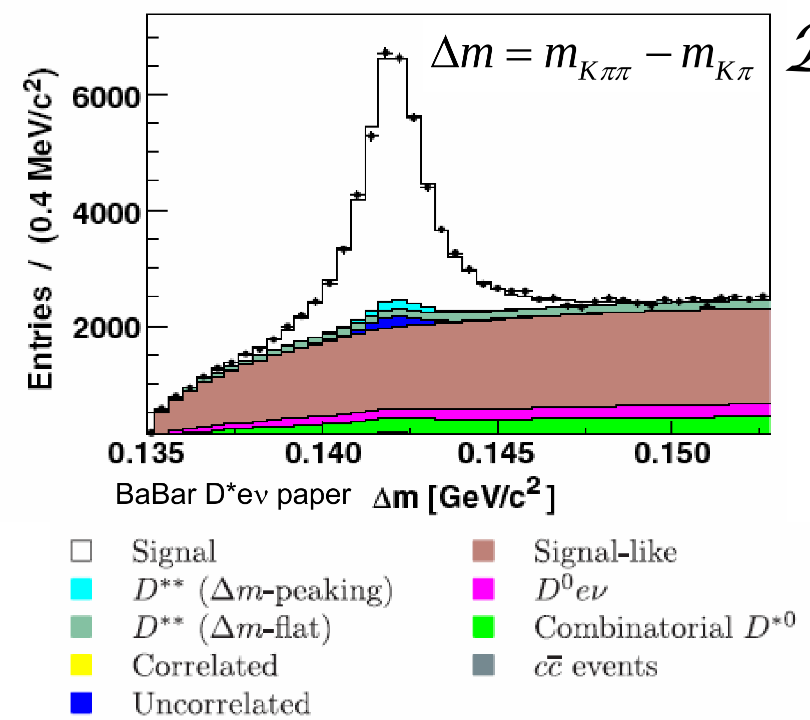
- Measurement is not statistically limited, so use clean signal mode for $D \to K\pi$ decay only.
- Extract signal yield, $F(1)|V_{cb}|$ and ρ from 3D binned fit to data.

Side measurements: V_{cb}

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

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

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



BaBar D*eν paper

$$\mathcal{B}(B^- \to D^{*0} e^- \overline{\nu}) = (5.56 \pm 0.08 \pm 0.41)\%$$

$$F(1)|V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \times 10^{-3}$$

$$|V_{cb}| = (39.0 \pm 0.6 \pm 2.0) \times 10^{-3}$$

- Using F(1)=0.919 ±0.033 from Hashimoto et al., PRD**66** 014503 (2002).

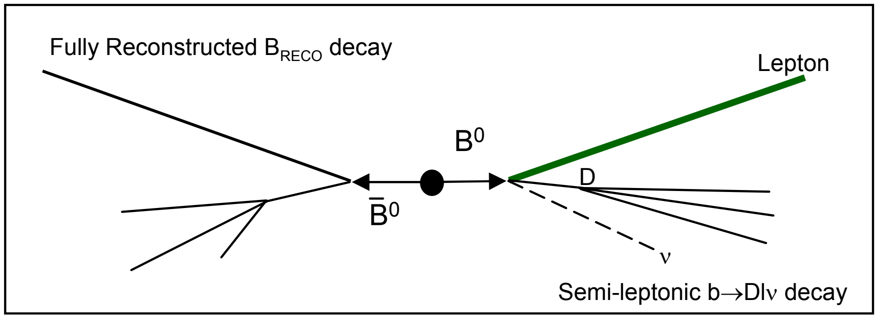
Side measurements: V_{cb}

- Use the differential decay rates of B→Dlν to determine $|V_{cb}|$:

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

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

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



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

- Reconstruct the following D decay channels:

$D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, $K_S^0\pi^+\pi^-$, $K_S^0\pi^+\pi^-\pi^0$, $K_S^0\pi^0$, K^+K^-, $\pi^+\pi^-$, $K_S^0K_S^0$

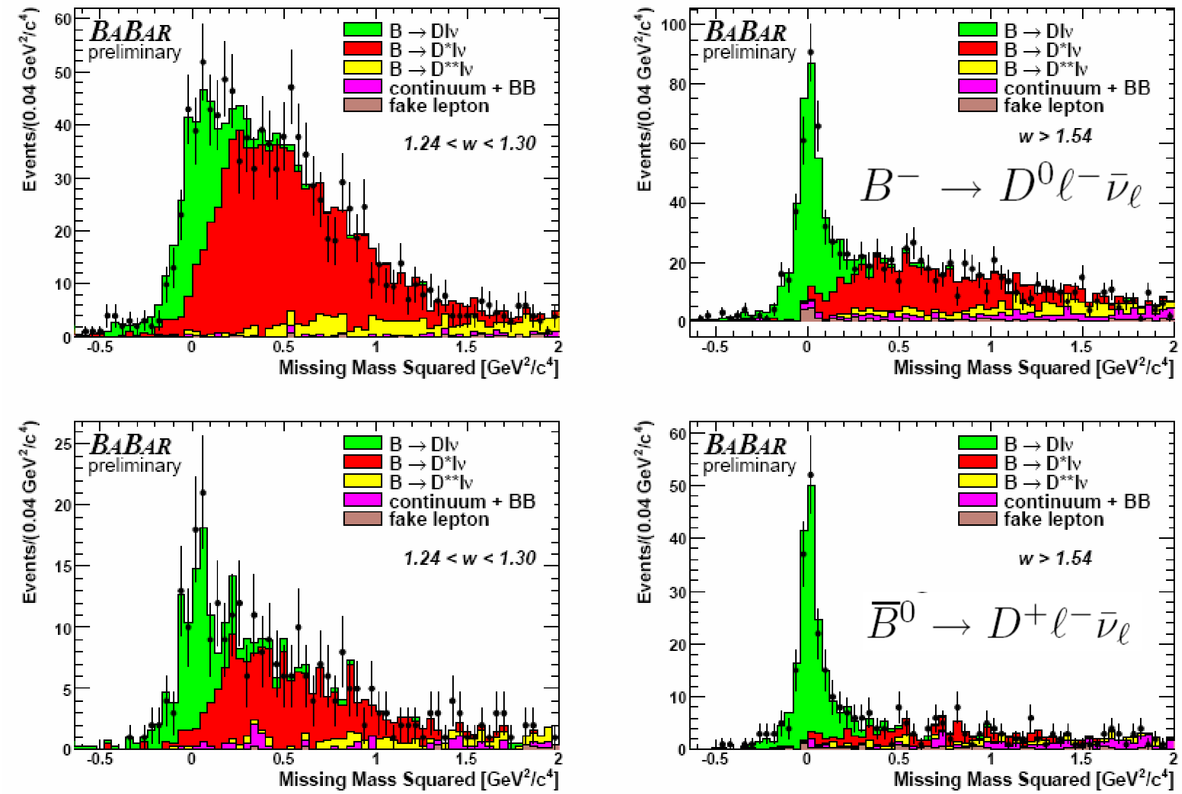
$D^+ \to K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K_S^0\pi^+$, $K_S^0\pi^+\pi^0$, $K^+K^-\pi^+$, $K_S^0K^+$, $K_S^0\pi^+\pi^+\pi^-$

Side measurements: V_{cb}

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

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

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



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

Side measurements: V_{cb}

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

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

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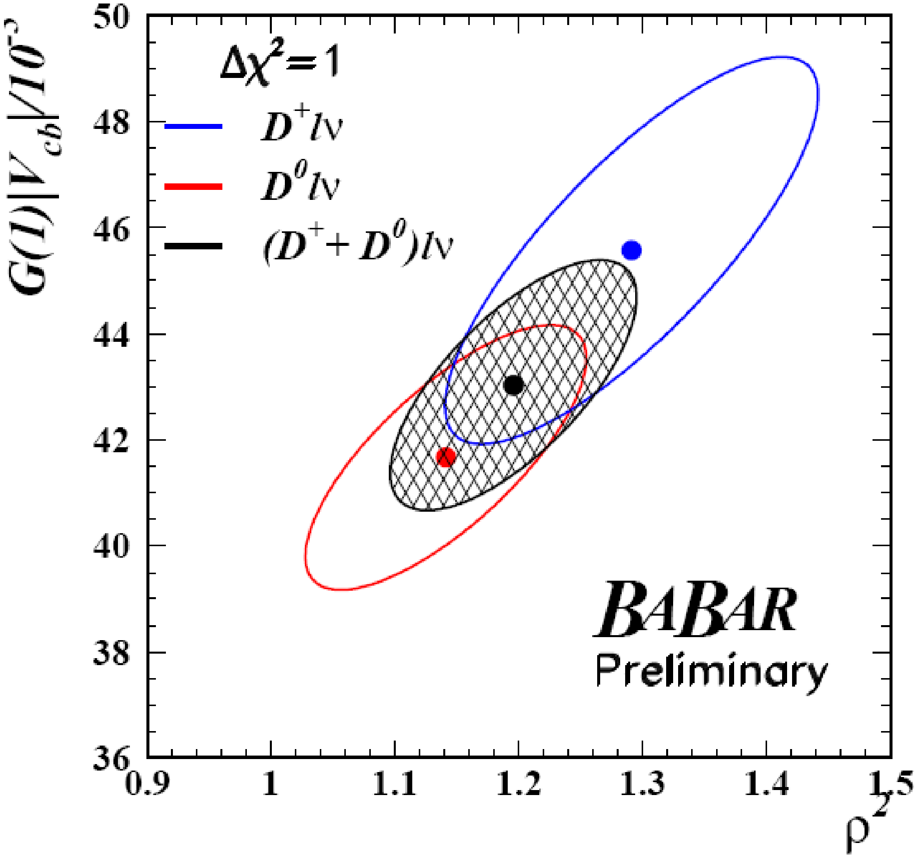


- Results of a combined fit to D^0 and $D^\pm$ modes gives:

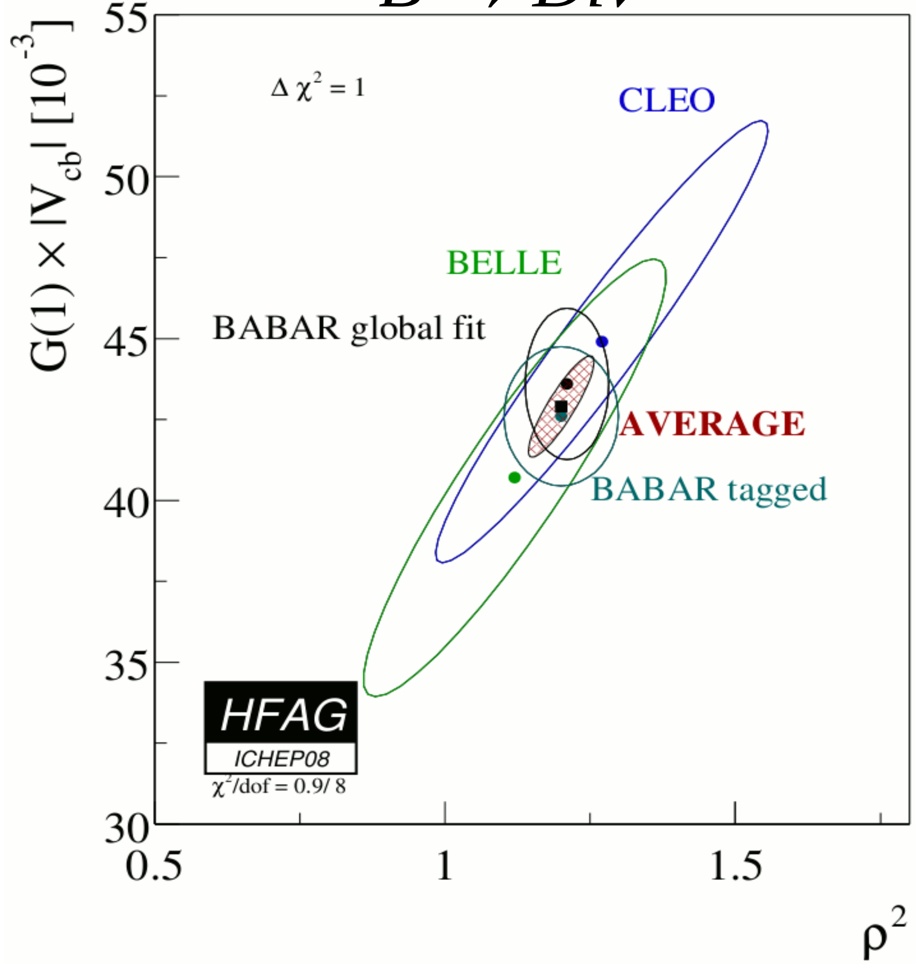
$$G(1)|V_{cb}| = (43.0 \pm 1.9 \pm 1.4) \times 10^{-3}$$

$$|V_{cb}| = (39.8 \pm 1.8_{\mathrm{stat}} \pm 1.3_{\mathrm{syst}} \pm 0.9_{\mathrm{FF}}) \times 10^{-3}$$

- Using G(1) from Okamoto et al., NPPS **140** 461 (2005) and correcting by 1.007 for QED effects.

$|V_{cb}|$

$B \to D l \nu$

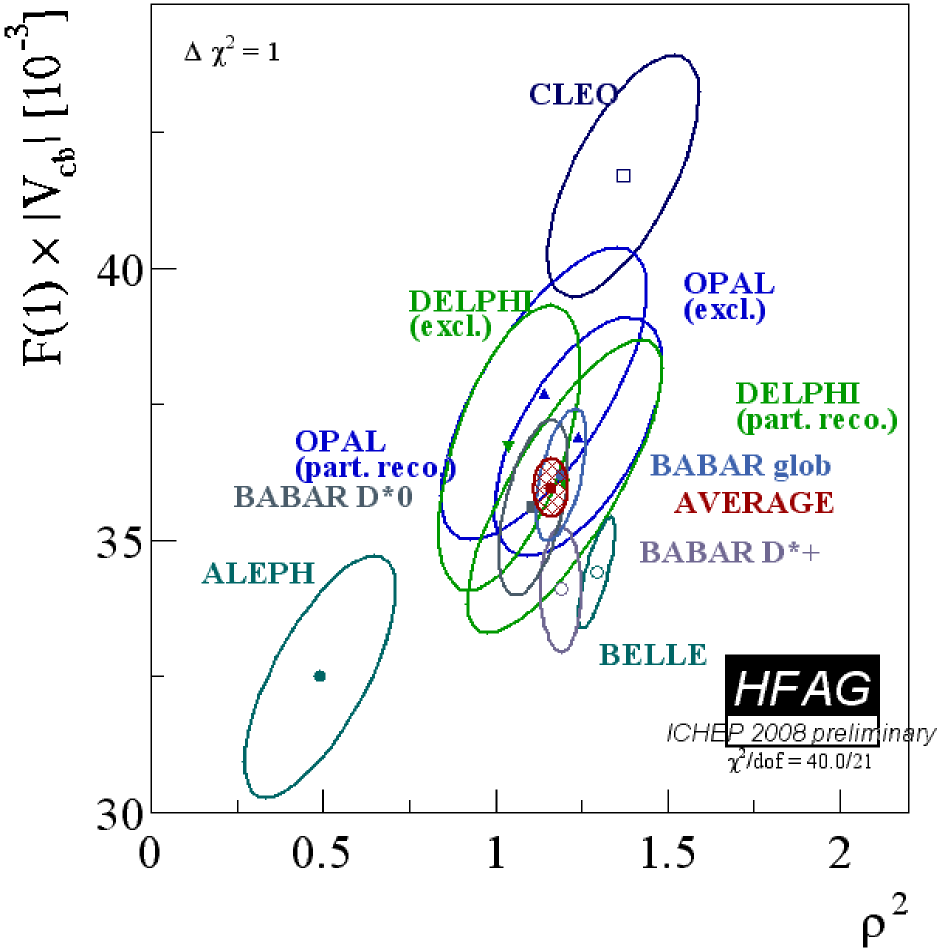


$$G(1)|V_{cb}| = (42 \pm 1.6) \times 10^{-3}$$

$$|V_{cb}| = (39.7 \pm 1.4_{exp} \pm 0.9_{theory}) \times 10^{-3}$$

- Using G(1)=1.074 ±0.018±0.016 from Okamoto et al., NPPS **140**, 461 (2005).

$B \to D^* l \nu$



$$F(1)|V_{cb}| = (35.97 \pm 0.53) \times 10^{-3}$$

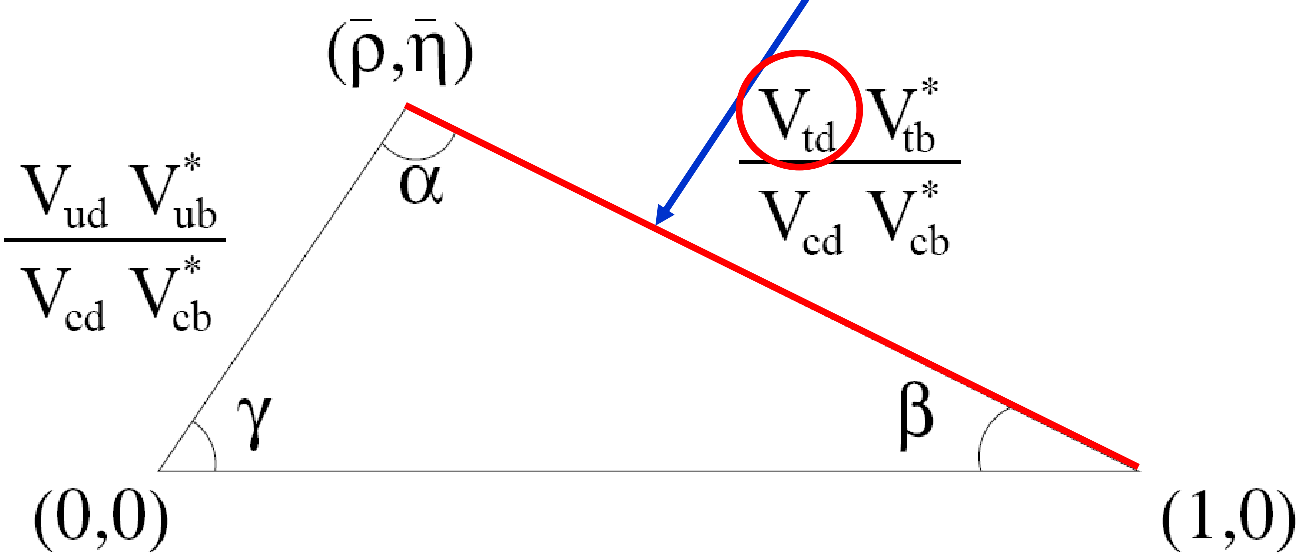
$$|V_{cb}| = (38.7 \pm 0.6_{exp} \pm 0.9_{theory}) \times 10^{-3}$$

- Using F(1)=0.924 ±0.012±0.019 from Laiho, arXiv:0710.1111 [hep-lat].

Sides of the Unitarity Triangle

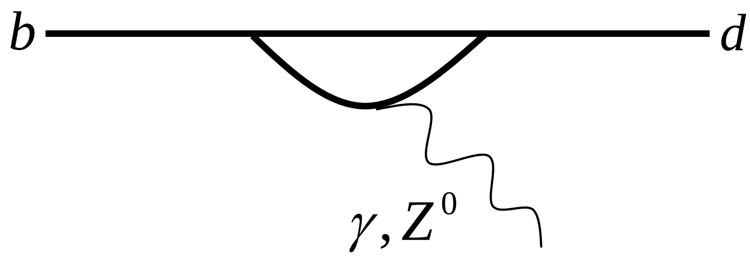
- Use inclusive measurements of $b \to d\gamma$ and $b \to s\gamma$ to measure the ratio $|V_{td}| / |V_{ts}|$.
- Able to compare results with Bs mixing results from the TeVatron.

$$b \to d\gamma$$
$$B \to X_d\gamma$$



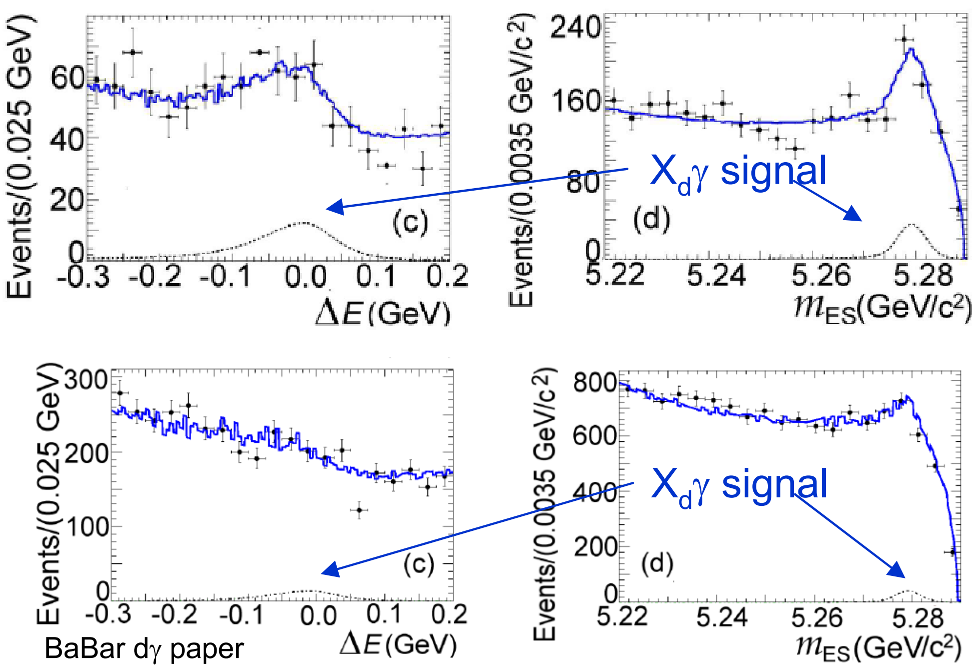
$B \rightarrow X_d\gamma$

- FCNC process (same topology as $B \rightarrow X_s\gamma$).
- Leading order contribution: electroweak penguin.
  - sensitive to NP



$B \rightarrow X_d\gamma$
$B^0 \rightarrow \pi^+\pi^-\gamma$
$B^+ \rightarrow \pi^+\pi^0\gamma$
$B^+ \rightarrow \pi^+\pi^-\pi^+\gamma$
$B^0 \rightarrow \pi^+\pi^-\pi^0\gamma$
$B^0 \rightarrow \pi^+\pi^-\pi^+\pi^-\gamma$
$B^+ \rightarrow \pi^+\pi^-\pi^+\pi^0\gamma$
$B^+ \rightarrow \pi^+\eta\gamma$

- Challenging analysis with large backgrounds at high m_X.
- Signal suppressed by V_{td}.
- Extract signal from a 2D Fit in m_{ES} and ΔE.



$M(X)[\mathrm{GeV}/c^2]$	N_S	ϵ	$\mathcal{B}(\times 10^{-6})$
$0.6 < M(X_d) < 1.0$	66 ± 26	7.0%	$1.2 \pm 0.5 \pm 0.1$
$1.0 < M(X_d) < 1.8$	107 ± 47	5.2%	$2.7 \pm 1.2 \pm 0.4$

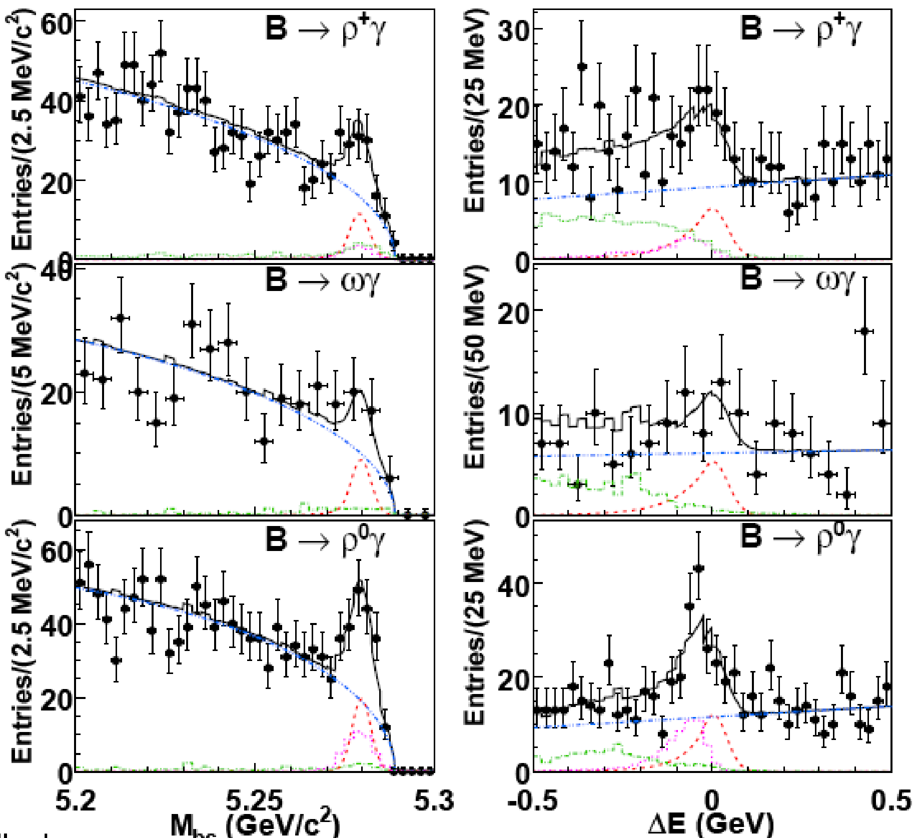
- Convert B(dγ) / B(sγ) into a measurement of $|V_{td}| / |V_{ts}|$ using Ali, Asatrian, and Greub PLB 429 87 (1998)

$top: \quad 0.6 < m_{X_d} < 1.0 GeV/c^2$

$bottom: 1.0 < m_{X_d} < 1.8 GeV/c^2$

$B \to X_d\gamma$

- Exclusive analysis of $b \to d\gamma$ recently performed by Belle



Belle dγ paper

$$\frac{\mathcal{B}(B^0 \to \rho^0\gamma)}{\mathcal{B}(B^0 \to K^{*0}\gamma)} = 0.0206\,^{+0.0045}_{-0.0043}\,^{+0.0014}_{-0.0016},$$

$$\frac{\mathcal{B}(B \to \rho\gamma)}{\mathcal{B}(B \to K^{*}\gamma)} = 0.0302\,^{+0.0060}_{-0.0055}\,^{+0.0026}_{-0.0028},$$

$$\frac{\mathcal{B}(B \to (\rho,\omega)\gamma)}{\mathcal{B}(B \to K^{*}\gamma)} = 0.0284 \pm 0.0050\,^{+0.0027}_{-0.0029}$$

- Converting results to $|V_{td}| / |V_{ts}|$ obtain

$$\frac{|V_{td}|}{|V_{ts}|} = 0.195^{+0.020}_{-0.019}(\text{exp}) \pm 0.015(\text{th}) \quad [Belle]$$

$$= 0.177 \pm 0.043(\text{exp}) \pm 0.001(\text{th}) \quad [BaBar]$$

Mainly from neglecting annihilation topologies.

N.B. Errors from fragmentation etc included in the quoted experimental error.

Mode	Yield	Significance	Efficiency (%)	$\mathcal{B}$ (10^{-7})
$B^+ \to \rho^+\gamma$	$45.8\,^{+15.2}_{-14.5}\,^{+2.6}_{-3.9}$	3.3	8.03 ± 0.59	$8.7\,^{+2.9}_{-2.7}\,^{+0.9}_{-1.1}$
$B^0 \to \rho^0\gamma$	$75.7\,^{+16.8}_{-16.0}\,^{+5.1}_{-6.1}$	5.0	14.81 ± 0.95	$7.8\,^{+1.7}_{-1.6}\,^{+0.9}_{-1.0}$
$B^0 \to \omega\gamma$	$17.5\,^{+8.2}_{-7.4}\,^{+1.1}_{-1.0}$	2.6	6.58 ± 0.76	$4.0\,^{+1.9}_{-1.7} \pm 1.3$
$B \to \rho\gamma$	—	5.8	—	$12.1\,^{+2.4}_{-2.2} \pm 1.2$
$B \to (\rho,\omega)\gamma$	—	6.2	—	$11.4 \pm 2.0\,^{+1.0}_{-1.2}$

Tests of **CPT**

CPT

- Discrete symmetry conserved in Lorentz invariant local QFT.
  - i.e. the SM and popular extensions.
  - Expect **CPT** to be conserved based on prejudice that we have not seen it violated.
    - But we have seen that the same prejudice had to be given up for **P**, **C**, and **CP** symmetries in Weak decay.
  - Possible to construct a theory that violates **CPT.**
  - Don't expect to see **CPT** violation, but we <u>must</u> look for it!

If **CPT** is conserved particles and antiparticles have:

- The same mass and lifetime.
- Symmetric electric charge.
- Opposite magentic dipole moments (or gyro-magnetic ratios for point like leptons)

CPT

- Discrete symmetry conserved in Lorentz invariant local QFT.
  - i.e. the SM and popular extensions.

  - Expect **CPT** to be conserved based on prejudice that we have not seen it violated.
    - But we have seen that the same prejudice had to be given up for **P**, **C**, and **CP** symmetries in Weak decay.

  - Possible to construct a theory that violates **CPT.**

  - Don't expect to see **CPT** violation, but we <u>must</u> look for it!

- Experimentally test CPT at the B factories via:
  - Measurements of the τ^+ / τ^- lifetime.
  - Measuring 'z' in B decays (recall mass eigen-states):

$$|B_{\mathrm{L,H}}\rangle = p\sqrt{1 \mp z}|B^0\rangle \pm q\sqrt{1 \pm z}|\overline{B}^0\rangle$$

$$z = \frac{(M_{11} - M_{22}) - \frac{i}{2}(\Gamma_{11} - \Gamma_{22})}{\Delta m - \frac{i}{2}\Delta\Gamma}$$

CPT: Using hadronic B decays

- Similar selection of events as used for the $c\bar{c}s$ sin2β analysis
  - BFlav decays: $B^0 \to D^{(*)-}\pi^+(\rho^+, a_1^+), B^0 \to J/\psi K^{*0}(K^{*0} \to K^+\pi^-)$
  - CP modes: $B^0 \to J/\psi K^0, \psi(2S)K_S^0, \chi_{1c}K_S^0$
  - Charged B control samples: $B^+ \to \bar{D}^{(*)0}\pi^+, J/\psi K^{(*)+}, \psi(2S)K^+, \chi_{1c}K^+$

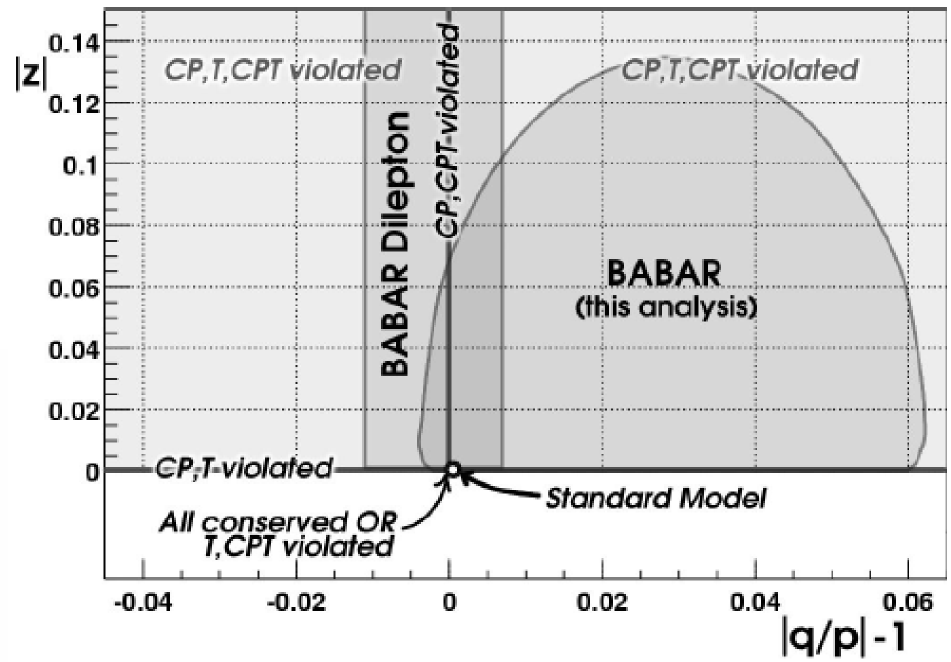
	CPT		$\not{C}\not{P}\not{T}$		
	CP, T	$\not{C}\not{P}, \not{T}$	$\not{C}\not{P}, T$	$CP, \not{T}$	$\not{C}\not{P}, \not{T}$
$\lvert q/p \rvert$	$=1$	$\neq 1$	$=1$	$=1$	$\neq 1$
z	$=0$	$=0$	$\neq 0$	$=0$	$\neq 0$

$$\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma/\Gamma = -0.008 \pm 0.037(\mathrm{stat.}) \pm 0.018(\mathrm{syst.})[-0.084, 0.068]\,,$$

$$|q/p| = 1.029 \pm 0.013(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})[\ \ 1.001, 1.057]\,,$$

$$(\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|)\,\mathrm{Re}\,\mathsf{z} = 0.014 \pm 0.035(\mathrm{stat.}) \pm 0.034(\mathrm{syst.})[-0.072, 0.101]\,,$$

$$\mathrm{Im}\,\mathsf{z} = 0.038 \pm 0.029(\mathrm{stat.}) \pm 0.025(\mathrm{syst.})[-0.028, 0.104]\,.$$

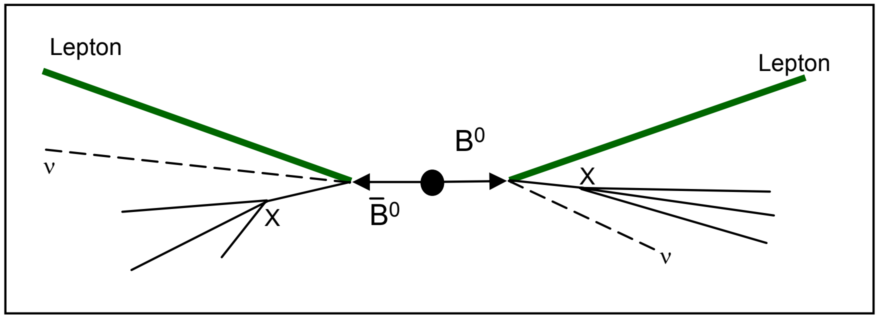


  - compatible with CPT, CP and T conservation.

BaBar Collaboration, PRD 70, 012007 (2004)

CPT: Using di-lepton events

- Reconstruct B$\overline{\text{B}}$ pairs where both B mesons decay via $b \to Xl\nu$
  - Sample includes direct b→l events: lepton charge tags the B flavor.



Δt = $t_1 - t_2$
= proper time difference between the decays of the two B mesons.

  - As B^0 mesons mix we can have ++, ––, and +– charge combinations for the two leptons: measure N^{++}, N^{--}, and N^{+-}.
  - We can measure two asymmetries:

$$N^{++} \propto \frac{e^{-\Gamma|\Delta t|}}{2}\left|\frac{p}{q}\right|^2\left\{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) - \cos(\Delta m\Delta t)\right\},$$

$$N^{--} \propto \frac{e^{-\Gamma|\Delta t|}}{2}\left|\frac{q}{p}\right|^2\left\{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) - \cos(\Delta m\Delta t)\right\},$$

$$N^{+-} \propto \frac{e^{-\Gamma|\Delta t|}}{2}\left\{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) - 2\,\mathrm{Re}\,z\,\sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + \cos(\Delta m\Delta t) + 2\,\mathrm{Im}\,z\,\sin(\Delta m\Delta t)\right\},$$

$$A_{T/CP} = \frac{P(\overline{B}^0 \to B^0) - P(B^0 \to \overline{B}^0)}{P(\overline{B}^0 \to B^0) + P(B^0 \to \overline{B}^0)} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}} = \frac{1 - |q/p|^4}{1 + |q/p|^4}.$$

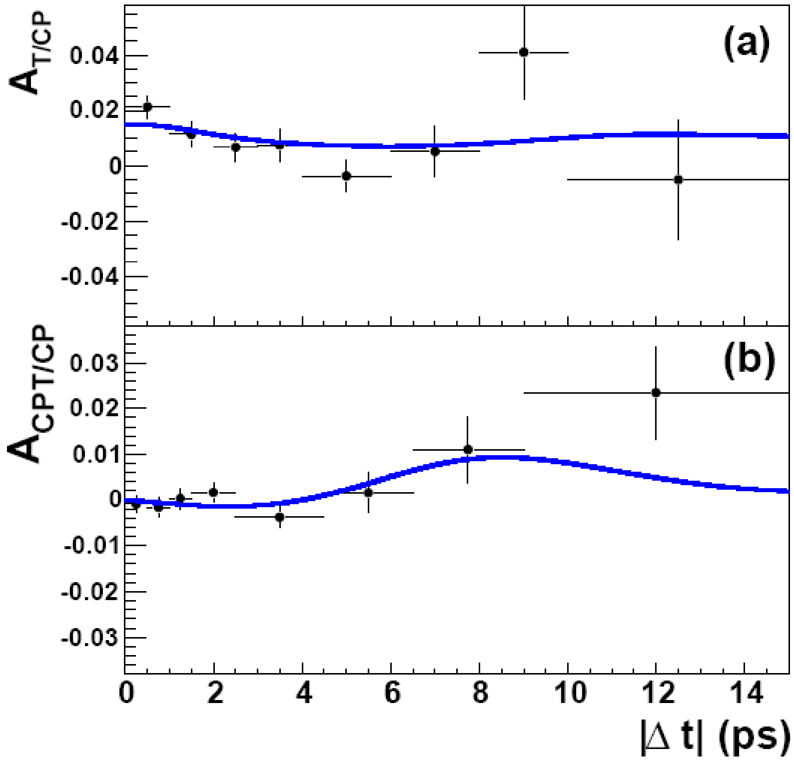
$$A_{CPT/CP}(|\Delta t|) = \frac{P(B^0 \to B^0) - P(\overline{B}^0 \to \overline{B}^0)}{P(B^0 \to B^0) + P(\overline{B}^0 \to \overline{B}^0)} = \frac{N^{+-}(\Delta t > 0) - N^{+-}(\Delta t < 0)}{N^{+-}(\Delta t > 0) + N^{+-}(\Delta t < 0)} \simeq 2\frac{\mathrm{Im}\,z\,\sin(\Delta m\Delta t) - \mathrm{Re}\,z\,\sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right)}{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + \cos(\Delta m\Delta t)}$$

$$A^{SM}_{T/CP} \sim 10^{-3}$$

$A_{CPT/CP}$ sensitive to $\Delta\Gamma \times \mathrm{Re}(z)$

M. Beneke *et al.*, Phys. Lett. B **576**, 173 (2003); M. Ciuchini *et al.*, JHEP **0308**, 031 (2003).

CPT: Using di-lepton events



$$|q/p| - 1 = (-0.8 \pm 2.7(\text{stat.}) \pm 1.9(\text{syst.})) \times 10^{-3},$$
$$\text{Im}\,z = (-13.9 \pm 7.3(\text{stat.}) \pm 3.2(\text{syst.})) \times 10^{-3},$$
$$\Delta\Gamma \times \text{Re}\,z = (-7.1 \pm 3.9(\text{stat.}) \pm 2.0(\text{syst.})) \times 10^{-3}\,\text{ps}^{-1}.$$

- Results are compatible with CPT conservation.

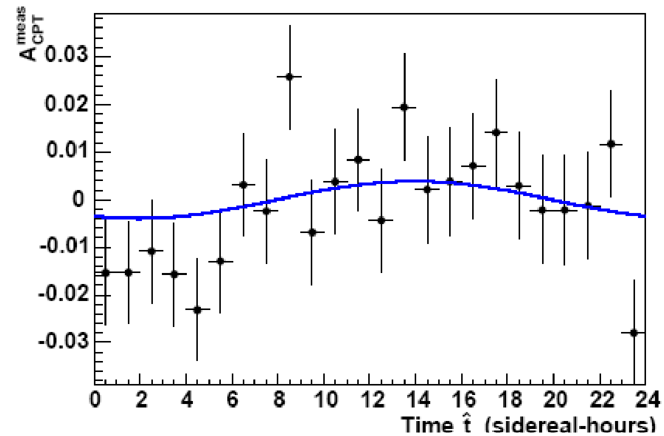
- Can also study variations as a function of sidereal time.

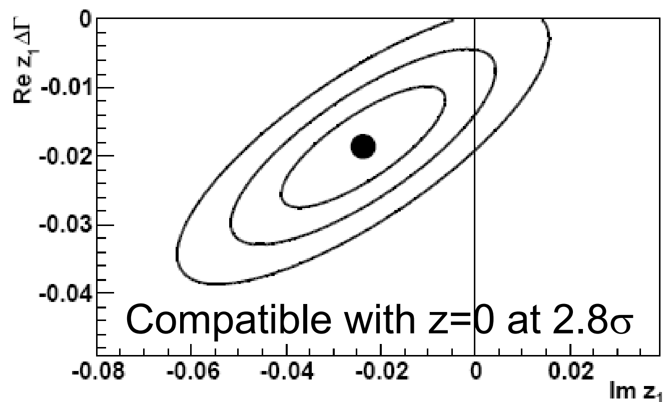
$$1\, d_{sidereal} \approx 0.99727\, d_{solar}$$

- z depends on the 4-momentum of the B candidate:

$$z \simeq \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

V. A. Kostelecký, Phys. Rev. Lett. **80**, 1818 (1998).





Results shown are from BaBar's di-lepton CPT papers

$B \rightarrow VV$ decays

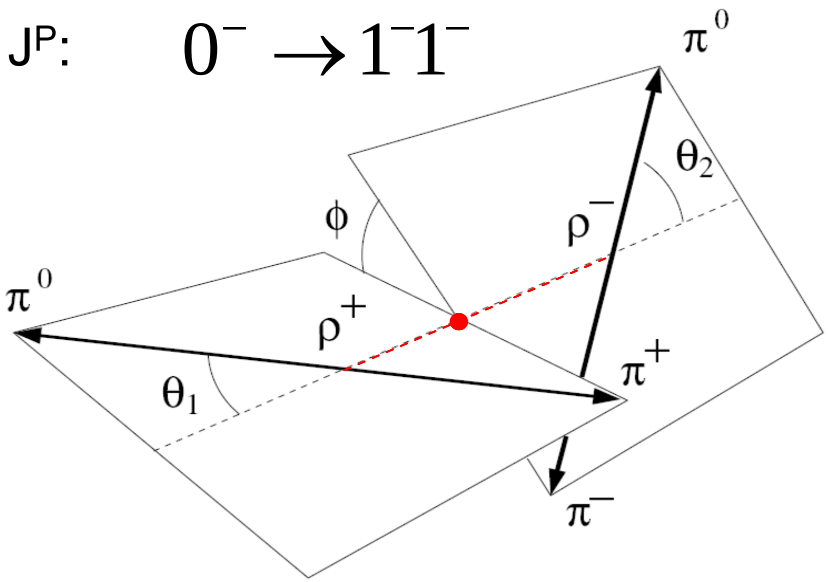
(and related channels)

Angular analysis

- With sufficient statistics one can perform a full angular analysis:

$$B \rightarrow V_1 V_2$$

J^P: $0^- \rightarrow 1^- 1^-$



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:

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

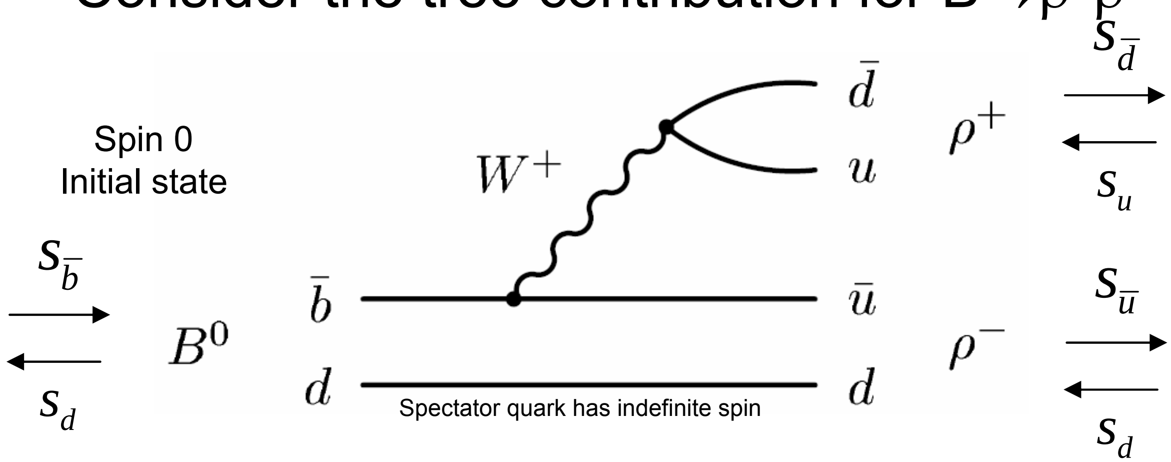
where the H_m are helicity amplitudes.

$$\frac{d^3\Gamma}{d\cos\theta_1 d\cos\theta_2 d\Phi} \propto \left| \sum_{m=-1,0,1} H_m Y_{1,m}(\theta_1,\Phi) Y_{1,-m}(\theta_2,\Phi) \right|^2$$

$$\propto \begin{Bmatrix} \frac{1}{4}\sin^2\theta_1 \sin^2\theta_2 (|H_{+1}|^2 + |H_{-1}|^2) + \cos^2\theta_1 \cos^2\theta_2 |H_0|^2 \\ +\frac{1}{2}\sin^2\theta_1 \sin^2\theta_2 [\cos 2\Phi \Re(H_{+1}H^*_{-1}) - \sin 2\Phi \Im(H_{+1}H^*_{-1})] \\ +\frac{1}{4}\sin 2\theta_1 \sin 2\theta_2 [\cos\Phi \Re(H_{+1}H^*_0 + H_{-1}H^*_0) - \sin\Phi \Im(H_{+1}H^*_0 - H_{-1}H^*_0)] \end{Bmatrix}$$

Angular analysis

- Consider the tree contribution for $B \to \rho^+\rho^-$



h=0

h=0 state preferred over h=+1 (overall J = 0)

- Neglecting motion within the mesons only H_0 is allowed.
- Relative quark motion in the mesons gives rise to the H_{+1} and H_{-1} contributions.
- $H_{+1/-1}$ require 1 and 2 spin flips, respectively.

- In the transversity basis we have three CP eigen-states:

$$A_0 = H_0$$

$$A_{\parallel} = \frac{1}{\sqrt{2}}\left(H_{+1} + H_{-1}\right)$$

} CP even

$$A_{\perp} = \frac{1}{\sqrt{2}}\left(H_{+1} - H_{-1}\right)$$

CP odd

- With sufficient statistics we can measure S and C for each of these three components.
- If $f_L \sim 1$ we just measure S and C for the longitudinal polarisation.

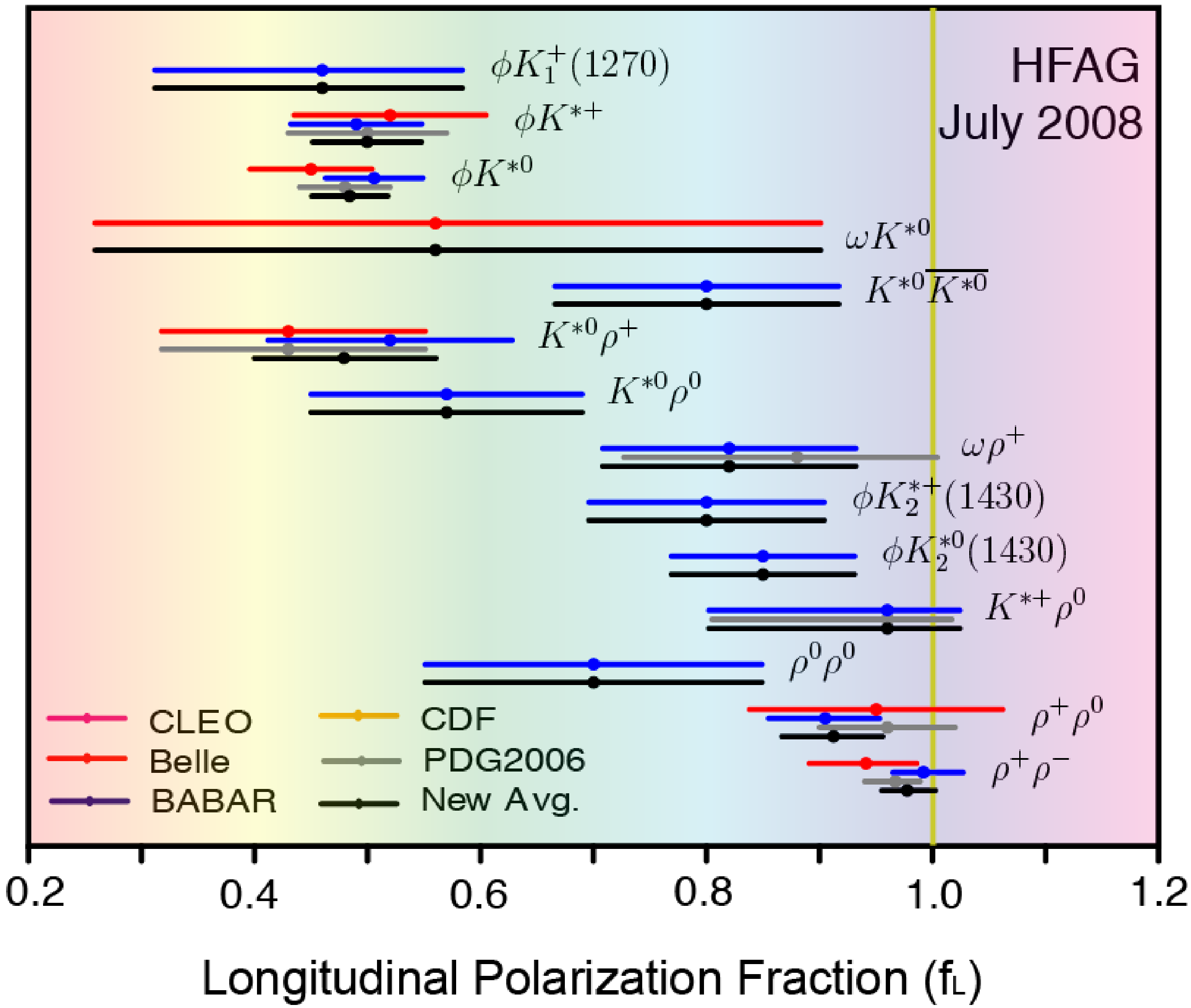
- Spin flip's are helicity suppressed:

$$A_0 \ : \ A_{\parallel} \ : \ A_{\perp} \sim O(1) \ : \ O\left(\frac{m_V}{m_B}\right) : O\left(\frac{m_V}{m_B}\right)^2 \quad \Rightarrow \quad f_L = 1 - \frac{m_V^2}{m_B^2}$$

Ali, Kagan, Kramer, Dunietz et al., Suzuki

B→VV decays

Polarizations of Charmless Decays



- B→ρρ decays fit the pattern:

$$f_L = 1 - \frac{m_V^2}{m_B^2}$$

- f_L is large for:

$$K^{*0}\overline{K}^{*0}$$
$$\omega\rho^+$$
$$\phi K_2^{*0}$$
$$\rho^0 K^{*+}$$

- f_L ~ 0.5 for some penguin dominated modes: notably ϕK*.

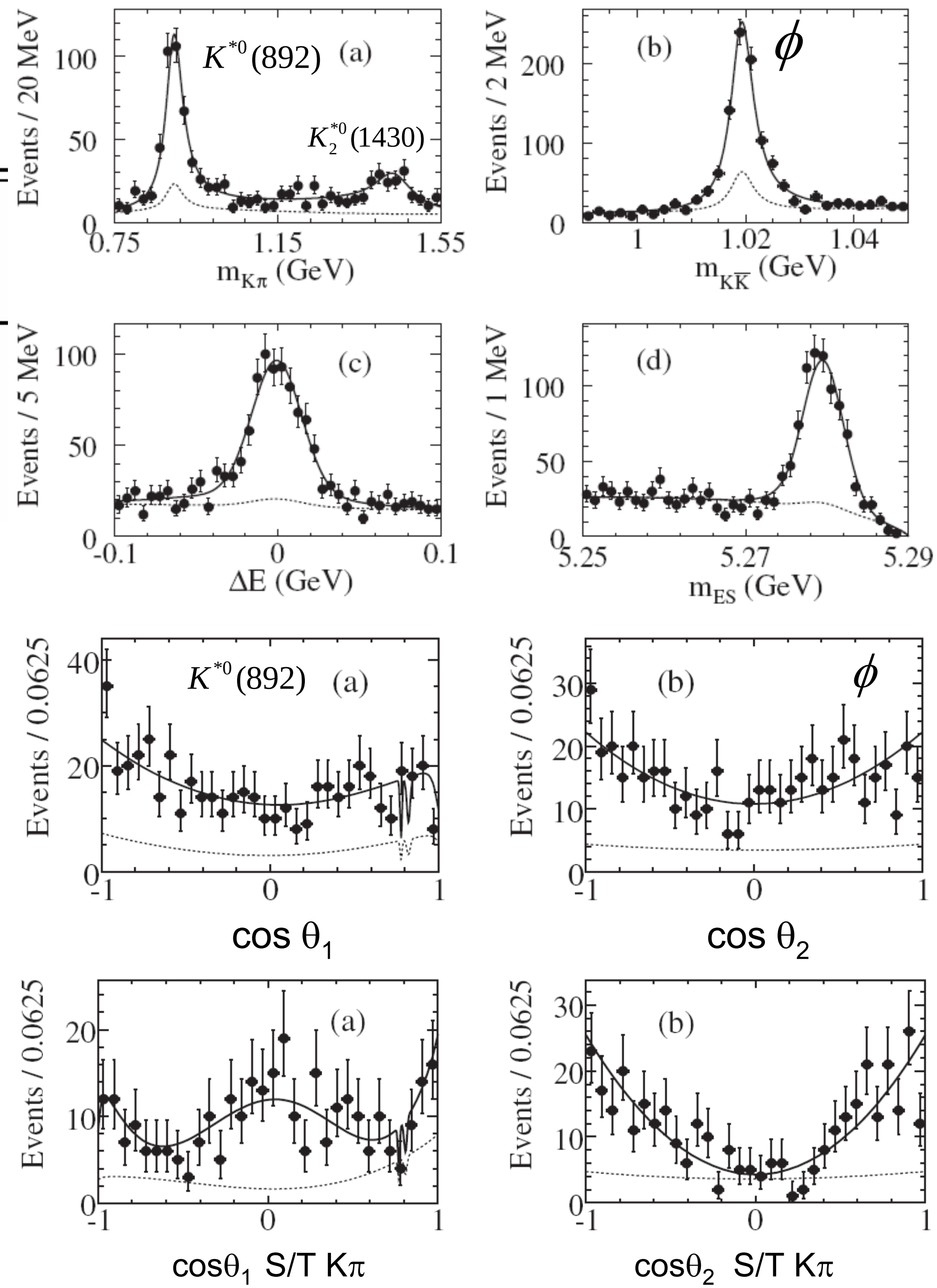
- What mechanism(s) result in the observed behaviour?

$B \to \phi K^*$

BaBar ϕK^{*0} analysis

- Able to simultaneously measure f_L, $f_{||}$ (and $f_\perp$).

parameter	$\varphi K^*(892)$ $J=1$	$\varphi K_2^*(1430)$ $J=2$
$\mathcal{B}_J\ (10^{-6})$	$9.7 \pm 0.5 \pm 0.5$	$7.5 \pm 0.9 \pm 0.4$
f_{LJ}	$0.494 \pm 0.034 \pm 0.013$	$0.901^{+0.046}_{-0.058} \pm 0.037$
$f_{\perp J}$	$0.212 \pm 0.032 \pm 0.013$	$0.002^{+0.018}_{-0.002} \pm 0.031$



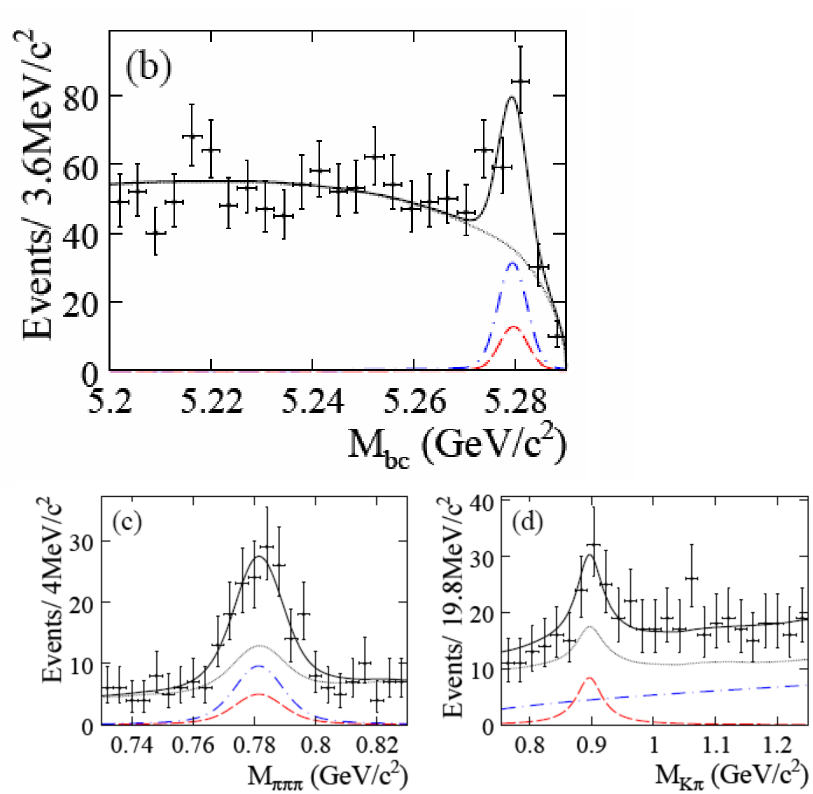
- VV ϕK^* has f_L~0.5 and $f_\perp$~0.2.
  - Doesn't fit naïve picture very well.
- VT ϕK^* has f_L~0.9 and $f_\perp$~0.0.
  - Fits naïve picture.
- $f_\perp$ << $f_{||}$ in the SM.
  - This ratio could be inverted in the presence of right handed currents.
- Important to study other similar decays!

August 2008

$B \to \omega K^*$

- When we don't have a large signal, it is not possible to do a full angular analysis.
  – Fit for the fraction of longitudinally polarised events (as with the $\rho\rho$ α analysis from Lecture 1).

$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4}(1 - f_L)\sin^2\theta_1 \sin^2\theta_2\right]$$



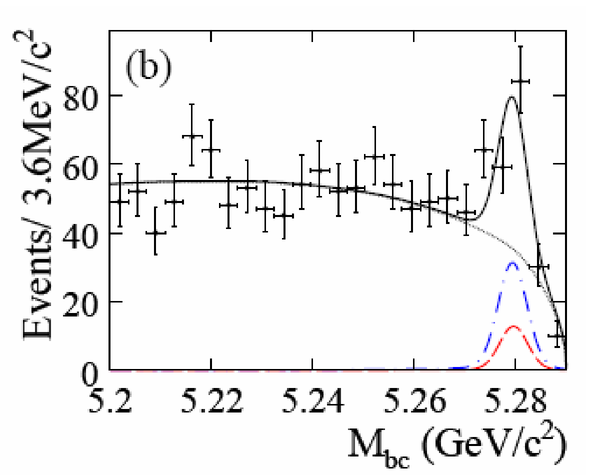
- Signal yield is extracted from a fit to mES, ΔE, $m_{K\pi}$, and $m_{3\pi}$ in bins of helicity angle.
- Perform a χ^2 fit only varying f_L to extract polarisation information.
- Signal significance: 3.0 σ

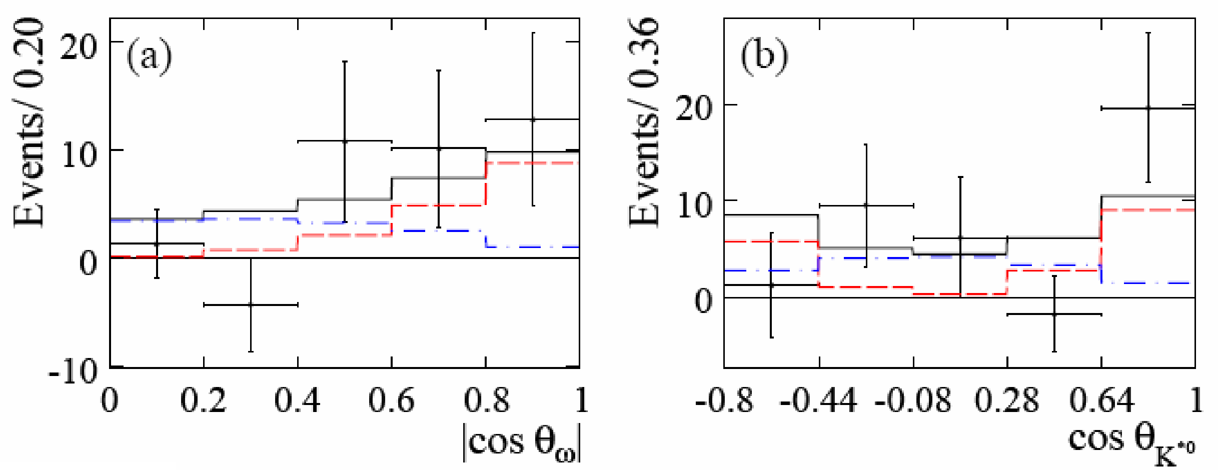
$$\mathcal{B} = \left(1.8 \pm 0.7^{+0.3}_{-0.2}\right) \times 10^{-6}$$

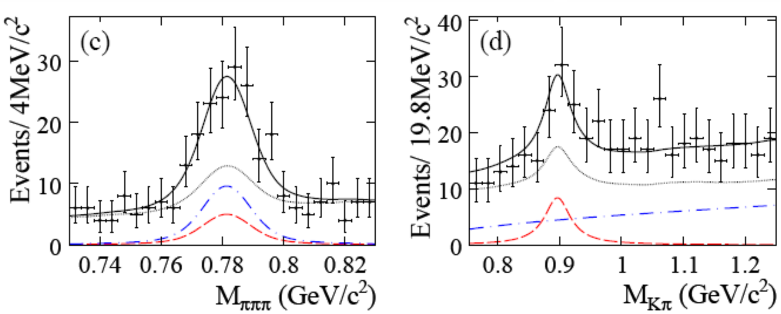
$B \to \omega K^*$

- When we don't have a large signal, it is not possible to do a full angular analysis.
  - Fit for the fraction of longitudinally polarised events (as with the $\rho\rho$ α analysis from Lecture 1).

$$\frac{d^2\Gamma}{\Gamma d\cos\theta_1 d\cos\theta_2} = \frac{9}{4}\left[f_L \cos^2\theta_1 \cos^2\theta_2 + \frac{1}{4}(1 - f_L)\sin^2\theta_1 \sin^2\theta_2\right]$$







$$f_L = 0.56 \pm 0.26^{+0.18}_{-0.08}$$

$B \to \phi\rho, \phi\phi$

- Rare decays:
  - $\phi\phi$ OZI suppressed.
  - $\phi\rho^{\pm,0}$ Electroweak penguin processes.
- Could be sensitive to new physics.
  - Different enhancements for different scenarios: RPV SUSY/2HDM/MSUGRA
- BR ~ 10^{-9}.
- $\phi\rho^{+}$ could be enhanced by ϕ-ω mixing up to $O(10^{-7})$; what about $\phi\rho^{0}$?

Note: $\varepsilon = \varepsilon(f_L)$; Fit for f_L^{eff} with a known $R = \varepsilon_L/\varepsilon_T$

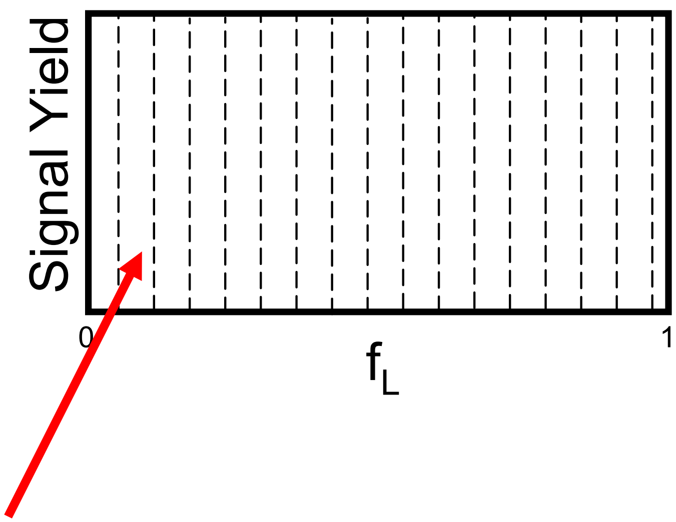
So:

$$f_L = \frac{f_L^{\rm eff}}{R + f_L^{\rm eff}(1-R)},$$

- What do we use for f_L when fitting the data if there is insufficient signal?

  i) Use prejudice from a theory calculation [OK if they agree].

  ii) Scan for signal for different f_L and take the largest upper limit/most significant result.



For each value of f_L compute the value of Nsig and its error, as well as the significance of the result, branching fraction and 90% CL upper limit.

M. Gronau and J. Rosner, arXiv:0806.3584.

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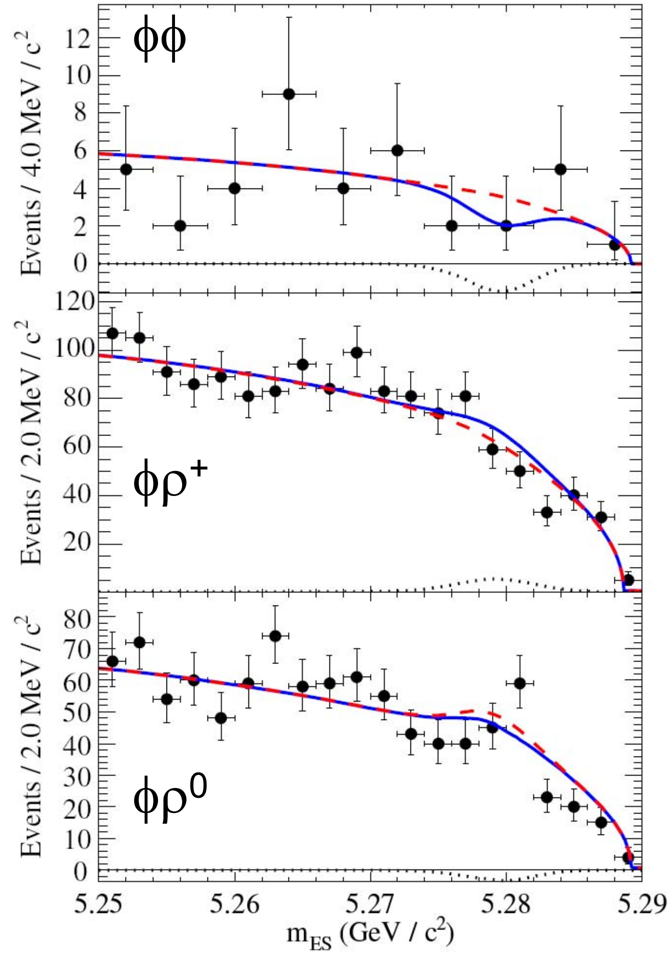
N	Mode	$\mathcal{Y}_S$	Bias	$\epsilon(\%)$	$\prod \mathcal{B}_i(\%)$	σ	$\mathcal{B}(\times 10^{-7})$	UL($\times 10^{-7}$)
209	$\phi\phi$	$-1.5^{+3.7}_{-2.9}$	-0.4 ± 0.2	40.4 [28.7]	24.3 ± 1.2	0.0	$-0.4^{+1.2}_{-0.9} \pm 0.3$	<2.0
3175	$\phi\rho^+$	$22.5^{+11.3}_{-9.7}$	$+2.3 \pm 1.1$	5.7 [9.8]	49.3 ± 0.6	2.2	$15^{+7}_{-6} \pm 9$	<30
3949	$\phi\rho^0$	$3.9^{+6.3}_{-4.4}$	$+0.8 \pm 0.4$	24.1 [26.5]	49.3 ± 0.6	1.0	$0.9^{+1.3}_{-0.9} \pm 0.9$	<3.3
	ϕf_0	$0.8^{+2.4}_{-1.4}$	-1.7 ± 0.5	22.1	...	0.0	$0.2^{+0.6}_{-0.3} \pm 0.3$	<3.8
	$f_0 f_0$	$-13.6^{+4.8}_{-3.5}$	-1.8 ± 0.5	25.5	...	0.0	$-1.4^{+0.5}_{-0.4} \pm 1.5$	<2.3

- No signal observed.

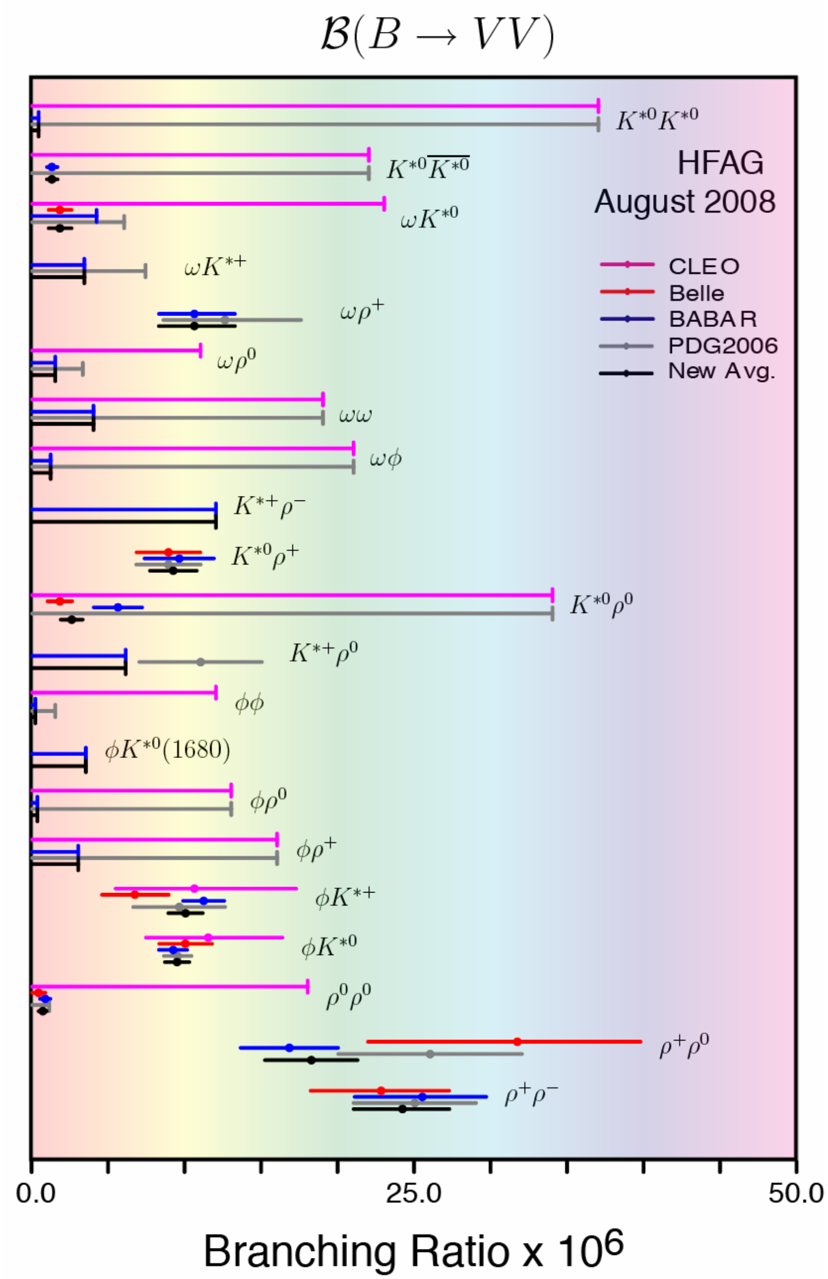
BaBar $\phi\phi$, $\phi\rho$ analysis



S. Bar-Shalom, G. Eilam, and Y. D. Yang, Phys. Rev. D **67**, 014007 (2003).
C. D. Lu *et al.*, Eur. Phys. Jour. C **41**, 311 (2005).
M. Beneke, J. Rohrer, and D. Yang, Nucl. Phys. B **774**, 64 (2007).
D. Du and Z. Xing, Phys. Lett. B **312**, 199 (1993).
A. Deandrea *et al.*, Phys. Lett. B **320**, 170 (1994).
A. Ali *et al.*, Phys. Rev. D **58**, 094009 (1998).
Y. H. Chen *et al.*, Phys. Rev. D **60**, 094014 (1999).
W. Zou and Z. Xiao, Phys. Rev. D **72**, 094026 (2005).
C. D. Lu *et al.*, Chin. Phys. Lett. **23**, 2684 (2006).
J. Li *et al.*, hep-ph/0607249.
S. Bao, F. S. Su, Y.-L. Wu, and C. Zhuang, Phys. Rev. D **77**, 095004 (2008).
M. Gronau and J. Rosner, arXiv:0806.3584.

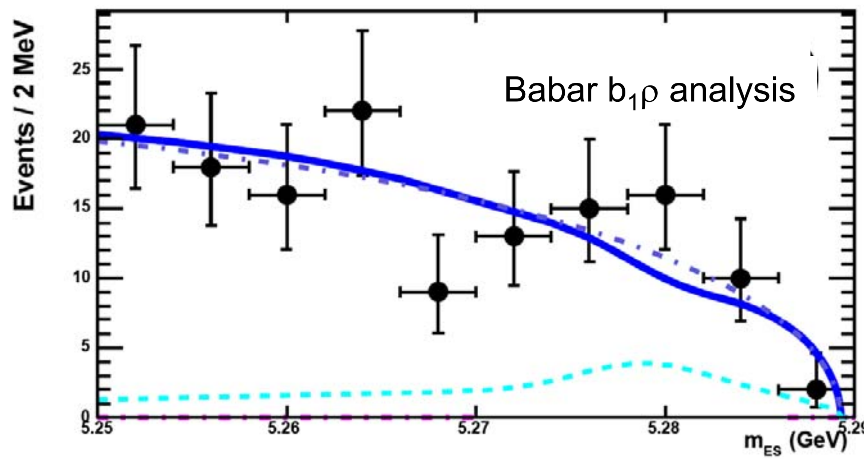
B→VV decays

- Have searched for a number of rare B→VV decays.



- Many rare penguin processes are suppressed to $\mathcal{B} \sim O(10^{-9})$.
  - These could be sensitive probes of NP!

- Also searched for B→AV:
  - $a_1\rho$ [$<61 \times 10^{-6}$]
  - $b_1^{+/-}\rho^{-/+}$ [$<1.7 \times 10^{-6}$]



  - Recent theory prediction gave $\mathcal{B}(b_1^{+/-}\rho^{-/+}) \sim 15$ to 48×10^{-6}

H.-Y. Cheng and K.-C. Yang, arXiv:0805.0329 [hep-ph] (2008).

G. Calderon, J. H. Munoz, and C. E. Vera, Phys. Rev. D **76**, 094019 (2007).

- We have a lot to learn from VV & AV decays!

Summary

- The B-factories have tested the CKM mechanism to an unprecedented level:

$$\sigma\left(\overline{\rho}\right) \sim 16\%, \quad \sigma\left(\overline{\eta}\right) \sim 4.7\%$$

- CKM works at this level.
  - Still not enough CP violation to explain the universal matter-antimatter asymmetry!
  - Is there NP in weak interactions with (s)quarks to make up the shortfall?
- CPT has been experimentally tested by the B-factories.
- Need more precise searches for new physics and possible deviations from CKM.
- Rare B decays to final states with V and A are not fully understood (from experimental or theoretical perspectives).
- Next generations of B factories will start to build on the knowledge of BaBar and Belle soon.

Outlook

- BaBar has finished taking data:
  - 467 million B pairs recorded at the Υ(4S)
  - Recorded 30fb^{-1} at the Υ(3S) and 14.5fb^{-1} at the Υ(2S)
  - Performed an energy scan above the Υ(4S)

- Belle
  - Will record 1ab^{-1} at the Υ(4S)
  - Has data at the Υ(1S), Υ(5S) and above the Υ(5S)
  - Will be upgraded to ~10^{35} (SuperKEKB)

- LHC-b
  - Should start taking data in September 2008.
    - We can look forward to results soon after!

- SuperB
  - Could start taking data as early as 2015. Would aim to record 75 ab^{-1} in the first 6 years of data taking.

Experimental References

- **Alternate β and CPT**

Belle Collaboration, Phys. Rev. Lett. D **77**, 071101 (2008).

BABAR Collaboration, Phys. Rev. Lett.**101**, 021801 (2008).

Belle Collaboration, Phys. Rev. Lett.**98**, 221802 (2007).

BABAR Collaboration, Phys. Rev. Lett.**99**, 161802 (2007).

BABAR Collaboration, Phys. Rev. Lett. D **76**, 091101 (2007).

BABAR Collaboration, arXiv:0708.2097.

Belle Collaboration, Phys. Rev. Lett.**98**, 031802 (2007).

Belle Collaboration, Phys. Rev. Lett. D **76**, 091103 (2007).

BABAR Collaboration, Phys. Rev. Lett.**99**, 161802 (2007).

Belle Collaboration, arXiv:0708.1845.

BABAR Collaboration, Phys. Rev. Lett. D **76**, 071101 (2007).

BABAR Collaboration, Phys. Rev. Lett.**99**, 161802 (2007).

CPT

BABAR Collaboration, Phys. Rev. Lett. D **70**, 012007 (2004).

BABAR Collaboration, Phys. Rev. Lett.**96**, 251802 (2006).

BABAR Collaboration, Phys. Rev. Lett.**100**, 131802 (2008).

- **Direct CP Asymmetries**

$B\to K\pi$ Belle Collaboration, Nature **452**, 332 (2008).

BABAR Collaboration, arXiv:0807.4226 (2008).

$B\to\rho\pi$ Belle Collaboration, Phys. Rev. Lett. D **77**, 072001 (2008).

BABAR Collaboration, Phys. Rev. Lett. D **76**, 012004 (2007).

- **Sides** (Also see the HFAG web site: Semi-leptonic group page for older publications)

V_{ub} CLEO Collaboration, Phys. Rev. Lett.**88**, 231803 (2002).

Belle Collaboration, Phys. Lett. B **621**, 28 (2005).

BABAR Collaboration, Phys. Rev. Lett. D **73**, 012006 (2006).

Belle Collaboration, Phys. Rev. Lett.**92**, 101801 (2004).

BABAR Collaboration, Phys. Rev. Lett. D **95**, 111801 (2005).

Belle Collaboration, Phys. Rev. Lett.**95**, 241801 (2005).

BABAR Collaboration, arXiv:0708.3702. …

$b\to d\gamma$ Belle Collaboration, Phys. Rev. Lett.**95**, 241801 (2005).

BABAR Collaboration, arXiv:0708.3702.

V_{cb} *BABAR* Collaboration, Phys. Rev. Lett.**100**, 231803 (2008).

BABAR Collaboration, Phys. Rev. Lett.**100**, 151802 (2008).

BABAR Collaboration, arXiv:0807.4978.

- **B→VV decays**

Belle Collaboration (J. Zhang, M. Nakao *et al.*), Phys. Rev. Lett. **91**, 221801 (2003).

Belle Collaboration, (K.-F. Chen *et al.*), Phys. Rev. Lett. **94**, 221804 (2005).

Belle Collaboration, (J. Zhang *et al.*), Phys. Rev. Lett. **95**, 141801 (2005).

Belle Collaboration, (A. Somov *et al.*), Phys. Rev. Lett. **96**, 171801 (2006).

(Also see α: $\rho\rho$ Refs. for Lecture 1)

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. Lett. **91**, 171802 (2003).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. Lett. **98**, 051801 (2007).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D **76**, 052007 (2007).

BABAR Collaboration (B. Aubert *et al.*), arXiv:0708.1630 (contributed to Lep-Pho07).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. D **74**, 051102 (2006).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. Lett. **97**, 201801 (2006).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. Lett. **97**, 261801 (2006).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. Lett. **99**, 201802 (2007).

BABAR Collaboration (B. Aubert *et al.*), Phys. Rev. Lett. **100**, 081801 (2008).

+ arXiv:0806.4467, arXiv:0807.3935, PRD74 031104 (2006), …