Measurements of CKM elements at BaBar

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on behalf of the BaBar collaboration

18th International Conference on Supersymmetry and Unification of Fundamental Interactions, Bonn
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Outline

<u>Recent measurements of CKM elements from BaBar</u>

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- magnitudes :
  - inclusive $|V_{ub}|$

    468 million $B\overline{B}$ events

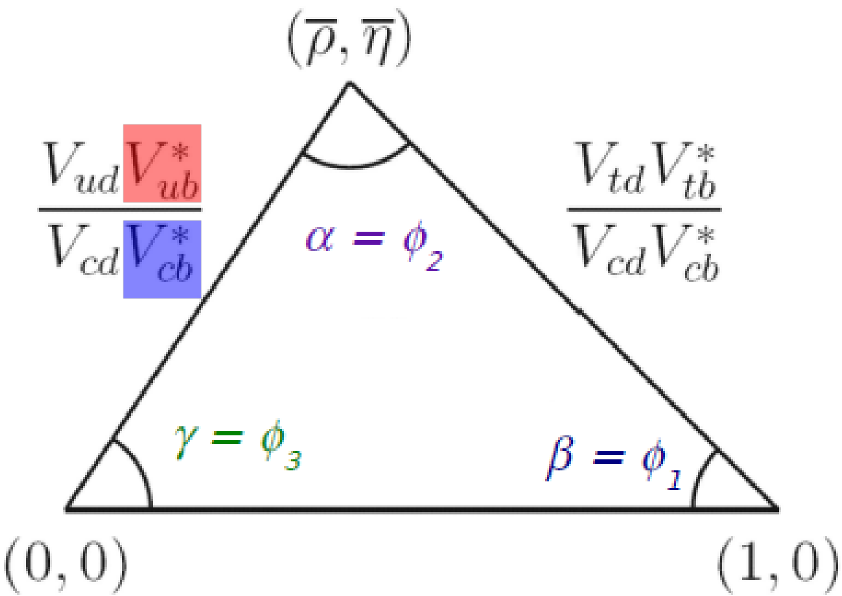
    update of PRL 100, 171802 (2008)
  - exclusive $|V_{ub}|$ from $B \to (\pi,\rho)\ \ell\ \nu$

    377 million $B\overline{B}$ events
  - exclusive $|V_{cb}|$ from $B \to D\ \ell\ \nu$

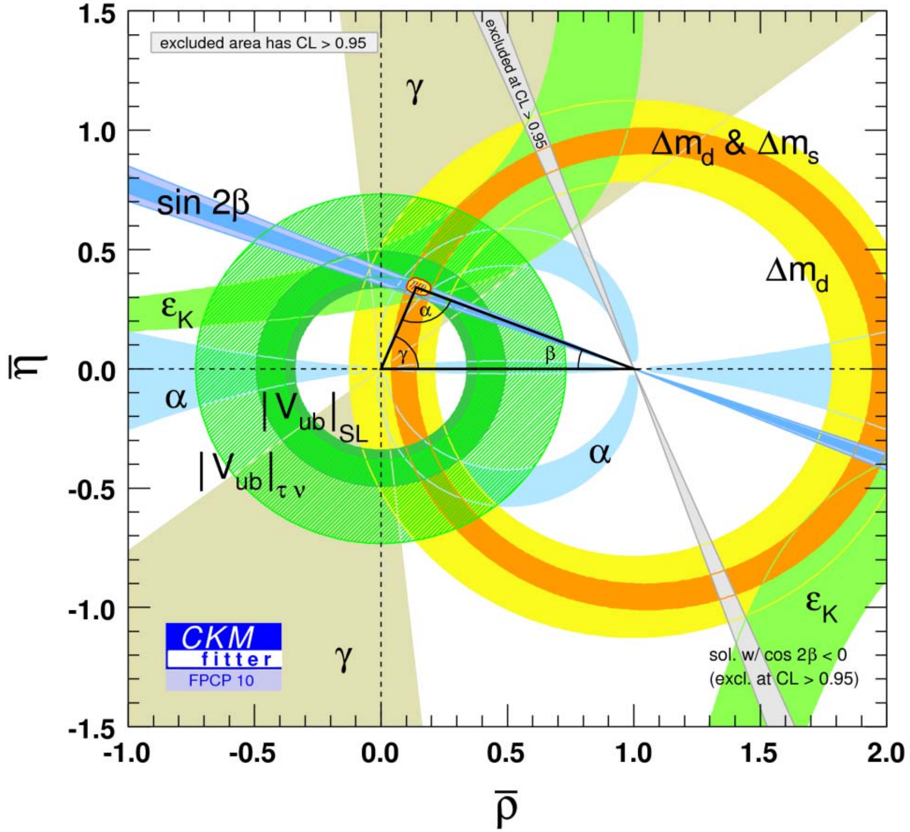
    468 million $B\overline{B}$ events
- angles:
  - γ from $B \to D^{(*)}\ K^{(*)}$

    (three different methods)

    468 million $B\overline{B}$ events



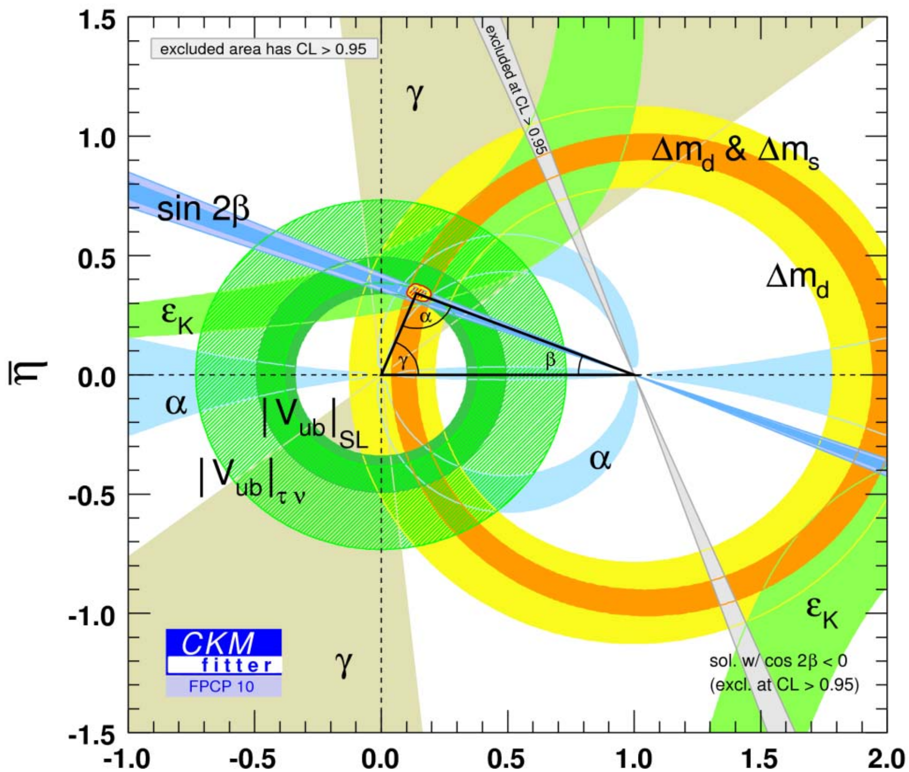
CKM quark mixing matrix $\xrightarrow{\text{complex phase}}$ Unitarity Triangle (UT)



- CKM matrix is source of *CP* violation in Standard Model
- Experimental goal: overconstrain the UT by precision measurements to:
  - test unitarity
  - look for signs of new physics

Introduction

CKM quark mixing matrix $\xrightarrow{\text{complex phase}}$ Unitarity Triangle (UT)



- CKM matrix is source of *CP* violation in Standard Model
- Experimental goal: overconstrain the UT by precision measurements to:
  - test unitarity
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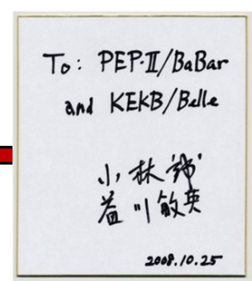
Nobel Prize in Physics 2008

Kobayashi and Maskawa

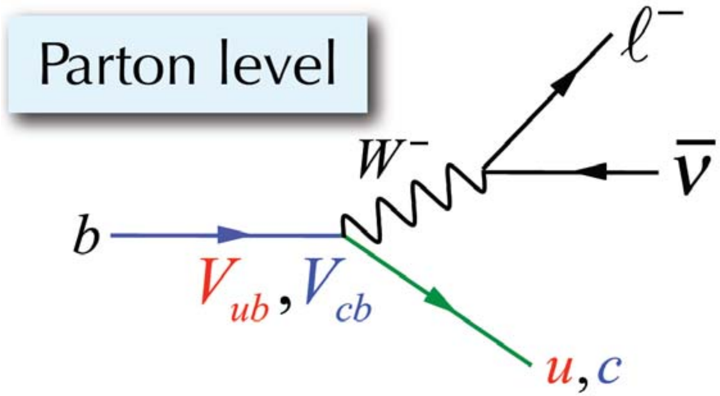


Experimental verification

BELLE BABAR

provided by the *B*-Factories!

Magnitudes most accessible in semileptonic B decays

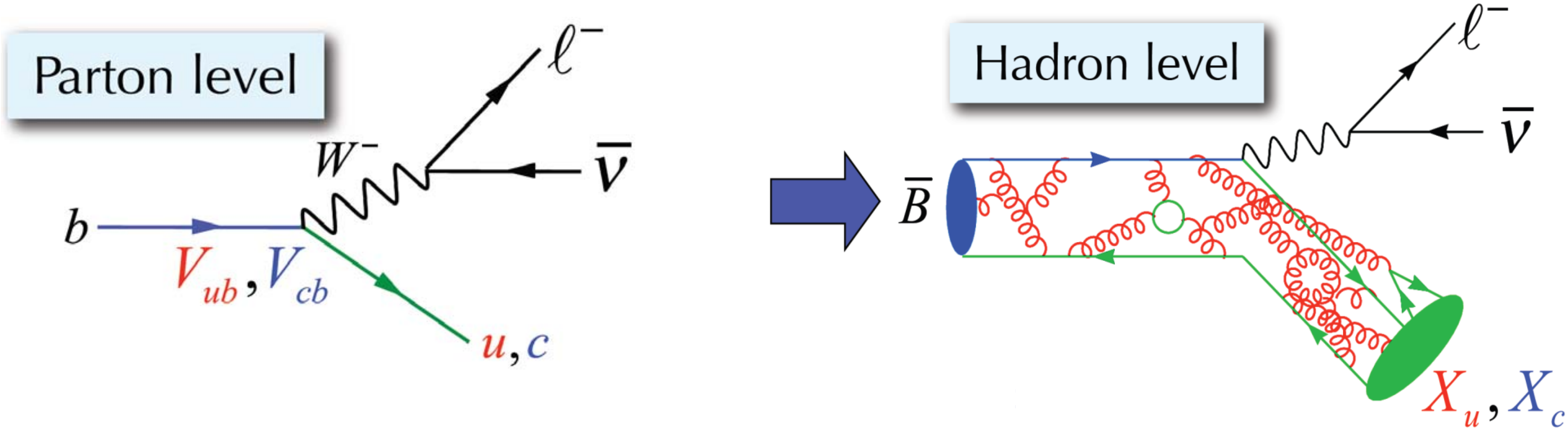


- Matrix element decouples into hadronic and leptonic components:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{qb} L_\mu H^\mu$$

CKM magnitudes: $|V_{ub}|$ and $|V_{cb}|$

Magnitudes most accessible in semileptonic B decays

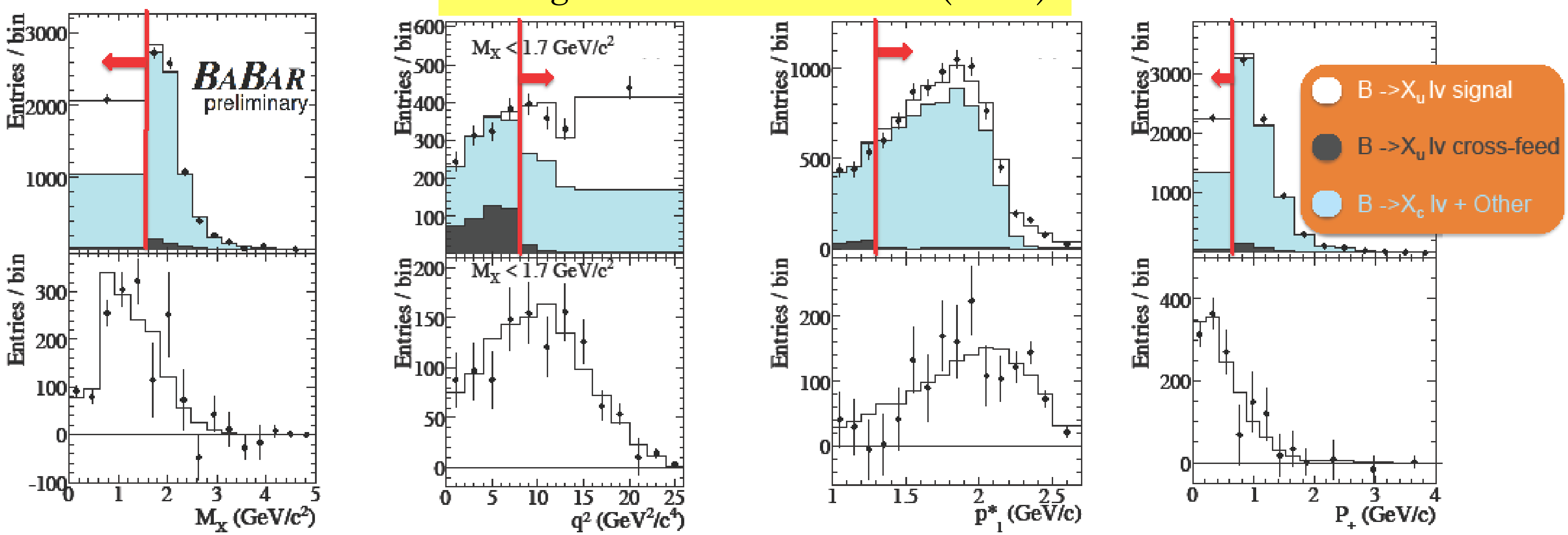


- Matrix element decouples into hadronic and leptonic components: $\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{qb} L_\mu H^\mu$
- Quarks bound to color-singlet hadrons → QCD corrections
- Inclusive approach
  - Study distributions from $B \to X_u\, \ell\, \nu$ (X_u = anything)
  - Theory: Operator Product Expansion (OPE)
- Exclusive approach:
  - Study a specific decay channel
  - Theory: form factors

independent theoretical uncertainties

- Tag B fully reconstructed in hadronic modes; lepton on signal side
- Experimental challenge: separate rare $B \to X_u \ell \nu$ signal from dominant $B \to X_c \ell \nu$ background
- Select phase space regions where charm background is suppressed, measure partial branching fraction
- Increases model-dependent theoretical uncertainties
- Use lepton momentum p_ℓ^*, hadronic invariant mass m_X, squared momentum transfer q^2, and $P_+ = E_X - |p_X|$ as discriminating variables

M. Sigamani – ICHEP 732 (2010)

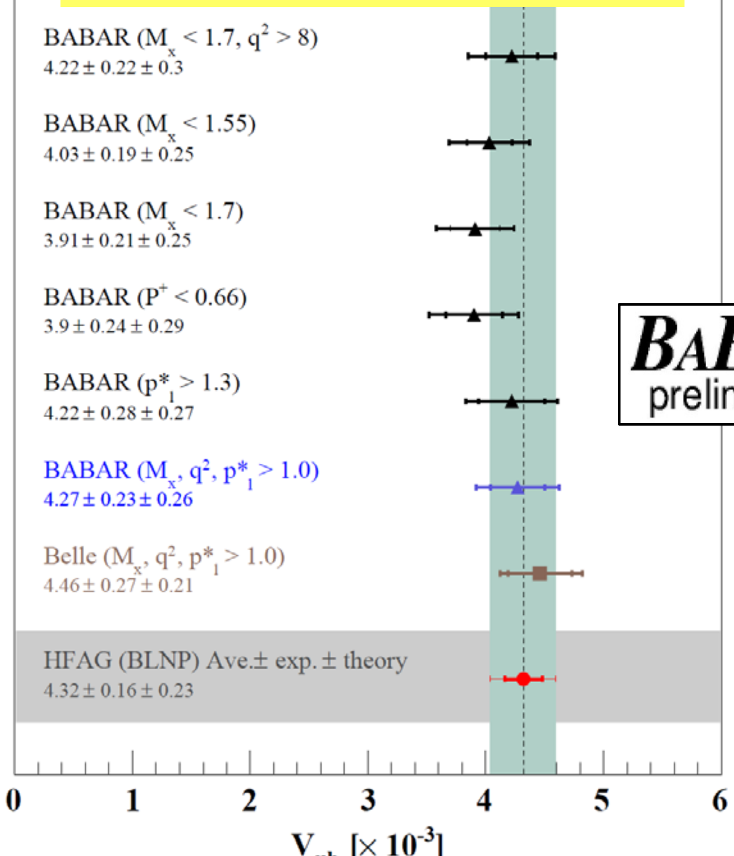


inclusive $|V_{ub}|$

- Determine signal yield with fit to $m_{ES} = (E^2_{\mathrm{beam}} - |\boldsymbol{p}_B|^2)^{1/2}$ distribution
- 6 BFs corresponding to different regions of phase space
- Most precise result for full (M_X, q^2) phase space with $p^*_\ell > 1.0$ GeV:

$$\Delta \mathrm{BF}\,(B \to X_u\, \ell\, \nu) = (1.80 \pm 0.13 \pm 0.15) \times 10^{-3}$$

M. Sigamani – ICHEP 732 (2010)



BABAR preliminary

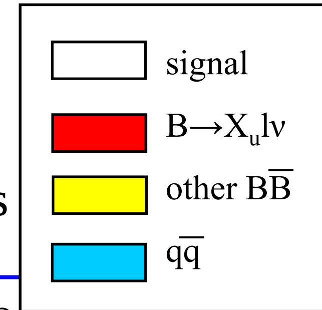
For each phase space region, translate partial BF into $|V_{ub}|$ using 4 theoretical calculations (BLNP, GGOU, DGE, ADFR)

unweighted average over 4 calculations:

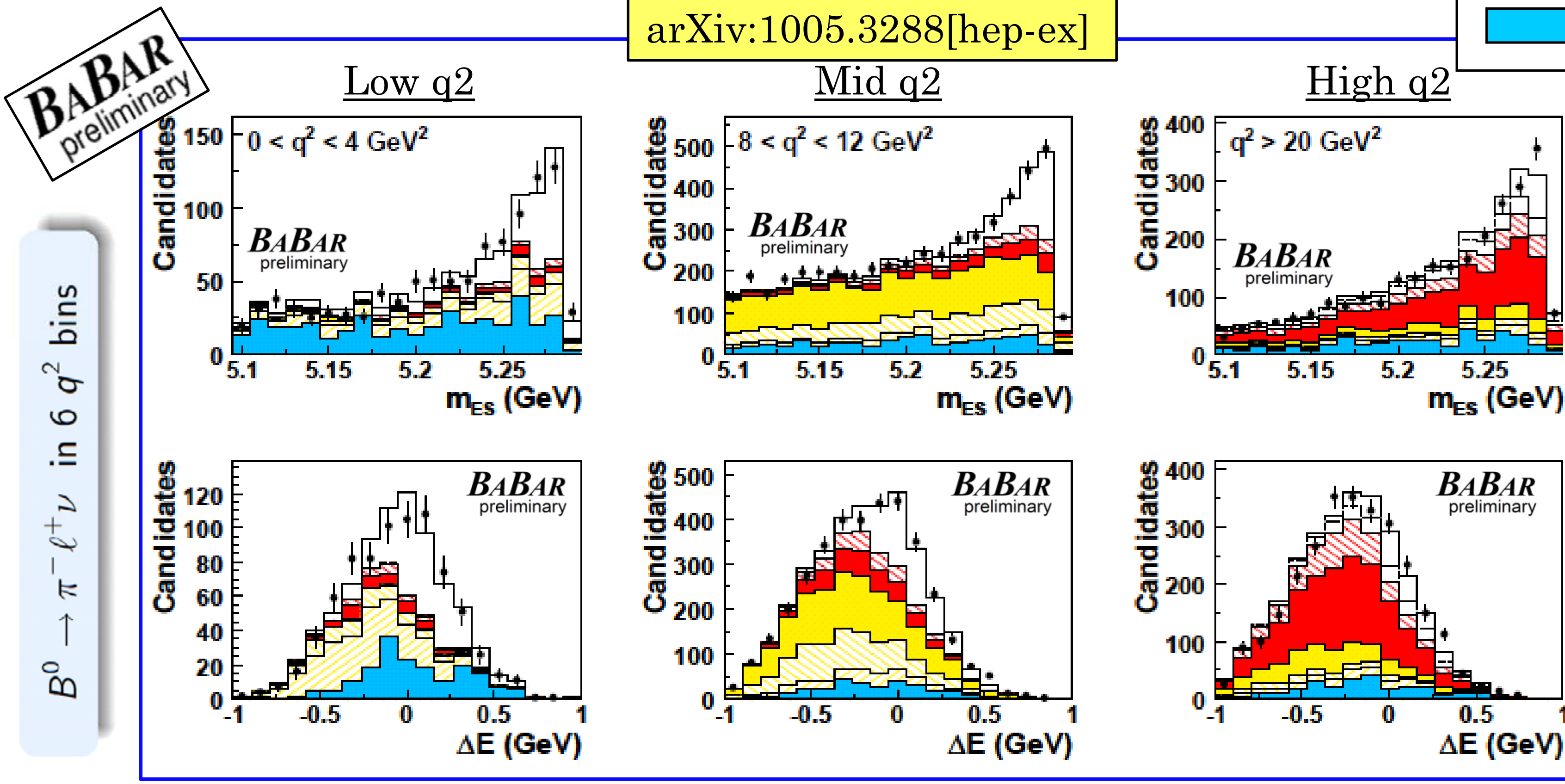
$$|V_{ub}| = (4.31 \pm 0.35) \times 10^{-3}$$

...for full (M_X, q^2) phase space fit with $p^*_\ell > 1.0$ GeV

- Combined analysis of $B \to \pi\,\ell\,\nu$ and $B \to \rho\,\ell\,\nu$ in untagged events
- Reconstruct neutrino from missing 4-momentum
- Large $B \to X_c\,\ell\,\nu$ background, suppressed by multivariate techniques



arXiv:1005.3288[hep-ex]



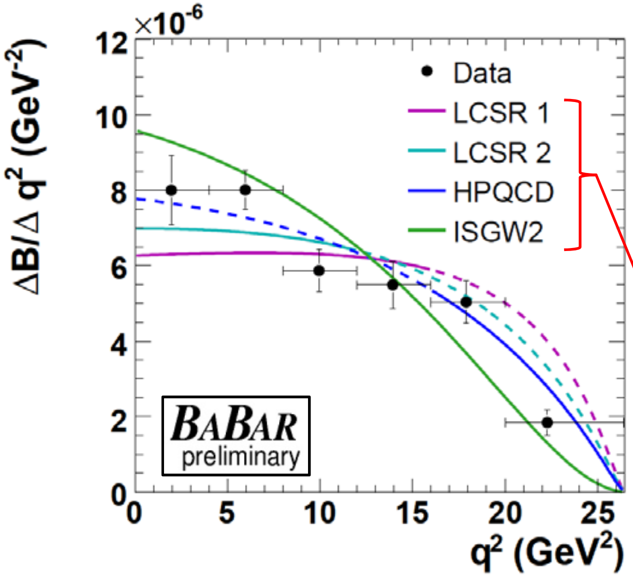
Binned ML fit in m_{ES}, ΔE, and q^2 for $B \to (\pi^\pm/\pi^0/\rho^\pm/\rho^0)\ell\nu$ simultaneously with isospin constraint

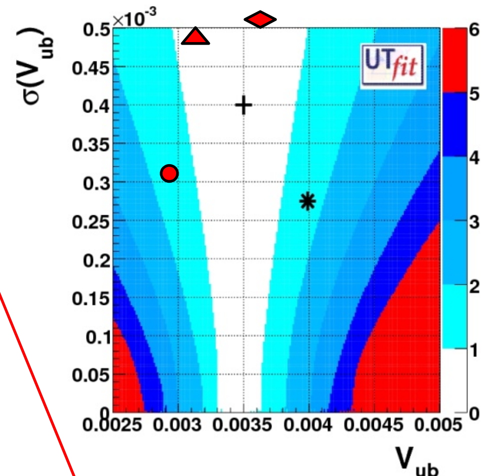
$$\mathrm{BF}\,(B^0 \to \pi^-\,\ell^+\,\nu) = (1.41 \pm 0.05 \pm 0.07) \times 10^{-4}$$

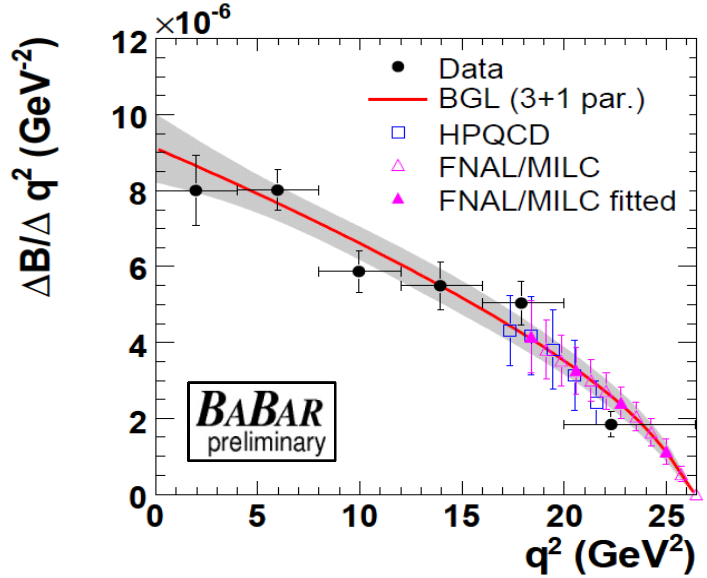
exclusive $|V_{ub}|$ from $B \to (\pi,\rho)\, \ell\, \nu$

differential decay rate: $$\frac{d\Gamma(B \to \pi\ell\nu)}{dq^2} = |V_{ub}|^2 \frac{G_F^2 |\vec{p}_\pi|^3}{24\pi^3} |f_+(q^2)|^2$$

arXiv:1005.3288[hep-ex]







form factor from theory

$$\Delta\zeta = \frac{G_F^2}{24\pi^3} \int_{q^2_{\min}}^{q^2_{\max}} |\vec{p}_\pi|^3 |f_+(q^2)|^2 dq^2$$

Extract $|V_{ub}|$

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to \pi\ell\nu)}{\tau_B \Delta\zeta}}$$

	q^2 Range (GeV^2)	$\Delta\mathcal{B}$ (10^{-4})	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
LCSR 1	$0-16$	1.10 ± 0.07	5.44 ± 1.43	$3.63 \pm 0.12^{+0.59}_{-0.40}$
LCSR 2	$0-12$	0.88 ± 0.06	$4.00^{+1.01}_{-0.95}$	$3.78 \pm 0.13^{+0.55}_{-0.40}$
HPQCD	$16-26.4$	0.32 ± 0.03	2.02 ± 0.55	$3.21 \pm 0.17^{+0.55}_{-0.36}$

FNAL/MILC: PRD 79, 054507 (2009)

Simultaneous fit to data and theory (lattice QCD), over full q^2 range:

$|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$

UT Fit Values

global "all other" fit = $(3.48 \pm 0.16) \times 10^{-3}$

average: + exclusive ✱ inclusive

$$\frac{d\Gamma(B\to D\ell\nu)}{dw} = \frac{G_F^2|V_{cb}|^2}{48\pi^3\hbar} M_D^3(M_B+M_D)^2(w^2-1)^{3/2}\mathcal{G}^2(w)$$

G(w) = form factor : Caprini et al., Nucl. Phys **B530**, 153 (1998)

$$w = \frac{M_B^2 + M_D^2 - q^2}{2M_BM_D}$$ ... D-boost in B rest frame

- $B \to D\,\ell\,\nu$ with hadronic tag
- Reconstruct neutrino from missing 4-momentum
- significant background from $B \to D^*\,\ell\,\nu$
  (larger BF, undetected slow π^0)
- inclusive $B \to X_c\,\ell\,\nu$ used as normalization sample
- most precise measurement of $B \to D\,\ell\,\nu$

$$\mathcal{B}(\bar{B}\to D\ell\bar{\nu}) = (2.15 \pm 0.06 \pm 0.09)\%$$

- unquenched lattice calculation of FF to extract $|V_{cb}|$:

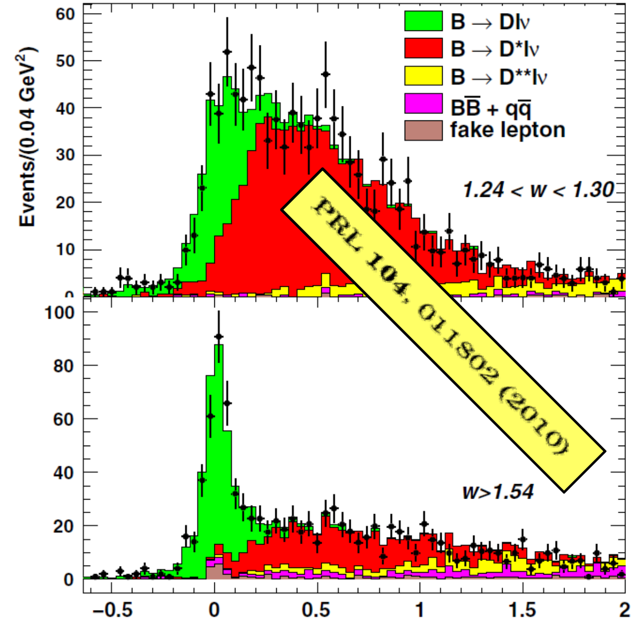
Okamoto et al., Nucl. Phys. **B**, Proc. Suppl. **140**, 461 (2005)

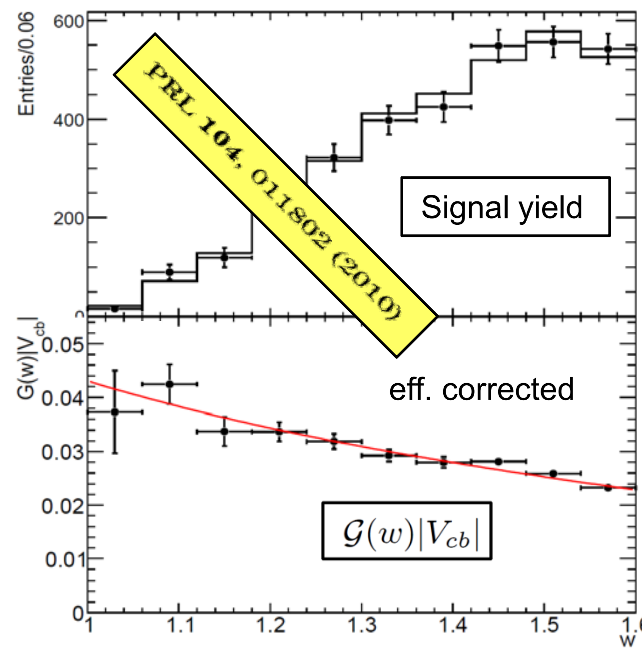
$$|V_{cb}| = (39.2 \pm 1.8 \pm 1.3 \pm 0.9_{FF}) \times 10^{-3}$$

- good agreement with $|V_{cb}|$ from exclusive $B \to D^*\,\ell\,\nu$

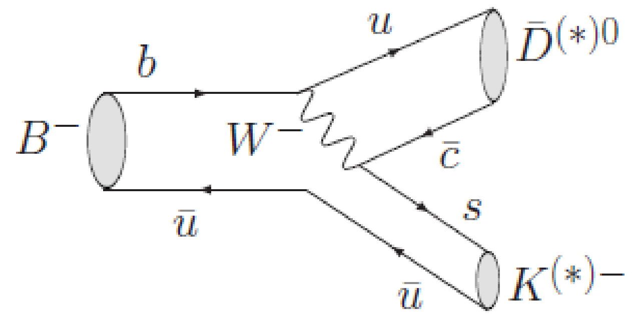
$$|V_{cb}| = (39.1 \pm 0.6 \pm 0.8_{FF}) \times 10^{-3}$$

PRD 79, 014506 (2009)

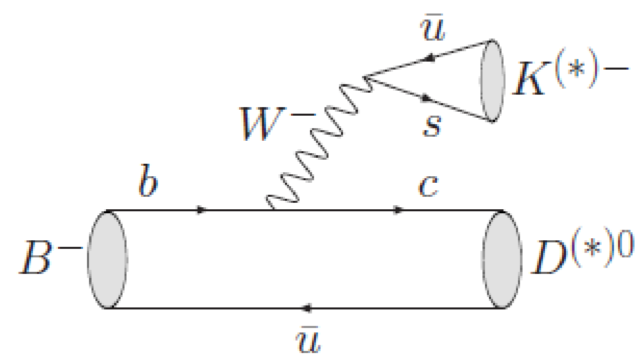




angle $\gamma \neq 0,\pi \Leftrightarrow$ direct CP violation



- measure interference between tree amplitudes $b \to u\bar{c}s$ and $b \to c\bar{u}s$
- use final states accessible from both D^0 and $\bar{D}^0$
- clear theoretical interpretation in terms of γ
- observables depend on γ, r_B, and δ_B



γ = relative weak phase

$$r_B = \left| \frac{A(b \to u)}{A(b \to c)} \right|$$

= magnitude ratio

δ_B = relative strong phase

- small BFs due to CKM- and/or color-suppression
- disparate magnitudes

$\Rightarrow$ Measurements are statistics limited

γ from $B \to D^{(*)} K^{(*)}$: three approaches

Giri, Grossman, Soffer, Zupan, PRD **68**, 054018 (2003)

GGSZ: Dalitz analysis of D decays into 3-body self-conjugate states

Interference term in decay rates proportional to , e.g. $D \to K_s \pi^+ \pi^-$

$$x_{\mp} = r_B \cos(\delta_B \mp \gamma) \qquad y_{\mp} = r_B \sin(\delta_B \mp \gamma)$$

… large in some regions of the Dalitz plot

Atwood, Dunietz, Soni, PRL **78**, 3357 (1997)

ADS: $D^0 \to K^+ \pi^-$ (doubly Cabibbo suppressed); $\bar{D}^0 \to K^+ \pi^-$ (Cabibbo favored)

branching fraction ratio

$$R_{ADS} = \frac{1}{2}(R^+ + R^-) = r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D)\cos\gamma$$

charge asymmetry

$$A_{ADS} = \frac{R^- - R^+}{R^- + R^+} = 2 r_B r_D \sin(\delta_B + \delta_D)\sin\gamma / R_{ADS}$$

Gronau, London, Wyler, PLB **253**, 483 (1991); PLB **265**, 172 (1991)

GLW: $D \to$ CP-even (K^+K^- …) and CP-odd ($K_s\pi^0$ …) eigenstates

both D and $\bar{D}$ are Cabibbo suppressed

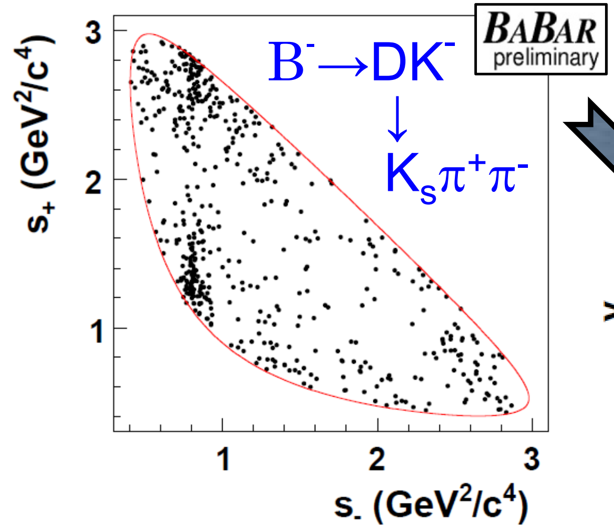
$$R_{CP\pm} = 1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma \qquad A_{CP\pm} = \frac{\pm 2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 \pm 2 r_B \cos\delta_B \cos\gamma}$$

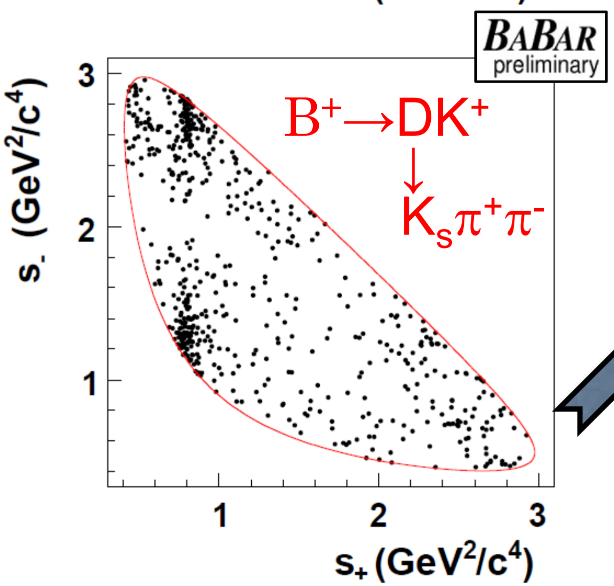
Updates based on complete BaBar data sample (468 million $B\bar{B}$ pairs $\Leftrightarrow$ 426 fb^{-1})

γ: Dalitz plot analysis (of D decay)

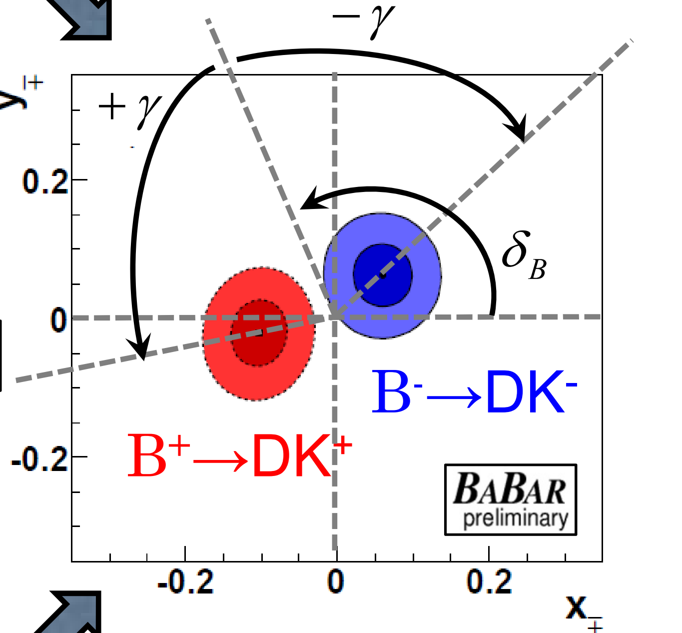
CP violation parameters are extracted from simultaneous unbinned ML fit to $B^{\pm} \rightarrow D^{(*)} K^{(*)\pm}$ data using m_{ES}, ΔE, *Fisher* and the Dalitz plot distributions ($s+$,$s-$)

$s_{\pm} = m^2(K_s\pi^{\pm})$

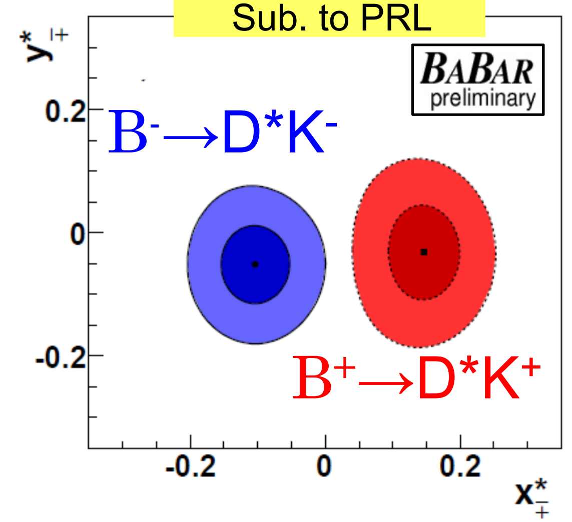


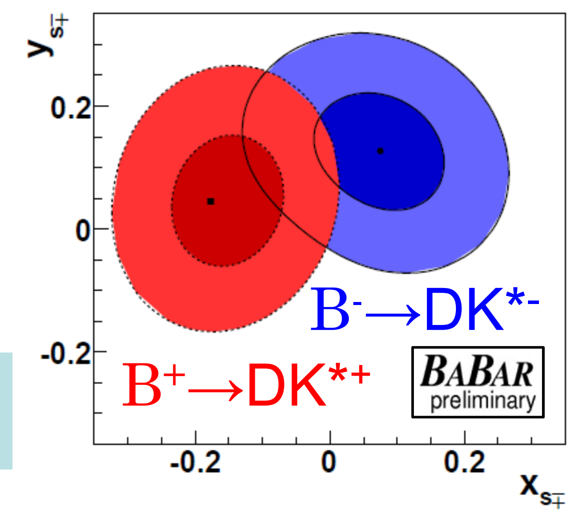


$$x_{\mp} = r_B \cos(\delta_B \mp \gamma)$$
$$y_{\mp} = r_B \sin(\delta_B \mp \gamma)$$



arXiv:1005.1096
Sub. to PRL





Differences between B^+ and B^- gives information on γ

γ: Dalitz plot analysis (of D decay)

CP violation parameters are extracted from simultaneous unbinned ML fit to $B^{\pm} \to D^{(*)} K^{(*)\pm}$ data using m_{ES}, ΔE, *Fisher* and the Dalitz plot distributions ($s+$,$s-$)

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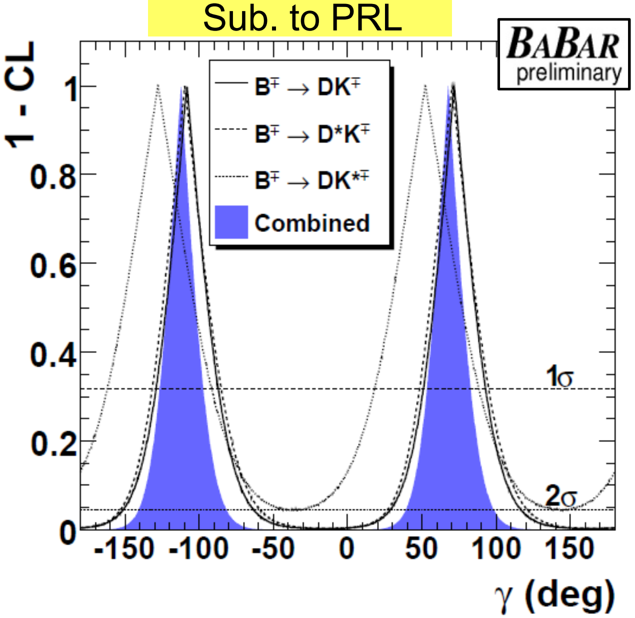

$$x_{\mp} = r_B \cos(\delta_B \mp \gamma)$$
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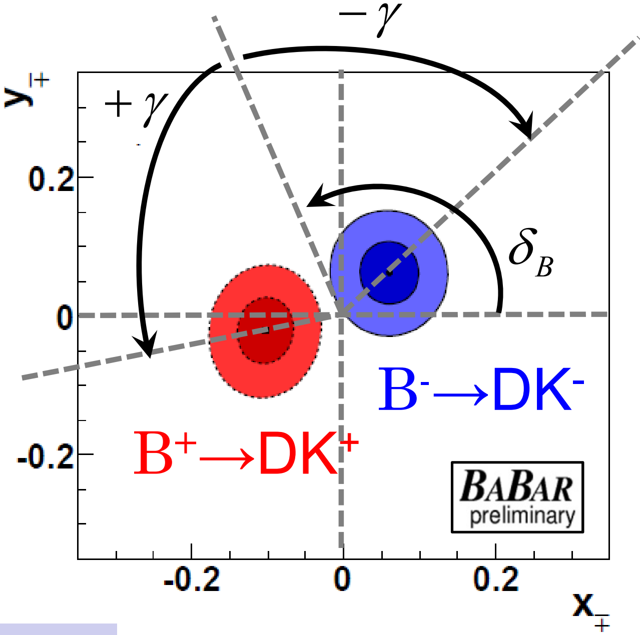

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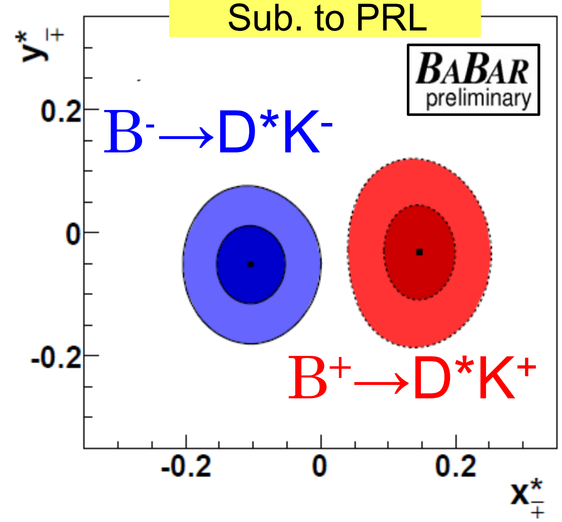
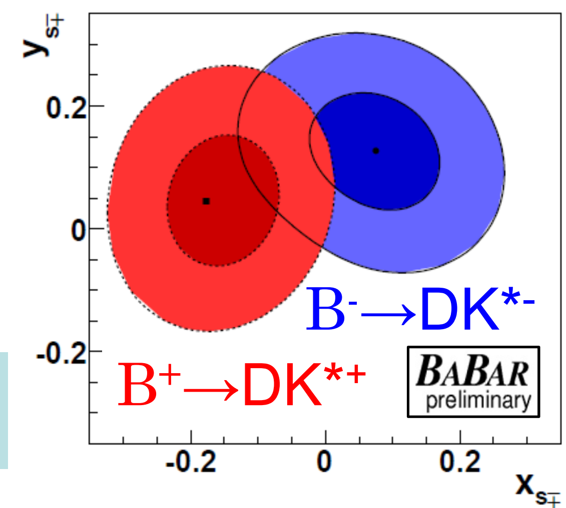




$\gamma \text{ (mod } 180°) = (68 \pm 14 \pm 4 \pm 3)°$

$r_B \cong 0.1$

BABAR preliminary

Differences between B⁺ and B⁻ gives information on γ

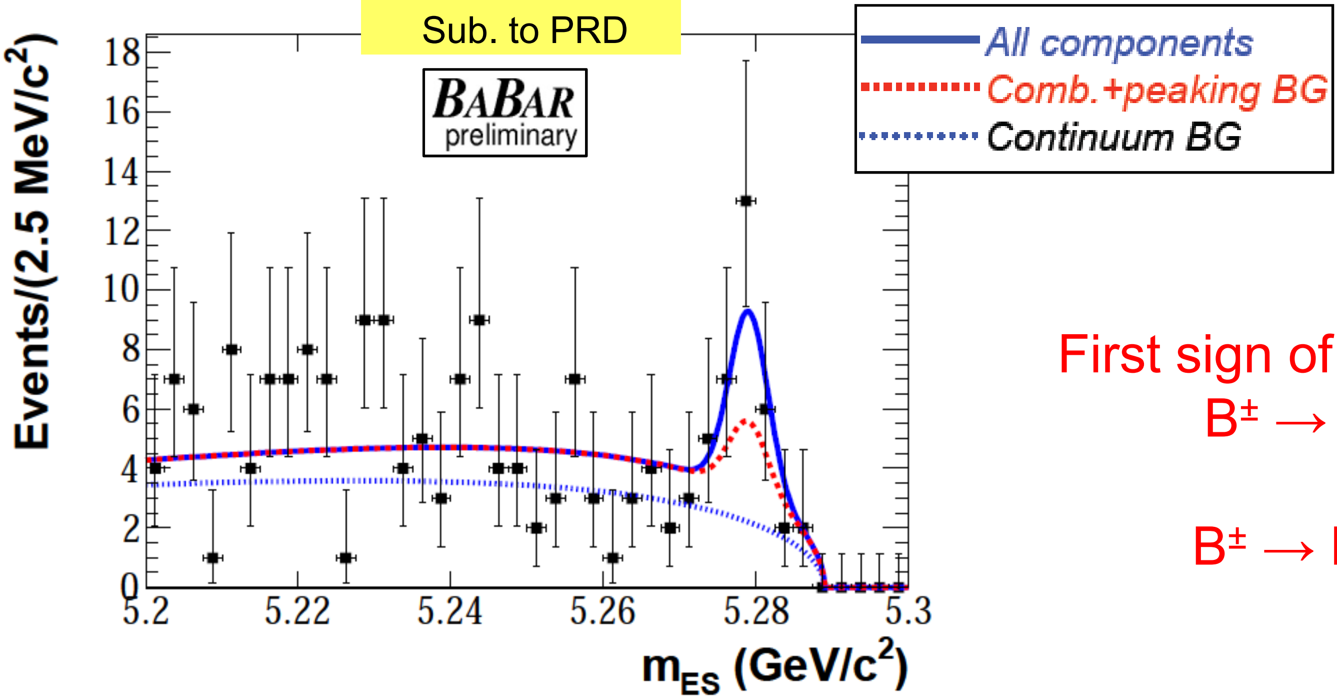
$B^- \to D^0 K^-$ favored $(b \to c)$ followed by $D^0 \to K^+\pi^-$ suppressed $(c \to d)$

interferes with

$B^- \to \bar{D}^0 K^-$ suppressed $(b \to u)$ followed by $\bar{D}^0 \to K^+\pi^-$ favored $(\bar{c} \to \bar{s})$

"Maximizes" CP asymmetry since "equalizes" the magnitudes of the interfering amplitudes

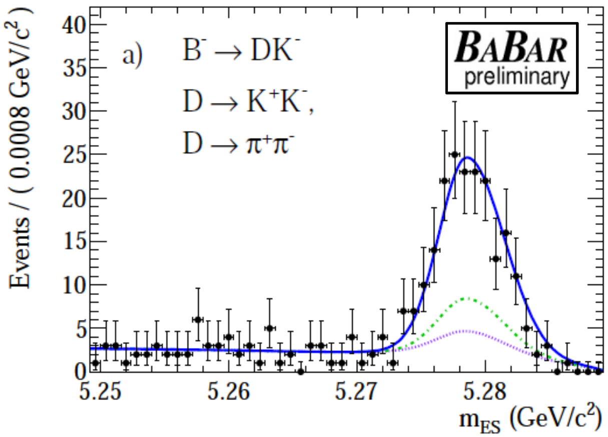
arXiv:1006.4241
Sub. to PRD

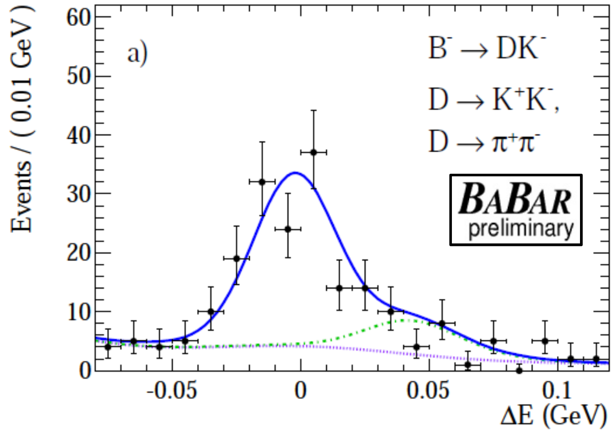


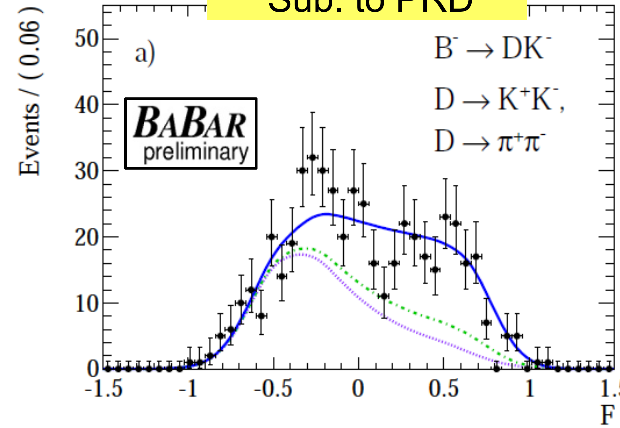
First sign of an ADS signal in
$B^\pm \to DK^\pm$ (2.1σ)
and
$B^\pm \to D^* K^\pm$ (2.2σ)

γ from $B \to D K$: GLW method

arXiv:1007.0504
Sub. to PRD





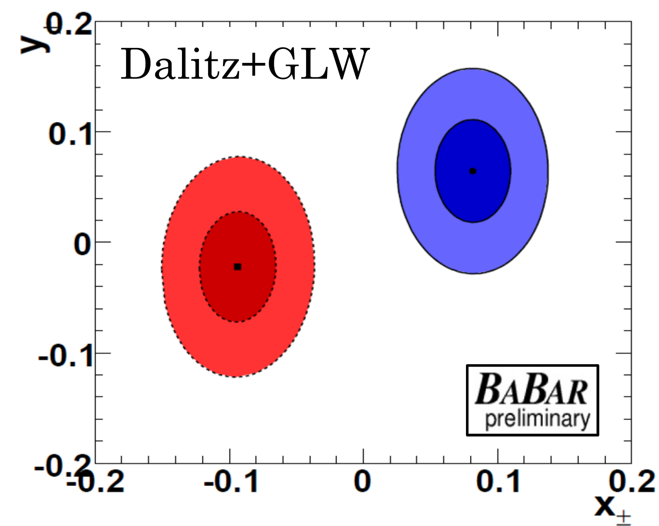


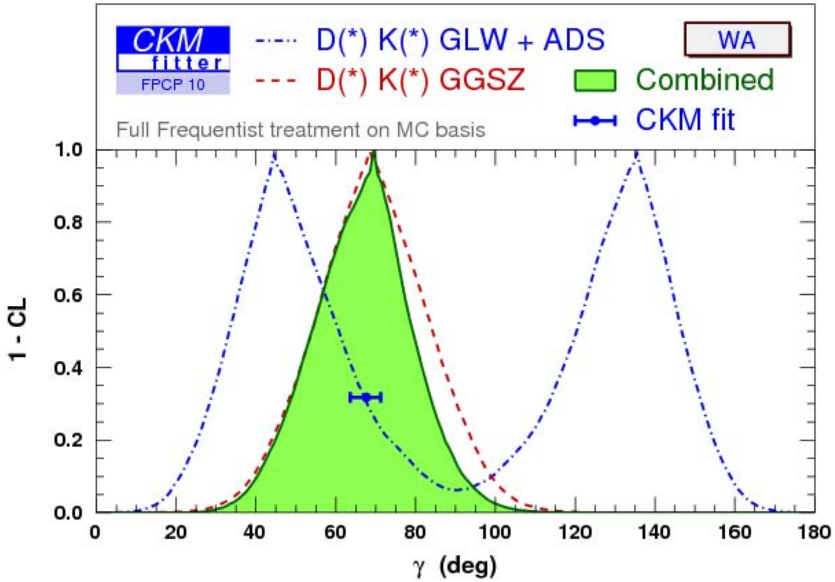
- Use frequentist interpretation (similar to Dalitz plot method) to obtain weak phase γ and hadronic parameters r_B, δ_B from observables $R_{CP\pm}$ and $A_{CP\pm}$

$$x_{\mp} = \frac{R_{CP+}(1 \pm A_{CP+}) - R_{CP-}(1 \pm A_{CP-})}{4}$$

$$x_+ = -0.057 \pm 0.039 \pm 0.015$$
$$x_- = +0.132 \pm 0.042 \pm 0.018$$

8-fold ambiguity and large uncertainty:
- no constrain on γ
- improved accuracy of Dalitz plot results





All methods combined :

$$\gamma = (70^{+14}_{-21})^\circ$$

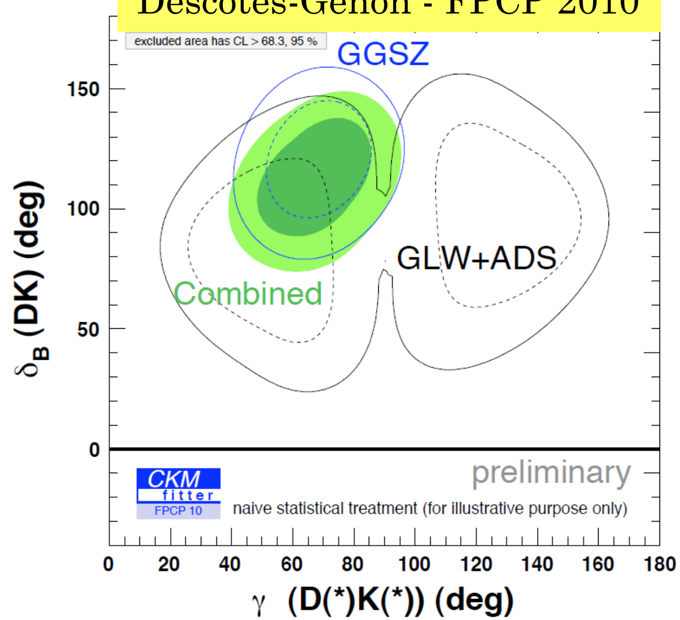
From the global fit :

$$\gamma = (67.7^{+3.6}_{-4.1})^\circ$$

(68%CL)

also extract strong phase δ_B

Descotes-Genon - FPCP 2010



First sign of an ADS signal in $B^\pm \to DK^\pm$ and $B^\pm \to D^* K^\pm$

Compelling evidence of direct CPV in $B^\pm \to D^{(*)}K^{(*)\pm}$ decays

4.4s significance of CPV in $B^\pm \to DK^\pm$ only, Dalitz+GLW combined

Summary

- inclusive $|V_{ub}|$:

  $|V_{ub}| = (4.31 \pm 0.35) \times 10^{-3}$ M. Sigamani – ICHEP 732 (2010) BaBar preliminary

- exclusive $|V_{ub}|$ from $B \to (\pi,\rho)\,\ell\,\nu$:

  $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$ arXiv:1005.3288[hep-ex] BaBar preliminary

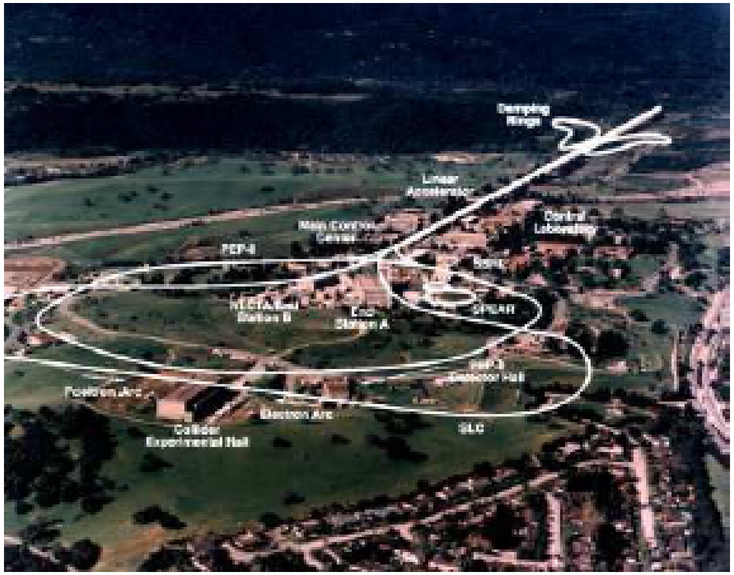
- exclusive $|V_{cb}|$ from $B \to D\,\ell\,\nu$:

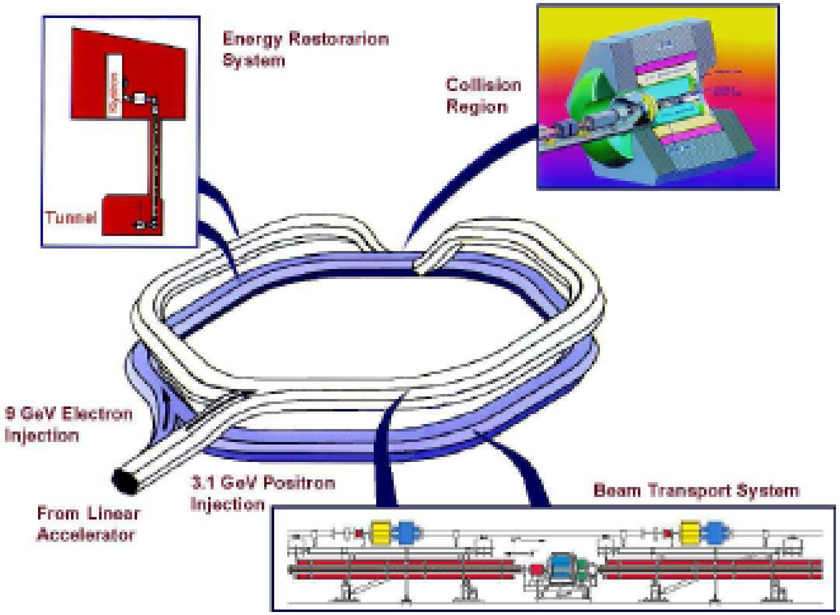
  $|V_{cb}| = (39.2 \pm 1.8 \pm 1.3 \pm 0.9_{FF}) \times 10^{-3}$ PRL **104**, 011802 (2010)

- γ from $B \to D^{(*)}\,K^{(*)}$: BaBar preliminary

  $\gamma = (68 \pm 14 \pm 4 \pm 3)°$ arXiv:1005.1096 arXiv:1006.4241 arXiv:1007.0504

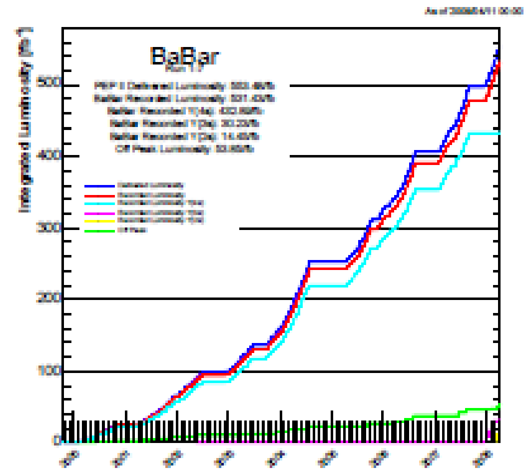
Backup slides



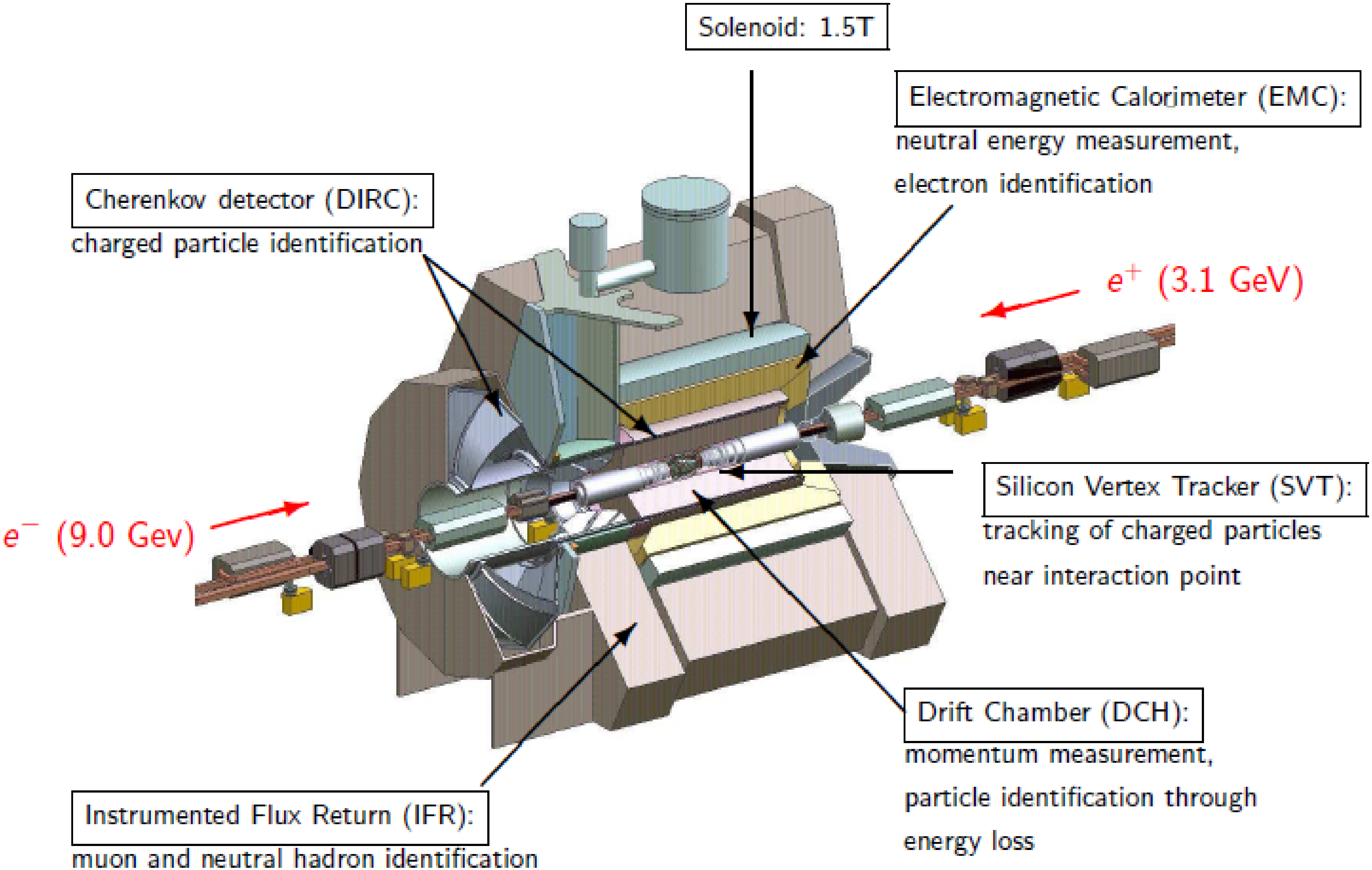


PEP-II Asymmetric B-Factory

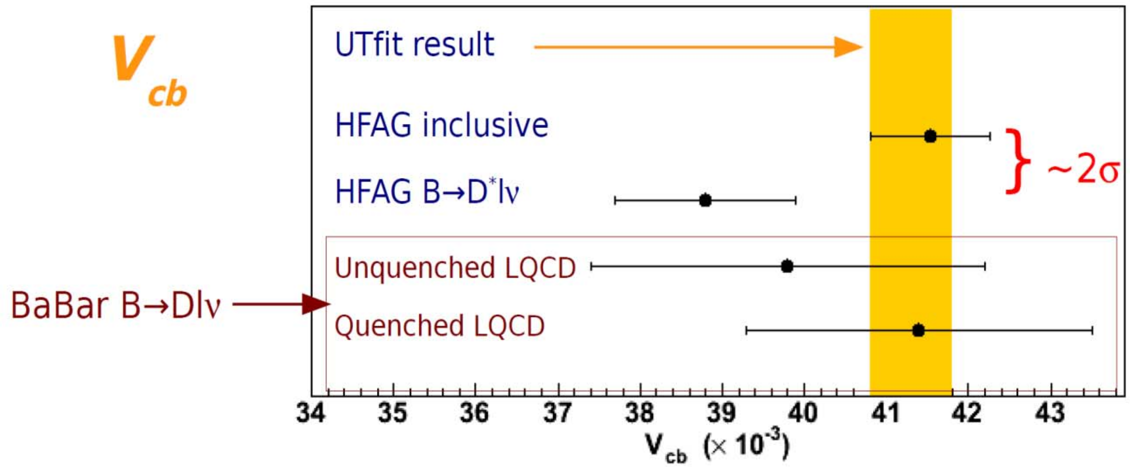
- collides 9.0 GeV e^- beams and 3.1 GeV e^+ beams
- operates at the $\Upsilon(4S)$ resonance at $E_{\mathrm{CM}} = 10.58$ GeV
- lightest $b\bar{b}$ resonance above $B\bar{B}$ threshold
- $\mathcal{B}(\Upsilon(4S) \to B\overline{B}) \approx 100\%$, B mesons almost at rest in CM frame
- boost $\beta\gamma = 0.56$ allows measurement of B decay times
- peak luminosity $> 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1} \Rightarrow B\overline{B}$ production $\sim$ 10 Hz

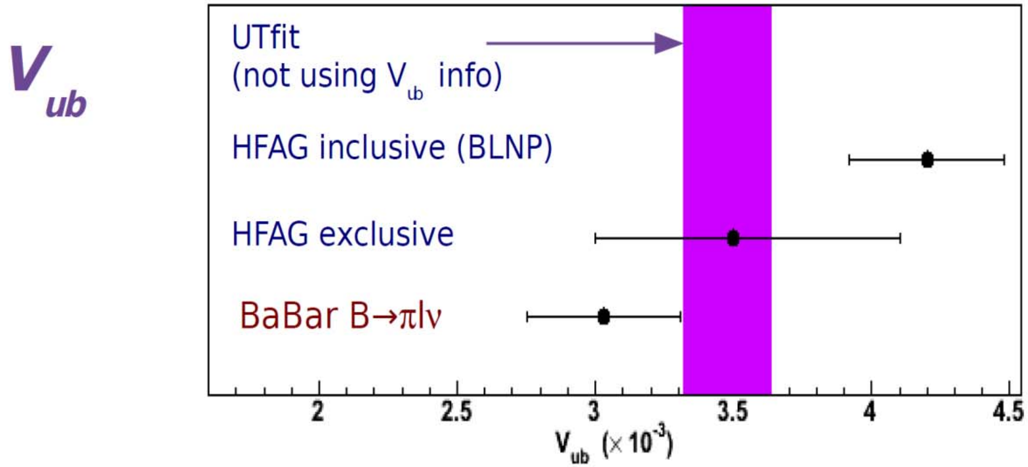


The BaBar detector



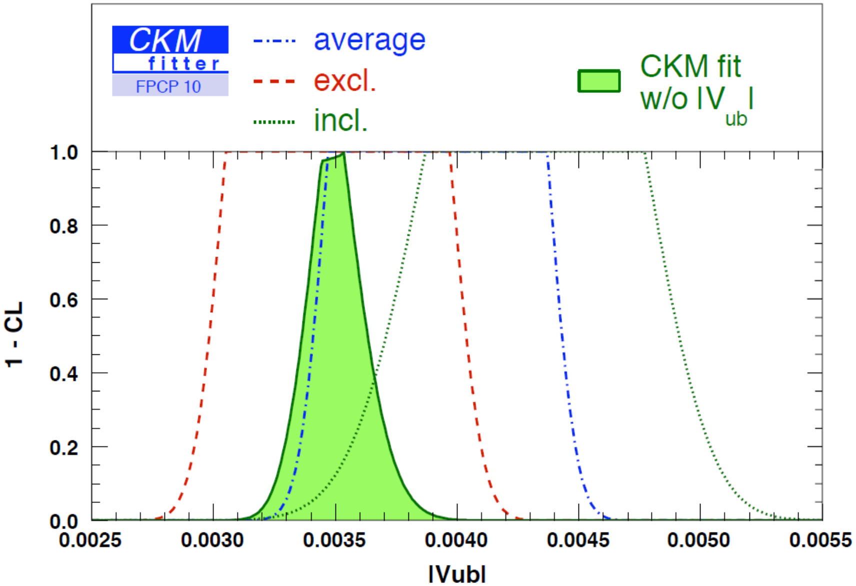
Discrepancy between inclusive and exclusive measurements of both $|V_{ub}|$ and $|V_{cb}|$ (also between $|V_{ub}|$ from $B \to \tau\nu$ and from semileptonics)

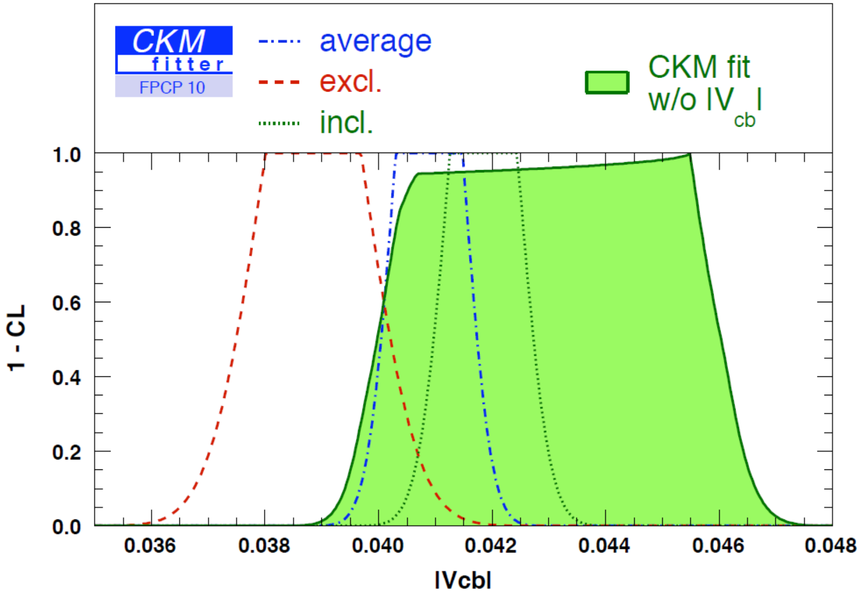




→ more insight from future B-Factories (Super-B?)

Summary on $|V_{ub}|$ and $|V_{cb}|$





$$|V_{ub}|_{inc} = 4.32^{+0.21}_{-0.24} \pm 0.45$$

$$|V_{ub}|_{exc} = 3.51 \pm 0.10 \pm 0.46$$

$$|V_{ub}|_{ave} = 3.92 \pm 0.09 \pm 0.45$$

$$|V_{cb}|_{inc} = 41.85 \pm 0.43 \pm 0.59$$

$$|V_{cb}|_{exc} = 38.85 \pm 0.77 \pm 0.84$$

$$|V_{cb}|_{ave} = 40.89 \pm 0.38 \pm 0.59$$

with all values $\times 10^{-3}$