Rencontres de Blois 2012

CKM Related Measurements

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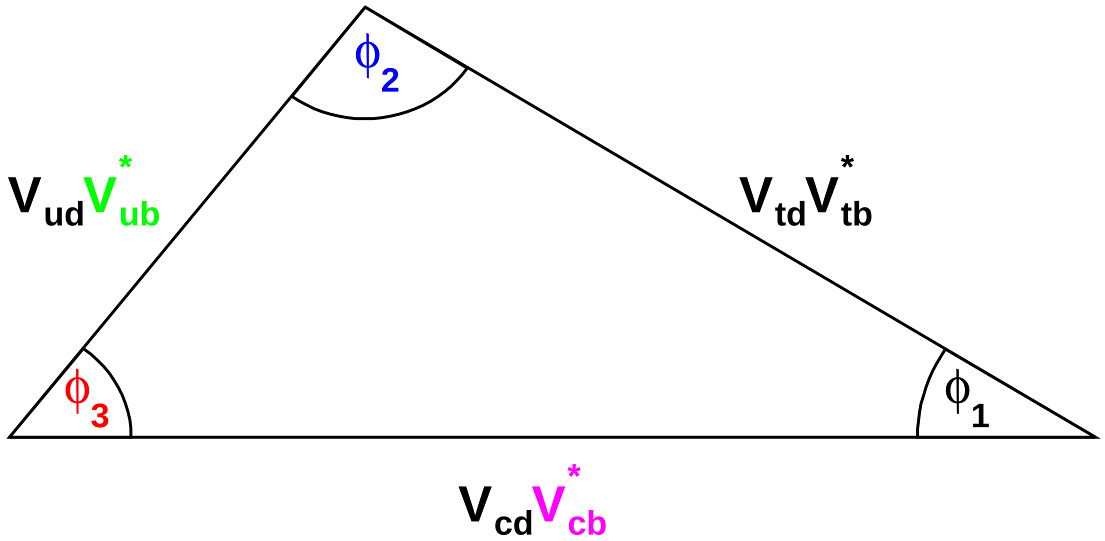
29 May 2012

Outline

1. $B^0 \to (c\bar{c})\, K^0$
2. $B^0 \to D^+\, D^-, \;\; B^0 \to D^{*\pm}\, D^{\mp}, \;\; B^0 \to D^{*+}\, D^{*-}$
3. $B^0 \to a_1(1260)^{\pm}\, \pi^{\mp}$
4. V_{ub}

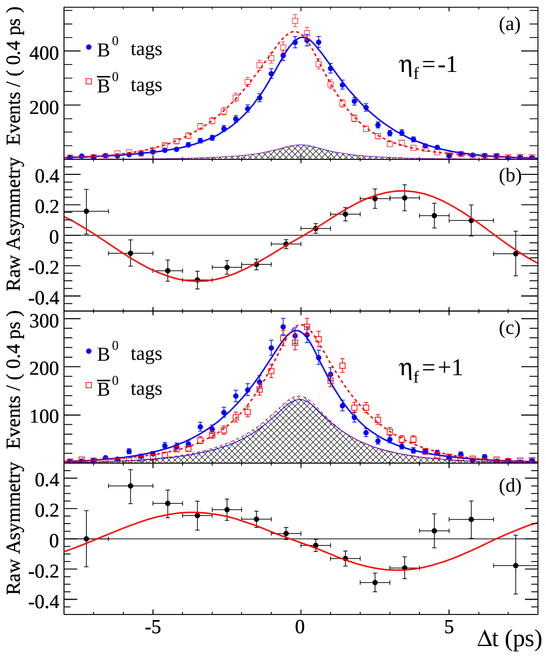


$B^0 \to (c\bar{c})\, K^0$

Provides a theoretically and experimentally clean measurement of $\sin 2\phi_1$

Final results from the B factories on golden channels including $B^0 \to J/\psi\, K^0$

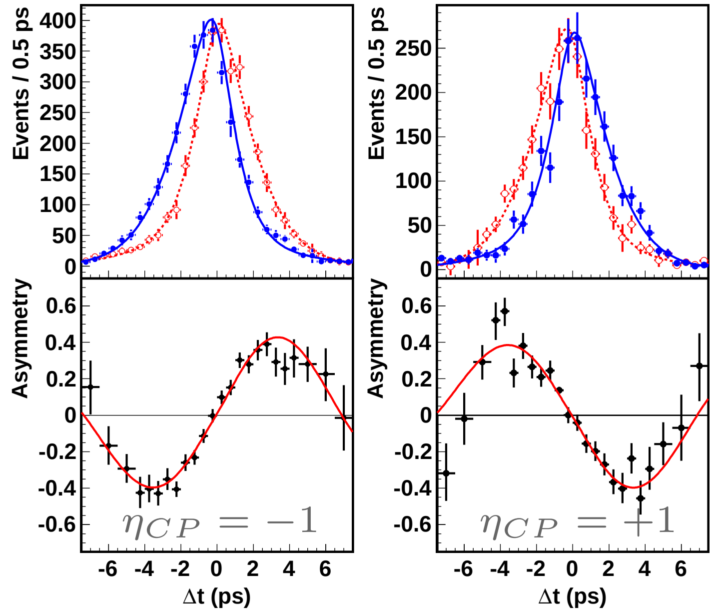
BaBar: PRD 79, 072009 (2009)



$$-\eta_{CP}\mathcal{S}_{CP} =$$

$+0.687 \pm 0.028$ (stat) $\pm\, 0.012$ (syst)

Belle: PRL 108, 171802 (2012)



$$-\eta_{CP}\mathcal{S}_{CP} =$$

$+0.667 \pm 0.023$ (stat) $\pm\, 0.012$ (syst)

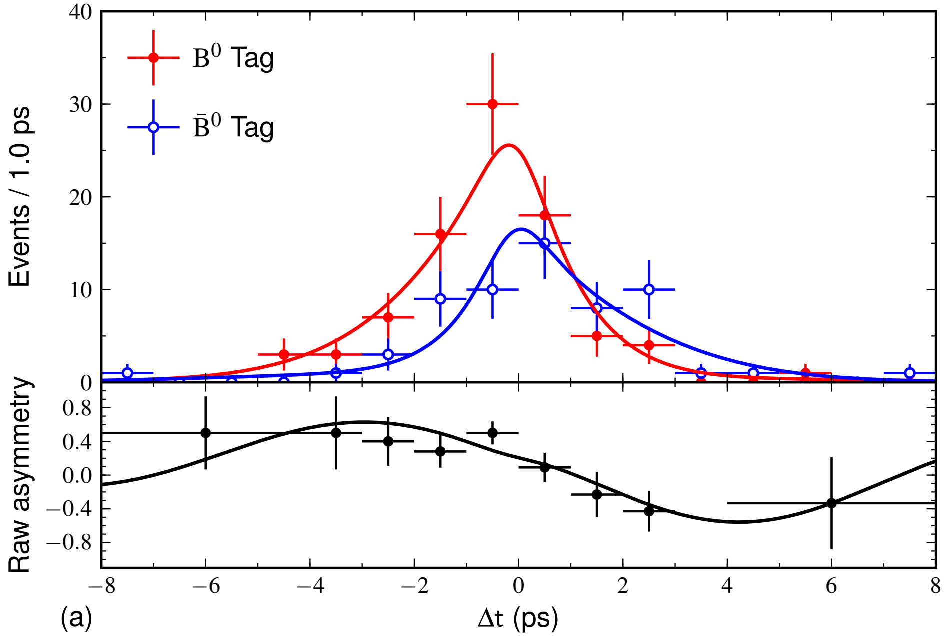
World's most precise measurements from the B factories: $-\eta_{CP}\mathcal{S}_{CP} = +0.679 \pm 0.020$

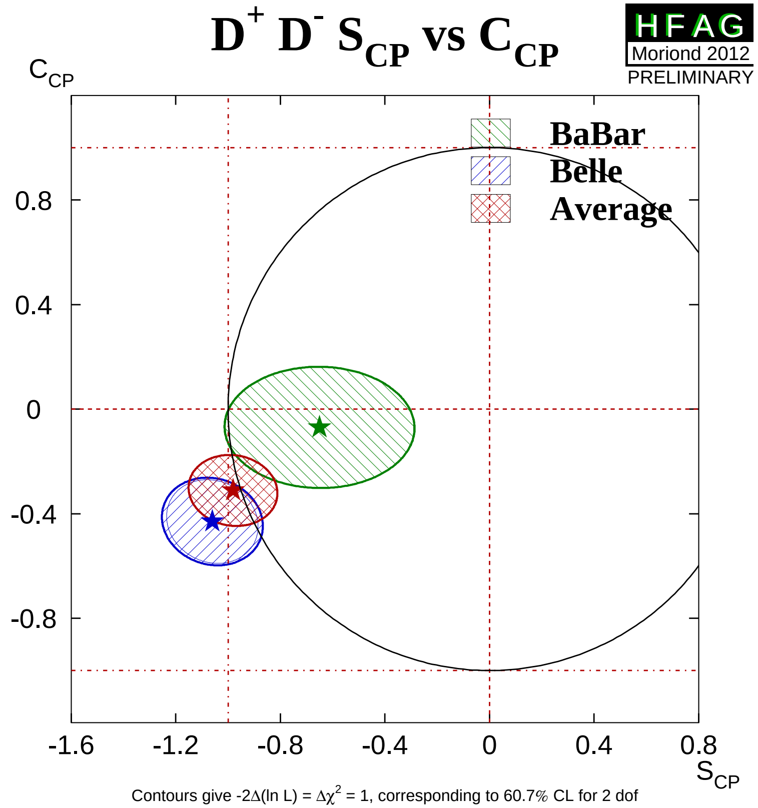
$B^0 \to D^+ D^-$

Sensitive to ϕ_1, presence of penguin contribution gives possibility of direct CP violation

Final result from Belle, neural networks used to provide better discrimation against continuum

Belle: PRD 85, 091106 (2012)





$\mathcal{A}_{CP} = +0.43 \pm 0.16$ (stat) $\pm\, 0.05$ (syst)

$\mathcal{S}_{CP} = -1.06\,^{+0.21}_{-0.14}$ (stat) $\pm\, 0.08$ (syst)

B factories in agreement and consistent with $\mathcal{S}_{CP}$ from $B^0 \to (c\bar{c})\,K^0$

$B^0 \to D^{*\pm} D^{\mp}$

Flavour non-specific final state, need to consider 4 flavour-charge configurations (q, c)

$$\mathcal{P}(\Delta t, q, c) = (1 + c\mathcal{A}_{CP})\frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}}\left\{1 + q\left[(\mathcal{S}_{CP} + c\Delta\mathcal{S})\sin\Delta m_d\Delta t - (\mathcal{C}_{CP} + c\Delta\mathcal{C})\cos\Delta m_d\Delta t\right]\right\}$$

Belle: PRD 85, 091106 (2012)

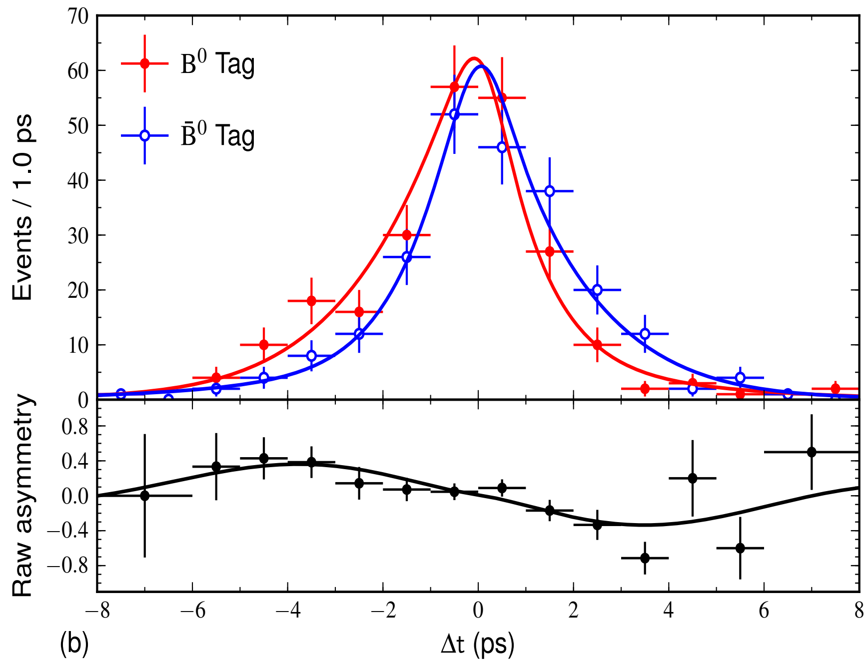
$\mathcal{A}_{CP}$: Time and flavour-integrated direct CP violation

$\mathcal{C}_{CP}$: Flavour-dependent direct CP violation

$\mathcal{S}_{CP}$: Mixing-induced CP violation

$\Delta\mathcal{C}$: Rate asymmetry between configurations where D^* does not and does contain the spectator quark

$\Delta\mathcal{S}$: Strong phase difference between configurations where D^* does not and does contain the spectator quark



$\mathcal{C}_{CP} = -0.01 \pm 0.11$ (stat) ± 0.04 (syst)

$\mathcal{S}_{CP} = -0.78 \pm 0.15$ (stat) ± 0.05 (syst)

B factories in agreement and consistent with $\mathcal{S}_{CP}$ from $B^0 \to (c\bar{c})\, K^0$

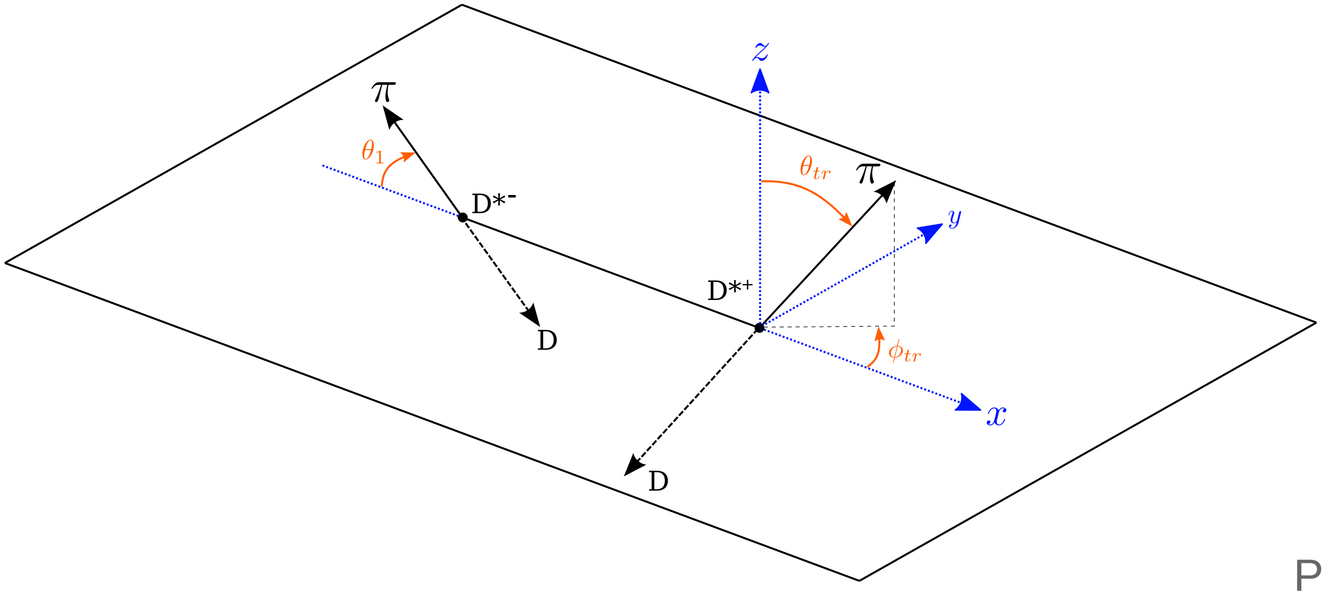
$B^0 \to D^{*+} D^{*-}$

CP composition depends on polarisation of the final state

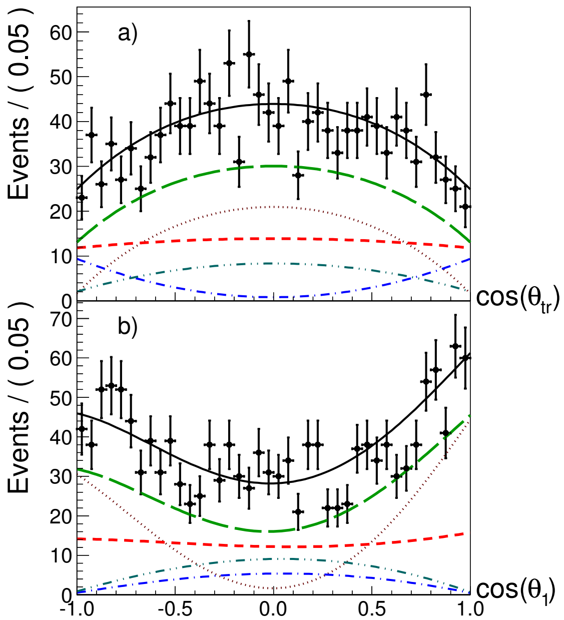
Decompose definite CP states with angular analysis in transversity basis

Benefits from new tracking algorithm

Transversity basis



Belle: Preliminary



Purple: CP-even, Blue: CP-odd

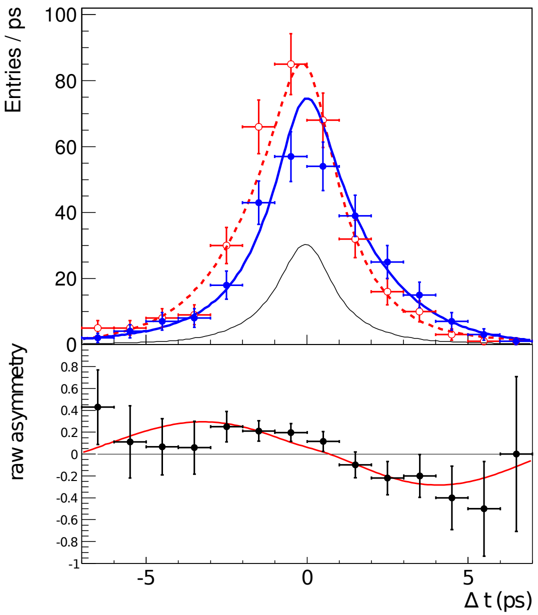
$R_\perp = 0.14 \pm 0.02$ (stat) ± 0.01 (syst)

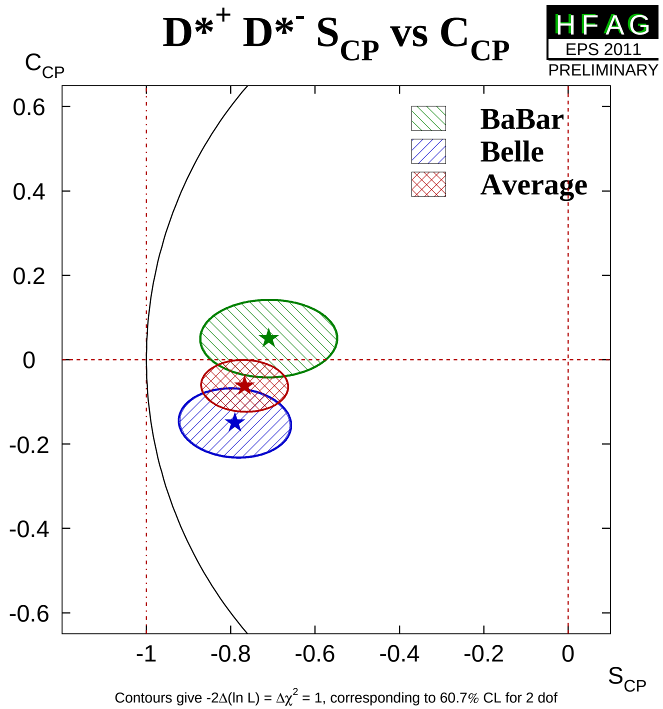
$B^0 \to D^{*+} D^{*-}$

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[\mathcal{A}_{CP} \cos \Delta m_d \Delta t + (1 - 2P_{\rm odd}) \mathcal{S}_{CP} \sin \Delta m_d \Delta t \right] \right\}$$

$$P_{\rm odd} = \frac{R_\perp H_\perp(\cos\theta_{\rm tr}, \cos\theta_1)}{\sum_{i=0,\|,\perp} R_i H_i(\cos\theta_{\rm tr}, \cos\theta_1)}$$

Belle: Preliminary





$\mathcal{A}_{CP} = +0.15 \pm 0.08$ (stat) $\pm\, 0.04$ (syst)

$\mathcal{S}_{CP} = -0.79 \pm 0.13$ (stat) $\pm\, 0.03$ (syst)

B factories in agreement and consistent with $\mathcal{S}_{CP}$ from $B^0 \to (c\bar{c})\, K^0$

$B^0 \to a_1(1260)^{\pm}\pi^{\mp}$

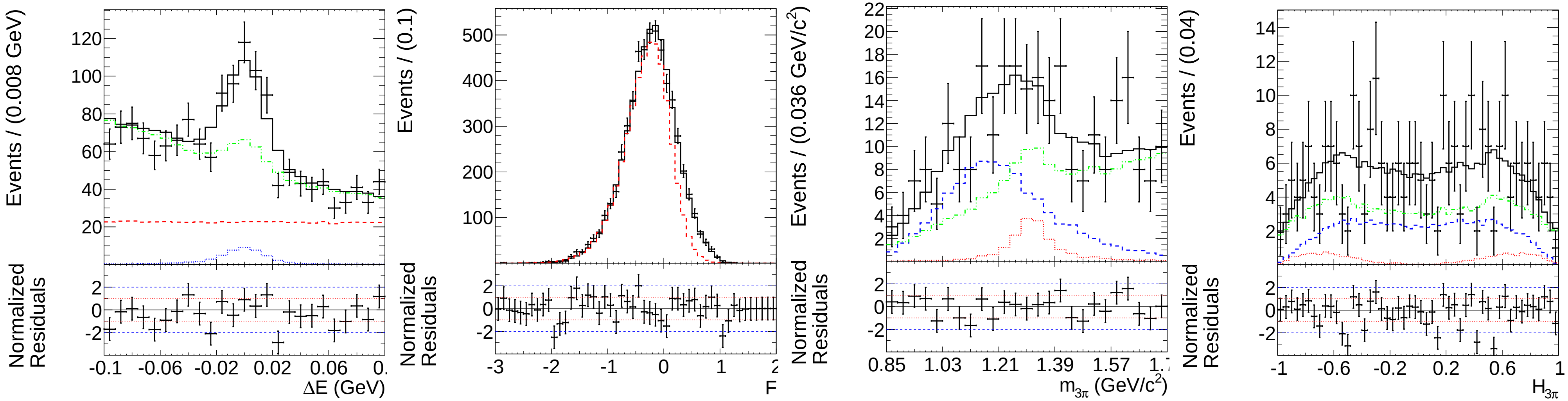
$b \to u\bar{u}d$ transition, sensitive to ϕ_2

Reconstructed in 4 charged pion final state

Difficulties from huge continuum background and other 4 pion backgrounds

Extract branching fraction from 4 discriminating variables

$E_B - E_{\mathrm{beam}}$ | Fisher discriminant | 3π mass | 3π helicity



Blue: 4π background | Red: Continuum | Blue: a_1, Red: a_2 | Blue: a_1, Red: a_2

$$\mathcal{B}(B^0 \to a_1(1260)^{\pm}\pi^{\mp}) \times \mathcal{B}(a_1^{\pm}(1260) \to \pi^{\pm}\pi^{\mp}\pi^{\pm}) = (11.1 \pm 1.0\ (\mathrm{stat}) \pm 1.4\ (\mathrm{syst})) \times 10^{-6}$$

$B^0 \to a_1(1260)^{\pm}\pi^{\mp}$

Flavour non-specific final state, need to consider 4 flavour-charge configurations (q, c)

$$\mathcal{P}(\Delta t, q, c) = (1 + c\mathcal{A}_{CP}) \frac{e^{-|\Delta t|/\tau_{B^0}}}{8\tau_{B^0}} \left\{ 1 + q \left[(\mathcal{S}_{CP} + c\Delta\mathcal{S}) \sin \Delta m_d \Delta t - (\mathcal{C}_{CP} + c\Delta\mathcal{C}) \cos \Delta m_d \Delta t \right] \right\}$$

$\mathcal{A}_{CP}$: Time and flavour-integrated direct CP violation

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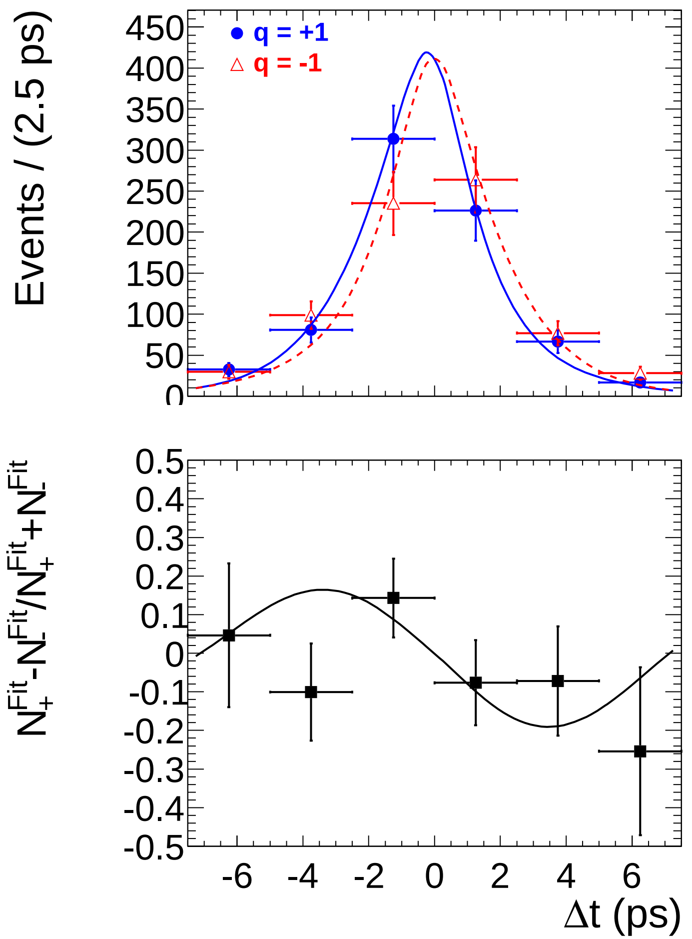
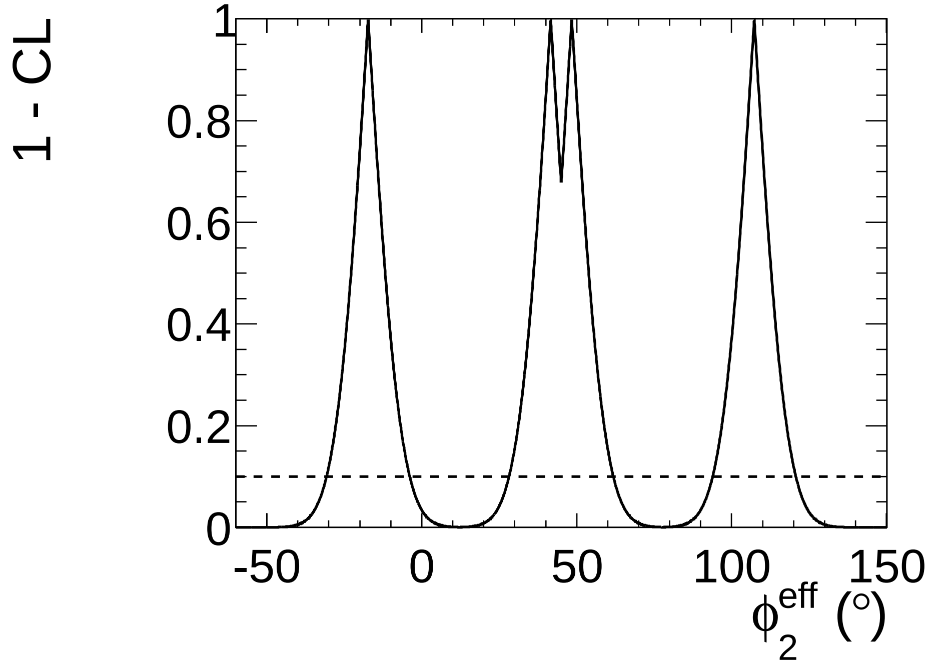


$\mathcal{S}_{CP} = -0.51 \pm 0.14$ (stat) ± 0.08 (syst)

3.1σ evidence for mixing-induced CP violation

$B^0 \to a_1(1260)^{\pm}\pi^{\mp}$

$$\phi_2^{\rm eff} = \frac{1}{4}\left[\arcsin\left(\frac{\mathcal{S}_{CP}+\Delta\mathcal{S}}{\sqrt{1-(\mathcal{C}_{CP}+\Delta\mathcal{C})^2}}\right)+\arcsin\left(\frac{\mathcal{S}_{CP}-\Delta\mathcal{S}}{\sqrt{1-(\mathcal{C}_{CP}-\Delta\mathcal{C})^2}}\right)\right]$$



4 solutions for $\phi_2^{\rm eff}$

At 1σ level,

$$\phi_2^{\rm eff} = [-25.5°, -9.1°]$$
$$= [34.7°, 55.3°]$$
$$= [99.1°, 115.5°]$$

Recover ϕ_2 with isospin pentagon analysis

M. Gronau and D. London, PRL 65 3381 (1990)

Or estimate bounds on $|\Delta\phi_2|$ with SU(3) flavour symmetry

M. Gronau and J. Zupan, PRD 73 057502 (2006)

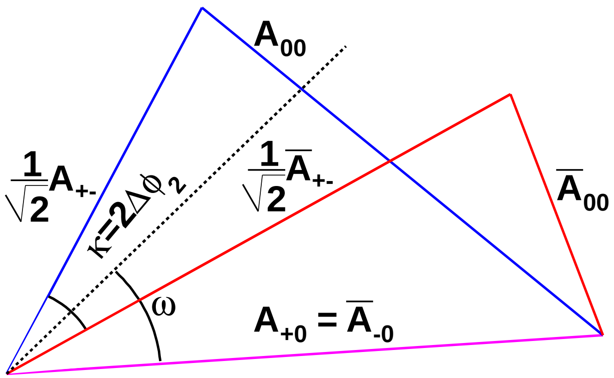
ϕ_2

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

ϕ_2 constrained with isospin analysis

Up to isospin breaking effects

No penguin in A_{+0}



8-fold ambiguity in ϕ_2

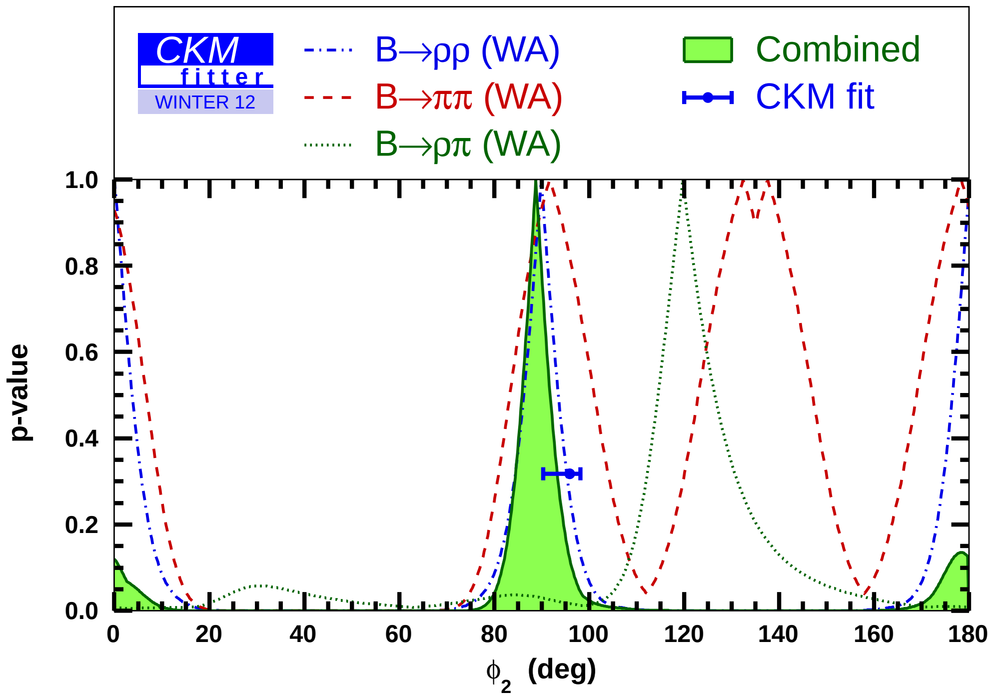
$B \to \rho\pi$ system

ϕ_2 directly constrained with Dalitz plot fit

Single solution for ϕ_2

$B \to \rho\rho$ system gives tightest ϕ_2 constraint

Due to relatively flat isospin triangles



$$\phi_2 = (88.7^{+4.6}_{-4.2})^\circ$$

Exclusive V_{ub}

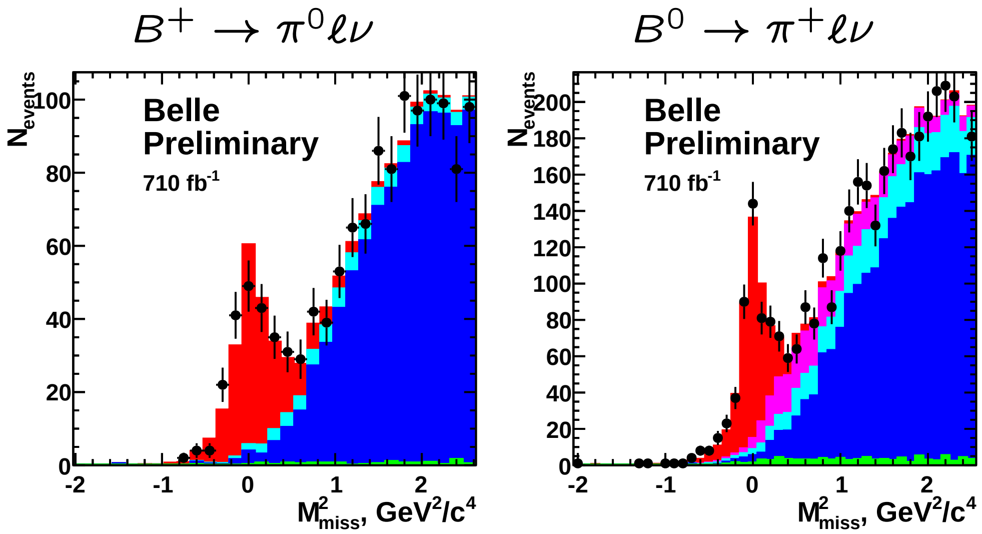
V_{ub} the least known CKM element

$$\frac{d\Gamma}{dq}(\bar{B} \to X_u l \bar{\nu}_l) = \frac{G_F^2}{24\pi^3} p_{X_u}^3 |V_{ub}|^2 |f_+(q^2)|^2$$

Improved tag-side reconstructing with Neural Networks

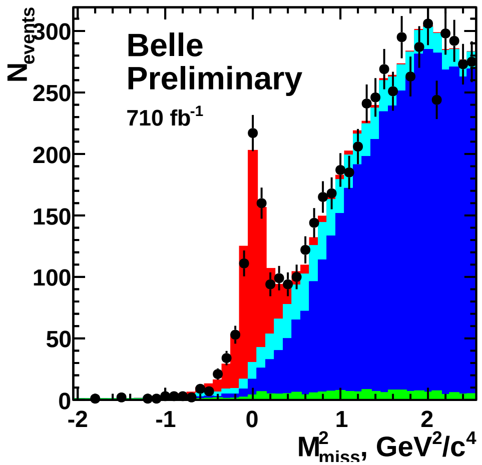
Extract signal yield from missing mass squared distribution

Belle: Preliminary

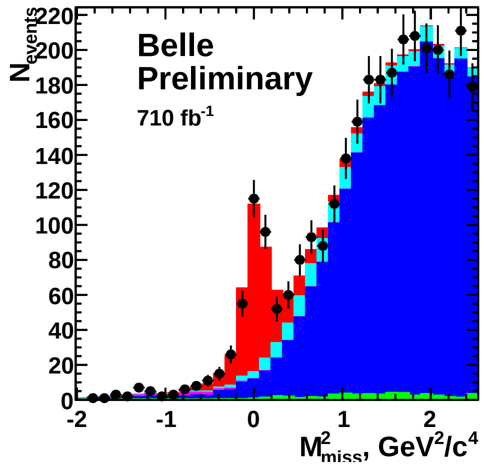


Exclusive V_{ub}

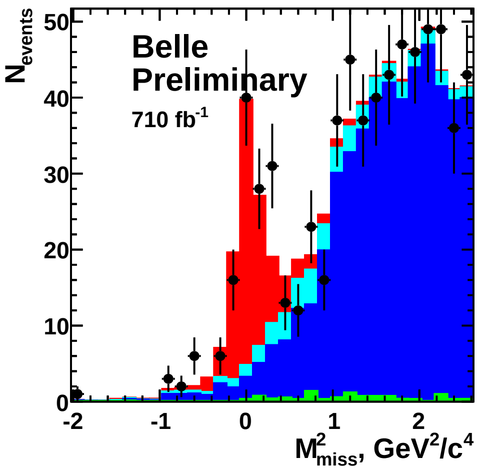
$B^+ \to \rho^0 \ell \nu$



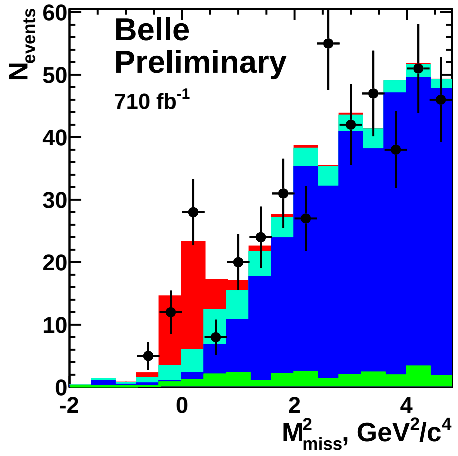
$B^0 \to \rho^+ \ell \nu$



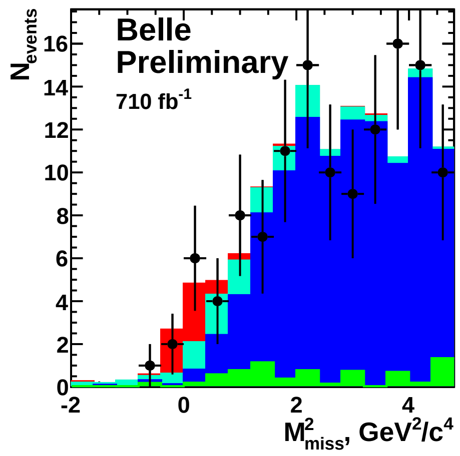
$B^+ \to \omega(\pi^+\pi^-\pi^0) \ell \nu$



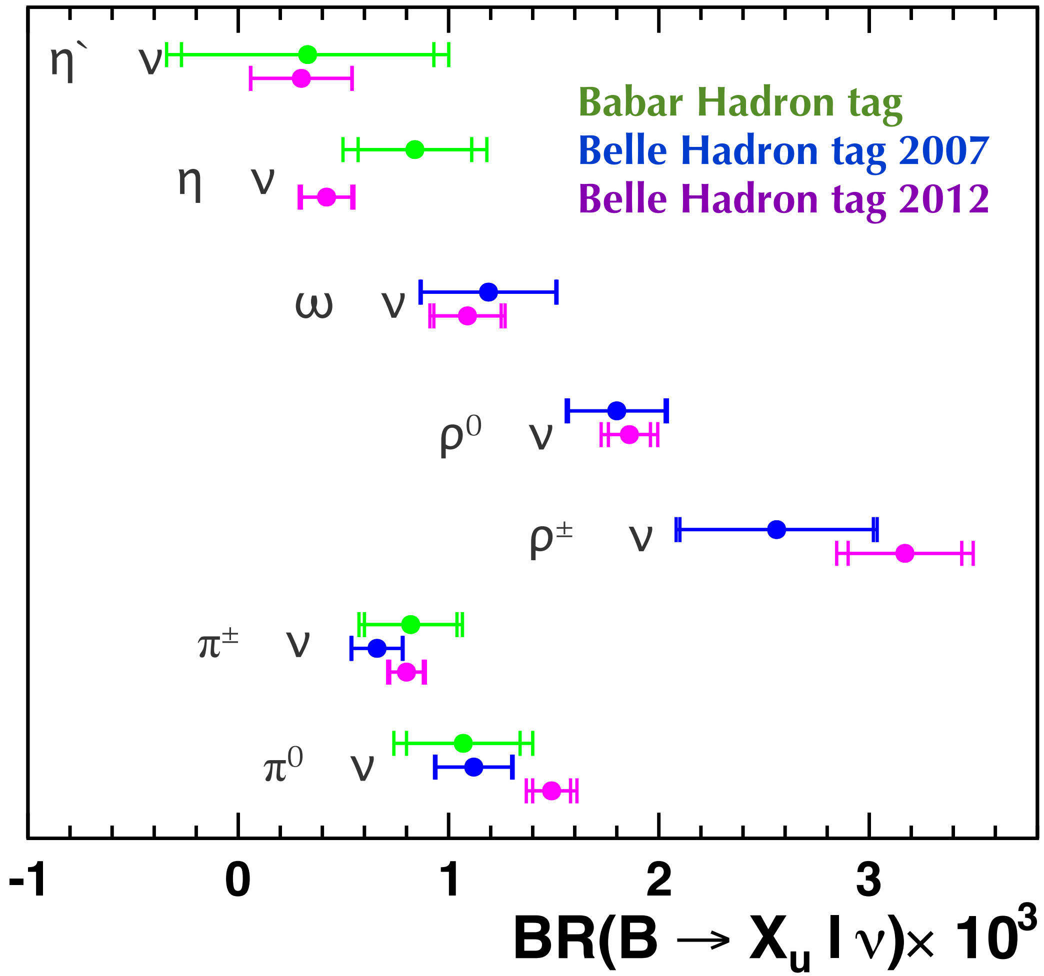
$B^+ \to \eta \ell \nu$



$B^+ \to \eta' \ell \nu$



Exclusive V_{ub}



Updated Belle measurements give the most precise branching fractions with hadronic tag

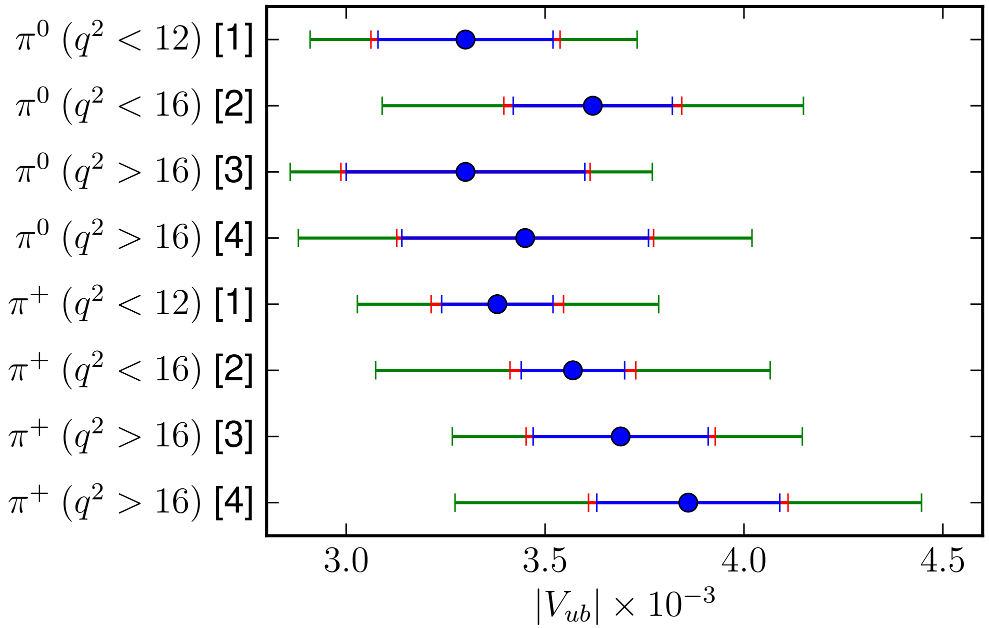
Exclusive V_{ub}

$$|V_{ub}| = \sqrt{\frac{C_\nu \mathcal{B}}{\tau_B \zeta}}$$

$C_\nu = 2$ for B^+, $C_\nu = 1$ for B^0

$\zeta = \int d\Gamma / |V_{ub}|^2$ form factors estimated from various theoretical models

Belle: Preliminary



Blue: Stat, Red: Stat $\oplus$ Syst, Green: Stat $\oplus$ Syst $\oplus$ Model

Models for estimating ζ

[1] KMOW, PRD 83 094031 (2011)

[2] Ball/Zwicky, PRD 71 014015 (2005)

[3] FNAL, NPPS 140 461 (2006)

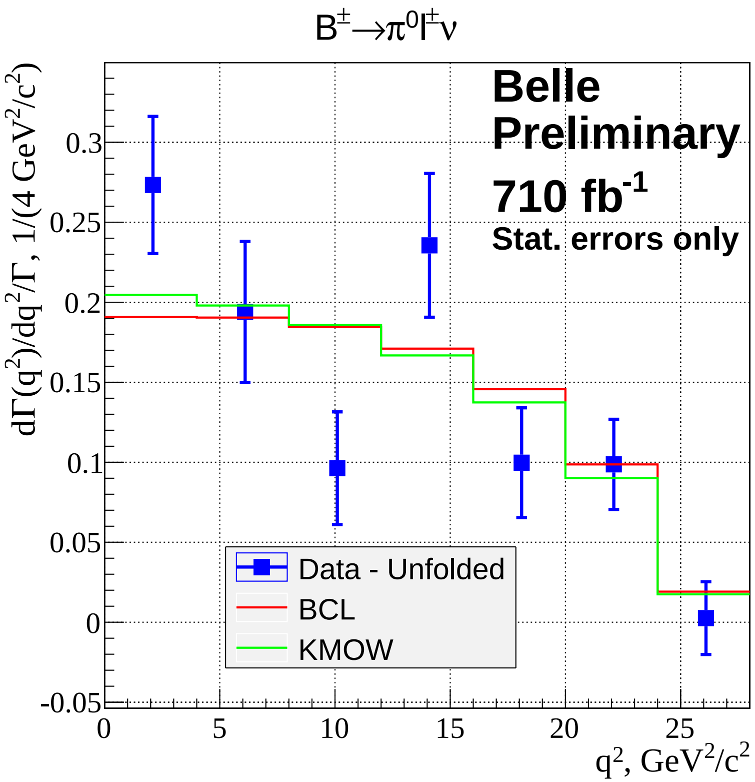
[4] HPQCD, PRD 73 074502 (2005)

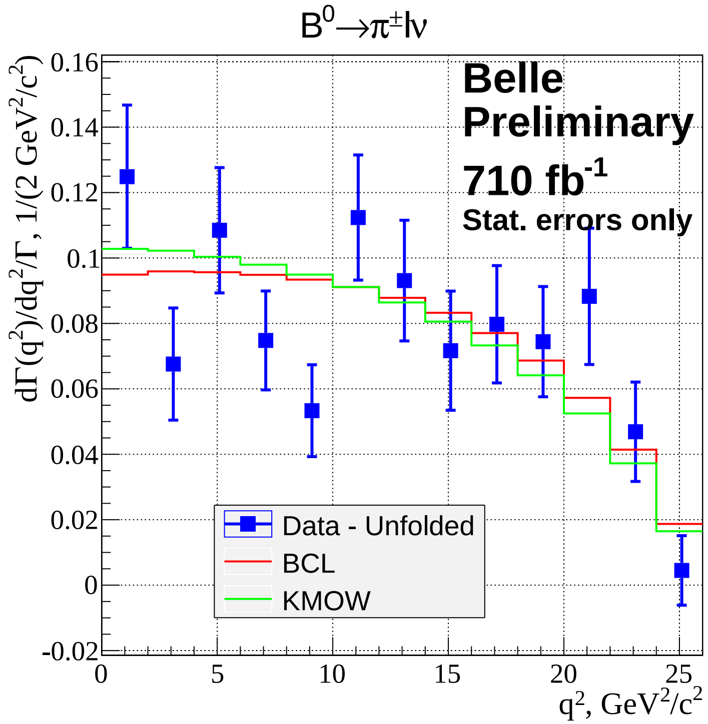
Exclusive V_{ub}

Performing $|V_{ub}|$ extraction in bins of q^2 reduces model dependence

Fit data & theory from q^2 distribution

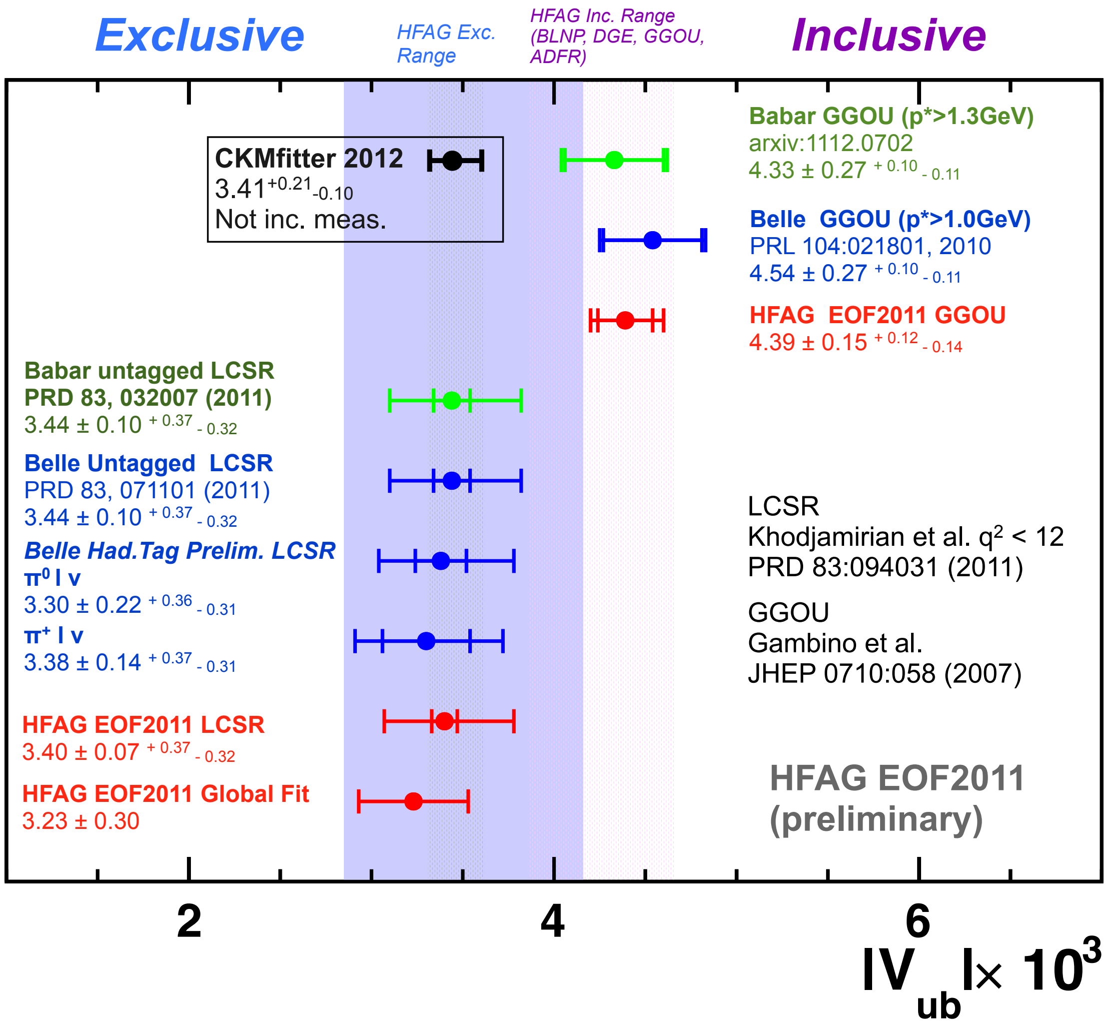
2-3 shape parameters and $|V_{ub}|$, include data & LQCD correlations





Not a fit, but plots show compatibility of q^2 data with various model expectations

V_{ub}



Tension between exclusive and inclusive V_{ub} determinations

Summary

Many final results from Belle

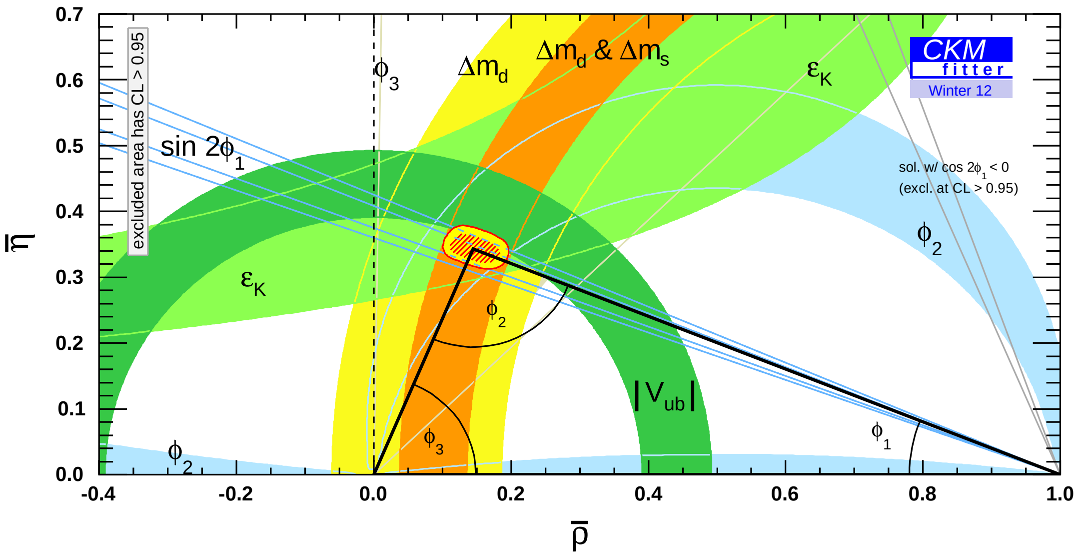
ϕ_1: Most precise measurements on Golden Channel and $b \to c\bar{c}d$ transitions

ϕ_2: First evidence of CP violation in $B^0 \to a_1(1260)^{\pm}\pi^{\mp}$

V_{ub}: Most precise branching fraction measurements of $\bar{B} \to X_u l \bar{\nu}_l$ channels

More final results on ϕ_2 and ϕ_3 expected soon

Standard Model confirmed to $\mathcal{O}(10\%)$



$$\phi_1 = (21.4 \pm 0.8)^\circ$$

$$\phi_2 = (88.7^{+4.6}_{-4.2})^\circ$$

$$\phi_3 = (66 \pm 12)^\circ$$

$$|V_{cb}| = (41.9 \pm 0.7) \times 10^{-3} \text{ (incl)}$$

$$|V_{cb}| = (39.6 \pm 0.9) \times 10^{-3} \text{ (excl)}$$

$$|V_{ub}| = (4.41 \pm 0.15^{+0.15}_{-0.17}) \times 10^{-3} \text{ (incl)}$$

$$|V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \text{ (excl)}$$

Backup

ϕ_3 With GLW

Interference between the dominant $b \to c\bar{u}s$ with the corresponding DCS $b \to u\bar{c}s$

Relative magnitude and strong phase between suppressed and favoured amplitude: r_B, δ_B

GLW method: $D^{(*)}$ decays to CP-even $(D^{(*)}_{CP+})$ and CP-odd $(D^{(*)}_{CP-})$ eigenstates

Measured observables

$$R_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D^0 K^-) + \mathcal{B}(B^+ \to] \bar{D}^0 K^+)}$$

$$A_{CP\pm} = \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}$$

Relationship between observables constrain ϕ_3

CP-even D_{CP+} decays

$$R_{CP+} = 1 + r_B^2 + 2r_B \cos\delta_B \cos\phi_3$$

$$A_{CP+} = \frac{2r_B \sin\delta_B \sin\phi_3}{1 + r_B^2 + 2r_B \cos\delta_B \cos\phi_3}$$

CP-odd D_{CP-} decays

$$R_{CP-} = 1 + r_B^2 - 2r_B \cos\delta_B \cos\phi_3$$

$$A_{CP-} = \frac{-2r_B \sin\delta_B \sin\phi_3}{1 + r_B^2 - 2r_B \cos\delta_B \cos\phi_3}$$

ϕ_3 With GLW

Interference between the dominant $b \to c\bar{u}s$ with the corresponding DCS $b \to u\bar{c}s$

Relationship between observables constrain ϕ_3

CP-even D_{CP} decays

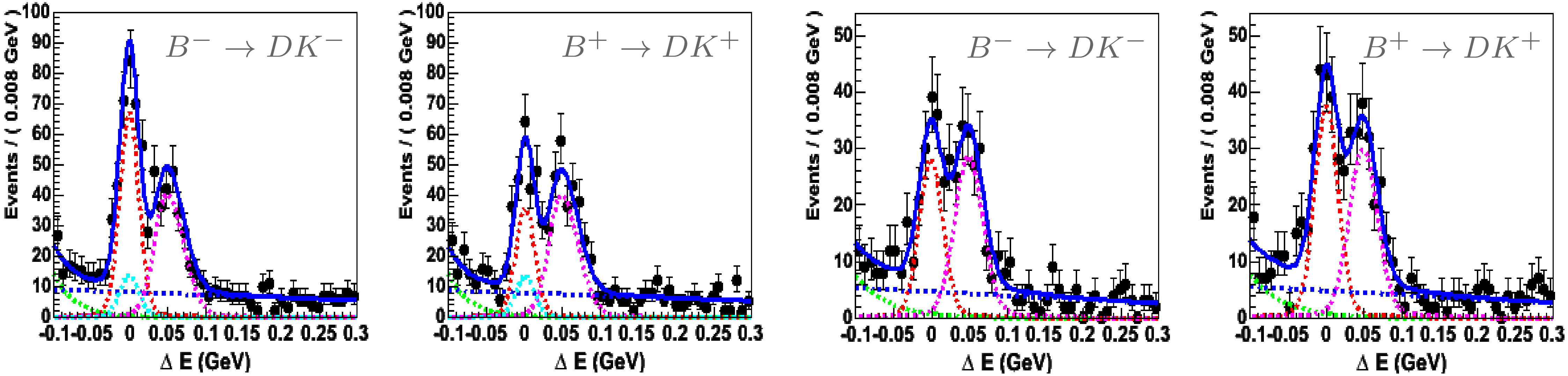
Belle: Preliminary

$D_{CP+} \to \pi^+\pi^-, K^+K^-$

CP-odd D_{CP} decays

Belle: Preliminary

$D_{CP-} \to K^0_S\pi^0, K^0_S\eta$



Red: $B \to DK$, Cyan: Charmless $K^+K^-K^+$ Pink: $B \to D\pi$, Green: $B\bar{B}$, Blue: Continuum

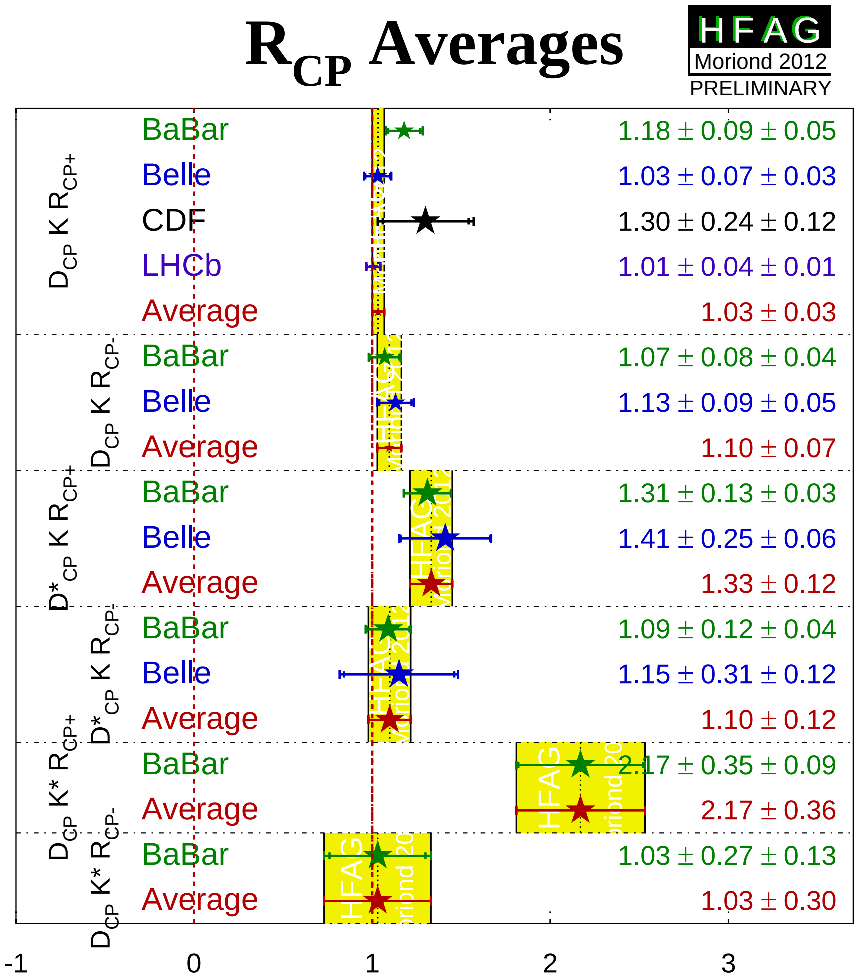
$R_{CP+} = (7.56 \pm 0.51)\%$

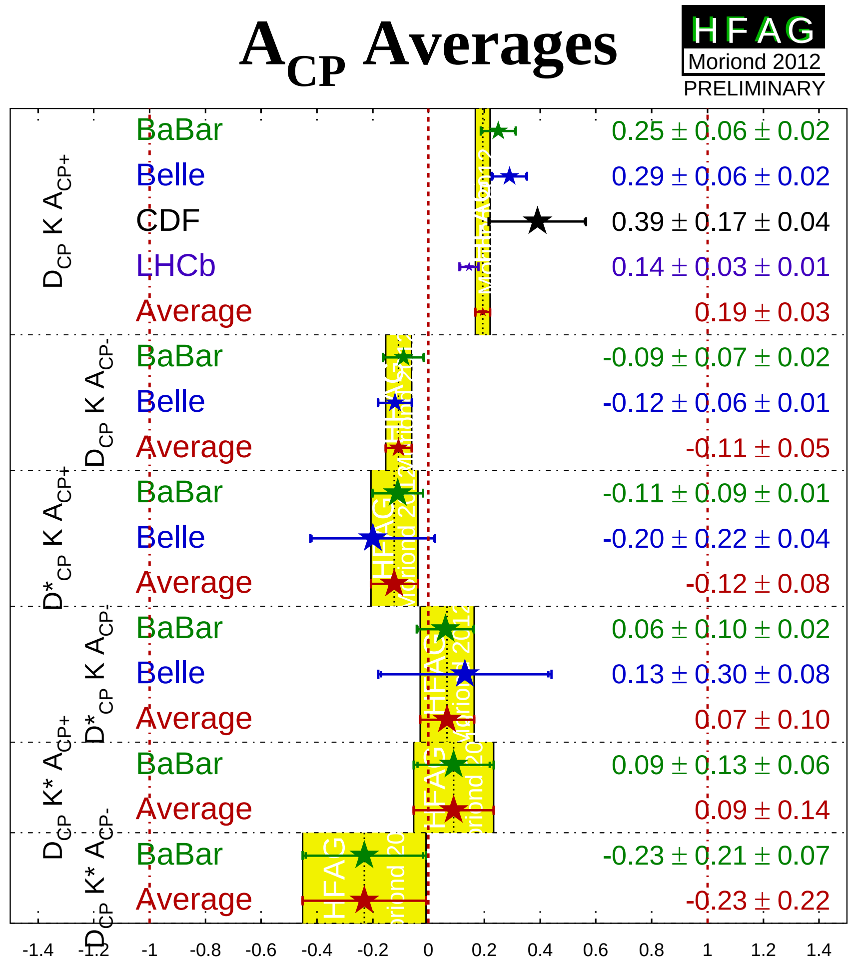
$A_{CP+} = (+28.7 \pm 6.0)\%$

$R_{CP-} = (8.29 \pm 0.63)\%$

$A_{CP-} = (-12.4 \pm 6.4)\%$

ϕ_3 With GLW





ϕ_3 With ADS

ADS method: $B^- \to DK^-$ with $D \to K^+\pi^-$ or similar

Favoured $(b \to c)$ B decay followed by DCS D decay interferes with suppressed $(b \to u)$ B decay followed by the CKM-favoured D decay

Measured observables

$$\mathcal{R}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]K^-) + \mathcal{B}([K^-\pi^+]K^+)}{\mathcal{B}([K^-\pi^+]K^-) + \mathcal{B}([K^+\pi^-]K^+)}$$

$$\mathcal{A}_{DK} \equiv \frac{\mathcal{B}([K^+\pi^-]K^-) - \mathcal{B}([K^-\pi^+]K^+)}{\mathcal{B}([K^+\pi^-]K^-) + \mathcal{B}([K^-\pi^+]K^+)}$$

Relationship between observables constrain ϕ_3

$$\mathcal{R}_{DK} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos\phi_3$$

$$\mathcal{A}_{DK} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin\phi_3}{\mathcal{R}_{DK}}$$

Amplitude ratio: $r_D = \frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)}$

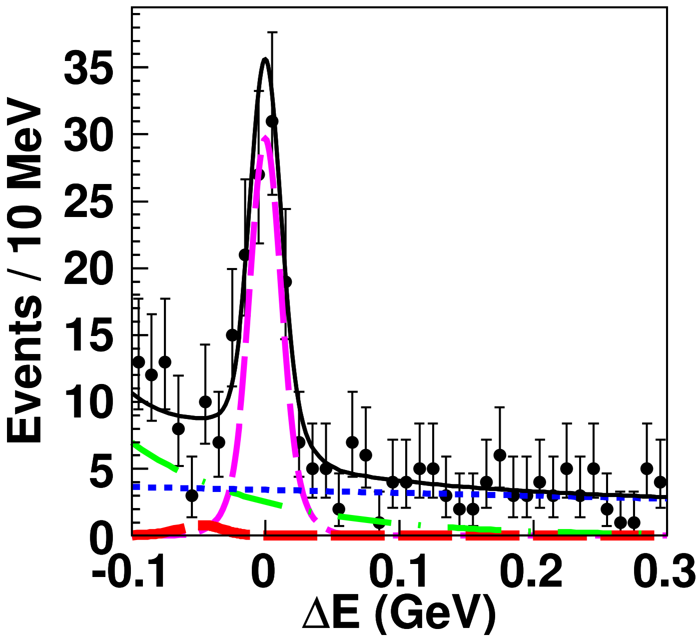
Strong phase difference, δ_D

ϕ_3 With ADS

Fit event shape Neural Network for better discrimination from dominant continuum background

Belle: PRL 106, 231803 (2011)

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



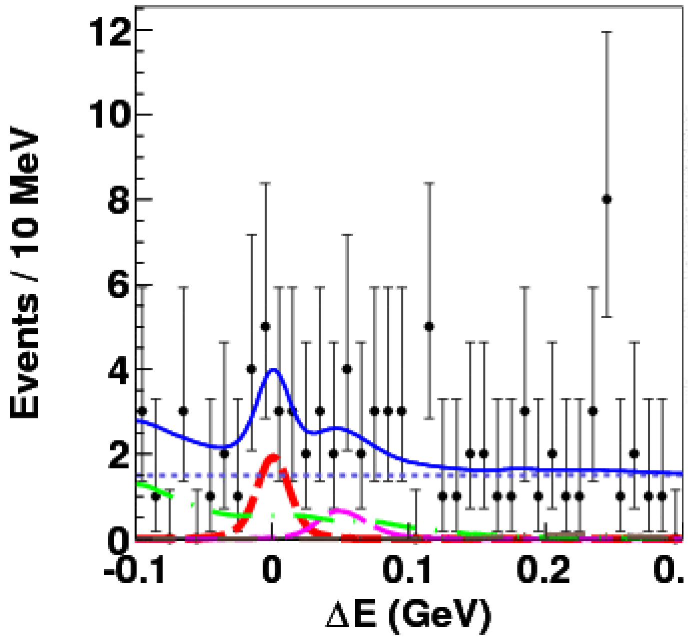
Pink: Signal

$\mathcal{R}_{DK} = (1.63^{+0.44+0.07}_{-0.41-0.13}) \times 10^{-2}$

$\mathcal{A}_{DK} = -0.39^{+0.26+0.04}_{-0.28-0.03}$

Belle: Preliminary

$D^{*0} \to D\pi^0, D \to K^+\pi^-$



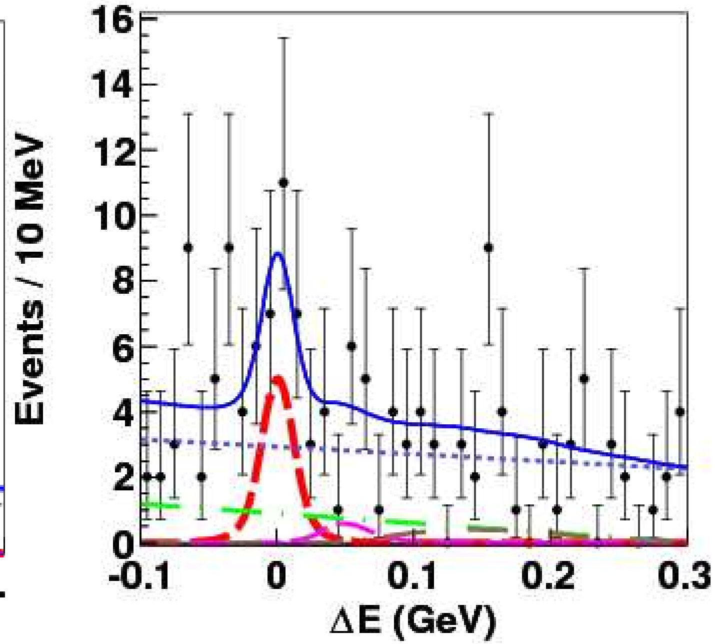
Red: Signal

$\mathcal{R}_{D\pi^0} = (1.0^{+0.8+0.1}_{-0.7-0.2}) \times 10^{-2}$

$\mathcal{A}_{D\pi^0} = +0.4^{+1.1+0.2}_{-0.7-0.1}$

Belle: Preliminary

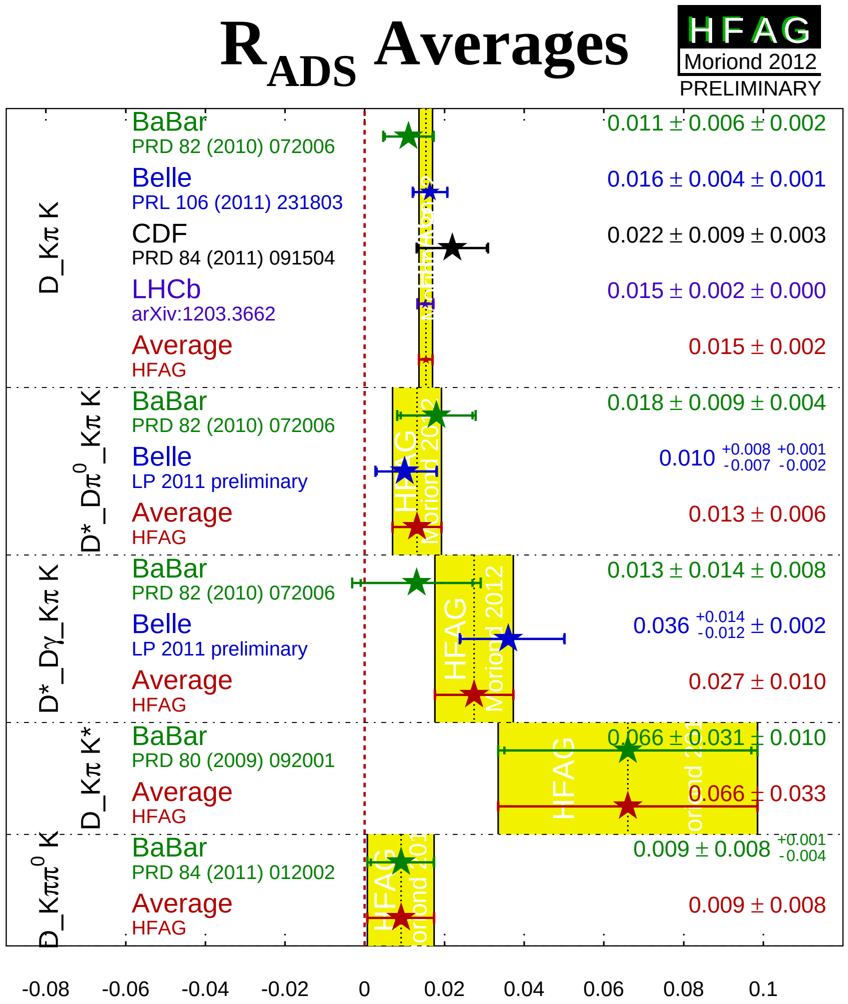
$D^{*0} \to D\gamma, D \to K^+\pi^-$

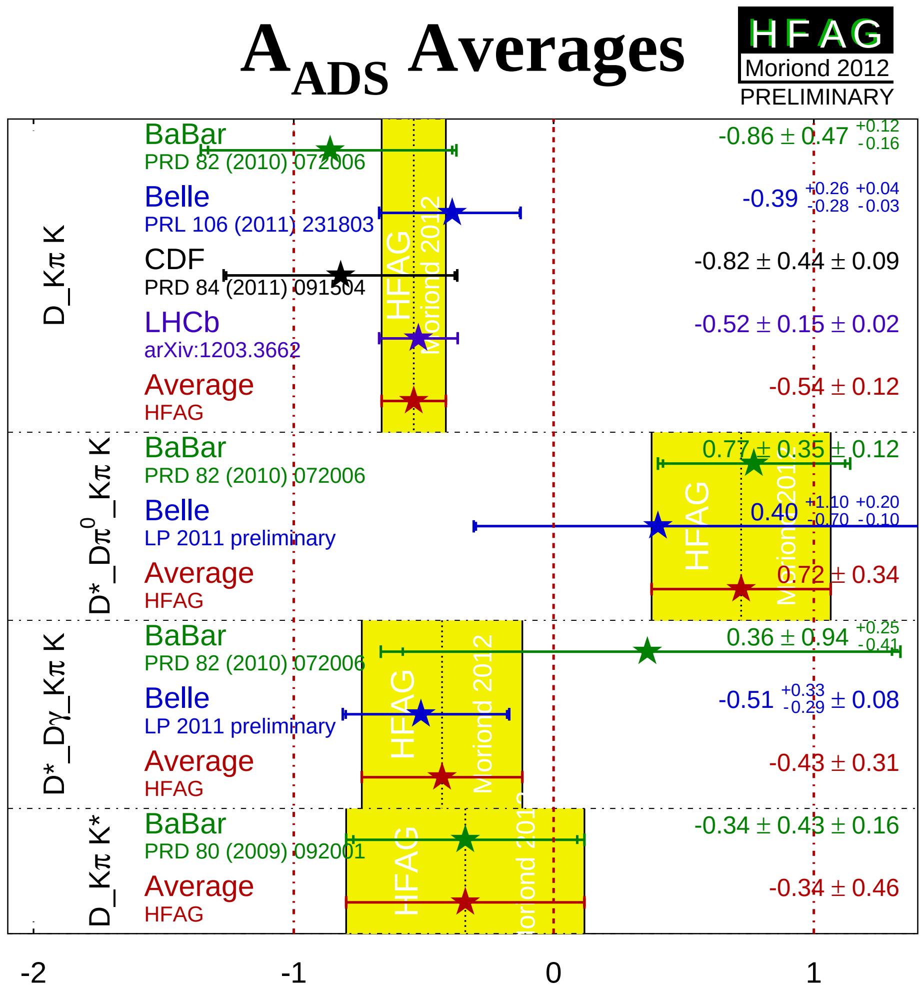


Red: Signal $\mathcal{R}_{D\gamma} = (3.6^{+1.4}_{-1.2} \pm 0.2) \times 10^{-2}$

$\mathcal{A}_{D\gamma} = -0.51^{+0.33}_{-0.29} \pm 0.08$

ϕ_3 With ADS



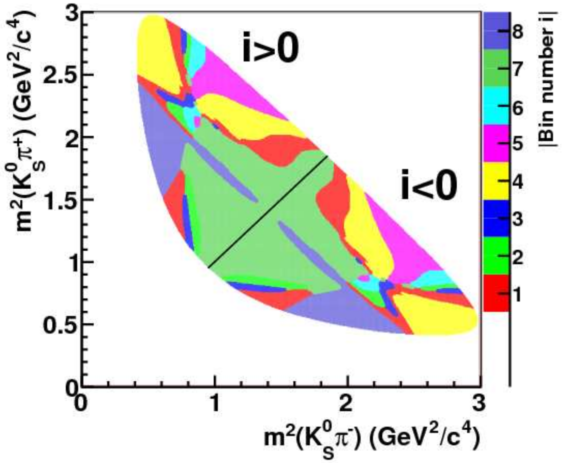


ϕ_3 With GGSZ

GGSZ method: Fit Dalitz plot of D decay to simultaneously determine r_B, δ_B and ϕ_3

However, model uncertainty is dominant systematic error $\rightsquigarrow$ remove with binned Dalitz method

Choice of binning affects ϕ_3 precision, but not $\phi_3$itself



Meausure yield in each bin i

And compare in a χ^2 fit with

$$N_i^{\pm} = h_B[K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(x_{\pm}c_i + y_{\pm}s_i)]$$

$$x_{\pm} = r_B \cos(\delta_B \pm \phi_3),\ y_{\pm} = r_B \sin(\delta_B \pm \phi_3)$$

$N_i^{\pm}$: Expected number of $B^{\pm} \to DK^{\pm}$ events in bin i

K_i: Number of events in bin i determined from a flavour-tagged sample ($D^{*\pm} \to D\pi^{\pm}$)

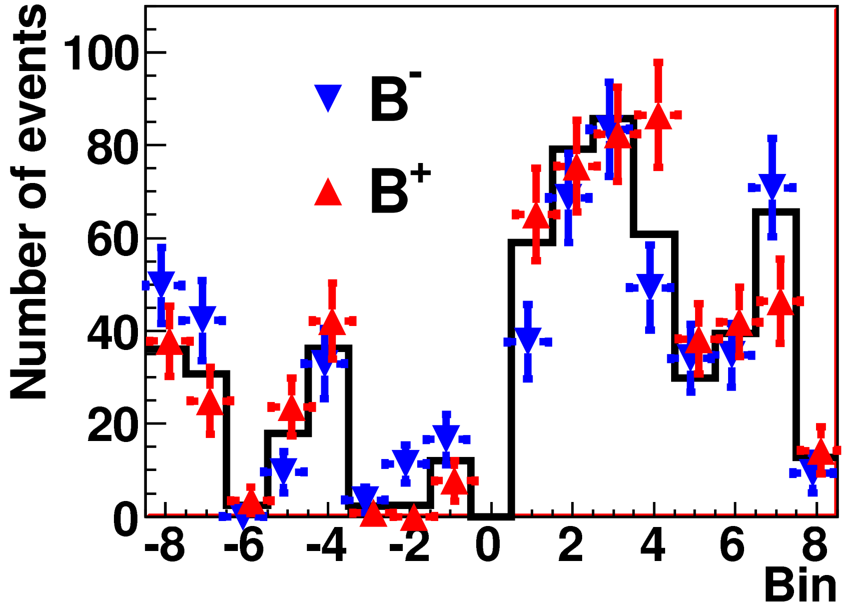
c_i, s_i: related to average strong phase difference in bin i

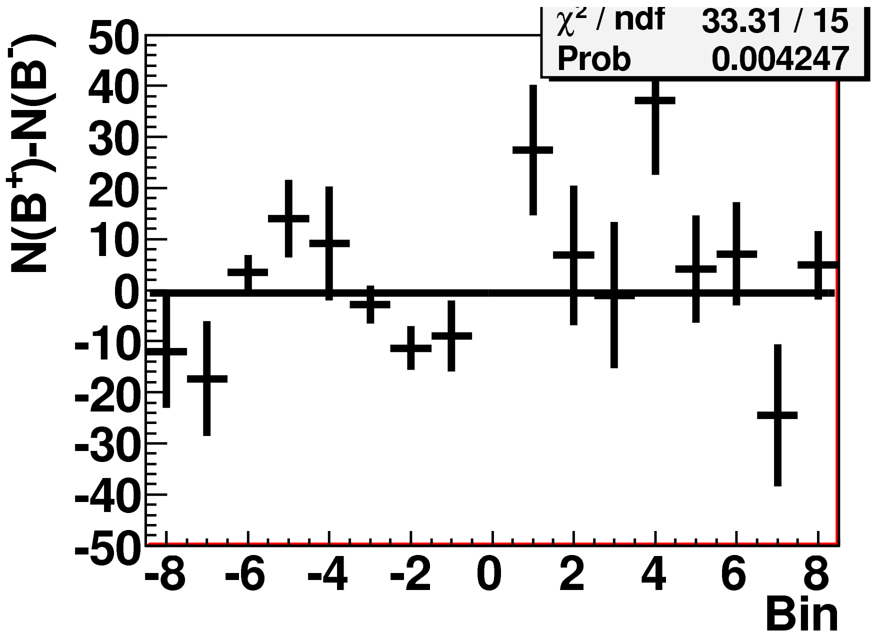
$$c_i = \langle \cos \Delta\delta_D \rangle_i,\ s_i = \langle \sin \Delta\delta_D \rangle_i$$

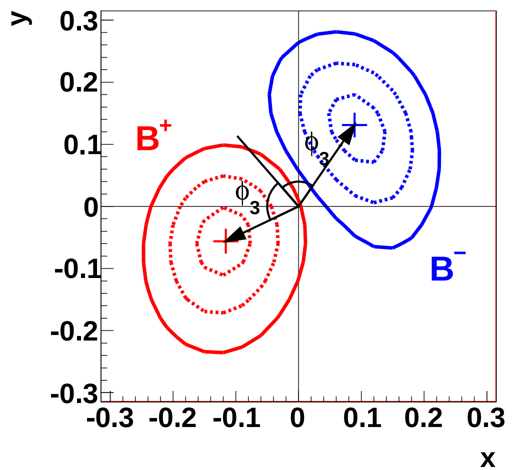
Measured by CLEO with $\psi(3770) \to D^0 \bar{D}^0$, can also be measured at BES-III

ϕ_3 With GGSZ

Belle: arXiv:1204.6561







Significant CP asymmetry can be seen

0.4% probability of statistical fluctuation

$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ$

3rd uncertainty from CLEO measurements of c_i, s_i

Dalitz method dominates ϕ_3 constraint

Exclusive V_{cb}

$\bar{B} \to D^* l \bar{\nu}_l$

$$\frac{d\Gamma}{dw}(\bar{B} \to D^* l \bar{\nu}_l) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 m_{D^*}^3 (w^2 - 1)^{1/2} P(w)(\eta_{\rm em}\mathcal{F}(w))^2$$

$\bar{B} \to D l \bar{\nu}_l$

$$\frac{d\Gamma}{dw}(\bar{B} \to D l \bar{\nu}_l) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 (m_B + m_D)^2 m_{D^*}^3 (w^2 - 1)^{3/2}(\eta_{\rm em}\mathcal{G}(w))^2$$

Extraction of $|V_{cb}|$ depends on w: the energy of the $D^{(*)}$ in the decay rest frame

HQS and Lattice QCD predicts form factors $\mathcal{F}(w)$, $\mathcal{G}(w)$ at $w = 1$, ie. when $D^{(*)}$ at rest

J. Bailey, PoS LATTICE2010 311 (2010)

M. Okamoto *et al.*, Nucl. Phys. (Proc. Supp.) **B140**, 461 (2005)

Form factors also parametrised in terms of ρ^2: the slope at $w = 1$

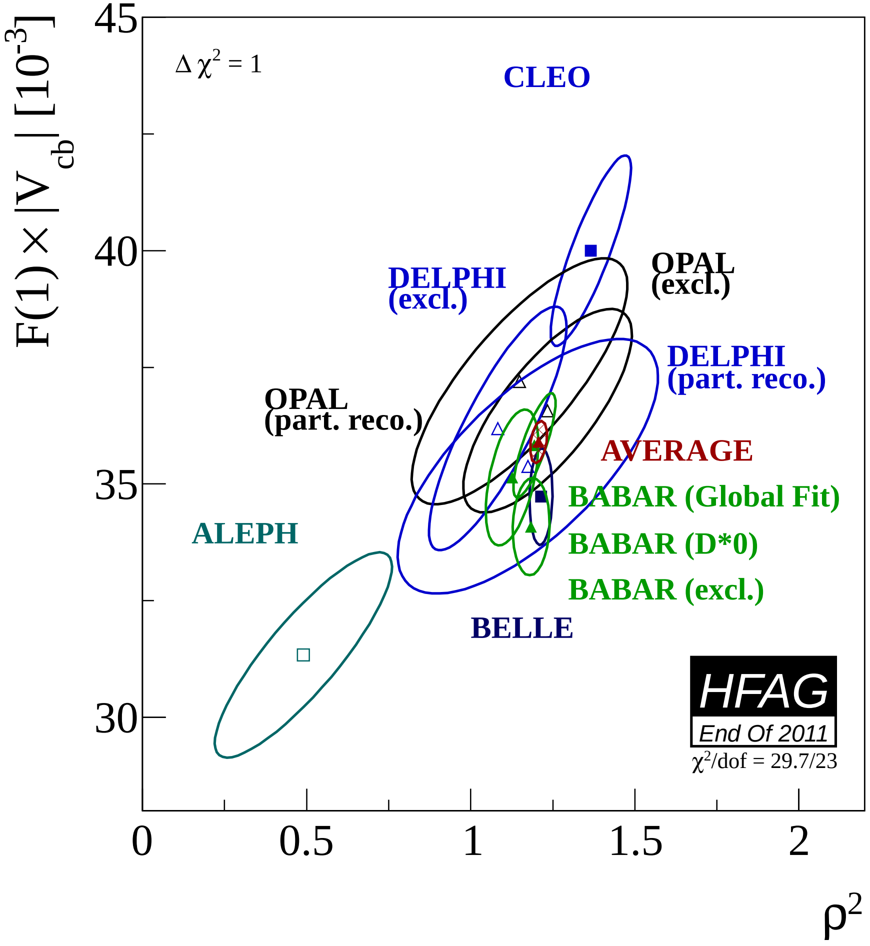
For $\bar{B} \to D^* l \bar{\nu}_l$, additional parametrisation from form factor ratios R_1, R_2

Constrained by angular analysis of $\bar{B} \to D^* l \bar{\nu}_l$ system

Then $|V_{cb}|$ can be obtained from extrapolation of measured spectrum to $w = 1$

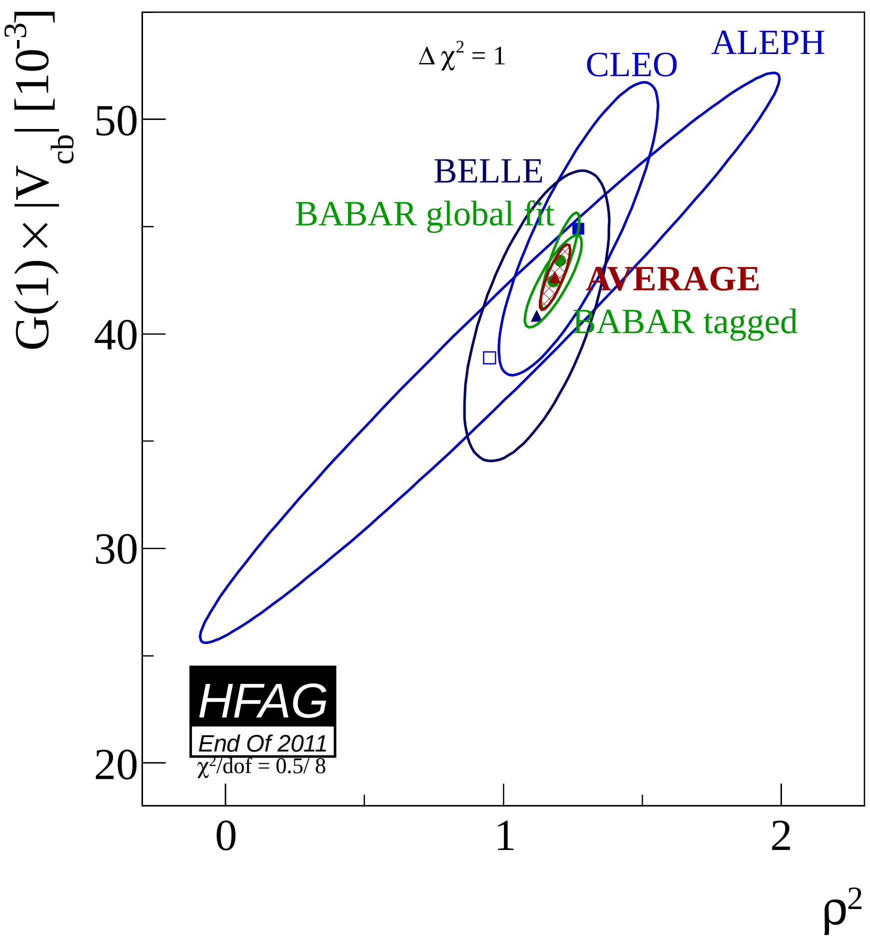
Exclusive V_{cb}

$\bar{B} \to D^* l \bar{\nu}_l$



$|V_{cb}|\mathcal{F}(1) = 35.90 \pm 0.11 \pm 0.44$

$\bar{B} \to D l \bar{\nu}_l$



$|V_{cb}|\mathcal{G}(1) = 42.64 \pm 0.72 \pm 1.35$

Inclusive V_{cb}

$$\Gamma(\bar{B} \to X_c l \bar{\nu}_l) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 (1 + A_{\rm ew}) A_{\rm nonpert} A_{\rm pert}$$

Experimental observables: leptonic energy and hadronic mass moments

In the Heavy Quark Expansion, total semileptonic rate expanded in $1/m_B$

Mass moments expressed in terms up to $\mathcal{O}(\alpha_s^2)$

Free parameters include m_c, m_b and μ_π^2

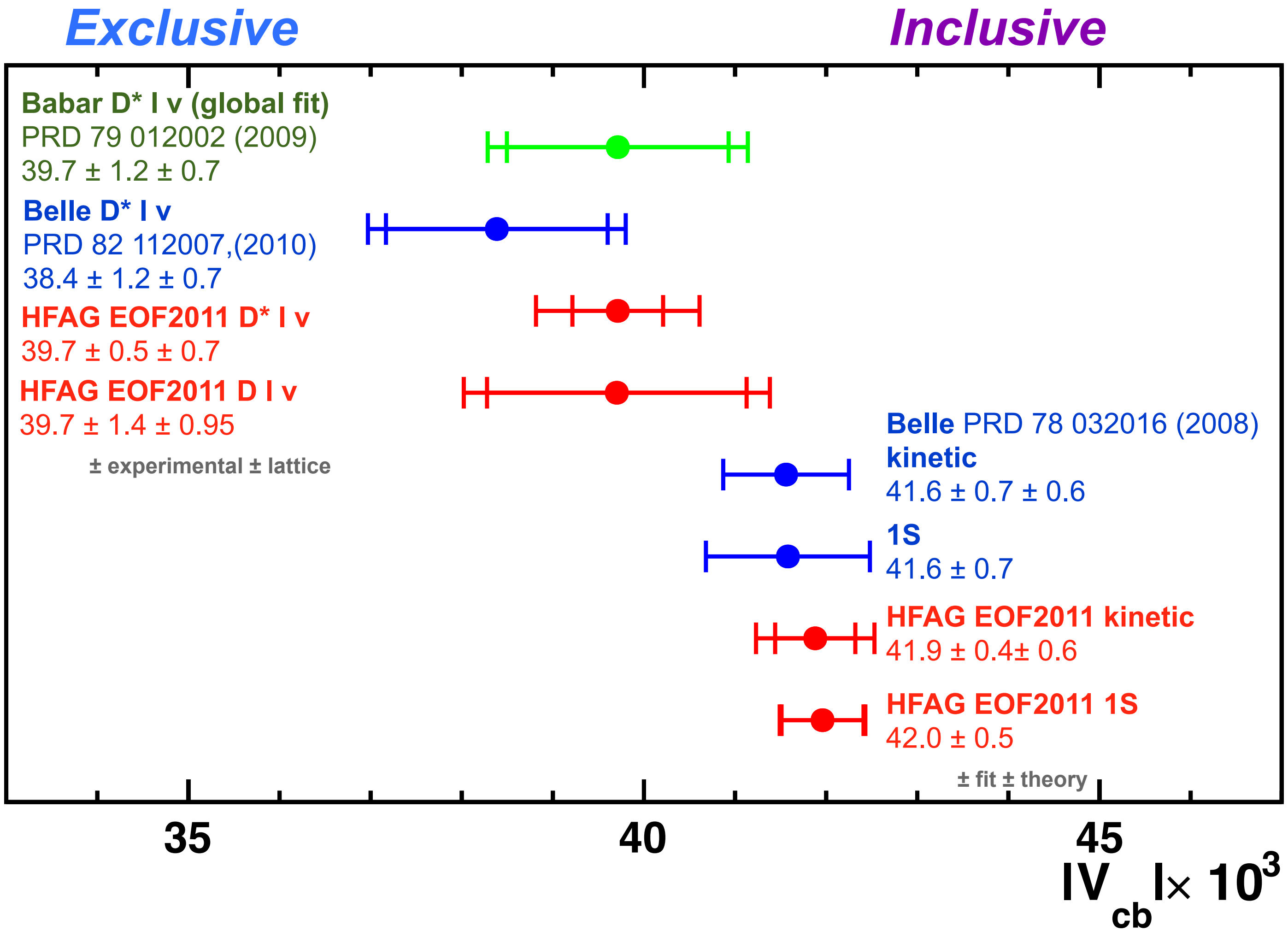
Two ways to deal with the b quark pole mass: Kinetic and $1S$ schemes

Fit to measure inclusive rate $\Gamma(\bar{B} \to X_c l \bar{\nu}_l)$ and $|V_{cb}|$

Semileptonic moments determine linear combination of m_b and m_c, need more information

- Precise charm quark mass to constrain m_c
- Radiative $B \to X_S \gamma$ moments which provide additional constraints on m_b and μ_π^2

V_{cb}



Inclusive measurements give the most precise determination of $|V_{cb}|$