Measurements of $|V_{cb}|$ and $|V_{ub}|$ -- mini review

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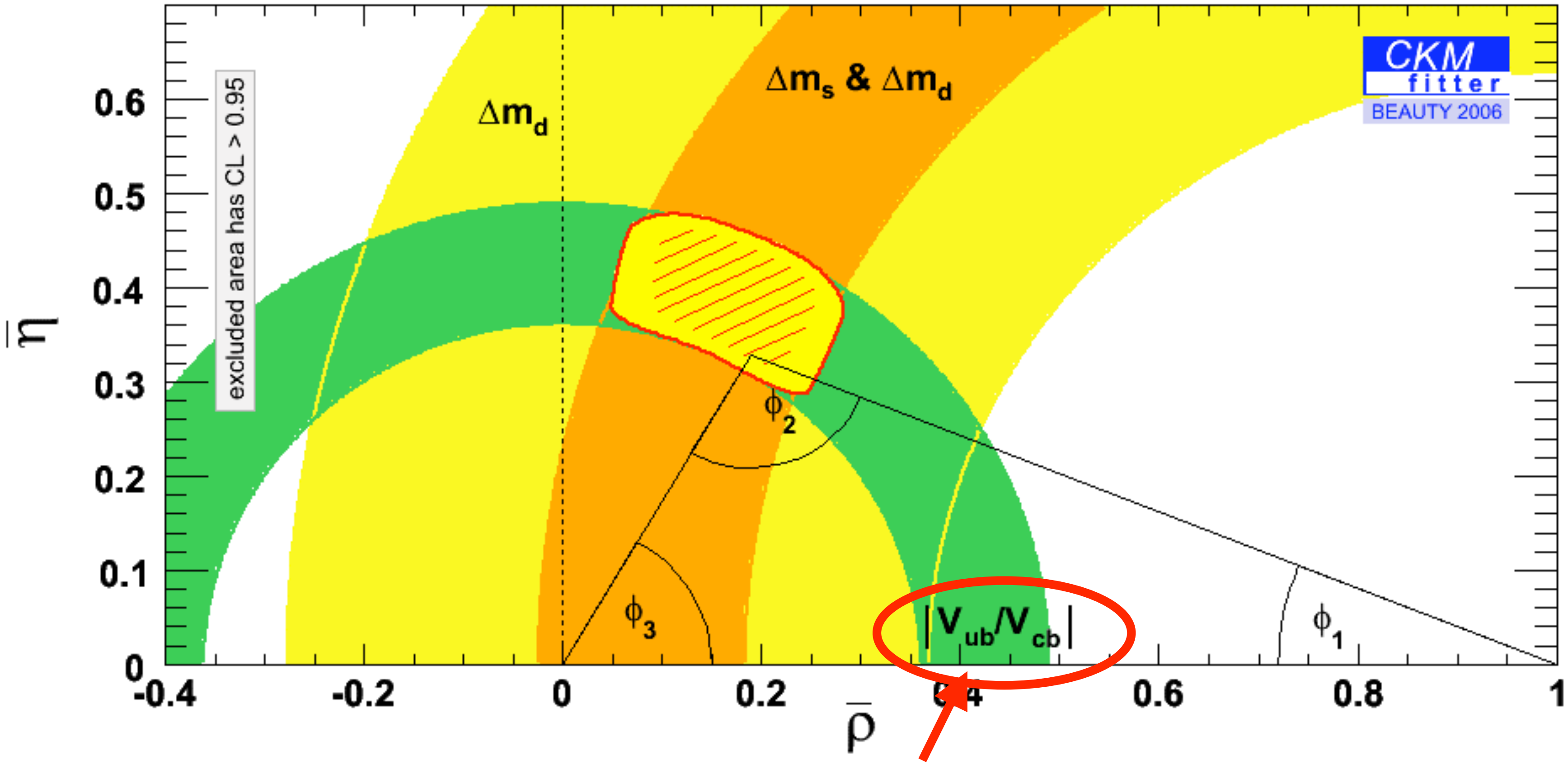
Motivation



- A precise determination of $|V_{ub}/V_{cb}|$ is crucial for constraining the CKM mechanism and searching for new physics processes
- "Old physics": $|V_{ub}|$ and $|V_{cb}|$ are determined from semileptonic B decays (dominated by tree diagrams)

$|V_{cb}|$ from exclusive semileptonic B decays

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

Theory of the measurement

- Decay rate for $B \to D^{(*)} l \nu$

$$\frac{d\Gamma}{dw}(\overline{B} \to D^* \ell \overline{\nu}_\ell) = \frac{G_F^2}{48\pi^3}|V_{cb}|^2 m_{D^*}^3 (w^2-1)^{1/2} P(w) (\mathcal{F}(w))^2$$

$$\frac{d\Gamma}{dw}(\overline{B} \to D \ell \overline{\nu}_\ell) =$$

$$\frac{G_F^2}{48\pi^3}|V_{cb}|^2 (m_B + m_D)^2 m_D^3 (w^2-1)^{3/2} (\mathcal{G}(w))^2$$

form factor

$$w \equiv v \cdot v'$$

- For infinite heavy quark masses: F(1)=G(1)=1;
  for finite masses from lattice QCD:

$$\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$$

[S. Hashimoto et al., Phys.Rev.D66,014503 (2002)]

- Experiments extrapolate $d\Gamma/dw$ to zero recoil (w=1) and measure $F(1)|V_{cb}|$ and $G(1)|V_{cb}|$

$B \rightarrow D^* l \nu$

[hep-ex/0607076]

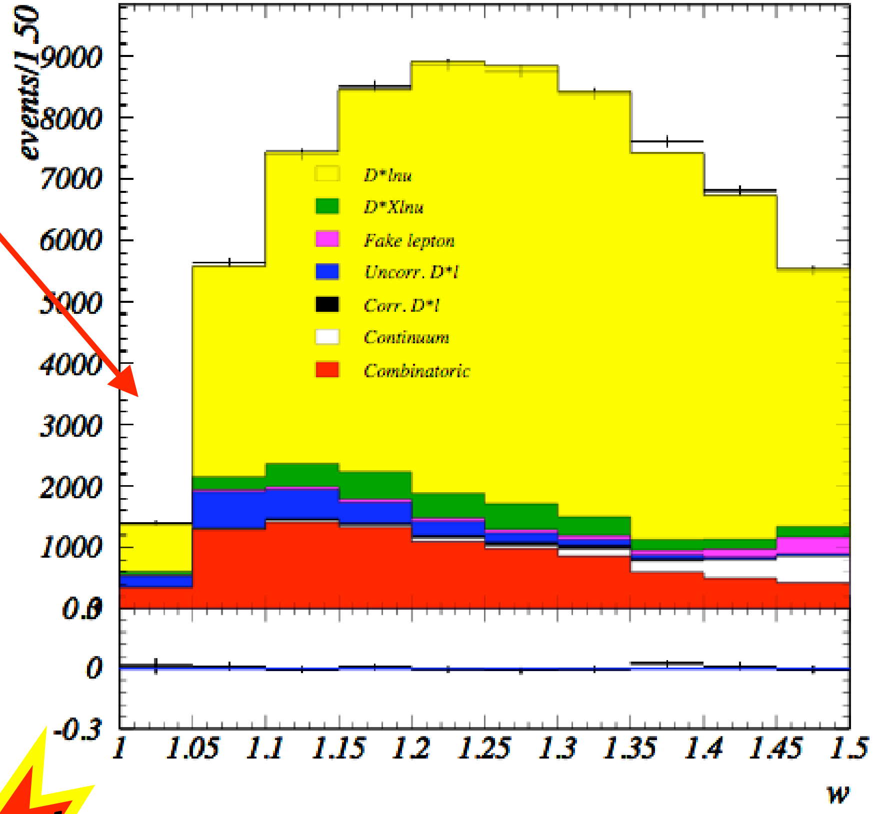
- Recent measurement of $|V_{cb}|F(1)$ by BaBar

$$\mathcal{F}(1)|V_{cb}| = (34.68 \pm 0.32 \pm 1.15) \times 10^{-3}$$

- Also measures $D^*l\nu$ form factors

$$\begin{aligned} \rho^2 &= 1.179 \pm 0.048 \pm 0.028 \\ R_1 &= 1.417 \pm 0.061 \pm 0.044 \\ R_2 &= 0.836 \pm 0.037 \pm 0.022. \end{aligned}$$

(important for the extrapolation to w=1)



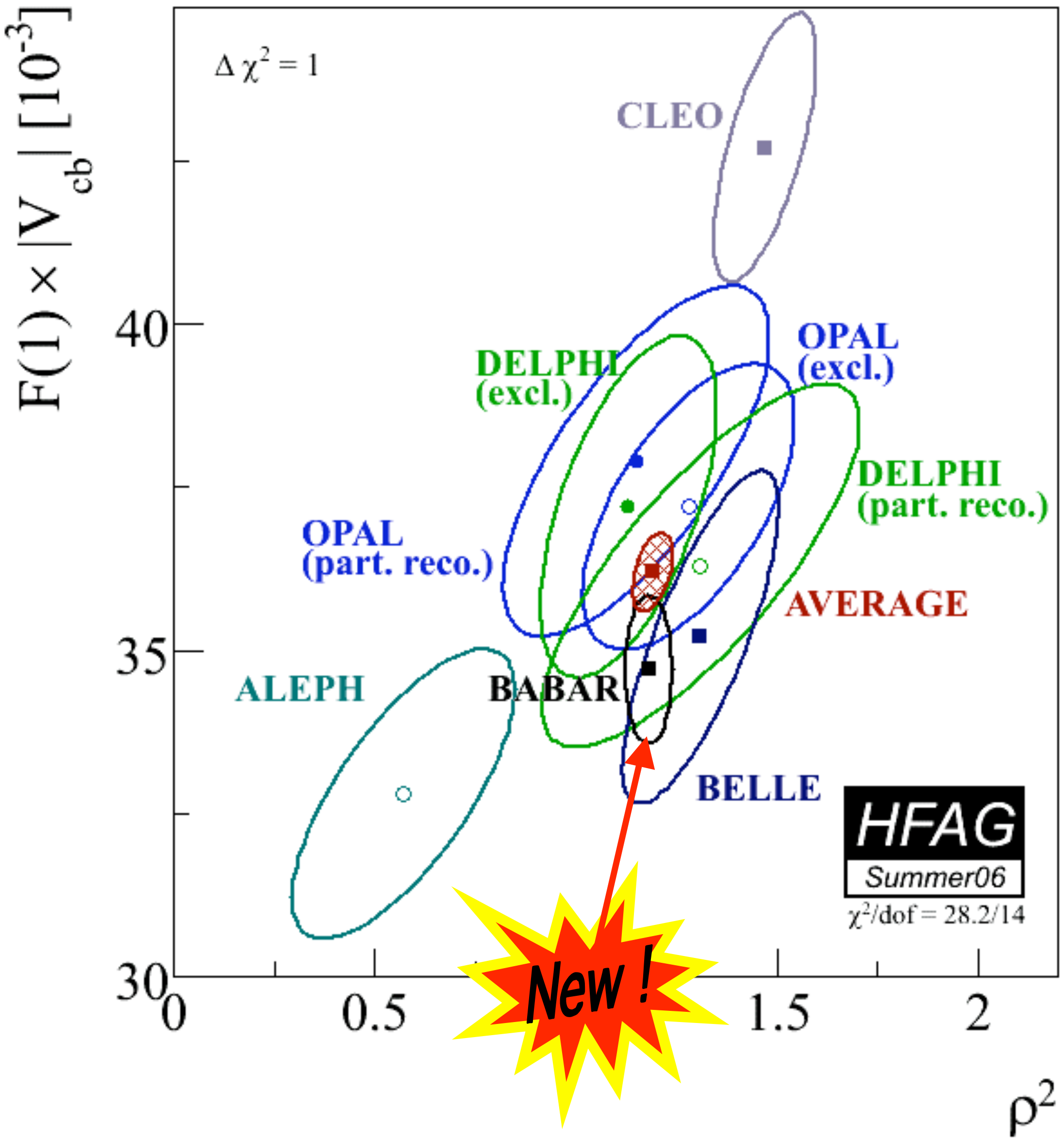
New !

$|V_{cb}|$ from $B \rightarrow D^* l \nu$

- HFAG average
  $F(1)|V_{cb}|$ =
  (36.2 +/- 0.6) x 10^{-3}
  χ^2/dof. = 28.2/14

- Using $\mathcal{F}(1) = 0.919^{+0.030}_{-0.035}$
  $|V_{cb}|$=
  (39.4 +/-
  0.7 $^{+1.5}/_{-1.3}$) x 10^{-3}

  1.6% experimental error,
  3.5% lattice QCD error



Prospects for $|V_{cb}|$ exclusive

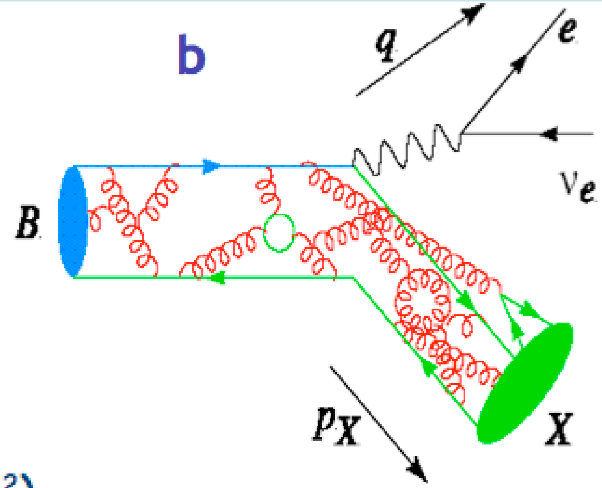
- $|V_{cb}|$ known to 4% from exclusive decays
- $B \rightarrow D^* l \nu$
  - Limited by form factor at zero recoil (3.5%)
  - New unquenched lattice calculations expected to reduce error to 2-3%
- B → D l n
  - Limited by experimental error (10.4%)
  - Form factor well known (2-3%)

$|V_{cb}|$ from inclusive decays $B \to X_c\, l\, \nu$

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

Theory of the measurement

- Semileptonic width in the framework of Heavy Quark Expansion



$$\Gamma_{sl}(B \to X_c \ell \nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 |(1 + A_{ew}) A_{nonpert} A_{pert}|$$

$A_{nonpert}$: in $1/m_b$ to $O(1/m_b^3)$

A_{pert}: in α_s to $O(\alpha_s^2)$

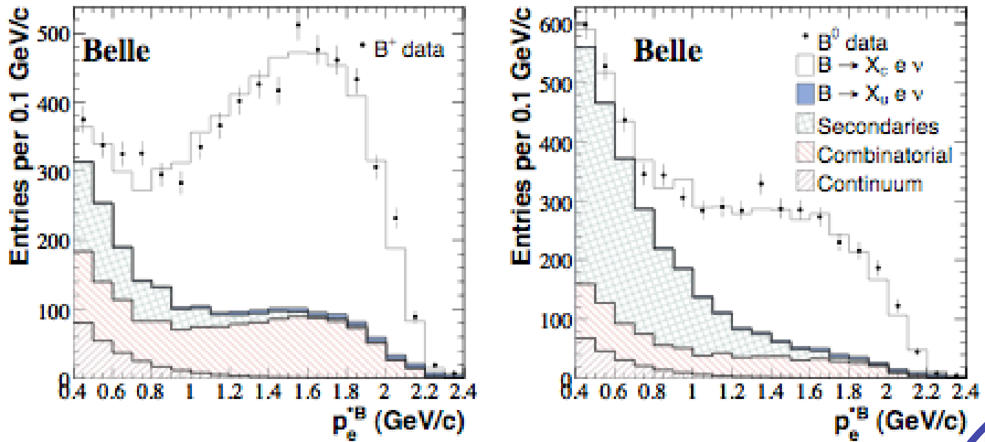
- Two separate calculations available:
  - kinetic running mass [P.Gambino, N.Uraltsev, Eur.Phys.J. C34, 181]
  - 1S mass [C.Bauer, Z.Ligeti, M.Luke, A.Manohar, Phys.Rev. D70, 094017]
- Non-perturbative parameters in the $1/m_b$ expansion

	Kinetic scheme	1S scheme
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ_D, ρ_{LS}	ρ_1, τ_{1-3}

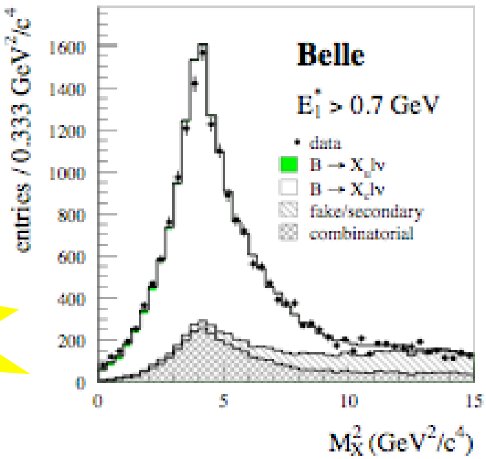
Contain soft QCD physics

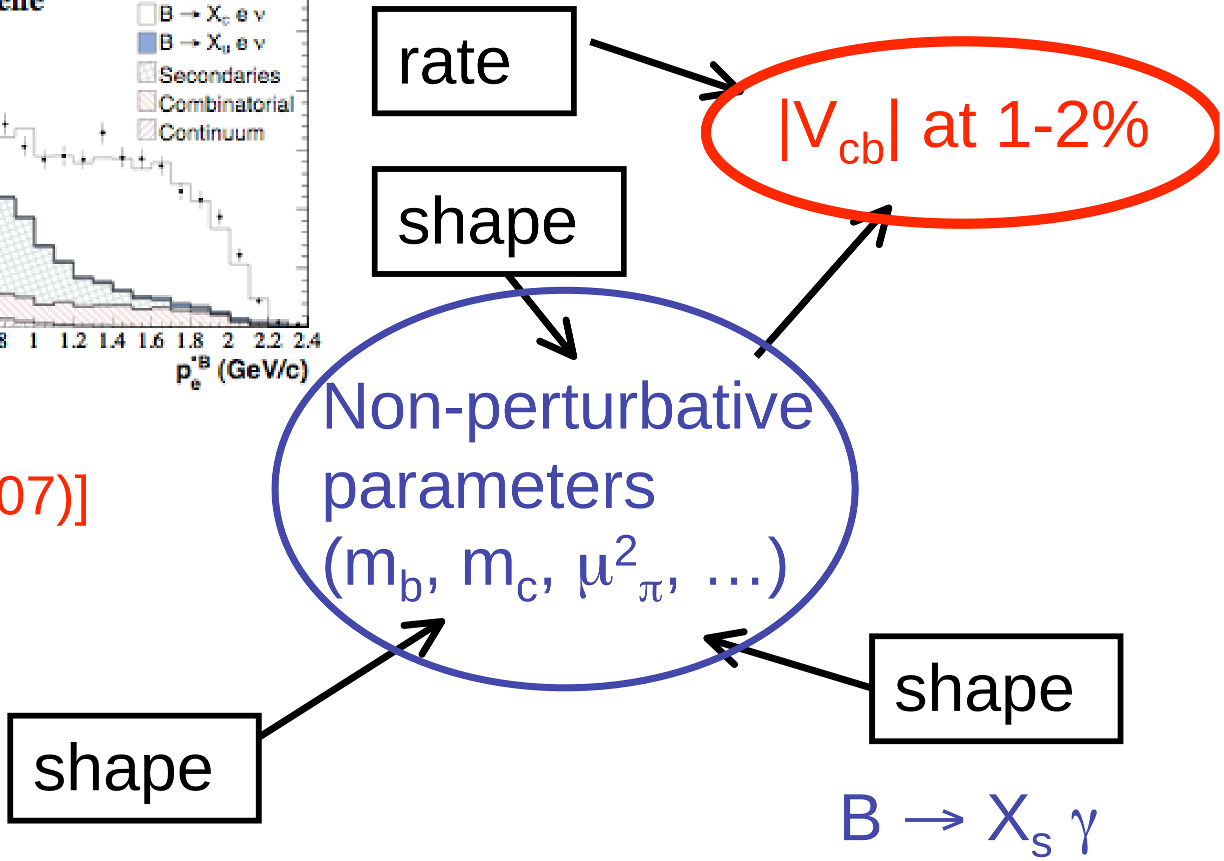
- Non-perturbative parameters can be measured from inclusive observables in B decays

Inclusive E_l spectrum
[Phys.Rev. D75, 032001 (2007)]



Inclusive M^2_X spectrum
[Phys.Rev. D75, 032005 (2007)]



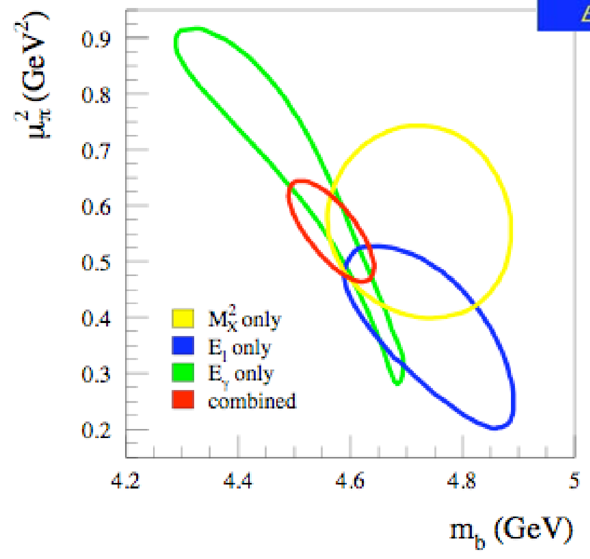


Global fit to Belle data

Kinetic scheme ($X_c l\nu + X_s\gamma$ data)

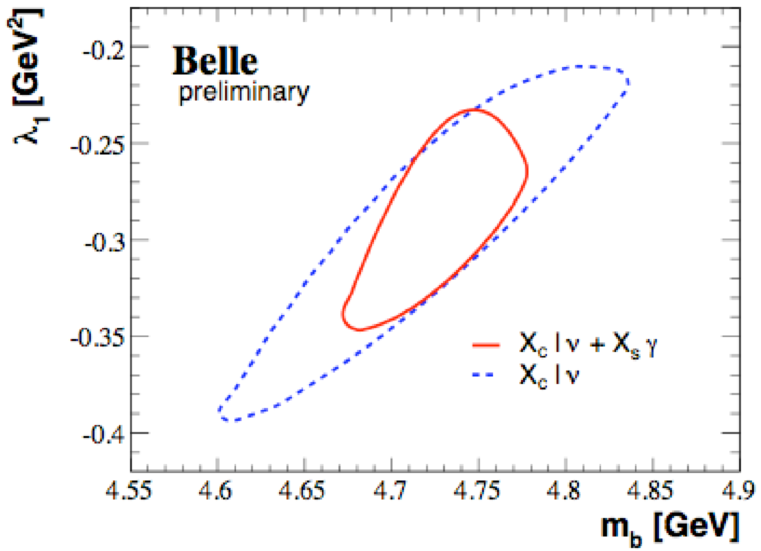
$|V_{cb}| = (41.93 \pm 0.65_{fit} \pm 0.07_{\alpha s} \pm 0.63_{th}) \times 10^{-3}$
$m_b = 4.564 \pm 0.076$ GeV
$m_c = 1.105 \pm 0.116$ GeV $\quad \chi^2/\text{dof.} = 17.8/24$

[hep-ex/0611047] preliminary **New !**



1S scheme ($X_c l\nu + X_s\gamma$ data)

$|V_{cb}| = (41.49 \pm 0.52_{fit} \pm 0.20_{\tau}) \times 10^{-3}$
$m_b = 4.729 \pm 0.048$ GeV
$\lambda_1 = -0.30 \pm 0.04$ GeV^2 $\quad \chi^2/\text{dof.} = 5.7/17$



The result for m_b compatible after scheme translation

$|V_{ub}|$ from inclusive decays $B \to X_u \, l \, \nu$

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

Theory of the measurement

- Also based on the Heavy Quark Expansion, as for $B \to X_c\, l\, \nu$ decays
- To isolate $X_u l\nu$ signal and suppress $X_c l\nu$ background, the $X_u l\nu$ phase space must be restricted
  - by cutting on E_l (lepton endpoint), M_X and/or $q^2 = (p_l + p_\nu)^2$
  - $\Rightarrow$ convergence of HQE compromised, need shape function
- (Leading order) shape function parameter can be determined from $B \to X_s\, \gamma$ and/or $B \to X_c\, l\, \nu$ data
- Available theory calculations
  - Bosch, Lange, Neubert, Paz (BLNP) [Phys.Rev. D72, 073006 (2005)]
  - Anderson, Gardi (DGE) [JHEP 0601:097 (2006)]
  - Bauer, Ligeti, Luke (BLL) [Phys.Rev. D64, 113004 (2001)]

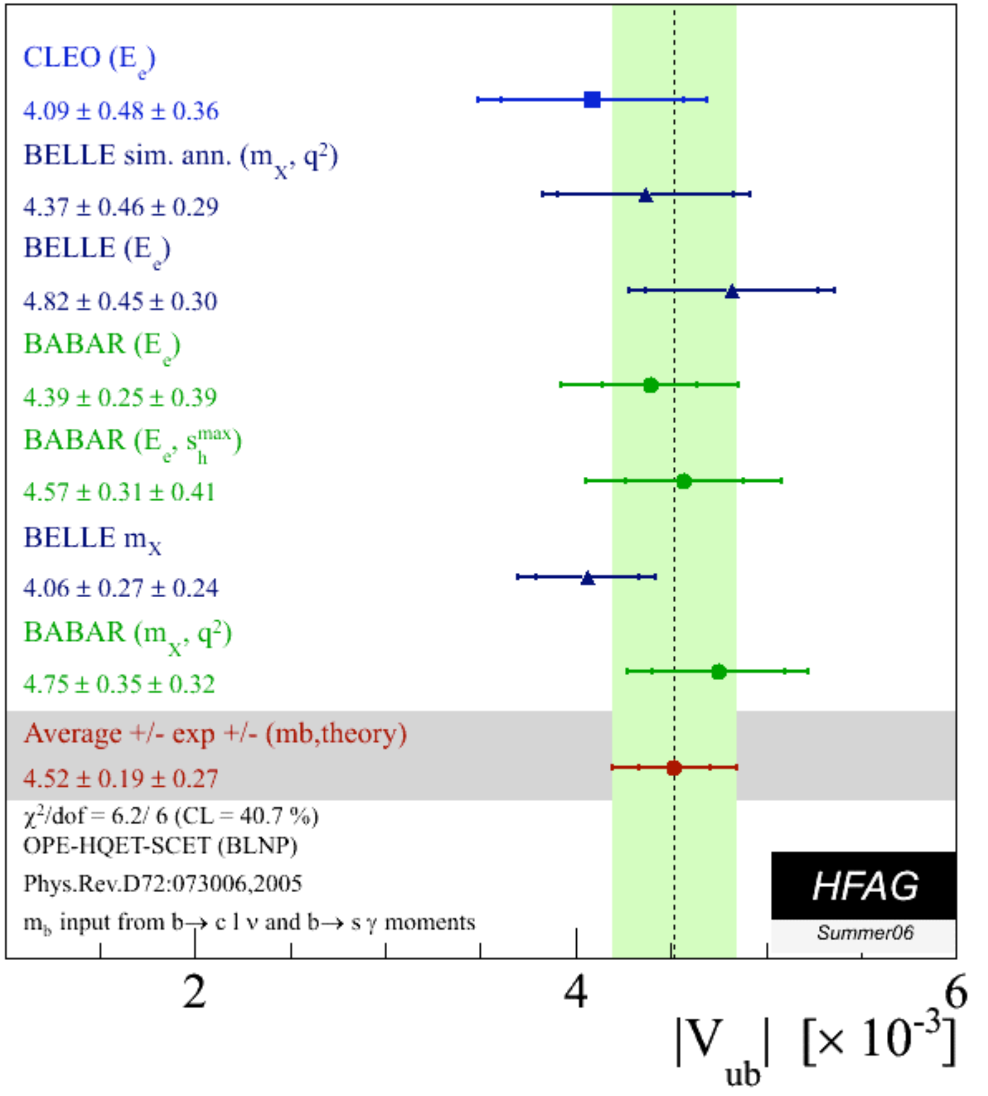
Determination of $|V_{ub}|$

BLNP

$|V_{ub}| = (4.52 \pm 0.19_{exp} \pm 0.27_{mb,th}) \times 10^{-3}$

7.4% total uncertainty

stat.	2.1%
exp. syst.	2.7%
b→c model	2.1%
b→u model	1.4%
HQ param.	4.1%
subl. SF.	0.9%
Matching	3.8%
Weak annih.	2.1%



DGE

$|V_{ub}| = (4.46 \pm 0.20_{exp} \pm 0.20_{mb,th}) \times 10^{-3}$

$|V_{ub}|$ from exclusive semileptonic decays $b \to u$

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

Theory of the measurement

- B → π l ν decay rate

$$\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{192\pi^3 m_b^3}\lambda(q^2)^{3/2}|f_+(q^2)|^2 , \quad q^2 = (p_\ell + p_\nu)^2$$

- Need form factor shape and normalization for $|V_{ub}|$
- Available form factor calculations
  - Relativistic quark models
    - ISGW2 [Phys. Rev. D52, 2783 (1995)]
  - Light cone sum rules (LCSR) in the region $q^2 < 14$ GeV^2
    - Ball-Zwicky [Phys. Rev. D71, 014015 (2005)]
  - Lattice QCD in the region $q^2 > 16$ GeV^2
    - HPQCD [Phys. Rev. D73, 074502 (2006)]
    - FNAL [Nucl. Phys. Proc. Suppl. 140, 461 (2005)]

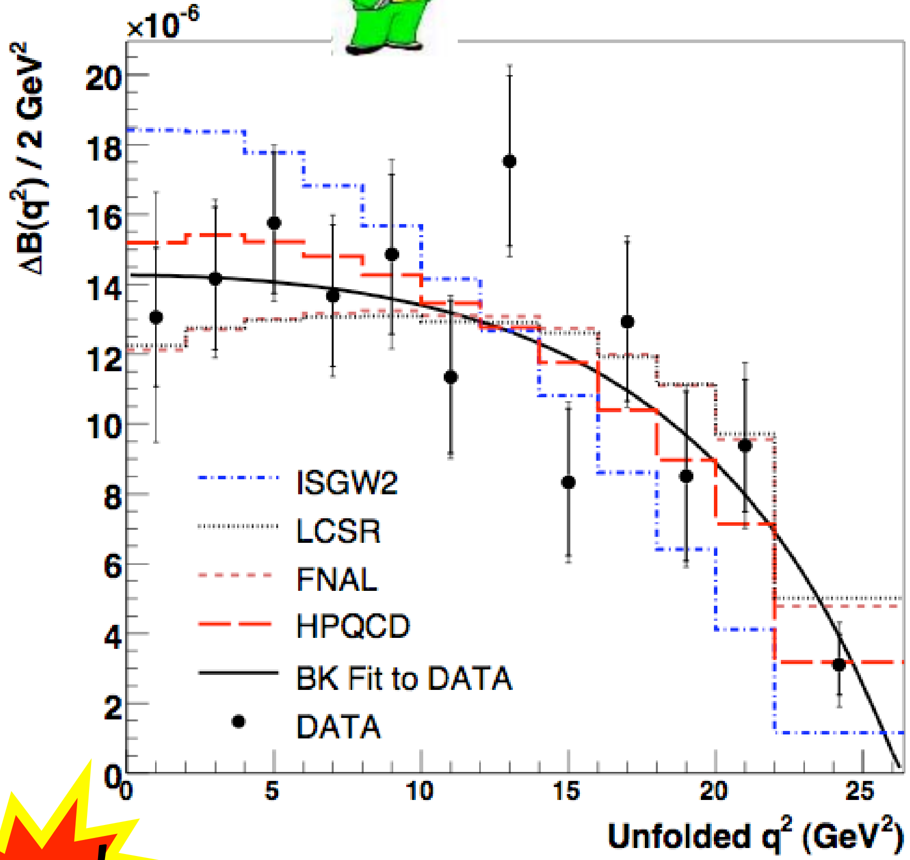
New BaBar $B^0 \rightarrow \pi^- l^+ \nu$

- No requirement on other B in the event
- Loose requirements for neutrino reconstruction
- Unfolding of the q^2-distribution

$Br = (1.46 \pm 0.07_{stat} \pm 0.08_{syst}) \times 10^{-4}$

$\Delta Br(q^2 > 16\ GeV^2) =$

$(0.38 \pm 0.04_{stat} \pm 0.03_{syst}) \times 10^{-4}$



[hep-ex/0612020]
submitted to Phys. Rev. Lett.

New !

Form factor shape consistent with lattice QCD and Becirevic-Kaidalov

New Belle B → πlν

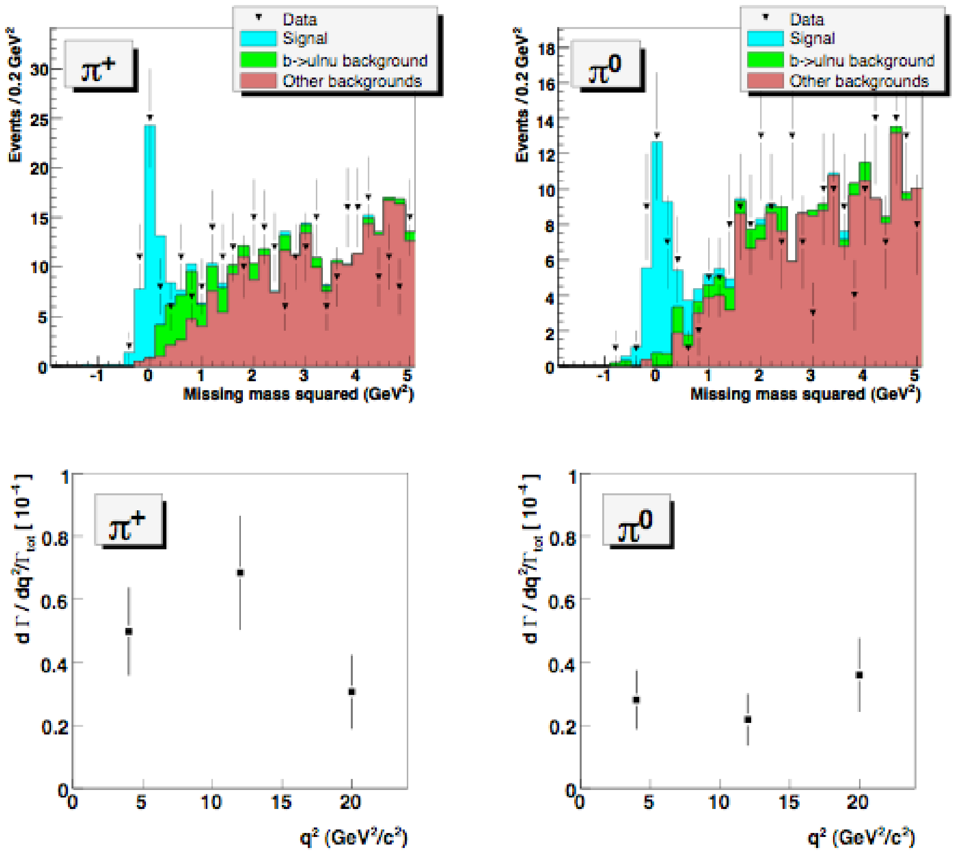
- Fully reconstruct the hadronic decay of the other B
  ⇒ very low backgrounds

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu) =$$
$$(1.49 \pm 0.26(stat) \pm 0.06(syst)) \times 10^{-4}$$

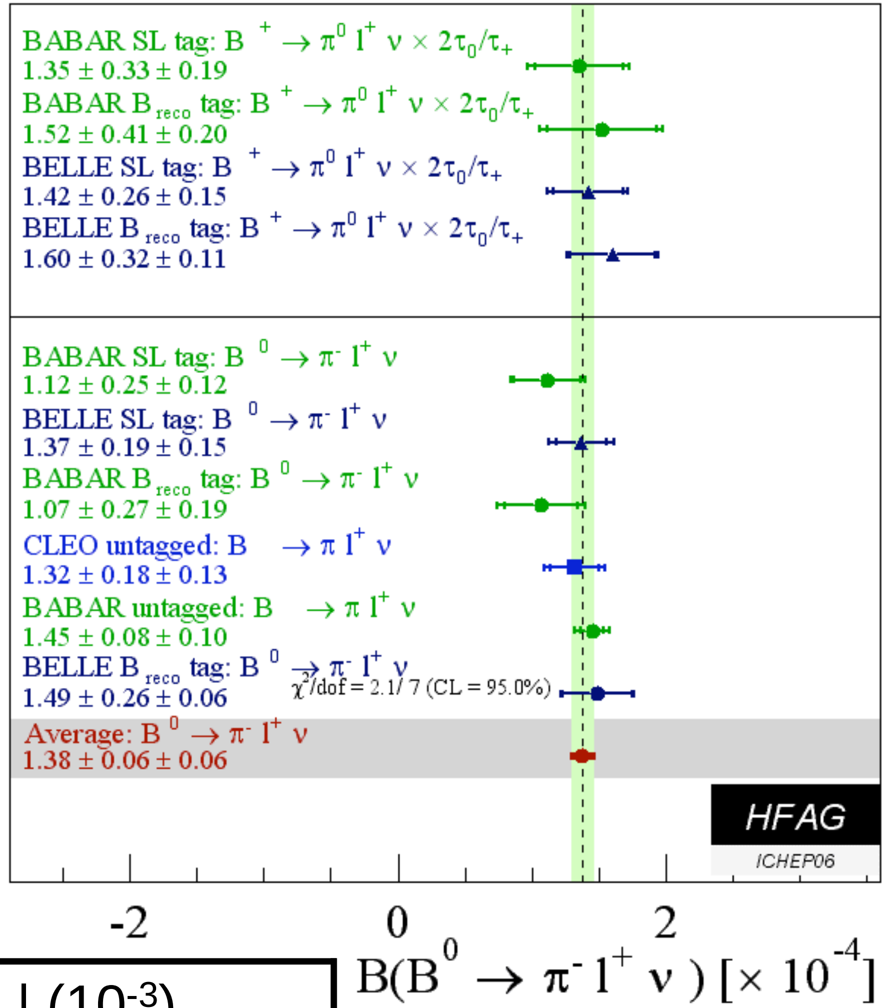
$$\mathcal{B}(B^+ \to \pi^0 \ell^+ \nu) =$$
$$(0.86 \pm 0.17(stat) \pm 0.06(syst)) \times 10^{-4}$$

[hep-ex/0610054] preliminary

48 ± 8 events 35 ± 7 events



Determination of $|V_{ub}|$



6% experimental error,
12% lattice QCD error

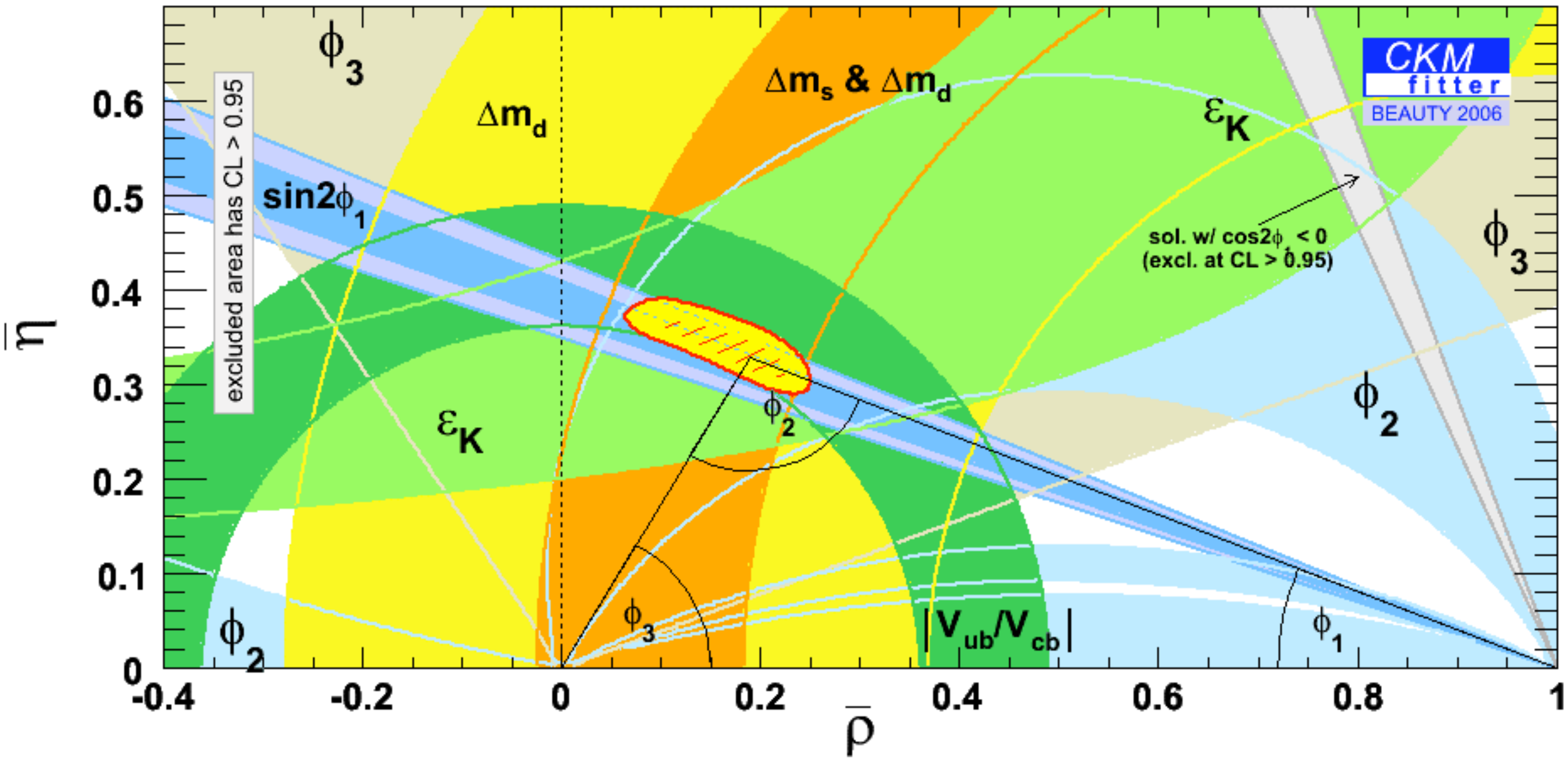
	q^2 range	$\lvert V_{ub}\rvert$ (10^{-3})
Ball-Zwicky	< 16 GeV^2	$3.41 \pm 0.12_{exp} {}^{+0.56}_{-0.38 th}$
HPQCD	> 16 GeV^2	$3.97 \pm 0.22_{exp} {}^{+0.59}_{-0.41 th}$
FNAL	> 16 GeV^2	$3.55 \pm 0.20_{exp} {}^{+0.61}_{-0.40 th}$

Summary and conclusions

	$\|V_{cb}\|$ (10^{-3})	$\|V_{ub}\|$ (10^{-3})
exclusive	39.4 +/- 1.6	3.97 +/- 0.55
inclusive	41.49 +/- 0.56	4.52 +/- 0.33

- Good consistency between exclusive and inclusive determinations of $|V_{cb}|$ and $|V_{ub}|$

- $|V_{ub}/V_{cb}|$ also consistent with expectations from unitarity triangle fits



- An ambitious though realistic goal for 2008: error on $|V_{ub}/V_{cb}|$ of ~5%
- Already now: the heavy flavor program restricts the parameter space of New Physics

Backup slides

The CKM mechanism

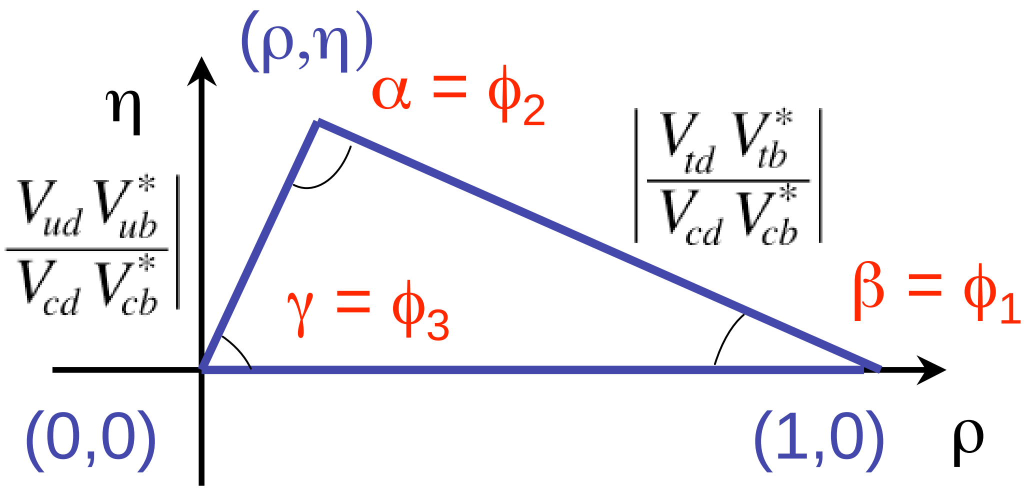
- The charged current interaction in the SM

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}} \overline{u_{Li}} \gamma^\mu (V_{\rm CKM})_{ij} d_{Lj} W_\mu^+ + \text{h.c.}$$

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

[Kobayashi, Maskawa, Prog. Theor. Phys. 49, 652 (1973)]

- $V_{\rm CKM}$ is a unitary 3x3 matrix;
  it contains three real parameters and one complex phase
- Its unitarity is commonly represented by the unitarity triangle



$$\left|\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right| \qquad \left|\frac{V_{td} V_{tb}^*}{V_{cd} V_{cb}^*}\right|$$

$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$