



Determination of $|V_{cb}|$ and m_b from inclusive B decays at Belle

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EPS High Energy and Particle Physics Prize 2007 awarded to Makoto Kobayashi and Toshihide Maskawa



Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

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All CP-violating phenomena are described by a single parameter in the Standard Model, the KM phase

The CKM mechanism

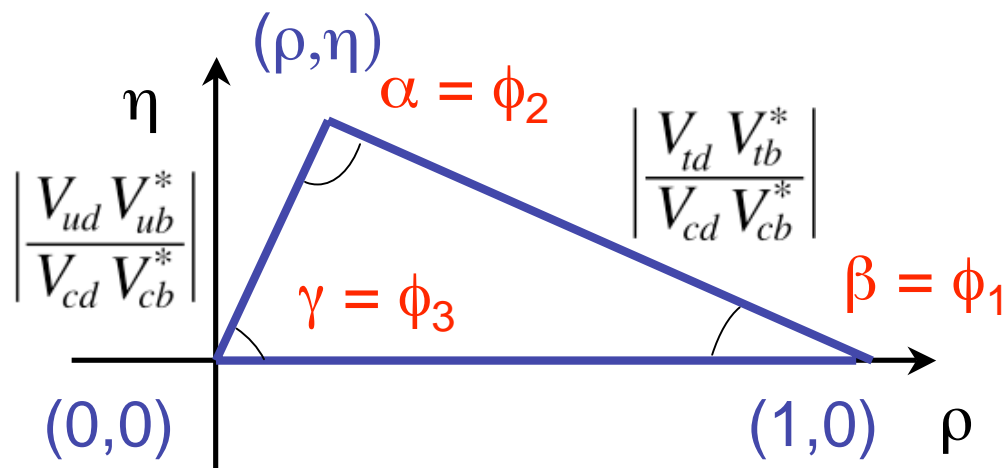
- The charged current interaction in the SM

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

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

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

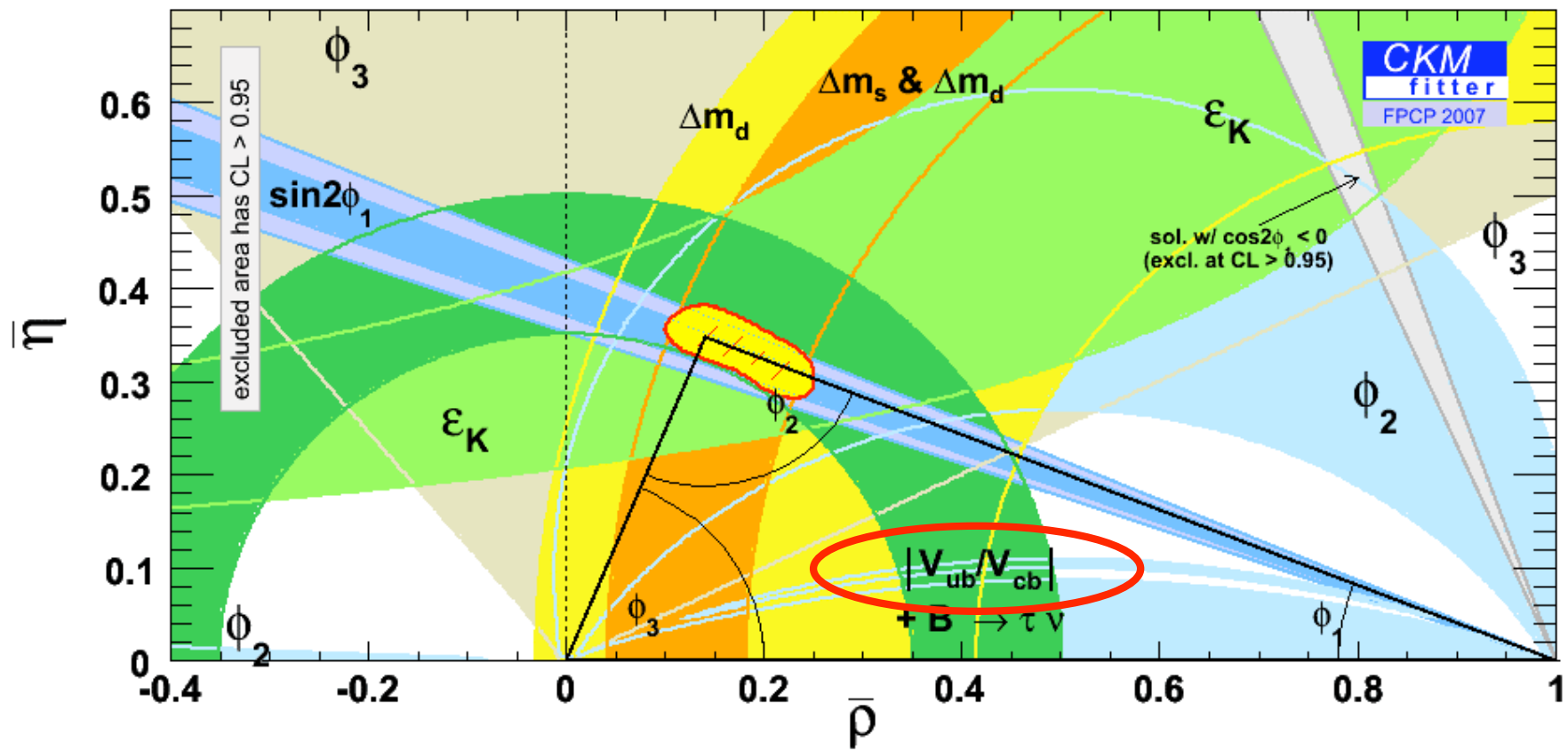
- V_{CKM} is a unitary 3x3 matrix; it contains three real parameters and one complex phase
- Its unitarity is commonly represented by the unitarity triangle



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

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

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

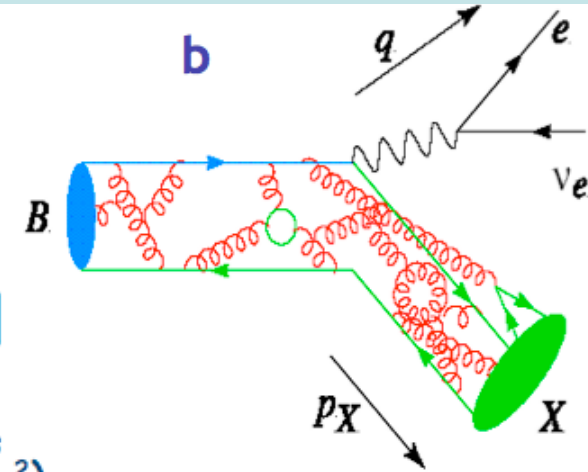


$|V_{cb}|$ from inclusive semileptonic B decays

- Semileptonic width in the framework of Heavy Quark Expansion

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

in $1/m_b$
to $O(1/m_b^3)$
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

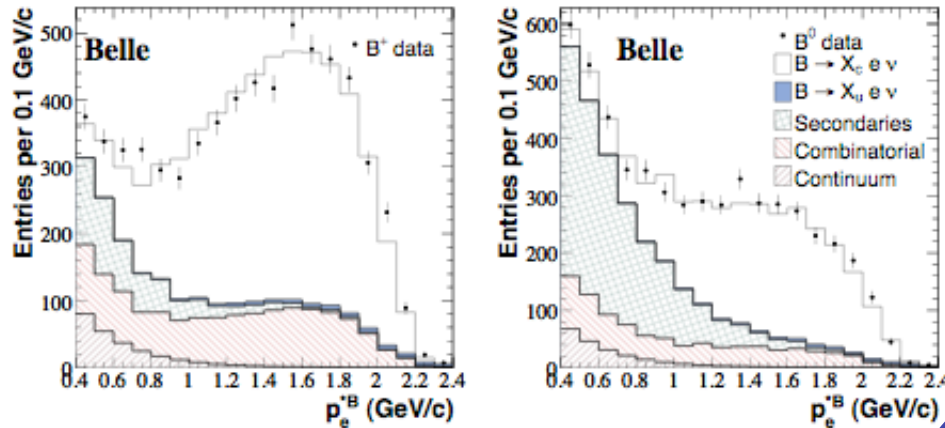
	Kinetic scheme	1S scheme
$O(1)$	m_b, m_c	m_b
$O(1/m_b^2)$	μ_π^2, μ_G^2	λ_1, λ_2
$O(1/m_b^3)$	ρ_D, ρ_{LS}	ρ_1, τ_{1-3}

Contain
soft QCD
physics

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

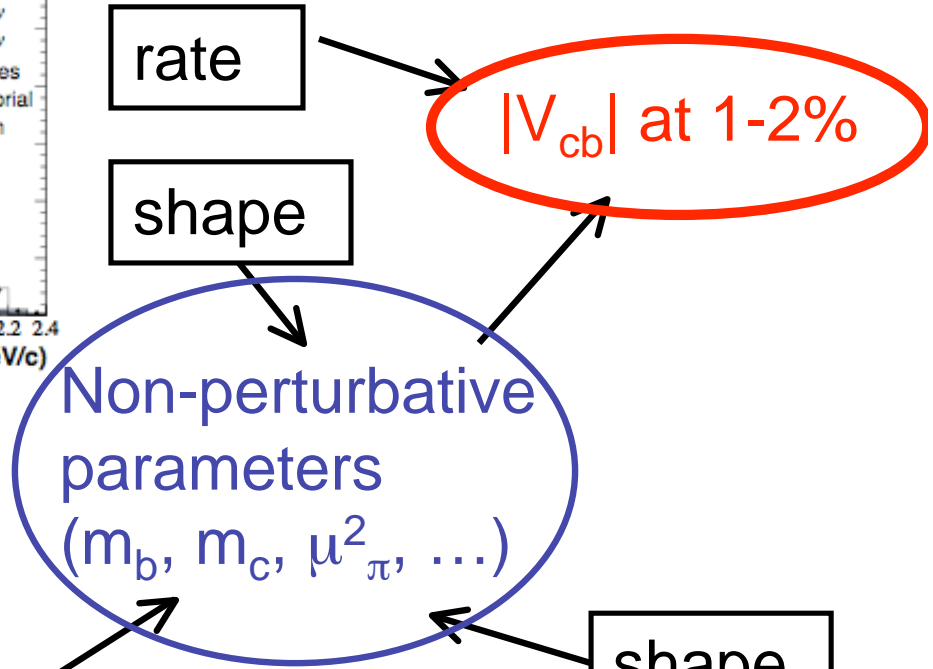
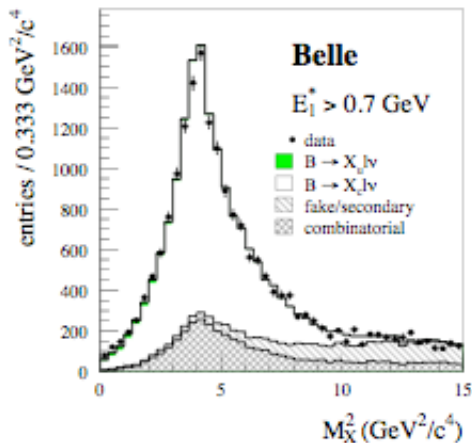
Inclusive E_1 spectrum

[Phys.Rev. D75, 032001 (2007)]



Inclusive M_X^2 spectrum

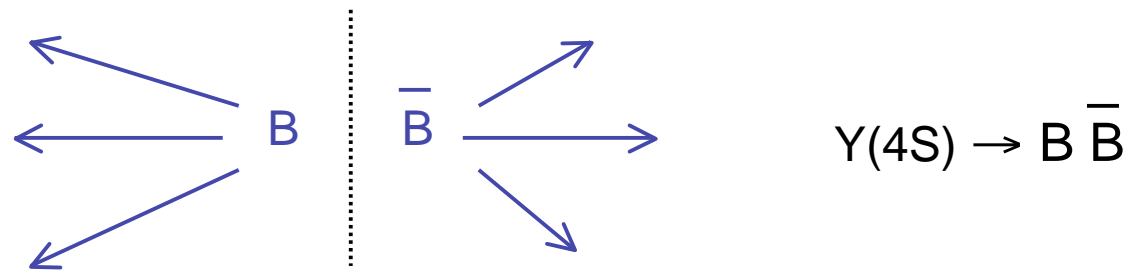
[Phys.Rev. D75, 032005 (2007)]



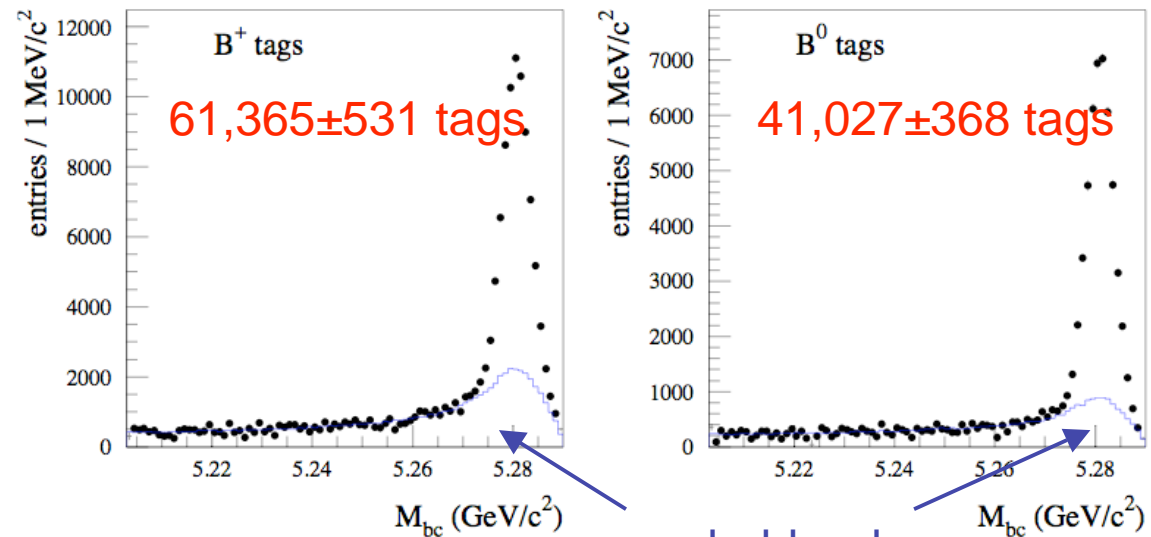
$B \rightarrow X_s \gamma$
[hep-ex/0508005]

Full reconstruction tag

- One B is fully reconstructed in the modes $B \rightarrow D^* \{\pi, \rho, a_1\}$



$$M_{bc} = \sqrt{(E_{\text{beam}})^2 - (\vec{p}_B)^2}$$

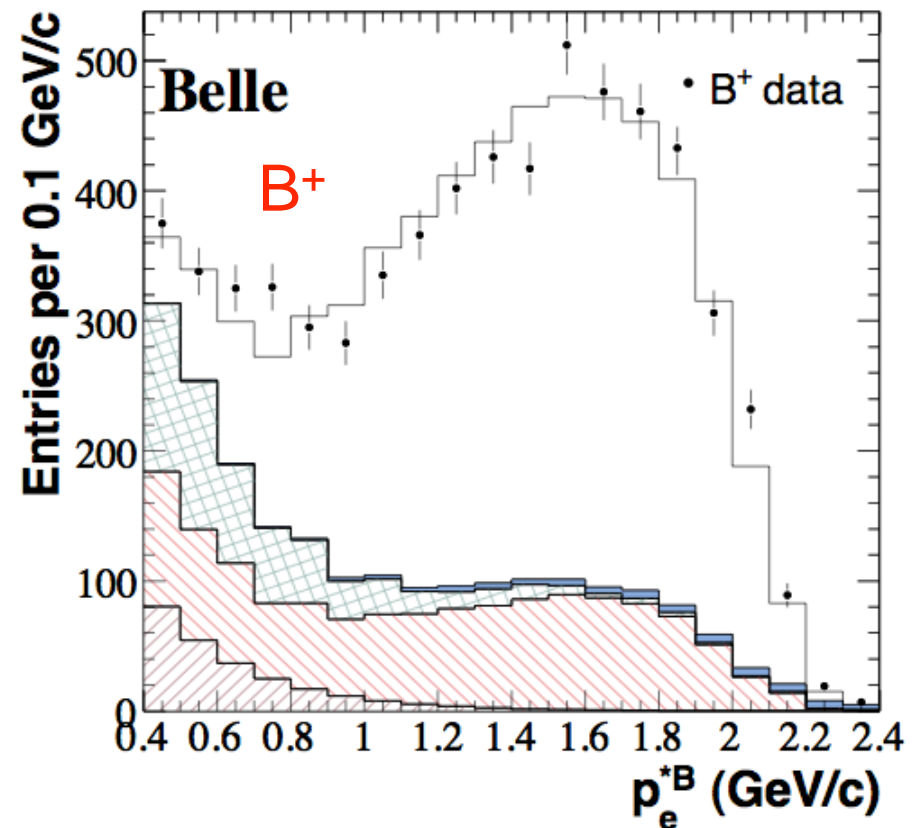
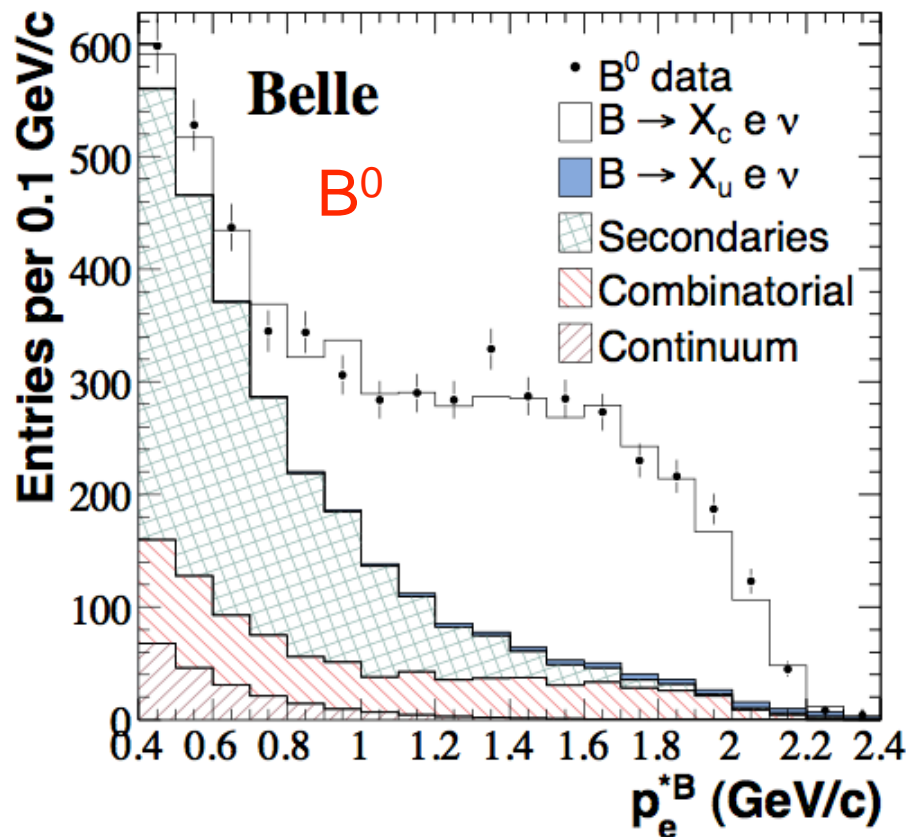


- Advantages
 - Low backgrounds (small background uncertainty)
 - Good M^2_x resolution ($0.8 \text{ GeV}^2/c^4$)

Electron energy spectrum in $B \rightarrow X_c l \nu$

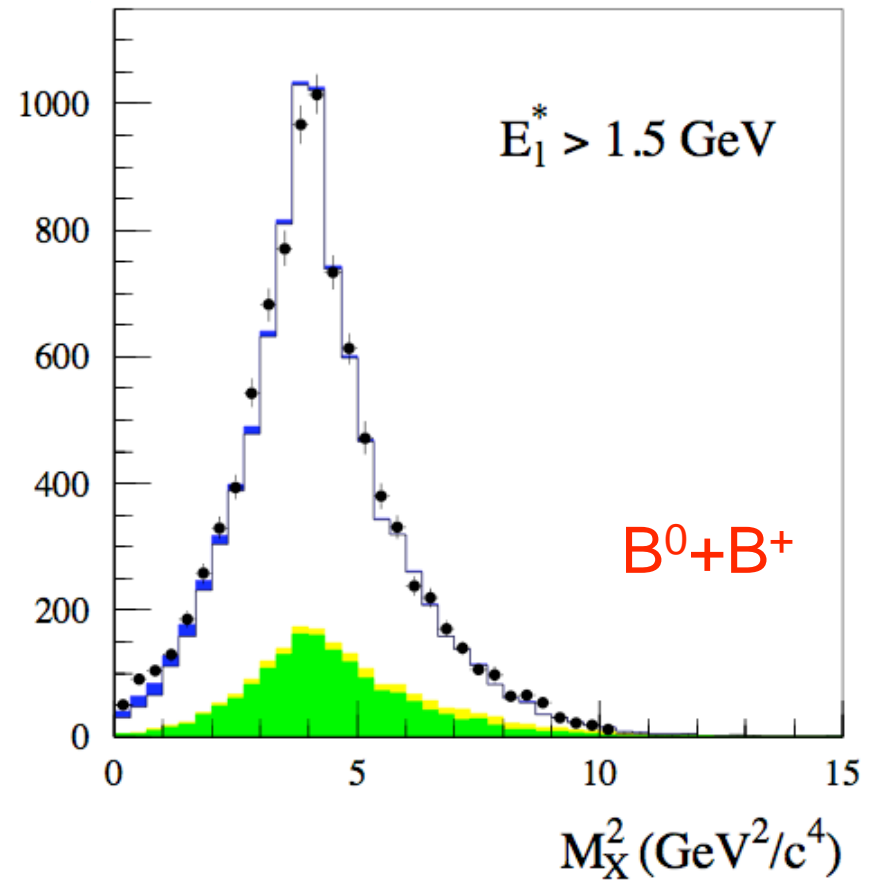
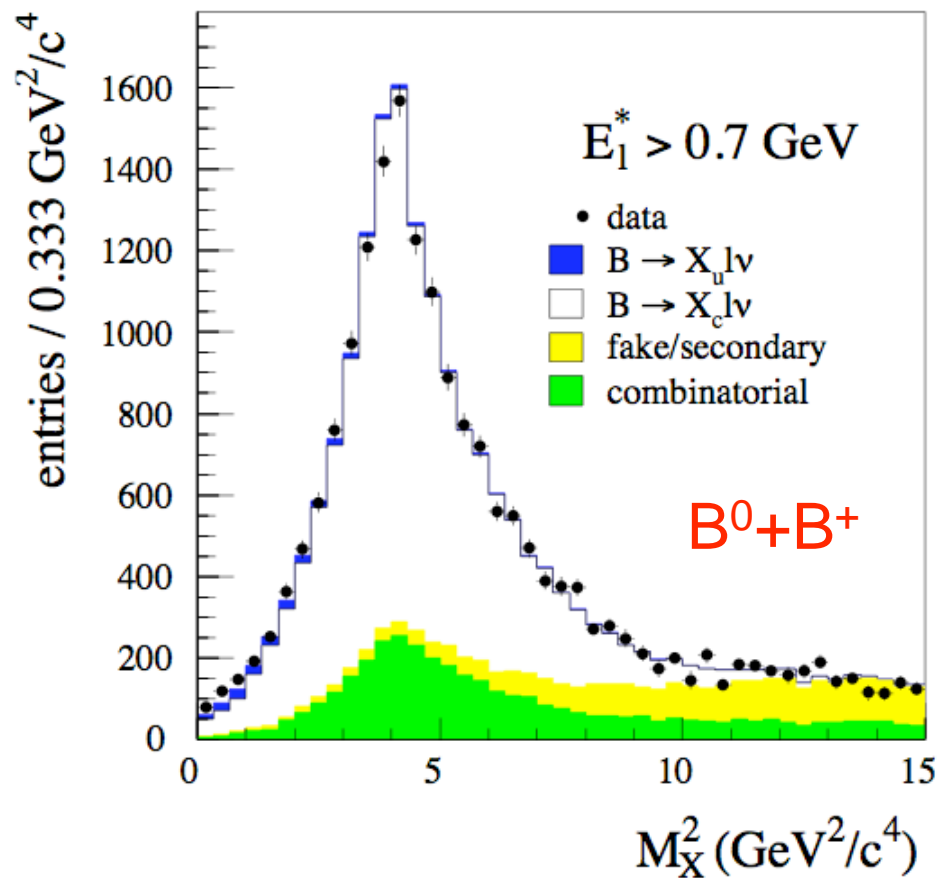
(in the B rest frame)

140 fb⁻¹ Y(4S) data



Hadronic mass spectrum in $B \rightarrow X_c \ell \nu$

140 fb⁻¹ Y(4S) data



- The moments are calculated from the unfolded spectra to minimize X_c | ν model dependence

electron energy moments as fct. of minimum lepton energy

$E_{\text{cut}} [\text{GeV}]$	$M_1 [\text{MeV}]$	$M_2 [10^{-3}\text{GeV}^2]$	$M_3 [10^{-3}\text{GeV}^3]$	$M_4 [10^{-3}\text{GeV}^4]$	$\Delta\mathcal{B} [10^{-2}]$
0.4	$1393.92 \pm 6.73 \pm 3.02$	$168.77 \pm 3.68 \pm 1.53$	$-21.04 \pm 1.93 \pm 0.66$	$64.153 \pm 1.813 \pm 0.935$	$10.44 \pm 0.19 \pm 0.22$
0.6	$1427.82 \pm 5.82 \pm 2.55$	$146.15 \pm 2.88 \pm 1.08$	$-11.04 \pm 1.35 \pm 0.49$	$45.366 \pm 1.108 \pm 0.548$	$10.07 \pm 0.18 \pm 0.21$
0.8	$1480.04 \pm 4.81 \pm 2.13$	$117.97 \pm 2.05 \pm 0.55$	$-3.45 \pm 0.83 \pm 0.30$	$28.701 \pm 0.585 \pm 0.247$	$9.42 \pm 0.16 \pm 0.19$
1.0	$1547.76 \pm 3.96 \pm 1.45$	$88.17 \pm 1.42 \pm 0.36$	$0.83 \pm 0.49 \pm 0.20$	$15.962 \pm 0.302 \pm 0.142$	$8.41 \pm 0.15 \pm 0.17$
1.2	$1627.79 \pm 3.26 \pm 1.08$	$61.36 \pm 1.02 \pm 0.36$	$2.40 \pm 0.30 \pm 0.11$	$7.876 \pm 0.162 \pm 0.106$	$7.11 \pm 0.13 \pm 0.14$
1.4	$1719.96 \pm 2.58 \pm 1.10$	$38.99 \pm 0.71 \pm 0.24$	$2.33 \pm 0.16 \pm 0.07$	$3.314 \pm 0.080 \pm 0.055$	$5.52 \pm 0.11 \pm 0.11$
1.6	$1826.15 \pm 1.80 \pm 1.03$	$21.75 \pm 0.47 \pm 0.22$	$1.45 \pm 0.08 \pm 0.05$	$1.129 \pm 0.033 \pm 0.032$	$3.71 \pm 0.09 \pm 0.07$
1.8	$1943.18 \pm 0.93 \pm 1.16$	$10.14 \pm 0.28 \pm 0.18$	$0.68 \pm 0.03 \pm 0.04$	$0.283 \pm 0.010 \pm 0.017$	$1.93 \pm 0.06 \pm 0.04$
2.0	$2077.59 \pm 0.21 \pm 1.23$	$3.47 \pm 0.13 \pm 0.19$	$0.19 \pm 0.01 \pm 0.03$	$0.047 \pm 0.002 \pm 0.007$	$0.53 \pm 0.02 \pm 0.02$

hadronic mass moments as fct. of minimum lepton energy

$E_{\text{min}}^* (\text{GeV})$	$\langle M_X^2 \rangle (\text{GeV}^2/c^4)$	$\langle (M_X^2 - \langle M_X^2 \rangle)^2 \rangle (\text{GeV}^4/c^8)$	$\langle M_X^4 \rangle (\text{GeV}^4/c^8)$
0.7	$4.403 \pm 0.036 \pm 0.052$	$1.494 \pm 0.173 \pm 0.327$	$20.88 \pm 0.48 \pm 0.77$
0.9	$4.353 \pm 0.032 \pm 0.041$	$1.229 \pm 0.138 \pm 0.244$	$20.18 \pm 0.40 \pm 0.58$
1.1	$4.293 \pm 0.028 \pm 0.029$	$0.940 \pm 0.098 \pm 0.137$	$19.37 \pm 0.33 \pm 0.36$
1.3	$4.213 \pm 0.027 \pm 0.024$	$0.641 \pm 0.071 \pm 0.080$	$18.40 \pm 0.29 \pm 0.26$
1.5	$4.144 \pm 0.028 \pm 0.022$	$0.515 \pm 0.061 \pm 0.064$	$17.69 \pm 0.28 \pm 0.23$
1.7	$4.056 \pm 0.033 \pm 0.022$	$0.322 \pm 0.058 \pm 0.040$	$16.77 \pm 0.32 \pm 0.21$
1.9	$3.996 \pm 0.041 \pm 0.021$	$0.143 \pm 0.056 \pm 0.038$	$16.11 \pm 0.38 \pm 0.20$

(averaged over charged and neutral tags)

Input to the $|V_{cb}|$ fit

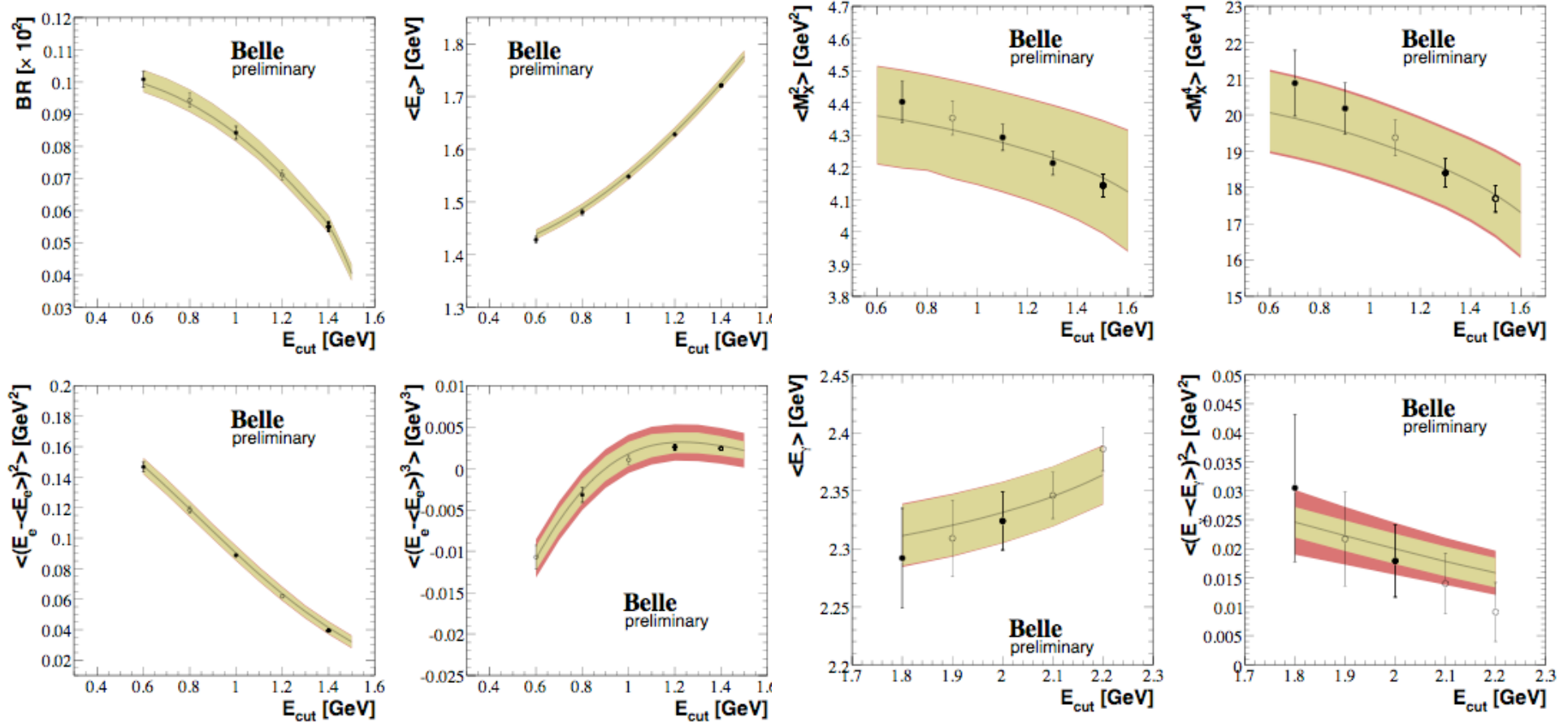
- Interpretation of the data using two sets of theoretical calculations

	1S scheme	kinetic scheme
Lepton moments $\langle E_\ell^n \rangle_{E_{\min}}$	$n = 0$ $E_{\min} = 0.6, 1.0, 1.4$	$n = 0$ $E_{\min} = 0.4, 0.8$
	$n = 1$ $E_{\min} = 0.6, 0.8, 1.0, 1.2, 1.4$	$n = 1$ $E_{\min} = 0.4, 0.8, 1.0, 1.2, 1.4$
	$n = 2$ $E_{\min} = 0.6, 1.0, 1.4$	$n = 2$ $E_{\min} = 0.4, 0.8, 1.0, 1.2, 1.4$
	$n = 3$ $E_{\min} = 0.8, 1.2$	$n = 3$ $E_{\min} = 0.4, 0.8, 1.0, 1.2, 1.4$
Hadron moments $\langle M_X^{2n} \rangle_{E_{\min}}$	$n = 1$ $E_{\min} = 0.7, 1.1, 1.3, 1.5$	$n = 1$ $E_{\min} = 0.7, 0.9, 1.1, 1.3$
	$n = 2$ $E_{\min} = 0.7, 0.9, 1.3$	$n = 2$ $E_{\min} = 0.7, 0.9, 1.1, 1.3$
Photon moments $\langle E_\gamma^n \rangle_{E_{\min}}$	$n = 1$ $E_{\min} = 1.8, 2.0$	$n = 1$ $E_{\min} = 1.8, 1.9, 2.0$
	$n = 2$ $E_{\min} = 1.8, 2.0$	$n = 2$ $E_{\min} = 1.8, 1.9, 2.0$

- Points with $E_{\min} > 1.5$ GeV ($X_c \ell \nu$) and $E_{\min} > 2$ GeV ($X_s \gamma$) are excluded for theoretical reasons
- Correlations of experimental and theoretical uncertainties are taken into account

Fit result in the 1S mass scheme

preliminary

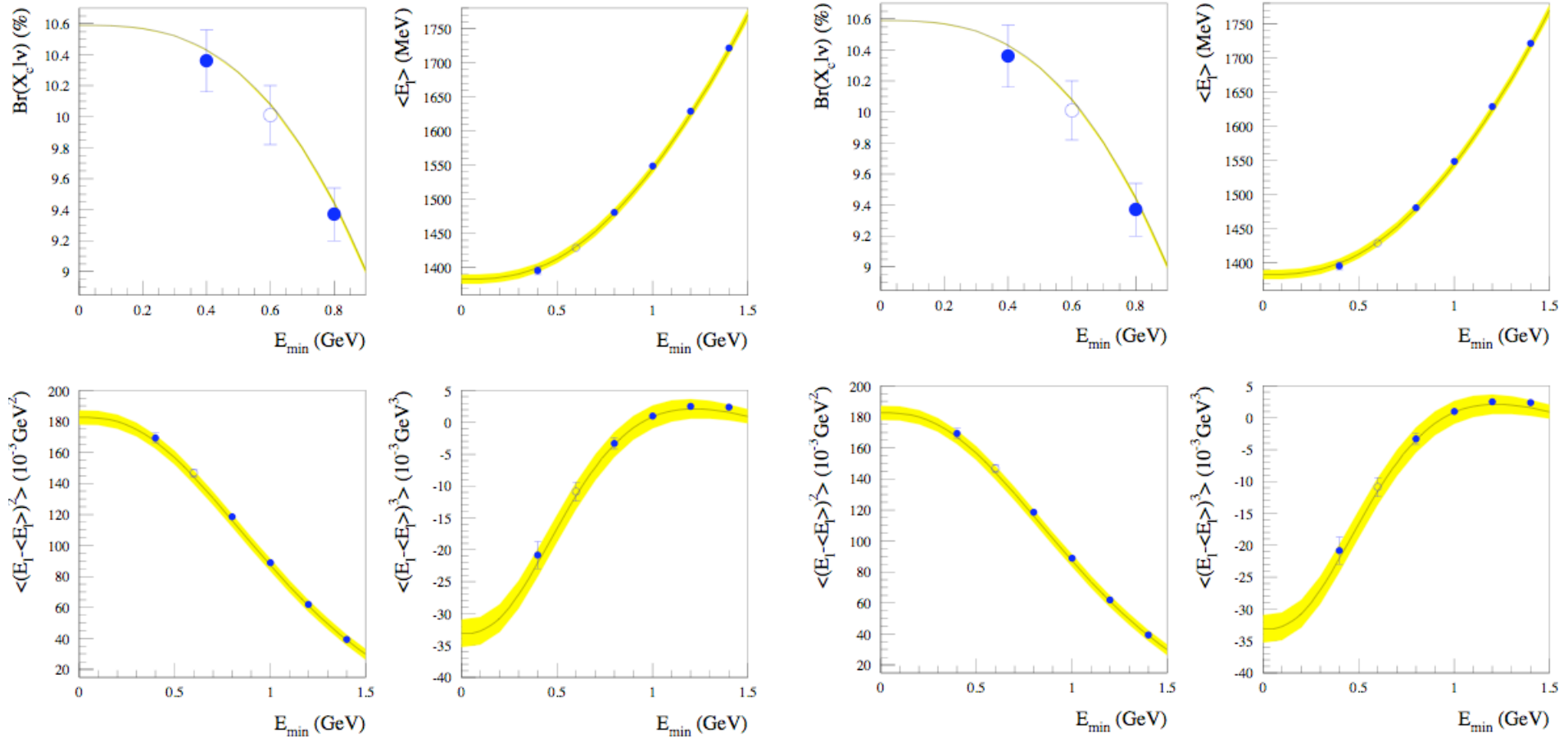


Green: fit error, red: theory error

$\chi^2/\text{dof.} = 5.7/17$

Fit result in the kinetic running mass scheme

preliminary



yellow: theory error

$\chi^2/\text{dof.} = 17.8/24$

Global fit to Belle data



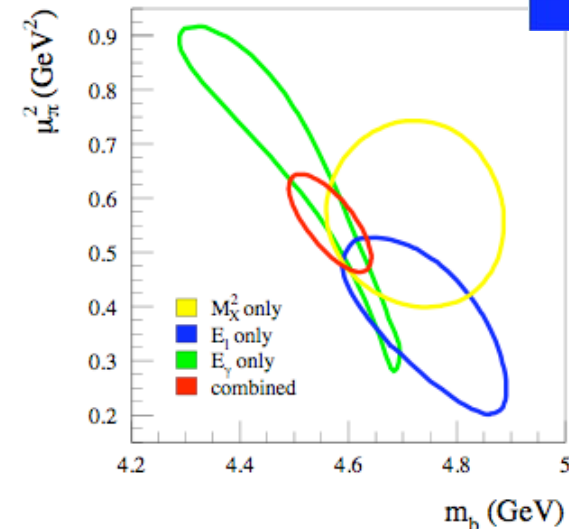
Kinetic scheme ($X_c l \nu + X_s \gamma$ data)

$$|V_{cb}| = (41.93 \pm 0.65_{\text{fit}} \pm 0.07_{\alpha_S} \pm 0.63_{\text{th}}) \times 10^{-3}$$

$$m_b = 4.564 \pm 0.076 \text{ GeV}$$

$$m_c = 1.105 \pm 0.116 \text{ GeV} \quad \chi^2/\text{dof.} = 17.8/24$$

[hep-ex/0611047] preliminary

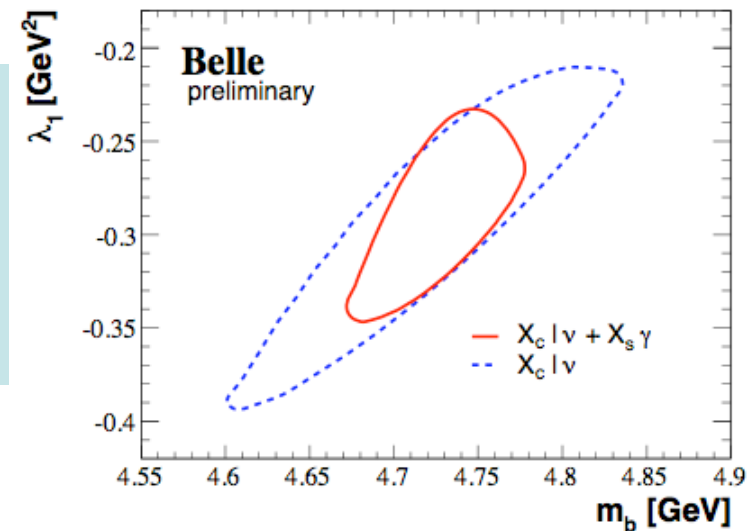


1S scheme ($X_c l \nu + X_s \gamma$ data)

$$|V_{cb}| = (41.49 \pm 0.52_{\text{fit}} \pm 0.20_{\tau}) \times 10^{-3}$$

$$m_b = 4.729 \pm 0.048 \text{ GeV}$$

$$\lambda_1 = -0.30 \pm 0.04 \text{ GeV}^2 \quad \chi^2/\text{dof.} = 5.7/17$$



The result for m_b compatible after scheme translation

Summary

- $|V_{cb}|$ inclusive [hep-ex/0611047] preliminary

	$ V_{cb} (10^{-3})$
1S scheme	$41.49 \pm 0.52_{\text{fit}} \pm 0.20_{\tau_B}$
kinetic scheme	$41.93 \pm 0.65_{\text{fit}} \pm 0.07_{\alpha_S} \pm 0.63_{\text{th}}$

- $|V_{cb}|$ has been measured to 1-2% precision using inclusive B decays
- Good agreement between different theoretical frameworks
- Consistent also with KM theory

Backup slides

Belle Detector

