XXV Physics in Collision, Prague, July 2005

Sides of "The" Unitarity Triangle: Results from Belle and Babar

- Triangles in CKM
- B factories & experiments
- Update on measurements
  - $|V_{td}|$
  - $|V_{cb}|$
  - $|V_{ub}|$
- Conclusion & Summary

Kay Kinoshita
University of Cincinnati
Belle Collaboration

Introduction

Cabibbo-Kobayashi-Maskawa (CKM) matrix

{weak<->mass} eigenstates

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathcal{M} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{array}$$

to make W-couplings generation-conserving

$$g_F \times \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} d' & s' & b' \end{array} \\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{array}$$

complex
preserves metric
" orthogonality
} ≡ unitary

Unitarity conditions $V_{ji}^{*} V_{jk} = \delta_{ik}$ **-> 4 free parameters**

explicit parametrization(Wolfenstein):

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & \lambda^3 A(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & \lambda^2 A \\ \lambda^3 A(1-\rho-i\eta) & -\lambda^2 A & 1 \end{pmatrix}$$

irreducibly complex! -> CP violation

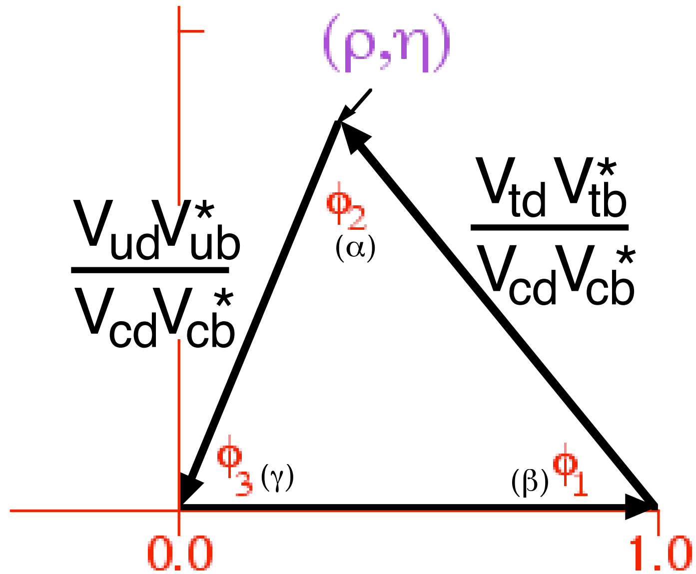
Unitarity conditions $V_{ji}{}^{*}V_{jk}=\delta_{ik}$

{i=1,k=3}: $V_{ub}{}^{*}V_{ud}+V_{cb}{}^{*}V_{cd}+V_{tb}{}^{*}V_{td}=0$

"unitarity triangle"

$$\Rightarrow \frac{V_{ub}{}^{*}V_{ud}}{V_{cb}{}^{*}V_{cd}} + 1 + \frac{V_{tb}{}^{*}V_{td}}{V_{cb}{}^{*}V_{cd}} = 0$$

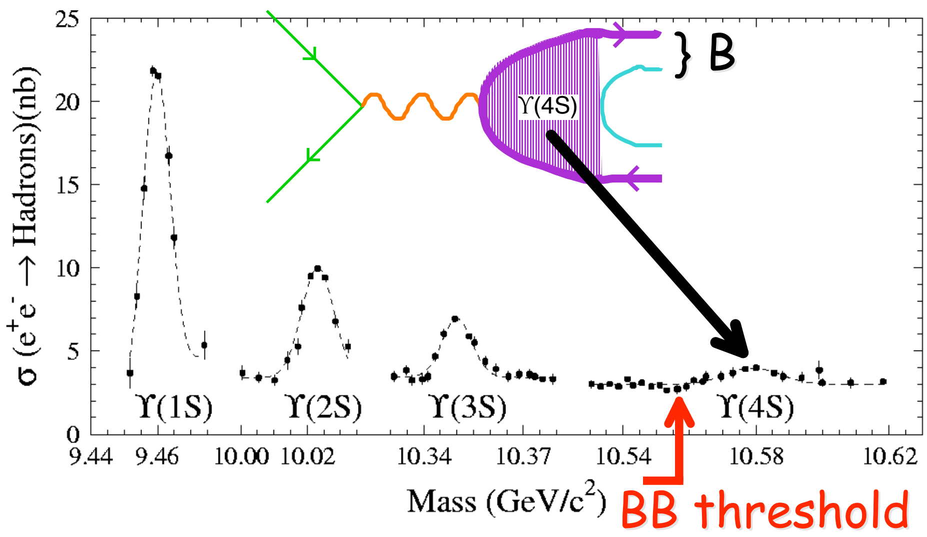
$$\frac{V_{ub}{}^{*}V_{ud}}{V_{cb}{}^{*}V_{cd}} \rightarrow -(\rho+\iota\eta) \qquad \frac{V_{tb}{}^{*}V_{td}}{V_{cb}{}^{*}V_{cd}} \rightarrow -(1-\rho-\iota\eta)$$



Objective of B-factories: test self-consistency of CKM

- Any 3 of {3 angles, 3 sides} fully constrains triangle
- Relevant magnitudes: $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$

B production: $e^+e^- \to \Upsilon(4S) \to B\bar{B}$

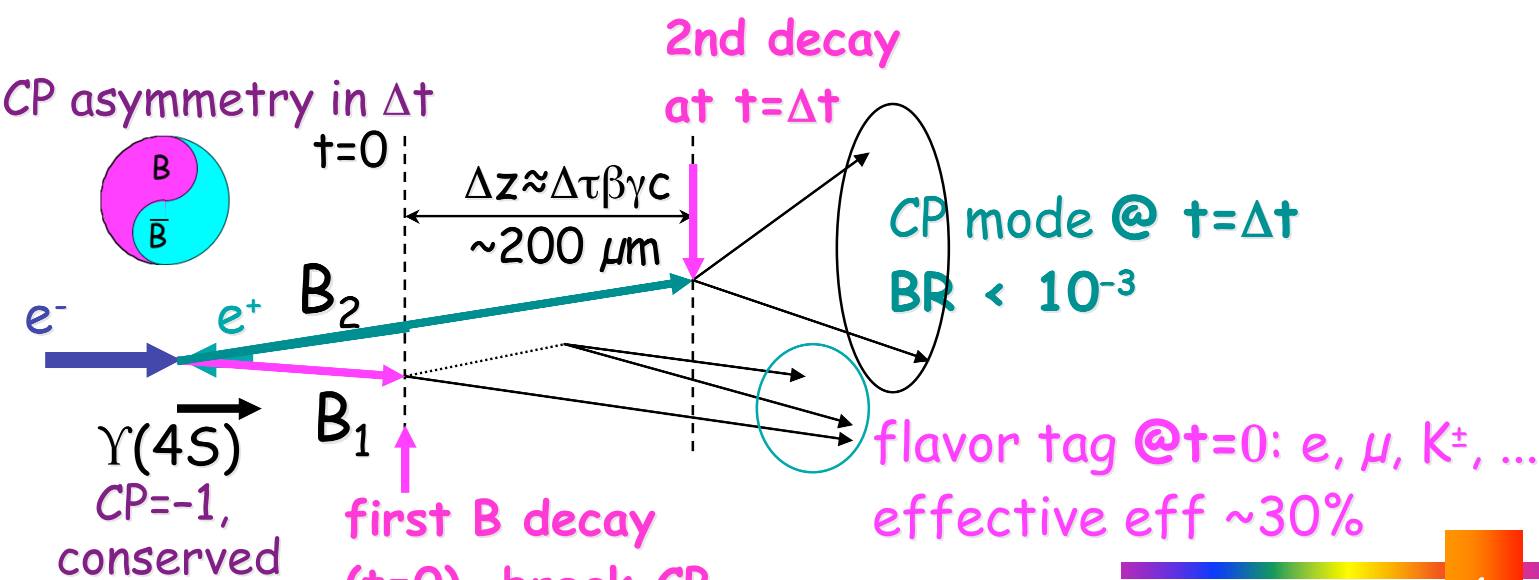


asymmetric energy $e^+e^- \to \Upsilon(4S)$

(symmetric Υ(4S): CLEO 1979-2001)

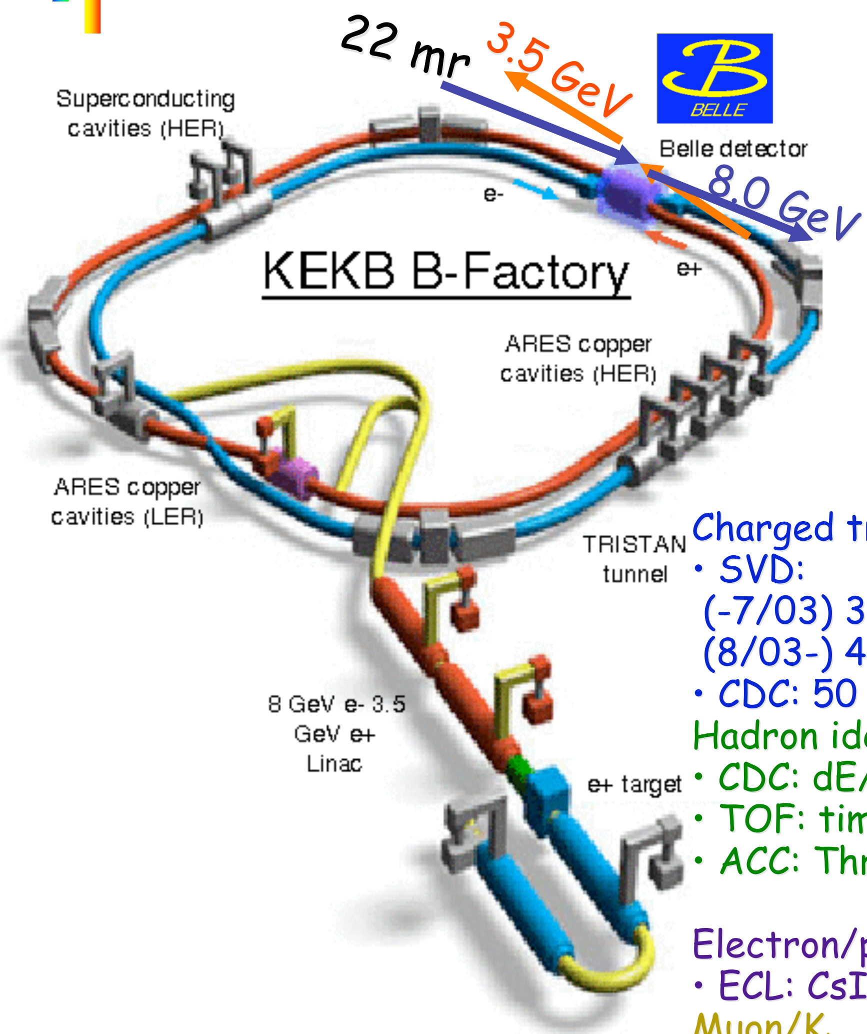
B factories:

designed for CP asymmetry in Δt



KEKB & Belle

- L_{max} = 1.588 X 10^{34} $cm^{-2}s^{-1}$ (world record)
- Data (6/1999-6/2005)
- $\int Ldt$ = 466 fb^{-1}@{Υ(4S)+off(~10%)}
- (>4.6x10^8 B events)



SVD1: 152M B pairs

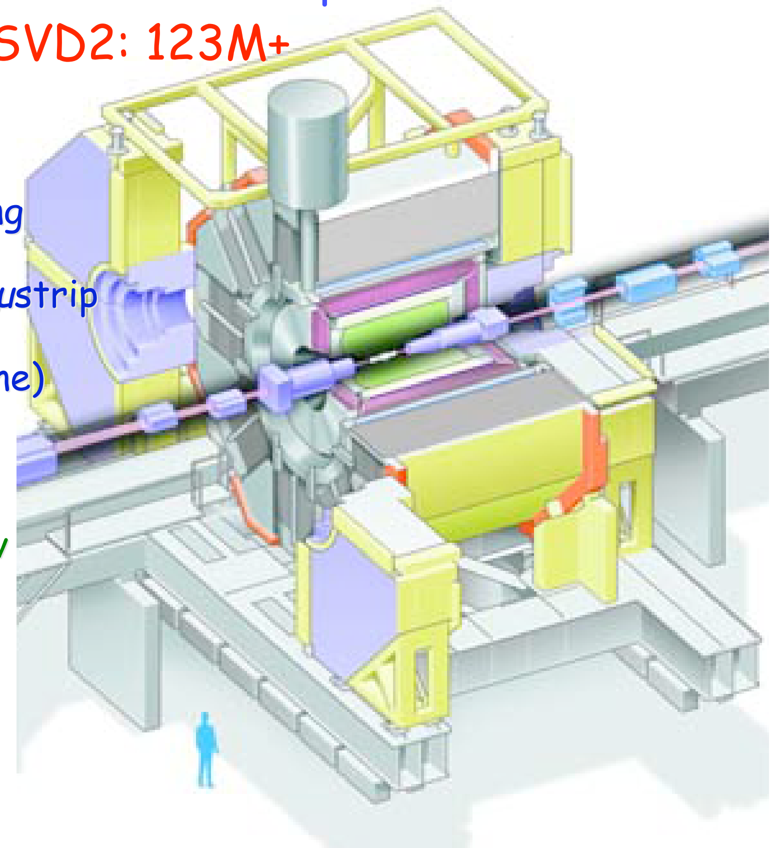
SVD2: 123M+

Charged tracking/vertexing
- SVD:
  (-7/03) 3-layer DSSD Si μstrip
  (8/03-) 4-layer
- CDC: 50 layers (He-ethane)

Hadron identification
- CDC: dE/dx
- TOF: time-of-flight
- ACC: Threshold Cerenkov (aerogel)

Electron/photon
- ECL: CsI calorimeter

Muon/K_L
- KLM: Resistive plate counter/iron

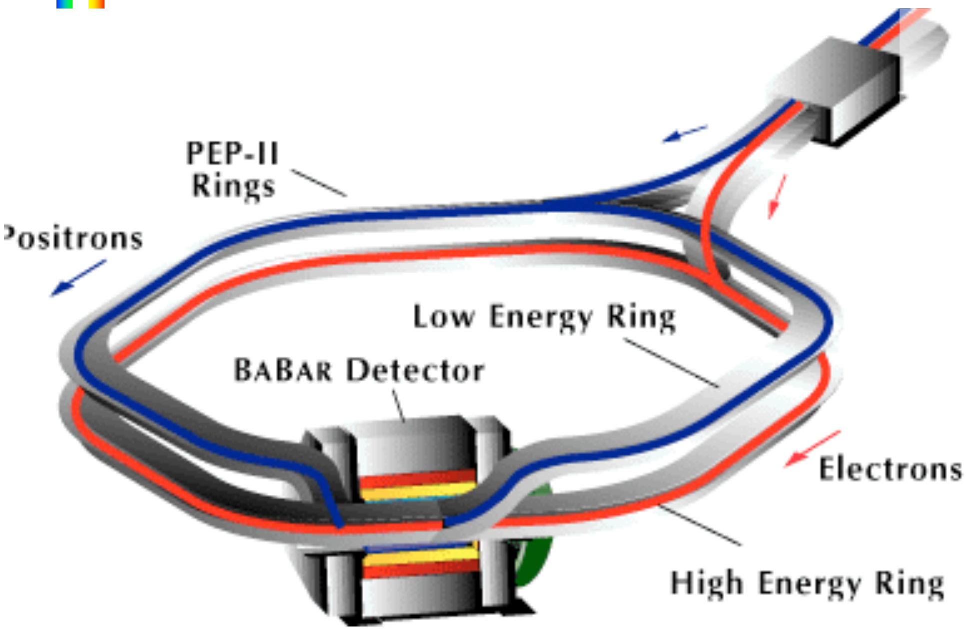


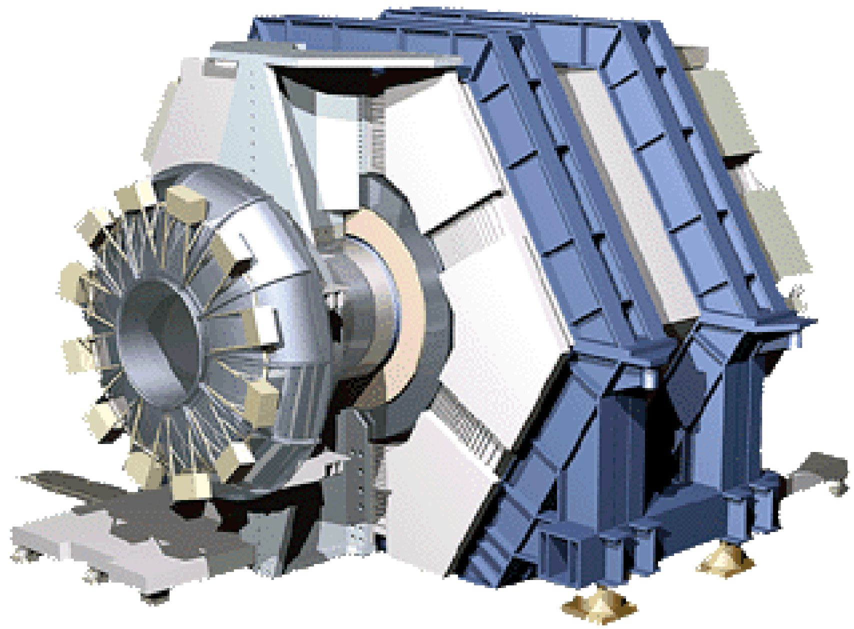
~13 nations, 57 institutes, ~400 persons

K. Kinoshita

PEP-II & Babar

- L_{max} = 9.2 X 10^{33} $cm^{-2}s^{-1}$
- Data (1999–4/2005)
- $\int Ldt$ = 262 fb^{-1}@{Υ(4S)+off(~10%)}
- (>2.6x10^8 B events)





Charged tracking/vertexing
• 5-layer DSSD Si μstrip
• 40 layers (He-isobutane)
Hadron identification
• tracker: dE/dx
• DIRC imaging Cerenkov
Electron/photon
• CsI calorimeter
Muon/K_L
• Instrumented flux return

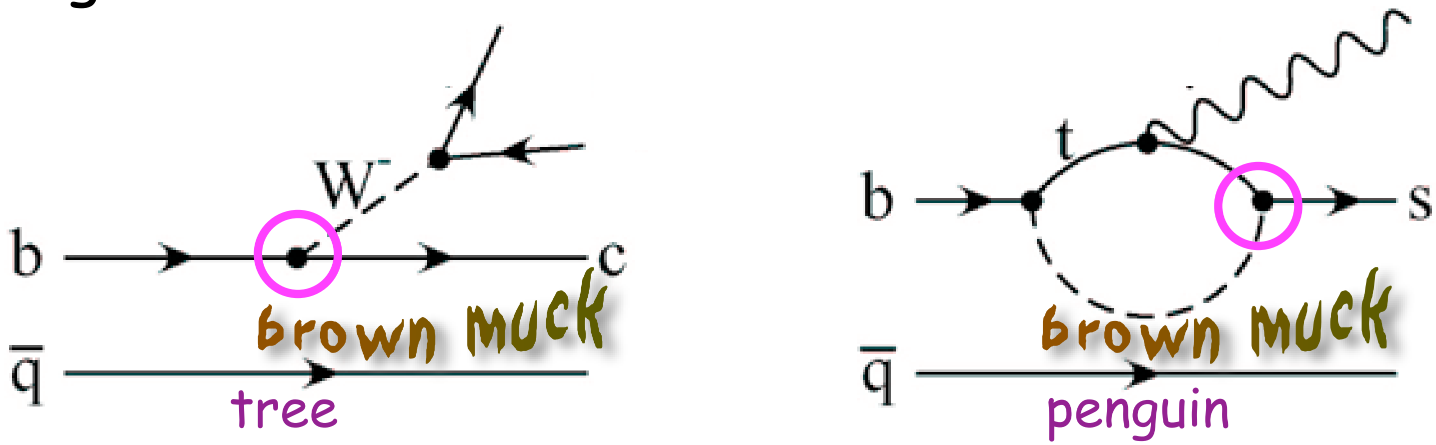
~11 nations, 80 institutes, ~650 persons

Approach to measuring $|V_{ij}|$

Decay rates: $\Gamma \propto \sum_{i}^{\#states} |\mathcal{M}|^2$

select mode(s):

- single dominant mechanism



- single unknown $|V_{ij}|$
- minimal hadronic uncertainty

unavoidable, limiting factor

continuing improvements

Experiment

Statistics -> rare decays, restricted kinematic regions, detailed examination.

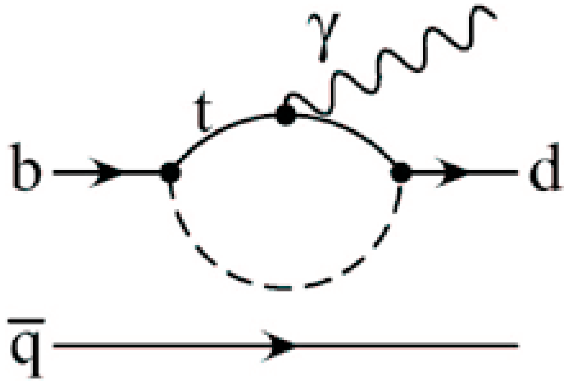
Theory

HQET, SCET, lattice, …

ratios - compare decays, "same" proc.

$$|V_{td}|$$

b->dγ



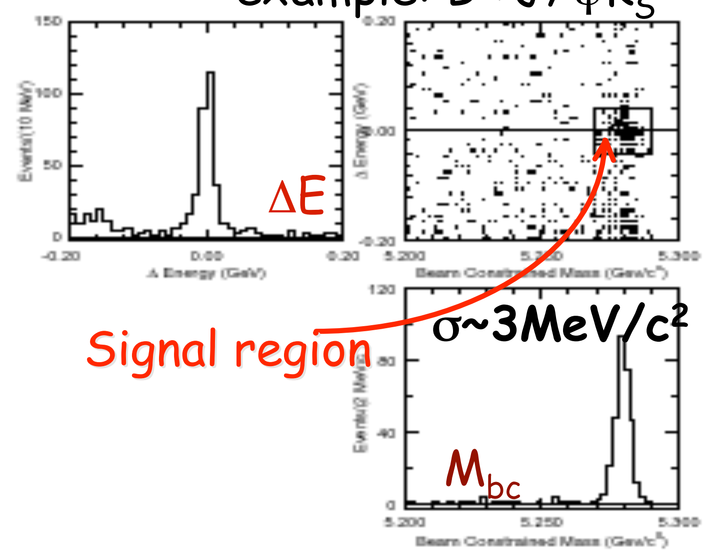
$$\frac{\Gamma(b \to d\gamma)}{\Gamma(b \to s\gamma)} \propto \left|\frac{V_{td}}{V_{ts}}\right|^2$$

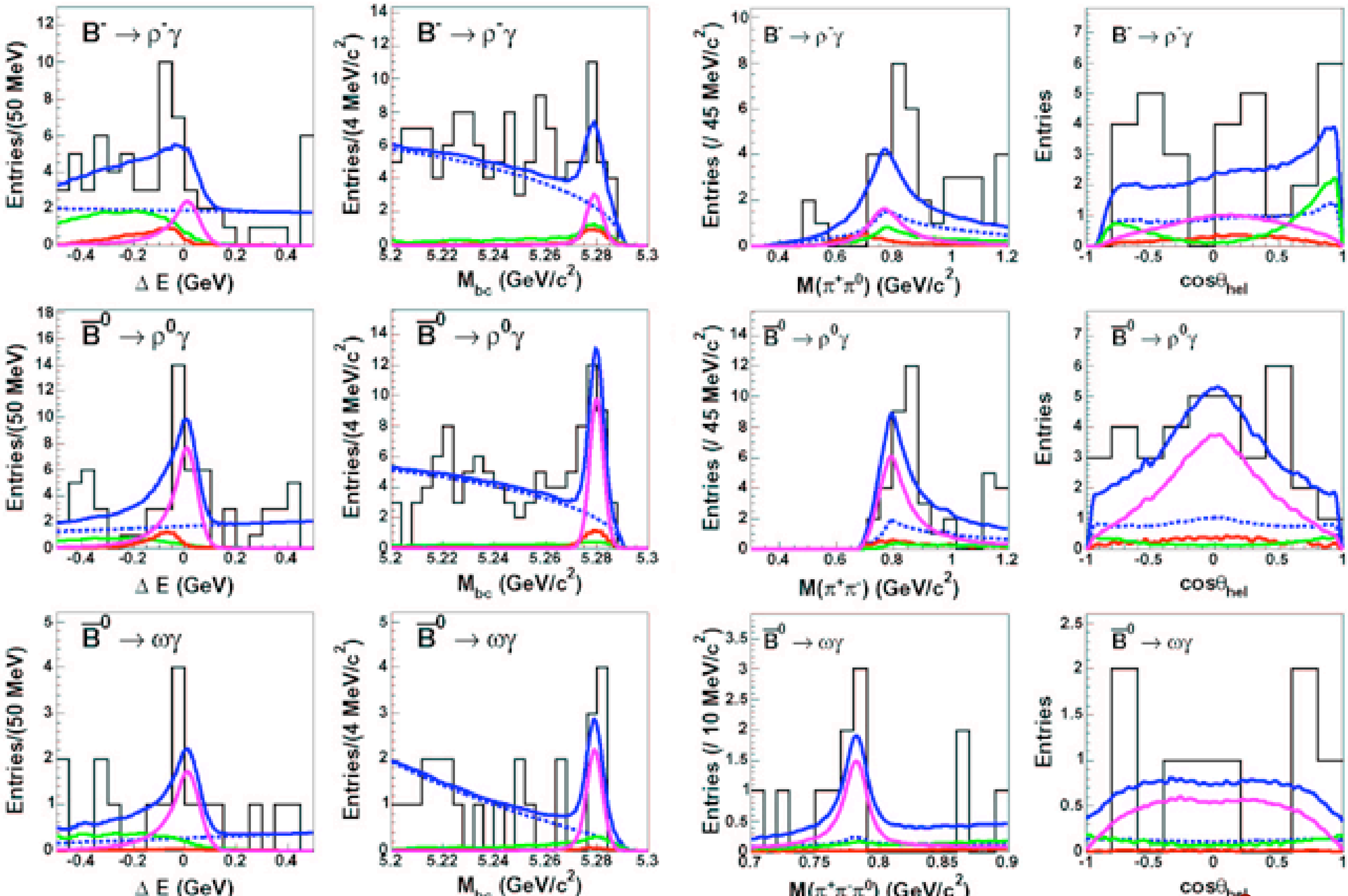
Ratio -> reduced theory error ~10%

- inclusive measurement - preferred by theory
  large (~30X) bg from b->sγ, similar kinematics
- exclusive B-> {ρ/ω}γ - experimentally feasible
  full reconstruction of decay
  exploit
  - exclusive pair production of B
  - narrow resolution of collision energy

  $\Delta E = E^*_{cand} - E^*_{beam} = 0$ ($E^*_{beam} = s^{1/2}/2$)
  σ~10-50 MeV, depends on mode
  M_{bc} (Beam-constrained mass)
  $M_{bc} = (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$

example: $B \to J/\psi K_S$





ΔE M_{bc} ρ/ω mass $\cos\,\theta_{hel}$

b->dγ

386 M B evts (5.5σ) Belle-CONF-0520 *preliminary*

(use isospin relations $\Gamma(B^- \to \rho^- \gamma) = 2\Gamma(B^0 \to \rho^0 \gamma) = 2\Gamma(B^0 \to \omega\gamma)$)

$$\mathcal{B}(B \to (\rho/\omega)\gamma) = (1.34^{+0.34+0.14}_{-0.31-0.10}) \times 10^{-6}$$

$$\{=\mathcal{B}(B^- \to \rho^- \gamma)\}$$

$$\frac{\mathcal{B}(B^- \to \rho^- \gamma)}{\mathcal{B}(B^- \to K^{*-} \gamma)} = 0.032 \pm 0.008^{+0.003}_{-0.002}$$

$$\left|\frac{V_{td}}{V_{ts}}\right| = (0.200^{+0.026+0.038}_{-0.025-0.029})$$

211 M B evts (2.1σ) PRL 94, 011801 (2005)

$$\mathcal{B}(B^- \to \rho^- \gamma) < 1.2 \times 10^{-6} (90\%\ CL)$$

$$\frac{\mathcal{B}(B^- \to \rho^- \gamma)}{\mathcal{B}(B^- \to K^{*-} \gamma)} < 0.029 (90\%\ CL)$$

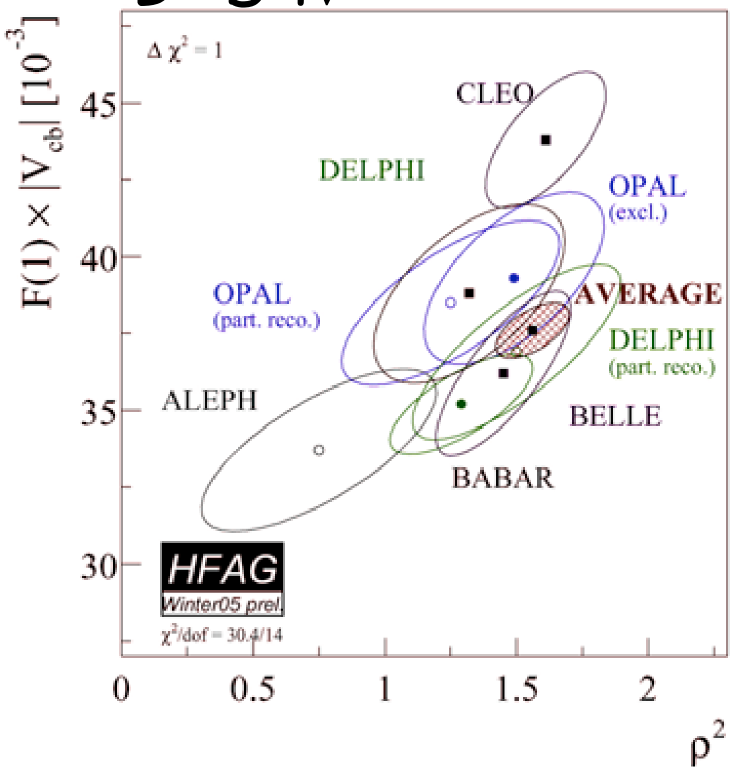
$$\left|\frac{V_{td}}{V_{ts}}\right| < 0.19\ (90\%\ CL)$$

$|V_{cb}|$

Semileptonic b->c decays (no new results since Winter)

Exclusive modes (form factors)

B->D*lν

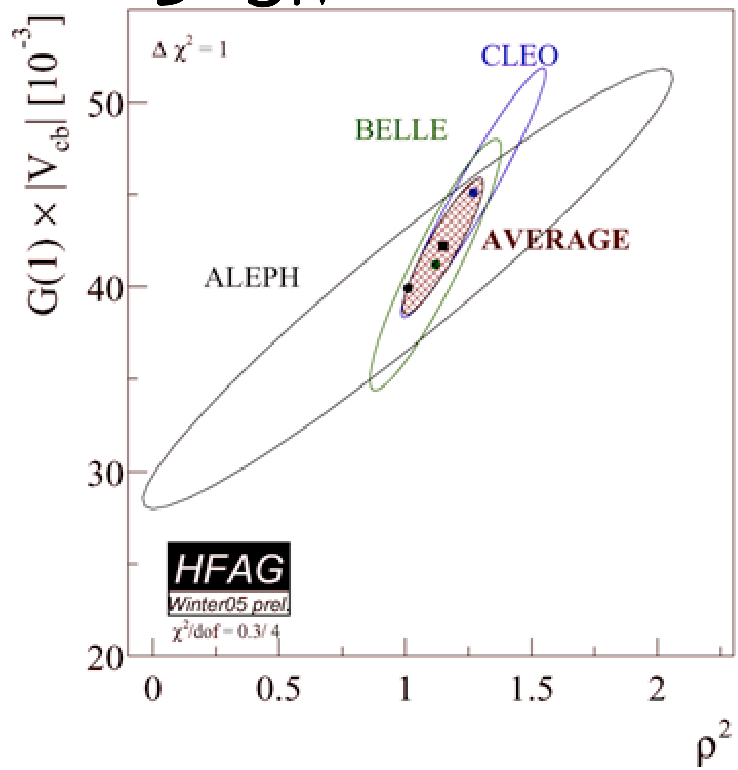


$F(1)|V_{cb}|=(37.6\pm0.9)\times10^{-3}$

$(F(1)=0.91\pm0.04)$

$|V_{cb}|=(41.3\pm1.0\pm1.8)\times10^{-3}$

B->Dlν



$G(1)|V_{cb}|=(42.2\pm3.7)\times10^{-3}$

$(G(1)=1.04\pm0.06)$

$|V_{cb}|=(40.6\pm3.6\pm1.3)\times10^{-3}$

Semileptonic b->c decays

hep-ex/0404017

Inclusive – opposite fully reconstructed B

- moments of E_l, M_X distributions

  fit for params in "kinetic mass" scheme

  -> $|V_{cb}|=(41.4\pm0.4\pm0.4\pm0.6)\times10^{-3}$

(Gambino&Uraltsev hep-ph/0401063)

hep-ex/0408139 *preliminary*

- moments of E_l, M_X distributions (140 fb^{-1})
- update in progress

Bauer et al, PRD70, 094017(2004) (hep-ph/0408002)

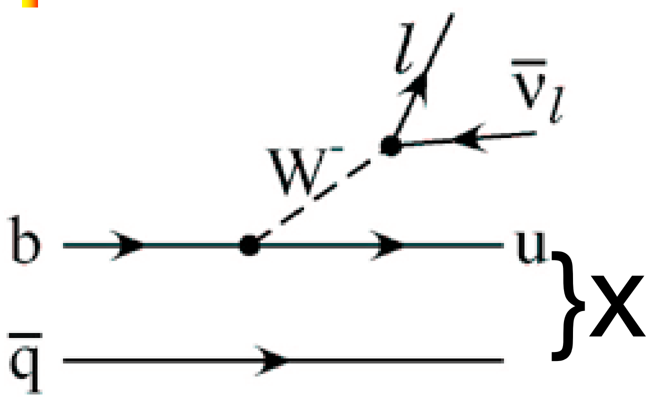
Global fit analysis: moments in the "1S" scheme → PRL 82, 277 (1999); PRD 59, 074017 (1999); PRD 60, 114027 (1999)

Using data from BaBar, Belle, CDF, CLEO & Delphi

$|V_{cb}|=(41.4\pm0.6\pm0.1(\tau_B))\times10^{-3}$

$|V_{ub}|$

Inclusive semileptonic b->u decays



Experimental methods

- inclusive lepton spectrum -> "endpoint"
- lepton + semi-inclusive hadronic
- lepton + "neutrino"
- w/wo (full reconstruction) tagging

Issues

- huge bg from b->c
- uncertainties on X_u, X_c
- Relevant kinematic variables

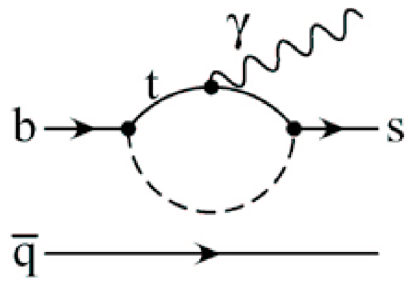
  Theory: 4-mom., polarization of W
  uncertainties vary w. region
  {OPE, HQET, SF, ...}
  Expt: lepton mom., missing E&p, M_X
  (not 1-to-1)

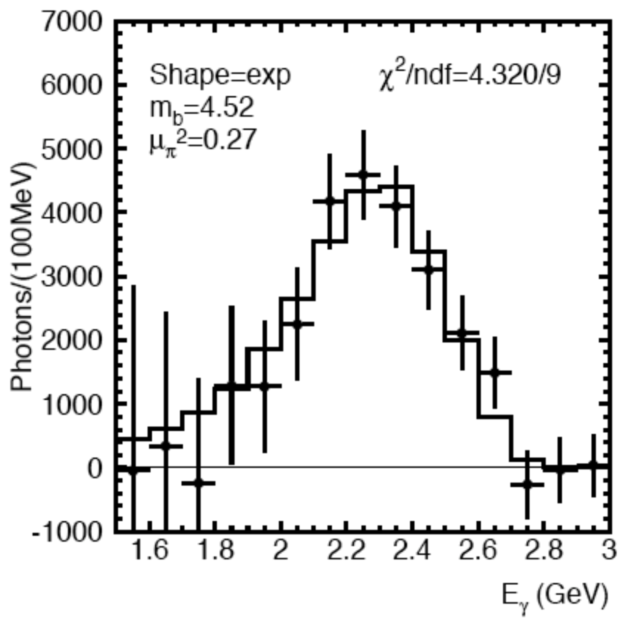
Recent improvements

- "shape function" - relate X:
  b->ulν, b->sγ, b->clν
- Variables balance theoretical
  & exp'tal relevance: q^2, M_X,
  $P_+=E_X-|P_X|$
- direct $|V_{ub}|$ from partial rate
  Lange,Neubert,Paz, hep-ph/0504071

HQET parameters for V_{ub}: spectrum of b->sγ

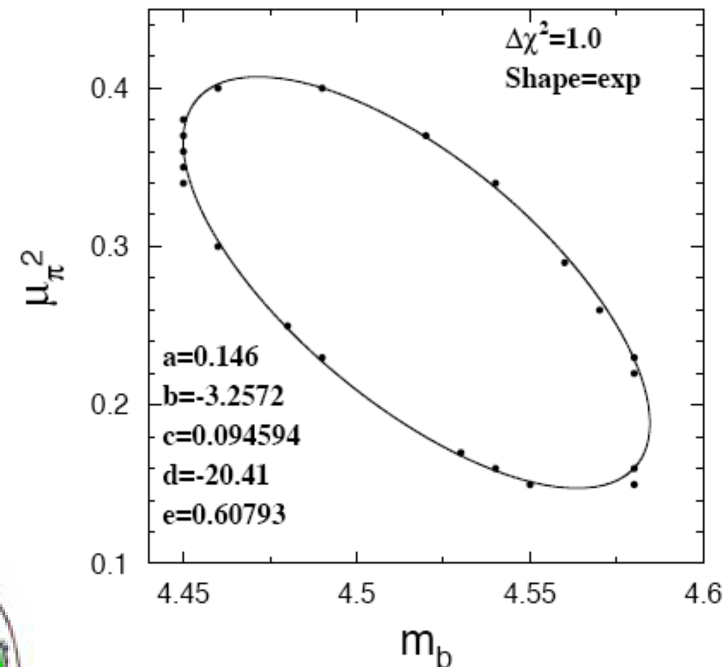
HQET parameters from fit to E_γ spectrum from b->sγ





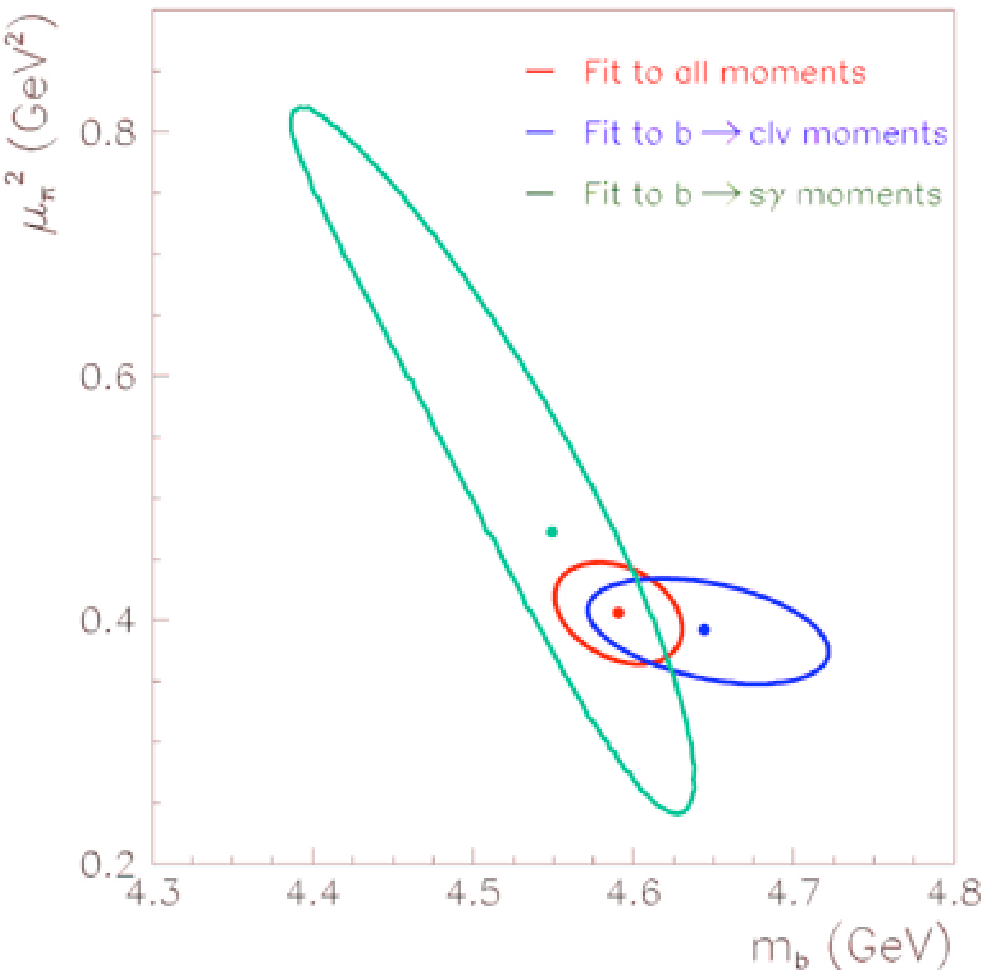
shape: Lange, Paz & Neubert hep-ph/0504071 (LNP)

Belle fit (hep-ex/0506057)
m_b(SF)=4.52 GeV/c^2;
μ_π^2(SF)=0.27 GeV^2/c^2



Babar: hep-ex/0506043

HQET parameters for V_{ub}: HFAG



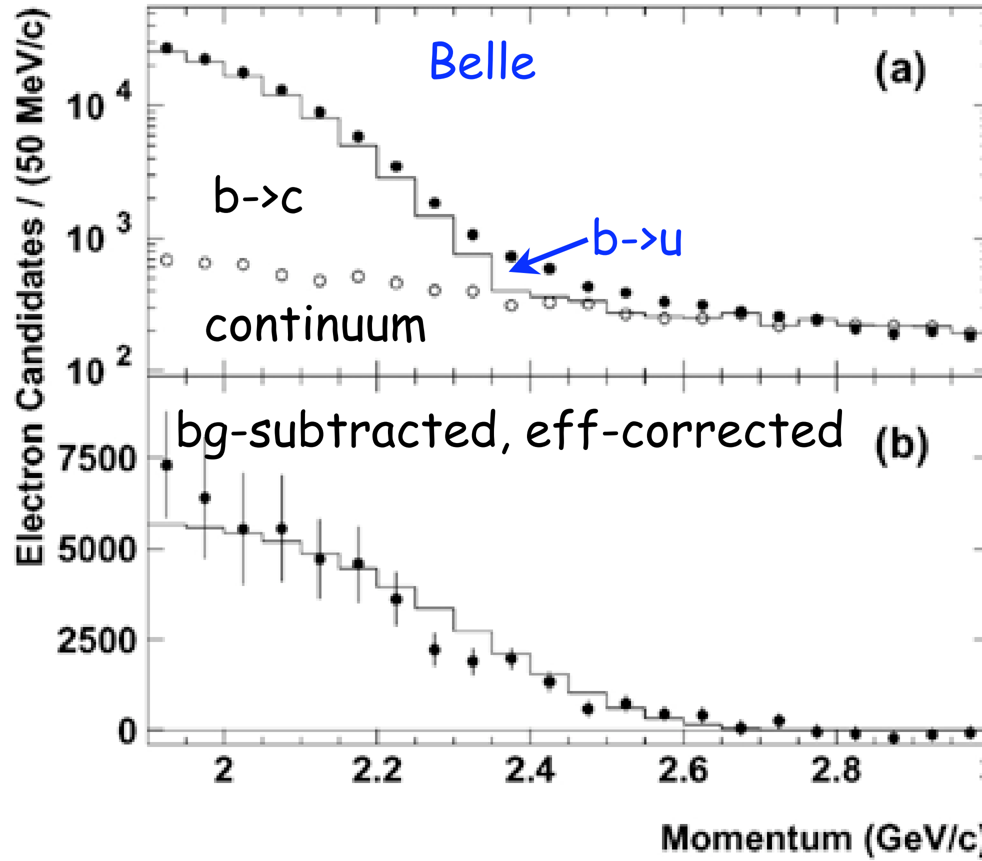
Fit for moments
to data: b->sγ and b->clnu
Kinetic Scheme
(Gambino&Uraltsev hep-ph/0401063)

Translated to
Shape Function Scheme
(Neubert Phys.Lett.B612:13-20,2005):
m_b(SF)=(4.60+-0.04)GeV/c^2;
M_π^2(SF)=(0.20+-0.04)GeV^2/c^2

http://www.slac.stanford.edu/xorg/hfag/semi/lp05/globalFit.html

Lepton momentum endpoint

$|V_{ub}|$: theory uncertainties
- exclusive modes
- inclusive: shape function



- cuts maximize q^2 acceptance
- endpt region 1.9-2.6 GeV/c to minimize err (expt+th)
- shape function: fit to b->s
- ΔB->$|V_{ub}|$ via LNP

- endpt region 2.0-2.6 GeV/c
- shape function: b->s from CLEO (also w Belle fit)
- ΔB->$|V_{ub}|$ via

Uraltsev Int. J. Mod. Phys. A14, 4641 (1999); Hoang,Ligeti,Manhar PRD 59, 074017 (1999)

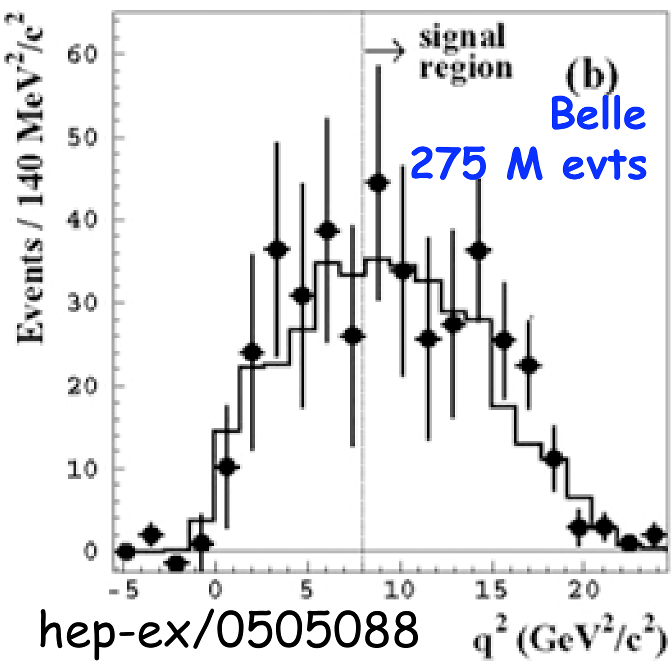
Exploring M_X, q^2, P_+

Full reconstruction tag + lepton + M_x

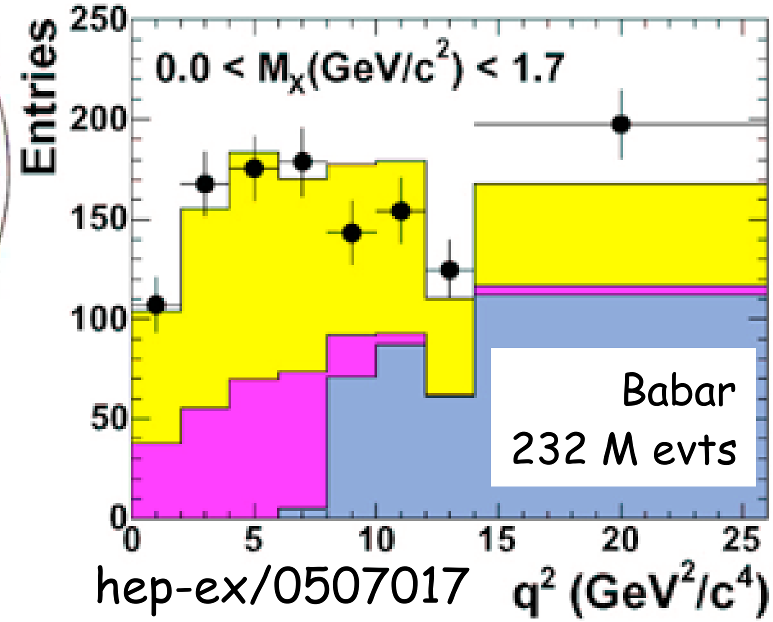
- high signal purity -> higher p_l acceptance
- explore phase space -> reduce sys errors
- cuts to reduce theory uncertainty

(q^2>8.0 Gev^2/c^2,M_X<1.7 GeV/c^2; Bauer, Ligeti & Luke, Phys.Rev.D64:113004 (2001)

- direct ΔB->$|V_{ub}|$ (LNP)



hep-ex/0505088



hep-ex/0507017

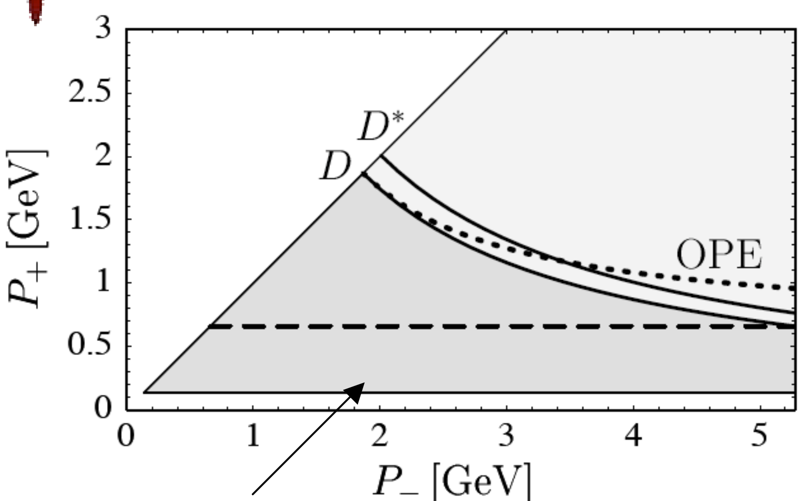
Exploring M_X, q^2, P_+

hep-ex/0505088

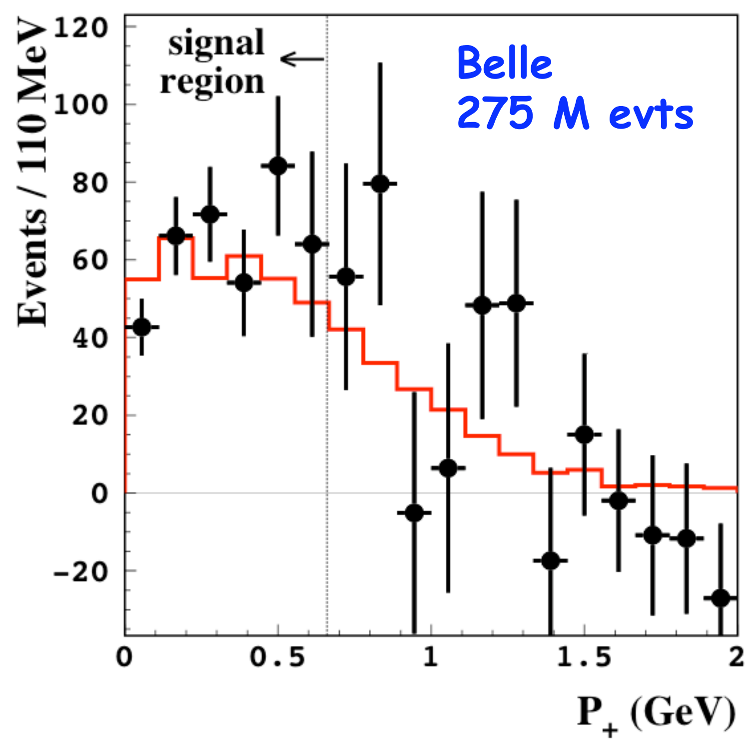
- measure distribution in P_+:
  higher yield w low background
  (PRL 93, 221801 (2004))
- direct ΔB->|V_{ub}| (LNP)

$P_+=E_X-P_X$

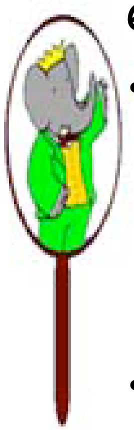
$P_-=E_X+P_X$



Avoid b->c background
Min. theory uncertainty
P+ < 0.66 GeV



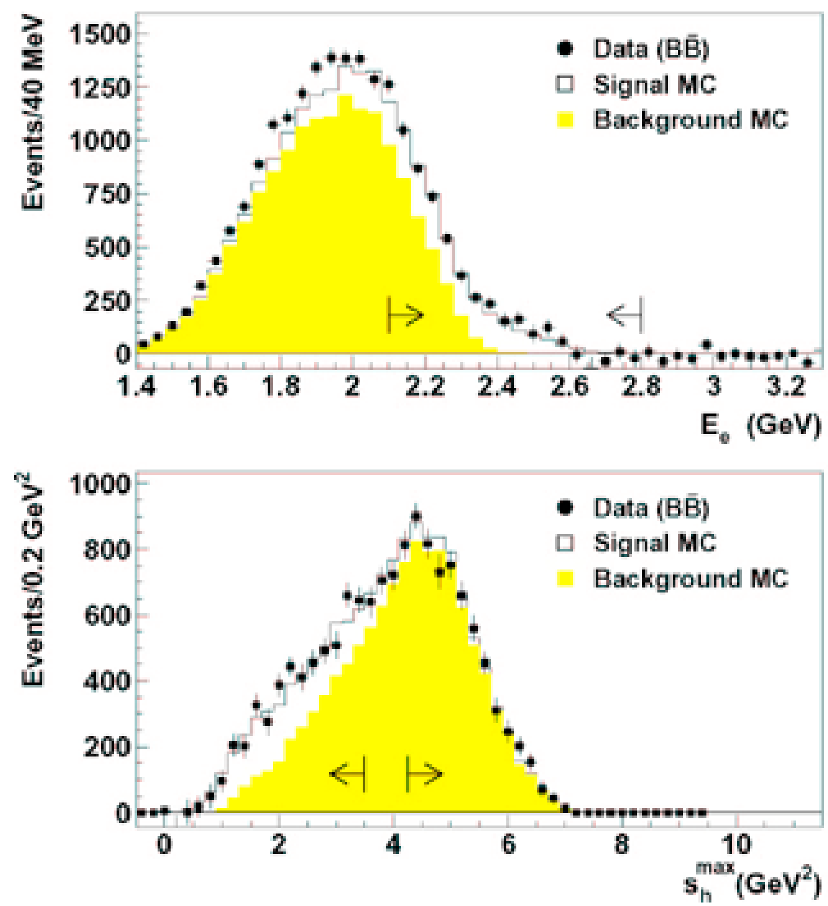
Exploring M_X, q^2, P_+



hep-ex/0506036

endpoint $e^{\pm}$ + ν reconstruction

- ΔB for cuts in rest frame of B
  - E_e>2.0 GeV
  - s_h^{max}<3.5 GeV^2 ({max hadronic recoil mass}^{2})
- direct ΔB->$|V_{ub}|$ via LNP



Summary of $|V_{ub}|$ measurements

($|V_{ub}|$ as reported; errors: ±(experimental)±(theory)

Belle	reference	$\Delta\mathcal{B} \times 10^4$	$\lvert V_{ub}\rvert \times 10^3$
Endpoint (29M $B\bar{B}$)	hep-ex/0504046		
$1.9 < p_\ell < 2.6$ GeV/c		$8.47 \pm 0.37 \pm 1.53$	$5.08 \pm 0.47 \pm 0.49$
Full reconstruction tag ($p_\ell^* > 1$ GeV/c)	hep-ex/0505088		
$M_X < 1.7$ GeV/c^2, $q^2 > 8$ GeV^2/c^2		$8.41 \pm 1.14 \pm 0.69$	$4.93 \pm 0.33 \pm 0.57$
$M_X < 1.7$ GeV/c^2		$12.4 \pm 1.5 \pm 0.8$	$4.35 \pm 0.25 \pm 0.46$
$P_+ < 0.66$ GeV/c		$11.0 \pm 1.5 \pm 1.2$	$4.56 \pm 0.30 \pm 0.59$
Babar			
Endpoint (88M $B\bar{B}$)	hep-ex/0408075		
$2.0 < p_\ell^* < 2.6$ GeV/c		$4.80 \pm 0.29 \pm 0.53$	$3.94 \pm 0.25 \pm 0.42$
E_e, ν reconstruction (88M $B\bar{B}$)	hep-ex/0506036		
$\tilde{E}_e > 2.0$ GeV, $\tilde{s}_h^{max} < 3.5$ GeV^2		$3.54 \pm 0.33 \pm 0.34$	$3.95 \pm 0.26^{+0.63}_{-0.49}$
Full reconstruction tag ($p_\ell^* > 1$ GeV/c)	hep-ex/0507017		
$M_X < 1.7$ GeV/c^2, $q^2 > 8$ GeV^2/c^2		$8.7 \pm 1.3 \pm 0.1$	$4.65 \pm 0.34 \pm 0.49$

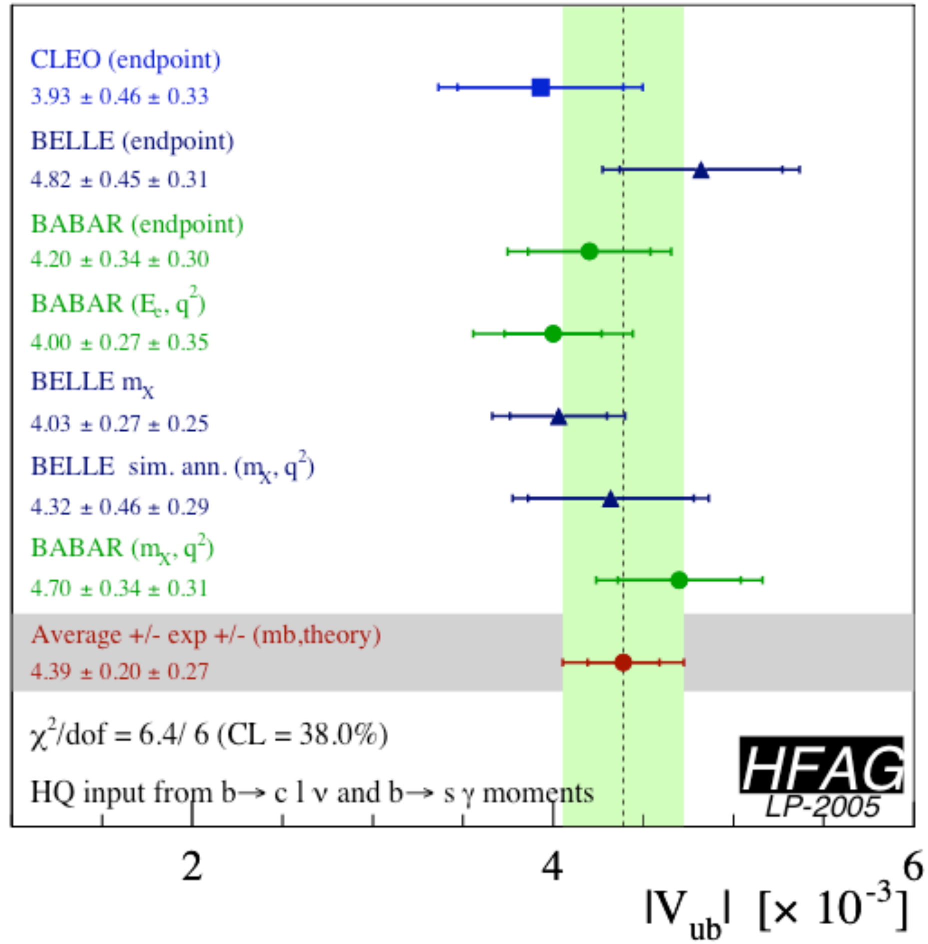
&more.

Warning! Can't compare $|V_{ub}|$ directly - different methods & inputs

Roundup of $|V_{ub}|$ via inclusive semileptonic: HFAG

Many results, hard to compare

- shape function, HQ parameter fits
  Belle/Babar/CLEO data
  parametrizations: SF, kinetic schemes
  fits included: b->clν and/or b->s
- kinematic cuts vary
- ΔB->$|V_{ub}|$ new results:
  dust may not have settled
- need unified presentation -->HFAG
  http://www.slac.stanford.edu/xorg/hfag
  * Common theoretical input
  •HQET parameters from global fit to moments of b->clν and/or b->sγ (3 combos)
  • BLNP hep-ph/0504071
  * Correlated b-Xlν modeling errors



preliminary

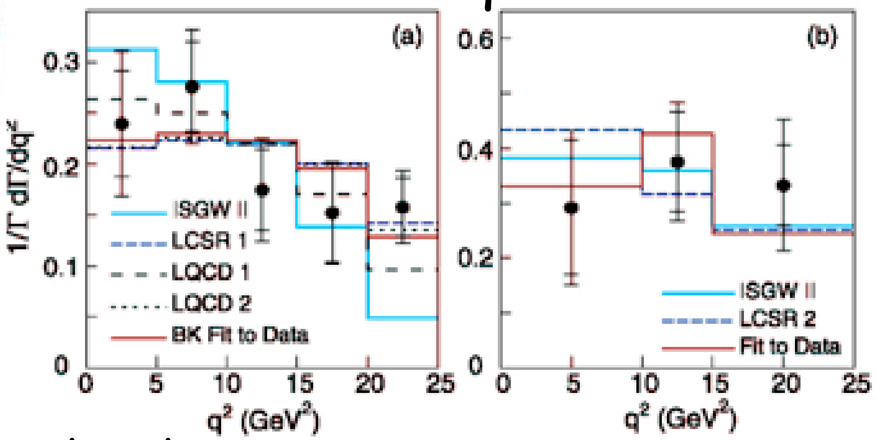
$$|V_{ub}| = (4.39 \pm 0.20(\text{exp}) \pm 0.27(m_b,\text{theory}))\times 10^{-3}$$ [b->clν and b->sγ]

Roundup … at the moment,

… still under discussion …

Exclusive semileptonic

π/ρlν; ν reconstruction) hep-ex/0507003
in bins of q^2



LCSR1: Ball&Zwicky, PRD71, 014015 (2005)
LCSR2: Ball&Zwicky, PRD71, 014029 (2005)
LQCD1:Shigemitsu&al, hep-lat/0408019
LQCD2: Okamoto&al, hep-lat/0409116
ISGWII: Scora&Isgur, PRD52, 2783 (1995)

	q^2 Range (GeV^2)	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
π FF			
LCSR1	0 − 15	5.1±1.3	$3.27 \pm 0.16 \pm 0.19 \pm 0.10^{+0.53}_{-0.36}$
LQCD1	15 − 25	1.5±0.4	$4.92 \pm 0.25 \pm 0.29 \pm 0.15^{+0.76}_{-0.52}$
LQCD2	15 − 25	2.0±0.5	$4.16 \pm 0.22 \pm 0.24 \pm 0.12^{+0.72}_{-0.47}$
LCSR1	0 − 25	7.7±2.3	$3.40 \pm 0.13 \pm 0.20 \pm 0.10^{+0.67}_{-0.42}$
LQCD1	0 − 25	5.7±1.7	$4.00 \pm 0.14 \pm 0.23 \pm 0.12^{+0.78}_{-0.49}$
LQCD2	0 − 25	6.1±2.1	$3.82 \pm 0.14 \pm 0.22 \pm 0.11^{+0.88}_{-0.52}$
ρ FF			
LCSR2	0 − 15	12.7	$2.82 \pm 0.18 \pm 0.30 \pm 0.18$
ISGW II	0 − 25	14.2	$2.91 \pm 0.12 \pm 0.33 \pm 0.19$
LCSR2	0 − 25	17.2	$2.85 \pm 0.14 \pm 0.32 \pm 0.19$

ΔB->$|V_{ub}|$:
Light-cone sum rules (low q^2 only)
Unquenched lattice QCD (high q^2)

preliminary
hep-ex/0408145

FF	q^2	$\lvert V_{ub}\rvert$ (10^{-3})
LQCD1	> 16 GeV²	$4.73 \pm 0.85 \pm 0.27^{+0.74}_{-0.50}$
LQCD2	> 16 GeV²	$3.87 \pm 0.70 \pm 0.22^{+0.85}_{-0.51}$

Exclusive semileptonic

Tag by exclusive semileptonic B->D$^{(*)}$ln;
require kinematic consistency

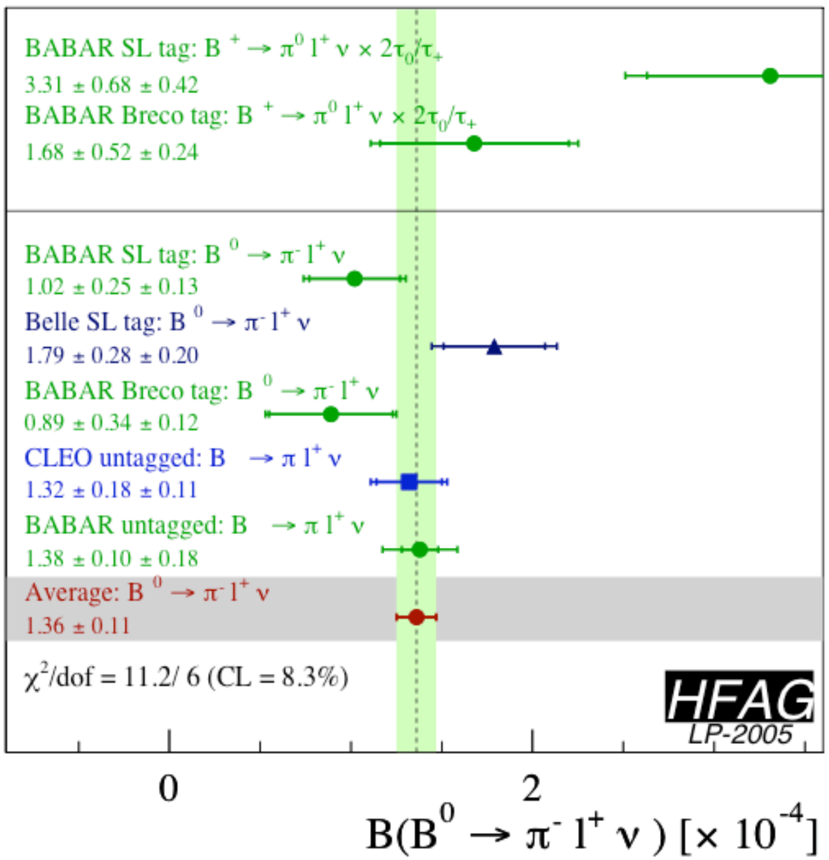
$\pi^+ l\nu$; hep-ex/0506064 (211 fb^{-1})
bins of q^2

preliminary

FF calculation	q^2 range	$\Delta\zeta$ (ps^{-1})	$\lvert V_{ub}\rvert$ (10^{-3})
Ball-Zwicky [2]	$< 16\,\mathrm{GeV}^2$	5.44 ± 1.43	$3.1 \pm 0.4_{\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}{}^{+0.5}_{-0.3}{}_{\mathrm{FF}}$
HPQCD [3]	$> 16\,\mathrm{GeV}^2$	1.29 ± 0.32	$3.3 \pm 1.1_{\mathrm{stat.}} \pm 0.5_{\mathrm{syst.}}{}^{+0.5}_{-0.3}{}_{\mathrm{FF}}$
FNAL [4]	$> 16\,\mathrm{GeV}^2$	1.83 ± 0.50	$2.7 \pm 0.9_{\mathrm{stat.}} \pm 0.4_{\mathrm{syst.}}{}^{+0.5}_{-0.3}{}_{\mathrm{FF}}$
Ball-Zwicky [2]	full	7.74 ± 2.32	$2.9 \pm 0.4_{\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}{}^{+0.6}_{-0.4}{}_{\mathrm{FF}}$
HPQCD [3]	full	5.70 ± 1.71	$3.4 \pm 0.4_{\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}{}^{+0.7}_{-0.4}{}_{\mathrm{FF}}$
FNAL [4]	full	6.24 ± 2.12	$3.3 \pm 0.4_{\mathrm{stat.}} \pm 0.2_{\mathrm{syst.}}{}^{+0.8}_{-0.4}{}_{\mathrm{FF}}$

$\pi^0 l\nu$; hep-ex/0506065 (81 fb^{-i})

Roundup of $|V_{ub}|$ via exclusive semileptonic: HFAG



preliminary

From avg ΔB (q^2> 16 GeV^2)

LQCD2->

$|V_{ub}| = (3.75 \pm 0.27 +0.64 -0.42)\times 10^{-3}$

LQCD1 ->

$|V_{ub}| = (4.45 \pm 0.32 +0.69 -0.47)\times 10^{-3}$

1st err: experimental

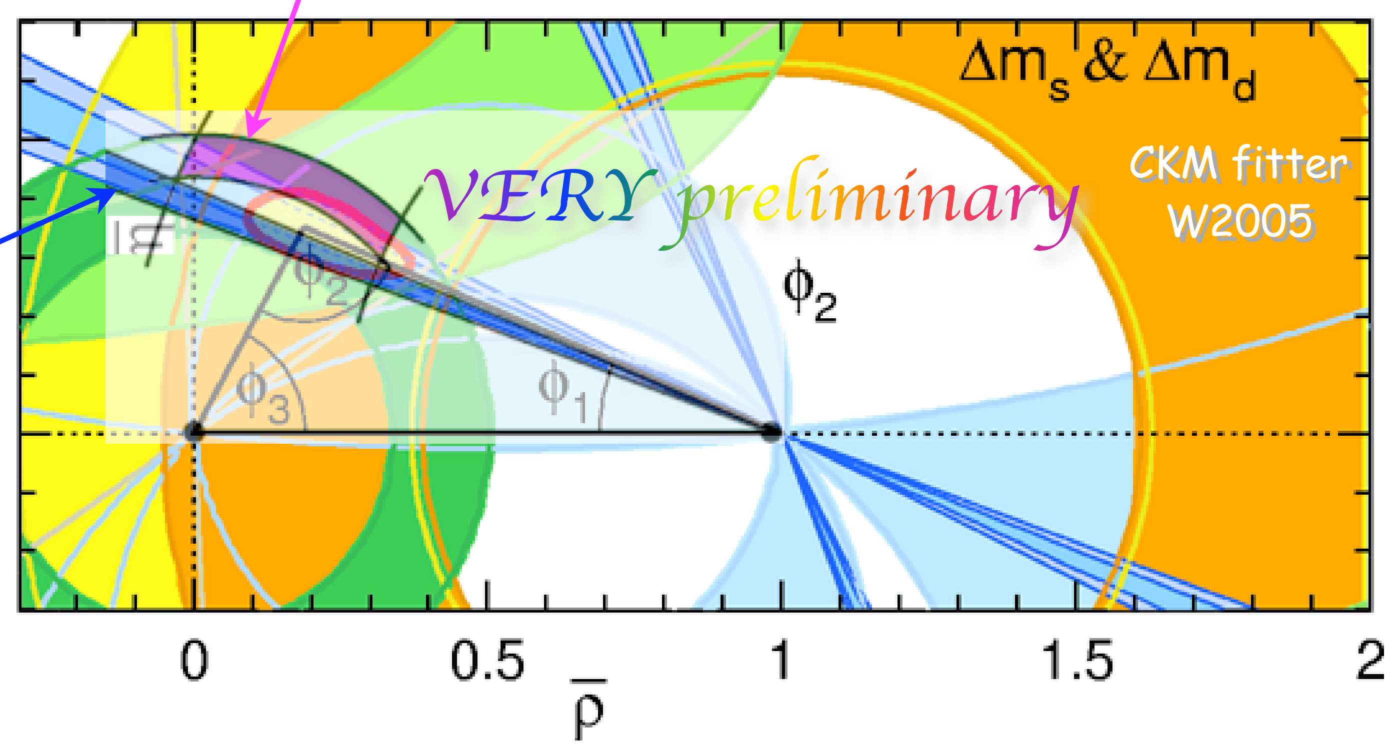
2nd err: normalization uncertainty in form factor calculation.

CKM status

$|V_{td}/V_{ts}|=\lambda|1-\rho-\iota\eta|$ => $|1-\rho-\iota\eta| = 0.91^{+0.21}_{-0.17}$ [b->dγ]

$|V_{ub}/V_{cb}|=\lambda|\rho-\iota\eta|$ => $|\rho-\iota\eta| = 0.48\pm0.04$ [b->ulν inclusive]

LP05
avg ϕ_1



Conclude: $|V_{ij}|$ can play a major role in (over)constraining CKM

Summary

B Factories 1999-2005:

- Total > 7.3 x 10^8 B pairs
- CKM Unitarity Triangle -
  precision measurement of sides -> overconstraint
- $|V_{td}|$ - first evidence for b->d -> ±13%
- $|V_{cb}|$ - continued progress, p_l/M_X moments -> <±2%!
- $|V_{ub}|$ – many semileptonic measurements,
  progress on theory (inclusive and exclusive modes)
  higher precision <±10% but accuracy?(under discussion)

Next

- complete unfinished LP05 abstracts -> EPS
- continue interaction w theorists
- more data

-> improving precision on sides as well as angles;
CKM challenge is heating up - stay tuned!