

Status of $|V_{ub}|$ and $|V_{cb}|$ determinations

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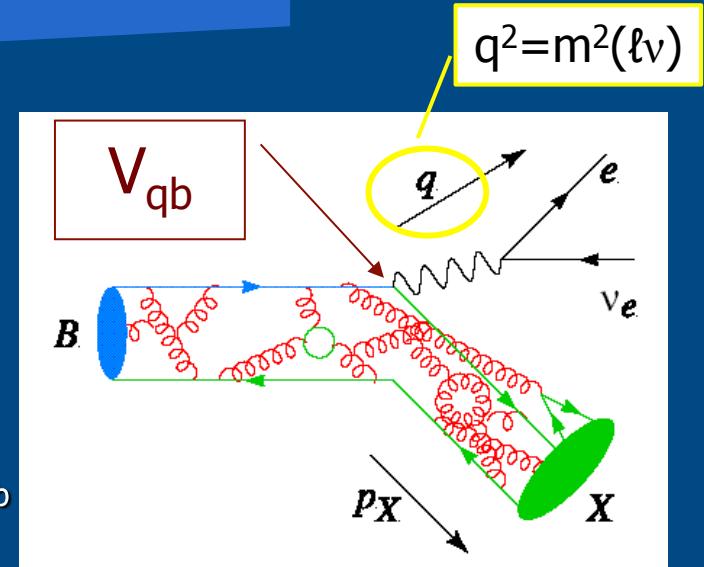
on behalf of the
BaBar Collaboration

Executive summary

- Determinations of $|V_{ub}|$ and $|V_{cb}|$ use well-established methods
- “Turning the crank” gives intriguing results
 - uncertainties of $\sim 2\%$ on $|V_{cb}|$ and $\sim 10\%$ on $|V_{ub}|$
 - complementary determinations (from inclusive and exclusive semileptonic B decays) not comfortably consistent
- This talk will give results based on HFAG averages and point out selected issues of concern
- Issues primarily concerned with theory are covered by T. Mannel

Semileptonic B decays

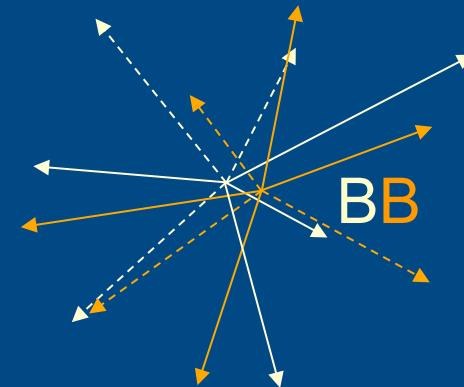
- Large BF, only one hadronic current
- Inclusive decays $b \rightarrow q\ell\nu$:
 - Weak quark decay + QCD corrections
 - Operator Product Expansion in α_s and Λ/m_b
- Exclusive decays $B \rightarrow X\ell\nu$:
 - Form factors need non-perturbative input, e.g. Lattice QCD



The uncertainties in the theory inputs for inclusive and exclusive determinations of $|V_{qb}|$ are independent

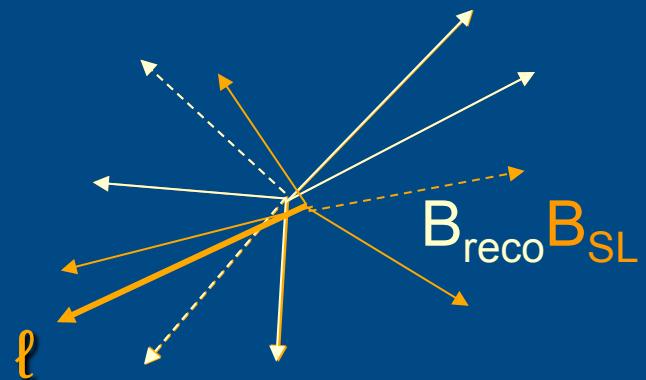
Measuring semileptonic B decays

- Inclusive decays $b \rightarrow q\ell\nu$:
 - Measure electron or muon
 - Measure \mathbf{p}_{miss} or associated hadrons
- Exclusive decays $B \rightarrow X_q \ell\nu$:
 - Measure lepton and specified hadron
- Data from $Y(4S) \rightarrow BB$; decay products overlap
 - proper assignment of particles difficult
- Determine non-B contribution using data below BB threshold



Measurements based on recoil samples

- Reconstruct 1 B and 1 lepton in event; remaining particles come from X in $B \rightarrow X \ell \nu$.
 - hadronic tags determine \mathbf{p}_B for one B; allow access to all kinematic variables but with low efficiency $\sim 0.3\%$
 - $D^{(*)} \ell \nu$ tags; no \mathbf{p}_B , but efficiency $\sim 0.6\%$
 - Can be used for both inclusive and exclusive semileptonic decays to reduce backgrounds

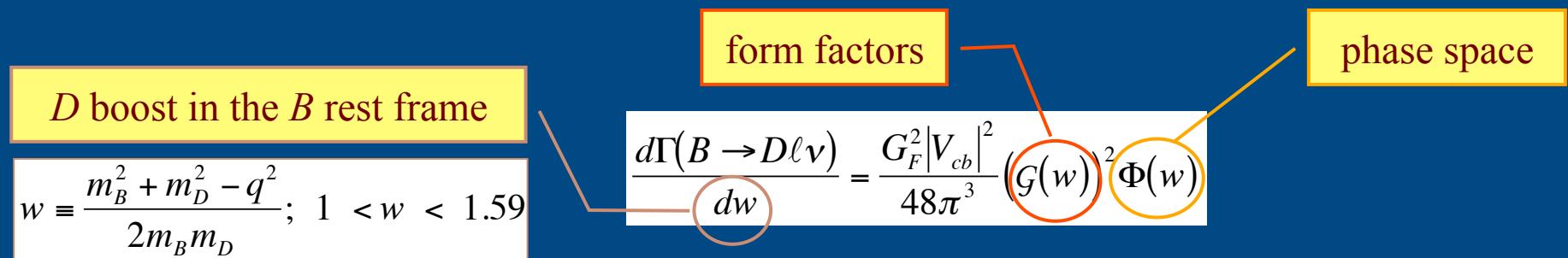


Plan of talk

- The remainder of this talk will review the status of
 - Exclusive $B \rightarrow D^* l \bar{\nu}$ and $B \rightarrow D l \bar{\nu}$ decays
 - Exclusive $B \rightarrow \pi l \bar{\nu}$ decays
 - Inclusive $b \rightarrow c l \bar{\nu}$ decays
 - Inclusive $b \rightarrow u l \bar{\nu}$ decays

Exclusive decay rates

- Differential decay rates are proportional to $|V_{qb}|^2$ and to the square of a form factor. For example, consider $B \rightarrow D\ell\nu$


$$\frac{d\Gamma(B \rightarrow D\ell\nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} (G(w))^2 \Phi(w)$$

D boost in the B rest frame

$$w \equiv \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}; \quad 1 < w < 1.59$$

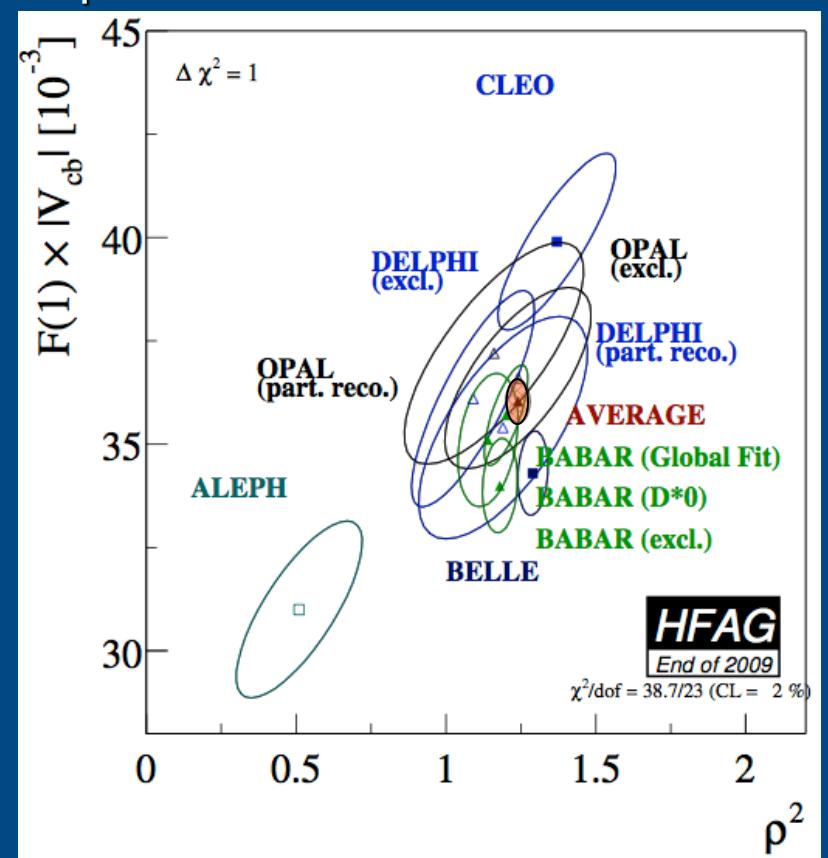
form factors

phase space

- Parameterization of FF uses unitarity and analyticity. Expansion is in a variable with limited range $z \equiv \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$; $0 < z < 0.065$; same approach used for $B \rightarrow D^*$ and $B \rightarrow \pi$
- Need normalization of FF at $w=1$ from theory. For $b \rightarrow c$ it is unity up to HQET corrections

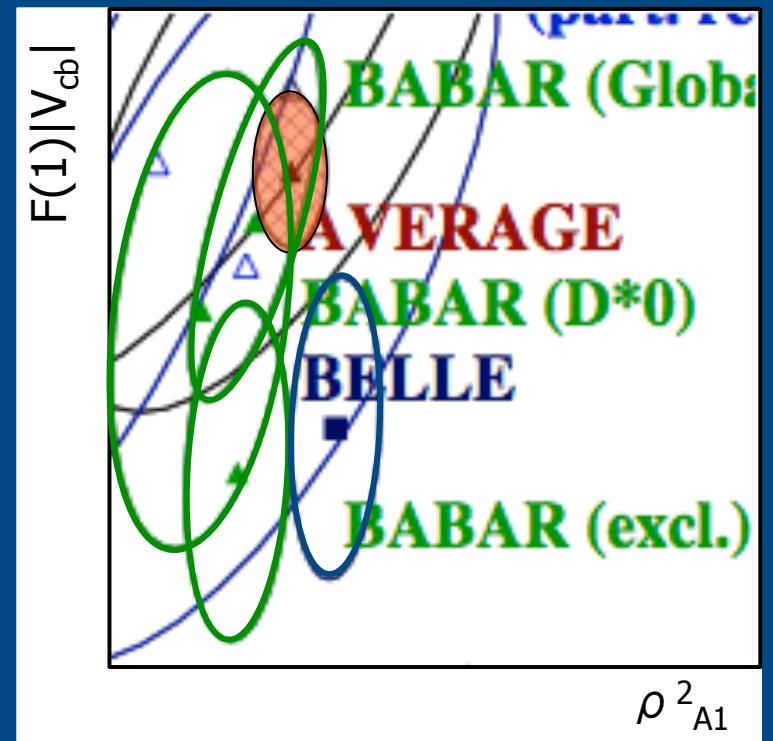
Exclusive $B \rightarrow D^* \ell \nu$ decays

- Long history; B factory measurements now dominate in precision
 - New Belle result at ICHEP 2008, 3 BaBar publications since 2008
- HFAG: $F(1)|V_{cb}| = (36.0 \pm 0.5) \times 10^{-3}$
 $\rho^2_{A1} = 1.24 \pm 0.04$
- Poor χ^2 ; PDG scale error by $\sqrt{\chi^2/ndf} \approx 1.3$



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 - zoom
- Using unquenched lattice result
 $F(1) = 0.927 (13) (20)$ [PRD79:014506(2009)]
 $|V_{cb}| = (38.9 \pm 0.7_{\text{exp}} \pm 1.0_{\text{th}}) \times 10^{-3}$



Issues for $B \rightarrow D^* \ell \nu$ decays

- Normalization $F(1)$ from theory
- Detector modeling (effic, PID, ...) significant part of error budget
 - slow pion reconstruction under control; good agreement in $D^{*+} \ell \nu$, $D^{*0} \ell \nu$ and in global fit (no π reco)
 - further improvements possible, but challenging
- Background from poorly known $B \rightarrow X_c \ell \nu$ decays
 - $\sim 15\%$ of inclusive $B \rightarrow X_c \ell \nu$ rate not accounted for in Σ (exclusive)
- FF parameterization:
 - z expansion works very well; quadratic term is sufficient
 - Theoretical w dependence assumed for FF ratios $R_1 \sim A_2/A_1$, $R_2 \sim V/A_1$
 - Measurements of $R_1(w=1)$ and $R_2(w=1)$ need to improve (hard)

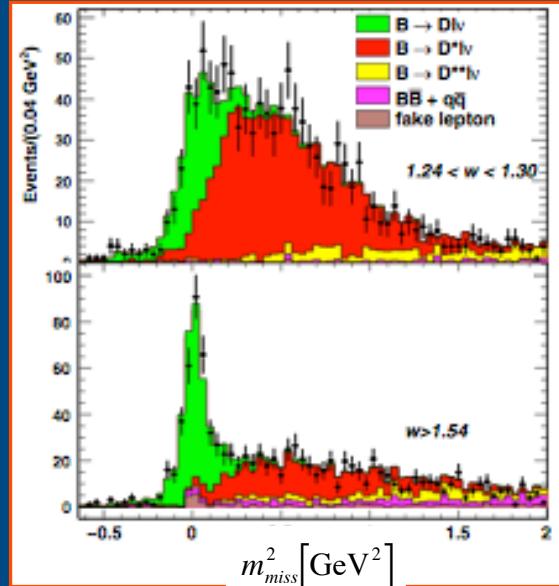
Exclusive $B \rightarrow D\ell\nu$ decays

- Background from $D^*\ell\nu$ is significant (larger BF, missing slow π)
- Rate doubly suppressed at $w=1$ (both phase space and spin)
- Recent BaBar measurements give improved accuracy on $B \rightarrow D\ell\nu$

$$\mathcal{G}(1)|V_{cb}| = (42.3 \pm 1.9 \pm 1.0) \times 10^{-3}$$

$$\rho_G^2 = 1.20 \pm 0.09 \pm 0.04$$

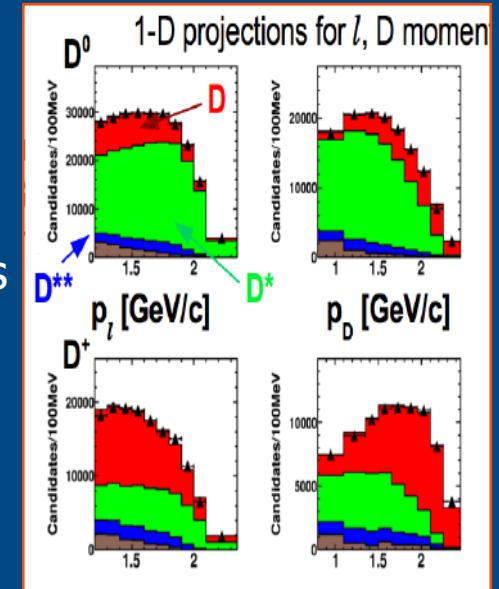
BaBar PRL104:011802 (2010)



$$\mathcal{G}(1)|V_{cb}| = (43.1 \pm 0.8 \pm 2.1) \times 10^{-3}$$

$$\rho_G^2 = 1.20 \pm 0.04 \pm 0.06$$

BaBar PRD 79:012002 (2009)



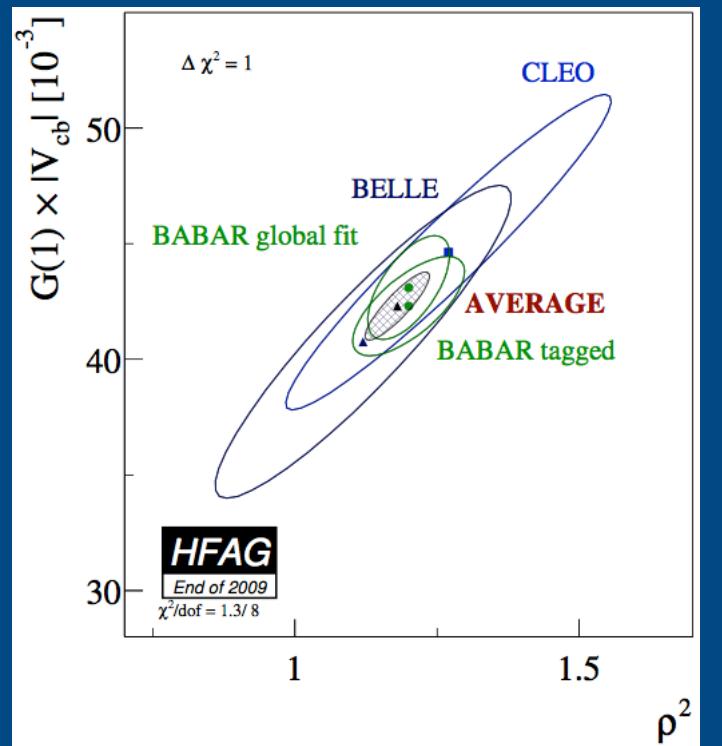
Recoil-based analysis

Global fit to $B \rightarrow D(X)\ell\nu$ decays

$|V_{cb}|$ from $B \rightarrow D \ell \nu$ decays

- Using[#] $G(1) = 1.074 (18) (16)$ from unquenched LQCD [heplat/0510113]
 $|V_{cb}| = (39.1 \pm 1.4_{\text{exp}} \pm 1.3_{\text{th}}) * 10^{-3}$
- Recall $D^* \ell \nu$ result: $|V_{cb}| = (38.9 \pm 0.7 \pm 1.0) * 10^{-3}$
- Issues:
 - Main systematics from detector modeling and backgrounds. Systematics smaller in tagged analysis
 - Further improvement ($0.8 * \text{error}$) possible with present B-factory data

[#] Other $G(1)$ values are discussed in T. Mannel talk



OPE for inclusive decays

- Description applies to $b \rightarrow c$ and $b \rightarrow u$ transitions
 - Phase space and energy release smaller in $b \rightarrow c$
 - Similar treatment for radiative $b \rightarrow s\gamma$ decays
- Schematically,

$$\Gamma(b \rightarrow q\ell\nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{qb}|^2 (1 + A_{ew}) A^{pert}(r, \mu) \left[z_0(r) + z_2(r) \left(\frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2} \right) + z_3(r) \left(\frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3} \right) + \dots \right] \quad \left(r = \frac{m_q}{m_b} \right)$$

- Leading correction is at $\mathcal{O}(\Lambda/m_b)^2$
- Matrix elements of local operators \rightarrow non-perturbative quantities
- **Same** non-perturbative input appears in spectral moments:

$$\langle E_\ell^n M_X^{2m} \rangle = \frac{1}{\Gamma_0} \int_{E_0}^{E_{\max}} dE_\ell \int dM_X^2 \frac{d\Gamma(\mu_\pi^2, \mu_G^2, \rho_D^3, \dots)}{dE_\ell dM_X^2} E_\ell^n M_X^{2m}$$

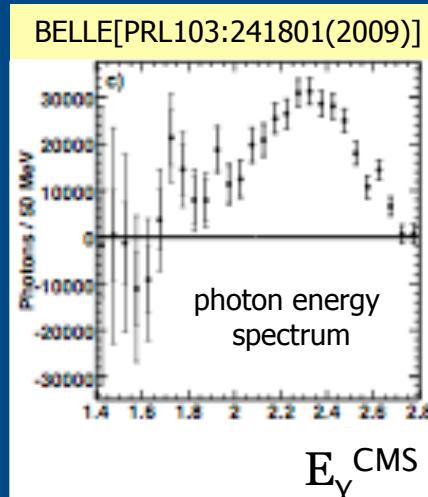
- Perturbative corrections known to α_s^2 on leading terms, α_s on $1/m_b$ terms; existing fit results do not yet incorporate all corrections

Inclusive $b \rightarrow c \ell \nu$ decays

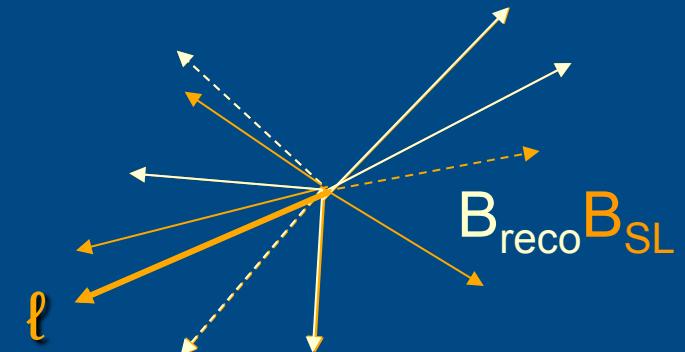
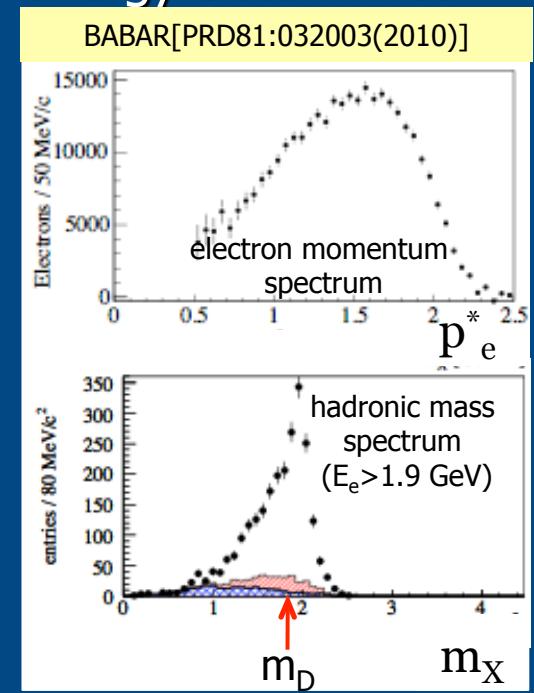
- Measure distributions from $b \rightarrow c \ell \nu$ decays
 - challenge to correctly assign particles to the semileptonic decay
 - must account for undetected particles
- Moments of lepton energy and hadronic mass or energy determined by BABAR, BELLE, CLEO, CDF, DELPHI

- Latest measurements

$b \rightarrow s \gamma$:

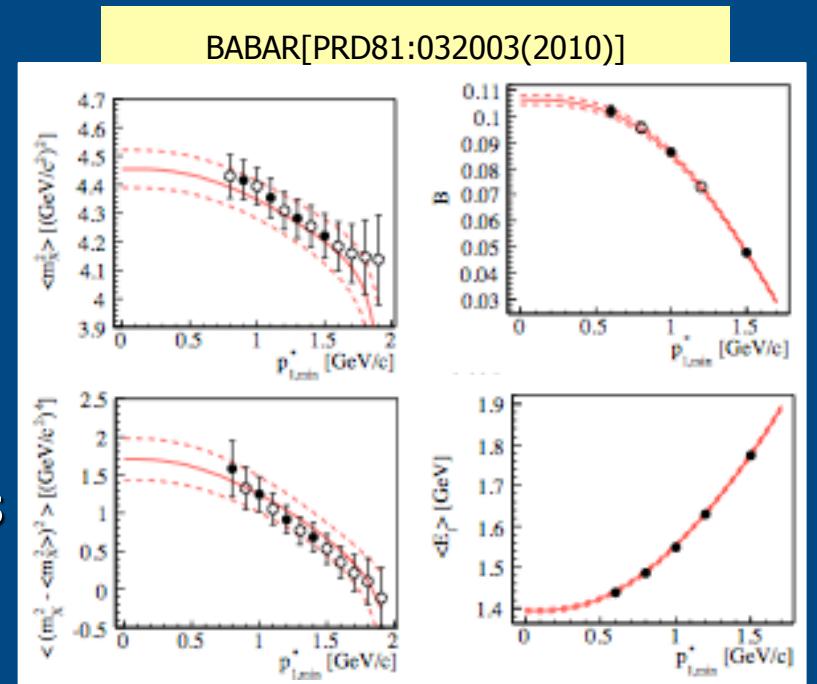


$b \rightarrow c \ell \nu$:



Global fit to mass, energy moments

- Fit of OPE to ~ 60 measured moments determines $|V_{cb}|$, m_b , m_c and non-perturbative pars
- Two mass renormalization schemes in use: "1S" and "Kinetic". Example shows Kinetic Scheme fit to BaBar
- Only a subset of moments shown, and not all points fitted due to high correlations (each moment integrates data above some $E_{e, \text{min}}$)
- Leading expt systematics due to modeling of detector, B & D decays

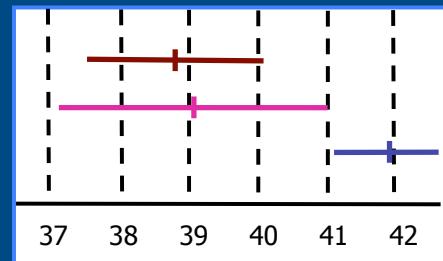


Global fit results, issues

- Global fit to moments from all experiments (HFAG):

Input	$ V_{cb} (10^{-3})$	$m_b^{\text{kin}} \text{ (GeV)}$	$\mu_n^2 \text{ (GeV}^2)$	χ^2 / ndf
all moments	$41.85 \pm 0.42 \pm 0.59$	4.591 ± 0.031	0.454 ± 0.038	$29.7 / (66-7)$
only $b \rightarrow c \ell v$	$41.68 \pm 0.44 \pm 0.58$	4.646 ± 0.047	0.439 ± 0.042	$24.2 / (55-7)$

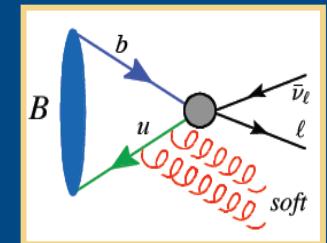
- Improved error on m_b with $b \rightarrow s \gamma$ included
- χ^2/ndf always too small (Prob ~ 0.9995)
 - Despite detailed evaluation of correlations, are they a problem?
 - What about theory correlations?
- 1S scheme fit: $|V_{cb}| = (41.87 \pm 0.25 \pm 0.08) * 10^{-3}$
- $|V_{cb}| \sim 2.3\sigma$ larger than for exclusives:



$ V_{cb} * 10^3$
D*lv: $38.8 \pm 0.8 \pm 1.0$
D lv: $39.1 \pm 1.4 \pm 1.3$
inclusive: $41.9 \pm 0.4 \pm 0.6$
average: 40.9 ± 1.0 (scaled)

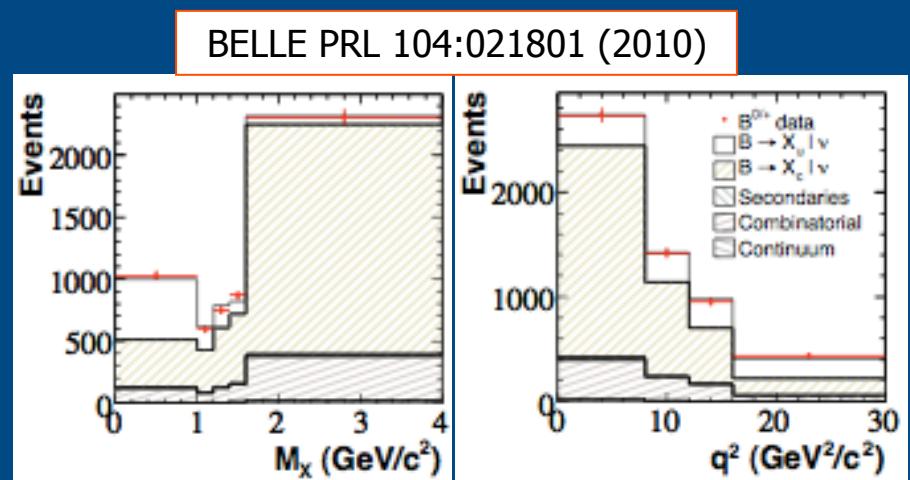
Inclusive $b \rightarrow u \ell \bar{\nu}$ decays

- Background from CKM-favored decays is ~ 50 times signal
- Most measurements restrict kinematics; OPE convergence destroyed
 - introduces reliance on a-priori unknown shape function (SF)
 - restricted kinematics further increase sensitivity to m_b
 - complicates theory – see talk of T. Mannel
- Weak annihilation (WA) contributions poorly known (but there is recent progress); matters for measurements with acceptance predominantly at high q^2
- Trade-off between theory errors (increase with tighter kinematic cuts) and $b \rightarrow c \ell \nu$ background errors (decrease with cuts)



Measurements of inclusive $b \rightarrow u \ell \nu$

- Fully inclusive analyses still relevant (e.g. lepton endpoint spectrum)
- Recoil analyses can measure m_X , q^2 , P_+ ($=E_X - |\vec{p}_X|$); separation between $b \rightarrow u$ and $b \rightarrow c$ better than for fully inclusive E_ℓ
- Additional cuts needed to reduce impact of K_L , extra ν
- Latest Belle result makes no *explicit* kinematic cut except $E_\ell > 1$ GeV
- Uses boosted decision tree that includes kinematic quantities, # of kaons, reconstruction quality, etc.
- Systematics mostly from $b \rightarrow u$ modeling, detector modeling



Summary of inclusive $b \rightarrow u\ell\nu$ measurements

- Partial BF measurements ($\times 10^5$); total $b \rightarrow u\ell\nu$ BF ~ 220

<i>CLEO</i>	<i>BaBar</i>	<i>Belle</i>	<i>BaBar</i>	<i>Belle</i>	<i>BaBar</i>	<i>BaBar</i>	<i>BaBar</i>	<i>Belle</i>
$E_\ell > 2.1$	$E_\ell - q^2$	$E_\ell > 1.9$	$E_\ell > 2.0$	$m_X - q^2$	$m_X < 1.55$	$m_X - q^2$	P_+	$E_\ell > 1$
$33 \pm 2 \pm 7$	$44 \pm 4 \pm 4$	$85 \pm 4 \pm 15$	$57 \pm 4 \pm 7$	$74 \pm 9 \pm 13$	$118 \pm 9 \pm 7$	$81 \pm 8 \pm 7$	$95 \pm 10 \pm 8$	$196 \pm 17 \pm 16$

- Sample different portions of phase space: important for testing theoretical partial rate predictions

- Stat and Sys errors comparable; systematic come from
 - detector modeling (K_L , acceptance and efficiency, PID)
 - $b \rightarrow c l \nu$ background, charm decay modeling
 - Modeling of $b \rightarrow u l \nu$ decay (***correlated with theoretical parameters***)
 - Yield biases in M_{ES} fits (recoil only)

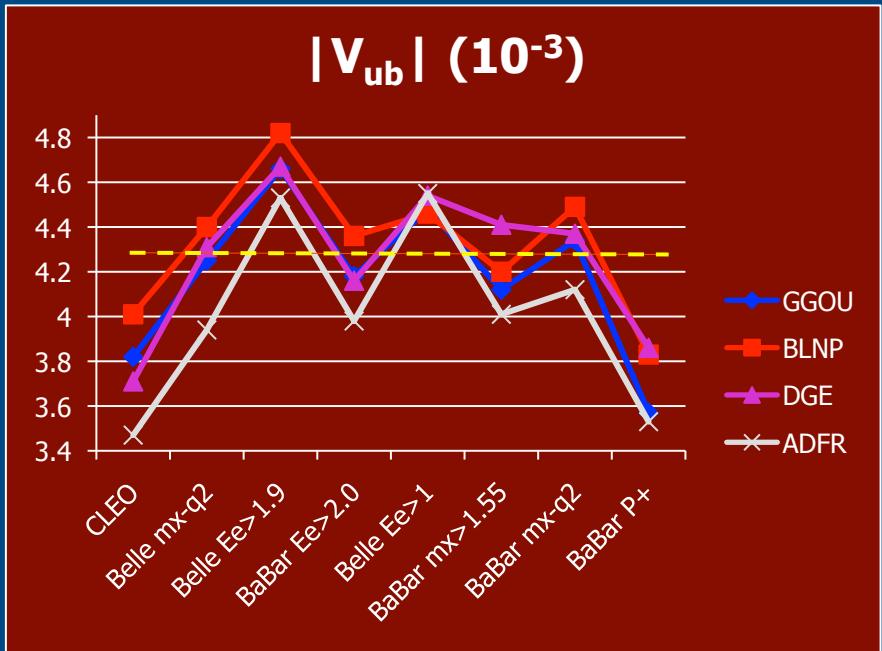
Theoretical calculations

- All calculations must agree for fully inclusive rate (OPE result), where m_b error is the dominant uncertainty
- Partial rate calculations differ in how to accommodate restricted PS
 - BLNP_{(Lange, Neubert, Paz) [PRD 72:073006, 2005]} uses multi-scale OPE based on SCET **H J S** convolution; leading SF is universal, but sub-leading are \sim unconstrained
 - GGOU_{(Gambino, Giordano, Ossola, Uraltsev) [JHEP 0710:058, 2007]} uses the distribution function (incorporates sub-leading f_{n^s}) per light-cone momentum component k_\perp ; large range of model functions. WA is modeled and included
 - DGE_{(Andersen, Gardi) [JHEP 0601:097, 2006]} uses resummed perturbation theory, including for SF; consistent with local OPE to order Λ^2/m_b^2
 - ADFR_{(Aglietti, DiLodovico, Ferrera, Ricciardi) [NuclPhysB 768:85, 2007]} model uses “analytic coupling”; violates local OPE at Λ/m_b
- The point is: they take different approaches
- Sample error analysis on $|V_{ub}|$ (in %) for GGOU calculation:

$$\pm 2.3_{\text{stat}} \pm 1.9_{\text{exp}} \pm 1.2_{b2c} \pm 1.6_{b2u} \pm 2.5_{\text{par}} \pm 1.5_{\text{pert}} \pm 1.7_{q^2} \begin{matrix} +0 \\ -3.9 \\ \text{WA} \end{matrix} \begin{matrix} +0.5 \\ -0.2 \\ \text{sff} \end{matrix} = \begin{matrix} +4.9 \\ -6.3 \\ \text{Total} \end{matrix}$$

Issues for inclusive $|V_{ub}|$

- Spread among calculations is comparable to quoted theory (non-parametric) errors
- Several common errors (e.g. m_b , WA) are important
- Theory error analyses differ but total errors are similar
- Recent calculations [arXiv:0909.1609] of NNLO perturbative terms for BLNP show large changes (*increase* $|V_{ub}|$ by $\sim 8\%$)



- “Average of the averages” given below; add error to allow for NNLO change (value unchanged)

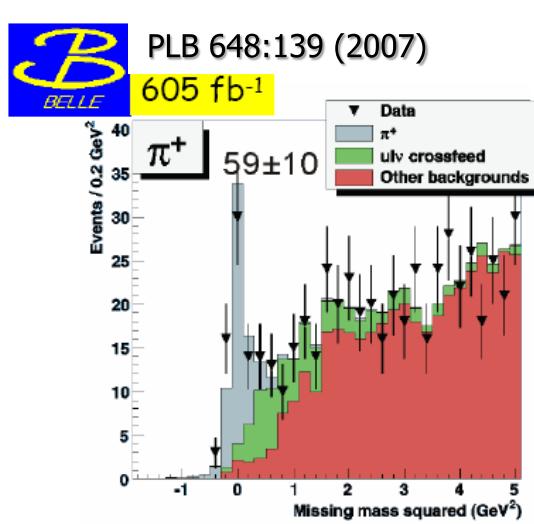
$$|V_{ub}| = (4.37 \pm 0.16_{\text{exp}} \pm 0.20_{\text{th}} \pm 0.30_{\text{NNLO}}) * 10^{-3}$$

Exclusive $B \rightarrow X_u \ell \nu$ decays

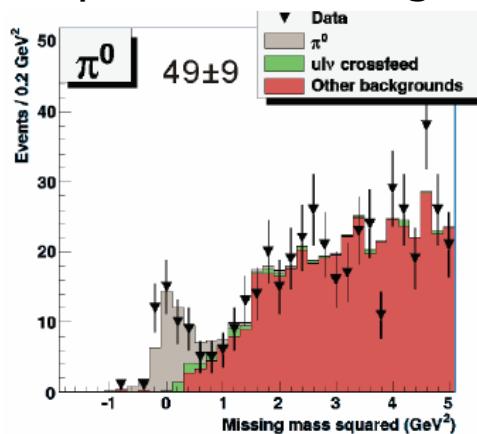
- Golden mode (theory and expt) for exclusive $|V_{ub}|$: $B \rightarrow \pi \ell \nu$
 - lower backgrounds than $B \rightarrow \rho \ell \nu$
 - Lattice has trouble with large width of ρ
- Experimental measurement done with/without recoil B tagging
 - Usual tradeoff between background rejection and efficiency
- Tagged measurements taken together improve precision of BF
- Untagged measurements give powerful information on q^2 shape

Tagged $B \rightarrow \pi \ell \nu$

- Tagged measurements very clean but have low efficiency
- Semileptonic ($D^{(*)} \ell \nu$) and hadronic tags both used
- Low statistics makes split into q^2 bins marginal



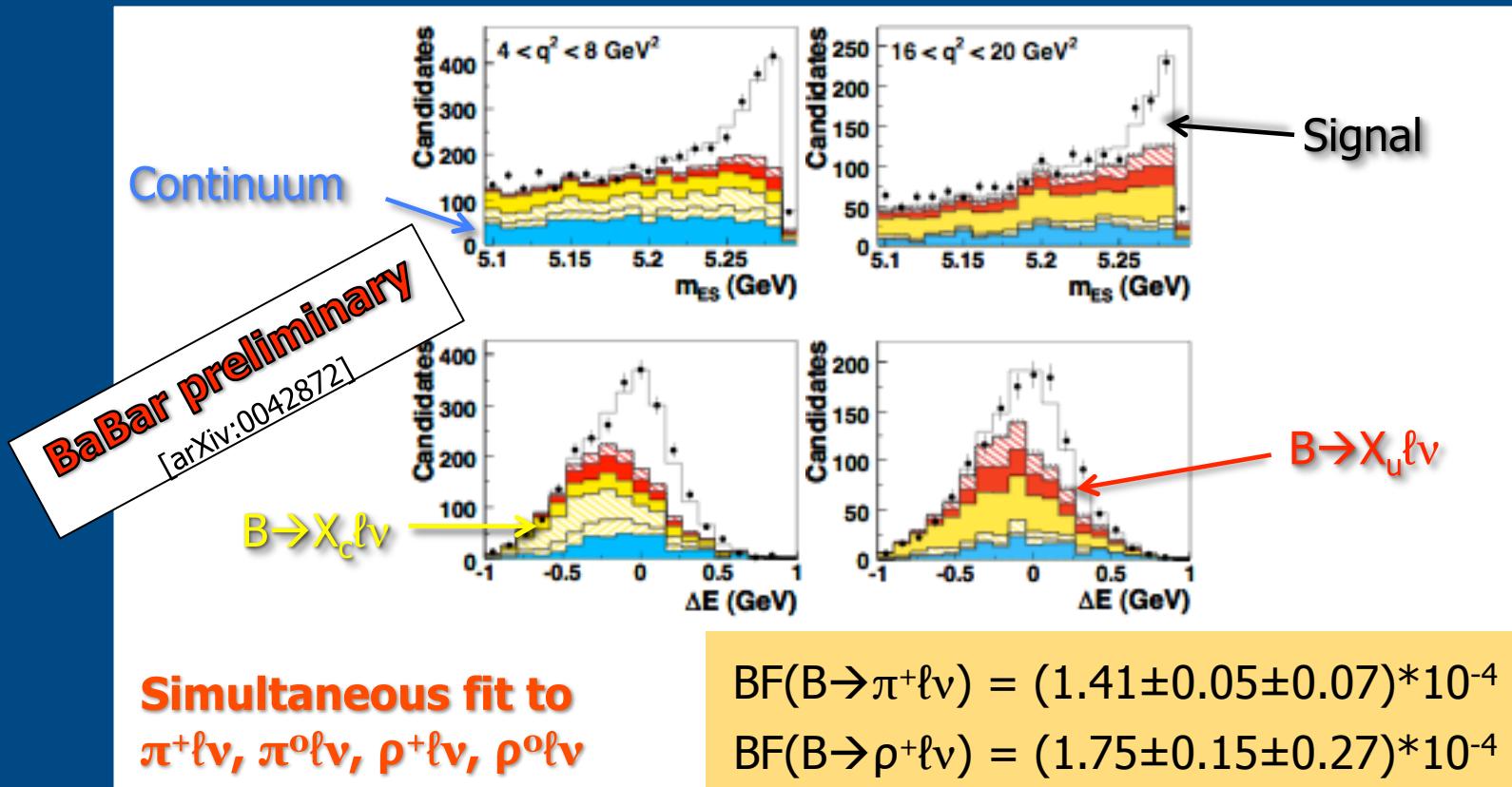
Example: hadronic tags



- Very promising for higher luminosity B factories

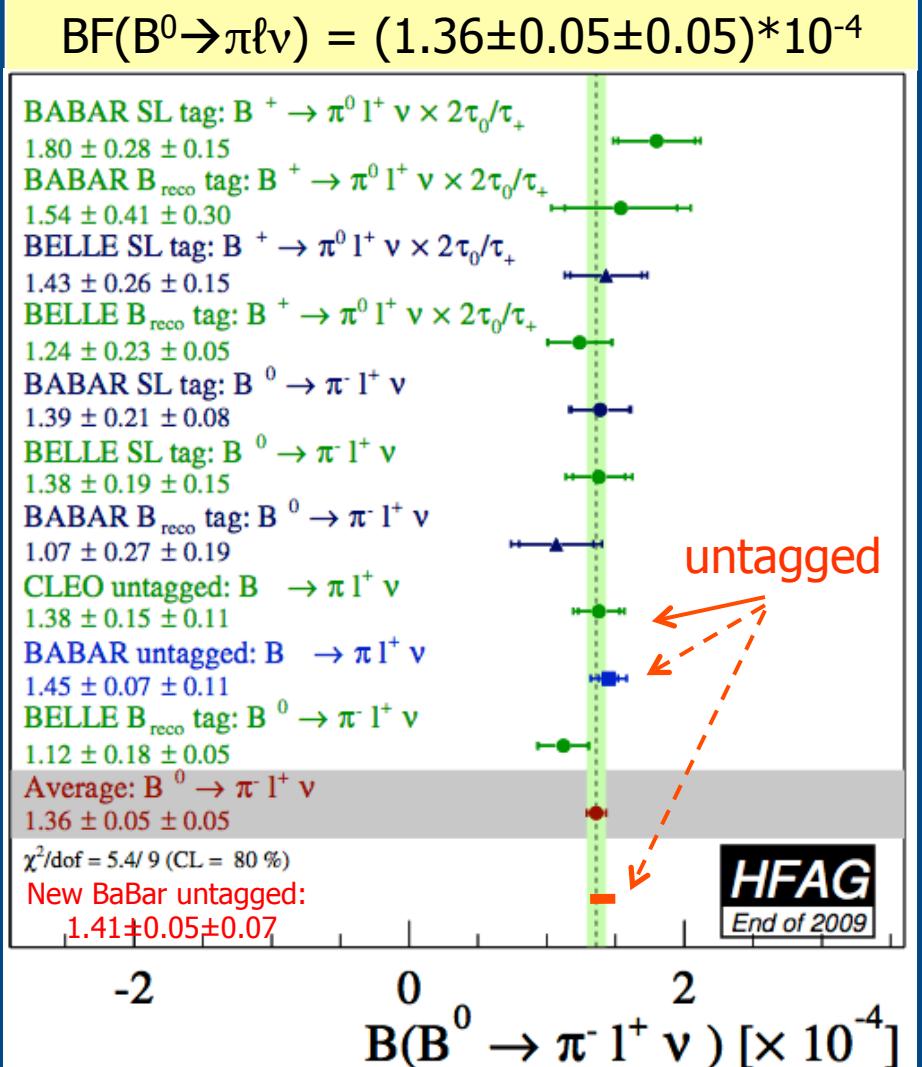
Untagged $B \rightarrow \pi^0\ell\nu$, $B \rightarrow \rho^0\ell\nu$

- Latest untagged measurement just submitted to PRD



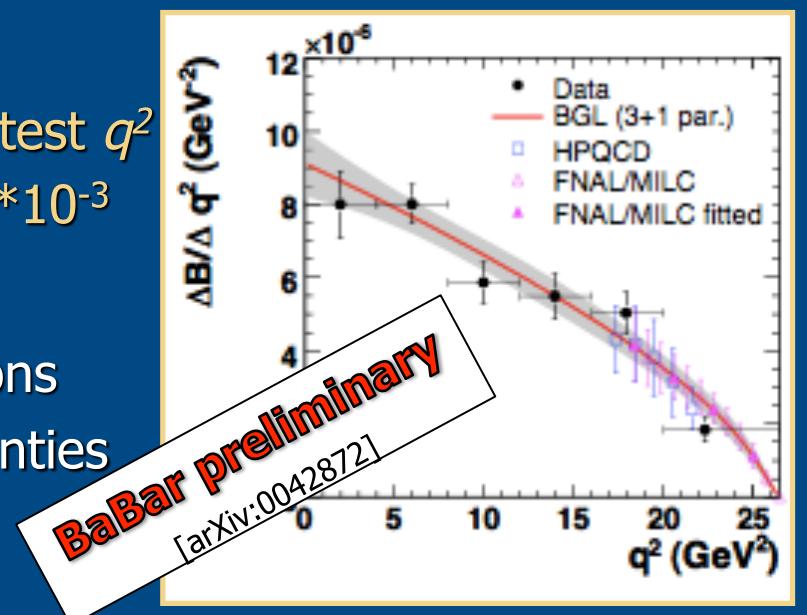
B \rightarrow $\pi\ell\nu$ average

- Averages of tagged and untagged results are similar
- Leading systematics from detector modeling, background, K_L (untagged)
- Most systematic errors can be reduced with more data
- Newest untagged measurement not yet in average



$|V_{ub}|$ from $B \rightarrow \pi l \nu$

- $|V_{ub}|$ determined in a simultaneous fit to calculated and measured points as a function of q^2 (or z)
- Lattice points based on 2+1 light flavors, staggered fermions
- Fermilab/MILC fit^[PRD79:054507(2009)] to lattice points and *previous* BaBar data^[PRL98:091801(2007)] gives $|V_{ub}| = (3.38 \pm 0.35) \times 10^{-3}$
- New preliminary BaBar result, using latest q^2 spectrum, gives $|V_{ub}| = (2.95 \pm 0.31) \times 10^{-3}$
- Total error has comparable contributions from lattice and experimental uncertainties



$|V_{ub}|$ comparisons

■ Source	$ V_{ub} * 10^3$	comments
■ $B \rightarrow \pi l \nu$	2.95 ± 0.31	Latest combined fit to data, lattice
■ $b \rightarrow u l \nu$	4.37 ± 0.39	2.7σ apart PDG2010 average; error inflated to account for NNLO result
■ UTfit	3.48 ± 0.16	(ICHEP 2008)
CKMFitter	$3.51^{+0.15}_{-0.16}$	(Beauty 2009)
■ Have to take this difference seriously		Predictions from CKM fits
– work of multiple experiments, multiple theoretical groups		
– m_b , WA and perturbative corrections are important for inclusive $ V_{ub} $		
– exclusive result relies on non-perturbative normalization input		

Summary and outlook

- $|V_{cb}|$ determinations (incl/excl) differ by $\sim 2.3\sigma$; their average, with inflated error, is $(40.9 \pm 1.0) \times 10^{-3}$
- $|V_{ub}|$ determinations (incl/excl) differ by $\sim 2.7\sigma$; latest updates have increased this long-standing discrepancy (moving to NNLO will further increase it)
 - $|V_{ub}|$ exclusive: 2.95 ± 0.31
 - $|V_{ub}|$ inclusive: 4.37 ± 0.39
- The naïve average of these nevertheless agrees with CKM fits ;^)
- There is still scope for improvements with existing B-factory data; several key measurements not yet done on full statistics

Backup slides

$B \rightarrow D^{**} \ell \nu$, other decays

- The $D\ell\nu$ and $D^*\ell\nu$ modes do not saturate the inclusive and $B \rightarrow X_c \ell \nu$ rate
- The addition of all known modes ($D^{(*)}\pi\ell\nu$) still leaves $\sim 15\%$ of the inclusive semileptonic BF unaccounted for
- While the BF for the narrow D^{**} states are well measured, the BF for broad states (S-wave decays) are controversial, as the determination of quantum numbers is not feasible at present

Determination of m_b

- Semileptonic moments determine $(m_b - m_c)$ very well (± 25 MeV); for precise m_b determination, independent input is needed
- Can include $b \rightarrow s\gamma$ in the fit (done by HFAG)
- Other possibilities include threshold or lattice determinations of m_b or m_c
- Crucial input for $|V_{ub}|$; $m_b \downarrow \rightarrow |V_{ub}| \uparrow$

