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

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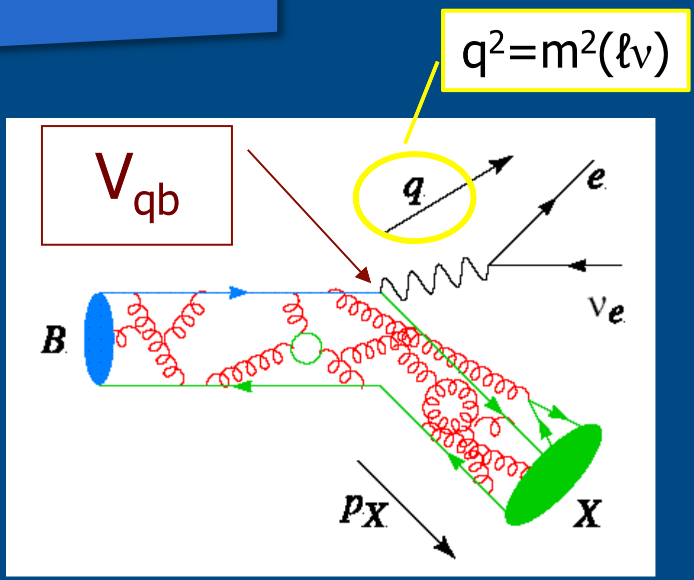
on behalf of the
BaBar Collaboration

Executive summary

- Determinations of $|V_{ub}|$ and $|V_{cb}|$ use well-established methods
- "Turning the crank" gives intriguing results
  - uncertainties of ~2% on $|V_{cb}|$ and ~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

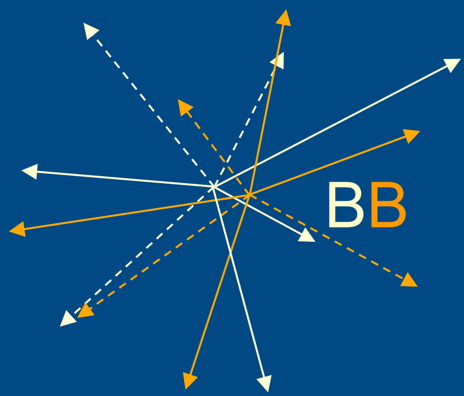
- Large BF, only one hadronic current
- Inclusive decays $b \rightarrow q\ell\nu$:
  - Weak quark decay + QCD corrections
  - Operator Product Expansion in α_s and Λ/m_b
- Exclusive decays $B \rightarrow X\ell\nu$:
  - Form factors need non-perturbative input, e.g. Lattice QCD

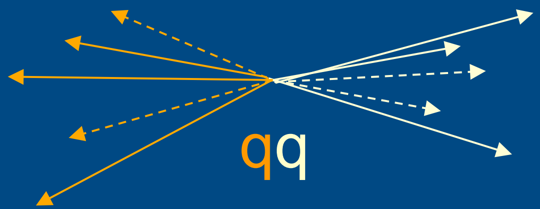


The uncertainties in the theory inputs for inclusive and exclusive determinations of $|V_{qb}|$ are independent

Measuring semileptonic B decays

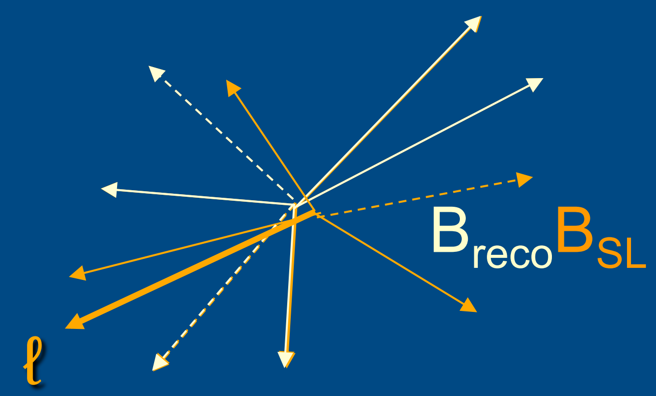
- Inclusive decays b → qℓν:
  - Measure electron or muon
  - Measure $\mathbf{p}_{\mathbf{miss}}$ or associated hadrons
- Exclusive decays B → X_qℓν:
  - Measure lepton and specified hadron
- Data from Υ(4S)→BB; decay products overlap
  - proper assignment of particles difficult
- Determine non-B contribution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





Measurements based on recoil samples

- Reconstruct 1 B and 1 lepton in event; remaining particles come from X in $B \to X\ell\nu$.
  - hadronic tags determine $\mathbf{p}_B$ for one B; allow access to all kinematic variables but with low efficiency ~ 0.3%
  - $D^{(*)}\ell\nu$ tags; no $\mathbf{p}_B$, but efficiency ~ 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 $B \rightarrow D^{*}\ell\nu$ and $B \rightarrow D\ell\nu$ decays
  - Exclusive $B \rightarrow \pi\ell\nu$ decays
  - Inclusive $b \rightarrow c\ell\nu$ decays
  - Inclusive $b \rightarrow u\ell\nu$ decays

Exclusive decay rates

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

form factors

phase space

D boost in the *B* rest frame

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

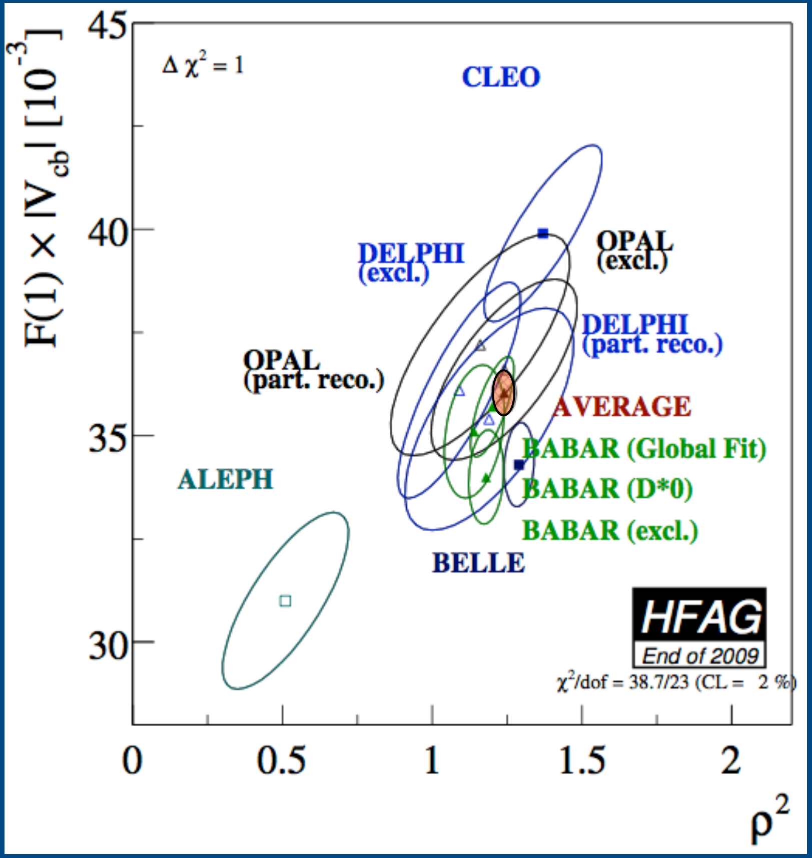
$$\frac{d\Gamma(B \to D\ell\nu)}{dw} = \frac{G_F^2 |V_{cb}|^2}{48\pi^3} \left(\mathcal{G}(w)\right)^2 \Phi(w)$$

- Parameterization of FF uses unitarity and analyticity. Expansion is in a variable with limited range $z \equiv \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}; \quad 0 < z < 0.065$; 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 $B \to D^* \ell \nu$ decays

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



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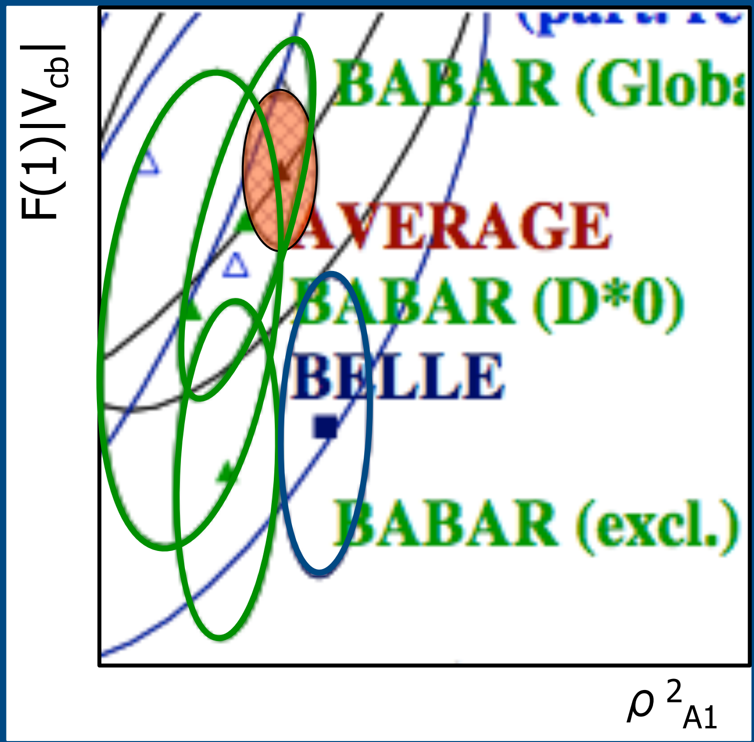
- Poor χ^2; PDG scale error by $\sqrt{\chi^2/ndf} \approx 1.3$
  - zoom
- Using unquenched lattice result
  $F(1) = 0.927\ (13)\ (20)$ [PRD79:014506(2009)]
  $|V_{cb}| = (38.9 \pm 0.7_{exp} \pm 1.0_{th})*10^{-3}$



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
  - ~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)

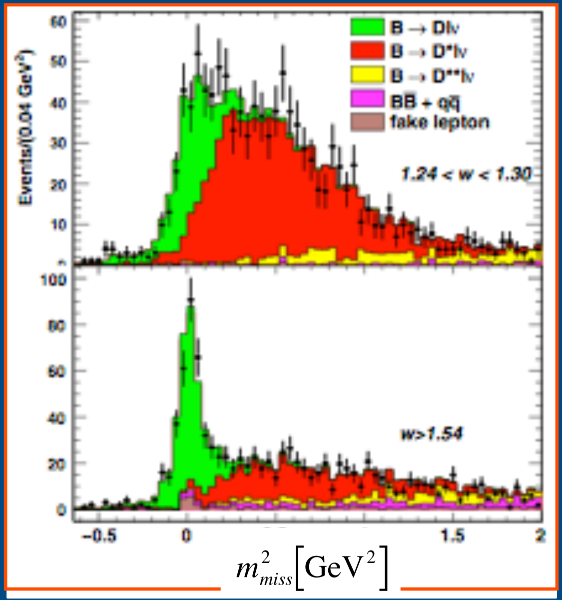
Exclusive B→Dℓν decays

- 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→Dℓν

$$\mathcal{G}(1)|V_{cb}| = (42.3 \pm 1.9 \pm 1.0) \times 10^{-3}$$
$$\rho_{\mathcal{G}}^2 = 1.20 \pm 0.09 \pm 0.04$$

BaBar PRL104:011802 (2010)

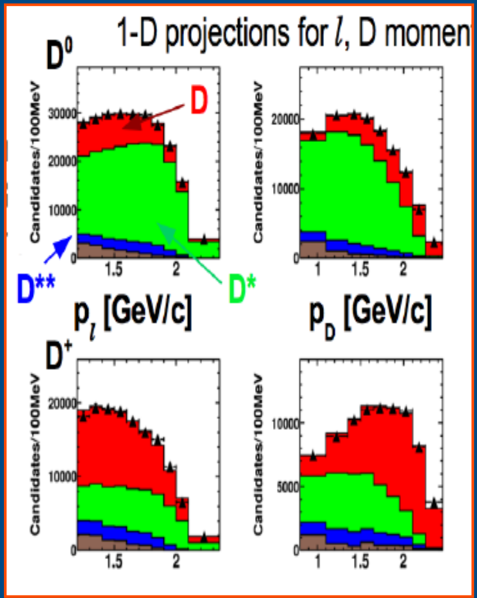
Recoil-based analysis



$$\mathcal{G}(1)|V_{cb}| = (43.1 \pm 0.8 \pm 2.1) \times 10^{-3}$$
$$\rho_{\mathcal{G}}^2 = 1.20 \pm 0.04 \pm 0.06$$

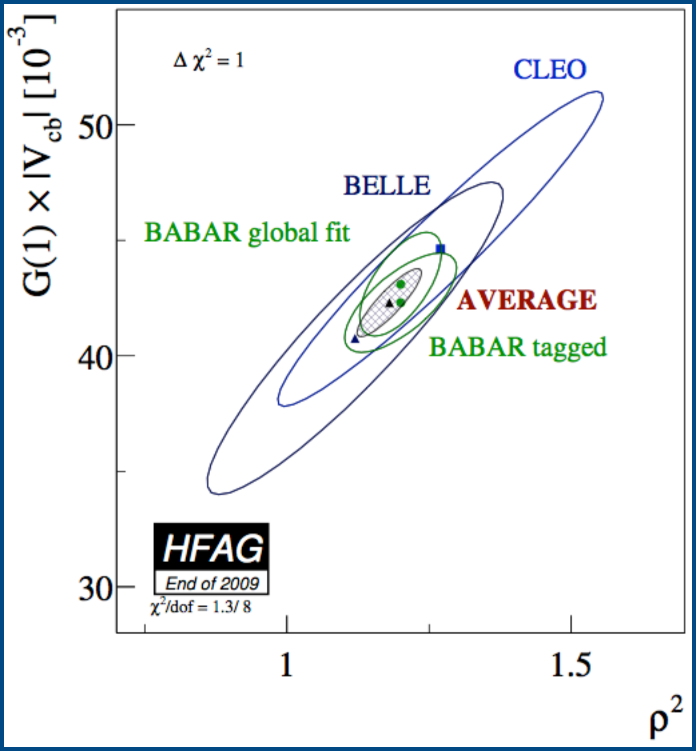
BaBar PRD **79**:012002 (2009)

Global fit to B→D(X)ℓν decays



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

- Using# $G(1) = 1.074\ (18)\ (16)$ from unquenched LQCD [heplat/0510113]
  $|V_{cb}| = (39.1 \pm 1.4_{exp} \pm 1.3_{th}) \times 10^{-3}$
- Recall $D^*\ell\nu$ result: $|V_{cb}| = (38.9 \pm 0.7 \pm 1.0) \times 10^{-3}$
- Issues:
  - Main systematics from detector modeling and backgrounds
  - Further gain (0.8 * error) possible with present B-factory data
  - Combined fit to data/Lattice versus *z* may lead to additional improvement



Other G(1) values are discussed in T. Mannel talk

OPE for inclusive decays

- Description applies to b→c and b→u transitions
  - Phase space and energy release smaller in b→c
  - Similar treatment for radiative b→sγ decays
- Schematically,

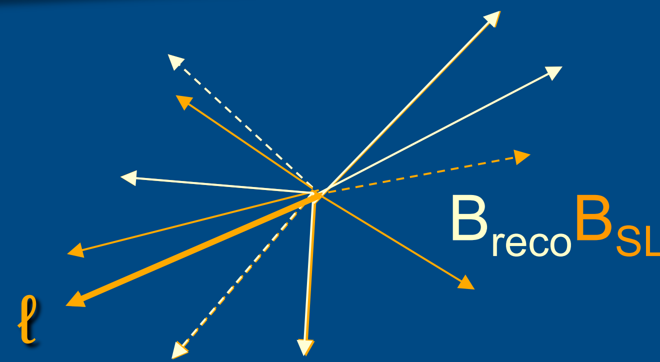
$$\Gamma(b \to q\ell\nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{qb}|^2 (1 + A_{ew}) A^{pert}(r,\mu) \left[z_0(r) + z_2(r)\left(\frac{\mu_\pi^2}{m_b^2}, \frac{\mu_G^2}{m_b^2}\right) + z_3(r)\left(\frac{\rho_D^3}{m_b^3}, \frac{\rho_{LS}^3}{m_b^3}\right) + \ldots \right] \quad \left(r = m_q / m_b\right)$$

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

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

- 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

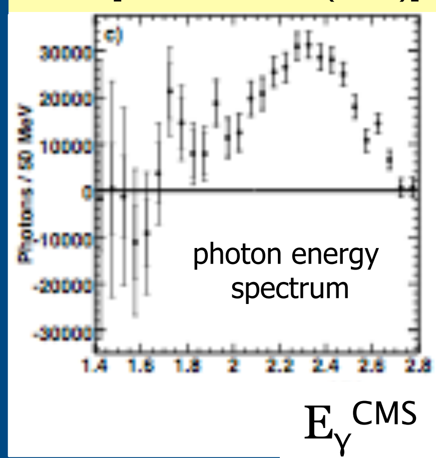
Inclusive b→cℓν decays



- Measure distributions from b→cℓν 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

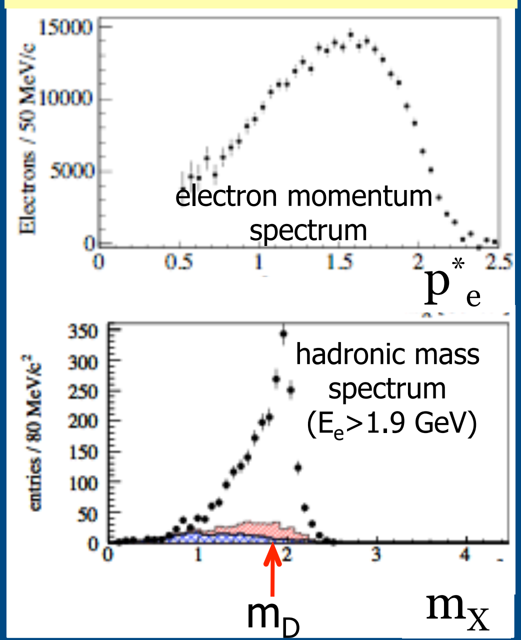
b→sγ:

BELLE[PRL103:241801(2009)]



b→cℓν:

BABAR[PRD81:032003(2010)]



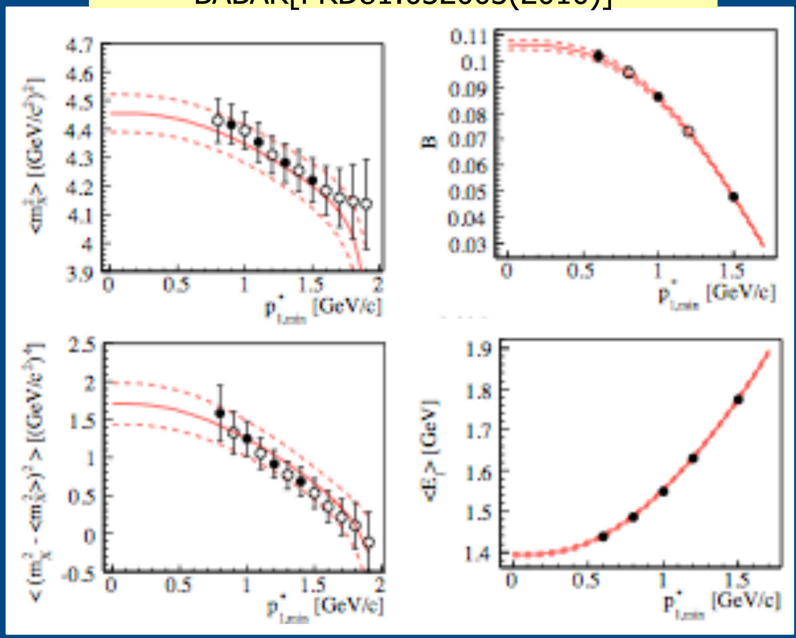
Global fit to mass, energy moments

- 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 $E_{e,\,min}$)

BABAR[PRD81:032003(2010)]



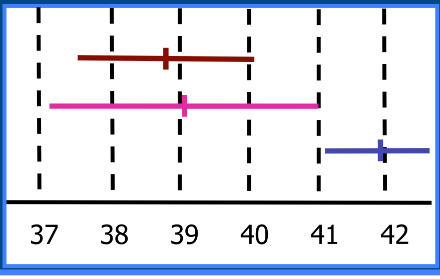
- Leading expt systematics due to modeling of detector, B & D decays

Global fit results, issues

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

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

- Improved error on m_b with $b \to s\gamma$ included
- χ^2/ndf always too small (Prob ~0.9995)
  - Despite detailed evaluation of correlations, are they a problem? (see backup slide)
  - What about theory correlations?
- 1S scheme fit: $\lvert V_{cb}\rvert=(41.87\pm0.25\pm0.08)*10^{-3}$
  - χ^2/ndf also too small
- $\lvert V_{cb}\rvert$ ~2.3 σ larger than for exclusives:



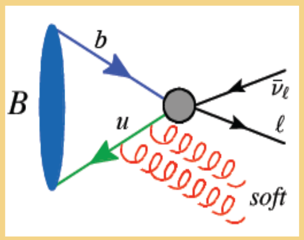
$\lvert V_{cb}\rvert*10^3$

$D^*\ell\nu$: 38.8±0.8±1.0
$D\ell\nu$: 39.1±1.4±1.3
inclusive: 41.9±0.4±0.6

average: 40.9±1.0 (scaled)

Inclusive $b \to u\ell\nu$ 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



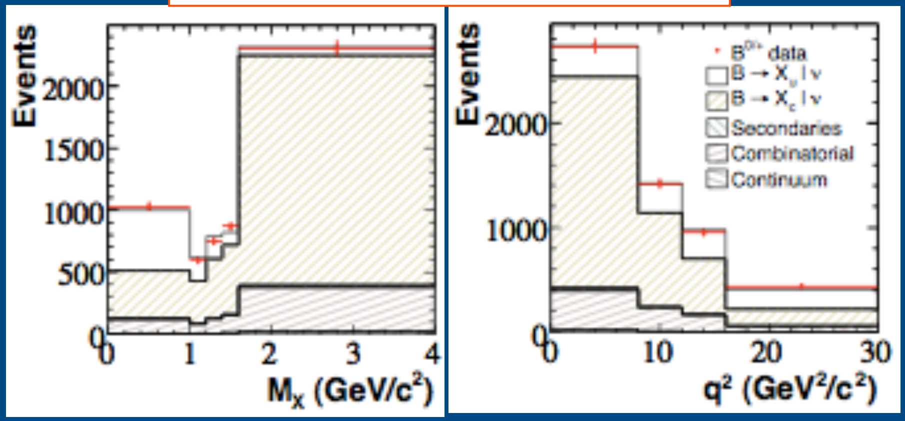
- Trade-off between theory errors (increase with tighter kinematic cuts) and $b \to c\ell\nu$ background errors (decrease with cuts)

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

- Fully inclusive analyses still relevant (e.g. lepton endpoint spectrum)
- Recoil analyses can measure m_X, q^2, P_+ ($=E_X-|p_X|$); separation between $b \to u$ and $b \to c$ 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.

BELLE PRL 104:021801 (2010)



- Systematics mostly from $b \to u$ modeling, detector modeling

Summary of inclusive b→uℓν measurements

- Partial BF measurements (*10^5); total b→uℓν BF ~220

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

Fully inclusive (CLEO through Belle $m_X - q^2$) — correlated (the three BaBar recoil measurements) — Recoil based (BaBar through Belle $E_\ell > 1$) — latest (Belle $E_\ell > 1$)

- 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→cℓν background, charm decay modeling
  - Modeling of b→uℓν 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 ~unconstrained
  - GGOU(Gambino, Giordano, Ossola, Uraltsev) [JHEP 0710:058,2007] uses one distribution function (incorporates sub-leading fn^s) per light-cone momentum component k_+; 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

See talk of T. Mannel

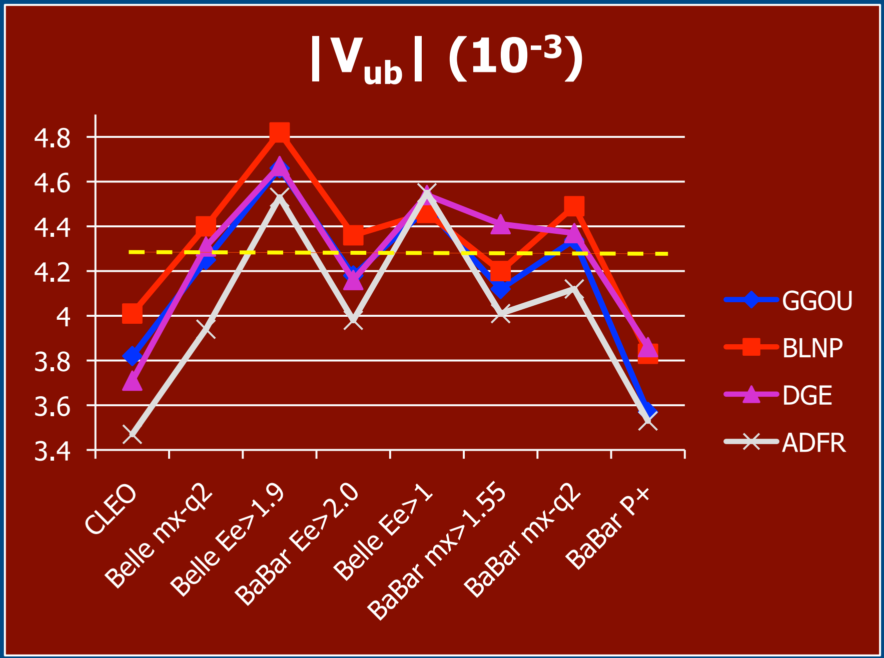
- <u>**The point is: they take different approaches**</u>
- Sample error analysis on $|V_{ub}|$ (in %) for GGOU calculation:

$$\pm 2.3_{stat} \pm 1.9_{\exp} \pm 1.2_{b2c} \pm 1.6_{b2u} \pm 2.5_{par} \pm 1.5_{pert} \pm 1.7_{q2} \begin{matrix}+0 \\ -3.9\end{matrix}_{WA} \begin{matrix}+0.5 \\ -0.2\end{matrix}_{sff} = \begin{matrix}+4.9 \\ -6.3\end{matrix}$$

m_b WA Total

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 ~8%)



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

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

Exclusive B → $X_u \ell \nu$ decays

- Golden mode (theory and expt) for exclusive $|V_{ub}|$: B → $\pi \ell \nu$
  - lower backgrounds than B → $\rho \ell \nu$
  - 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

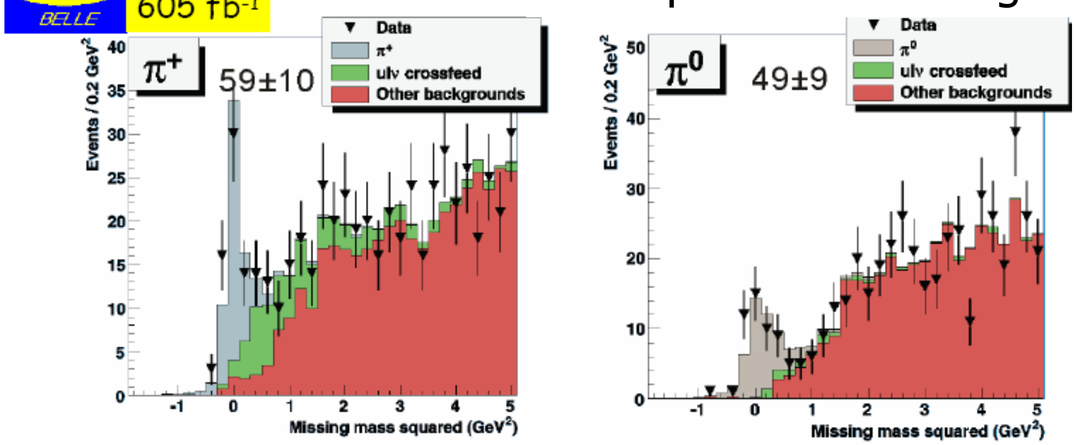
Tagged $B \to \pi \ell \nu$

- 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

PLB 648:139 (2007)

605 fb^{-1}

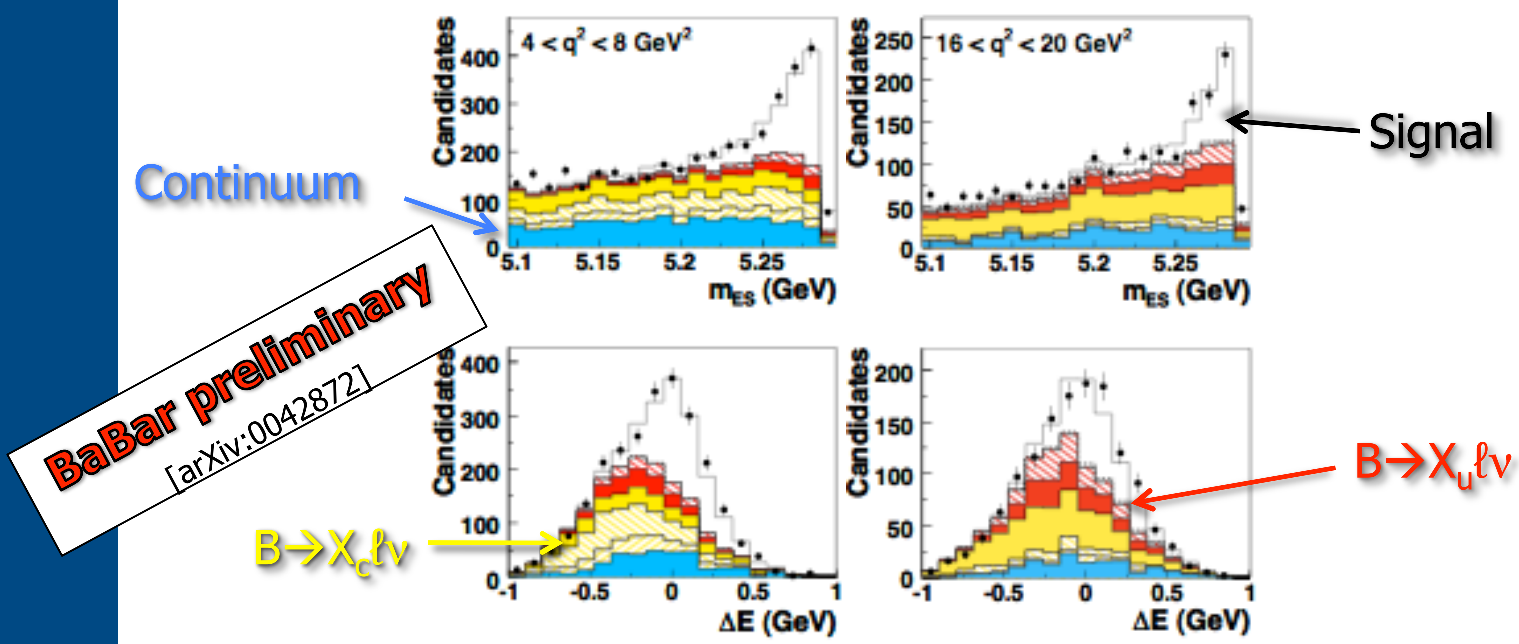
Example: hadronic tags



- Very promising for higher luminosity B factories

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

- Latest untagged measurement just submitted to PRD



Simultaneous fit to
$\pi^+\ell\nu$, $\pi^0\ell\nu$, $\rho^+\ell\nu$, $\rho^0\ell\nu$

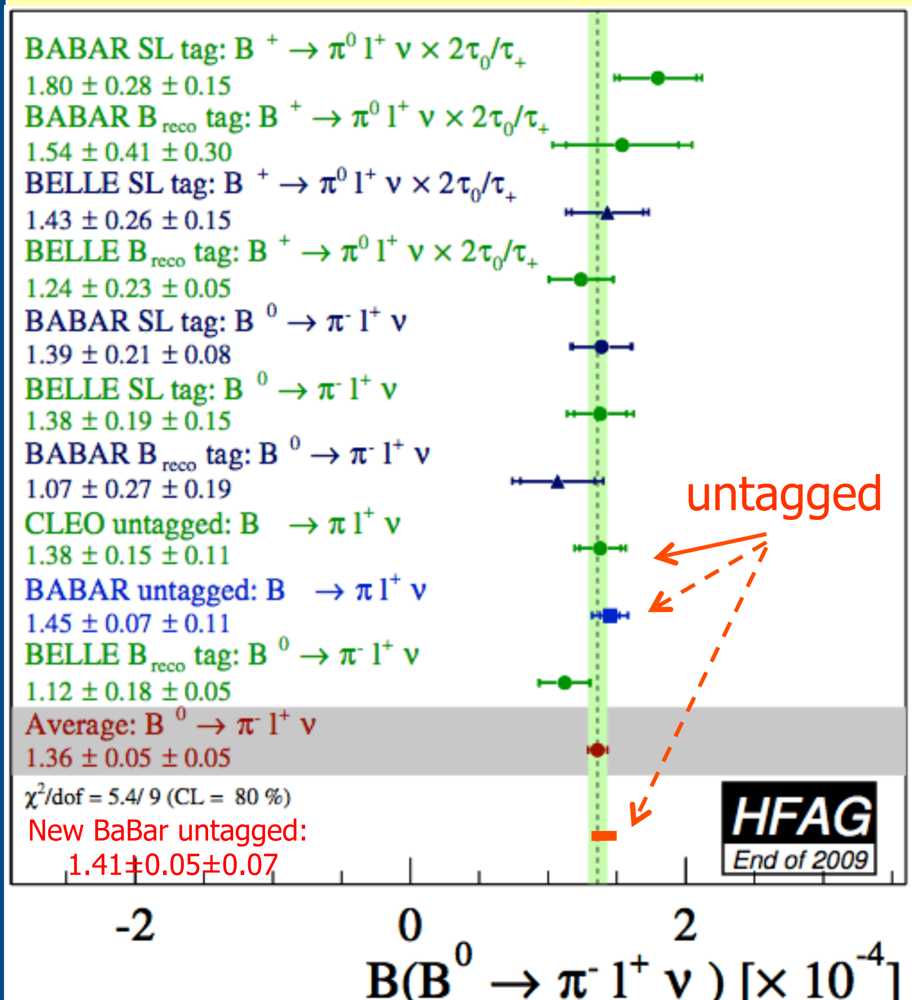
$BF(B \rightarrow \pi^+\ell\nu) = (1.41 \pm 0.05 \pm 0.07) * 10^{-4}$

$BF(B \rightarrow \rho^+\ell\nu) = (1.75 \pm 0.15 \pm 0.27) * 10^{-4}$

B→πℓν average

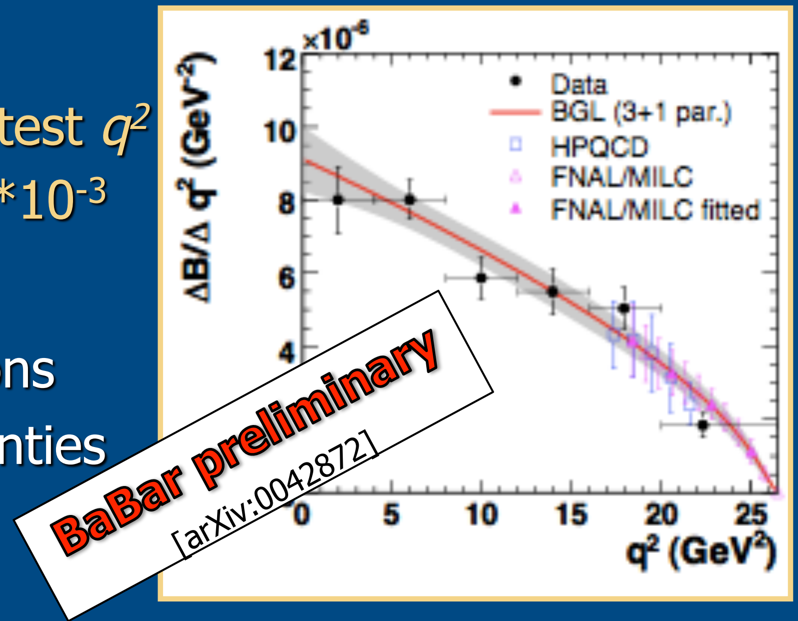
- Averages of tagged and untagged results are similar
- Leading systematics from detector modeling, background, K_L (untagged)
- Most systematic errors can be reduced with more data
- Newest untagged measurement not yet in average

$BF(B^0 \to \pi\ell\nu) = (1.36 \pm 0.05 \pm 0.05) * 10^{-4}$



$|V_{ub}|$ from $B \to \pi \ell \nu$

- $|V_{ub}|$ 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 $|V_{ub}| = (3.38 \pm 0.35)*10^{-3}$
- New preliminary BaBar result, using latest q^2 spectrum, gives $|V_{ub}| = (2.95 \pm 0.31)*10^{-3}$
- Total error has comparable contributions from lattice and experimental uncertainties



$|V_{ub}|$ comparisons

Source	$\lvert V_{ub}\rvert \times 10^3$	comments
$B \to \pi \ell \nu$	2.95 ± 0.31	Latest combined fit to data, lattice
		2.7 σ apart
$b \to u \ell \nu$	4.37 ± 0.39	PDG2010 average; error inflated to account for NNLO result
UTFit	3.48 ± 0.16	(ICHEP 2008) — Predictions from CKM fits
CKMFitter	$3.51^{+0.15}_{-0.16}$	(Beauty 2009) — Predictions from CKM fits

- Have to take this difference seriously
  - 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 ~2.3 σ; their average, with inflated error, is $(40.9\pm1.0)*10^{-3}$

- $|V_{ub}|$ determinations (incl/excl) differ by ~2.7 σ; 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

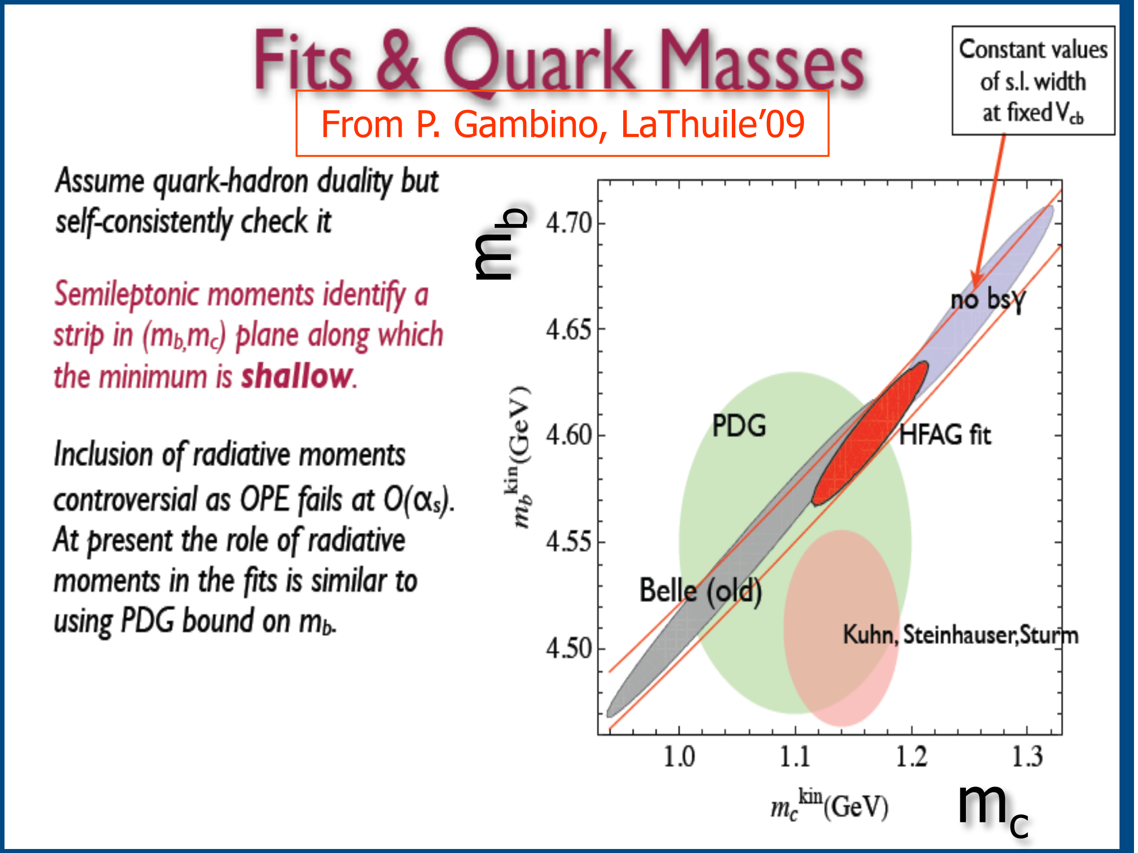
Backup slides

$B \rightarrow D^{**}\ell\nu$, 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 ~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 $b \to s\gamma$ in the fit (done by HFAG)
- Other possibilities include threshold or lattice determinations of m_b or m_c
- Crucial input for $|V_{ub}|$; $m_b \downarrow \;\to\; |V_{ub}| \uparrow$



Global fit to moments - issues

- Current fit inputs are 7 or 8 different moments, each integrated above several different lepton momentum cuts
  - e.g. $E_e>0.8$, $E_e>1.0$, $E_e>1.2$, $E_e>1.4$
  - resulting moments are highly correlated
  - recall that χ^2/dof is way too small
- If the correlations are all properly accounted for, this is equivalent to using moments in slices of E_e, e.g. $\langle M_x^2 \rangle_{0.8<E_e<1.0}$
  - Sanity check 1 – do the fit in disjoint slices and compare results
  - Sanity check 2 – reduce number of input moments until you reach the point that uncertainties on fitted parameters start to blow up