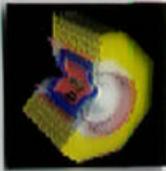


# Precision determination of $V_{ub}$ at an $e^+e^-$ B factory

Jik Lee & Ian Shipsey  
Purdue University

- **Current Methods of determining  $V_{ub}$** 
  - I. Endpoint of the inclusive lepton spectrum CLEO 93
  - II. Exclusive decays ( $B \rightarrow \rho l \nu$ ) CLEO 96 + 2000
- **Methods of determining  $V_{ub}$  with small theoretical errors**
- **1) Inclusive: low hadronic mass region**
- **2) Inclusive: endpoint of the  $q^2$  spectrum**
- **3) Exclusive: lattice**
  - Calibration with charm semileptonic decays
  - Rate and slope in  $B \rightarrow \pi l \nu$

# PROLOGUE



## Determination of $V_{ub}$

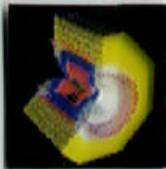
- Although the quark process  $b \rightarrow ulv$  is simple
- very difficult to calculate strong interaction effects when a heavy B meson becomes a light  $\rho, \pi, \dots$
- theoretical uncertainties enter twice, first the shape of the form factors determines the acceptance and hence Br
- second, the absolute normalization is needed to get  $V_{ub}$  :
- Severe backgrounds from  $b \rightarrow clv$  lead to measurements in small regions of phase space



The dangers of extrapolation

$$B(b \rightarrow ulv) = \frac{N_{sig}}{\epsilon \cdot N_{BB}}$$

$$V_{ub} = \sqrt{\frac{B(b \rightarrow ulv)}{\tau_B \cdot \Gamma_{theory}}}$$



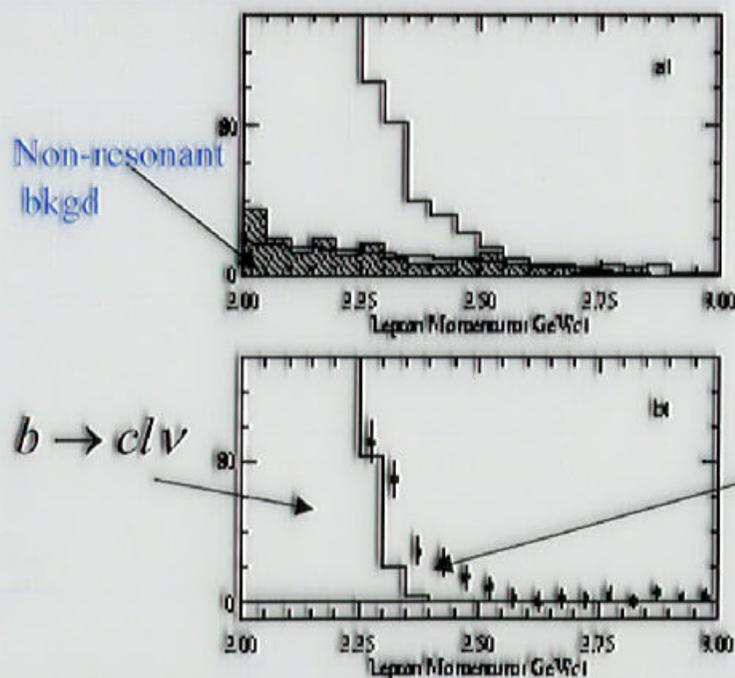
# I. Endpoint Determination of $V_{ub}$

- lepton endpoint, beyond the kinematic limit for  $b \rightarrow c$
- 1% of lepton spectrum, (CLEO'93)
- Measures  $|V_{ub}/V_{cb}|$

Challenges: Large  $b$  to charm bkgd  
 Limited understanding of decay spectrum/form factors

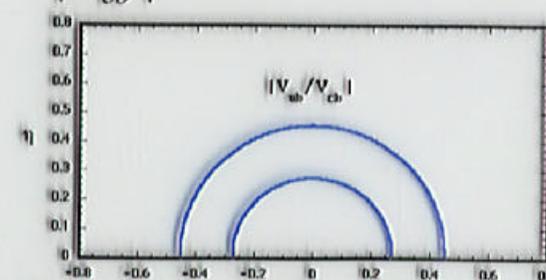
Large extrapolation (5-20%  
 $b \rightarrow u$  in endpoint)

endpoint dominated by several exclusive modes, so models must be used  
 limited by theoretical error

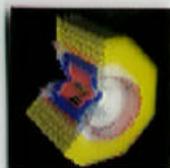


$$\frac{|V_{ub}|}{|V_{cb}|} = 0.076 \pm 0.008_{\text{exp}} \pm 0.016_{\text{thy}}$$

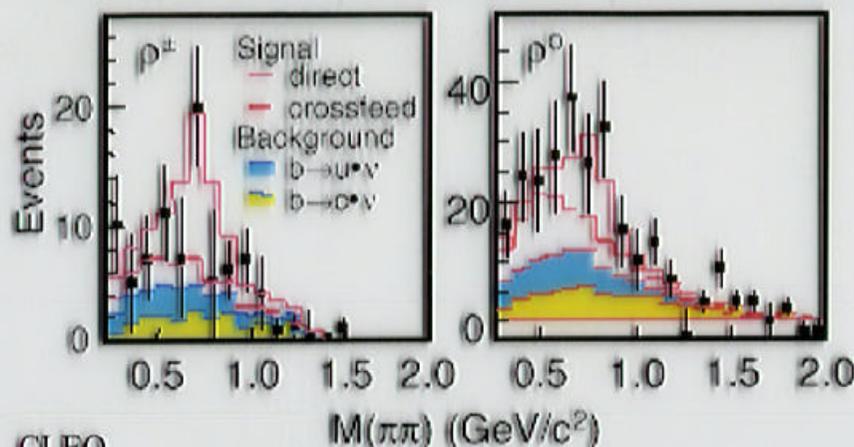
$$\frac{|V_{ub}|}{|V_{cb}|} = 0.08 \pm 0.02$$



Endpoint useful as reality check of more precise methods



# Vub method II : Exclusive decays



- \* Method 2: exclusive reconstruction require neutrino consistency.
- \* To keep bkgd tractable work in endpoint
- \* Measures Vub
- \* Drawback: extracted Vub relies on poorly known form factors
- \* Model dependence dominates

CLEO  
PRD 61  
052001  
3.3 x 10<sup>6</sup>  
BB

$$BR(B \rightarrow \rho^- l^+ \nu) = (2.57 \pm 0.29^{+0.33}_{-0.46} \pm 0.41) \times 10^{-4}$$

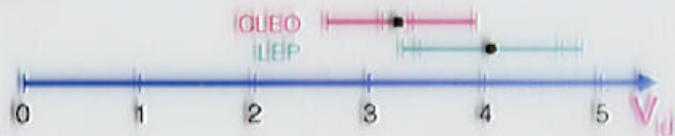
$$\frac{\delta V_{ub}}{V_{ub}} = 20\%$$

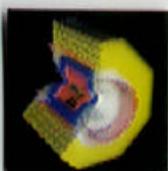
$$|V_{ub}| = (3.25 \pm 0.14 \pm_{0.29}^{0.21} \pm 0.55) \times 10^{-3}$$

(Averaged with published  
CLEO  $B \rightarrow \rho l \nu$ )

stat sys model

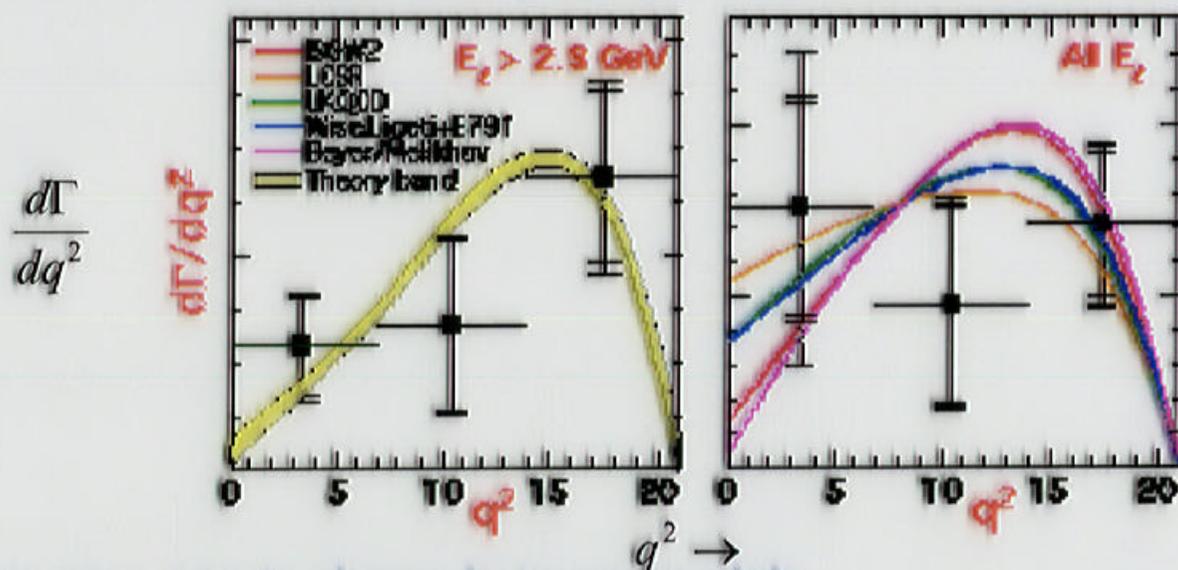
- to reduce theory error by X2 need to know:
- how much of the rate is in acceptance ? ~10%
- the overall normalization? ~ 15%
- 2 solutions: theory provides an absolute normalization point (as in b→c)
- minimise extrapolation i.e. maximize acceptance and test theory



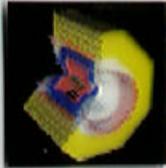


## Exclusive Decays and $V_{ub}$

- Beginning to probe  $q^2$  distribution
- but little discriminating power between models at high lepton energy (where the measurement is performed)



- no easy way to choose between models
- hard to quantify systematic error associated with a model
- although experimental statistical errors on  $V_{ub}$  will tend to zero with large data sets dominant uncertainties are theoretical



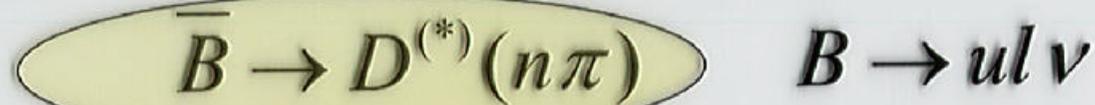
## New Inclusive Methods for $V_{ub}$

To distinguish  $b \rightarrow u$  from  $b \rightarrow c$  theoretically:

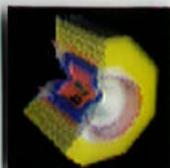
                                better                                better  
 $q^2$  spectrum  $>$   $m_{\text{had}}$  spectrum  $>$   $E_{\text{lepton}}$  spectrum

But experimental difficulty is in opposite order

- To make major *experimental* progress in  $V_{ub}$  need powerful suppression of  $b \rightarrow clv$  provided by full reconstruction of **companion**  $B$

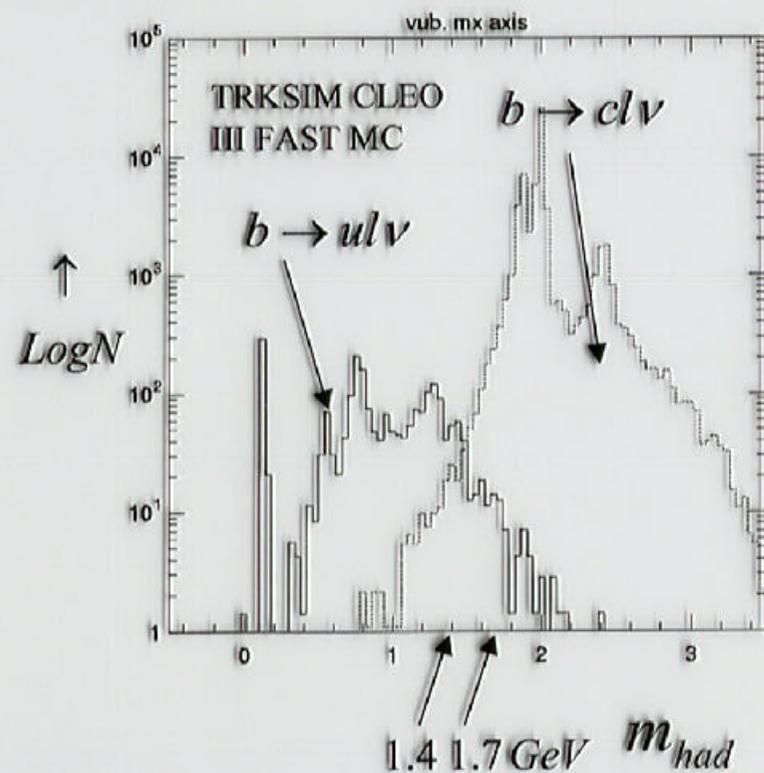
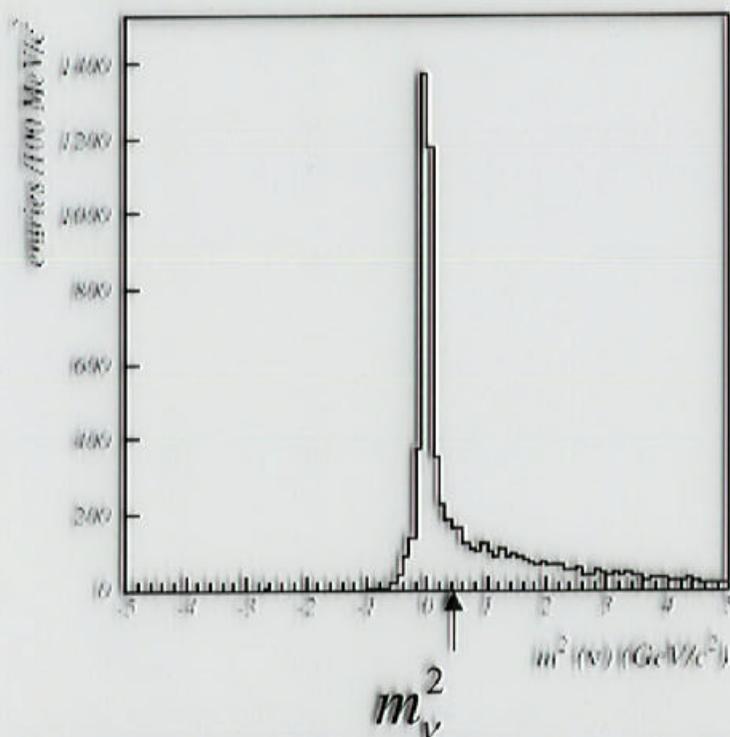


- $B$  tagging efficiency CLEO II/II.V is  $\sim 4.2 \times 10^{-3}$   $B \rightarrow \tau\nu$ ,  $B \rightarrow K\nu\bar{\nu}$  ( $5.7 \times 10^{-3}$  BaBar book improved PID/vertexing, use this number)
- technique impractical for (most) analyses with pre- $B$  factory samples, but will be used extensively in future

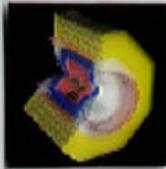


## Inclusive: Hadronic mass spectrum

- select  $b \rightarrow u$  with  $m_x < m_p$  (~90% acceptance for  $b \rightarrow u$ ) 😊
- require:  $Q(\text{event}) = 0, 1$  lepton/event, missing mass consistent with neutrino



- just look at  $m_{had} < 1.7$ , cut with largest acceptance and hence least theoretical uncertainty, keep bkgd small with  $p(\text{lepton}) > 1.4$  GeV



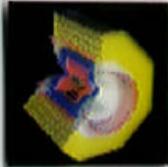
## Inclusive: Hadronic mass spectrum

- ~100 b  $\rightarrow$  ulv events/30 fb-1 Method attractive with large data samples:

year	Ldt /expt.	# b $\rightarrow$ ulv	#b $\rightarrow$ clv	$\delta V_{ub}$ (stat)	$\delta V_{ub}$ (sys)	$\delta V_{ub}$ (expt)
2002	100 fb-1	335	127	3.2%	1.9%	3.7%
2005	500 fb-1	1675	635	1.5%	1.0%	1.8%
2010	2000 fb-1	6700	2540	0.7%	1.0%	1.2%

- expt. systematic error is dominated by charm leakage into signal region. Depends on S/B ratio & uncertainty on B,  $\delta B$ .
- S/B can be improved by vertexing
- $\delta B$  can be reduced as  $\text{Br}(B \rightarrow [D^*/D^{**}/D/D \pi]lv)$  and the form factors in these decays become better measured
- $\delta B$  can also be reduced through better knowledge of D branching ratios
- S/B=3/1 (BaBar book S/B=5/1) Assume vertexing : S/B =9/1, & eventually  $\delta B = 0.1$ . Then systematic error dominates Ldt larger than  $\sim 1000\text{fb}^{-1}$
- $\delta \text{Br}(b \rightarrow ulv) \sim 2.4\%$  ,  $\delta V_{ub} \sim 1.2\%$ .
- Recall theoretical error is  $\sim 10\%$

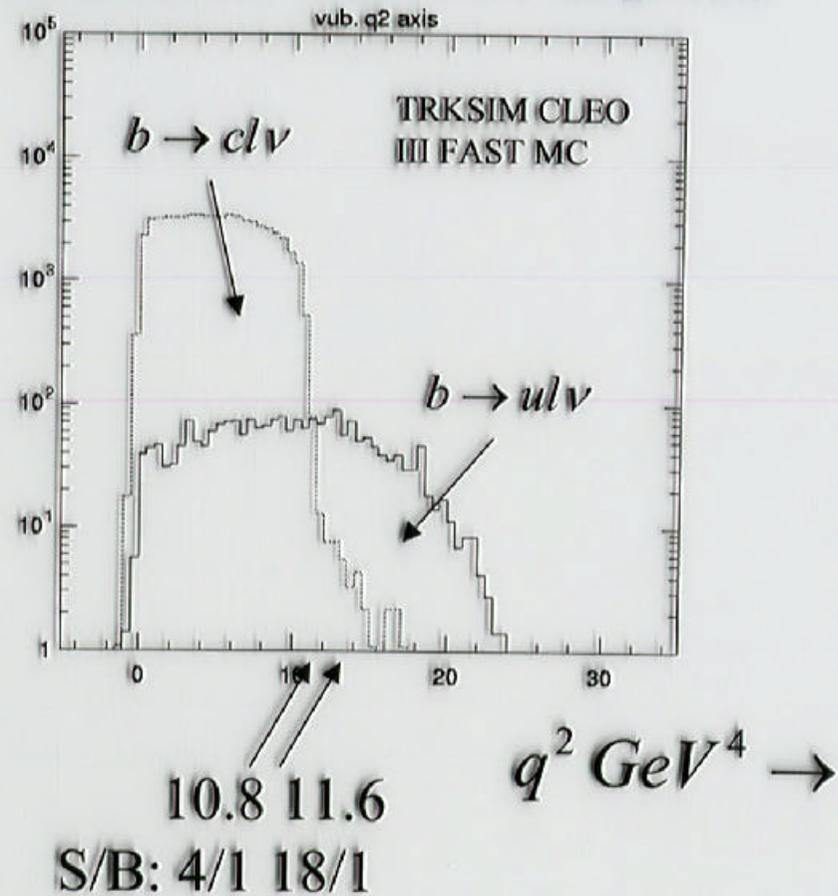
5-10%

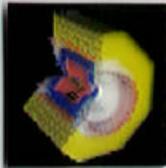


# Inclusive: endpoint $q^2$ spectrum

- Inclusive  $q^2$  endpoint, lose statistics, gain in theoretical certainty
- $\sim 40 b \rightarrow ulv$  events/30 fb-1 Method attractive with VERY large data samples.

look at  $q^2 > 11.6$ , and 10.8 keep bkgd small with  $p(\text{lepton}) > 1.4$  GeV  
One experimental advantage compared to  $m_{\text{had}}$  is that S/B is more favorable



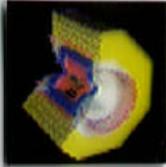


## Inclusive: endpoint $q^2$ spectrum

for  $q^2 > 11.6$ :

year	Ldt /expt.	# $b \rightarrow ulv$	# $b \rightarrow clv$	$\delta V_{ub}$ (stat)	$\delta V_{ub}$ (sys)	$\delta V_{ub}$ (expt)
2002	100 fb-1	127	7	4.6% 8%	5.2% 2.9%	8.9% 5.4%
2005	500 fb-1	635	36	2%	1.7% 0.8%	2.2%
2010	2000 fb-1	2538	144	1%	1.7% 0.5%	1.3%

- systematic error is dominated by charm leakage into signal region for  $q^2 > 10.8$ . (S/B ratio & uncertainty on B,  $\delta B$ , same issues as  $m_{had}$ )
- for  $q^2 > 11.6$ , S/B = 18/1 systematic error (tracking and lepton ID) dominates Ldt larger than  $\sim 1000 \text{fb}^{-1}$
- $2000 \text{fb}^{-1}$   $\delta Br(b \rightarrow ulv) \sim 2.6\%$ ,  $\delta V_{ub} \sim 1.3\%$ .
- Recall theoretical uncertainty  $\sim 10\%$   
5-10%



## Charm Semileptonic Decay and $V_{ub}$

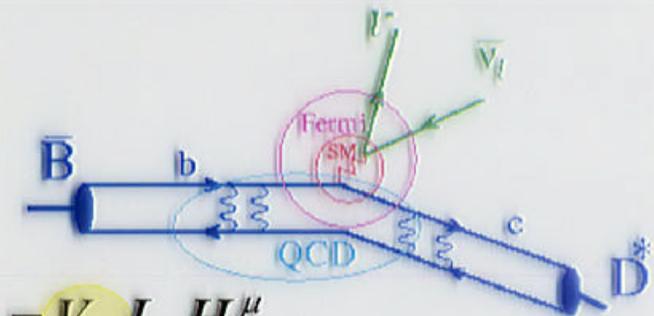
- Semileptonic B decays are used to determine the quark couplings  $V_{ub}$  and  $V_{cb}$  as the strong interaction is confined to the lower vertex

$$M \propto V_{ub} \langle \nu | \gamma_\mu (1 - \gamma_5) | l \rangle \langle H_u | J^\mu(0) | H_b \rangle \equiv V_{ub} L_\mu H_b^\mu$$

- In charm semileptonic decays, as  $V_{cs}$  (or  $V_{cd}$ ) is known from three generation unitarity the hadronic current can be measured

$$M \propto V_{cs} \langle \nu | \gamma_\mu (1 - \gamma_5) | l \rangle \langle H_s | J^\mu(0) | H_c \rangle \equiv V_{cs} L_\mu H_c^\mu$$

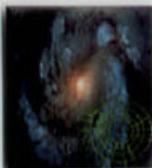
- D system provide a way to test ideas about hadronic physics needed to get  $V_{ub}$   $V_{cb}$  in B decays. Ideas = HQS, lattice....



model

known

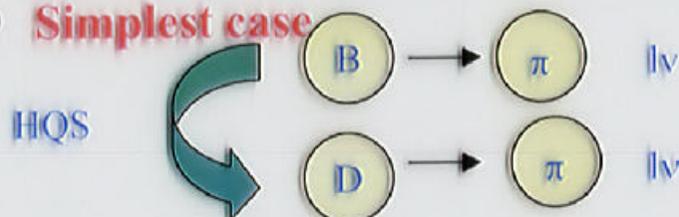
unitarity



## Charm Semileptonic Decays

- The complexity of the hadronic current depends on the spin of the initial and final state meson and the mass of the final state quark

- Simplest case**



- at same pion energy:

$$\frac{d\Gamma(B \rightarrow \pi l \nu) / dE_\pi}{d\Gamma(D \rightarrow \pi l \nu) / dE_\pi} = \frac{|V_{ub}|^2 \cdot (\text{phase space}) \cdot f(B \rightarrow \pi)^2}{|V_{cd}|^2 \cdot (\text{phase space}) \cdot f(D \rightarrow \pi)^2}$$

- form factor ratio equal by Heavy Quark Symmetry, corrections order 20%
- but little known about heavy to light transitions need  $q^2$  dependence in both B and D decay to assess the size of the  $1/m$  corrections.
- Lattice also determines the form factors, in principle it may be most precise method. Will concentrate on this method here...



## A lattice determination of $V_{ub}$

- The lattice is capable of predicting ~~the absolute normalization of the decay rate form factor in  $B \rightarrow \pi l \nu$  or  $D \rightarrow \pi l \nu$~~  to  $\sim$  few%.  $\rightarrow \delta(V_{ub})/V_{ub} \sim 1-2\%$  (theory) <sup>of</sup> *\* Private Communications between Ian Shipsey and a Lattice expert.*
- But lattice must be calibrated!

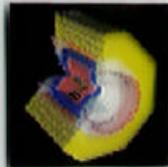
### STEP ONE: CALIBRATE LATTICE WITH $D \rightarrow \pi l \nu$

- Within the quenched approximation all systematic errors are accounted for and smaller than statistical errors
- A comparison of lattice and expt. in  $D \rightarrow \pi l \nu$  can give an estimate of the size of the effect of using the quenched approximation

### STEP TWO: MEASURE $d\Gamma/dq^2$ in $B \rightarrow \pi l \nu$

- compare lattice to data, if quenching is understood shape should be same

### STEP THREE: MEASURE $\Gamma(B \rightarrow \pi l \nu)$ + lattice $\rightarrow V_{ub}$

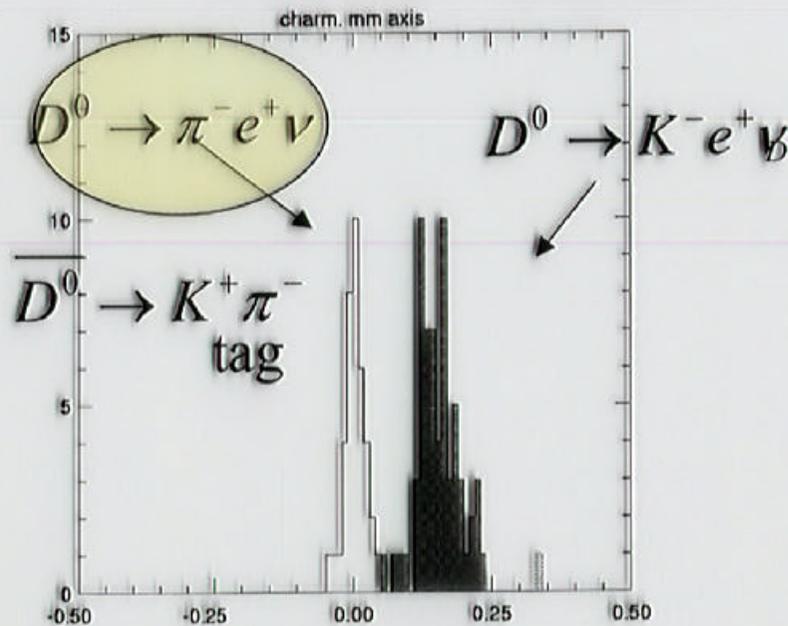


# Charm Factory vs. B Factory

- The best way to  $d\Gamma/dq^2$  in  $D \rightarrow \pi l \nu$  is at a charm factory (e.g. CLEO-C)
- Kinematics at threshold cleanly separates signal from background

Charm Factory  
no background

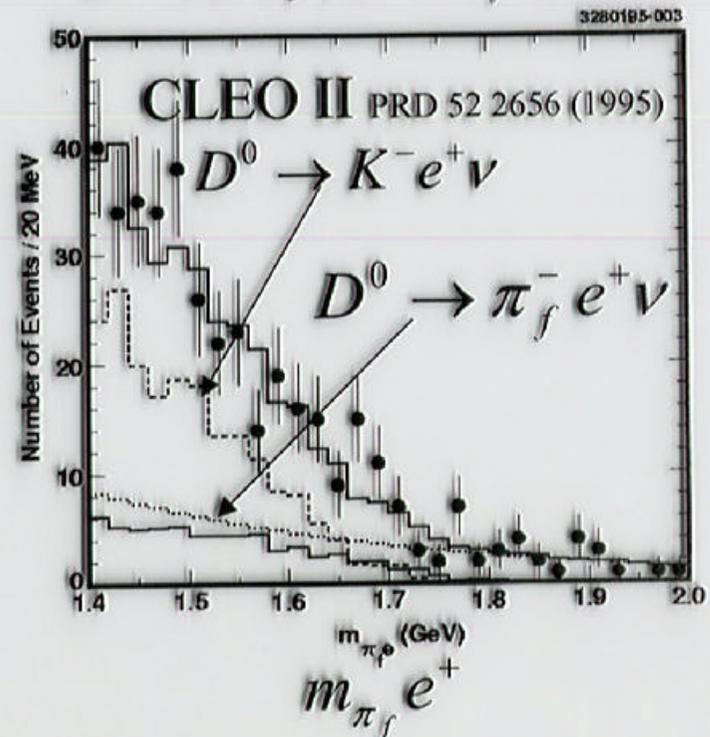
TRKSIM CLEO  
III FAST MC

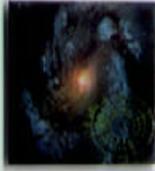


$$U = E_{miss} - P_{miss}$$

B Factory S/B ~1.3  
of CLEO II S/B 1/3

$D^{*+} \rightarrow D^0 \pi_s^+$ ,  $D^0 \rightarrow \pi_f^- / K^- e^+ \nu$





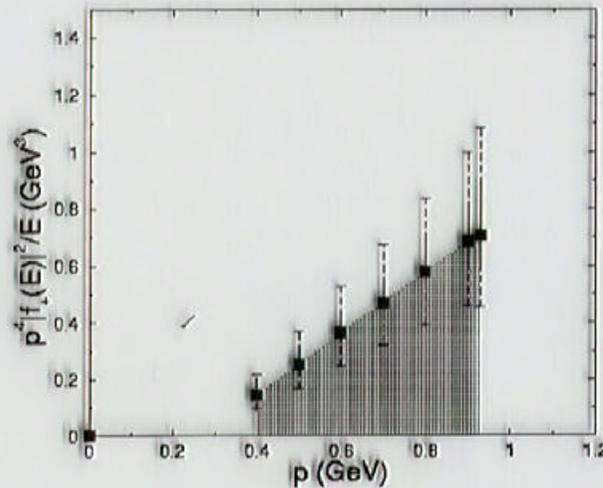
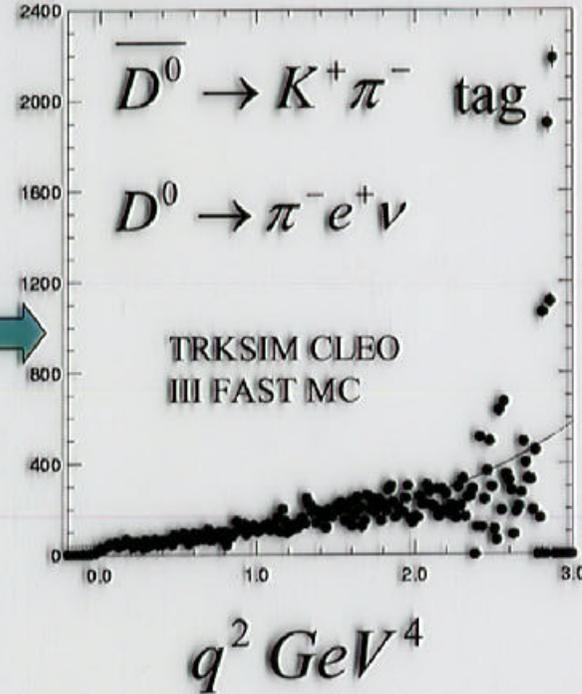
# Step I Calibrate Lattice: $D \rightarrow \pi l \nu$

● Measure:

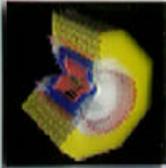
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cs}|^2 P_\pi^3}{24\pi^3} |f_+(q^2)|^2$$

$$\frac{1}{p_\pi^3} \frac{d\Gamma(D \rightarrow \pi l \nu)}{dq^2} = |f_+(q^2)|^2 = f_+(0)^2 e^{2\alpha q^2}$$

$$f_+(q^2) = f_+(0) e^{\alpha q^2} \quad \frac{\delta\alpha}{\alpha} \approx 1 - 2\%$$



compare to lattice prediction  
 ex: hep-ph/0101023 El-Khadra  
 Note: lattice error large ~15%  
 on normalization but in future  
 1-few % predicted



## Step II $d\Gamma(B \rightarrow \pi l \nu)/dq^2$

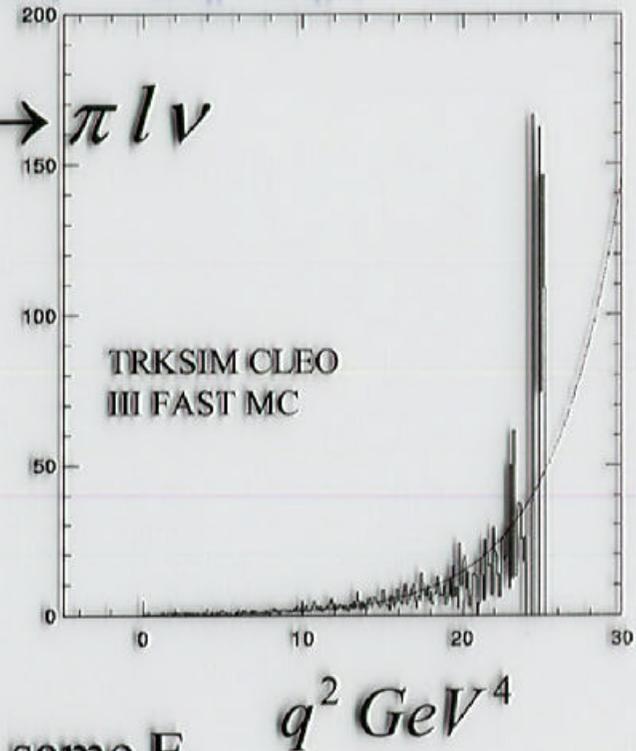
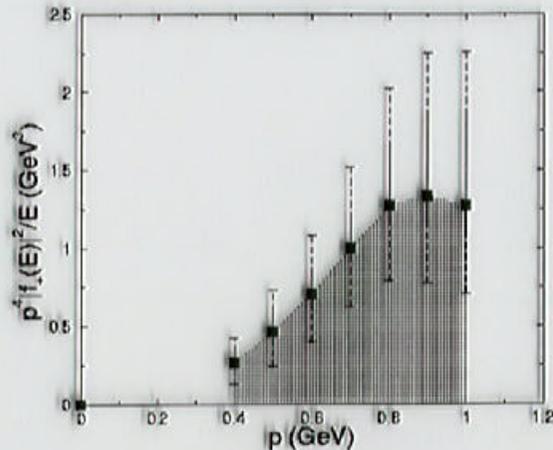
- Reconstruct **companion B**, select  $b \rightarrow u$  with  $q^2 \rightarrow (m_B^2 - m_D^2)^2$   $B \rightarrow \pi l \nu$



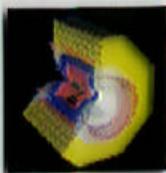
$$\frac{1}{p_\pi^3} \frac{d\Gamma(B \rightarrow \pi l \nu)}{dq^2} = |f_+(q^2)|^2 = f_+^2(0) e^{2\alpha q^2}$$



$$\frac{1}{p_\pi^3} \frac{d\Gamma(B \rightarrow \pi l \nu)}{dq^2}$$



For same  $E_\pi$   
as  $D \rightarrow \pi l \nu$ :  
compare to lattice prediction  
ex: hep-ph/0101023 El-Khadra



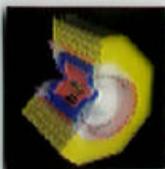
## Step III $V_{ub}$

- if data and lattice agree for  $E_\pi < 1$  GeV, still need faith that lattice is correct for  $E_\pi > 1$  GeV.
- Lattice can compute  $V_{ub}$  rate to  $\pm$  few % <sup>1-2</sup> how much data would we need to have a comparably small experimental error?

year	Ldt /expt.	# $b \rightarrow ulv$	S/B (10/1)	$\delta V_{ub}$ (stat)	$\delta V_{ub}$ (sys)	$\delta V_{ub}$ (expt)
2008	1000 $\text{fb}^{-1}$	590	59	4.3%	1.4%	4.5%
????	9500 $\text{fb}^{-1}$	5612	561	0.7%	0.8%	1.1%

- | Ldt $\text{fb}^{-1}$ | S/B  |
|----------------------|------|
| 9500                 | 10/1 |
| 11,500               | 3/1  |
| 17,300               | 1/1  |

Such large data samples are beyond the reach of existing B factories that expect to accumulate  $\sim 2,000 \text{ fb}^{-1}$  by 2010



## Conclusions

- All possible theoretically clean measurements are very important, even if they are redundant within the standard model
- Must pursue both CP violating and CP conserving measurements (i.e.  $V_{ub}$ ) to test SM and look for new physics
- Inclusive methods will achieve  $\delta V_{ub} \sim \text{few \% (expt)} \sim 10\% \text{ (theory)}$   
 $q^2$  endpoint is the method of choice.
- The first test of CKM at the 10% level will come from this measurement and  $V_{cb}$ ,  $\sin 2\beta$ , and  $V_{td}/V_{ts}$
- If the lattice can reach the predicted accuracy (1-2%) it will become the method of choice for future measurements of  $V_{ub}$  (and  $V_{cb}$ )
- Lattice must be calibrated. A charm factory can provide crucial tests of lattice predictions.
- A  $\sim 10,000\text{-}20,000 \text{ fb}^{-1}$  data sample is required to attain a total experimental error of 1% on  $V_{ub}$  commensurate with the lattice error.