Partial branching fractions and extraction of $|V_{ub}|$ from inclusive semileptonic B decays

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$|V_{ub}|$ Determination

Limiting factor in CKM precision tests; known much less well than $|V_{cb}|$

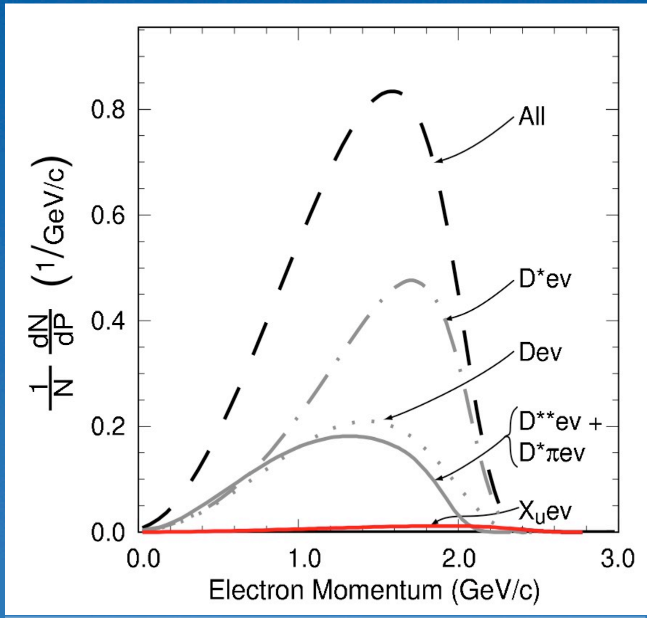
CKM suppressed $V_{ub} \sim 0.1 \times V_{cb}$ - therefore harder to measure

V_{ub}: @**8%** precision, dominated by theoretical uncertainties

$$\Gamma(b \to u \ell \bar{\nu}) = \frac{G_F^2}{192\pi^2} |V_{ub}|^2 m_b^5 \left(1 + 補正項\right)$$

The problem: $b \to c l \nu$ decay

$$\frac{\Gamma(b \to u \ell \bar{\nu})}{\Gamma(b \to c \ell \bar{\nu})} \approx \frac{|V_{ub}|^2}{|V_{cb}|^2} \approx \frac{1}{50}$$



How can we suppress 50× larger background?

How can we reach 4% precision on |Vub|?

|Vub| Measurement

- Cut away b → clv Lose a part of the b → ulv signal

  - We measure

$$\Gamma(B \to X_u \ell \nu) \times f_C = |V_{ub}|^2 \zeta_C$$

Total b → ulv rate

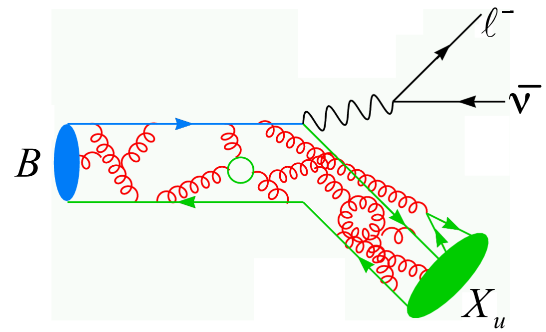
Cut-dependent constant predicted by theory

Fraction of the signal that pass the cut

Requires the knowledge of the b quark's motion inside the B meson

- Must be corrected for QCD

$$\Gamma(B \to X_u \ell \nu) = \frac{G_F^2 |V_{ub}|^2 m_b^5}{192\pi^3}\left[1 - O\left(\frac{\alpha_s}{\pi}\right) - \frac{9\lambda_2 - \lambda_1}{2m_b^2} + \cdots\right]$$



  - Main uncertainty (±5%) from m_b^5 → ±2.5% on $|V_{ub}|$, correlated between all measurements/experiments!

- But we need the reasonable fraction (e.g., E_ℓ > 2 GeV) of the rate.

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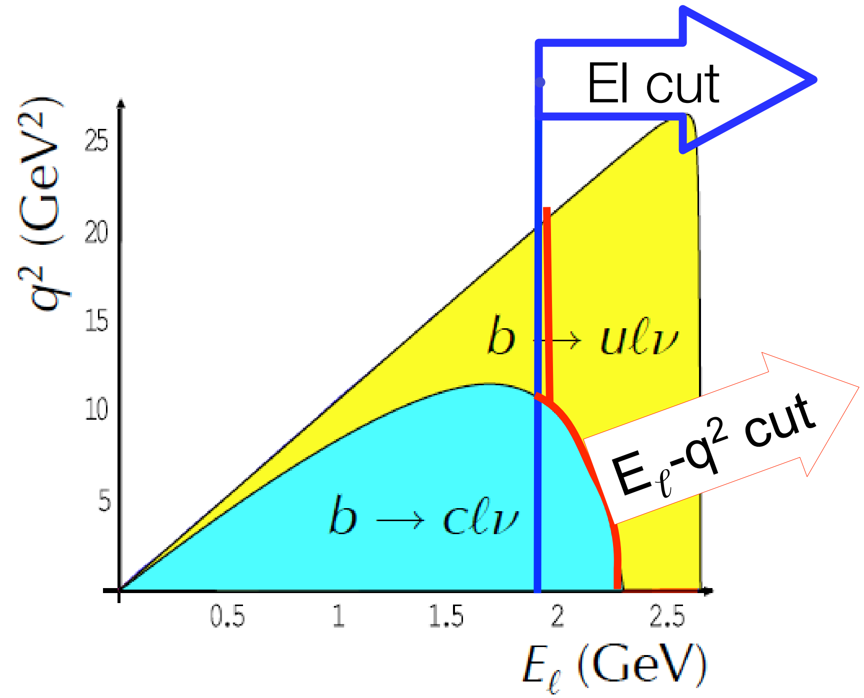
Detecting $b \to u l \nu$

Inclusive: Use $m_u << m_c$ difference in kinematics

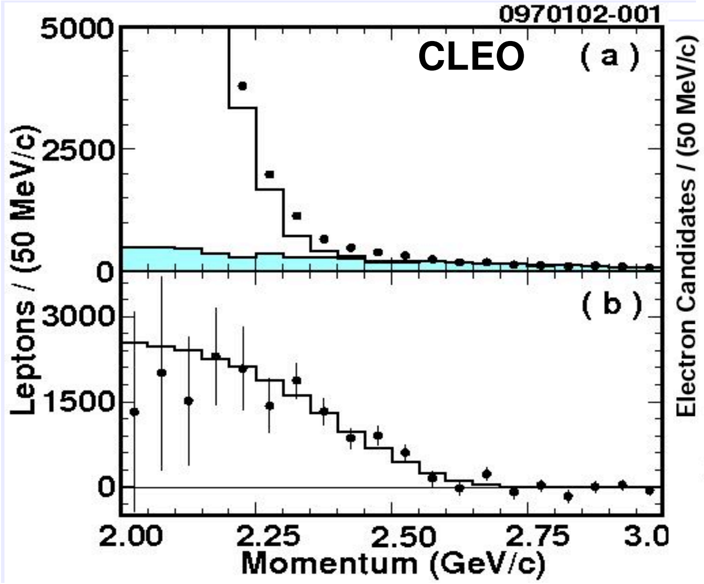
- Maximum lepton energy 2.64 vs. 2.31 GeV
- First observations (1990) used this technique
- Only 6% of signal accessible

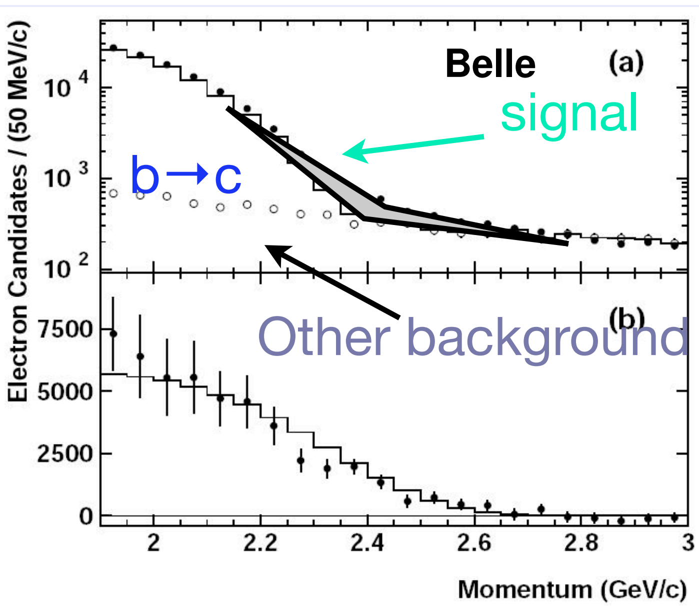
- Small theory error requires low E_{lepton} cut
- Small BG uncertainty requires high E_{lepton} cut
- Measure partial BR in a region where S/N is acceptable and that the width is reliably calculable.

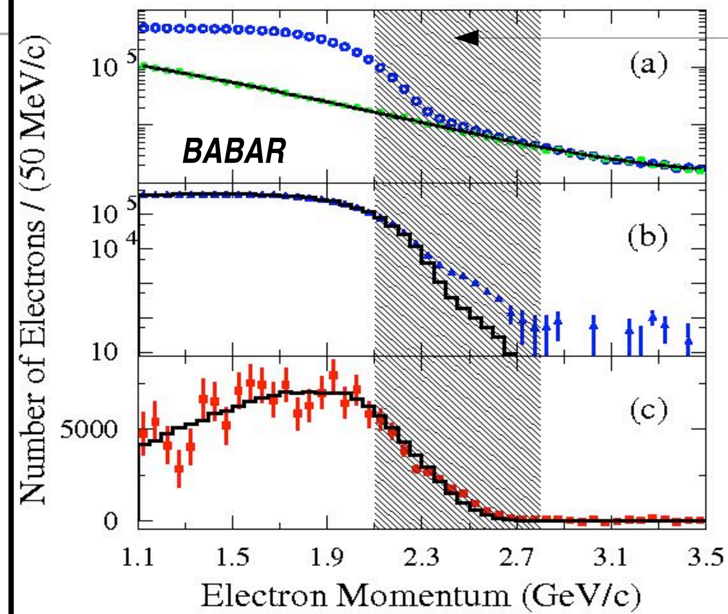


- Many techniques used:
- Endpoint, Improved Endpoint, Simulated Annealing, SF factorisation, Full Reconstruction tagging etc.

Endpoint method







Subtract offpeak data scaled to onpeak luminosity bin-by-bin.

Fit MC to data in low energy region to constrain B->Xc l ν from data.

$B\to X_u l\nu$, $B\to Dl\nu + B\to D^*l\nu$ (ratio fixed)
$B\to D^{**}l\nu$, $B\to D^{(*)}\pi l\nu$ (Goity & Roberts)

$B\to X_u l\nu$, $B\to Dl\nu + B\to D^*l\nu$ (D/D* fixed)
$B\to D^{**}l\nu$ D/D+D* fitted ((D_1+D_2)/D** fixe**

Simultaneous fit for non-$B\bar{B}$, $B\to X_u l\nu$, $B\to Dl\nu$
$B\to D^*l\nu$, $B\to D^{**}l\nu$, $B\to D^{(*)}\pi l\nu$, other BG

		$\Delta BR \times 10^{-4}$	$\lvert V_{ub}\rvert \times 10^{-3}$ %Δ(exp -the. + the.)
(PRL 88, 231803, 2002)	Belle $27 fb^{-1}$:E_e>1.9 GeV	$8.47 \pm 0.37_{stat} \pm 1.53_{sys}$	4.61(±9.3 + 5.0 - 6.7)
(PLB621, 28, 2005)	BaBar: E_e > 2.0 GeV	$5.72 \pm 0.41_{(stat)} \pm 0.65_{(syst)}$	4.13(±5.6 + 5.6 - 8.2)
((PRD 73, 012006, 2006)	CLEO: Ee > 2.0 GeV	$4.22 \pm 0.33_{stat} \pm 1.78_{sys}$	3.77(±12. + 6.9 - 10.)

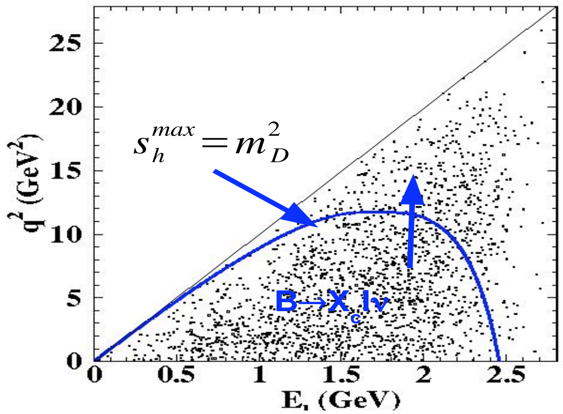
~25 % acceptance

Improved Endpoint method

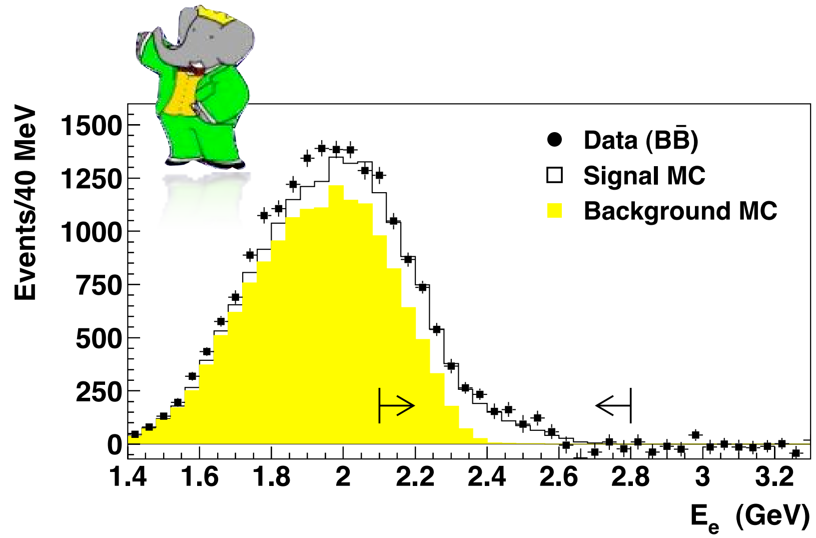
Maximally allowed hadronic mass for given El & q2 can be determined:

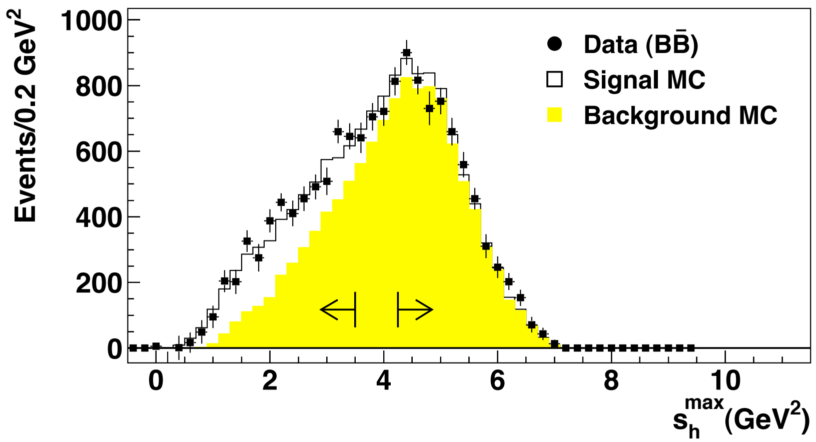
$$s_h^{max} = m_B^2 + q^2 - 2m_B(E_l \eta_- + q^2 \eta_+ / 4E_e), \pm 2E_e > \pm \sqrt{q^2}\eta_\pm \qquad \eta_\pm = \sqrt{(1 \pm \beta)/(1 \mp \beta)}$$

$$s_h^{max} = m_B^2 + q^2 - 2m_B\sqrt{q^2}, \quad \text{otherwise} \qquad \beta \approx 0.06$$



BaBar (PRL 95, 111801, 2005
PRL 97, 019903 (2006) Err.)





Principal ingredients (*BABAR*):

1) $p_\nu = p_{miss} = (E_{miss}, \vec{p}_{miss}) \rightarrow (|\vec{p}_{miss}|, \vec{p}_{miss})$

2) * track & neutral selection
   * Only one high energetic lepton
   * $|\vec{p}_{miss}|, E_{miss} - |\vec{p}_{miss}|, \cos\theta_{miss}, \cos\theta_{thrust,e}$

3) Signal region: E_l^* & s_h^{max} => B→X_clν suppression

   core $|\vec{p}_{miss}|/q^2$ - resolution: 0.32 GeV/2.5 GeV^2

   * dominated by particle losses
   * complicated by K_L, split-offs, etc.

Summary of Endpoint methods

ΔBR Errors in %

		El cut	Integrated Luminosities (fb-1)		Uncertainties on BF (%)			
Method			**onpeak**	**offpeak**	**El > 2.1 GeV**		**El > 2.3 GeV**	
					Stat	Sys	Stat	Sys
El	CLEO (PRL 88, 231803, 2002)	2.0	9.1	4.3	7.0	22.3	7.0	9.1
	Belle (PLB621, 28, 2005)	1.9	27	8.8	5.3	12.7	8.5	5.9
	BaBar (PRD 73, 012006, 2006)	2.1	80	9.5	5.7	9.4	4.1	6.9
El-q2	BaBar (PRL 95, 111801, 2005 PRL 97, 019903 (2006) Err.)	2.0	81	9.6	9.3 (>2.0 GeV)	9.6 (>2.0 GeV)		

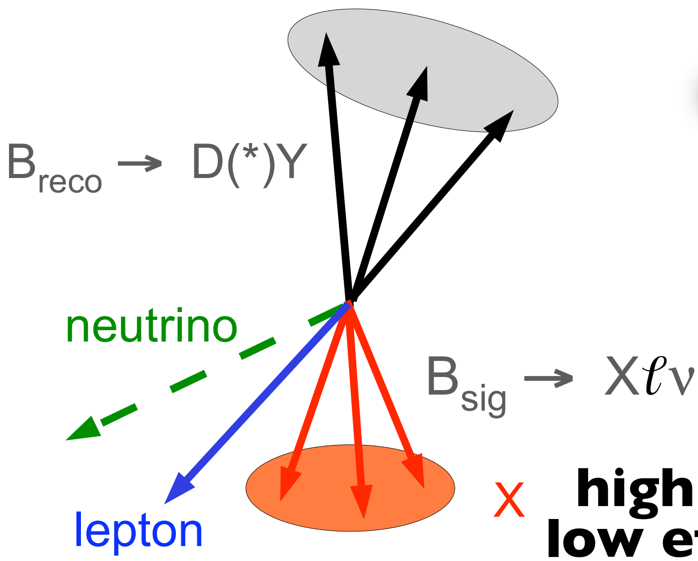
Systematics							**D-> Xs l nu**		**B → cl v**	
	Select	**non-BB**	**FSR/Brem**	**KL**	**Neutral**	**B → Xu l v**	**D-> e, mu**	**D->KL**	**FF**	**Excl BR**
El	6.8	2.4	1.0		-	1.1	<0.5	-	2.4	2.8
El-q2	-	-	3.8	2.0	3.4	4.4	2.1	4.5	0.3	2.0

- Current data sets from Belle and BaBar have low offpeak/onpeak ratios.
- Prospect for stat. error <2.5% by relaxing continuum suppression techniques.
- B->Xc l v systematics have improved significantly over 5 years.

B meson "beam" method

Best access to kinematics with ***B meson "beam"***

➡ **tag - charge - momentum**



high purity, low efficiency

E_l = lepton energy (in B rest frame)

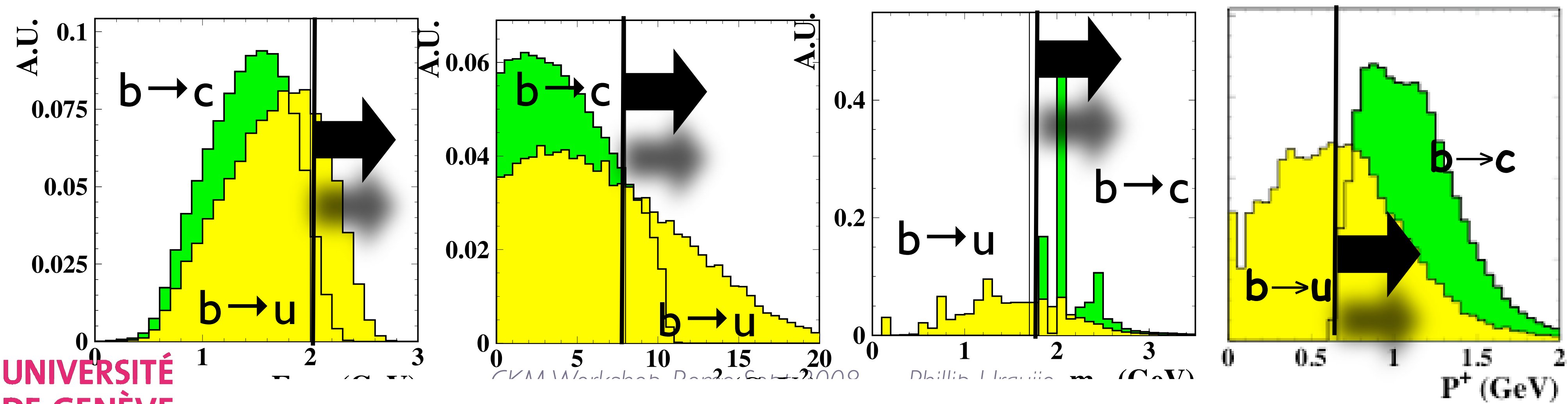
q^2 = lepton-neutrino mass squared

m_X = hadron system mass (all remaining particles)

$P^+ = E_X - |P_X|$ ($P_X = p_{beam} - p_{Btag} - p_l - p_\nu$)

Signal events have smaller M_X and P_+ → Larger E_l and q^2

Not to scale!



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Measurement technique

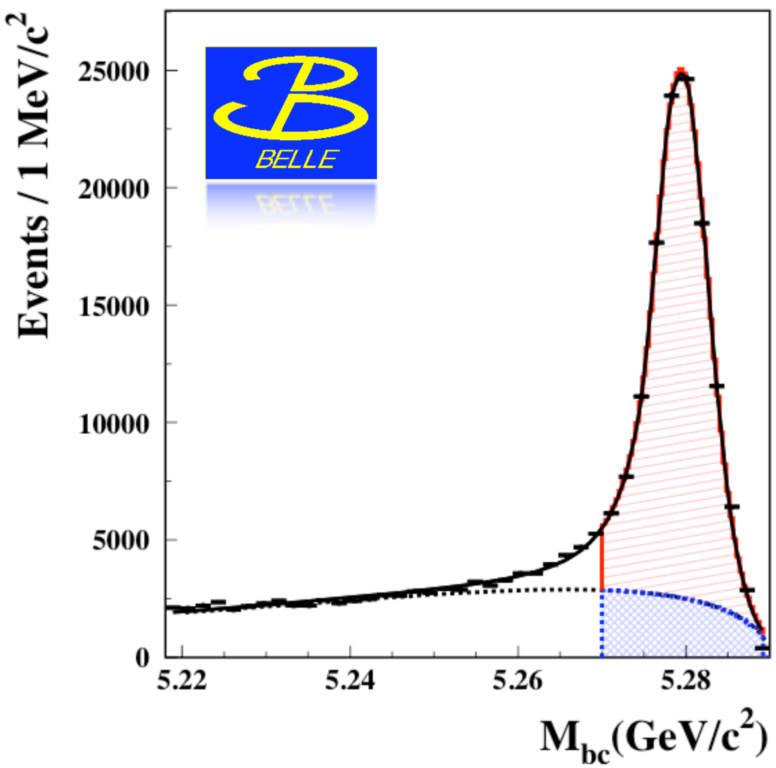
1. Signal side

Reconstruct high momentum lepton

$p_{lep}^{CMS} > 1$ GeV/c

No strangeness

N(K±, K^0_S) = 0 (KL cut used by Belle 2005)



2. Event Level

ΣQ=0,

Q(B_{reco}+) x Q(lep) = -1

M_{miss}, etc.

3. Fit M_{bc} in bins of P_+, M_X, q^2

4. Fit to P_+, M_X, q^2 with various background and signal floated to determine background yield.

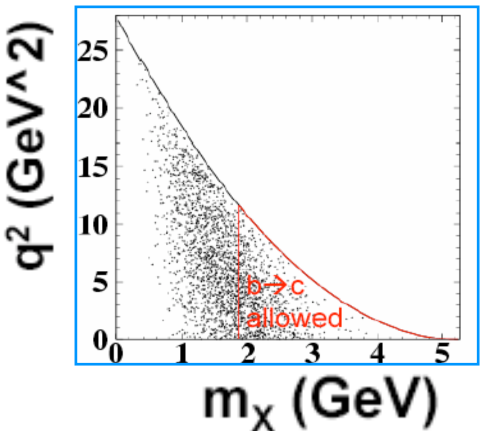
5. Measure relative BR to control systematics

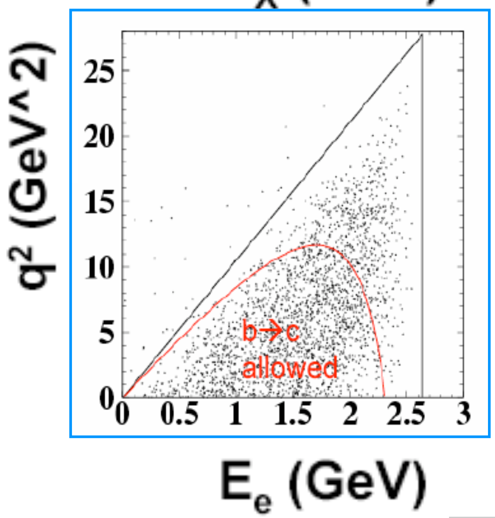
e.g.

$$\frac{\Delta Br(X_u l \nu)}{Br(X l \nu)} = \frac{N_{b\to u}}{N_{sl}} \cdot \frac{F}{\varepsilon_{sel}} \cdot \frac{\varepsilon^{b\to u}_{frec}}{\varepsilon^{sl}_{frec}} \frac{\varepsilon^{b\to u}_{\ell}}{\varepsilon^{sl}_{\ell}}$$

- PDG
- Number of excess events
- Unfolding factor F
- Number of semileptonic events
- selection efficiency
- Ratio of efficiencies for $b \to u$ and sl

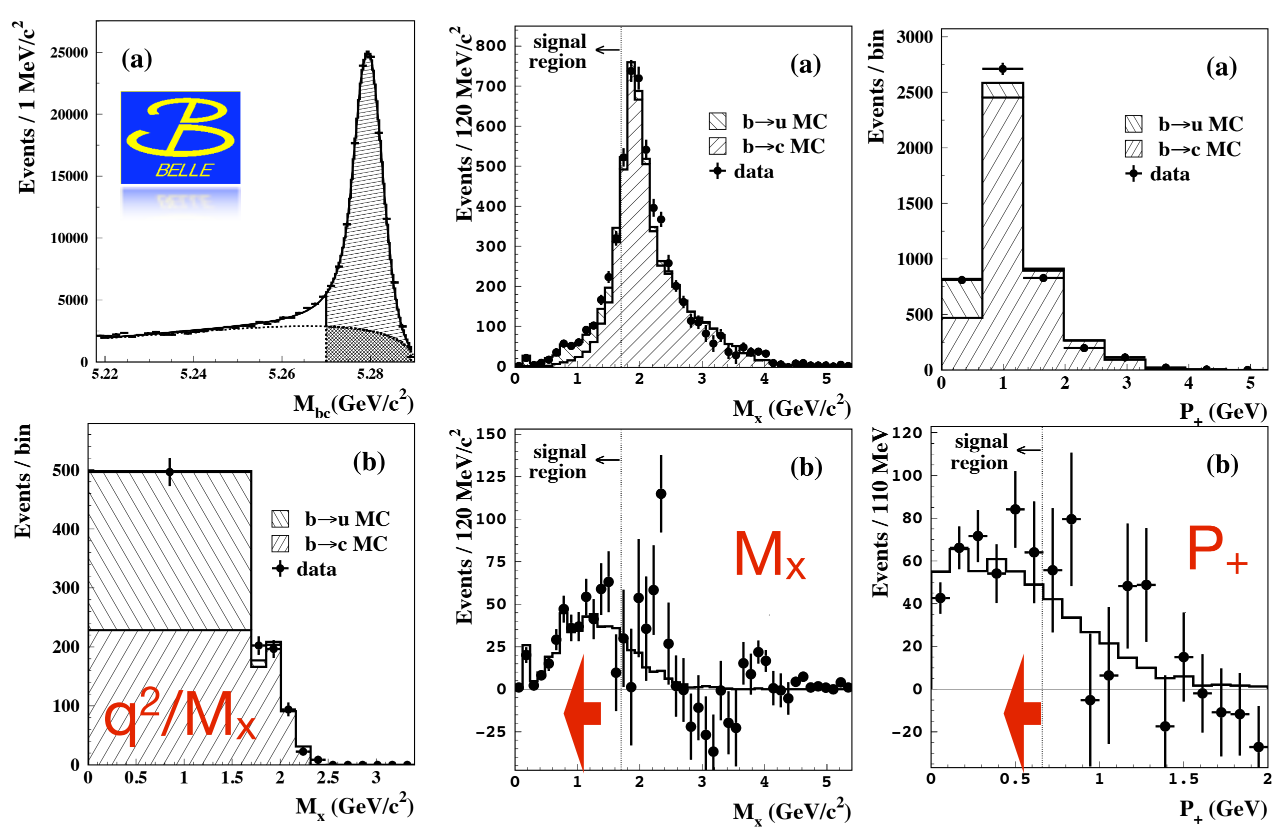
Belle tagged method





PRL .95:241801 (2005)

253 fb^{-1}



	$\lvert V_{ub}\rvert \times 10^{-3}$ BLNP %Δ(stat. sys. sf. th.)	Δ$\lvert V_{ub}\rvert$
$m_X < 1.7$	4.70(±5.1±6.0±4.2±5.1)	10%
$m_X < 1.7$, $q^2 > 8$	4.09(±4.6±4.9±4.4±3.7)	9%
P+<0.66	4.19(±4.8±7.2±5.7±3.3)	11%

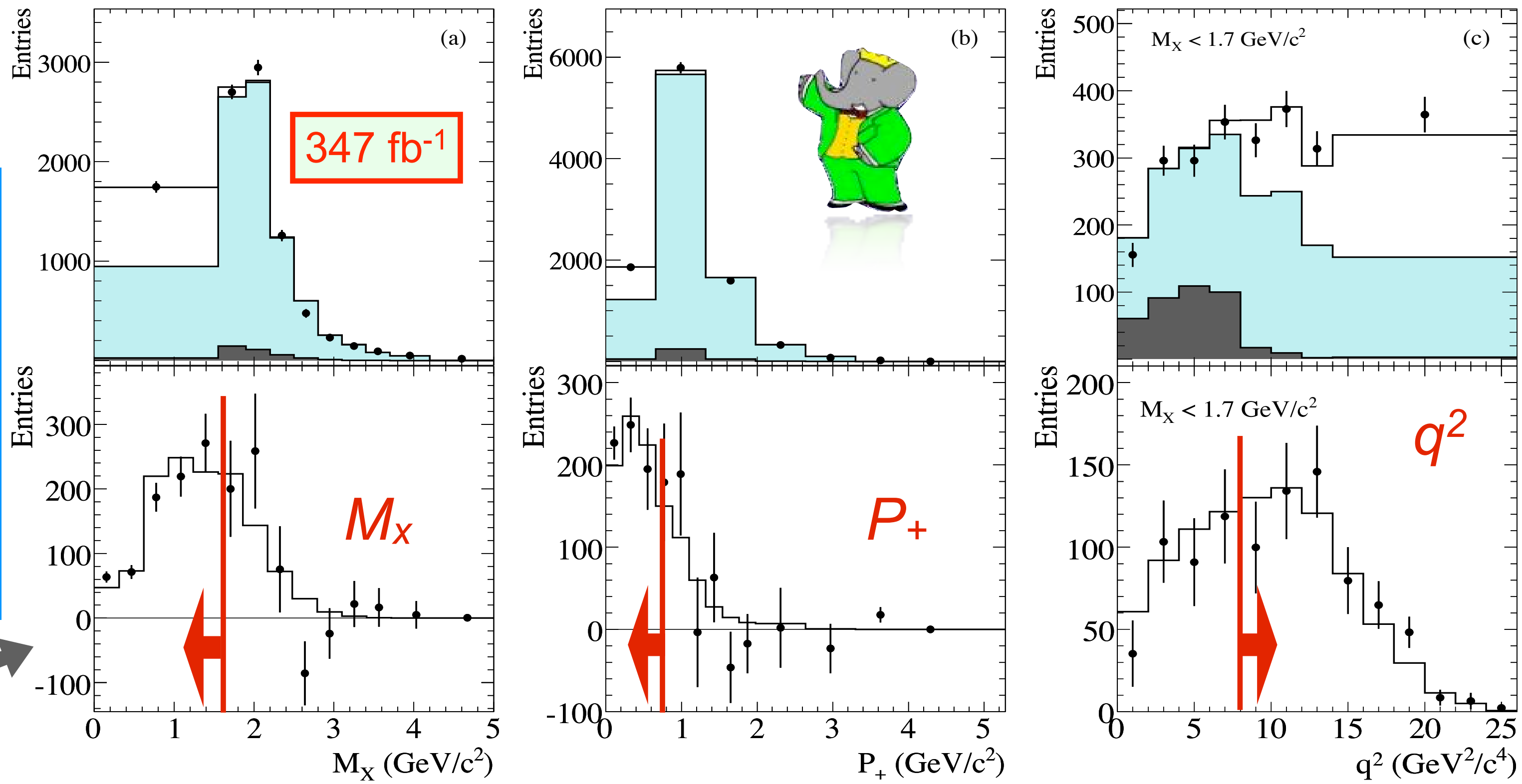
~40-60 % acceptance

Babar tagged method

PRL 100, 171802 (2008)

- $B \to X_u l n$
- $B \to X_c l n$ (bkgd)
- $B \to X_u l n$ (outside selected region)

Background subtracted

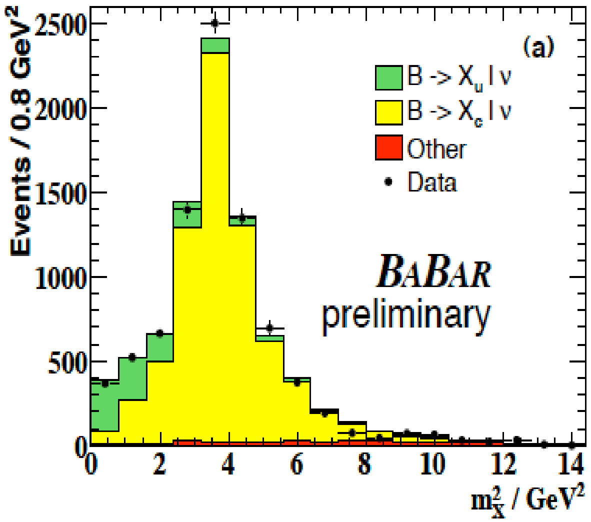


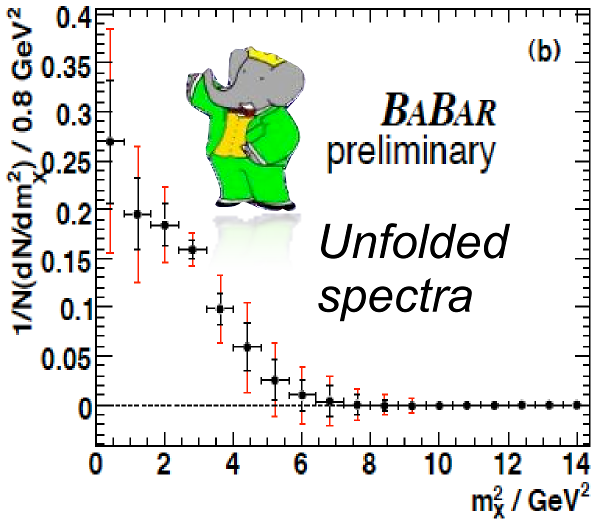
Kinematic Region	$B(B \to X_u l \nu) \times 10^{-3}$ Δ(stat. sys. th.)	$\lvert V_{ub} \rvert$ (10^{-3}) %Δ(stat. sys. th.)	Theory
M_X<1.55 GeV/c^2	1.18 ± 0.09 ± 0.07 ± 0.01	4.27 (± 3.7 ± 3.0 ± 7.0)	BLNP
		4.56 (± 3.7 ± 3.0 ± 7.0)	DGE
P_+<0.66 GeV/c^2	0.95 ± 0.10 ± 0.08 ± 0.01	3.88 (± 4.9 ± 4.1 ± 7.2)	BLNP
		3.99 (± 4.9 ± 4.1 ± 6.0)	DGE
M_X<1.7 GeV/c^2 & q^2>8.0 GeV^2/c^2	0.81 ± 0.08 ± 0.07 ± 0.02	4.57 (± 5.0 ± 4.2 ± 4.6)	BLNP
		4.64 (± 5.0 ± 4.2 ± 5.4)	DGE
		4.93 (± 5.0 ± 4.2 ± 7.3)	BLL

~40-60 % acceptance

Extension: Hadronic mass Moments

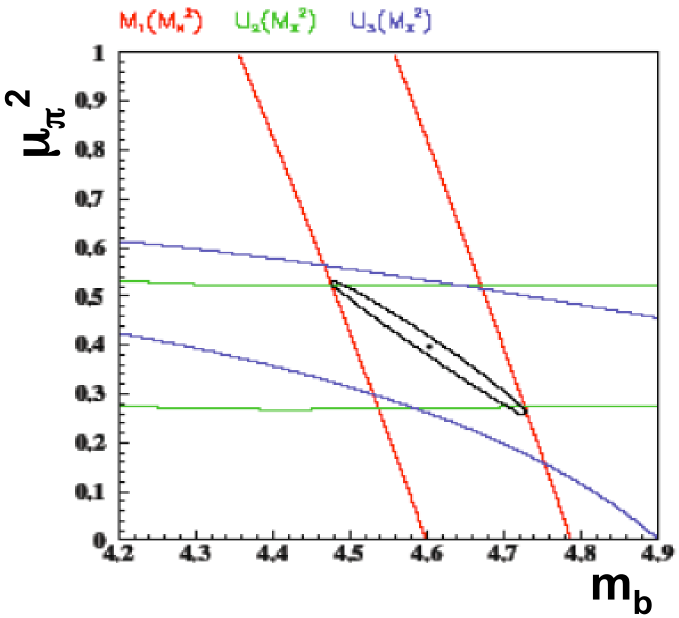
Measure hadronic mass spectrum over full Mx range
Mass moments related to mb, with $m_X^2 < 6.4$ GeV^2





ArXiv: 0801.2985[hep-ex]

Mom		Stat.	Syst.	
M1	1.96	±0.34	±0.53	GeV^2
U2	1.92	±0.59	±0.87	GeV^4
U3	1.79	±0.62	±0.78	GeV^6



Calculations of Gambino, Ossola, Uraltsev
JHEP09(2005)010

First measurement of m_b in $B \to X_u \ell \nu$ decays
(in the Kinetic scheme)

m_b = 4.604 ± 0.250 GeV

compatible with Global Fit

Belle Multivariate analysis (NEW @ CKM2008) 1/2

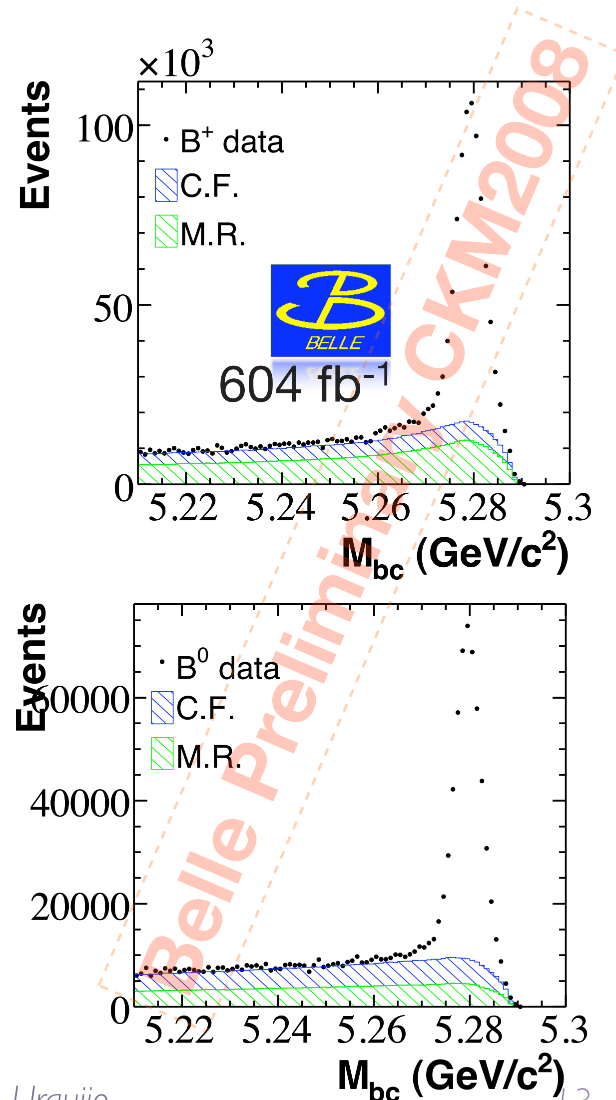
The irreducible uncertainties in the measurements to date are related to limited phase space.

Solution: exploit the many non-linear correlations between kinematic and event variables available in B-beam sample that separate $b \to u$ and $b \to c$.

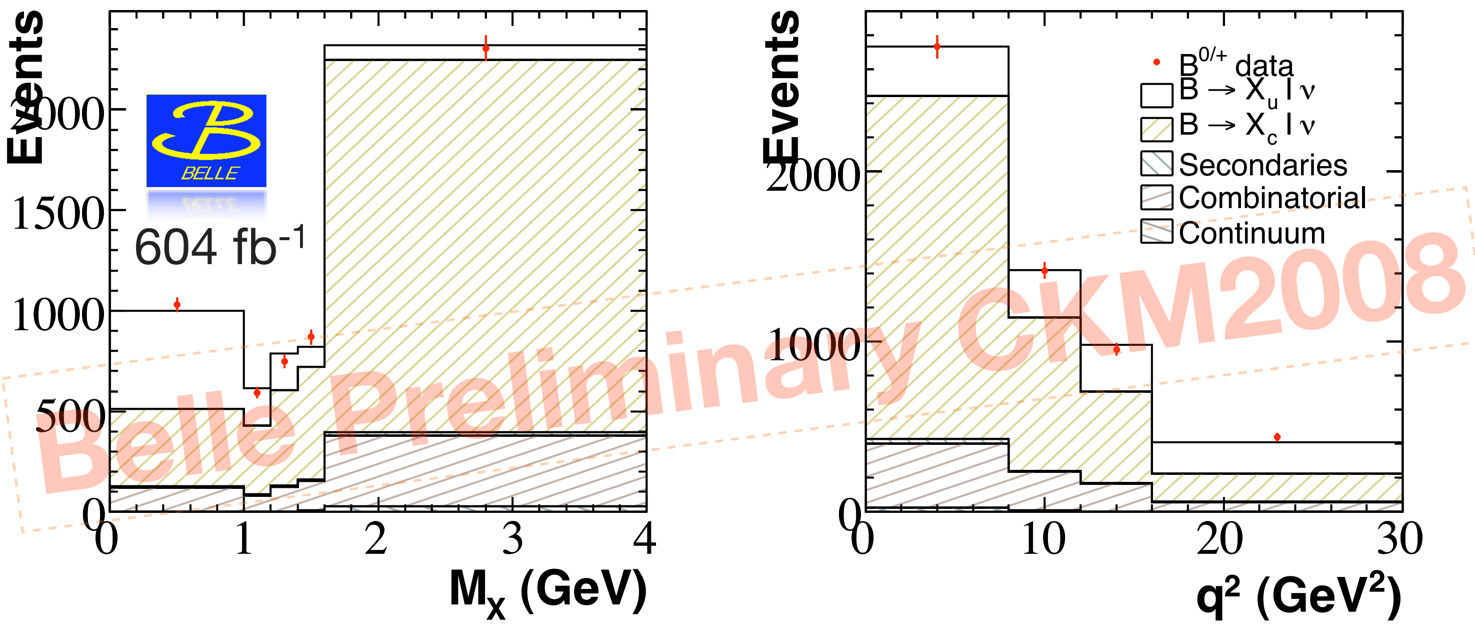
Boosted decision tree based selection, use ~20 event parameters from the full reconstruction sample.

No need to place stringent, hard cuts that result in zero efficiency!

1. Signal side: Reconstruct high momentum lepton: $p_{lep}^{B*} > 1$ GeV/c
2. Event Level: $Q(B_{reco}^{+}) \times Q(lep) = -1$
3. BDT cut with many input par's: M_{miss}^2, dZ, dr, Q_{total}, Qlepton, Nlepton, Q(B), D* partial reco etc.....
4. Combinatorial estimated from MC, normalisation from sideband region. (same approach as Vcb moments analyses)
5. 2D fit to M_x, q^2 with backgrounds and signal floated to determine background yield.
6. Measure absolute rate.



Belle Multivariate analysis (NEW @ CKM2008) 2/2



~1035 Evts

2D fit in q2 mx. (projections shown)

Kinematic Region	$\mathcal{B}(B \to X_u l \nu) \times 10^{-3}$ Δ(stat. sys.)	m_b	$\lvert V_{ub}\rvert$ (10^{-3}) % error	*Theory*
$P_{lepton} > 1.0$ GeV	1.96 x (1 ± 0.088 ± 0.076)	(kinetic) 4.613 GeV, mupi=0.440 GeV^2	4.42 (± 3.1 ± 5.1)	GGOU (thanks P. Giordano)
		(MSbar) 4.243 GeV	4.47 (± 6.7)	DGE (thanks E. Gardi)

~90† % total phase space, thus theory error less correlated to other Vub determinations

Tagged method Uncertainty Breakdown

ΔBR Errors in %

		stat	sys.	MC stat	detector/other		B → Xu l ν			B → cl ν		
	P_l>1.0 GeV				Det.	$M_{bc/ES}$	SF	Excl	ss	Inc.	FF	Excl BR
PRL 100, 171802 (2008)	Mx/q2	8.0	7	4.3	3.8	5.2	2.4	2.7	1.0	1.2	0.6	0.8
	Mx	9.0	7	3.2	1.9	3.7	0.9	2.1	1.6	0.9	0.2	0.4
	P+	10.0	8	4.6	3.9	4.0	1.3	2.2	1.5	2.8	0.4	0.7
Phys.Rev.Lett. 95:241801 (2005)	M_X/q^2	10.0	8.9		8.9		6.2			5.3		
	Mx	9.1	7.1		7.1		6.1			2.2		
	P+	9.4	9.3		9.3		6.4			8.7		
Belle Preliminary CKM2008	BDT	8.8	7.6		4.8		3.6	4.0	1.5	1.7		

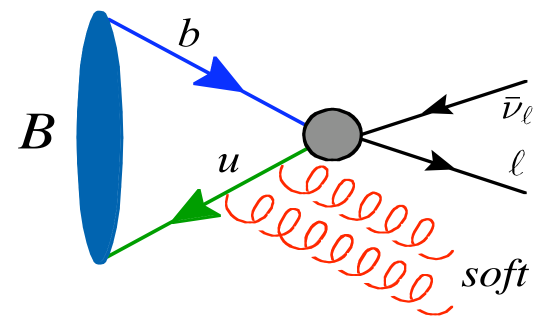
- Detector effects are better understood and no longer dominate.
- Selection often involves complex fitting techniques (m_{ES})
  - more data improves fit convergence in mES method.
  - more data will mean more detail in $q^2/M_X/P+$ to account for!

KL cut powerful (used in Belle $M_X/P+/q^2$ analysis) but modelling/understanding needs huge improvments.

- Dominant systematics are in the modelling of signal and background contributions
  - b->u l ν (resonances, non-resonant contributions)
  - b->c l ν (D, D*, D** very small)
  - Continuum error large in $q^2/M_X/P_+$ analyses.

Weak Annihilation

- Small contribution to B → Xu l ν decays
- Introduces difference between B^0 and B^+ decays.
- Tag with partial reconstructed $B^0 \rightarrow D^{*+} l \nu$
- Neutrino mass from $m_\nu^2 = (P_B - P_D - P_l)^2$
- Compare B0 partial rate to B+ averaged rate over large Pl region (to enhance the WA contribution) PRD73, 012006 (2006)

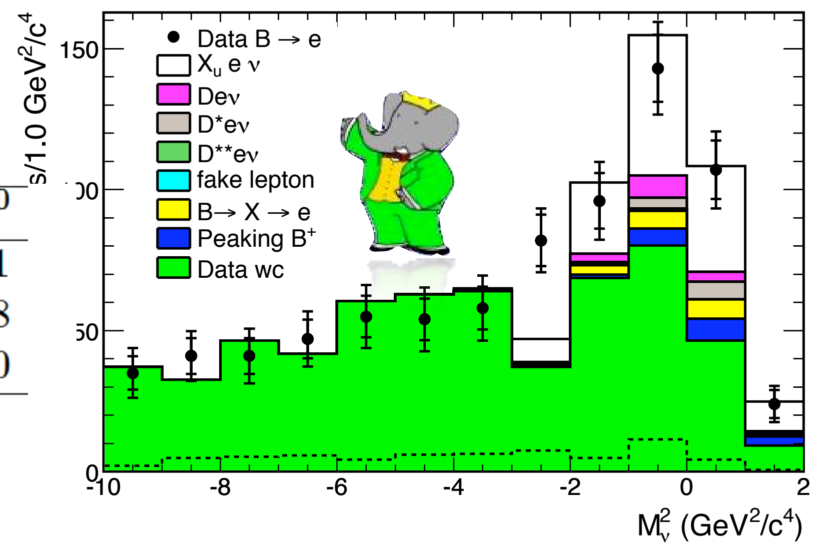


$$\frac{|\Gamma_{WA}|}{.\Gamma_u} < 7.4\% \ at\ 90\% C.L.$$

CLEO, studing the q^2 spectra PRL96,121801 (2006)

Δp	$\Delta\mathcal{B}(B)\cdot 10^4$[8]	$\Delta\mathcal{B}(B^0)\cdot 10^4$	$A^{+/0}$
$2.2-2.6\,\mathrm{GeV}/c$	2.31±0.10±0.18	2.62±0.33±0.16	-0.17±0.15±0.11
$2.3-2.6\,\mathrm{GeV}/c$	1.46±0.06±0.10	1.30±0.21±0.07	0.08±0.15±0.08
$2.4-2.6\,\mathrm{GeV}/c$	0.75±0.04±0.06	0.76±0.15±0.05	-0.05±0.20±0.10

$$\frac{|\Gamma_{WA}|}{\Gamma_u} < \frac{3.8\%}{f_{WA}(2.3-2.6)} \ at\ 90\% C.L.$$



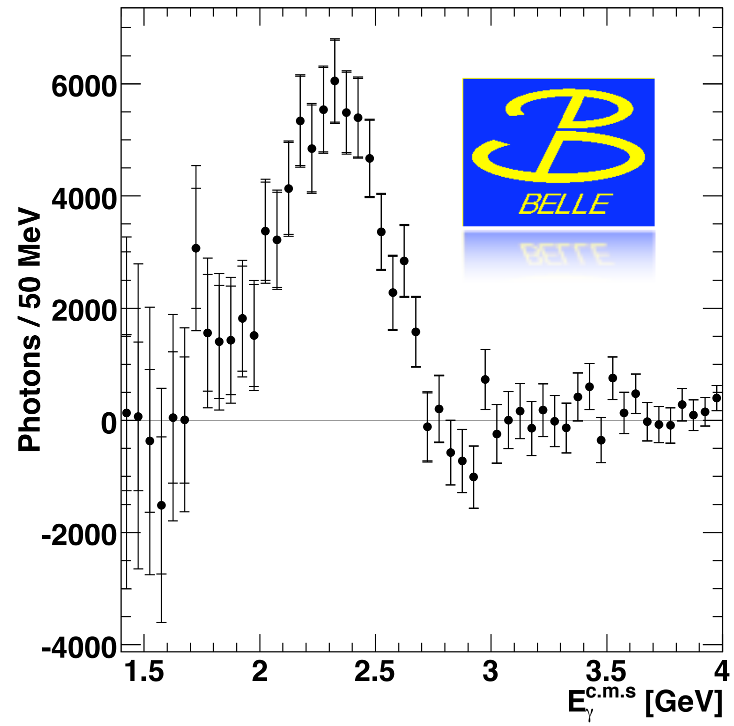
arXiv: 0708.1753 383 M BB

Shape Function

Theory doesn't work everywhere in the phase space → re-sum turn non-perturbative terms

We can determine mean and width of shape function.

- Fit the $b \to s\gamma$ spectrum to constrain the shape function
- b-quark: mass and kinetic energy from $b \to cl\nu$ and $b \to s\gamma$ decays
- Plug the SF into the $b \to ul\nu$ spectrum calculations
- Ready to extract $|V_{ub}|$



Theory calculation for SF >= 2-loop.

Shape Function needs to be determined from experimental data.

alternatives: cut out SF region, or factorise out the SF

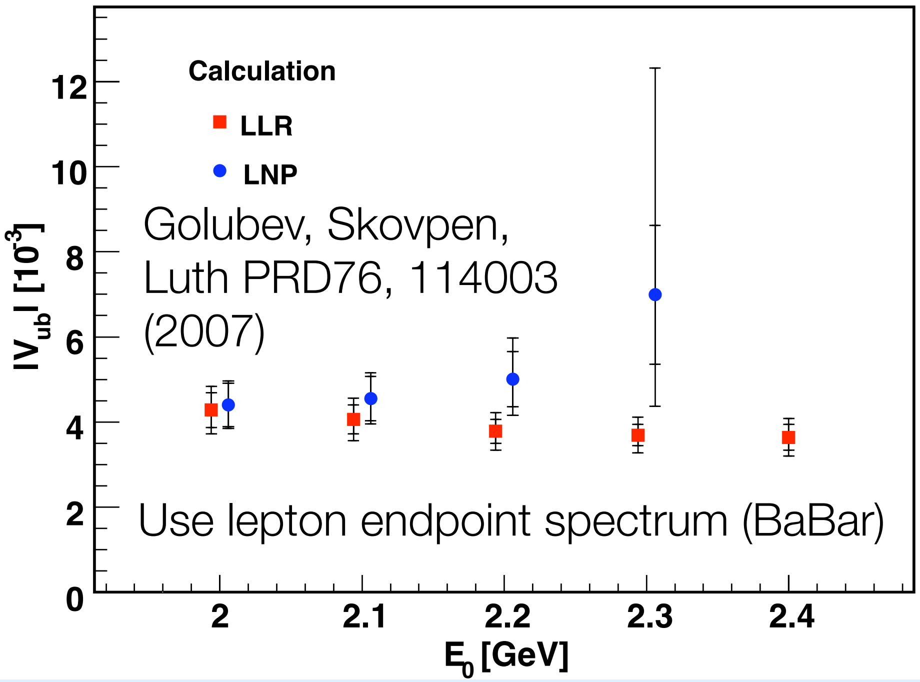
SF independent analyses

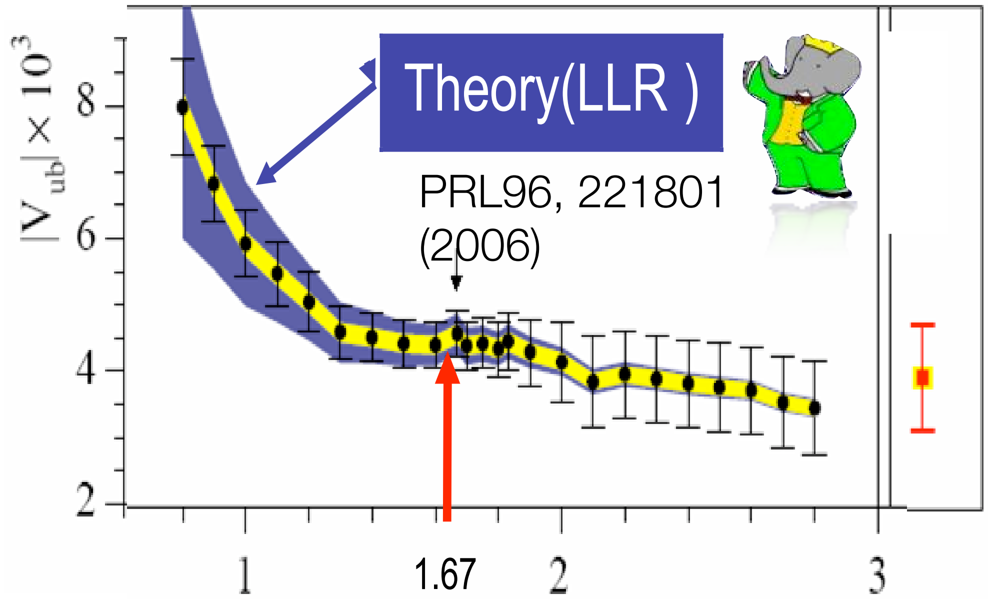
Exploit the assumption that the leading shape functions are the same for all b→q transitions.

LNP **Lange,Neuber,Paz JHEP0510:084 (2005)**

LLR **Leibovich,Low,Rothstein PRD61,053006(2000) PLB513,83 (2001)**

$$\int_0^{m_{max}} \frac{d\Gamma(b\to u)}{dm_X} dm_X \Longleftrightarrow \int_{E_{min}}^{m_B/2} \frac{d\Gamma(b\to s\gamma)}{dE_\gamma} W(E_\gamma, E_{min}) dE_\gamma$$





Uncertainties due to non-perturbative power corrections increase rapidly near the kinematic end point (not included in LLR).
The results agree with analyses that rely on an assumed shape function form.

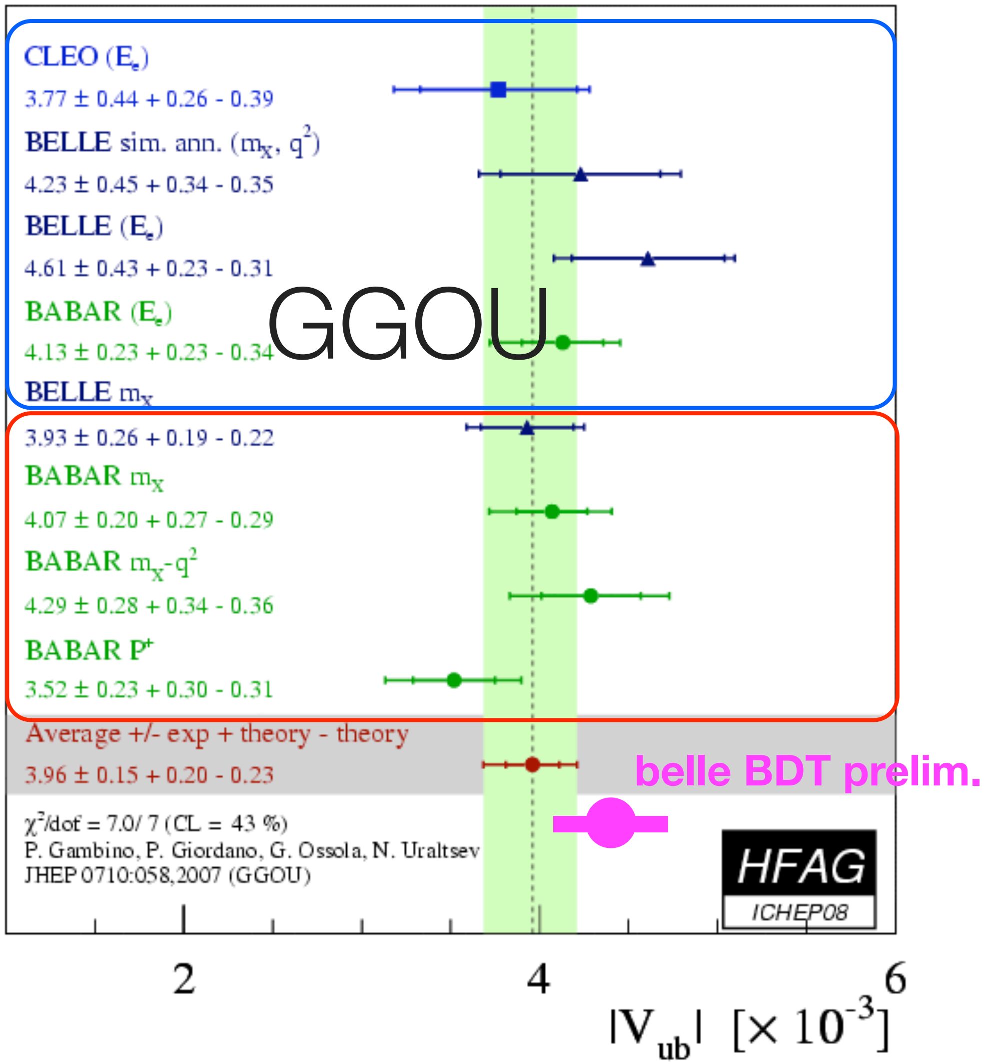
Measure Mx in Breco sample (89 MBB)

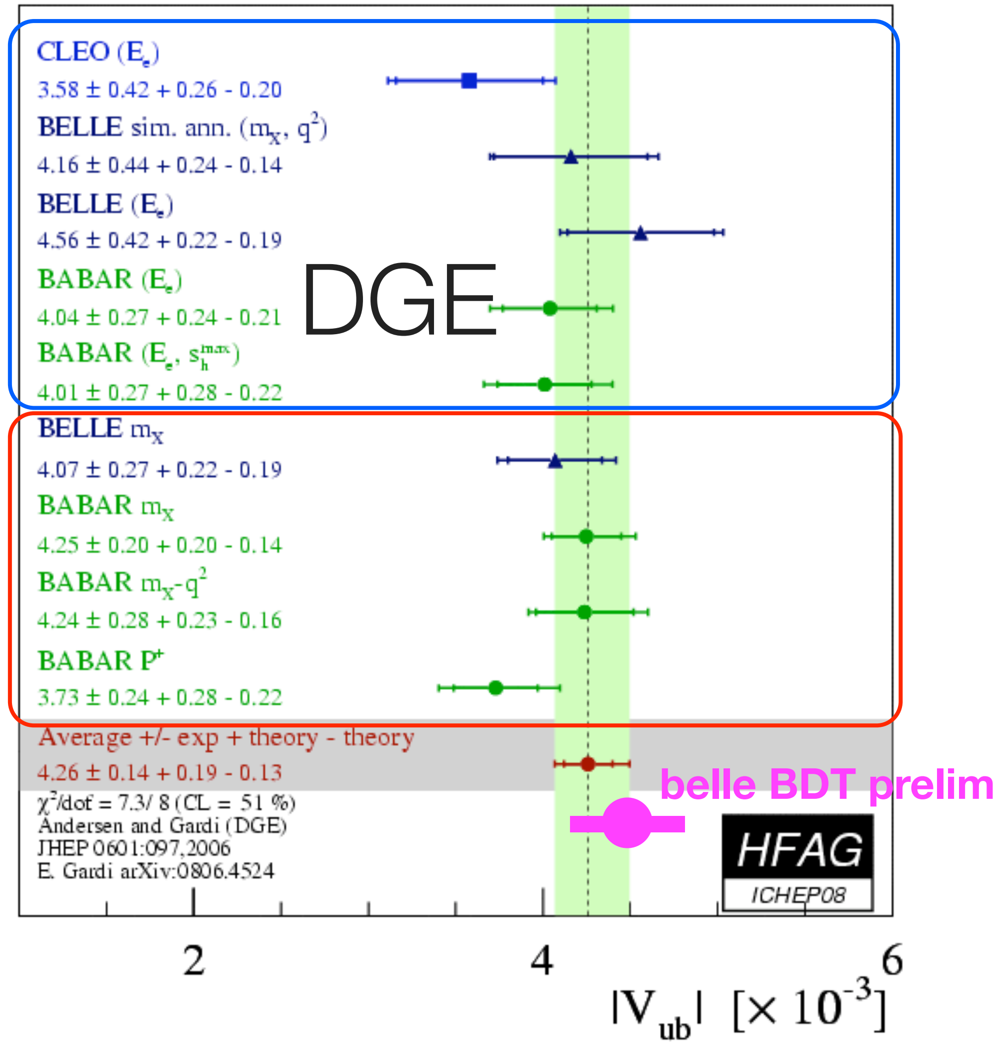
$|V_{ub}|=(4.43 \pm 0.30_{stat} \pm 0.25_{syst} \pm 0.29_{theo})\times 10^{-3}$

Inclusive $|V_{ub}|$

m_b(kin) = 4.601 ± 0.034 GeV HFAG

m_b (MSbar) = 4.243 ± 0.042 GeV HFAG





no systematic difference between tagged and untagged results

Inclusive $|V_{ub}|$ Error Breakdown

	BLNP	DGE	GGOU
	+8.2 -7.2	+5.7 -4.7	+6.3 - 7.0
Statistical	2.1	2.2	2.2
Experimental Systematics	2.3	2.1	2.2
b->c l v model	1.3	1.2	1.3
b->u l v model	1.4	1.3	1.5
HQ parameters/non. pert	5.7	+4.0 - 2.7	3.9
SF + Sub. SF	2.4		
matching	3.7		
Weak Annihilation	1.6	1.5	+0.0 -3.1
DGE theory		+1.2 -0.5	
R_{cut}		+0.7 -0.3	
q2 tail model			2.6
Higher order parameters			+1.3 -0.6

what can improve?

More data (ab^{-1}) for better background suppression, more off-res in endpoint.

B Beam

Reduced significantly in tagged meas.

Exclusive B→ρ/ω/η lν recently dominate

HQE/$|V_{cb}|$ fits/ Υ(1S) (hit theory and expt. wall!)

Most theory uncertainties can be reduced significantly if we increase the measured phase space.

The power dependence of m_b and related theoretical uncertainties scale inversely with phase space coverage.

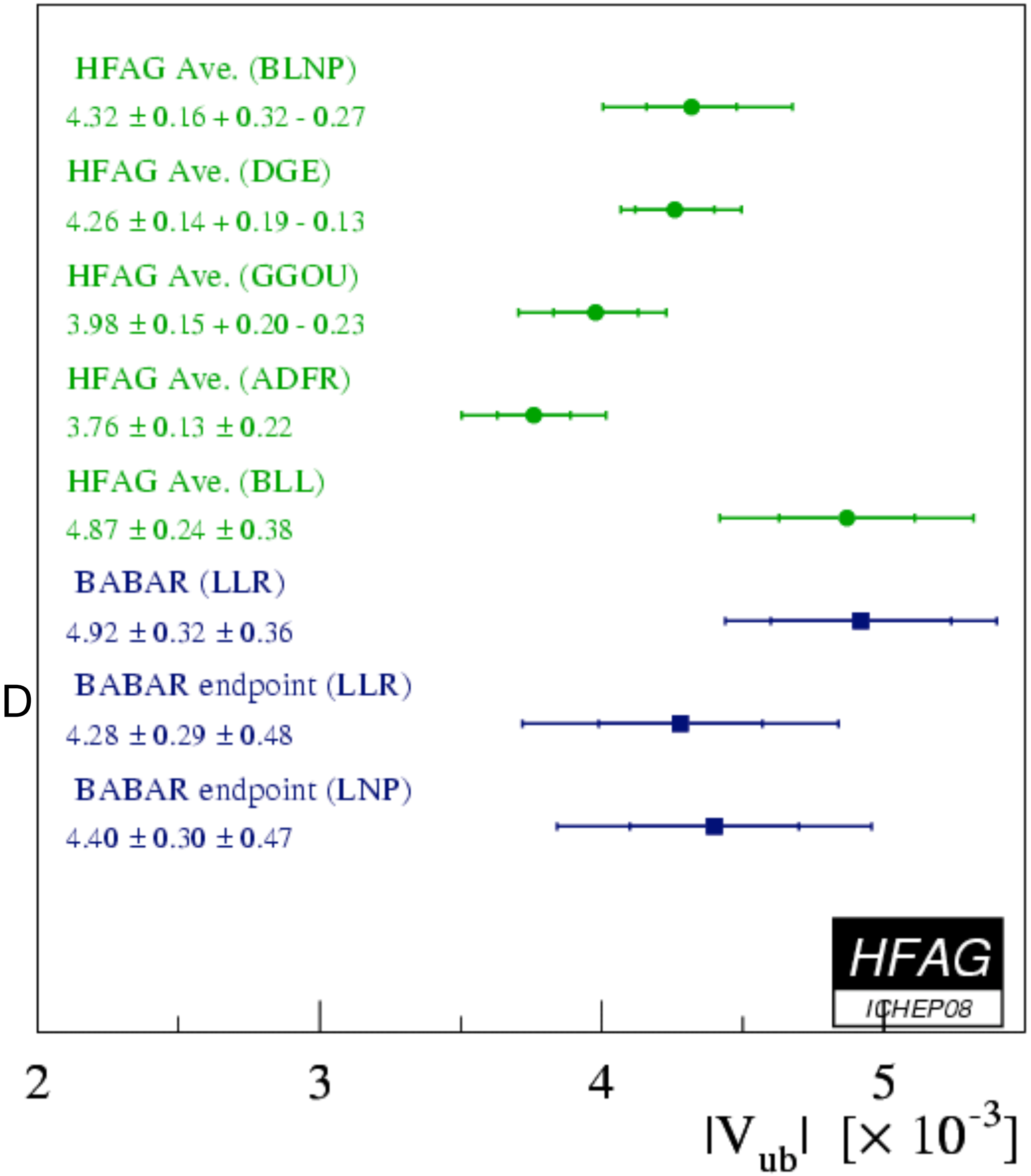
Comparison of $|V_{ub}|$ extraction

OPE based + SF

- **BLNP**: HQE with systematic introduction of SF
  PRD71:073006 (2005)
- **BLL**: phase space in m_X-q^2 with reduced SF
  PRD64:113004 (2001)
- **GGOU**: kinetic scheme
  JHEP 10(2007) 058
- **LNP (LLR)**: b→sγ directly related to b→ u ℓ ν
  JHEP 0510:084 (PLB 486:86)

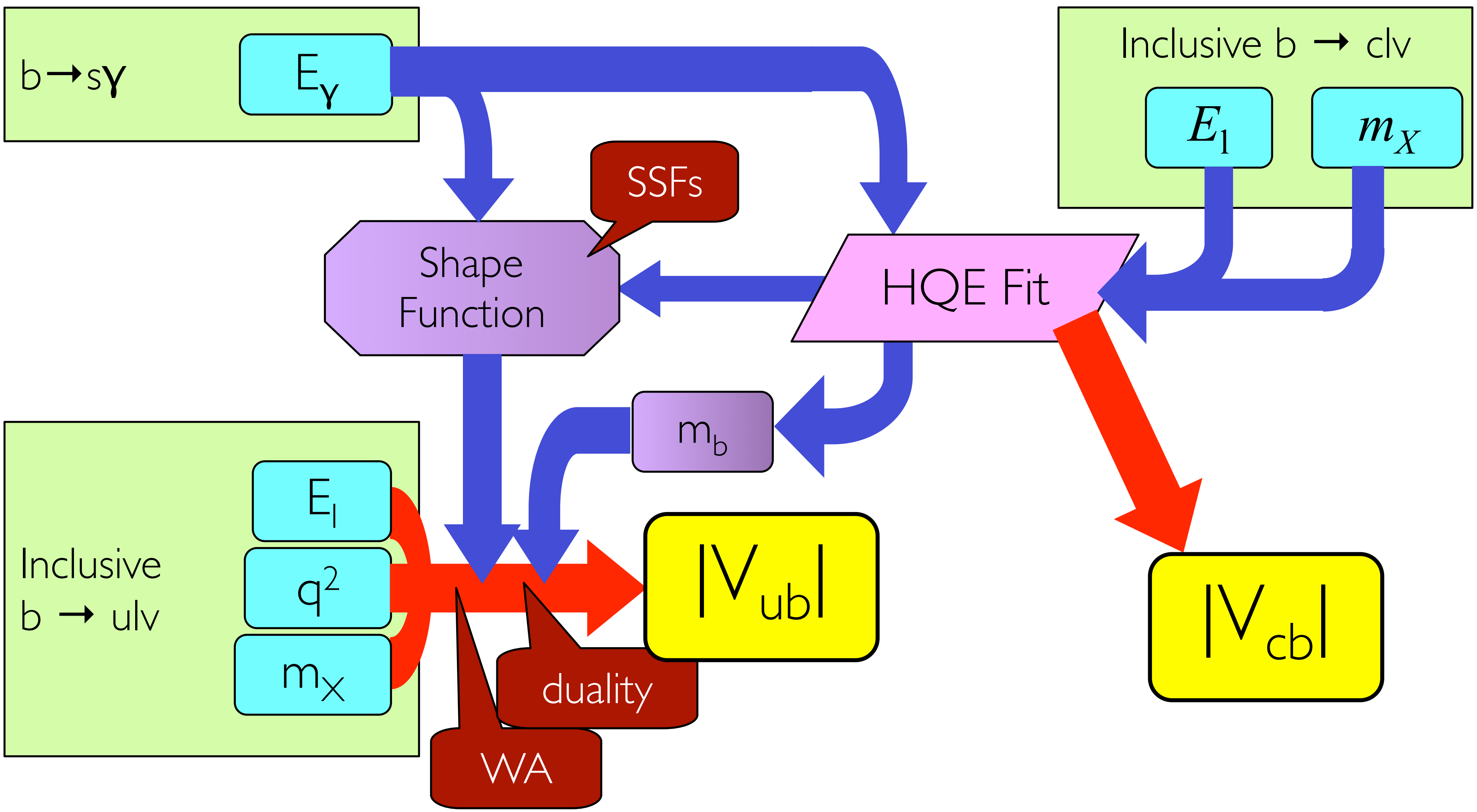
No SF introduced ➢ model non-perturbative QCD

- **DGE**: Dressed Gluon Exponentiation
  JHEP 0601:097 (2006)
- **ADFR**: Analytic coupling
  PRD74:03400(4,5,6) (2006)

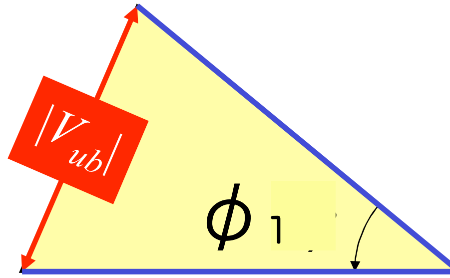


How Things Mesh Together

AKA: M. Morii's HQE plumbing diagram



Conclusions



Untagged methods

Endpoint:

Goal: lower lepton energy cut to reduce theoretical uncertainty

- Will require improved knowledge of charmed semileptonic background.
- Stat. error will be relatively small if we have enough off-resonance data.

Improved Endpoint:

Prospects for reducing systematics, phase space cuts can be relaxed

Gain from relaxing S_h^{max} , however, there is fast BG increase

Tagged Methods

Full Reconstruction:

Better knowledge of exclusive states crucial.

Data has become quite sensitive to the underlying hybrid model MC (though HQ parameters have become better known with charmed semileptonic decays).

Novel BDT approach by Belle promises to reduce phase space dependent uncertainties.

Overall

Novel approaches eliminating SF dependence agree with SF, and QCD Model results.

WA tied down.

Inclusive V_{ub} ~8% error shared between theoretical and experimental. Static in the past 2 years.

- Why? |Vub| theory errors are highly correlated.