CKM elements from semileptonic B decays

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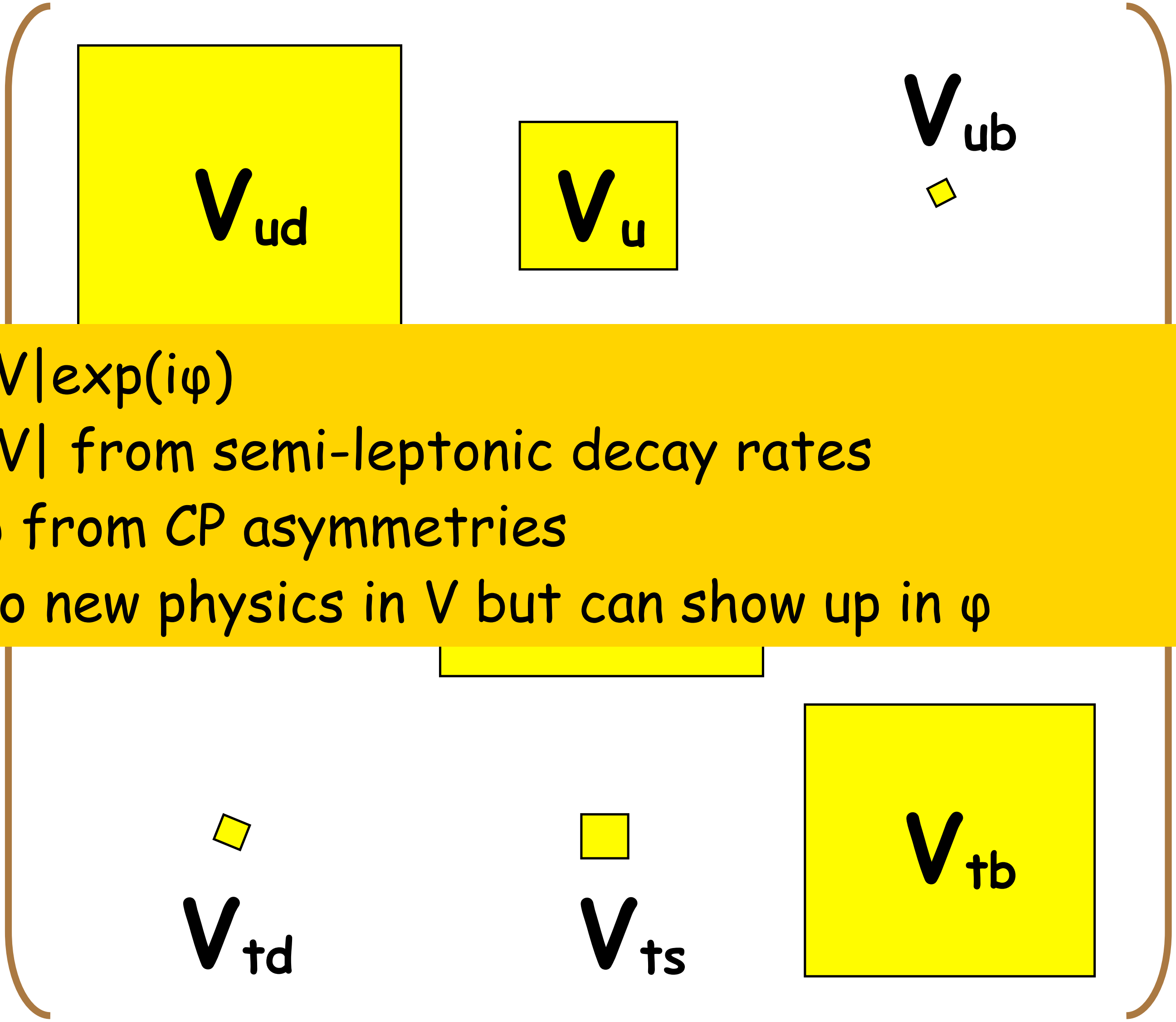
La Thuille February 2008

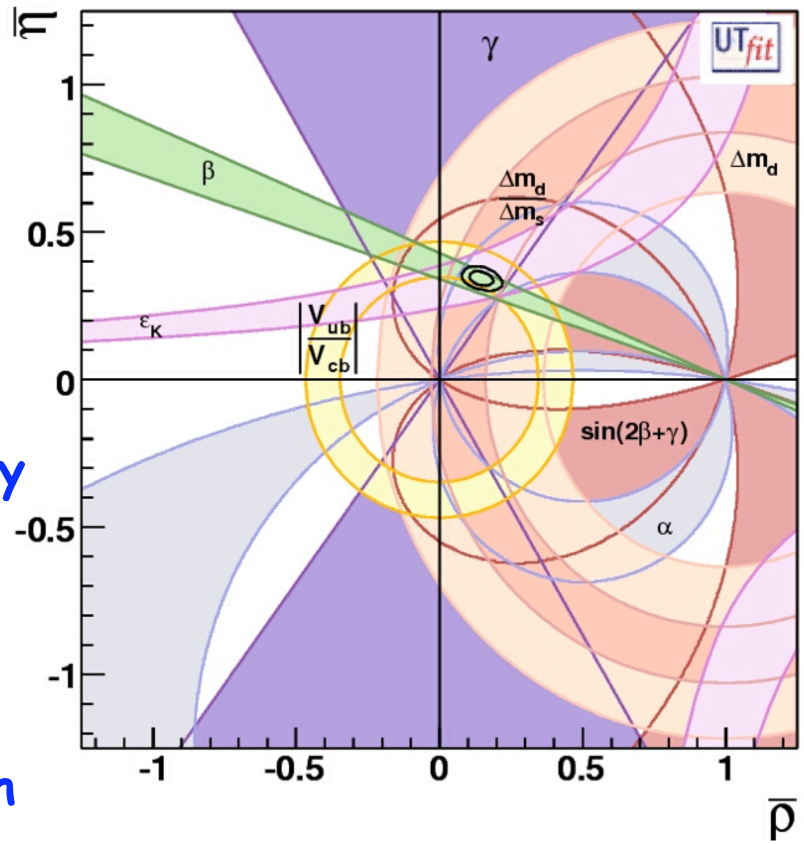


- $V = |V| \exp(i\varphi)$
  - $|V|$ from semi-leptonic decay rates
  - φ from CP asymmetries
  - No new physics in V but can show up in φ

They are fundamental parameters of the Standard Model and cannot be predicted

New Physics?

- exploit the unitarity constraint to look for new physics → geometrical relation between CKM elements:
  - angle from CP asymmetries
  - size from V

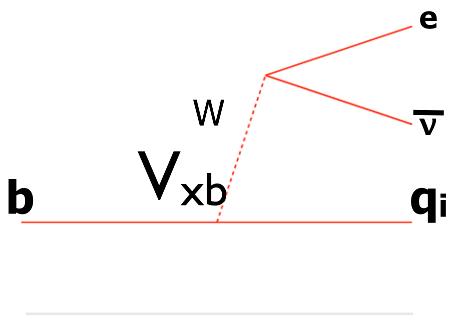


- New precision era where new physics may appear as a few percent disagreement:
- Large new physics contributions to penguins would have already been seen.
- New physics contributions to decays such as $B \to \tau\ \nu$ is still open (e.g. minimum flavour violation)

Semileptonic decays

tree level, short distance:

B→ Xi l ν

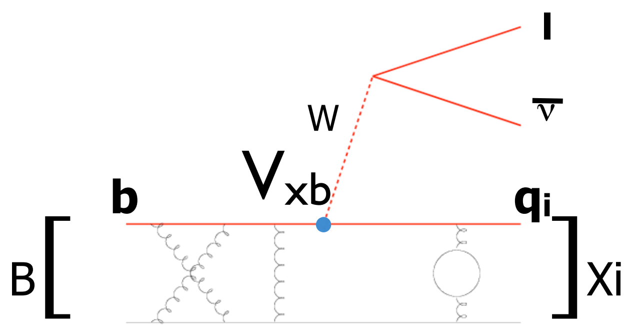


decay properties depend directly on $|V_{xb}|$ and m_b in perturbative regime (α_s^n)

Semileptonic decays

tree level, short distance:

B→ Xi l ν



+ long distance:

decay properties depend directly on $|V_{xb}|$ and m_b in perturbative regime (α_s^n)

But quarks are bound by soft gluons: non-perturbative

long distance interactions of b quark with light quark

two way to go:

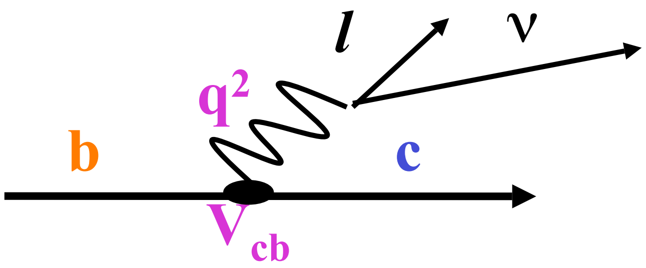
- Measure exclusive states
- Measure inclusively b → xln spectrum

V_{cb}

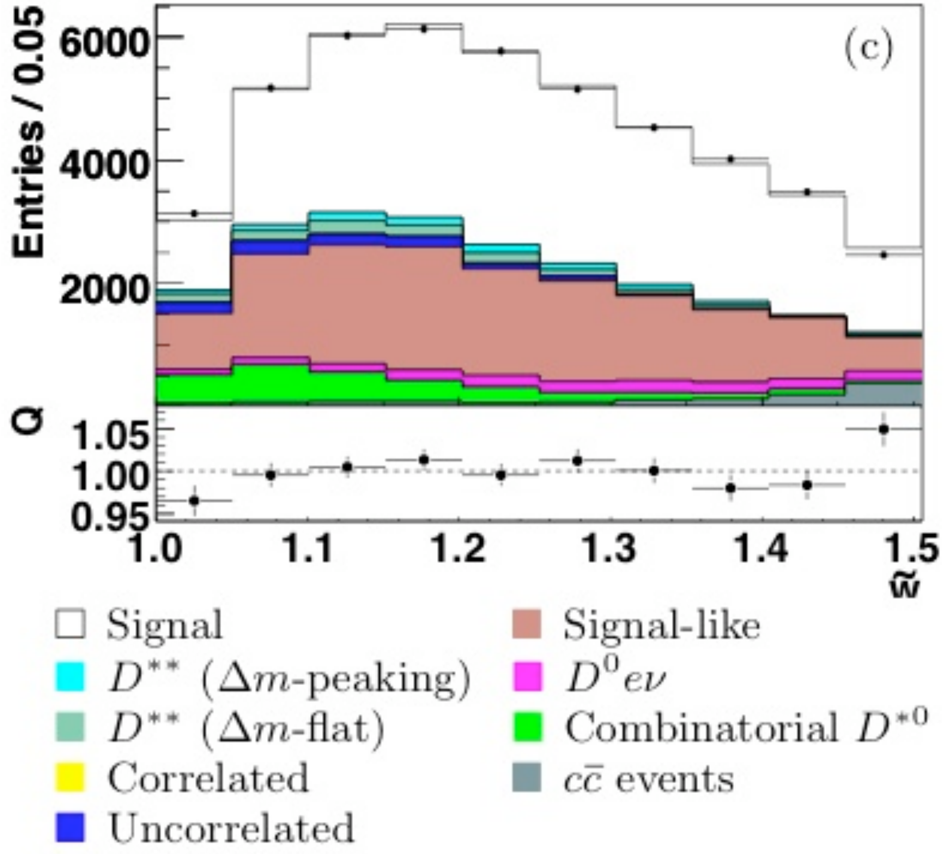
V_{cb} exclusive $B^- \rightarrow D^{*0} e^- \nu$

$B^- \rightarrow D^{*0} e^- \nu;\ D^* \rightarrow \pi^0 D^0$

$$\frac{d\Gamma(B \to D^* l\nu)}{dw} = K(w)\mathcal{F}^2(w)|V_{cb}|^2$$



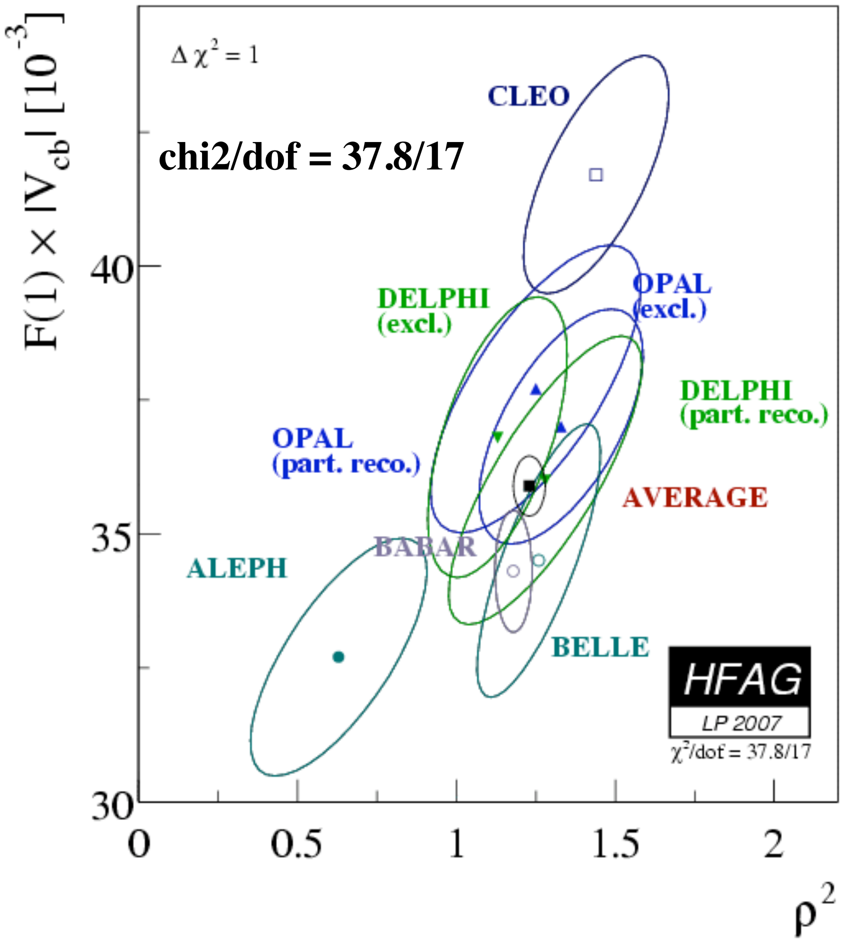
$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$$



$$F(1) \cdot |V_{cb}| = (35.9 \pm 0.6 \pm 1.4) \cdot 10^{-3}\ ,$$
$$\rho^2_{A_1} = 1.16 \pm 0.06 \pm 0.08\ ,$$
$$\mathcal{B}(B^- \to D^{*0} e^- \overline{\nu}_e) = (5.56 \pm 0.08 \pm 0.41)\%\ .$$

Main physics background $B \rightarrow D^{**} l \nu$

$\mathcal{F}(1)|V_{cb}|$



$\mathcal{F}(1)|V_{cb}|=(35.9\pm0.6)10^{-3}$ $\rho_A^2 = 1.23\pm0.05$

From $F(1)=0.919\pm0.033$:

$|V_{cb}|=(39.1\pm0.65\pm1.4)10^{-3}$

error is dominated by the lattice calculation, no improvement in the near future

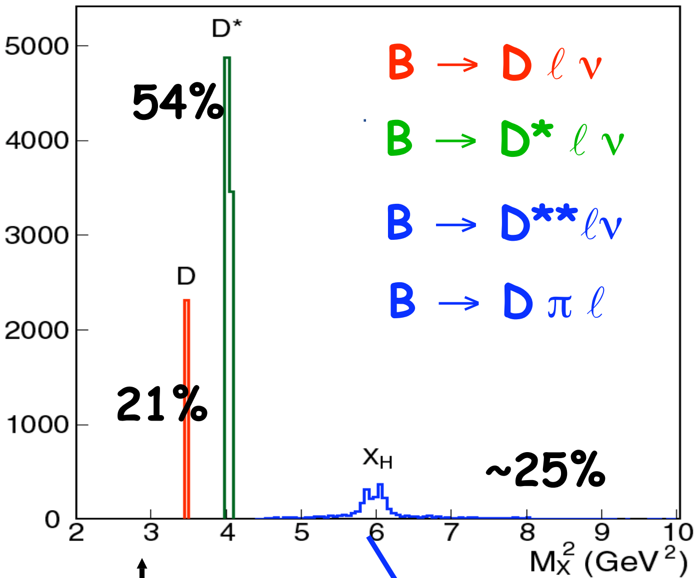
$B \to D^0 l \nu$ has a small theoretical error but it's more difficult experimentally and very few measurement

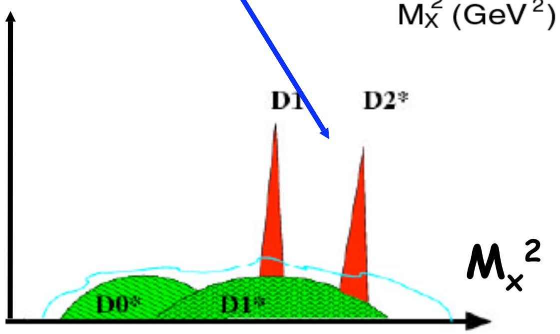
HFAG average uses R_1, R_2 from BaBar this decrease $\mathcal{F}(1)|V_{cb}|$

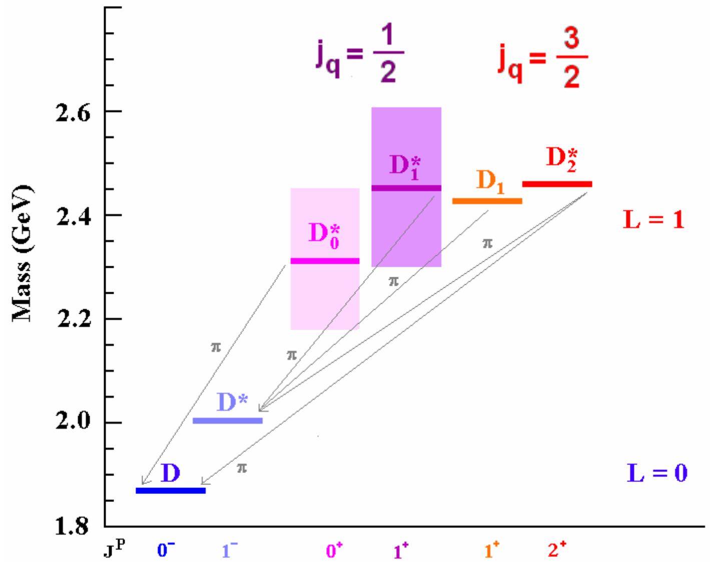
Hadronic X_c system

	B^0 BR(%)	B^+ BR(%)
inc.-Σ excl.	2.22±0.38	1.27±0.37

PDG&HFAG& Babar & Belle







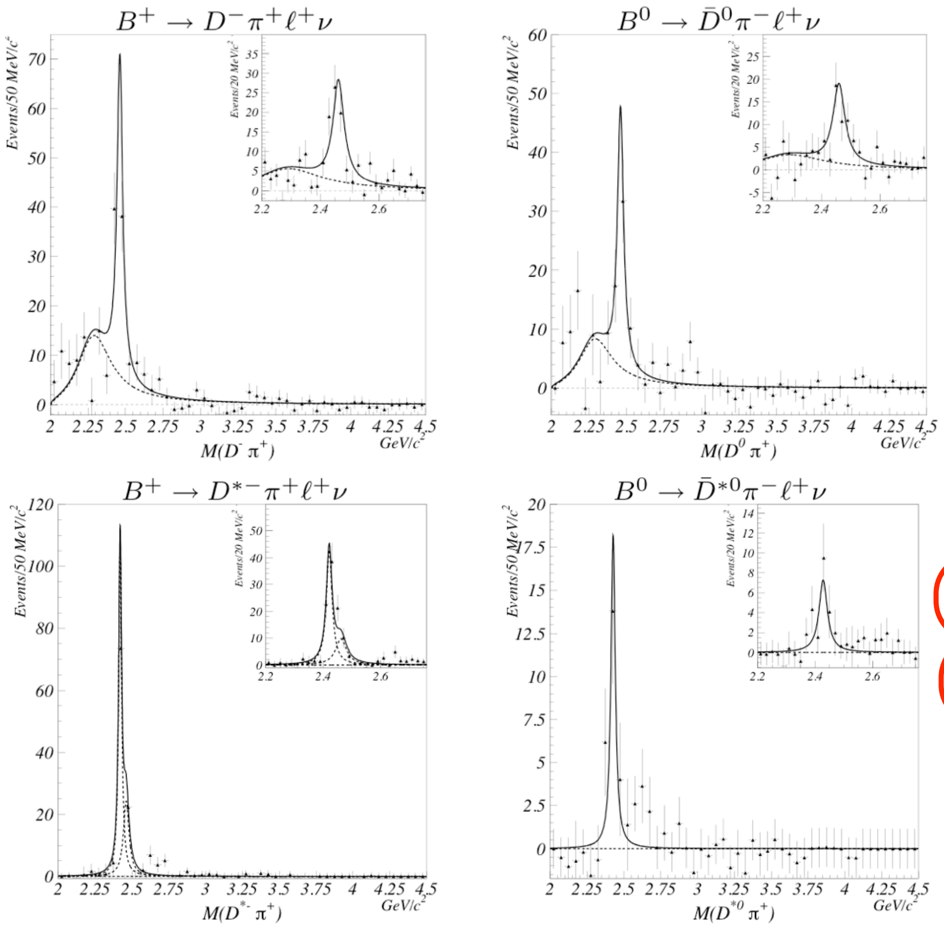
Grounds states **Broad states** **Narrow states**

Heavy Quark Symmetry predicts

Br(B → Narrow l) >> Br(B → Broad l)

Experiment seems to point towards the opposite !!!!

Hadronic X_c system



Theory predicts the rate of broad D^*_0 ~ 10 times smaller than narrow D^*_2

Belle measure comparable branchings fractions

$$\mathcal{B}(\text{mode}) \equiv \mathcal{B}(B \to D^{**}\ell\nu) \times \mathcal{B}(D^{**} \to D^{(*)}\pi^+)$$

$D\pi$ invariant mass study

Mode	Yield	$\mathcal{B}$, %	Signif.
$B^+ \to D_0^{*0}\ell^+\nu$	102 ± 19	$0.24 \pm 0.04 \pm 0.06$	5.4
$B^+ \to \bar{D}_2^{*0}\ell^+\nu$	94 ± 13	$0.22 \pm 0.03 \pm 0.04$	8.0
$B^0 \to D_0^{*-}\ell^+\nu$	61 ± 22	$0.20 \pm 0.07 \pm 0.05$	2.6
$B^0 \to D_2^{*-}\ell^+\nu$	68 ± 13	$0.22 \pm 0.04 \pm 0.04$	5.5

$D^*\pi$ invariant mass study

Mode	Yield	$\mathcal{B}$, %	Signif.
$B^+ \to \bar{D}_1^{\prime 0}\ell^+\nu$	-5 ± 11	< 0.07 @ 90% C.L.	
$B^+ \to \bar{D}_1^0\ell^+\nu$	81 ± 13	$0.42 \pm 0.07 \pm 0.07$	6.7
$B^+ \to \bar{D}_2^{*0}\ell^+\nu$	35 ± 11	$0.18 \pm 0.06 \pm 0.03$	3.2
$B^0 \to D_1^{\prime -}\ell^+\nu$	4 ± 8	< 0.5 @ 90% C.L.	
$B^0 \to D_1^-\ell^+\nu$	20 ± 7	$0.54 \pm 0.19 \pm 0.09$	2.9
$B^0 \to D_2^{*-}\ell^+\nu$	1 ± 6	< 0.3 @ 90% C.L.	

V_{cb} from inclusive semileptonic decays

$$\Gamma_{sl}(b \to c\ell^-\bar{\nu}) = \gamma_{th} |V_{cb}|^2 = \frac{BR(b \to c\ell^-\bar{\nu})}{\tau_b}$$

exp. $\Delta|V_{cb}| < 1\%$

Γ_{sl} described by Heavy Quark Expansion in $(1/m_b)^n$ and α_s^k

$$\Gamma(B \to X_c l\nu) = \frac{G_F^2 m_b^5}{192\pi^3} |V_{cb}|^2 \left[[1 + A_{ew}] A_{nonpert} A_{pert} \right]$$

non perturbative parameters need to be measured and arise at each order

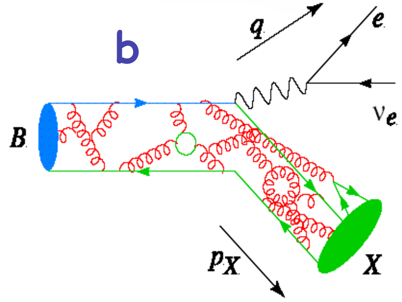
$$< X^n > (E_{cut}) = \frac{\int (X - X^0)^n \frac{d\Gamma}{dX} dX}{\int \frac{d\Gamma}{dX} dX} \cong f'_{OPE}(m_b, m_c, a_i)$$

X^n: sensitivity to non-perturbative parameters evaluated on part of the spectrum ($p_l > p_{min}$) in the B rest frame

expansions depend on m_b definition

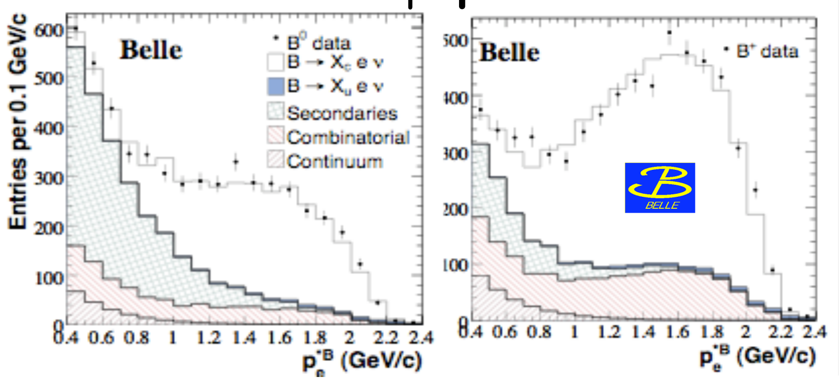
Heavy quark parameter determination- Big Picture

Semileptonic B decay

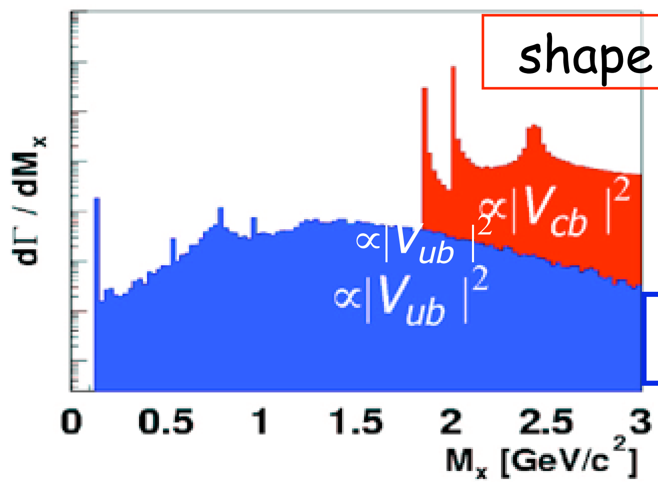


Experimental Challenge: go from the measured shape to the true shape

Inclusive E_l spectrum



Inclusive M_x spectrum



shape

shape

rate

rate

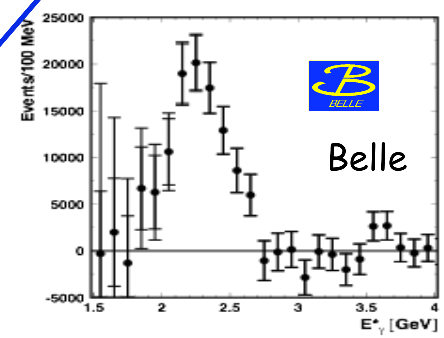
shape

$|V_{cb}|$

m_b, m_c
μ^2_G, μ^2_π

$|V_{ub}|$

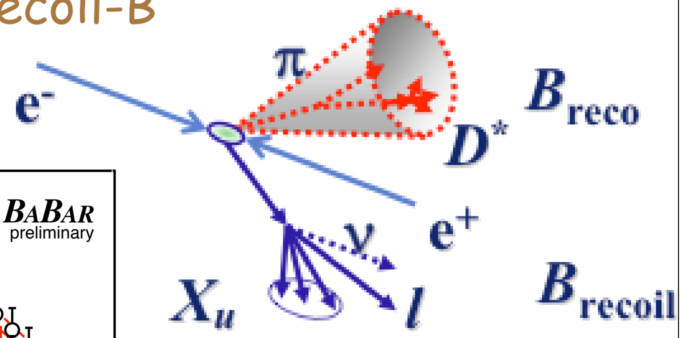
$Shape(B \to X_s \gamma)$

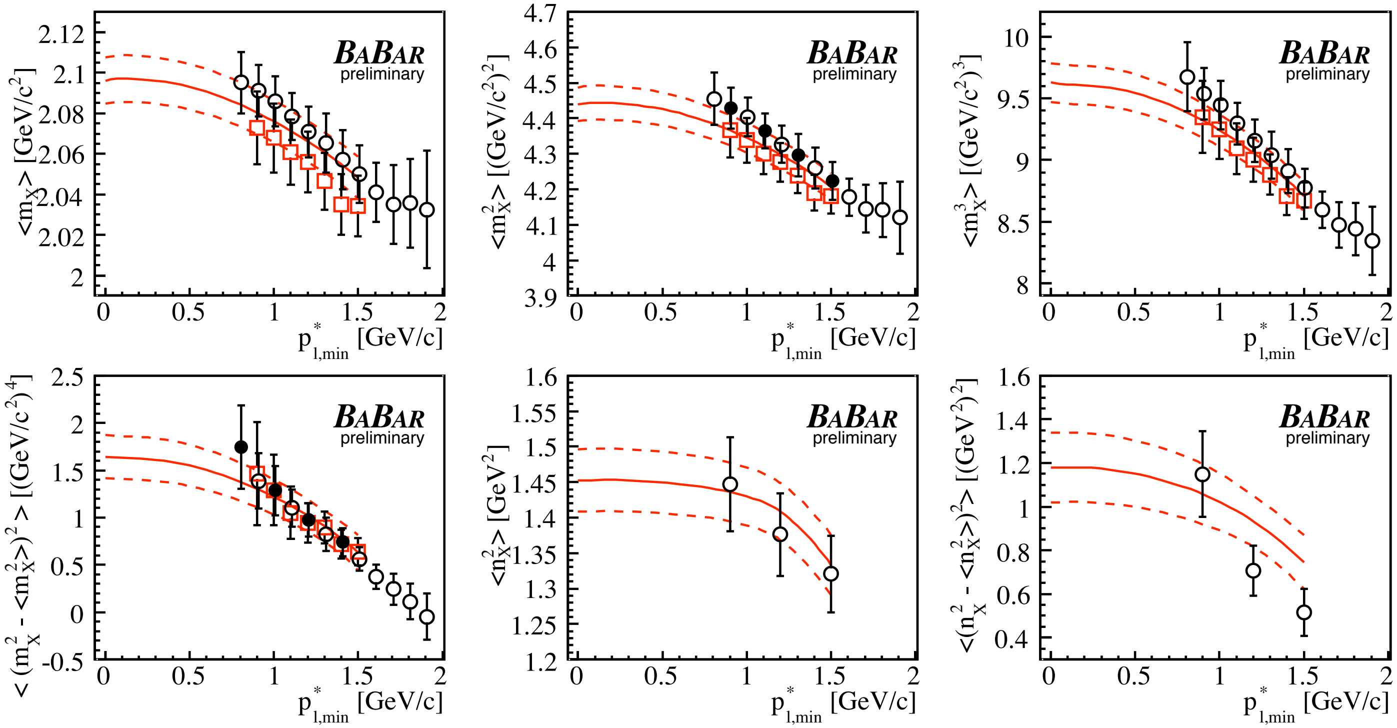


moments in semileptonic decays

fully-reconstructed B meson B flavor and momentum known.

rest of the event contains one "recoil" lepton in the recoil-B





$\langle m_X^n \rangle$ new

$\langle m_X^n \rangle$ old

Fit moments of these distribution to get V_{cb} and HQ parameters

Heavy quark parameters

E_l : lepton energy spectrum in $B \to X_c l \nu$ (BaBar Belle CLEO DELPHI)

$M_X{}^2$: hadronic mass spectrum in $B \to X_c l \nu$ (BaBar CDF CLEO DELPHI)

E_γ : photon energy spectrum in $B \to X_s \gamma$ (Babar Belle CLEO)

Decay rate in terms of Operator Product Expansion up to $1/m_b{}^3$

Two approaches:

Kinetic running mass

(P. Gambino and N.Uraltsev, Eur. Phys. J. C 34, 181 (2004))

1S mass

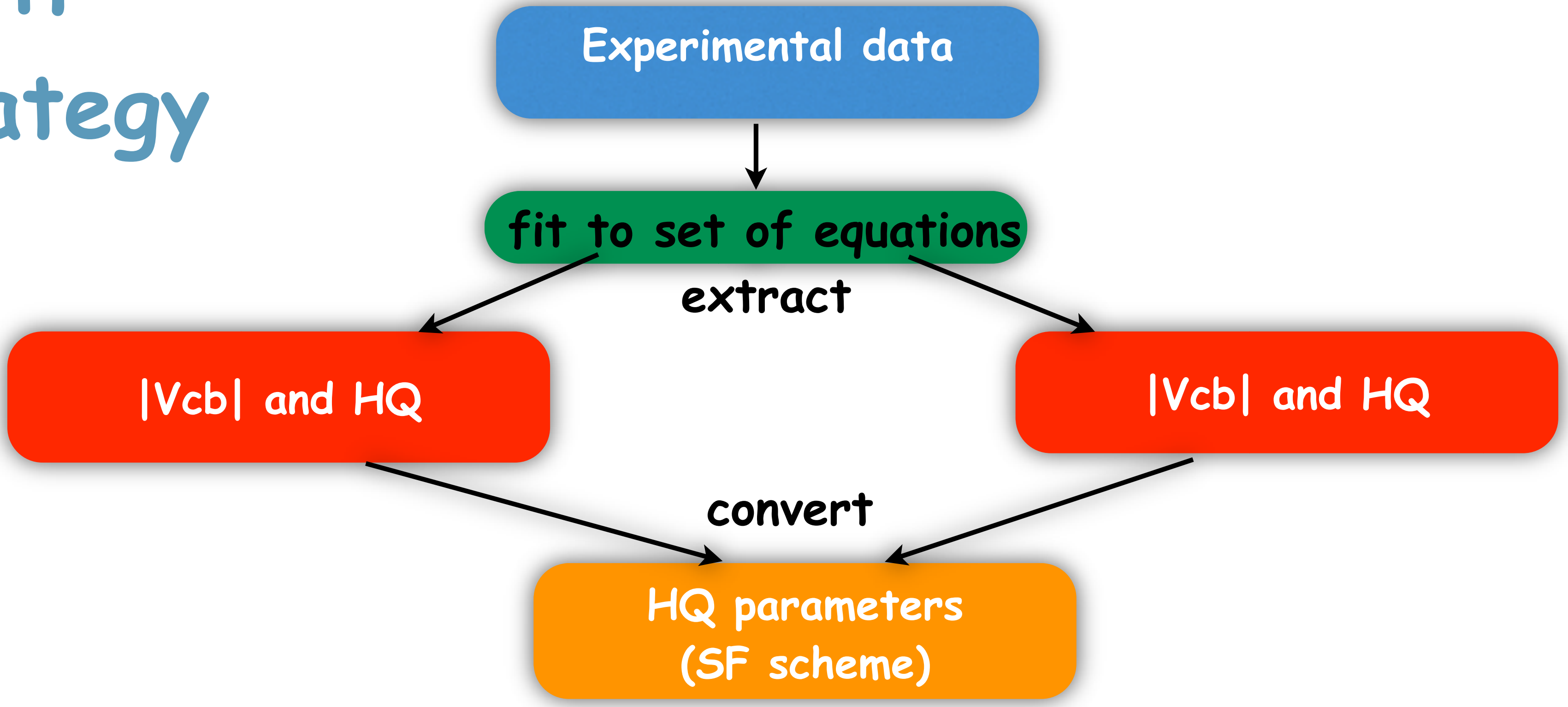
(C.Bauer, Z.Ligeti, M.Luke, A.Manohar, M.Trott PRD 70 094017)

Expansions in terms of:

	m^{kin}_b, m^{kin}_c (m^{1S}_b) - mass of b and c quarks
$\Lambda_{QCD}{}^2/m_b{}^2$	$\mu_\pi{}^2(\lambda_1)$ - kinetic energy of b quark, $\mu_G{}^2(\lambda_2)$ - chromomagnetic coupling
$\Lambda_{QCD}{}^3/m_b{}^3$	ρ_D, ρ_{LS} (ρ_1, τ_{1-3})

... and $|V_{cb}|^2$ dependence on partial branching fractions

Fit Strategy



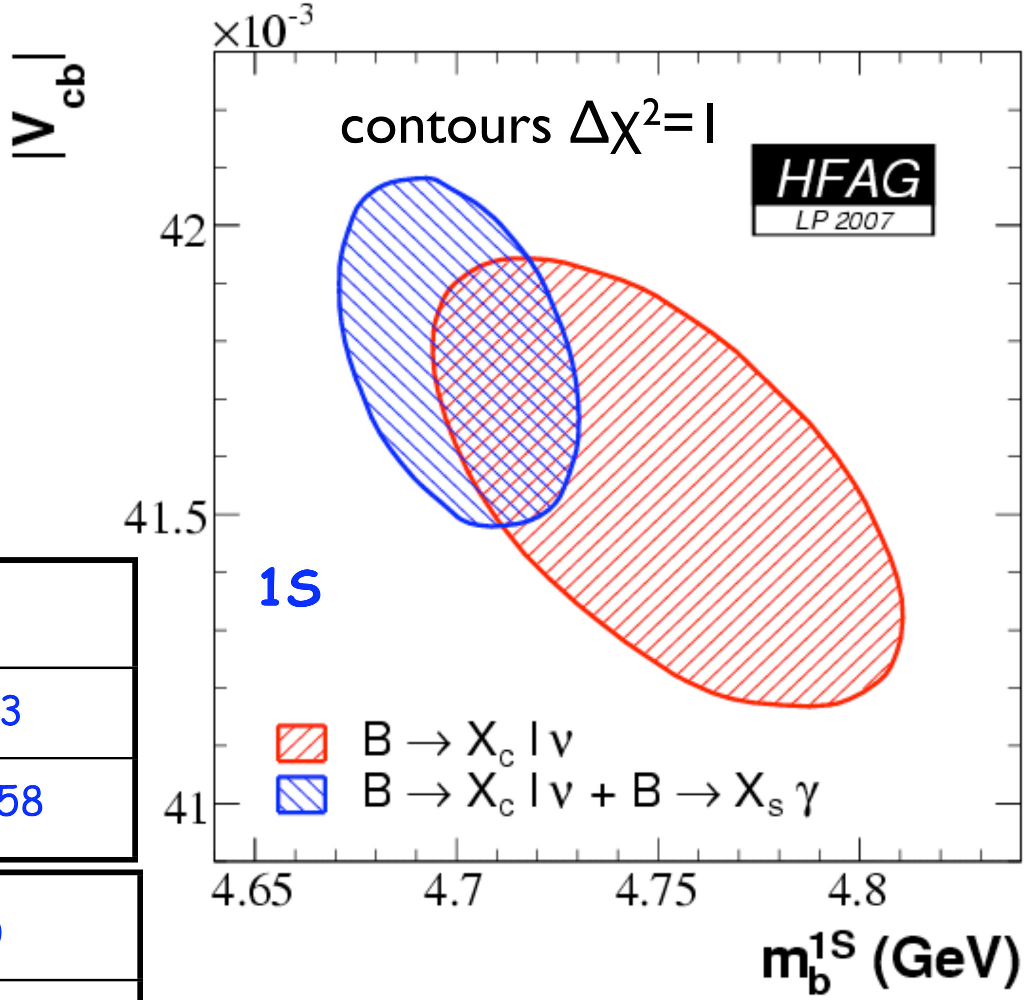
Without truncation of perturbation theory, any path to a given scheme would lead to the same result, e.g.:

[Fit in kinetic scheme] = [Fit in 1S scheme] $\oplus$ [Translation: 1S $\rightarrow$ kinetic]

In practice, results differ at finite order in α_s.

V_{cb} and HQ parameters

Global fit with all available results (except the latest BaBar moments)



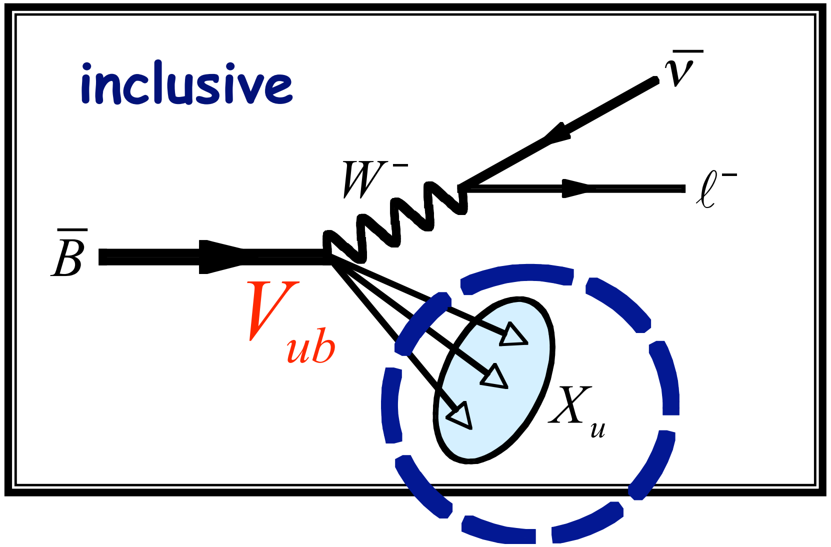
1S	V_{cb} (10^{-3})	m_b (GeV)
	41.78±0.30±0. 08	4.70±0.03
no $b\to s\gamma$	41.56±0.39±0.08	4.751±0.058

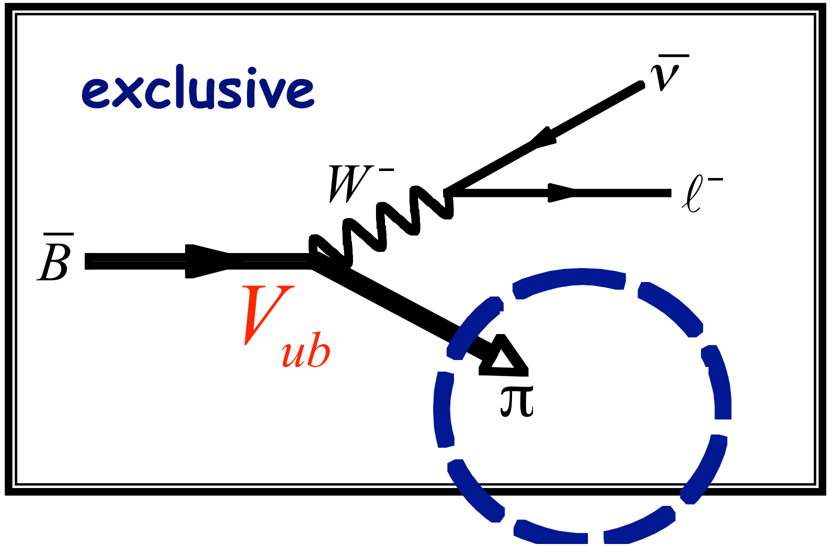
Kinetic	V_{cb} (10^{-3})	m_b (GeV)
	41.91±0.19±0.28±0.5	4.613±0.022+0.027
no $b\to s\gamma$	41.68±0.39±0.58	4.677±0.053

$|V_{cb}|^{excl}=(39.1\pm0.7\pm1.4)10^{-3}$

V_{ub}

V_{ub} determination





Uncertainty dominated by theory errors, measurements with different methods

- Inclusive $B \to X_u \ell \nu$
  - Use difference in kinematics to separate $u\ell\nu$ from $c\ell\nu$
  - Theory must predict signal spectrum
- Exclusive $B \to \pi\ell\nu, \rho\ell\nu, \omega\ell\nu, \ldots$
  - Better S/B, esp.
  - Theory must predict form factor

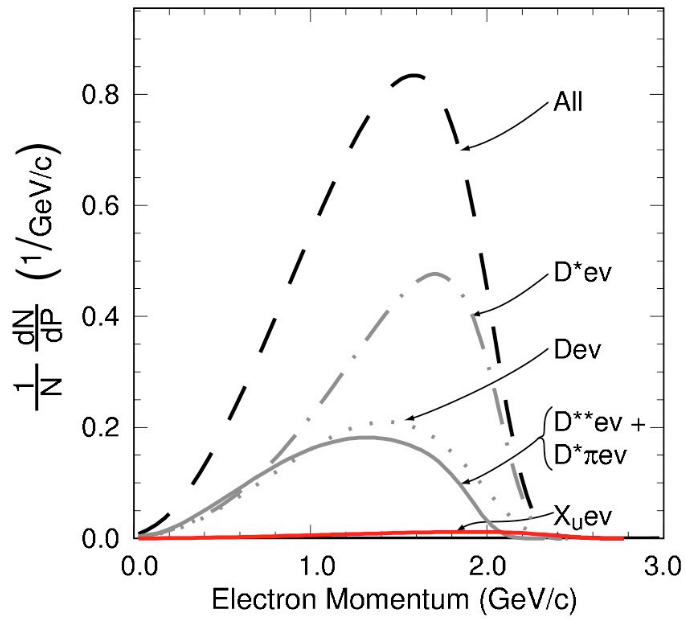
V_{ub} inclusive determination

B→ X_ulν tree level rate same as B→ X_clν

very small, very difficult to measure

the problem is the b→ clν decay

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



selection to remove background removes a sizeble part of the phase space. Need theoretical extrapolation for the full phase space (Shape Function, DGE, Aglietti et at,....).

V_{ub} inclusive determination

- Cut away b → clν Lose a part of the b → uℓν signal

  - We measure

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

Total b → uℓν

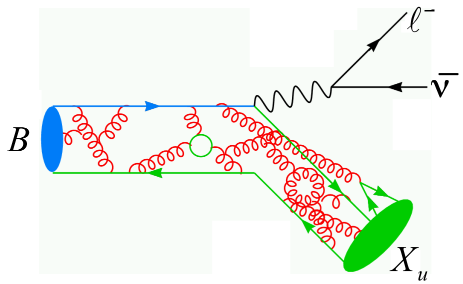
Cut-dependent constant predicted

Fraction of the signal that surviving

Need knowledge of b quark's motion inside B meson

- Must be corrected for QCD

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



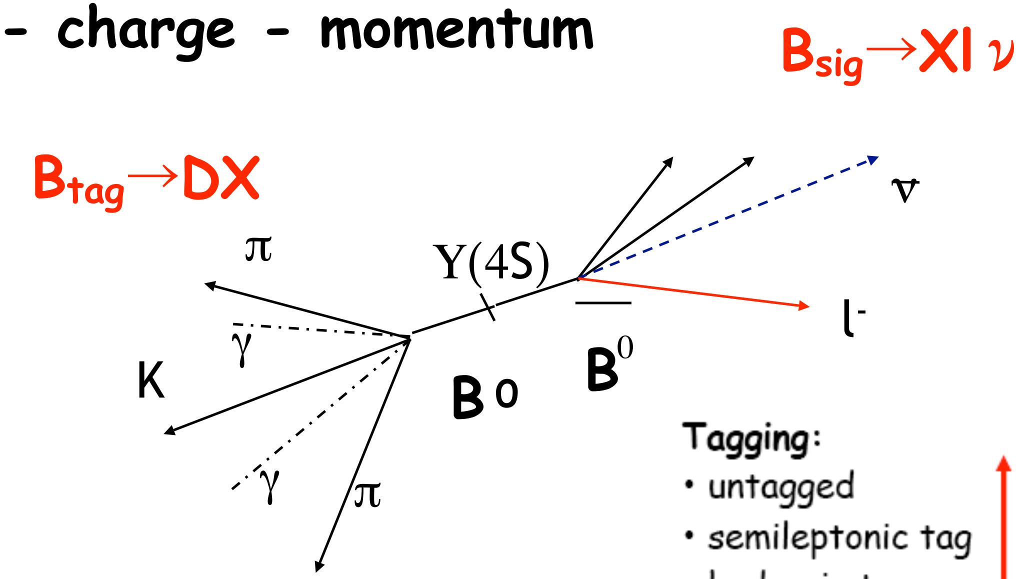
- Main uncertainty (±5%) from m_b^5 → ±2.5% on $|V_{ub}|$, correlated between all measurements/experiments!

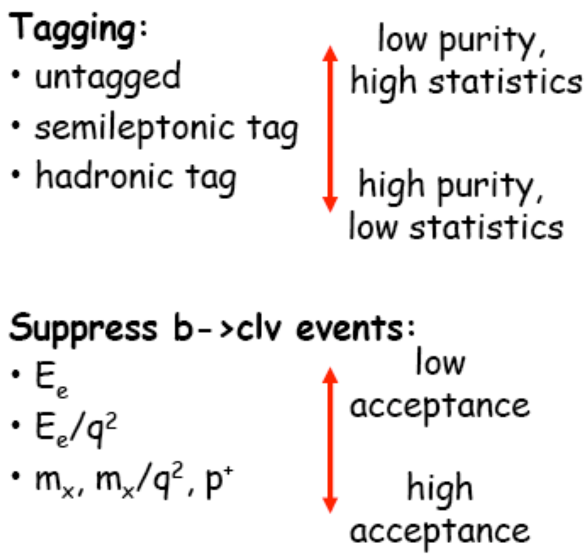
B meson - "Beam"

Fully reconstruct the tag-side B meson by searching the decay modes

→ tag - charge - momentum

B^+ and B^0 decays studied separately



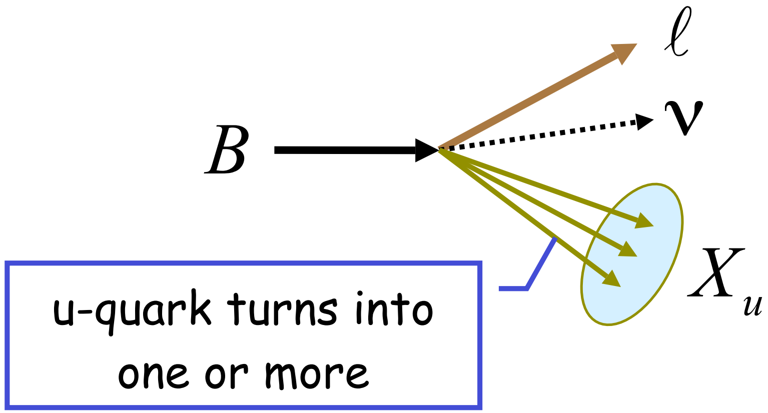


E_{lepton}: in rest frame of signal B

M_X: all remaining particles (X),

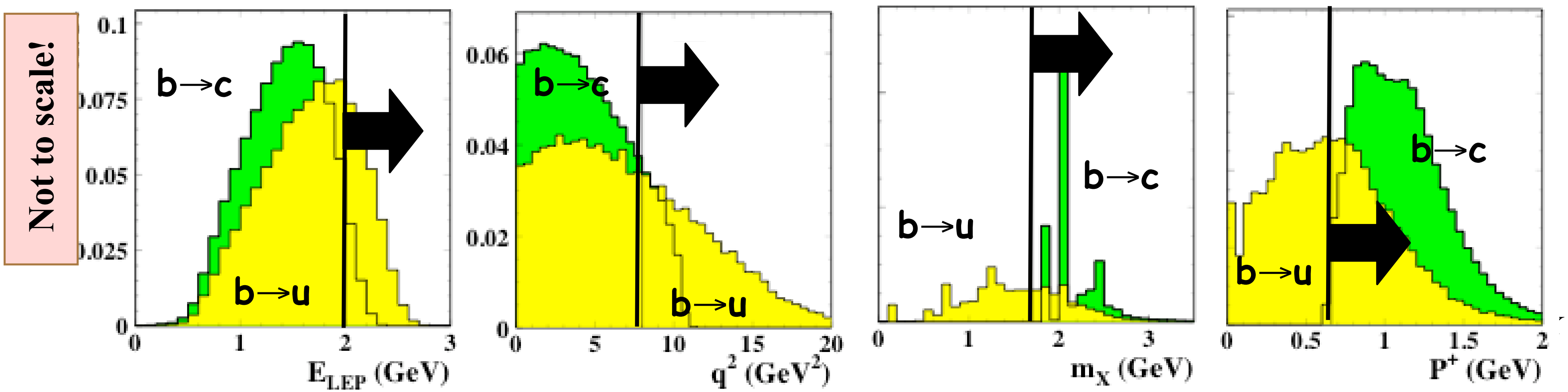
Inclusive $b \to u l \nu$

$m_u \ll m_c \to$ difference in kinematics



- E_l = lepton energy
- q^2 = lepton-neutrino mass squared
- m_X = hadron system mass
- $P^+ = E_X - |P_X|$

Signal events have smaller M_X and $P_+ \to$ Larger E_l and q^2



Relative branching fractions

BELLE

Number of excess events

Unfolding factor F

PDG

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

Number of semileptonic events

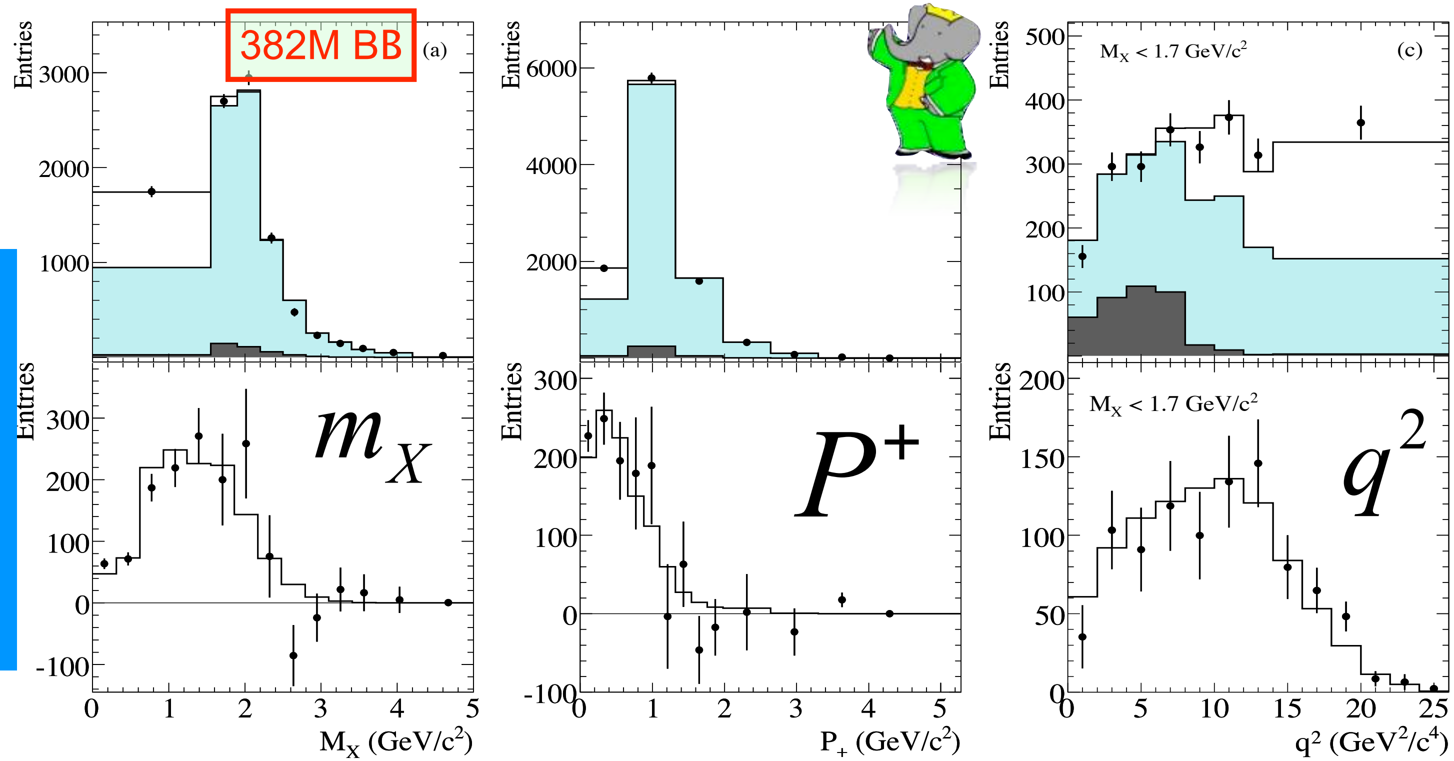
Ratio of efficiencies for *b→u* and *sl*

selection efficiency

$$\frac{\Delta\mathcal{B}(X_u\ell\bar{\nu}_\ell)}{\mathcal{B}(X\ell\bar{\nu}_\ell)} = \frac{(N_u - N_u^{\mathrm{out}} - BG_u)/(\epsilon_{\mathrm{sel}}^u \epsilon_{\mathrm{kin}}^u)}{(N_{\mathrm{sl}} - BG_{\mathrm{sl}})} \times \frac{\epsilon_\ell^{\mathrm{sl}}\epsilon_t^{\mathrm{sl}}}{\epsilon_\ell^u \epsilon_t^u},$$

Inclusive V_{ub}

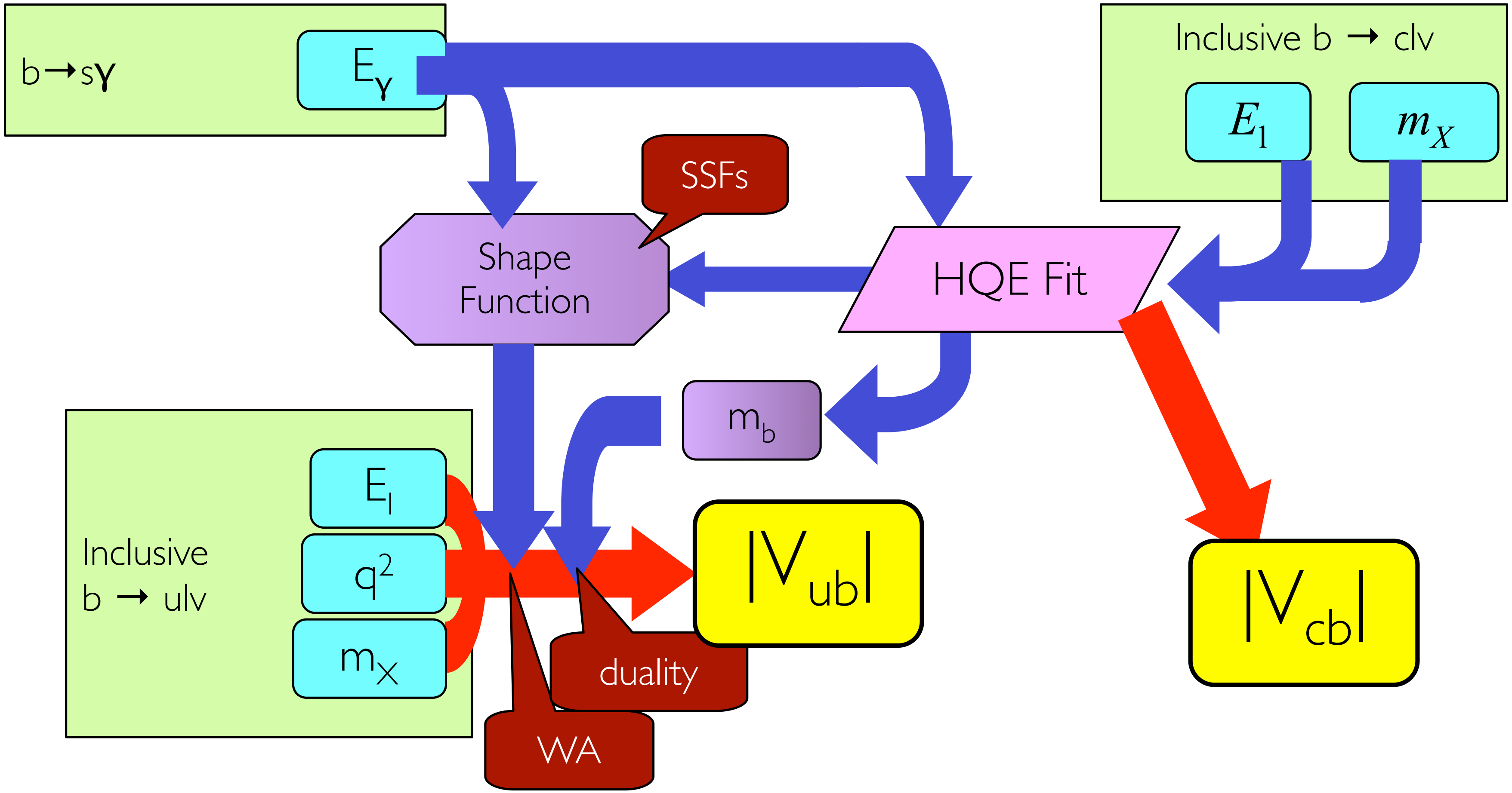
- $B \rightarrow X_u l \nu$
- $B \rightarrow X_c l \nu$
- $B \rightarrow X_u l \nu$ (outside selected region)



Kinematic Region	$\mathcal{B}(B \rightarrow X_u l \nu) \times 10^{-3}$ 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 ± 0.16 ± 0.13 ± 0.30	BLNP
		4.56 ± 0.17 ±0.14 ± 0.32	DGE
P_+<0.66 GeV/c^2	0.95 ± 0.10 ± 0.08 ± 0.01	3.88 ± 0.19 ± 0.16 ± 0.28	BLNP
		3.99 ± 0.20 ± 0.16 ± 0.24	DGE
M_X<1.7 GeV/c^2 & q^2>8.0 GeV^2/c^2	0.76 ± 0.08 ± 0.07 ± 0.02	4.48 ± 0.22 ± 0.19 ± 0.30	BLNP
		4.53 ± 0.22 ± 0.19 ± 0.25	DGE
		4.81 ± 0.23 ± 0.20 ± 0.36	BLL

How Things Mesh Together

AKA: M. Morii's HQE plumbing diagram



m_b more in details

comparison from
A. Hoang
Vxb workshop 2007
Heidelberg

1S	m_b (GeV)
	4.70±0.03
no b→sγ	4.751±0.058

Kinetic	m_b (GeV)	
	4.613±0.022+0.027	→ $m^{1S} = 4.76$
no b→sγ	4.677±0.053	→ $m^{1S} = 4.83$

	1S fit		Kin fit	
	b→sγ	no b→sγ	b→sγ	no b→sγ
m^{1S}	4.70	4.75	4.76	4.83
$\overline{m}(\overline{m})$	4.18	4.22	4.23	4.30

$\overline{m}(\overline{m})_{PDG}$ = 4.20 ± 0.07 GeV

(2008, only BELLE)

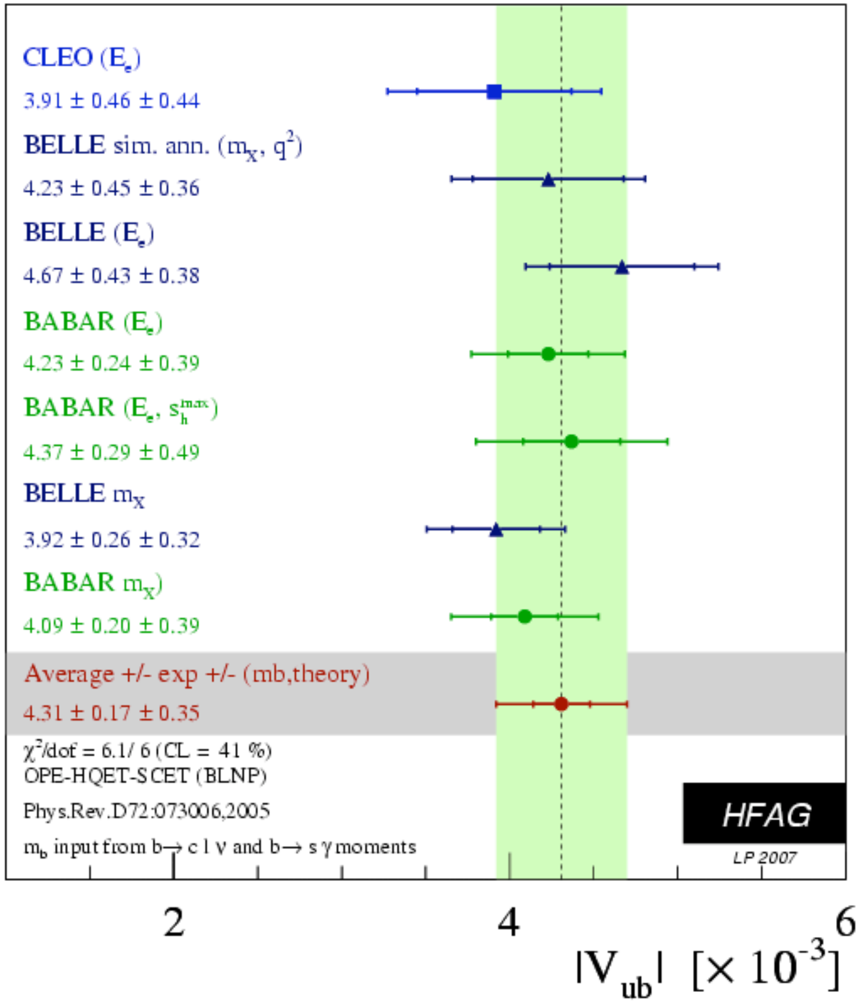
	$m_1^{\rm kin}$ GeV	m^{1S}
	4.57 ± 0.13	4.72 ± 0.12
no b→sγ	4.54 ± 0.075	4.72 ± 0.06

Belle fits are consistent.

It's not the theory!

Inclusive $|V_{ub}|$: BLNP framework

$|V_{ub}|$ world average



$|V_{ub}|$ determined to ± 8.9%

HQ parameters from $b \to cl\nu$ and $b \to sg$

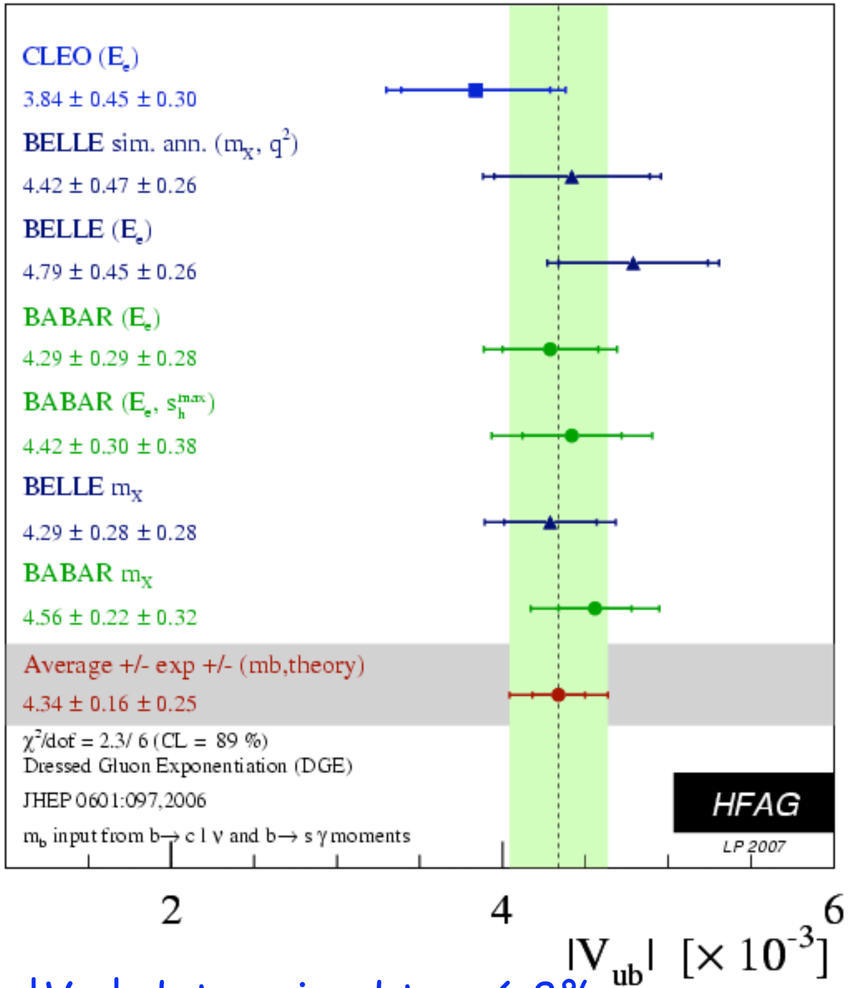
- m_b(SF) = 4.63 ± 0.06 GeV
- μ_π^2(SF) = 0.18 ± 0.06 GeV^2

$|V_{ub}|$ = (4.31 ± 0.17 ± 0.35) 10^{-3}

Statistical	±2.0%
Expt. syst.	±2.6%
$b \to cl\nu$ model	±1.8%
$b \to ul\nu$ model	±1.1%
SF params.	±3.8%
HQE param.	±6.9%
WA	±1.7%

Inclusive $|V_{ub}|$: DGE framework

$|V_{ub}|$ world average



$|V_{ub}|$ determined to ± 6.8%

b-mass form PDG

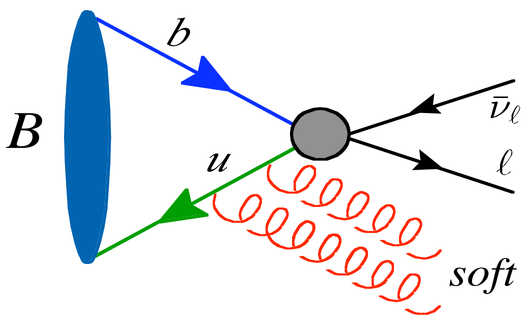
- m_b(MSbar) = 4.20 ± 0.07 GeV

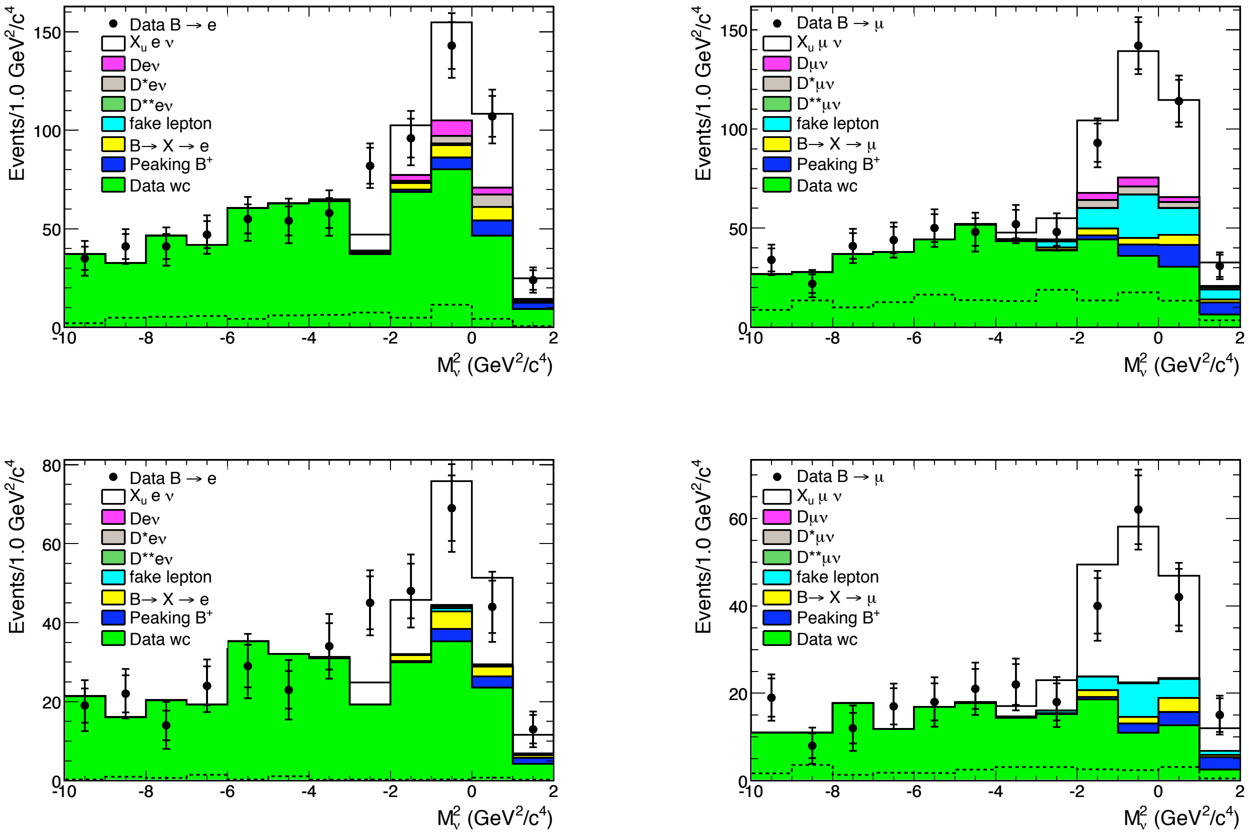
$|V_{ub}|$= (4.34 ± 0.16 ± 0.25) 10^{-3}

Statistical	±2.0%
Expt. syst.	±2.4%
b → clν model	±1.9%
b → ulν model	±1.0%
DGE theory	±3.1%
Rcut+total width	±4.2%
WA	±1.9%

Weak anihilation

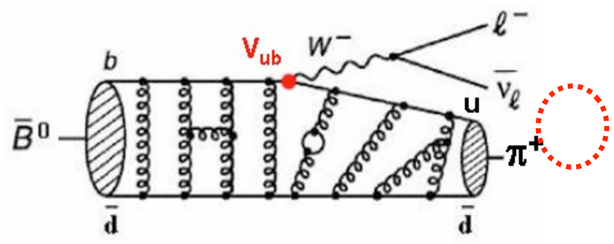
Different BR between B^+ and B^0





Δp	ΔB(B) 10^4	ΔB(B^0) 10^4	$A^{+/0}$
2.3-2.6	2.31±0.10±0.18	1.30±0.21±0.07	0.08±0.15±0.08
2.4-2.6	0.75±0.04±0.06	0.76±0.15±0.05	-0.05±0.20±0.10

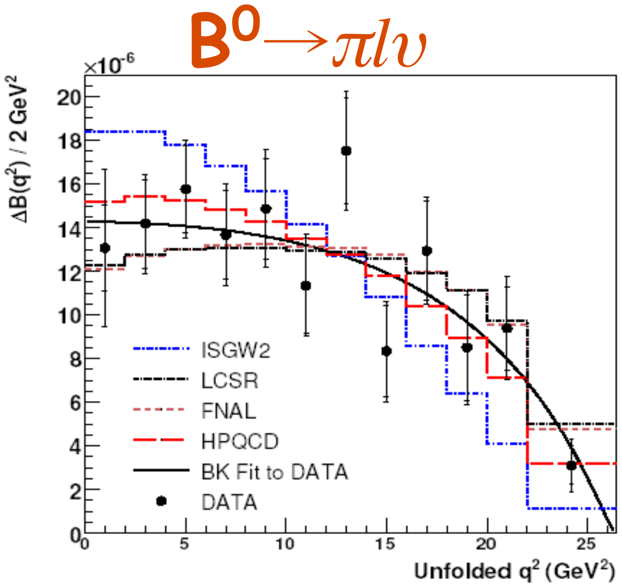
Exclusive $|V_{ub}|$



$$\frac{d\Gamma(B \to \pi \ell \nu)}{dq^2} = \frac{G_F^2}{24\pi^2}|V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

Experimentally clean

Currently only $B \to \pi l \nu$ for $|V_{ub}|$ - one dominant form factor (q^2 shape and normalization needed)



- Form factor calculations from various methods:
  - "unquenched" lattice QCD (HPQCD, Fermilab, …)
  - Light-Cone Sum Rules (Ball & Zwicky, …)
  - quark models (ISGW2, …)

FF dominates |Vub| error

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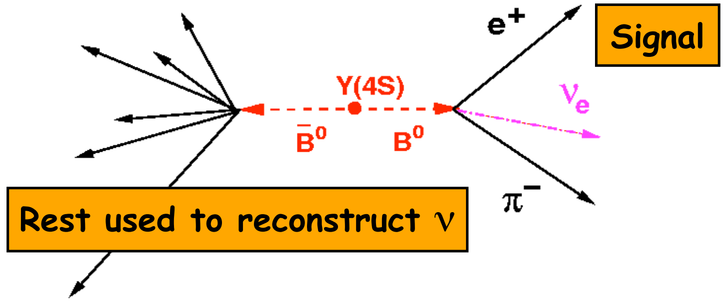
LQCD and LCSR compatible with data
ISGW2 quark-model incompatible (Prob<0.06%).

Approaches to Measuring $\mathcal{B}(B \rightarrow X_u \, l \, \nu)$ Exclusive

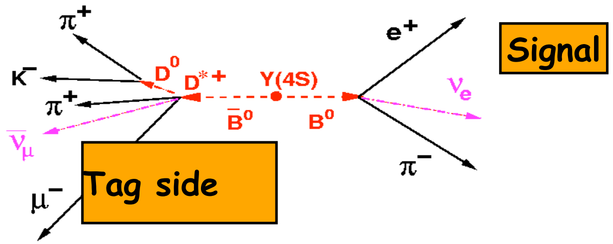
Untagged

- Initial 4-momentum known.
- Missing 4-momentum = ν.
- Reconstruct $B \rightarrow X_u \, l \, \nu$ using m_B (beam-constrained) and $\Delta E = E_B - E_{beam}$.



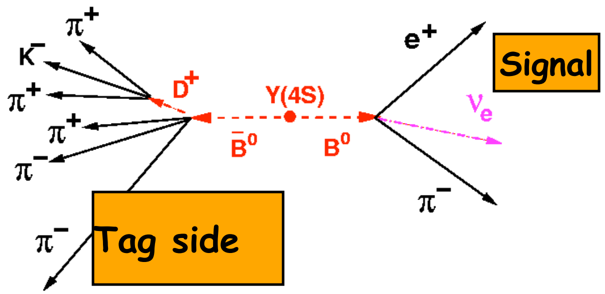
Semileptonic Tag

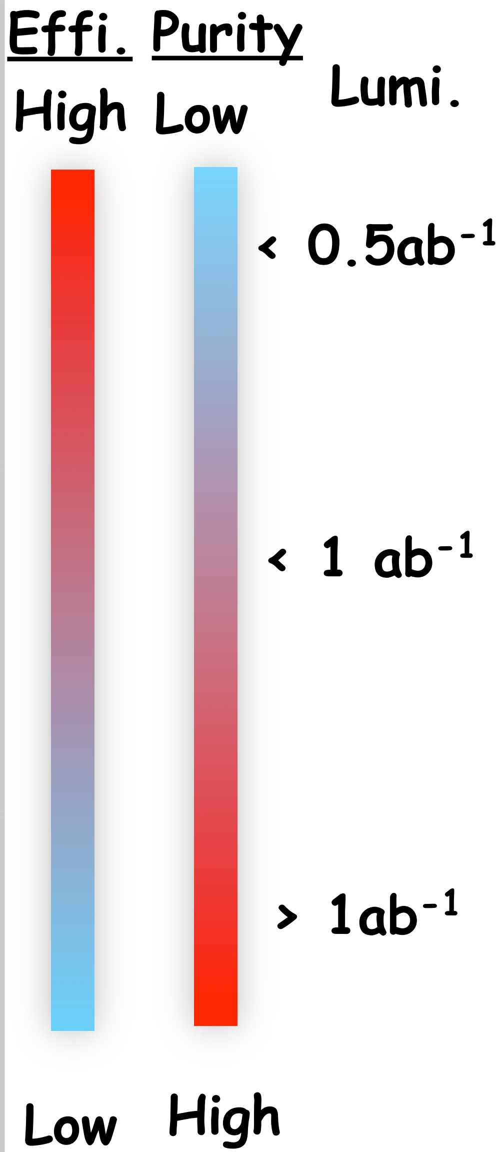
- One B reconstructed in a selection of $D^{(*)} \, l \, \nu$ modes.
- Two missing νs in event.
- Use kinematic constraints.



Full Reconstruction Tag

- One B reconstructed completely in known $b \rightarrow c$ mode.
- Many modes used.

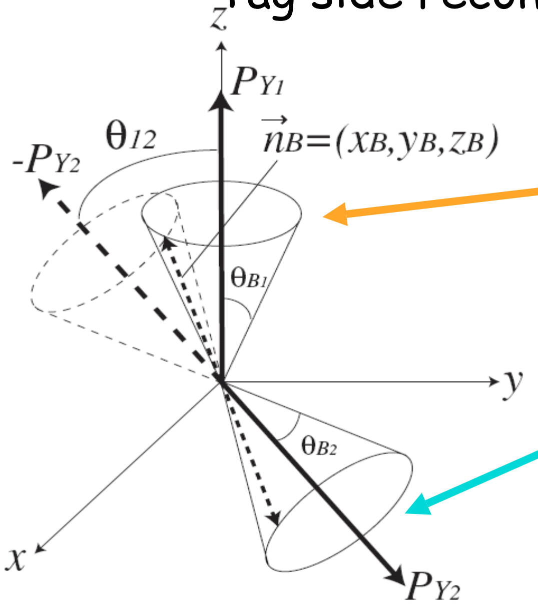




E. Barberio

$D^{(*)} l \nu$ tag Method

Tag side reconstruction



$B^0_{tag} \to D^{*+} l^- \bar{\nu} / D^+ l^- \bar{\nu}$

$B^-_{tag} \to D^{*0} l^- \bar{\nu} / D^0 l^- \bar{\nu}$

Signal

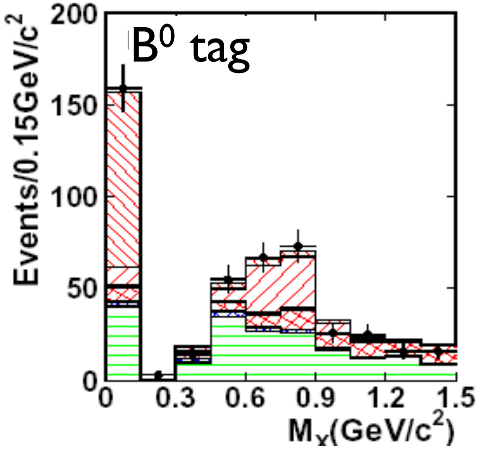
$B^0_{sig} \to \pi^- l^+ \nu$ / $\pi^- \pi^0 l^+ \nu$ → ρ^-

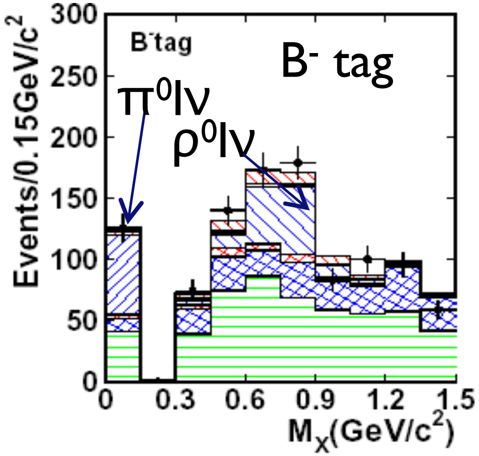
$B^+_{sig} \to \pi^0 l^+ \nu$ / $\pi^+ \pi^- l^+ \nu$ → ρ^0

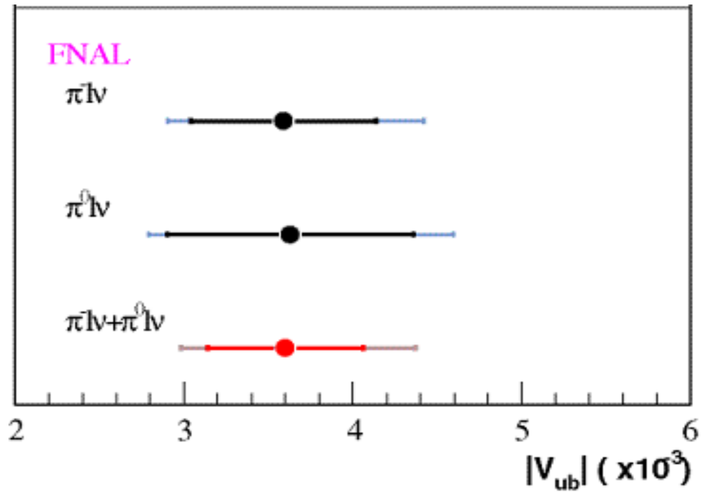
253 fb^{-1}

(275M BB pairs)

Full q^2 region







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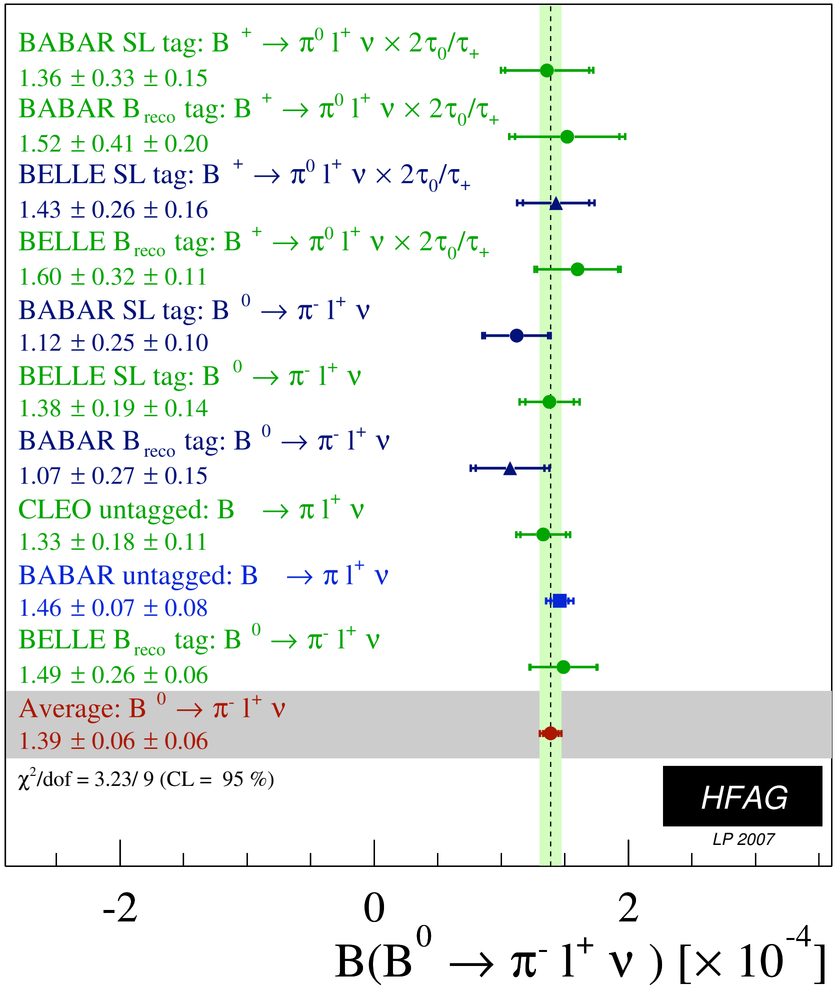
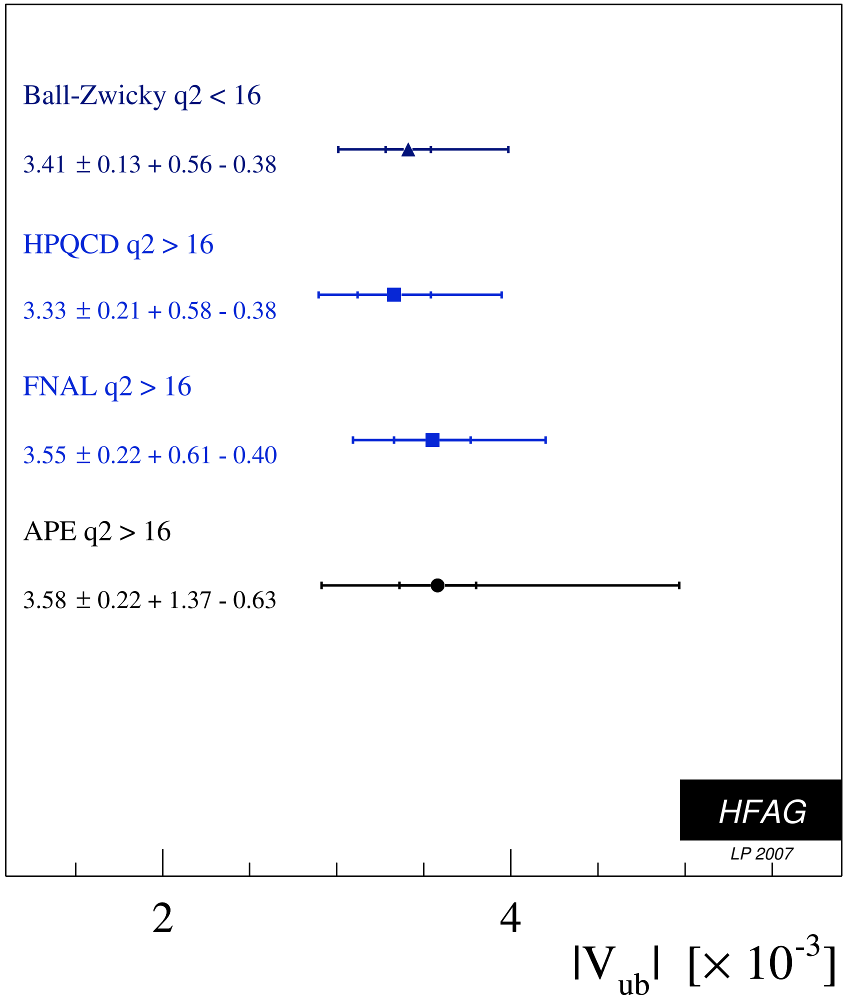
Current status of $Br(B^0 \to \pi^- l^+ \nu)$ & $|V_{ub}|$





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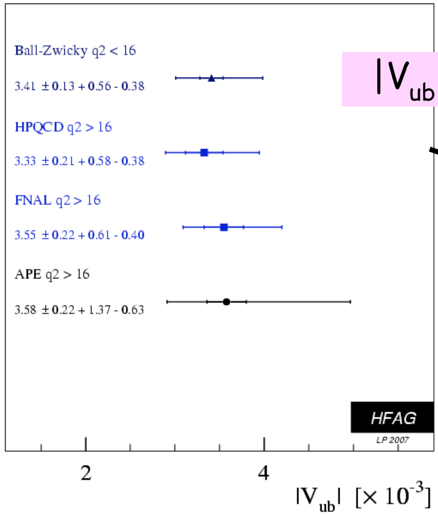
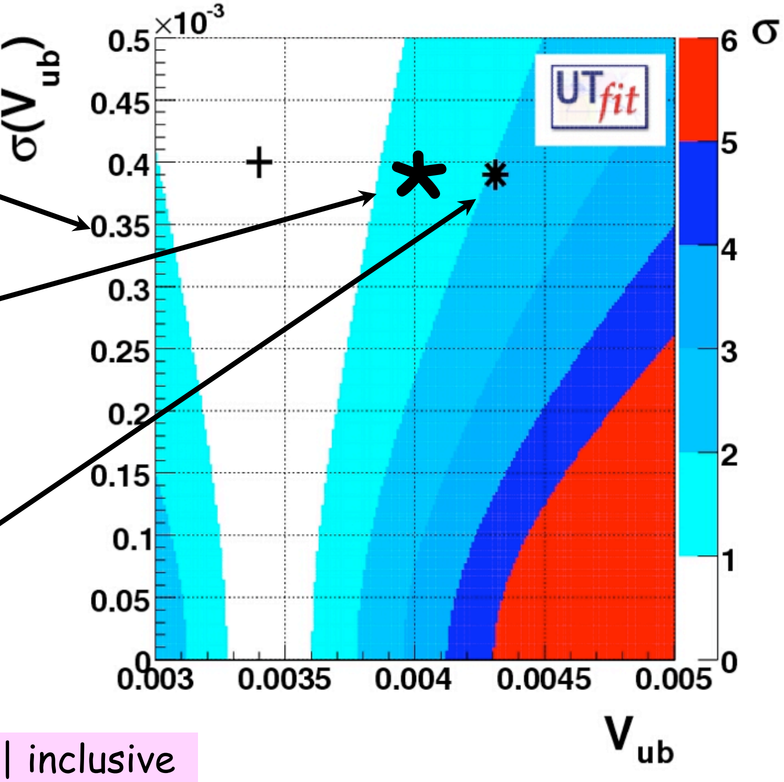
$|V_{ub}|$: inclusive vs exclusive

Most probable value of V_{ub} from measurements of other CKM parameters

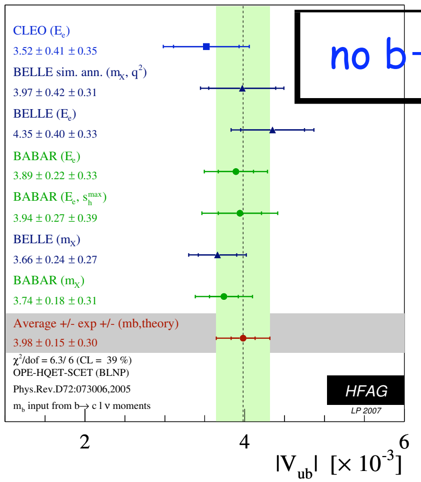
$|V_{ub}|$ exclusive

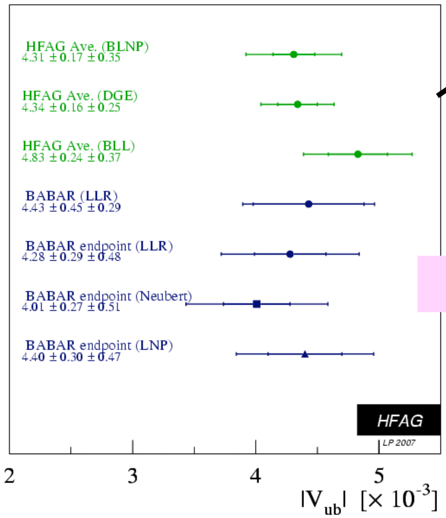




$|V_{ub}|$ inclusive

no $b \to s\gamma$





$|V_{ub}|$ inclusive

$b \to s\gamma$

E. Barberio

CONCLUSION AND OUTLOOK

$b \rightarrow c l \nu$

V_{cb} 1% error with the inclusive determination dominated by theory and inclusive versus exclusive are increasing the gap ~2 σ

$b \rightarrow u l \nu$

V_{ub} ~8% error shared between theoretical and experimental inclusive vs exclusive are decreasing the gap but....

The $B \rightarrow D^{**} l \nu$ decays are challenging the theory...