Determination of $|V_{cb}|$, m_b and m_c from Inclusive B Decay Distributions

Henning Flächer

Royal Holloway,
University of London

Overview

- Will cover results of hep-ph/0507253 and their applications
- Motivation
  - Short Introduction to theoretical framework
- Experimental Measurements
  - hadron and lepton moments from $B \rightarrow X_c l\nu$
  - photon energy moments from $B \rightarrow X_s \gamma$
- Results of the combined fit
  - Extraction of $|V_{cb}|$, m_b, m_c and higher order heavy quark parameters
- Applications
- Conclusions

CKM matrix and Unitarity Triangle

In the Standard Model, couplings between quarks of different flavour are described by the CKM matrix.
It relates weak to mass eigenstates.

CKM matrix has 4 free parameters:
- 3 Euler angles
- 1 free phase

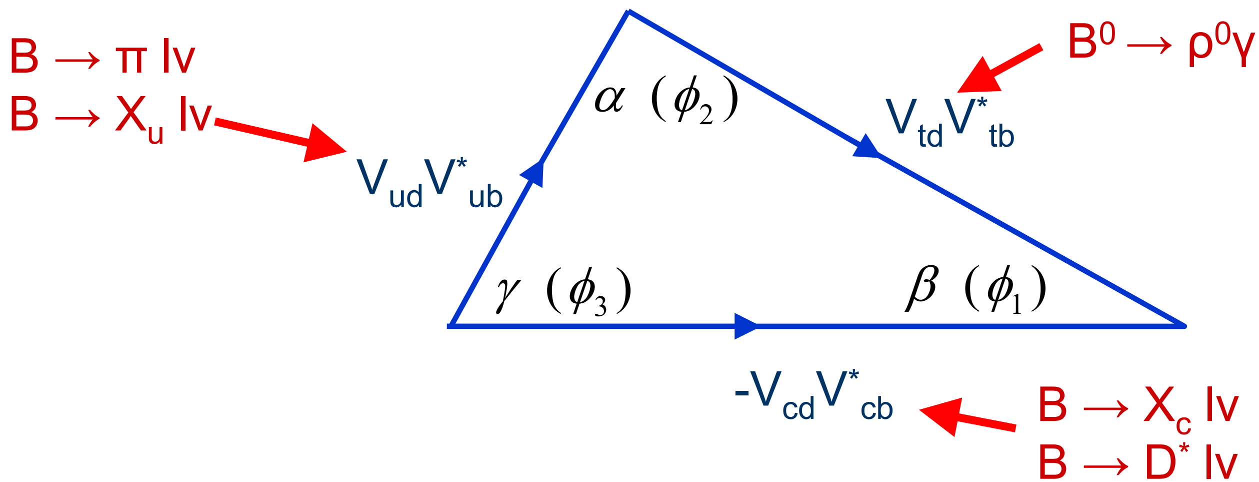
Unitary!

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

semi-leptonic decays

radiative decays

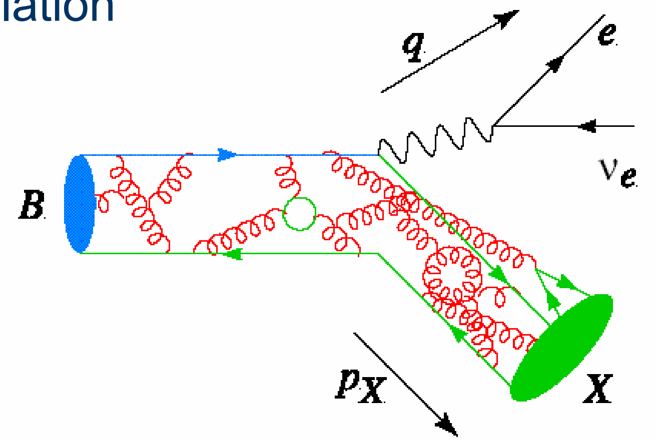
Can be visualised as triangle:



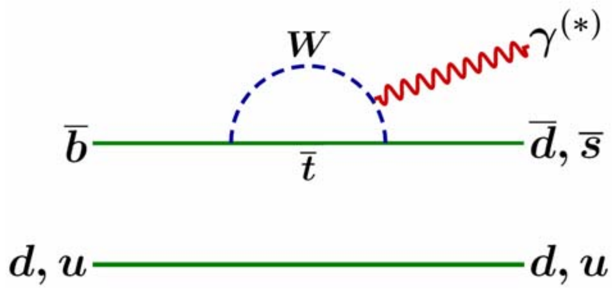
Semileptonic and Radiative B Decays

Why semileptonic decays?

$|V_{ub}|$ and $|V_{cb}|$ are crucial in testing CKM unitarity and SM mechanism for CP violation



Hadronic and leptonic currents factorise, theoretical uncertainties are under control giving access to $|V_{ub}|$ and $|V_{cb}|$



`radiative penguin'

- b → s,d transition is a Flavour Changing Neutral Current
  - forbidden in the standard model at tree-level
  - exists only at loop level
- heavy particles dominate in the loop
  - in SM: sensitive to 'top' CKM parameters: $V_{tb}V^*_{tq}$

Both decays can be treated in the framework of Heavy Quark Effective Theory, relating parton level decay rate to meson decay rate with the help of Operator Product Expansions

Heavy Quark Expansions

Heavy Quark Expansions connect the inclusive decay width to $|V_{cb}|$:

Γ_{SL} proportional to $|V_{cb}|^2$, but perturbative and non-perturbative corrections to free quark decay needed → double expansion in α_s and $1/m_b$

$$\Gamma_{clv} = \frac{G_F m_b^5}{192\pi^3}|V_{cb}|^2(1+A_{ew})A_{pert}A_{nonpert} \cong |V_{cb}|^2 f_{OPE}(m_b, m_c, a_i)$$

4 parameters at order α_s^2 and $1/m_b^3$

Need to determine non-perturbative parameters!

⟶ Use moments of inclusive distributions where same parameters appear:

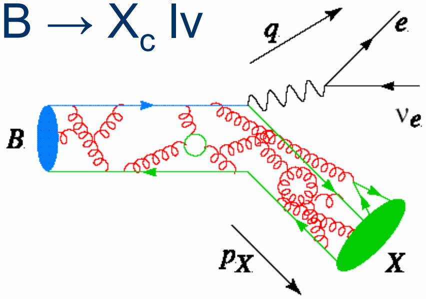
$$\langle X^n \rangle (E_{cut}) = \left. \frac{\int (X - X^0)^n \frac{d\Gamma}{dX} dX}{\int \frac{d\Gamma}{dX} dX} \right|_{E_l > E_{cut}} \cong f'_{OPE}(m_b, m_c, a_i)$$

mb and μ_π^2 are used to parameterise both $B\rightarrow X_s \gamma$ and $B\rightarrow X l\nu$ spectra

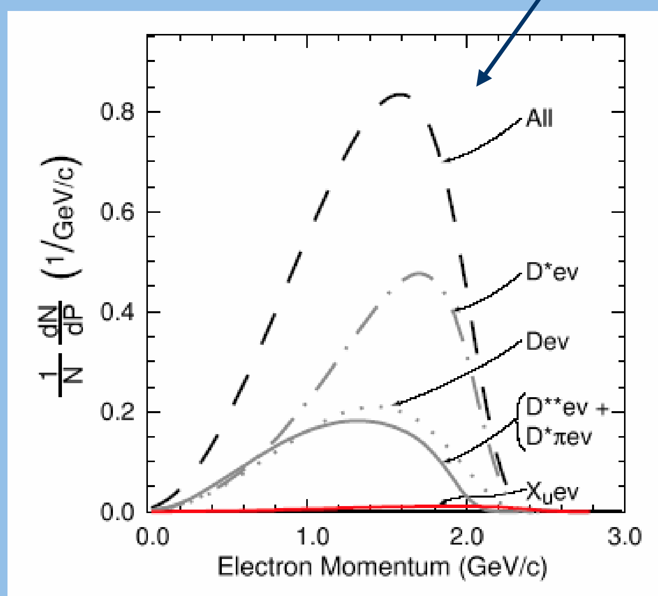
- Hadronic Mass distribution $\langle M_X^n \rangle \rightarrow \langle M_X \rangle (m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$
- Lepton Energy spectrum $\langle E_\ell^n \rangle \rightarrow \langle E_\ell^n \rangle (m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$
- Photon Energy spectrum $\langle E_\gamma^n \rangle \rightarrow \langle E_\gamma^n \rangle (m_b, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$.

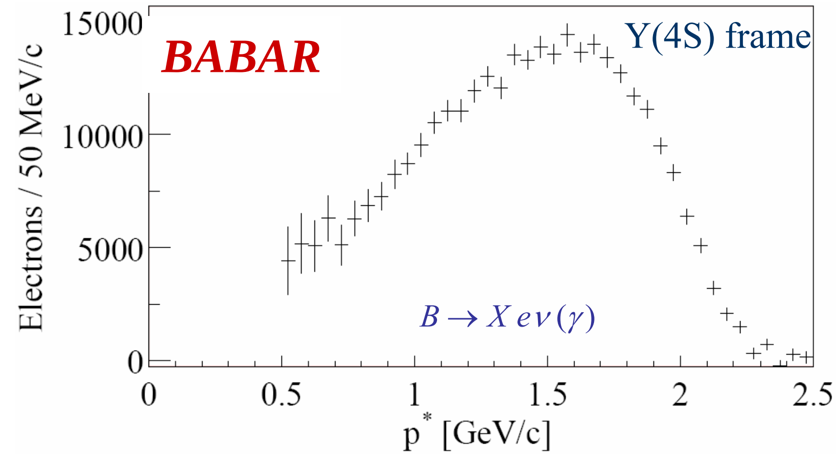
Lepton Energy Moments

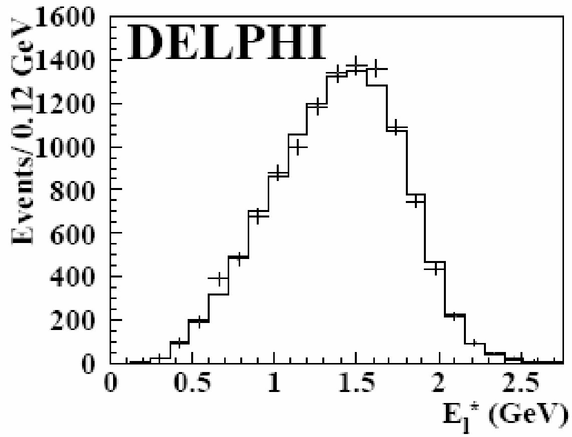
$B \to X_c l\nu$

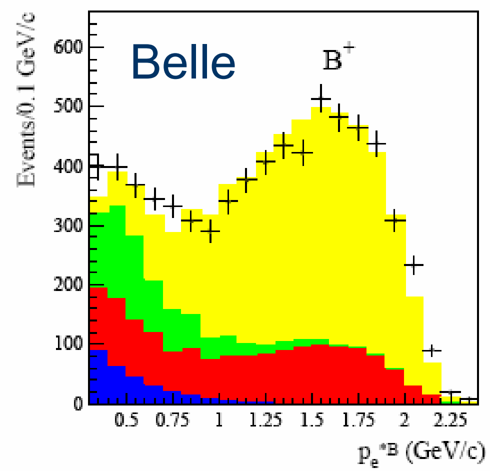


Observable





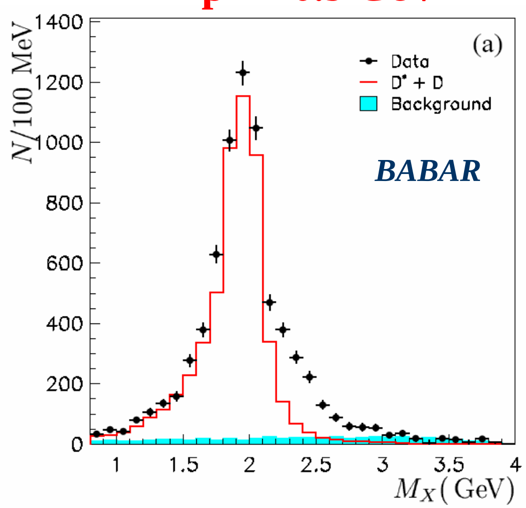




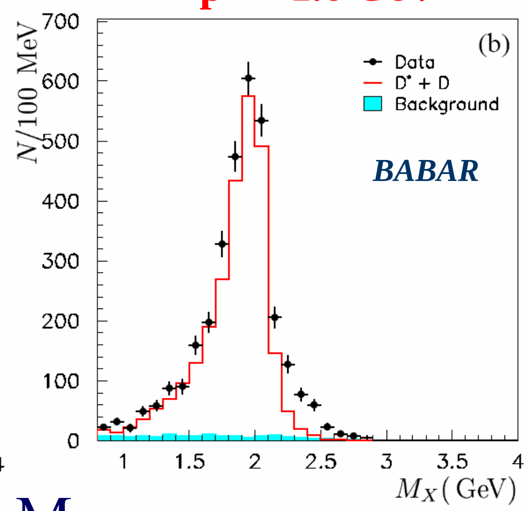
Hadronic Mass Moments

BaBar, Belle and CLEO measure full spectrum

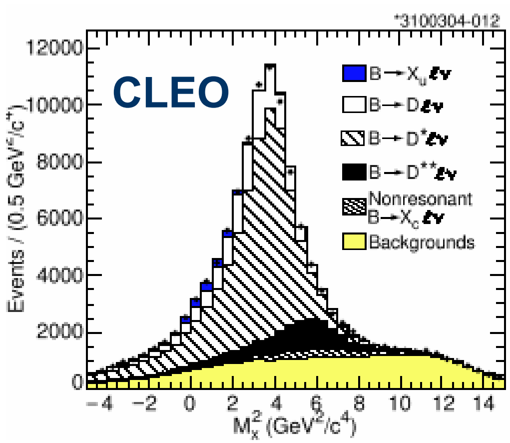
p* > 0.9 GeV

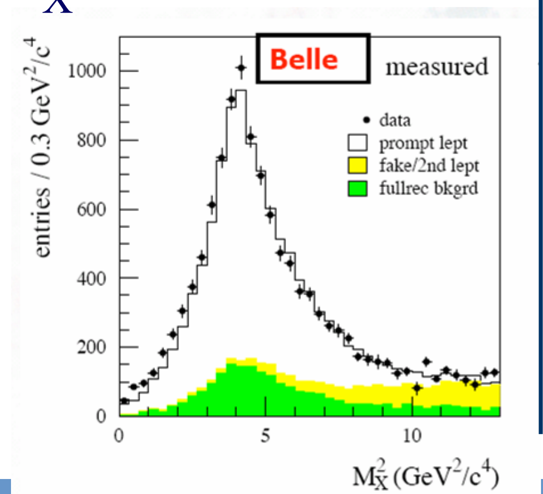


p* > 1.6 GeV

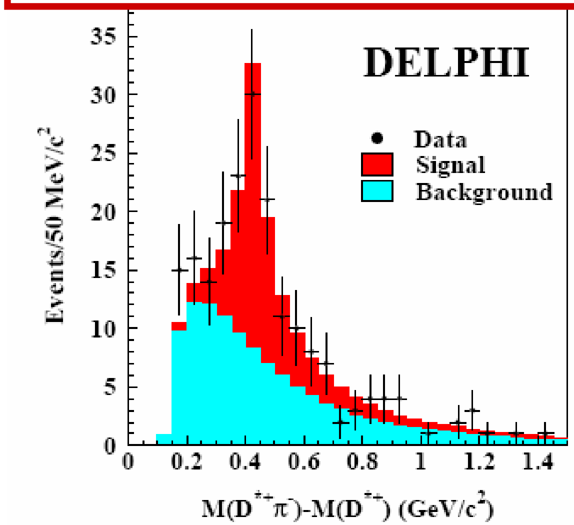


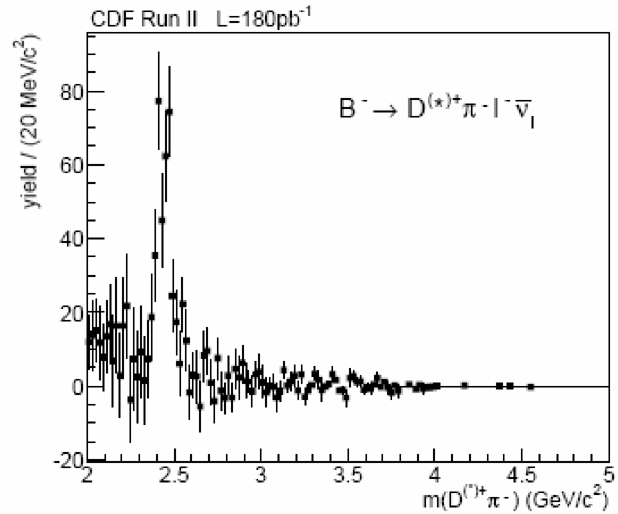
M_X





Delphi and CDF only measure higher resonances





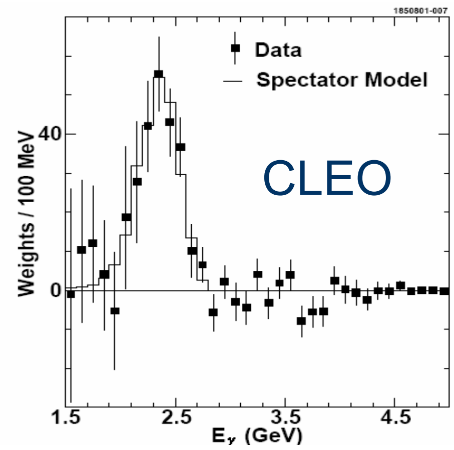
b→sγ Spectra and Moments

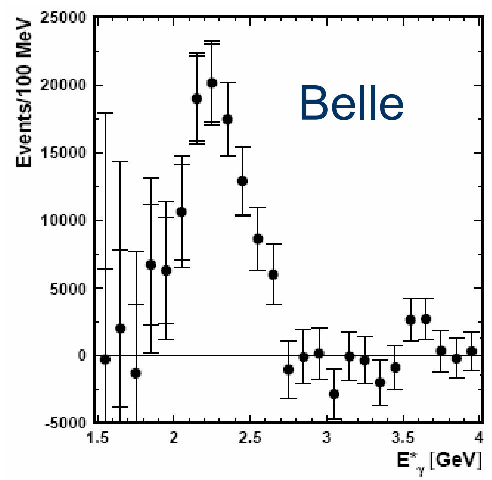
Measure photon spectrum in b→sγ decays:

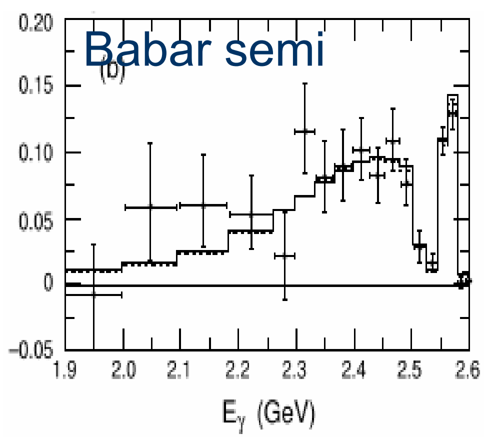
<u>Two main approaches:</u>

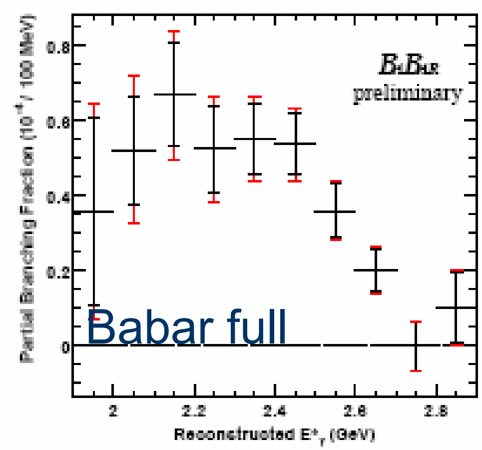
- Inclusive:
  - identify photon
- Semi-Inclusive:
  - reconstruct many exlusive final states (up to 38!)

Difficult measurement:
Overwhelming background
from π^0s for E_γ < 1.8 GeV









Measurement of photon spectrum and its moments gives information about inner structure of B meson:

- **b quark mass**
- **Fermi momentum**

Available moment measurements

Legend:

n = order of (central) moment of observable M_X, E_l and E_γ
l = min. lepton momentum
g = min. photon energy

☑ published with covariance matrix and used in fit
☒ not used in fit as covariance matrices not available

	Hadron Moments		Lepton Moments		Photon Moments	
BaBar	n=1,2,3,4 l=0.9-1.6	☑	n=0,1,2,3 l=0.6-1.5	☑	n=1,2,3 g=1.9-2.3	☑
Belle	n= 1,2 l=0.9-1.6	☒	n=1,2 l=0.6-1.5	☒	n=1,2 g=1.8	☑
CLEO	n=2,4 l=1.0-1.5	☑	n=1,2 l=0.6-1.5	☒	n=1,2 g=2.0	☑
Delphi	n=2,4,6 l=0.0	☑	n= 1,2,3 l=0.0	☑		
CDF	n=2,4 l=0.7	☑				

Total of 51 measurements!

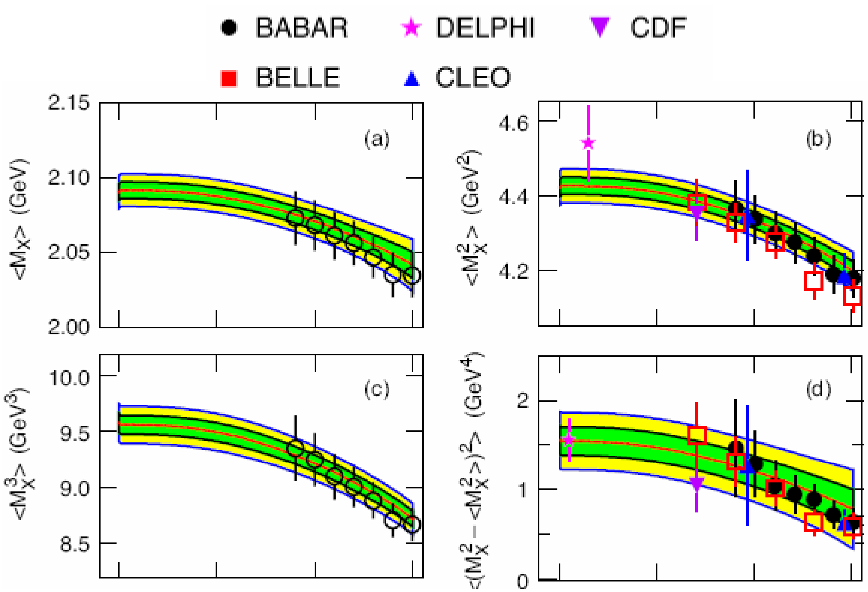
Important to take correlations between moments with different min. lepton/photon energies into account

Inclusive $|V_{cb}|$ - Fit to Moments

Based on calculations in kinetic scheme:

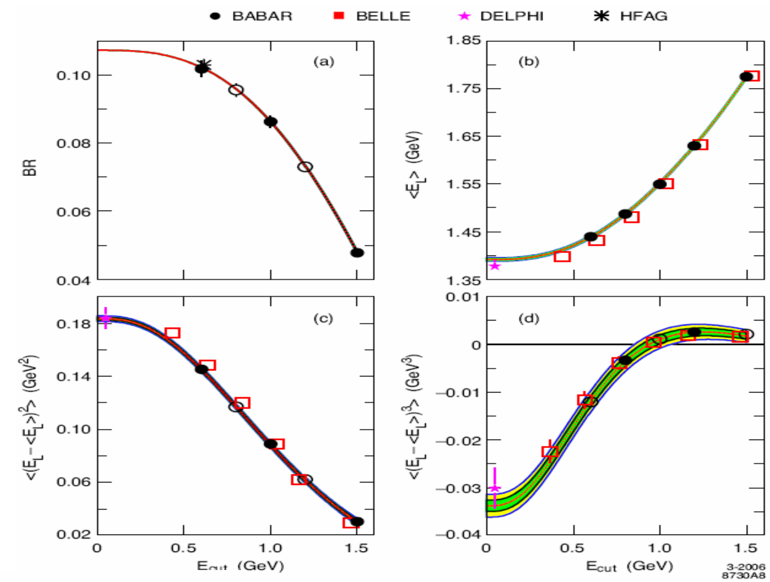
Benson, Bigi, Mannel & Uraltsev, hep-ph/0410080
Gambino & Uraltsev, hep-ph/0401063
Benson, Bigi & Uraltsev, hep-ph/0410080

Hadron Moments



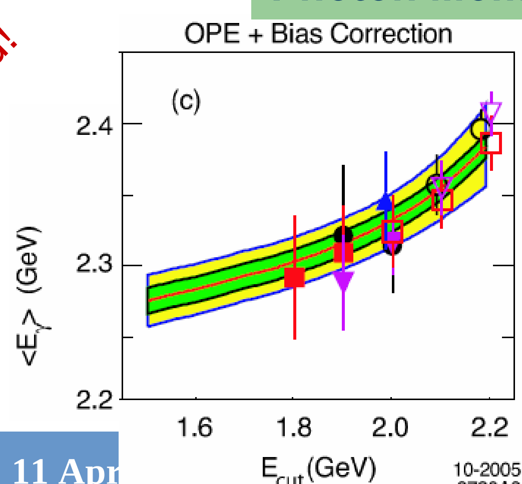
E_{cut} (GeV)

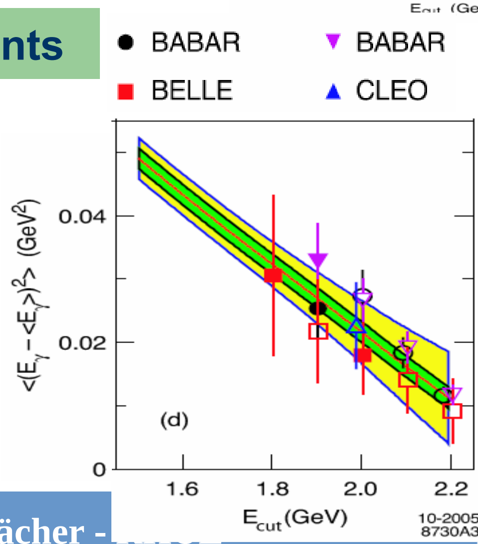
Lepton Moments



Photon Moments

Measurements highly correlated!





O. Buchmueller, H.F.
hep-ph/0507253

Inclusive $|V_{cb}|$

New!

Result of fit to all moment measurements:

$|V_{cb}|$ @ 2%
m_b < 1%
m_c @ 5%

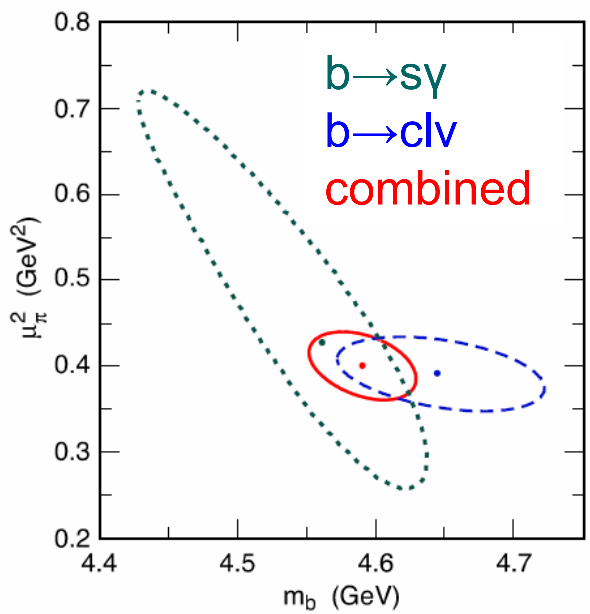
			exp	HQE	Γ_{SL}
$\vert V_{cb}\vert$ =	(41.96	± 0.23	± 0.35	± 0.59) 10^{-3}
m_b =	4.590	± 0.025	± 0.030	GeV	
m_c =	1.142	± 0.037	± 0.045	GeV	
μ_π^2 =	0.401	± 0.019	± 0.035	GeV^2	
μ_G^2 =	0.297	± 0.024	± 0.046	GeV^2	
ρ_D^3 =	0.174	± 0.009	± 0.022	GeV^3	
ρ_{LS}^3 =	-0.183	± 0.054	± 0.071	GeV^3	
BR_{clv} =	10.71	± 0.10	± 0.08	%	

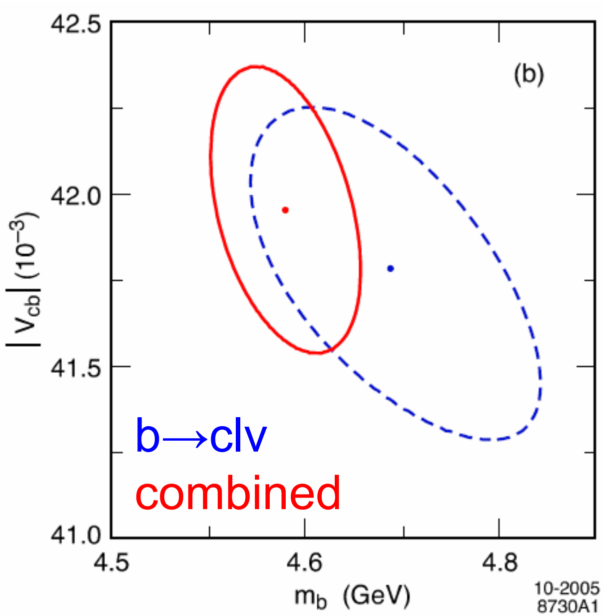
hep-ph/0507253

In $\overline{MS}$ scheme:
$\overline{m}_b(\overline{m}_b)$ = 4.20 ± 0.04 GeV
$\overline{m}_c(\overline{m}_c)$ = 1.24 ± 0.07 GeV
$\overline{m}_c(\mu)/\overline{m}_b(\mu)$= 0.235 ± 0.012

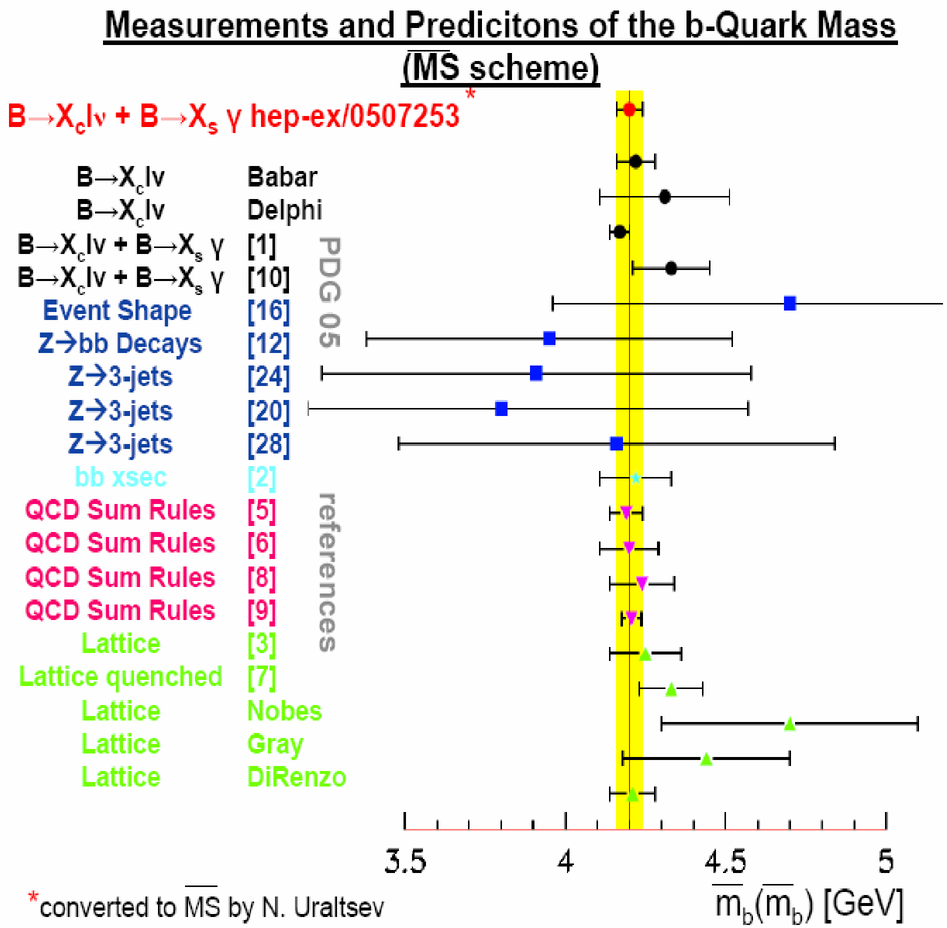
courtesy of N.Uraltsev

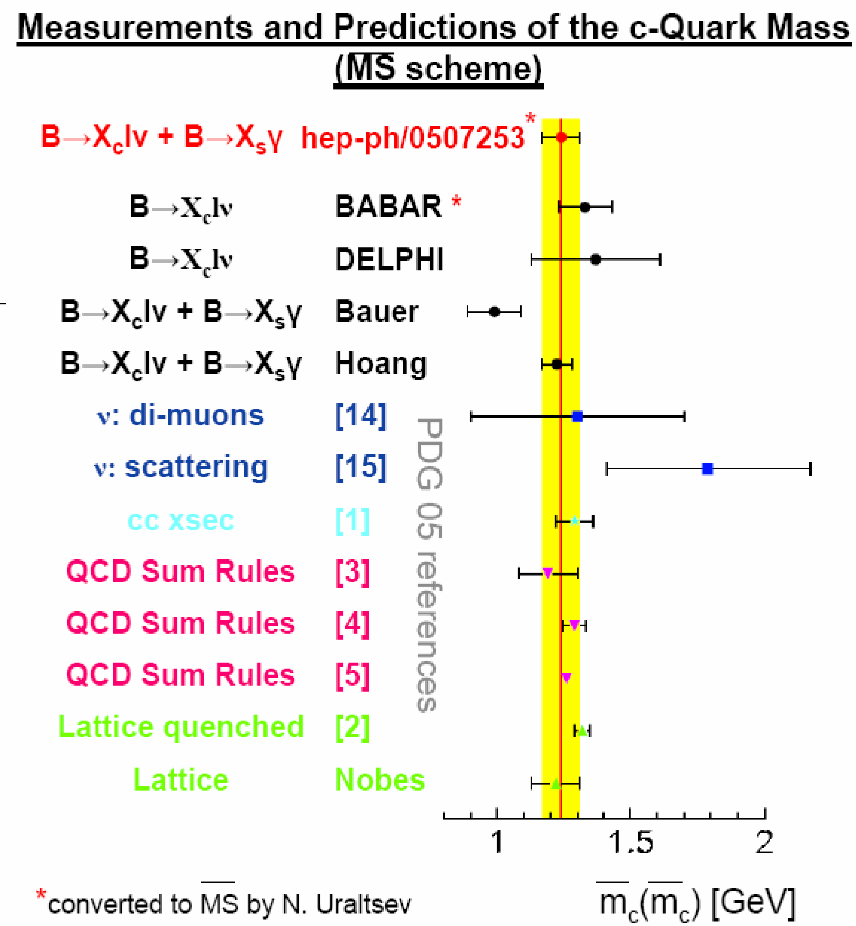
Good agreement with other similar analyses:
Bauer et al. hep-ph/0408002
DELPHI hep-ex/0510024





Comparison with other determinations





$$\overline{m}_b(\overline{m}_b) = 4.20 \pm 0.04 \text{ GeV}$$

$$\overline{m}_c(\overline{m}_c) = 1.24 \pm 0.07 \text{ GeV}$$

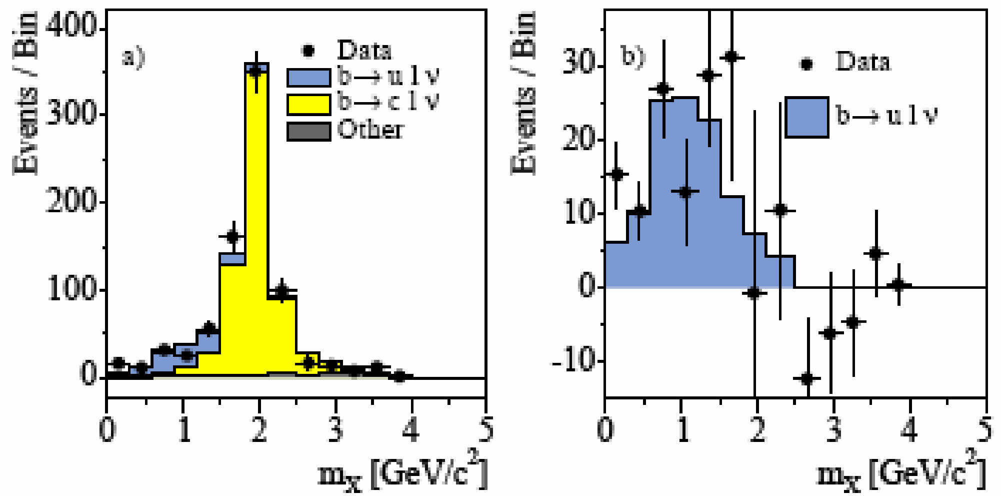
Conversion from kinetic mass scheme to MS scheme with hep-ph/9708372, hep-ph/0302262
See also report from CKM WS hep-ph/0304132

Inclusive $|V_{ub}|$

New!

hep-ex/0601046

Measurement of hadronic mass spectrum in B->Xu lν decays:



- Measure hadronic mass spectum on the recoil of fully reconstructed B mesons
- Measurement of spectrum up to 2.5 GeV includes 96% of total rate

Standard local OPE for full rate:
Uraltsev hep-ph/9905520
Hoang,Ligeti, Manohar hep-ph/9811239

$$|V_{ub}| = 4.268 \cdot 10^{-3} \cdot \sqrt{\frac{BR(B \to X_u \ell \nu)}{0.002} \frac{1.61 ps}{\tau_B}} \times (1 \pm 0.012_{\mathrm{QCD}} \pm 0.022_{\mathrm{HQE}}) .$$

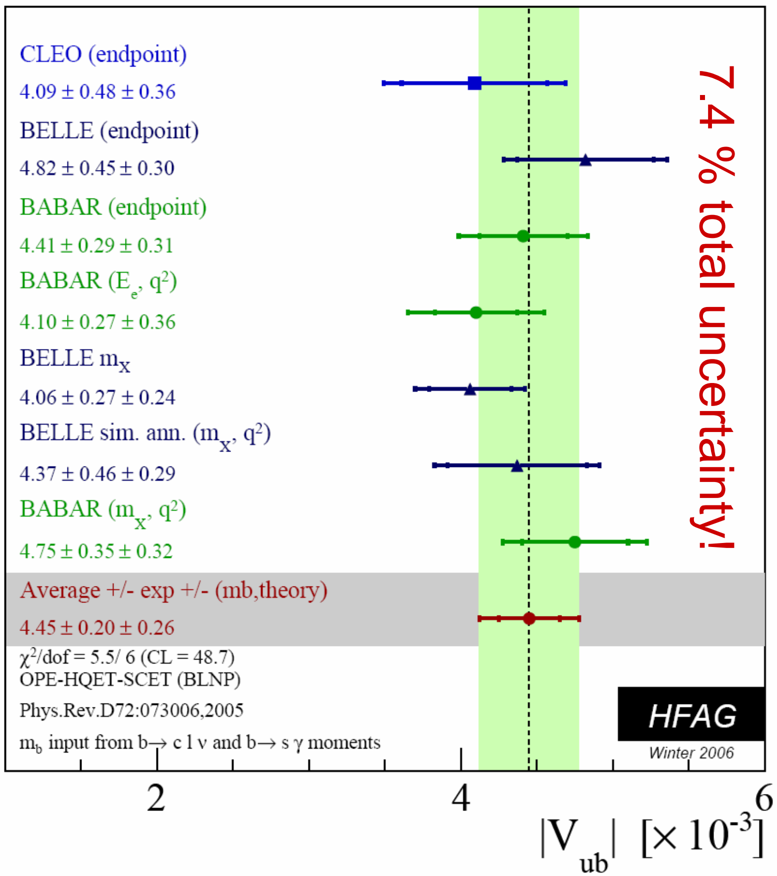
reduced theory error as no extrapolation to full rate necessary

OPE: M_X < 2.50 GeV:

$|V_{ub}| = (3.84 \pm 0.70_{stat} \pm 0.30_{syst} \pm 0.10_{theo})\ 10^{-3}$

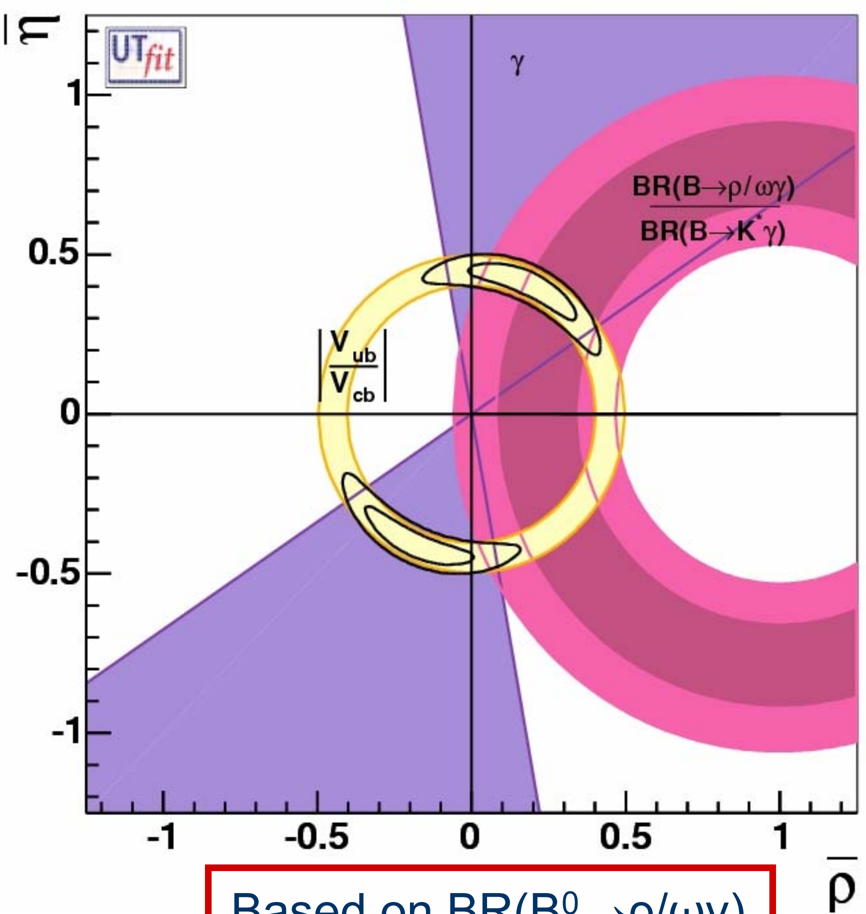
$|V_{ub}|$ Summary and UT Constraints from Sides and Tree Processes

Inclusive $|V_{ub}|$:



$|V_{ub}| = (4.45 \pm 0.20 \pm 0.26) \times 10^{-3}$

Main improvement due to better knowledge of "shape function" parameters



Based on $BR(B^0 \rightarrow \rho/\omega\gamma) = (0.94 +0.25 -0.22)\ 10^{-6}$

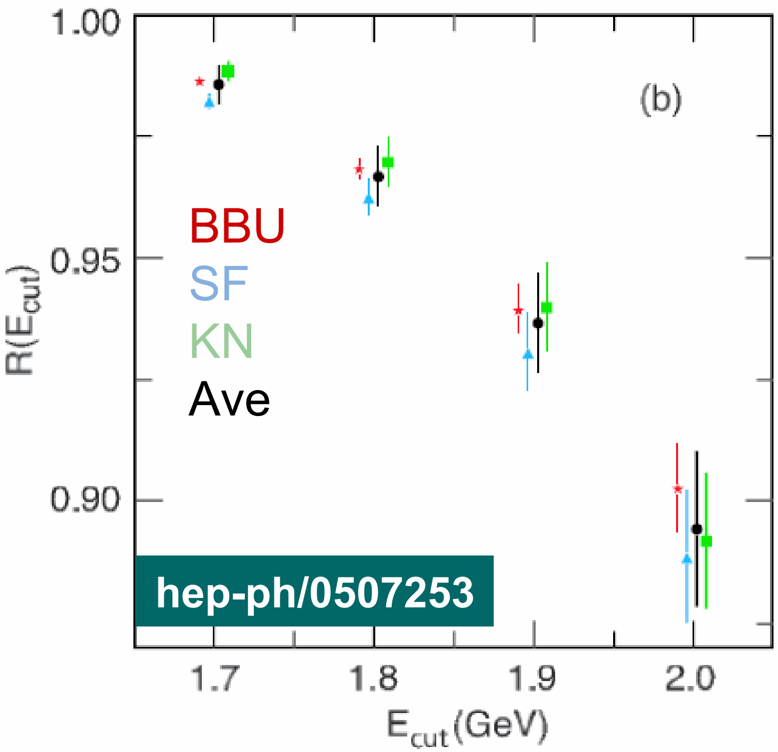
$|V_{td}/V_{ts}| = 0.18 \pm 0.03$

b→sγ Branching Fraction

- Partial branching fractions are measured above different photon energies
- Need to be extrapolated to E_γ > 1.6 GeV to compare with theory
- Extrapolation factors based on HQE fit to clv and bsg moments

Mode	Reported $\mathcal{B}$	E_{min}	$\mathcal{B}$ at E_{min}
CLEO Inc. [3]	$321 \pm 43 \pm 27^{+18}_{-10}$	2.0	$306 \pm 41 \pm 26$
Belle Semi.[4]	$336 \pm 53 \pm 42^{+50}_{-54}$	2.24	–
Belle Inc.[5]	$355 \pm 32^{+30+11}_{-31-7}$	1.8	$351 \pm 32 \pm 29$
BABAR Semi.[6]	$335 \pm 19^{+56+4}_{-41-9}$	1.9	$327 \pm 18^{+55+4}_{-43-9}$
BABAR Inc.[7]	–	1.9	$367 \pm 29 \pm 34 \pm 29$

Extrapolation Factors for BF



New HFAG Average:

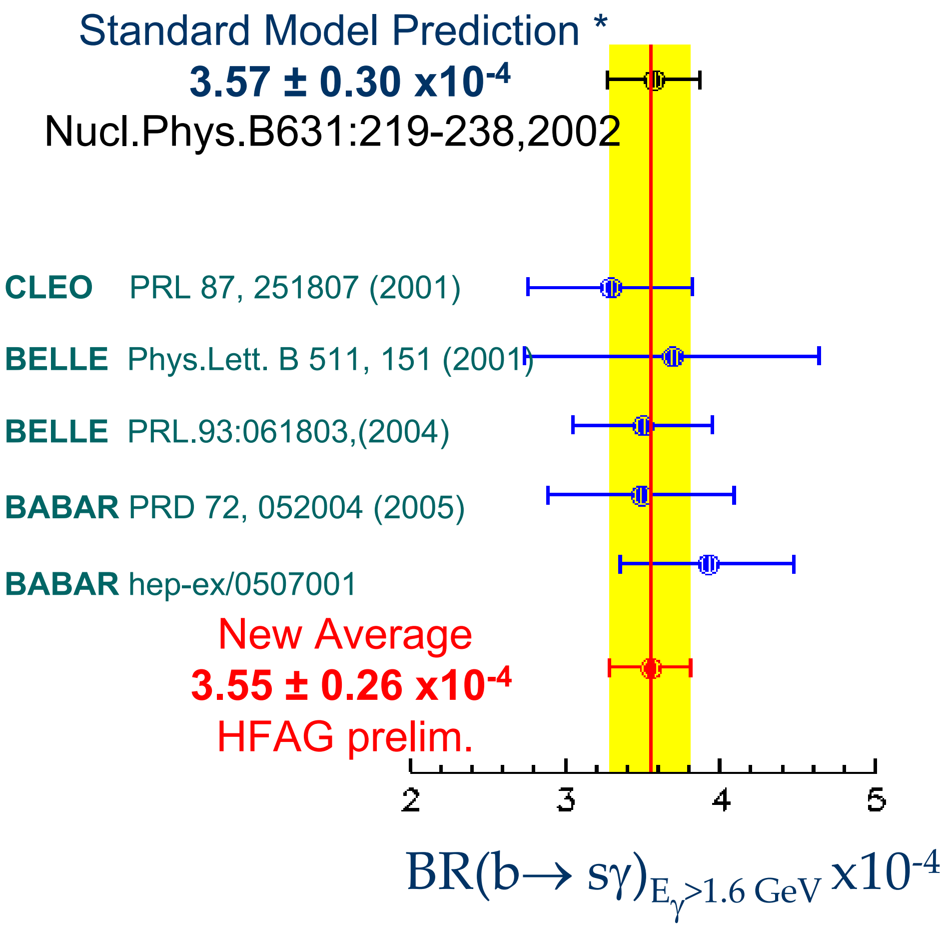
$BR(B \rightarrow X_s\gamma)$ =
$(3.55 \pm 0.24 \pm 0.10 +\!-0.03)\ 10^{-4}$

7% uncertainty

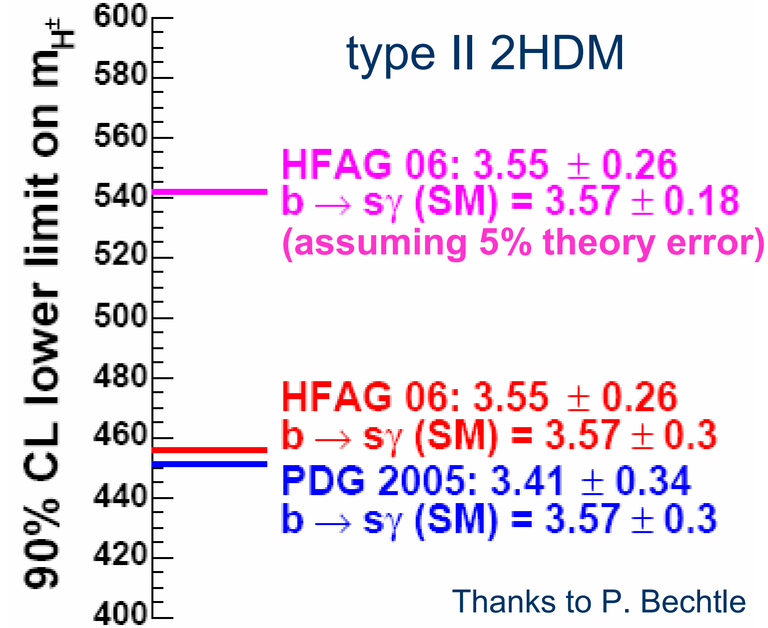
SM prediction:
3.57 ± 0.3 x10^{-4} Buras et al. (hep-ph/0203135)
3.44 ± 0.4 x10^{-4} Neubert (hep-ph/0408179)
3.61 ± 0.42 x10^{-4} Hurth et al. (hep-ph/0312260)

BR($b \to s\gamma$) Average

- Experiments measure PBF's above different photon energies
- Need to be extrapolated to E_γ > 1.6 GeV to compare with theory
- Extrapolation factors based on HQE fit to b→clν and b→sγ moments:



* Neubert & Hurth etal have slightly different theo. errors



Thanks to P. Bechtle

Outlook:

Exp. error will decrease with luminosity
Factor ~10 more data by 2008
Theo. uncertainty of 5% realistic with NNLO calculation

Conclusions

- Consistency between experimental results
- Good agreement of results from semileptonic and radiative B decays
- Precison measurements of SM parameters:
  - $|V_{cb}|$ at 2% level
  - $|V_{ub}|$ at ~7% probing consistency with sin(2β) and hence SM
  - m_b (<1%) and m_c (5%)
- Radiative B decays
  - BR($B \rightarrow X_s \gamma$) @ 7% - important constraint on many NP models

Backup Slides

Fit to Moments of Inclusive Decay Distributions

The Operator Product Expansion separates perturbative from non-perturbative scales in a systematic way:

$$\Gamma_{SL}(B \to X_c l\nu) = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 (1+A_{ew})A_{pert}(r,\mu)$$

$$\times \left[z_0(r)\left(1 - \frac{\mu_\pi^2 - \mu_G^2 + \frac{\rho_D^3+\rho_{LS}^3}{m_b}}{2m_b^2}\right) - 2(1-r)^4 \frac{\mu_G^2 + \frac{\rho_D^3+\rho_{LS}^3}{m_b}}{m_b^2} + d(r)\frac{\rho_D^3}{m_b^3} + O(1/m_b^4) \right]$$

kinetic expec. value (μ_π^2)

chromomagnetic expec. value (μ_G^2)

Darwin term (ρ_D^3)

spin-orbit (ρ_{LS}^3)

kinetic scheme

$r \equiv (m_c / m_b)^2$

Benson, Bigi, Mannel & Uraltsev, hep-ph/0410080
Gambino & Uraltsev, Eur.Phys.J. C34, 181 (2004)

Moments of hadronic mass, lepton energy and photon energy in b→sg distribution depend on same heavy quark parameters:

$$\langle M_X^n \rangle \rightarrow \langle M_X \rangle (m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$$
$$\langle E_\ell^n \rangle \rightarrow \langle E_\ell^n \rangle (m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$$
$$\langle E_\gamma^n \rangle \rightarrow \langle E_\gamma^n \rangle (m_b, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s) \quad .$$

mb and μ_π^2 are used to parameterise both B→Xs γ and B→Xu lν spectra

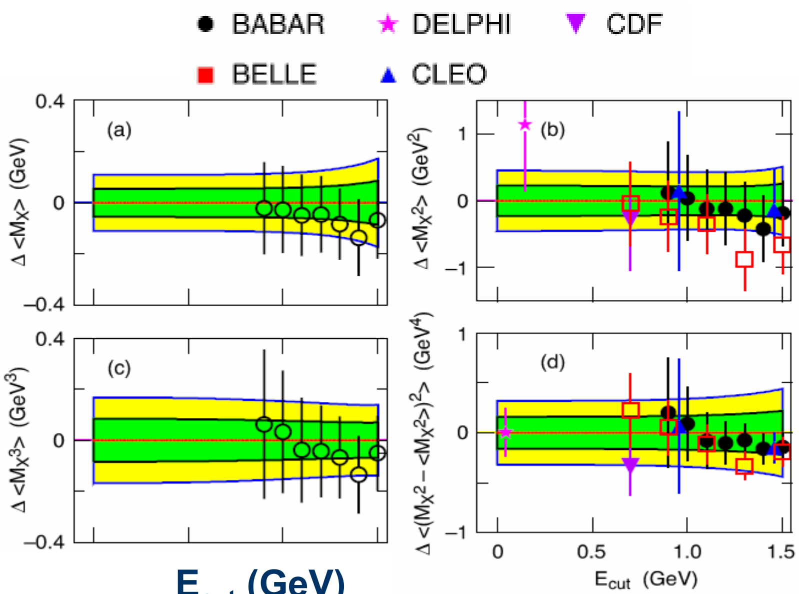
Many moment measurements (~50) allow to fit for all parameters up to $1/m_b^3$

Inclusive $|V_{cb}|$ - Fit to Moments

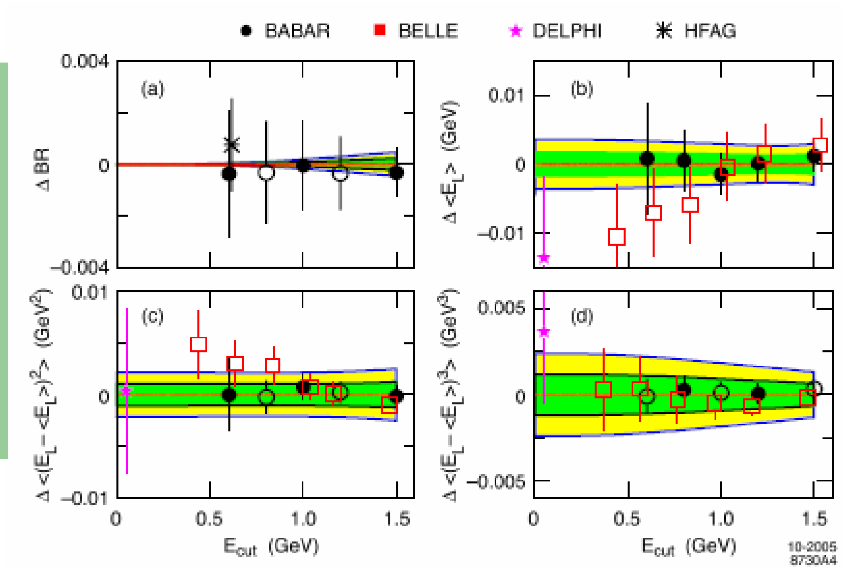
Based on calculations in kinetic scheme:

Benson, Bigi, Mannel & Uraltsev, hep-ph/0410080
Gambino & Uraltsev, hep-ph/0401063
Benson, Bigi & Uraltsev, hep-ph/0410080

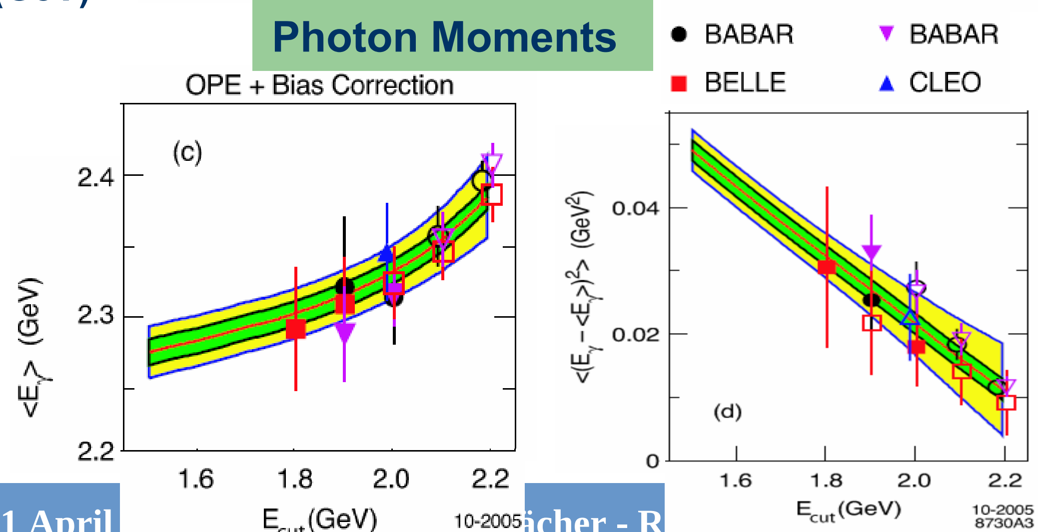
Hadron Moments



Lepton Moments



Photon Moments



Measurements highly correlated!

O. Buchmueller, H.F.
hep-ph/0507253