Rare B decays at the B Factories

Henning Flächer

Royal Holloway,
University of London

Overview

- Motivation
- Semileptonic B Decays
  - Exclusive Decays
    - V_{cb}, V_{ub} and Form Factors
  - Inclusive Decays
    - V_{cb} & V_{ub}
- Radiative Penguin Decays
  - $b \rightarrow s\gamma$, $b \rightarrow d\gamma$
- Charmless Hadronic B Decays
  - Bounds on ΔS and sin2 β from $B \rightarrow \eta' K_s$
  - $B^+ \rightarrow K^+ \pi^- \pi^+$
- B → Charm Decays via W-exchange and Annihilation
  - $B \rightarrow D_s D_s$
  - $B \rightarrow D_s \varphi$
- 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

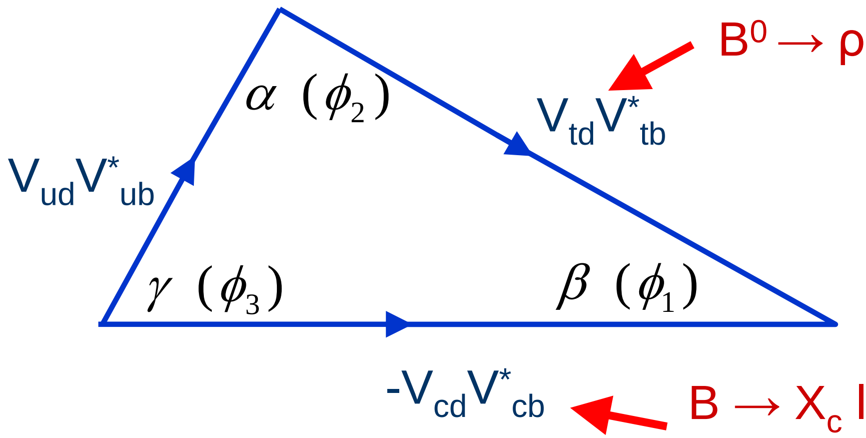
Unitary!

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

semi-leptonic decays

radiative decays

Can be visualised as triangle:



$B \rightarrow \pi\, l\nu$

$B \rightarrow X_u\, l\nu$

$B^0 \rightarrow \rho^0\gamma$

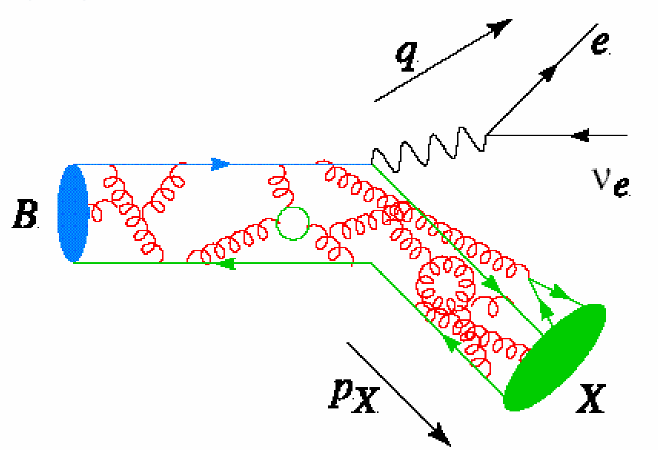
$B \rightarrow X_c\, l\nu$

$B \rightarrow D^*\, l\nu$

Semileptonic Decays

Why semileptonic decays?

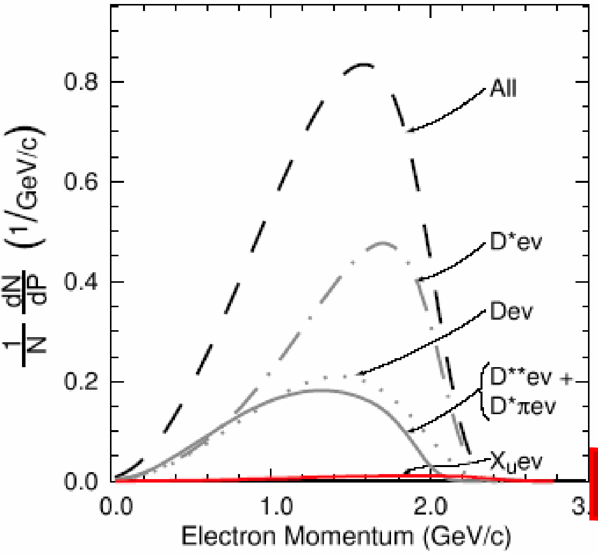
|V_{ub}| and |V_{cb}| are crucial in testing CKM unitarity and SM mechanism for CP violation



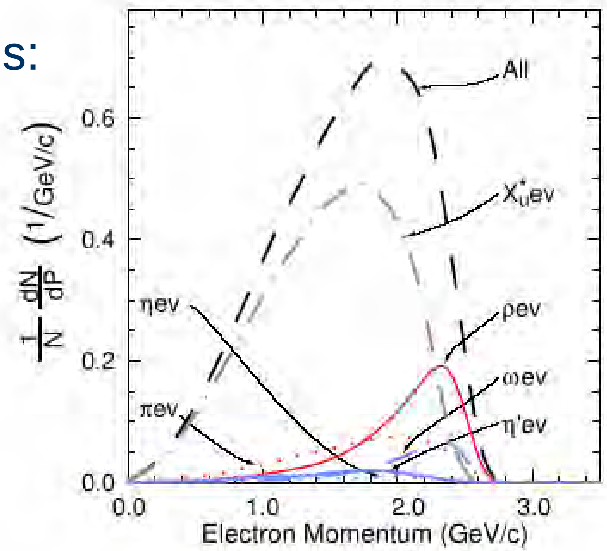
Hadronic and leptonic currents factorise, theoretical uncertainties are under control giving access to |V_{ub}| and |V_{cb}|

Different uncertainties in inclusive and exclusive decays → study both!

b → c lν transitions:



b → u lν transitions:



Exclusive $|V_{cb}|$

- In exclusive decays we need formfactors to relate $B \to D^*\ell\nu$ decay rate to $|V_{cb}|$

$\mathrm{BR}(B \rightarrow D^*l\nu) \sim |V_{cb}\ F_{D^*}(w{=}1)|^2$

w: D* boost in B rest frame

  - F(w) is calculable at $w = 1$, i.e. zero-recoil
    - encodes QCD ignorance of hadronisation
    - F(w) = 1 at the heavy-quark limit ($m_b = m_c = \infty$)
    - Lattice calculation gives $F(1)=0.919^{+0.030}_{-0.035}$

Hashimoto et al,
PRD 66 (2002) 014503

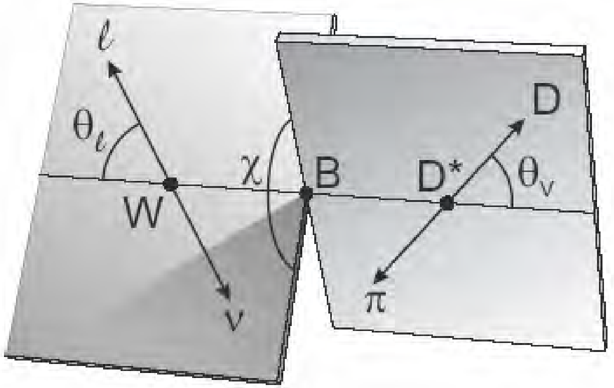
  - Shape of F(w) unknown
    - Parameterized with ρ^2 (slope at $w = 1$) and R_1, R_2

- $B \rightarrow D^*l\nu$ decay rate in terms of helicity amplitudes is given by:

$$\frac{d\Gamma(B\to D^*\ell\nu)}{dq^2 d\cos\theta_\ell d\cos\theta_V d\chi} = \frac{3G_F^2|V_{cb}|^2 P_{D^*} q^2}{8(4\pi)^4 M_B^2}\times$$

$$\{H_+{}^2(1-\cos\theta_\ell)^2\sin^2\theta_V + H_-{}^2(1+\cos\theta_\ell)^2\sin^2\theta_V$$
$$+4H_0{}^2\sin^2\theta_\ell\cos^2\theta_V - 2H_+H_-\sin^2\theta_\ell\sin^2\theta_V\cos 2\chi$$
$$-4H_+H_0\sin\theta_\ell(1-\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi$$
$$+4H_-H_0\sin\theta_\ell(1+\cos\theta_\ell)\sin\theta_V\cos\theta_V\cos\chi\}$$

Angular kinematic variables :



The Helicity amplitudes H_i depend on Form Factor ratios R1 and R2

Exclusive $|V_{cb}|$: B→D* lν

New!

Extract D*lν form factors from unbinned maximum likelihood fit to full 4-dim PDF

stat. MC stat. syst.

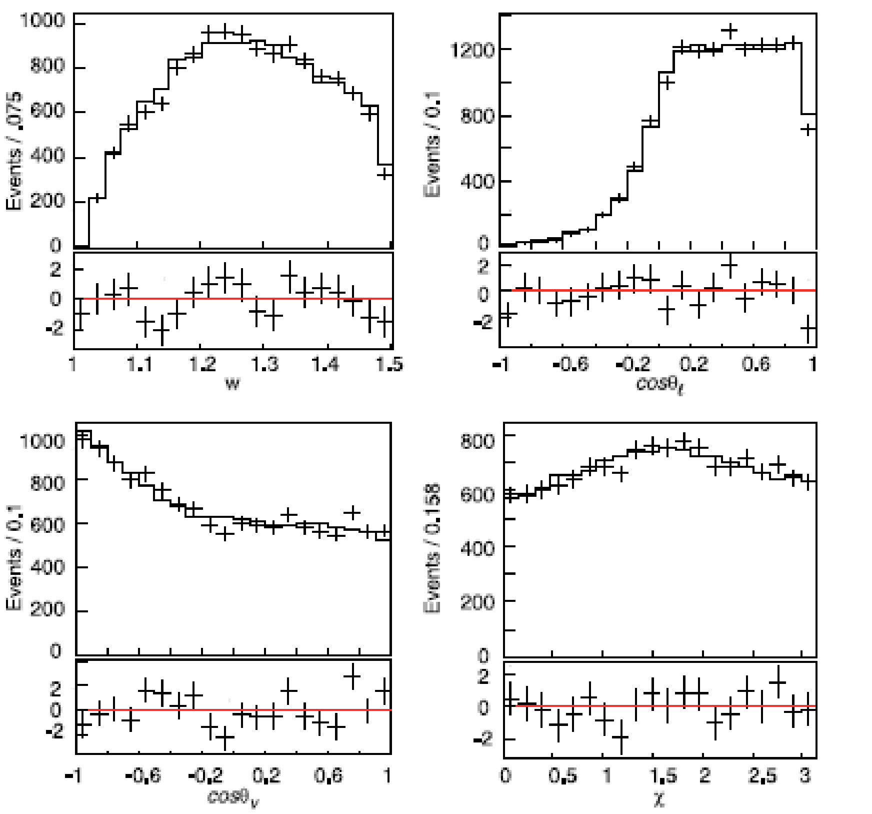
$$
\begin{aligned}
R_1 &= 1.396 \pm 0.060 \pm 0.035 \pm 0.027, \\
R_2 &= 0.885 \pm 0.040 \pm 0.022 \pm 0.013, \\
\rho^2 &= 1.145 \pm 0.059 \pm 0.030 \pm 0.035,
\end{aligned}
$$

Compared to FF from previous CLEO measurement, uncertainty on $|V_{cb}|$ is reduced from +2.9% -2.6% → ± 0.5%

Factor 5 improvement of FF uncertainty

Systematic error on $|V_{cb}|$ from 4.5% →3.5%

One dimensional projections of the fit result:



$$|V_{cb}| = 37.6 \pm 0.3(stat) \pm 1.3(syst)\ {}^{+1.5}_{-1.3}(theory) \times 10^{-3}$$

hep-ex/0602023

Also leads to a reduction in systematic error on $|V_{ub}|$ from Babar endpoint analysis
Systematic error on BF reduced from 6.7% → 2.8%

Exclusive $|V_{ub}|$

- Measure specific final states, e.g., $B \to \pi l v$, $B \to \rho l v$
  - Can achieve good signal-to-background ratio
  - Branching fractions are $O(10^{-4})$ → statistics limited
- Need form factors to extract $|V_{ub}|$

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

One FF for $B \to \pi l v$
(massless lepton)

- Theo. Uncertainties complementary to inclusive approach !

- $f_+(q^2)$ calculations exist based on:
  - Lattice QCD ($q^2 > 16$ GeV^2)
    - recent “unquenched” calculations → ~11% uncertainty
  - Light Cone Sum Rules ($q^2 < 14$ GeV^2) → ~10% uncertainty
  - Quark models (ISGW2) … and other approaches

HPQCD
hep-lat/0408019
Fermilab
hep-lat/0409166

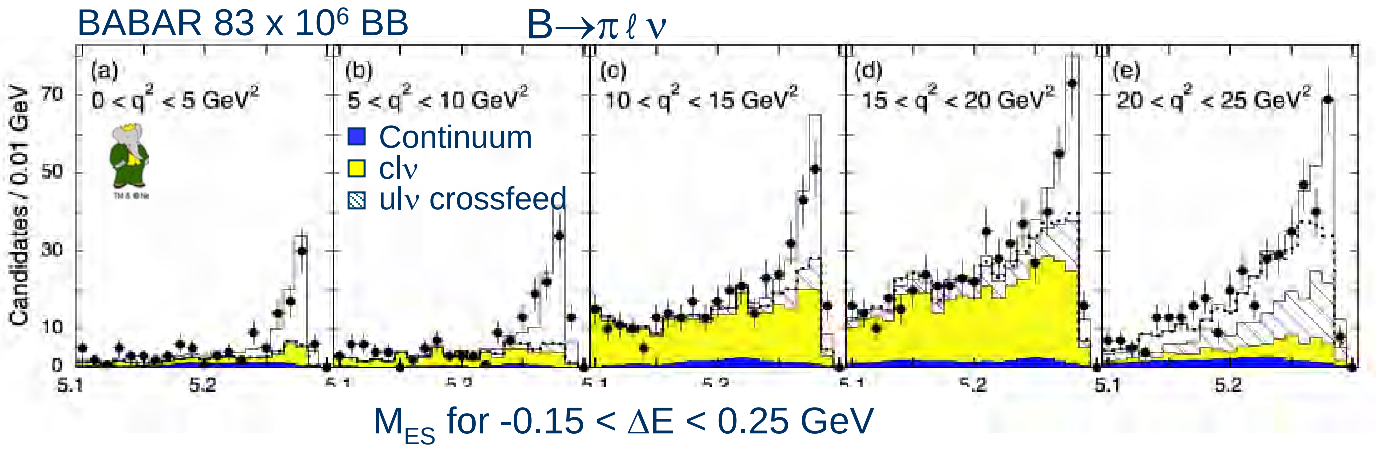
Ball,Zwicky
hep-ph/0406232

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

Babar untagged analysis:

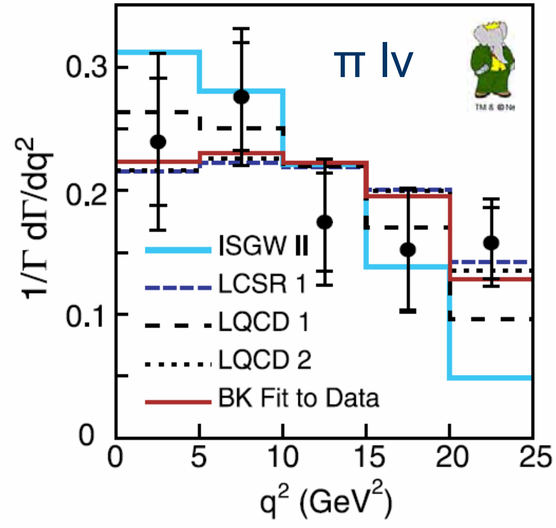
ν = missing $\left(E, \vec{p}\right)$ of the event

Fit of the signal yield using the B mass and ΔE in bins of q^2.



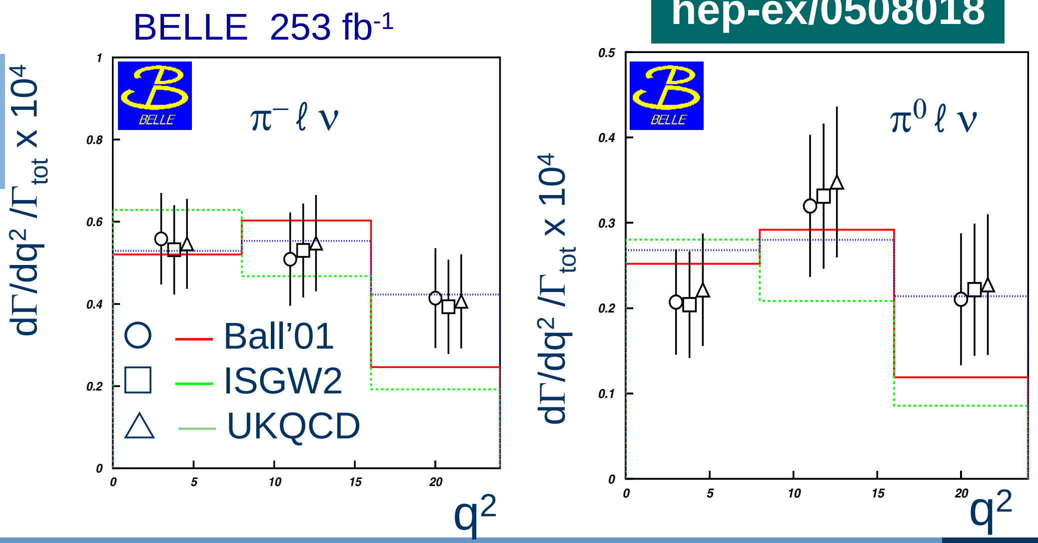
- Measure q^2-dependence of the form factor
- Compare with theoretical calculations

hep-ex/0507003



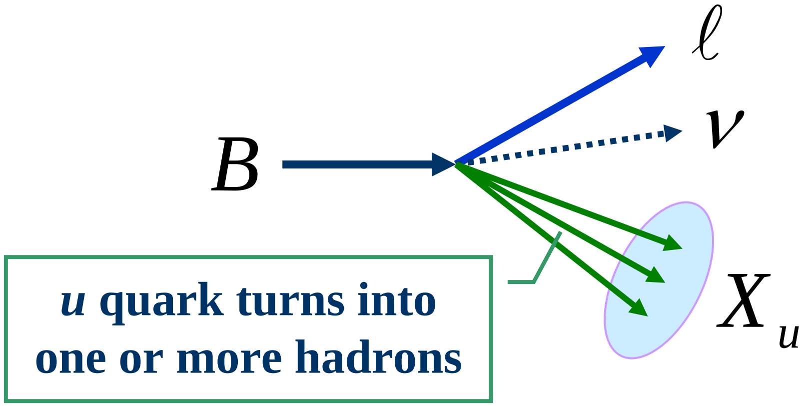
Belle with D*lv tag

hep-ex/0508018



Inclusive $b \to u l \nu$: Strategies

- We use 3 variables to describe $B \to X l \nu$ decays:



***u* quark turns into one or more hadrons**

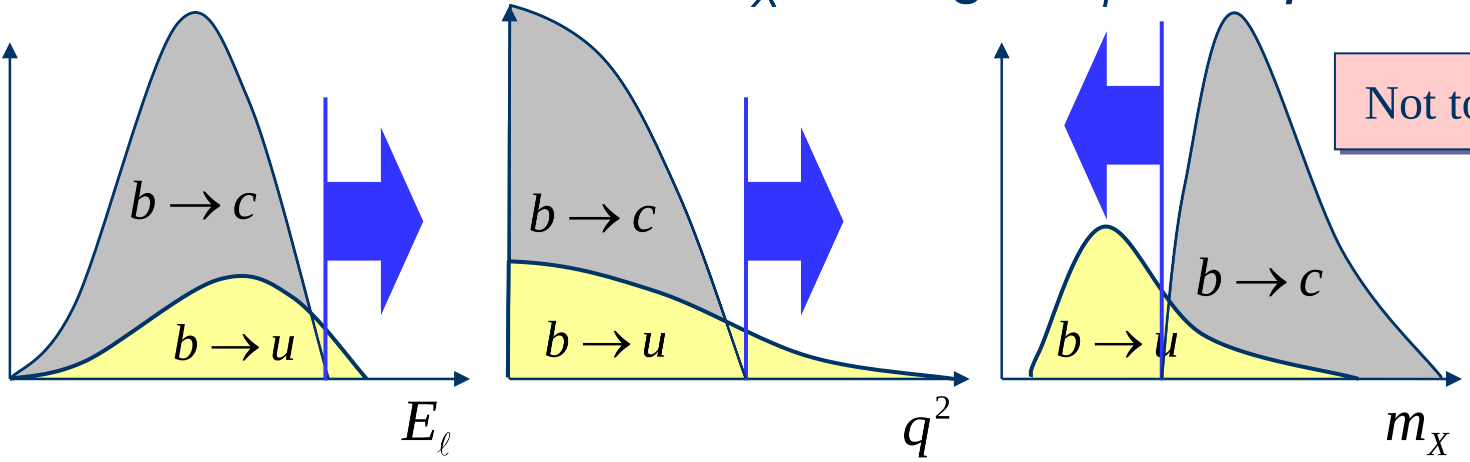
E_l = lepton energy

q^2 = lepton-neutrino mass squared

m_X = hadron system mass

Combine cuts on these variables to maximise phase space and minimise theory uncertainty

- Signal events have smaller m_X → larger E_l and q^2



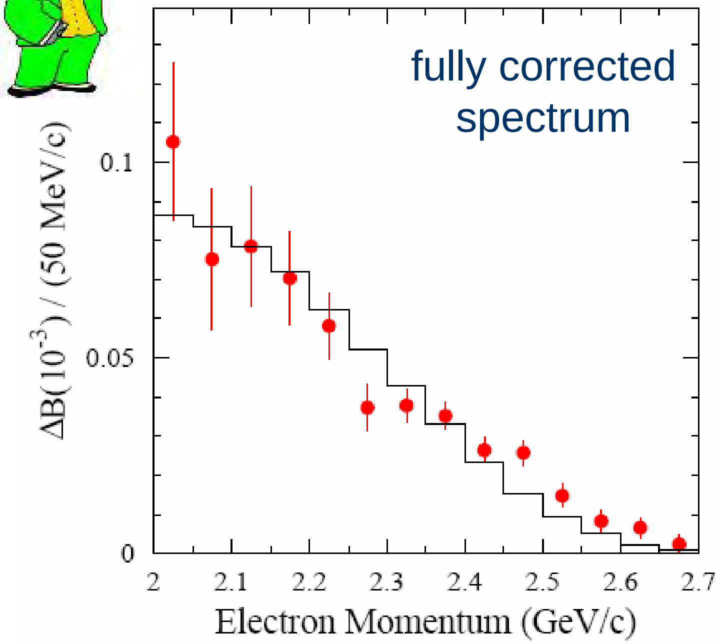
Not to scale!

Inclusive $|V_{ub}|$: Endpoint

Measure rate in region where b→clν is largely forbidden, previously large extrapolation

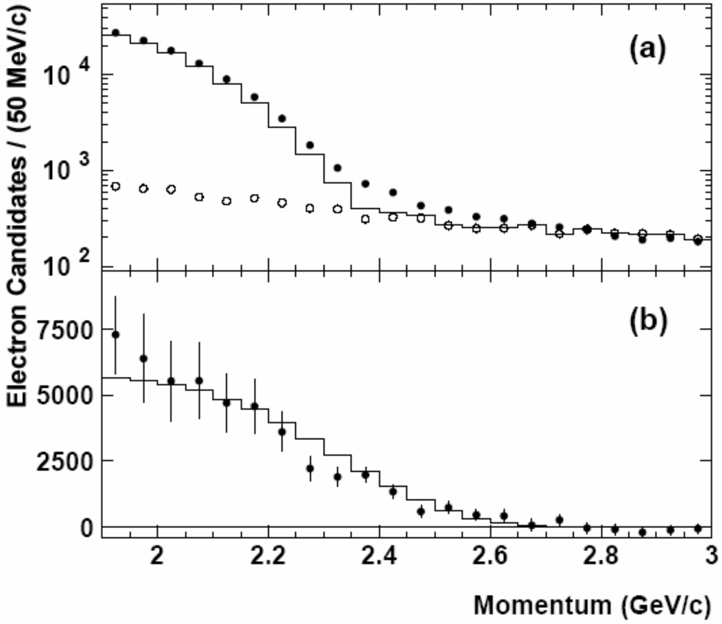
hep-ex/0509040

2.0 GeV < E_l <2.6 GeV



hep-ex/0504046

1.9 GeV < E_l <2.6 GeV



Calculations by Bosch, Lange, Neubert & Paz translate partial rate directly into $|V_{ub}|$:

Babar: $$|V_{ub}| = (4.44 \pm 0.25_{exp}\ {}^{+0.42}_{-0.38\ SF} \pm 0.22_{theory}) \times 10^{-3}$$

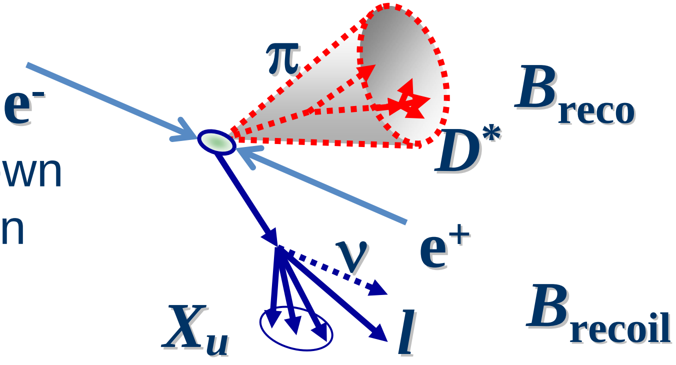
Belle: $$|V_{ub}| = (5.08 \pm 0.47_{exp} \pm 0.42_{SF}\ {}^{+0.26}_{-0.23}{}_{theo}) \times 10^{-3}$$

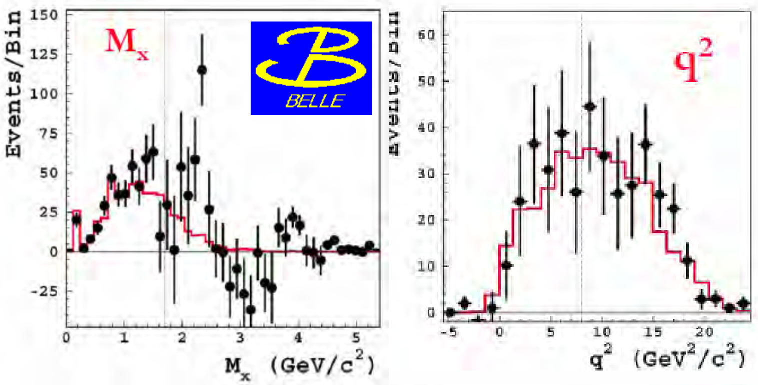
Inclusive $|V_{ub}|$: Hadronic B tag

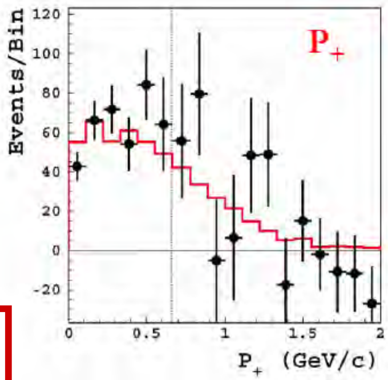
Fully reconstructed *B* recoil analysis:

Advantages:
- clean sample
- kinematics known
- B flavour known

Disadvantage:
- low statistics







Calculations of Bosch,Lange,Neubert,Paz hep-ph/0402094,0504071

Different phase space acceptances result in different theory errors!

Belle:

hep-ex/0505088

$\Delta\Phi$	$\lvert V_{ub}\rvert \times 10^3$	stat	syst	$b \to u$	$b \to c$	SF	th.
M_X/q^2	4.70	5.0	4.4	3.1	2.7	4.2	$^{+4.8}_{-5.2}$
M_X	4.09	4.6	3.5	3.1	1.1	4.5	$^{+3.5}_{-3.8}$
P_+	4.19	4.7	4.6	3.2	4.4	5.8	$^{+3.4}_{-3.5}$

M_X<1,7GeV, q^2>8GeV

M_X<1,7GeV

$P_+=E_X-|p_X|$ >0.66

Babar:

hep-ex/0507017

$$|V_{ub}| = (4.65 \pm 0.24_{stat} \pm 0.24_{syst} {}^{+0.46}_{-0.38 SF} \pm 0.23_{th}) \times 10^{-3}$$

M_X<1.7GeV, q^2>8GeV

Inclusive $|V_{ub}|$

New!

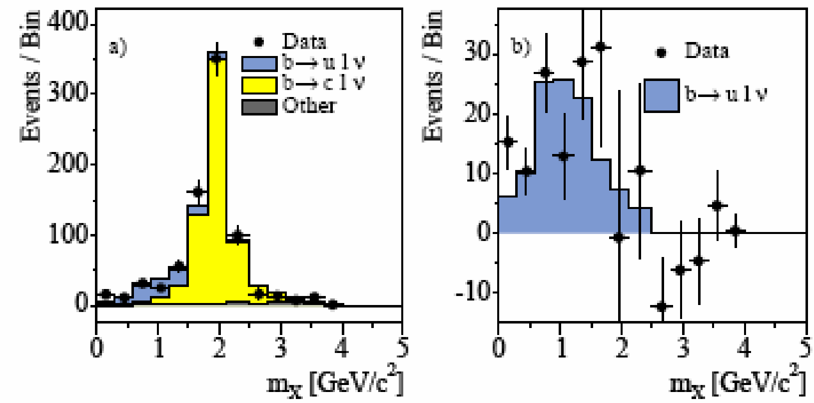
Relating $b \rightarrow u l \nu$ to $b \rightarrow s \gamma$ using weight functions:

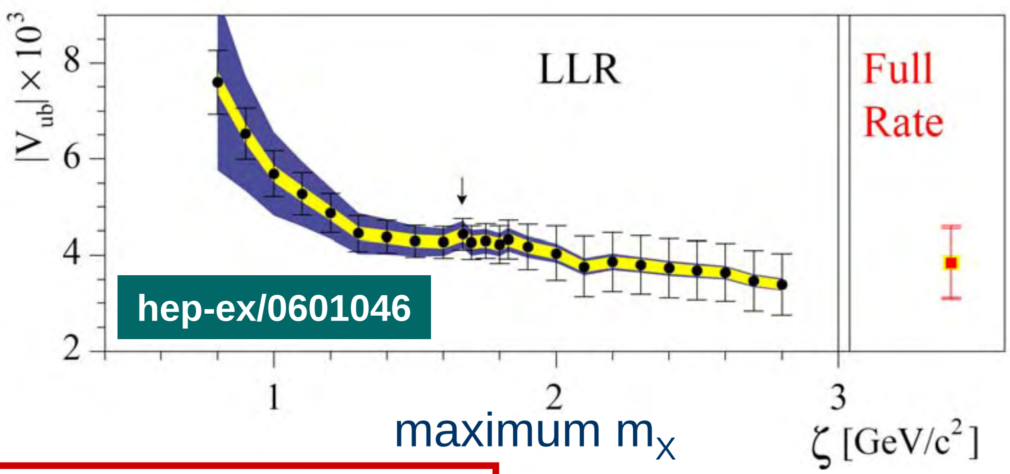
largely SF independent!

Leibovich, Low, Rothstein
hep-ph/0005124,0105066

$$\Gamma(B \to X_u \ell \nu) = \frac{|V_{ub}|^2}{|V_{ts}|^2} \int W(E_\gamma) \frac{d\Gamma(B \to X_s \gamma)}{dE_\gamma} dE_\gamma$$

Weight function





hep-ex/0601046

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

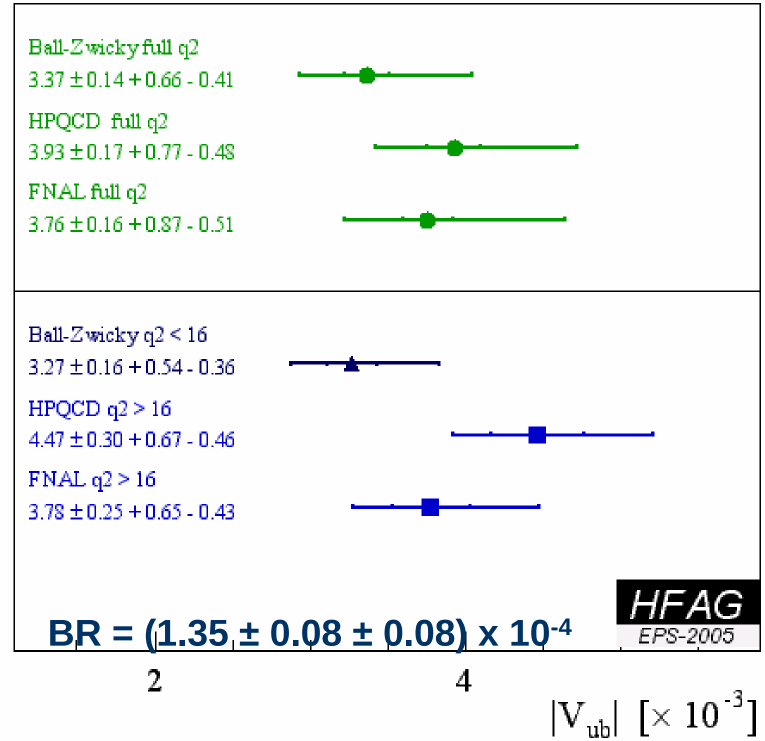
LLR : M_X < 1.67 GeV:
$|V_{ub}| = (4.43 \pm 0.38_{stat} \pm 0.25_{syst} \pm 0.29_{theo})\ 10^{-3}$

OPE: M_X < 2.50 GeV:
$|V_{ub}| = (3.84 \pm 0.70_{stat} \pm 0.30_{syst} \pm 0.10_{theo})\ 10^{-3}$

reduced theory error as no extrapolation to full rate necessary

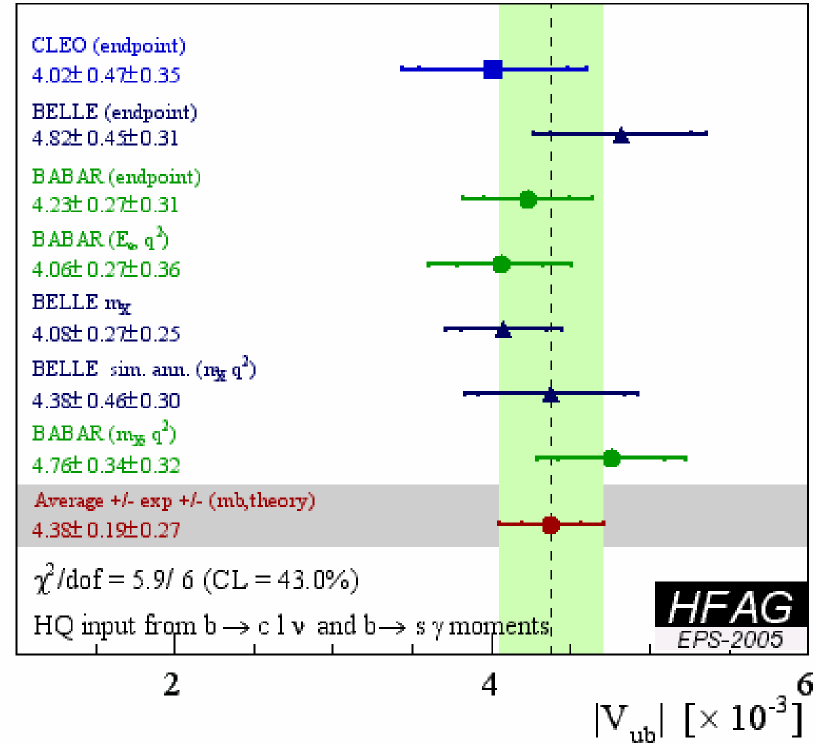
$|V_{ub}|$ Summary

Exclusive $|V_{ub}|$:



BR = (1.35 ± 0.08 ± 0.08) x 10^{-4}

Inclusive $|V_{ub}|$:



4% exp., ~11% theory uncertainty

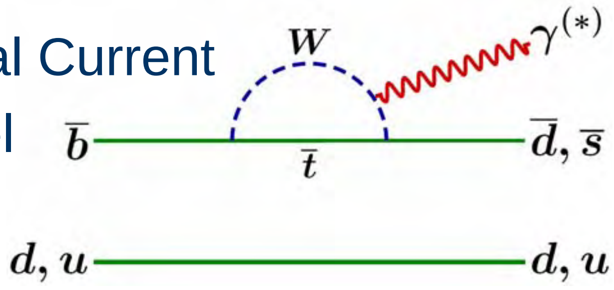
$|V_{ub}|$ =(4.38 ± 0.19 ± 0.27) x 10^{-3}

7.6 % total uncertainty!

Errors on $|V_{ub}|$ dominated by FF normalization

Main improvement due to better knowledge of “shape function” parameters

Radiative B Decays: b→s,d γ



`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: $V_{tb}V^*_{tq}$
  - sensitive to high virtual mass scale, e.g. from new physics

- We are unable to measure the parton level decay rate for b→sγ, however:

HQET ⇒ $$\Gamma\left(B \rightarrow X_s\gamma\right) = \Gamma(b \rightarrow s\gamma) + \Delta^{nonpert}$$

Theoretical Framework: Operator Product Expansion
separate weak scale from *B*-mass scale

- Theoretical uncertainty ~ 10%, mainly from contribution of higher order diagrams in the expansion.

b→sγ Spectra and Moments

Measure photon spectrum in b→sγ decays:

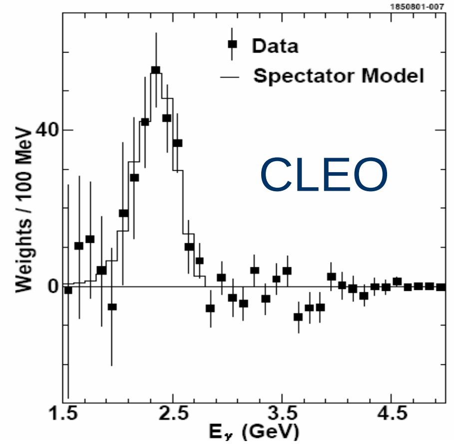
Two main approaches:

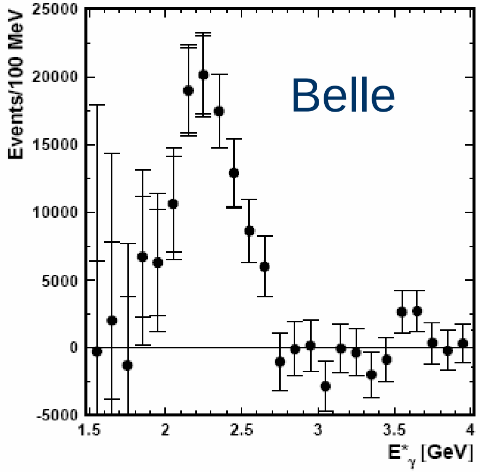
- Inclusive:
  - identify photon
- Semi-Inclusive:
  - reconstruct many exlusive final states (up to 38!)

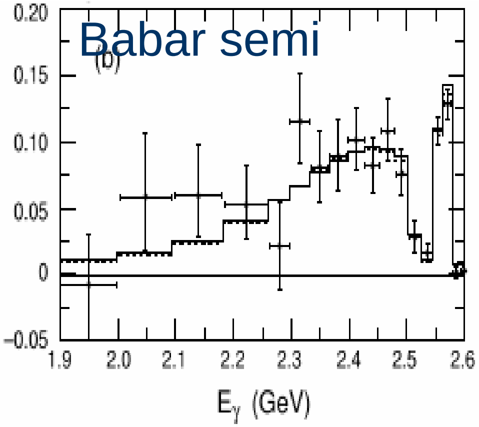
Difficult measurement:
Overwhelming background
from π^0s for E_γ < 1.8 GeV

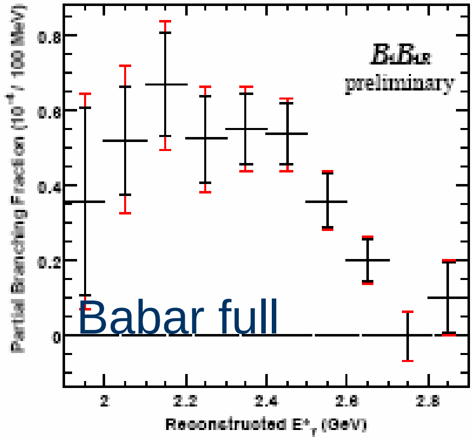
Measurement of photon spectrum and its moments gives information about inner structure of B meson:

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



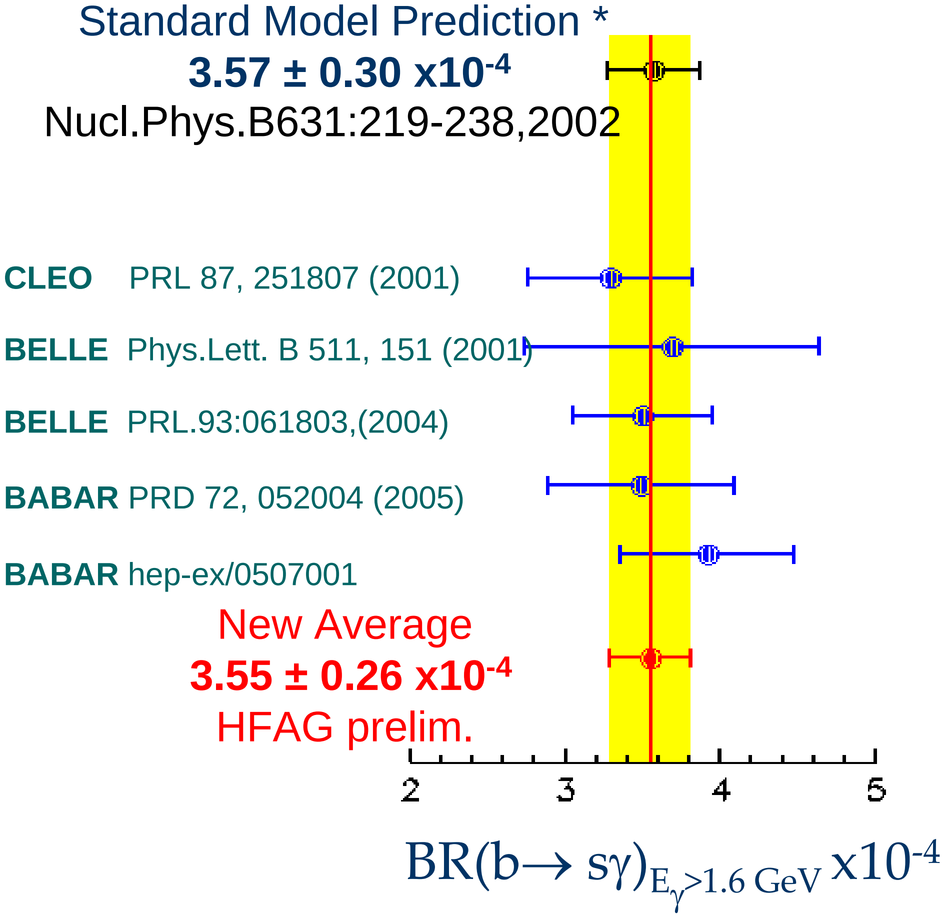






BR($b \to s\gamma$) Average

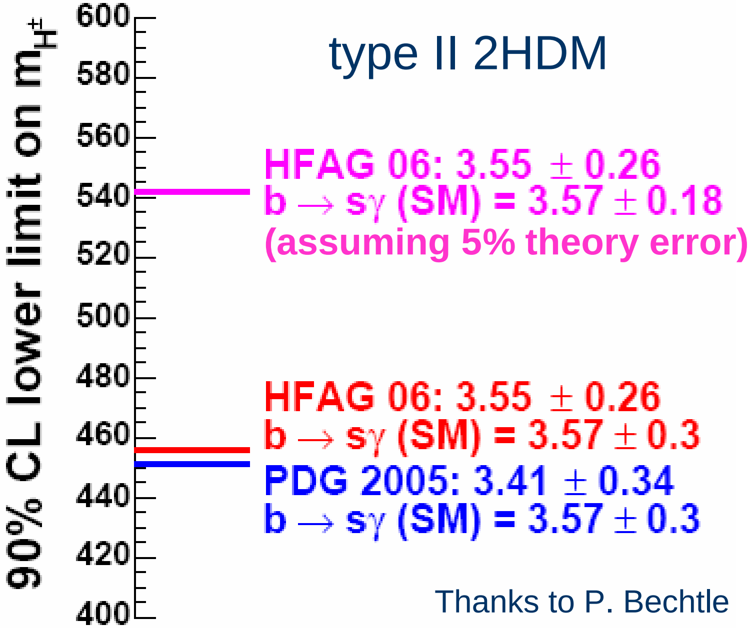
- Experiments measure PBF’s above different photon energies
- Need to be extrapolated to E_γ > 1.6 GeV to compare with theory
- Extrapolation factors based on HQE fit to b→clν and b→sγ moments:



Standard Model Prediction *
3.57 ± 0.30 x10^{-4}
Nucl.Phys.B631:219-238,2002

CLEO PRL 87, 251807 (2001)
BELLE Phys.Lett. B 511, 151 (2001)
BELLE PRL.93:061803,(2004)
BABAR PRD 72, 052004 (2005)
BABAR hep-ex/0507001

New Average
3.55 ± 0.26 x10^{-4}
HFAG prelim.



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

* Neubert & Hurth etal have slightly different theo. errors

Fit to Moments of Inclusive Decay Distributions

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 $1/m_b$

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

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:

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

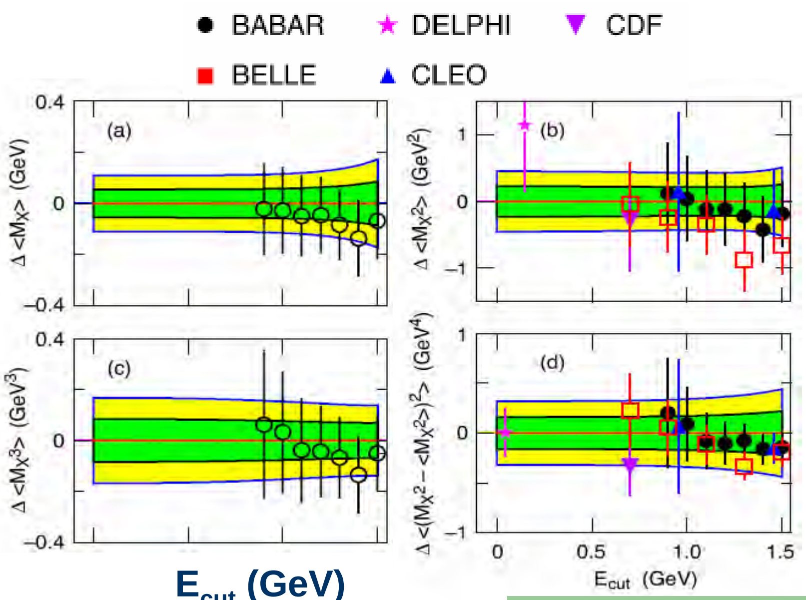
- Hadronic Mass distribution $\langle M_X^n \rangle \rightarrow \langle M_X \rangle (m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$
- Lepton Energy spectrum $\langle E_\ell^n \rangle \rightarrow \langle E_\ell^n \rangle (m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3, \alpha_s)$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

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

Based on calculations in kinetic scheme:

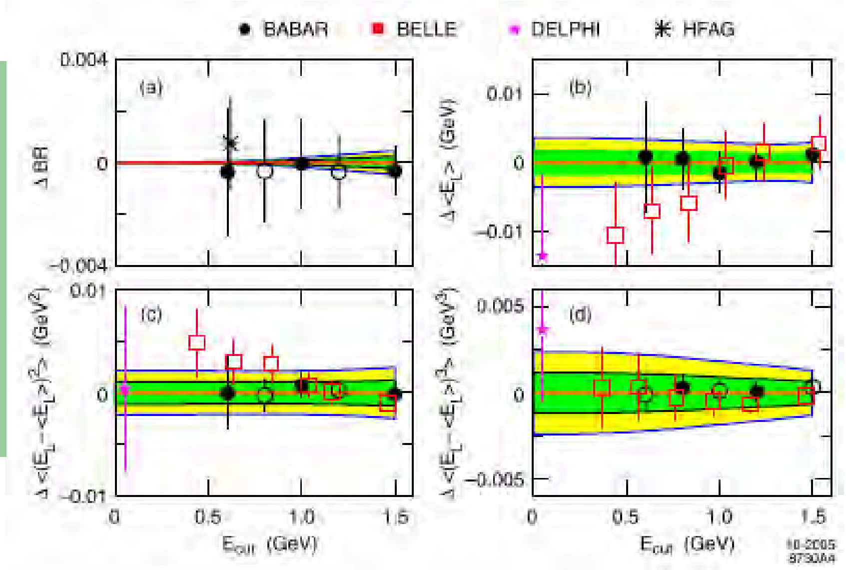
Benson, Bigi, Mannel & Uraltsev, hep-ph/0410080
Gambino & Uraltsev, hep-ph/0401063
Benson, Bigi & Uraltsev, hep-ph/0410080

Hadron Moments



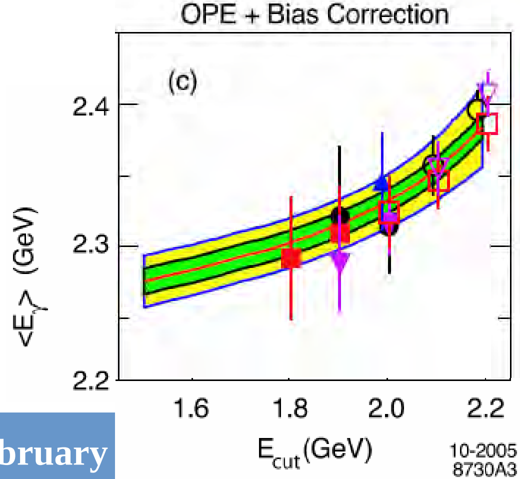
E_{cut} (GeV)

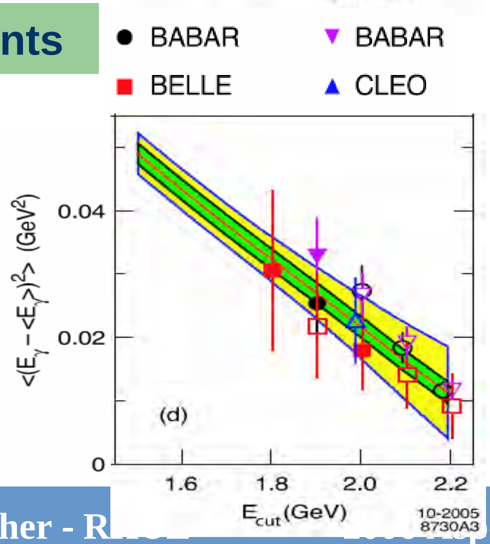
Lepton Moments



Photon Moments

Measurements highly correlated!





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

Inclusive $|V_{cb}|$

New!

Result of fit to all moment measurements:

		exp	HQE	Γ_{SL}
$|V_{cb}|$ =	(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
$BR_{cl\nu}$ =	10.71	± 0.10	± 0.08	%

hep-ph/0507253

$|V_{cb}|$ @ 2%

$m_b < 1\%$

m_c @ 5%

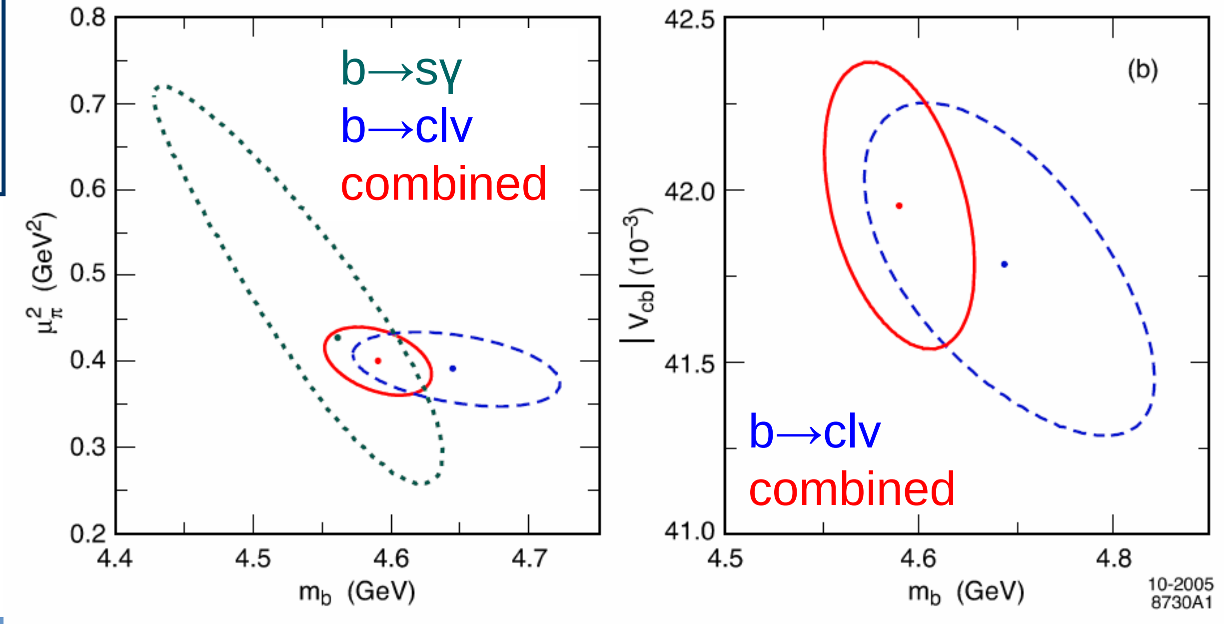
In $\overline{\text{MS}}$ scheme:

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

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

$\overline{m}_c(\mu)/\overline{m}_b(\mu) = 0.235 \pm 0.012$

courtesy of N.Uraltsev



Good agreement with other similar analyses:

Bauer et al. hep-ph/0408002

DELPHI hep-ex/0510024

b→dγ

Motivation:

- *b*→*d*γ transition, BF ∝|V_{td} V_{tb}|^2
- SM prediction: 0.9 - 1.8 x 10^{-6}
- clean SM prediction for ratio of *B* → ρ/ωγ and *B* → K*γ:

Ali and Parkhomenko,
Eur.Phys.JC 23,89 (2002)
Ali et al, PLB 595,323 (2004)

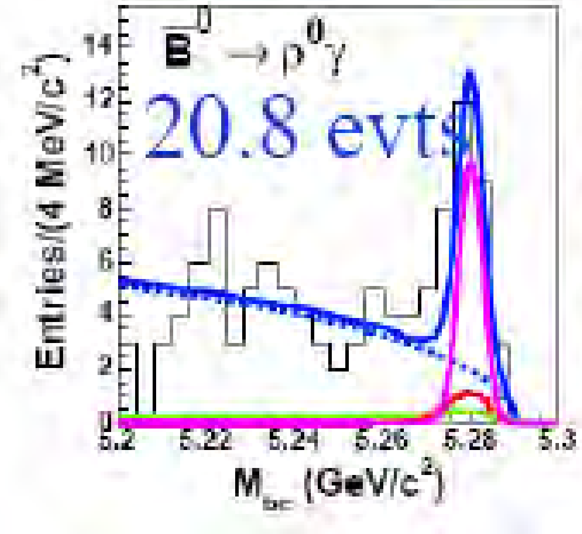
$$\frac{\overline{\mathcal{B}}[B \to (\rho/\omega)\gamma]}{\mathcal{B}(B \to K^*\gamma)} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \left(\frac{1-m_\rho^2/M_B^2}{1-m_{K^*}^2/M_B^2}\right)^3 \zeta^2[1+\Delta R]$$

Average branching fractions

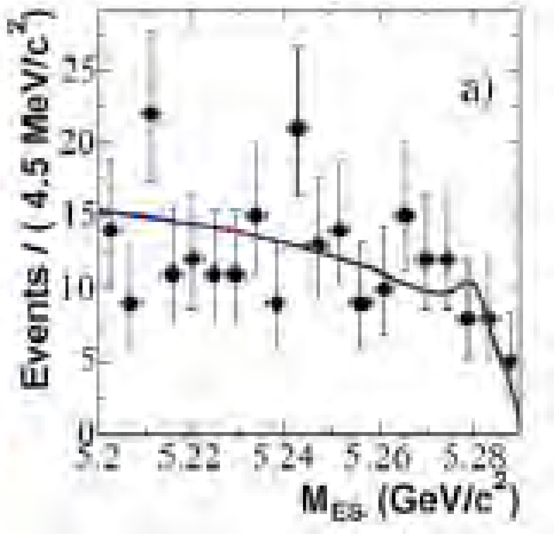
difference in dynamics
(such as W-annihilation)
ΔR ≈ 0.1±0.1

form factor ratio
$\zeta^2 \approx 0.85 \pm 0.1$
(largest uncertainty)

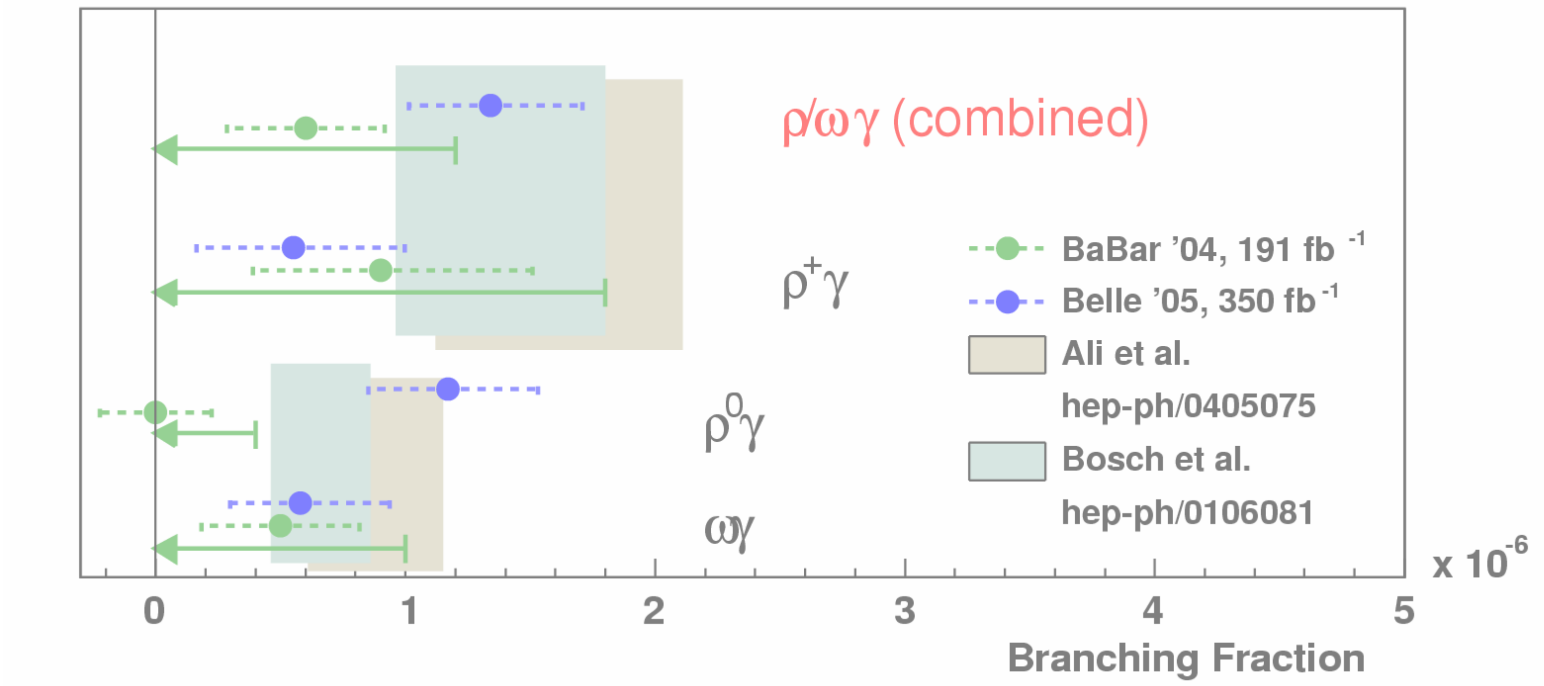
Belle: **hep-ex/0506079**



Babar: **hep-ex/0408034**



b→dγ



- BaBar and Belle are 2.7σ apart in $B^0 \to \rho^0\gamma$

- BaBar low compared to theory prediction

B→ K* γ:

Good agreement between Babar and Belle!

$\mathrm{B}(B^0 \to K^{*0}\gamma) = (40.1 \pm 2.0) \times 10^{-6}$

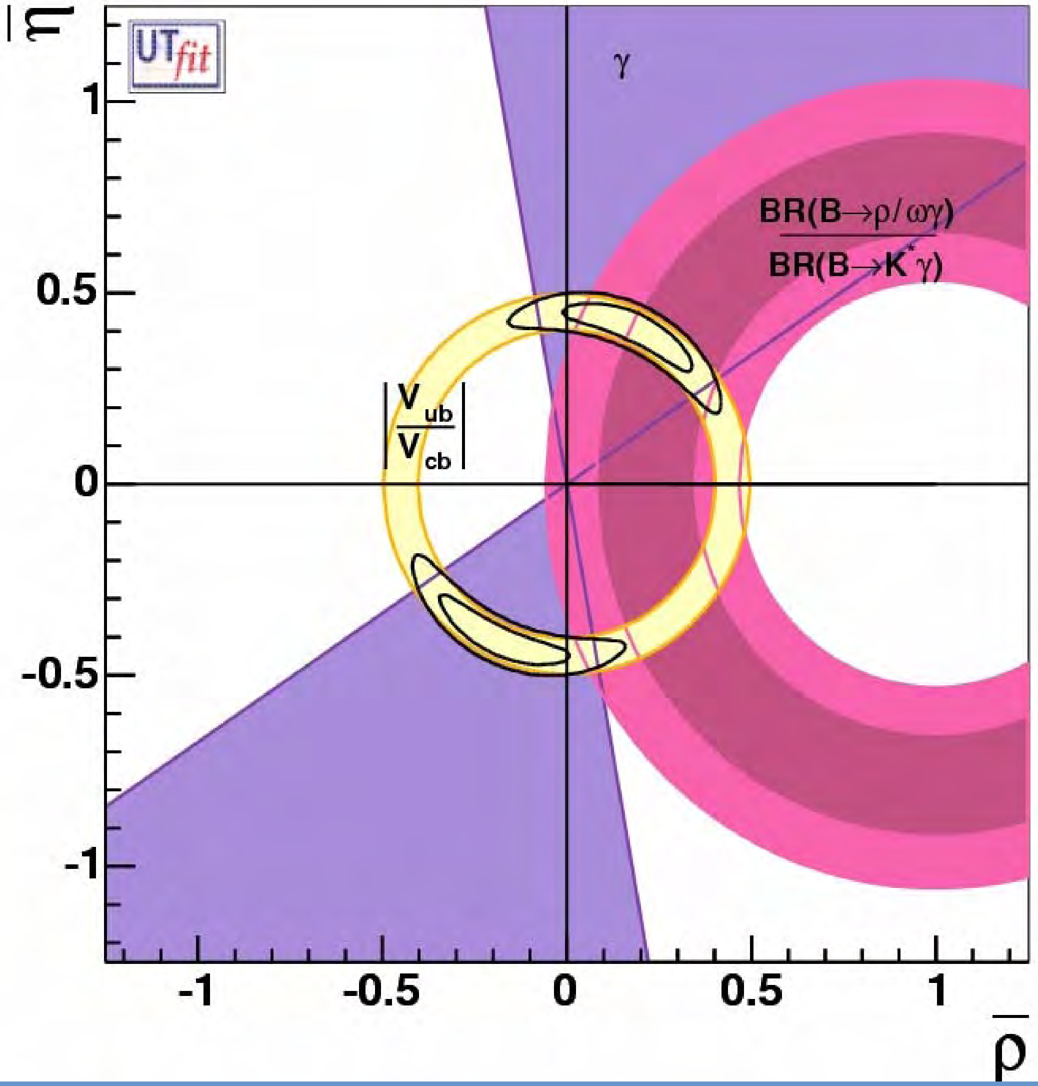
$\mathrm{B}(B^+ \to K^{*+}\gamma) = (40.3 \pm 2.6) \times 10^{-6}$

HFAG Summer 2005

UT Constraints from Sides and Tree Processes

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

$|V_{td}/V_{ts}|$ = 0.18 ± 0.03



Other Rare B Decays

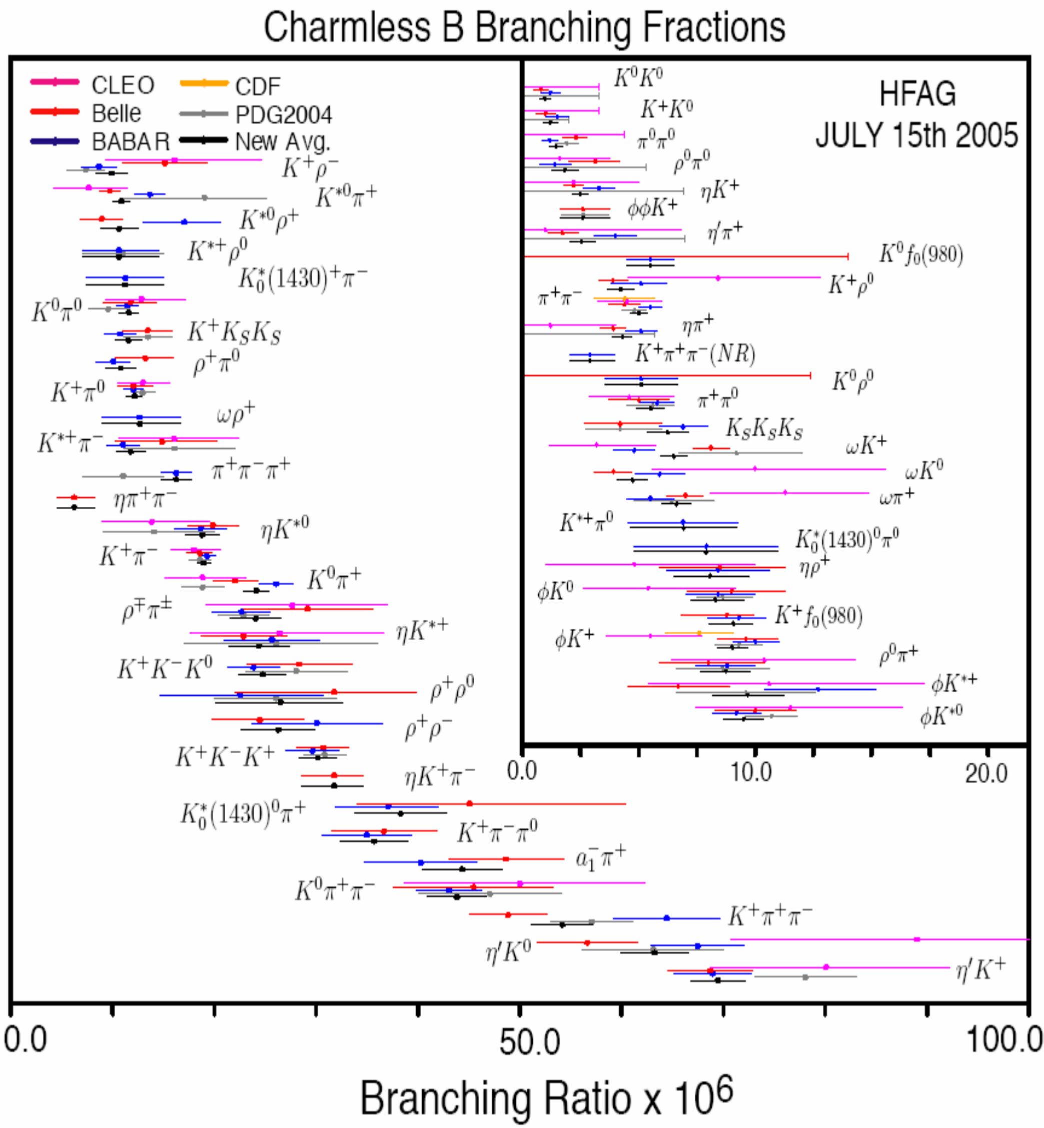
- Charmless Hadronic B Decays
  - I will be selective and only pick 2 examples:
    - Bounds on ΔS and sin2 β from $B \rightarrow \eta' K_s$
    - $B^+ \rightarrow K^+ \pi^- \pi^+$
- B → Charm Decays via W-exchange
  - $B \rightarrow D_s D_s$
- B → Charm Decays via Annihilation
  - $B \rightarrow D_s\, \varphi$
  - No decay that occurs through annihilation has been observed
- Decays are suppressed in the Standard Model
  - Standard Model BR of order $10^{-5} - 10^{-7}$
- Potential for New Physics
  - Beyond SM contributions can lead to enhanced BR's

Rare Charmless B Decays

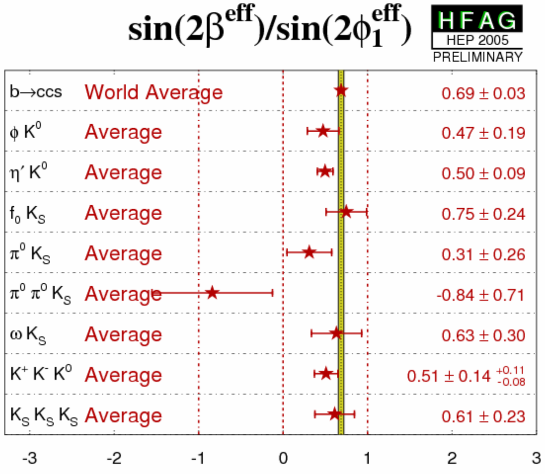
- Too many decays to be discussed in detail…

- Rare Charmless *B* decays can be used to study
    - Interfering standard model amplitudes
    - Amplitudes of CKM parameters and angles
    - Effects of higher mass particles in loops

- Measurements are used to improve theoretical models



Bounds on the tree contribution in B→η’ K_s



Difference in sin(2β) from b→c$\bar{c}$s and b→q$\bar{q}$s penguin

B→ψK_s sin2β = 0.69 ± 0.03

B→η’K_s $\sin 2\beta_{eff}$ = 0.50 ± 0.09

It’s possible to set theoretical bounds on this difference:

$$\Delta S_{th} = S(\eta' K_S) - \sin 2\beta < |\xi_{\eta' K}|$$

is a function of BF for Flavour SU(3) related decay modes:

$$|\xi_{\eta' K_S}| < \left|\frac{V_{us}}{V_{ud}}\right| \left[0.59\sqrt{\frac{\mathcal{B}(\eta'\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.33\sqrt{\frac{\mathcal{B}(\eta\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.14\sqrt{\frac{\mathcal{B}(\pi^0\pi^0)}{\mathcal{B}(\eta' K^0)}} + 0.53\sqrt{\frac{\mathcal{B}(\eta'\eta')}{\mathcal{B}(\eta' K^0)}} + 0.38\sqrt{\frac{\mathcal{B}(\eta\eta)}{\mathcal{B}(\eta' K^0)}} + 0.96\sqrt{\frac{\mathcal{B}(\eta\eta')}{\mathcal{B}(\eta' K^0)}}\right]$$

hep-ph/0303171

Will improve with more measurements!

Theory: Δ S < 0.05
Experiment: Δ S = 0.19+-0.09

If ΔS >> 0.1
→ signature for new physics

HFAG Summer 2005

η’ π^0	**< 3.7 x10^{-6}**	**90% CL**
η π^0	**< 2.5 x10^{-6}**	**90% CL**
π^0 π^0	**= 1.45 ± 0.29 x10^{-6}**	
η’ η’	**< 10 x10^{-6}**	**90% CL**
η η	**< 2.0 x10^{-6}**	**90% CL**
η η’	**< 4.6 x10^{-6}**	**90% CL**
η’K^0	**= 63.2 ± 3.3 x10^{-6}**	

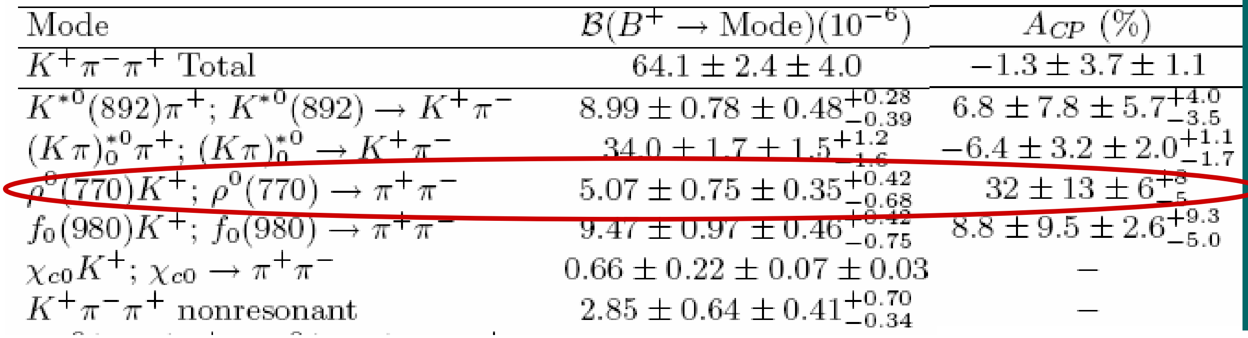
Other approaches: Buchalla etal., Beneke

Dalitz plot analysis of $B^+ \to K^+\pi^-\pi^+$

$B^+ \to K^+\pi^-\pi^+$ occurs via intermediate quasi two-body resonances (e.g. K*π, ρK) as well as non-resonant

Theoretical models predict BR and CP asymmetries for B→K* π and B→ρ K

Babar :



Mode	$\mathcal{B}(B^+ \to \text{Mode})(10^{-6})$	A_{CP} (%)
$K^+\pi^-\pi^+$ Total	$64.1 \pm 2.4 \pm 4.0$	$-1.3 \pm 3.7 \pm 1.1$
$K^{*0}(892)\pi^+;\ K^{*0}(892) \to K^+\pi^-$	$8.99 \pm 0.78 \pm 0.48^{+0.28}_{-0.39}$	$6.8 \pm 7.8 \pm 5.7^{+4.0}_{-3.5}$
$(K\pi)^{*0}_0\pi^+;\ (K\pi)^{*0}_0 \to K^+\pi^-$	$34.0 \pm 1.7 \pm 1.5^{+1.2}_{-1.6}$	$-6.4 \pm 3.2 \pm 2.0^{+1.1}_{-1.7}$
$\rho^0(770)K^+;\ \rho^0(770) \to \pi^+\pi^-$	$5.07 \pm 0.75 \pm 0.35^{+0.42}_{-0.68}$	$32 \pm 13 \pm 6^{+8}_{-5}$
$f_0(980)K^+;\ f_0(980) \to \pi^+\pi^-$	$9.47 \pm 0.97 \pm 0.46^{+0.42}_{-0.75}$	$8.8 \pm 9.5 \pm 2.6^{+9.3}_{-5.0}$
$\chi_{c0}K^+;\ \chi_{c0} \to \pi^+\pi^-$	$0.66 \pm 0.22 \pm 0.07 \pm 0.03$	–
$K^+\pi^-\pi^+$ nonresonant	$2.85 \pm 0.64 \pm 0.41^{+0.70}_{-0.34}$	–

hep-ex/0507004

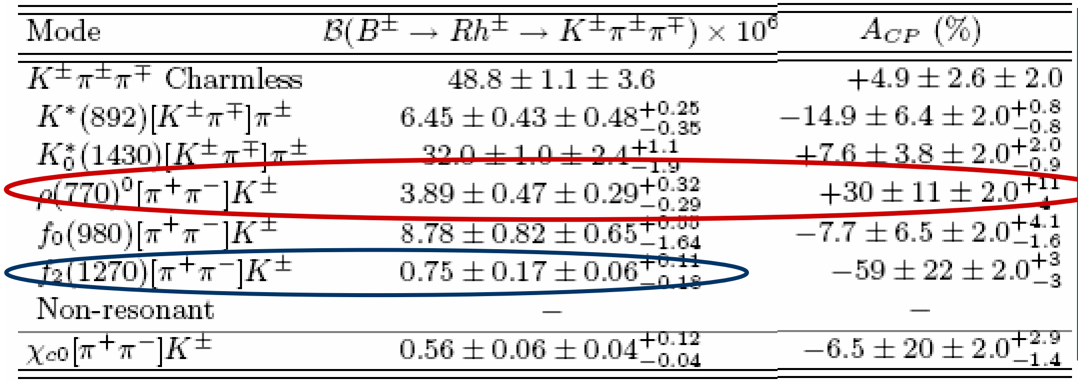
General good agreement!

Belle finds 3.9σ evidence for direct CP violation in $B^+ \to \rho K^+$ from a phase and magnitude analysis

Babar finds 2.4σ for A_{cp}

(Distinguish A_{cp} from direct CP violation)

Belle:



Mode	$\mathcal{B}(B^\pm \to Rh^\pm \to K^\pm\pi^\pm\pi^\mp) \times 10^6$	A_{CP} (%)
$K^\pm\pi^\pm\pi^\mp$ Charmless	$48.8 \pm 1.1 \pm 3.6$	$+4.9 \pm 2.6 \pm 2.0$
$K^*(892)[K^\pm\pi^\mp]\pi^\pm$	$6.45 \pm 0.43 \pm 0.48^{+0.25}_{-0.35}$	$-14.9 \pm 6.4 \pm 2.0^{+0.8}_{-0.8}$
$K^*_0(1430)[K^\pm\pi^\mp]\pi^\pm$	$32.0 \pm 1.0 \pm 2.4^{+1.1}_{-1.9}$	$+7.6 \pm 3.8 \pm 2.0^{+2.0}_{-0.9}$
$\rho(770)^0[\pi^+\pi^-]K^\pm$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$+30 \pm 11 \pm 2.0^{+11}_{-4}$
$f_0(980)[\pi^+\pi^-]K^\pm$	$8.78 \pm 0.82 \pm 0.65^{+0.55}_{-1.64}$	$-7.7 \pm 6.5 \pm 2.0^{+4.1}_{-1.6}$
$f_2(1270)[\pi^+\pi^-]K^\pm$	$0.75 \pm 0.17 \pm 0.06^{+0.11}_{-0.13}$	$-59 \pm 22 \pm 2.0^{+3}_{-3}$
Non-resonant	–	–
$\chi_{c0}[\pi^+\pi^-]K^\pm$	$0.56 \pm 0.06 \pm 0.04^{+0.12}_{-0.04}$	$-6.5 \pm 20 \pm 2.0^{+2.9}_{-1.4}$

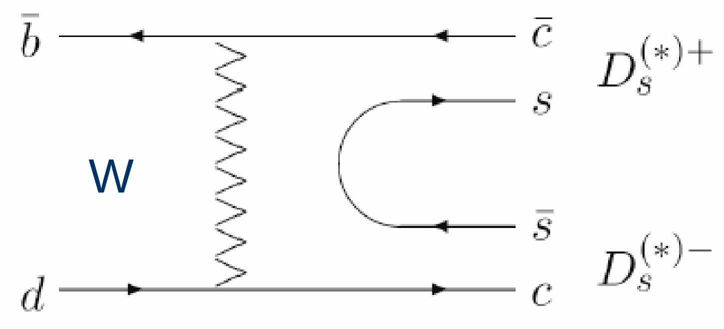
hep-ex/0512066

First observation of $B \to f_2K$

First evidence of direct CP violation in a charged B decay

$B^0 \rightarrow D^{(*)+}_s D^{(*)-}_s$

Decay proceeds via W-exchange
highly suppressed in SM



Difficult to calculate using factorisation approach as energy release only ~1 GeV

Theoretical predictions:
- perturbative QCD (pQCD) hep-ph/0308243
- estimates of non-factorisable contributions (CL-GC) hep-ph/0501031
  - chiral loops and tree level amplitudes generated by soft gluon emission forming a gluon condensate

B Decays	Branching Fraction $(\times 10^{-5})$	
	pQCD [2]	CL-GC [3]
$B^0 \rightarrow D_s^- D_s^+$	$7.8\pm^{2.0}_{1.6}$	25.0
$B^0 \rightarrow D_s^{*-} D_s^+$	$6.0\pm^{1.6}_{1.1}$	33.0
$B^0 \rightarrow D_s^{*-} D_s^{*+}$	$8.5\pm^{2.0}_{1.8}$	54.0

disfavoured

Babar (hep-ex/0510051) @ 90% C.L.

$$\mathcal{B}(B^0 \rightarrow D_s^- D_s^+) \; < \; 1.0 \times 10^{-4},$$
$$\mathcal{B}(B^0 \rightarrow D_s^{*-} D_s^+) \; < \; 1.3 \times 10^{-4},$$
$$\mathcal{B}(B^0 \rightarrow D_s^{*-} D_s^{*+}) \; < \; 2.4 \times 10^{-4}.$$

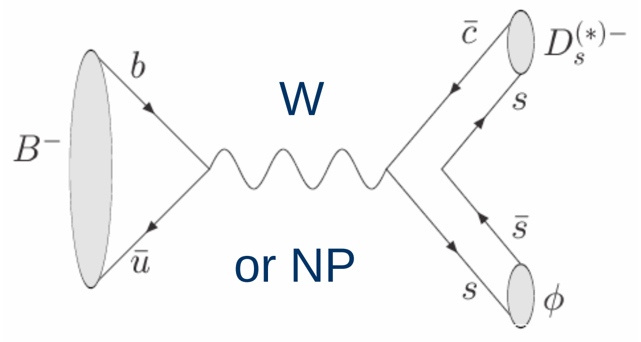
Belle (hep-ex/0508040) @ 90% C.L.
$B(B^0 \rightarrow D_s^- D_s^+) < 2.0 \times 10^{-4}$

No signal observed and no evidence of significant W-exchange component in $B^0 \rightarrow D^+ D^-$, but:

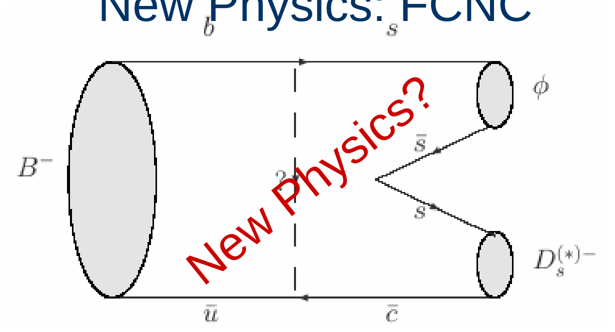
Sensitivity to test SM prediction

$B \to D_s\ \varphi$

Standard Model:

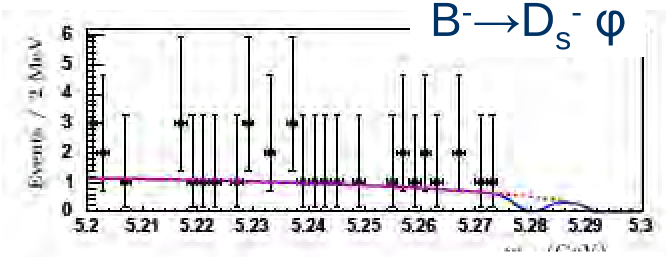


New Physics: FCNC

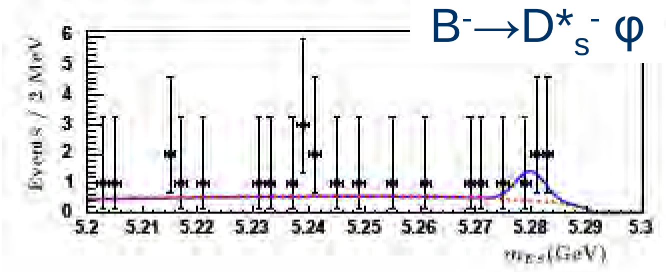


Highly suppressed in SM:
perturbative QCD: 3×10^{-7}
QCD improved factorisation 7×10^{-7}

Sensitivity to New Physics:
type II 2Higgs Doublet Model: 8×10^{-6}
MSSM with R-parity violation: 3×10^{-4}



$B^- \to D_s^-\ \varphi$



$B^- \to D^{*}{}_s^-\ \varphi$

Babar limit @ 90% C.L.
BR($B^- \to D_s^-\ \varphi$) < 1.9×10^{-6}
BR($B^- \to D^{*}{}_s^-\ \varphi$) < 1.2×10^{-5}

hep-ex/0512028

Previous CLEO limit @ 90% C.L.
BR($B^- \to D_s^-\ \varphi$) < 3×10^{-4}
BR($B^- \to D^{*}{}_s^-\ \varphi$) < 4×10^{-4}

Phys.Lett.B319: 365,1993

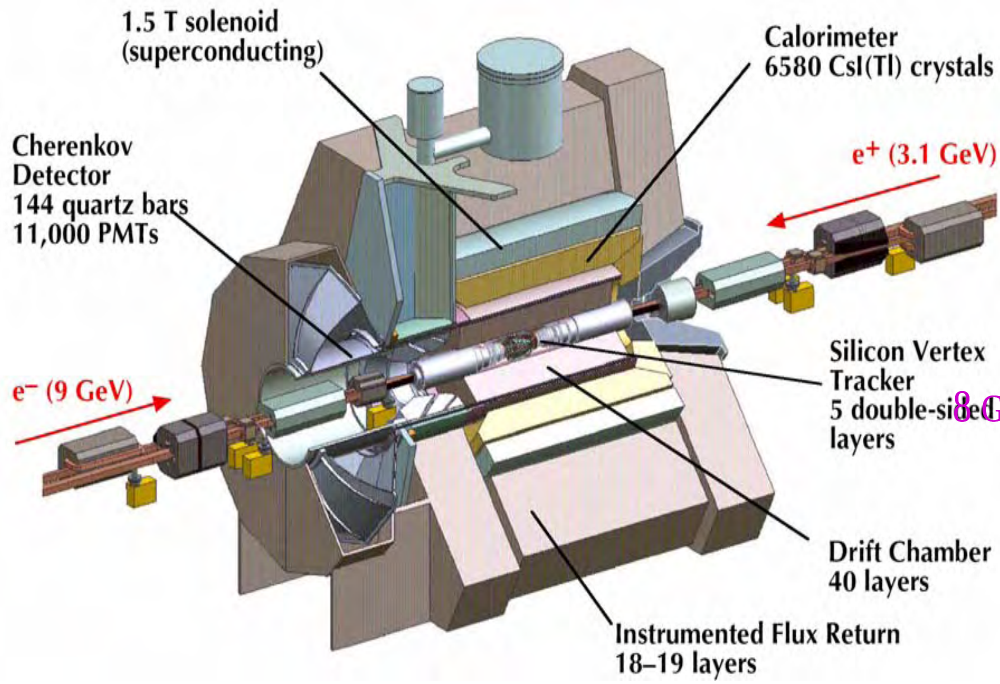
Measurement still one order of magnitude away from SM prediction but limits on NP possible.

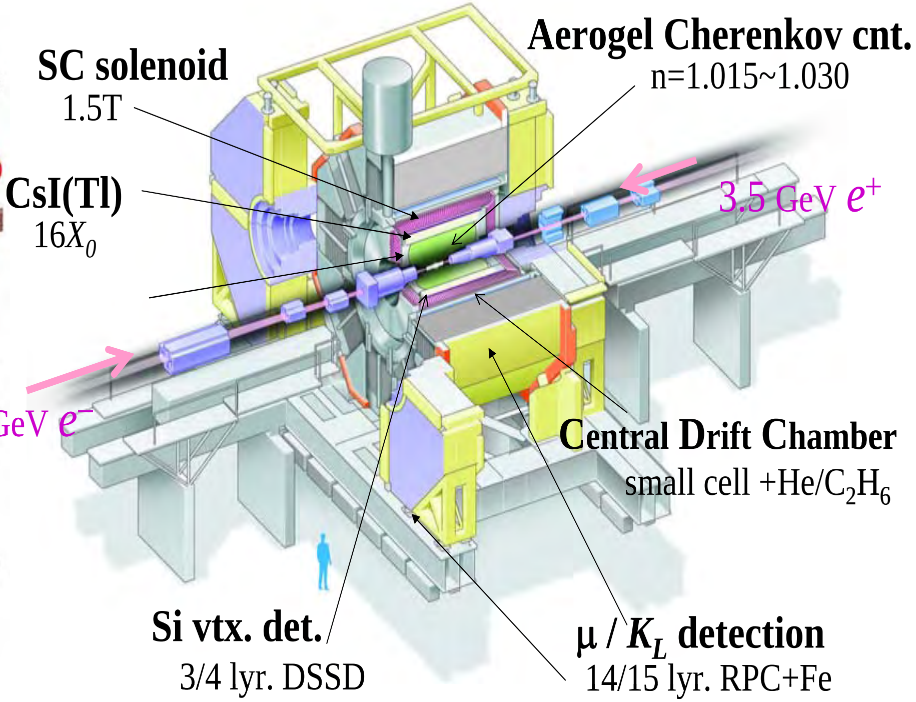
Conclusions

- Precison measurements of SM parameters from Semileptonic Decays:
  - $|V_{cb}|$ at 2% level
  - $|V_{ub}|$ at 8% 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
  - $b \rightarrow d\, \gamma$ constraining $V_{td}V_{tb}^*$ – complementary to B_s mixing
- Wide variety of charmless hadronic B decays
  - evidence for direct CPV in $B^+ \rightarrow \rho^0 K^+$
- First results from B decays via W-exchange & annihilation
  - sensitivity starting to test SM
- Many more results to come

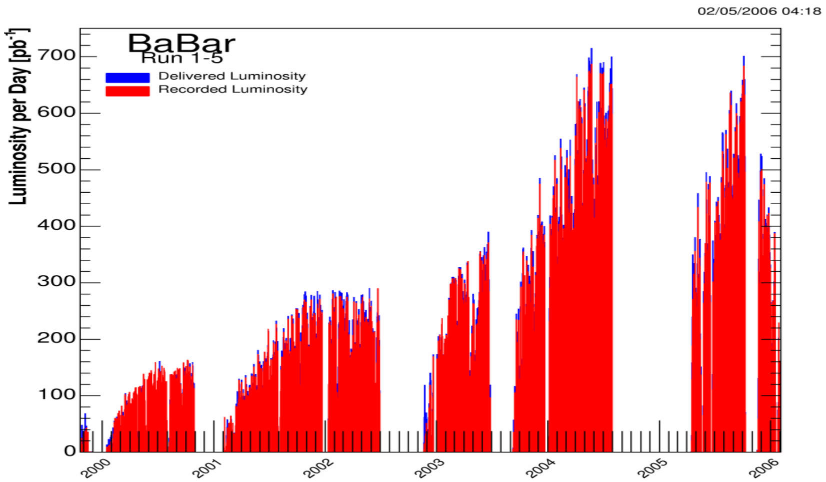
Backup Slides

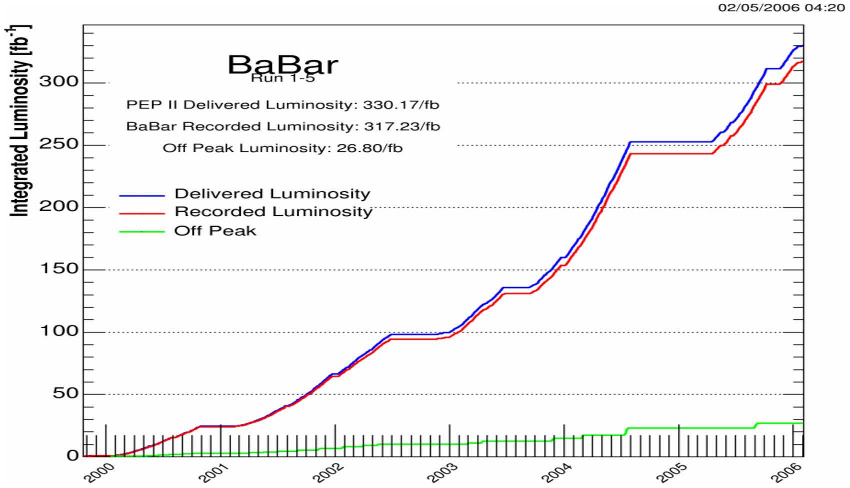
BaBar & Belle Detectors

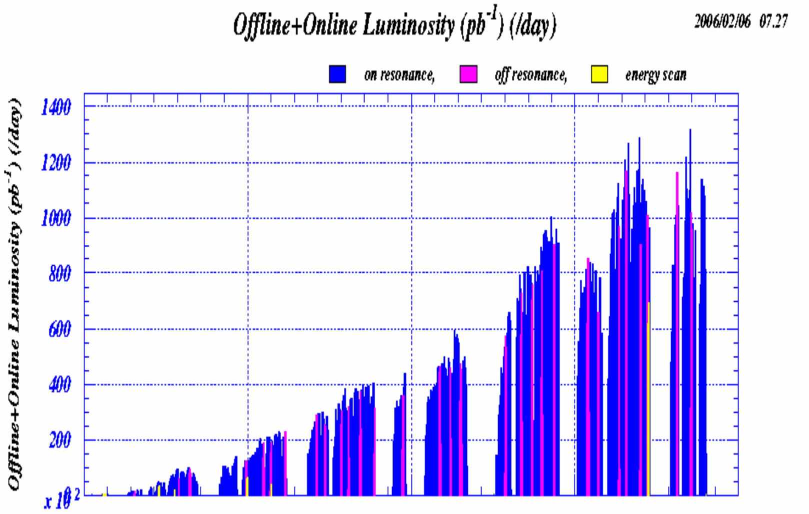


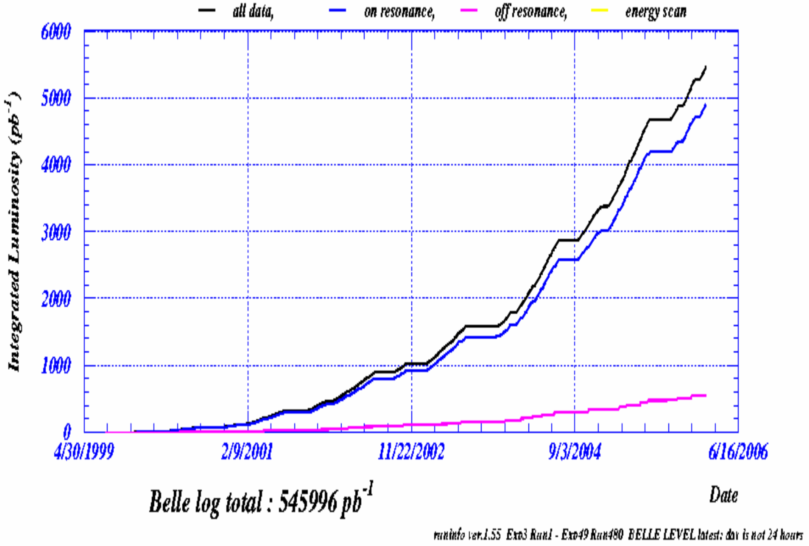


BFactory Performances









Fit to Moments of Inclusive Decay Distributions

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

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

chromomagnetic expec. value

Darwin term

spin-orbit

kinetic expec. value

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

kinetic 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:

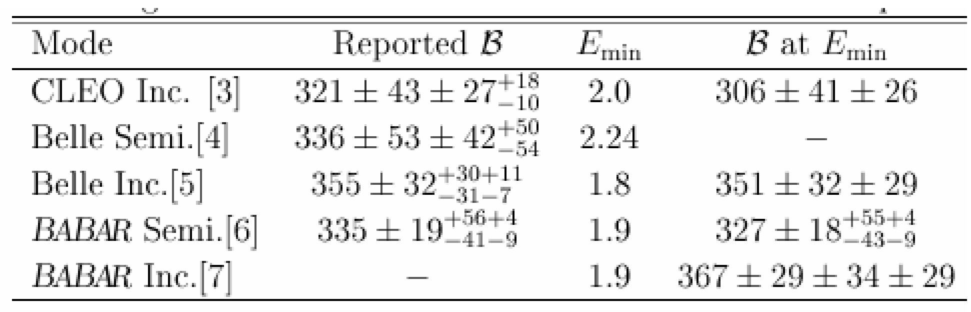
$$\begin{aligned}
\langle M_X^n\rangle &\to \langle M_X\rangle(m_b,m_c,\mu_\pi^2,\mu_G^2,\rho_D^3,\rho_{LS}^3,\alpha_s)\\
\langle E_\ell^n\rangle &\to \langle E_\ell^n\rangle(m_b,m_c,\mu_\pi^2,\mu_G^2,\rho_D^3,\rho_{LS}^3,\alpha_s)\\
\langle E_\gamma^n\rangle &\to \langle E_\gamma^n\rangle(m_b,\mu_\pi^2,\mu_G^2,\rho_D^3,\rho_{LS}^3,\alpha_s)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

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 $1/m_b^3$

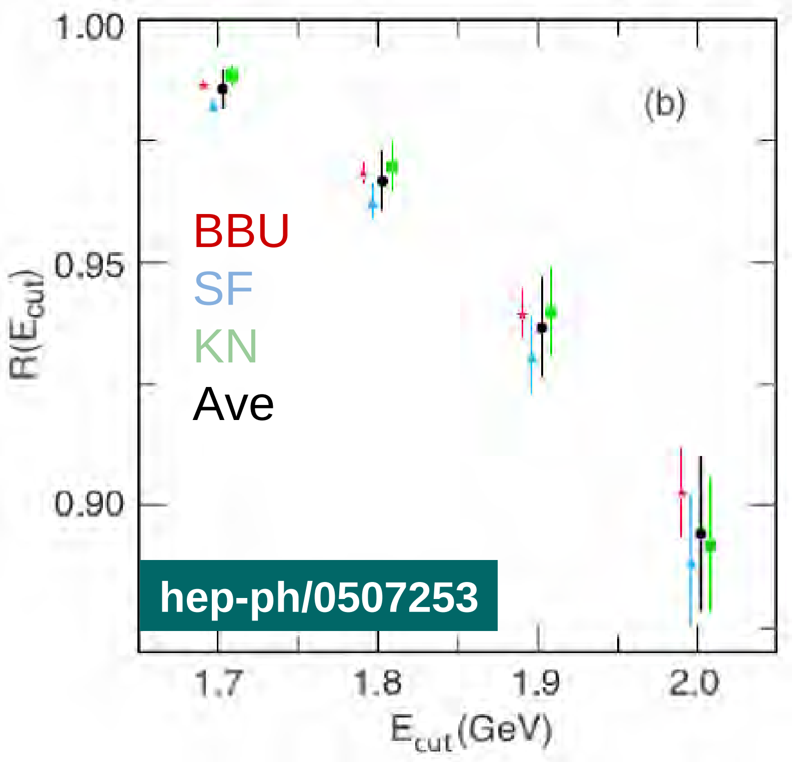
b→sγ Branching Fraction

- 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 $\mathcal{B}$	$E_{\rm min}$	$\mathcal{B}$ at $E_{\rm min}$
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



hep-ph/0507253

New HFAG Average:

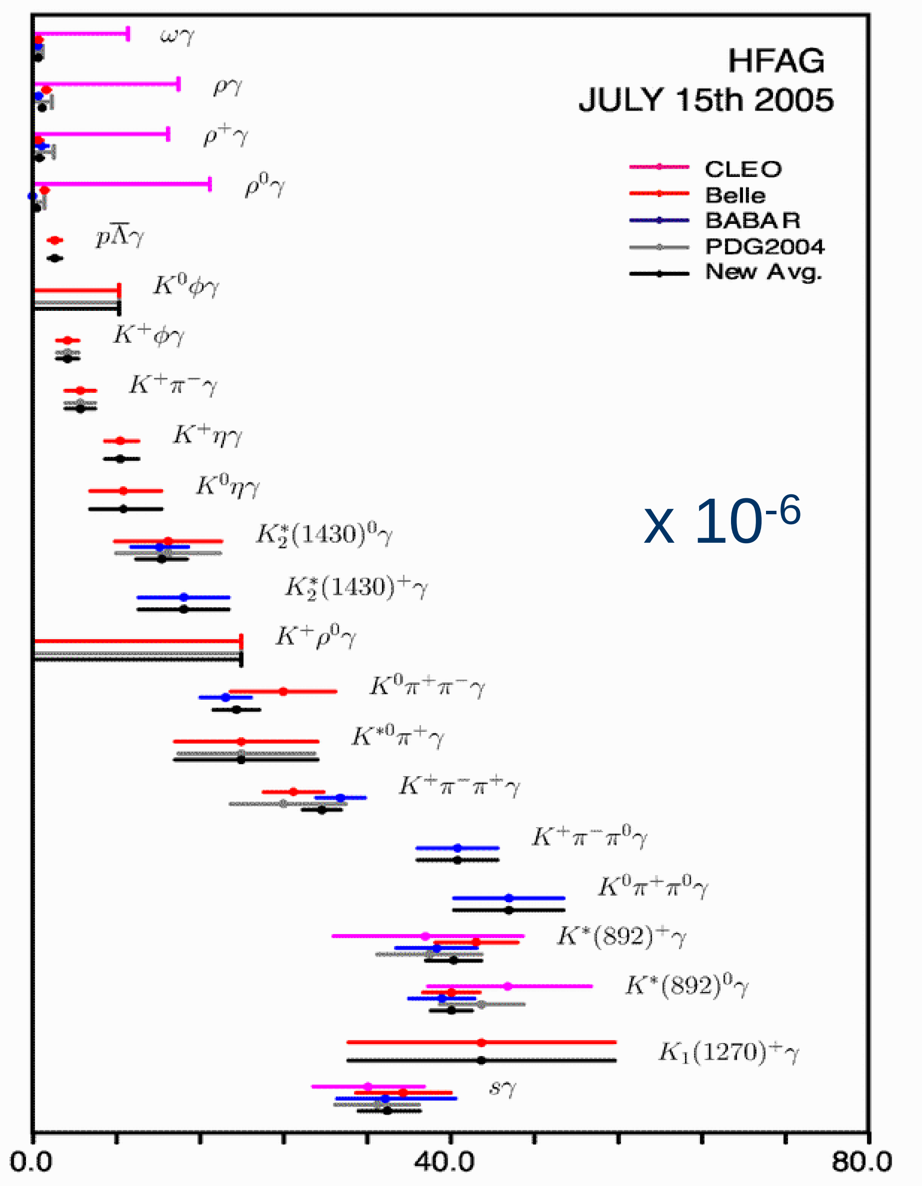
BR(B→$X_s\gamma$) =
(3.55 ± 0.24 ± 0.10 +-0.03) 10^{-4}

7% uncertainty

SM prediction:

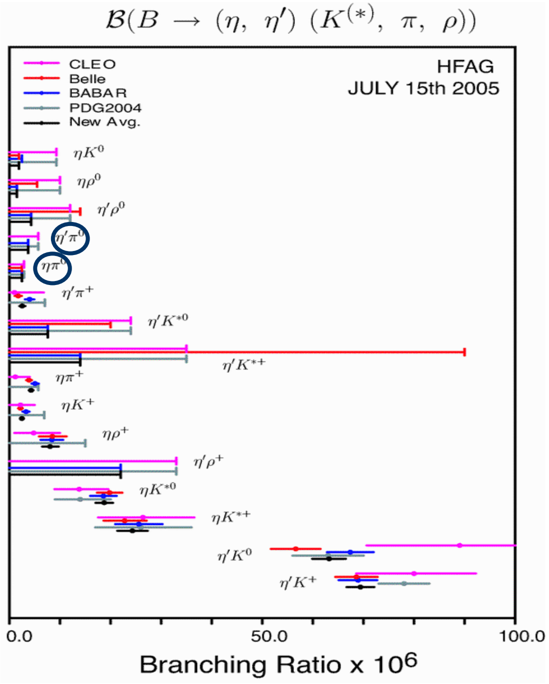
3.57 ± 0.3 x10^{-4} Buras et al. (hep-ph/0203135)
3.44 ± 0.4 x10^{-4} Neubert (hep-ph/0408179)
3.61 ± 0.42 x10^{-4} Hurth et al. (hep-ph/0312260)

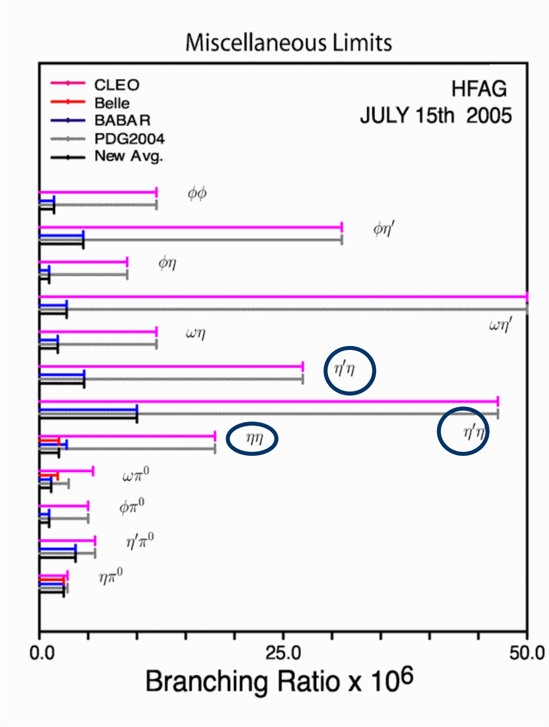
Radiative B Decays

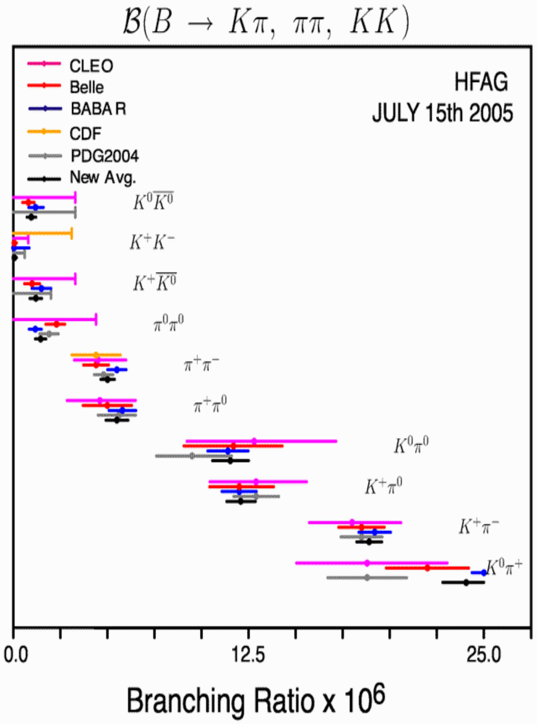


x 10^{-6}

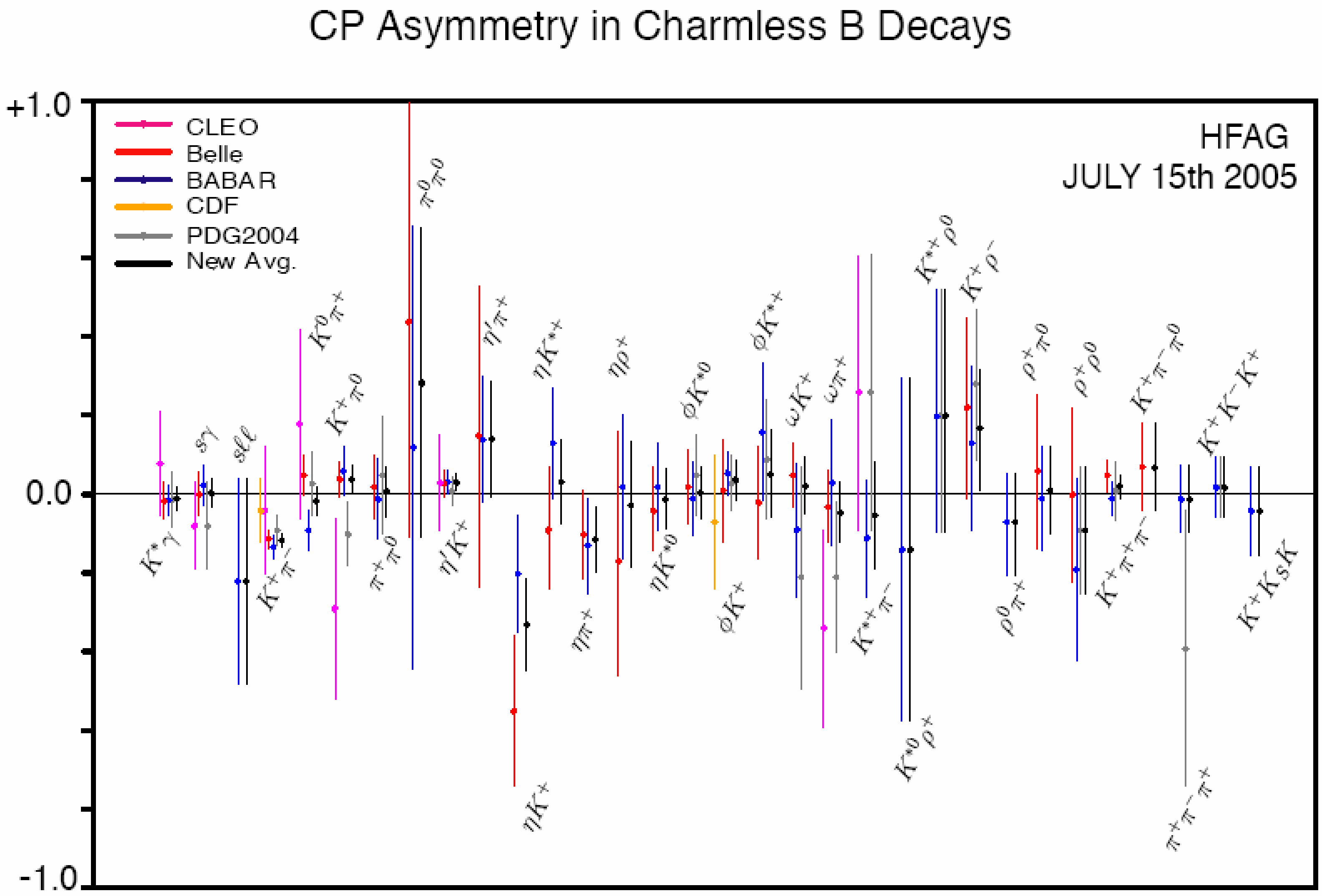
Rare charmless hadronic B decays





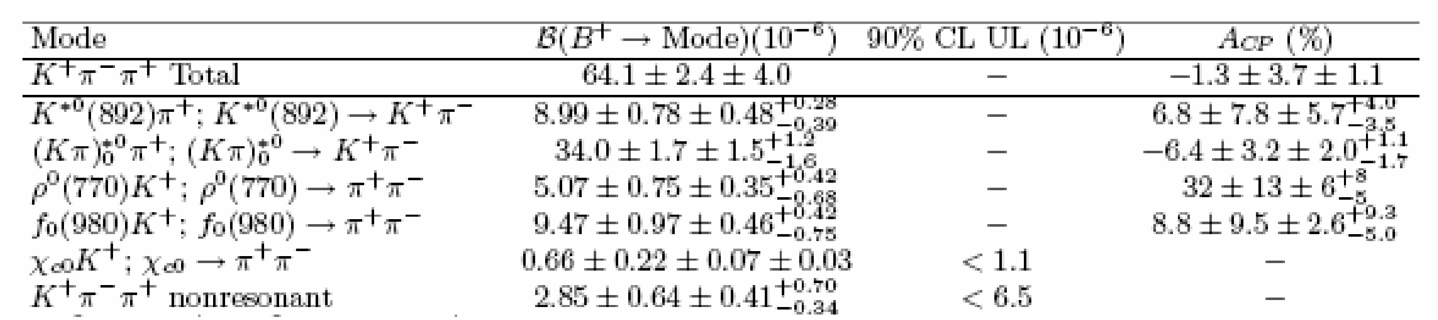


A_{cp} in Rare Charmless B Decays



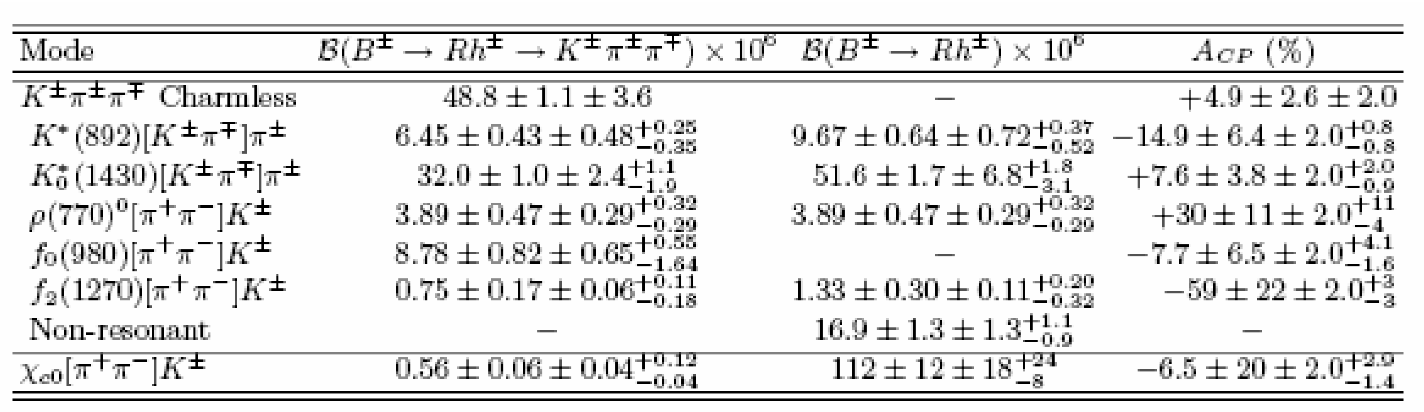
Dalitz plot analysis of $B^+ \rightarrow K^+\pi^+\pi^-$

Babar (hep-ex/0507004):



Mode	$\mathcal{B}(B^+ \rightarrow \text{Mode})(10^{-6})$	90% CL UL (10^{-6})	A_{CP} (%)
$K^+\pi^-\pi^+$ Total	$64.1 \pm 2.4 \pm 4.0$	–	$-1.3 \pm 3.7 \pm 1.1$
$K^{*0}(892)\pi^+$; $K^{*0}(892) \rightarrow K^+\pi^-$	$8.99 \pm 0.78 \pm 0.48^{+0.28}_{-0.39}$	–	$6.8 \pm 7.8 \pm 5.7^{+4.0}_{-3.5}$
$(K\pi)^{*0}_0\pi^+$; $(K\pi)^{*0}_0 \rightarrow K^+\pi^-$	$34.0 \pm 1.7 \pm 1.5^{+1.2}_{-1.6}$	–	$-6.4 \pm 3.2 \pm 2.0^{+1.1}_{-1.7}$
$\rho^0(770)K^+$; $\rho^0(770) \rightarrow \pi^+\pi^-$	$5.07 \pm 0.75 \pm 0.35^{+0.42}_{-0.68}$	–	$32 \pm 13 \pm 6^{+8}_{-5}$
$f_0(980)K^+$; $f_0(980) \rightarrow \pi^+\pi^-$	$9.47 \pm 0.97 \pm 0.46^{+0.42}_{-0.75}$	–	$8.8 \pm 9.5 \pm 2.6^{+0.3}_{-5.0}$
$\chi_{c0}K^+$; $\chi_{c0} \rightarrow \pi^+\pi^-$	$0.66 \pm 0.22 \pm 0.07 \pm 0.03$	< 1.1	–
$K^+\pi^-\pi^+$ nonresonant	$2.85 \pm 0.64 \pm 0.41^{+0.70}_{-0.34}$	< 6.5	–

Belle (hep-ex/0512066):



Mode	$\mathcal{B}(B^\pm \rightarrow Rh^\pm \rightarrow K^\pm\pi^\pm\pi^\mp) \times 10^6$	$\mathcal{B}(B^\pm \rightarrow Rh^\pm) \times 10^6$	A_{CP} (%)
$K^\pm\pi^\pm\pi^\mp$ Charmless	$48.8 \pm 1.1 \pm 3.6$	–	$+4.9 \pm 2.6 \pm 2.0$
$K^*(892)[K^\pm\pi^\mp]\pi^\pm$	$6.45 \pm 0.43 \pm 0.48^{+0.25}_{-0.35}$	$9.67 \pm 0.64 \pm 0.72^{+0.37}_{-0.52}$	$-14.9 \pm 6.4 \pm 2.0^{+0.8}_{-0.8}$
$K^*_0(1430)[K^\pm\pi^\mp]\pi^\pm$	$32.0 \pm 1.0 \pm 2.4^{+1.1}_{-1.9}$	$51.6 \pm 1.7 \pm 6.8^{+1.8}_{-3.1}$	$+7.6 \pm 3.8 \pm 2.0^{+2.0}_{-0.9}$
$\rho(770)^0[\pi^+\pi^-]K^\pm$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$3.89 \pm 0.47 \pm 0.29^{+0.32}_{-0.29}$	$+30 \pm 11 \pm 2.0^{+11}_{-4}$
$f_0(980)[\pi^+\pi^-]K^\pm$	$8.78 \pm 0.82 \pm 0.65^{+0.55}_{-1.64}$	–	$-7.7 \pm 6.5 \pm 2.0^{+4.1}_{-1.6}$
$f_2(1270)[\pi^+\pi^-]K^\pm$	$0.75 \pm 0.17 \pm 0.06^{+0.11}_{-0.18}$	$1.33 \pm 0.30 \pm 0.11^{+0.20}_{-0.32}$	$-59 \pm 22 \pm 2.0^{+3}_{-3}$
Non-resonant	–	$16.9 \pm 1.3 \pm 1.3^{+1.1}_{-0.9}$	–
$\chi_{c0}[\pi^+\pi^-]K^\pm$	$0.56 \pm 0.06 \pm 0.04^{+0.12}_{-0.04}$	$112 \pm 12 \pm 18^{+24}_{-8}$	$-6.5 \pm 20 \pm 2.0^{+2.9}_{-1.4}$

Belle parameterises $A_{cp} = -(2b \cos\varphi)/(1+b^2)$

b!=0 is condition for DCPV!
(even if A_{cp} =0)

First evidence of direct CP violation in a charged B decay