Measurement of the CKM Sides at the B-Factories

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On behalf of the BaBar and Belle Collaborations
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- CKM matrix and Unitarity Triangle
- Semileptonic B decays ($|V_{ub}|$, $|V_{cb}|$)
- Summary

CKM Matrix and Unitarity Triangle

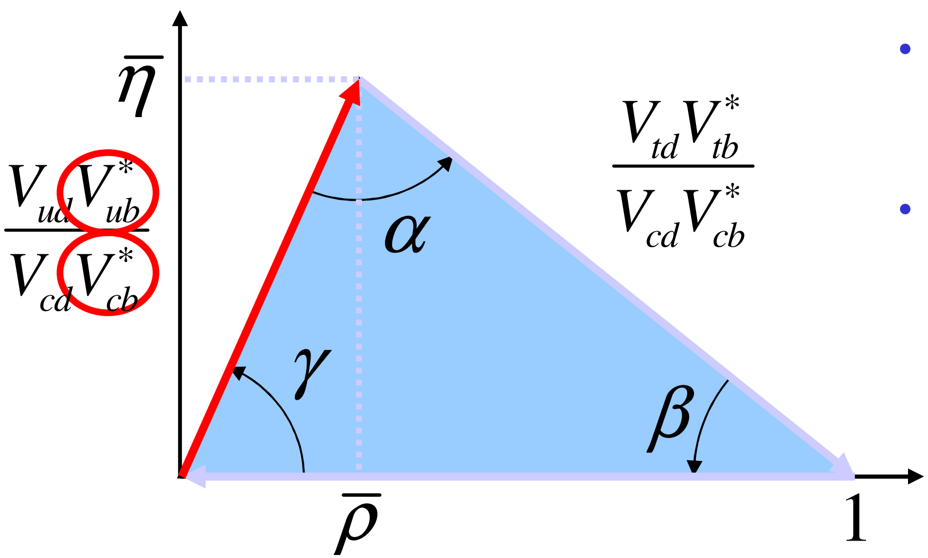
- weak and mass eigenstates of the quarks are not the same
- changes in base are described by unitarity transformations
- Cabibbo Kobayashi Maskawa (CKM) matrix

Wolfenstein parametrisation

$$\begin{pmatrix} 1-\lambda_c^2 & \lambda_c & A\lambda_c^3(\rho-i\eta) \\ -\lambda_c & 1-\lambda_c^2/2 & A\lambda_c^2 \\ A\lambda_c^3(1-\rho-i\eta) & -A\lambda_c^2 & 1 \end{pmatrix}$$

CP violation $+ O(\lambda_c^4)$ $[\lambda_c = \sin\theta_c]$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



See talk by Y. Iwasaki

- angles α, β, γ can be measured with CPV of B decays
- sides from:
  - semileptonic B decays ($|V_{cb}|$ and $|V_{ub}|$)
  - rare B decays ($|V_{ts}|$, $|V_{td}|$ and $|V_{ub}|$)

See talk by Y. Kwon

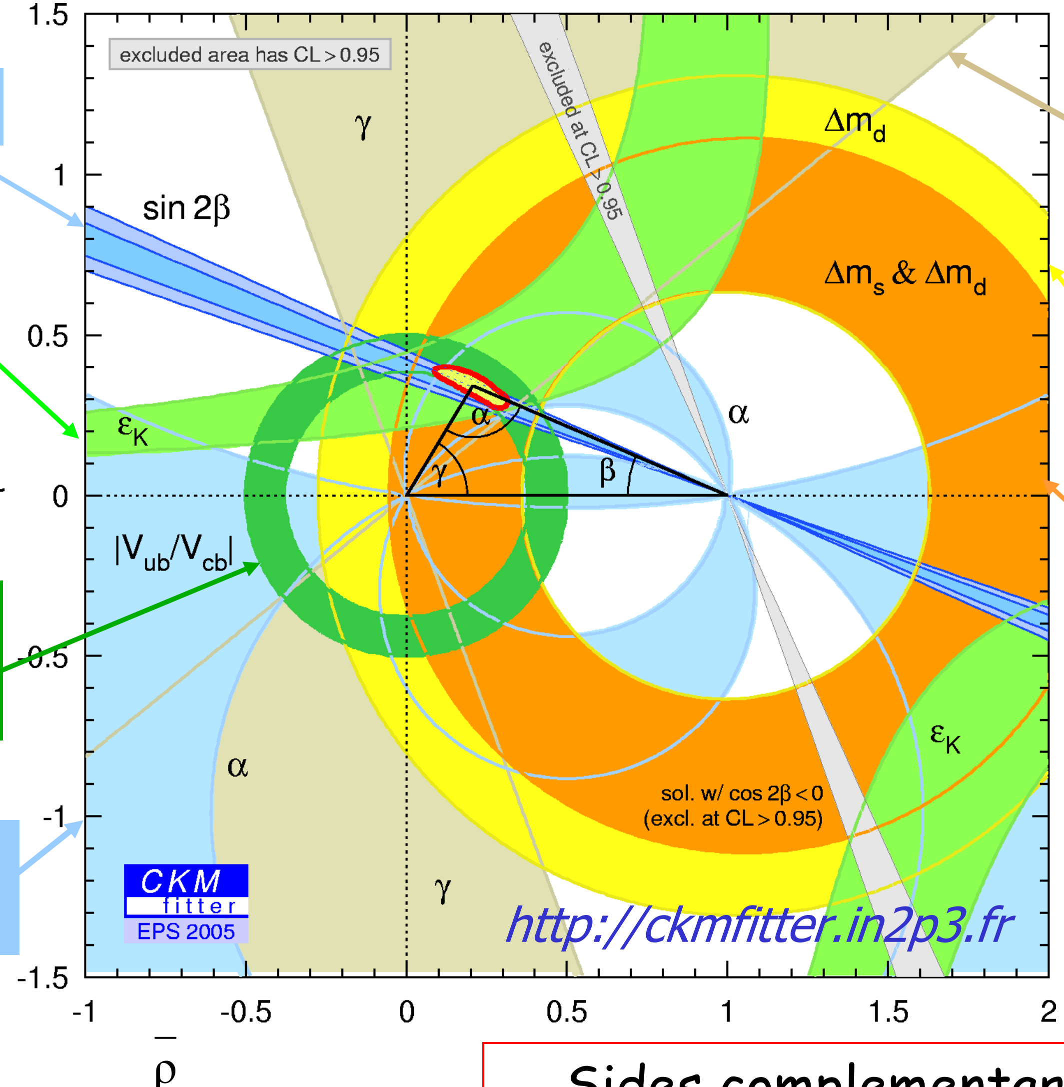
Unitarity Triangle Fits

$J/\psi K^0$: $\sin 2\beta$

kaon decays: ε_K

$b \to u l \nu$: $|V_{ub}|$
$b \to c l \nu$: $|V_{cb}|$

charmless two-body: α



interference in $B \to DK$: γ

B_d mixing: Δm_d

B_s mixing: $\Delta m_s / \Delta m_d$

Sides complementary to angles
$|V_{ub}|/|V_{cb}|$ complementary to $\sin 2\beta$

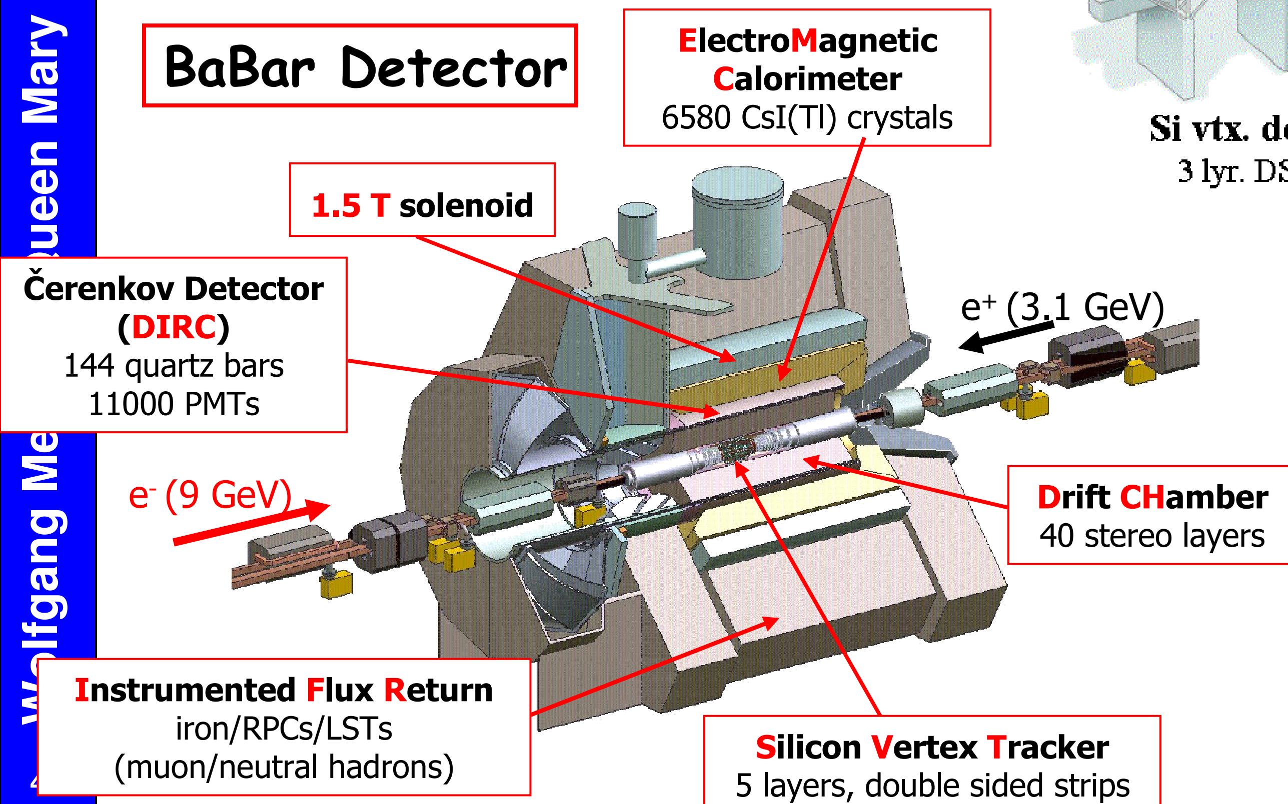
B Factories

PEPII:

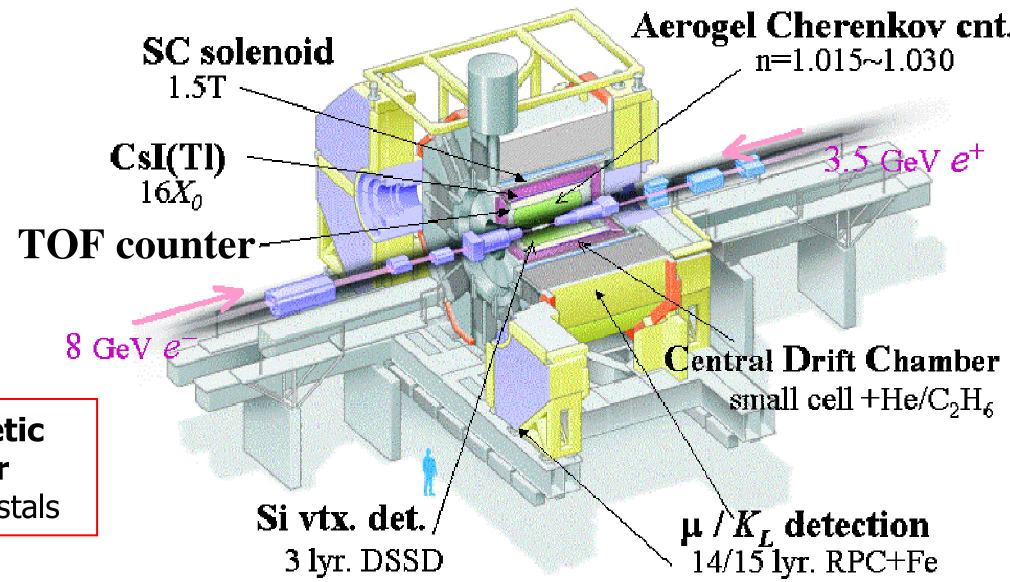
$L_{peak} \sim 10^{34} cm^{-2}s^{-1}$

$L_{int} \sim 330\ fb^{-1}$

BaBar Detector



Belle Detector

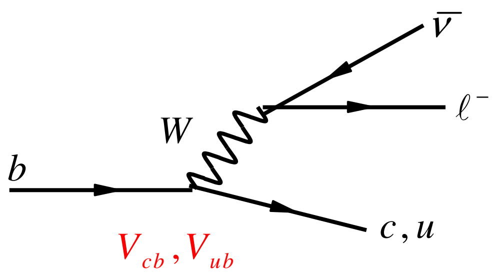


KEKB:

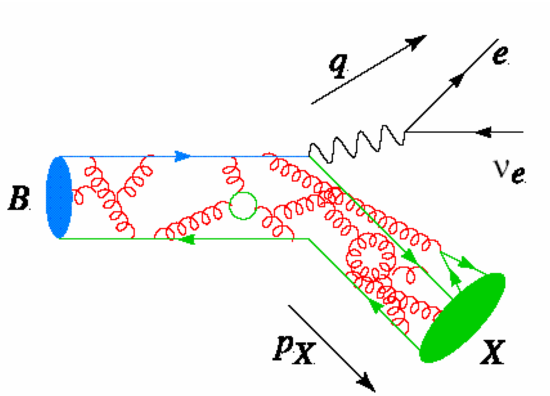
$L_{peak} \sim 1.6\ 10^{34} cm^{-2}s^{-1}$

$L_{int} \sim 560\ fb^{-1}$

Semileptonic B Decays



Semileptonic B decays allow measurement of $|V_{cb}|$ and $|V_{ub}|$ from tree level processes.

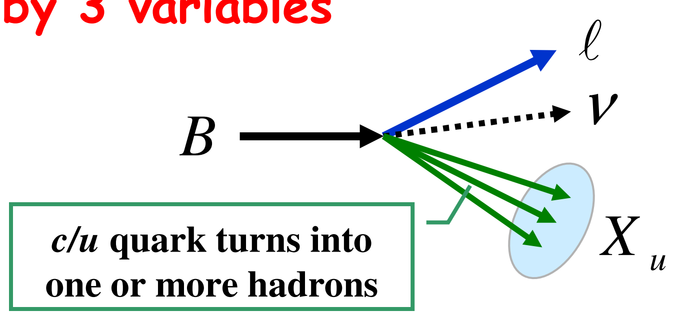


Presence of a single hadronic current allows control of theoretical uncertainties.

$b \rightarrow c l \nu$ is background to $b \rightarrow u l \nu$:

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

$B \rightarrow X l \nu$ decays are described by 3 variables



E_l = lepton energy

q^2 = lepton-neutrino mass squared

m_X = hadron system mass

$P_+ = E_X - |p_X|$

favoured by theory

$|V_{cb}|$ from $b \to cl\nu$ decays

Inclusive Decays: $|V_{cb}|$ from $b \to cl\nu$

- Operator Product Expansion (OPE): double expansion in α_s and m_b^{-1}

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

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

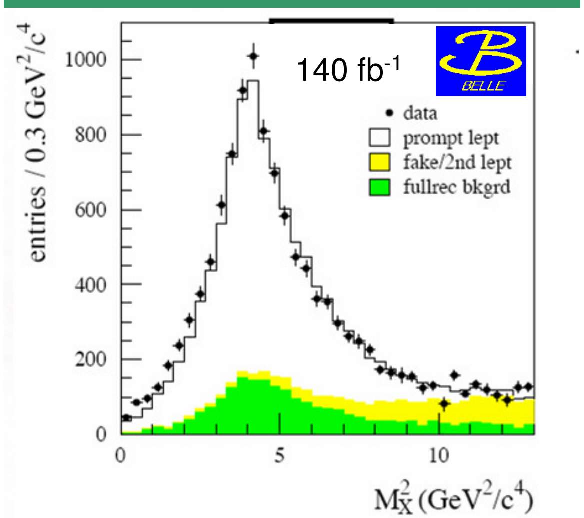
Depends on scheme, order of expansion

- Fit moments of inclusive distributions
  - lepton energy, hadron invariant mass
  - Determine OPE parameters and $|V_{cb}|$

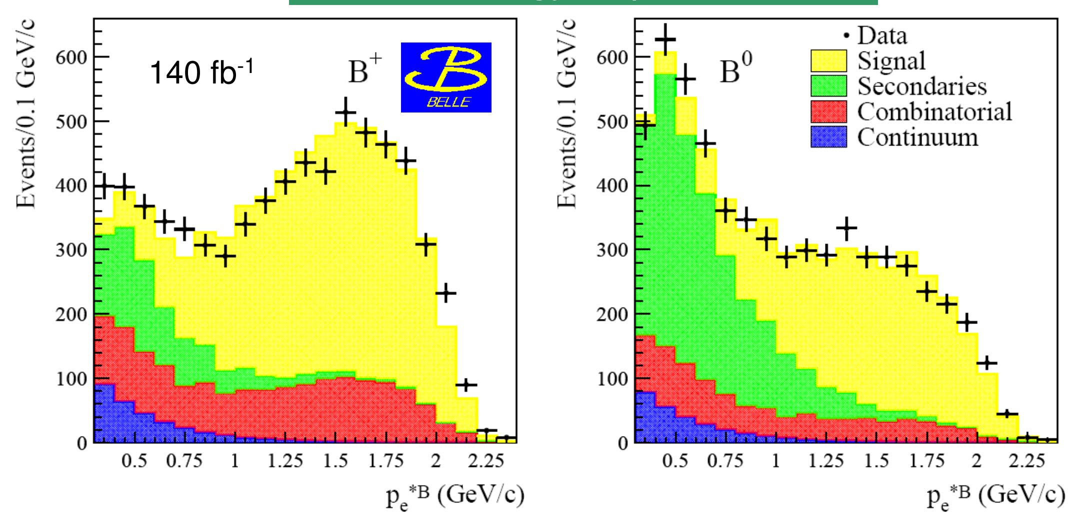
$$< X^n > (E_{cut}) = \frac{\int (X - X^0)^n \frac{d\Gamma}{dX} dX}{\int \frac{d\Gamma}{dX} dX}$$

- Measurements from B Factories, CDF, Delphi
- Recent measurements from Belle:

Hadronic mass, hep-ex/0509013



Electron energy, hep-ex/0508056



Results

Global fit in the kinetic scheme

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

Buchmüller, Flächer: hep-ph/0507253

			exp	HQE	Γ_{SL}	
	$\|V_{cb}\|$	=	(41.96 ± 0.23	± 0.35	± 0.59)	10^{-3}
	BR_{clv}	=	10.71 ± 0.10	± 0.08		%
	m_b	=	4.590 ± 0.025	± 0.030		GeV
	m_c	=	1.142 ± 0.037	± 0.045		GeV
a_i	μ_π^2	=	0.401 ± 0.019	± 0.035		GeV^2
	$\mu_G^2,\ \rho_D^3, \rho_{LS}^3$					

Based on:

Babar:
- PRD69, 111103 (2004)
- PRD69, 111104 (2004)
- PRD72, 052004 (2005)
- hep-ex/0507001

Belle:
- PRL93, 061803 (2004)
- hep-ex/0508005

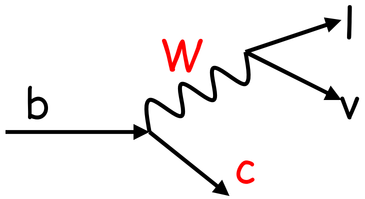
CLEO:
- PRD70, 032002 (2004)
- PRL87, 251807 (2001)

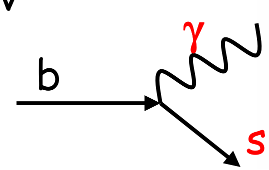
CDF: PRD71, 051103 (2005)

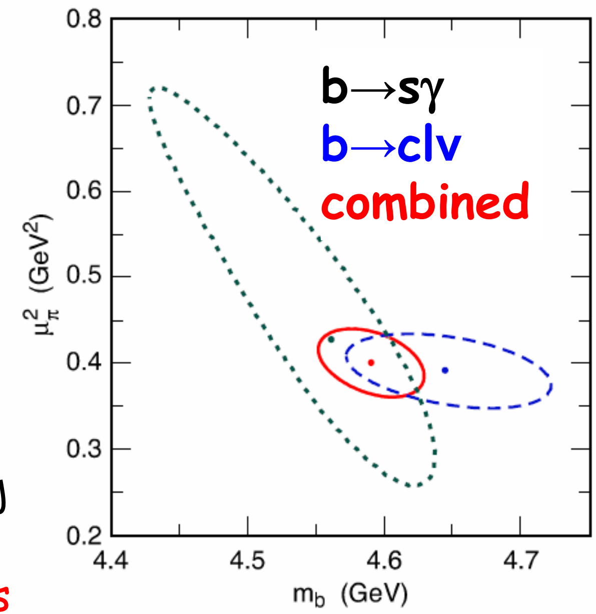
DELPHI: EPJ C45, 35 (2006)

Use inputs from BaBar, Belle, CLEO, CDF & DELPHI:

b->clν and b->sγ







Exclusive $|V_{cb}|$ and Form Factors

Reconstruct B -> $D^{*+} e \nu$ as $D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow K\pi$

BABAR hep-ex/0602023

$$\boxed{\frac{d\Gamma}{dw} \propto \mathcal{G}(w)\mathcal{F}(w)^2 |V_{cb}|^2}$$

G(w) known phase space factor
F(w) Form Factor (FF)
w = D* boost in B rest frame

- F(1)=1 in heavy quark limit; lattice QCD says: F(1) = $0.919^{+0.030}_{-0.035}$
- Shape of F(w) unknown

Hashimoto et al, PRD 66 (2002) 014503

- Parametrized with ρ^2 (slope at w = 1) and form factor ratios

  R_1, R_2 ~ independent on w

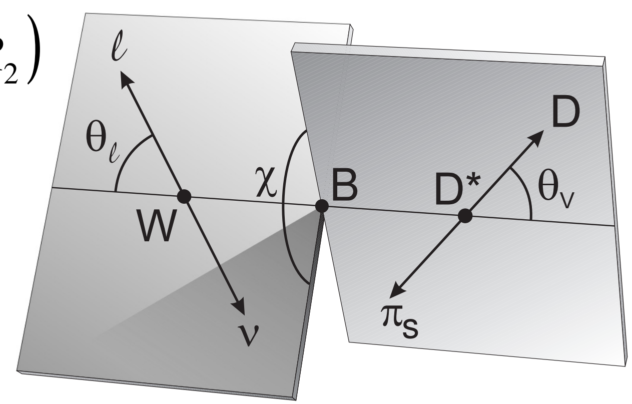
  h_{A1} expansion a-la Caprini-Lellouch-Neubert

Nucl. Phys. B 530, 153 (1998)

$$\frac{d\Gamma(B \rightarrow D^* \ell \nu)}{dq^2 d\cos\theta_\ell d\cos\theta_V d\chi} = |V_{cb}|^2 f(q^2, \theta_\ell, \theta_V, \chi, \rho^2, R_1, R_2)$$

-> measure form factors from multi-dimensional fit to diff rate

-> measure $|V_{cb}|$ with



Wolfgang Menges, Queen Mary

$B \to D^* l \nu$ Form Factors and $|V_{cb}|$

	stat	sys	theo
$R_1 = 1.396$	$\pm\, 0.060$	$\pm\, 0.035$	$\pm\, 0.027$
$R_2 = 0.885$	$\pm\, 0.040$	$\pm\, 0.022$	$\pm\, 0.013$
$\rho^2 = 1.145$	$\pm\, 0.059$	$\pm\, 0.030$	$\pm\, 0.035$

Factor 5 improvement of FF uncertainty from previous CLEO measurement (1996).

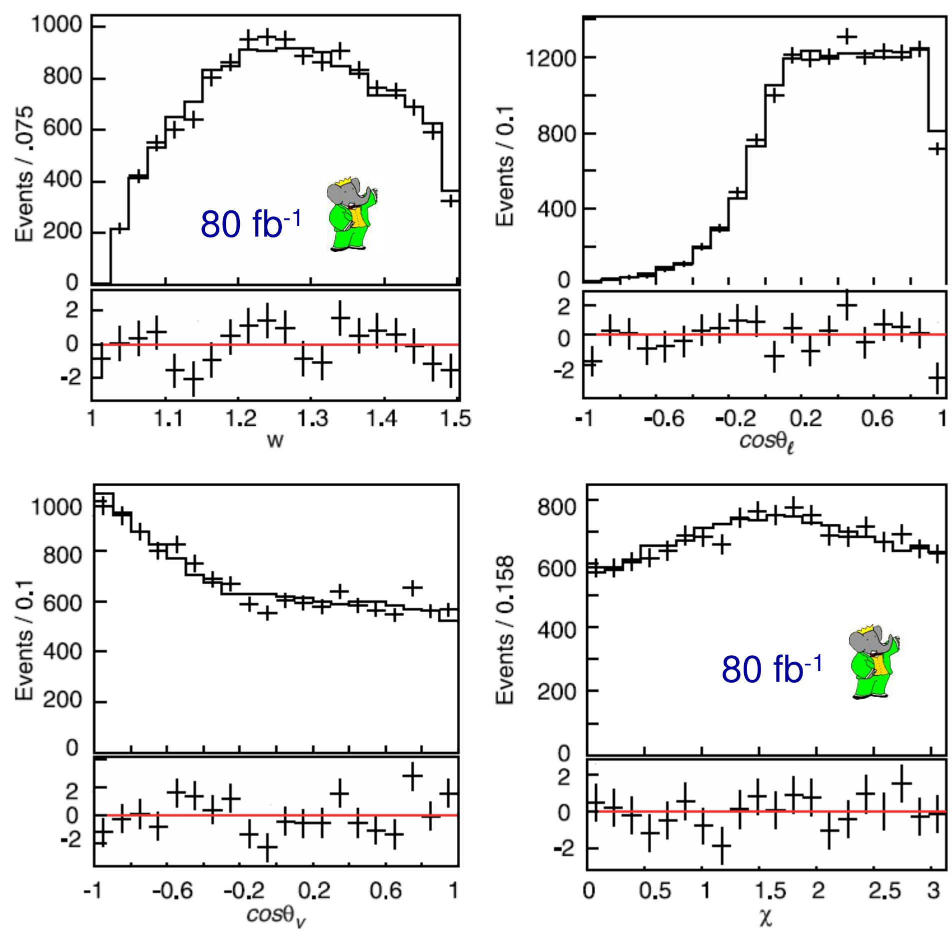
Using latest form factors with previous BaBar analysis: PRD71, 051502(2005)

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

Reducing FF error: 2.8% -> 0.5%
Total sys error: 4.5% -> 3.5%

1D projections of fit result

hep-ex/0602023



Summary of $|V_{cb}|$ Results

The new BaBar form factors are not included.
Work is going on.

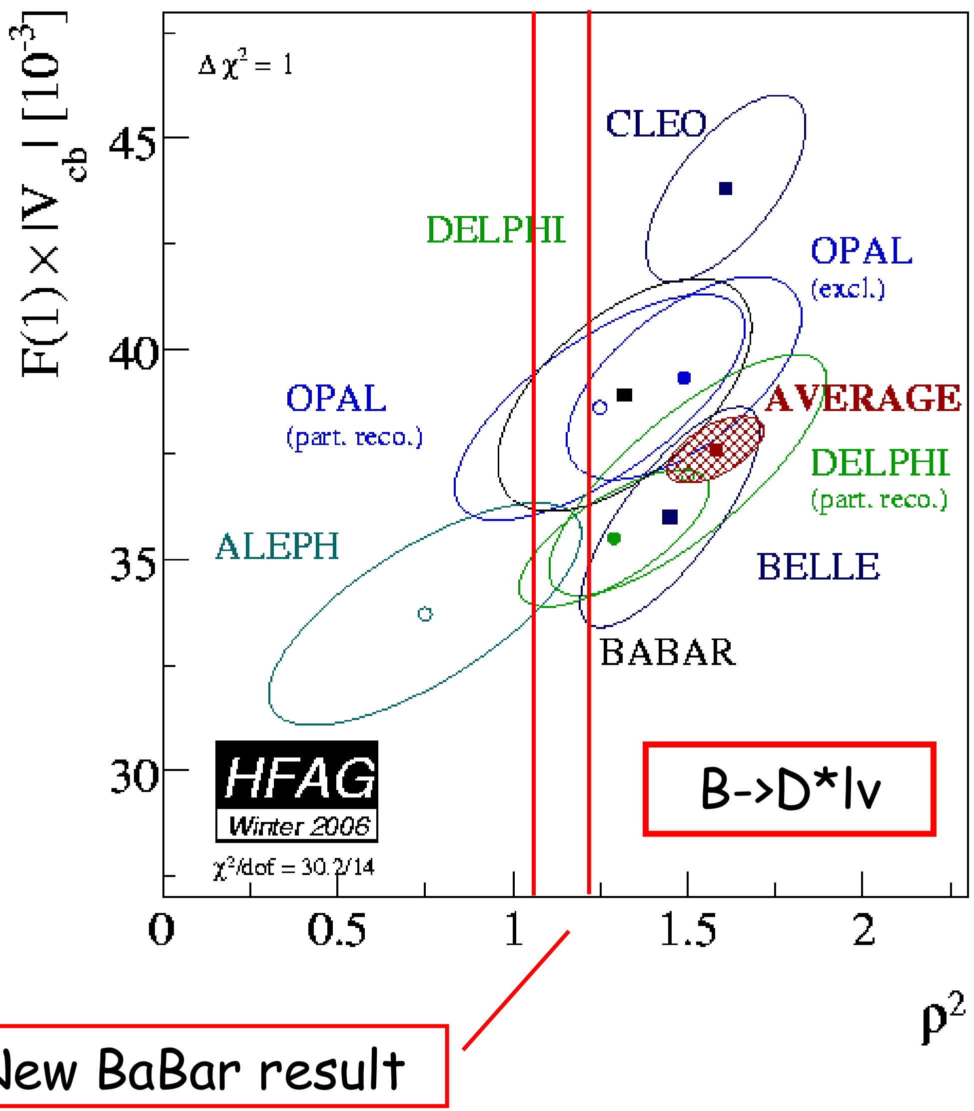
$|V_{cb}|[\times 10^{-3}]$ from B->D*lv:

$40.9 \pm 1.0_{exp}{}^{+1.1}_{-1.3}{}_{F(1)}$

$|V_{cb}|[\times 10^{-3}]$ from b->clv:

$42.0 \pm 0.2_{exp} \pm 0.4_{HQE} \pm 0.6_{\Gamma}$

➔ good agreement!



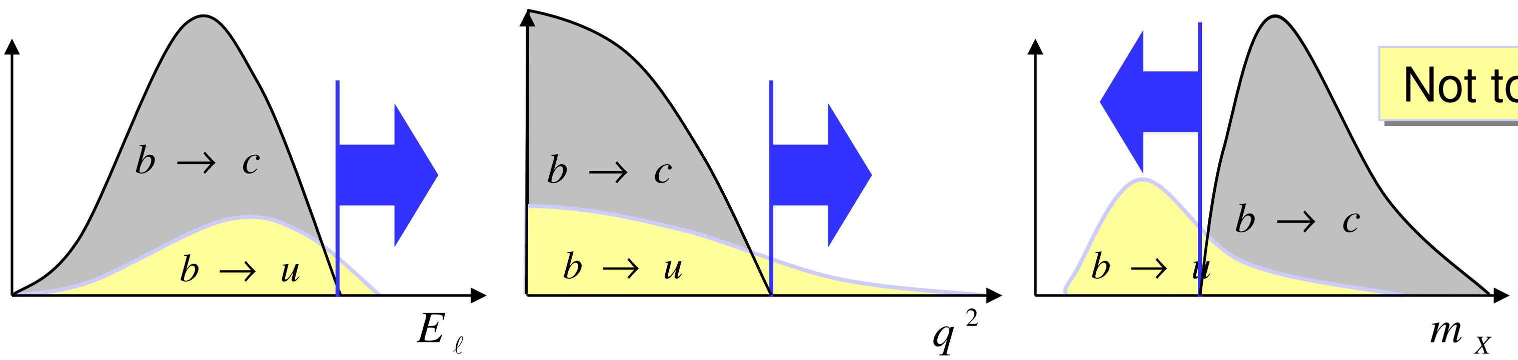
$|V_{ub}|$ from $b \to ul\nu$ decays

Inclusive b → ulν : Strategies

Use kinematic cuts to separate b→ulν from b→clν decays:

Experimental resolution not included!

Not to scale!



- smaller acceptance -> theory error increase
  - OPE breaks down
  - shape function to resum non-pert. corrections
- measure partial branching fraction ΔB
- get predicted partial rate Δζ from theory

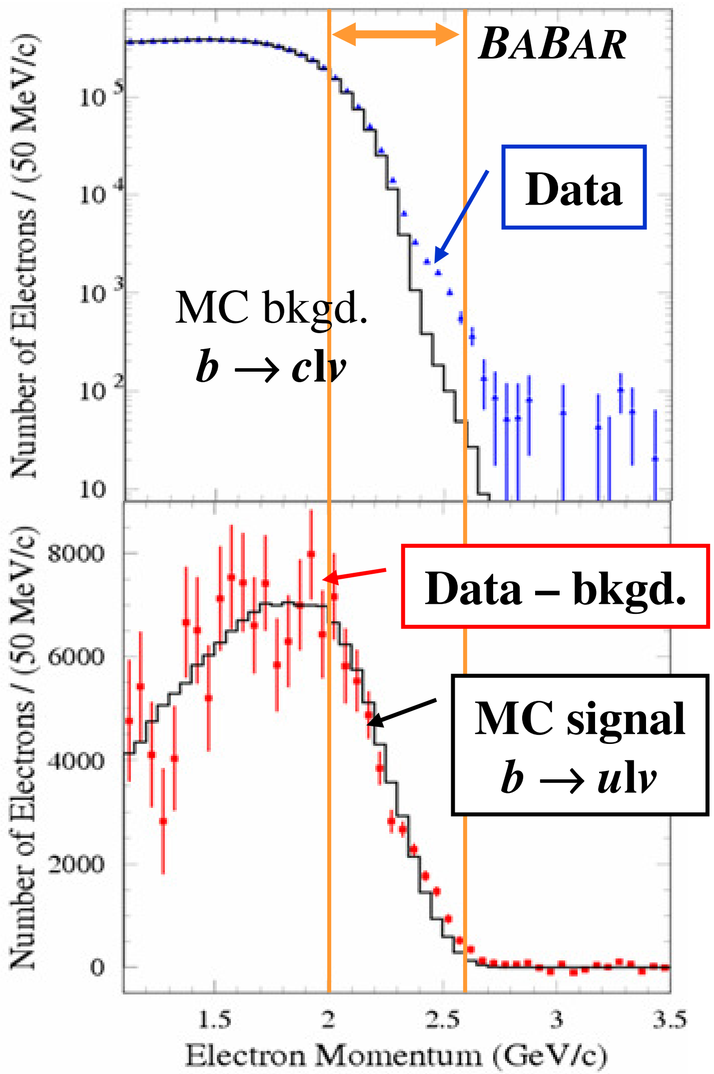
$$|V_{ub}| = \sqrt{\frac{\Delta B(B \to X_u \ell \nu)}{\Delta \zeta \cdot \tau_B}}$$

Lepton Endpoint

BABAR PRD73, 012006 (2006)

Select electrons with 2.0(1.9) < E_l < 2.6 GeV

- Push below the charm threshold
  - ➔ Larger signal acceptance
  - ➔ Smaller theoretical error
- Accurate subtraction of background is crucial!
  - off-resonance data
  - events with p_e > 2.8 GeV
  - fit b->clv composition in bkg subtraction
- Measure the partial BF



$|V_{ub}|$ $[10^{-3}]$:

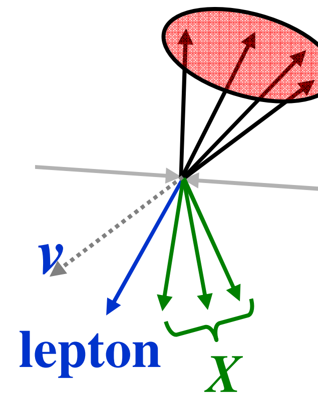
BaBar: L = 80 fb^{-1}, E_l = 2.0-2.6 GeV

$4.44 \pm 0.25_{exp}\ ^{+0.42}_{-0.38}{}_{SF} \pm 0.22_{theo}$

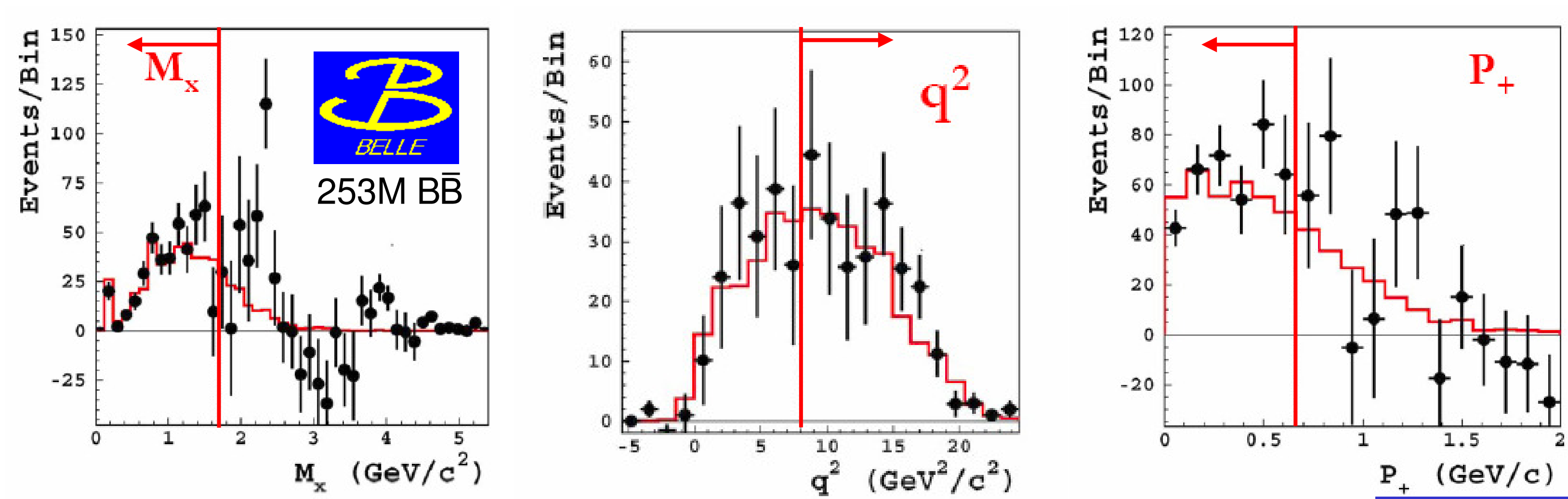
Belle: L = 27 fb^{-1}, E_l = 1.9-2.6 GeV

$5.08 \pm 0.47_{stat} \pm 0.42_{SF}\ ^{+0.26}_{-0.23}{}_{theo}$

Hadronic B Tag



- fully reconstruct one B in hadronic decay mode
- study the recoiling B -> known momentum and flavour
- access to all kinematic variables (m_X, q^2, P_+)



error[%]

253M $B\bar{B}$

hep-ex/0505088

m_X<1.7GeV, q^2>8GeV

$$|V_{ub}| = (4.70 \pm 0.24_{stat} \pm 0.28_{syst} \pm 0.20_{SF}\ {}^{+0.23}_{-0.24}{}_{theo}) \times 10^{-3} \quad 10\%$$

m_X<1.7GeV

$$|V_{ub}| = (4.09 \pm 0.19_{stat} \pm 0.20_{syst} \pm 0.18_{SF}\ {}^{+0.14}_{-0.16}{}_{theo}) \times 10^{-3} \quad 9\%$$

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

$$|V_{ub}| = (4.19 \pm 0.20_{stat} \pm 0.30_{syst} \pm 0.24_{SF}\ {}^{+0.14}_{-0.15}{}_{theo}) \times 10^{-3} \quad 11\%$$

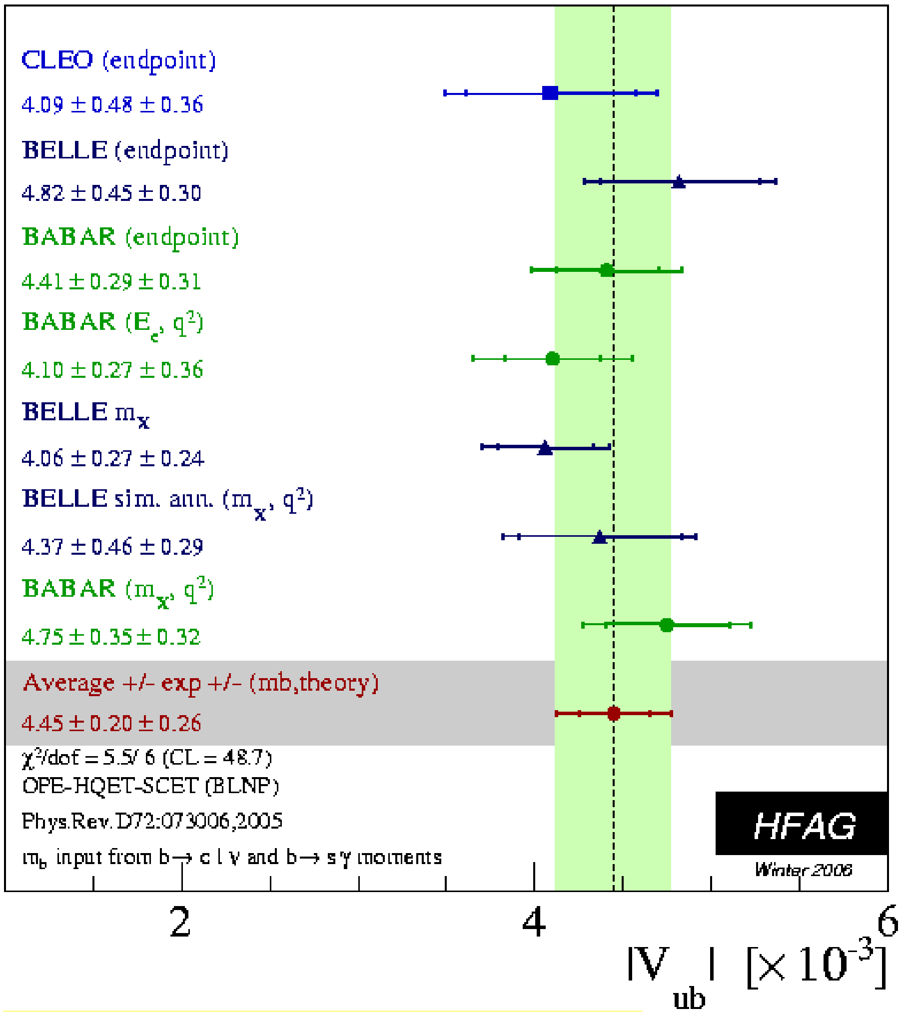
210M $B\bar{B}$

m_X<1.7GeV, q^2>8GeV

hep-ex/0507017

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

Status of Inclusive $|V_{ub}|$



Numbers rescaled by HFAG.
SF parameters from hep-ex/0507243,
predicted partial rates from BLNP

$|V_{ub}|$ world average winter 2006

$|V_{ub}|$ determined to ±7.4%

Experimental Error	±4.5%
SF parameters (m_b,μ_π^2)	±4.1%
Theory Error	±4.2%

$|V_{ub}|$ [x10^{-3}]:

BLNP: Shape Function
PRD72:073006(2005)
$4.45 \pm 0.20_{exp} \pm 0.18_{SF} \pm 0.19_{theo}$

Andersen-Gardi: DGE NEW!
JHEP0601:097(2006)
$4.41 \pm 0.20_{exp} \pm 0.20_{theo}$

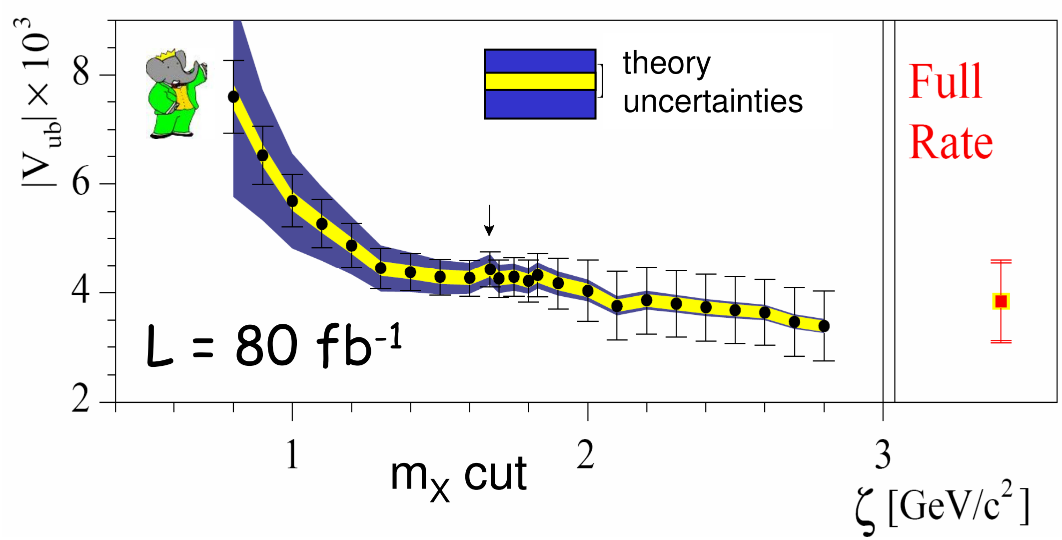
Reducing Model Dependence

- relate charmless SL rate to b→sγ spectrum

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

Weight function

- reduced dependence from shape function



hep-ex/0601046

following

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

Acceptance:

LLR : $M_X < 1.67$ GeV: $|V_{ub}| = (4.43 \pm 0.38_{stat} \pm 0.25_{syst} \pm 0.29_{theo})\ 10^{-3}$ 72%

OPE: $M_X < 2.50$ GeV: $|V_{ub}| = (3.84 \pm 0.70_{stat} \pm 0.30_{syst} \pm 0.10_{theo})\ 10^{-3}$ 98%

Exclusive b → ulν

- measure specific final states, e.g., B → πlν
  - can achieve good signal-to-background ratio
  - branching fractions are $O(10^{-4})$ → statistics limited

- need form factors to extract $|V_{ub}|$

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

One FF for B → πlν (massless lepton)

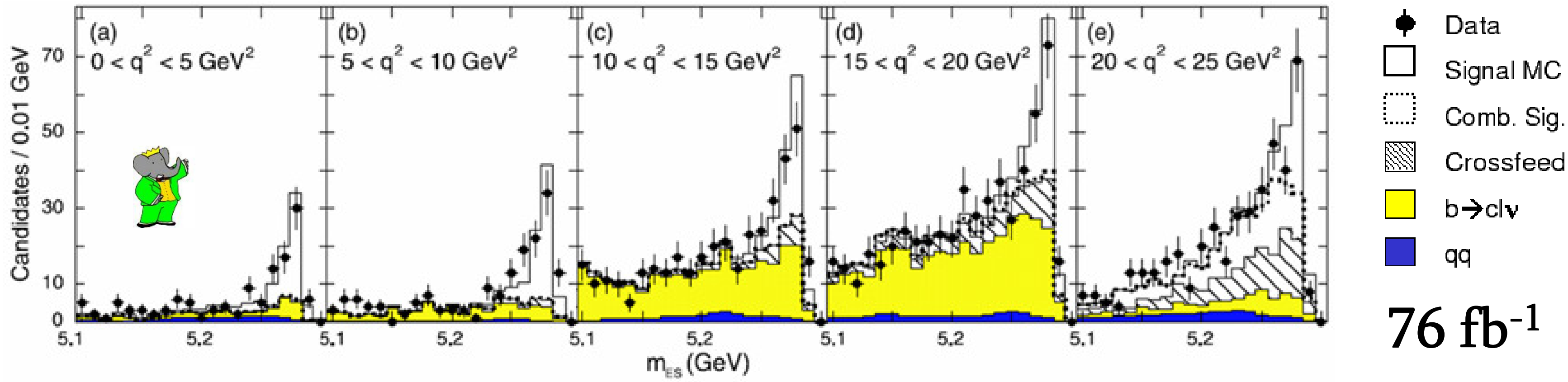
Need to measure q^2

  - theo. uncertainties complementary to inclusive approach!

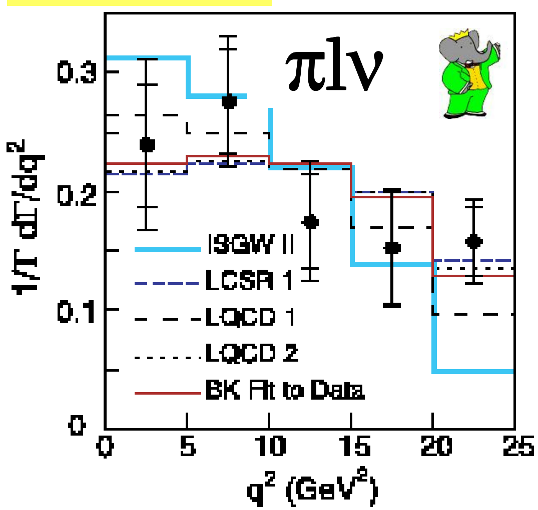
- $f_+(q^2)$ calculations exist based on:
  - Lattice QCD (q^2 > 15 GeV²) → 11% uncertainty
    hep-lat/0409116, PRD73, 074502(2006)
  - Light Cone Sum Rules (q^2 < 14 GeV²) → 10% uncertainty
    PRD71, 014015(2005), PRD71, 014029(2005)
  - Quark models (ISGW2) … and other approaches
    PRD52, 2783(1995)

q^2 Distributions and FF Calculations

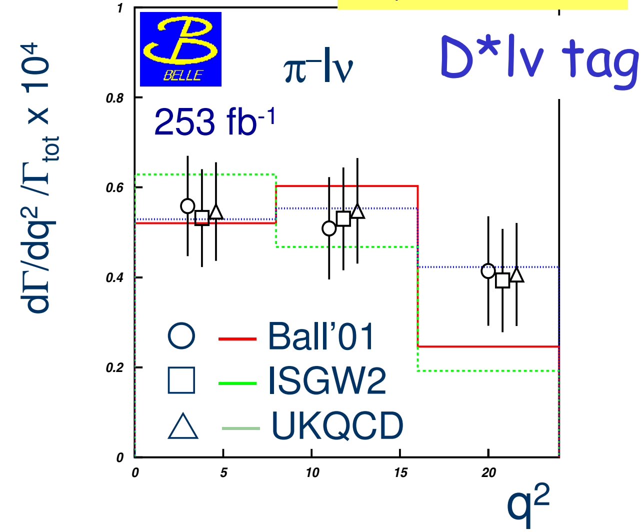
- select B -> $\pi l \nu$ and $\rho l \nu$ without reconstructing other B
  - well-identified high energetic lepton, $\pi^\pm$, $\pi^0(\gamma\gamma)$, $\rho^0(\pi^+\pi^-)$, $\rho^\pm(\pi^\pm\pi^0)$
  - missing momentum and energy in event → reconstruct neutrino



PRD 72:051102

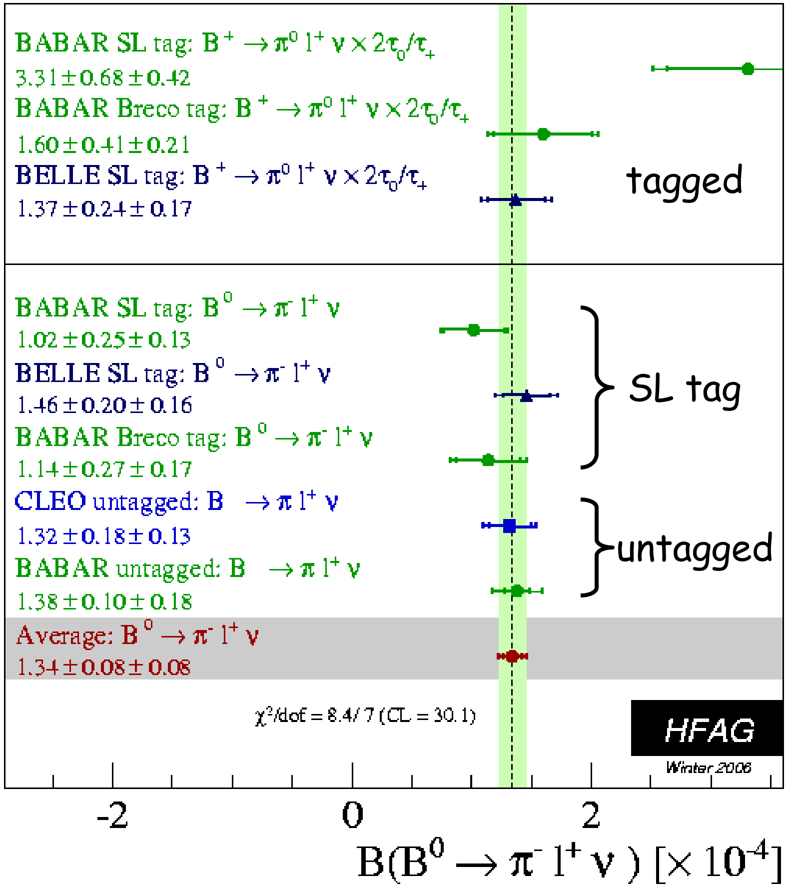


hep-ex/0508018

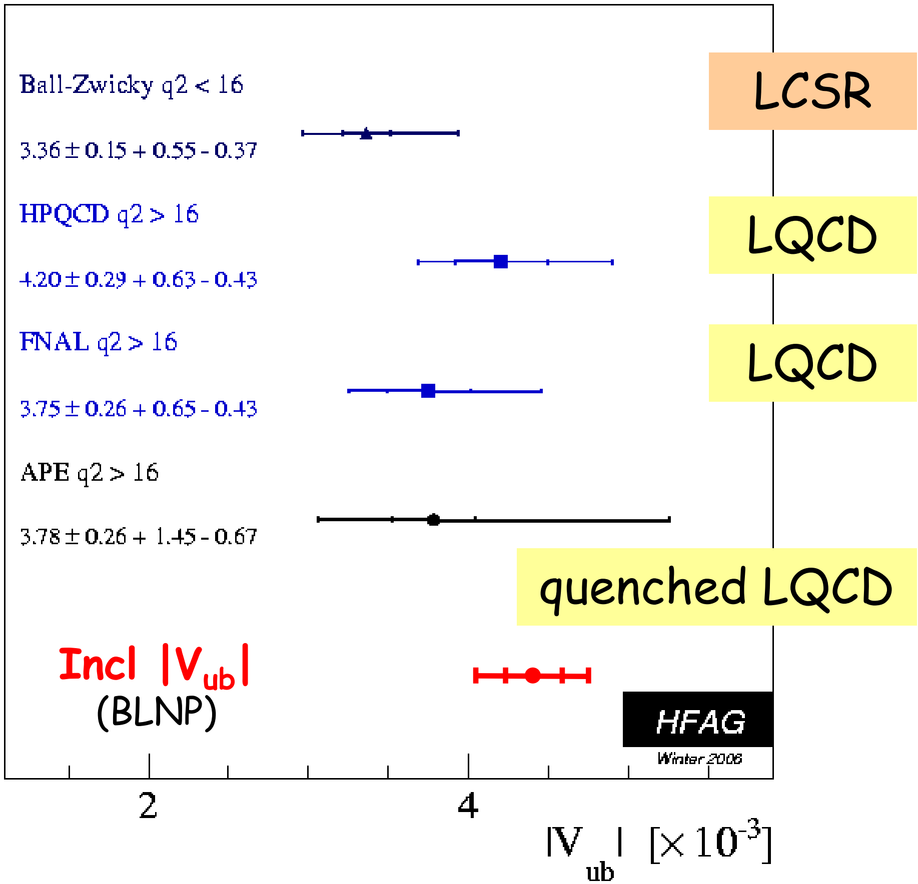


- recent LQCD and LCSR calculations agree well with data
- ISGW II shows marginal agreement
- $\rho l \nu$ also measured, exp. error still large

Status of Exclusive $|V_{ub}|$



Use BF and FF predictions to calculate $|V_{ub}|$.



Good agreement!

FF calculations dominate error on $|V_{ub}|$!

Summary

The Unitarity Triangle

- $|V_{cb}|$ determined with high precision (2%) → Now $|V_{ub}|$ is important!
- Precise determination of $|V_{ub}|$ complements sin2β to test the validity of the Standard Model

- Close collaboration between theory and experiment is important

  Inclusive $|V_{ub}|$:
  - 7.4% accuracy achieved so far → 5% possible?
  - much experimental and theoretical progress in the last 2 years

  Exclusive $|V_{ub}|$:
  - Significant exp. progress in the last year
  - FF calculations need to improve

- Important to cross-check inclusive vs. exclusive results

The Unitarity Triangle

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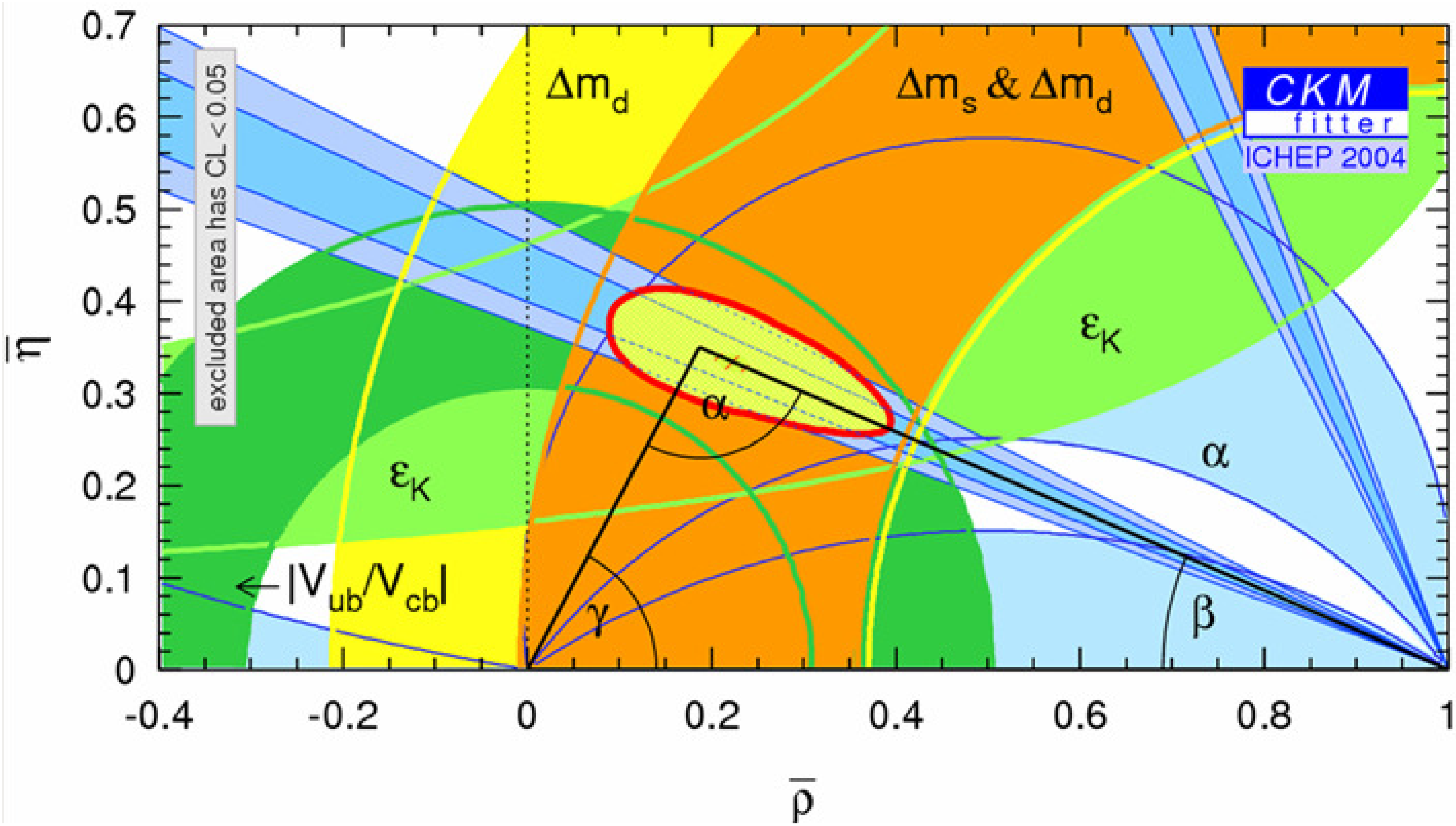

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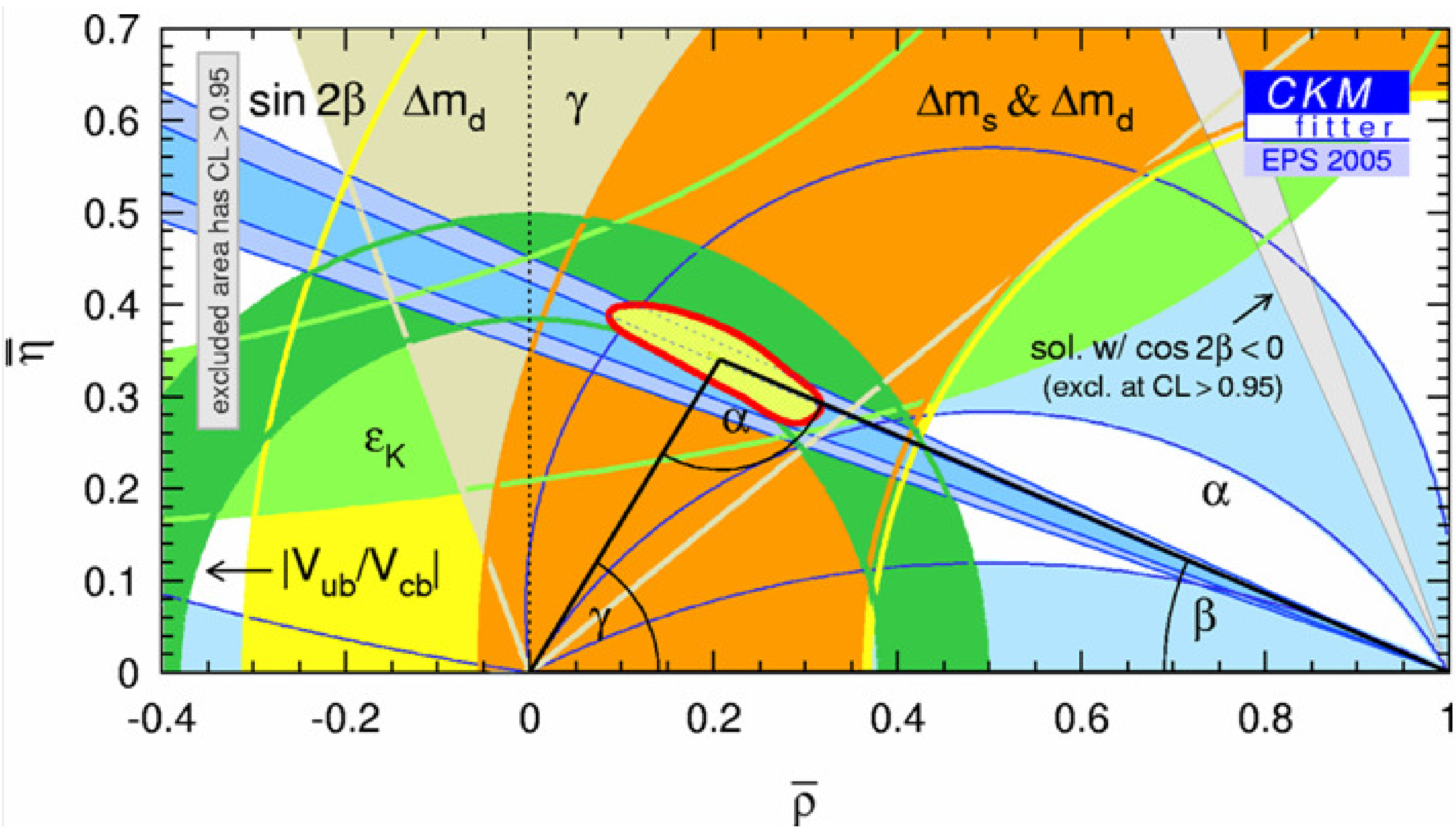
The Unitarity Triangle

- $|V_{cb}|$ determined with high precision (2%) → Now $|V_{ub}|$ is important!
- Precise determination of $|V_{ub}|$ complements $\sin 2\beta$ to test the validity of the Standard Model



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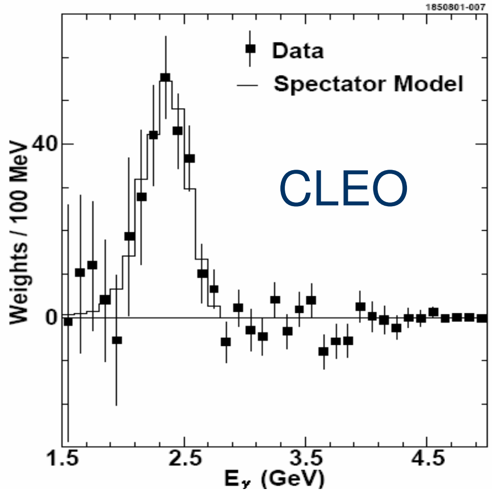
Backup

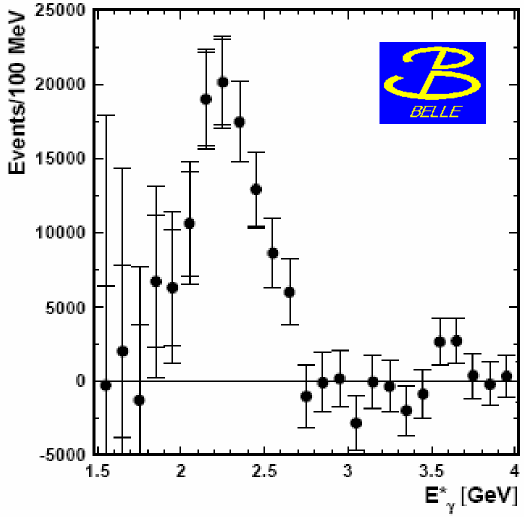
b→sγ helps too…

Photon Spectrum

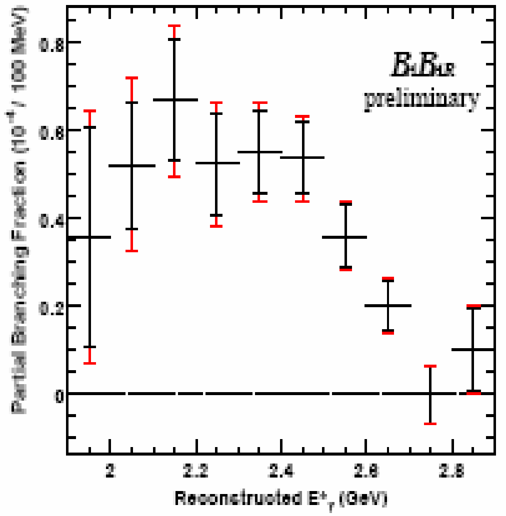
PRL87:251807(2001)



PRL93:061803(2004)

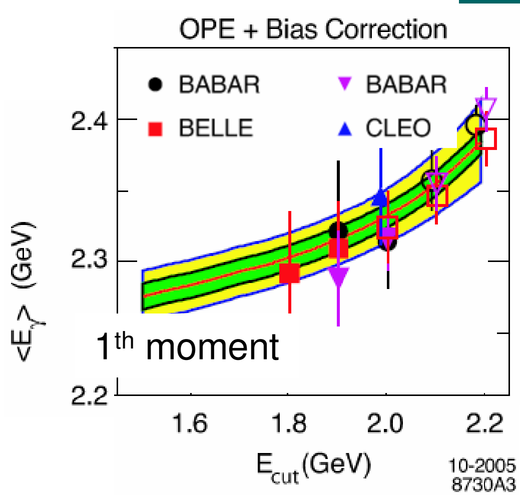


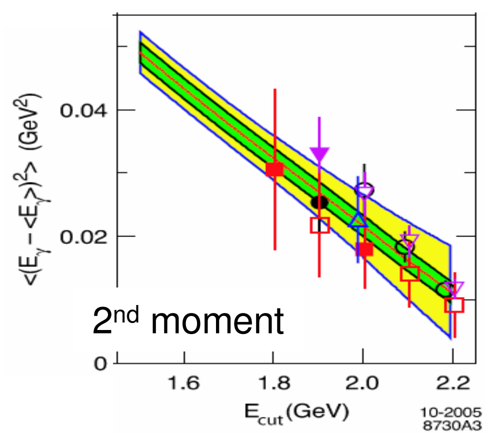
hep-ex/0507001



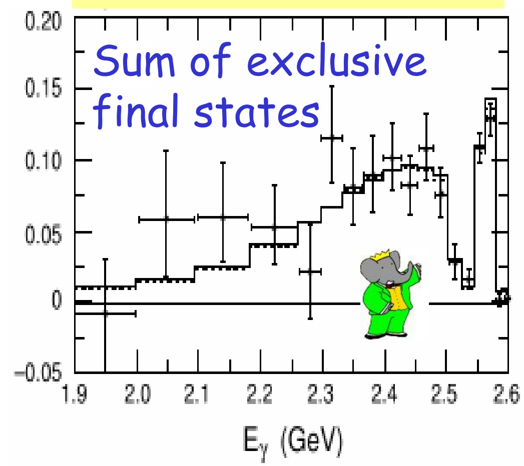
Photon Moments

Buchmüller, Flächer hep-ph/0507253





PRD72:052004(2005)



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