Review of $|V_{ub}|$ and $|V_{cb}|$ measurements at the B-factories

Christoph Schwanda
Institute of High Energy Physics
Austrian Academy of Sciences

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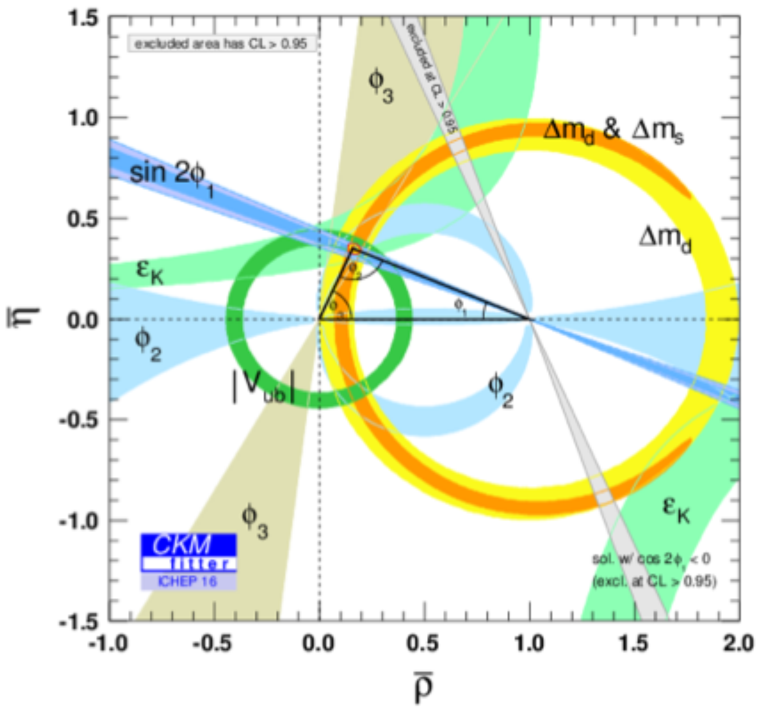
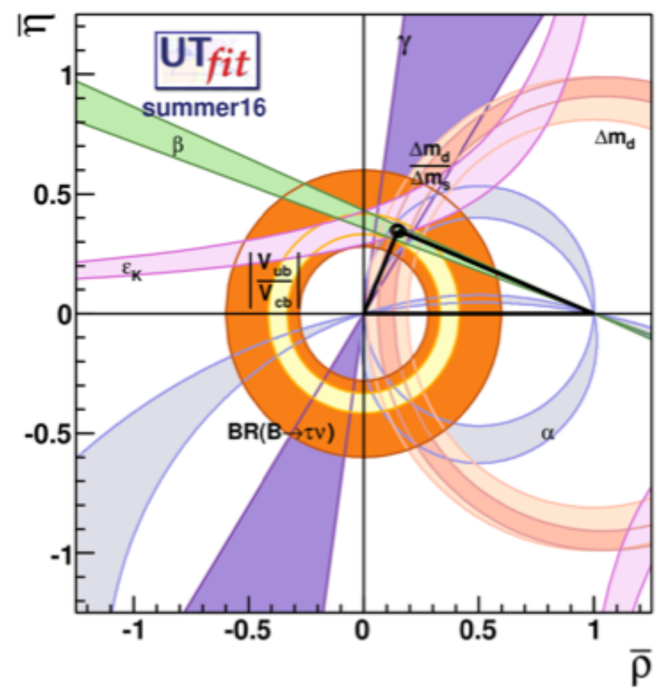
Current status (summer 2016)

http://ckmfitter.in2p3.fr/

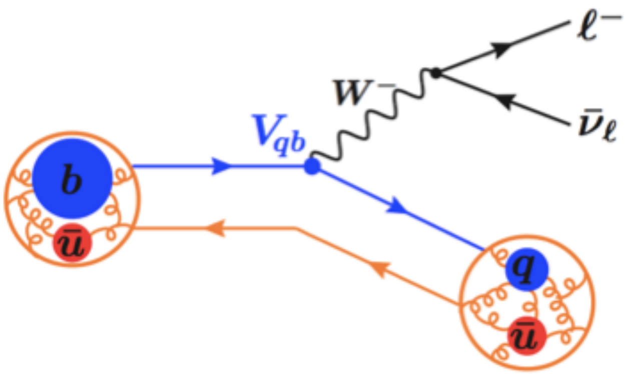


http://www.utfit.org/



- Largest pull: V_{ub} inclusive (UTfit)

$|V_{xb}|$ from semileptonic B decays



$$d\Gamma \propto G_F^2 |V_{qb}|^2 \left| L_\mu \langle X | \bar{q} \gamma_\mu P_L b | B \rangle \right|^2$$

- $|V_{cb}|$
  - Exclusive ($D l \nu$, $D^* l \nu$)
    $\rightarrow$ talk by Kilian Lieret in the session yesterday
  - Inclusive ($X_c l \nu$)
- $|V_{ub}|$
  - Exclusive ($\pi l \nu$)
  - Inclusive ($X_u l \nu$)
    $\rightarrow$ talk by Raynette Van Tonder in the session yesterday

$|V_{cb}|$

Inclusive vs. exclusive

	Experiment	Theory
Exclusive $\|V_{cb}\|$	$B \to D l \nu$, $D^* l \nu$ (low backgrounds)	Lattice QCD, light cone sum rules
Inclusive $\|V_{cb}\|$	$B \to X l \nu$ (higher background)	Operator product expansion

- Consistency between exclusive and inclusive is a crucial cross-check of our understanding…

Let's look at B → $D^{(*)}l\nu$

$$w = \frac{P_B \cdot P_{D^{(*)}}}{m_B m_{D^{(*)}}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$$

B → D*lν

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_{D^*}^3}{48\pi^3} (m_B - m_{D^*})^2 \sqrt{w^2 - 1}\, \chi(w) \mathcal{F}^2(w) |V_{cb}|^2$$

B → Dlν

$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3} (m_B + m_D)^2 (w^2 - 1)^{3/2} \mathcal{G}^2(w) |V_{cb}|^2$$

Form factor parameterizations

- Caprini, Lellouch, Neubert [Nucl.Phys. B530, 153(1998)]

$B \to D^* l\nu$

$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right],$$
$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2,$$
$$R_2(w) = R_2(1) + 0.11(w-1) - 0.06(w-1)^2,$$

$B \to D l\nu$

$$\mathcal{G}(z) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$

Parameters: $F(1)$, ρ^2, $R_1(1)$, $R_2(1)$
$G(1)$, ρ^2

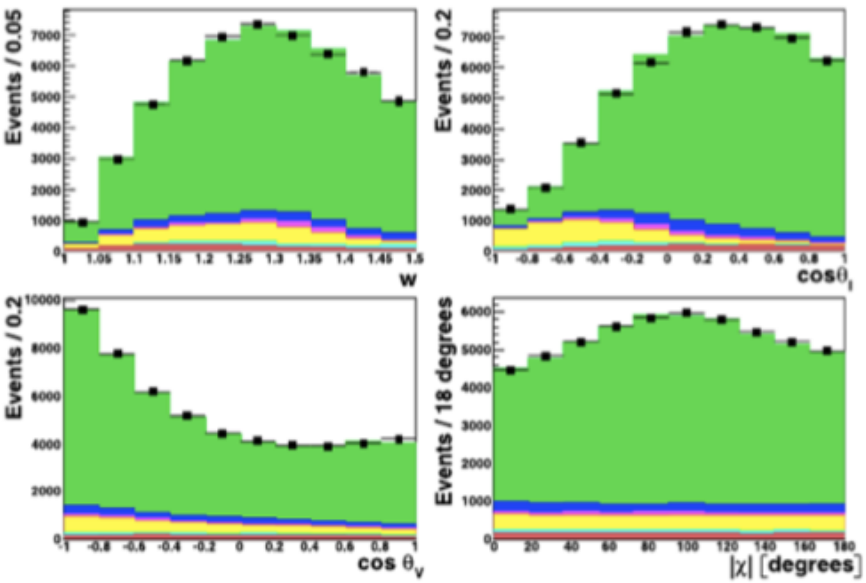
- Boyd, Grinstein, Lebed [Phys. Rev. Lett. 74, 4603 (1995)]

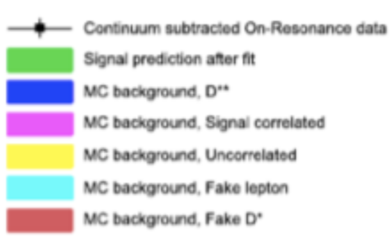
$$f_i(z) = \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n, \qquad z(w) = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

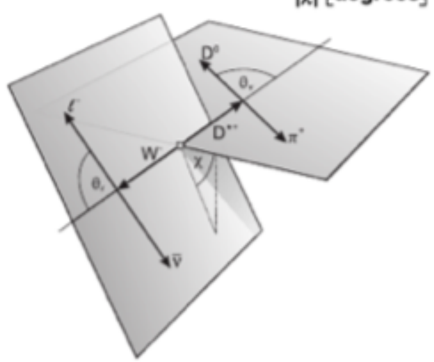
Parameters: coefficients $a_{i,n}$

$B^0 \to D^{*-} l^+ \nu$ at Belle

[W. Dungel, CS, Phys. Rev. D 82, 112007 (2010)]



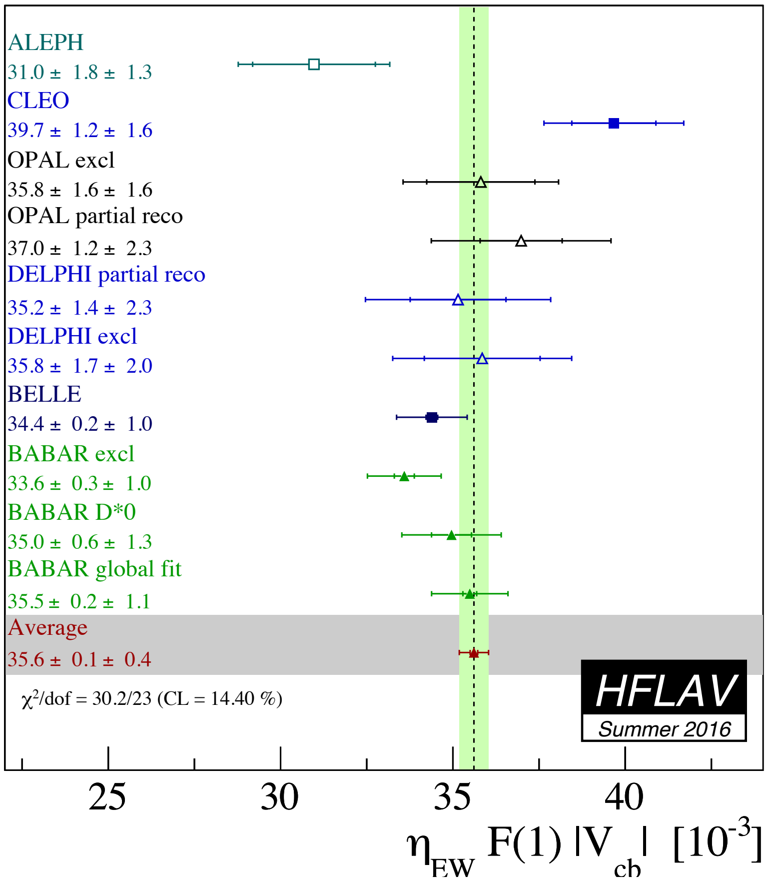


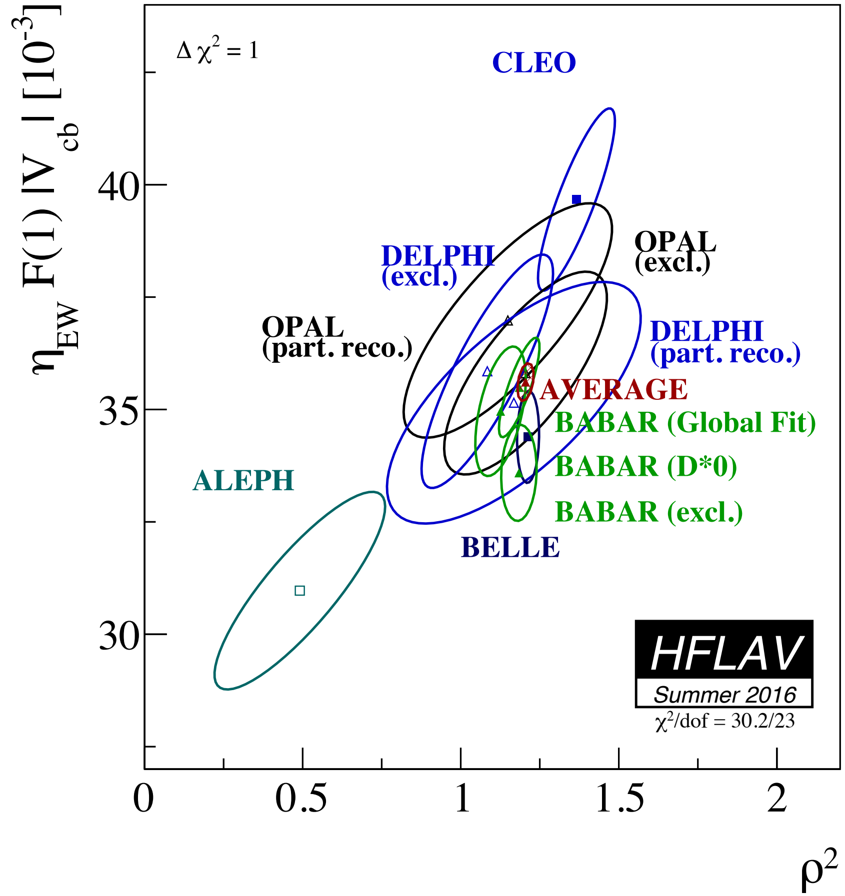


- 711/fb of Belle Y(4S) data
- About 120,000 reconstructed $B^0 \to D^{*-} l^+ \nu$ decays
- Fit in 40 bins of w, $\cos\theta_l$, θ_V and χ to obtain CLN F.F. parameters
- Dominant experimental systematics: tracking

$$\mathcal{F}(1)|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$$
$$\rho^2 = 1.214 \pm 0.034 \pm 0.009$$
$$R_1(1) = 1.401 \pm 0.034 \pm 0.018$$
$$R_2(1) = 0.864 \pm 0.024 \pm 0.008$$
$$\chi^2/ndf = 138.8/155$$

$\eta_{EW}F(1)|V_{cb}|$ $(B \rightarrow D^*l\nu)$ [Eur. Phys. J. C77 (2017) 895]





$$\eta_{EW}F(1)|V_{cb}| = (35.61 +/- 0.11 +/- 0.41) \times 10^{-3}$$

HFLAV analysis of $|V_{cb}|$ exclusive (2016)

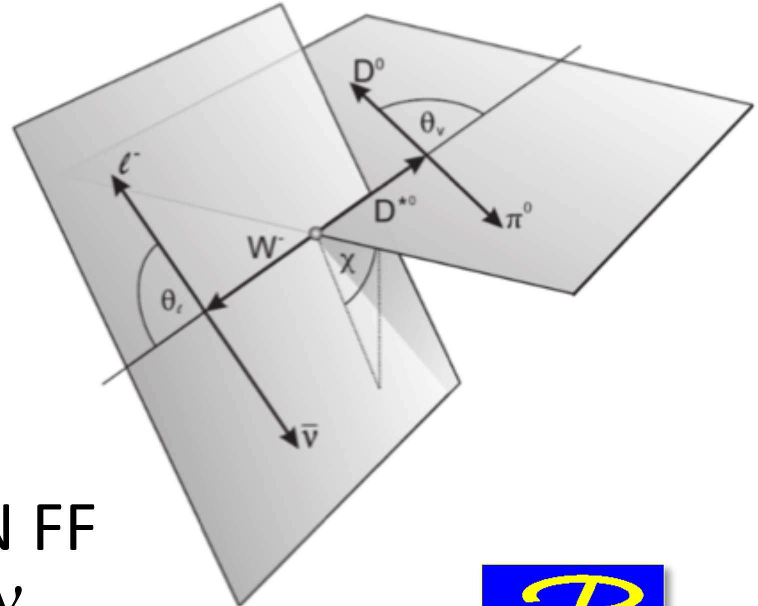
- HFLAV average $B \to D^* l \nu$
  - $\eta_{EW}F(1)|V_{cb}|$ = (35.61 +/- 0.11_{stat} +/- 0.41_{syst}) x 10^{-3}
- Lattice input [FNAL/MILC, PRD89, 114504]
  - $\eta_{EW}F(1)$ = (0.912 +/- 0.014)
- Value of |Vcb| assuming the CLN FF
  - $|V_{cb}|$ = (39.05 +/- 0.47_{exp} +/- 0.58_{th}) x 10^{-3}

B → D*lν hadronic tag [arXiv:1702.01521]

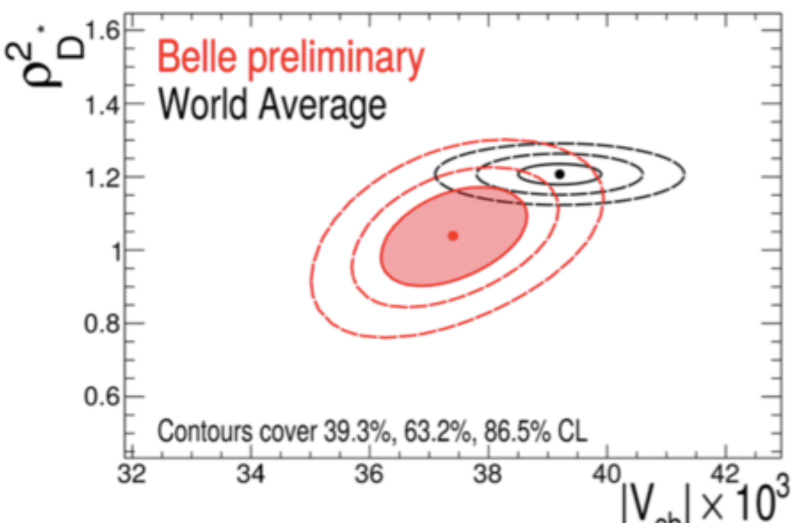
- CLN FF parameterization
  [NPB 530, 153 (1998)]

$$\frac{d^4\Gamma(B \to D^*\ell\nu)}{dw\, d\cos\theta_v\, d\cos\theta_\ell\, d\chi} = f(|V_{cb}|^2, \underbrace{\rho^2_{D^*}, R_1, R_2}_{\text{form factor parameters}})$$

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



- Belle measured $|V_{cb}|$ and the CLN FF parameters in the decay B → D*lν



Parameter	Measurement	World average
$\|V_{cb}\| \cdot 10^3$	37.4 ± 1.2	39.2 ± 0.7
$\rho^2_{D^*}$	1.04 ± 0.13	1.20 ± 0.03
R_1	1.38 ± 0.07	1.40 ± 0.03
R_2	0.86 ± 0.10	0.85 ± 0.02

CLN parametrisation

Model-independent analysis of arXiv:1702.01521 data

- D.Bigi, P. Gambino, S.Schacht, Phys.Lett. B769 (2017) 441

BGL Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	27.9/32	31.4/35
$\lvert V_{cb}\rvert$	$0.0417\,(^{+20}_{-21})$	$0.0404\,(^{+16}_{-17})$
a_0^f	0.01223(18)	0.01224(18)
a_1^f	$-0.054\,(^{+58}_{-43})$	$-0.052\,(^{+27}_{-15})$
a_2^f	$0.2\,(^{+7}_{-12})$	$1.0\,(^{+0}_{-5})$
$a_1^{\mathcal{F}_1}$	$-0.0100\,(^{+61}_{-56})$	$-0.0070\,(^{+54}_{-52})$
$a_2^{\mathcal{F}_1}$	0.12 (10)	$0.089\,(^{+96}_{-100})$
a_0^g	$0.012\,(^{+11}_{-8})$	$0.0289\,(^{+57}_{-37})$
a_1^g	$0.7\,(^{+3}_{-4})$	$0.08\,(^{+8}_{-22})$
a_2^g	$0.8\,(^{+2}_{-17})$	$-1.0\,(^{+20}_{-0})$

CLN Fit:	Data + lattice	Data + lattice + LCSR
χ^2/dof	34.3/36	34.8/39
$\lvert V_{cb}\rvert$	0.0382 (15)	0.0382 (14)
$\rho^2_{D^*}$	$1.17\,(^{+15}_{-16})$	1.16 (14)
$R_1(1)$	$1.391\,(^{+92}_{-88})$	1.372 (36)
$R_2(1)$	$0.913\,(^{+73}_{-80})$	$0.916\,(^{+65}_{-70})$
$h_{A_1}(1)$	0.906 (13)	0.906 (13)

- B.Grinstein, A.Kobach, Phys.Lett. B771 (2017) 359

$$|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3} \qquad \text{(CLN)}$$

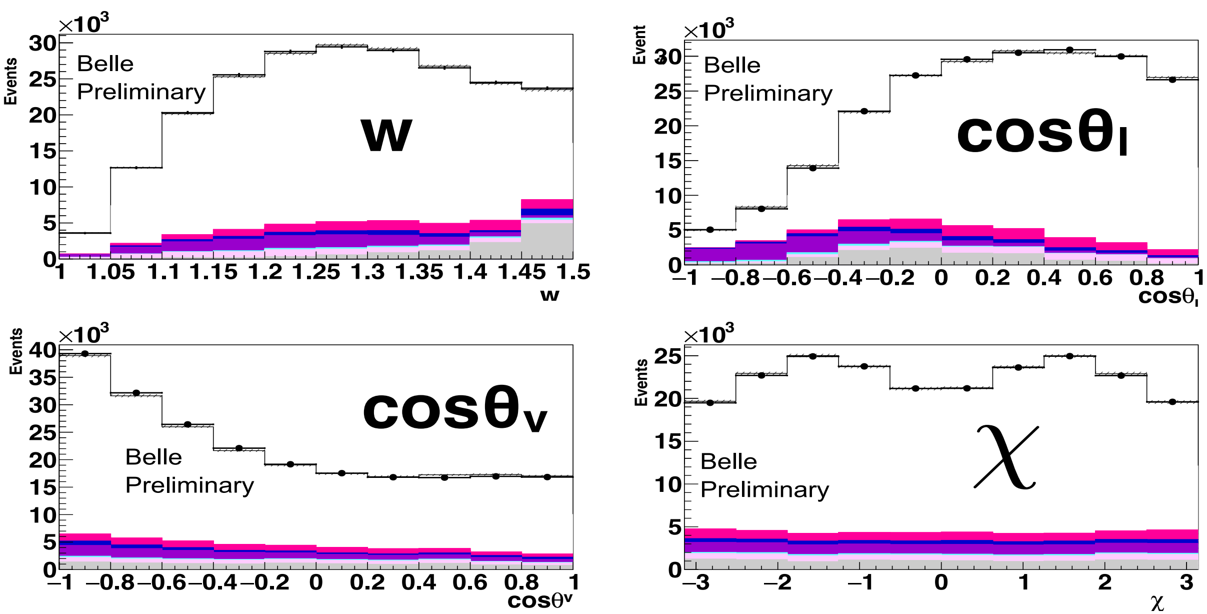
$$|V_{cb}| = (41.9\ ^{+2.0}_{-1.9}) \times 10^{-3} \qquad \text{(BGL)}$$

Belle update $B^0 \to D^{*-} l \nu$ untagged [arXiv:1809.032090]

Simultaneous fit of 1D projections of w, $\cos\theta_l$, $\cos\theta_v$, X to extract the coefficients of the BGL expansion (up to 3rd order) and $F(1)|V_{cb}|$

$F(1)|V_{cb}|\eta_{EW}\, 10^3 = 38.7 \pm 0.3 \pm 0.6$ ← **First Model independent measurement of exclusive $F(1)|V_{cb}|$**

Parameters	Value
$\tilde{a}_0^f \times 10^2$	0.05635 ± 0.0004
$\tilde{a}_1^f \times 10^2$	-0.0701 ± 0.01834
$\tilde{a}_1^F \times 10^2$	-0.0276 ± 0.0071
$\tilde{a}_2^F \times 10^2$	-0.3242 ± 0.1388
$\tilde{a}_0^g \times 10^2$	-0.1037 ± 0.0020



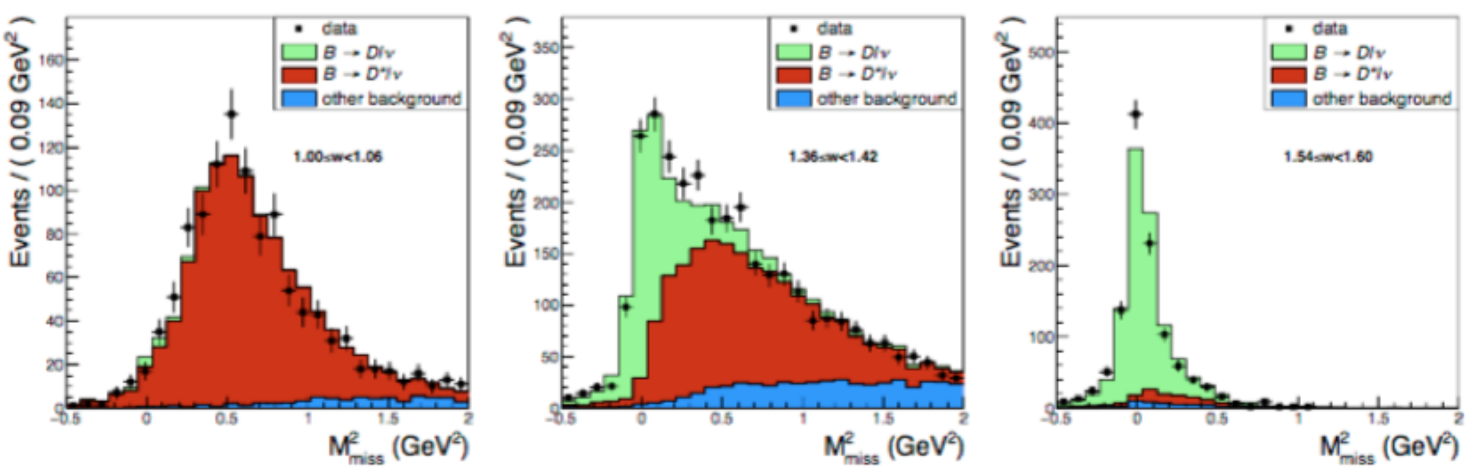
$|V_{cb}| = (42.5 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$ **Exclusive $|V_{cb}|$ (BGL)**

$|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$ **Exclusive $|V_{cb}|$ (CLN)**

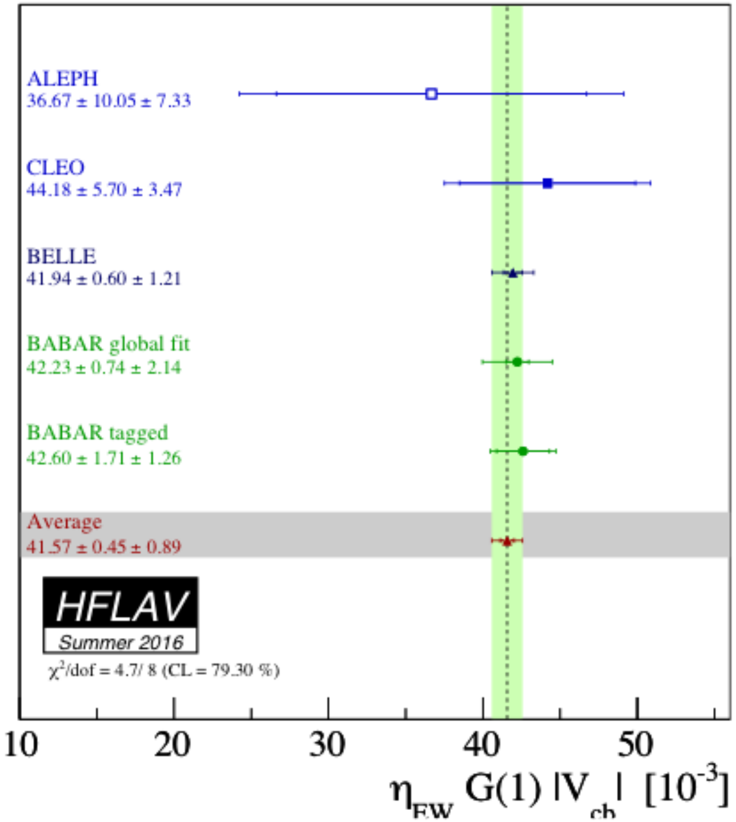
B → Dlν at Belle

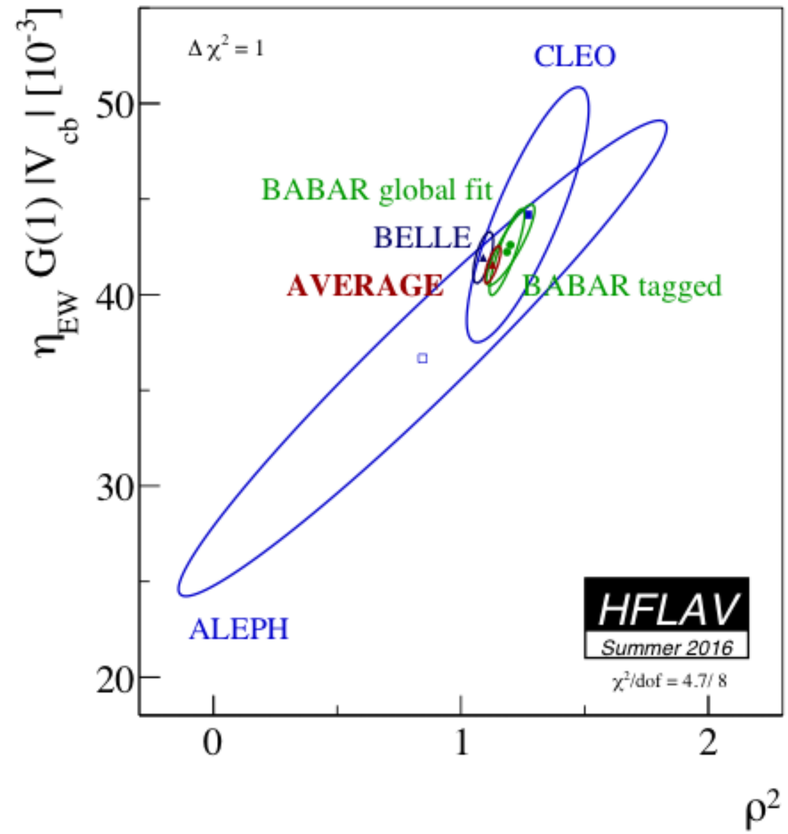
[R. Glattauer, CS, Phys. Rev. D93, 032006 (2016)]

- 711/fb of Belle Υ(4S) data
- Full reconstruction of one B (hadronic tag)
- 10 D^+ and 13 D^0 modes are used on the signal side, covering 28.9% and 40.1% of the width
- Signal extraction from M^2_{miss} in 10 bins of w
- 16,992 +/- 192 signal events
  (5150 +/- 95 neutral, 11,843 +/- 167 charged B events)



$\eta_{EW}G(1)|V_{cb}|$ $(B \rightarrow Dl\nu)$



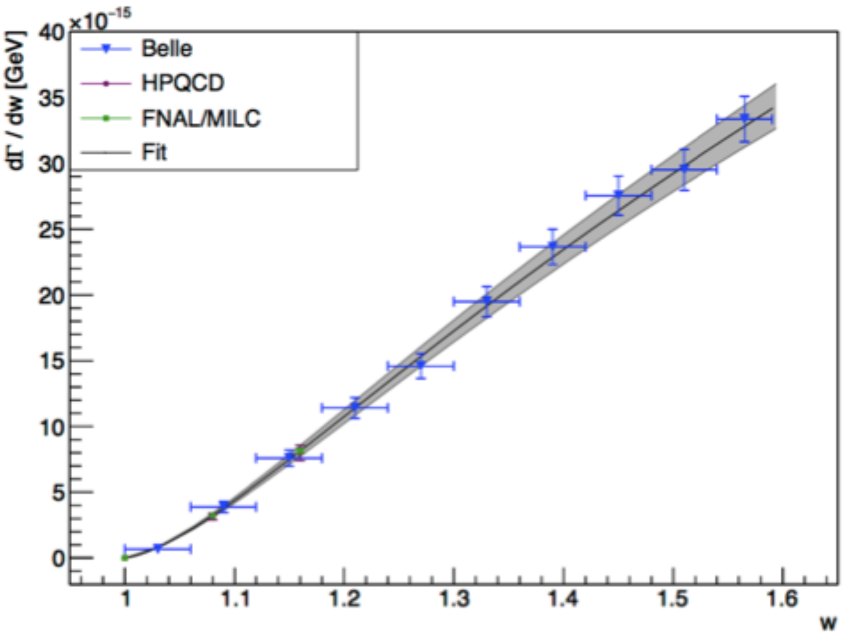


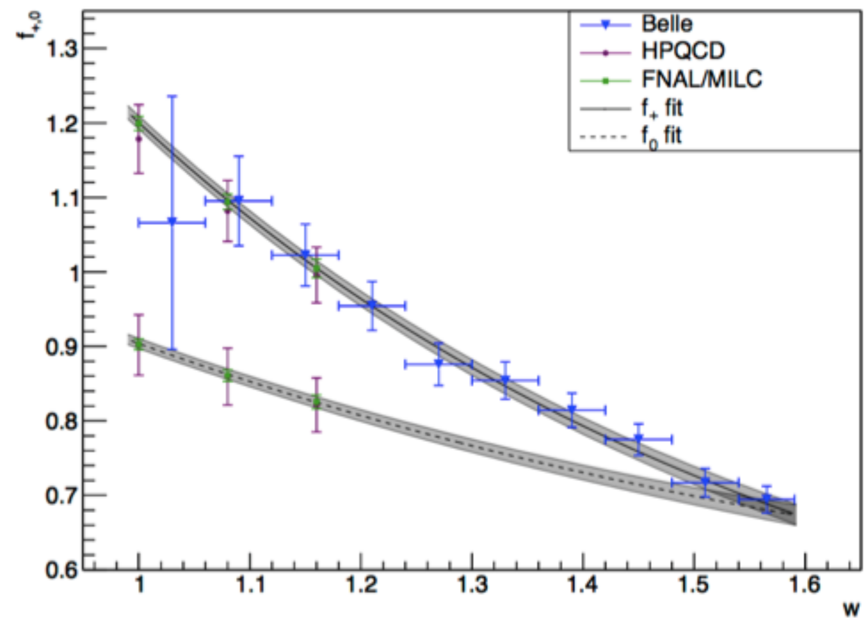
$$\eta_{EW}G(1)|V_{cb}| = (41.57 +/- 0.45 +/- 0.89) \times 10^{-3}$$

HFLAV analysis of $|V_{cb}|$ exclusive (2016)

- $B \to Dl\nu$
  - $\eta_{EW}G(1)|V_{cb}|$ = (41.57 +/- 0.45 +/- 0.89) x 10^{-3}
  - G(1) = 1.0541 +/- 0.0083 [FNAL/MILC, PRD92, 034506]
  - η_{EW} = 1.0066 +/- 0.0016 [NPB 196, 83]
  - $|V_{cb}|$ = (39.18 +/- 0.94_{exp} +/- 0.36_{th}) x 10^{-3}

Belle 2016: BGL fit with lattice data





	$N=2$	$N=3$	$N=4$
$a_{+,0}$	0.0127 ± 0.0001	0.0126 ± 0.0001	0.0126 ± 0.0001
$a_{+,1}$	-0.091 ± 0.002	-0.094 ± 0.003	-0.094 ± 0.003
$a_{+,2}$	0.34 ± 0.03	0.34 ± 0.04	0.34 ± 0.04
$a_{+,3}$	–	-0.1 ± 0.6	-0.1 ± 0.6
$a_{+,4}$	–	–	0.0 ± 1.0
$a_{0,0}$	0.0115 ± 0.0001	0.0115 ± 0.0001	0.0115 ± 0.0001
$a_{0,1}$	-0.058 ± 0.002	-0.057 ± 0.002	-0.057 ± 0.002
$a_{0,2}$	0.22 ± 0.02	0.12 ± 0.04	0.12 ± 0.04
$a_{0,3}$	–	0.4 ± 0.7	0.4 ± 0.7
$a_{0,4}$	–	–	0.0 ± 1.0
$\eta_{EW}\lvert V_{cb}\rvert$	40.01 ± 1.08	41.10 ± 1.14	41.10 ± 1.14
χ^2/n_{df}	24.7/16	11.4/16	11.3/16
Prob.	0.075	0.787	0.787

Lattice data	$\eta_{EW}\lvert V_{cb}\rvert [10^{-3}]$	χ^2/n_{df}	Prob.
FNAL/MILC [15]	40.96 ± 1.23	6.01/10	0.81
HPQCD [32]	41.14 ± 1.88	4.83/10	0.90
FNAL/MILC & HPQCD [15, 32]	41.10 ± 1.14	11.35/16	0.79

$|V_{cb}|$ from inclusive decays

$B \to X l \nu$

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 (1 + \frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_b^3} + \mathcal{O}(\frac{1}{m_b^4}))$$

- Based on the Operator Product Expansion (OPE)
- $\langle O_i \rangle$: hadronic matrix elements (non-perturbative)
  c_i: coefficients (perturbative)
- Parton-hadron duality $\to$ the hadronic ME depend only on the initial state

	Kinetic [JHEP 1109 (2011) 055]	1S [PRD70, 094017 (2004)]
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ^3_D, ρ^3_{LS}	ρ_1, τ_{1-3}

Moments of the E_l and M^2_X spectrum

Also other observables in $B \rightarrow Xl\nu$ can be expanded into an OPE with the same heavy quark parameters, e.g.,

- The nth moment of the (truncated) lepton energy spectrum

$$R_n(E_{\rm cut}, \mu) = \int_{E_{\rm cut}} (E_\ell - \mu)^n \, \frac{{\rm d}\Gamma}{{\rm d}E_\ell} \, {\rm d}E_\ell \,, \quad \langle E_\ell^n \rangle_{E_{\rm cut}} = \frac{R_n(E_{\rm cut}, 0)}{R_0(E_{\rm cut}, 0)}$$

- The nth moment of the (truncated) M^2_X spectrum

$$\langle m_X^{2n} \rangle_{E_{\rm cut}} = \frac{\int_{E_{\rm cut}} (m_X^2)^n \, \frac{{\rm d}\Gamma}{{\rm d}m_X^2} \, {\rm d}m_X^2}{\int_{E_{\rm cut}} \frac{{\rm d}\Gamma}{{\rm d}m_X^2} \, {\rm d}m_X^2}$$

Master plan:

- Measure the quark masses and heavy quark parameters using moments
- Substitute them in the formula of the semileptonic width
- Determine $|V_{cb}|$ from the semileptonic branching fraction

Two sets of theoretical calculations

- "Kinetic running mass"
  - P. Gambino, N. Uraltsev, Eur. Phys. J. C34, 181 (2004)
  - P. Gambino, JHEP 1109 (2011) 055
  - A. Alberti, P. Gambino, K.J. Healey, S. Nandi, Phys. Rev. Lett. 114, 061802 (2015)
- "1S mass"
  - C. Bauer, Z. Ligeti, M. Luke, A. Manohar, M. Trott, Phys. Rev. D70, 094017 (2004)
- Non-perturbative parameters in the $1/m_b$ expansion

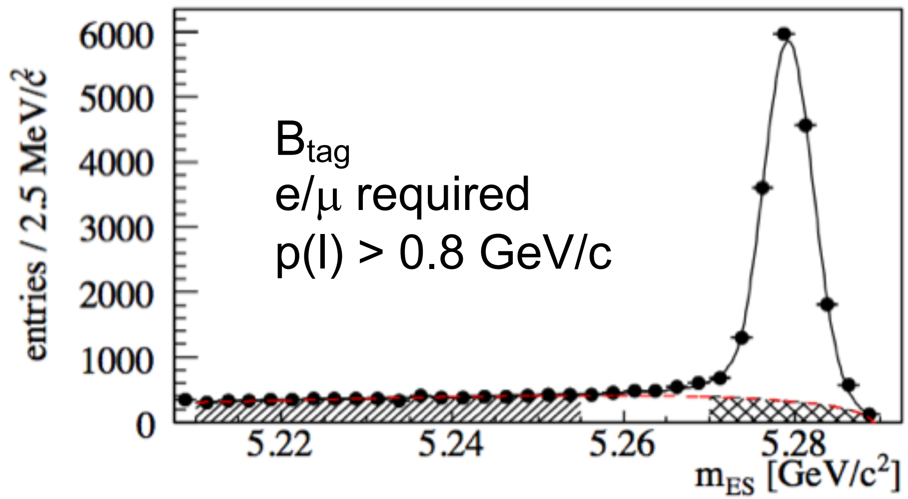
	Kinetic	1S
O(1)	m_b, m_c	m_b
$O(1/m^2_b)$	μ^2_π, μ^2_G	λ_1, λ_2
$O(1/m^3_b)$	ρ^3_D, ρ^3_{LS}	ρ_1, $\tau_{1\text{-}3}$

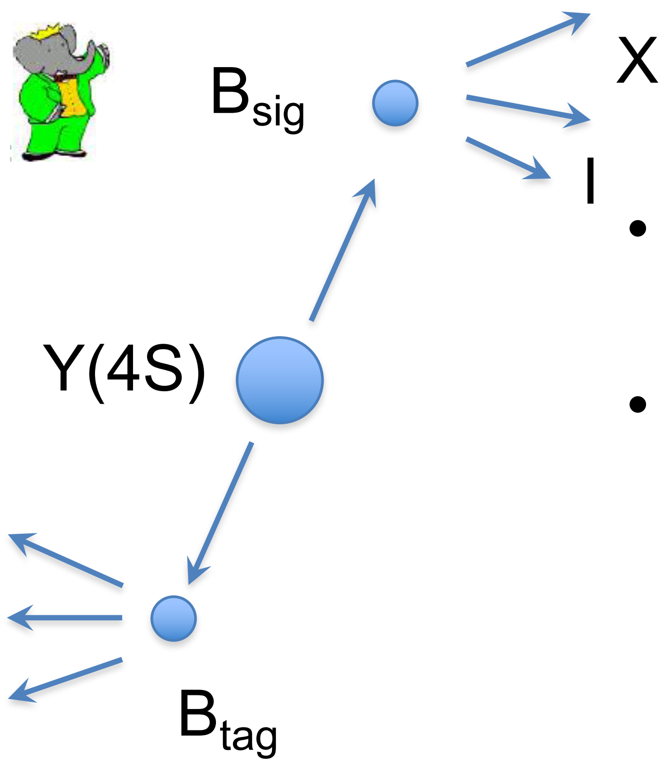
PRD 81, 032003 (2010)

BaBar hadronic moments

232M BB

- Fully reconstruct the hadronic decay of one B in Y(4S) → BB (efficiency ~0.4%, purity ~80%)





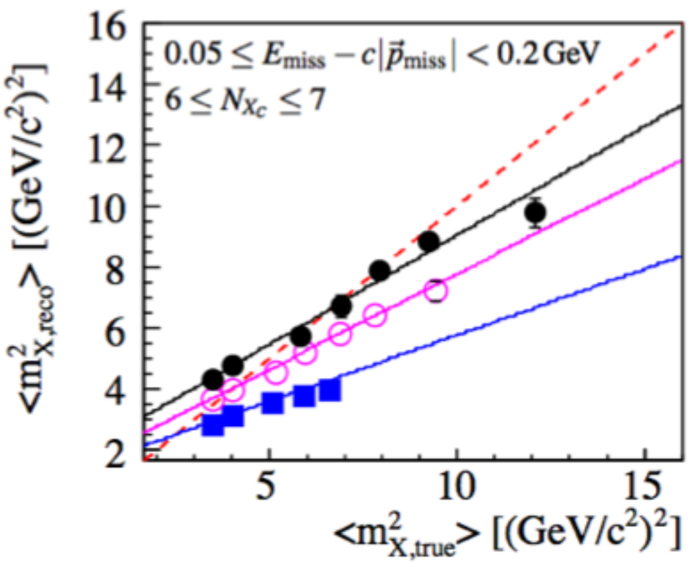
- Require one identified lepton amongst the signal-side particles (p > 0.8 GeV/c)
- Combine all remaining particles to the X system and do a kinematic fit
  - 4-momentum conservation
  - Missing mass consistent with zero mass neutrino

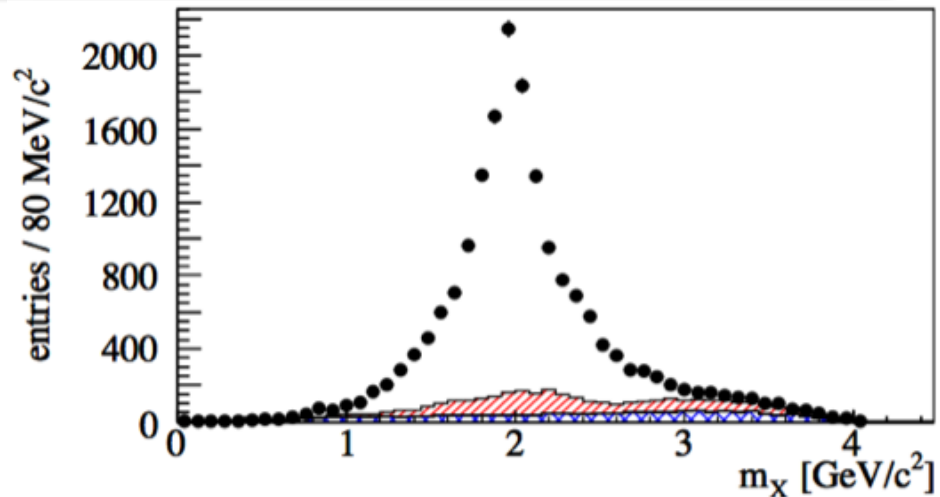
Moment measurement

PRD 81, 032003 (2010)

232M BB

- Hadronic mass spectrum after kinematic fit





- Linear correction of the measured moments in bins of X multiplicity, E_{miss}-cp_{miss} and lepton momentum

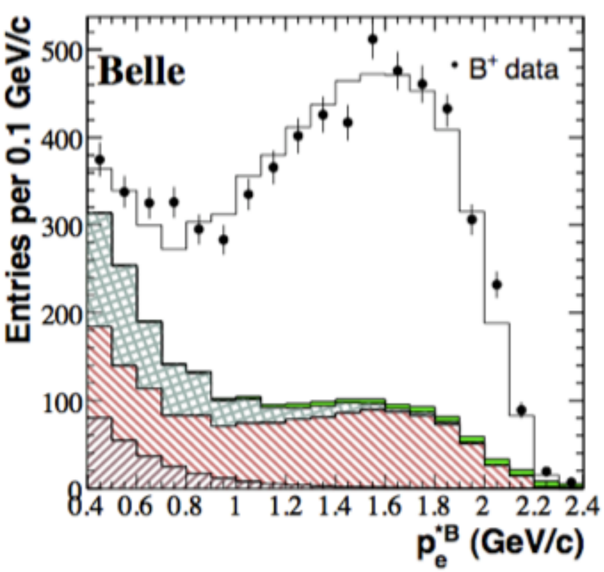
- Moments of the hadronic mass spectrum up to M^6_X for E_{cut} between 0.8 and 1.9 GeV are measured
- Also mixed mass-energy moments are determined and the electron energy moments from [PRD69, 111104] are re-evaluated

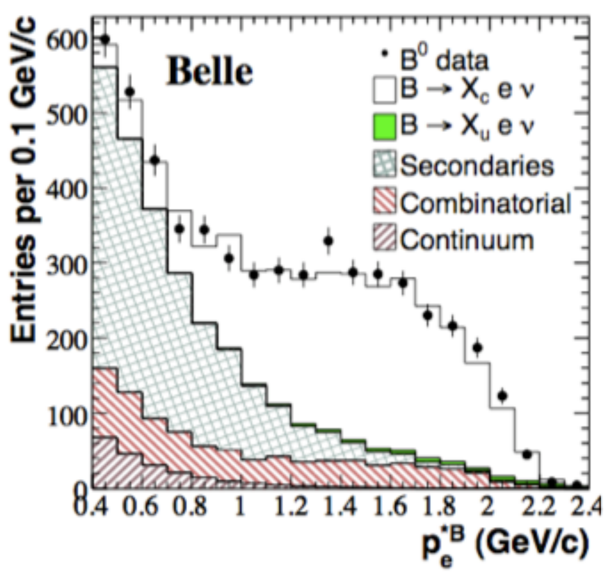
Belle E_l and M^2_X moments

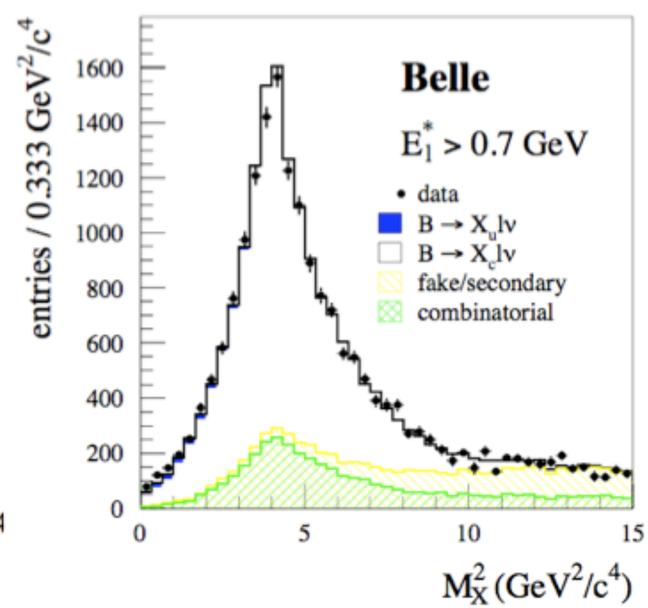
PRD 75, 032001 (2007)
PRD 75, 032005 (2007)

152M BB

- For both the E_l and M^2_X measurements, similar experimental method using fully reconstructed events
- The finite detector resolution is unfolded with SVD algorithm [NIM A372, 469 (1996)]
- $<E^n_e>$ measured for n=0,…,4 and E_{cut}=0.4-2.0 GeV
- $<M^{2n}_X>$ measured for n=1,2 and E_{cut}=0.7-1.9 GeV







Data used in $b \to c$ inclusive analyses

BaBar	$\langle E^n_l \rangle$: n=0,1,2,3 [PRD 69, 111104 (2004), PRD 81, 032003 (2010)] $\langle M^{2n}_X \rangle$: n=1,2, 3 [PRD 81, 032003 (2010)]
Belle	$\langle E^n_l \rangle$: n=0,1,2,3 [PRD 75, 032001 (2007)] $\langle M^{2n}_X \rangle$: n=1,2 [PRD 75, 032005 (2007)]
CDF	$\langle M^{2n}_X \rangle$: n=1,2 [PRD 71, 051103 (2005)]
CLEO	$\langle M^{2n}_X \rangle$: n=1,2 [PRD 70, 032002 (2004)] $\langle E^n_\gamma \rangle$: n=1 [PRL 87, 251807 (2001)]
DELPHI	$\langle E^n_l \rangle$: n=1,2,3 $\langle M^{2n}_X \rangle$: n=1,2 [EPJ C45, 35 (2006)]

- Newest measurement is from the year 2010!

Moments used in the HFLAV analysis

HFLAV

Summer 2016

Experiment	Hadron moments $\langle M_X^n \rangle$	Lepton moments $\langle E_\ell^n \rangle$
BABAR	$n = 2,\ c = 0.9, 1.1, 1.3, 1.5$ $n = 4,\ c = 0.8, 1.0, 1.2, 1.4$ $n = 6,\ c = 0.9, 1.3$ [495]	$n = 0,\ c = 0.6, 1.2, 1.5$ $n = 1,\ c = 0.6, 0.8, 1.0, 1.2, 1.5$ $n = 2,\ c = 0.6, 1.0, 1.5$ $n = 3,\ c = 0.8, 1.2$ [495, 496]
Belle	$n = 2,\ c = 0.7, 1.1, 1.3, 1.5$ $n = 4,\ c = 0.7, 0.9, 1.3$ [497]	$n = 0,\ c = 0.6, 1.4$ $n = 1,\ c = 1.0, 1.4$ $n = 2,\ c = 0.6, 1.4$ $n = 3,\ c = 0.8, 1.2$ [498]
CDF	$n = 2,\ c = 0.7$ $n = 4,\ c = 0.7$ [499]	
CLEO	$n = 2,\ c = 1.0, 1.5$ $n = 4,\ c = 1.0, 1.5$ [500]	
DELPHI	$n = 2,\ c = 0.0$ $n = 4,\ c = 0.0$ $n = 6,\ c = 0.0$ [489]	$n = 1,\ c = 0.0$ $n = 2,\ c = 0.0$ $n = 3,\ c = 0.0$ [489]

- 23 measurements from BaBar, 15 measurements from Belle, 12 from other experiments

Kinetic scheme analysis

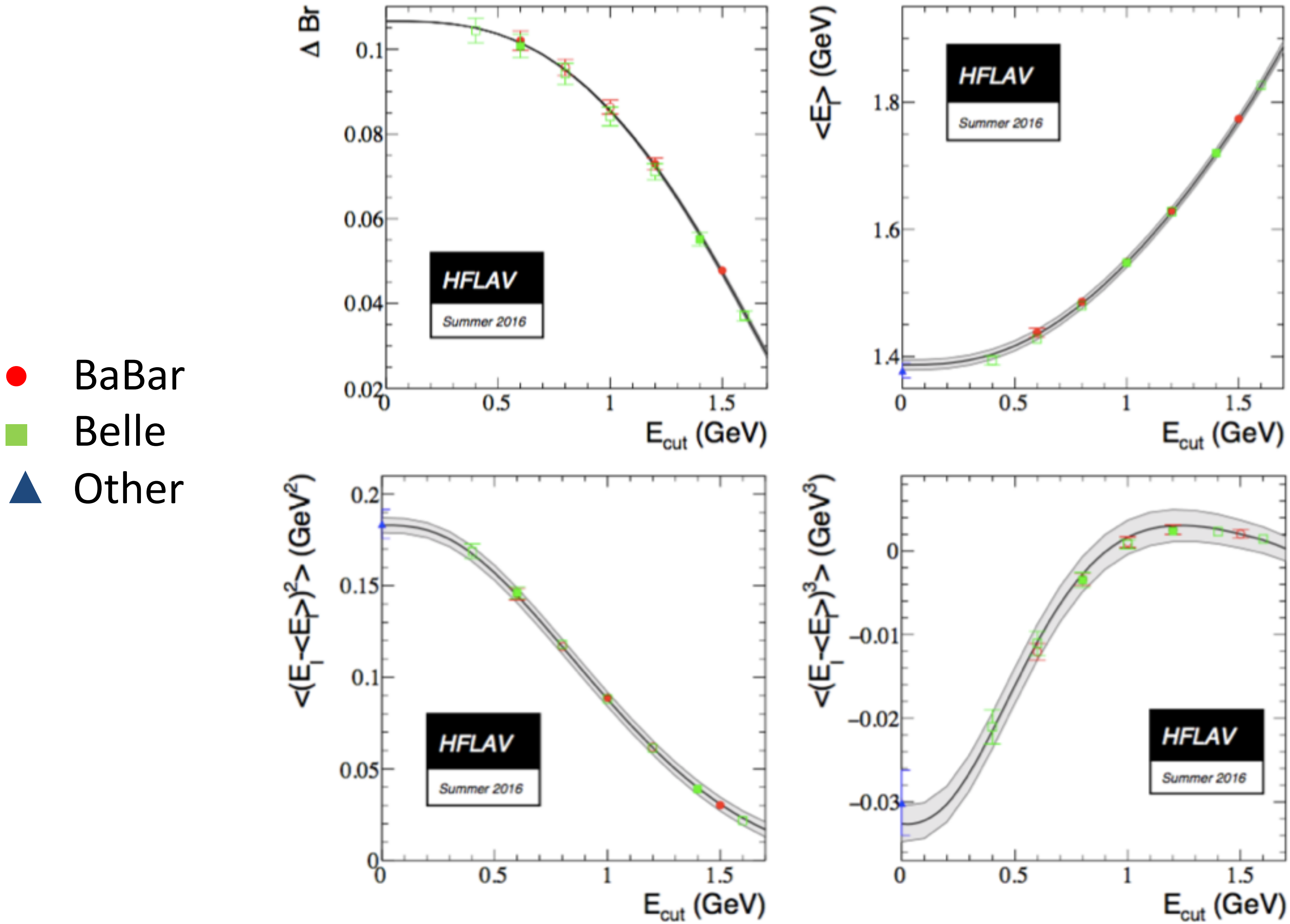
HFLAV
Summer 2016

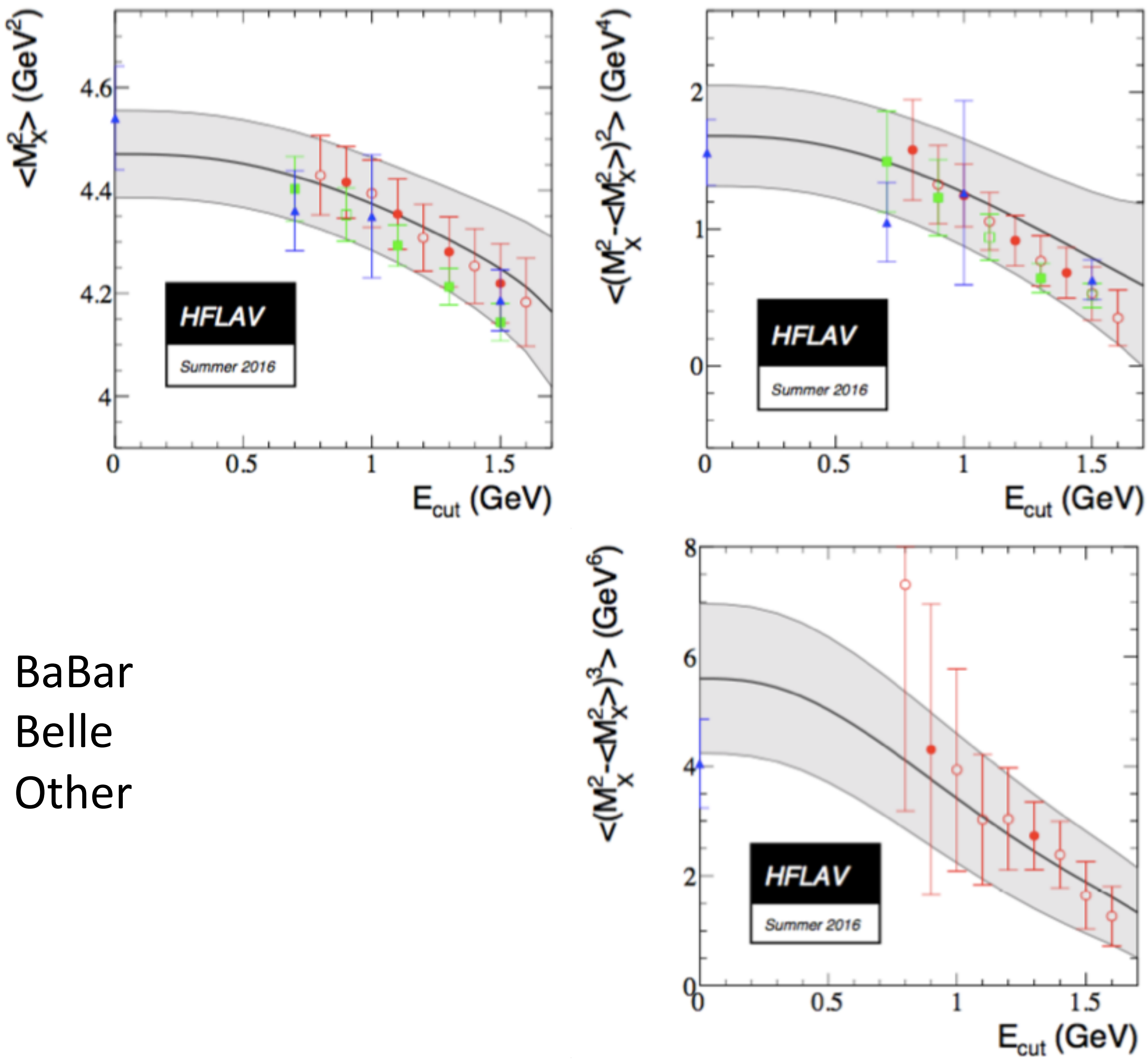
	$\lvert V_{cb}\rvert$ [10^{-3}]	$m_b^{\rm kin}$ [GeV]	$m_c^{\overline{\rm MS}}$ [GeV]	μ_π^2 [GeV^2]	ρ_D^3 [GeV^3]	μ_G^2 [GeV^2]	ρ_{LS}^3 [GeV^3]
value	42.19	4.554	0.987	0.464	0.169	0.333	−0.153
error	0.78	0.018	0.015	0.076	0.043	0.053	0.096
$\lvert V_{cb}\rvert$	1.000	−0.257	−0.078	0.354	0.289	−0.080	−0.051
$m_b^{\rm kin}$		1.000	0.769	−0.054	0.097	0.360	−0.087
$m_c^{\overline{\rm MS}}$			1.000	−0.021	0.027	0.059	−0.013
μ_π^2				1.000	0.732	0.012	0.020
ρ_D^3					1.000	−0.173	−0.123
μ_G^2						1.000	0.066
ρ_{LS}^3							1.000

$$\mathcal{B}(\overline{B} \to X_c \ell^- \overline{\nu}_\ell) = (10.65 \pm 0.16)\%$$

χ^2 of 15.6 for 43 degrees of freedom.

- c quark mass constraints $m_c^{\overline{\rm MS}}(3\ {\rm GeV}) = 0.986 \pm 0.013\ {\rm GeV}$
- Average B lifetime: (1.579 +/- 0.004) ps


BaBar
Belle
Other
Δ Br
<E_l> (GeV)
<(E_l−<E_l>)²> (GeV²)
<(E_l−<E_l>)³> (GeV³)
E_cut (GeV)
HFLAV
Summer 2016



- BaBar
- Belle
- Other

1S scheme analysis

HFLAV
Summer 2016

	m_b^{1S} [GeV]	λ_1 [GeV^2]	ρ_1 [GeV^3]	τ_1 [GeV^3]	τ_2 [GeV^3]	τ_3 [GeV^3]	$\|V_{cb}\|$ [10^{-3}]
value	4.691	−0.362	0.043	0.161	−0.017	0.213	41.98
error	0.037	0.067	0.048	0.122	0.062	0.102	0.45
m_b^{1S}	1.000	0.434	0.213	−0.058	−0.629	−0.019	−0.215
λ_1		1.000	−0.467	−0.602	−0.239	−0.547	−0.403
ρ_1			1.000	0.129	−0.624	0.494	0.286
τ_1				1.000	0.062	−0.148	0.194
τ_2					1.000	−0.009	−0.145
τ_3						1.000	0.376
$\|V_{cb}\|$							1.000

χ^2 of 23.0 for 59 degrees of freedom

- B quark mass constrained with $B \to X_s \gamma$ data
- Average B lifetime: (1.579 +/- 0.004) ps

$|V_{ub}|$

Determination of $|V_{ub}|$

Exclusive

$B \to \pi l \nu$

$$\frac{d\Gamma(B^0 \to \pi^- \ell^+ \nu)}{dq^2} = \frac{G_F^2}{24\pi^3}|V_{ub}|^2 p_\pi^3 |f_+(q^2)|^2$$

- Form factor f_+ from lattice QCD or from QCD sum rules

Inclusive

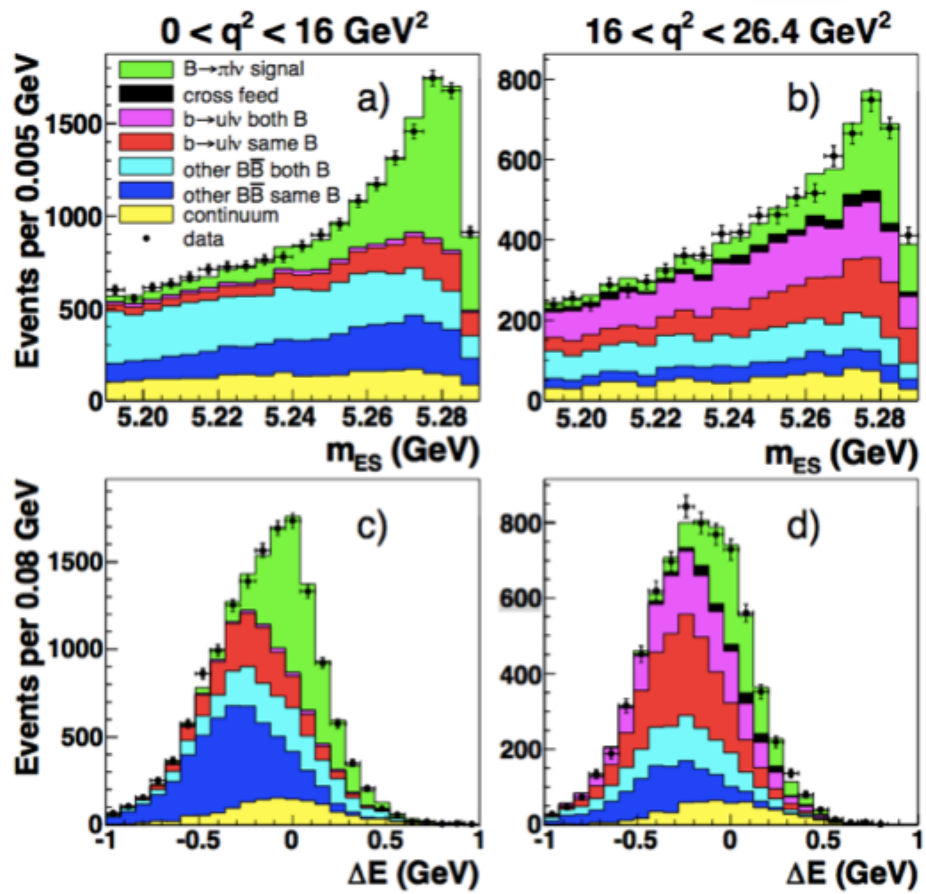
$B \to X_u l \nu$

- Also based on the OPE as for $b \to c$
- Experimental selections can comprise the convergence of the OPE $\to$ shape function
- Calculations used by HFLAV
  - BLNP [PRD 72, 073006(2005)]
  - DGE [JHEP 0601:097 (2006)]
  - GGOU [JHEP 0710:058 (2007)]

$B \to \pi l \nu$ untagged

[PRD 86, 092004 (2012)]

- 416/fb of BaBar Y(4S) data
- Reconstruct only $\pi e/\pi\mu$, infer neutrino momentum from p_{miss} (loose neutrino reconstruction technique)
- About 12,000 signal events, S/N ~0.1
- Partial branching fractions obtained in 12 q^2 bins
- Systematics: detector effects, $b \to u$ background



$$m_{ES} = \sqrt{E^{*2}_{beam} - \mathbf{p}^{*2}_{\pi\ell\nu}}$$
$$\Delta E = E^{*}_{\pi\ell\nu} - E^{*}_{beam}$$

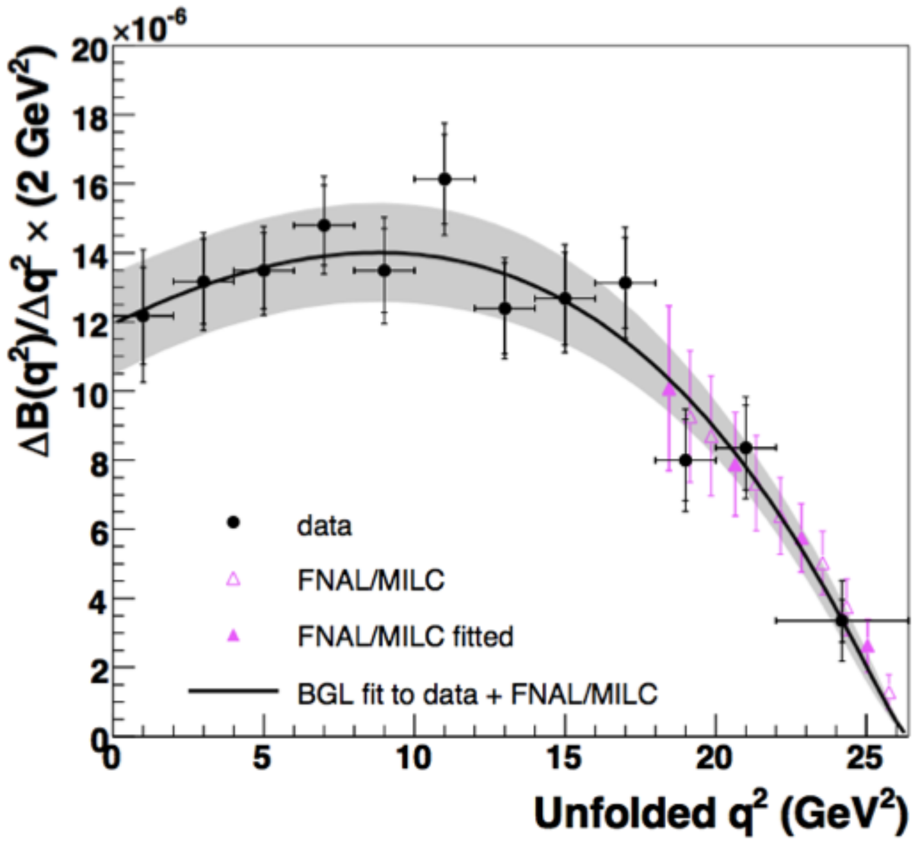
$B \to \pi l \nu$ untagged

[PRD 86, 092004 (2012)]

- FF parameterization: Boyd-Grinstein-Lebed

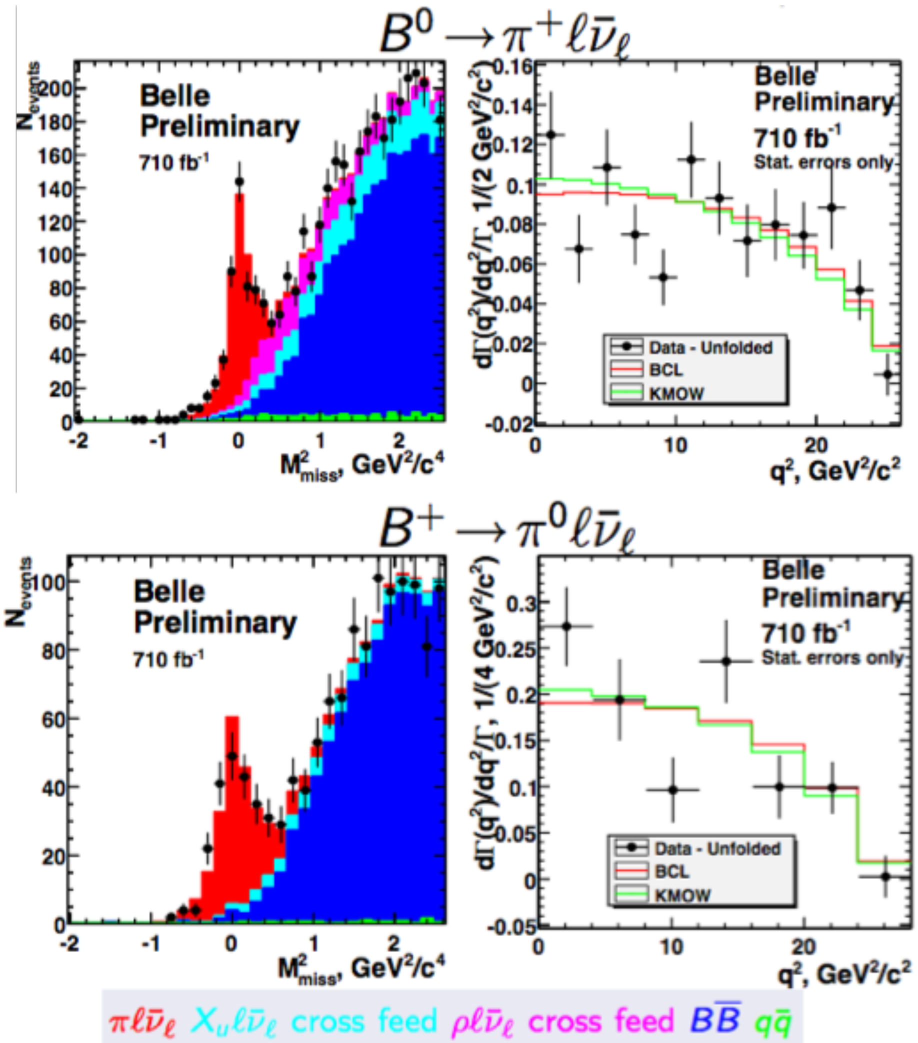
$$f_+(q^2) = \frac{1}{\mathcal{P}(q^2)\phi(q^2,q_0^2)} \sum_{k=0}^{k_{max}} a_k(q_0^2)[z(q^2,q_0^2)]^k \qquad z(q^2,q_0^2) = \frac{\sqrt{m_+^2-q^2}-\sqrt{m_+^2-q_0^2}}{\sqrt{m_+^2-q^2}+\sqrt{m_+^2-q_0^2}}$$

- Combined fit with FNAL/MILC lattice data yields $|V_{ub}|$ = (3.25 +/- 0.31) x 10^{-3}
- Alternative extractions of $|V_{ub}|$ (using LCSR/LQCD in regions of q^2) consistent with the combined fit



$B \to \pi l \nu$ with hadronic tag

[PRD 88, 032005 (2013)]

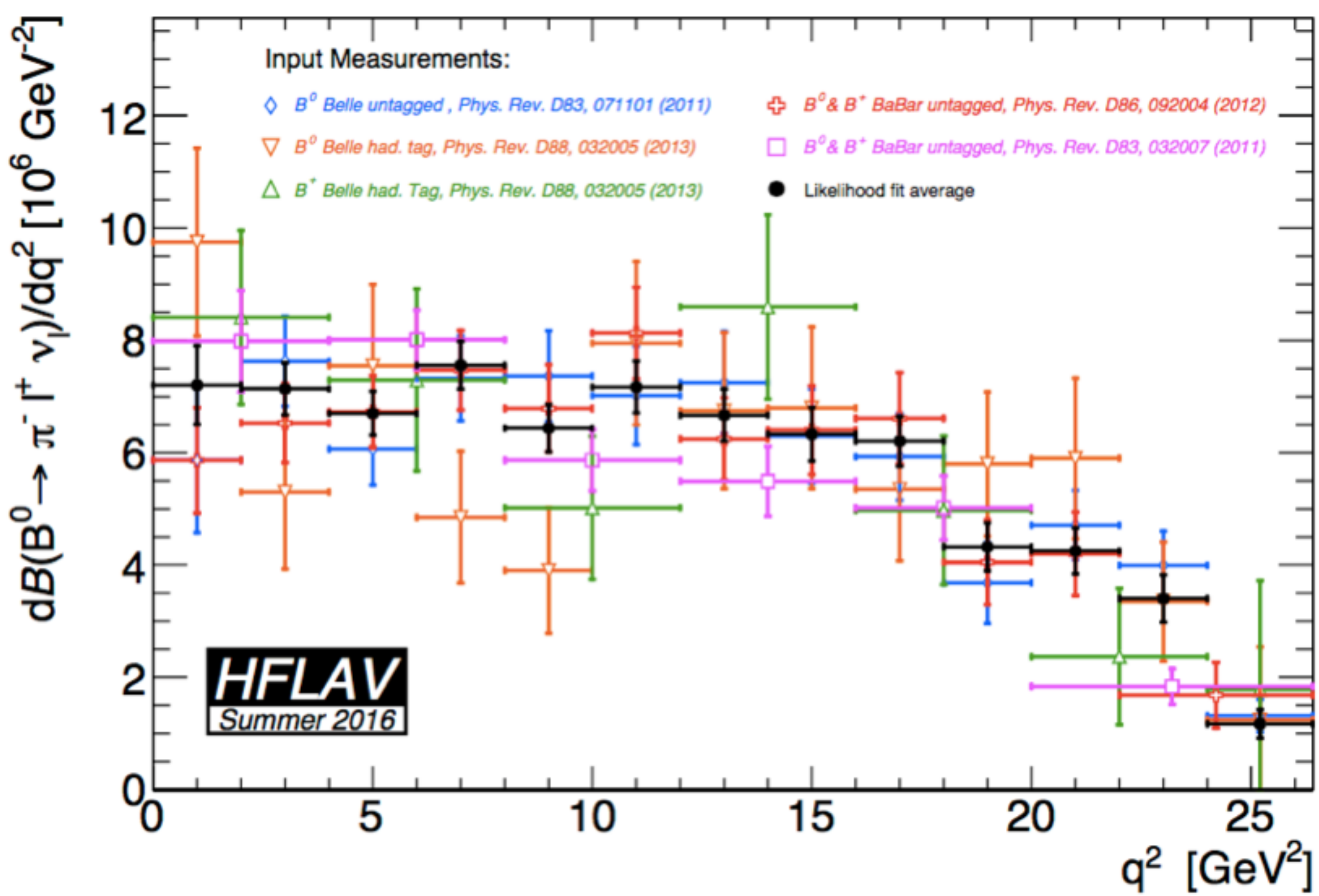


- 703/fb of Belle Y(4S) data
- Hadronic tag
- Yield extracted from M^2_{miss} in 13 (7) bins of q^2 for $B^0 \to \pi^+ l \nu$ ($B^+ \to \pi^0 l \nu$)
- Main systematics: tag calibration

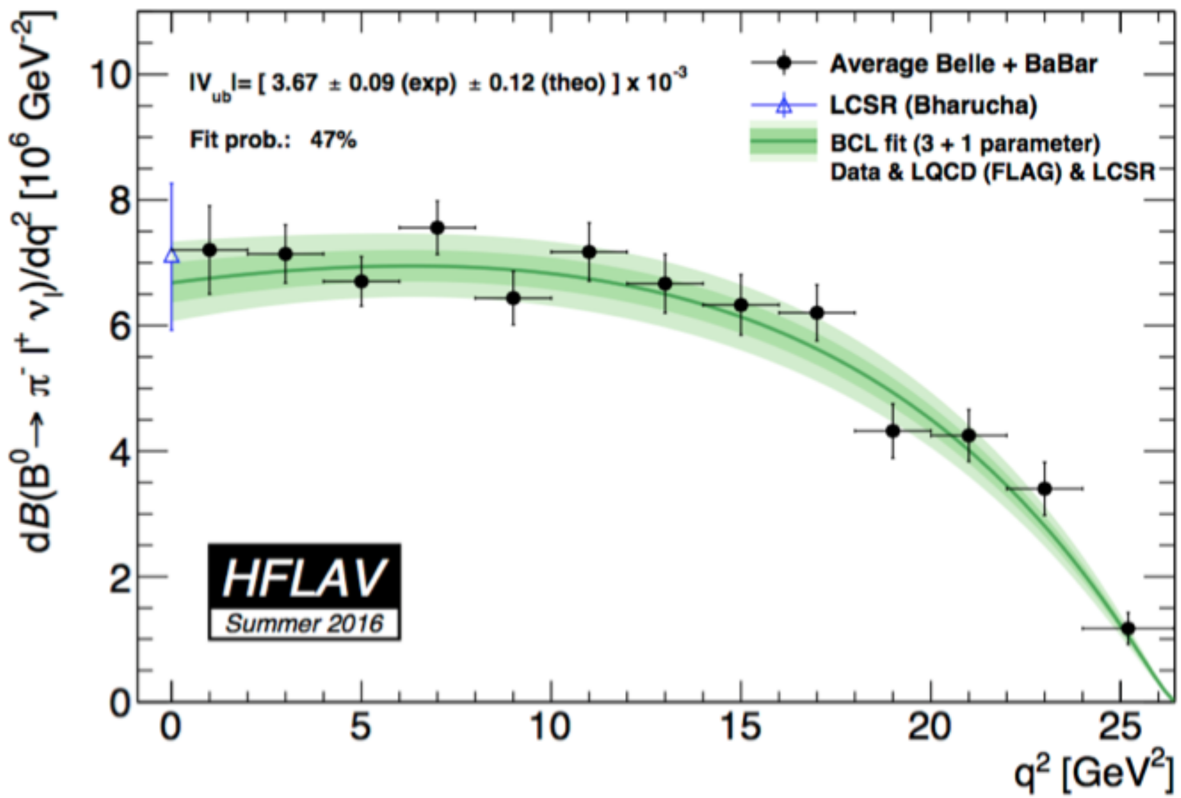
X_u	Yield	$\mathcal{B} \times 10^4$
π^+	461 ± 28	$1.49 \pm 0.09 \pm 0.07$
π^0	230 ± 22	$0.80 \pm 0.08 \pm 0.04$

X_u	Theory	q^2, GeV/c^2	$\lvert V_{ub}\rvert \times 10^3$
π^0	LCSR1	< 12	$3.30 \pm 0.22 \pm 0.09^{+0.35}_{-0.30}$
	LCSR2	< 16	$3.62 \pm 0.20 \pm 0.10^{+0.60}_{-0.40}$
	HPQCD	> 16	$3.45 \pm 0.31 \pm 0.09^{+0.58}_{-0.38}$
	FNAL/MILC	> 16	$3.30 \pm 0.30 \pm 0.09^{+0.36}_{-0.30}$
π^+	LCSR1	< 12	$3.38 \pm 0.14 \pm 0.09^{+0.36}_{-0.32}$
	LCSR2	< 16	$3.57 \pm 0.13 \pm 0.09^{+0.59}_{-0.39}$
	HPQCD	> 16	$3.86 \pm 0.23 \pm 0.10^{+0.66}_{-0.44}$
	FNAL/MILC	> 16	$3.69 \pm 0.22 \pm 0.09^{+0.41}_{-0.34}$

HFLAV 2016: Average q^2 spectrum…



…and BCL fit



Proportional to

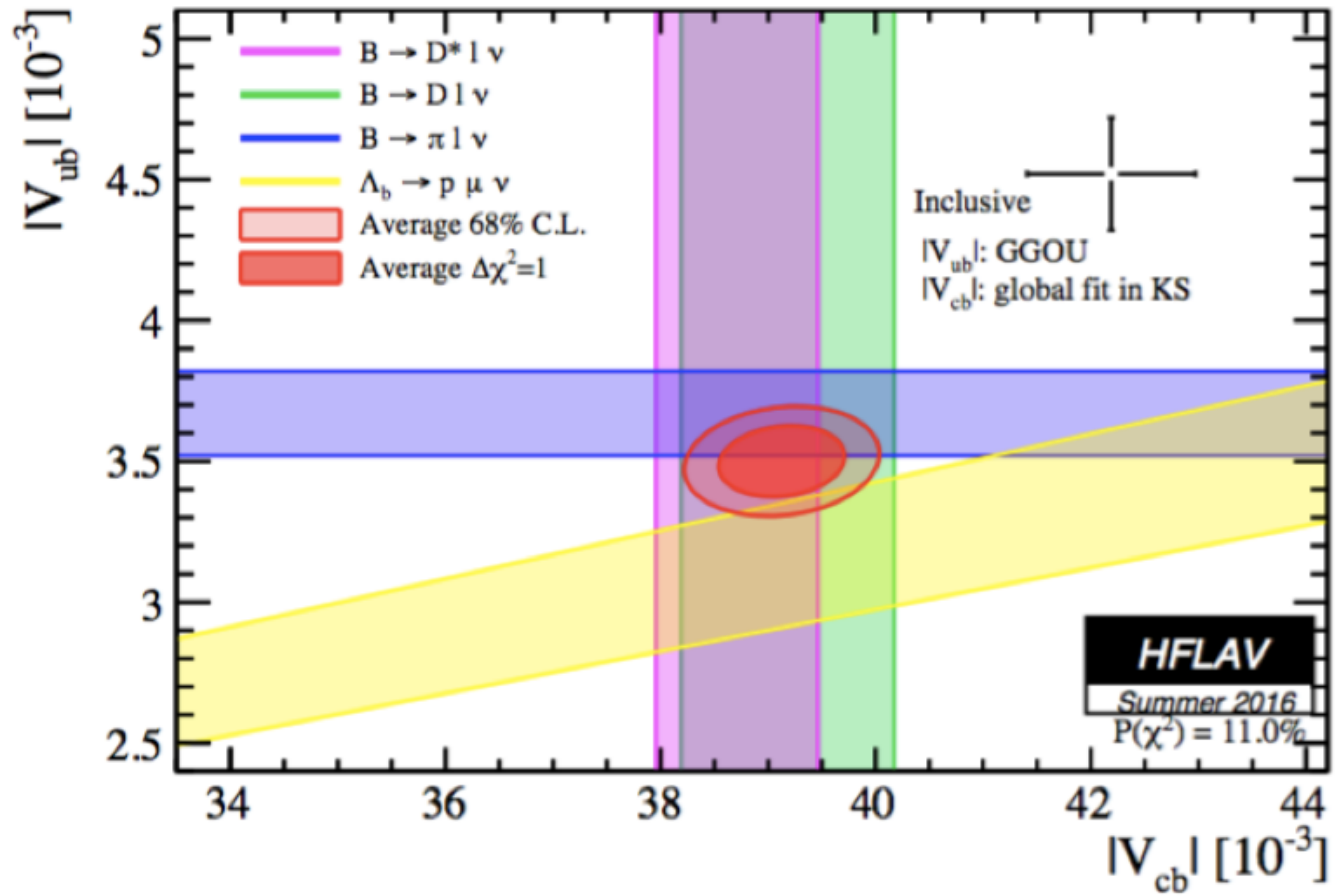
$$|V_{ub}|^2 |f_+(q^2)|^2$$

$$\chi^2 = \left(\vec{\mathcal{B}} - \Delta\vec{\Gamma}\,\tau\right)^T C^{-1} \left(\vec{\mathcal{B}} - \Delta\vec{\Gamma}\,\tau\right) + \chi^2_{\rm LQCD} + \chi^2_{\rm LCSR}$$

Lattice QCD enters the fit through a constraint on the BCL parameters (FLAG lattice average [arXiv:1203.1359 [hep-ph]])

HFLAV 2016 results for $|V_{ub}|$

- Exclusive
  - Data + LQCD:
    $(3.70 \pm 0.10(\text{exp}) \pm 0.12(\text{th})) \times 10^{-3}$
  - Data + LQCD + LCSR:
    $(3.67 \pm 0.09(\text{exp}) \pm 0.12(\text{th})) \times 10^{-3}$
- Inclusive
  - BLNP: $(4.44 \pm 0.15 {}^{+0.21}_{-0.22}) \times 10^{-3}$
  - DGE: $(4.52 \pm 0.16 {}^{+0.15}_{-0.16}) \times 10^{-3}$
  - GGOU: $(4.52 \pm 0.15 {}^{+0.11}_{-0.14}) \times 10^{-3}$



$|V_{ub}|$ [10^{-3}]
5
4.5
4
3.5
3
2.5
34
36
38
40
42
44
$|V_{cb}|$ [10^{-3}]
B → D* l ν
B → D l ν
B → π l ν
Λ_b → p μ ν
Average 68% C.L.
Average $\Delta\chi^2$=1
Inclusive
$|V_{ub}|$: GGOU
$|V_{cb}|$: global fit in KS
HFLAV
Summer 2016
$P(\chi^2)$ = 11.0%

Summary

- $|V_{cb}|$
  - HFLAV 2016 results
    - exclusive ($D^*l\nu$): (39.05 +/- 0.47(exp) +/- 0.58(th)) x 10^{-3}
    - inclusive: (42.19 +/- 0.78) x 10^{-3}
  - Evidence has been mounting in the past two years that the CLN parameterization is biasing the exclusive result
    - On two independent $D^*l\nu$ data sets BGL results in $|V_{cb}|$ being ~2σ higher than CLN
- $|V_{ub}|$
  - HFLAV 2016 results
    - $\pi l\nu$: (3.70 +/- 0.10(exp) +/- 0.12(th)) x 10^{-3}
    - inclusive (BLNP): (4.44 +/- 0.15 +0.21/-0.22) x 10^{-3}
  - For $|V_{ub}|$ however, the ~3σ discrepancy remains to be understood

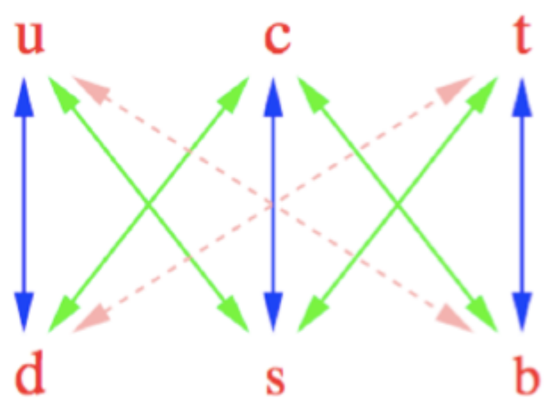
Backup

Cabibbo-Kobayashi-Maskawa quark mixing

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathbf{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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

$$\mathbf{V}\,\mathbf{V}^{\dagger} = \mathbf{V}^{\dagger}\,\mathbf{V} = 1$$



- The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix transforms the flavour eigenstates into the physical quark states
- The CKM element magnitudes determine the possible quark flavour transitions in charged current processes

$$-\mathcal{L}_{W^\pm} = \frac{g}{\sqrt{2}}\,\overline{u_{Li}}\,\gamma^{\mu}\,(V_{\rm CKM})_{ij}\,d_{Lj}\,W_{\mu}^{+} + \text{h.c.}$$

CP violation

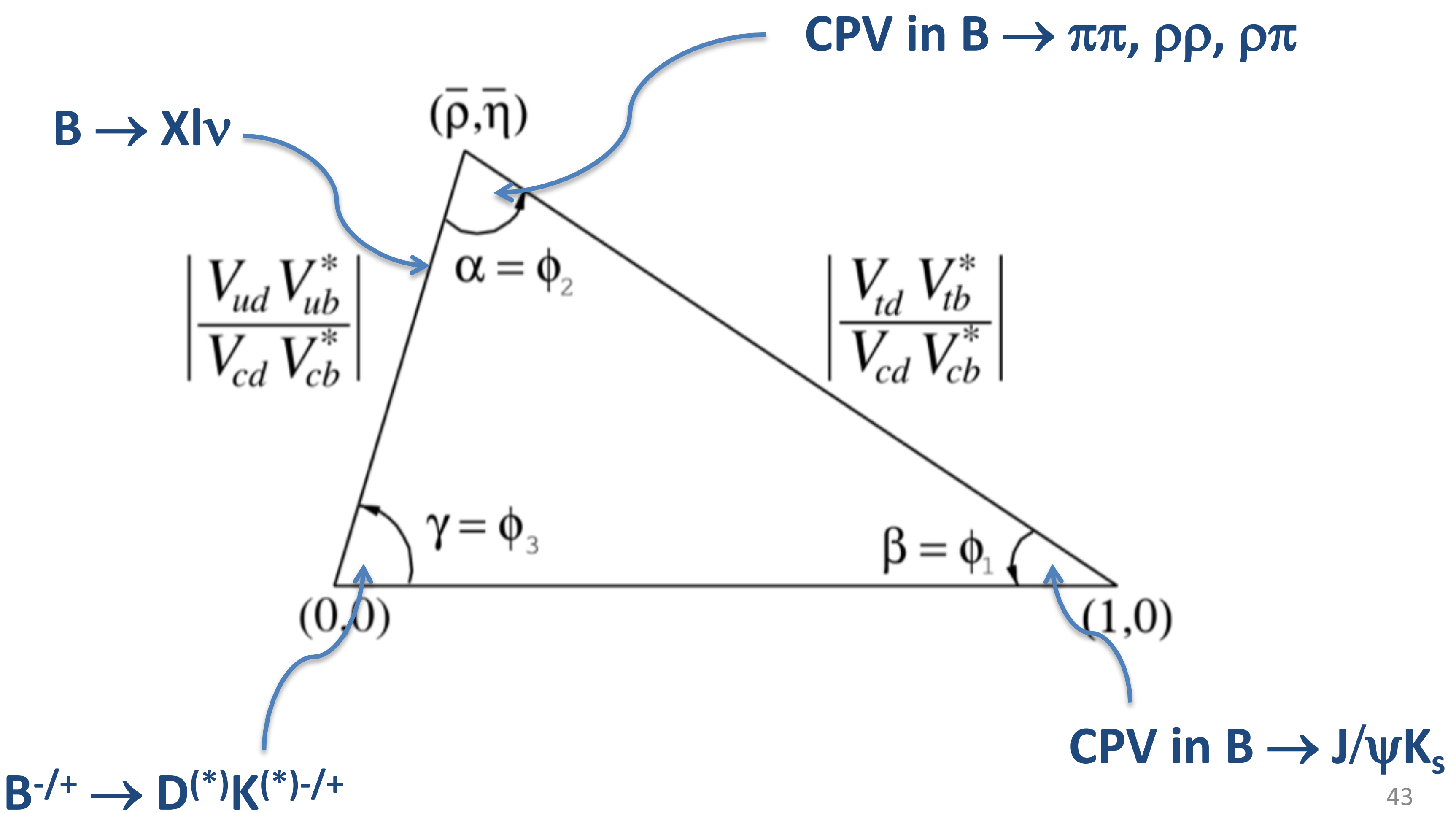
Wolfenstein parametrization of V_{CKM}

$$V_{\rm CKM} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

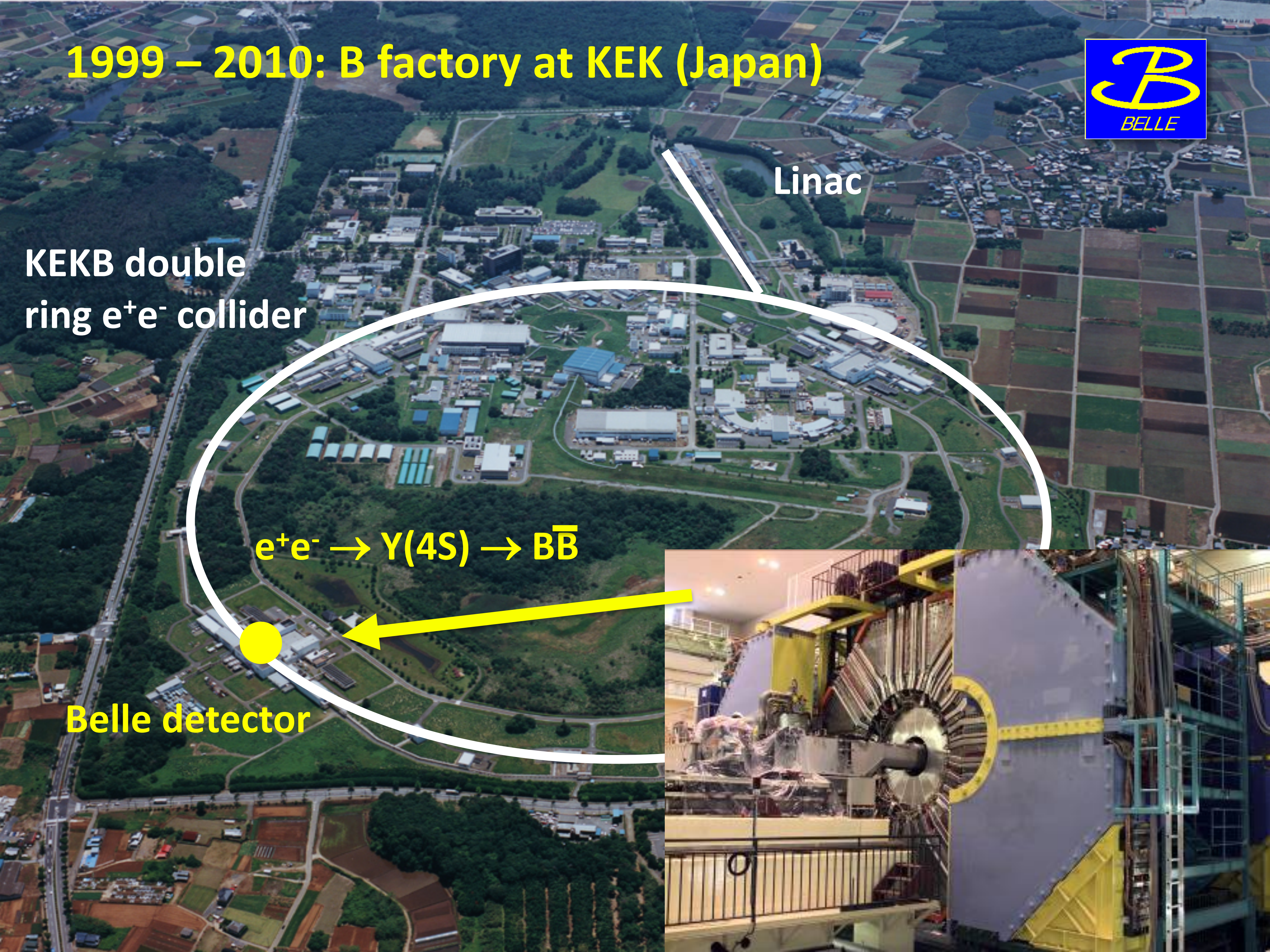
- However, V_{CKM} also contains a complex phase, responsible for all CP-violating phenomena in the SM
- CPV established ($>5\sigma$) in 17 observables (in K and B physics) $\rightarrow$ extremely constrained system
- New physics would typically disturb the SM pattern of CPV

The CKM unitarity triangle

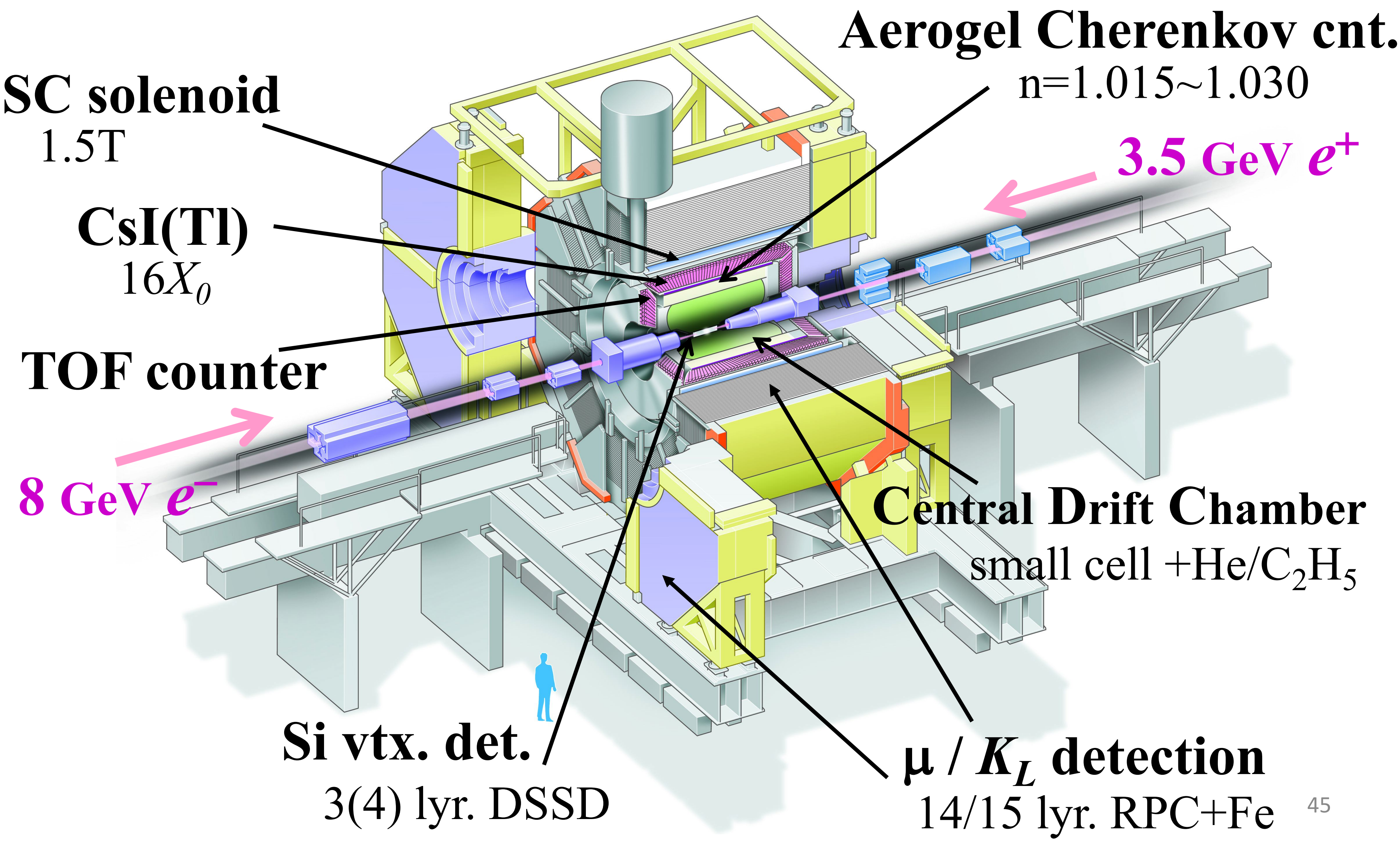
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



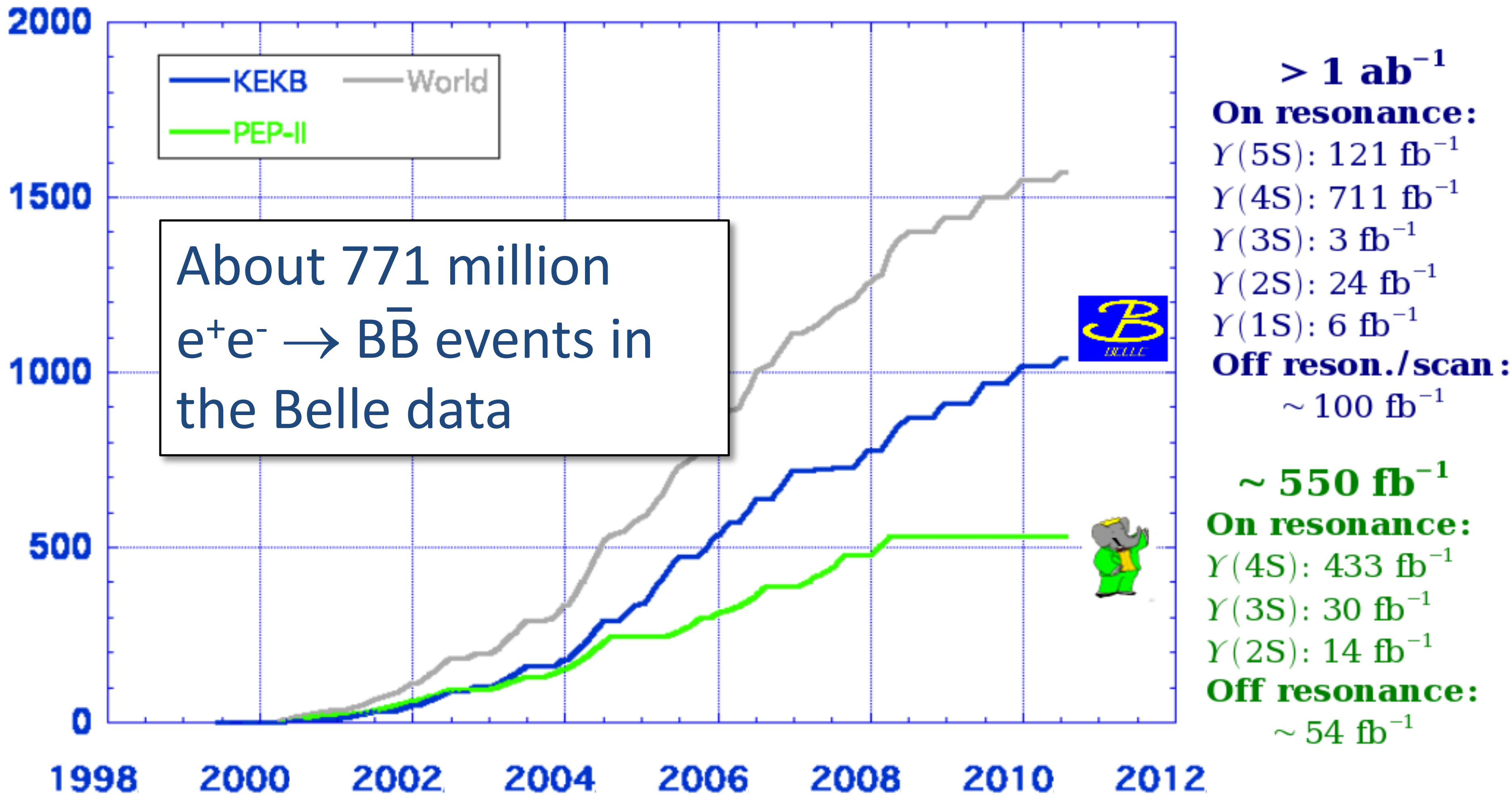
1999 – 2010: B factory at KEK (Japan)



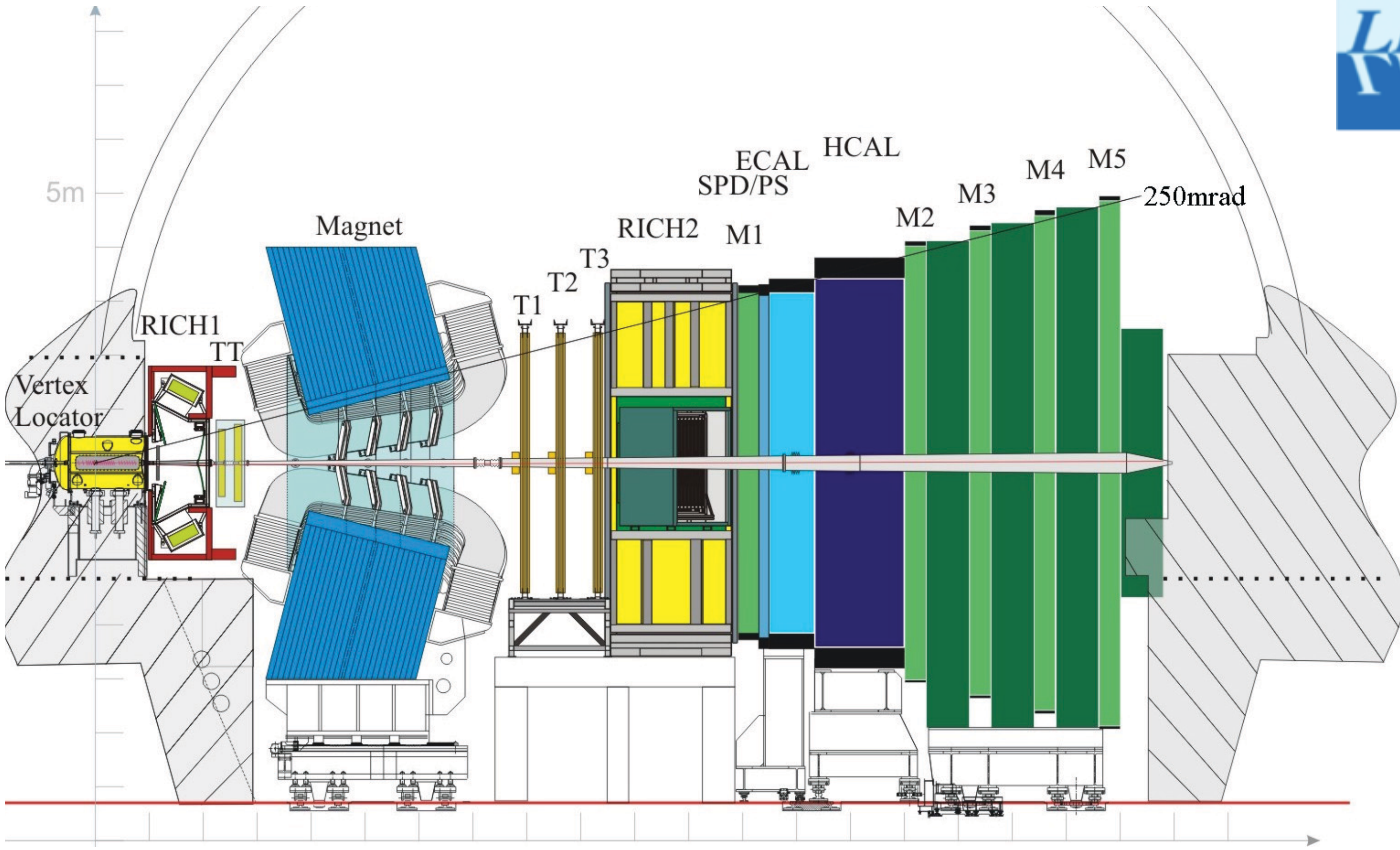
The Belle detector



Belle and BaBar luminosity



The LHCb experiment



- General purpose LHC experiment covering the forward region
- Precise tracking, excellent particle identification

LHCb data taking