Exclusive $|V_{cb}|$ at Belle

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Outline of this talk

1. Belle $B^0 \to D^{*-} l^+ \nu$ with hadronic tag (CKM 2016 preliminary)
   BELLE-CONF-1612

2. Belle $B \to \overline{D} l^+ \nu$ with hadronic tag
   Phys. Rev. D93, 032006 (2016)

3. HFAG summer 2016 averages

$B \to D^{(*)} l\nu$ decay width

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

$B \to D^* l\nu$

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

$B \to D l\nu$

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

Form factor parameterizations

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

B → D*lν

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

B → Dlν

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

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

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

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

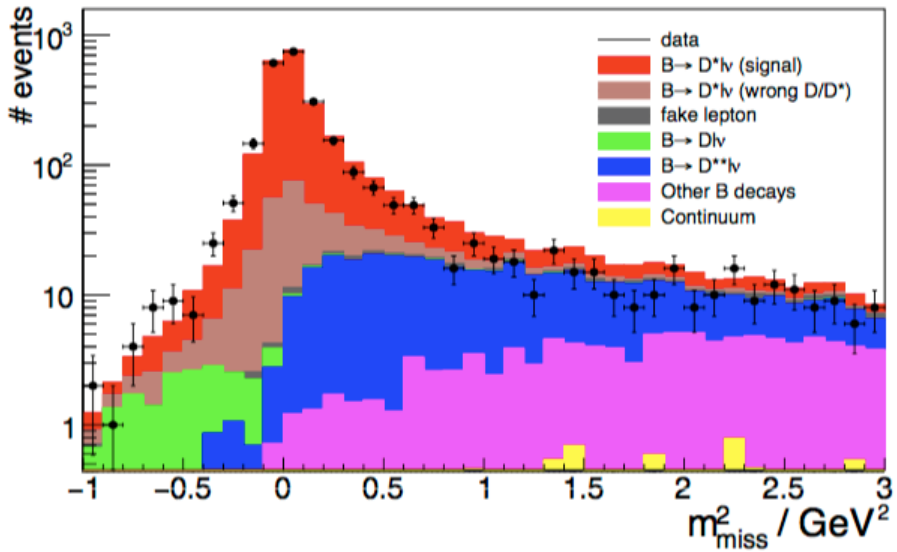
Parameters: coefficients $a_{i,n}$

Belle $B^0 \to D^{*-} l^+ \nu$ with hadronic tag

BELLE-CONF-1612 (preliminary)

Event reconstruction and inclusive fit

- *Tag side*: B_{tag} reconstructed in over 1100 hadronic modes, 0.2% efficiency for neutral B mesons
- *Signal side*: B_{sig} assembled from an identified charged lepton (electron or muon) and a D^{*+} candidate
- $D^0 \rightarrow K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$ (26.3%), $D^+ \rightarrow K^-\pi^+\pi^+$ (9.4)%
- $D^{*+} \rightarrow D^0\pi^+$, $D^+\pi^0$ (98.4%)
- Signal is extracted from the missing mass distribution by an unbinned maximum likelihood fit



ℓ	ν^{sig}
$e+\mu$	2374 ± 53
e	1306 ± 40
μ	1066 ± 34

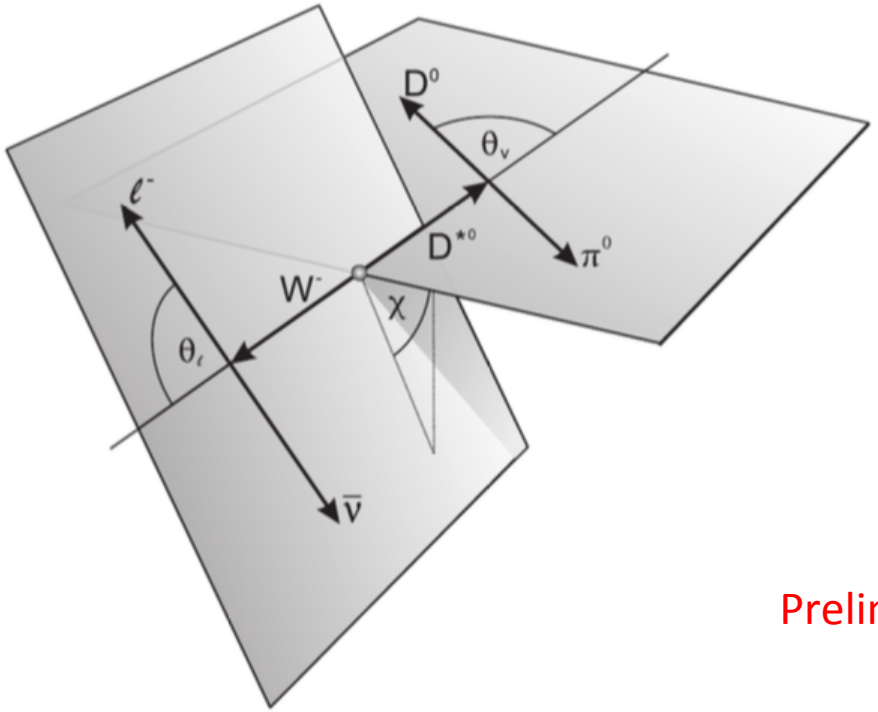
Preliminary!

$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.95 \pm 0.11 \pm 0.21) \times 10^{-2}$$

$$R_{e\mu} = \frac{\mathcal{B}(B^0 \to D^{*-}e^+\nu_e)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu_\mu)} = 1.04 \pm 0.05 \pm 0.01$$

Largest syst: tag calibration

Differential fit result



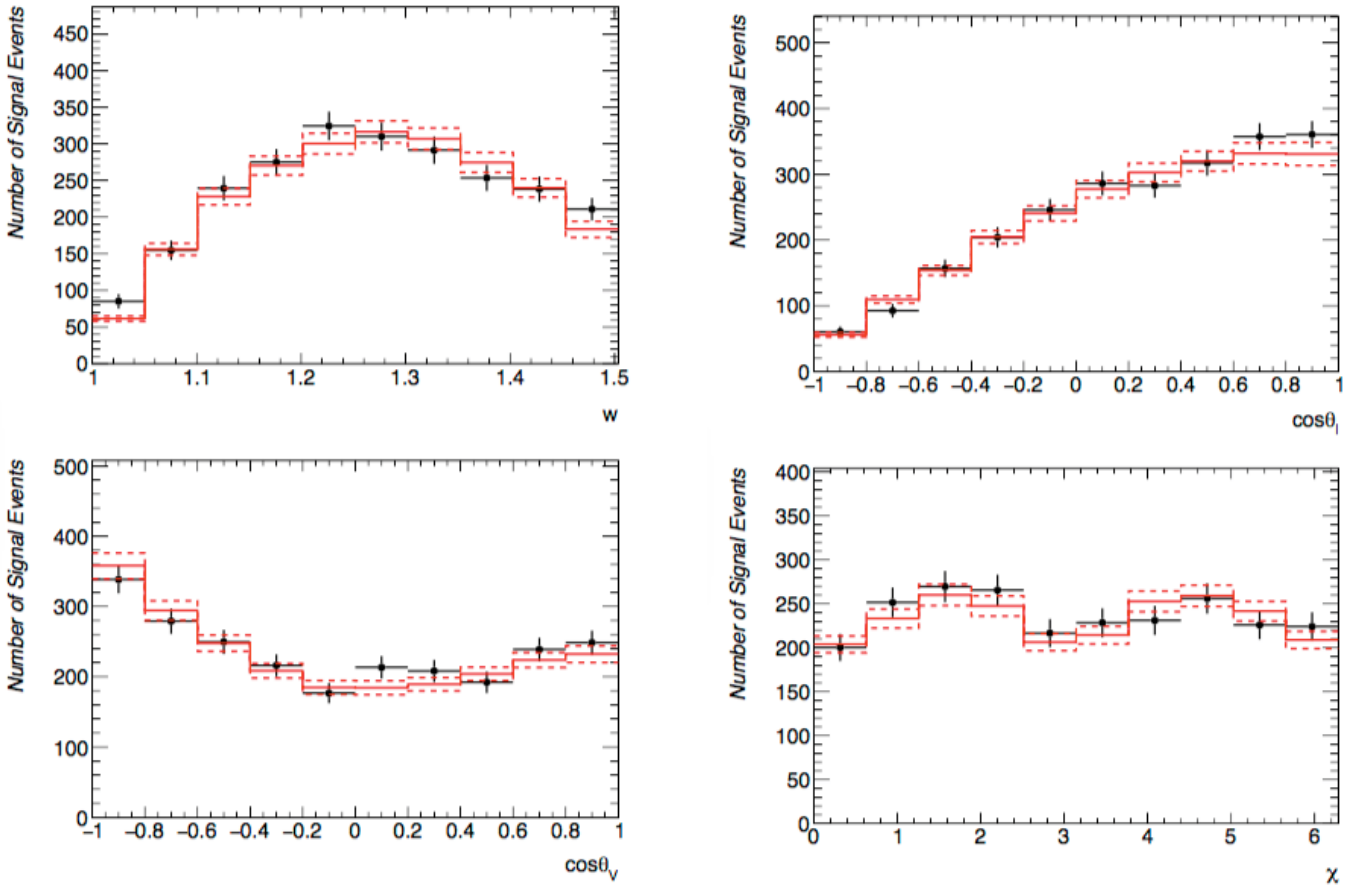
Preliminary!

Variable	Bin	$\Delta\Gamma/\Delta x$ $[10^{-15}\text{GeV}]$
w	1	1.32 ± 0.11
	2	2.08 ± 0.15
	3	2.39 ± 0.15
	4	2.57 ± 0.16
	5	2.63 ± 0.15
	6	2.46 ± 0.14
	7	2.25 ± 0.14
	8	2.08 ± 0.13
	9	1.99 ± 0.12
	10	1.83 ± 0.13
$\cos\theta_v$	1	2.80 ± 0.19
	2	2.30 ± 0.14
	3	1.95 ± 0.13
	4	1.70 ± 0.11
	5	1.58 ± 0.11
	6	1.65 ± 0.11
	7	1.77 ± 0.12
	8	2.00 ± 0.14
	9	2.50 ± 0.16
	10	3.19 ± 0.25
$\cos\theta_\ell$	1	0.73 ± 0.07
	2	1.18 ± 0.09
	3	1.64 ± 0.11
	4	2.04 ± 0.13
	5	2.34 ± 0.14
	6	2.50 ± 0.15
	7	2.54 ± 0.15
	8	2.68 ± 0.16
	9	2.83 ± 0.20
	10	2.82 ± 0.24
χ	1	1.86 ± 0.16
	2	2.31 ± 0.15
	3	2.59 ± 0.16
	4	2.37 ± 0.15
	5	1.95 ± 0.13
	6	1.87 ± 0.15
	7	2.11 ± 0.15
	8	2.33 ± 0.15
	9	2.15 ± 0.15
	10	1.89 ± 0.16

- Yield is also extracted in 4x10 bins of w, cos θ_l, cos θ_v and χ
- Overlapping samples → statistical correlations between partial widths, determined with bootstraping technique
- Unfolding of resolution effect with the SVD algorithm [Nucl.Instr.Meth. A372, 469 (1996)]

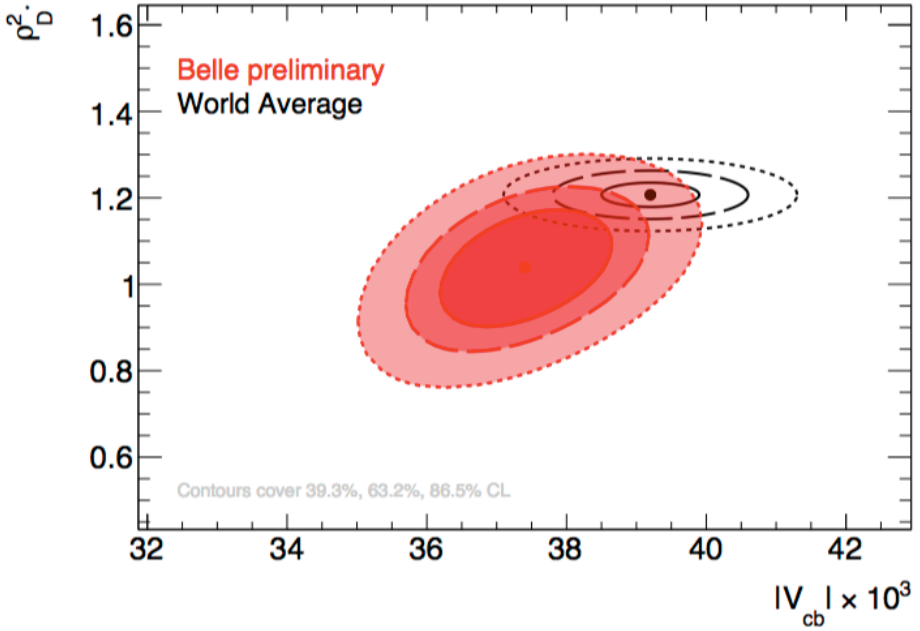
CLN fit to the differential widths

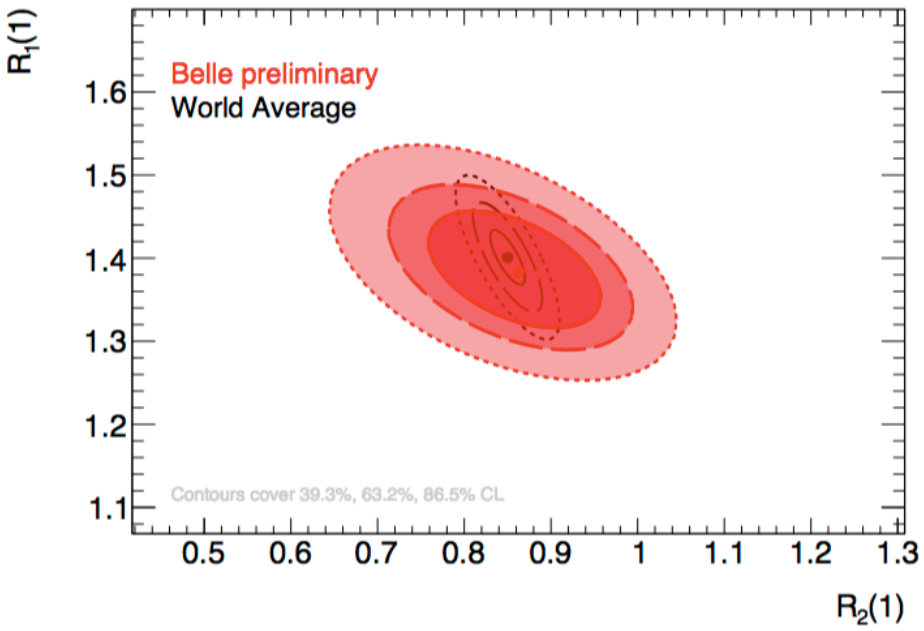
$$\chi^2 = \left(\boldsymbol{\nu}_{\rm sig} - \boldsymbol{\nu}_{\rm sig}^{\rm pred}\right) C^{-1} \left(\boldsymbol{\nu}_{\rm sig} - \boldsymbol{\nu}_{\rm sig}^{\rm pred}\right) + \left(h_{A1}(1) - h_{A1}^{\rm la}(1)\right)^2 / \left(\sigma_{h_{A1}(1)}^{\rm la}\right)^2$$



Points with error bars: Belle data,
red histogram: fit result, dashed histogram: $\Delta\chi^2$=1 contour

CLN fit to the differential widths (2)





Parameter	This result
$\|V_{cb}\| \times 10^3$	37.4 ± 1.2
$\rho^2_{D^*}$	1.04 ± 0.13
$R_1(1)$	1.38 ± 0.07
$R_2(1)$	0.86 ± 0.10

$$C = \begin{pmatrix} 1 & 0.42 & -0.20 & -0.16 \\ 0.42 & 1 & 0.21 & -0.87 \\ -0.20 & 0.21 & 1 & -0.47 \\ -0.16 & -0.87 & -0.47 & 1 \end{pmatrix}$$

χ^2 = 39.8 for 40-4 degrees of freedom

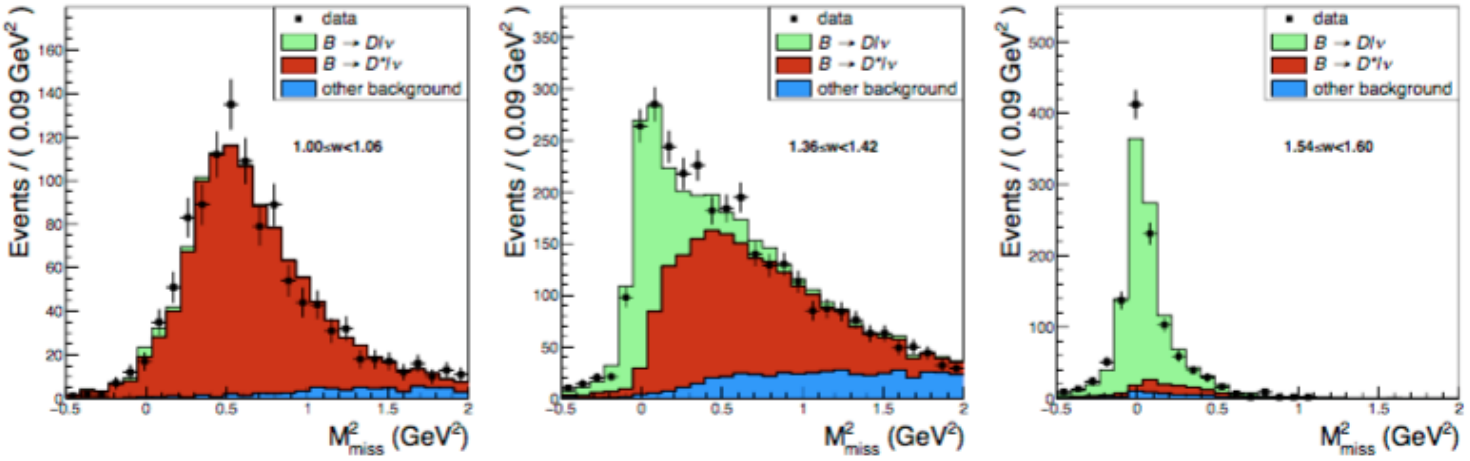
Preliminary!

Belle $B \to \bar{D} l \nu$ with hadronic tag

Phys. Rev. D93, 032006 (2016)

Event reconstruction

- Identical event reconstruction method
- 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)



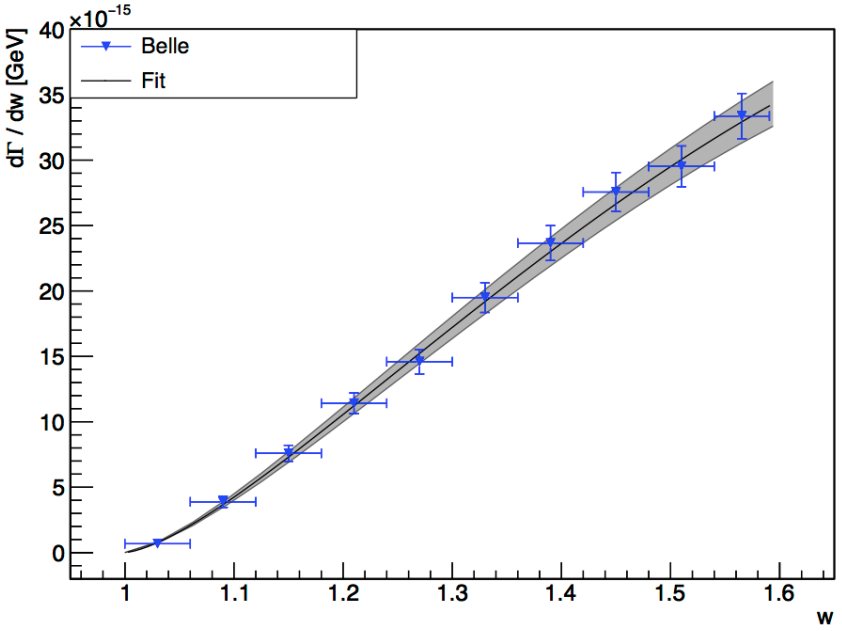
Differential width and branching fraction

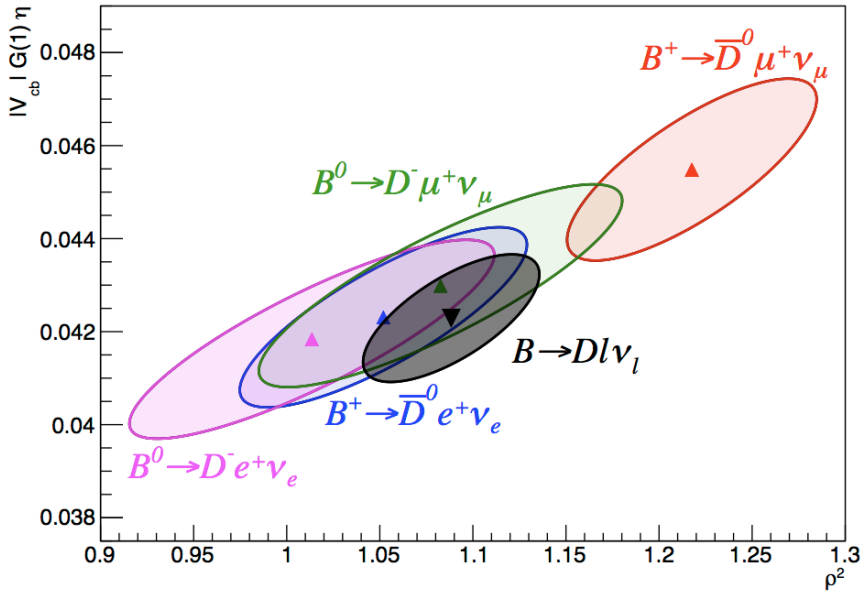
				$\rho_{ij,\mathrm{syst}}$									
i	$w_{i,\min}$	$w_{i,\max}$	$\Delta\Gamma_i/\Delta w[10^{-15}\mathrm{GeV}]$	0	1	2	3	4	5	6	7	8	9
0	1.00	1.06	$0.68 \pm 0.21 \pm 0.05$	1.000	0.682	0.677	0.663	0.654	0.656	0.664	0.648	0.608	0.560
1	1.06	1.12	$3.88 \pm 0.38 \pm 0.18$		1.000	0.976	0.974	0.969	0.972	0.972	0.961	0.933	0.900
2	1.12	1.18	$7.59 \pm 0.50 \pm 0.35$			1.000	0.991	0.987	0.990	0.989	0.980	0.959	0.929
3	1.18	1.24	$11.42 \pm 0.58 \pm 0.54$				1.000	0.993	0.993	0.990	0.980	0.961	0.934
4	1.24	1.30	$14.59 \pm 0.64 \pm 0.69$					1.000	0.996	0.992	0.985	0.972	0.952
5	1.30	1.36	$19.49 \pm 0.69 \pm 0.91$						1.000	0.996	0.991	0.979	0.956
6	1.36	1.42	$23.66 \pm 0.76 \pm 1.10$							1.000	0.995	0.981	0.952
7	1.42	1.48	$27.56 \pm 0.79 \pm 1.27$								1.000	0.992	0.968
8	1.48	1.54	$29.52 \pm 0.80 \pm 1.34$									1.000	0.985
9	1.54	$w_{\max}$	$33.37 \pm 0.86 \pm 1.50$										1.000

Sample	Signal yield	$\mathcal{B}$ [%]
$B^0 \to D^- e^+ \nu_e$	$2848 \pm 72 \pm 17$	$2.44 \pm 0.06 \pm 0.12$
$B^0 \to D^- \mu^+ \nu_\mu$	$2302 \pm 63 \pm 13$	$2.39 \pm 0.06 \pm 0.11$
$B^+ \to \bar{D}^0 e^+ \nu_e$	$6456 \pm 126 \pm 66$	$2.57 \pm 0.05 \pm 0.13$
$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$5386 \pm 110 \pm 51$	$2.58 \pm 0.05 \pm 0.13$
$B^0 \to D^- \ell^+ \nu_\ell$	$5150 \pm 95 \pm 29$	$2.39 \pm 0.04 \pm 0.11$
$B^+ \to \bar{D}^0 \ell^+ \nu_\ell$	$11843 \pm 167 \pm 120$	$2.54 \pm 0.04 \pm 0.13$
$B \to D \ell \nu_\ell$	$16992 \pm 192 \pm 142$	$2.31 \pm 0.03 \pm 0.11$

$$R_D^{\mu/e} = \mathcal{B}(B \to D\mu\nu)/\mathcal{B}(B \to De\nu) = 0.995 \pm 0.022(\mathrm{stat}) \pm 0.039(\mathrm{syst})$$

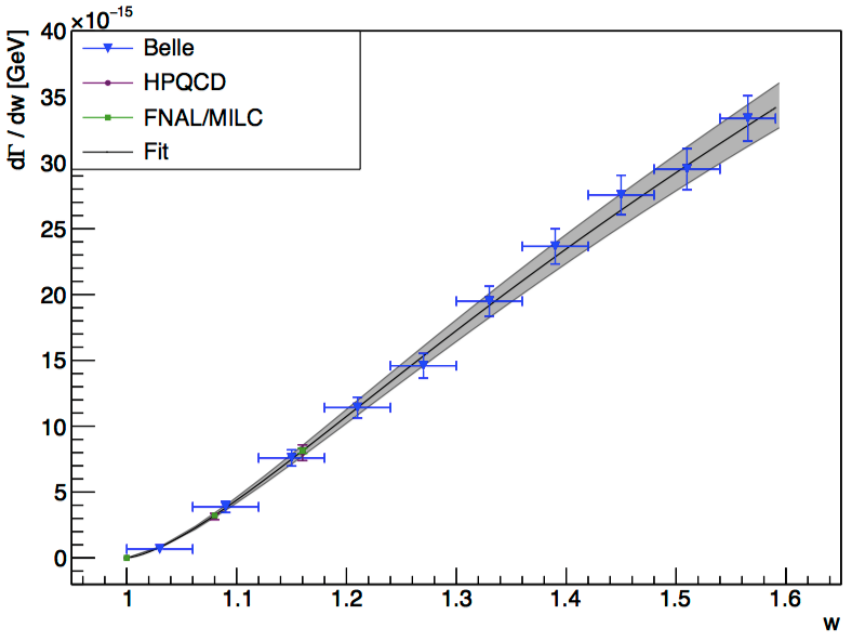
CLN fit to the differential widths

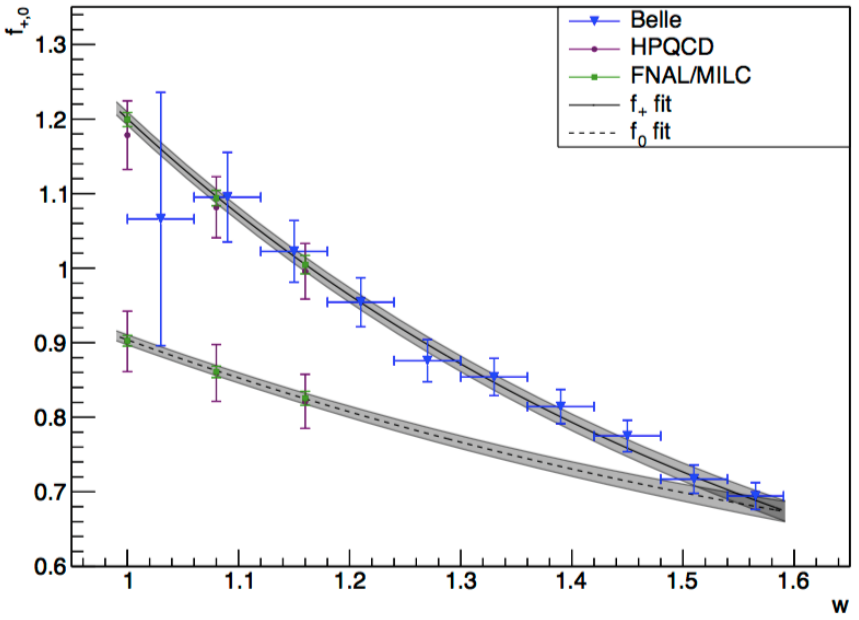




	$B^+ \to \bar{D}^0 e^+ \nu_e$	$B^+ \to \bar{D}^0 \mu^+ \nu_\mu$	$B^0 \to D^- e^+ \nu_e$	$B^0 \to D^- \mu^+ \nu_\mu$	$B \to D \ell \nu_\ell$
$\eta_{\rm EW}\mathcal{G}(1)\lvert V_{cb}\rvert[10^{-3}]$	42.31 ± 1.94	45.48 ± 1.96	41.84 ± 2.14	42.99 ± 2.18	42.29 ± 1.37
ρ^2	1.05 ± 0.08	1.22 ± 0.07	1.01 ± 0.10	1.08 ± 0.10	1.09 ± 0.05
Correlation	0.81	0.77	0.85	0.84	0.69
$\eta_{\rm EW}\lvert V_{cb}\rvert[10^{-3}]$	40.14 ± 1.86	43.15 ± 1.89	39.69 ± 2.05	40.78 ± 2.09	40.12 ± 1.34
$\chi^2/n_{\rm df}$	2.19/8	2.71/8	9.65/8	4.36/8	4.57/8
Prob.	0.97	0.95	0.29	0.82	0.80

BGL fit to differential widths and lattice data



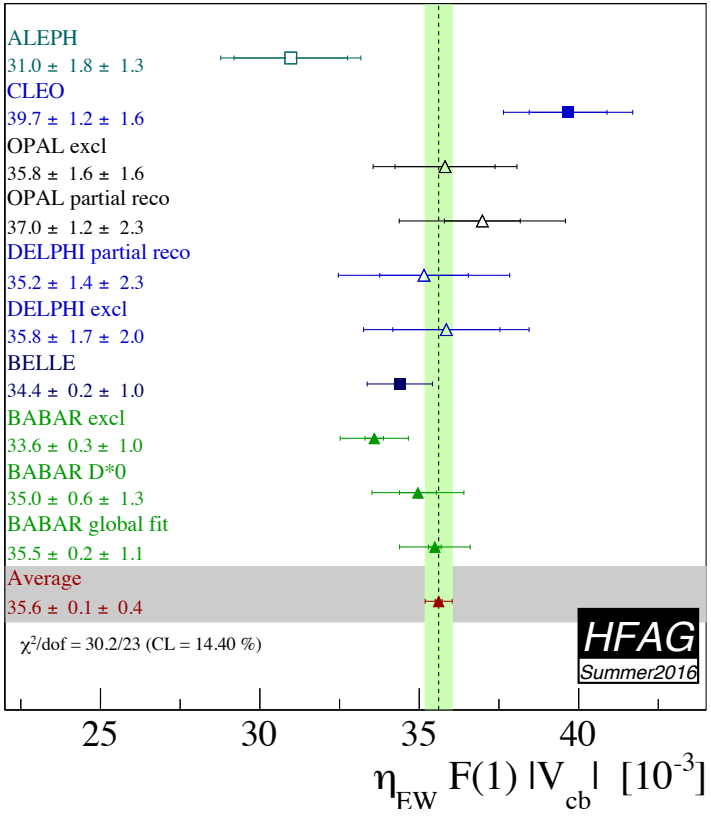


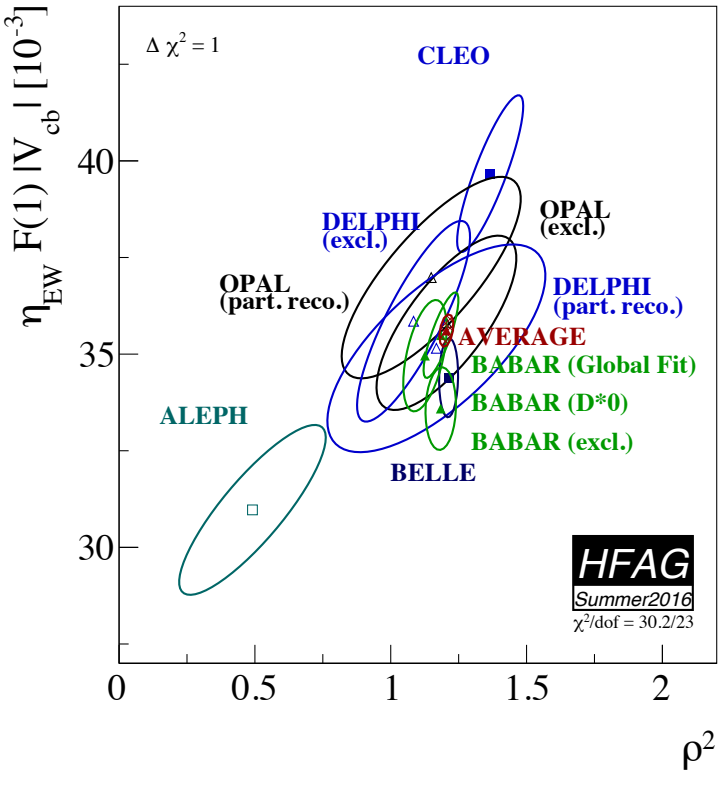
	$N=2$	$N=3$	$N=4$
$a_{+,0}$	0.0127 ± 0.0001	0.0126 ± 0.0001	0.0126 ± 0.0001
$a_{+,1}$	-0.091 ± 0.002	-0.094 ± 0.003	-0.094 ± 0.003
$a_{+,2}$	0.34 ± 0.03	0.34 ± 0.04	0.34 ± 0.04
$a_{+,3}$	–	-0.1 ± 0.6	-0.1 ± 0.6
$a_{+,4}$	–	–	0.0 ± 1.0
$a_{0,0}$	0.0115 ± 0.0001	0.0115 ± 0.0001	0.0115 ± 0.0001
$a_{0,1}$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

Lattice data	$\eta_{\rm EW}\lvert V_{cb}\rvert[10^{-3}]$	$\chi^2/n_{\rm df}$	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

Summer 2016 HFAG results for $|V_{cb}|$exclusive

$\eta_{EW}F(1)|V_{cb}|$ ($B \rightarrow D^*l\nu$)

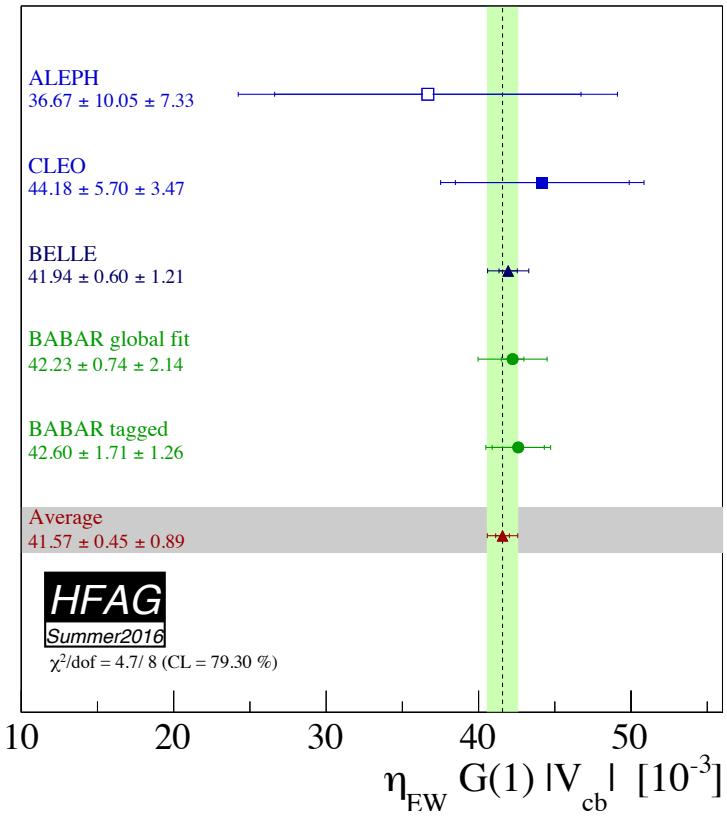


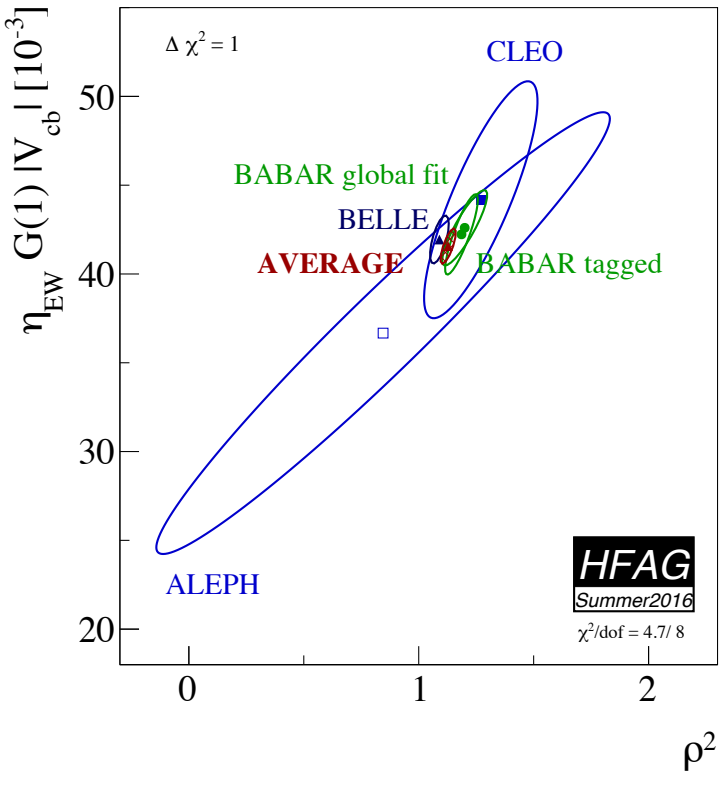


$\eta_{EW}F(1)|V_{cb}| = (35.61 \pm 0.11 \pm 0.41) \times 10^{-3}$

[2014: $\eta_{EW}F(1)|V_{cb}| = (35.81 \pm 0.11 \pm 0.44) \times 10^{-3}$]

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





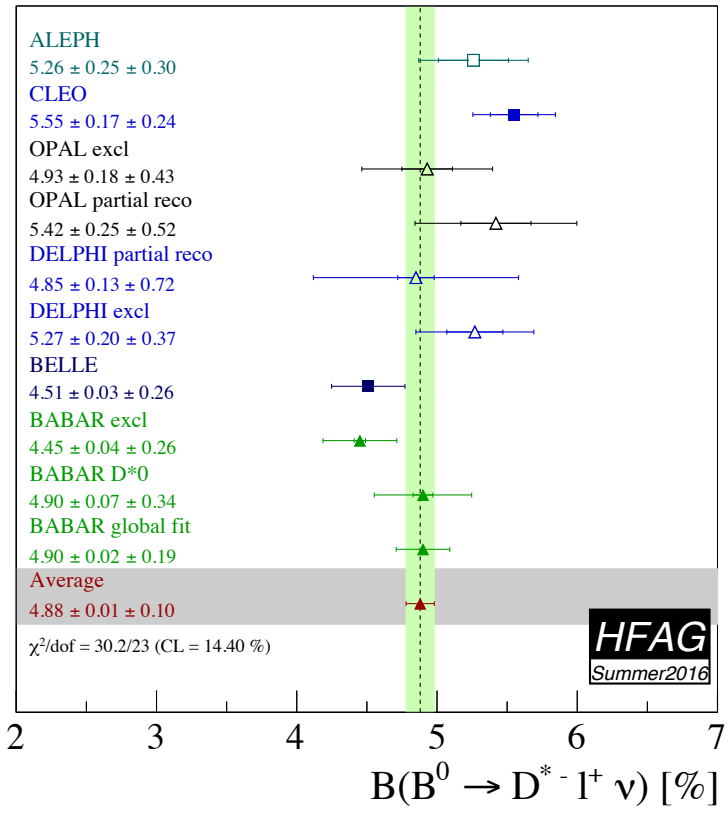
$\eta_{EW}G(1)|V_{cb}| = (41.57 +/- 0.45 +/- 0.89) \times 10^{-3}$

[2014: $\eta_{EW}G(1)|V_{cb}| = (42.65 +/- 0.72 +/- 1.35) \times 10^{-3}$]

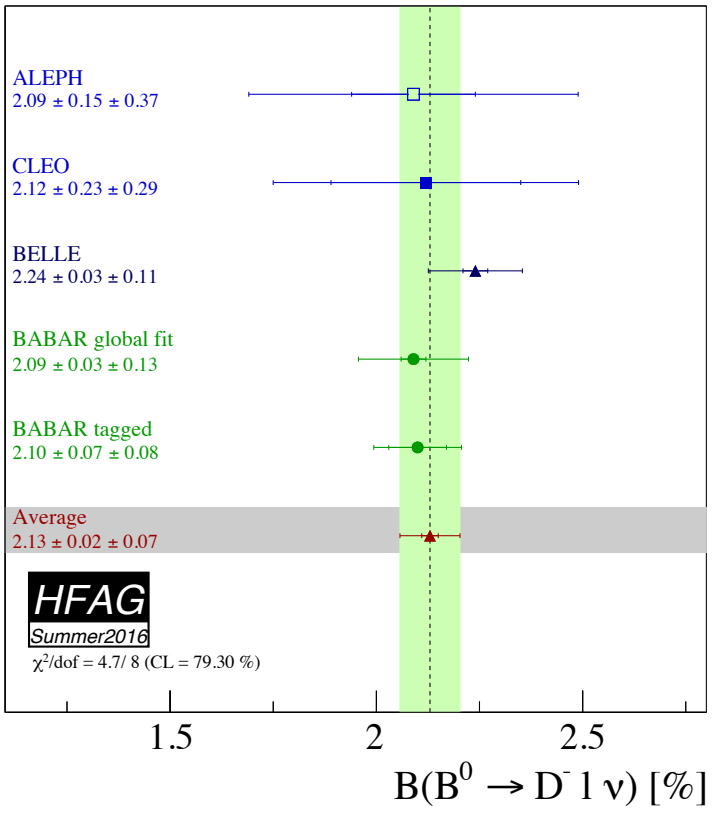
$|V_{cb}|$ exclusive

- $B \rightarrow D^* l\nu$
  - $\eta_{EW} F(1) |V_{cb}| = (35.61 \pm 0.11_{stat} \pm 0.41_{syst}) \times 10^{-3}$
  - $\eta_{EW} F(1) = (0.920 \pm 0.014)$ [FNAL/MILC, PRD89, 114504]
  - $|V_{cb}| = (38.71 \pm 0.47_{exp} \pm 0.59_{th}) \times 10^{-3}$
- $B \rightarrow D l\nu$
  - $\eta_{EW} G(1) |V_{cb}| = (41.57 \pm 0.45 \pm 0.89) \times 10^{-3}$
  - $G(1) = 1.0541 \pm 0.0083$ [FNAL/MILC, PRD92, 034506]
  - $\eta_{EW} = 1.0066 \pm 0.0016$ [NPB 196, 83]
  - $|V_{cb}| = (39.18 \pm 0.94_{exp} \pm 0.31_{th}) \times 10^{-3}$

Branching fractions



$$\mathcal{B}(\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}) = (4.88 \pm 0.10)\%$$



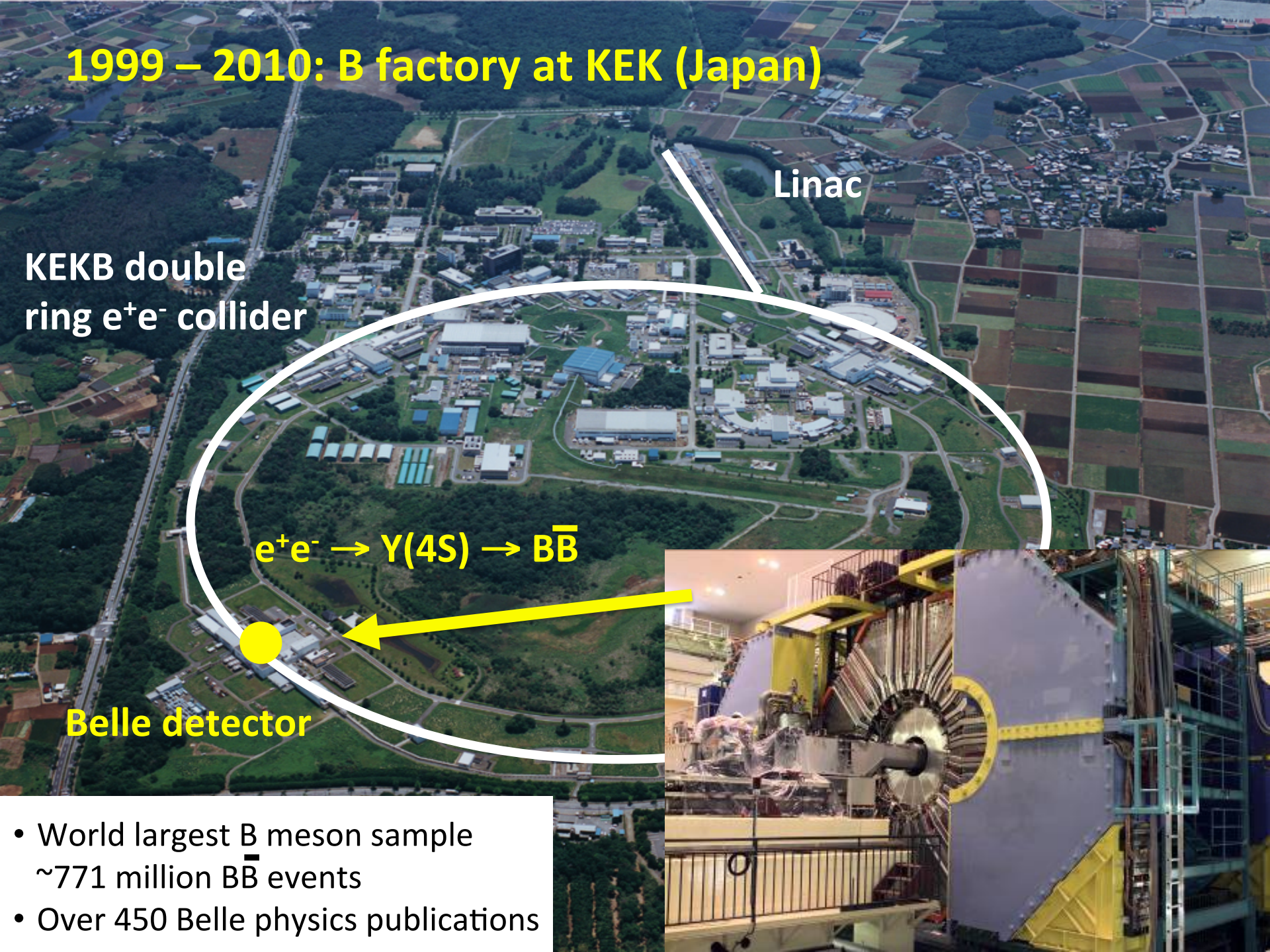
$$\mathcal{B}(\overline{B}^0 \to D^{+}\ell^-\overline{\nu}) = (2.13 \pm 0.07)\%$$

Summary

- Belle $B^0 \to D^{*-} l^+ \nu$ with hadronic tag [BELLE-CONF-1612]
  - About 2400 reconstructed decays
  - $Br(B^0 \to D^{*-} l^+ \nu) = (4.95 \pm 0.11_{stat} \pm 0.21_{syst})\%$
  - CLN fit: $|V_{cb}| = (37.4 \pm 1.2) \times 10^{-3}$
- Belle $B \to Dl\nu$ with hadronic tag [PRD93, 032006 (2016)]
  - About 17,000 signal events (charged and neutral)
  - $Br(B^0 \to Dl\nu) = (2.31 \pm 0.03_{stat} \pm 0.11_{syst})\%$
  - CLN fit: $|V_{cb}| = (39.86 \pm 1.33) \times 10^{-3}$
  - BGL fit: $|V_{cb}| = (40.83 \pm 1.13) \times 10^{-3}$
- HFAG summer 2016 averages
  - $B \to D^* l\nu$: $|V_{cb}| = (38.71 \pm 0.47_{exp} \pm 0.59_{th}) \times 10^{-3}$
  - $B \to Dl\nu$: $|V_{cb}| = (39.18 \pm 0.94_{exp} \pm 0.31_{th}) \times 10^{-3}$

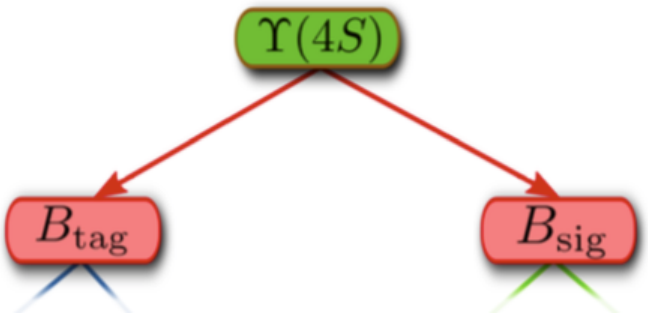
BACKUP

1999 – 2010: B factory at KEK (Japan)



- World largest B meson sample ~771 million $B\bar{B}$ events
- Over 450 Belle physics publications

Tagging techniques for Y(4S) events



- Tagging provides:
  - Background suppression
  - Information on B_{sig} (4-momentum)

PURITY

EFFICIENCY

Untagged
- No requirement on B_{tag}
- High efficiency, low purity

Semileptonic tag
- $B_{tag} \rightarrow D^* l \nu$
- Efficiency ~O(0.2%)

Hadronic tag
- $B_{tag} \rightarrow$ hadrons
- Efficiency ~O(0.1%)

Systematic uncertainties on BR($B^0 \to D^{*-} l^+ \nu$)

Error Source	$\Delta\mathcal{B}$ [%]
Tagging Calibration	3.6
$N_{B\bar{B}}$	1.4
f_{+0}	1.1
PDF shapes	0.9
$\mathcal{B}(D \to K\pi(\pi)(\pi))$	0.4
$\mathcal{B}(D^* \to D\,\pi)$	0.2
$\mathcal{B}(\bar{B} \to D^{**}\,\ell\,\bar{\nu}_\ell)$	0.2
e PID	0.2
μ PID	0.1
π_{slow} Eff.	0.1
$\mathcal{B}(\bar{B} \to D\,\ell\,\bar{\nu}_\ell)$	< 0.1
$B \to D^{(*,**)}\,\ell\,\bar{\nu}_\ell$ FFs	< 0.1
Lepton Fakerates	< 0.1
K PID	< 0.1
Total	4.2