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

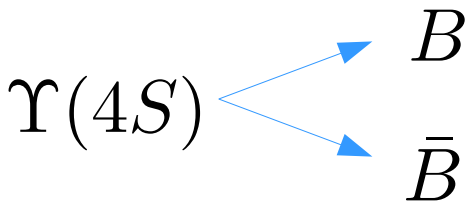
V_{cb} experimental review

Robin Glattauer

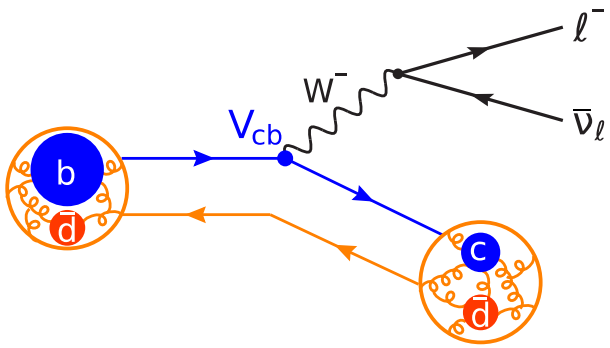
for the Belle Collaboration

Funded by the Austrian Science Fund (FWF): P22742-N16

V_{cb} measurements



- Mainly B-factories (Belle, BaBar) at Y(4S) resonance
  - Low background
  - Many $B\overline{B}$ pairs
- Measure V_{cb} with semileptonic decays (lepton = e,μ)
- Inclusive: $B \to X_c \ell \nu$
  - reconstruct lepton
  - sum over all final states with charm quark
  - measure moments of lepton energy and hadronic mass
- Exclusive: $B \to D^{(*)} \ell \nu$
  - Describe differential decay width using form factors
  - Extract V_{cb} times a form factor constant F(1) or G(1)
  - F(1) and G(1) can be calculated by Lattice QCD or Light Cone Sum Rules



Analyses (the more recent ones)

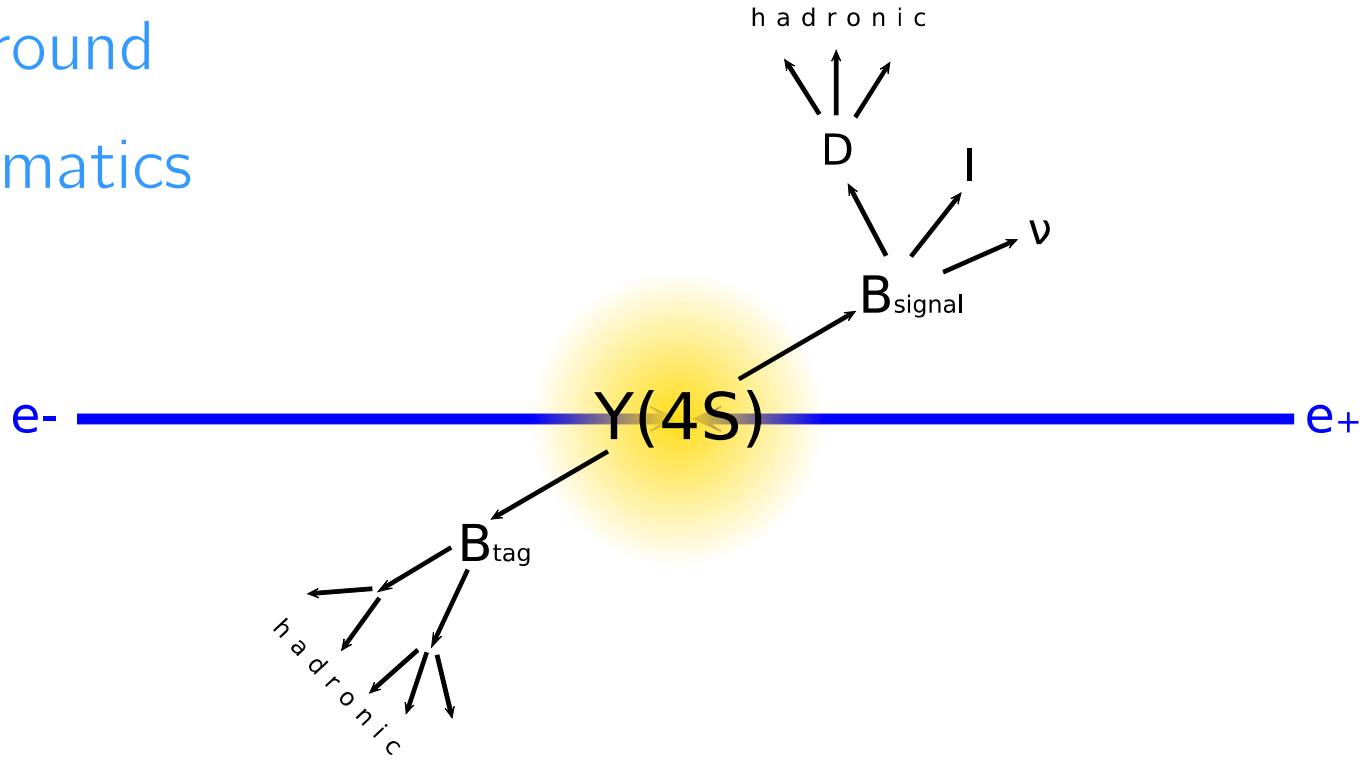
- Inclusive: $B \to X_c \ell \nu$
  - Lepton energy moments BaBar [PRD 69:111104, 2004; PRD 81:032003, 2010]
  - Lepton energy moments Belle [PRD 75:032001, 2007]
  - Hadronic mass moments BaBar [PRD 81:032003, 2010]
  - Hadronic mass moments Belle [PRD 75:032005, 2007]
- Exclusive
  - $B \to D^* \ell \nu$ BaBar [PRD 77:032002, 2008]
  - $B \to D^* \ell \nu$ Belle [PRD 82:112007, 2010]
  - $B \to D \ell \nu$ BaBar [PRD 77:032002, 2008]
  - $B \to D \ell \nu$ Belle ["Semileptonic and leptonic B and Bs decays at Belle" ICHEP 2014, preliminary]
  - BaBar Global Fit [PRD 79:012002, 2009]

Inclusive-Exclusive discrepancy: up to 3σ

Exclusive $B \to D^* \ell \nu$ $F(1)\lvert V_{cb}\rvert = (35.90 \pm 0.11_{stat} \pm 0.44_{syst}) \times 10^{-3}$	**F(1)**	**$\lvert V_{cb}\rvert$ (10^{-3})**
Lattice QCD [PoS LATTICE2010, 311 (2010)]	0.908 ± 0.017	$39.54 \pm 0.50_{exp} \pm 0.74_{th}$
Lattice QCD [arXiv:1403.0635]	0.920 ± 0.013	$39.04 \pm 0.49_{exp} \pm 0.56_{th}$
Sum rules [PRD 81: 113002 (2010)]	0.866 ± 0.020	$41.47 \pm 0.52_{exp} \pm 0.96_{th}$
Exclusive $B \to D \ell \nu$ $G(1)\lvert V_{cb}\rvert = (42.64 \pm 0.72_{stat} \pm 1.35_{syst}) \times 10^{-3}$	**G(1)**	**$\lvert V_{cb}\rvert$ (10^{-3})**
Lattice QCD [NPPS 140, 461-463 (2005)]	1.081 ± 0.024	$39.44 \pm 1.42_{exp} \pm 0.88_{th}$
Sum rules [PLB585, 253-262 (2004)]	1.047 ± 0.020	$40.73 \pm 1.46_{exp} \pm 0.78_{th}$
Inclusive		**$\lvert V_{cb}\rvert$ (10^{-3})**
[PRD 89:014022 (2014)]		42.42 ± 0.86

Important tool for inclusive analyses and B→Dℓν:
Hadronic tagging

- Y(4S) decays into two B mesons
- Reconstruct one of them in a hadronic mode (B_{tag})
- Reduces background
- Constrains kinematics

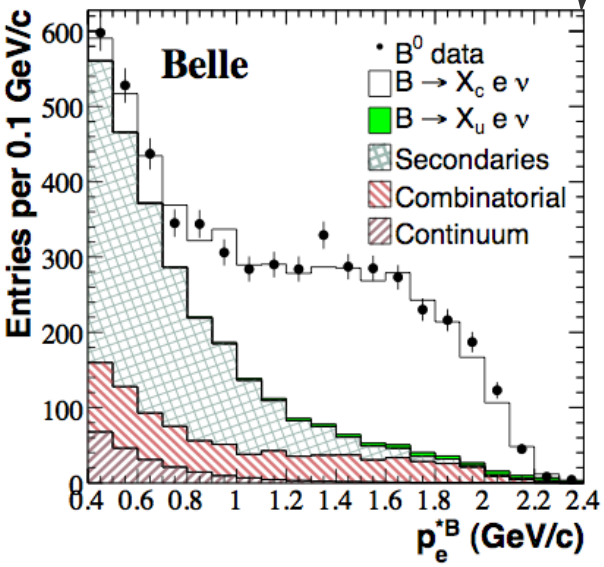


Inclusive B→Xcℓν

BaBar [PRD 69:111104, 2004] 52×10⁶ BB pairs
BaBar [PRD 81:032003, 2010] 232×10⁶ BB pairs
Belle [PRD 75:032001, 2007] 152×10⁶ BB pairs
Belle [PRD 75:032005, 2007] 152×10⁶ BB pairs

- Measure moments of lepton energy and hadronic mass
- Reconstruct lepton
- (Most analyses) use hadronic tag:
  - Second B meson is known
  - Especially useful for measuring hadronic mass:
    →Sum up 4-momenta of everything that is not B_{tag} or signal lepton
- For lepton energy: only electrons used in analyses so far

e.g.



- Measured moments include resolution and acceptance effects, corrected with:
  - Linear correction factors at BaBar
  - Unfolding function at Belle
- For theory and most recent fit paper [PRD 89:014022 (2014)] see the next talk *Extraction of Vcb from the inclusive decay B→Xcℓν*
  - Biggest errors from theory

Exclusive B→D*ℓν & B→Dℓν

- Theory:
  - Express differential decay width with form factors (describing the hadronic part)

$$\frac{d\Gamma_{B^-\to D^0\ell^-\bar{\nu}}}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B+m_D)^2(w^2-1)^{3/2}\times|\eta_{\rm EW}|^2|V_{\rm cb}|^2|\mathcal{G}(w)|^2$$

$$\frac{d\Gamma_{B^-\to D^{0*}\ell^-\bar{\nu}}}{dw} = \frac{G_F^2 m_{D^*}^3}{4\pi^3}(m_B-m_{D^*})^2(w^2-1)^{1/2}\times|\eta_{\rm EW}|^2|V_{\rm cb}|^2\chi(w)|\mathcal{F}(w)|^2$$

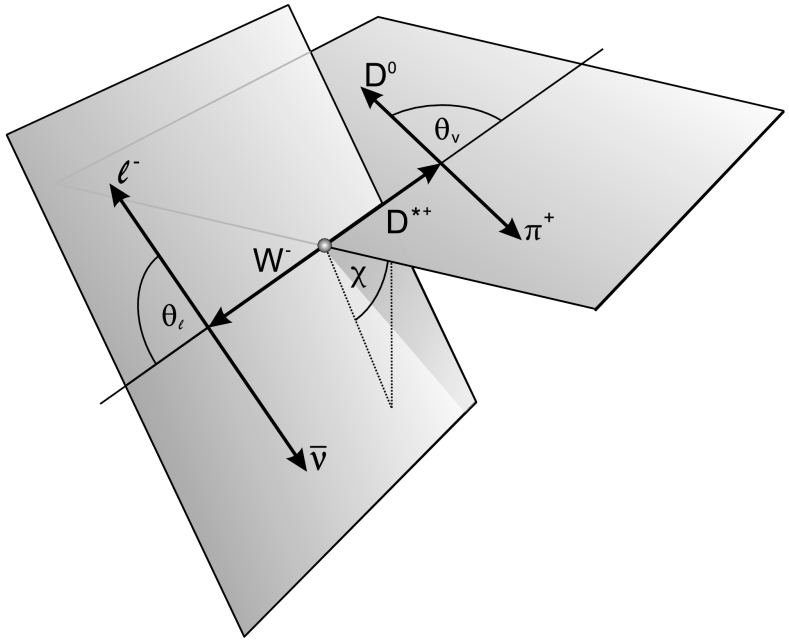
$$w = (M_B^2 + M_{D^{(*)}}^2 - q^2)/(2M_B M_{D^{(*)}})$$

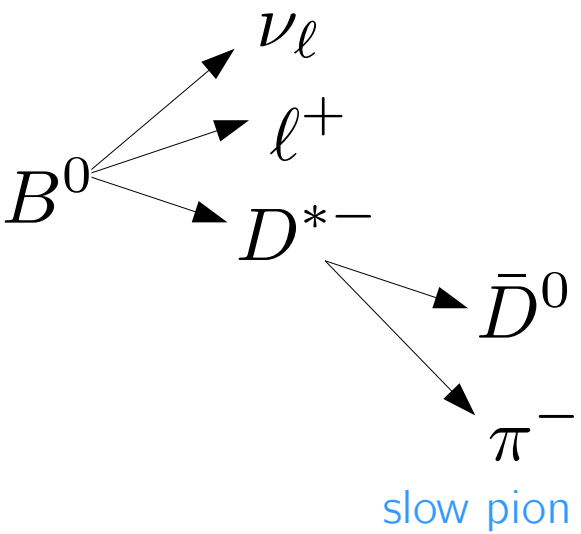
  - Parametrize form factors
    - currently with method by Caprini et al [Nuc.Phys.B, 530(1), 153-181]
    - D*: F(1), ρ_{D^*}, R1(1) and R2(1)
    - D: G(1), ρ_D

Calculate from LQCD, LCSR — Measure

Exclusive: B→D*ℓν

- Variables:
  - w
  - $cos(\theta_\nu)$
  - $cos(\theta_\ell)$
  - χ





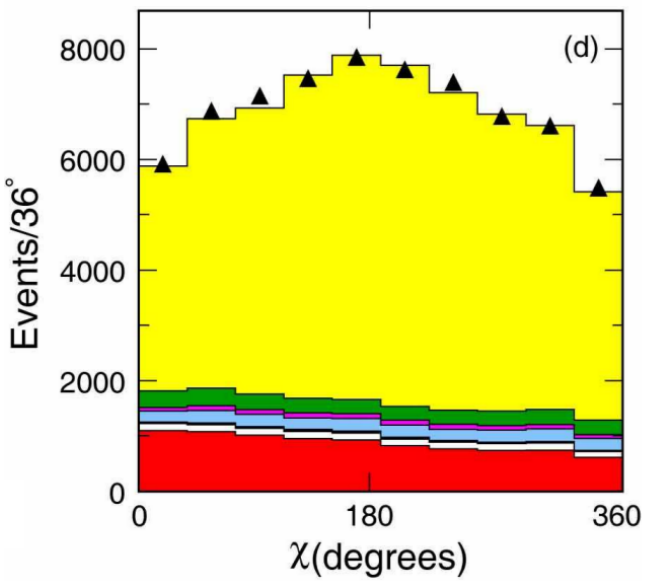
- Simultaneous fit in all 4 parameters: statistics too low →fit 1D projections (40 bins instead of 10000)
- Biggest error source: tracking (e.g. low momentum pion)

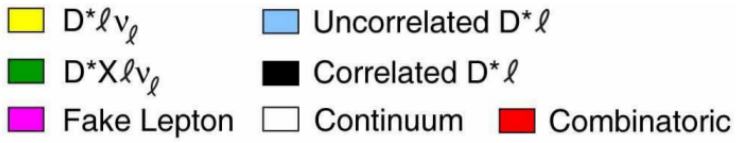
$B \to D^* \ell \nu$ BaBar

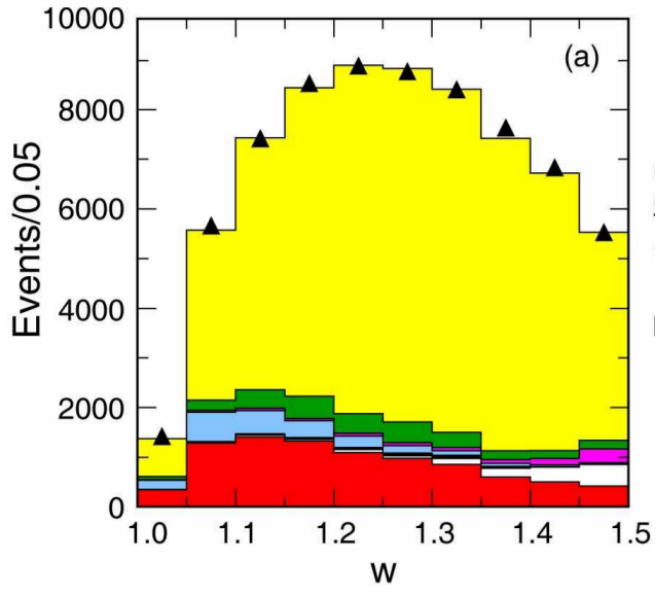
[PRD 77:032002, 2008]

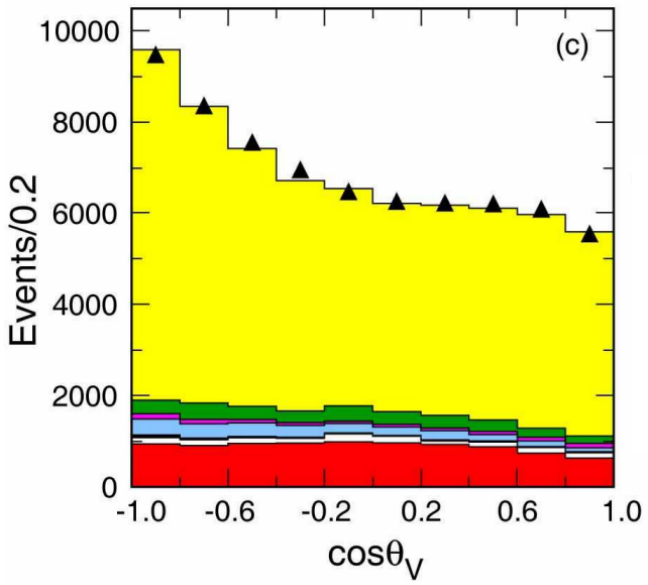
$$\mathcal{F}(1)|V_{cb}| = (34.7 \pm 0.4 \pm 1.0) \times 10^{-3}$$
$$\rho^2 = 1.157 \pm 0.094 \pm 0.027$$
$$R_1(1) = 1.327 \pm 0.131 \pm 0.043$$
$$R_2(1) = 0.859 \pm 0.077 \pm 0.021$$
$$\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu_\ell) = (4.72 \pm 0.05 \pm 0.34)\%$$

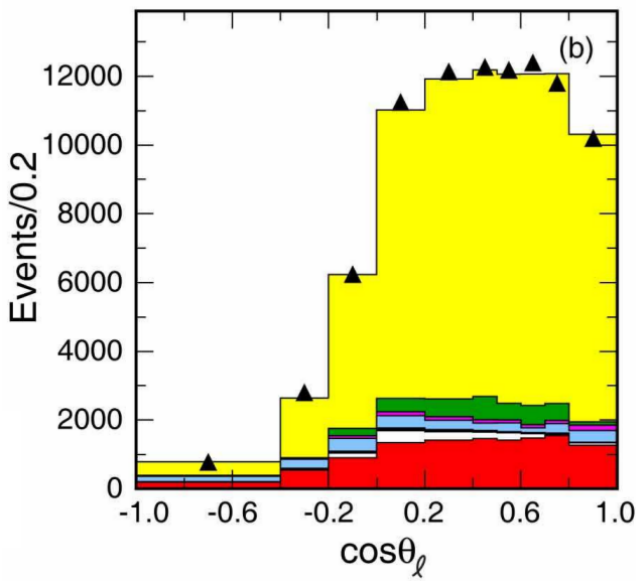
79fb^{-1}







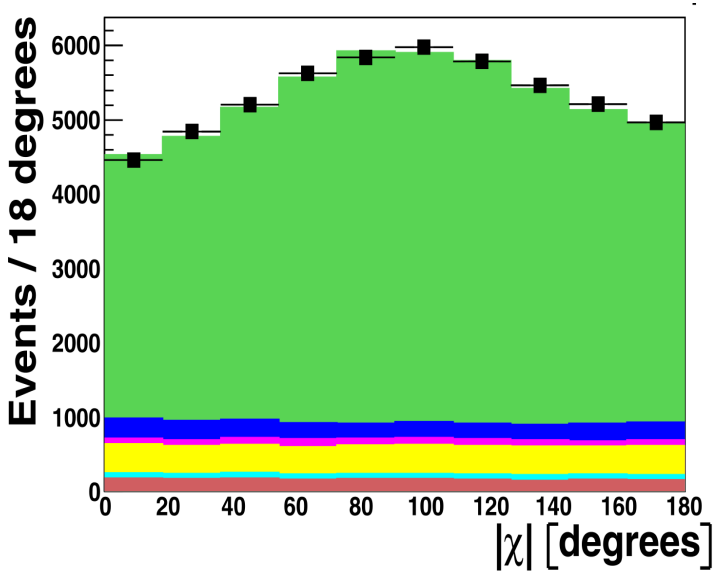




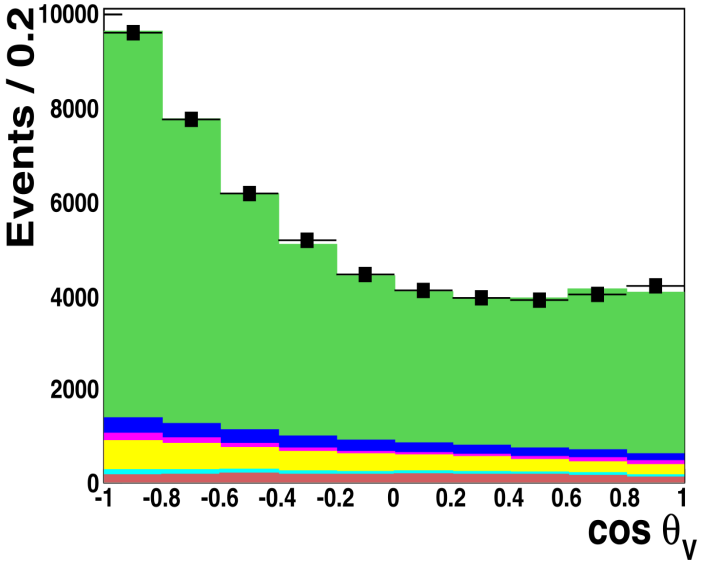
$B \to D^* \ell \nu$ Belle

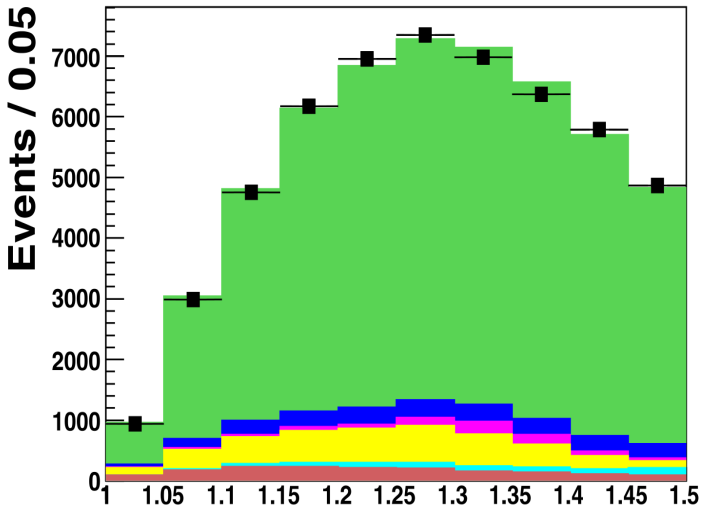
[PRD 82:112007, 2010]

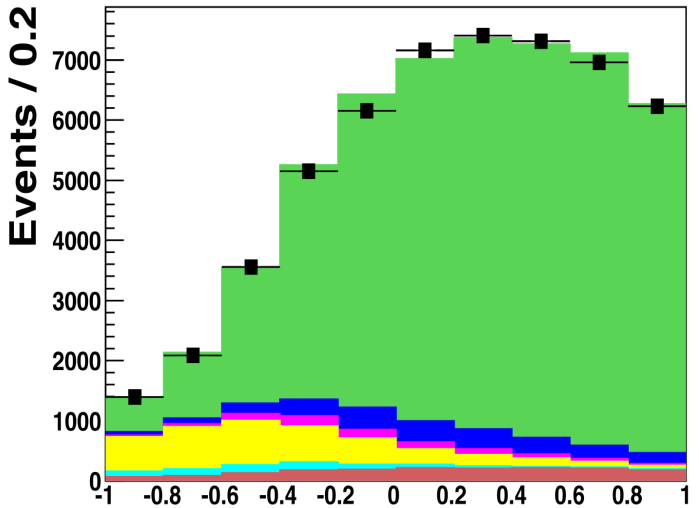
$$\mathcal{F}(1)|V_{cb}| = (34.6 \pm 0.2 \pm 1.0) \times 10^{-3}$$
$$\rho^2 = 1.214 \pm 0.034 \pm 0.009$$
$$R_1(1) = 1.401 \pm 0.034 \pm 0.018$$
$$R_2(1) = 0.864 \pm 0.024 \pm 0.008$$
$$\mathcal{B}(B^0 \to D^{*-} \ell^+ \nu_\ell) = (4.58 \pm 0.03 \pm 0.26)\%$$



711fb^{-1}

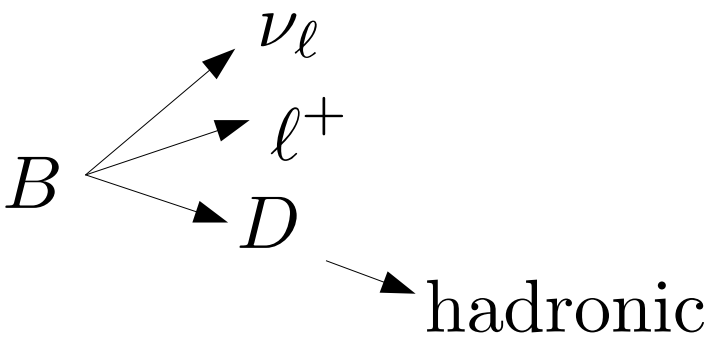






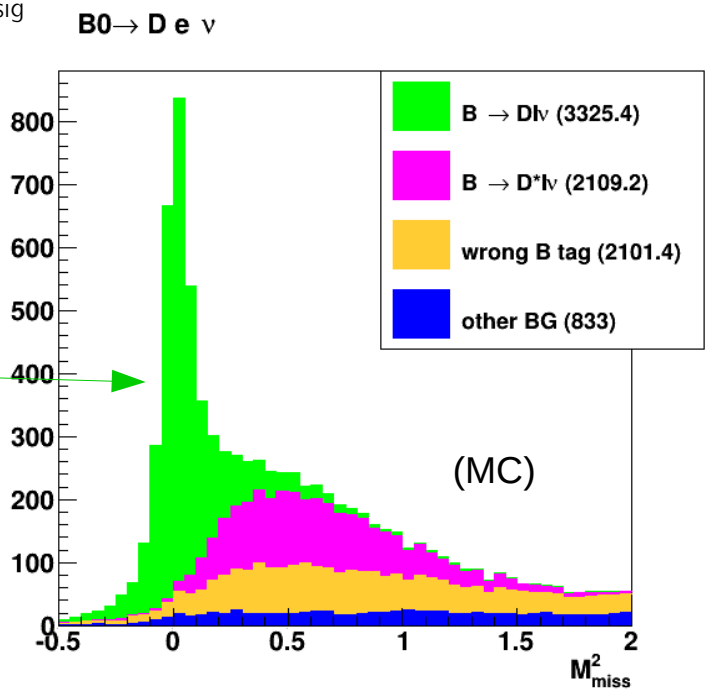
Exclusive B→Dℓν

- In comparison to B→D*ℓν:
  - Easier form factor
  - No low momentum pion
- But:
  - Best theory prediction at w=1
    ($w = (M_B^2 + M_{D^{(*)}}^2 - q^2)/(2M_B M_{D^{(*)}})$)
    but high phase space suppression there
  - D* decay has very small phase space available
    → almost no background
  - D has lots → much more background – also from D*
- Help comes from: hadronic tagging
  - second B meson is reconstructed in a hadronic decay mode



B→Dℓν (Belle): reconstruction

- 4 samples: $\bar{B}^0 \to D^+ e^- \bar{\nu}_\ell, \bar{B}^0 \to D^+ \mu^- \bar{\nu}_\ell, B^- \to \bar{D}^0 e^- \bar{\nu}_\ell, B^- \to \bar{D}^0 \mu^- \bar{\nu}_\ell$
- Tracks and photons from B_{tag} are removed
- Reconstruct D in multiple hadronic channels →
- Combine D with a lepton (e,μ) to B_{sig}
- Determine the missing mass
  $M^2_{miss} = (p_{\mathrm{beam}} - p_{B_{\mathrm{tag}}} - p_{B_{\mathrm{sig}}})^2$
- If only the neutrino is missing (i.e. genuine reconstruction)
  $M^2_{miss} = 0$ →

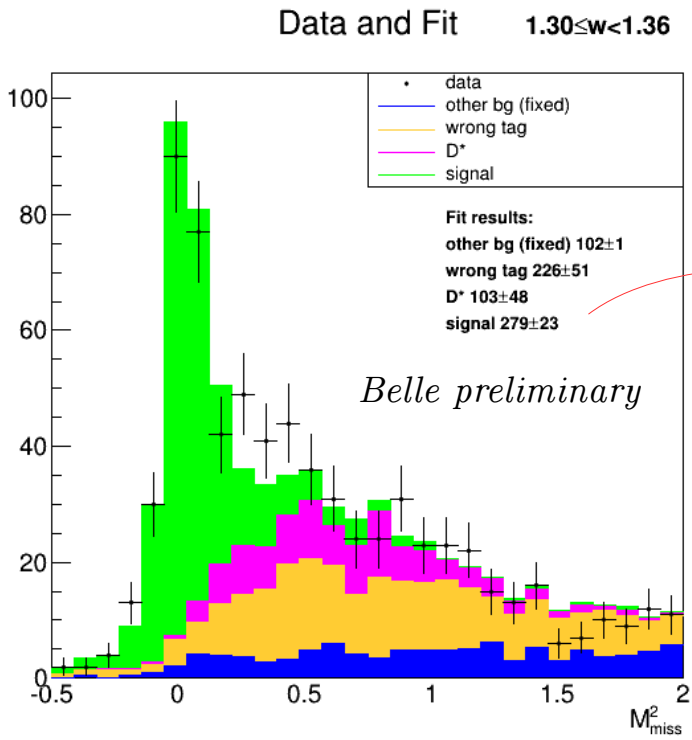


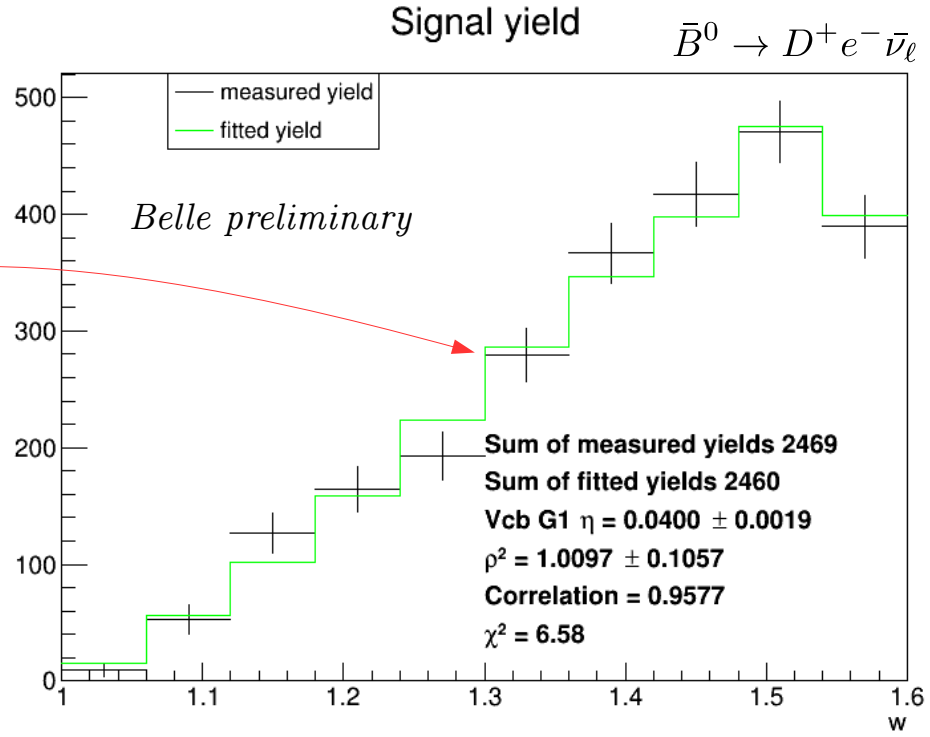
- $D^+ \to K^-\pi^+\pi^+$
- $D^+ \to K^-\pi^+\pi^+\pi^0$
- $D^+ \to K^0_s\pi^+$
- $D^+ \to K^0_s\pi^+\pi^0$
- $D^+ \to K^+K^-\pi^+$
- $D^+ \to K^0_s K^+$
- $D^+ \to K^0_s\pi^+\pi^+\pi^-$
- $D^0 \to K^-\pi^+$
- $D^0 \to K^-\pi^+\pi^0$
- $D^0 \to K^-\pi^+\pi^+\pi^-$
- $D^0 \to K^0_s\pi^+\pi^-$
- $D^0 \to K^0_s\pi^+\pi^-\pi^0$
- $D^0 \to K^0_s\pi^0$
- $D^0 \to K^+K^-$
- $D^0 \to \pi^+\pi^-$

["Semileptonic and leptonic B and Bs decays at Belle" ICHEP 2014, preliminary]

B→Dℓν (Belle): Signal yield extraction and final fit

- Extract signal yield in 10 different w-bins (from 1.0 to 1.6)





- χ^2 fit of predicted yield (based on differential decay width) to measured yield

B→Dℓν (Belle): results *(preliminary)*

["Semileptonic and leptonic B and Bs decays at Belle" ICHEP 2014, preliminary] **711fb^{-1}**

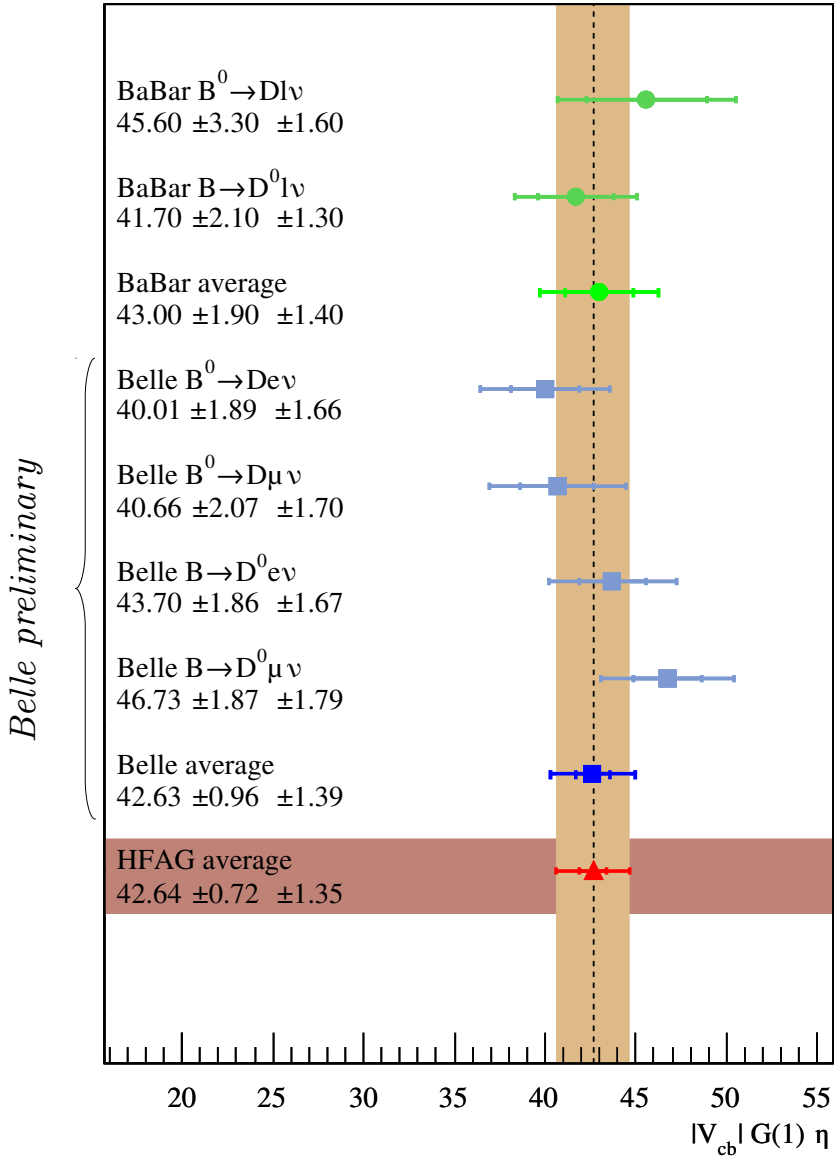
Sample	$\eta_{\rm EW}\mathcal{G}(1)\lvert V_{cb}\rvert$ $[10^{-3}]$	ρ^2	correlation
$\bar{B}^0 \to D^+ e^- \bar{\nu}_\ell$	$40.01 \pm 1.89(\text{stat}) \pm 1.66(\text{syst})$	$1.010 \pm 0.106(\text{stat}) \pm 0.029(\text{syst})$	0.692
$\bar{B}^0 \to D^+ \mu^- \bar{\nu}_\ell$	$40.66 \pm 2.07(\text{stat}) \pm 1.70(\text{syst})$	$1.075 \pm 0.115(\text{stat}) \pm 0.031(\text{syst})$	0.713
$B^- \to \bar{D}^0 e^- \bar{\nu}_\ell$	$43.70 \pm 1.86(\text{stat}) \pm 1.67(\text{syst})$	$0.909 \pm 0.099(\text{stat}) \pm 0.014(\text{syst})$	0.711
$B^- \to \bar{D}^0 \mu^- \bar{\nu}_\ell$	$46.73 \pm 1.87(\text{stat}) \pm 1.79(\text{syst})$	$1.075 \pm 0.091(\text{stat}) \pm 0.014(\text{syst})$	0.680
Average	$42.63 \pm 0.96(\text{stat}) \pm 1.39(\text{syst})$	$1.001 \pm 0.051(\text{stat}) \pm 0.018(\text{syst})$	0.494

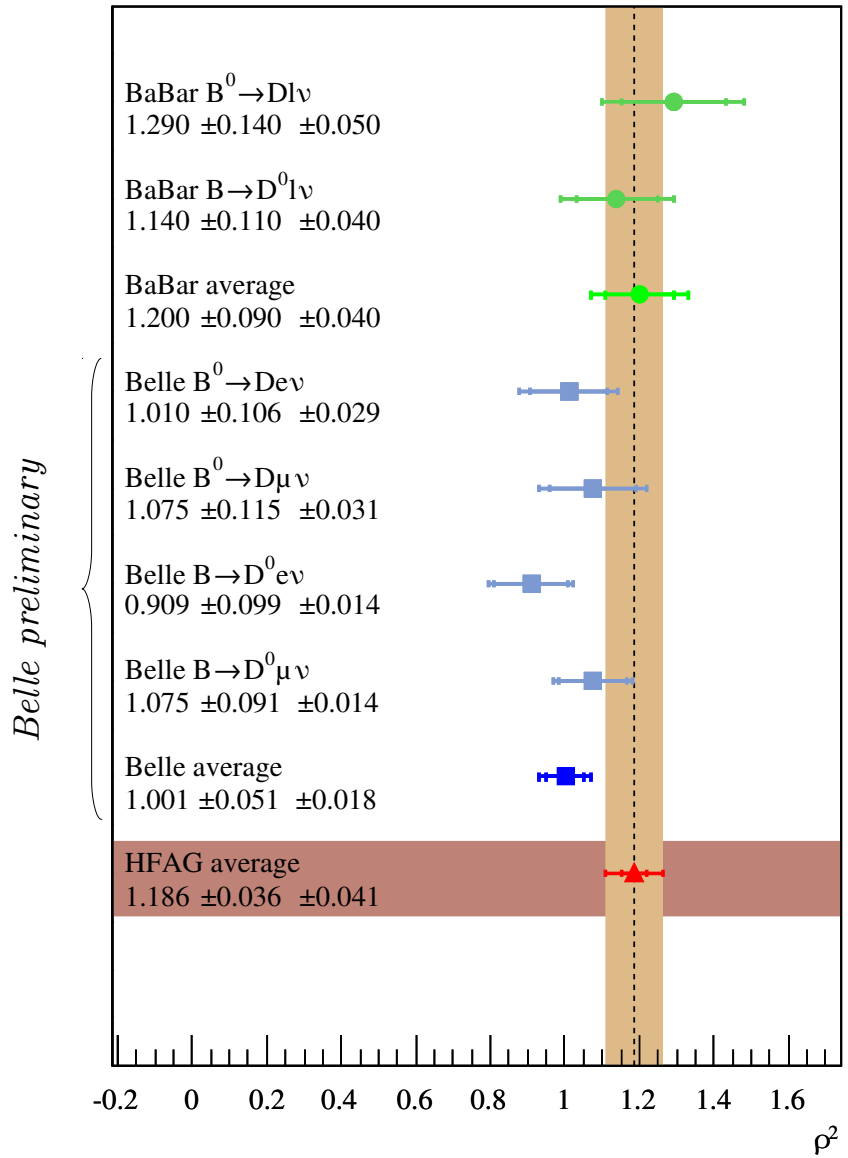
B→Dℓν (BaBar): results

[PRD 77:032002, 2008] **417fb^{-1}**

Sample	$\eta_{\rm EW}\mathcal{G}(1)\lvert V_{cb}\rvert$ $[10^{-3}]$	ρ^2	correlation
$\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$	$45.6 \pm 3.3(\text{stat}) \pm 1.6(\text{syst})$	$1.29 \pm 0.14(\text{stat}) \pm 0.05(\text{syst})$	0.950
$B^- \to \bar{D}^0 \ell^- \bar{\nu}_\ell$	$41.7 \pm 2.1(\text{stat}) \pm 1.3(\text{syst})$	$1.14 \pm 0.11(\text{stat}) \pm 0.04(\text{syst})$	0.943
Average	$43.0 \pm 1.9(\text{stat}) \pm 1.4(\text{syst})$	$1.20 \pm 0.09(\text{stat}) \pm 0.04(\text{syst})$	0.952

B→Dℓν results



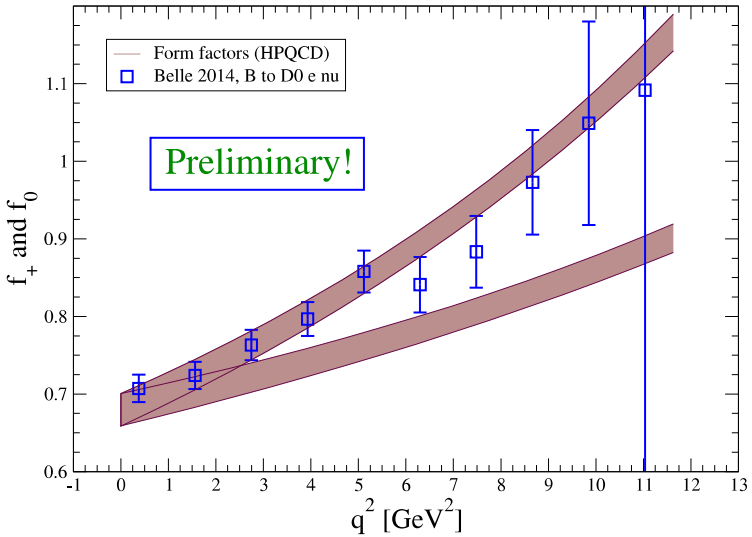


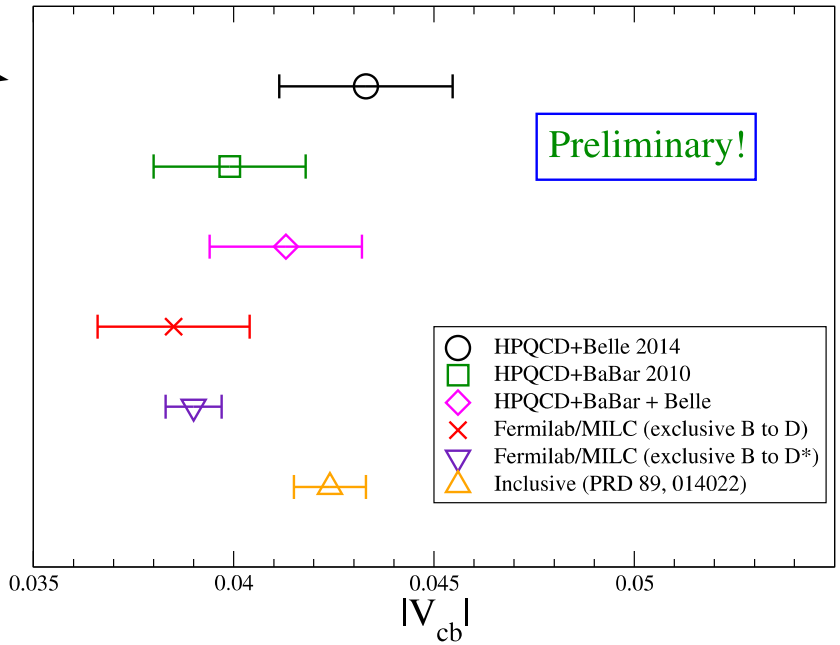
The future

- Belle II: Limitting factors will be theoretical or systematical
  (see talk *Prospects of Belle II in B-meson semileptonic decays* on Thursday)
- Need to consistently apply electroweak corrections on all analyses
- V_{cb} via $B_s \to D_s^{(*)} \ell \nu$, $\Lambda_b \to \Lambda_c \ell \nu$
  - At LHCb
    - Big dataset, but kinematics and background are difficult
    - Use separation of primary and secondary vertex
    - Direct V_{cb} or V_{ub} not possible
    - But: ratio V_{ub}/V_{cb} can be measured with exclusive B_s and Λ_b - is currently investigated
    - See talk *Semileptonic b-hadron decays at LHCb* on Wednesday
  - At Belle (or Belle II)
    - $B_s \to D_s^{(*)} X \ell \nu$ at the Belle $\Upsilon(5S)$ resonance currently in progress
      see ["Semileptonic and leptonic B and Bs decays at Belle" ICHEP 2014, preliminary]
    - Maybe hadronic tag for $\Upsilon(5S)$ can help advance to $B_s \to D_s^* \ell \nu$

The future

- $B \to D^{(*)} \ell \nu$:
  - Error on form factor parametrization by Caprini et al not quantified (<2% is all we know)
  - Switch from using form factor parametrization and calculation of G(1) and F(1) to model-indepent fits fitting LQCD parameters and reconstructed data together
  - In contact with MILC and HPQCD





Plots by HPQCD, from private communication with Heechang Na. Preliminary fit using preliminary $B \to D \ell \nu$ data from Belle. MILC data points are from LATTICE 2013 proceedings [arXiv: 1312.0155]
Left plot shows example of fit for a subsample of preliminary $B \to D \ell \nu$.
Red bands are the form factors (f_+ and f_0) from a lattice simulation by HPQCD.

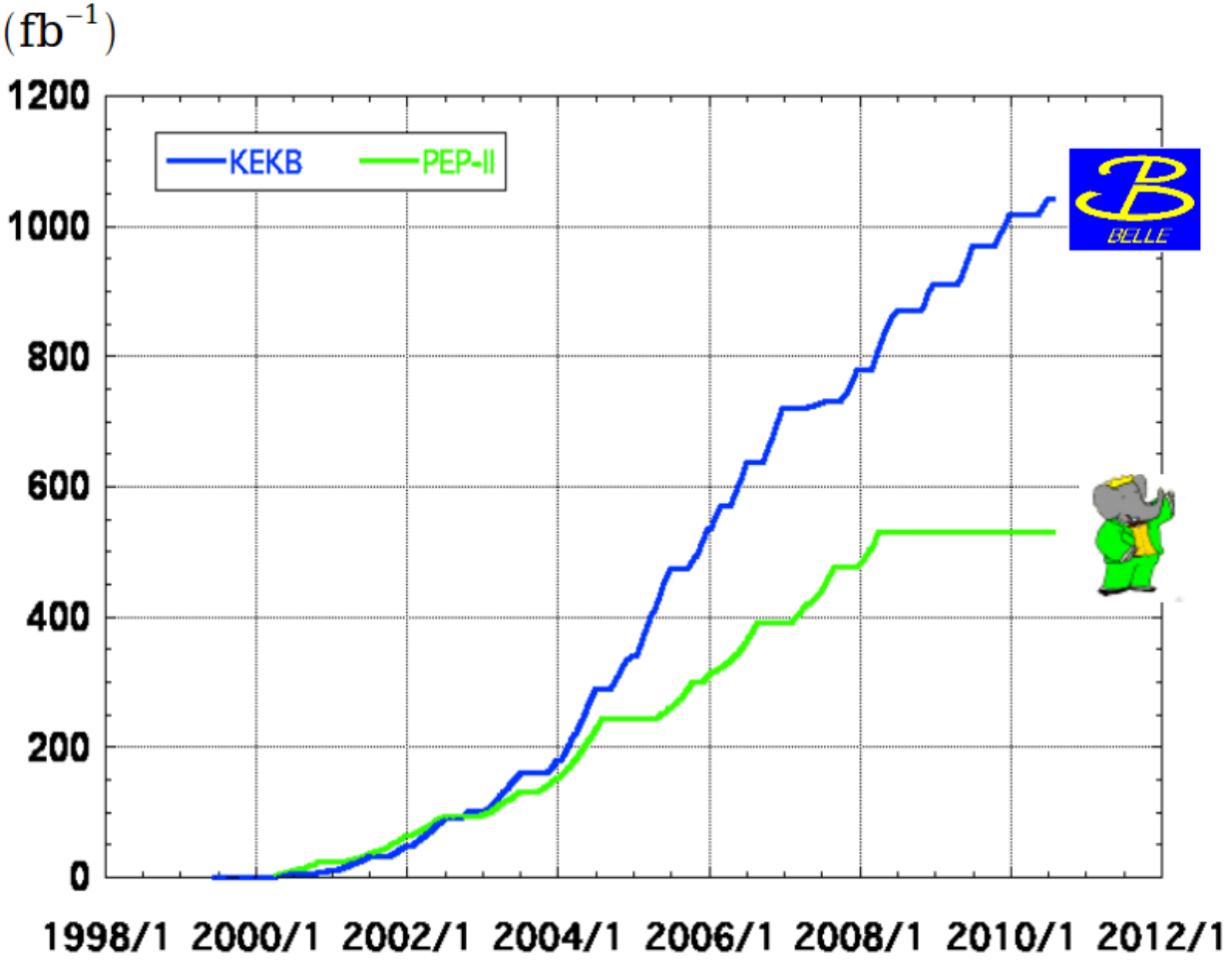
Summary

- V_{cb} currently measured with semileptonic decacys at B-factories
- Inclusive and exclusive analyses have different experimental and theoretical approach $\rightarrow$ complimentary
- V_{cb} is now determined to an accuracy of $\sim 2\%$
- Exclusive – Inclusive V_{cb} discrepancy still present
- $B \rightarrow D^{(*)} \ell \nu$: Fitting data and LQCD parameters together seems promising
- Alternative decays ($B_s \rightarrow D_s \ell \nu$, $\Lambda_b \rightarrow \Lambda_c \ell \nu$) at LHCb (and maybe Belle/Belle II) could add insights

Thank you!

Back Up

B-factory luminosity



$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

$\sim 54\ fb^{-1}$

Measuring V_{cb} = semileptonic decays

- Pure leptonic: B_c decays experimentally difficult
  - At B-factories: not available
  - At LHCb: low production rate, low BR to $\mu\nu$
- Pure hadronic: very hard theoretically
- Semileptonic:
  - Theory can handle it well:
    - In Hamiltonian leptonic and hadronic currents factorize
    - Small electroweak corrections necessary
  - Experimentally:
    - Branching fractions are good (~20% of B decays are semileptonic with charm)
    - Only one neutrino not reconstructable

B→Dℓν: extracting |Vcb|G(1)η_{EW} and ρ^2

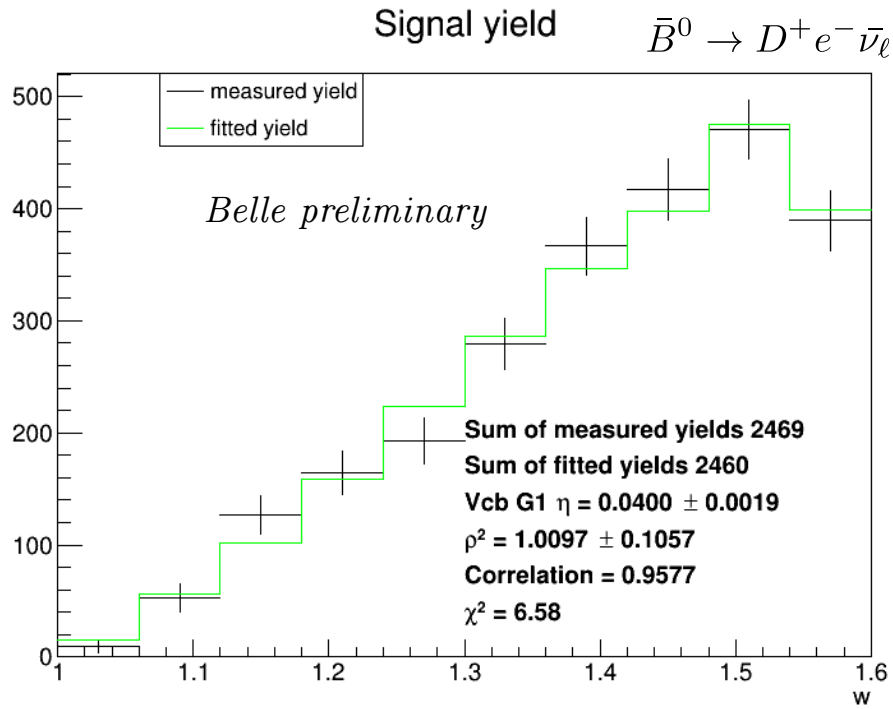
- Measured the signal yield in each w-bin
- Calculate the predicted signal yield for given |Vcb|G(1)η_{ew} and ρ^2: (relative to MC)

$$N_i = \frac{\int_{w_i}^{w_i+\Delta w} \frac{d\Gamma(\eta_{EW} G(1)|V_{cb}|,\rho^2)}{dw} dw}{\int_{w_i}^{w_i+\Delta w} \frac{d\Gamma_{\mathrm{MC}}}{dw} dw} \mathrm{N}_{\mathrm{MC},i}$$

Predicted signal in bin i

differential decay width using MC parameters

- χ^2 fit of predicted yield to measured yield



B→Dℓν: systematic errors

	relative error in %			
	$\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$		$B^- \to \bar{D}^0 \ell^- \bar{\nu}_\ell$	
Source	$\eta_{\rm EW}\mathcal{G}(1)\lvert V_{cb}\rvert$	ρ^2	$\eta_{\rm EW}\mathcal{G}(1)\lvert V_{cb}\rvert$	ρ^2
Charged track reconstruction	2.00	0.00	1.50	0.00
Neutral reconstruction	1.00	0.00	1.00	0.00
Lepton ID	1.00	0.00	1.00	0.00
D branching fractions	0.60	0.20	0.30	0.20
Background branching ratios and F.F.	1.63	2.22	1.39	1.00
Hadronic tag calibration	2.90	1.65	2.90	0.90
Total	4.17	2.77	3.83	1.36