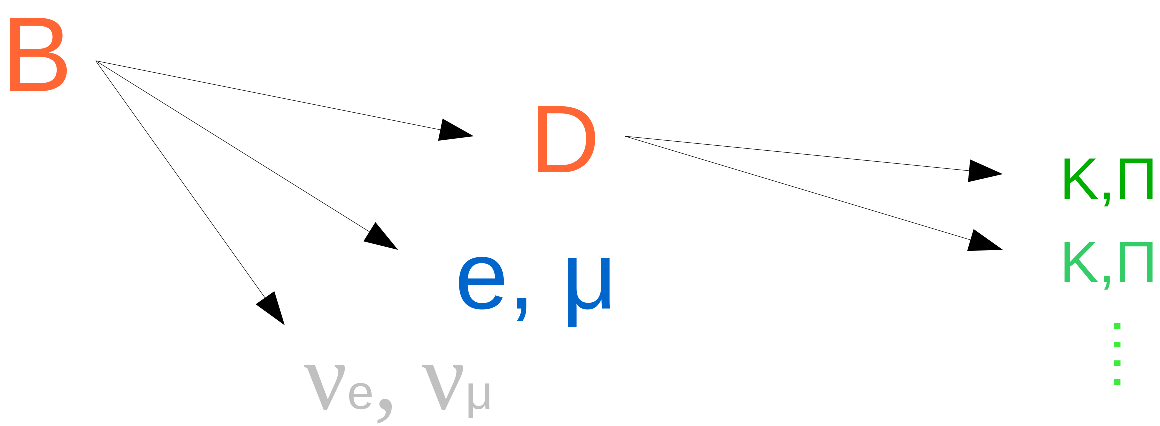
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{cb} measurement with B→D$\ell\nu$ at *Belle*

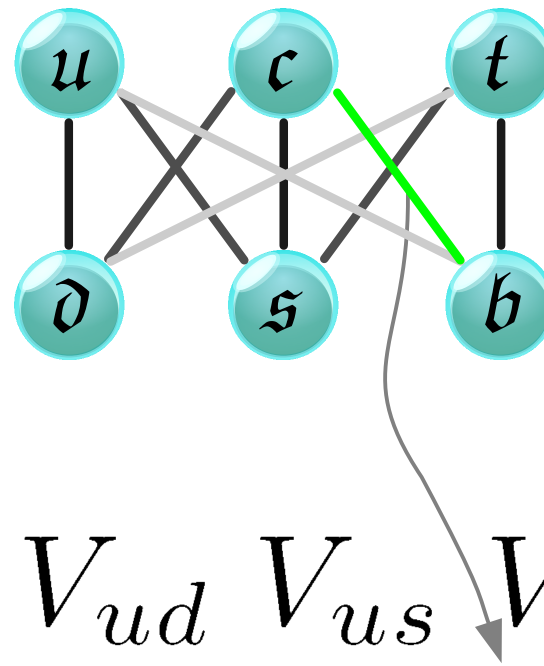
Robin Glattauer

for the Belle Collaboration



V_{cb}: the CKM matrix

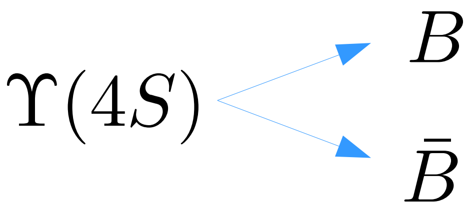
- 3x3 unitary complex matrix
- Quantifies quark mixing
- Can be reduced to 3 mixing angles
- And one complex phase:
  source of weak CP violation

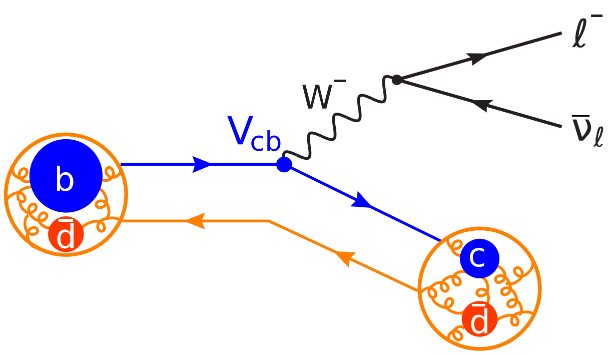


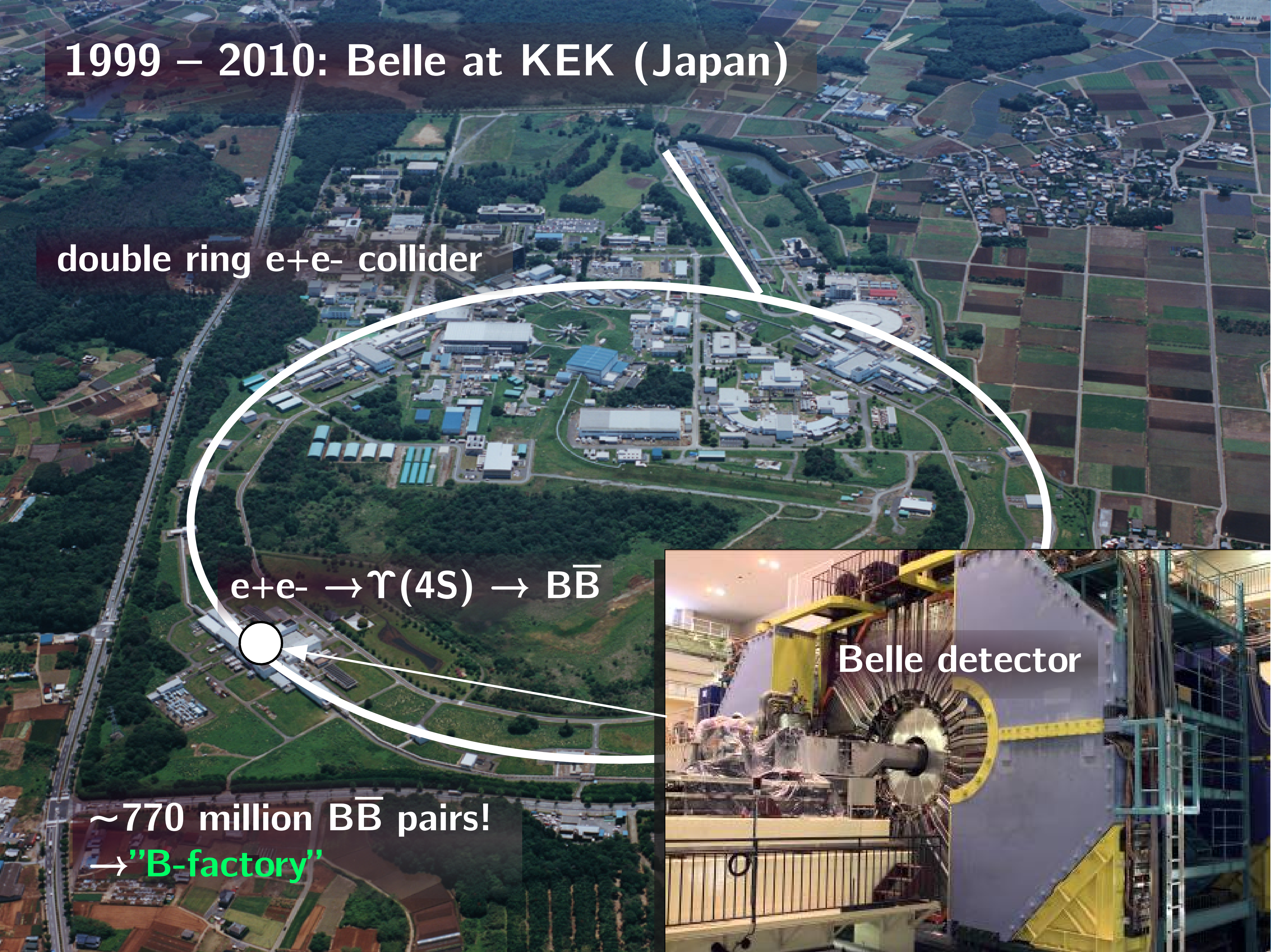
$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{cb} measurements

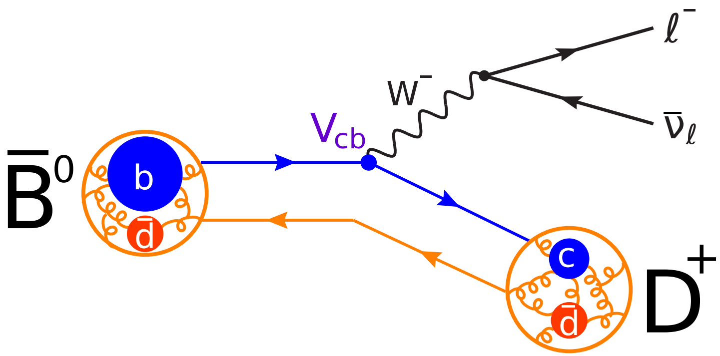
- Measure b→c quark transitions
- Mainly B-factories (Belle, BaBar) at $\Upsilon(4S)$ resonance
  - Low background
  - Many $B\bar{B}$ pairs
- Measure V_{cb} with semileptonic decays (lepton = e,μ)
- Inclusive: $B \to X_c \ell \nu$
  - Integrate over all final states with c quark
  - $|V_{cb}| = [42.42 \pm 0.86] \times 10^{-3}$
- Exclusive: $B \to D^{(*)} \ell \nu$
  - Pick one exclusive final state with a c quark
  - $(B \to D \ell \nu$, LQCD$)$ $|V_{cb}| = [39.45 \pm 1.42_{exp} \pm 0.88_{th}] \times 10^{-3}$
  - $(B \to D^* \ell \nu$, LQCD$)$ $|V_{cb}| = [38.92 \pm 0.49_{exp} \pm 0.56_{th}] \times 10^{-3}$






1999 – 2010: Belle at KEK (Japan)
double ring e+e- collider
e+e- $\to \Upsilon(4S) \to B\bar{B}$
Belle detector
~770 million $B\bar{B}$ pairs!
→"B-factory"

B→Dℓν theoretical description



- Differential decay width:

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

constants

electroweak correction

form factor

Parametrization from Caprini et al (arXiv:hep-ph/9712417)

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

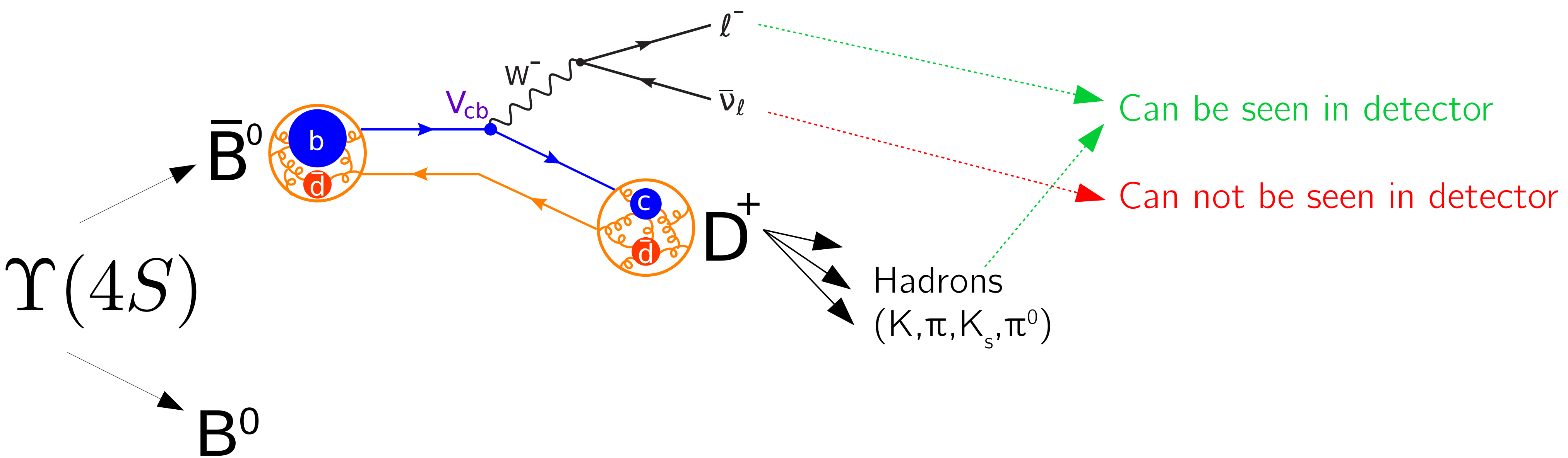
$$z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

- Kinematics: $w = v_B \cdot v_D = \dfrac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$

- We want to measure: $\rho^2, |V_{cb}|\eta_{EW}\mathcal{G}(1)$

Can be calculated by e.g. Lattice QCD

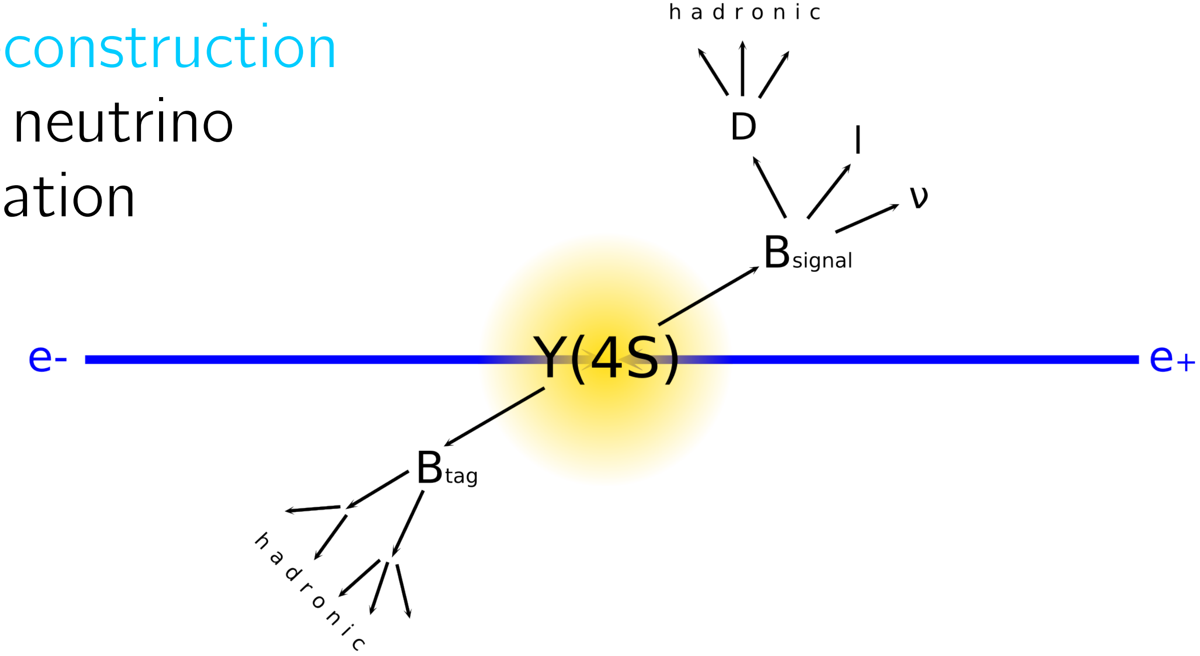
B→Dℓν reconstruction



- Neutrino cannot be (directly) reconstructed
- Use that $\Upsilon(4S)$ decays to $B\bar{B}$ and reconstruct the second B-meson
- In one of 1104 exclusive hadronic decay modes → hadronic tagging

Hadronic Tagging

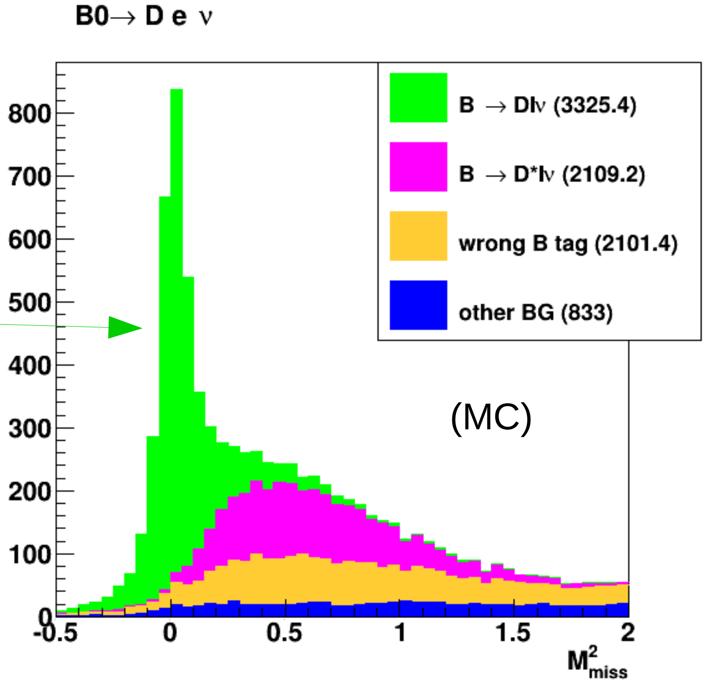
- Reconstruct one of them in a hadronic mode (B_{tag})
- Using a neural network for optimized efficiency/purity
- Reduces background
- Allows full kinematic reconstruction
  $\rightarrow$ gain information on neutrino
  via momentum conservation



B→Dℓν: reconstruction

- Reconstruct the tag side B-meson
- Tracks and photons from B_{tag} are removed
- Reconstruct D in multiple hadronic channels →
- Combine D with a lepton (e,μ)
- Determine the missing mass
  $$M^2_{miss} = (p_{\text{beam}} - p_{B_{\text{tag}}} - p_D - p_\ell)^2$$
- If only the neutrino is missing (i.e. genuine reconstruction)

$$M^2_{miss} = 0$$ →



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

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

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

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

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

$D^+ \to K^0_sK^+$

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

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

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

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

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

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

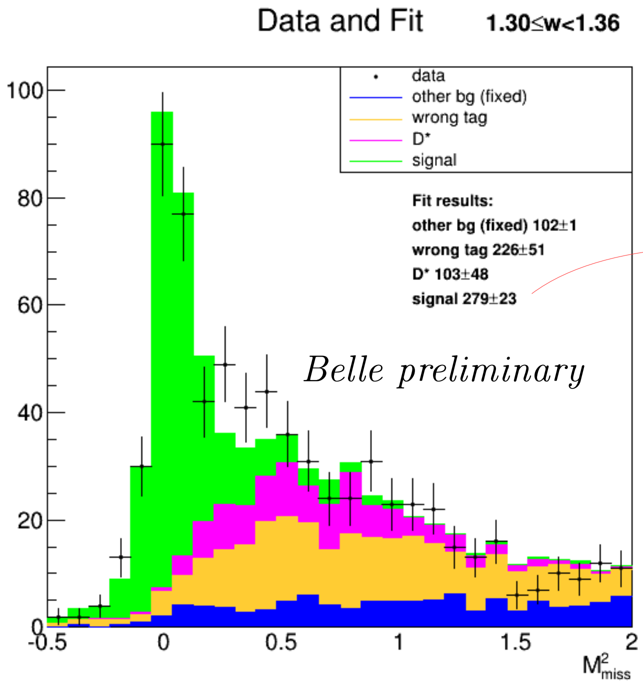
$D^0 \to K^0_s\pi^0$

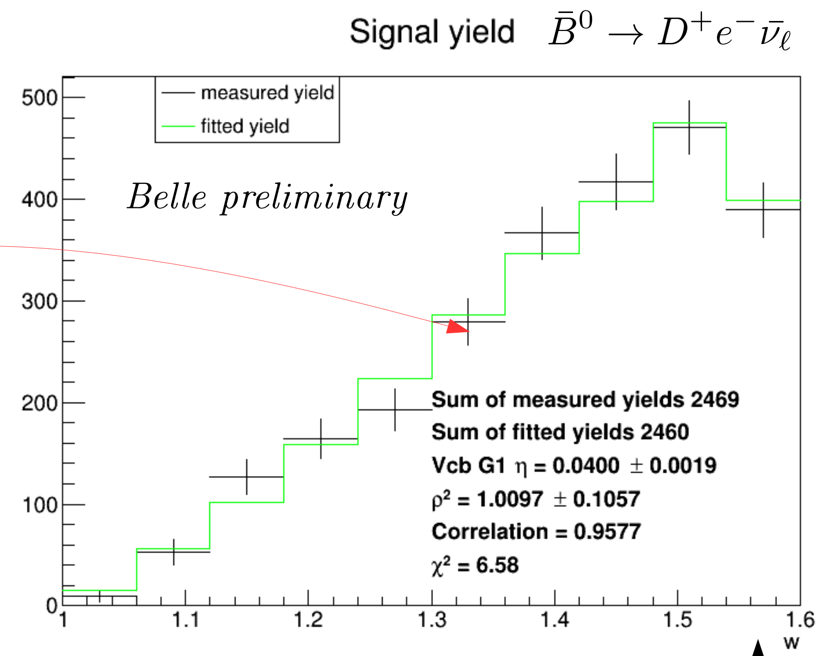
$D^0 \to K^+K^-$

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

B→Dℓν: Signal yields extraction and fit of dΓ/dw

- Extract signal yield in 10 different w-bins (from 1.0 to 1.6)
- Use MC distribution as template
  - Floating: signal, D*- and wrong tag background
  - Fixed to MC: other bg (e.g. fake- and non prompt leptons etc.)





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

Results *(preliminary)*

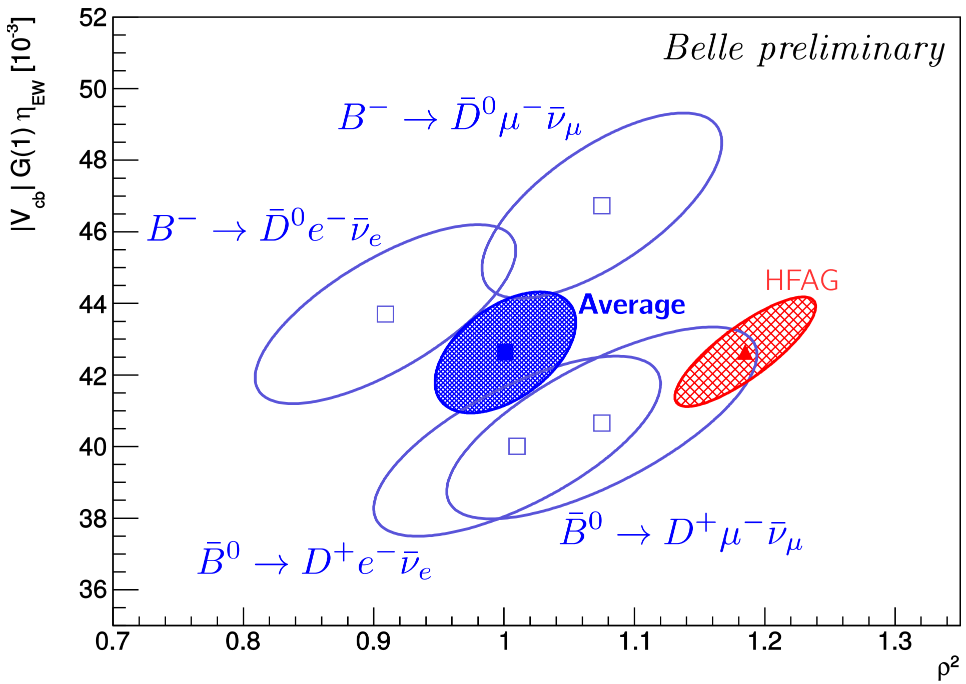
Sample	$\eta_{\rm EW}\mathcal{G}(1)\lvert V_{cb}\rvert$ $[10^{-3}]$	ρ^2	correlation
$\bar{B}^0 \to D^+e^-\bar{\nu}_\ell$	$40.01 \pm 1.89(\text{stat}) \pm 1.66(\text{syst})$	$1.010 \pm 0.106(\text{stat}) \pm 0.029(\text{syst})$	0.692
$\bar{B}^0 \to D^+\mu^-\bar{\nu}_\ell$	$40.66 \pm 2.07(\text{stat})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

- This results in

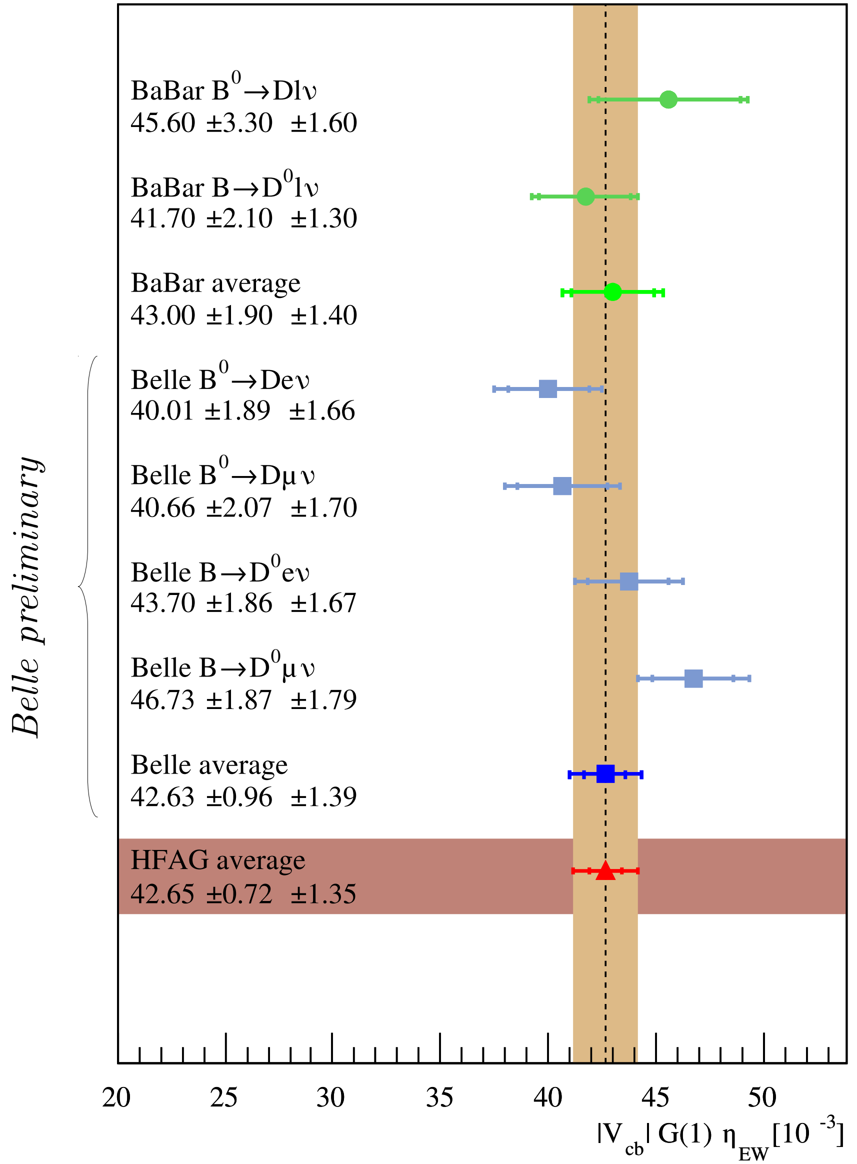
$$\mathcal{B}(\bar{B}^0 \to D^+\ell^-\bar{\nu}_\ell) = [2.49 \pm 0.17]\%$$
$$\mathcal{B}(B^- \to \bar{D}^0\ell^-\bar{\nu}_\ell) = [2.70 \pm 0.19]\%$$

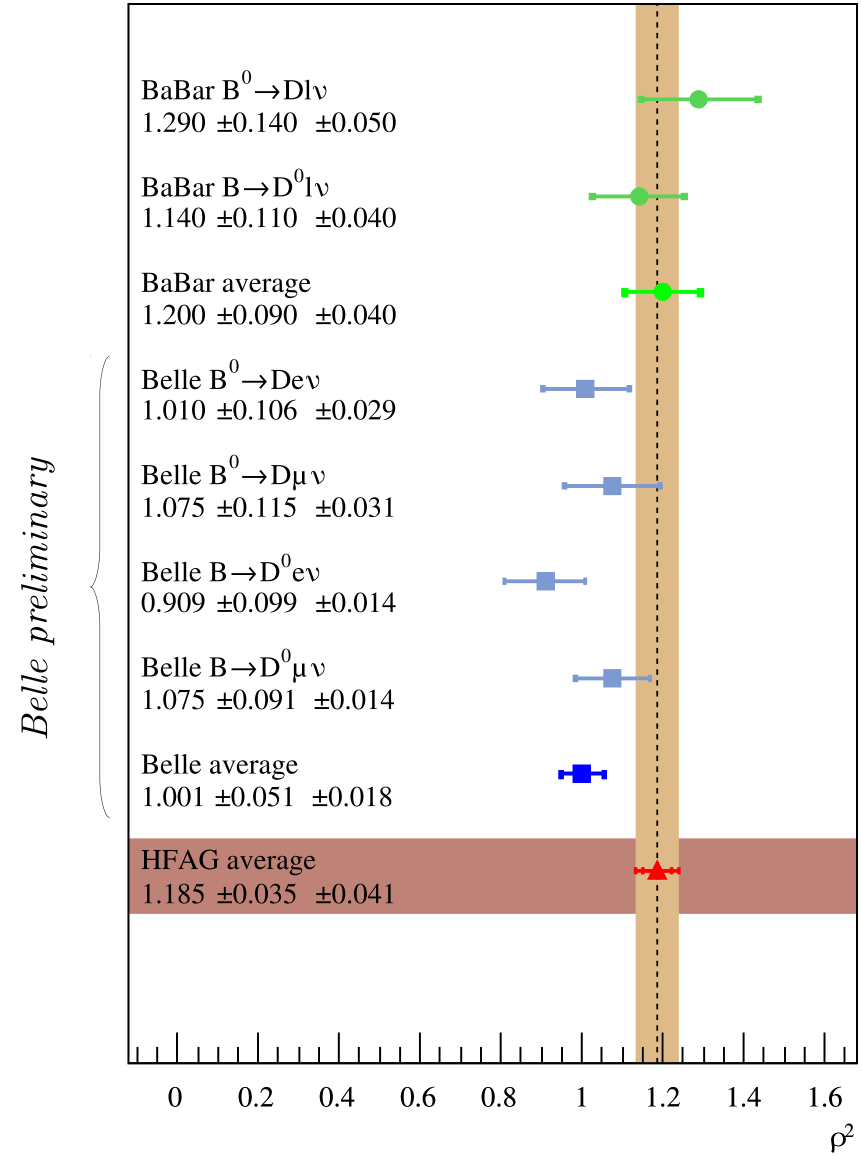
- Current HFAG averages:

$$\eta_{EW}\mathcal{G}(1)|V_{cb}| = [42.65 \pm 0.72 \pm 1.35] \times 10^{-3}$$
$$\rho^2 = 1.185 \pm 0.035 \pm 0.041$$



Results


BaBar B^0→Dlν
45.60 ±3.30 ±1.60
BaBar B→D^0lν
41.70 ±2.10 ±1.30
BaBar average
43.00 ±1.90 ±1.40
Belle B^0→Deν
40.01 ±1.89 ±1.66
Belle B^0→Dμν
40.66 ±2.07 ±1.70
Belle B→D^0eν
43.70 ±1.86 ±1.67
Belle B→D^0μν
46.73 ±1.87 ±1.79
Belle average
42.63 ±0.96 ±1.39
HFAG average
42.65 ±0.72 ±1.35
Belle preliminary
20
25
30
35
40
45
50
|V_cb| G(1) η_EW [10^-3]


BaBar B^0→Dlν
1.290 ±0.140 ±0.050
BaBar B→D^0lν
1.140 ±0.110 ±0.040
BaBar average
1.200 ±0.090 ±0.040
Belle B^0→Deν
1.010 ±0.106 ±0.029
Belle B^0→Dμν
1.075 ±0.115 ±0.031
Belle B→D^0eν
0.909 ±0.099 ±0.014
Belle B→D^0μν
1.075 ±0.091 ±0.014
Belle average
1.001 ±0.051 ±0.018
HFAG average
1.185 ±0.035 ±0.041
Belle preliminary
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
ρ^2

The future

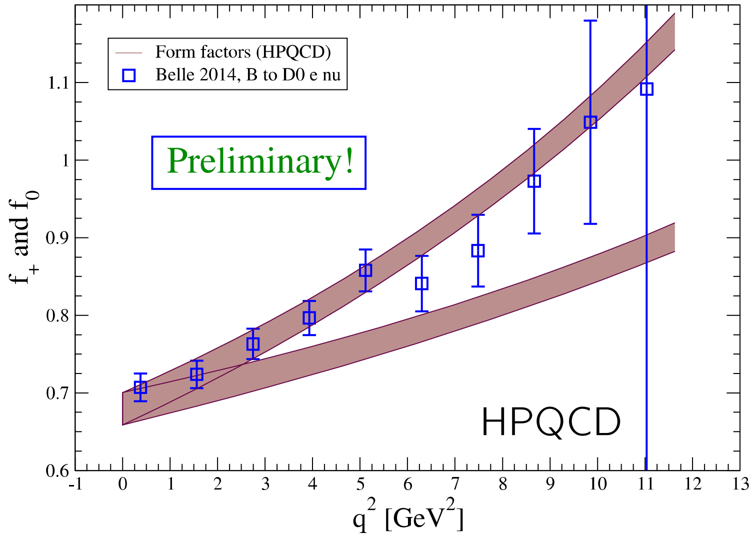
$$\frac{d\Gamma}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2(w^2-1)^{3/2}|\eta_{\rm EW}|^2|V_{\rm cb}|^2|\mathcal{G}(w)|^2$$

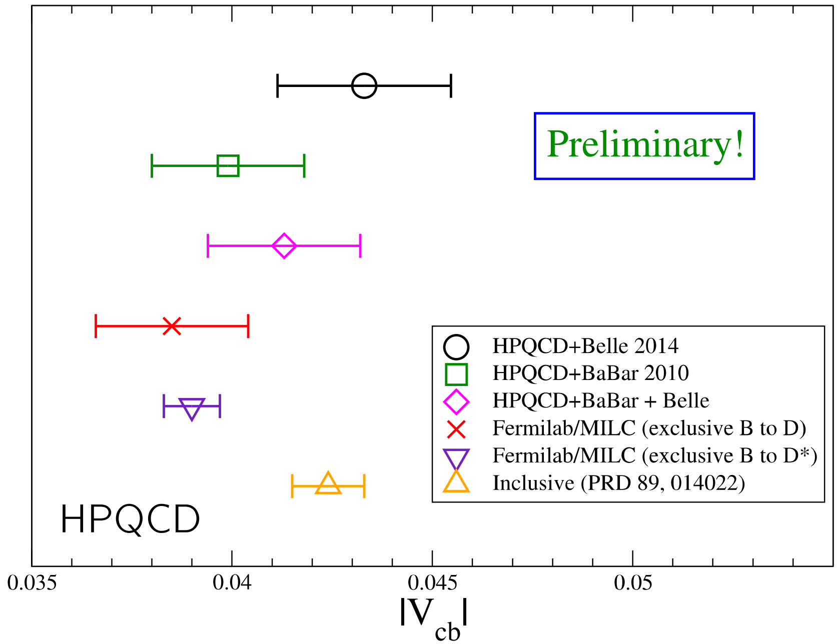
$$\mathcal{G}(w) = \mathcal{G}(1)(1 - 8\rho^2 z + (51\rho^2 - 10)z^2 - (252\rho^2 - 84)z^3)$$ *(arXiv:hep-ph/9712417)*

- Error on form factor parametrization by Caprini et al not well quantified
  <2% is all we know
- The parametrization allowed to separate fits of experimental data and theoretical parameters
- Switch to model-independent fit:
  fitting LQCD parameters and reconstructed data together
- In contact with MILC and HPQCD
- G(w) can be written as function of two parameters $f_+(q^2)$ and $f_0(q^2)$ which can be calculated in a lattice simulation
  (q^2 and w are equivalent, could also be written as f(w))

The future

- From HPQCD:





- From private communication with Heechang Na
- 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 represent $f_+(q^2)$ and $f_0(q^2)$ from lattice simulation extrapolated to physical regions
  $\to$ this gives G(w) and thus can be fitted with extracted signal yields to get Vcb directly

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

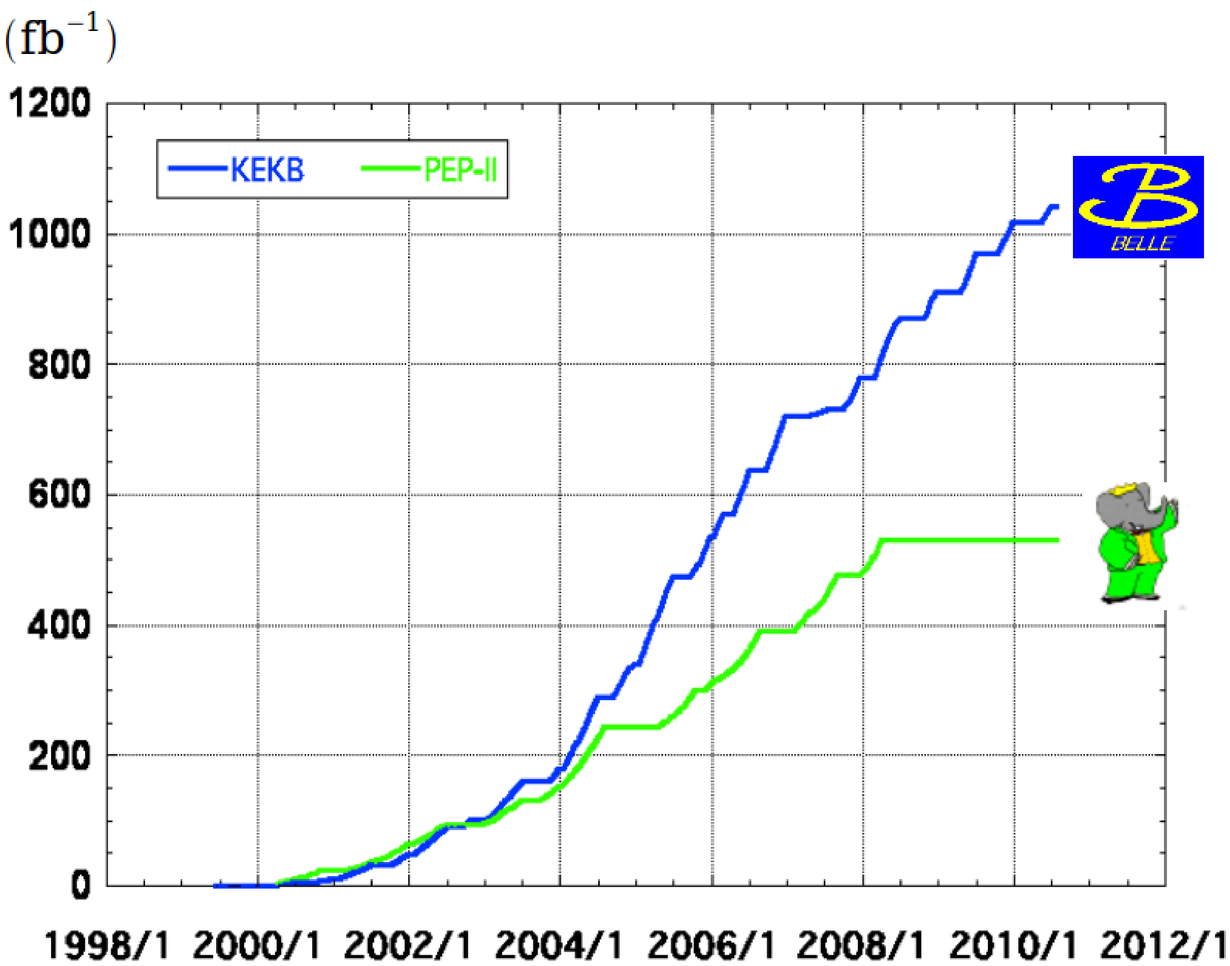
Summary

- Measure V_{cb} with $B \to D\ell\nu$
- Full reconstruction of events using hadronic tag
- M_{miss}^2 allows extraction of $B \to D\ell\nu$ signal
- Measure in 10 bins of w and fit differential decay width
- $$\eta_{EW}\mathcal{G}(1)|V_{cb}| = [42.63 \pm 0.96(\text{stat}) \pm 1.39(\text{syst})] \times 10^{-3}$$
  $$\rho^2 = 1.001 \pm 0.051(\text{stat}) \pm 0.018(\text{syst})$$
  Belle preliminary
- Most precise single measurement of $\rho^2, |V_{cb}|\eta_{EW}\mathcal{G}(1)$
- $|V_{cb}|\eta_{EW}\mathcal{G}(1)$ in agreement with world average, ρ^2 is ~2σ lower
- Future: model independent fit

Thank you!

Back Up

Belle 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:

~ 100 fb^{-1}

Worlds largest
B meson sample
~772 million BB events

~ 550 fb^{-1}

On resonance:

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

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

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

Off resonance:

~ 54 fb^{-1}

Inclusive-Exclusive discrepancy: up to 3σ

Exclusive $B \to D^* \ell \nu$ $F(1)\lvert V_{cb}\rvert = (35.81 \pm 0.11_{stat} \pm 0.44_{syst}) \times 10^{-3}$	**F(1)**	**$\lvert V_{cb}\rvert$ (10^{-3})**
Lattice QCD [PoS LATTICE2010, 311 (2010)]	0.908 ± 0.017	$39.44 \pm 0.50_{exp} \pm 0.74_{th}$
Lattice QCD [arXiv:1403.0635]	0.920 ± 0.013	$38.92 \pm 0.49_{exp} \pm 0.56_{th}$
Sum rules [PRD 81: 113002 (2010)]	0.866 ± 0.020	$41.35 \pm 0.52_{exp} \pm 0.96_{th}$

Exclusive $B \to D \ell \nu$ $G(1)\lvert V_{cb}\rvert = (42.65 \pm 0.72_{stat} \pm 1.35_{syst}) \times 10^{-3}$	**G(1)**	**$\lvert V_{cb}\rvert$ (10^{-3})**
Lattice QCD [NPPS 140, 461-463 (2005)]	1.081 ± 0.024	$39.45 \pm 1.42_{exp} \pm 0.88_{th}$
Sum rules [PLB585, 253-262 (2004)]	1.047 ± 0.020	$40.74 \pm 1.46_{exp} \pm 0.78_{th}$

Inclusive	**$\lvert V_{cb}\rvert$ (10^{-3})**
[PRD 89:014022 (2014)]	42.42 ± 0.86

Extracting $|V_{cb}|G(1)\eta_{EW}$ and ρ^2

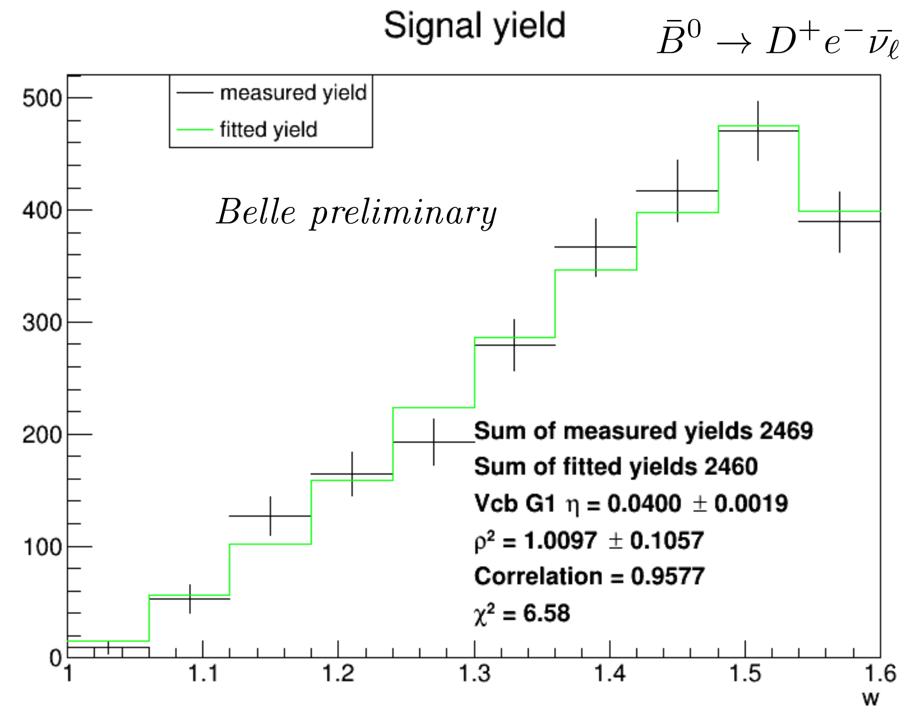
- Measured the signal yield in each w-bin
- Calculate the predicted signal yield for given $|V_{cb}|G(1)\eta_{ew}$ and ρ^2:
  (relative to MC)

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

Predicted signal in bin i

differential decay width using MC parameters

- χ^2 fit of predicted yield to measured yield



systematic errors

	relative error in %			
	$\bar{B}^0 \to D^+ \ell^- \bar{\nu}_\ell$		$B^- \to \bar{D}^0 \ell^- \bar{\nu}_\ell$	
Source	$\eta_{\text{EW}} \mathcal{G}(1) \lvert V_{cb} \rvert$	ρ^2	$\eta_{\text{EW}} \mathcal{G}(1) \lvert V_{cb} \rvert$	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