Semileptonic B and B_s decays at Belle

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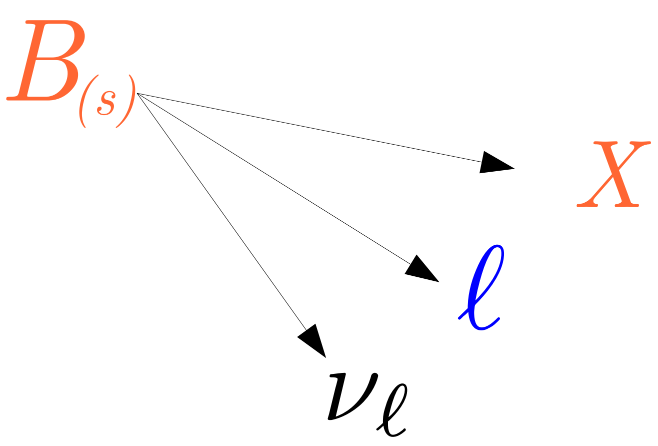
for the Belle Collaboration



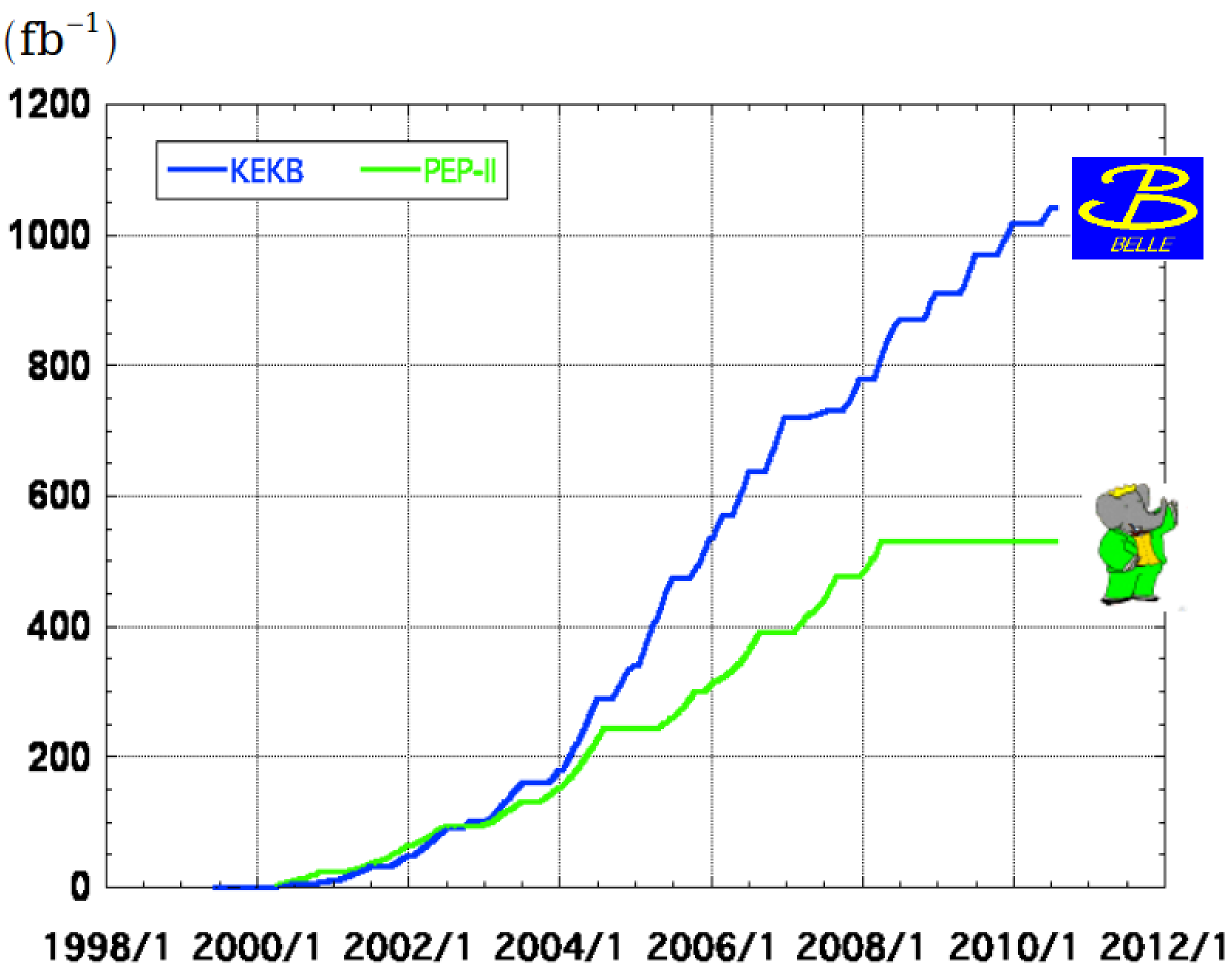
Outline and Motivation

- $B \to D \ell \nu$ (exclusive)
  - Determination of $|V_{cb}|$
  - First measurement of the channel with full Belle data sample
  - New results shown the first time today
  - Inclusive ($B \to X_c \ell \nu$) – exclusive ($B \to D^* \ell \nu$) discrepancy
- $B_s \to D_s^{(*)} X \ell \nu$ (semi-inclusive)
  - Measurement of branching fractions
  - Test theory predictions for B_s

$\ell = e, \mu$

Belle luminosity

used in $B_s \to D_s^{(*)} X \ell \nu$



> 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}

Unique $\Upsilon(5S) \to B_s \bar{B}_s$ data sample at a lepton collider

Worlds largest B meson sample ~772 million $B\bar{B}$ events

used in $B \to D \ell \nu$

~ 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}

The CKM element V_{cb}

- Inclusive: $B \to X_c \ell \nu$
  - (Heavy Quark expansion) $|V_{cb}| = [42.42 \pm 0.86] \times 10^{-3}$
- Exclusive: $B \to D^{(*)} \ell \nu$
  - ($B \to D^* \ell \nu$, LQCD) $|V_{cb}| = [39.27 \pm 0.75] \times 10^{-3}$
  - ($B \to D \ell \nu$, LQCD) $|V_{cb}| = [40.19 \pm 1.48] \times 10^{-3}$

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  - $(B \to D \ell \nu$, LQCD) $|V_{cb}| = [40.19 \pm 1.48] \times 10^{-3}$ → Improve to clarify

$B \to D \ell \nu$

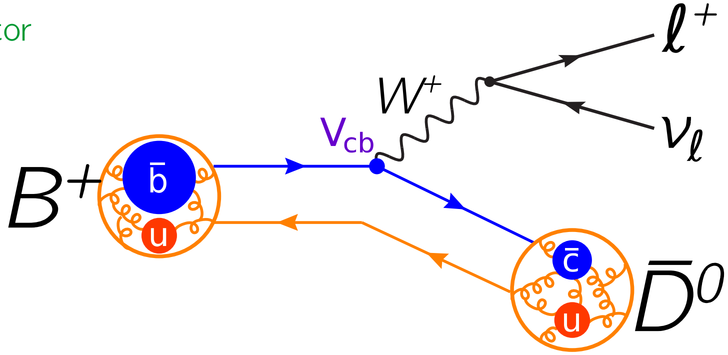
- V_{cb} via differential decay width:

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

electroweak correction — form factor

$\ell = e, \mu$

- Kinematics: $w = v_B \cdot v_D$



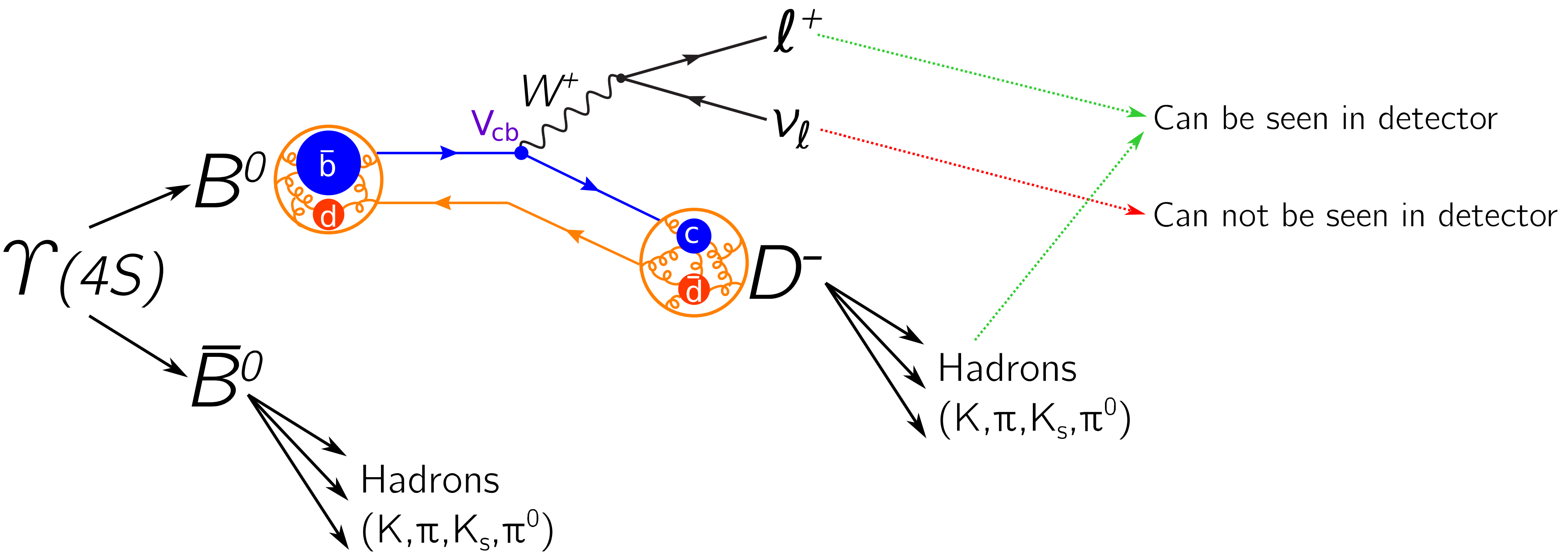
- Measure $\Delta\Gamma/\Delta w$ spectrum and fit V_{cb}
- Form factor $G(w)$:
  - Need points/parameters from Lattice QCD or Light Cone Sum Rules
  - Which parametrization?
  - Until recently: Caprini, Lelouch, Neubert (CLN) parametrization

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

  - Meanwhile: e.g. Boyd Grinstein Lebed (BGL) parametrization (less model assumptions)

$$\mathcal{G}(w) = \frac{\sqrt{4M_D/M_B}}{1 + M_D/M_B} \quad \frac{1}{P_i(z)\phi_i(z)} \sum_{n=0}^{N} a_{i,n} z^n$$

$B \to D \ell \nu$: Reconstruction



- $\Upsilon(4S)$ decays into two B mesons
- Reconstruct one of them in a hadronic mode B_{tag} = hadronic tag
- Allows full kinematic reconstruction

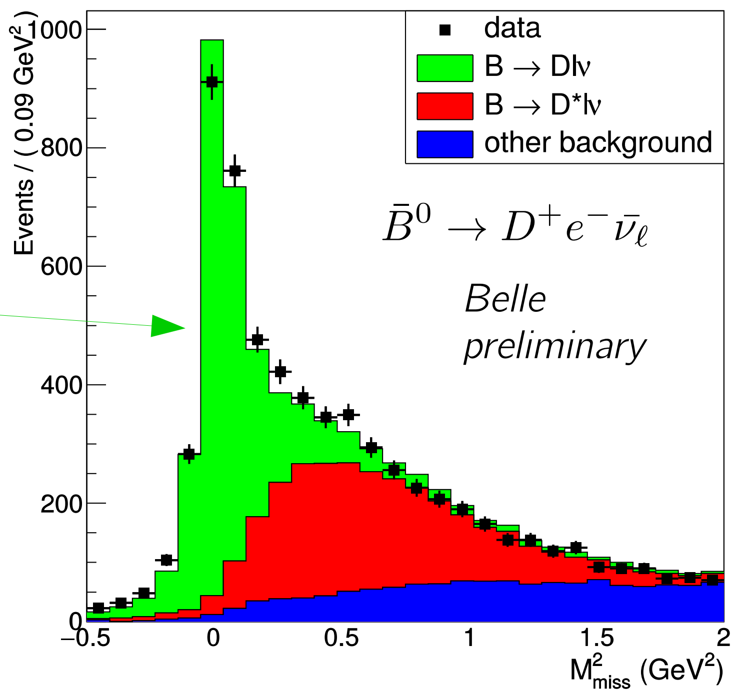
$B \to D \ell \nu$: Reconstruction

- Tracks and photons from B_{tag} are removed
- Reconstruct *D* in multiple hadronic channels
- Identify the lepton e or μ
- Determine the missing mass²

$$M^2_{miss} = (p_{\rm beam} - p_{B_{\rm tag}} - p_D - p_\ell)^2$$

- If only neutrino is missing (*i.e.* genuine reconstruction)

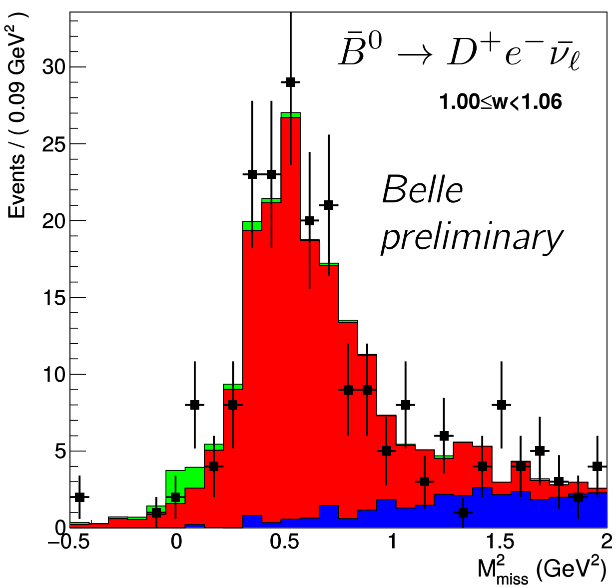
$$M^2_{miss} = 0$$

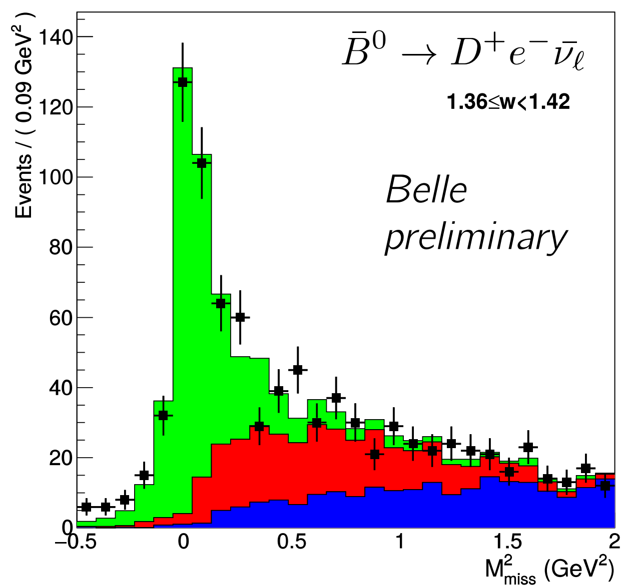


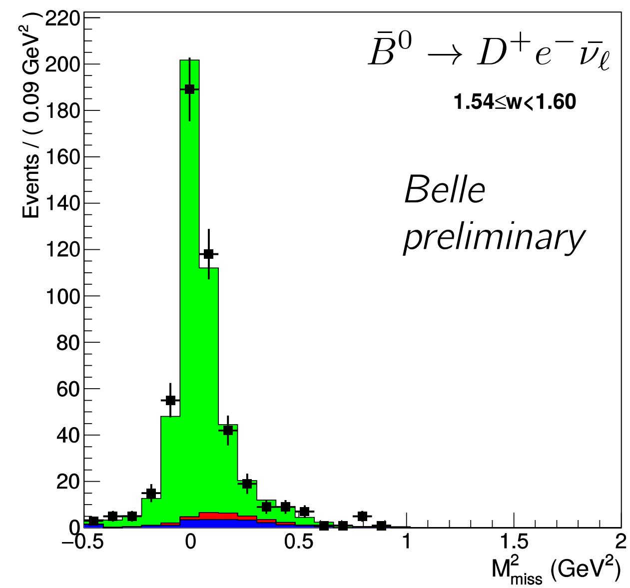
$D^+ \to K^-\pi^+\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$
$D^+ \to K^0_s\pi^+$
$D^+ \to K^0_s\pi^+\pi^0$
$D^+ \to K^+K^-\pi^+$
$D^+ \to K^0_s K^+$
$D^+ \to K^0_s\pi^+\pi^+\pi^-$
$D^+ \to \pi^+\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$
$D^+ \to K^-\pi^+\pi^+\pi^+\pi^-$
$D^0 \to K^-\pi^+$
$D^0 \to K^-\pi^+\pi^0$
$D^0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

$B \to D\ell\nu$: Signal yield extraction

- Extract signal yield in 10 different w-bins (from 1.0 to 1.6)
- Use MC distribution as template
  - Floating: signal and $B \to D^*\ell\nu$ *background*
  - Fixed to MC: other bg (e.g. fake- and non prompt leptons, D^{**} etc.)
- Determine $\Delta\Gamma/\Delta w$ from the signal yields relative to callibrated MC

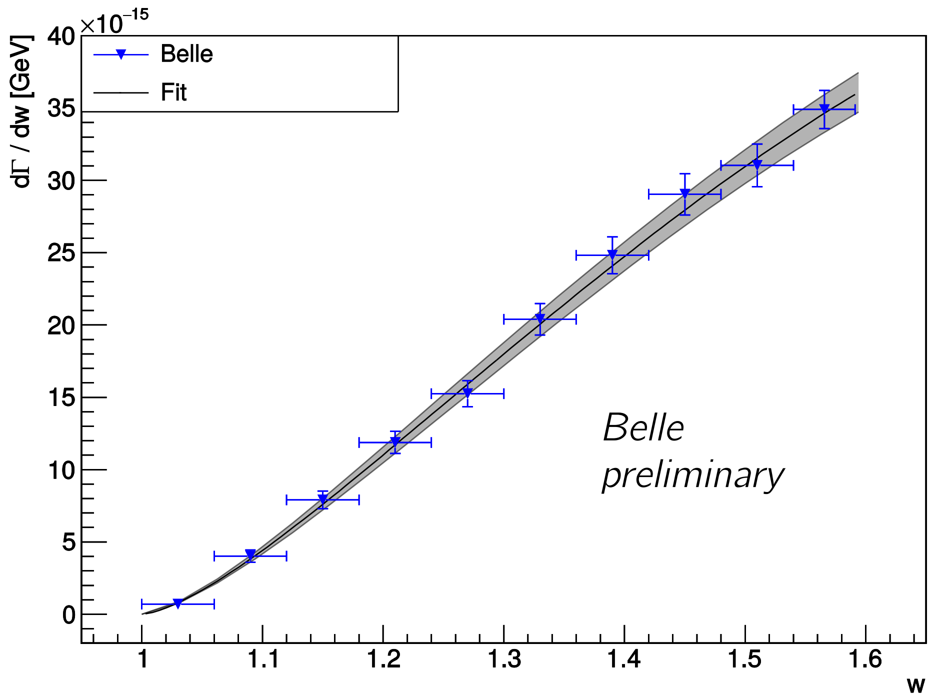


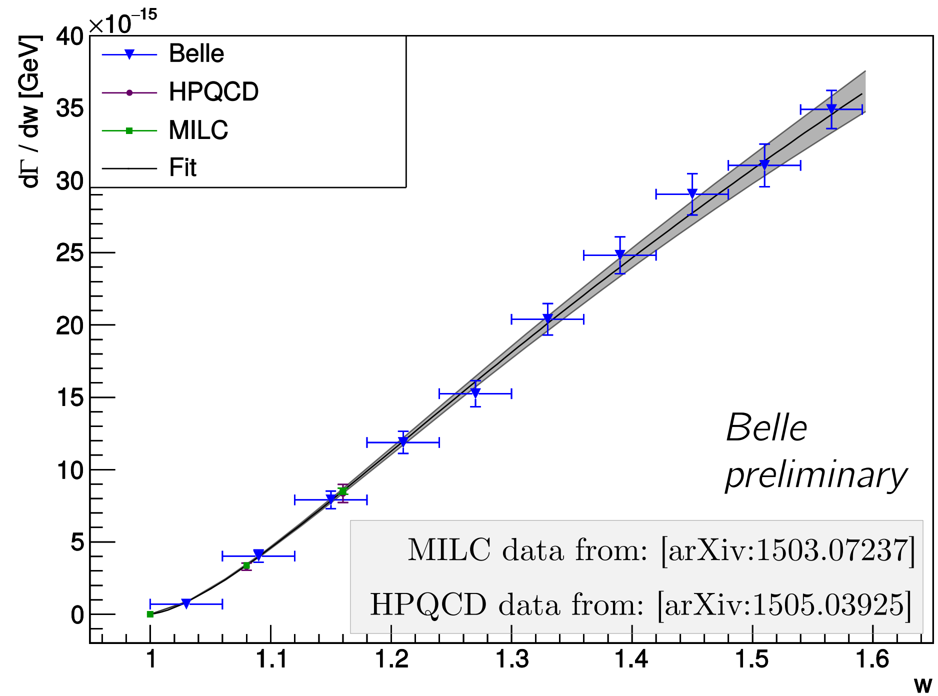




$B \to D \ell \nu$: Vcb Fit

- We extracted $\Delta\Gamma/\Delta w$ in different w bins
- Fit with:
  CLN (two params, heavy quark symmetry) or BGL (more params, less constraints)





$$|V_{cb}|\eta_{EW} = (40.93 \pm 1.33) \times 10^{-3}$$ *Belle preliminary* $$|V_{cb}|\eta_{EW} = (42.09 \pm 1.07) \times 10^{-3}$$

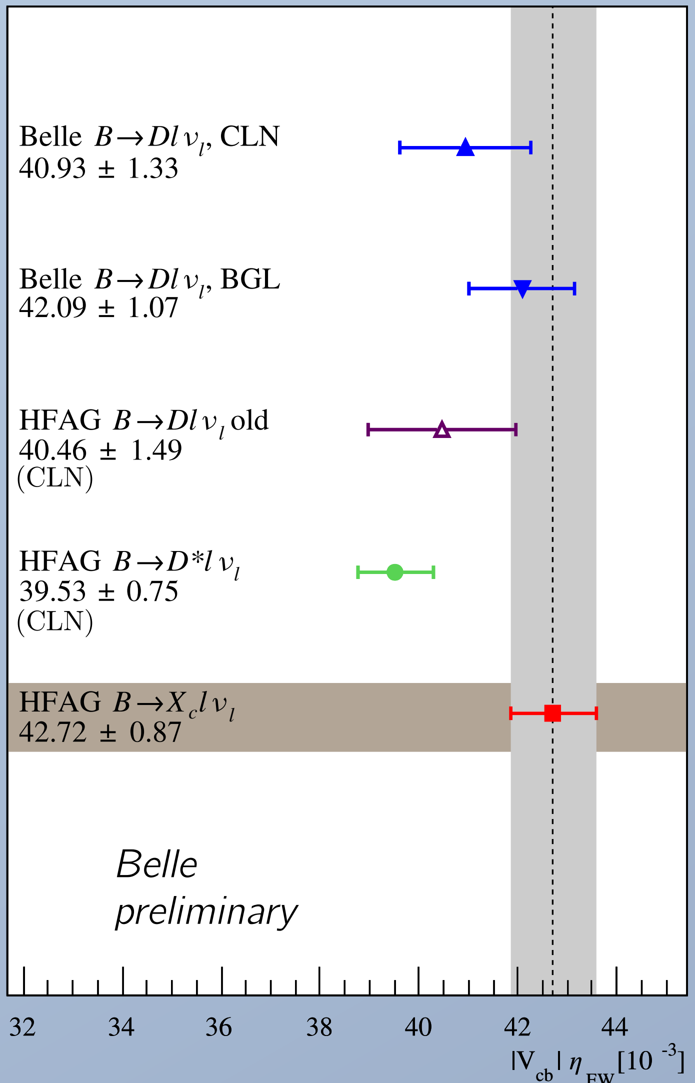
Using $G(1) = 1.0541 \pm 0.0083$ from MILC [arXiv:1503.07237]

$B \to D \ell \nu$: results *(preliminary)*

Vcb

$$|V_{cb}|\eta_{EW}(\text{CLN}) = (40.93 \pm 1.33) \times 10^{-3}$$

$$|V_{cb}|\eta_{EW}(\text{BGL}) = (42.09 \pm 1.07) \times 10^{-3}$$



Branching fractions

Belle preliminary

$$\mathcal{B}(B^0 \to D^- \ell^+ \nu_\ell) = (2.35 \pm 0.04 \pm 0.11)\%$$

$$\mathcal{B}(\mathrm{B}^+ \to \bar{D}^0 \ell^+ \nu_\ell) = (2.67 \pm 0.04 \pm 0.12)\%$$

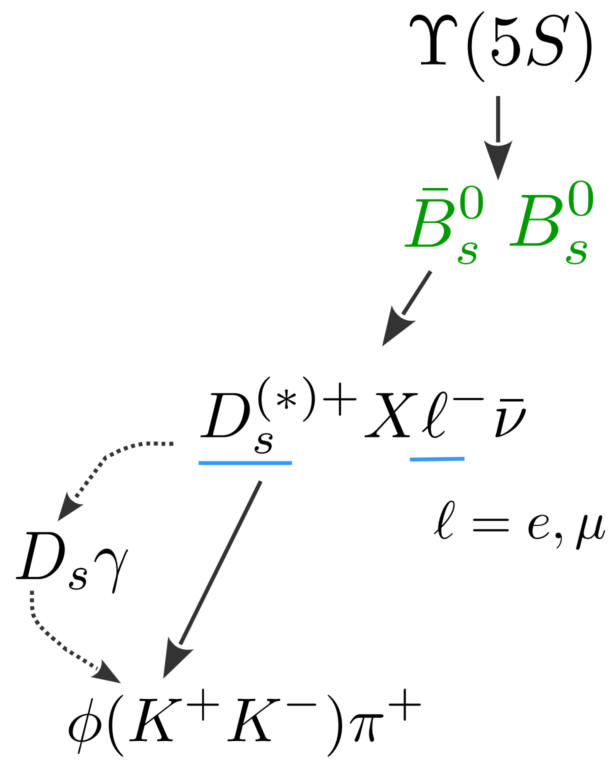
$$\mathcal{B}(B \to D \ell \nu_\ell) = (2.43 \pm 0.03 \pm 0.10)\%$$

(stat) (syst)

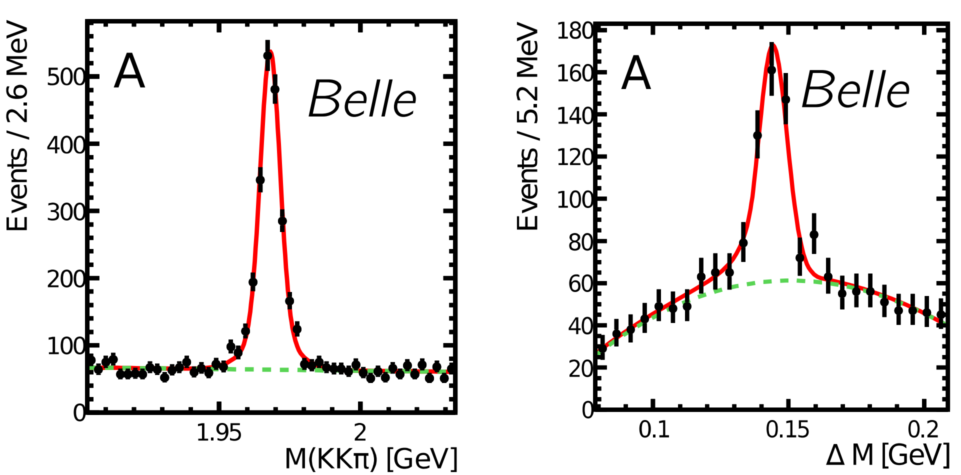
(in terms of B^0)

$B_s \to D_s^{(*)} X \ell \nu$

[arXiv:1504.02004, submitted to PRD]



- X = feed down from higher D_s states
- $D_s \to \Phi(K^+K^-)\pi$
- $D_s^* \to D_s\gamma$
- Combine $D_s^{(*)}$ with lepton of opposite charge
- Determine the number of $D_s^{(*)}$:
  - D_s: fit m($KK\pi$)
  - D_s^*: fit Δm = m($KK\pi\gamma$)-m($KK\pi$)

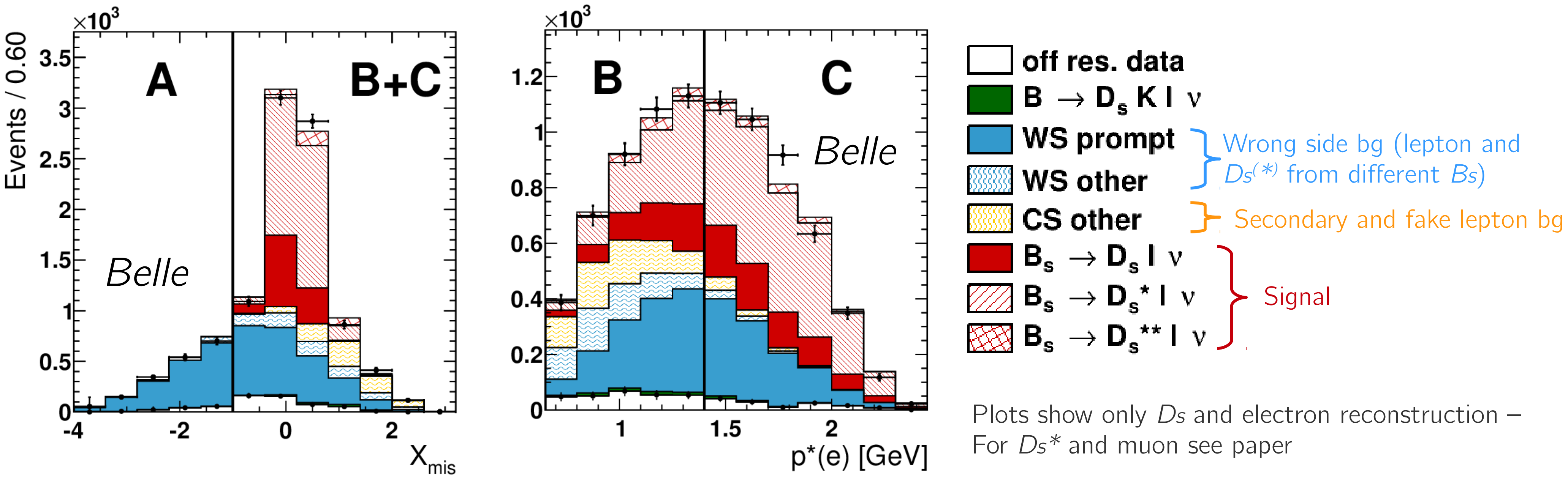


$B_s \to D_s^{(*)} X \ell \nu$ signal yield extraction

- Determine number of genuine $B_s \to D_s(*) X \ell \nu$ events with X_{mis} distribution

$$X_{\mathrm{mis}} = \frac{E^*_{B_s} - (E^*_{D_s\ell} + p^*_{D_s\ell})}{\sqrt{s/4 - m^2_{B_s}}}$$

  - $E_{Bs}{}^*$: B_s energy in CM system (approx. by $\sqrt{s}/2$)
  - $E_{Ds\ell}{}^*$ and $p_{Ds\ell}{}^*$: reconstructed energy and momentum
- Use 3 counting regions A,B and C:



Plots show only D_s and electron reconstruction – For D_s* and muon see paper

$B_s \to D_s^{(*)} X \ell \nu$ signal yield extraction

- 3 components:
  - Wrong side (lepton and $D_s^{(*)}$ from different B_s)
  - Secondary and fake leptons
  - Signal
- Each region enhances one component
- 3 unknowns and 3 equations →solve to know N_{signal}
- Knowing number of B_s mesons, BRs of $D_s^{(*)}$ and efficiencies we get $\mathcal{B}(B_s \to D_s^{(*)} X \ell \nu)$
- Or: If we can estimate $\mathcal{B}(B_s \to D_s X \ell \nu)$ we can calculate the number of B_s mesons – very useful for many $\Upsilon(5S)$ analyses
  - Start from $B_s \to X_c \ell \nu$: can be inferred from $B^0 \to X_c \ell \nu$ (correct for small differences in semileptonic widths and lifetimes)
  - Remove all states without D_s: D_{s1}, D_{s2}^* decay into $D^{(*)}$
  - $\mathcal{B}_{\text{est}}(B_s \to D_s X \ell \nu) = \mathcal{B}(B_s \to X_c \ell \nu) - \mathcal{B}(B_s \to D_s X \ell \nu) = (8.6 \pm 0.5)\%$

$B_s \to D_s^{(*)} X \ell \nu$: results

$$\mathcal{B}(D_s X e\nu) = [8.1 \pm 0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 1.4(\text{ext})]\%$$
$$\mathcal{B}(D_s X \mu\nu) = [8.3 \pm 0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 1.5(\text{ext})]\%$$
$$\mathcal{B}(D_s^* X e\nu) = [5.2 \pm 0.6(\text{stat}) \pm 0.4(\text{syst}) \pm 0.9(\text{ext})]\%$$
$$\mathcal{B}(D_s^* X \mu\nu) = [5.7 \pm 0.6(\text{stat}) \pm 0.4(\text{syst}) \pm 1.0(\text{ext})]\%$$

Combined:

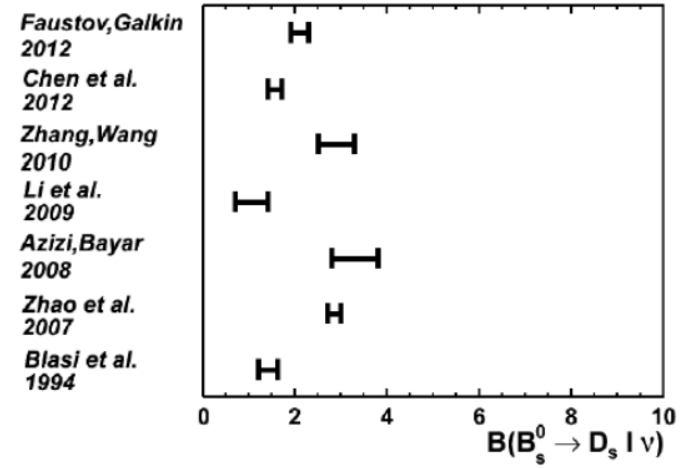
$$\mathcal{B}(D_s X \ell\nu) = [8.2 \pm 0.2(\text{stat}) \pm 0.6(\text{syst}) \pm 1.4(\text{ext})]\%$$
$$\mathcal{B}(D_s^* X \ell\nu) = [5.4 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.9(\text{ext})]\%$$

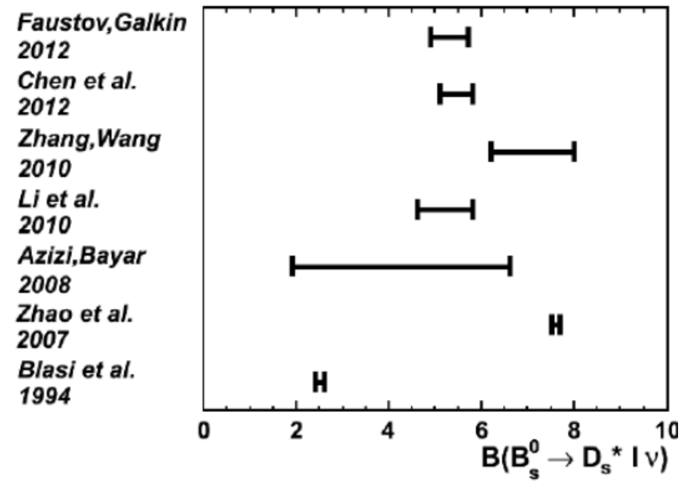
- Theory predictions don't include "X" $\rightarrow$should be lower than our results

Number of B_s pairs at $\Upsilon(5S)$ at Belle

$$N_{B_s \bar{B}_s} = [6.93 \pm 0.18(\text{stat}) \pm 0.52(\text{syst}) \pm 0.51(\text{ext})] \times 10^6$$

Theory predictions:





Summary

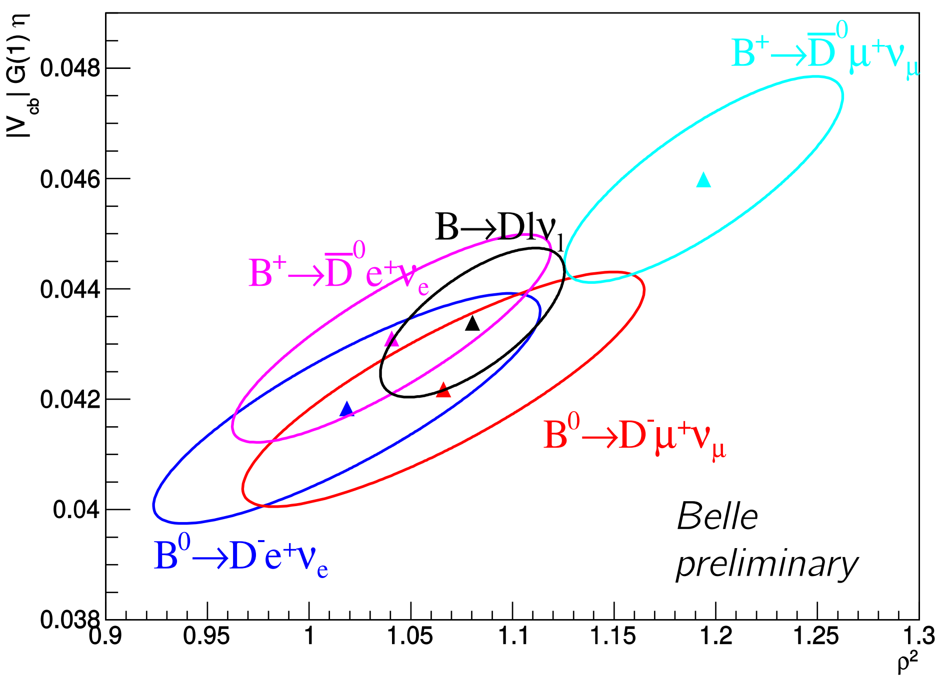
- $B \to D \ell \nu$
  - Full reconstruction of events using hadronic tag
  - Fit differential decay width
  - $$|V_{cb}|\eta_{EW}(\mathrm{CLN}) = (40.93 \pm 1.33) \times 10^{-3}$$
    $$|V_{cb}|\eta_{EW}(\mathrm{BGL}) = (42.09 \pm 1.07) \times 10^{-3}$$
  - Inclusive – Exclusive Discrepancy not confirmed
- $B_s \to D_s^{(*)} X \ell \nu$
  - Use decays $D_s^* \to D_s \gamma$ and $D_s \to \Phi(KK)\pi$
  - Determine number of $D_s^{(*)}$ with fits to m($KK\pi$) and Δm
  - Using 3 counting regions enhancing different yields
  - $$\mathcal{B}(D_s X \ell \nu) = [8.2 \pm 0.2(\mathrm{stat}) \pm 0.6(\mathrm{syst}) \pm 1.4(\mathrm{ext})]\%$$
    $$\mathcal{B}(D_s^* X \ell \nu) = [5.4 \pm 0.4(\mathrm{stat}) \pm 0.4(\mathrm{syst}) \pm 0.9(\mathrm{ext})]\%$$
    $$N_{B_s \bar{B}_s} = [6.93 \pm 0.18(\mathrm{stat}) \pm 0.52(\mathrm{syst}) \pm 0.51(\mathrm{ext})] \times 10^6$$

Thank you!

Back Up

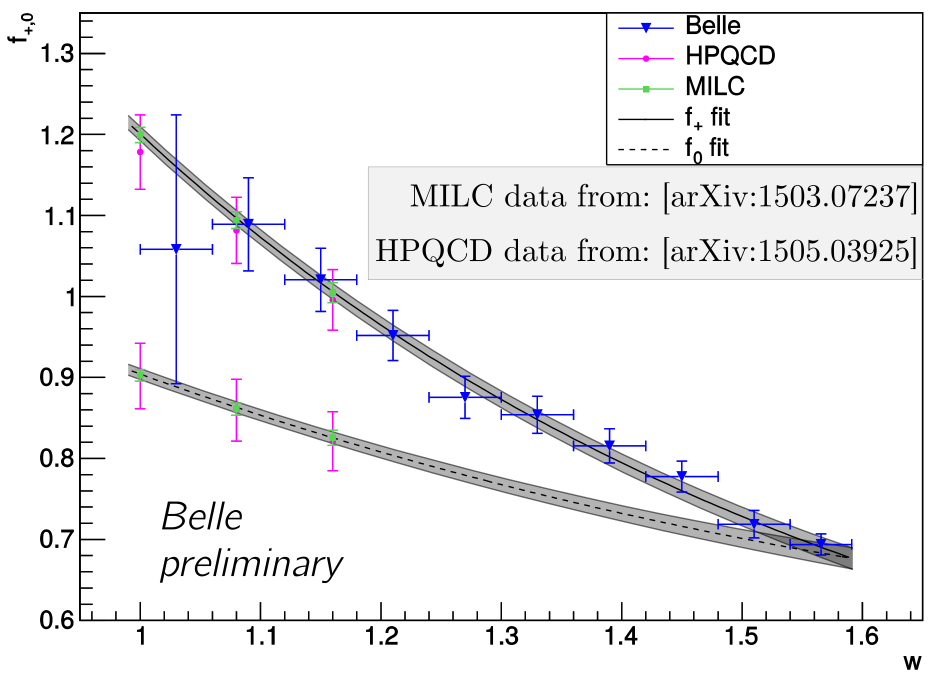
$B \to D \ell \nu$: Vcb Fit

- Additional plots
- CLN (two params, heavy quark symmetry) Lepton – and B^+/B^0 separated fit results:



$|Vcb|G(1)\eta_{EW}$ and ρ^2 are the two free parameters of the fit

- BGL (more params, less constraints) Form factors f_+, f_0



Relation between f_+ and G(w):

$$f_+(w)^2 = \frac{(1+M_D/M_B)^2}{4M_D/M_B}\mathcal{G}(w)^2$$

$B \to D \ell \nu$: systematic errors

	$\sigma\,(\Delta\Gamma_i/\Delta w)[\%]$									
	0	1	2	3	4	5	6	7	8	9
Tag Correction	3.08	3.26	3.31	3.35	3.36	3.35	3.41	3.25	3.30	3.16
Charged tracks	1.78	1.65	1.62	1.61	1.66	1.65	1.65	1.65	1.65	1.69
$\mathcal{B}(D \to$ hadronic $)$	0.71	0.60	0.57	0.54	0.61	0.55	0.54	0.52	0.51	0.50
$\mathcal{B}(B \to D^{*(*)}\ell\nu)$	1.45	0.91	0.90	0.97	0.84	0.77	0.56	0.26	0.13	0.44
$\mathcal{B}(B \to X_u\ell\nu)$	0.48	0.09	0.04	0.06	0.04	0.03	0.03	0.03	0.03	0.01
$\mathrm{FF}(B \to D^{*}\ell\nu)$	0.58	0.25	0.16	0.23	0.20	0.09	0.10	0.09	0.09	0.23
$\mathrm{FF}(B \to D^{**}\ell\nu)$	1.98	1.17	0.81	0.70	0.49	0.56	0.70	0.53	0.10	0.30
Lifetimes	0.30	0.20	0.18	0.19	0.19	0.19	0.18	0.18	0.19	0.18
π^0 efficiency	0.64	0.62	0.71	0.64	0.64	0.67	0.66	0.72	0.72	0.76
K/π efficiency	1.27	0.88	0.89	0.92	0.98	0.96	0.95	0.94	0.97	0.96
K_s efficiency	0.45	0.19	0.22	0.21	0.22	0.21	0.20	0.21	0.21	0.21
Luminosity	1.59	1.40	1.39	1.38	1.44	1.40	1.39	1.36	1.44	1.39
All	5.14	4.50	4.35	4.41	4.27	4.22	4.22	4.19	4.08	3.79

$B \to D \ell \nu$: Comparison of different BGL set-ups

Using different lattice data

Lattice data	$\eta_{EW}\lvert V_{cb}\rvert[10^{-3}]$	χ^2/df	p
MILC [12]	41.77 ± 1.20	7.32/10	0.69
HPQCD [27]	42.10 ± 1.89	5.92/8	0.66
MILC & HPQCD [12, 27]	42.09 ± 1.07	12.93/16	0.68

Using different series truncations N

	$N=2$	$N=3$	$N=4$
$a_{+,0}$	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	0.0114 ± 0.0001	0.0114 ± 0.0001
$a_{0,1}$	-0.058 ± 0.002	-0.057 ± 0.002	-0.057 ± 0.002
$a_{0,2}$	0.23 ± 0.02	0.12 ± 0.04	0.12 ± 0.04
$a_{0,3}$	–	0.4 ± 0.6	0.4 ± 0.6
$a_{0,4}$	–	–	0.0 ± 1.0
$\eta_{EW}\lvert V_{cb}\rvert$	40.63 ± 0.98	42.09 ± 1.07	42.09 ± 1.07
χ^2/df	30.3/16	12.9/16	12.9/16
p	0.016	0.678	0.678

= default

[12] = [arXiv:1503.07237]
[27] = [arXiv:1505.03925]

$B_s \to D_s^{(*)} X \ell \nu$ systematic errors [%]

	$D_s X e\nu$	$D_s X \mu\nu$	$D_s^* X e\nu$	$D_s^* X \mu\nu$
Detector				
Tracking efficiency	1.4	1.4	1.4	1.4
Photon efficiency	—	—	2.0	2.0
Kaon and pion ID	1.4	1.4	1.4	1.4
Lepton efficiency	1.0	1.6	1.0	1.6
Hadron misidentification	0.1	1.3	0.1	1.9
Signal and background modeling				
PDF for $M_{KK\pi}$ and ΔM fits	3.0	3.0	5.0	5.0
Continuum shape	1.2	0.3	1.2	0.3
$B \to D_s^{(*)} K \ell \nu$ modeling	0.3	0.3	0.1	0.1
Signal				
Composition	4.8	4.8	0.3	< 0.1
Form factors	0.9	1.0	1.0	1.0
Efficiency	3.1	3.1	3.0	3.0
Wrong-side				
Composition	1.6	2.2	1.0	2.5
B_s fraction	0.2	0.2	< 0.1	< 0.1
Shape	1.0	1.0	1.0	1.0
Other				
Composition and shape	0.3	0.3	0.4	0.7
B_s production mode	0.1	0.1	0.3	0.3
Beam energy	1.0	1.0	0.5	0.5
Total	7.3	7.6	6.9	7.6