$|V_{cb}|$ from inclusive tag $B \to D\ell\nu$

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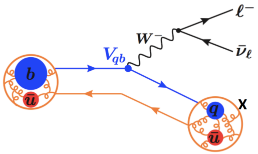
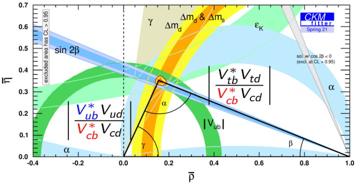
Status of $|V_{cb}|$ and $|V_{ub}|$



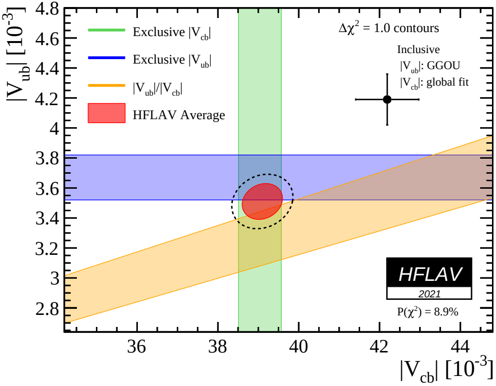


- $|V_{cb}|$ and $|V_{ub}|$ constrain the SM through unitarity triangle
- Important input in SM predictions
- Semileptonic B decays are studied to measure $|V_{cb}|$ and $|V_{ub}|$
  - Factorizable leptonic and hadronic currents

- **Exclusive**: Reconstruct specific final states
- *i.e.:*
  - $|V_{cb}| : B \to D^{(*)}\ell\nu$
  - $|V_{ub}| : B \to \pi\ell\nu$
- Theory input: Lattice QCD (LQCD)

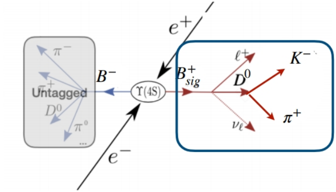
- **Inclusive**: Measure general $X\ell\nu$ decay
- *i.e.:*
  - $|V_{cb}| : B \to X_c\ell\nu$
  - $|V_{ub}| : B \to X_u\ell\nu$
- Theory input: Heavy Quark Expansion Theory (HQET)

Status of $|V_{cb}|$ and $|V_{ub}|$



- $\sim 3\sigma$ discrepancy between inclusive and exclusive $|V_{cb}|$ and $|V_{ub}|$ measurements
- Limiting factor in precision flavor physics

Analysis overview



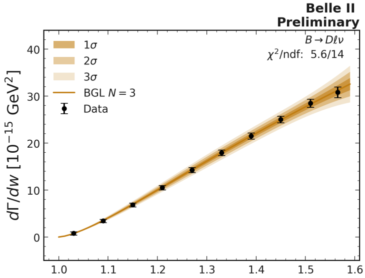
- Untagged/Inclusive tag analysis of $B \to D\ell\nu$ final state
- Extract differential decay rates in bins of w to measure V_{cb}
- Modes:
  - Charged B mode $B^- \to D^0\ell^-\overline{\nu}_\ell$ with $D^0 \to K^-\pi^+$
  - Neutral B mode $B^0 \to D^-\ell^+\nu_\ell$ with $D^- \to K^+\pi^-\pi^-$
- Parameters of interest:
  - Differential decay rates in bins of momentum transfer $\Delta\Gamma/\Delta w$
  - Absolute branching ratios $\mathcal{B}(B \to D\,\ell\,\overline{\nu}_\ell)$
  - V_{cb}, BGL form factor parameters
  - Lepton universality $R_{e/\mu}$

$|V_{cb}|$ extraction

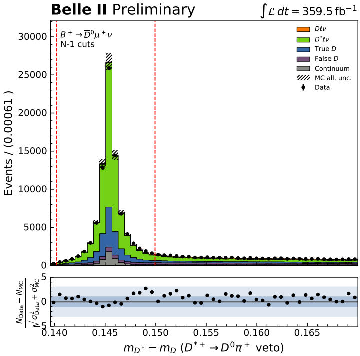
- From measuring signal yields in bins of w, calculate differential decay rates
- Differential decay rate:

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

- with the form factor $\mathcal{G}(w)$
- with the kinematic variable $w = v_B \cdot v_D = \frac{p_B \cdot p_D}{m_B m_D} = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$
- $w_{min} = 1$: zero-recoil point, q^2_{max}, D at rest in B rest frame



- Analyze $B^+ \to \bar{D}^0\ell^+\nu_\ell$ and $B^0 \to D^-\ell^+\nu_\ell$
- Final state particles ℓ and hadrons from $D^{0(+)} \to K^-\pi^+(\pi^+)$
- Dominant background from $B \to D^*\ell\nu$ decays
  - Explicit vetoes
- Vertex fitting full decay chain to suppress combinatorial background

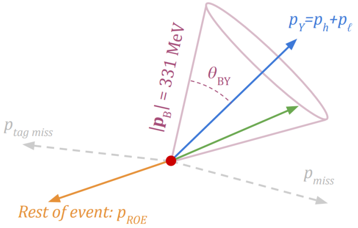


Variable	Charged B	Neutral B
$KSFW^{02}_{hso}$	[-0.371,0.485]	[-0.361,0.457]
E^*_Y [GeV]	[3.247,5.169]	[3.340, 5.174]
p^*_{miss} [GeV]	[0.698,4.345]	[0.745, 4.389]
m_{ROE} [GeV]	[0.510, 7.967]	[0.756,6.771]
$\cos\theta_{\ell,W}$	[-0.821, 0.553]	[-0.828, 0.866]
p_{ROE} [GeV]	[0.069, 2.858]	[0.091, 2.738]
$\theta_{D,\ell}$	[0.120, 3.137]	[0.339, 3.136]

- Suppress backgrounds by simultaneously optimizing rectangular selections using simulated annealing
- Kinematic variables
- Event shape variables
- rest-of-event variables

Reconstruction of kinematic variable q^2

- How to reconstruct kinematic variable w in untagged approach?
- Need to know direction of signal B meson
- Novel approach : (extension of BaBar's diamond frame [Phys. Rev. D 74, 092004])



- Calculate $\cos\theta_{BY}$ from reconstructed D and ℓ
- $B\overline{B}$ production: angularly distributed according to $\sin^2\theta_B$
- Sum up left-over tracks and clusters as Rest-of-Event (ROE) and calculate momentum p^*_{ROE}
- Likely direction on $\cos\theta_{BY}$ cone: Back-to-back with ROE

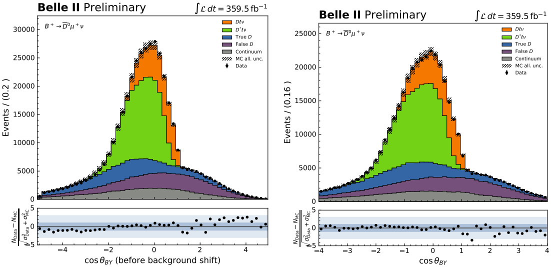
- Weighted average over 10 uniformly distributed vectors on cone
- Each vector has weight combining ROE and kinematic information:

$$\frac{1}{2}(1 - \hat{p}_{\text{ROE}} \cdot \hat{p}_{\text{B}}) \sin^2\theta_B$$

$\hookrightarrow$ Improved resolution compared to previous methods!

Corrections to MC

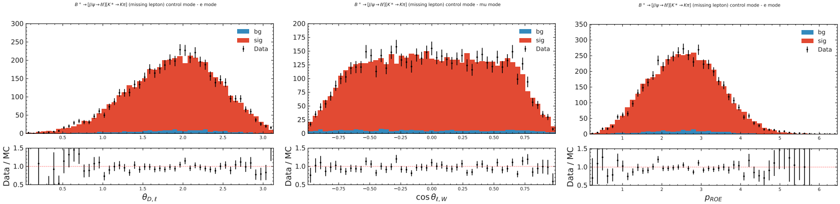
- Use sidebands and control samples to calibrate backgrounds
- Important to have good Data-MC agreement in fitting variable $\cos\theta_{BY}$
- Calibration samples including sideband m_D sideband, wrong charge combination reconstruction, off-resonance data
- Calibrate correction on sidebands and apply to nominal reconstruction



- Additionally correct for known effects:
  - ParticleID
  - Track momentum scale
  - Decay file branching fractions
  - $D^{(*)}\ell\nu$ form factors
  - etc.

Checking signal distribution with control samples

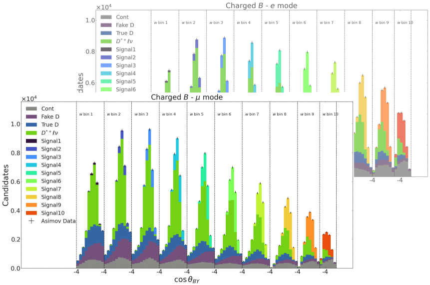
- To make sure signal distributions are well understood in all selection variables:
  - Reconstruct control samples that look similar to signal and have high purity
- Fully hadronic:
  - $B \to D\pi$: Treat π as lepton
- Missing energy/momentum through partial reconstruction:
  - $B \to [D^* \to D\pi_{slow}]\pi$: Treat slow π as missing
  - $B \to [J/\psi \to \ell\ell][K^* \to K^-\pi^+]\pi$: Treat second ℓ as missing

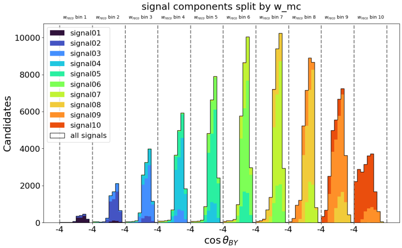


- Good Data/MC agreement in variables
- Correct for disagreement in vertex fit probability and assign systematic

Signal extraction

- Simultaneously fit signal yields in 10 windows of w for each of 4 decay modes
- Binned template fit using `pyhf`
- Fitting variable: $\cos\theta_{BY}$

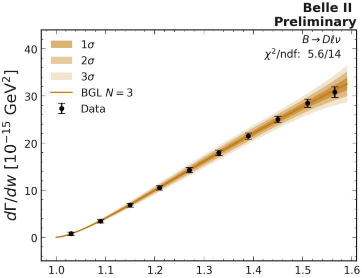




- Novel approach: directly unfold migration effects between w bins in fit
- Include all systematic uncertainties into the fit as nuisance parameters
  - Directly maps into correlation matrix between signal yields

Form factor fit and V_{cb} measurement

- From fitted yields we can calculate $\Delta\Gamma/\Delta w$
- Average over all 4 modes
- Fit form factor to differential decay rates (BGL/BCL parameterization)
- Include data from Lattice QCD in fit as nuisance parameter



$V_{cb,BGL}$	
Stat. Error	0.74%
MC Stat. Error	0.37%
N_{bb}	0.77%
f_{00}/f_{+-}	0.04%
$\mathcal{B}(D \to K\pi(\pi))$	0.45%
Selection	0.25%
$\mathcal{B}(B \to X_c\ell\nu)$	0.16%
LeptonID	0.14%
KaonID	0.45%
Tracking efficiency	0.50%
$B \to D\ell\nu$ form factor	0.79%
$B \to D^*\ell\nu$ form factor	0.11%
$\cos\theta_{BY}$ background modelling	0.13%
w background modelling	0.46%
$\tau_{B^{0/\pm}}$	0.10%
Total systematic	1.50%
Theory	1.24%
Total	2.07%

- Currently pre-unblinding
- Estimate impact of systematic uncertainty sources by drawing toys from nuisance parameters
- Estimated $\sim 2.1\%$ sensitivity $\to$ more sensitive than Belle $D\ell\nu$ measurement ($\sim 2.7\%$)

Summary

- Long-standing tension between inclusive and exclusive determinations of V_{cb}
- Analysis of untagged $B^- \to D^0 \ell^- \overline{\nu}_\ell$ events to measure V_{cb} exclusively
- New analysis techniques to optimize selections and reconstruct kinematic variables
- Define control samples to validate signal and background distributions
- Projected total uncertainty on V_{cb}: 2%
- Currently in review committee stage

Thank you!