EXPERIMENTAL CHALLENGES IN EXCLUSIVE $|V_{cb}|$ MEASUREMENTS

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Outline – and spoiler

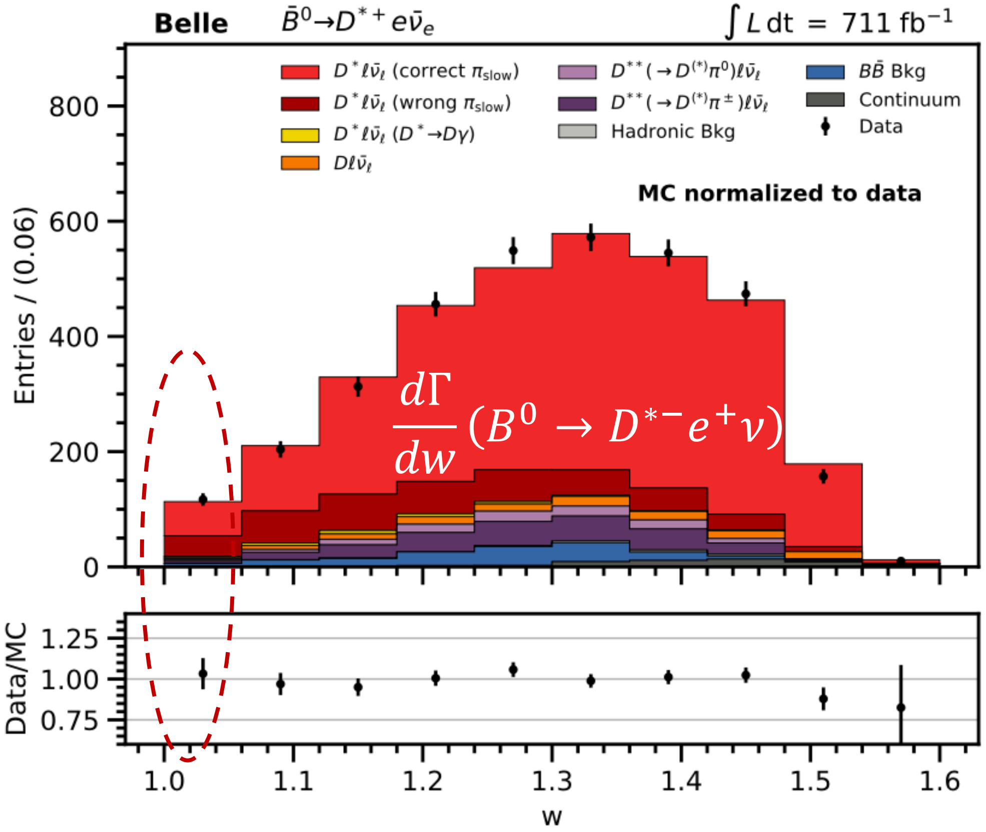
- Review of methods and limiting uncertainties in existing $|V_{cb}|$ measurements using exclusive $B \to D^{(*)}\ell\nu$ decays
- What is needed from experiment?
- How can Belle II deliver?

- Further improve FF determination
- Improve absolute normalization
- Improve MC modeling, statistics
- Handle $D^* \to D\pi$ feeddown
- Measure gap modes
- Tags, simultaneous measurements

- Fewer and more comprehensive analyses
- Cohesive analysis teams
- Move beyond “1 PhD student = 1 paper” mentality

Exclusive $|V_{cb}|$ analyses - overview

- Total and partial rates for $B \to D^{(*)}\ell\nu$ depend on $|V_{cb}|^2$
- Soft QCD enters through form factors $FF(q^2)$ – we can only predict the FF size with lattice QCD near the zero recoil (max q^2) point ($D^{(*)}$ at rest in the B frame)
- The rate there is phase-space suppressed and can't be measured directly (extrapolation)
- **Challenge:** need to measure both FF shape and overall normalization (BF/lifetime) to determine $|V_{cb}|$
- In practice, combined experiment+lattice(+BF) fits are used. Different analyses are best adapted to measuring shape versus normalization

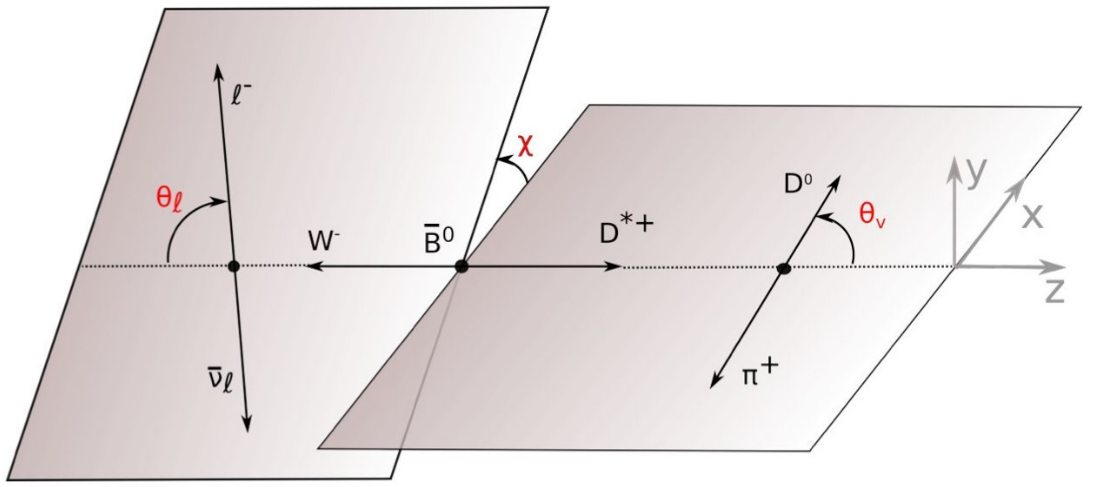


PRD 108, 012002 (2023)

$B \to D^*\ell\nu$ analyses – full 4D rate

- Fully differential $B \to D^*\ell\nu$ rate depends on $\theta_\ell, \theta_V, \chi$ and $q^2 = (p_B - p_{D^*})^2$
- In practice we use $w = \frac{m_B^2+m_{D^*}^2-q^2}{2m_B m_{D^*}}$, or $z = \frac{\sqrt{t_+-q^2}-\sqrt{t_+-t_0}}{\sqrt{t_+-q^2}+\sqrt{t_+-t_0}}$ (t_+, $t_0$fixed) for expansions
- Three form factors for light leptons parameterized (next talk) using expansions in z
- Measuring the full 4D rate requires high stats and good modeling of acceptance

- Heavy Quark Effective Theory relates all FFs to a universal Isgur-Wise function, but HQET constraints are no longer needed to interpret data



Untagged decays – still important

Untagged decays will continue to be useful for the dominant channels, $B \to D^* \ell \nu$, $B \to X \ell \nu$

Provide a precise BF for normalization

Only the cleanest $D^{(*)}$ decay modes are used; only 3 or 4 particles reconstructed, so efficiencies have "small" uncertainty

Sensitive to $e^+ e^- \to q\bar{q}$ background, background from other B

"Inclusive tagging" (examining the ROE for compatibility with a B meson –the details vary per analysis) can reduce backgrounds and provide higher efficiency than full tagging

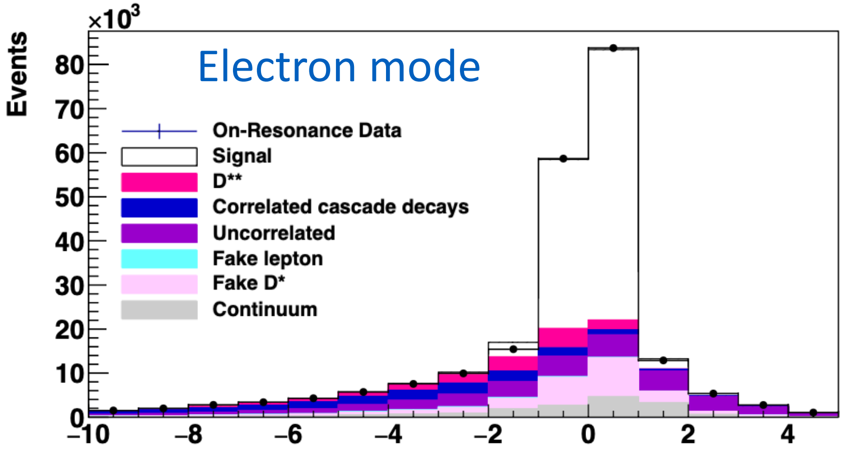
The efficiency uncertainty of inclusive tag analyses depends on how the severity of the added requirements

Best untagged measurement of $B \to D^*\ell\nu$

Belle $B \to D^*\ell\nu$ PRD 103, 079901(E) (2018/2021)

Overall uncertainty on $\mathcal{F}(1)|V_{cb}|$ = 1.6%, dominated by normalization.

$$\cos\theta_{BY} \equiv \frac{2E_B E_Y - m_B^2 - m_Y^2}{2|\vec{p}_B||\vec{p}_Y|}$$



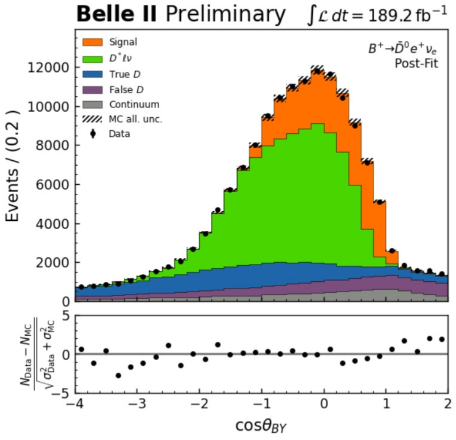
Source	ρ^2	$R_1(1)$	$R_2(1)$	$\mathcal{F}(1)\lvert V_{cb}\rvert$ [%]
Slow pion efficiency	0.005	0.002	0.001	0.65
Lepton ID combined	0.001	0.006	0.004	0.68
$\mathcal{B}(B \to D^{**}\ell\nu)$	0.002	0.001	0.002	0.26
$B \to D^{**}\ell\nu$ form factors	0.003	0.001	0.004	0.11
f_{+-}/f_{00}	0.001	0.002	0.002	0.52
Fake e/μ	0.004	0.006	0.001	0.11
Continuum norm.	0.002	0.002	0.001	0.03
K/π ID	< 0.001	< 0.001	< 0.001	0.39
Fast track efficiency	-	-	-	0.53
$N\Upsilon(4S)$	-	-	-	0.68
B^0 lifetime	-	-	-	0.13
$\mathcal{B}(D^{*+} \to D^0\pi_s^+)$	-	-	-	0.37
$\mathcal{B}(D^0 \to K\pi)$	-	-	-	0.51
Total systematic error	0.008	0.009	0.007	1.60

$B \to D\ell\nu$ analyses – isolating signal

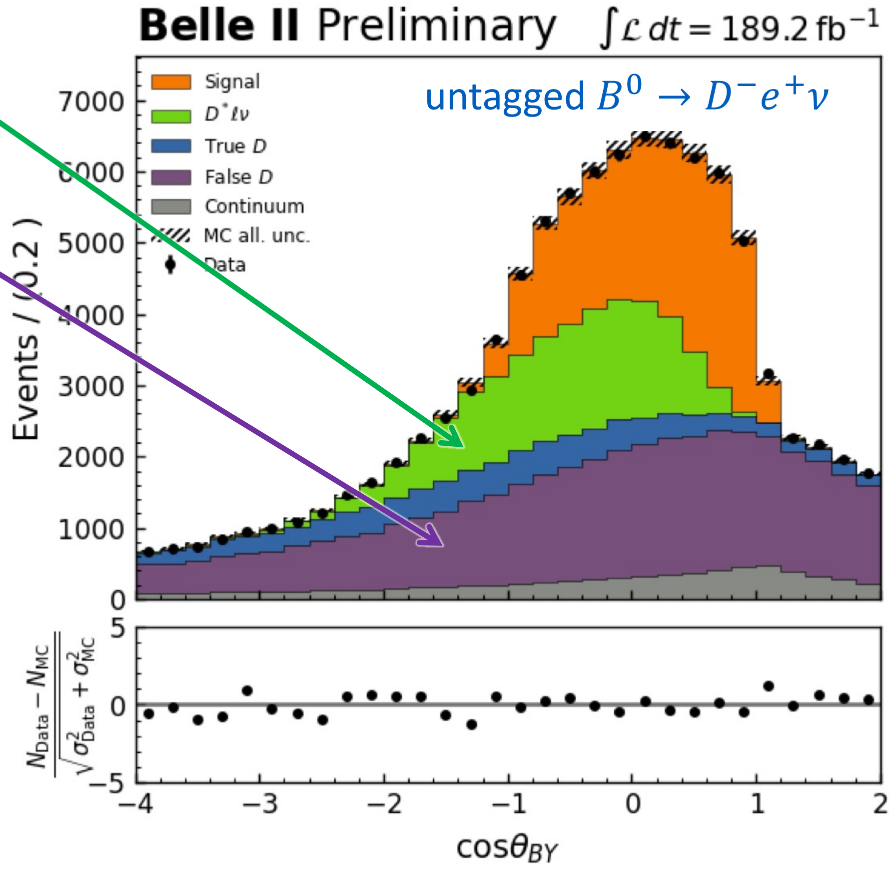
Fundamental: isospin breaking

BF	$D\pi^{\pm}$	$D\pi^{0}$	$D\gamma$
D^{*+}	0.677	0.317	0.016
D^{*0}	**0**	0.65	0.35

- Challenge: large feed-down from $B \to D^*\ell\nu$ decays with missing π, γ
- Background in untagged analyses from misreconstructed D
- Untagged $B \to D\ell\nu$ analyses are difficult!
- Measuring $B^0 \to D^-\ell^+\nu$ different from measuring $B^+ \to D^0\ell^+\nu$ due to isospin violation. Feed-down much bigger for $D^0\ell^+\nu$.



untagged $B^+ \to D^0 e^+\nu$



Tagged analyses

Reduce background, provide kinematic information, but have low efficiency

If signal mode is specified, constraints apply:

- Require no unused tracks (N^{trk}_{Extra}=0)
- Measure additional neutral ECL activity (E_{ECL})

Hadronic tags

- Tag side fully reconstructed – we determine p_{miss} and calculate $U \equiv E_{\mathrm{miss}} - |\vec{p}_{\mathrm{miss}}|$ or $M^2_{\mathrm{miss}} \equiv U \times (E_{\mathrm{miss}} + |\vec{p}_{\mathrm{miss}}|)$
- For high efficiency, include decays with high multiplicity ⇒ lots of activity, increases E_{ECL}
- High multiplicity tag modes are less clean ⇒ many candidates per event

Semileptonic tags

- Tag side has neutrino – don't know $\vec{p}_{B_{tag}}$
- Weaker kinematic constraint: single missing neutrino → $-1 < \cos\theta_{BY} < 1$
- Fewer decay modes and somewhat higher efficiency than hadronic tags

Note: we can reconstruct hadronic D^0 decays much better than D^+ decays
As a result, **we tag B^+ more efficiently than B^0**

Hadronic tagged decays

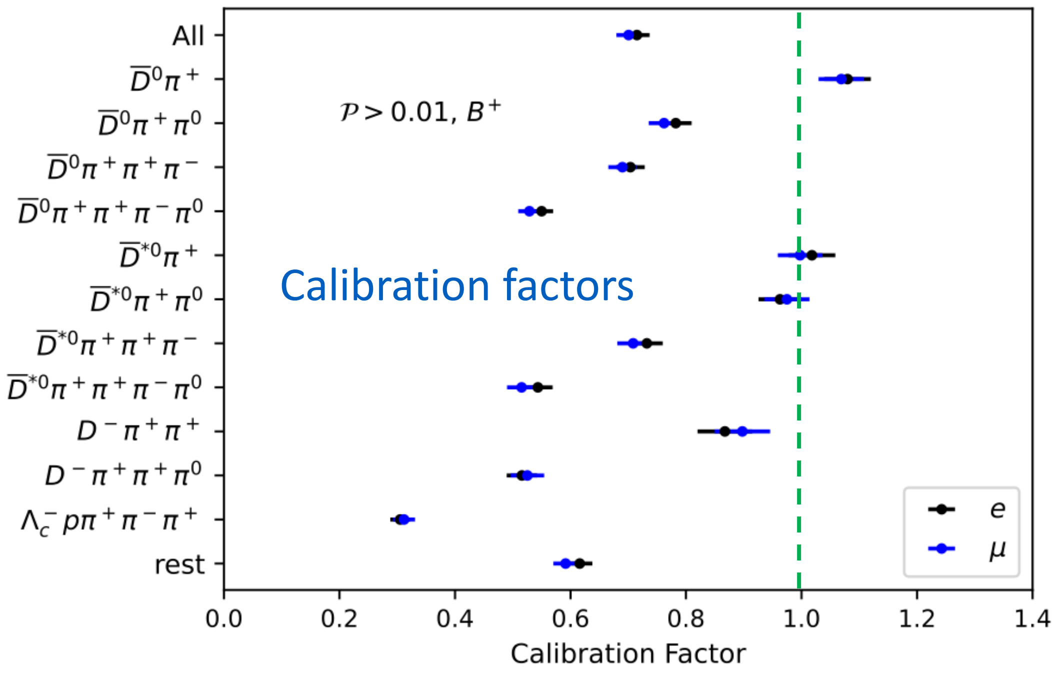
M^2_{miss} is a powerful discriminant against missing particles, mis-reconstruction, and to $q\bar{q}$ background

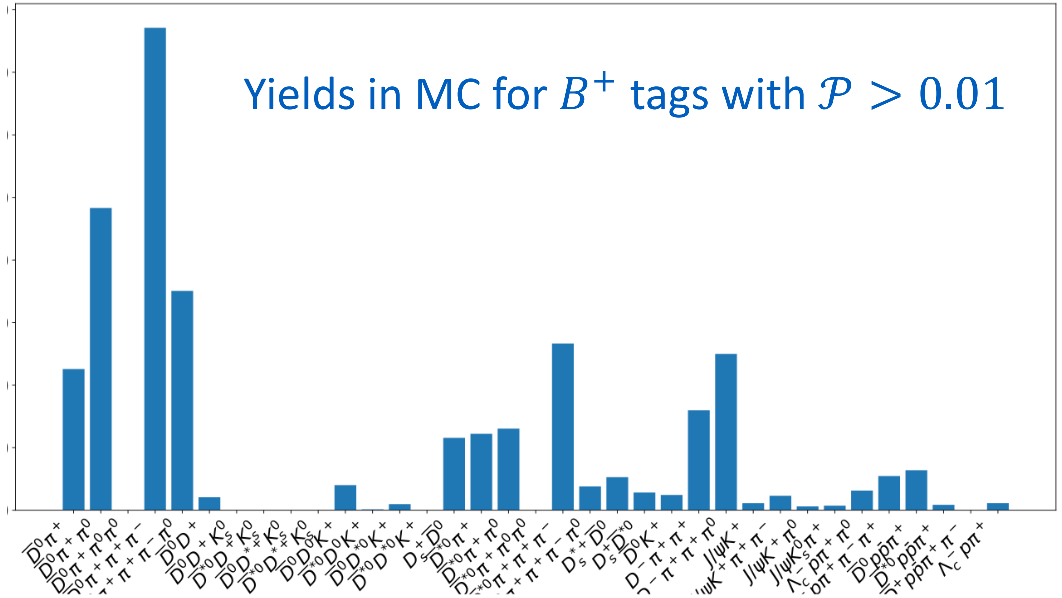
Many modes contribute; leading modes shown

Calibration factors have statistical and systematic uncertainties

Need to improve simulation of B, D decays to bring them closer to unity

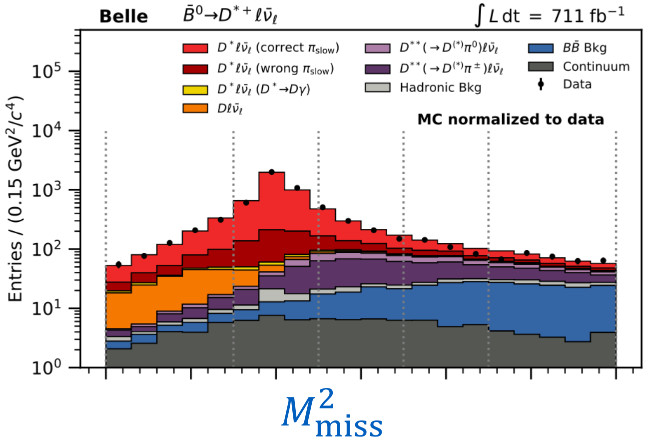
Tag efficiency for $B^+(B^0)$ is $\sim 0.3\%(0.2\%)$





Best tagged measurement of $B \to D^* \ell \nu$

Belle (prelim) $B \to D^* \ell \nu$. Fit angular coefficients for FF and use HFLAV BF for normalization. Method based on PRD 90, 094003 (2014)



Had. tagged sample (notice log scale)

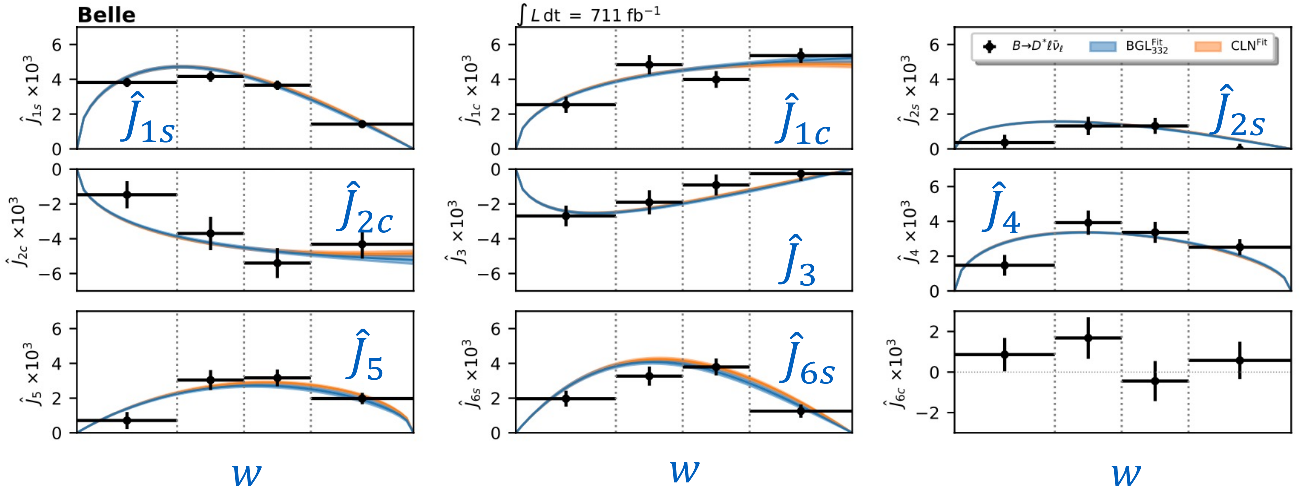
$$|V_{cb}| = (41.0 \pm 0.3 \pm 0.4 \pm 0.5) \times 10^{-3}\ (\mathrm{BGL}_{332}),$$
$$|V_{cb}| = (40.9 \pm 0.3 \pm 0.4 \pm 0.4) \times 10^{-3}\ (\mathrm{CLN}),$$

Exp* BF LQCD

∗ Dominated by MC statistics

$$\frac{d\Gamma(B \to D^* \ell \nu_\ell)}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} =$$
$$\frac{2G_F^2 \eta_{EW}^2 |V_{cb}|^2 m_B^4 m_{D^*}}{2\pi^4} \times \Big(J_{1s} \sin^2\theta_V + J_{1c} \cos^2\theta_V$$
$$+ (J_{2s} \sin^2\theta_V + J_{2c} \cos^2\theta_V) \cos 2\theta_\ell + J_3 \sin^2\theta_V \sin^2\theta_\ell \cos 2\chi$$
$$+ J_4 \sin 2\theta_V \sin 2\theta_\ell \cos\chi + J_5 \sin 2\theta_V \sin\theta_\ell \cos\chi + (J_{6s} \sin^2\theta_V + J_{6c} \cos^2\theta_V) \cos\theta_\ell$$
$$+ J_7 \sin 2\theta_V \sin\theta_\ell \sin\chi + J_8 \sin 2\theta_V \sin 2\theta_\ell \sin\chi + J_9 \sin^2\theta_V \sin^2\theta_\ell \sin 2\chi \Big).$$

Fully differential rate – coefficients are measured in bins of w



Best measurement of $B \to D\ell\nu$

Belle had. tagged $B \to D\ell\nu$ determines $\Delta\Gamma_i$ in bins of w

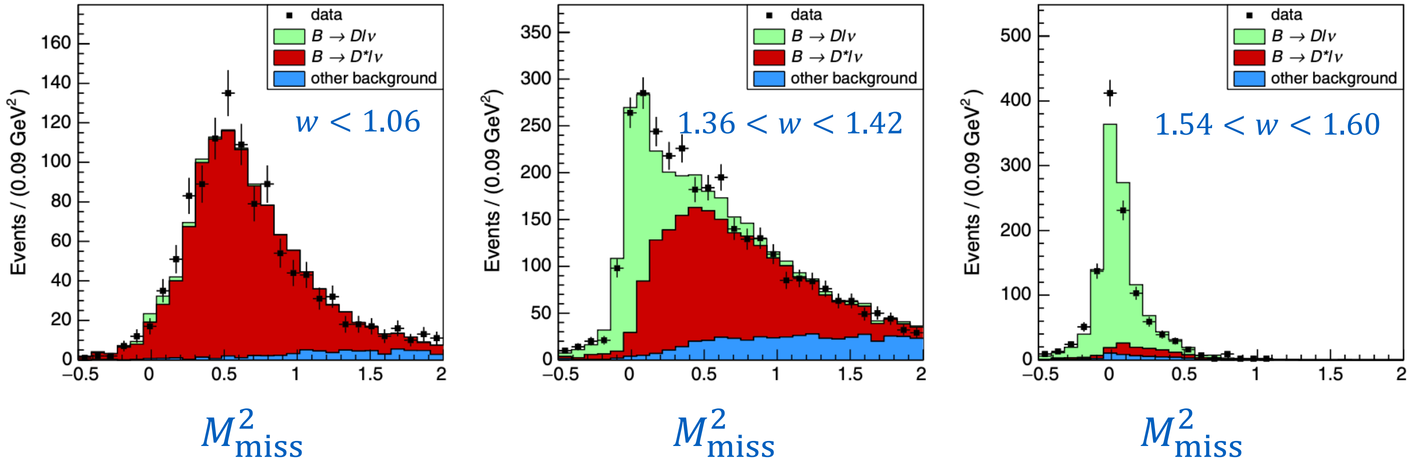
PRD 93, 032006 (2016)

Measures both $B^- \to D^0\ell^-\nu$ and $\bar{B}^0 \to D^+\ell^-\nu$

Separates $D\ell\nu$ from $D^*\ell\nu$ using $M^2_{\rm miss}$

	$B^+ \to \bar{D}^0 e^+\nu_e$	$B^+ \to \bar{D}^0 \mu^+\nu_\mu$	$B^0 \to D^- e^+\nu_e$	$B^0 \to D^- \mu^+\nu_\mu$	$B \to D\ell\nu_\ell$
$\eta_{\rm EW}\mathcal{G}(1)\|V_{cb}\|$ $[10^{-3}]$	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
$\eta_{\rm EW}\|V_{cb}\|$ $[10^{-3}]$	40.14 ± 1.86	43.15 ± 1.89	39.69 ± 2.05	40.78 ± 2.09	40.12 ± 1.34

3.2% on $\mathcal{G}(1)|V_{cb}|$



Correlated uncertainty on $\Delta\Gamma_i/\Delta w_i$ dominated by tag efficiency (~3.2%), D BFs, detection efficiencies

$\sigma(\Delta\Gamma_i/\Delta w_i)$ source	Lowest 2 w bins 0	1
Tag correction	3.0	3.2
Charged tracks	1.7	1.6
$\mathcal{B}(D \to \text{hadronic})$	2.0	1.8
$\mathcal{B}(B \to D^{*(*)}\ell\nu)$	1.3	0.8
$\mathcal{B}(B \to X_u\ell\nu)$	0.4	0.1
FF$(B \to D^*\ell\nu)$	0.4	0.2
FF$(B \to D^{**}\ell\nu)$	2.5	1.2
Signal shape	5.0	0.8
Lifetimes	0.2	0.2
π^0 efficiency	0.9	0.6
K/π efficiency	1.1	0.9
K_S efficiency	0.4	0.2
Luminosity	1.4	1.4
Total	7.3	4.7

What will the limiting factors be in a few years?

- FF shape information will be improved from both experiment and LQCD; it will remain an important but not dominant uncertainty on $|V_{cb}|$

- Normalization uncertainties (efficiencies, BFs) will be prominent:
  - N_{BB}
  - f_{00} (avoid by combining B^+, B^0 results)
  - D meson BFs
  - Lepton, kaon ID efficiencies

- MC statistics
- Modeling uncertainties

- Residual backgrounds will be important in some analyses:
  - unmeasured $B \to X_c \ell \nu$ modes
  - $B \to \bar{D}^{(*)} D_{(s)}^{(*)} (X)$
  - $e^+e^- \to q\bar{q}$ continuum

Needed from Belle II

- Further improvements in measurements of FF for $B \to D^*$ and $B \to D$ transitions
- Reduce normalization uncertainties
- Reduce MC statistical uncertainties
- Reduce modeling uncertainties
- Measure “gap” modes

- Path is clear – continue to determine FF shape using fits for $B \to D^* \ell \nu$ angular coefficients in bins of w (hadronic tagged)
- Improve $B \to D$ FF using hadronic tagged analysis
- Simultaneous fits to these measurements and lattice input determines FF shape parameters
- Add external BF to determine $|V_{cb}|$

Needed from Belle II

- Further improvements in measurements of FF for $B \to D^*$ and $B \to D$ transitions
- Reduce normalization uncertainties
- Reduce MC statistical uncertainties
- Reduce modeling uncertainties
- Measure “gap” modes

- Normalization uncertainties based on control sample size are expected to go down with larger datasets:
    - Particle ID
    - tracking efficiency
- Residual uncertainties (dependence on environment/isolation) will require dedicated analyses; ultimately will require larger data and MC samples
- Not clear how quickly the uncertainties will fall for $N_{B\bar{B}}$, f_{00}, f_{+-}, external D BFs
  → Need dedicated effort on all these

Needed from Belle II

- Further improvements in measurements of FF for $B \to D^*$ and $B \to D$ transitions
- Reduce normalization uncertainties
- Reduce MC statistical uncertainties
- Reduce modeling uncertainties
- Measure "gap" modes

- MC samples are used directly for normalization (e.g. efficiencies); here $N_{MC} \sim 4N_{data}$ is reasonable.
- MC is also used to make fit templates; statistical uncertainties in the template *are often a leading source* of overall uncertainty
- MC/data comparisons are used to correct inadequacies in the modeling of physics or detector response; also sensitive to MC sample size
- Promising approaches to improve MC stats include generator filtering (prior to expensive Geant4 simulation), fast simulation methods (ML)

Needed from Belle II

- Further improvements in measurements of FF for $B \to D^*$ and $B \to D$ transitions
- Reduce normalization uncertainties
- Reduce MC statistical uncertainties
- Reduce modeling uncertainties
- Measure "gap" modes

- The main shortcoming tends to be from EVTGEN decay modeling ($\sim 50\%$ of the total B meson decay width remains unmeasured)
- Dedicated "tuning" measurements need to be identified and made. These include, e.g., inclusive distributions, e.g. dN_K/dp, dN_D/dp, in well defined (e.g. $B^{0/+}$-tagged) samples
- Detector simulation will also need to improve, but it will never be perfect;
  → it's wise to avoid relying on the *detailed* simulation of variables like E_{ECL} (cut on them, don't fit to them)

Needed from Belle II

- Further improvements in measurements of FF for $B \to D^*$ and $B \to D$ transitions
- Reduce normalization uncertainties
- Reduce MC statistical uncertainties
- Reduce modeling uncertainties
- Measure "gap" modes

- Unmeasured semileptonic decays account for ~8% of the total $b \to c\ell\nu$ rate
- They aren't estimated to contribute much uncertainty on $|V_{cb}|$ (but are important for LFV studies)
- We can't really be sure until we quantify them from data
- The $B \to D^{(*)}X\ell\nu$ modes where X is some set of pions and/or photons (other than a single $\pi^{\pm}$) are surprisingly difficult to measure

Measurement strategies – dealing with feed-down

Challenge: large feed-down from $B \to D^{*}\ell\nu$ to $B \to D\ell\nu$

Soft π^{+}, π^{0} from $D^{*} \to D\pi$ have low efficiency and/or high combinatorial background

Simultaneous fits of these samples provide better sensitivity (use feed-down) and incorporate correlations

Another strategy is to ignore the soft π or γ

Reconstruct $B \to D(X)\ell\nu$ (just the D and the ℓ) and ***use kinematics to separate*** vector from pseudo-scalar final state hadrons

$B \to D(X)\ell\nu$

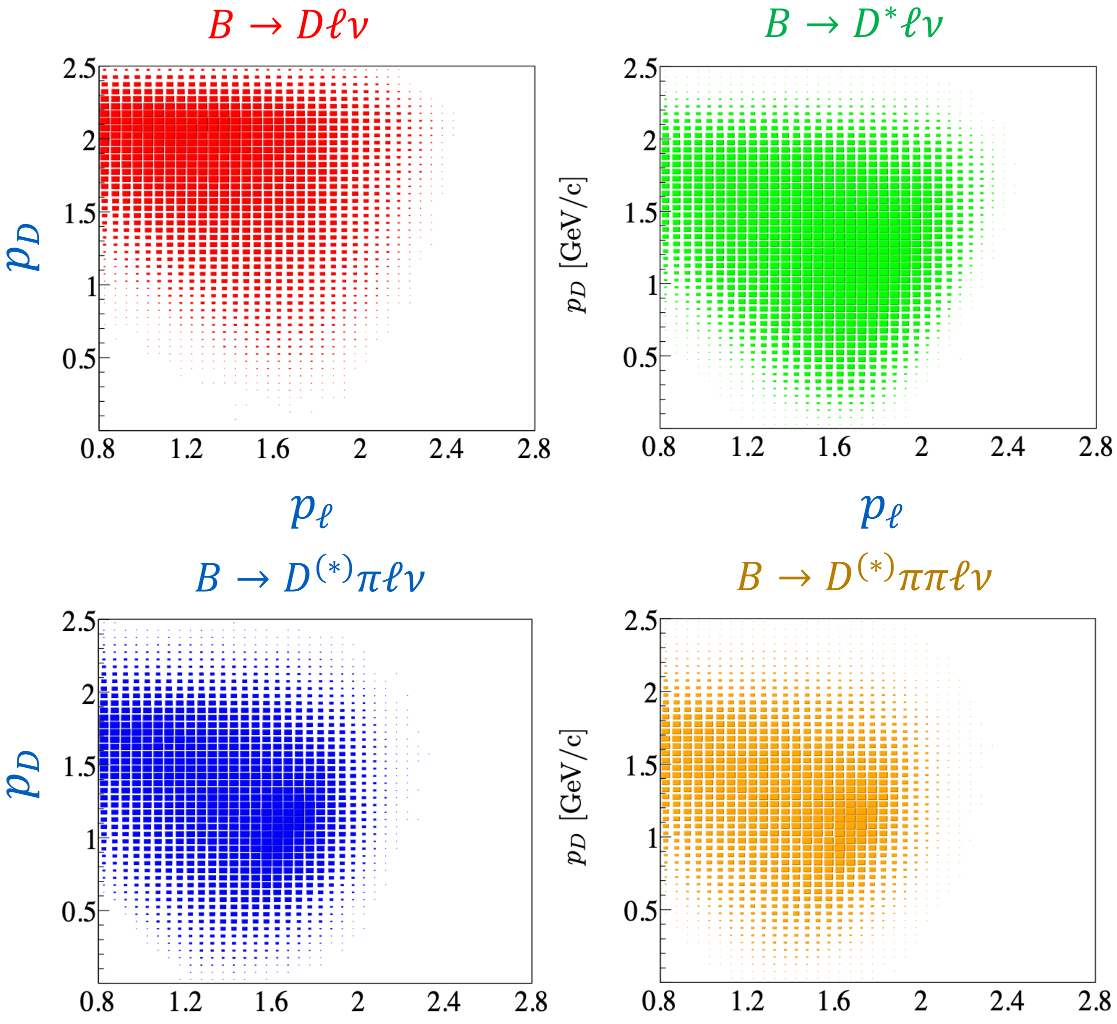
Reconstruct just ℓ and D – independent of slow π reconstruction

Well-understood dynamics allows good statistical separation of $B \to D^*\ell\nu$ from $B \to D\ell\nu$

Three separation variables: $p_D, p_\ell, \cos\theta_{BY}$

Method works with untagged or tagged samples

BaBar measurements of $B^- \to D^{(*)0}\ell\nu$ BFs using $207\ \mathrm{fb}^{-1}$ are still competitive in HFLAV average



From Florian Bernlochner’s PhD dissertation

Double semileptonic decays

Reconstruct $\Upsilon(4S) \to D^{(*)}\ell^-\bar{\nu},\ \bar{D}^{(*)}\ell^+\nu$

Require no unused tracks, small E_{ECL}

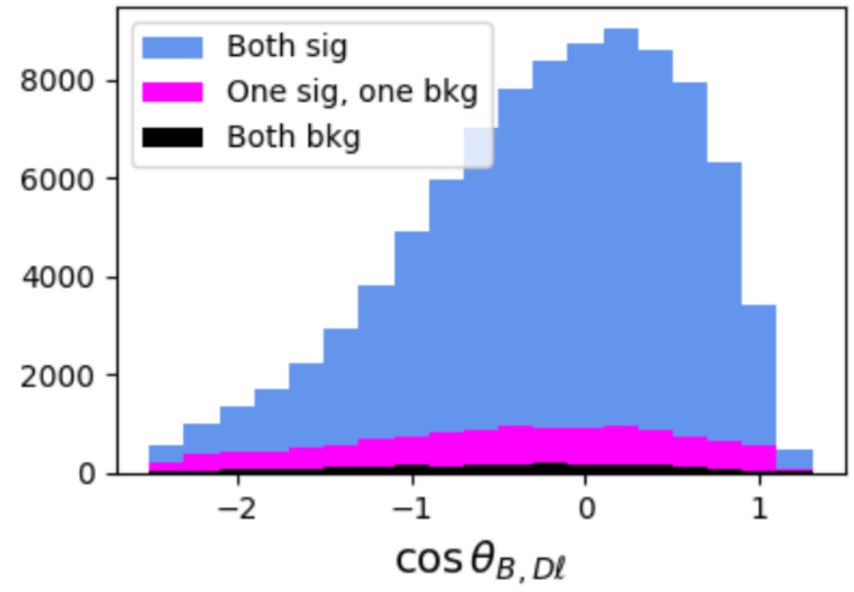
$-2.5 < \cos\theta_{BY} < 1.2$ *to keep feed-down*

Insensitive to $e^+e^- \to q\bar{q}$ ($\ll 1\%$ level)

Separate $B \to D^*$ from $B \to D$ using kinematics

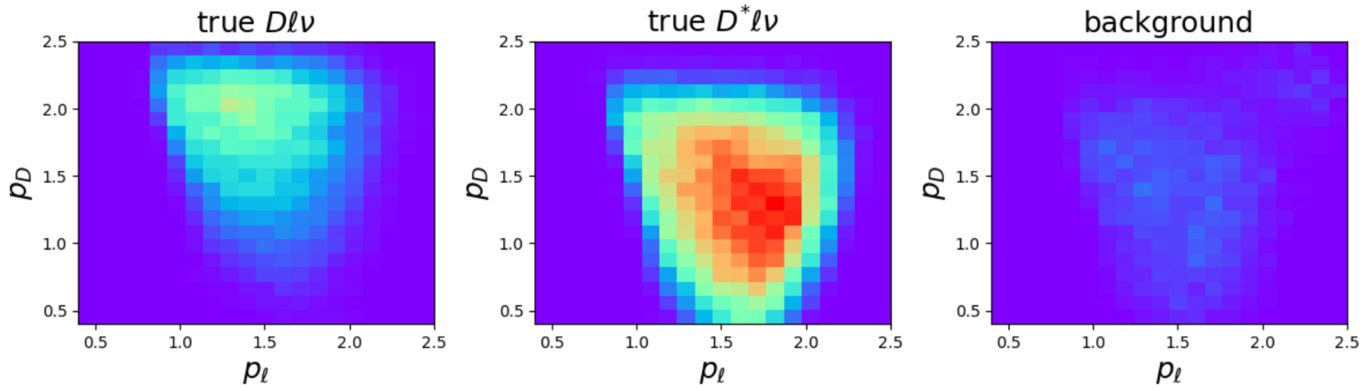
Leverage precise external $\mathcal{B}(B \to D^*\ell^-\bar{\nu})$ measurement to improve $\mathcal{B}(B \to D\ell^-\bar{\nu})$

Yield: (B^+B^- $\sim 40K/\text{ab}^{-1}$, $B^0\bar{B}^0$ $\sim 12K/\text{ab}^{-1}$)



Tag efficiency for $B^+(B^0)$ is $\sim 0.9\%(0.5\%)$ *(for $D^{(*)}(X)\ell^-\bar{\nu}$ on signal side)*

Background mostly from $D^{(*)}\pi\ell^-\bar{\nu}$, $D^{(*)}\tau^-\bar{\nu}$



Analysis topics

There are three essential analysis efforts needed from Belle II on exclusive $|V_{cb}|$

1. Hadronic-tagged measurement of form factor shapes for $D^*\ell\nu$ and $D\ell\nu$ (simultaneous fit)
2. Untagged measurement of $\mathcal{B}(B \to D^*\ell\nu)$
3. Simultaneous double-semileptonic measurements of $\mathcal{B}(B \to D^*\ell\nu)$ and $d\Gamma/dw(B \to D\ell\nu)$

In addition, dedicated supporting measurements needed for

- Lepton (and hadron) ID efficiency
- $N_{B\bar{B}}$
- f_{00}/ f_{+-}
- measurements of gap modes

1. Form factors using angular analysis of tagged decays

Hadronic-tagged measurement of form factors for $D^*\ell\nu$ and $D\ell\nu$ (using simultaneous fit to both samples)

Measure fully differential rate in bins of w where, in each bin (for $D^*\ell\nu$), angular coefficients J_k are determined

Use external normalization (from HFLAV or other Belle II analyses) in fit for FF, $|V_{cb}|$

Estimated person-power:

- 2-3 PhD students
- 1-2 PDFs
- 1 or more senior physicists

based in at most 2 regions (Asia, Europe, Americas)

Tight coordination – weekly meetings

2. Untagged $B \to D^*\ell\nu$ branching fractions

Measure branching fractions for
$B^- \to D^{*0}\ell^-\nu$ and $\bar{B}^0 \to D^{*+}\ell^-\nu$

Measure rates in bins of $p^*_{D^*}, p^*_\ell$ and $\cos\theta_{BY}$ to allow characterization of backgrounds, cross-feeds

Simultaneous measurement needed since cross-feed is important

Estimated person-power:

- 2 PhD students
- 1-2 PDFs or senior physicists to supervise

based in at most 2 regions (Asia, Europe, Americas)

Regular coordination – bi-weekly meetings

3. Double semileptonic decays for $B \to D^{(*)}\ell\nu$

Measure $d\Gamma/dw$ for
$B^- \to D^0\ell^-\nu$ and $\bar{B}^0 \to D^+\ell^-\nu$,
and branching fractions for
$B^- \to D^{*0}\ell^-\nu$ and $\bar{B}^0 \to D^{*+}\ell^-\nu$

Fit for rates in bins of p_D, p_ℓ and $\cos\theta_{BY}$ to make full use of down-feed and cross-feed information

Simultaneous determination of $|V_{cb}|$ with or without assuming isospin; if isospin assumed, N_{BB} can also be measured

Estimated person-power:

- 2-3 PhD students
- 1-2 PDFs
- 1 or more senior physicists

based in at most 2 regions (Asia, Europe, Americas)

Tight coordination – weekly meetings

Supporting measurements

Dedicated supporting analyses are needed:

- lepton ID efficiency (vs. $\theta, p,$ isolation); push well below 1%
- $N_{B\bar{B}}$ distinguish $B\bar{B}$ from continuum
- f_{00}/f_{+-} : $\Upsilon(4S)$ BFs
- measure gap modes and their kinematics
  - $B \to D^{(*)}\eta\ell^{-}\nu$
  - $B \to D^{(*)}\eta\pi\ell^{-}\nu$
  - $B \to D^{(*)}3\pi\ell^{-}\nu$

  } Simultaneous measurements
- MC tuning measurements (tagged inclusive momentum distributions)

Some of these map onto a single PhD student working alone

Others (e.g. gap modes) do not. These would use similar methods to tagged $|V_{cb}|$ analyses

Analysis teams

To get the best science out of the Belle II data we'll need to work in multi-analyst teams

Close coordination – weekly (or bi-weekly) meetings. Time zones matter for this (as someone 9 hours from CEST and 16 hours from JST I know of what I speak)

Teams should have senior PDF or faculty in addition to grad students

Having a PhD student working alone on a topic has its logic, but

- It's not necessarily best for the student
- It's not best for Belle II scientific output

Analysis teams are the norm in ATLAS and CMS

They were used in Belle and BaBar for certain high-profile measurements

This requires support from both Belle II management and university PIs to make it work

Summary

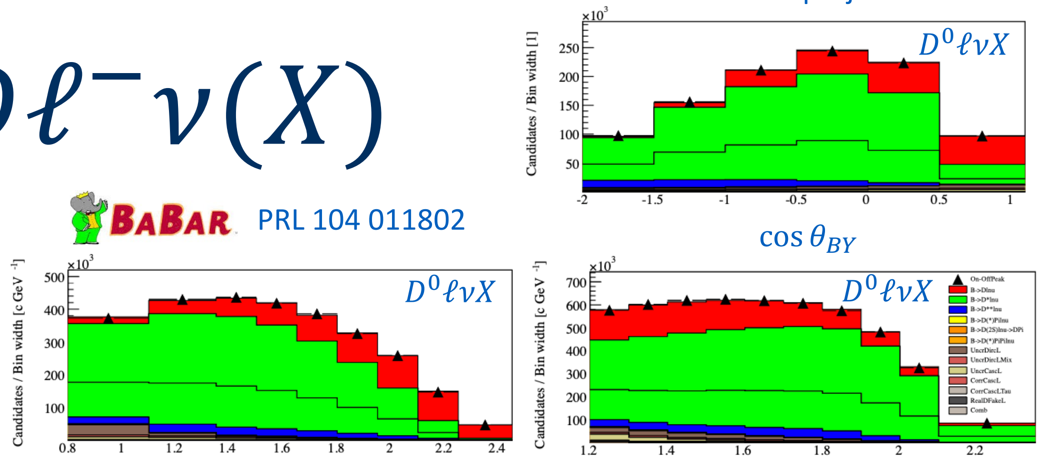
- Belle II data will allow significant improvements in the determination of $|V_{cb}|$ from exclusive decays
- Using hadronic-tagged analyses and updated LQCD results will enable substantial improvements in form factor determinations
- Normalization uncertainties are important for $|V_{cb}|$; these will require untagged analyses and/or double semileptonic decays
- To maximize the impact of Belle II data, analyses need to be more comprehensive: simultaneous analyses and fits of many channels are needed
- This requires a shift from "1 GS = 1 analysis" to working in coordinated teams

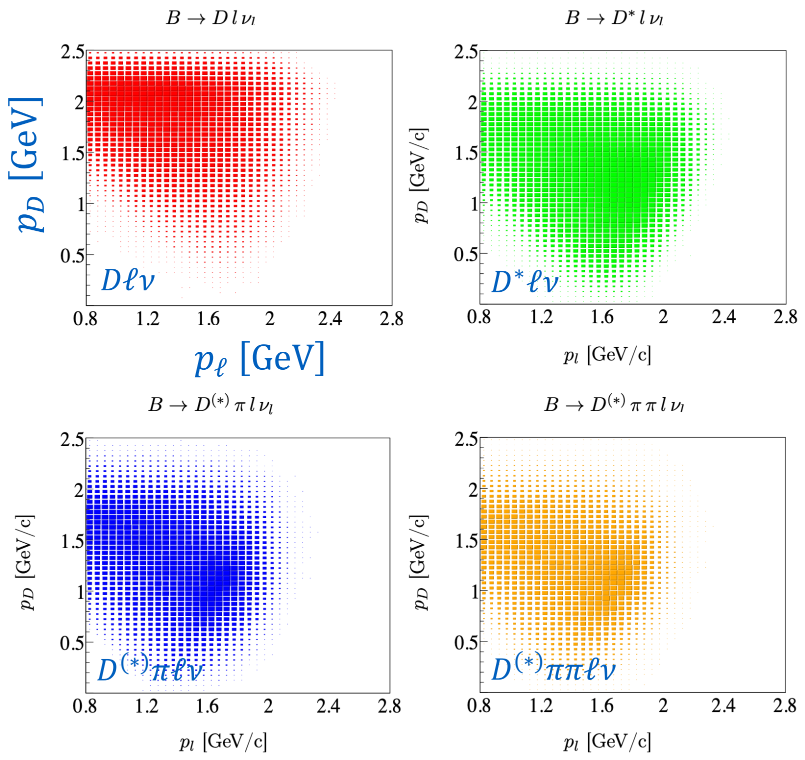
Global fit to untagged $B \to D\ell^- \nu(X)$

- High statistics: about 8000 $D\ell^-$ pairs / fb^{-1}
- Three independent variables for B decays: $p_D, p_\ell, \cos\theta_{BY}$
- W helicity state populations differ for $B \to D$ and $B \to D^*$ transitions, leading to different p_D and p_ℓ distributions; $\cos\theta_{BY}$ is also shifted. Decays to heavier X_c states shift p_D, p_ℓ and $\cos\theta_{BY}$ to still lower values
- Global fit to $B \to D\ell^-\nu X$ can determine BFs and FF slopes for both $B \to D\ell^-\nu$ and $B \to D^*\ell^-\nu$ ***without ever reconstructing soft π^+/π^0***
- Leading uncertainties arise from modeling of heavier X_c states, D decay BFs and detector modeling
- 2009 measurement (207 fb^{-1}) still gives competitive precision on BF($B^- \to D^{*0}\ell^-\nu$) (4%) and BF($B^- \to D^0\ell^-\nu$) (5.5%)

Electron fit projections

BABAR PRL 104 011802





(My) expectations from theory, lattice

- Perturbative corrections (EW, QED) are under control
- Input needed at zero recoil, $h_{A_1}(w = 1)$
- Lattice calculations currently give uncertainties on $h_{A_1}(1)$ of $\sim 0.8\%$
- On the timescale of a few ab^{-1} of Belle II data this should improve; I hope to learn at this workshop by how much!

- Simultaneous experimental determinations of differential decay rates for $B \to D^* \ell \nu$ and $B \to D \ell \nu$ are likely

  → It would be useful to have joint predictions of these decay rates, FFs

B tagging: the fine print

Tagging (Full Event Interpretation in Belle II) is powerful but has challenges

- Purity – is the "best" tag the true one?
  - The answer depends on the signal side decay mode and multiplicity
  - Unfortunately, the overall tag+signal efficiency depends on purity: if you choose the wrong tag you can fail to reconstruct the signal
  - The hardest case is for analyses where the ROE is unconstrained (e.g. when we try to measure the X_c system in $B \to X_c \ell \nu$); signal-side constraints help a lot

- Calibration
  - B decays involve millions of individual modes $\Rightarrow$ EVTGEN does not agree with data when we sum over reconstructed B decay chains
  - The modeling of the detector is also imperfect
  - We therefore "calibrate" (compare data with MC) to correct the simulated FEI efficiency; these calibration factors are large ($\sim 30\%$)
  - Unfortunately, we have very few high-stats calibration channels and the correction can differ (in principle) for different signal modes

Experimental challenges in exclusive measurements – topic list I

- Review limiting uncertainties in existing measurements
- List assumptions about evolution of outside input (theory, Lattice)
- What is needed from experiment (in particular Belle II)?
  - Lots of recent progress in FF predictions and measurements; important for $|V_{cb}|$
  - Reduce normalization uncertainties
  - Reduce MC statistical uncertainties
  - Reduce uncertainties on uncertainties

- Normalization uncertainties
  - Lepton ID efficiency (control samples, isolation / environment corrections), Kaon ID efficiency
  - tracking efficiency, kinematic fit efficiency
  - B tagging “calibration”
  - B counting (luminosity)
- MC statistics
  - Enters through fit template shapes for signals, cross-feeds, backgrounds as well as in signal efficiency. Need better $N_{MC}/\$$ as sample sizes increase
  - Also enters into reweightings that correct for modeling problems
  - Hard to justify generating huge samples if the modeling is poor, so it also needs to improve

Experimental challenges in exclusive measurements – topic list II

- Large feed-down from $D^* \to D\pi$ decays
  - Simultaneous analysis of $B \to D^*\ell\nu, B \to D\ell\nu$ helps
  - Statistical discrimination between $B \to V\ell\nu$ and $B \to P\ell\nu$ transitions using kinematics works well even if the slow π is ignored
  - Revive $B \to D(X)\ell\nu$ approach
- Content of "gap" not well understood

$$\mathcal{B}(B \to X_c\ell\nu) - \sum_j \mathcal{B}(B \to H_j\ell\nu) \sim 0.8\%$$

Measured — Measured or isospin conj

- Untagged analyses will not be competitive at some point due to higher backgrounds (for $|V_{cb}|$ this is probably at ~few ab^{-1})

- Hadronic tags + $D^{(*)}\ell\nu$
  - M^2_{miss} is a good discriminant against additional missing particles ($D^{**}\ell\nu, D^{(*)}D_s^{(*)-}, c\bar{c}, \ldots$)
  - Had tagging efficiency for $B^+(B^0)$ is $\sim 0.3\%(0.2\%)$
  - Large "calibration factors" needed to correct MC modeling (mostly from modeling large number of un/poorly measured decay modes)
- Double semileptonic decays, $D^{(*)}\ell^-\nu, \overline{D}^{(*)}\ell^+\nu$
  - $\cos\theta_{BY}$ is a weaker discriminant than M^2_{miss}
  - SL tagging efficiency for $B^+(B^0)$ is $\sim 0.9\%(0.5\%)$
  - Dominated by a few decay modes ($D^{(*)}\ell\nu$, a few well-measured $D^0$and D^+ decays); easier to "calibrate" so better for normalization