Analysis presentation V_{cb}

Part 1: Overview and tag side

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Overview

- Part 1 (Kilian): Why V_{cb}? How V_{cb}? Measurements at Belle.
- Part 2 (Kilian): Tagging calibration for $|V_{cb}|$ measurement with $B \longrightarrow D^* \ell \bar{\nu}_\ell$ (but the calibration looks at $B \longrightarrow X \ell \nu$)
- Part 3 (Markus): $|V_{cb}|$ measurement with $B \longrightarrow D^* \ell \bar{\nu}_\ell$

Caveats:

- Not a physics talk: We'll cut corners and go on tangents about doing analysis
- I'm a bit out of the loop with recent $|V_{cb}|$ papers...
- Not a rockstar presentation :/

Part 1

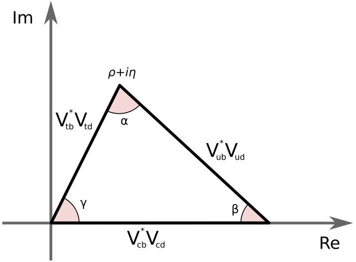
1 Why?

2 How?

- Measuring $|V_{cb}|$
- Exclusive vs Inclusive Analyses
- Tagging

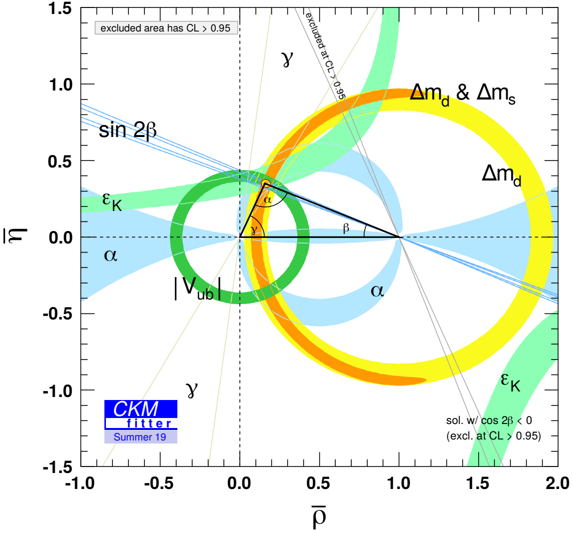
Why $|V_{cb}|$?

- The CKM matrix $V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cb} & V_{cs} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$ is unitary in the SM, i.e. $VV^\dagger = 1 = V^\dagger V$
- Thus $\sum_k |V_{ik}|^2 = 1$ for all k (weak unitarity) and
- $\sum_k V_{ik} V_{jk}^* = 0$ for all i, j
- Most popular: $V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$
- Powerful test of the SM
- Can also be visualized as a triangle "unitarity triangle"



[wiki]

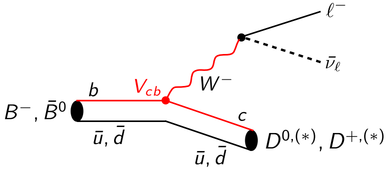
Why $|V_{cb}|$


excluded area has CL > 0.95
excluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
|V_ub|
CKM fitter
Summer 19
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
η̄
ρ̄
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
2.0

Measuring $|V_{cb}|$

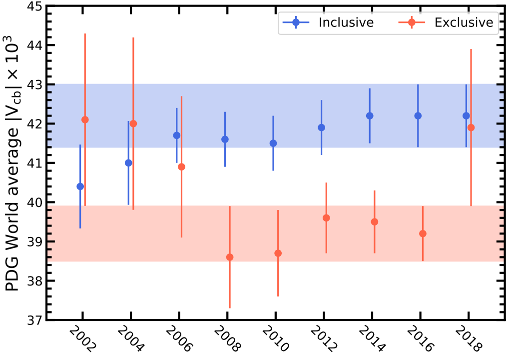
- Pure leptonic: $B_c \longrightarrow \ell\bar{\nu}$. Unavailable @$B$-factories
- Pure hadronic: Hard theoretically
- **Semileptonic**:
  Theory: Small EW corrections; QCD uncertainties under control
  Experiment: Only one neutrino missing, good BRs ($\approx 10\%$)
  $\Longrightarrow$ Best opportunity to measure $|V_{cb}|$
  - Exclusively: Either $B \longrightarrow D^*\ell\bar{\nu}_\ell$ (this analysis) or $B \longrightarrow D\ell\bar{\nu}_\ell$
  - Inclusively: $B \longrightarrow X_c\ell\nu$

Exclusive decays



Exclusive vs Inclusive Analyses

- Tension between inclusive $(B \longrightarrow X_c \ell \nu)$ and exclusive $(B \longrightarrow D^{(*)} \ell \bar{\nu}_\ell)$ determination of V_{cb}! $> 3\sigma$ (2018)



[1902.09412]

- Speculation about tension being related to FF parametrization in exclusive mode (CLN vs BGL)

How to extract $|V_{cb}|$ (exclusive)

- Say we want to extract $|V_{cb}|$ from $B \longrightarrow D^* \ell \bar{\nu}_\ell$

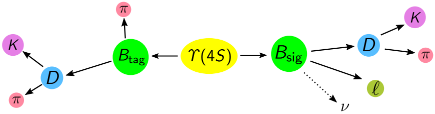
$$\frac{\mathrm{d}\Gamma(B \longrightarrow D^* \ell \bar{\nu}_\ell)}{\mathrm{d}w} = \text{stuff we know} \cdot \mathrm{FF}^2(w) \cdot |V_{cb}|^2,$$

- $w = \vec{v}_B \vec{v}_{D^{(*)}} = \frac{m_B^2 + m_{D^{(*)}}^2 - q^2}{2 m_B m_{D^{(*)}}}$, $q^2 = (p_B - p_{D^{(*)}})^2$
- $\mathrm{FF}^2(w)$: form factors
- in order to get $|V_{cb}|^2$ we need to know something about $\mathrm{FF}^2(w)$
- Lattice QCD can only confidently tell us $\mathrm{FF}^2(1)$ (but this corresponds to $q^2 = 0$ and we don't have data there)
- Only solution: Use parameterized model for $\mathrm{FF}^2(w)$ (model dependency! CLN vs BGL etc.), fit parameters, extrapolate to $w = 1$ and then use lattice result to get $|V_{cb}|^2$
- In other words: need to fit form factor parameters $\Longrightarrow$ measure kinematic distributions
- $B \longrightarrow D \ell \bar{\nu}_\ell$ is similar

Tagged vs Untagged Analyses

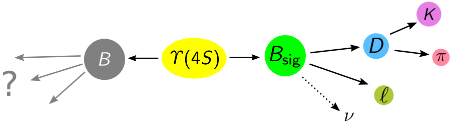
Tagged Analysis

- + High purity
- – Low efficiency
  (0.3% @Belle $\rightarrow$ 0.55% @Belle II)
- + Get B meson momentum from tag side!



Untagged Analysis

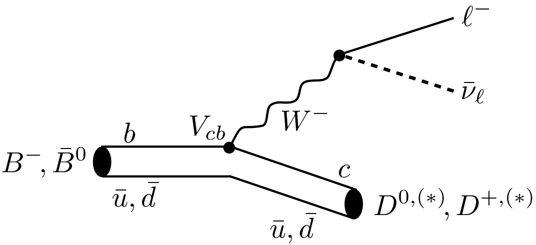
- – Low purity
- + High efficiency
  (11% @Belle $\rightarrow$ 20% @Belle II)



Part 2: $|V_{cb}|$ from hadronically tagged $B \longrightarrow D^* \ell \bar{\nu}_\ell$ at Belle: Tag side & tagging calibration

Goals

Reanalysis of hadronically tagged $B \to D^* \ell \bar{\nu}_\ell$ at Belle



- Previous measurement: [1702.01521] (preliminary)
- Extract $|V_{cb}|$, form factors, kinematic distributions (separately for e/μ, potentially also investigating model dependencies)
- Belle dataset still exceeds Belle II dataset by large margin
- Expect around $2\times$ efficiency when using Belle II software (FEI)

$\Longrightarrow$ Use Belle II software on Belle data! (b2bii)

Improved hadronic tagging @Belle II

[1808.10567]

Hadronic tagging @Belle II:
Around 5000 channels!
2.5× efficiency!

Algorithm	MVA	Efficiency	Purity
Belle v1	Cut	–	–
Belle v3	Cut	0.1%	0.25%
Belle NB	NB	0.2%	0.25%
Belle II FEI	BDT	0.5%	0.25%

Calibration for excl. $B \longrightarrow D^{(*)}\ell\bar{\nu}_\ell$:
$B \longrightarrow X\ell\nu$ (systematics limited)

B^+ modes	B^0 modes
$B^+ \to \bar{D}^0\pi^+$	$B^0 \to D^-\pi^+$
$B^+ \to \bar{D}^0\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^0\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-$	$B^0 \to D_s^+D^-$
$B^+ \to D_s^+\bar{D}^0$	$B^0 \to D^{*-}\pi^+$
$B^+ \to \bar{D}^{*0}\pi^+$	$B^0 \to D^{*-}\pi^+\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-$	$B^0 \to D^{*-}\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D_s^{*+}D^-$
$B^+ \to D_s^{*+}\bar{D}^0$	$B^0 \to D_s^+D^{*-}$
$B^+ \to D_s^+\bar{D}^{*0}$	$B^0 \to D_s^{*+}D^{*-}$
$B^+ \to \bar{D}^0K^+$	$B^0 \to J/\psi K_S^0$
$B^+ \to D^-\pi^+\pi^+$	$B^0 \to J/\psi K^+\pi^+$
$B^+ \to J/\psi K^+$	$B^0 \to J/\psi K_S^0\pi^+\pi^-$
$B^+ \to J/\psi K^+\pi^+\pi^-$	
$B^+ \to J/\psi K^+\pi^0$	
$B^+ \to D^-\pi^+\pi^+\pi^0$	$B^0 \to D^-\pi^+\pi^0\pi^0$
$B^+ \to \bar{D}^0\pi^+\pi^+\pi^-\pi^0$	$B^0 \to D^-\pi^+\pi^+\pi^-\pi^0$
$B^+ \to \bar{D}^0D^+$	$B^0 \to \bar{D}^0\pi^+\pi^-$
$B^+ \to \bar{D}^0D^+K_S^0$	$B^0 \to D^-D^0K^+$
$B^+ \to \bar{D}^{*0}D^+K_S^0$	$B^0 \to D^-D^{*0}K^+$
$B^+ \to \bar{D}^0D^{*+}K_S^0$	$B^0 \to D^{*-}D^0K^+$
$B^+ \to \bar{D}^{*0}D^{*+}K_S^0$	$B^0 \to D^{*-}D^{*0}K^+$
$B^+ \to \bar{D}^0D^0K^+$	$B^0 \to D^-D^+K_S^0$
$B^+ \to \bar{D}^{*0}D^0K^+$	$B^0 \to D^{*-}D^+K_S^0$
$B^+ \to \bar{D}^0D^{*0}K^+$	$B^0 \to D^-D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}D^{*0}K^+$	$B^0 \to D^{*-}D^{*+}K_S^0$
$B^+ \to \bar{D}^{*0}\pi^+\pi^0\pi^0$	$B^0 \to D^{*-}\pi^+\pi^0\pi^0$

D^+, D^{*+}, D_s^+ modes	D^0,D^{*0} modes
$D^+ \to K^-\pi^+\pi^+$	$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0$
$D^+ \to K^-K^+\pi^+$	$D^0 \to K^-\pi^+\pi^+\pi^-$
$D^+ \to K^-K^+\pi^+\pi^0$	$D^0 \to \pi^-\pi^+$
$D^+ \to K_S^0\pi^+$	$D^0 \to \pi^-\pi^+\pi^0$
$D^+ \to K_S^0\pi^+\pi^0$	$D^0 \to K_S^0\pi^0$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$D^0 \to K_S^0\pi^+\pi^-$
$D^{*+} \to D^0\pi^+$	$D^0 \to K_S^0\pi^+\pi^-\pi^0$
$D^{*+} \to D^+\pi^0$	$D^0 \to K^-K^+$
$D_s^+ \to K^+K_S^0$	$D^0 \to K^-K^+K_S^0$
$D_s^+ \to K^+\pi^+\pi^-$	$D^{*0} \to D^0\pi^0$
$D_s^+ \to K^+K^-\pi^+$	$D^{*0} \to D^0\gamma$
$D_s^+ \to K^+K^-\pi^+\pi^0$	
$D_s^+ \to K^+K_S^0\pi^+\pi^-$	
$D_s^+ \to K^-K_S^0\pi^+\pi^+$	
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	
$D_s^+ \to \pi^+\pi^+\pi^-$	
$D_s^{*+} \to D_s^+\pi^0$	
$D^+ \to \pi^+\pi^0$	$D^0 \to K^-\pi^+\pi^0\pi^0$
$D^+ \to \pi^+\pi^+\pi^-$	$D^0 \to K^-\pi^+\pi^+\pi^-\pi^0$
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	$D^0 \to \pi^-\pi^+\pi^+\pi^-$
$D^+ \to K^+K_S^0K_S^0$	$D^0 \to \pi^-\pi^+\pi^0\pi^0$
$D^{*+} \to D^+\gamma$	$D^0 \to K^-K^+\pi^0$
$D_s^+ \to K_S^0\pi^+$	
$D_s^+ \to K_S^0\pi^+\pi^0$	
$D_s^{*+} \to D_s^+\pi^0$	

Calibration of hadronic tagging

Tagging

- The FEI returns a list of B_{tag} candidates with a likelihood and the decay channel
- Often we need to know the efficiency of this selection
- Unfortunately this efficiency can be different between MC and data $\Longrightarrow$ calibration!

How?

- Reconstruct $\Upsilon(4S) \longrightarrow B_{\text{tag}} B_{\text{sig}}$ on MC and data
- Idea: Find B_{sig} channel with large BF that we trust
- Compare yields and blame all differences on B_{tag} reconstruction, i.e. the FEI
- Here: Inclusive $B_{\text{sig}} \longrightarrow X\ell\nu$
- Need to do this in bins of the decay channel and the likelihood output

Dataset & MC fixes

The dataset

- Full Belle (1!) dataset ($710\,\mathrm{fb}^{-1}$, $771 \times 10^6\ B\bar{B}$) + 1 stream of MC
- In total there are 10 streams of Belle MC (1 stream = MC equivalent of total data taken)
- "Generic" MC types: Charged (B^+B^-), Mixed ($B^0\bar{B}^0$), Charm ($c\bar{c}$), UDS ($q\bar{q}$)
- There is also special/rare/signal MC for special purposes

MC updates

- Belle MC was produced long ago $\Longrightarrow$ need to update to match better understanding
- Most simple updates: branching fractions (BFs)
- Only need to do this for most relevant BFs: $B \longrightarrow D^{(*)}$

In practice: MC reweighting

Simplest case

- Let's say our MC was generated with $BF(B \longrightarrow XYZ) = 0.5$ (this is written in the decay file), but it's actually 0.25!
- Do we need to regenerate our MC? 😱
- Easy fix: Simply add weight of 0.5 to all $B \longrightarrow XYZ$ events

Uncertainties

- What if we only know $BF(B \longrightarrow XYZ) = 0.5 \pm 0.1$?
- Uncertainty needs to be propagated to later results
- Add varied weight columns, i.e. `__weight__`, `__weight_xyz_up__`, `__weight_xyz_down__`
- Either repeat analysis for different weights or have other way to incorporate them ($\longrightarrow$ fitting)

Form factors (FF)

- Can also set weights to adjust *differential* cross sections! $\Longrightarrow$ Update FFs and more!

Dataset & MC fixes

- Lepton PID corrections
- Updated BFs for $B \to D^{(*)}$, FF reweighted for $B \to D, D^*, D^{**}$
- Generate dedicated D^{**} samples (family of poorly known particles)
- Big issue: The gap
  - Sum up all exclusive $B \longrightarrow X\ell\nu$ modes in MC, e.g. $B \longrightarrow D^{(*)}\ell\bar{\nu}_\ell, \ldots$
  - Much smaller than direct measurement of $B \longrightarrow X\ell\nu \Longrightarrow$ Gap between sum of exclusive and inclusive
  - We need to fill this gap somehow $\longrightarrow$ educated guesses + large uncertainties
- Update Belle gap filling with dedicated samples $D_1(\to D\pi\pi)\ell^+\nu_\ell$, $D^*\eta\ell^+\nu_\ell$ and $D^{(*)}\pi\pi\ell^+\nu_\ell$ (currently 100% scaling uncertainty for total gap component)

🚀 In practice: Generating signal MC

- ⚠️ You normally shouldn't generate MC yourself ⟶ data production liaison
- MC generation is governed by decay files ⟶ read them to understand your MC!
- There's a online book lesson about it

```
Define dm 0.507e12

Alias myB0 B0
Alias myAnti-B0 anti-B0
ChargeConj myB0 myAnti-B0

Decay Upsilon(4S)
1.00000 B0 anti-B0 myB0 myAnti-B0  VSS_BMIX dm;
Enddecay

Alias myD_1- D_1-
Alias myD_1+ D_1+
ChargeConj myD_1- myD_1+

Decay myB0
1.000  myD_1-  e+ nu_e  PHOTOS ISGW2;
Enddecay
CDecay myAnti-B0

Decay myD_1-
1.000    anti-D*0 pi-   PHOTOS VVS_PWAVE  0.0 0.0 0.0 0.0 1.0 0.0;
Enddecay
CDecay myD_1+

End
```

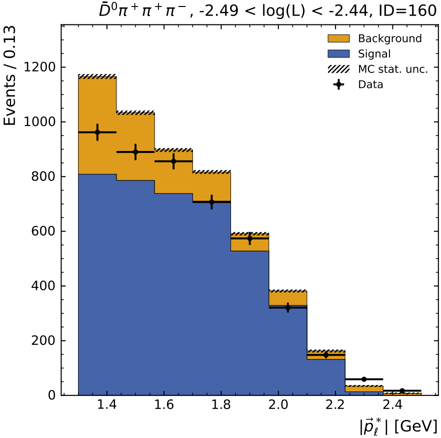
In practice: Cuts & Best candidate selection

- Cuts & best candidate selection drastically reduce memory/disk requirements
- Dilemma: Do them "online" (using basf2) or "offline" (e.g. pandas)
- Online: Change cut value needs reprocessing with basf2 to (takes a lot of time)
- Offline: Dealing with a lot of data (memory & disk space issues for Belle dataset – Belle 2 data is smaller, so you might be fine) $\longrightarrow$ consider looking into `dask` and friends for an intermediate step
- Makes sense to use soft online cuts and harder offline cuts
- Similar problem: Which columns to write out? $\longrightarrow$ columnar data formats might at least help with fast reading of partial column set
- No golden rule, but deliberate choices are better

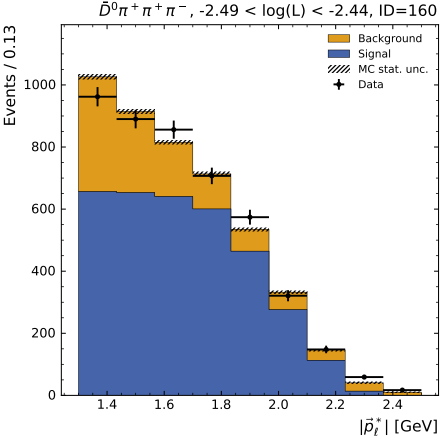
Example fits

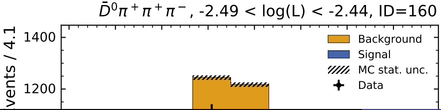
$B_{\text{sig}} \longrightarrow X\ell\nu,\ B_{\text{tag}} \longrightarrow \bar{D}^0\pi^+\pi^+\pi^-$

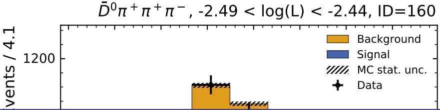
Before fitting



Fitted







In practice: Fitting frameworks

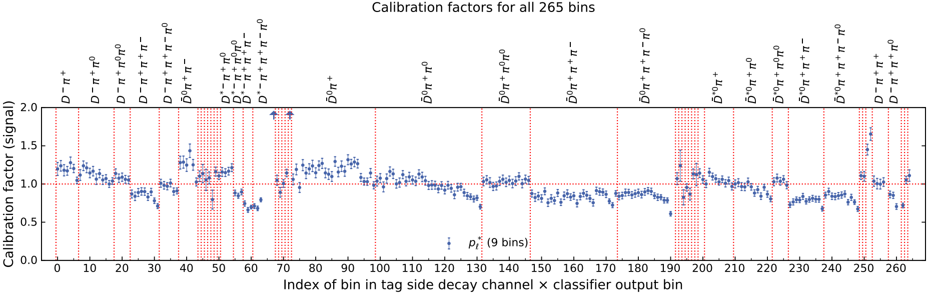
- Many fitting frameworks: `ROOFit`, `zFit`, `pyHF`, ... $\longrightarrow$ choose wisely!
  - Vary a lot in usability and quality of documentation!
  - Good to think ahead! (Features? How are uncertainties handled? Integration in your code? Help?)
- Different ways to incorporate uncertainties: Either
  - fits with fixed templates/weights $\longrightarrow$ repeat fits with varied templates/weights $\longrightarrow$ collect results and calculate uncertainty from differences
  - have more complicated likelihood where uncertainties are nuisance parameters

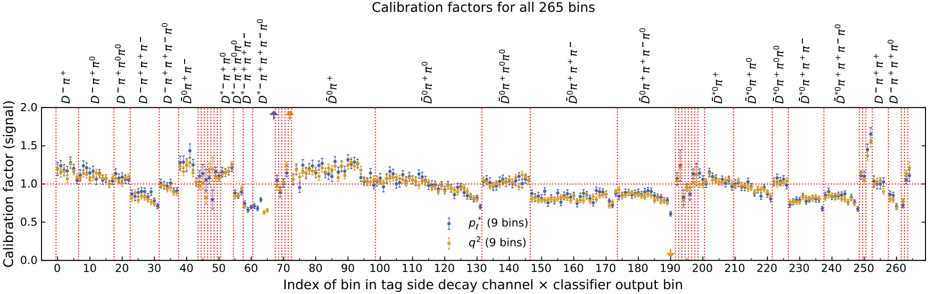
$$\mathcal{L} = \prod_i \mathcal{P}(n_i; \nu_i) \times \prod_k \mathcal{G}_k(\vec{0}, \vec{\theta}_k, \Sigma_k)$$

$$\nu_i = \sum_k \eta_k \prod_s (1 + \tilde{\theta}_{ks}) \frac{\eta_{ik}(1 + \theta_{ik})}{\sum_j \eta_{jk}(1 + \theta_{jk})},$$

The calibration factors

CFs and uncertainties

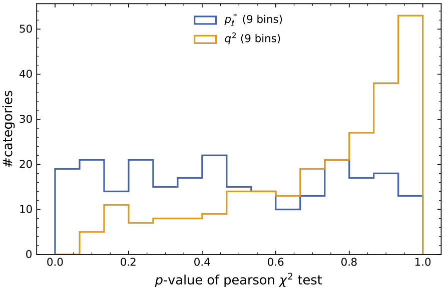




In practice: Validating fits

How do we know to trust our fits?

- Expect to repeat fits very, very, often...
- Simple validation: Linearity check
  - Generate artificial dataset from MC "bootstrapping" with different signal strengths
  - Fit this
  - Expect to get back signal strength that we put in
- Can also look at p-value distribution (should be flat!)



Summary

$|V_{cb}|$

- $|V_{cb}|$ needed to test unitarity of CKM matrix
- $\mathrm{BR}(B \longrightarrow D^{(*)}\ell\bar{\nu}_\ell) =$ stuff we know $\cdot\, \mathrm{FF}^2(w) \cdot |V_{cb}|^2 \longrightarrow$ exclusive measurement
- Form factors $\mathrm{FF}^2(w)$ make trouble
- Other method of extraction: Inclusive measurement; in tension with exclusive measurements

This analysis: $|V_{cb}|$ from hadronically tagged $B \longrightarrow D^*\ell\bar{\nu}_\ell$ at Belle

- B_{tag} reconstructed by the FEI
- The FEI has different efficiencies on data and MC $\longrightarrow$ Calibration
- For calibration need something we trust: $B_{\mathrm{sig}} \longrightarrow X\ell\nu$
- Reconstruct $\Upsilon(4S) \longrightarrow B_{\mathrm{tag}}B_{\mathrm{sig}}$; blame efficiency difference on FEI $\longrightarrow$ calibration factors

Backup

Cuts & best candidate selection

Electrons, Muons

e	μ
$\mathrm{d}r < 2\,\mathrm{cm}$	
$\lvert \mathrm{d}z \rvert < 4\,\mathrm{cm}$	
$\lvert p_T^* \rvert > 0.1\,\mathrm{GeV/c}$	
$p > 0.3\,\mathrm{GeV/c}$	$p > 0.6\,\mathrm{GeV/c}$
`eIDBelle` > 0.6	`muIDBelle` > 0.9
	`muIDBelleQuality = 1`

Photon

`goodBelleGamma` $= 1$

Event

Number of tracks with $\mathrm{d}r < 2\,\mathrm{cm}$ and $\lvert \mathrm{d}z \rvert < 4\,\mathrm{cm}$: ≤ 17
Number of FS photons: < 18

B_{tag}

$M_{\mathrm{bc}} > 5.27\,\mathrm{GeV/c^2}$
signal probability > 0.001
CS output > 0.2 (CS via BDT)

Best Candidate Selection

- Pick B_{tag} with smallest ΔE
- Pick lepton with highest $\lvert p_\ell^* \rvert$
- Still multiple candidates $\longrightarrow$ pick random

Fit strategies

- Decay channels vary significanly in number of events $\Longrightarrow$ number of bins in FEI classifier depends on decay channel (currently aiming for $>$ 4500 events per bin)
- Perform a fit to extract yields for signal
- Calibration factor = fitted yield / MC yield
- Binned maximum likelihood fit (systematics included in likelihood $\Longrightarrow$ pull on the shape of the distributions $\longrightarrow$ Backup)

Current strategy: 2 component fit

- Fake leptons + secondary leptons + continuum are fitted as one component (background) $\longrightarrow$ Requires additional systematic uncertainty $\longrightarrow$ todo
- Fitted with 2 components: Signal + background
- Number of bins fixed to 9 (will be made dynamic later)

Fitting and systematics

Maximize binned likelihood, allowing systematics to pull on the shapes:

$$\mathcal{L} = \prod_i \mathcal{P}(n_i; \nu_i) \times \prod_k \mathcal{G}_k(\vec{0}, \vec{\theta}_k, \Sigma_k)$$

$$\nu_i = \sum_k \eta_k \prod_s (1 + \tilde{\theta}_{ks}) \frac{\eta_{ik}(1 + \theta_{ik})}{\sum_j \eta_{jk}(1 + \theta_{jk})},$$

where

- $\mathcal{P}$: Poisson distribution
- n_i: Measured events in bin i
- ν_i: Expected events in bin i
- k: Component of fit
- η_k: Yield of fit template k
- η_{ik}: Bin content of fit template k, bin i
- θ_{ik}: Additive nuisance parameter bin i, fit component k
- $\tilde{\theta}_{is}$: Multiplicative nuisance parameter from source s for fit component k
- $\mathcal{G}$: Multivariate Gaussian with covariance matrix Σ_k

Fitted: η_k, θ_{ik}, $\tilde{\theta}_{ks}$

Reconstruction signal side

π, K meson

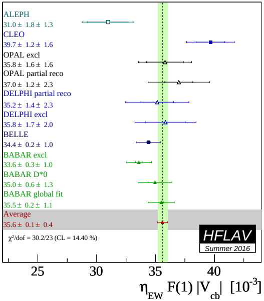
Identification via PID likelihood ratio, impact parameters.
π^0: From γ candidates (clusters in calorimeter not matched to any track)

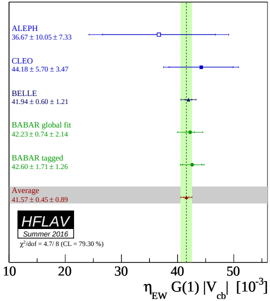
D, D^* meson

arXiv	Signal	Tag	D^0 modes	D^+ modes	D^{*-} modes
[1010.5620] [1809.03290]	$D^*\ell\bar{\nu}_\ell$	No	$K^-\pi^+$		$D^-\pi^-$
[1702.01521]	$D^*\ell\bar{\nu}_\ell$	Had.	$K^-\pi^+(\pi)(\pi)$	$K^-\pi^+\pi^+$	$\bar{D}^0\pi^-$, $D^-\pi^0$
[1510.03657]	$D\ell\bar{\nu}_\ell$	Had.	$K^-\pi^+(\pi)(\pi)$, $K_S^0\pi^+\pi^-(\pi^0)$, $K_S^0\pi^0$, K^+K^-, $\pi^+\pi^-(\pi^0)$, $K_S^0K_S^0$, $\pi^0\pi^0$, $K_S^0\pi^0\pi^0$, $K^-\pi^+\pi^+\pi^-\pi^0$	$K^-\pi^+\pi^+(\pi^0)$, $K_S^0\pi^+(\pi^0)$, $K^+K^-\pi^+$, $K_S^0K^+$, $K_S^0\pi^+\pi^+\pi^-$, $\pi^+\pi(\pi)$, $K^-\pi^+\pi^+\pi^+\pi^-$	

Results and Outlook @Belle

Link	Channel	Tag	CLN	BGL	Unfold	Notes
[1010.5620]	$D^*\ell\bar{\nu}_\ell$	No				
[1809.03290]	$D^*\ell\bar{\nu}_\ell$	No	38.4 ± 0.9	42.5 ± 1.0		
[1702.01521]	$D^*\ell\bar{\nu}_\ell$	Had.	37.4 ± 1.3		Prelim.	Soon: Separate results $\ell = e$ and $\ell = \mu$
[1510.03657]	$D\ell\bar{\nu}_\ell$	Had.	39.86 ± 1.33	40.83 ± 1.13		





Projection in bins of kinematic variable

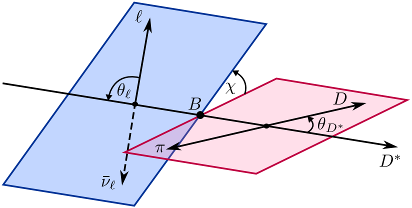
$B \longrightarrow D\ell\bar{\nu}_\ell$

10 equal-size bins in w.

Good resolution (0.005) vs bin width (0.06) $\Longrightarrow$ Bin migration neglected

$B \longrightarrow D^*\ell\bar{\nu}_\ell$

- 10 equal size bins in w, χ, $\cos\theta_\ell$, $\cos\theta_{D^*}$ (Projections)
- Correlation between the 4 distributions ($\longrightarrow$ toy experiments)
- Finite resolution $\Longrightarrow$ Migration!
  $\longrightarrow$ Mig. matrix from truth vs reco MC.
  $\longrightarrow$ Fold theory (easy) or
  unfold measurement (hard)



Fit variables

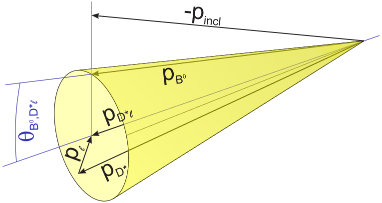
Tagged analyses

Fit variable: $m^2_{\text{miss}} := (p_B - p_{D^{(*)}} - p_\ell)^2$ with $p_B = p_{\text{LER}} + p_{\text{HER}} - p_{\text{tag}}$

Correct reco $\Longrightarrow$ Peak at 0; Missed particles $\Longrightarrow$ Peak > 0; Particles from tag side $\Longrightarrow$ Peak < 0

Untagged analyses

Fit variables:

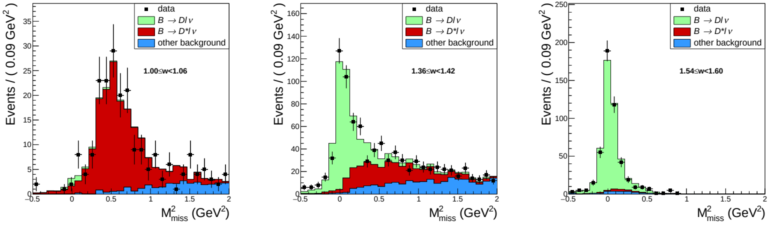


- $$\cos\theta_{B,D^*\ell} := \frac{2E^*_B E^*_{D^*\ell} - m^2_B - m^2_{D^*\ell}}{2|\vec{p}^*_B||\vec{p}^*_{D^*\ell}|}$$
  Correct reco $\Longrightarrow -1 \leq \cos\theta_{B,D^*\ell} \leq 1$
- $\Delta m = m_{D^*} - m_D$
- p_ℓ

Fit strategies

Belle tagged $B \longrightarrow D\ell\bar{\nu}_\ell$ [1510.03657]

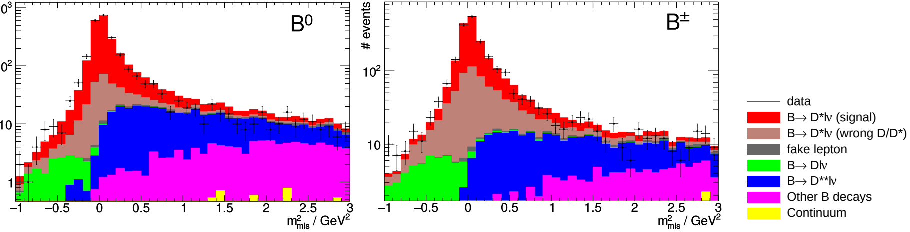
$B = B^0,\ \ell = e$



Fit	Binned extended likelihood fit (Barlow, Beeston, 1993)
Fit variable	$m^2_{\text{miss}} := (p_B - p_D - p_\ell)^2$
Templates	From MC
Fixed Norm.	"other" background from MC
Float. Norm.	**2**: $B \longrightarrow D\ell\bar{\nu}_\ell$ and $B \longrightarrow D^*\ell\bar{\nu}_\ell$ normalization

Fit strategies

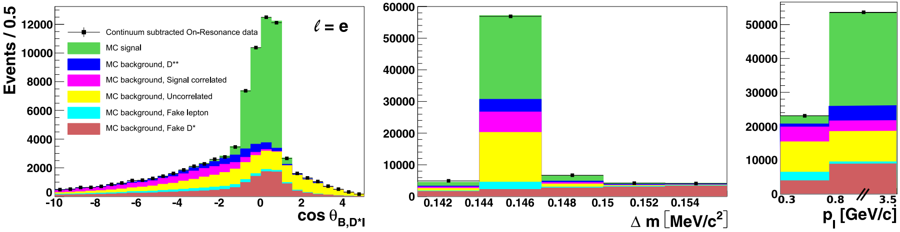
Belle tagged $B \longrightarrow D^* \ell \bar{\nu}_\ell$ [1702.01521]



Fit	Unbinned likelihood fit
Fit variable	$m^2_{\text{miss}} := (p_B - p_{D^*} - p_\ell)^2$
Templates	From MC
Fixed Norm.	Ratios of background normalizations from MC
Float. Norm.	**2**: Correctly reco. sig. + sig. with $D^{(*)}$ wrongly reco. norm.; total background normalization

Fit strategies

Belle untagged $B \longrightarrow D^{*}\ell\bar{\nu}_{\ell}$ [1010.5620]

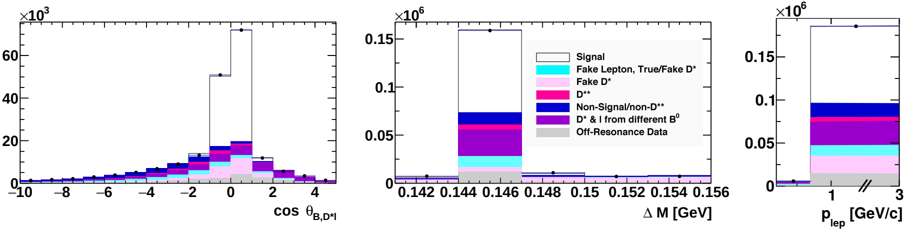


Fit	Binned likelihood fit
Fit variable	$\cos\theta_{B,D^{*}\ell}$, Δm, p_{ℓ}
Templates	Continuum from off-resonance, rest from MC[1]
Fixed Norm.	Continuum from off-resonance (corrected for $1/s$ dependency)
Float. Norm.	**6**: Normalizations for signal and backgrounds

[1] For $\ell = \mu$: Shape of fake ℓ corr. with data from $K_s^0 \longrightarrow \pi^+\pi^-$; ℓ PID eff. corr. with data from $2\gamma \longrightarrow e^+e^-/\mu^+\mu^-$

Fit strategies

Belle untagged $B \longrightarrow D^*\ell\bar{\nu}_\ell$ (new) [1809.03290]



Fit	Binned likelihood fit
Fit variable	$\cos\theta_{B,D^*\ell}$, Δm, p_ℓ
Templates	Continuum from off-resonance, rest from MC[2]
Fixed Norm.	Continuum from off-resonance (corrected for $1/s$ dependency, kinematics)
Float. Norm.	**6**: Normalizations for signal and backgrounds

[2]Shape of fake ℓ corr. with data from $D^* \longrightarrow D^0\pi$, $D^0 \longrightarrow K\pi$; lepton PID eff. corr. with data from $ee \longrightarrow ee\gamma$, $ee \longrightarrow \mu\mu(\gamma)$ and $J/\psi \longrightarrow \ell^+\ell^-$; low momentum track reco. eff. corr. with control sample of $B \longrightarrow D^*\ell\bar{\nu}_\ell$

V_{cb} and form factors fit

χ^2 fit

$$\chi^2 = \left(\vec{\nu}_{\text{sig}} - \vec{\nu}^{\text{pred}}_{\text{sig}}\right) C^{-1} \left(\vec{\nu}_{\text{sig}} - \vec{\nu}^{\text{pred}}_{\text{sig}}\right) + \chi^2_{\text{nuisance}},$$

where:

- $\vec{\nu}_{\text{sig}}$ yields in bins of kinematic variables ($D\ell\bar{\nu}_\ell$: w, $D^*\ell\bar{\nu}_\ell$: w, χ, $\cos\theta_\ell$, $\cos\theta_{D^*}$)
- $\vec{\nu}^{\text{pred}}_{\text{sig}} = (\epsilon_{\text{reco}}\epsilon_{\text{tag}})\mathcal{M}_{\text{mig}}\vec{\Delta\Gamma}$
  $\Delta\Gamma_i$: theory expectation diff. CS in bin i
  (depends on FF param, $|V_{cb}|$),
  $\mathcal{M}_{\text{mig}}$: migration matrix
- C: Covariance matrix
- χ^2_{nuisance}: Account for multiplicative factors degenerate with $|V_{cb}|$