Semileptonic B decays at Belle and Belle II

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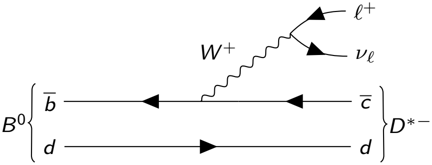
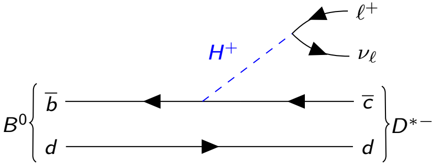
Why semileptonic decays?

- Easier to describe theoretically due to less QCD influence compared to fully hadronic decays
- Higher branching fractions (e.g. $10.33 \pm 0.28\%$ of B^0 decays), and easier to reconstruct than fully leptonic decays
- Well suited for determining CKM matrix elements and probing new physics



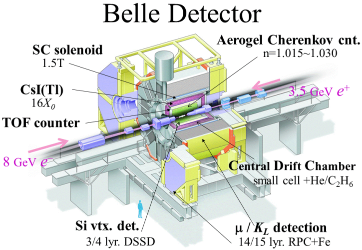
Standard Model $B^0 \to D^{*-}\ell^+\nu_\ell$



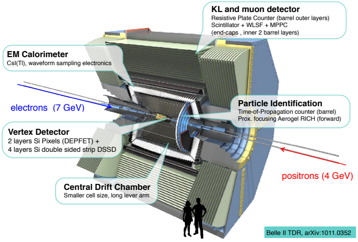
Same decay via a BSM charged Higgs

Belle

- Collected $772 \times 10^6 B\bar{B}$ at the $\Upsilon(4S)$ resonance



Belle



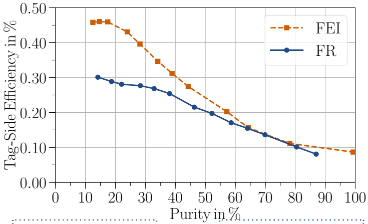
Belle II

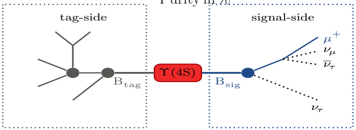
Belle II

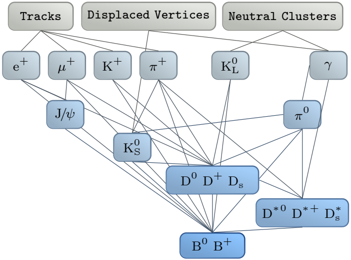
- Upgraded in combination with accelerator to achieve $40\times$ the luminosity
- Data taking started in March this year

Full Event Interpretation (FEI)

- $\Upsilon(4S)$ always decays to $B\bar{B}$ pairs, reconstruct one called B_{tag} in over 1000 channels with boosted decision trees (BDTs)
- Choice between hadronic and semileptonic B decay modes
- Known initial state allows to use the other B-meson(B_{sig}) in signal analysis







Keck, T. et al. Comput Softw Big Sci (2019) 3: 6.

- Comes at a price of low efficiency for high purity
- Untagged analyses not considering second B-meson have higher efficiency, but also higher backgrounds

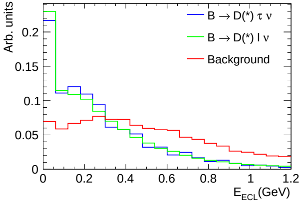
Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method

Semitauonic B decays are an important probe towards BSM processes, due to the high masses involved. The ratio with lighter mesons

$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

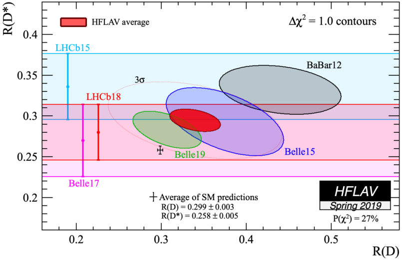
has been both experimentally and theoretically determined and is a source of tension in the Standard Model.

- B_{tag} reconstructed semileptonically using FEI
- Reconstruct B_{sig} in $D^{+/0(*)}\ell^-$ $D^* \to D\pi$ and D to a number of K and π
- Many ν in event: One from B_{tag}, one($\ell = e, \mu$) or three($\ell = \tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$) from B_{sig} $\Rightarrow$ Extra energy left in the calorimeter strongly hints at background event with additional particles



Calorimeter energy not used in the reconstructed

Caria, G. et al. (Belle Collaboration) arxiv:1904.08794



Combined results

- Data contains three components: $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$, $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ and background
- To distinguish τ from e, μ events, train a BDT sensitive to the additional ν
- Fit to BDT output and E_{ECL} to determine event numbers

Results

First measurement of $\mathcal{R}(D)$ with semileptonic tag

	This analysis	Updated HFLAV average	SM prediction
$\mathcal{R}(D)$:	$0.307 \pm 0.037 \pm 0.016$	$0.340 \pm 0.027 \pm 0.013$	0.299 ± 0.003
$\mathcal{R}(D^*)$:	$0.283 \pm 0.018 \pm 0.014$	$0.295 \pm 0.011 \pm 0.008$	0.258 ± 0.005

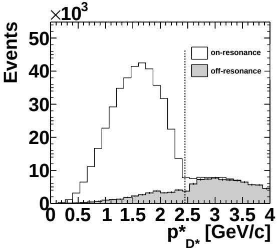
Belle results combined now agree with the SM within 1.8σ, closer than before.

Measurement of the CKM Matrix Element $|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$ at Belle

- There has been a long-standing tension between inclusive and exclusive measurements of $|V_{cb}|$.
- The decay $B^0 \to D^{*-}\ell^+\nu_\ell$ allows measuring both $|V_{cb}|$ and form factors describing the decay.
- To achieve high statistics, use an untagged approach and only reconstruct the signal side.

- Further decays considered are $D^{*-} \to \bar{D}^0\pi^-$, $\bar{D}^0 \to K^-\pi^+$
- Clean reconstruction channel, use vertex fits and momentum cuts to select particles
- Signal D^{*-} have a lower momentum than D^{*-} directly from $e^+e^- \to c\bar{c}$

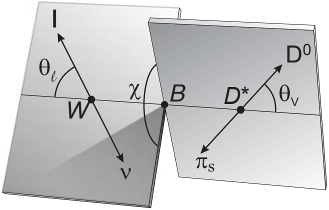
Waheed, E. et al. (Belle Collaboration). Phys. Rev. D 100, 052007 (2019)



CoM momentum of reconstructed D^{*-}

Background subtraction

- Untagged analysis comes with large backgrounds
- Determine bkg yields by three-dim. fit to kinematic variables, use result to subtract bkg for



Angles used to describe the decay

CLN form factor fit

- Parametrization used in the Monte Carlo and fits so far
- Fit three form factors plus normalization to projections of the three decay angles and the D^* momentum

BGL form factor fit

- Model independent alternative parametrization
- Truncated to fit five parameters to the same variables as CLN

CLN: I. Caprini, L. Lellouch and M. Neubert, Nucl. Phys. B 530 153 (1998)

BGL: C. G. Boyd, B. Grinstein, and R. F. Lebed, Phys. Rev. D 56, 6895 (1997)

Results

The results are for the CLN parametrization:

$$|V_{cb}| = (38.4 \pm 0.2 \pm 0.6 \pm 0.6) \times 10^{-3}$$
$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.90 \pm 0.02 \pm 0.16)\%$$

And for BGL:

$$|V_{cb}| = (38.3 \pm 0.3 \pm 0.7 \pm 0.6) \times 10^{-3}$$
$$\mathcal{B}(B^0 \to D^{*-}\ell^+\nu_\ell) = (4.90 \pm 0.02 \pm 0.16)\%$$

Compared with the world average for $|V_{cb}|$, both agree well with other inclusive measurements, the tension with the exclusive measurements remains

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (39.1 \pm 0.4) \times 10^{-3} \text{ (CLN, exclusive)}$$

Lepton universality check

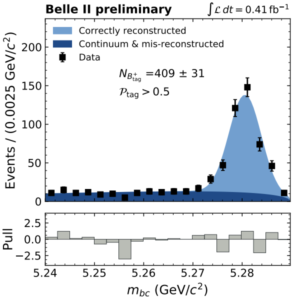
Separate fits to e and μ allow a stringent bound on lepton universality violations:

$$\frac{\mathcal{B}(B^0 \to D^{*-}e^+\nu)}{\mathcal{B}(B^0 \to D^{*-}\mu^+\nu)} = 1.01 \pm 0.01 \pm 0.03$$

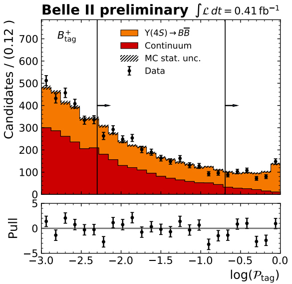
FEI reconstruction performance at Belle II

Use $0.41 fb^{-1}$ of measured data and $10 fb^{-1}$ of MC to evaluate the hadronic FEI performance in the Belle II setup

- Output of the classifier shows good agreement with the expectation, and allows a high purity selection
- However, signal extends over a wide range showing the trade-off between efficiency and purity to consider



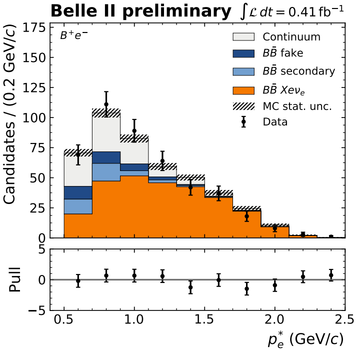
Reconstruction for $B^{\pm}_{tag}$



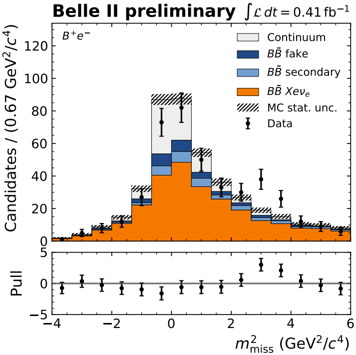
FEI output distribution

- Beam-constrained mass $m_{bc} = \sqrt{(0.5 \times E_{Beam})^2 - \vec{p}_B^2}$ measures reconstruction quality

To later calibrate the FEI, after making a selection on the classifier a signal mode is reconstructed by selecting a lepton and summing up the remaining particles.



Signal electron momentum



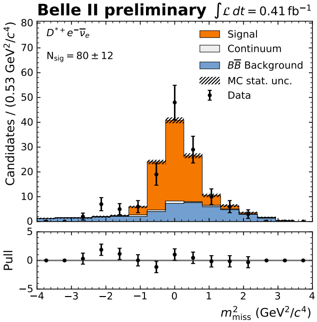
Reconstructed m^2_{miss} after selecting an electron

Belle II untagged analysis of $\bar{B}^0 \to D^{*+}\ell^-\nu$

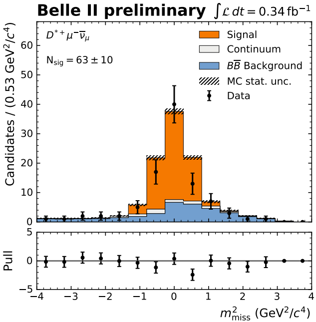
- Use $0.41 fb^{-1}$ of early data for a first analysis

- Reconstruct $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$
- Difference between initial state and sum of final states, needs precise knowledge of beam state: $m^2_{miss} = \left(\frac{p_{Beam}}{2} - p_{D^*\ell}\right)^2$

- No particle ID requirements for hadrons
- The reconstruction and fit already show a clear signal peak to later extract the branching fraction



m^2_{miss} with electrons



m^2_{miss} with muons

Conclusion

- Belle still produces new interesting results years after ending data taking.
- Belle II taking data and analyses on the way.

Thank you for your attention!