Measurement of $B \to D^{**}\ell\nu_\ell$ branching fraction using Belle data

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BELLE

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Introduction

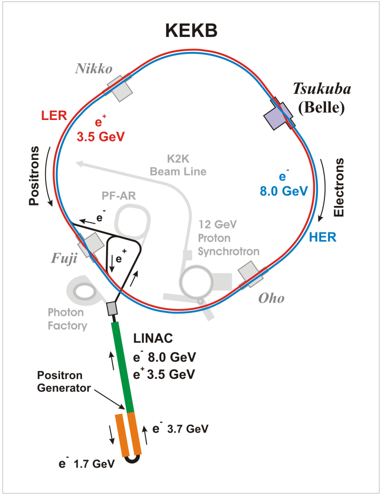
- inclusive: BR($B^+ \to X_c \ell \nu_\ell$) = $(10.8 \pm 0.4)\,\%$ / BR($B^0 \to X_c \ell \nu_\ell$) = $(10.1 \pm 0.4)\,\%$
- sum of BR($B \to D^{(*)} \ell \nu_\ell$) and BR($B \to D^{(*)} \pi \ell \nu_\ell$) = 9.05 % / 8.35 %
- gap of ~1.75 % between inclusive and exclusive branching fraction measurements of $B \to X_c \ell \nu_\ell$
- $B \to D \ell \nu_\ell$ and $B \to D^* \ell \nu_\ell$ known at 3 - 4 % level
- $B \to D \pi \ell \nu_\ell$ and $B \to D^* \pi \ell \nu_\ell$ only known at 7 - 9 % / 12 - 14 % level for charged / neutral modes
- $B \to D^{(*)} \pi \pi \ell \nu_\ell$ observed by BaBar (Phys. Rev. Lett. 116, 041801 (2016))
- $B \to D^{(*)} \eta \ell \nu_\ell$ not yet measured

- $B \to D^{(*)} \pi \ell \nu_\ell$ and $B \to D^{(*)} \pi \pi \ell \nu_\ell$ important background contributions in measurements of $R(D)$ / $R(D^*)$

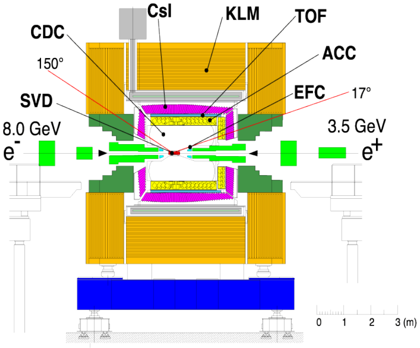
Scope and goals of this analysis

- measure branching fraction of $B \to D^{(*)}\pi\ell\nu_\ell$
  - improve on previously published Belle analysis (Phys. Rev. D. 98, 012005 (2018))
    - replace tagging algorithm
    - revisit D reconstruction decay modes
    - change fit variable to extract signal yields
    - measure branching fraction relative to $B \to D^*\ell\nu_\ell$
  - study D^{**} mass spectrum with $D^{**} \to D^{(*)}\pi$
    - calculate sWeights
    - measure peak mass and width of D_0^*, D_1, D_1', and D_2^* using Breit-Wigner fit model
    - measure BR($B \to D_0^*\ell\nu$), BR($B \to D_1\ell\nu_\ell$), BR($B \to D'_1\ell\nu_\ell$), and BR($B \to D_2^*\ell\nu_\ell$)
- confirm / add precision to BR($B \to D^{(*)}\pi\pi\ell\nu_\ell$) and look at $D^{(*)}\pi\pi$ spectrum
- study of q^2-dependence in $B \to D^{(*)}\pi\ell\nu_\ell$
- measure BR($B \to D^{(*)}\eta\ell\nu_\ell$) or set upper limit

Experimental Setup

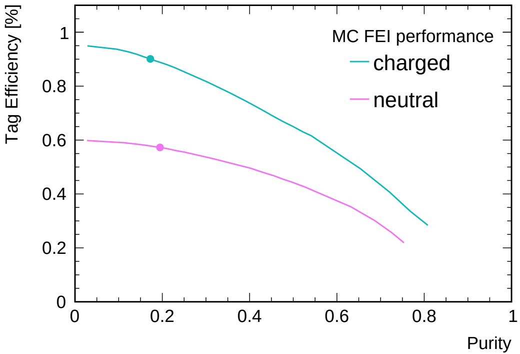


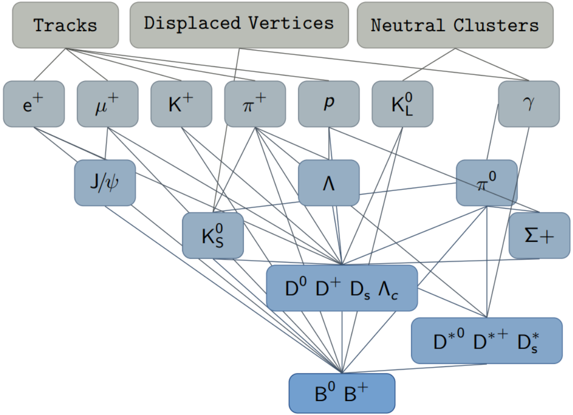
- asymmetric collision of e^+e^-
- center-of-mass energy mostly at $\Upsilon(4S)$ resonance
- $\Upsilon(4S) \to B^+B^-$ (~51.5 %), $\Upsilon(4S) \to B^0\overline{B}^0$ (~48.5 %)
- Belle collected ~770M $B\overline{B}$ pairs over the course of 10 years



Full Event Interpretation

- fully reconstruct one of the B mesons (tag-side)
- hadronic and semileptonic version:
  trade-off between efficiency and purity
- train BDT for each stage
  $\Rightarrow$ signal probability



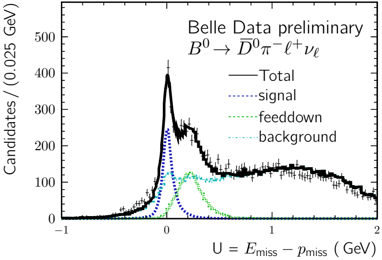


Analysis in a nut shell

- read in and convert data from Belle to Belle II format using B2BII   Comput. Softw. Big Sci. 2 (2018)
- run hadronic Full Event Interpretation with Belle training
  - B_{tag} selection: $|\Delta E| < 180$ MeV, $M_{\text{bc}} > 5.27$ GeV/c^2, signal probability > 0.005
- final state particle selection ($e^\pm$, $\mu^\pm$, $K^\pm$, $\pi^\pm$, π^0, and K_S^0)
- reconstruct D from final state particles and D^* by adding slow pion
  - $D^+ \to K^-\pi^+\pi^+$, $D^+ \to K_S^0\pi^+$, $D^+ \to K_S^0\pi^+\pi^0$, $D^+ \to K^-K^+\pi^+$, $D^+ \to K_S^0\pi^+\pi^-\pi^+$, $D^+ \to K_S^0 K^+$ new D modes
  - $D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^0$, $D^0 \to K_S^0\pi^+\pi^-$, $D^0 \to K^-K^+$, $D^0 \to K_S^0\pi^0$, $D^0 \to K_S^0\pi^+\pi^-\pi^0$, $D^0 \to \pi^+\pi^-$
- combine $D^{(*)}$ with 0, 1, and 2 bachelor pions + 1 lepton to form 24 different B_{sig} modes
- reconstruct $\Upsilon(4S)$ from B_{tag} + B_{sig} (B^+B^-, $B^0\overline{B}^0$, B^0B^0)
- check that there are no additional tracks in the rest of the event
- best $\Upsilon(4S)$ candidate selection based on tag-side signal probability and preference of D^* over D modes
- measure branching fractions of $B \to D^{(*)}\pi\ell\nu_\ell$ and $B \to D^{(*)}\pi\pi\ell\nu_\ell$ relative to $B \to D^*\ell\nu_\ell$

Fit model

- fit dimension: $U = E_{\text{miss}} - p_{\text{miss}}$ with $E_{\text{miss}} = E_{e^+e^-} - E_{\text{tag}} - E_{D^{**}} - E_l$
  - better sensitivity than fitting missing mass squared $M_\nu^2 = E_{\text{miss}}^2 - p_{\text{miss}}^2$
- PDF constructed as histograms with 120 bins in $[-1\,;2]$ based on MC
  - weighting applied to correct known data-MC differences in PID, tracking efficiency, π^0 and K_S^0 efficiency, charm branching fractions, tagging mode composition
  - additional Gaussian smearing of signal PDF
- components:
  - signal
  - feeddown (π^0 missed in reconstruction of $D^* \to D\pi^0$)
  - background
    - $B\overline{B}$ background (charged + neutral samples merged)
    - continuum background (uds + charm samples merged)
    - constrain ratio between $B\overline{B}$ and continuum
- simultaneous fit of D and D^* modes

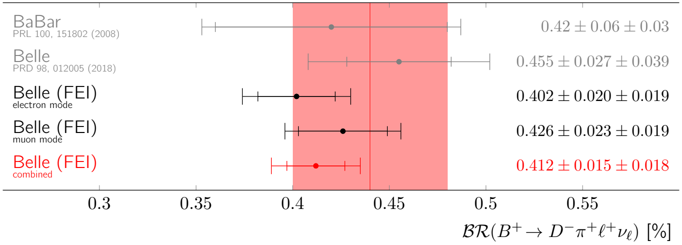


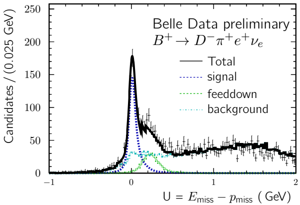
Relative systematic uncertainties in %

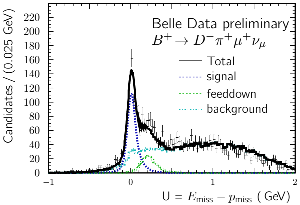
- largest systematic uncertainties from external branching fractions
- conservative estimate of modeling uncertainties
- partial cancellation of PID, tracking and selection efficiencies in ratio
- number of $B\overline{B}$ + tag efficiency in direct measurement would be a lot larger

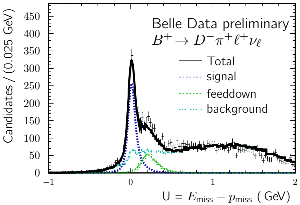
	$B^0 \to \overline{D}^0\pi^-\mu^+\nu_\mu$	$B^0 \to \overline{D}^0\pi^-e^+\nu_e$	$B^+ \to D^-\pi^+\mu^+\nu_\mu$	$B^+ \to D^-\pi^+e^+\nu_e$
BR($B \to D^*\ell\nu_\ell$)	1.90	1.90	3.89	3.89
charm branching ratios	0.95	0.95	1.42	1.42
fit model	0.94	0.56	0.53	1.14
efficiency MC statistic	0.78	0.87	0.75	0.69
$B \to D^*\ell\nu_\ell$ & $B \to D\pi\ell\nu_\ell$ form factors	0.40	0.66	0.03	0.71
charged hadron PID	0.26	0.30	1.53	1.51
tracking efficiency	0.30	0.29	0.59	0.62
π^0 efficiency	0.13	0.13	0.44	0.43
lepton PID	0.14	0.23	0.15	0.23
K_S^0 efficiency	0.01	0.01	0.03	0.03
sum	2.52	2.50	4.57	4.72

$B^+ \to D^- \pi^+ \ell^+ \nu_\ell$



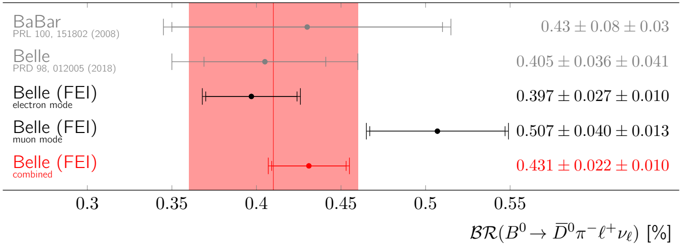


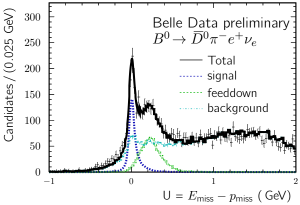


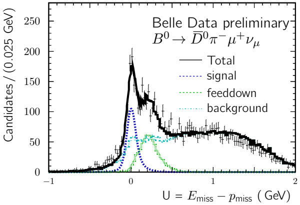


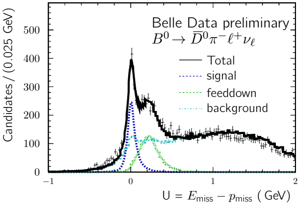
- good agreement between electron and muon mode
- combined value compatible with world average but twice as precise

$B^0 \to \overline{D}^0 \pi^- \ell^+ \nu_\ell$





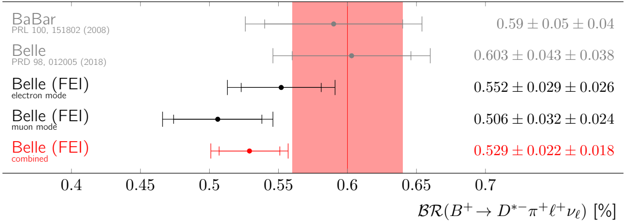


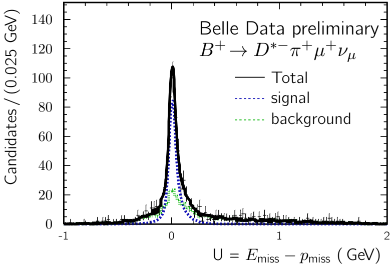


- slight tension between electron and muon mode
- combined value compatible with world average but twice as precise

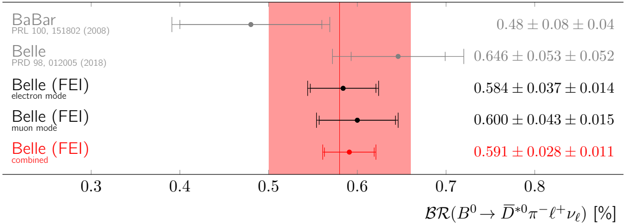
$B \to D^* \pi \ell \nu_\ell$

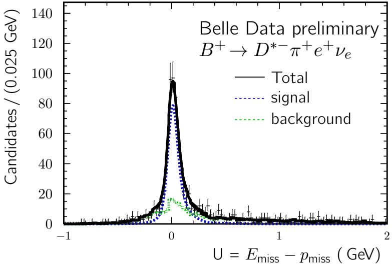
- fit result considerably smaller than PDG average





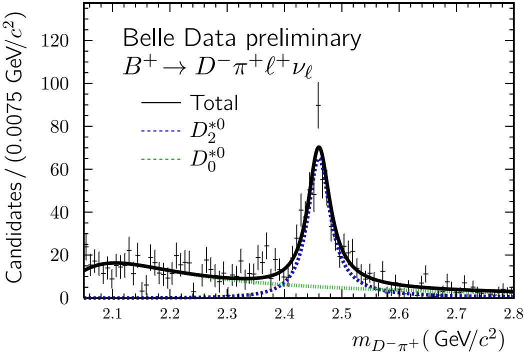
- almost all sensitivity from feeddown

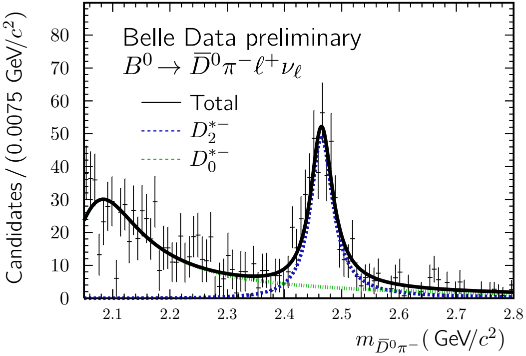




D^{**} mass spectrum

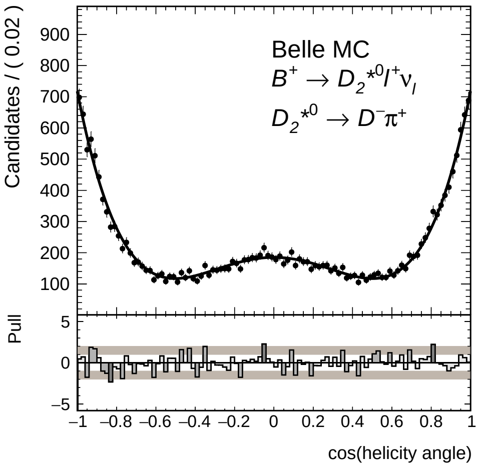
- use fit of $E_{\text{miss}} - p_{\text{miss}}$ to calculate sWeights and statistically subtract background

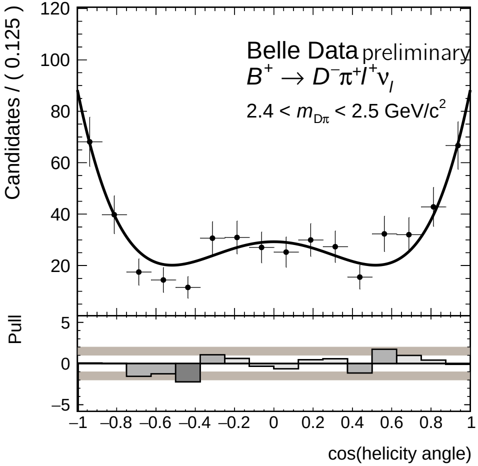




- fit D^{**} mass spectrum with relativistic Breit-Wigner distributions
- narrow D_2^* resonance at expected position and with expected width

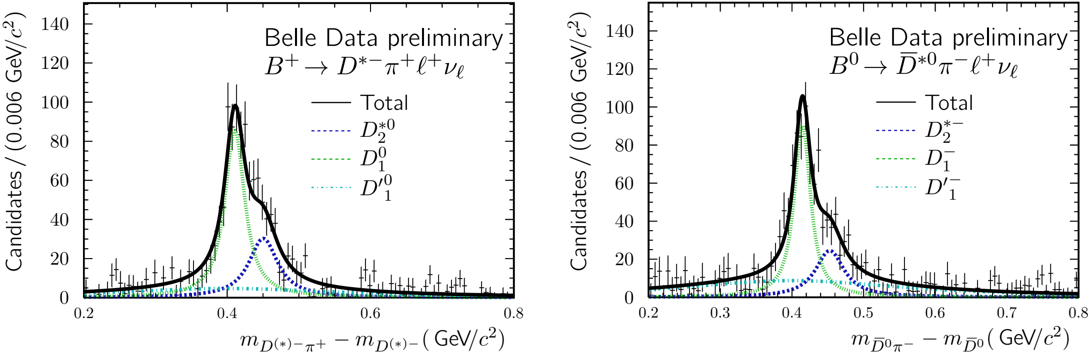
Helicity distribution around D_2^* resonance





- fit with Legendre polynomials for spin-2 resonance looks good and compatible with MC shape

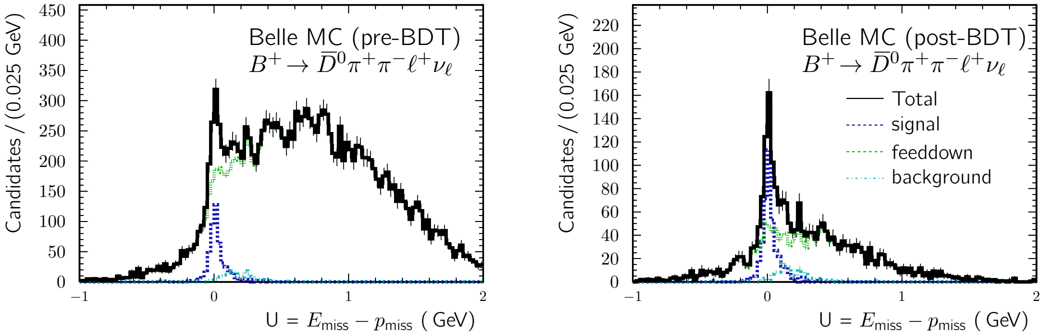
Exclusive $B \to D^*\pi\ell\nu_\ell$ branching fractions



- simultaneous fit of signal and feeddown reconstruction for $B^+ \to D^{*-}\pi^+\ell^+\nu_\ell$
- for $B^0 \to \overline{D}^{*0}\pi^-\ell^+\nu_\ell$ only feeddown component fitted
- all shape parameters fixed to PDG values

Study of $B^+ \to \overline{D}^0\pi^+\pi^-\ell^+\nu_\ell$

- main background sources
  - continuum $\Rightarrow$ suppress via BDT using event shape variables and training with off-resonance data
  - peaking background $\Rightarrow$ veto $B^+ \to D^{*-}\pi^+\ell^+\nu_\ell$ with $D^{*-} \to \overline{D}^0\pi^-$



- sensitivity expected to be about twice as good as BaBar

Conclusion

- world's best measurements of $B \to D^{(*)}\pi\ell\nu_\ell$ branching fractions thanks to new tagging algorithm
  - excellent prospect for Belle II measurements once statistics is sufficient
- all results of combined branching fractions compatible with previous world averages
- extraction of individual $B \to D^{**}\ell\nu_\ell$ using sPlot technique
- study of $B \to D^{(*)}\pi\pi\ell\nu_\ell$ almost ready as well