A STUDY OF HADRONIC TAGGED $B \to D^{(*)}\ell\nu$ AT THE BELLE II EXPERIMENT

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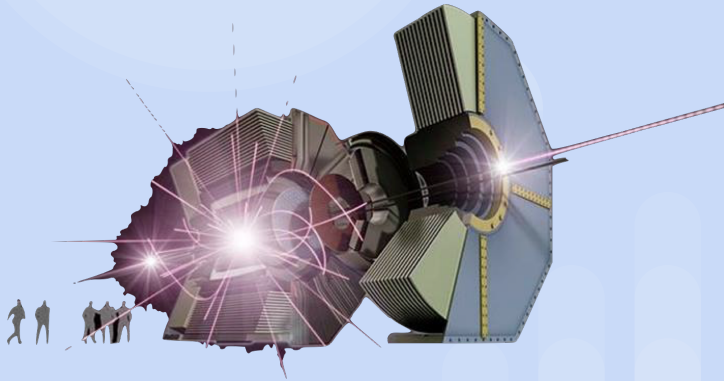
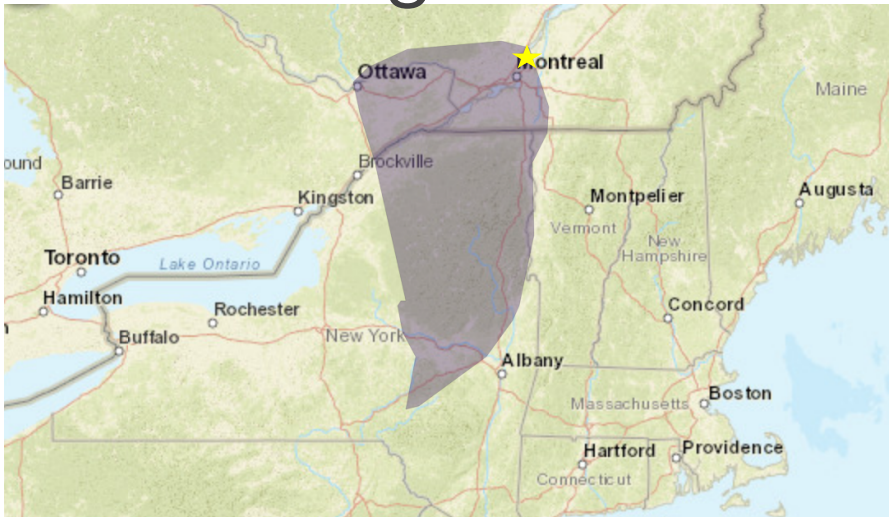


CAP Congress 2022
Hamilton, ON

Traditional Territory Acknowledgement

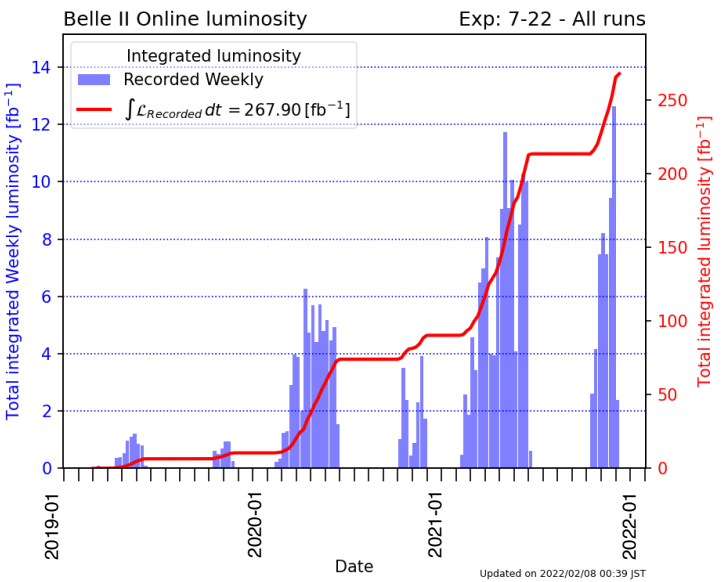
McGill is situated on unceded, Kanien'kehá:ka traditional territory. This means that this land was taken, not paid for or given by the Kanien'kehá:ka people.

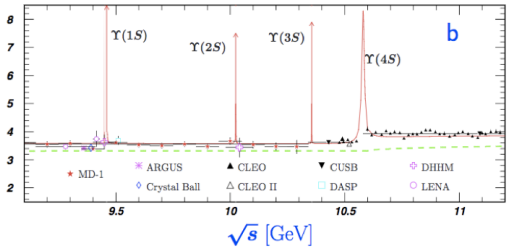


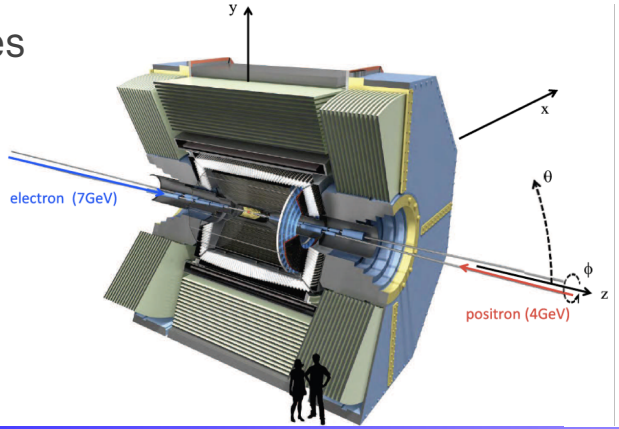
This site has long served as a site of meeting and exchange amongst Indigenous peoples, including the Haudenosaunee and Anishinabeg nations. Through this acknowledgement I hope to respect the diverse Indigenous peoples connected to this territory on which I work and live in today.

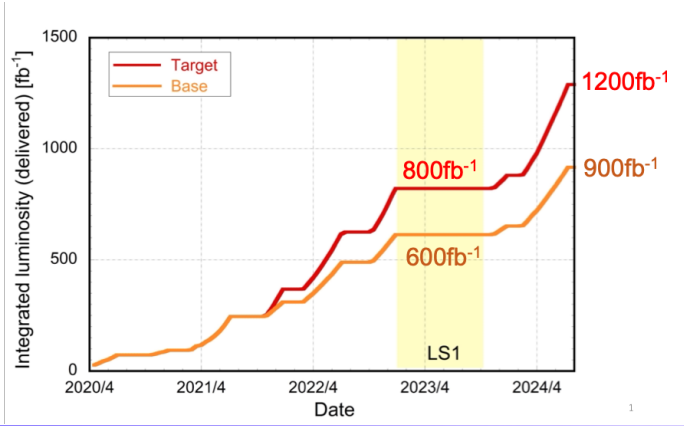
The Belle II Experiment & SuperKEKB

- Asymmetric e^-e^+ collider at 7 GeV and 4 GeV
- B meson factory (~1.1x10^9 $B\bar{B}$ pairs per ab^{-1}) 1 b = 100 fm^2
- Target luminosity of 50 ab^{-1} (Belle ~710 fb^{-1}, BaBar ~424 fb^{-1})
- Studying B, D and τ physics, hadron spectroscopy and dark-sector searches



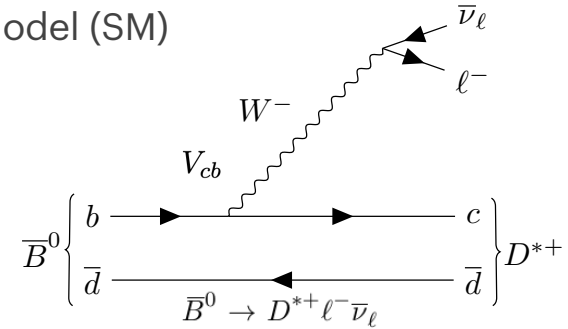






Semileptonic decays

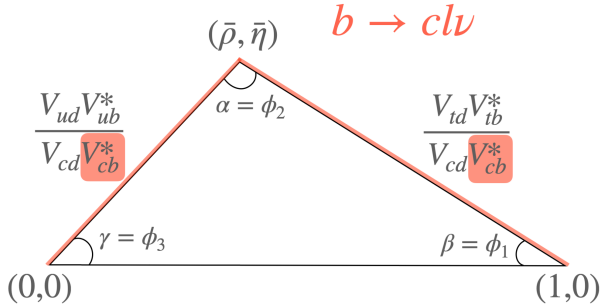
- Decays with 1 or more hadrons, 1 charged lepton l and corresponding neutrinos ν; mediated by the W boson in the Standard Model (SM)



- $b \to c l \nu$ and $b \to u l \nu$ transitions are crucial for the determination of Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix elements
- The ν are inferred as missing energy in our detector

$$V_{\mathrm{CKM}} = \begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



A unitary CKM triangle highlighting $|V_{cb}|$ in $b \to c l \nu$

The Belle II Physics Book arXiv:1808.10567

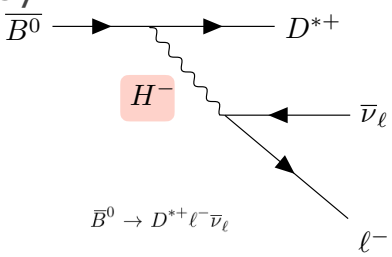
Semileptonic decays

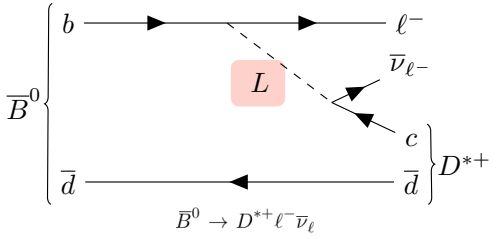
- Measured inclusively $B \to X\ell\nu$ or exclusively $B \to D^*\ell\nu$
- Existing tension between inclusive and exclusive approaches in measurements of $|V_{ub}|$ and $|V_{cb}|$

$$|V_{cb}| = (42.2 \pm 0.8) \times 10^{-3} \text{ (inclusive)}$$
$$|V_{cb}| = (39.5 \pm 0.9) \times 10^{-3} \text{ (exclusive)}$$

(PDG values. Tension of order 3σ)

- Could be sensitive to New Physics
- Full projected Belle II dataset will be key in understanding this tension through examination at higher precision and through accessing other variables





Example models: Two-Higgs Doublet Model and leptoquark model

The Belle II Physics Book arXiv:1808.10567

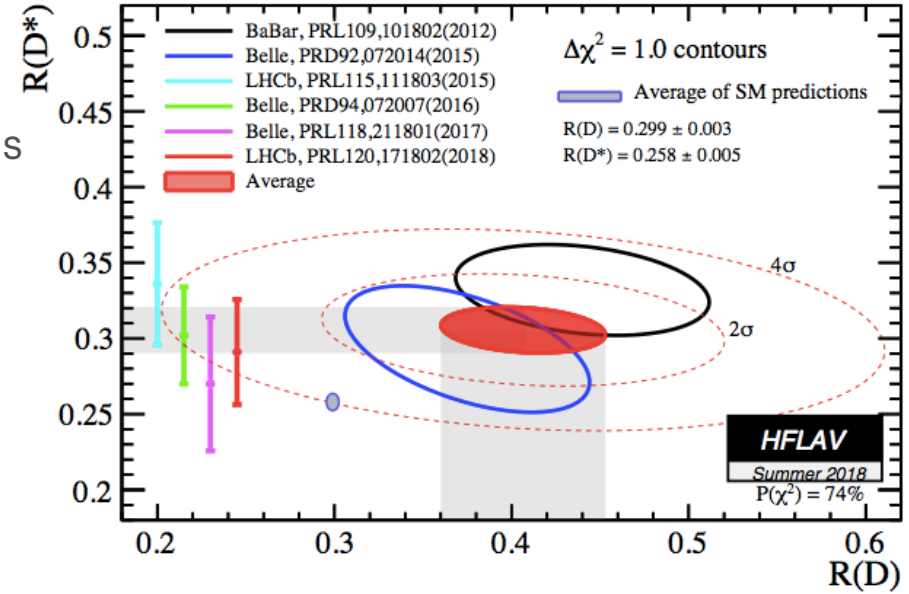
P.A. Zyla *et al.* (Particle Data Group),Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

$R(D^{(*)})$

$$R(D^*) \equiv \frac{\mathcal{B}\left(B \to D^{(*)}\tau^-\bar{\nu}_\tau\right)}{\mathcal{B}\left(B \to D^{(*)}\ell^-\bar{\nu}_\ell\right)}$$

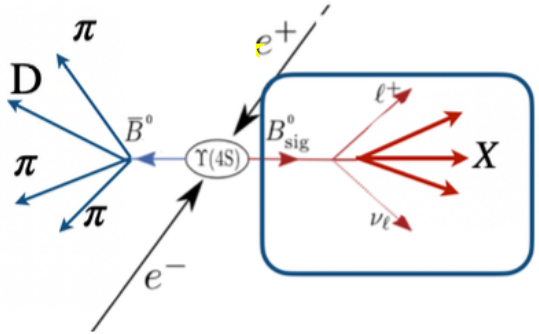
- CKM matrix elements are a significant source of uncertainty in semileptonic branching fraction measurements
- The ratio $R(D^{(*)})$ of the branching fractions cancels various sources of uncertainty! ($|V_{cb}|$ & Hadronic Form Factors)
- A very well defined value in SM, so gives sensitivity to New Physics (2HDMII, leptoquarks,...)

✴ Test of Lepton Flavour Universality



Phys. Rev. D **98**, 030001 (2018)

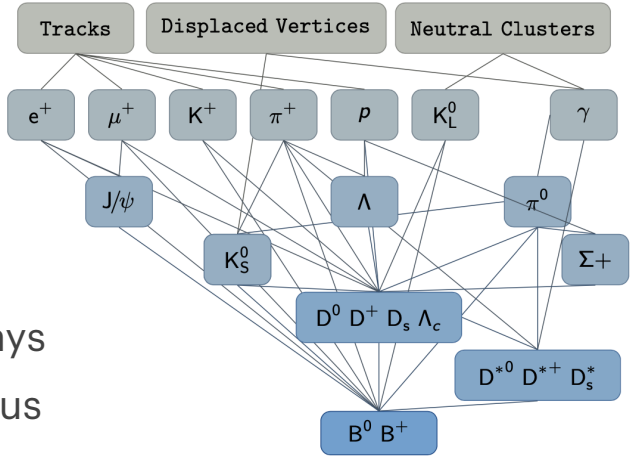
Reconstruction methods



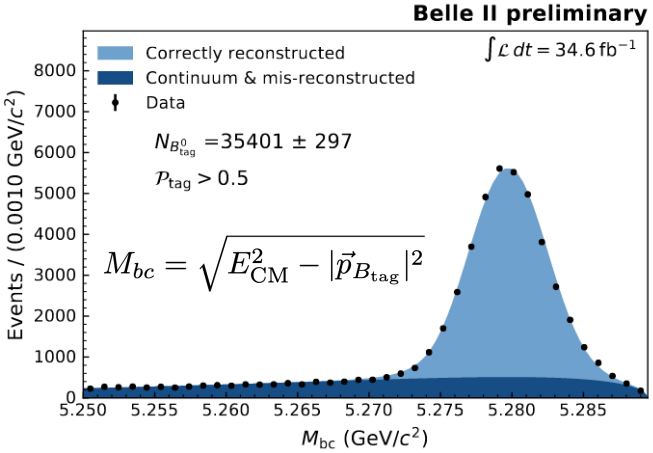
- Untagged approach
  - Signal decay B_{sig} is reconstructed
  - Rest of event is assumed to be the other B
  - Very efficient but low purity
- Tagged approach (semileptonic and hadronic tags)
  - Both B mesons in event are reconstructed: B_{sig} and B_{tag}
  - B_{tag} is exclusively reconstructed using
    - semileptonic decay modes (only partial B_{tag} knowledge)
    - hadronic decay modes (exact knowledge of the B_{tag})
  - Hadronic tagging essential in missing energy measurements

The Belle II Physics Book arXiv:1808.10567

Full Event Interpretation



- A multivariate analysis (MVA) tagging algorithm with a hierarchical approach
- 200+ Boosted Decision Trees (BDT) and 10000+ B decays
- 30-50% improvement in efficiency compared to previous equivalent method at Belle
- FEI calibrated against data to obtain reconstruction efficiencies
- Hadronic FEI calibration strategy is established using $B \to X l \nu$ with subset of data
- Semileptonic FEI calibration and performance studies projected for summer 2022



[The Full Event Interpretation arXiv:1807.08680]
[A Hadronic FEI Calibration arXiv:2008.06096]

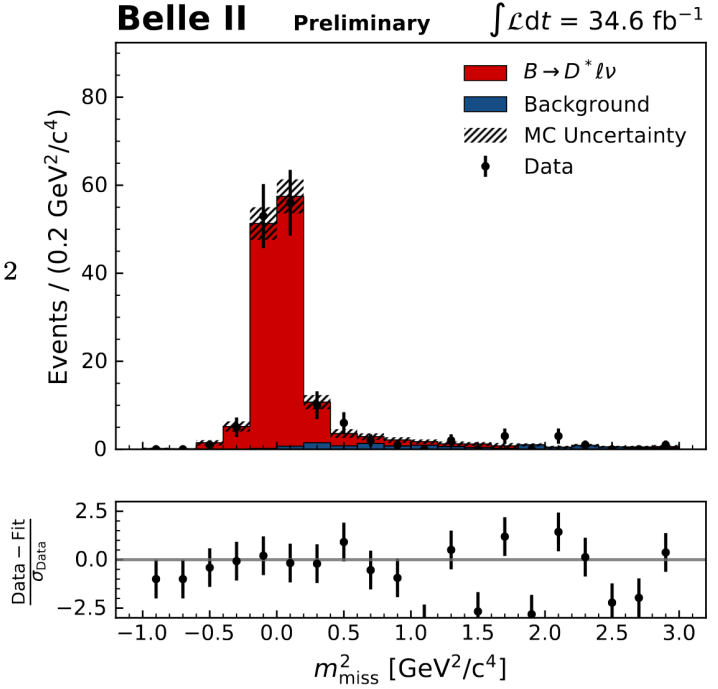
$$\mathcal{B}_{\mathrm{PDG}} = (5.06 \pm 0.12)\,\%$$

Exclusive $\bar{B}^0 \to D^{*+}\ell\bar{\nu}_\ell$

towards $R(D^{(*)})$

- Using hadronic tagged FEI
- With $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$ (golden decay mode)
- Signal extraction via $m^2_{\mathrm{miss}} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D_*} - p_\ell\right)^2$

  $\mathcal{B}\left(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_l\right) = (4.51 \pm 0.41_{\mathrm{stat}} \pm 0.27_{\mathrm{syst}} \pm 0.45_{\pi_s})\,\%$
- Dominant systematics:
  - slow pion efficiency $(D^{*+} \to D^0\pi_s^+)$
  - D^{**} backgrounds
- What's next?



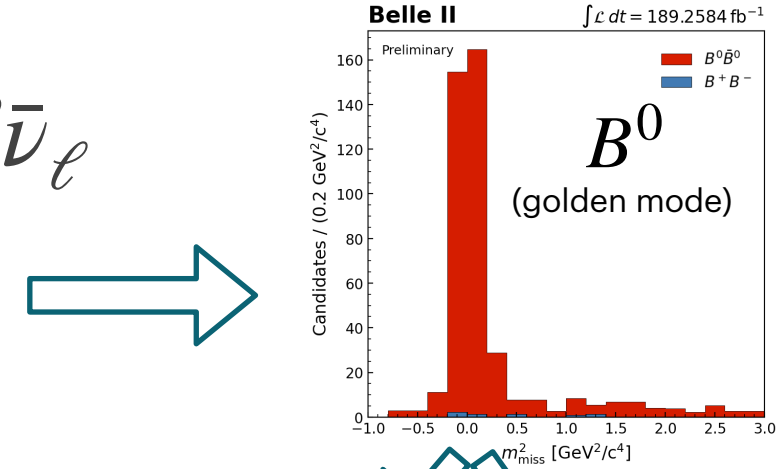
Exclusive B → D* l nu Decay arXiv:2008.10299

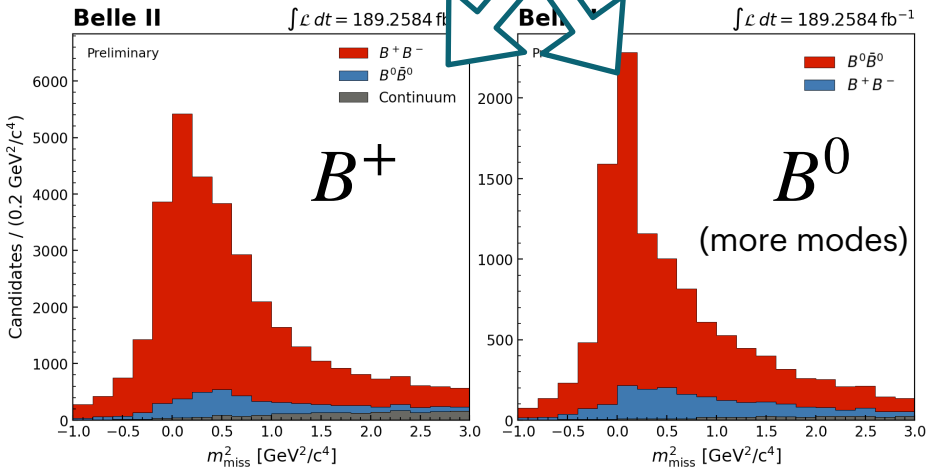
PDG value P.A. Zyla *et al.* (Particle Data Group),Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Exclusive $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$

towards $R(D^{(*)})$

- Study expanded to include more data and modes than just the golden mode.
- MVA in development for D^{**} background, crossfeed and continuum suppression.
- Study replicates and extends from the [BaBar publication](#).
- Generic MC is boosted with $B \to D^{(*)}\ell\nu$, $B \to D^{(*)}\tau\nu$ and $B \to D^{**}\ell\nu$ MC.
- MVA is trained on generator truth level $B \to D^{(*)}\ell\nu$ and $B \to D^{(*)}\tau\nu$ events.

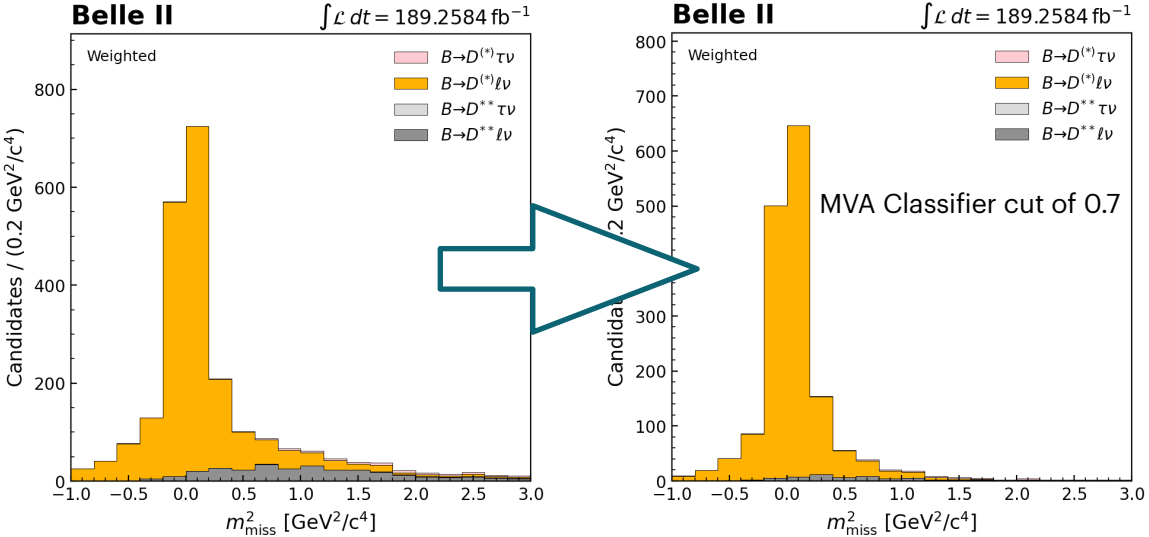


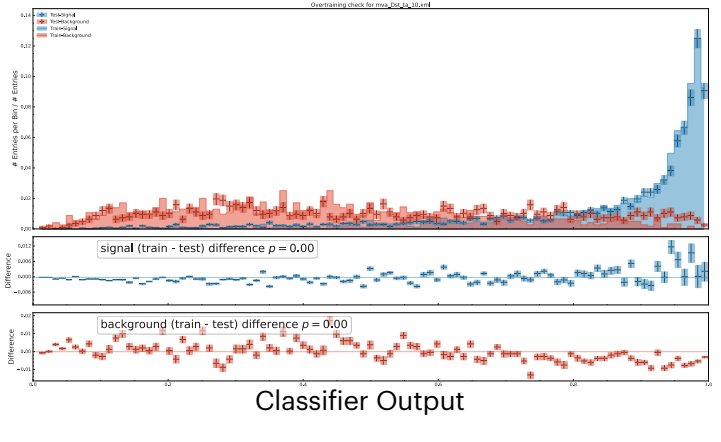


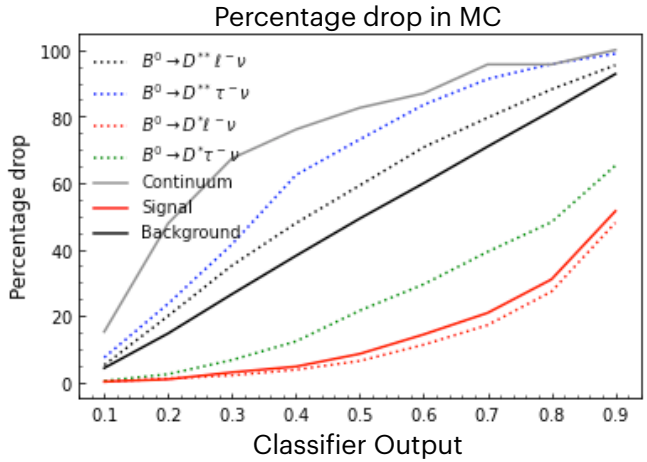
Measurement of an Excess of B -> D(*) Tau Nu Decays and Implications for Charged Higgs Bosons, arXiv:1303.0571v1

Exclusive $\bar{B} \to D^{(*)}\ell\bar{\nu}_\ell$
towards $R(D^{(*)})$

- $B \to D^{**}\ell\nu$ and crossfeed events are suppressed.
- Continuum backgrounds also suppressed.







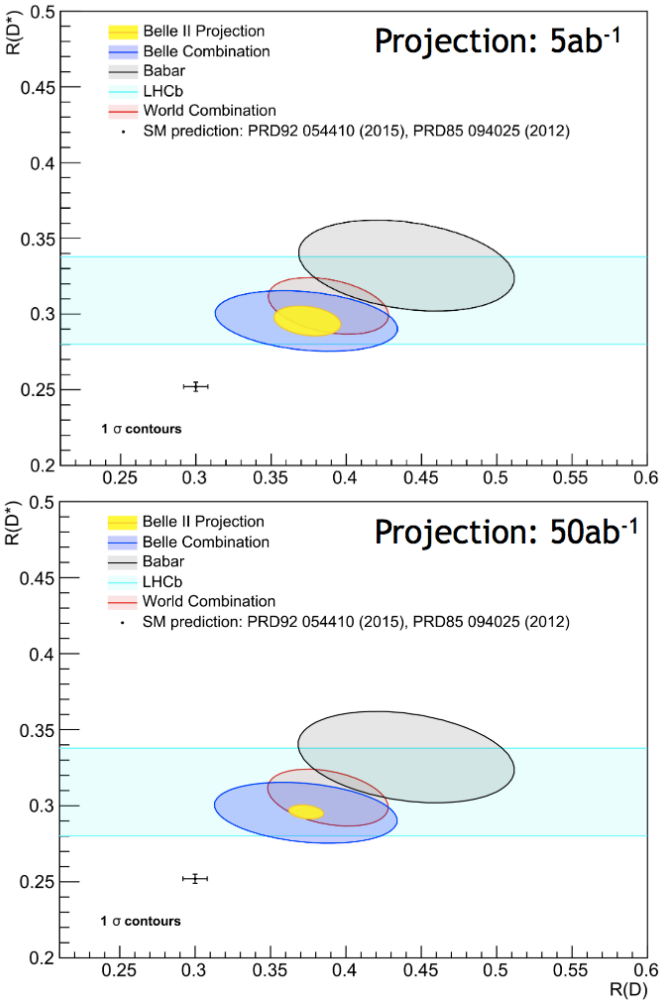
Measurement of an Excess of B -> D(*) Tau Nu Decays and Implications for Charged Higgs Bosons, arXiv:1303.0571v1

$R(D^{(*)})$ at Belle II

- 5σ confirmation of $R(D^{(*)})$ anomalies at 5 ab^{-1}
- Using FEI:

Total Uncertainty	Belle 0.7ab^{-1}	Belle II 5ab^{-1}	Belle II 50ab^{-1}
R(D)	16%	6%	3%
R(D*)	7%	3%	2%

- Aim of first result summer 2022
- Systematic uncertainty is dominated by
  - D** branching fractions
  - Efficiency of slow πs



Summary

- Belle II is an ideal environment in which to study semileptonic decays (with missing energy)
- Full Event Interpretation algorithm developed and calibrated, with improvements in the works
- Investigating the deviation from/consistency with the Standard Model of $B \rightarrow D^{(*)}\tau\nu$ and $R(D^{(*)})$.
- Potentially sensitive to indirect NP effects! Could be resolved with just a few ab^{-1} of data!
- Relevant publications:
  - FEI Calibration arXiv:2008.06096
  - Exclusive $B^0 \rightarrow D^{*+}l^-\nu_l$ arXiv:2008.10299

Stay tuned for more this year!

Belle II

Back-up