

Measurement of $R(D)$ and $R(D^*)$ using semileptonic tagging and leptonic τ decays



Fergus Wilson

On behalf of the BaBar Collaboration

PASCOS 2026, 22nd – 26th June 2026

Outline

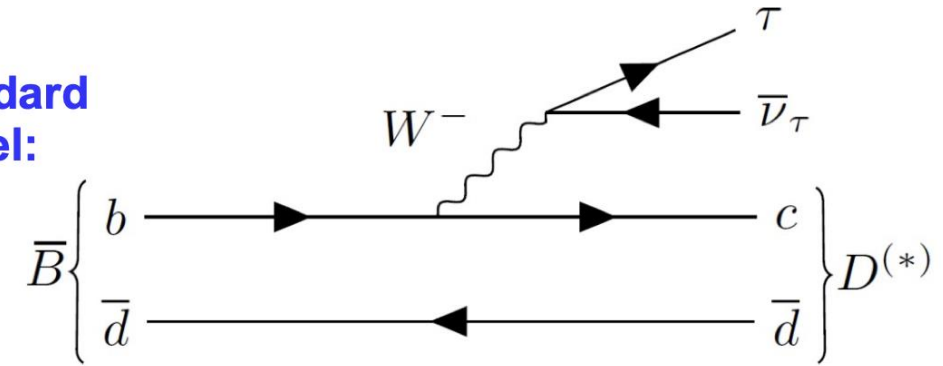
- Introduction.
- Charged Lepton Flavour Universality and definition of $R(D)$ and $R(D^*)$.
- Current status of $R(D)$ and $R(D^*)$ experiment and theory.
- $R(D)$ and $R(D^*)$ measurement at BaBar with semi-leptonic tagging.
- Results and Conclusion.

All plots and results are currently preliminary.

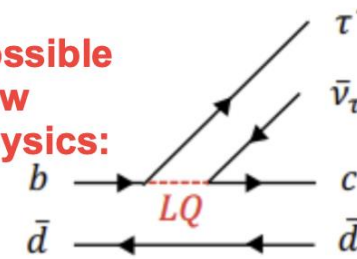
Introduction

- In the Standard Model (SM), the decay $B \rightarrow D^{(*)} l \nu$ proceeds through a tree diagram.
- The W^\pm couples equally to all charged leptons - Charged Lepton Flavour Universality (CLFU).
- Physics Beyond the Standard Model (BSM) could introduce new couplings:
 - If mass-dependent, τ lepton predicted to see largest effect.
- Individual $B \rightarrow D^{(*)} l \nu$ decays suffer from large hadronic uncertainties. Taking a ratio cancels many of the experimental and theoretical uncertainties.

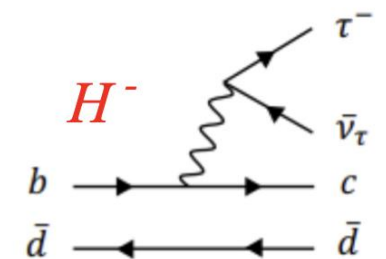
Standard Model:



Possible new physics:



Leptoquark



Charged Higgs

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu})}{\mathcal{B}(\bar{B} \rightarrow D^{(*)} l \bar{\nu})} \quad (l = e, \mu)$$

Signal

Normalization

R(D) and R(D*) status in 2025

- Standard Model predictions:

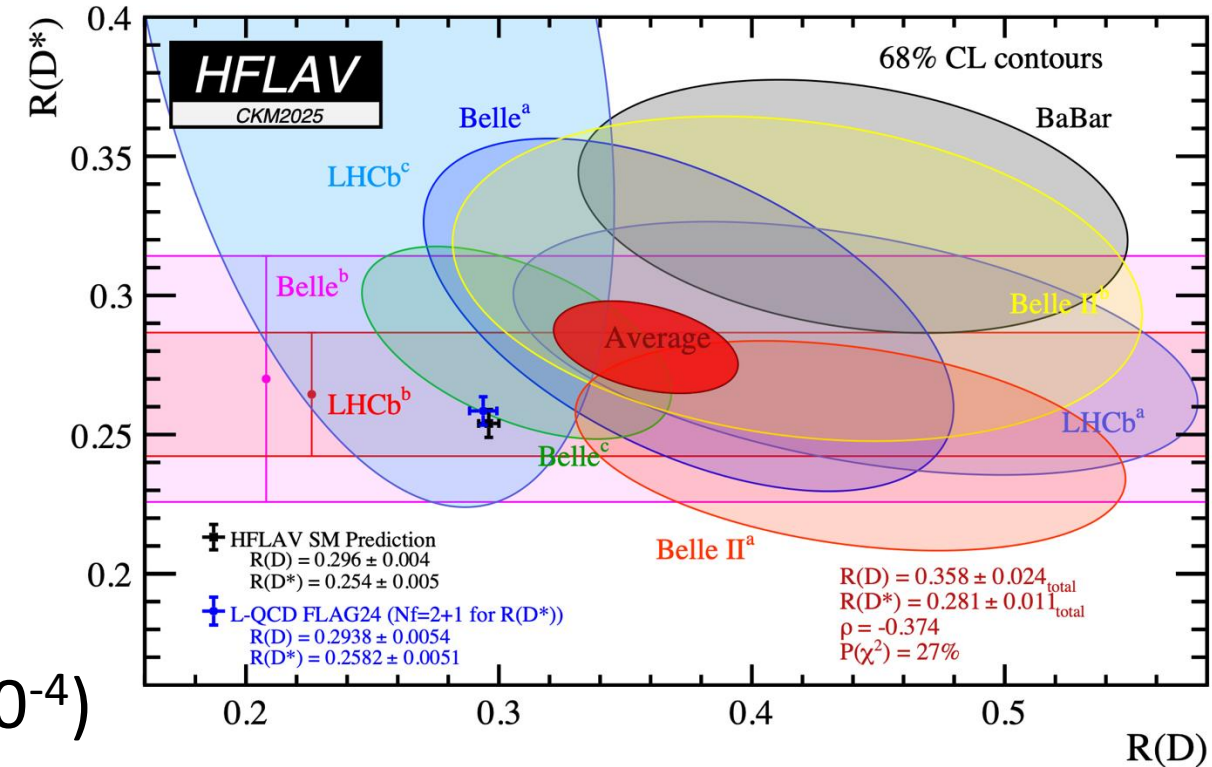
- [HFLAV HQET average](#): $R_{SM}(D) = 0.296 \pm 0.004$ $R_{SM}(D^*) = 0.254 \pm 0.005$
- [L-QCD HFLAG-24](#) $R_{SM}(D) = 0.2938 \pm 0.054$ $R_{SM}(D^*) = 0.2582 \pm 0.0051$

- Experiment measurements ([CKM 2025](#))

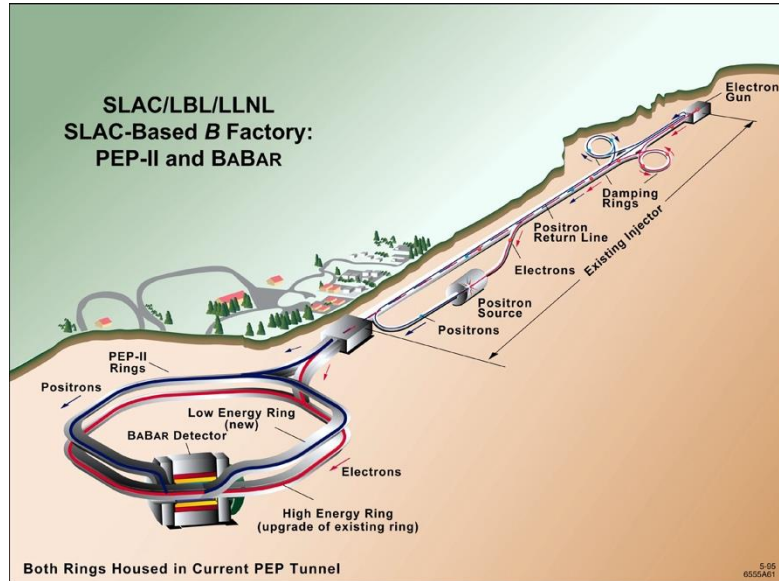
Experiment	R(D*)	R(D)	Correlation	Publication/Year
BaBar	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$	-0.45 ± 0.27	PRL 109, 101802 (2012)
Belle ^a	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$	-0.56 ± 0.49	PRD 92, 072014 (2015)
Belle ^b	$0.270 \pm 0.035^{+0.028}_{-0.025}$			PRL 118, 211801 (2017)
Belle ^c	$0.283 \pm 0.018 \pm 0.014$	$0.307 \pm 0.037 \pm 0.016$	-0.53 ± 0.51	PRL 124, 161803 (2020)
LHCb ^a	$0.281 \pm 0.018 \pm 0.024$	$0.441 \pm 0.060 \pm 0.066$	-0.49 ± 0.43	PRL 131, 111802 (2023)
LHCb ^b	$0.267 \pm 0.012 \pm 0.019$			PRD 108, 012018 (2023)
LHCb ^c	$0.402 \pm 0.081 \pm 0.085$	$0.248 \pm 0.043 \pm 0.047$	-0.48 ± 0.39	PRL 134, 061801 (2025)
Belle II ^b	$0.306 \pm 0.034 \pm 0.018$	$0.418 \pm 0.074 \pm 0.051$	-0.27 ± 0.22	PRD 112, 032010 (2025)
Belle II ^a	$0.242 \pm 0.018 \pm 0.016$	$0.429 \pm 0.055 \pm 0.046$	-0.40 ± 0.20	CKM 2025
Average	0.281 ± 0.011	0.358 ± 0.024	-0.374	

- Average*: $R(D) = 0.358 \pm 0.024$
 $R(D^*) = 0.281 \pm 0.011$

- Tension with SM 3.8σ (p-value = 1.48×10^{-4})

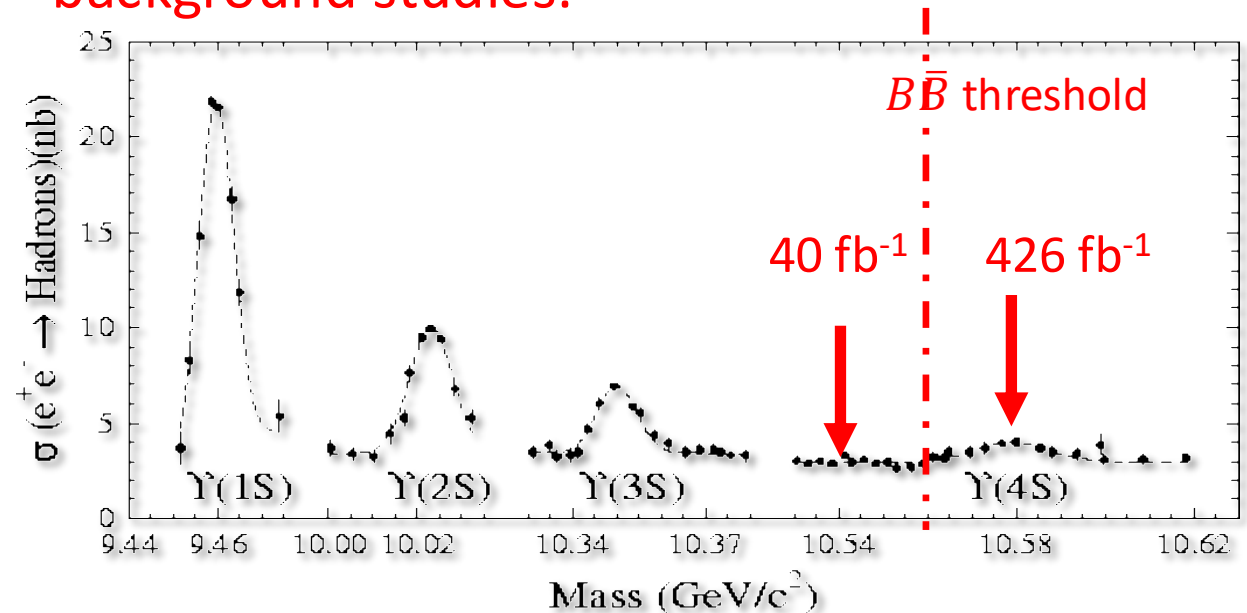
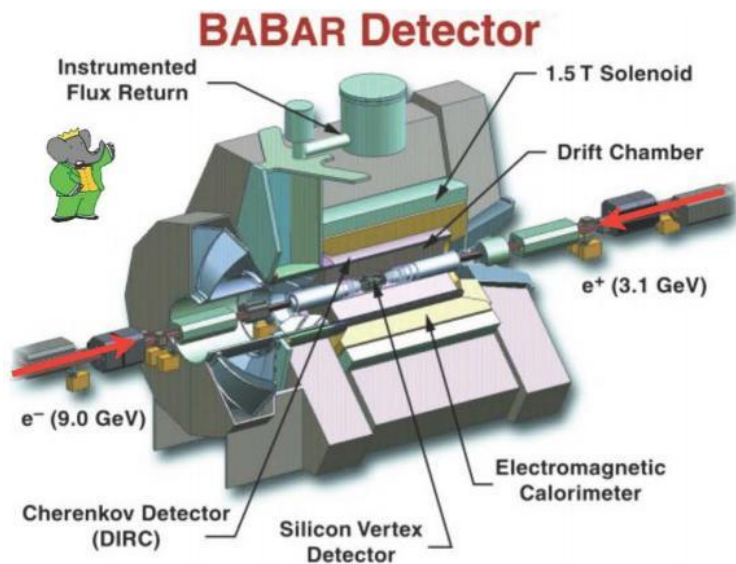


BaBar Detector at SLAC PEP-II: 1999 – 2008



- Asymmetric beam: Mostly 3.1 GeV e^+ on 9.0 GeV e^- at $\Upsilon(4S)$ resonance:

- $\Upsilon(4S) \rightarrow B\bar{B}$ pair is major decay process
- “On-peak”: 426 fb^{-1} ($\sim 471 \times 10^6 B\bar{B}$ pairs)
- “Off-peak” : 40 fb^{-1} 40 MeV below $\Upsilon(4S)$ for background studies.

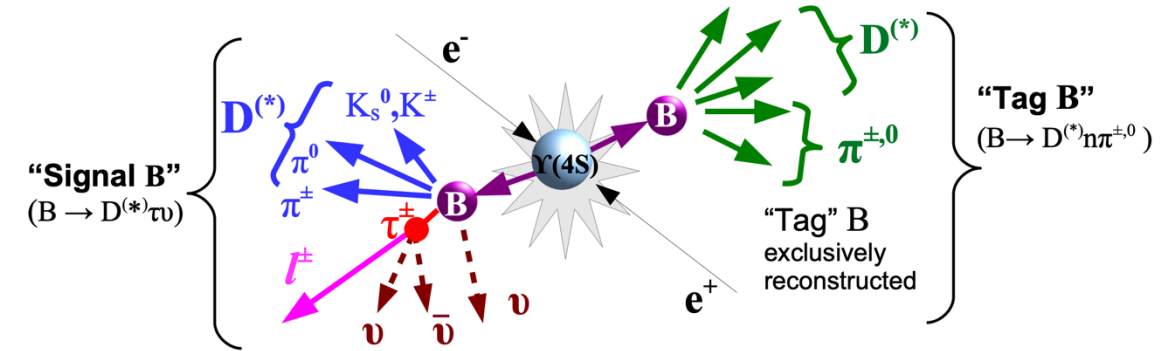


- One of the first HEP experiments to think seriously about data and software preservation.

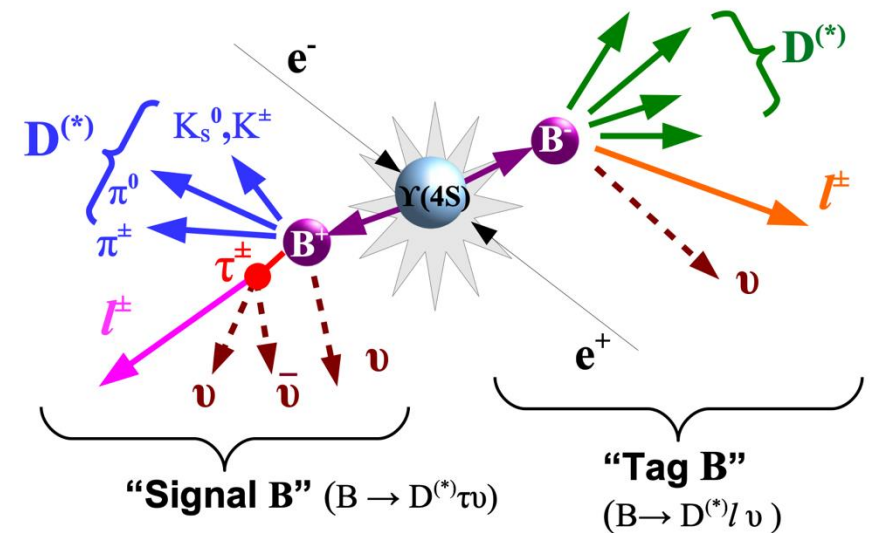
Analysis Strategy: “Tagging” at BaBar

- A blinded analysis (signal data region is opened when analysis strategy is complete).
- Tag one B meson through semi-leptonic decays (B_{tag}) and one B meson as signal (B_{sig}).
- Hadronic tagging required $O(10^3)$ exclusive hadronic decays. (See earlier “BaBar” result on earlier [slide](#)).
- In this analysis, semi-leptonic tagging uses only 3 D^* and 10 D decays.
- The BaBar hadronic and semi-leptonic tagged samples are statistically independent.

“Hadronic” Tagging: previous BaBar results



“Semi-leptonic” Tagging: this result



Event Classification

1. Signal:

- D event: $B_{tag} \rightarrow \bar{D}^{(*)} l \nu$, $\bar{B}_{sig} \rightarrow D \tau \nu$; $\tau \rightarrow e, \mu + 2\nu$
- D* event: $B_{tag} \rightarrow \bar{D}^* l \nu$, $\bar{B}_{sig} \rightarrow D^* \tau \nu$; $\tau \rightarrow e, \mu + 2\nu$

B_{sig} decays reconstructed in 4 “subsets”:

$$D^+ \ell^-, D^{*+} \ell^-, D^0 \ell^-, D^{*0} \ell^-$$

2. Normalization:

- D event: $B_{tag} \rightarrow \bar{D}^{(*)} l \nu$, $\bar{B}_{sig} \rightarrow D l \nu$
- D* event: $B_{tag} \rightarrow \bar{D}^{(*)} l \nu$, $\bar{B}_{sig} \rightarrow D^* l \nu$

$$R(D^{(*)}) = \frac{BF(\bar{B} \rightarrow D^{(*)} \tau \bar{\nu})}{BF(\bar{B} \rightarrow D^{(*)} l \bar{\nu})}$$

3. D^{**} background: At least one $B \rightarrow D^{**}(l, \tau) \nu$ decay, where D^{**} is any excited charmed meson not in ground state 1S doublet e.g. includes 1P states D_0^*, D_1, D_1', D_2^* ; 2S states; and non-resonant states $D^{(*)} \pi$

4. Other backgrounds:

- Combinatorial $B\bar{B}$: any $B\bar{B}$ decay not selected as signal, normalization or D^{**} .
- Continuum: non- $B\bar{B}$ events $e^+ e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$.

Simulation

- Simulation is used to calculate reconstruction efficiencies and distribution of observables for selection criteria and classifiers.
- Simulation at BaBar is very well understood (EvtGen+JetSet+Geant4):
 - Simple initial state; clean events; only one primary vertex; no pileup; typically ~ 5 charged/ ~ 5 neutral particles in a BB event; trigger threshold is a step function.
- However, there are large uncertainties in hadronic decays, so simulation uses form factor (FF) models:
 - There are different models available e.g. [CLN](#), [BGL](#), [ISGW](#), [LLSW](#), [linear \$q^2\$](#) , ...
 - All model parameters come with uncertainties.
 - Different decay simulation e.g. D^* and D^{**} use different models.
- Some PDG branching fractions have changed in the last ~ 25 years.
- We deal with this by:
 - Reweighting events by different FF models and repeating analysis.
 - Reweighting events by FF parameter uncertainties and repeating analysis.
 - Reweighting events by latest PDG branching fractions + uncertainties and repeating analysis.
 - We can compare simulation with data in the on-peak sidebands or off-peak data; any discrepancies can be used to reweight the simulation in the on-peak region.

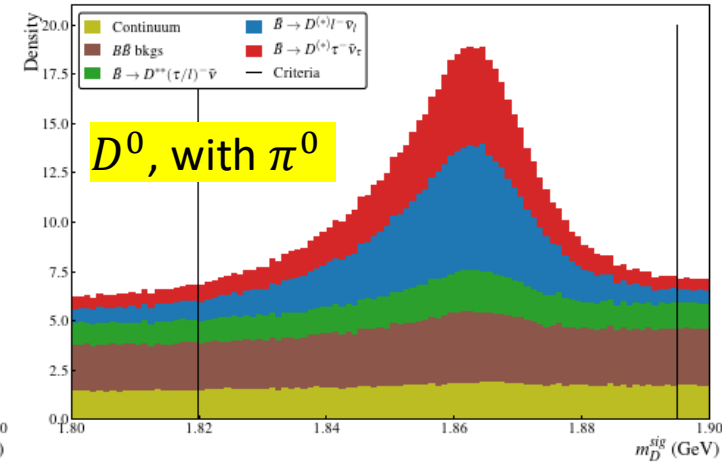
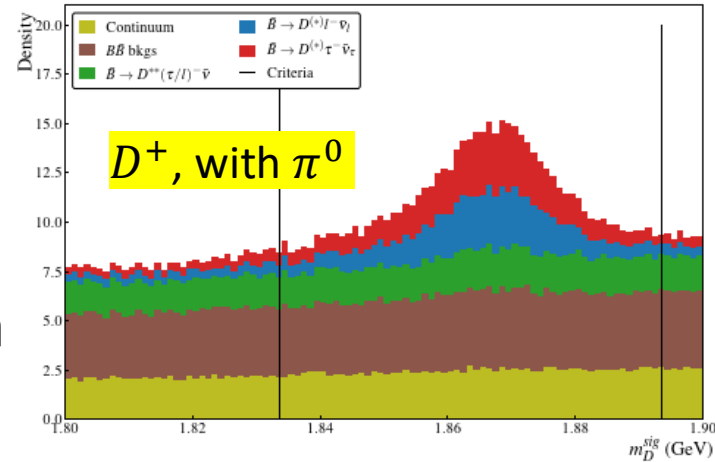
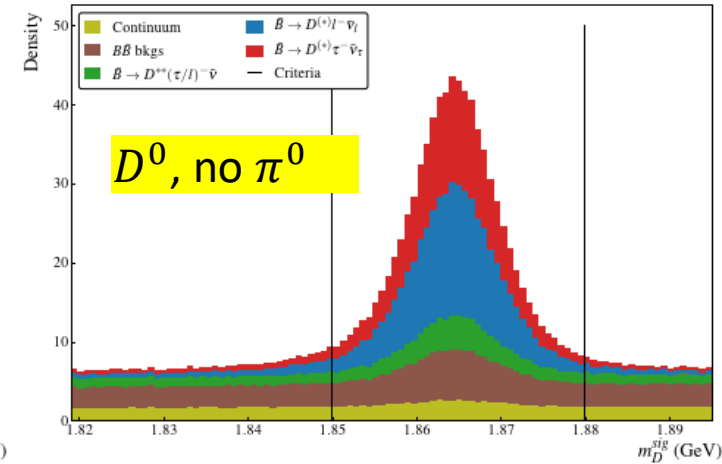
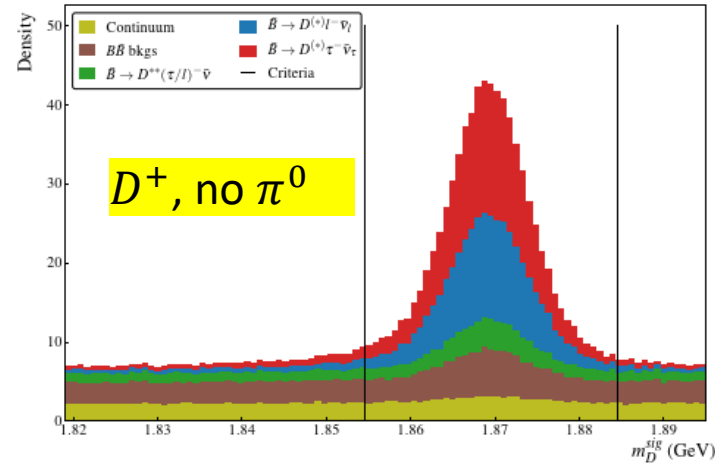
D^+ and D^0 selection

- Reconstruct 4 D^+ and 6 D^0 decay modes:

Decay Modes	Branching Fraction (%)
$D^+ \rightarrow K^- \pi^+ \pi^+$	9.46 ± 0.24
$D^+ \rightarrow K_S \pi^+$	1.53 ± 0.06
$D^+ \rightarrow K_S \pi^+ \pi^0$	7.24 ± 0.17
$D^+ \rightarrow K^- K^+ \pi^+$	0.99 ± 0.026
$D^0 \rightarrow K^- \pi^+$	3.88 ± 0.05
$D^0 \rightarrow K^- \pi^+ \pi^0$	14.3 ± 0.80
$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	8.06 ± 0.23
$D^0 \rightarrow K_S \pi^+ \pi^-$	2.85 ± 0.20
$D^0 \rightarrow K_S \pi^0$	1.20 ± 0.04
$D^0 \rightarrow K^- K^+$	0.40 ± 0.007

~20%

~30%



$$|m_D - \text{PDG}| \in \begin{cases} [-15, 15] \text{ MeV,} & \text{no } \pi^0 \\ [-45, 30] \text{ MeV,} & D^0 \rightarrow \pi^0 \\ [-36, 24] \text{ MeV,} & D^+ \rightarrow \pi^0 \end{cases}$$

- Other D^{+0} decays have higher backgrounds or lower reconstruction efficiencies.

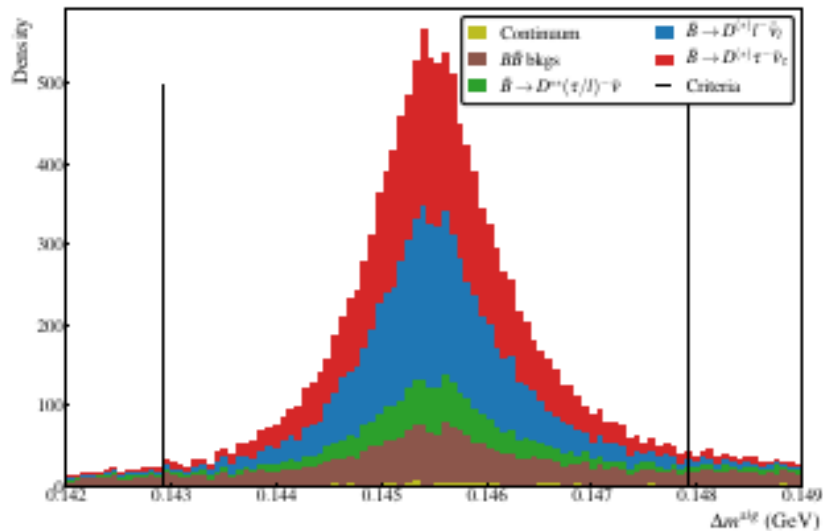
D^* selection

- D^* reconstruction through 3 modes:

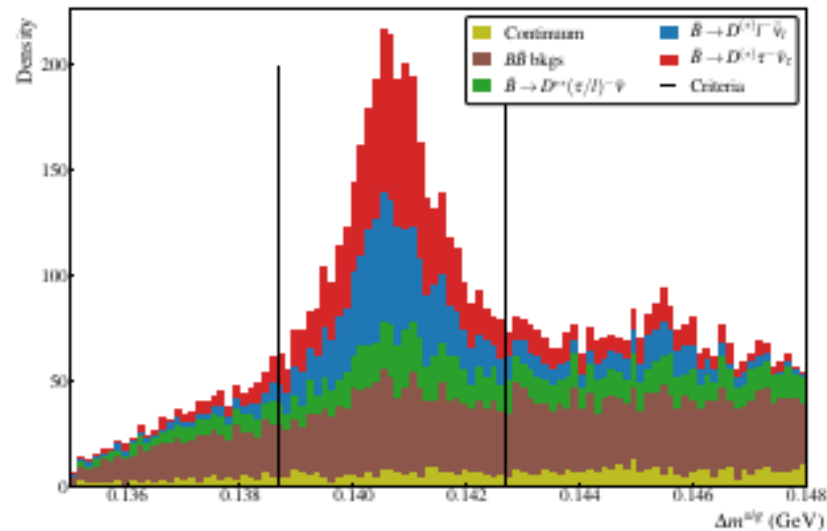
- $D^{*+} \rightarrow D^0\pi^+, D^+\pi^0$
- $D^{*0} \rightarrow D^0\pi^0$

$$|m_{D^*} - m_D - \text{PDG}| < \begin{cases} 2.5 \text{ MeV}, & D^0\pi^+ \\ 2.0 \text{ MeV}, & D\pi^0 \end{cases}$$

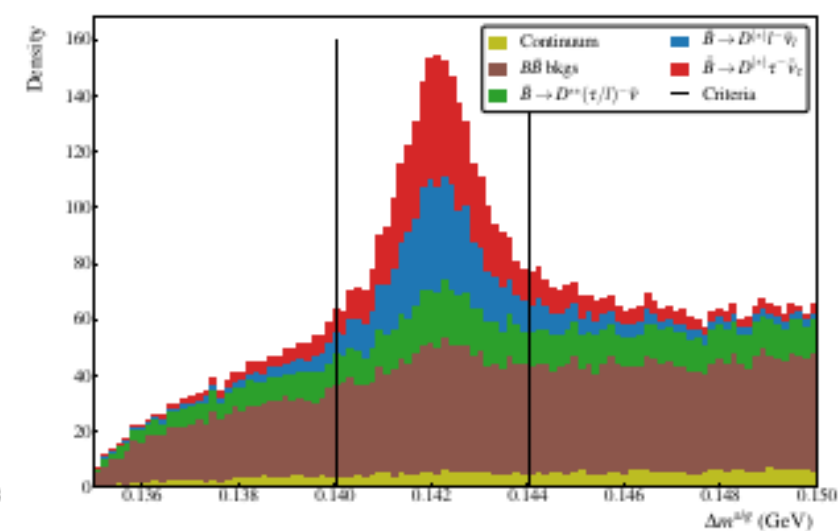
$D^{*+} \rightarrow D^0\pi^+$



$D^{*+} \rightarrow D^+\pi^0$



$D^{*0} \rightarrow D^0\pi^0$



$\Upsilon(4S) \rightarrow B_{tag} \bar{B}_{sig}$ selection

- B_{tag} decay modes:

- $m(D^{(*)}lv) < 5.28 \text{ GeV}$ + reconstructed B -vertex quality criteria.

- Expect to have $\cos(\Theta_{B-D^{(*)}l}^{tag})$ in range $[-2,1]$ where: $\cos(\Theta_{B-D^{(*)}l}^{tag}) = \frac{2E_{beam}E_{D^{(*)}lv} - M_B^2 - m_{D^{(*)}lv}^2}{2|p_B||p_{D^{(*)}lv}|}$

- \bar{B}_{sig} decay modes:

- Search among remaining tracks and calorimeter clusters for $D^{(*)}l$.

- $m(D^{(*)}lv) < 5.28 \text{ GeV}$ + reconstructed B vertex quality criteria.

- $\cos(\Theta_{B-D^{(*)}l}^{sig}) < 1$

- $\Upsilon(4S)$:

- Combine B_{tag} and \bar{B}_{sig} conserving charge. No extra charged tracks, K_S^0 or π^0 particles.

- Extra (unassigned) neutral energy $E_{extra} < 1.2 \text{ GeV}$.

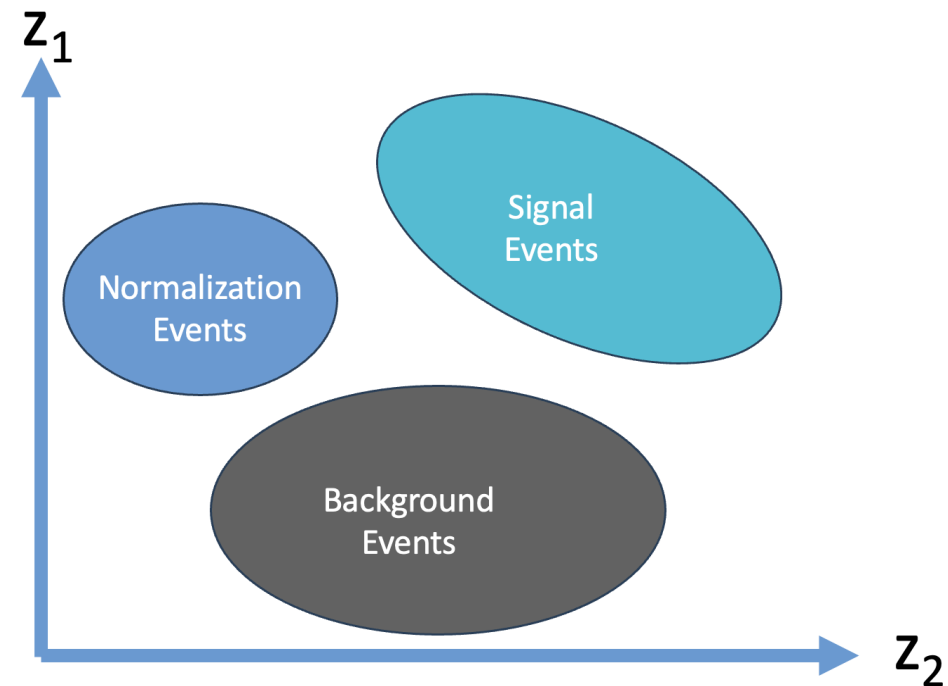
- Second Fox-Wolfram moment $R_2 < 0.4$

- \bar{B}_{sig} lepton daughter 3-momenta in Center-of-Mass (CM) frame $|p_l^{sig}| \leq 2 \text{ GeV}$.

- Allocate to 4 \bar{B}_{sig} subsets: $B^+ \rightarrow \bar{D}^0 l^+$; $B^0 \rightarrow D^- l^+$; $B^+ \rightarrow \bar{D}^{*0} l^+$; $B^0 \rightarrow D^{*-} l^+$

Signal Extraction strategy

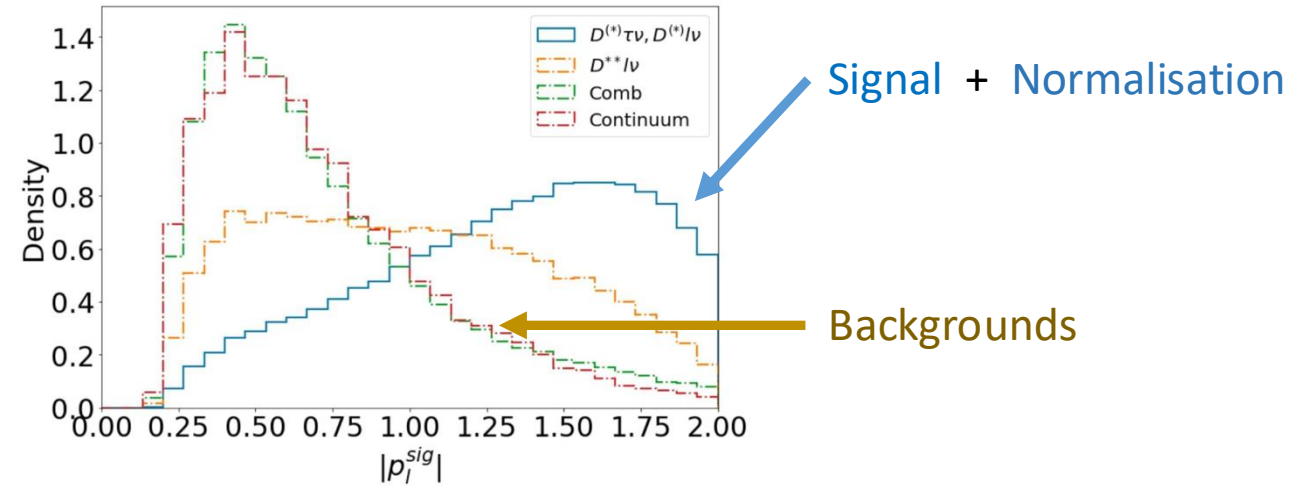
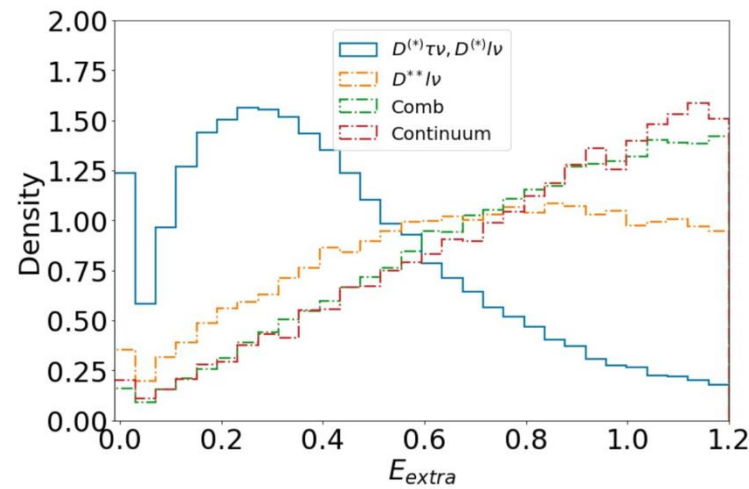
- Train two binary classifiers C_1 and C_2 to generate scores z_1 and z_2 for each event:
 - C_1 : Normalization+Signal v. Background events
 - C_2 : Signal v. Normalization events.
- Gradient Boosting Decision Tree (BDT) from *scikit-learn*.
- Classifier observables are chosen based on their importance to the discrimination.
- Create a 2-dimensional density function $f(z_1, z_2)$ by fitting z_1, z_2 distributions with a **non-parametric Kernel Density Estimator (KDE)**.
- Extract data yields with Maximum Likelihood fit to $f(z_1, z_2)$ in each subset and with $N=6$ event classes:
 - $D^{(*)}$ signal, $D^{(*)}$ signal cross-feed, $D^{(*)}$ normalisation, $D^{(*)}$ normalisation cross-feed, D^{**} , and “other backgrounds”.



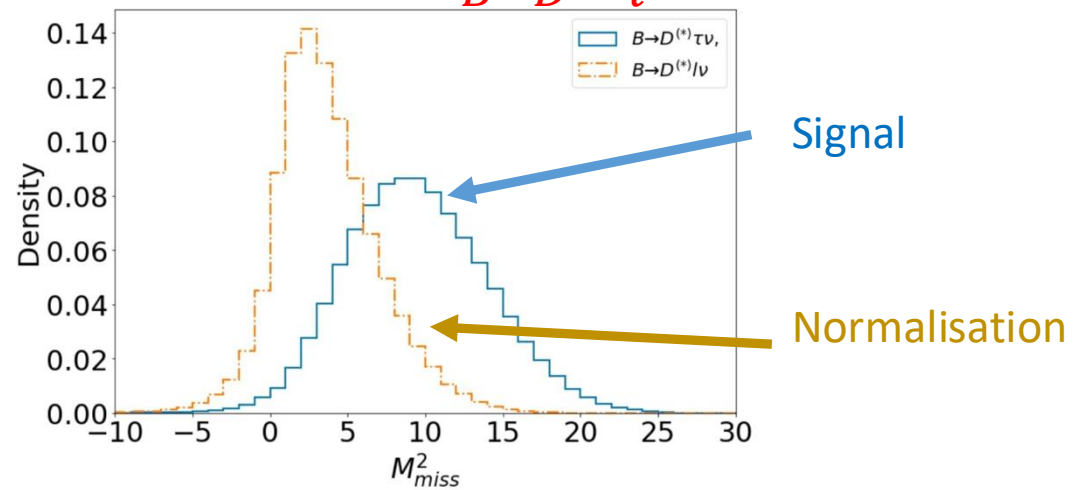
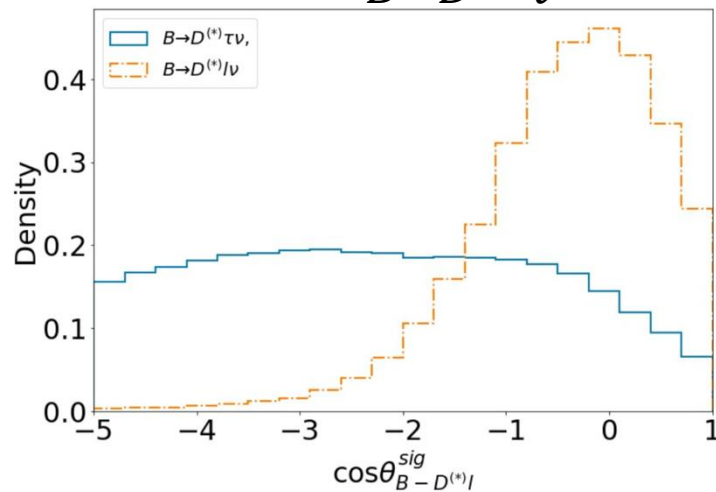
$$Prob(z_1, z_2) = \sum_{j=1}^N p_j f_j(z_1, z_2)$$

Classifier input: example. observables

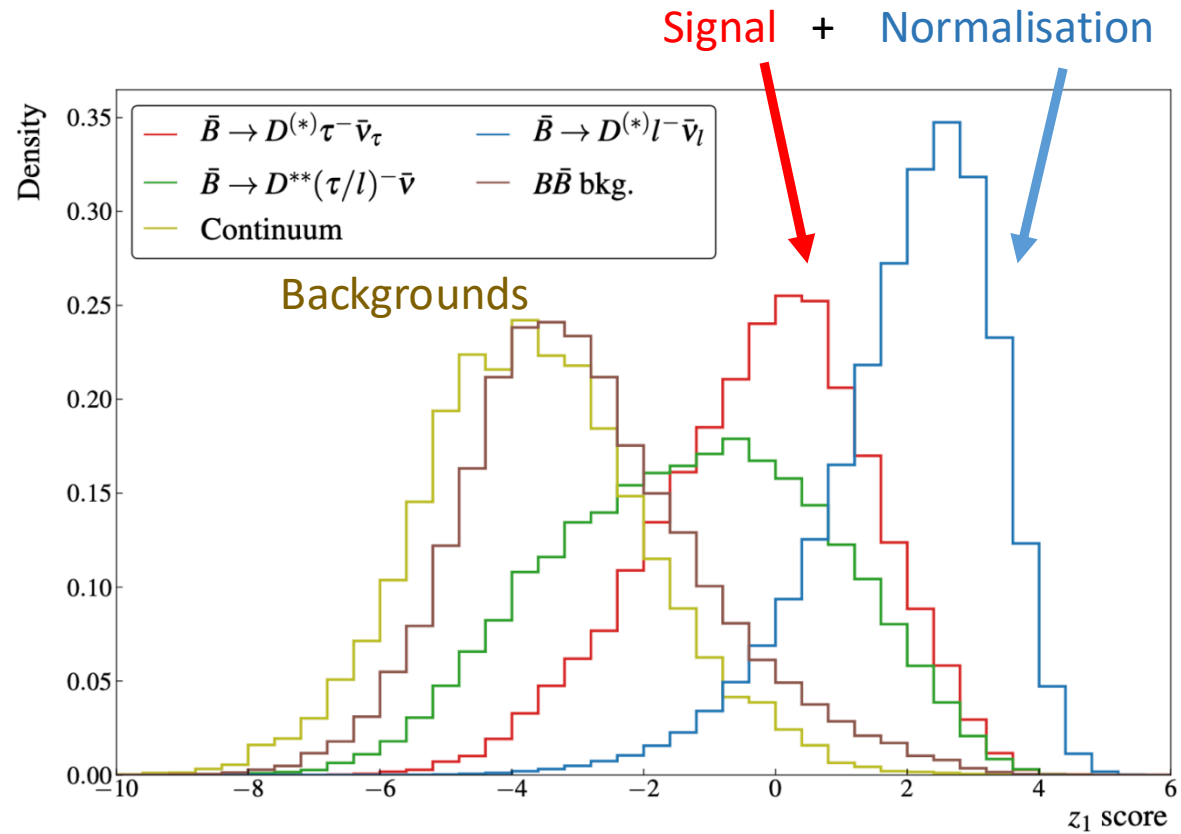
C_1 : 24 observables. Most important: E_{extra} and signal-side lepton momentum $|p_l^{sig}|$



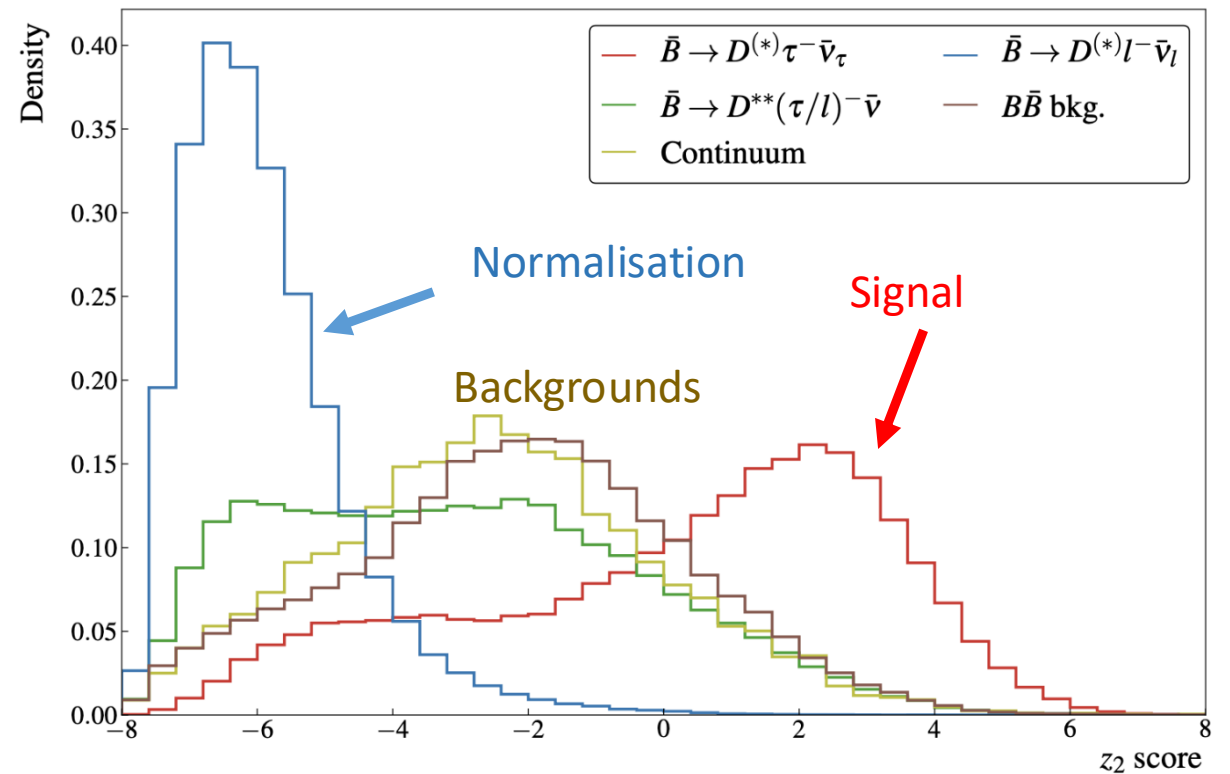
C_2 : C_1 observables + $\cos\theta_{B-D^{(*)}l}^{sig}$: Most important: $\cos\theta_{B-D^{(*)}l}^{sig}$ and M_{miss}^2



Classifier output: Boosted Decision Tree

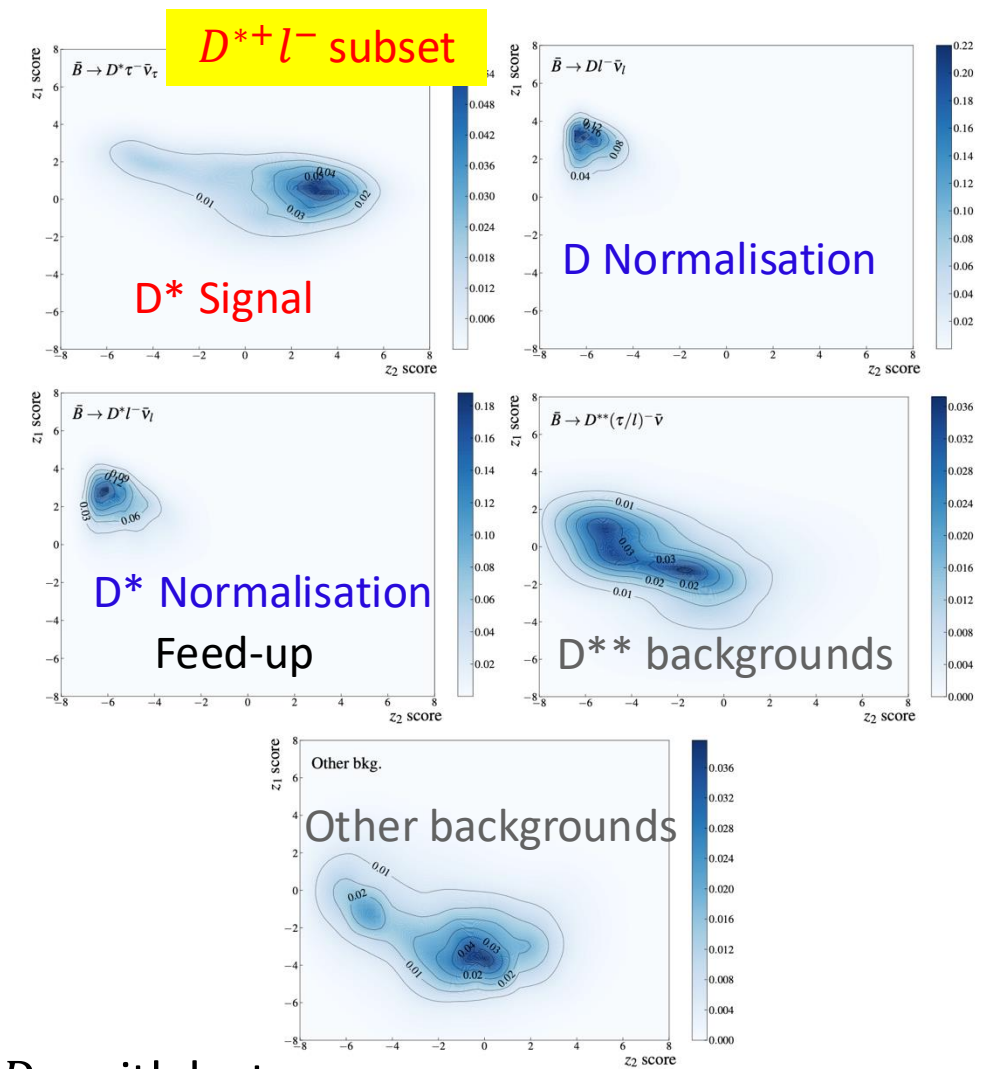
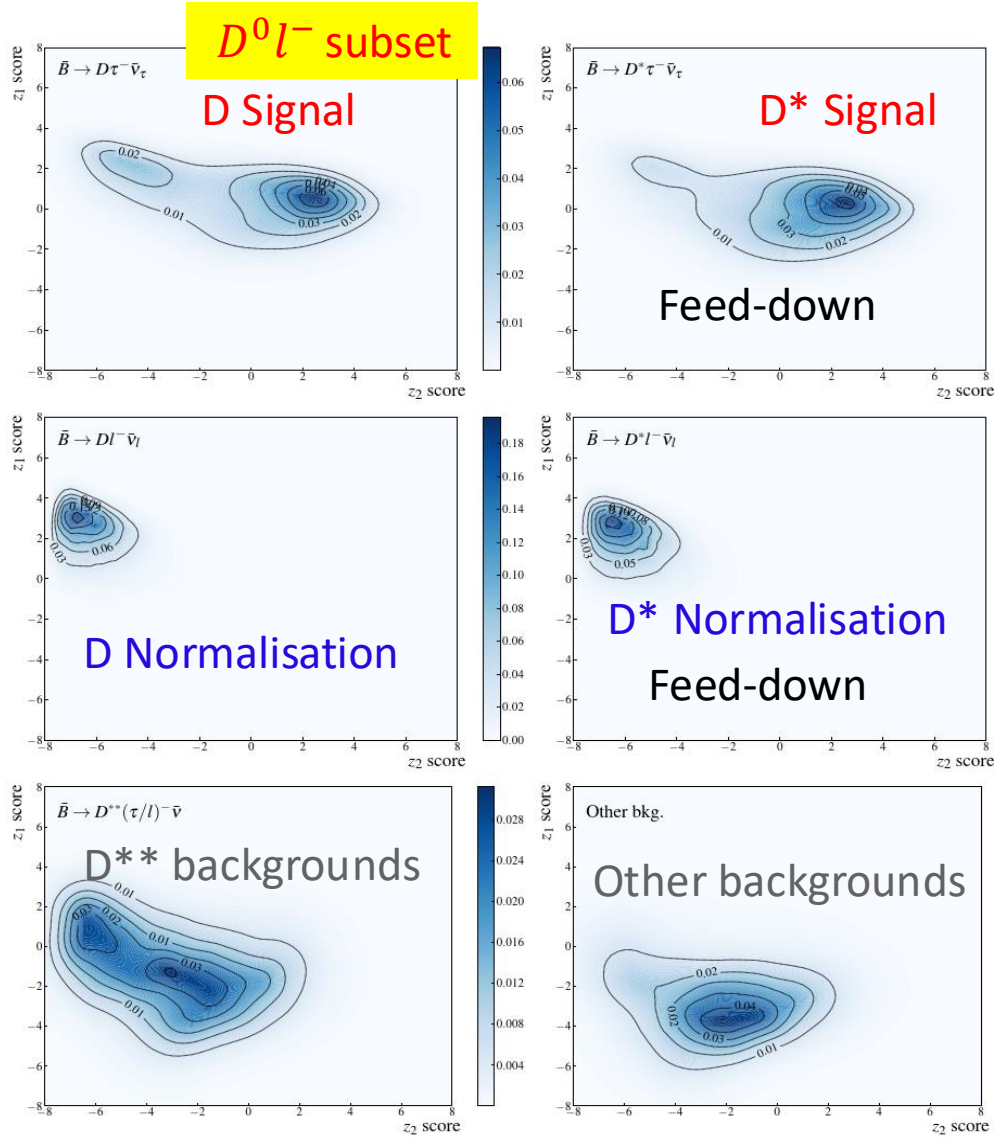


C_1 Classifier



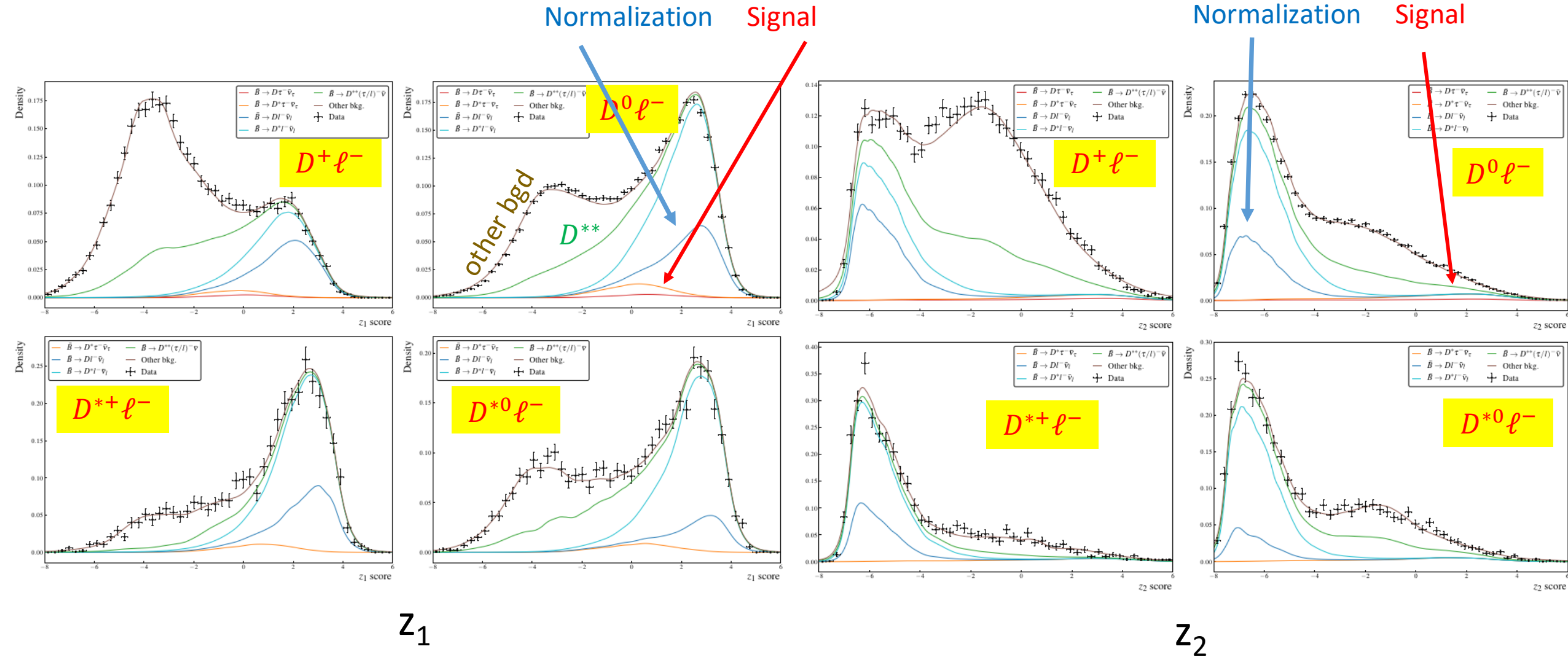
C_2 Classifier

Two-dimensional KDE Probability Density Functions (PDFs)



Feed-down: $D^* \rightarrow D\pi$ with lost π
 Feed-up: D plus random π to form D^*

Classifier projections z_1 and z_2 for fitted data



Measured Yields and Ratio Formulae

- Extract event yields y_j with Maximum Likelihood fit to $f(z_1, z_2)$ in 4 B_{sig} subsets and up to 6 event classes.
- No constraints on feed-up/feed-down between D and D^* channels or background yields.
- Overall yield \hat{N} calculated by combining y_j scaled by reconstruction efficiency to calculate $R(D^{(*)})$.

$$R(D) = \frac{1}{\mathcal{B}(\tau \rightarrow \text{leptons})} \cdot \frac{\hat{N}(\text{signal } D)}{\sqrt{\hat{N}(\text{norm } D) + \hat{N}(\text{norm } D^*)} \cdot \left(\sqrt{\hat{N}(\text{norm } D) + \hat{N}(\text{norm } D^*)} - \sqrt{\hat{N}(\text{norm } D^*)} \right)}$$

$$R(D^*) = \frac{1}{\mathcal{B}(\tau \rightarrow \text{leptons})} \cdot \frac{\hat{N}(\text{signal } D^*)}{\sqrt{\hat{N}(\text{norm } D) + \hat{N}(\text{norm } D^*)} \cdot \sqrt{\hat{N}(\text{norm } D^*)}}$$

Subset	Component	Extracted Yield
D^{+l}	$B \rightarrow D\tau\nu$	117 ± 44
	$B \rightarrow D^*\tau\nu$	191 ± 57
	$B \rightarrow Dl\nu$	1965 ± 110
	$B \rightarrow D^*l\nu$	1261 ± 146
	$B \rightarrow D^{**}l\nu$	3248 ± 233
	Other Bkgs	7258 ± 182
D^{0l}	$B \rightarrow D\tau\nu$	726 ± 273
	$B \rightarrow D^*\tau\nu$	2452 ± 285
	$B \rightarrow Dl\nu$	12012 ± 555
	$B \rightarrow D^*l\nu$	22808 ± 648
	$B \rightarrow D^{**}l\nu$	15594 ± 445
	Other Bkgs	22065 ± 307
D^{*+l}	$B \rightarrow D^*\tau\nu$	110 ± 17
	$B \rightarrow Dl\nu$	614 ± 127
	$B \rightarrow D^*l\nu$	1246 ± 139
	$B \rightarrow D^{**}l\nu$	292 ± 54
	Other Bkgs	665 ± 42
D^{*0l}	$B \rightarrow D^*\tau\nu$	175 ± 25
	$B \rightarrow Dl\nu$	479 ± 126
	$B \rightarrow D^*l\nu$	2154 ± 149
	$B \rightarrow D^{**}l\nu$	1387 ± 101
	Other Bkgs	1415 ± 70

$$\mathcal{B}(\tau \rightarrow \text{leptons}) = \mathcal{B}(\tau \rightarrow e\bar{\nu}_e\nu_\tau) + \mathcal{B}(\tau \rightarrow \mu\bar{\nu}_\mu\nu_\tau)$$

$$= (35.24 \pm 0.05)\%$$

Systematic Uncertainties

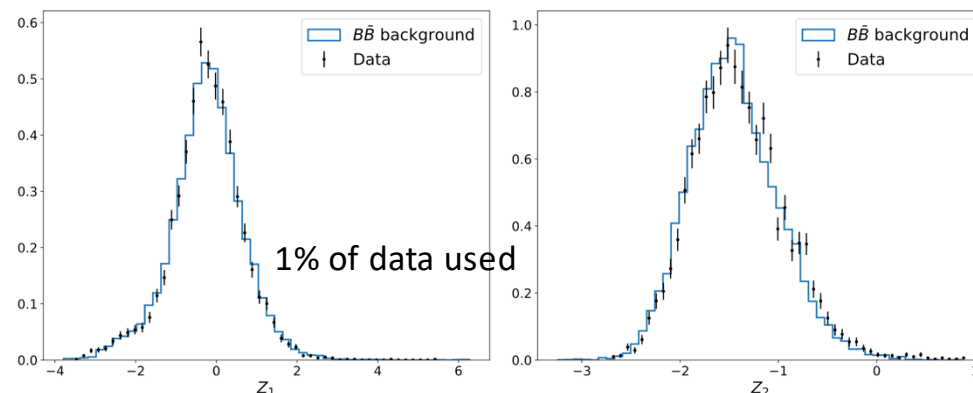
Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \rightarrow Dl\nu$ form factor	0.42	0.13	-0.18
$B \rightarrow D^*l\nu$ form factor	0.92	0.31	-0.19
$B \rightarrow D^{**}l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \rightarrow D^{(*)}l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \rightarrow c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \rightarrow D^{**}l\nu)$	2.83	1.60	-0.97
$\mathcal{B}(D)$	0.84	0.70	-0.40
PDF shapes MC statistics	4.12	4.37	-0.15
On-peak background calibration	2.45	0.44	-0.05
$\mathcal{B}(\Upsilon(4S))$	0.48	0.43	1
PID efficiency	0.29	0.40	1
Soft π^0 efficiency	0.84	1.25	1
$\mathcal{B}(\tau \rightarrow l^-\bar{\nu}_l\nu_\tau)$	0.16	0.16	1
Systematic Total	5.86	4.96	-0.20
Statistical Uncertainty	19.8	9.9	-0.92
Total	20.65	11.07	-0.82

Reweight 1P states by PDG uncertainties.
 Add 1.5% 2S inclusive states to exclusive sample.
 Vary non-resonant $\mathcal{B}(B \rightarrow D^{**}l\nu)$ by $\pm 10\%$.

Limited simulation statistics in each subset after reconstruction. Resample distributions using bootstrap method.

Use difference in on-peak sideband data and off-peak data to reweight simulated background z_1 and z_2 distributions.

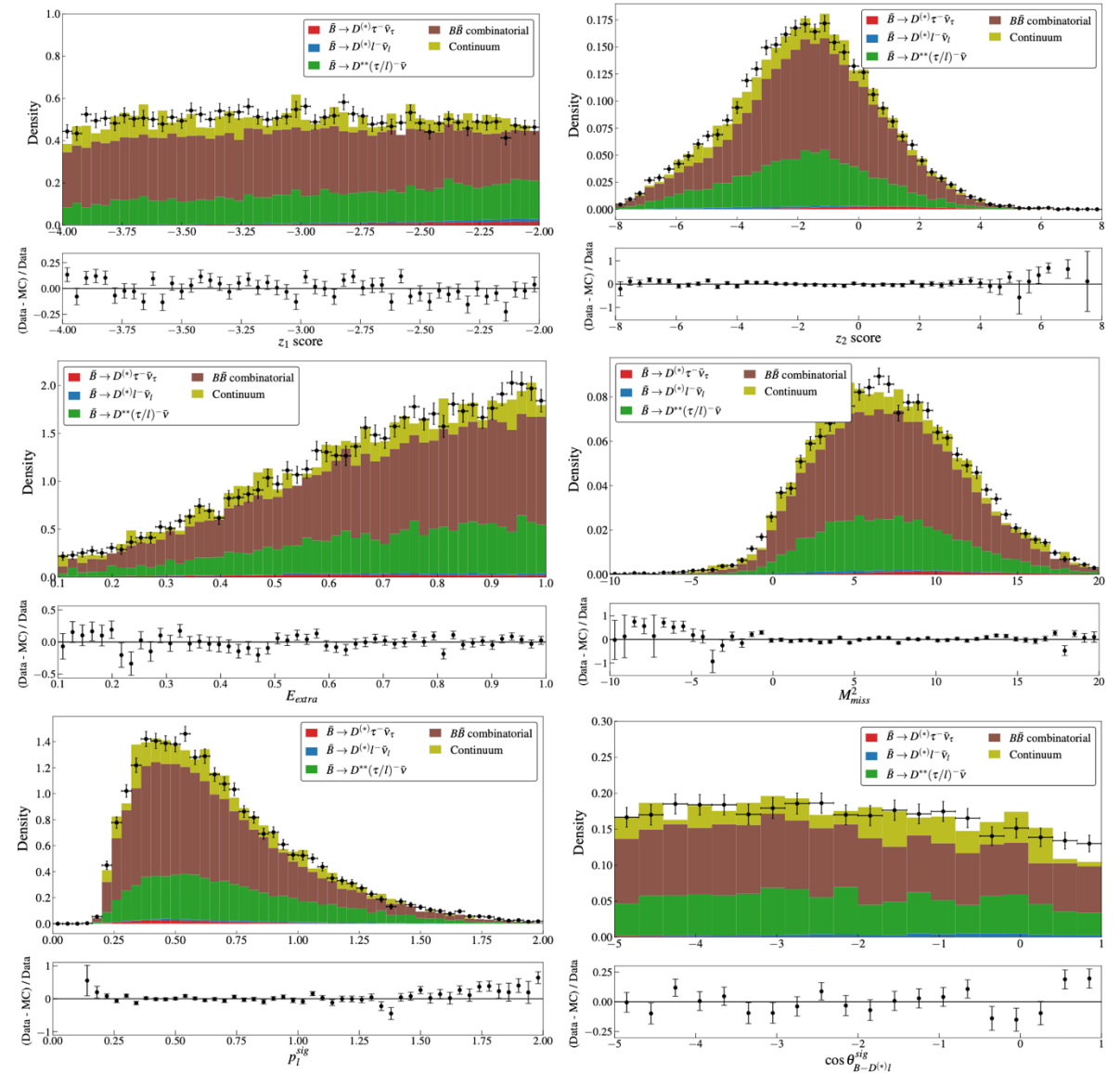
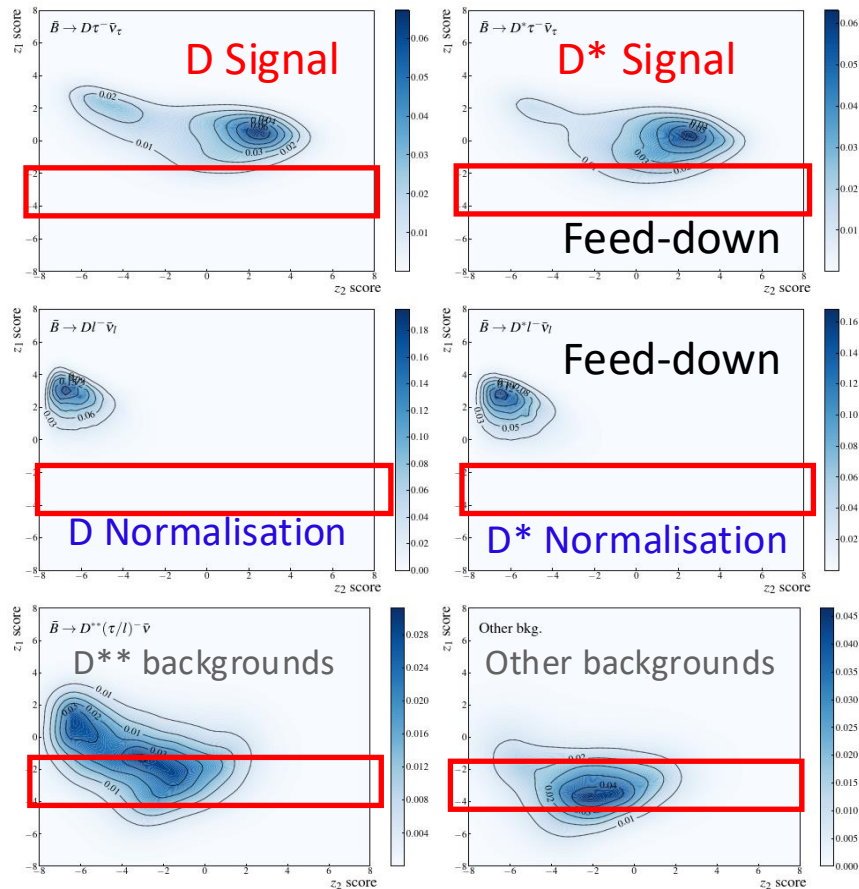
- Sideband: $E_{extra} > 1.0 \text{ GeV}$; $|p_l^{sig}| < 0.4 \text{ GeV}$



Example of validation checks: Background classifier inputs.

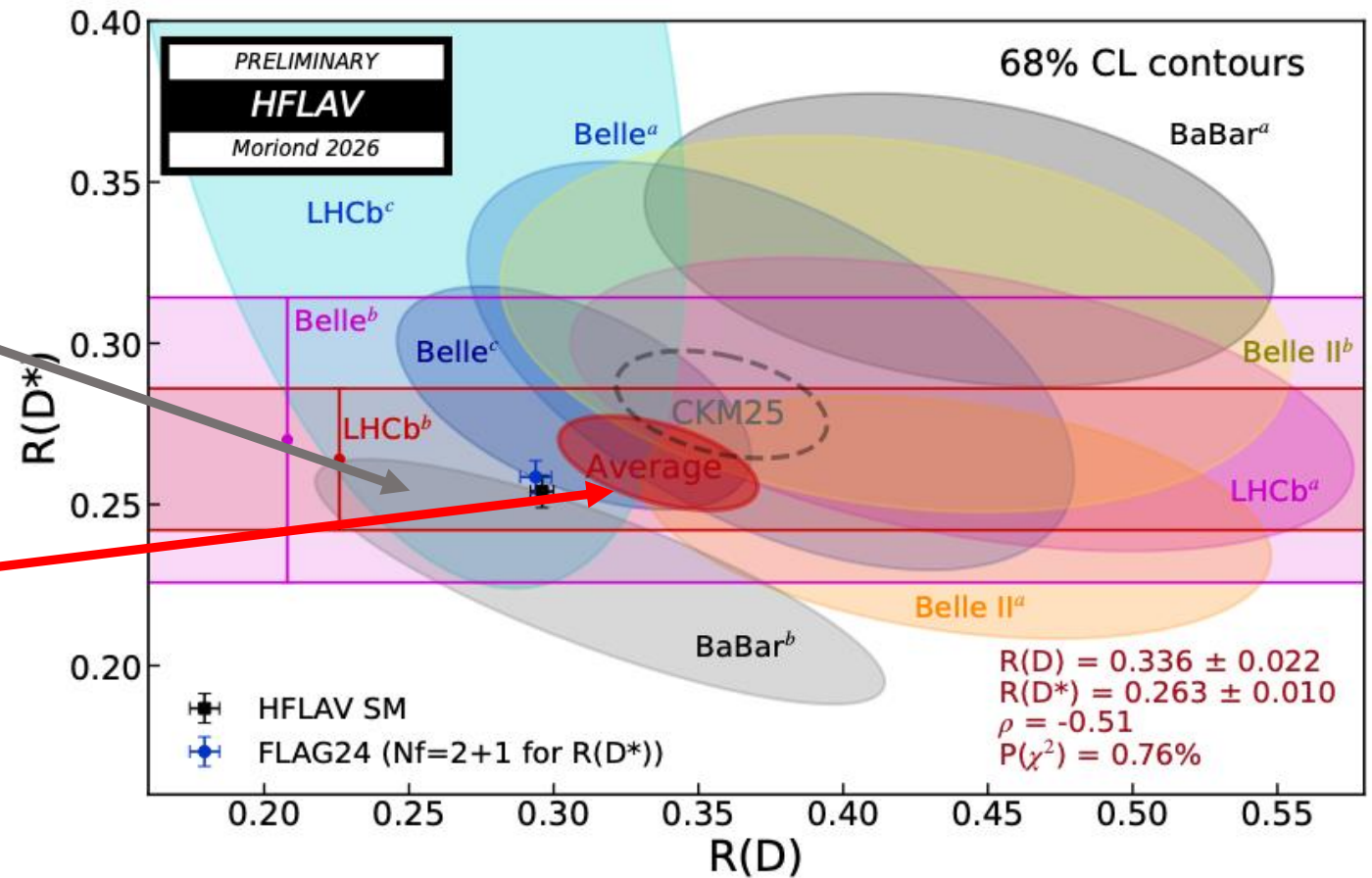
- Compare data and simulation in **background-enriched** region:

- $-4 \leq z_1 \leq -2$



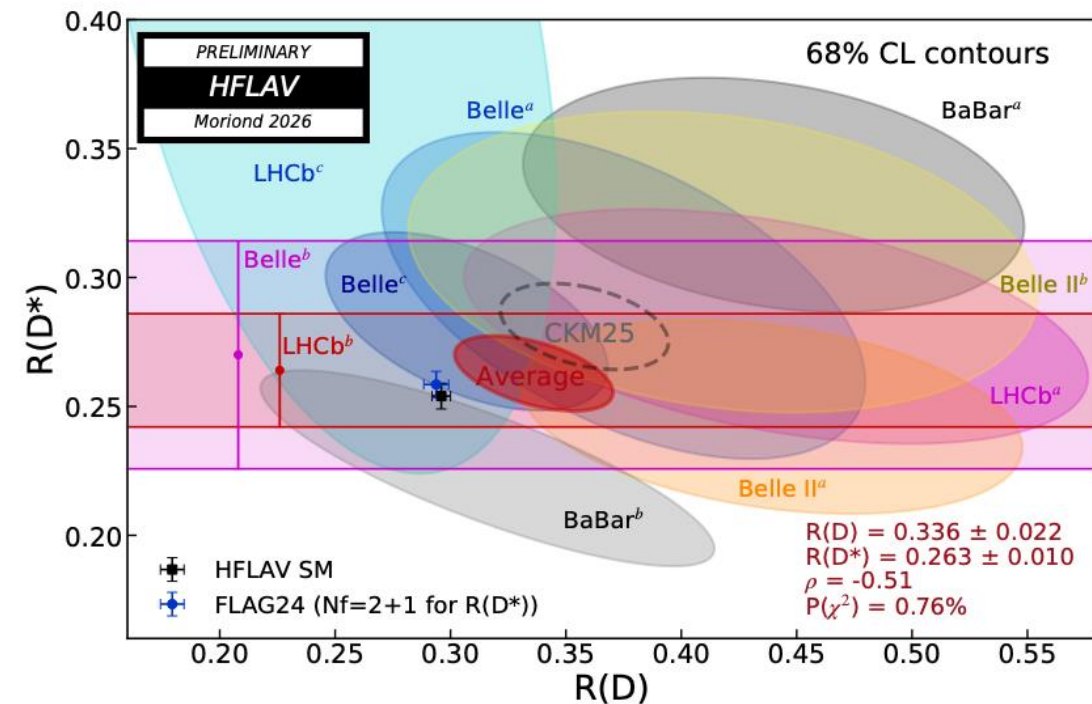
Preliminary Ratios:

- This result BaBar^b:
 - $R(D) = 0.316 \pm 0.062 \pm 0.019$
 - $R(D^*) = 0.226 \pm 0.022 \pm 0.012$
 - Correlation: -0.82
- New WA with this result:
 - $R_{WA}(D) = 0.336 \pm 0.022$
 - $R_{WA}(D^*) = 0.263 \pm 0.010$
 - Correlation: -0.51
 - (D^{**} and form factor systematics considered 100% correlated)



Summary and Conclusion

- We present a new measurement of $R(D^{(*)})$ using semileptonic B tagging and leptonic τ decays. This result is statistically independent of the published BaBar measurement using hadronic tagging.
- D^{**} 1P, 2S and $D^{(*)}\pi$ states are considered as backgrounds.
- Detailed studies of systematic uncertainties are still ongoing but result is dominated by statistical uncertainty.
- The preliminary BaBar result is:
 - $R(D) = 0.316 \pm 0.062 \pm 0.019$
 - $R(D^*) = 0.226 \pm 0.022 \pm 0.012$
- The agreement between ratios presented here and the SM HFLAV prediction is 1.5σ , taking correlations into account.
- The “new” estimated WA is now 2.0σ from SM HFLAV (down from 3.8σ).
- Paper will be published soon.



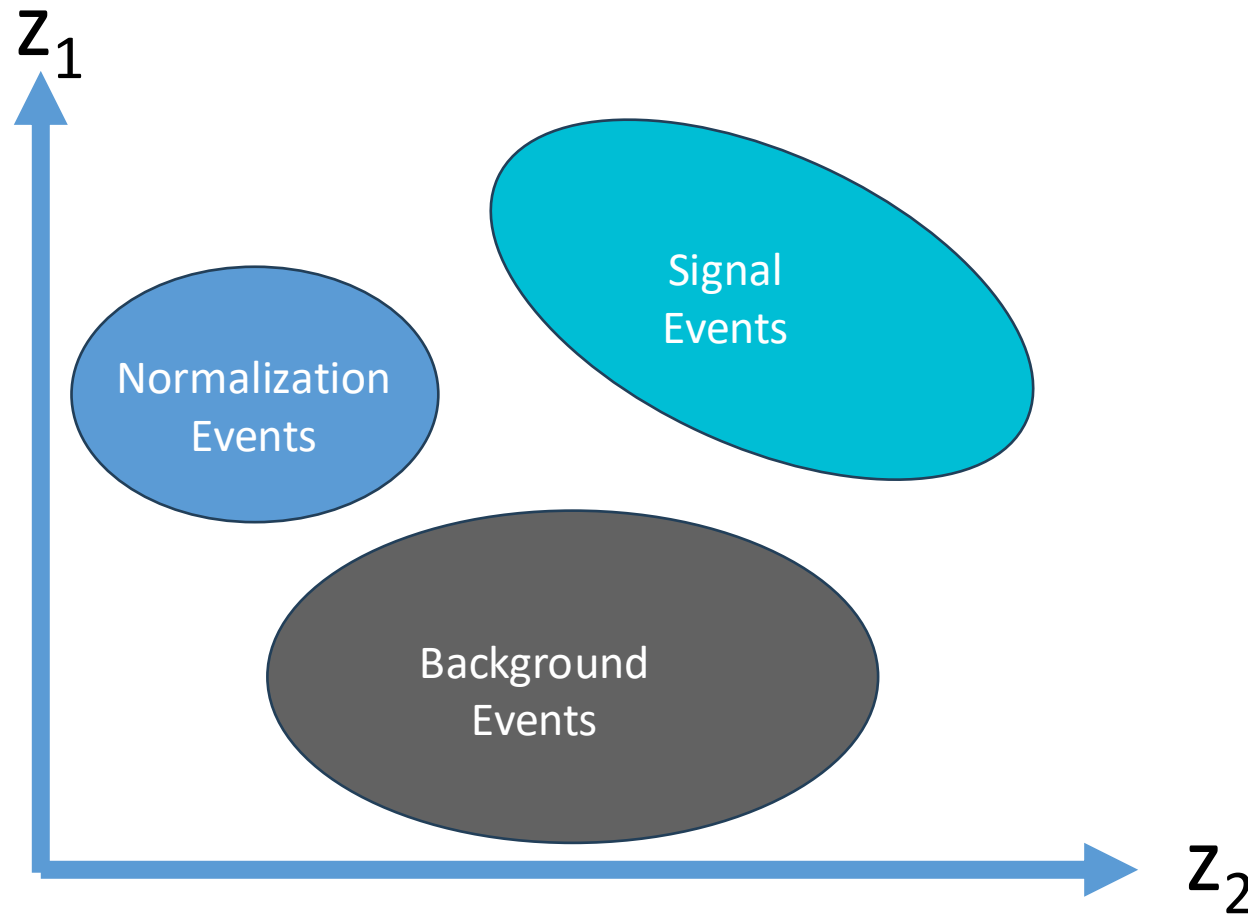
Additional information

References:

- HFLAV: [Heavy Flavour Averaging Group](#)
- L-QCD HFLAG: [FLAG Review 2024](#)
- CLN: I. Caprini, L. Lellouch, and M. Neubert, Nuclear Physics B 530, 153 (1998).
- BGL: C. Glenn Boyd, B. Grinstein, R. F. Lebed, Nucl. Phys. B461 (1996) 493-511.
- ISGW: N. Isgur and D. Scora, PRD 52, 2783 (1995).
- LLSW: A. K. Leibovich, Z. Ligeti, I. W. Stewart, and M. B. Wise, PRD 57, 308 (1998).
- Linear q^2 : J. Duboscq, R. Fulton, D. Fujino, K. Gan, K. Honscheid, H. Kagan, R. Kass, J. Lee, M. Sung, C. White, et al., PRL 76, 3898 (1996).
- Goity-Roberts: J. L. Goity and W. Roberts, PRD 51, 3459 (1995).

24 Classification Observables

- number of charged tracks;
- second Fox-Wolfram moment;
- missing mass squared of the event in the CM frame (m_{miss}^2);
- extra neutral energy in the calorimeter (E_{extra});
- angle between the thrust axis of the event and the beam momentum;
- 3-momentum magnitude of B_{tag} 's and B_{sig} 's leptons in the CM frame;
- cosine of the angle between the 3-momentum of B_{tag} and the sum of its $D^{(*)}$ and charged lepton daughters in the CM frame ($\cos \theta_{B-D^{(*)}l}^{\text{tag}}$);
- angle between the 3-momentum of the D meson and the lepton for both the tag and the signal side;
- reconstructed mass of D meson in both tag and signal side;
- ΔM on both the tag and the signal side if applicable;
- the CM angle between the D^* mesons' daughters in both tag and signal side;
- 3-momentum magnitude of the D^* 's pion daughter in the CM frame for both tag and signal side;
- χ^2 of the B_{sig} vertex fit;
- angle between the tag and signal side $D^{(*)}l$ systems in the CM frame;
- electron and muon PID level for both tag and signal side.



Simulation Samples and Form Factor reweighting

- Simulations of hadronic decays rely on Form Factor parameterizations.
- Signal and Normalization:
 - $\bar{B} \rightarrow D^{(*)}\tau^{-}\bar{\nu}$ and $\bar{B} \rightarrow Dl^{-}\bar{\nu}$: generated with hadronic form factors based on [ISGW2](#).
 - $\bar{B} \rightarrow D^*l^{-}\bar{\nu}$: generated with [linear \$q^2\$](#) model.
 - Each event is reweighted to match the [CLN](#) form factor parametrization (same parameterization used in BaBar 2012 hadronic tagged result).
- D^{**} background:
 - Resonant $D^{**}(1P)$ states: $\bar{B} \rightarrow D^{**}(1P)l^{-}/\tau^{-}\bar{\nu}$ generated with ISGW2 model and reweighted to [LLSW B1](#) parameterisation.
 - Resonant $D^{**}(2S)$ states: used to fill nominal 1.5% difference between inclusive and sum of exclusive $\bar{B} \rightarrow D^{(*)}l^{-}\bar{\nu}$ branching fractions.
 - Non-resonant states: $\bar{B} \rightarrow D^{**}l^{-}\bar{\nu}, D^{**} \rightarrow D^*\pi$ generated with [Goity-Roberts](#) model.
- Generic $Y(4S) \rightarrow B\bar{B}, c\bar{c}, uds$:
 - Produced in ratio based on cross-sections: $B\bar{B}, c\bar{c}, uds :: 1.05 \text{ nb} : 1.3 \text{ nb} : 2.1 \text{ nb}$.

Systematic Uncertainties – Form Factors

- Form Factors affect simulation samples used to train event selection:
 - $B \rightarrow D^{(*)}l\nu, l = e, \mu, \tau$: vary [CLN](#) form factor by uncertainties; reweight each event; repeat analysis.
 - $B \rightarrow D^{**}l\nu, l = e, \mu, \tau$: change form [LLSW](#) B1 model to LLSW B2; reweight each event; repeat analysis.

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \rightarrow D l \nu$ form factor	0.42	0.13	-0.18
$B \rightarrow D^* l \nu$ form factor	0.92	0.31	-0.19
$B \rightarrow D^{**} l \nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \rightarrow D^{(*)} l \nu)$	0.47	0.38	0.97
$\mathcal{B}(b \rightarrow c \bar{c})$	0.34	0.13	1
$\mathcal{B}(B \rightarrow D^{**} l \nu)$	2.83	1.60	-0.97
$\mathcal{B}(D)$	0.84	0.70	-0.40
PDF shapes MC statistics	4.12	4.37	-0.15
On-peak background calibration	2.45	0.44	-0.05
$\mathcal{B}(\Upsilon(4S))$	0.48	0.43	1
PID efficiency	0.29	0.40	1
Soft π^0 efficiency	0.84	1.25	1
$\mathcal{B}(\tau \rightarrow l^- \bar{\nu}_l \nu_\tau)$	0.16	0.16	1
Systematic Total	5.86	4.96	-0.20
Statistical Uncertainty	19.8	9.9	-0.92
Total	20.65	11.07	-0.82

Systematic Uncertainties – Branching Fractions

- Branching Fractions used in simulation not necessarily accurate.

- $B \rightarrow D^{(*)}l\nu$: use World Average (WA) + uncertainties; reweight each event; repeat analysis.
- $B \rightarrow D^{**}l\nu$: use WA or generate inclusive samples or adjust phase-space as function of possible $m(D^{**})$ excited states in range [2300, 3300] MeV; reweight each event; repeat analysis.
- D decays: Not feasible to fluctuate all D decays so use most common decay $D \rightarrow K\pi\pi$; reweight each event by 0.992; repeat analysis.
- $B(\tau^- \rightarrow l^- \bar{\nu}_l \nu_\tau)$: propagate World Average uncertainties as systematic.

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \rightarrow Dl\nu$ form factor	0.42	0.13	-0.18
$B \rightarrow D^*l\nu$ form factor	0.92	0.31	-0.19
$B \rightarrow D^{**}l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \rightarrow D^{(*)}l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \rightarrow c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \rightarrow D^{**}l\nu)$	2.83	1.60	-0.97
$\mathcal{B}(D)$	0.84	0.70	-0.40
PDF shapes MC statistics	4.12	4.37	-0.15
On-peak background calibration	2.45	0.44	-0.05
$\mathcal{B}(\Upsilon(4S))$	0.48	0.43	1
PID efficiency	0.29	0.40	1
Soft π^0 efficiency	0.84	1.25	1
$\mathcal{B}(\tau \rightarrow l^- \bar{\nu}_l \nu_\tau)$	0.16	0.16	1
Systematic Total	5.86	4.96	-0.20
Statistical Uncertainty	19.8	9.9	-0.92
Total	20.65	11.07	-0.82

Systematic Uncertainties – Detector Efficiencies

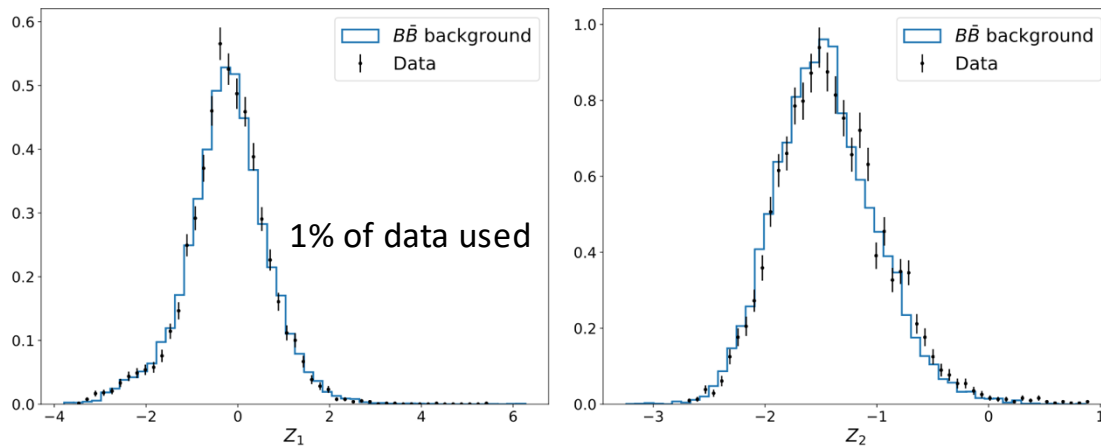
- $B(\Upsilon(4S))$:
 - Uncertainty in $B^0\bar{B}^0$ and B^+B^- ratio. Vary ratio by 1.1%
- PID efficiency:
 - Mostly cancels in ratio except for signal side lepton due to different momentum distribution.
- π^0 efficiency:
 - Momentum-dependent but majority in range [0.1-1.0] GeV/c so reweight by 0.958 ± 0.009 .

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \rightarrow Dl\nu$ form factor	0.42	0.13	-0.18
$B \rightarrow D^*l\nu$ form factor	0.92	0.31	-0.19
$B \rightarrow D^{**}l\nu$ form factor	0.48	0.18	-0.90
$B(B \rightarrow D^{(*)}l\nu)$	0.47	0.38	0.97
$B(b \rightarrow c\bar{c})$	0.34	0.13	1
$B(B \rightarrow D^{**}l\nu)$	2.83	1.60	-0.97
$B(D)$	0.84	0.70	-0.40
PDF shapes MC statistics	4.12	4.37	-0.15
On-peak background calibration	2.45	0.44	-0.05
$B(\Upsilon(4S))$	0.48	0.43	1
PID efficiency	0.29	0.40	1
Soft π^0 efficiency	0.84	1.25	1
$B(\tau \rightarrow l^-\bar{\nu}_l\nu_\tau)$	0.16	0.16	1
Systematic Total	5.86	4.96	-0.20
Statistical Uncertainty	19.8	9.9	-0.92
Total	20.65	11.07	-0.82

Systematic Uncertainties – On-peak background validation

- On-peak background calibration:

- Use difference in on-peak sideband data and off-peak data to reweight simulated background z_1 and z_2 distributions.
- Sideband:
 - $E_{extra} > 1.0 \text{ GeV}; |p_l^{sig}| < 0.4 \text{ GeV}$



- Discrepancies mainly due to mis-modelling of $B\bar{B}$ background

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \rightarrow D l \nu$ form factor	0.42	0.13	-0.18
$B \rightarrow D^* l \nu$ form factor	0.92	0.31	-0.19
$B \rightarrow D^{**} l \nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \rightarrow D^{(*)} l \nu)$	0.47	0.38	0.97
$\mathcal{B}(b \rightarrow c \bar{c})$	0.34	0.13	1
$\mathcal{B}(B \rightarrow D^{**} l \nu)$	2.83	1.60	-0.97
$\mathcal{B}(D)$	0.84	0.70	-0.40
PDF shapes MC statistics	4.12	4.37	-0.15
On-peak background calibration	2.45	0.44	-0.05
$\mathcal{B}(\Upsilon(4S))$	0.48	0.43	1
PID efficiency	0.29	0.40	1
Soft π^0 efficiency	0.84	1.25	1
$\mathcal{B}(\tau \rightarrow l^- \bar{\nu}_l \nu_\tau)$	0.16	0.16	1
Systematic Total	5.86	4.96	-0.20
Statistical Uncertainty	19.8	9.9	-0.92
Total	20.65	11.07	-0.82

Normalization PDF shape validation

- Compare data and simulation in **normalization-enriched** region:

- $z_1 \geq 2, z_2 \leq -4$

