UKRI Science and Technology Facilities Council

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

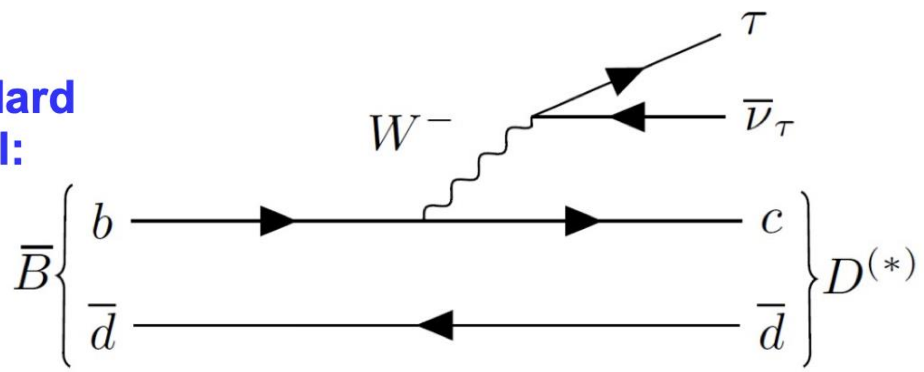
- Introduction.
- Charged Lepton Flavour Universality and definition of R(D) and R(D*).
- Current status of R(D) and R(D*) experiment and theory.
- R(D) and R(D*) measurement at BaBar with semi-leptonic tagging.
- Results and Conclusion.

All plots and results are currently preliminary.

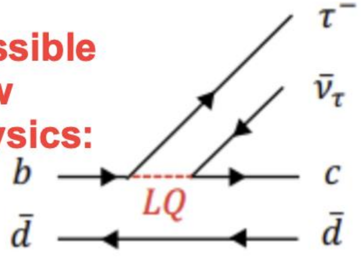
Introduction

- In the Standard Model (SM), the decay $B \to D^{(*)} l\nu$ 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 $B \to D^{(*)} l\nu$ decays suffer from large hadronic uncertainties. Taking a ratio cancels many of the experimental and theoretical uncertainties.

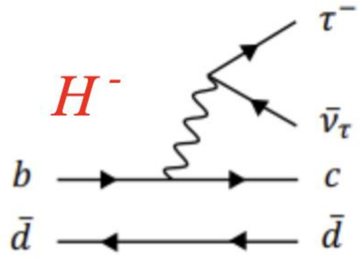
Standard Model:



Possible new physics:



Leptoquark



Charged Higgs

Signal

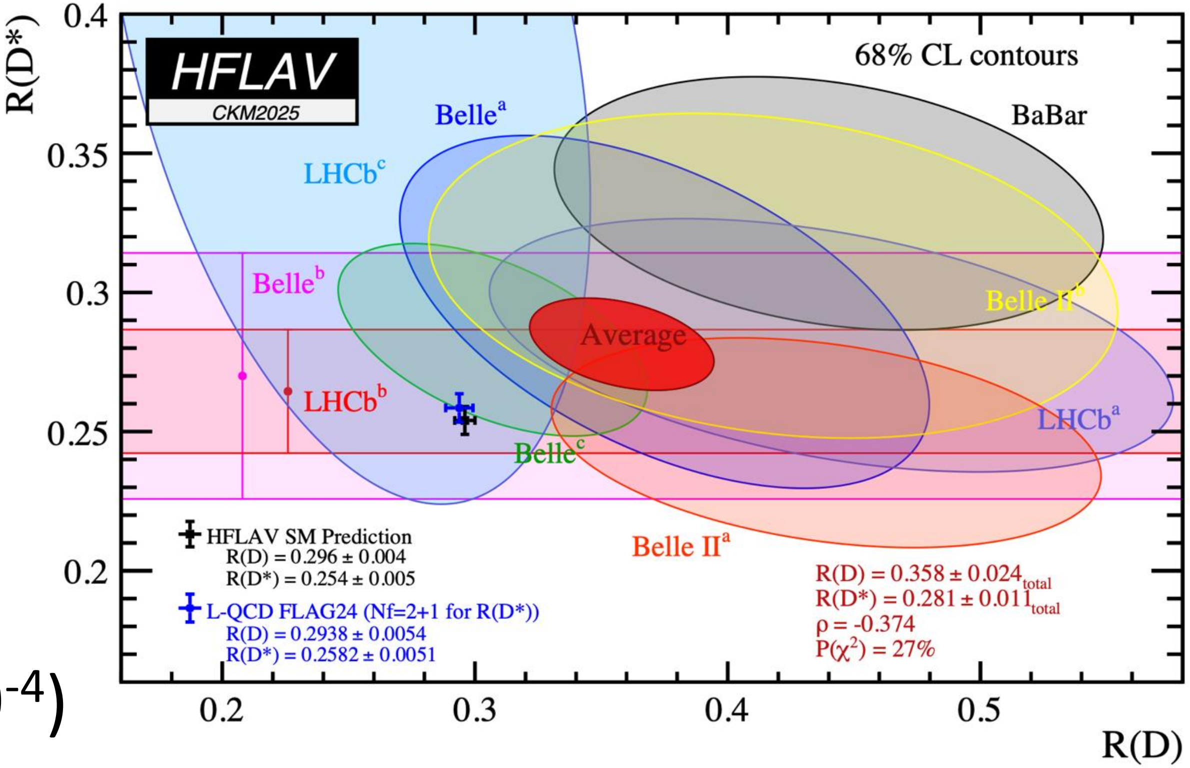
$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\upsilon})}{\mathcal{B}(\bar{B} \to D^{(*)}l\bar{\upsilon})} \; (\mathrm{l} = \mathrm{e}, \mu)$$

Normalization

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

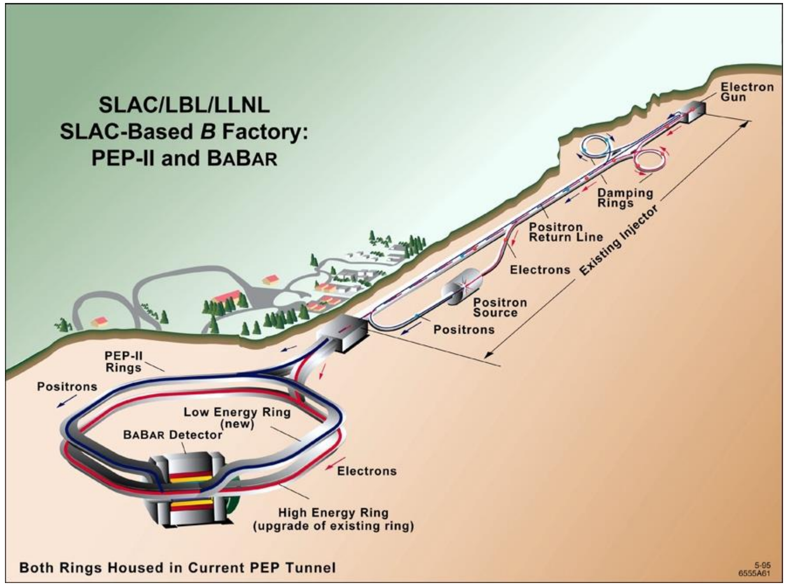
- Standard Model predictions:
  - HFLAV HQET average: $R_{SM}(D) = 0.296 \pm 0.004 \quad R_{SM}(D^*) = 0.254 \pm 0.005$
  - L-QCD HFLAG-24 $R_{SM}(D) = 0.2938 \pm 0.054 \quad R_{SM}(D^*) = 0.2582 \pm 0.0051$
- Experiment measurements (CKM 2025)

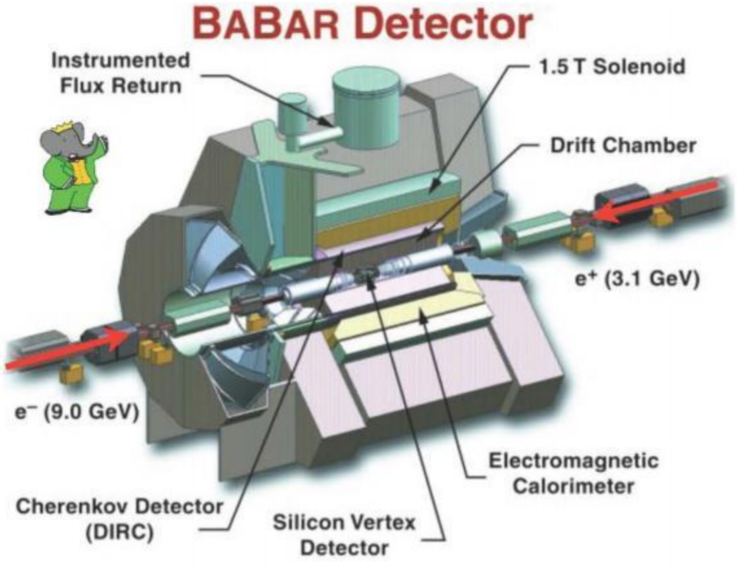
Experiment	R(D*)	R(D)	Correlation	Publication/Year
BaBar	$0.332 \pm 0.024 \pm 0.018$	$0.440 \pm 0.058 \pm 0.042$	-0.45 ± 0.27	PRL 109, 101802 (2012)
Belle[a]	$0.293 \pm 0.038 \pm 0.015$	$0.375 \pm 0.064 \pm 0.026$	-0.56 ± 0.49	PRD 92, 072014 (2015)
Belle[b]	$0.270 \pm 0.035^{+0.028}_{-0.025}$			PRL 118, 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	



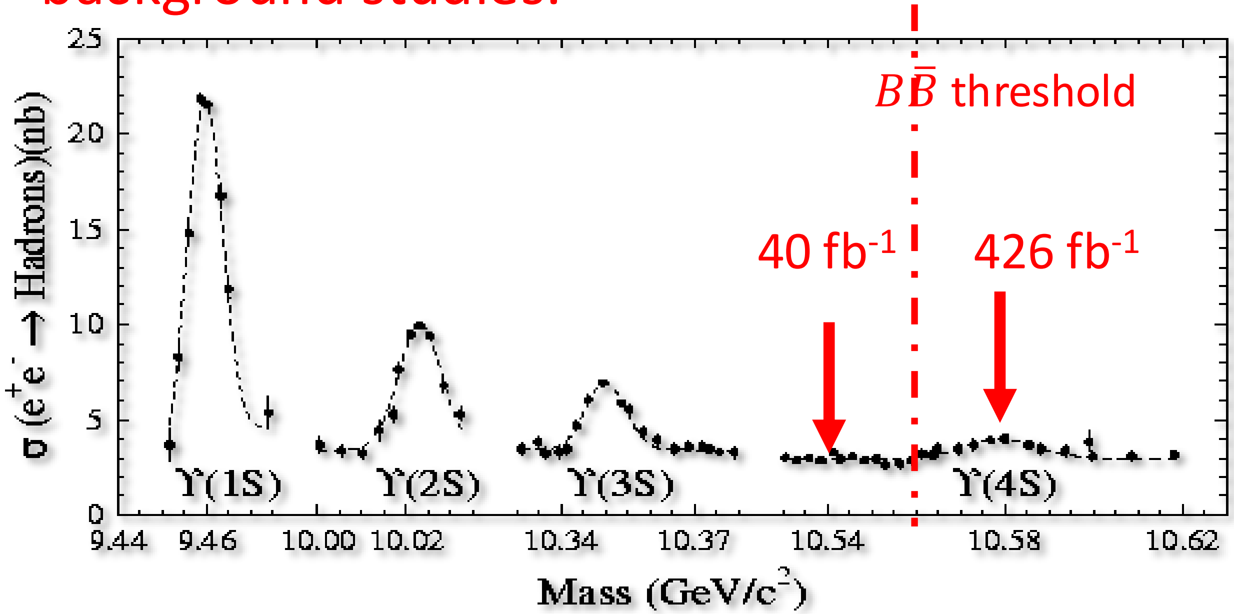
- *Average*: $R(D) = 0.358 \pm 0.024$ $R(D^*) = 0.281 \pm 0.011$
- Tension with SM 3.8σ (p-value = 1.48 x 10^{-4})

BaBar Detector at SLAC PEP-II: 1999 – 2008





- Asymmetric beam: Mostly 3.1 GeV e^+ on 9.0 GeV e^- at Υ(4S) resonance:
  - $\Upsilon(4S) \rightarrow B\bar{B}$ pair is major decay process
  - “On-peak”: 426 fb^{-1} (~471 x 10^6 $B\bar{B}$ pairs)
  - “Off-peak” : 40 fb^{-1} 40 MeV below Υ(4S) for background studies.

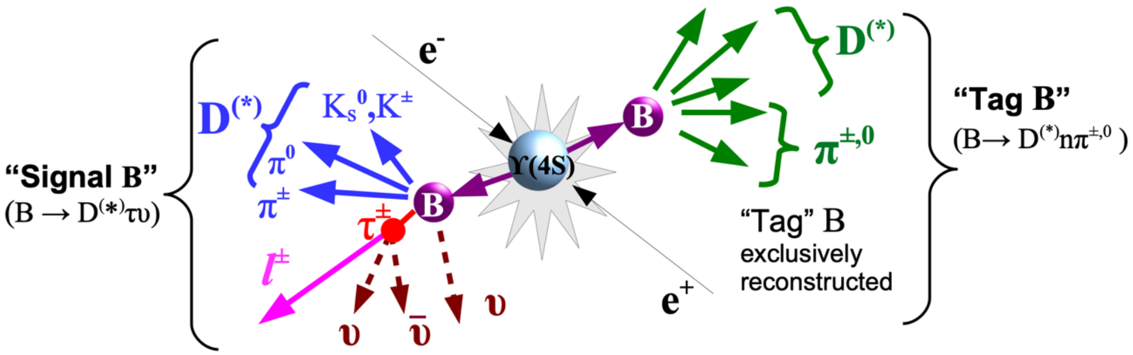


  - One of the first HEP experiments to think seriously about data and software preservation.

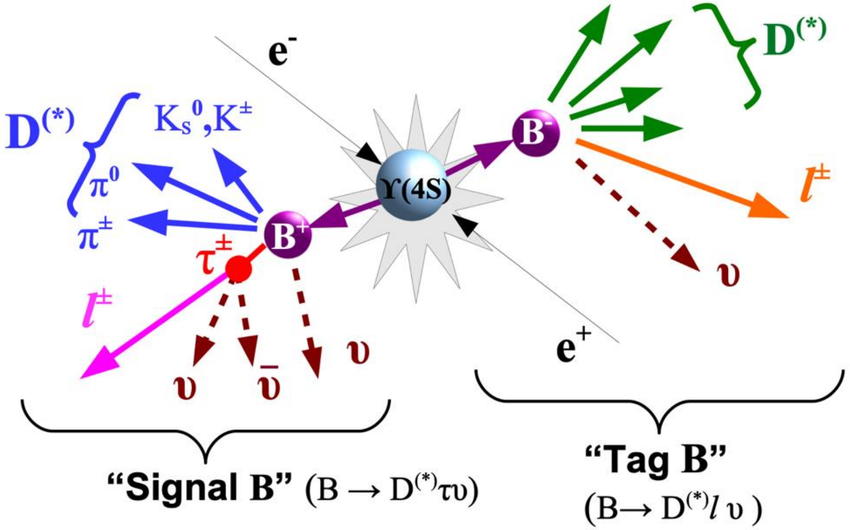
Analysis Strategy: “Tagging” at BaBar

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

B_{sig} decays reconstructed in 4 "subsets":
$D^{+}\ell^{-}, D^{*+}\ell^{-}, D^{0}\ell^{-}, D^{*0}\ell^{-}$

2. Normalization:
   - D event: $B_{tag} \rightarrow \bar{D}^{(*)} l\upsilon$, $\bar{B}_{sig} \rightarrow Dl\upsilon$
   - D* event: $B_{tag} \rightarrow \bar{D}^{(*)} l\upsilon$, $\bar{B}_{sig} \rightarrow D^{*} l\upsilon$

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

3. *D^{**} background*: At least one $B \rightarrow D^{**}(l,\tau)\upsilon$ 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 $B\bar{B}$ event; trigger threshold is a step function; lumi known to +/- 0.7%.
- 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 q2, …
  - 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:

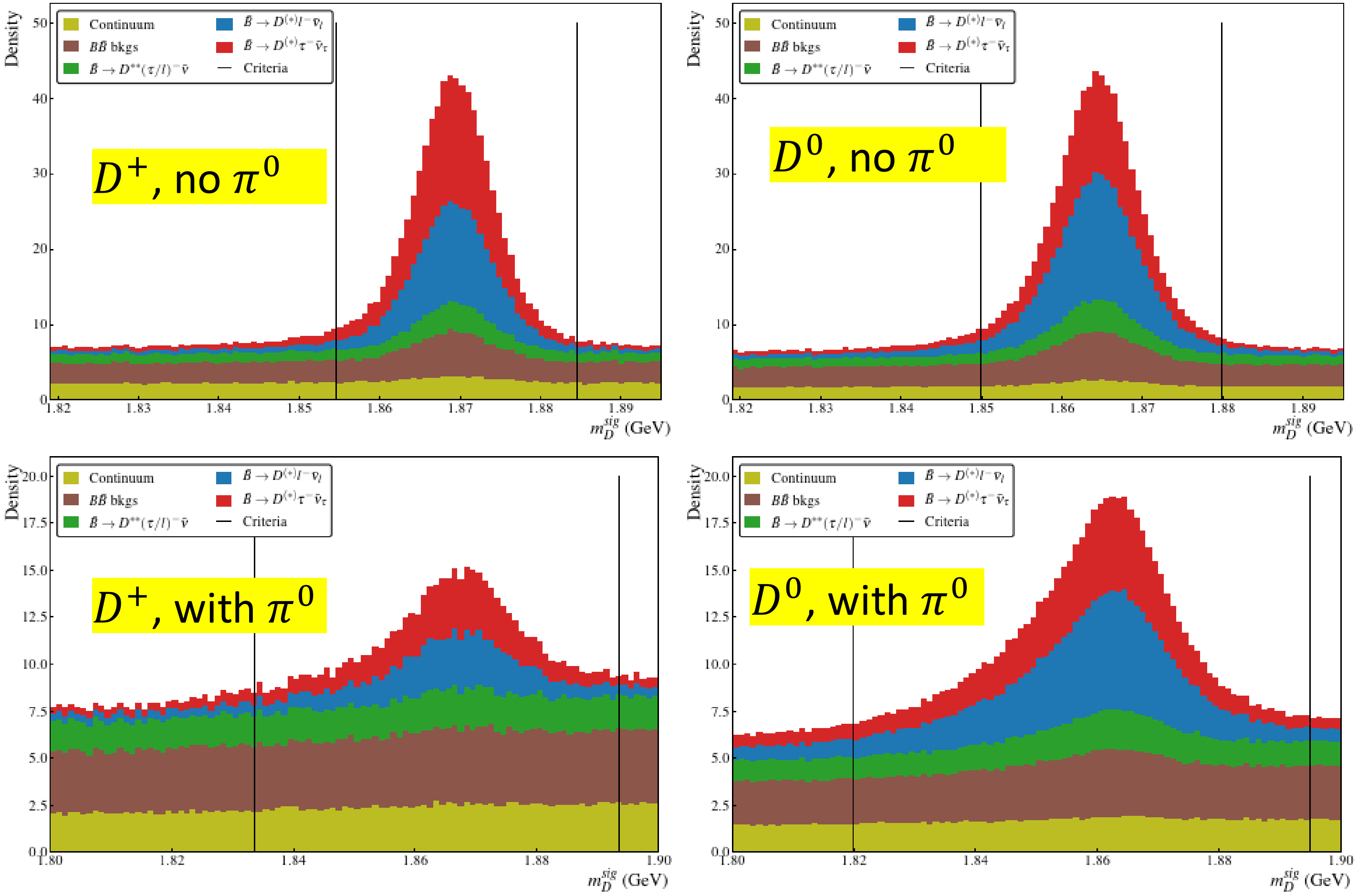
Decay Modes	Branching Fraction (%)
$D^+ \to K^-\pi^+\pi^+$	9.46 ± 0.24
$D^+ \to K_S\pi^+$	1.53 ± 0.06
$D^+ \to K_S\pi^+\pi^0$	7.24 ± 0.17
$D^+ \to K^-K^+\pi^+$	0.99 ± 0.026
$D^0 \to K^-\pi^+$	3.88 ± 0.05
$D^0 \to K^-\pi^+\pi^0$	14.3 ± 0.80
$D^0 \to K^-\pi^+\pi^-\pi^+$	8.06 ± 0.23
$D^0 \to K_S\pi^+\pi^-$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

~20%

~30%

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

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

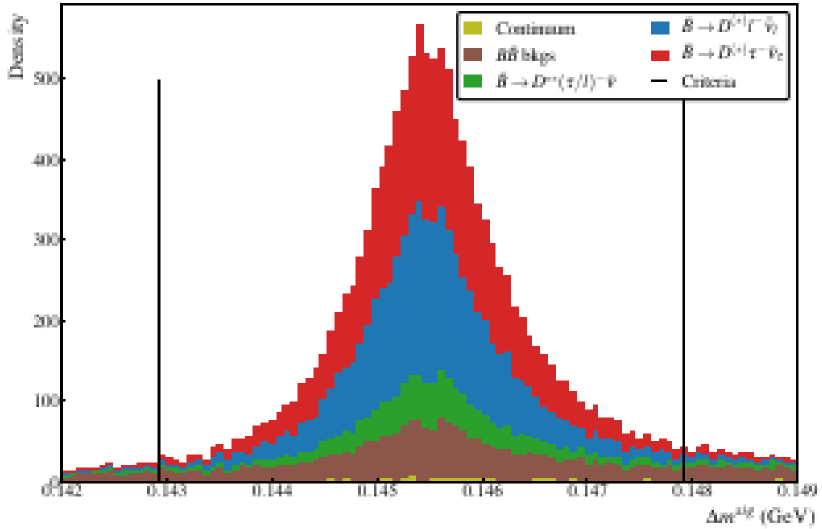


D^* selection

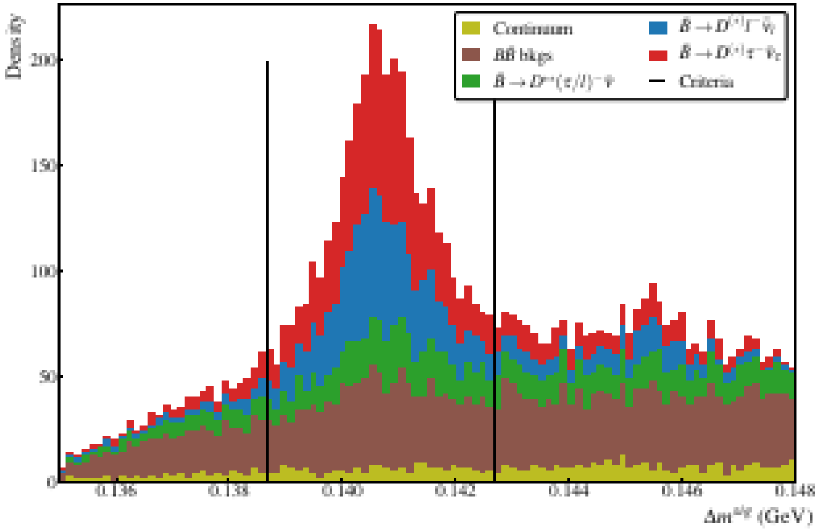
- D* reconstruction through 3 modes:
  - $D^{*+} \to D^0\pi^+, D^+\pi^0$
  - $D^{*0} \to D^0\pi^0$

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

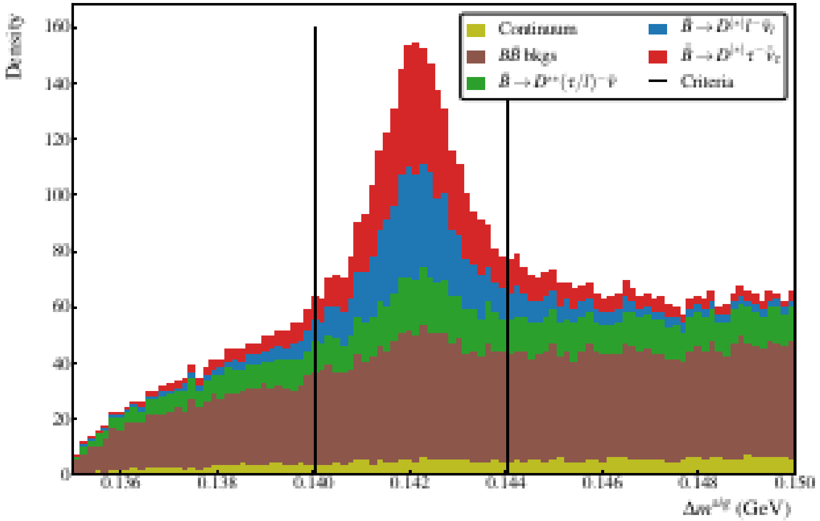
$D^{*+} \to D^0\pi^+$



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



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

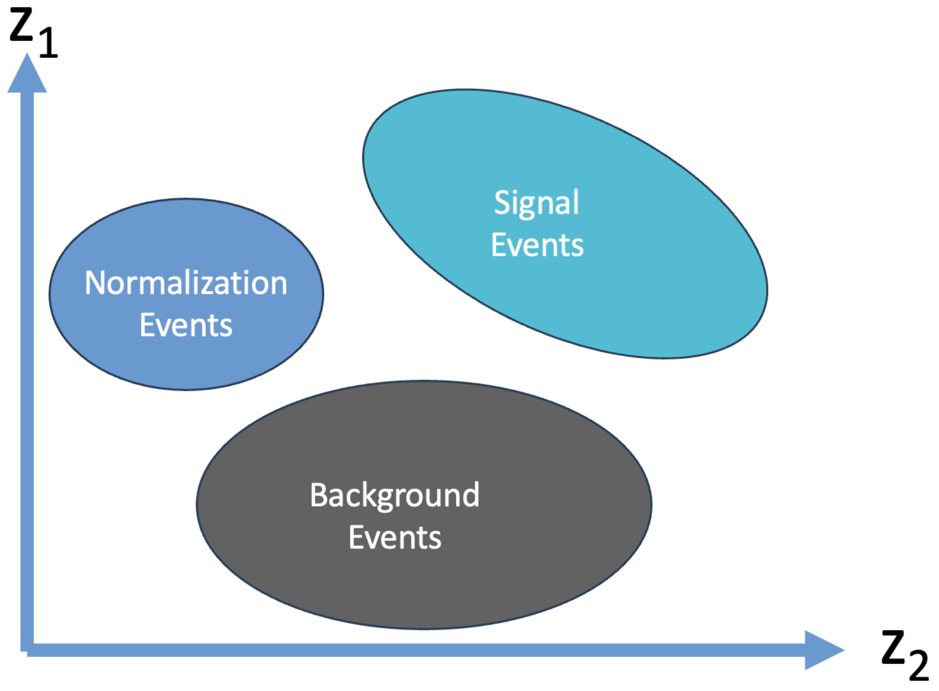


$\Upsilon(4S) \rightarrow B_{tag}\bar{B}_{sig}$ selection

- B_{tag} decay modes:
  - $m(D^{(*)}l\upsilon) < 5.28$ GeV + reconstructed *B*-vertex quality criteria.
  - Expect to have $\cos(\Theta^{tag}_{B-D^{(*)}l\upsilon})$ in range [-2,1] where: $\cos(\Theta^{tag}_{B-D^{(*)}l\upsilon}) = \frac{2E_{beam}E_{D^{(*)}l\upsilon} - M_B^2 - m^2_{D^{(*)}l\upsilon}}{2|\boldsymbol{p}_B||\boldsymbol{p}_{D^{(*)}l\upsilon}|}$
- $\bar{B}_{sig}$ decay modes:
  - Search among remaining tracks and calorimeter clusters for $D^{(*)}l$.
  - $m(D^{(*)}l\upsilon) < 5.28$ GeV + reconstructed *B* vertex quality criteria.
  - $\cos(\Theta^{sig}_{B-D^{(*)}l}) < 1$
- $\Upsilon(4S)$:
  - Combine B_{tag} and $\bar{B}_{sig}$ conserving charge. No extra charged tracks, K_S^0 or π^0 particles.
  - Extra (unassigned) neutral energy $E_{extra} < 1.2$ GeV.
  - Second Fox-Wolfram moment $R_2 < 0.4$
  - $\bar{B}_{sig}$ lepton daughter 3-momenta in Center-of-Mass (CM) frame $|p_l^{sig}| \leq 2$ 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

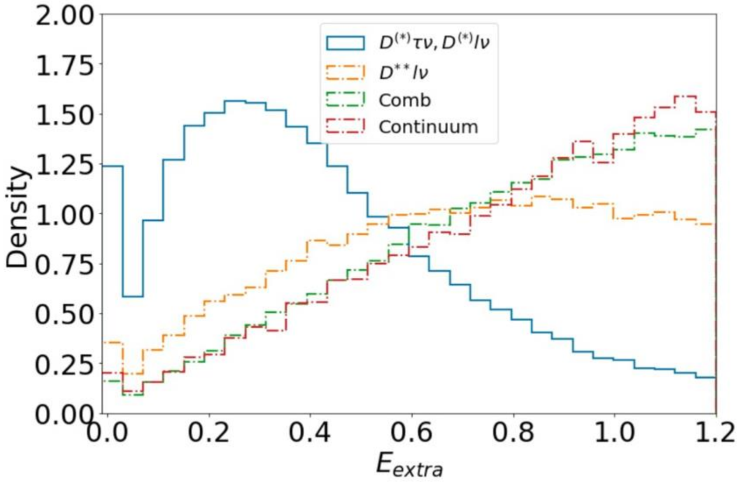
- Train two binary classifiers C_1 and C_2 to generate scores z_1 and z_2 for each event:
  - C_1: Normalization+Signal v. Background events
  - C_2: Signal v. Normalization events.
- Gradient Boosting Decision Tree (BDT) from *scikit-learn*.
- Classifier observables are chosen based on their importance 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 in each of the 4 subsets with Maximum Likelihood fit to $f(z_1,z_2)$ with N=6 event classes:
  - $D^{(*)}$ signal, $D^{(*)}$ signal cross-feed, $D^{(*)}$ normalisation, $D^{(*)}$ normalisation cross-feed, D^{**}, and "other backgrounds".

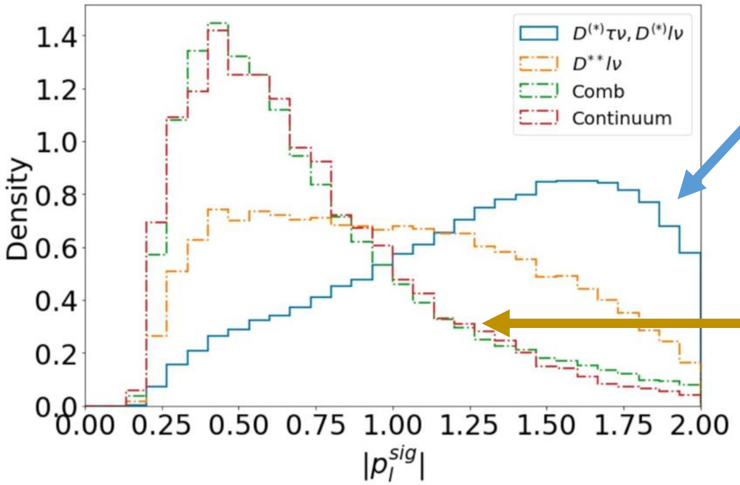


$$Prob(z_1, z_2) = \sum_{j=1}^{N} p_j f_j(z_1, z_2)$$

Classifier input: example. observables

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

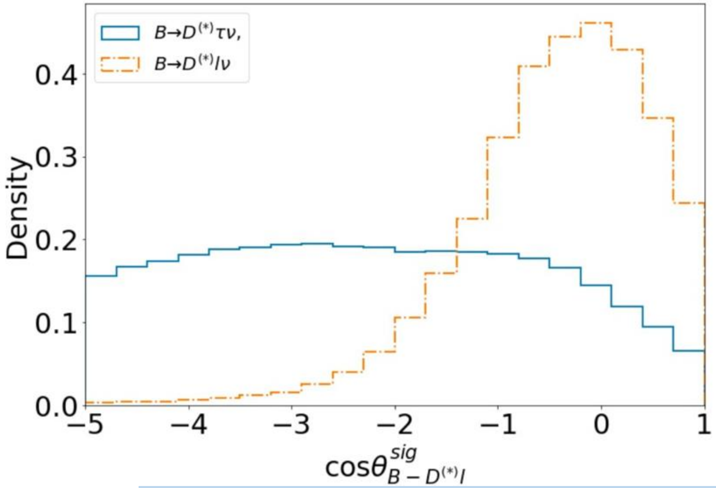


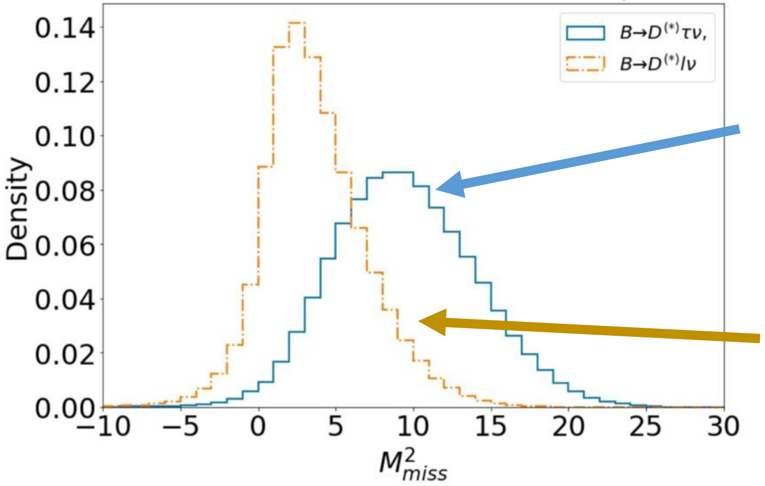


Signal + Normalisation

Backgrounds

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



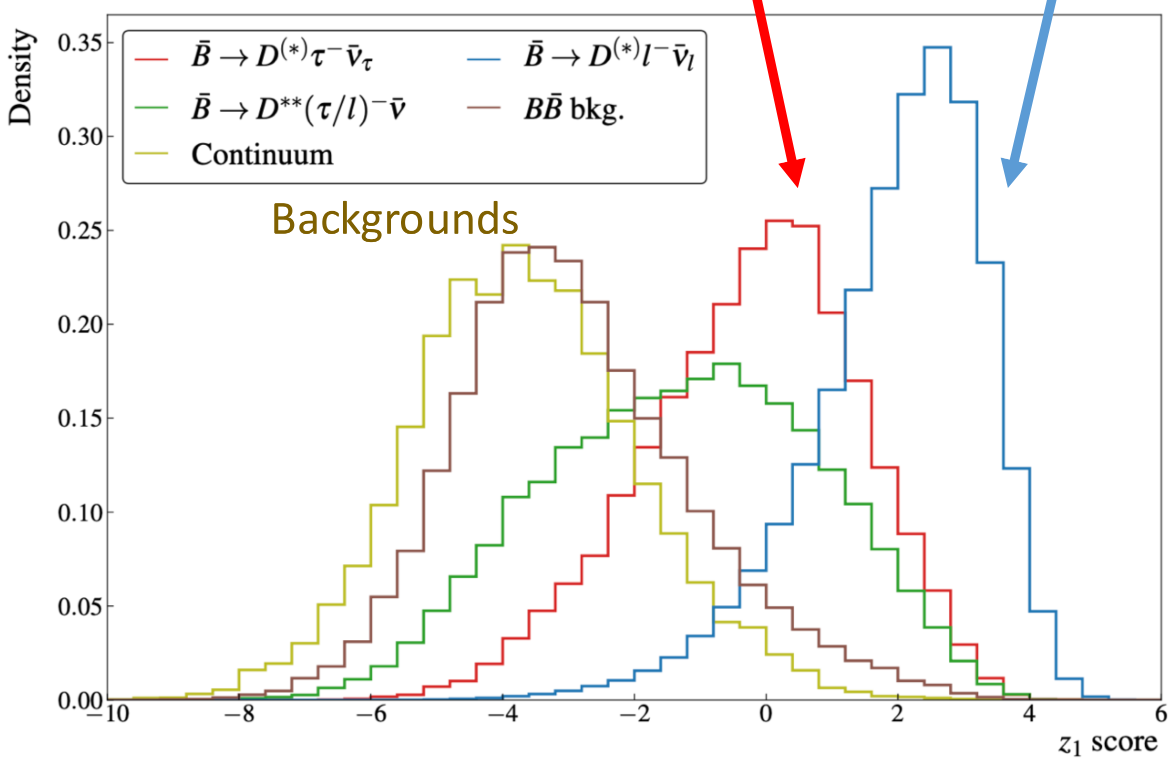


Signal

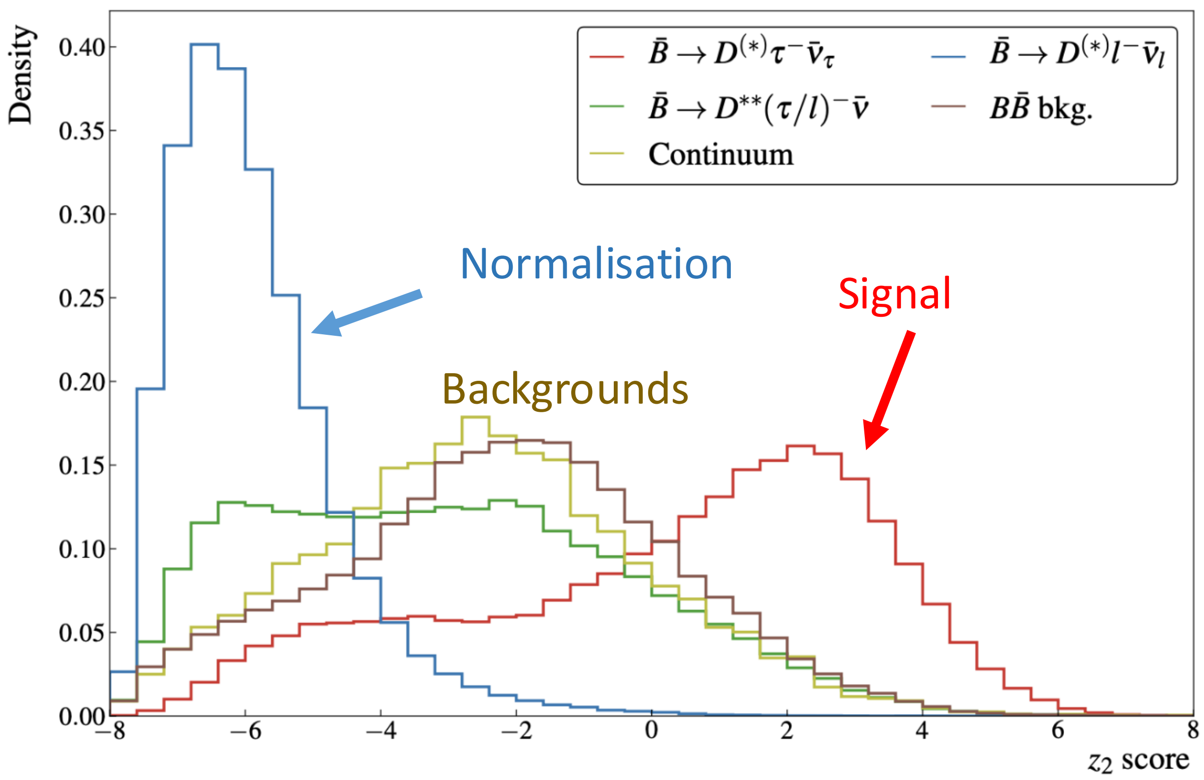
Normalisation

Classifier output: Boosted Decision Tree

Signal + Normalisation

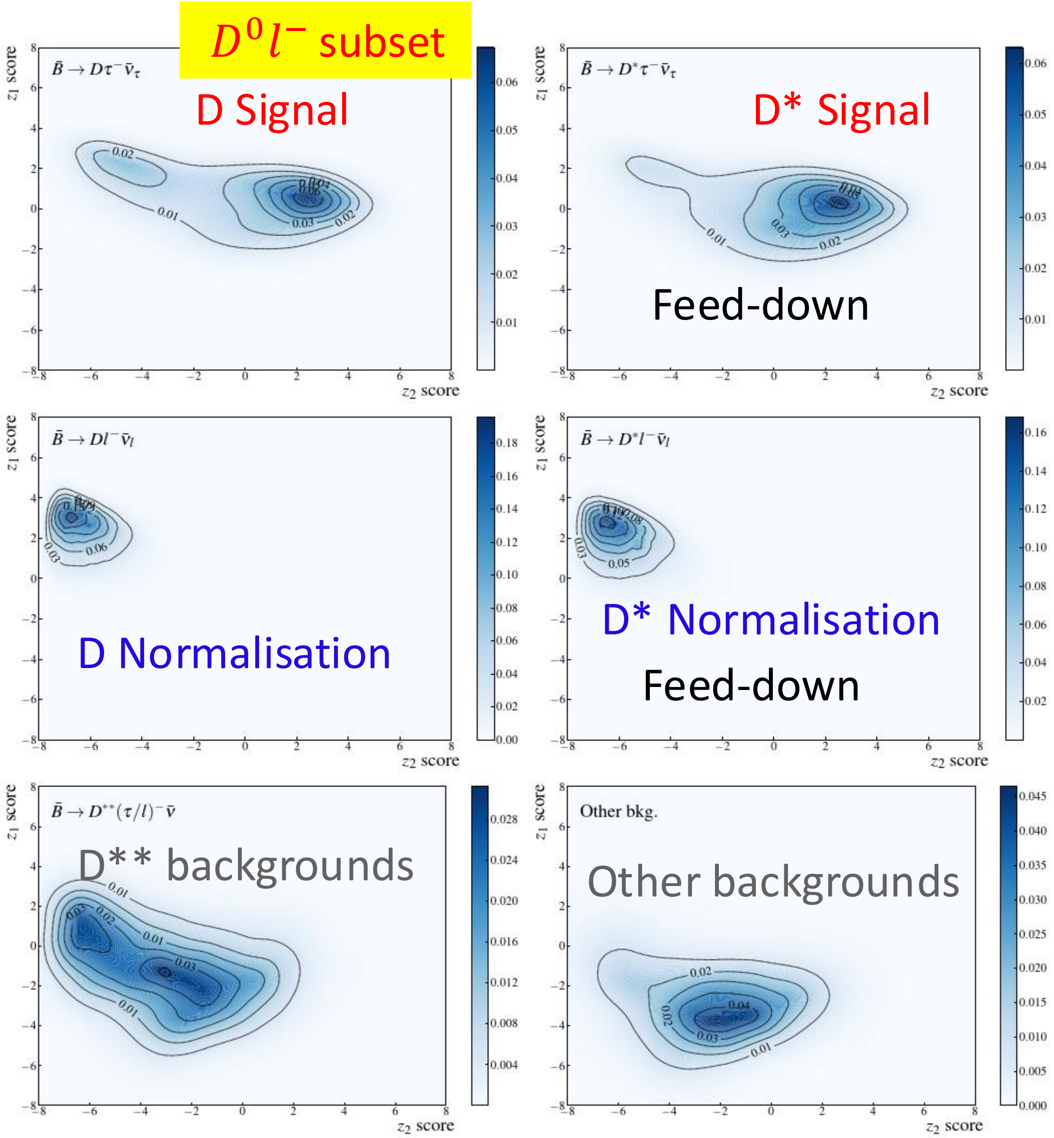


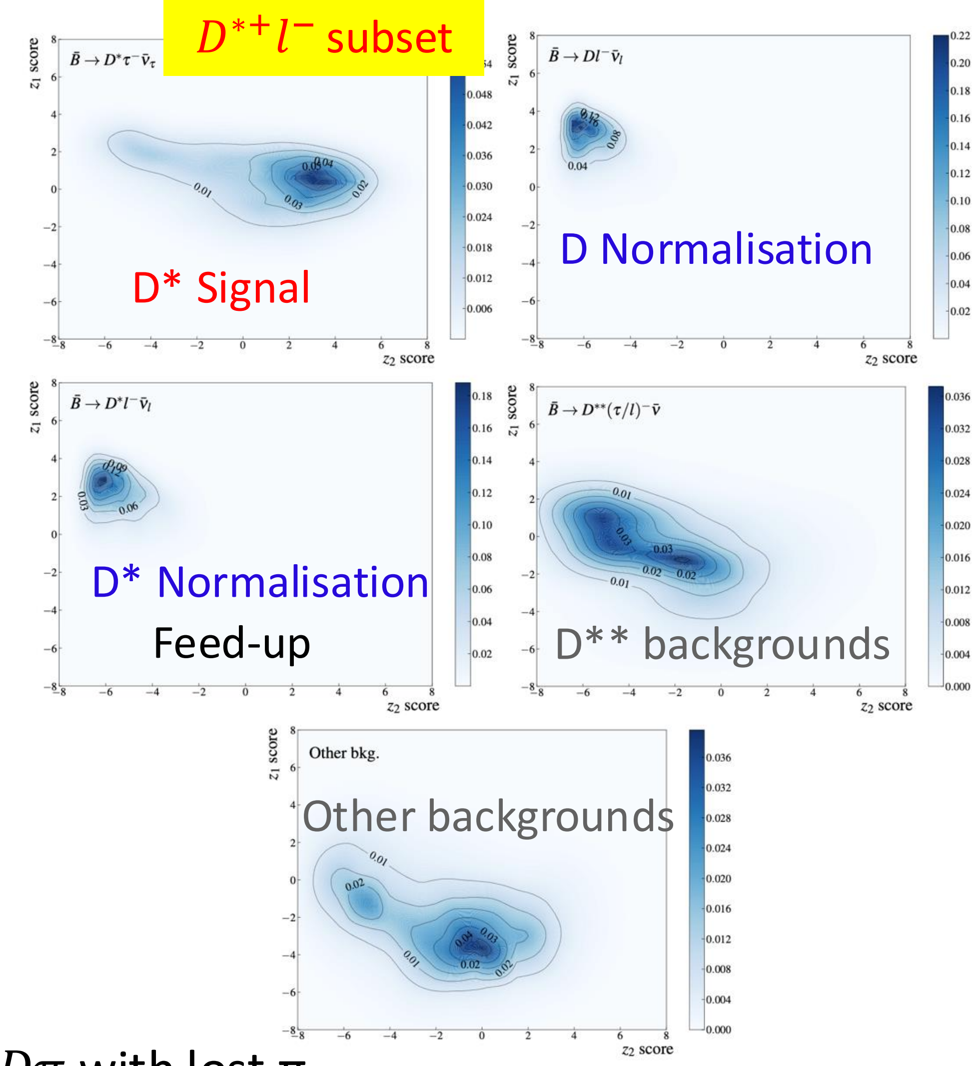
C_1 Classifier



C_2 Classifier

Two-dimensional KDE Probability Density Functions (PDFs)

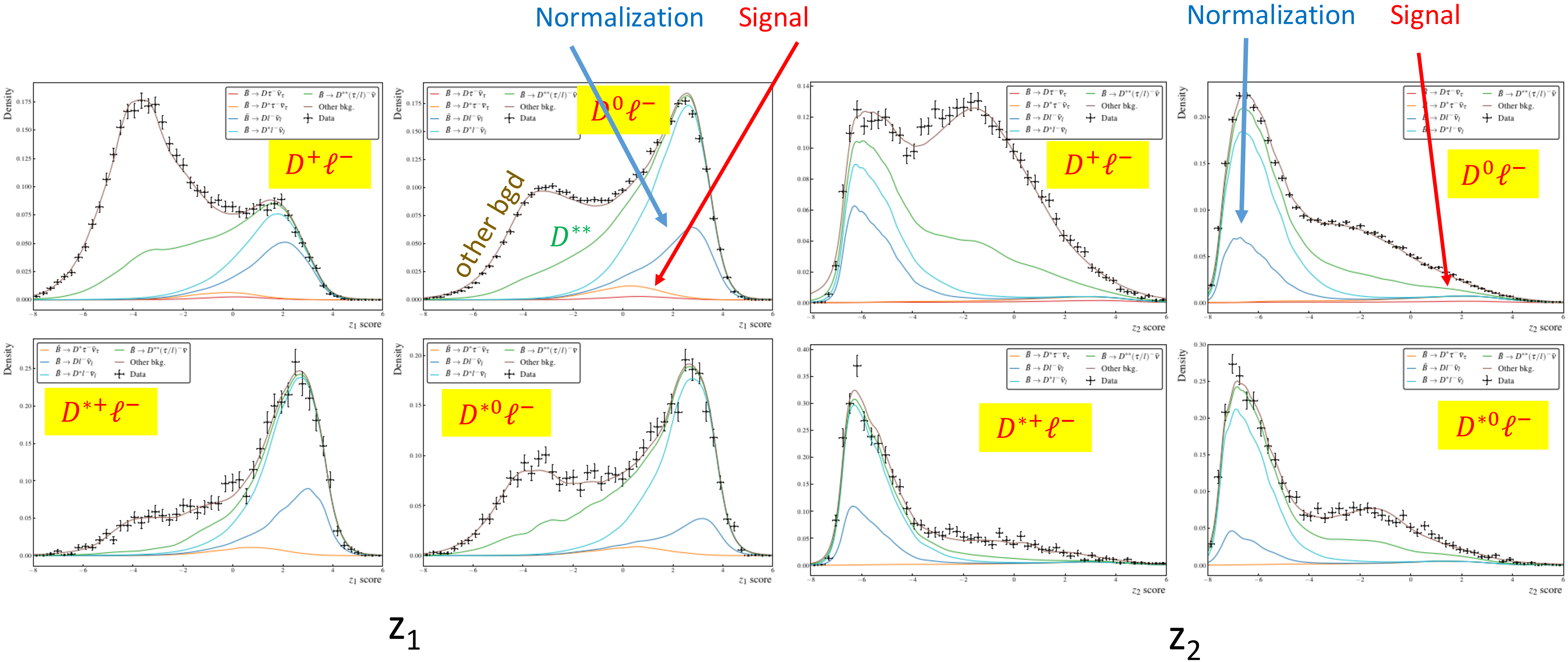




Feed-down: $D^* \to D\pi$ with lost π

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 $\widehat{N}$ calculated by combining y_j scaled by reconstruction efficiency to calculate R(D$^{(*)}$).

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

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

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

$$\mathcal{B}(\tau \to \text{leptons}) = \mathcal{B}(\tau \to e\bar{\nu}_e\nu_\tau) + \mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$$
$$= (35.24 \pm 0.05)\%$$

Systematic Uncertainties

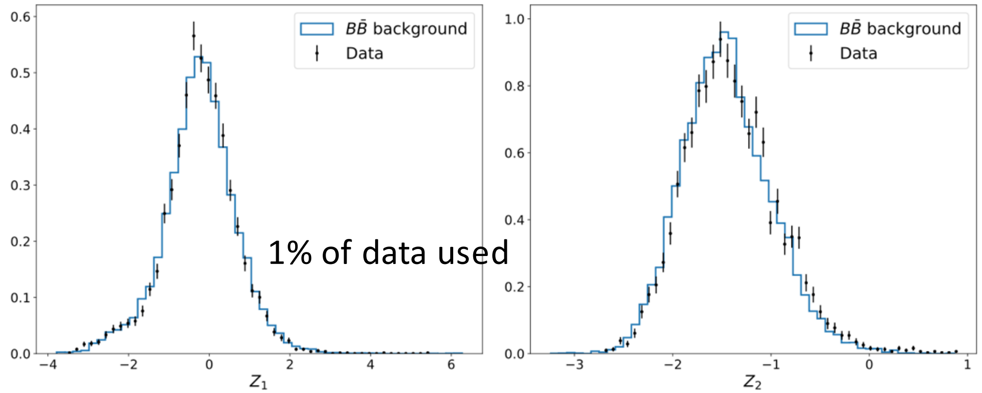
Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \to Dl\nu$ form factor	0.42	0.13	-0.18
$B \to D^*l\nu$ form factor	0.92	0.31	-0.19
$B \to D^{**}l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \to D^{(*)}l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \to c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \to D^{**}l\nu)$	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
$\mathcal{B}(\tau \to l^-\bar{\nu}_l\nu_\tau)$	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 $\mathcal{B}(B \to D^{**}lv)$ by ±10%.

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

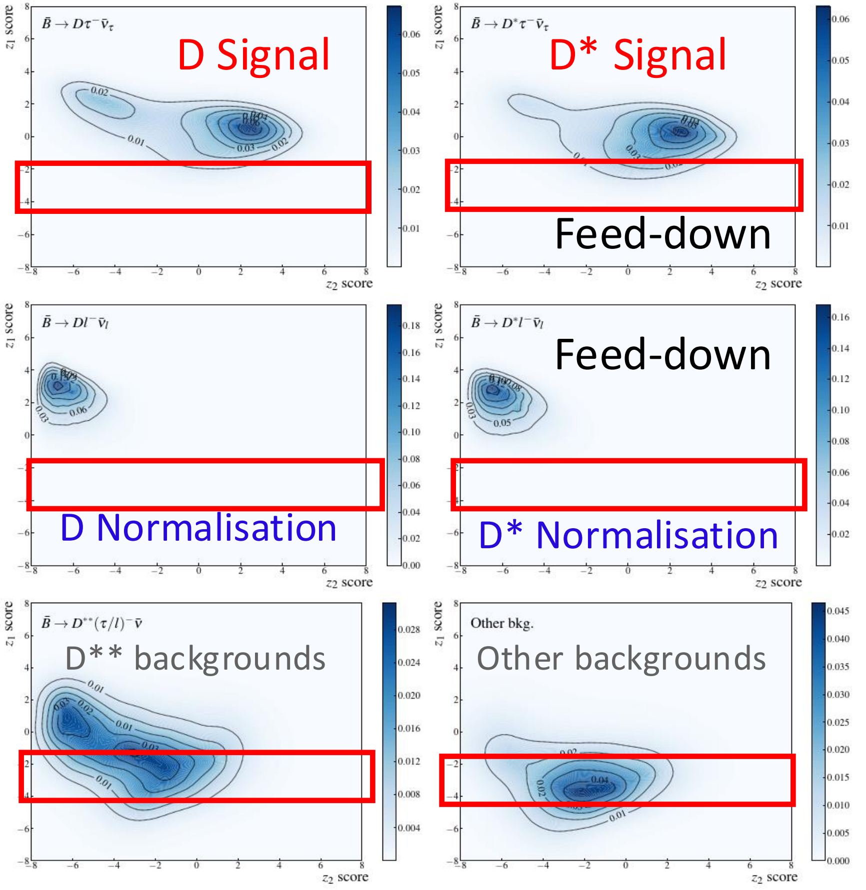
Use difference in on-peak sideband data and off-peak data to reweight simulated background z_1 and z_2 distributions.

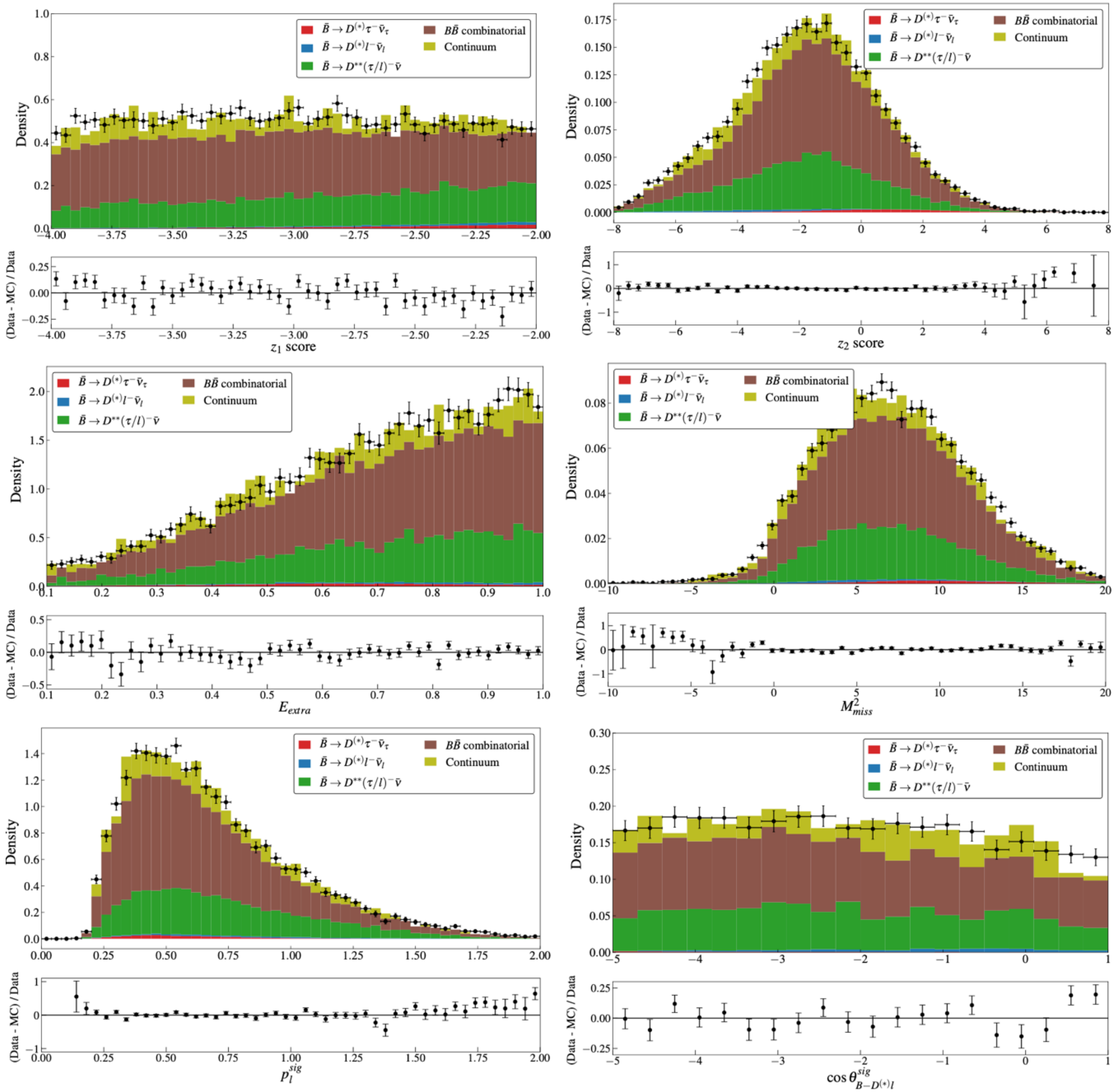
- Sideband: $E_{extra} > 1.0\ GeV$; $|p_l^{sig}| < 0.4\ GeV$



Example of validation checks: Background classifier inputs.

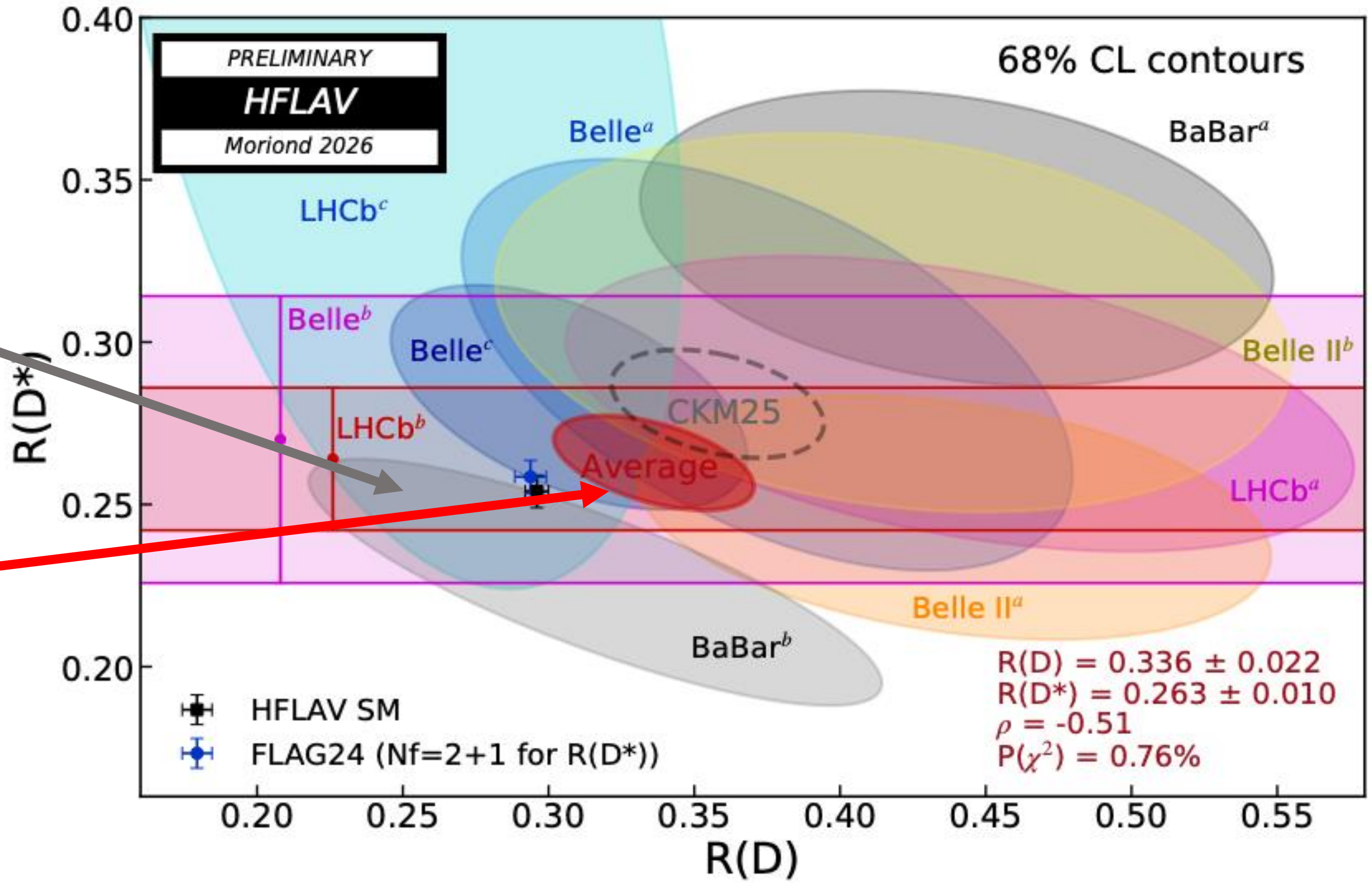
- Compare data and simulation in background-enriched region:
  - $-4 \leq z_1 \leq -2$





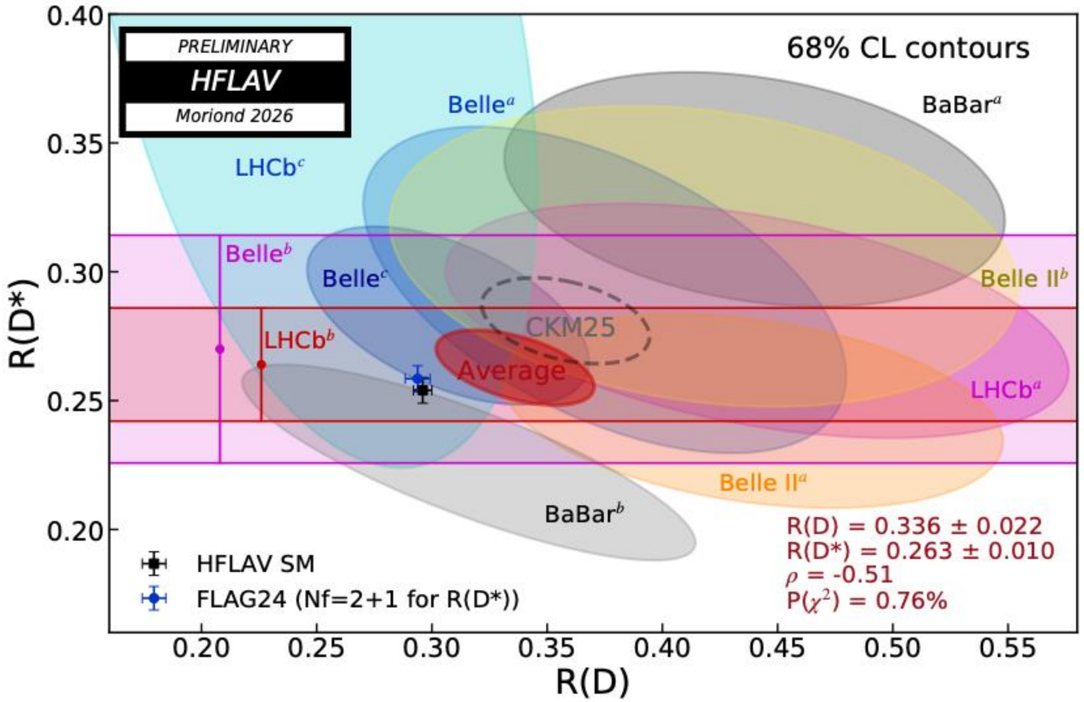
Preliminary Ratios:

- This result BaBar[b]:
  - $R(D) \quad = 0.316 \ \pm 0.062 \pm 0.019$
  - $R(D^{*}) = 0.226 \pm 0.022 \pm 0.012$
  - Correlation: -0.82
- New WA with this result:
  - $R_{WA}(D) \quad = 0.336 \ \pm 0.022$
  - $R_{WA}(D^{*}) = 0.263 \pm 0.010$
  - 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 ($m^2_{\rm miss}$);
- extra neutral energy in the calorimeter ($E_{\rm extra}$);
- angle between the thrust axis of the event and the beam momentum;
- 3-momentum magnitude of $B_{\rm tag}$'s and $B_{\rm sig}$'s leptons in the CM frame;
- cosine of the angle between the 3-momentum of $B_{\rm tag}$ and the sum of its $D^{(*)}$ and charged lepton daughters in the CM frame ($\cos\theta^{\rm tag}_{B-D^{(*)}l}$);
- 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 $B_{\rm sig}$ 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 $\Upsilon(4S) \rightarrow B\bar{B}, c\bar{c}, uds$:
  - Produced in ratio based on cross-sections: $B\bar{B}, c\bar{c}, uds :: 1.05\, nb: 1.3\, nb: 2.1\, nb$.

Systematic Uncertainties – Form Factors

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

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \to Dl\nu$ form factor	0.42	0.13	-0.18
$B \to D^*l\nu$ form factor	0.92	0.31	-0.19
$B \to D^{**}l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \to D^{(*)}l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \to c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \to D^{**}l\nu)$	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
$\mathcal{B}(\tau \to l^-\bar{\nu}_l\nu_\tau)$	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.
  - $B \to D^{(*)} l\upsilon$: use World Average (WA) + uncertainties; reweight each event; repeat analysis.
  - $B \to D^{**} l\upsilon$: 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 $D \to K\pi\pi$; reweight each event by 0.992; repeat analysis.
  - $B(\tau^- \to l^- \bar{\upsilon}_l \upsilon_\tau)$: propagate World Average uncertainties as systematic.

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \to D l\nu$ form factor	0.42	0.13	-0.18
$B \to D^* l\nu$ form factor	0.92	0.31	-0.19
$B \to D^{**} l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \to D^{(*)} l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \to c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \to D^{**} l\nu)$	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
$\mathcal{B}(\tau \to l^- \bar{\nu}_l \nu_\tau)$	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

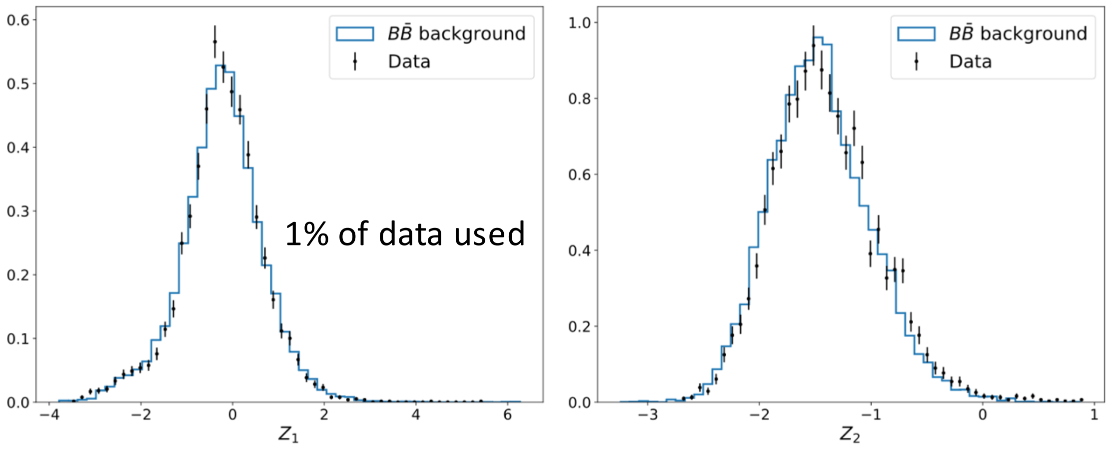
Systematic Uncertainties – Detector Efficiencies

- $B(\Upsilon(4S))$:
  - 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
$B \to Dl\nu$ form factor	0.42	0.13	-0.18
$B \to D^*l\nu$ form factor	0.92	0.31	-0.19
$B \to D^{**}l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \to D^{(*)}l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \to c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \to D^{**}l\nu)$	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
$\mathcal{B}(\tau \to l^-\bar{\nu}_l\nu_\tau)$	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:
    - $E_{extra} > 1.0\ GeV;\ |p_l^{sig}| < 0.4\ GeV$



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

Source	$\Delta R(D)$ (%)	$\Delta R(D^*)$ (%)	Correlation
$B \to Dl\nu$ form factor	0.42	0.13	-0.18
$B \to D^*l\nu$ form factor	0.92	0.31	-0.19
$B \to D^{**}l\nu$ form factor	0.48	0.18	-0.90
$\mathcal{B}(B \to D^{(*)}l\nu)$	0.47	0.38	0.97
$\mathcal{B}(b \to c\bar{c})$	0.34	0.13	1
$\mathcal{B}(B \to D^{**}l\nu)$	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
$\mathcal{B}(\tau \to l^-\bar{\nu}_l\nu_\tau)$	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:
  - $z_1 \geq 2$, $z_2 \leq -4$