Precision Measurement on $R\left(D^{(*)}\right)$ with Inclusive Tagging Methods at Belle II

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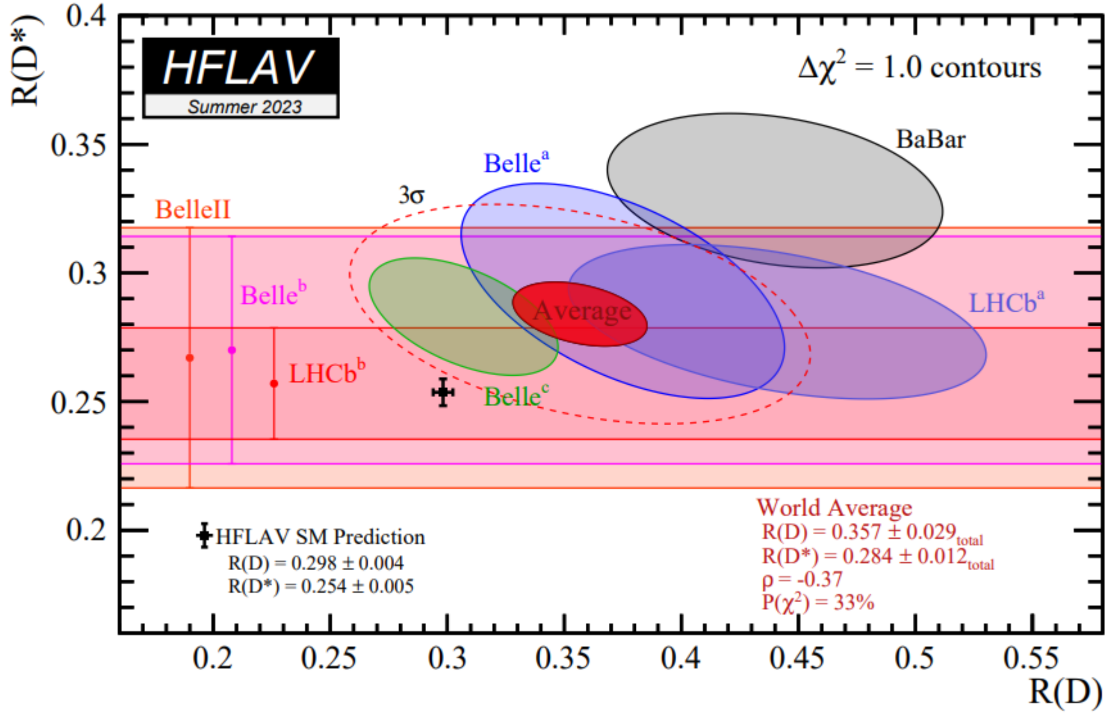
Belle II Summer School 2023 – Duke University
July 28, 2023

Results and Predictions

- The standard model predicts all leptons have the same coupling ($g_{\ell=e,\mu,\tau}$) to electroweak bosons ($W^{\pm}, Z^0$)
- HFLAV average tension of 3.3σ
- OUR GOAL: Increase precision of $R(D^{(*)})$ measurement with *inclusive tagging* to further test lepton flavor universality…



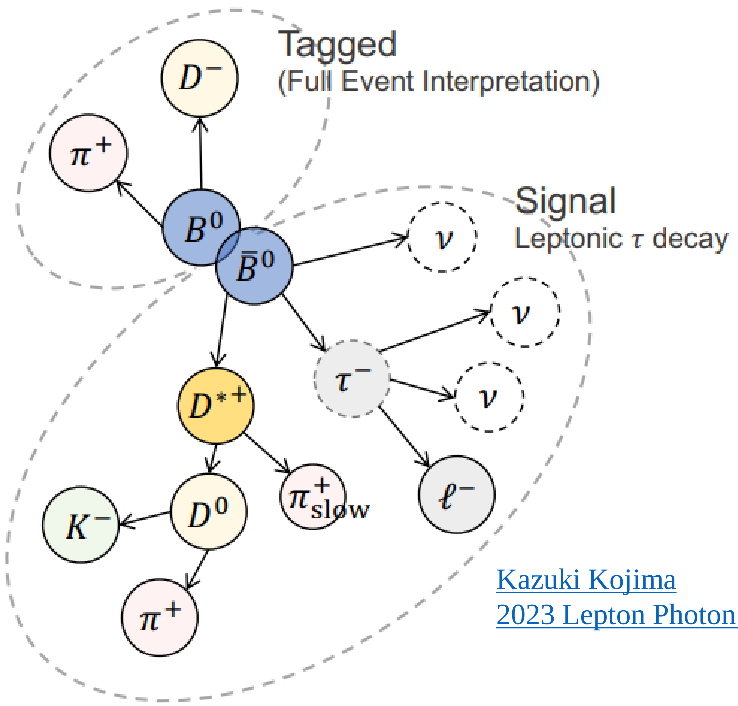
$$\Gamma(B^- \to D^0 \ell^- \bar{\nu}_\ell) \propto \frac{g_\ell^2}{M_W^2}\frac{g^2}{M_W^2} m_B^5$$

$$\mathrm{R}(D) = \frac{\Gamma(B^- \to D^0 \tau^- \bar{\nu}_\tau)}{\Gamma(B^- \to D^0 \ell^- \bar{\nu}_\ell)} \propto \frac{g_\tau^2}{g_\ell^2}$$

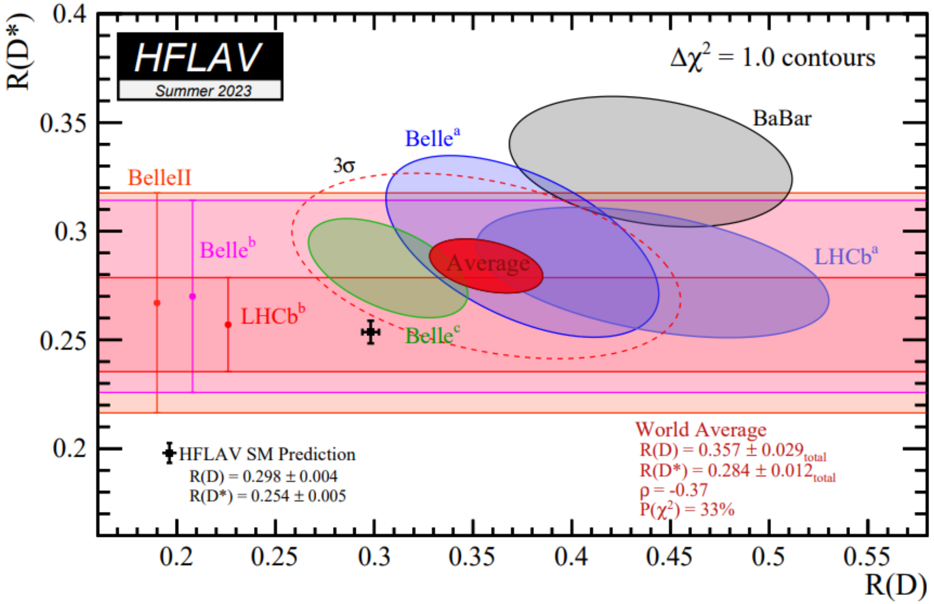
$$R\left(D^{(*)}\right) = \frac{N\left(D^{(*)}\tau\nu\right)}{N\left(D^{(*)}\ell\nu\right)} \frac{\varepsilon\left(D^{(*)}\ell\nu\right)}{\varepsilon\left(D^{(*)}\tau\nu\right)} \frac{1}{\mathcal{B}(\tau)}$$

Removes most systematic uncertainties

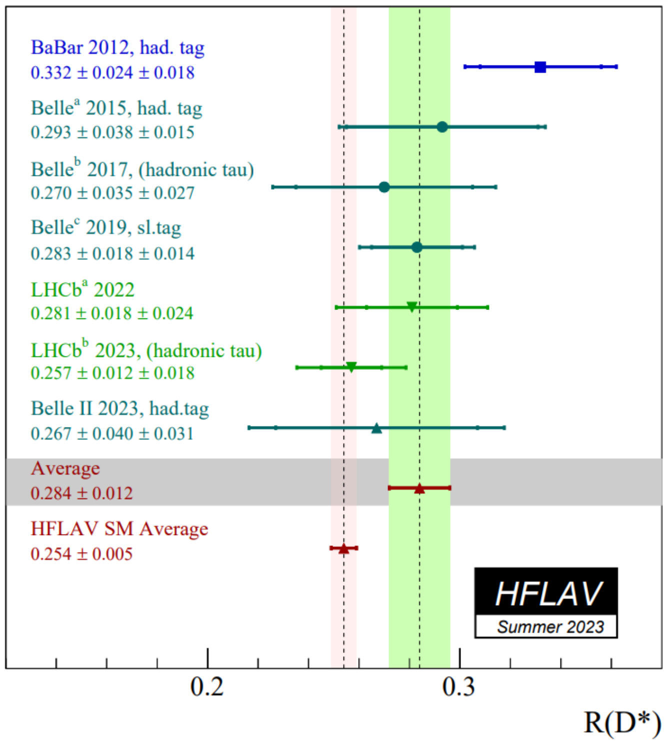
Belle II Results



Kazuki Kojima
2023 Lepton Photon Conference



HFLAV



$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$

First lepton flavor universality (LFU) results from Belle II!

Shifts difference (exceeding) standard model (SM) predictions from 3.2σ to 3.3σ

Standard Model (SM) predictions:

$$R(D) = 0.298 \pm 0.004$$
$$R(D^*) = 0.254 \pm 0.005$$

Inclusive Tagging Method

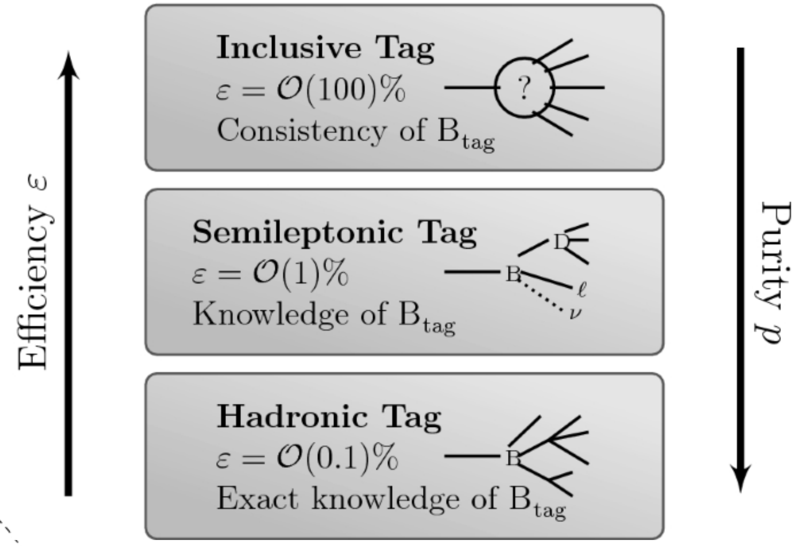
[FEI Thomas Keck]

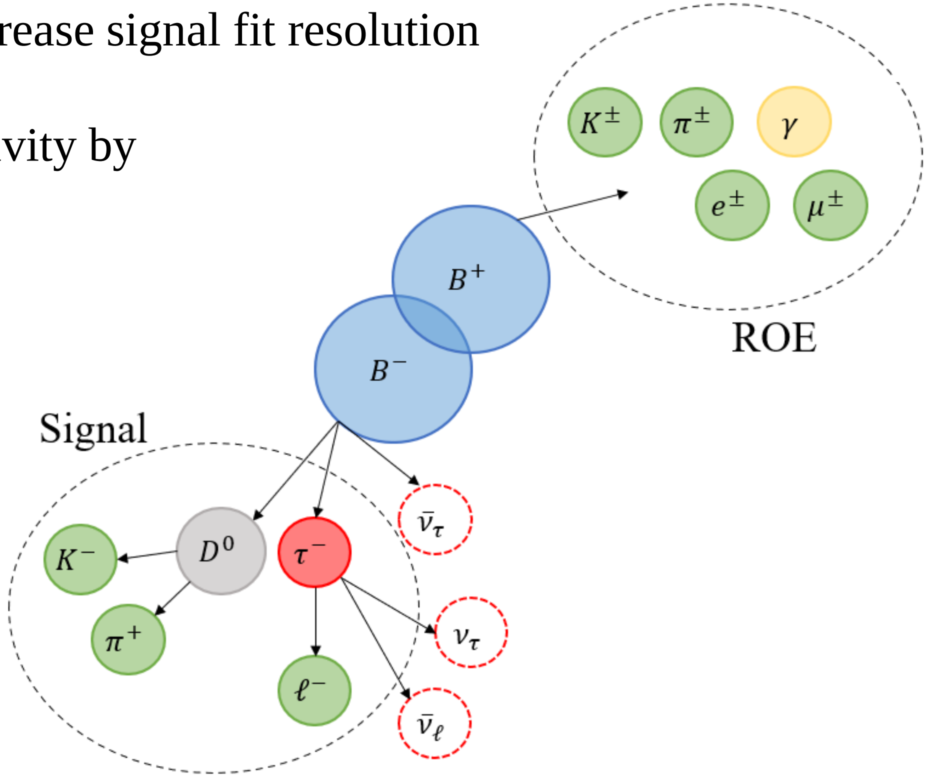
- With good ROE, exploit Belle II high resolution tracking, impact parameter, and small beam spot

- Exact topology of tag side is not important, but simple masks placed to ensure "good" B_{tag}
    - Apply lepton veto to ROE to ensure there is no missing energy on the tag side → increase signal fit resolution

- ADVANTAGE: Maximize sensitivity by increasing signal efficiency

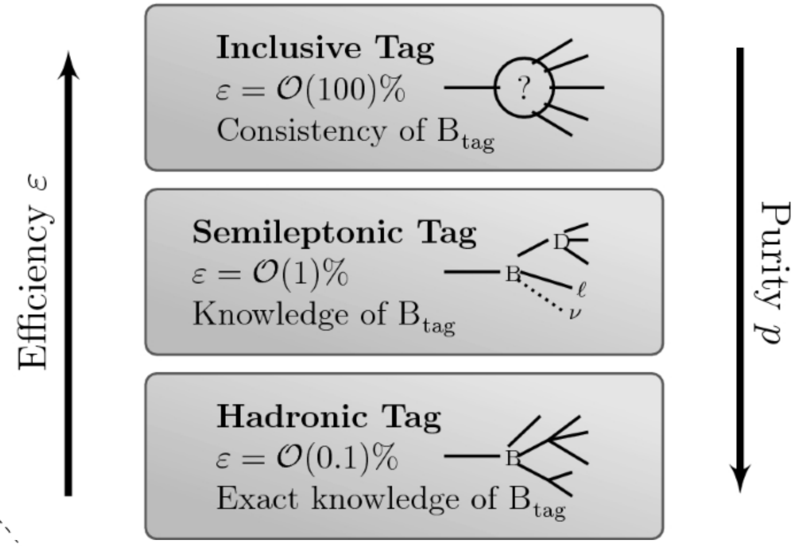
- DISADVANTAGE: Yields lower purity compared to FEI tagging





Inclusive Tagging Method

[FEI Thomas Keck](#)



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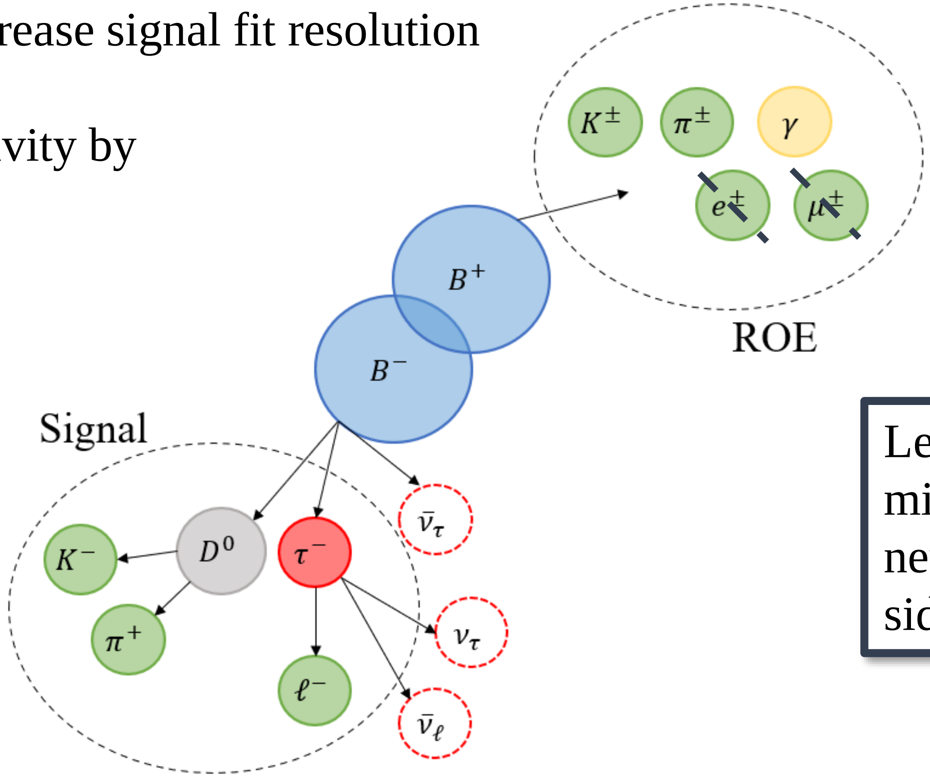

Lepton veto applied to ensure no missing information due to neutrinos is present on the tag side

Analysis Procedure

Signal Reconstruction
Simultaneously reconstruct signal and normalization modes.

Variable	$B \to De\nu$	$B \to D\tau\nu$
binary K-ID	> 0.1	
binary π-ID	> 0.1	
$e^{\pm}$-p [GeV/c]	> 0.2	
MVA e-ID	> 0.9	
D^0 InvM [GeV/c^2]	$1.85 < \text{InvM} < 1.88$	
ε	$(27.1 \pm 0.1)\%$	$(22.2 \pm 0.1)\%$

Analysis Procedure

ROE Mask	
Track	thetaInCDCAcceptance, pValue > 0.001,
	$\left[pt < 0.15 \ and \ \left(\frac{dr}{3}^2 + \frac{dz}{6}^2\right) < 1\right]$
	or $\left[0.15 < pt < 0.25 \ and \ \left(\frac{dr}{2}^2 + \frac{dz}{3}^2\right) < 1\right]$
	or $\left[0.25 < pt < 0.5 \ and \ \left(\frac{dr}{2}^2 + \frac{dz}{3}^2\right) < 1\right]$
	or $\left[0.5 < pt < 1.0 \ and \ \left(\frac{dr}{2}^2 + \frac{dz}{3}^2\right) < 1\right]$
	or $\left[1.0 < pt \ and \ (dr^2 + dz^2) < 1\right]$
Energy Cluster	beamBackgroundSuppression > 0.15,
	fakePhotonSuppression > 0.15,
	(FWD Endcap, clusterE > 0.075),
	or (BRL, clusterE > 0.05),
	or (BWD Endcap, clusterE > 0.1)

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Rest Of Event
Select only good B_{tag} candidates via minimizing Mbc_{ROE} and ΔE_{ROE} widths

Lepton Veto
Ensure no missing mass for better resolution of signal fit

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Signal Reconstruction
Simultaneously reconstruct signal and normalization modes.

Background Suppression
Application of XGBoost MVA with signal classification:

$$B \to (D^0 \to K\pi)(\tau \to e\nu\bar{\nu})\nu$$

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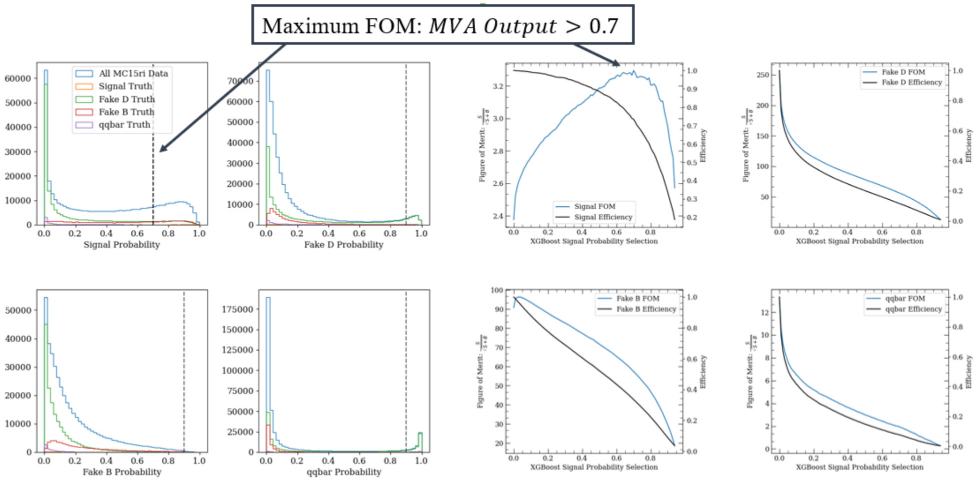

Analysis Procedure

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Track	thetaInCDCAcceptance, pValue > 0.001,
	$\left[pt < 0.15 \ and \ \left(\frac{dr}{3}^2 + \frac{dz}{6}^2\right) < 1\right]$
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Signal Reconstruction
Simultaneously reconstruct signal and normalization modes.

Background Suppression
Application of XGBoost MVA with signal classification:

$$B \rightarrow (D^0 \rightarrow K\pi)(\tau \rightarrow e\nu\bar{\nu})\nu$$

Signal Fit
Employ RooFit to complete KDE template construction and MLE of composite model

Variable	$B \to De\nu$	$B \to D\tau\nu$
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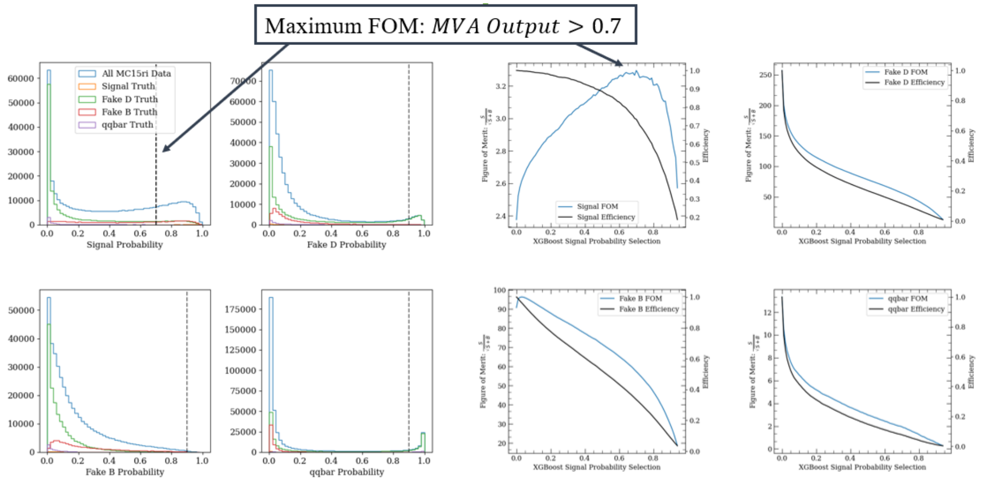
Ensure no missing mass for better resolution of signal fit



Signal Efficiency

$$B^{\pm} \rightarrow (D^0 \rightarrow K\pi)\ell^{\pm}\nu$$

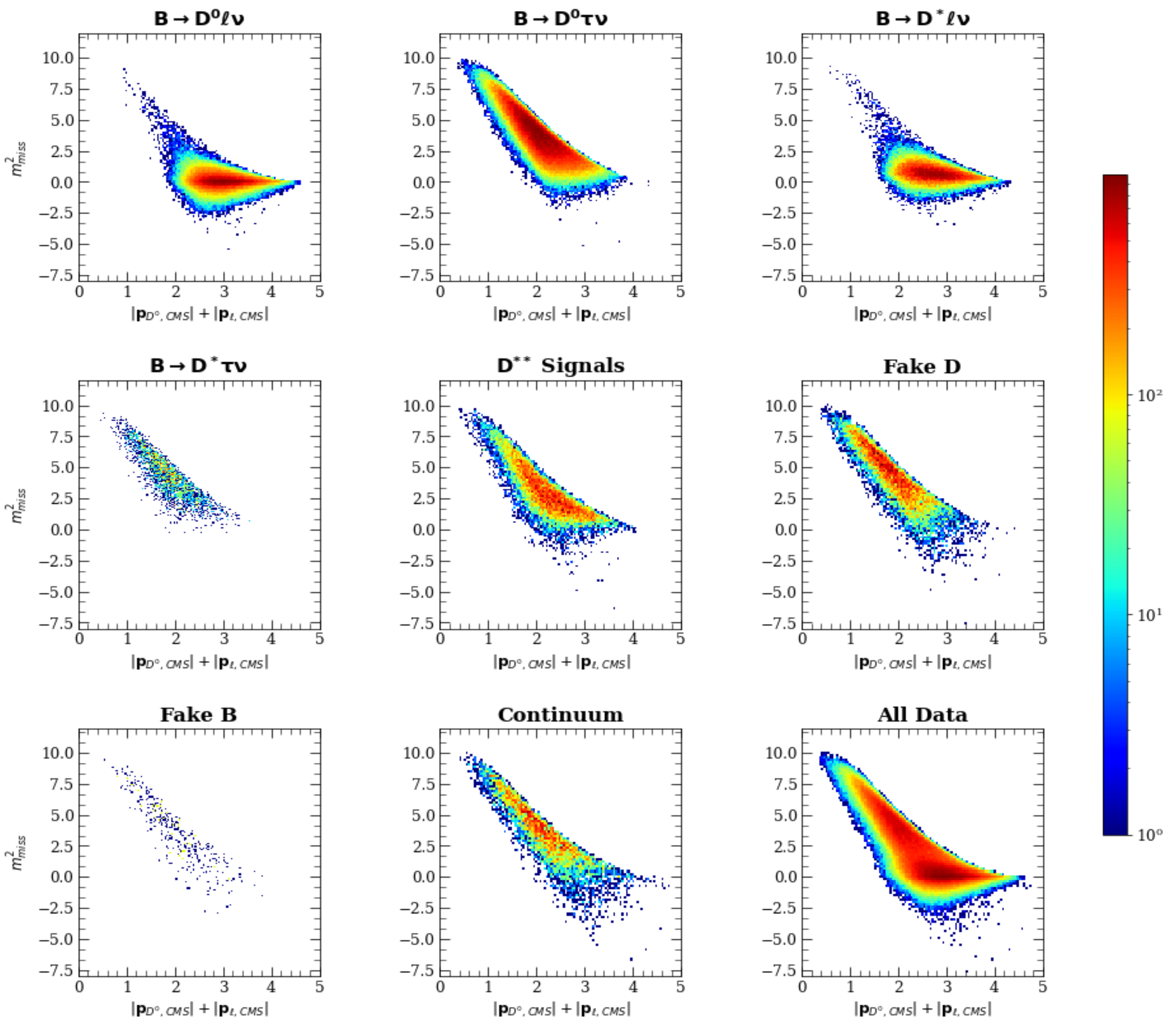
With *hadronic and semi-leptonic tagging*, the efficiency is $\mathcal{O}(\leq 0.5\%)$

$B \rightarrow D^0\ e\ \nu$	Kpi
Reconstruction	0.271 ± 0.001
Rest of Event	
ℓ Veto2	0.253 ± 0.001
5.2<Mbc	0.191 ± 0.001
-4<deltaE<2	0.190 ± 0.001
Background Suppression	
SignalProb>0.7	0.077 ± 0.002
Best Candidate Selection	
B vertex chiProb	0.077 ± 0.002

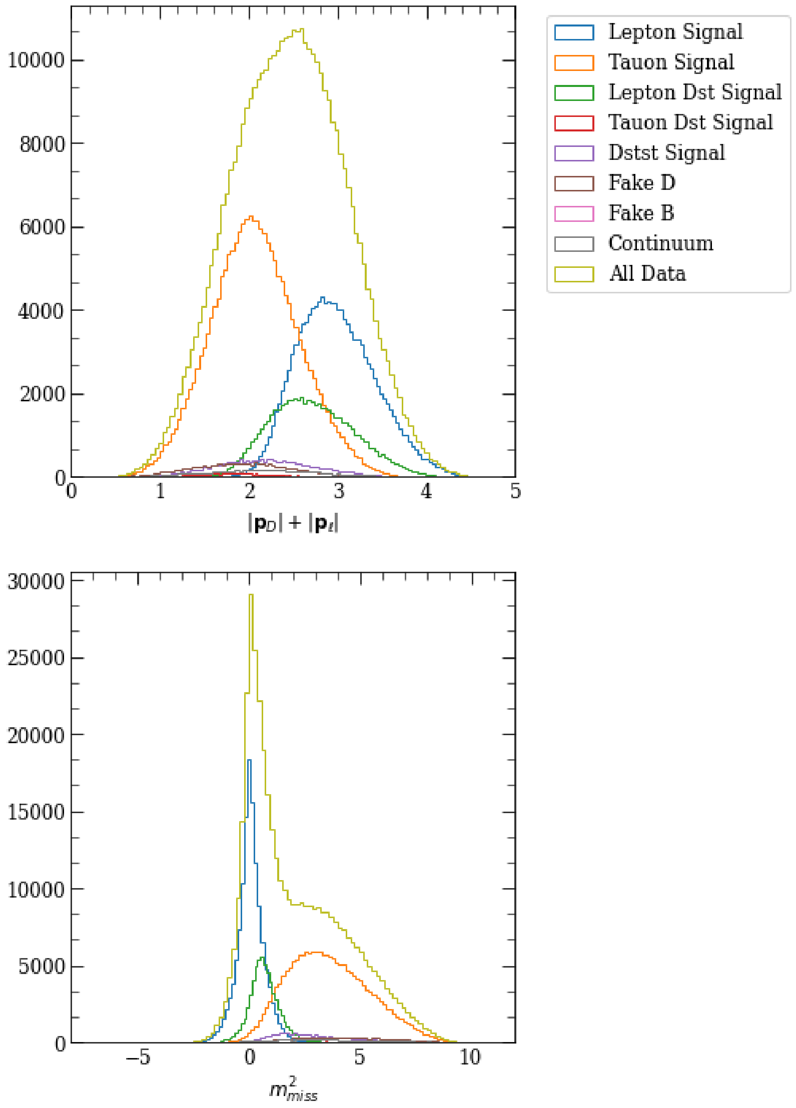
$B \rightarrow D^0\ \tau(\rightarrow e\nu\nu)\ \nu$	Kpi
Reconstruction	0.222 ± 0.001
Rest of Event	
ℓ Veto2	0.207 ± 0.001
5.2<Mbc	0.158 ± 0.001
-4<deltaE<2	0.157 ± 0.001
Background Suppression	
SignalProb>0.7	0.126 ± 0.002
Best Candidate Selection	
B vertex chiProb	0.126 ± 0.002

With *inclusive tagging* we get efficiency of $\mathcal{O}(10\%)$

MC Truth



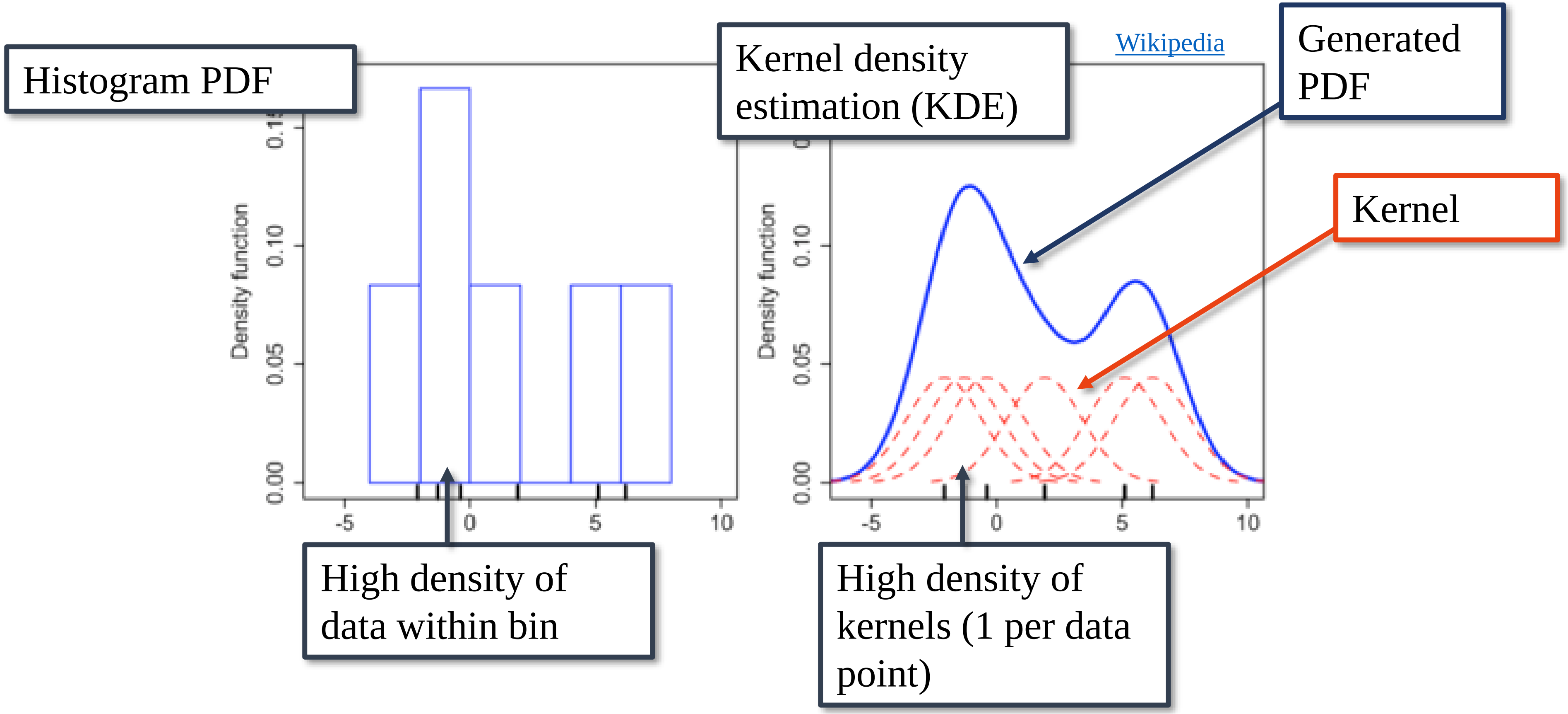
$B \to D^0 \ell \nu$
$B \to D^0 \tau \nu$
$B \to D^* \ell \nu$
$B \to D^* \tau \nu$
D^{**} Signals
Fake D
Fake B
Continuum
All Data
m^2_{miss}
$|\mathbf{p}_{D^0,CMS}| + |\mathbf{p}_{\ell,CMS}|$



Lepton Signal
Tauon Signal
Lepton Dst Signal
Tauon Dst Signal
Dstst Signal
Fake D
Fake B
Continuum
All Data
$|\mathbf{p}_D| + |\mathbf{p}_\ell|$
m^2_{miss}

Kernel Density Estimation

- Non-parametric method of constructing a continuous PDF based on dataset
- Each data point is assigned a multi-dimensional kernel (Gaussian)



Kernel Density Estimation

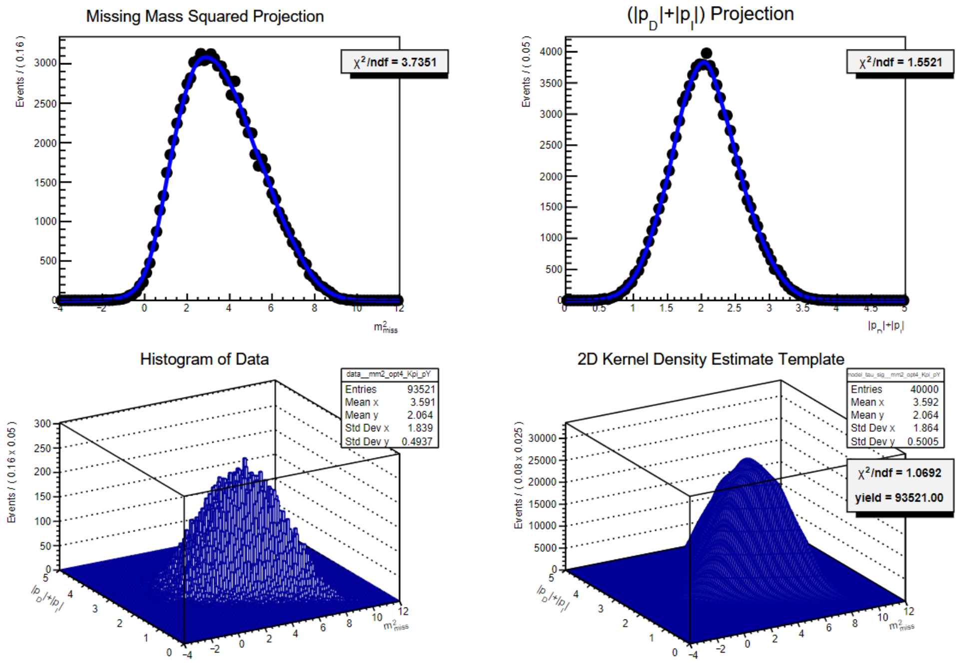
Statistics	
Signal Component	Events Used for Template Construction
$B \to D^0 \tau \nu$	93438
$B \to D^0 e \nu$	64741
$B \to D^* \tau \nu$	1468
$B \to D^* e \nu$	30278

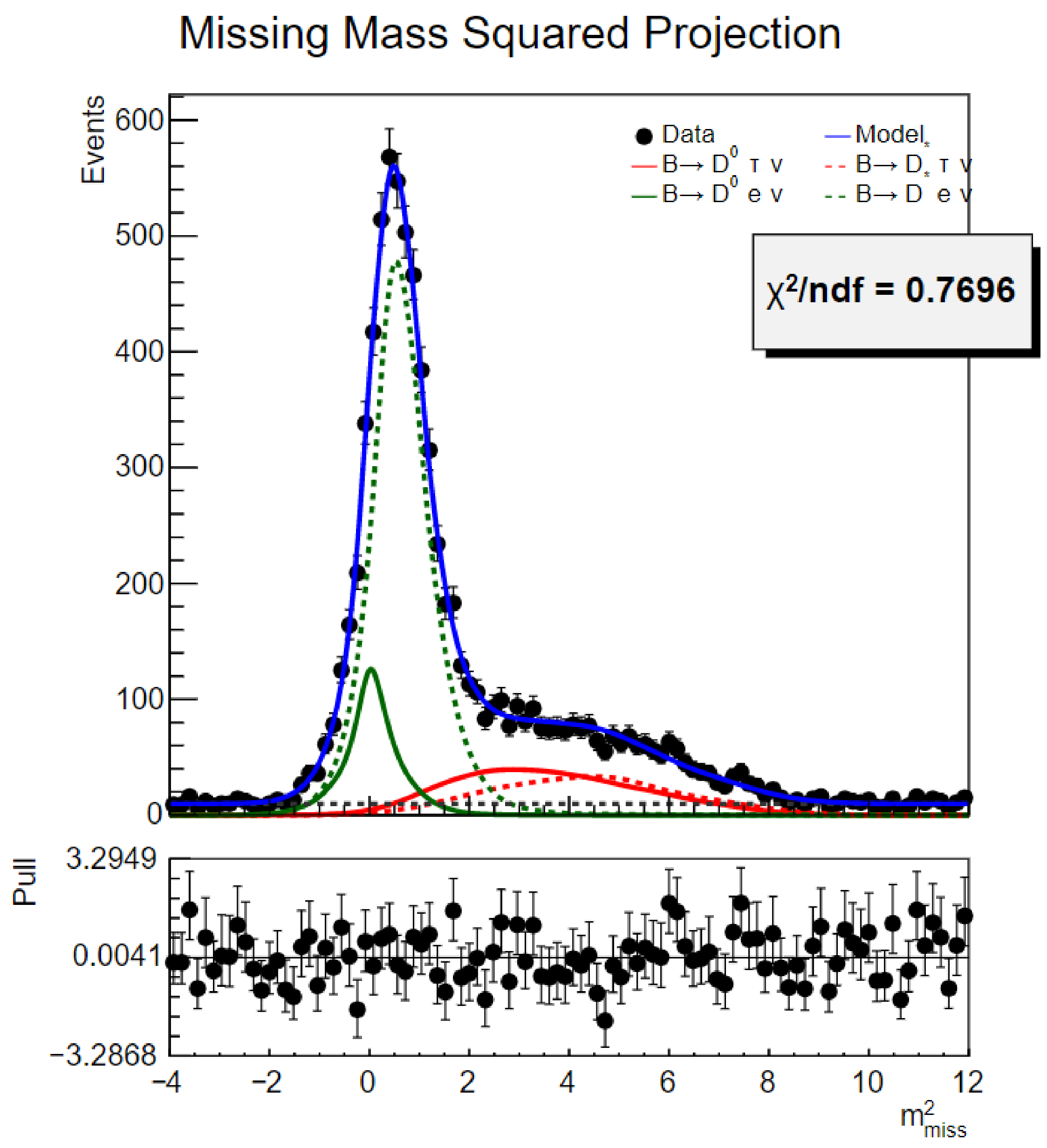
- Non-parametric method of constructing a continuous PDF based on dataset
- Each data point is assigned a multi-dimensional kernel (Gaussian)
- User defines bandwidth (# datapoints associated with kernel) which controls the tradeoff between smoothness and fine-scale fluctuations

ADVANTAGE: Avoid bias of binning associated with a histogram (binned) PDF → increase sensitivity

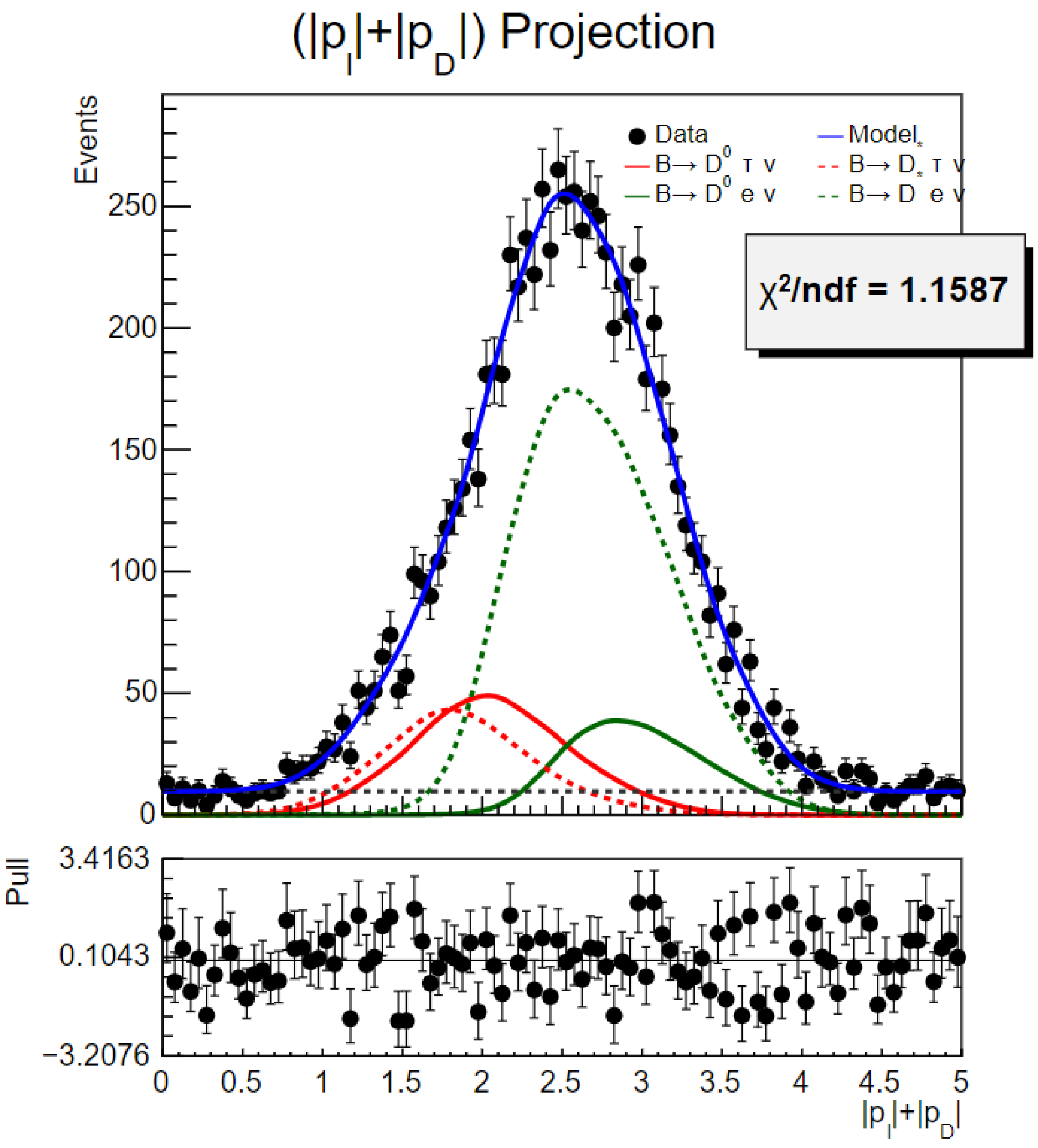
DISADVANTAGE: Unbinned fit requires extended processing time

$B \to (D^0 \to K\pi)\tau\nu$ Template
Bandwidth = 2
Any smaller leads to *overfitting* (PDF fits each data point and microscopic fluctuations present)
Any larger leads to *underfitting* (greatly worsen χ^2/ndf and unable to extract macroscopic properties, ie amplitude)

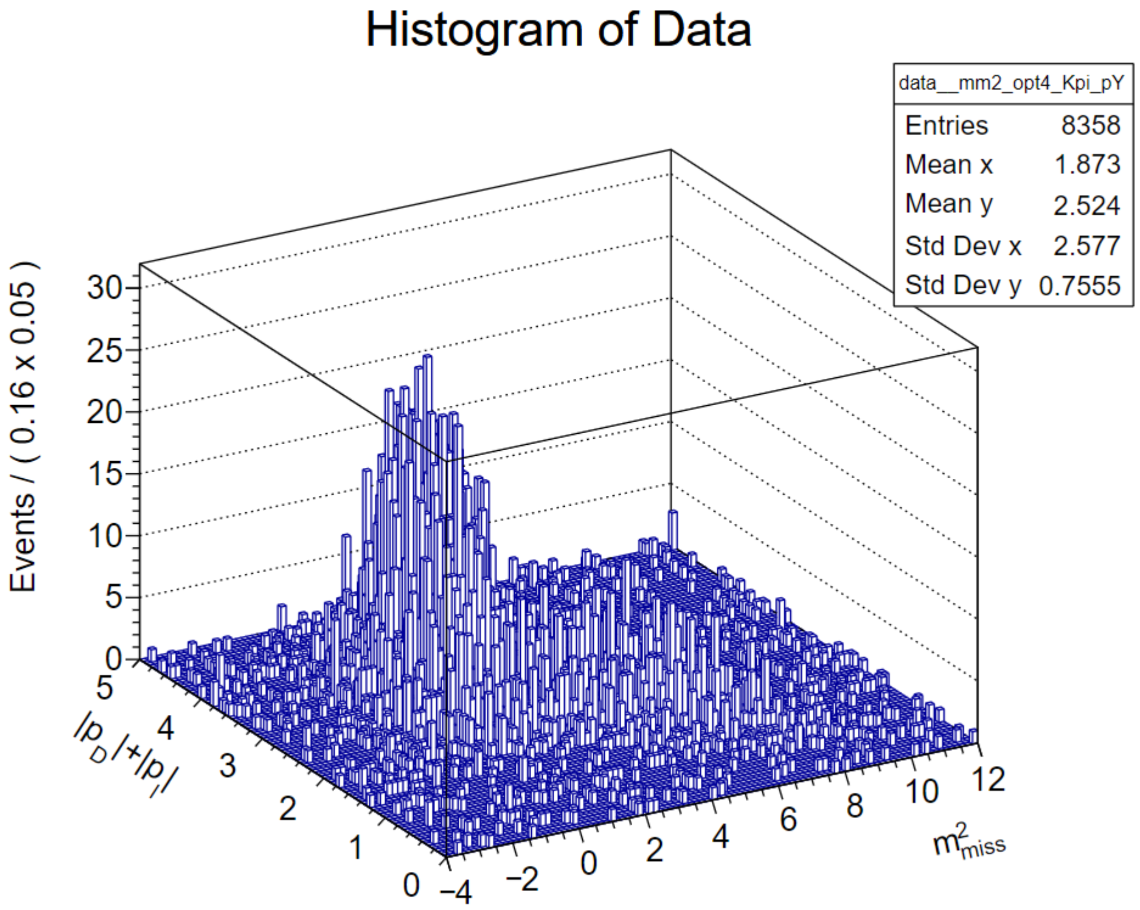


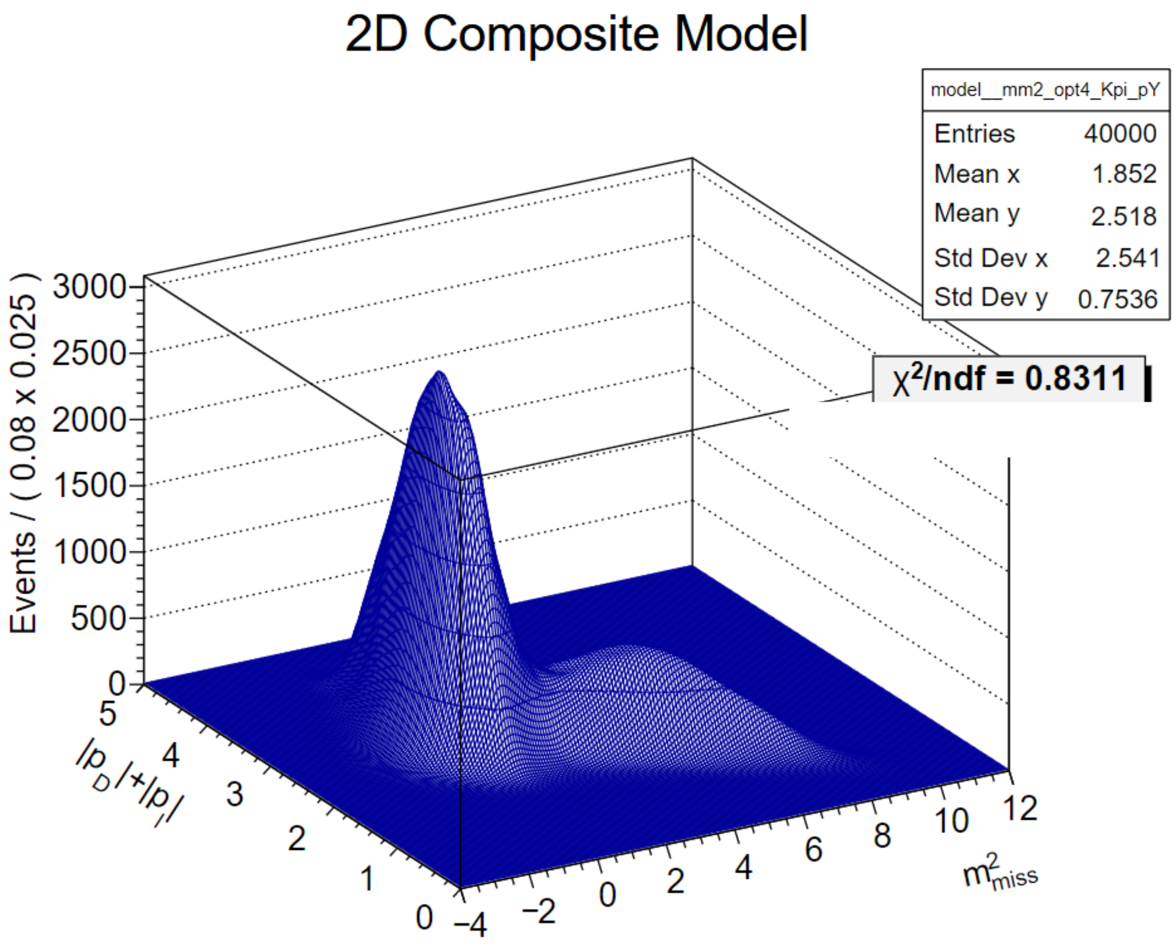


Missing Mass Squared Projection
Events
Data
Model
B→ D0 τ ν
B→ D* τ ν
B→ D0 e ν
B→ D e ν
χ2/ndf = 0.7696
Pull
3.2949
0.0041
−3.2868
m2miss



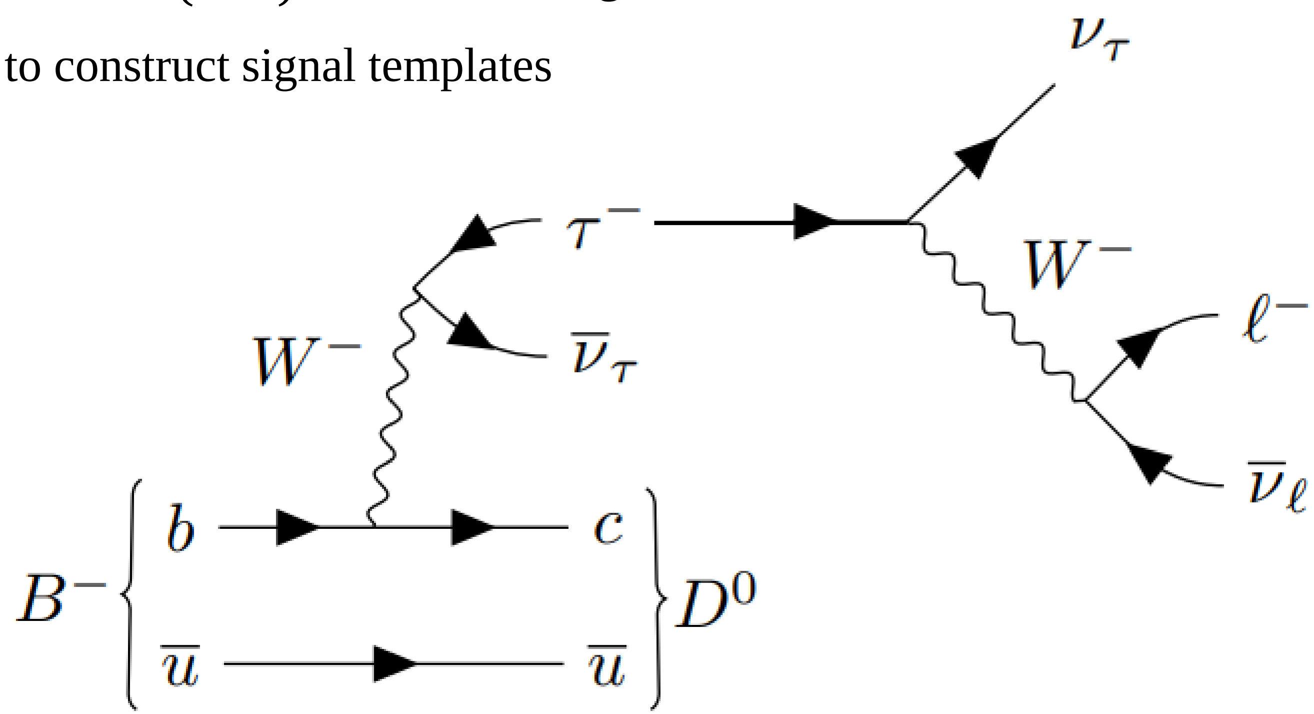
(|pl|+|pD|) Projection
Events
Data
Model
B→ D0 τ ν
B→ D* τ ν
B→ D0 e ν
B→ D e ν
χ2/ndf = 1.1587
Pull
3.4163
0.1043
−3.2076
|pl|+|pD|


Histogram of Data
data__mm2_opt4_Kpi_pY
Entries 8358
Mean x 1.873
Mean y 2.524
Std Dev x 2.577
Std Dev y 0.7555
Events / (0.16 x 0.05)
|p_D|+|p_l|
m²_miss


2D Composite Model
model__mm2_opt4_Kpi_pY
Entries 40000
Mean x 1.852
Mean y 2.518
Std Dev x 2.541
Std Dev y 0.7536
χ²/ndf = 0.8311
Events / (0.08 x 0.025)
|p_D|+|p_l|
m²_miss

Concluding Remarks

- A test of lepton flavor universality via a precision measurement on $R\left(D^{(*)}\right)$ → deviation from the SM prediction could be signs of new physics!
- *Inclusive tagging* permits high efficiency → increased sensitivity
- Simultaneous reconstruction of signal and normalization modes
- Most errors cancel out in $R\left(D^{(*)}\right)$ as we are taking the ratio
- KDE is employed to construct signal templates



Backup Slides

MetaData

D^0 Signal Metadata	
Release	release-06-00-08
Generated Signal Events	20M Events
$K\pi + K2\pi$ File	13.5e6
$\rightarrow K\pi$ (0.0395)	2905995
$\rightarrow K2\pi$ (0.144)	10594005
$K3\pi$ File	6.5e6

D^{*0} Signal Metadata	
Release	release-06-00-08
Generated Signal Events	5M Events
$K\pi + K2\pi$ File	3.4e6
$\rightarrow K\pi$ (0.0395)	731880
$\rightarrow K2\pi$ (0.144)	2668120
$K3\pi$ File	1.6e6

D^{*+} Signal Metadata	
Release	release-06-00-08
Generated Signal Events	5M Events
$K\pi + K2\pi$ File	3.4e6
$\rightarrow K\pi$ (0.0395)	731880
$\rightarrow K2\pi$ (0.144)	2668120
$K3\pi$ File	1.6e6

Reconstruction Release: light-2303-iriomote
MC15ri_b Samples

Signal Selection

Standard lists with [recommended corrections]

Final State Selection	
lepton veto	
kaon goodTrack binary kaonID (no SVD)	
pion goodTrack (no pt>0.1 for K3pi) binary pionID (noSVD) (not for K3pi)	
pi0 eff50_May2020Fit pi0 goodGamma pi0 pt > 0.15 [GeV/c]	
electron pt > 0.2 [GeV/c] MVA electronID > 0.9	muon pt > 0.6 [GeV/c] MVA muonID > 0.9 [GeV/c]

Composite State Selection: electron		
Kpi	**K2pi**	**K3pi**
1.85386 < InvM < 1.87562 D0 vertex fit (conf_level=0.001)	1.83637 < InvM < 1.88824 D0 vertex fit (conf_level=0.001, pi0 mass constraint)	1.85342 < InvM < 1.8756 D0 vertex fit (conf_level=0.001)
B vertex fit (conf_level=0.001)	B vertex fit (conf_level=0.001)	B vertex fit (conf_level=0.001)

Signal Definition

The signal is defined through...

1. The intermediate resonance structure for the respective decay branch (TopoAna)
   - nSigIncCascDcyBr_(decay branch) and B_mcPDG=-521
   - nCcSigIncCascDcyBr_(decay branch) and B_mcPDG=521
2. (B_mcPDG*D_mcPDG)=-521*421 or (B_mcPDG*D_mcPDG)=-511*421
   - The multiplication of the mcPDGs ensures the mode is properly reconstructed (i.e. proper D associated with the proper B)
3. (D_mcPDG*l_mcPDG)=lrec*421
   - lrec $\in \{11, 13\}$
4. B_mcErrors $< \{16, 32, 64, 152\}$.
   - D^0:
     - electron/muon: B_mcErrors < 16
     - tauon: B_mcErrors < 32
   - D^{*0} and D^{**0}: B_mcErrors < 64
   - D^{*+} and D^{**+}: B_mcErrors < 521
5. (l_mcPDG*l_genMotherPDG)=lrec*lmother
   - lrec $\in \{11, 13\}$
   - lmother $\in \{521, 511, 15\}$

Signal Efficiency

$$B \rightarrow (D^{*0} \dashrightarrow K\pi)\ell\nu$$

$\mathbf{B \rightarrow D^{*0}\ e\ \nu}$	Kpi
Reconstruction	0.227 ± 0.002
Rest of Event	
ℓ Veto2	0.212 ± 0.002
5.2<Mbc	0.158 ± 0.003
-4<deltaE<2	0.157 ± 0.003
Background Suppression	
MVA Output>0.7	0.067 ± 0.004
Best Candidate Selection	
B vertex chiProb	0.067 ± 0.004

$\mathbf{B \rightarrow D^{*0}}\ \tau(\rightarrow e\nu\nu)\ \nu$	Kpi
Reconstruction	0.182 ± 0.002
Rest of Event	
ℓ Veto2	0.170 ± 0.002
5.2<Mbc	0.129 ± 0.003
-4<deltaE<2	0.128 ± 0.003
Background Suppression	
MVA Output>0.7	0.088 ± 0.004
Best Candidate Selection	
B vertex chiProb	0.088 ± 0.004

Signal Efficiency

$$B \to (D^{*+} \dashrightarrow K\pi)\ell\nu$$

$\mathbf{B} \to \mathbf{D}^{*+}$ e ν	Kpi
Reconstruction	0.273 ± 0.002
Rest of Event	
ℓ Veto2	0.254 ± 0.002
5.2<Mbc	0.188 ± 0.003
-4<deltaE<2	0.150 ± 0.003
Background Suppression	
MVA Output>0.7	0.077 ± 0.004
Best Candidate Selection	
B vertex chiProb	0.077 ± 0.004

$\mathbf{B} \to \mathbf{D}^{*+}\ \tau(\to$ e $\nu\nu)\ \nu$	Kpi
Reconstruction	0.216 ± 0.002
Rest of Event	
ℓ Veto2	0.201 ± 0.002
5.2<Mbc	0.151 ± 0.003
-4<deltaE<2	0.187 ± 0.003
Background Suppression	
MVA Output>0.7	0.102 ± 0.004
Best Candidate Selection	
B vertex chiProb	0.102 ± 0.004

MVA and BCS Statistics

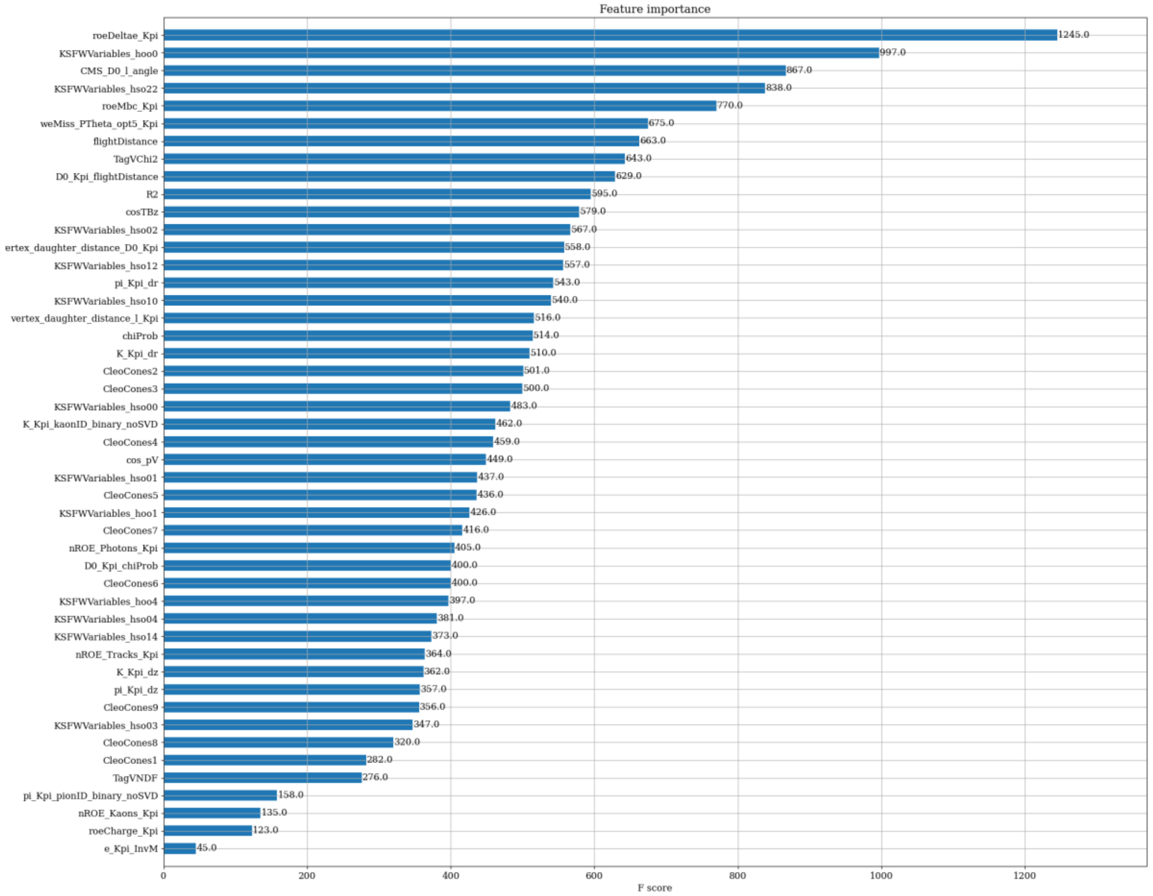
	Efficiency (SigProb>0.7)	Figure of Merit: $\frac{S}{\sqrt{S+B}}$	Candidates Before	Candidates After
Relative Sample Signal	0.7343	3.2958		
Fake D	0.1158	56.2299		
Fake B	0.3347	57.3869		
qqbar	0.0772	1.9459		
TOTAL			965644	414869

MVA Background Suppression

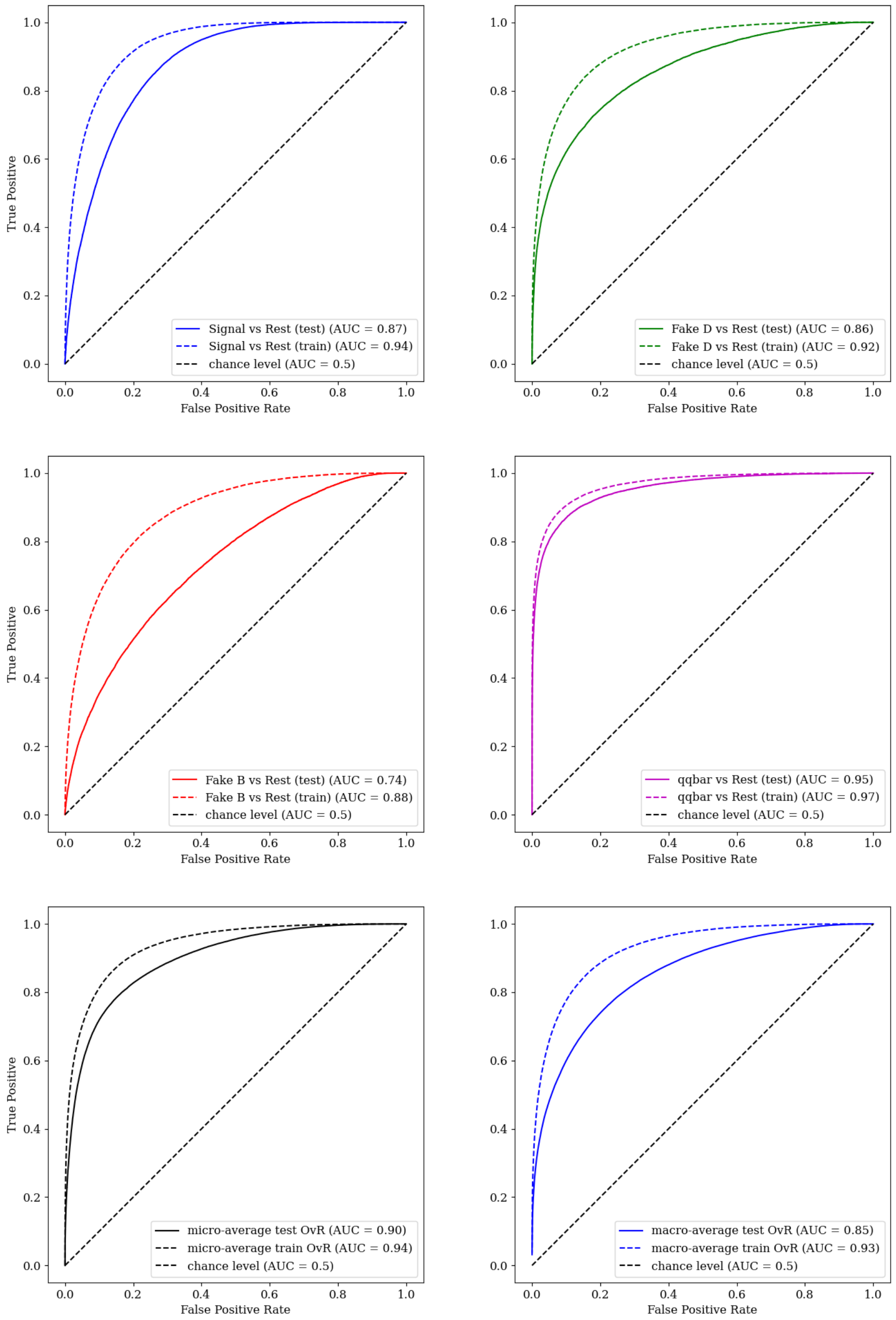
	Mean # Candidates Before	# Candidates Before	Mean # Candidates After	# Candidates After
TOTAL	1.005	414869	1.003	414256

Best Candidate Selection

MVA Output

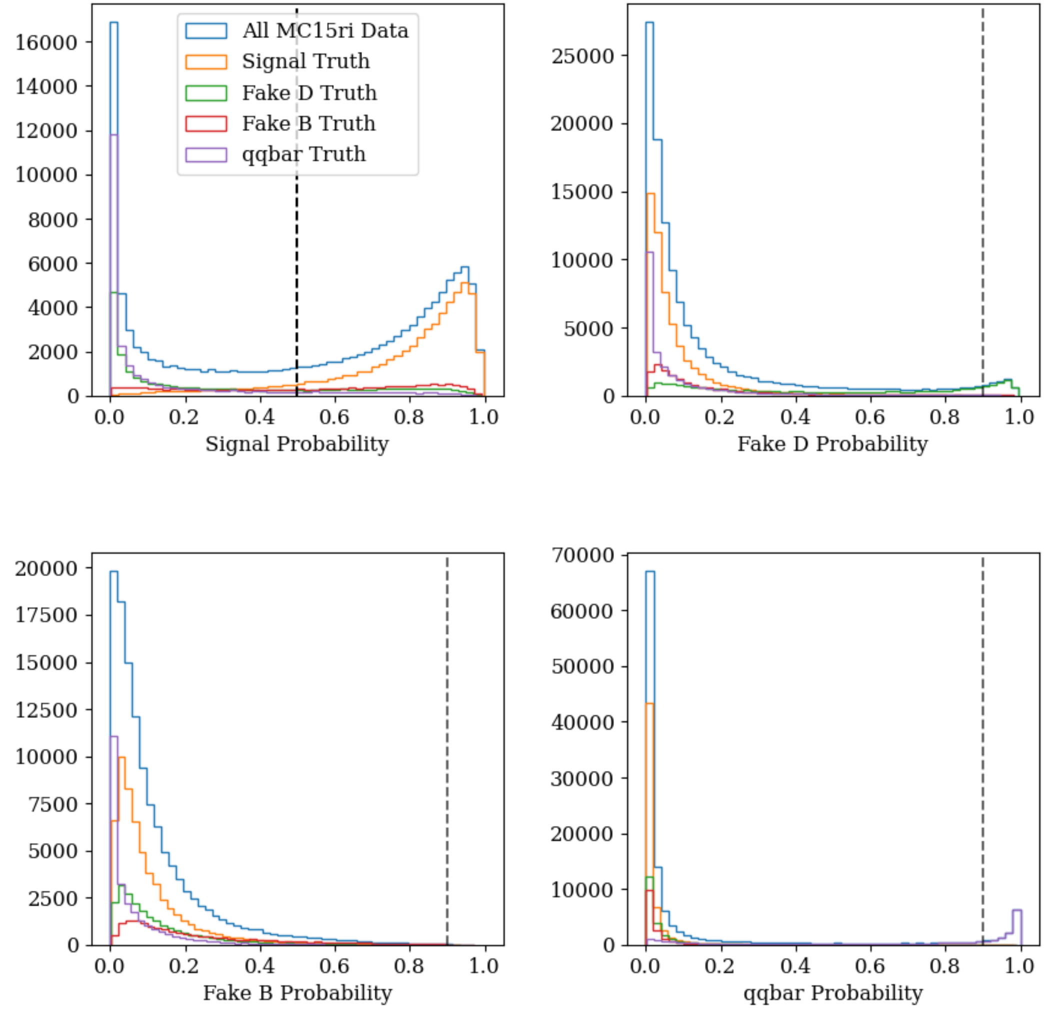


Test Data:

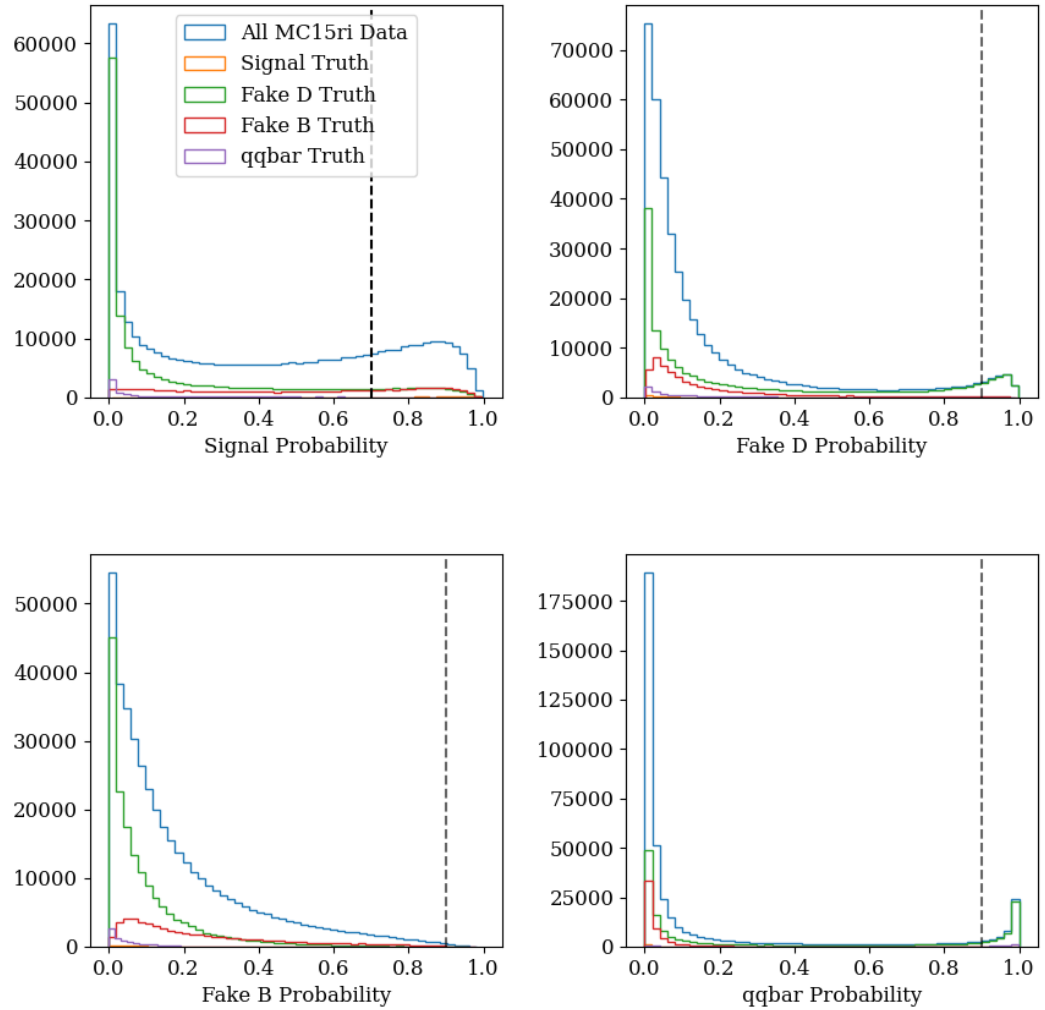


MVA Output

Train Data:

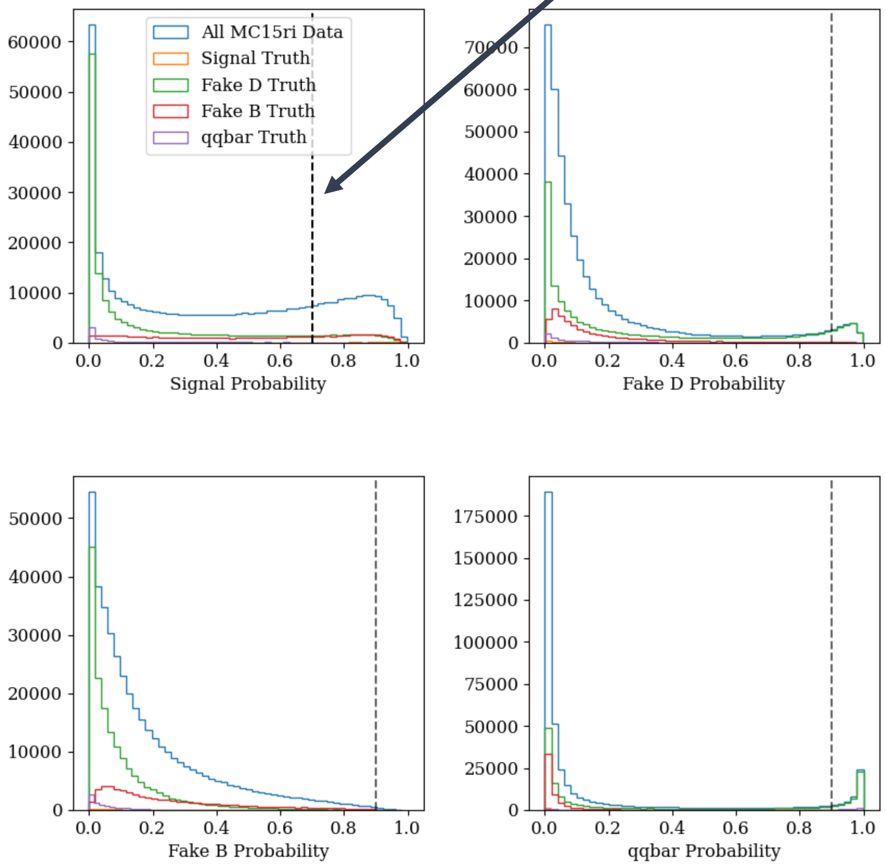


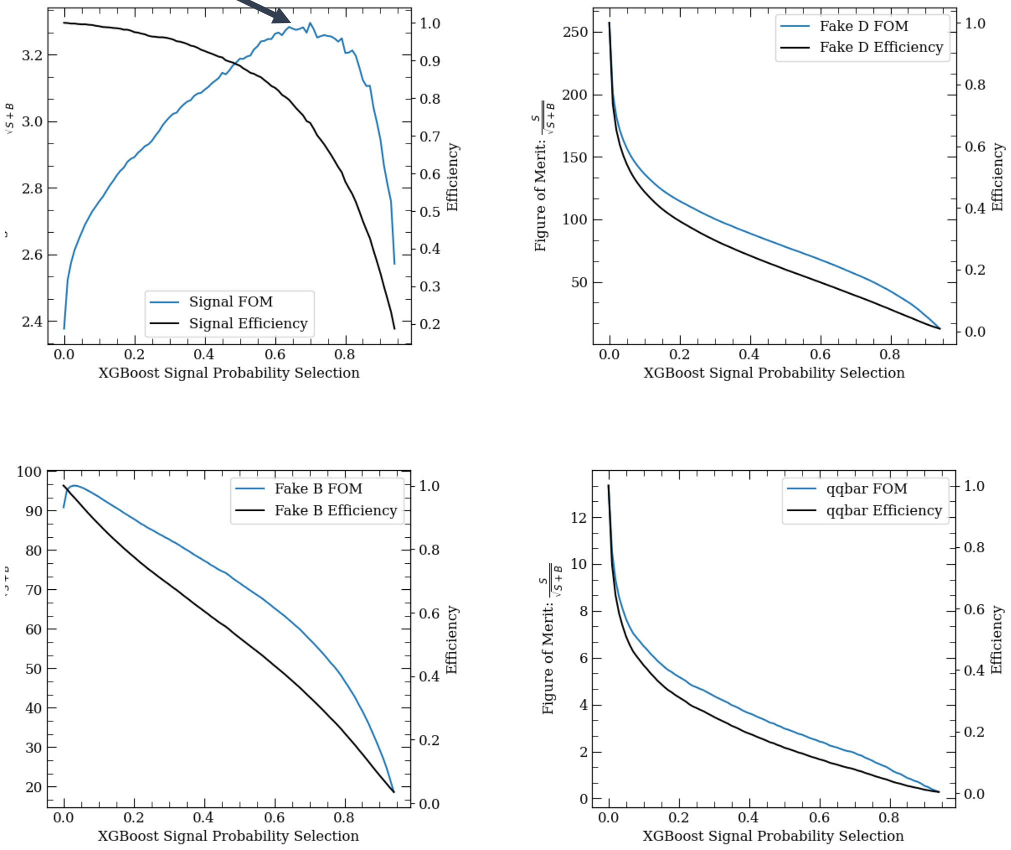
Independent Data (w/o Signal MC):



MVA Output

Maximum FOM: $MVA\ Output > 0.7$





Dominant Generated Signals

Number of B- cases

Number of B+ cases

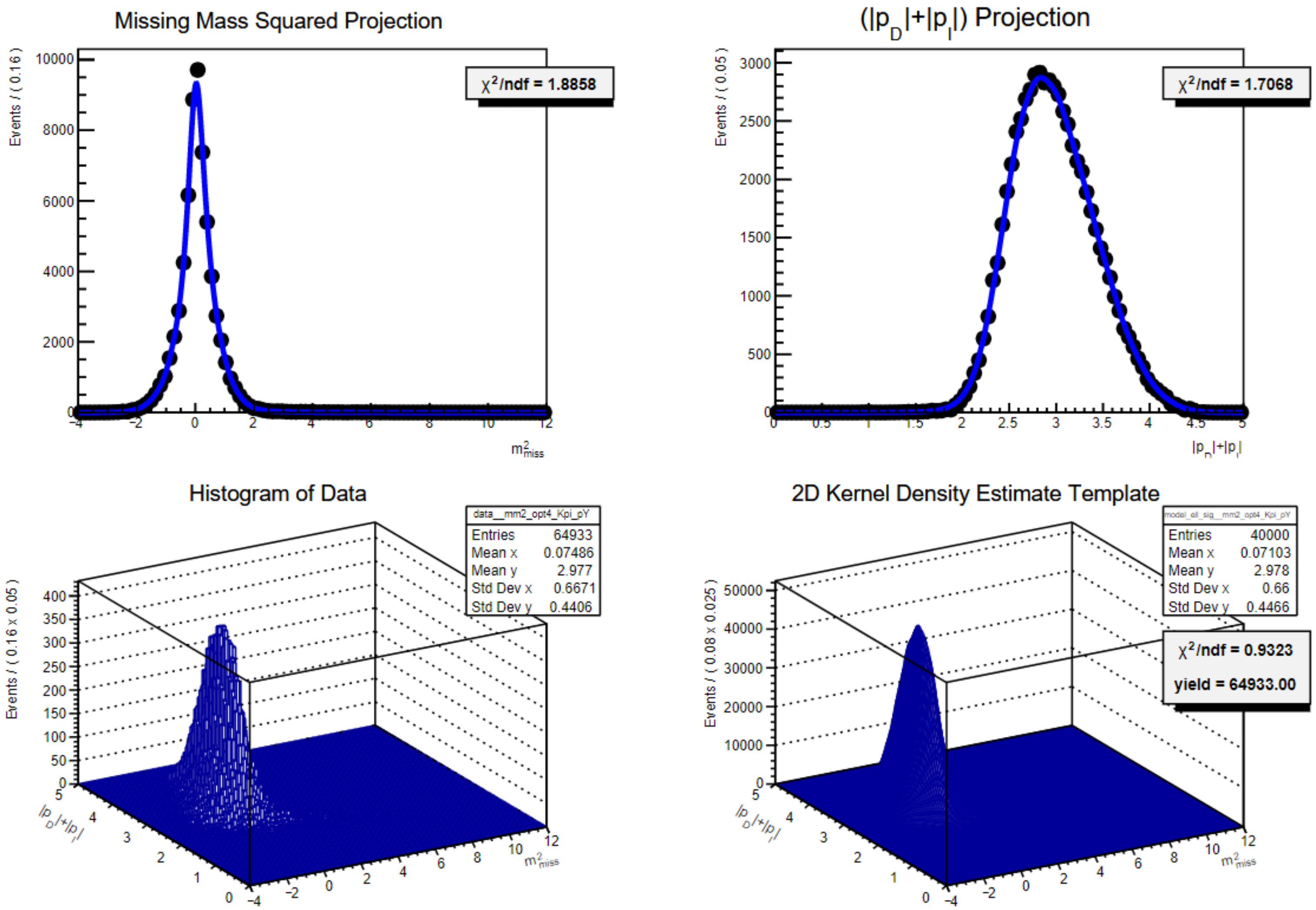
Total cases (B- and B+)

Cumulative cases

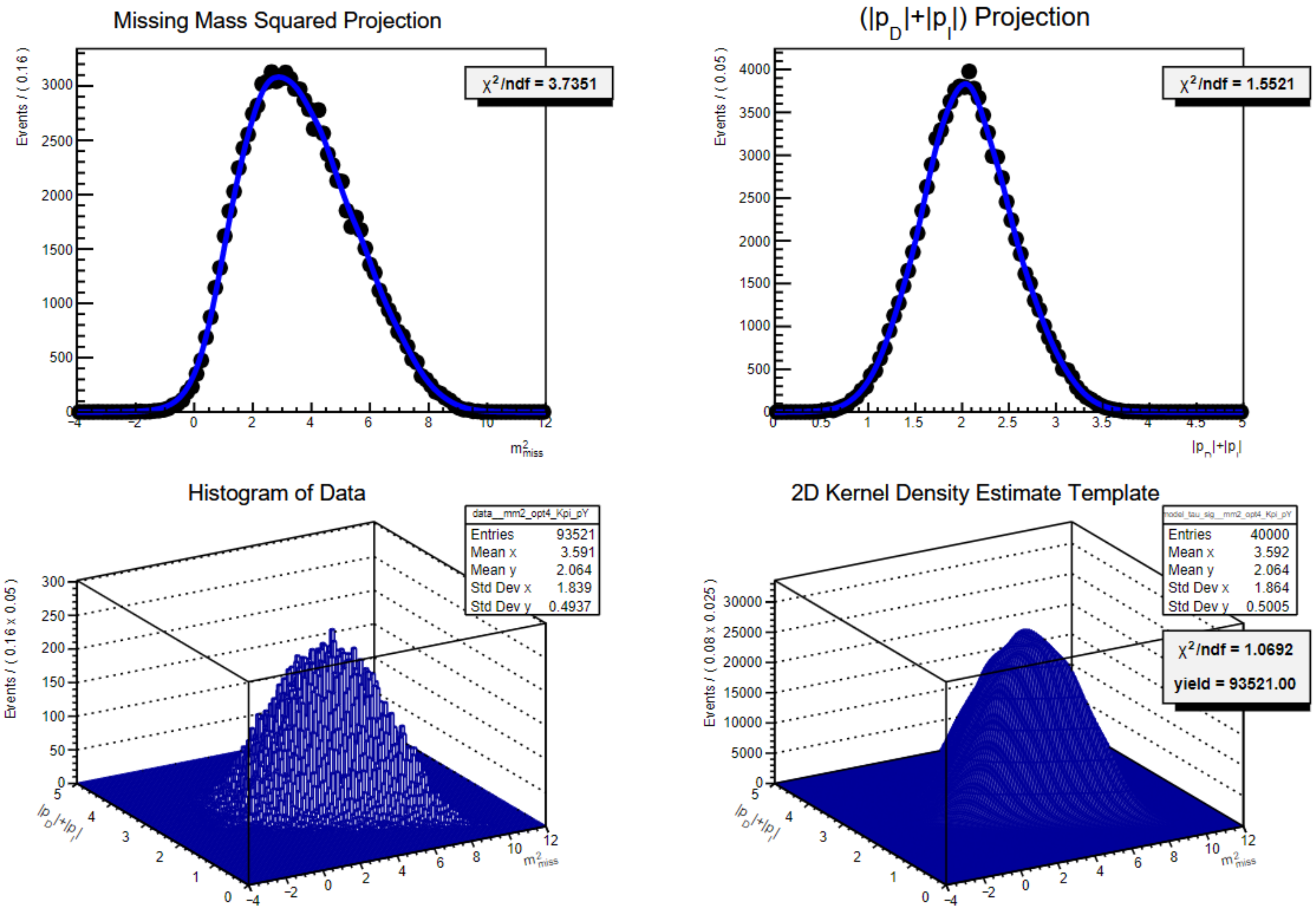
rowNo	cascade decay branch of B^-	iCascDcyBrP	nCase	nCcCase	nAllCase	nCCase
1	$B^- \to e^- \bar{\nu}_e D^{*0}, D^{*0} \to \pi^0 D^0, D^0 \to \pi^+ K^-$	4	12151	12431	24582	24582
2	$B^- \to e^- \bar{\nu}_e D^0, D^0 \to \pi^+ K^-$	0	7663	7765	15428	40010
3	$B^- \to e^- \bar{\nu}_e D^{*0}, D^{*0} \to D^0 \gamma, D^0 \to \pi^+ K^-$	28	6681	6701	13382	53392
4	$B^- \to \tau^- \bar{\nu}_\tau D^0, \tau^- \to e^- \bar{\nu}_e \nu_\tau, D^0 \to \pi^+ K^-$	32	612	603	1215	54607
5	$B^- \to \tau^- \bar{\nu}_\tau D^{*0}, \tau^- \to e^- \bar{\nu}_e \nu_\tau, D^{*0} \to \pi^0 D^0, D^0 \to \pi^+ K^-$	16	503	544	1047	55654
6	$B^- \to e^- \bar{\nu}_e D_1^0, D_1^0 \to \pi^- D^{*+}, D^{*+} \to \pi^+ D^0, D^0 \to \pi^+ K^-$	44	324	304	628	56282
7	$B^- \to \tau^- \bar{\nu}_\tau D^{*0}, \tau^- \to e^- \bar{\nu}_e \nu_\tau, D^{*0} \to D^0 \gamma, D^0 \to \pi^+ K^-$	7	308	316	624	56906
8	$B^- \to e^- \bar{\nu}_e D_1^{\prime 0}, D_1^{\prime 0} \to \pi^- D^{*+}, D^{*+} \to \pi^+ D^0, D^0 \to \pi^+ K^-$	38	269	237	506	57412
9	$B^- \to e^- \bar{\nu}_e D_1^0, D_1^0 \to \pi^+ \pi^- D^0, D^0 \to \pi^+ K^-$	36	223	206	429	57841
10	$B^- \to e^- \bar{\nu}_e D_0^{*0}, D_0^{*0} \to \pi^0 D^0, D^0 \to \pi^+ K^-$	119	205	221	426	58267

$B \to (D^0 \to K\pi)e\nu$ Train-Test Template

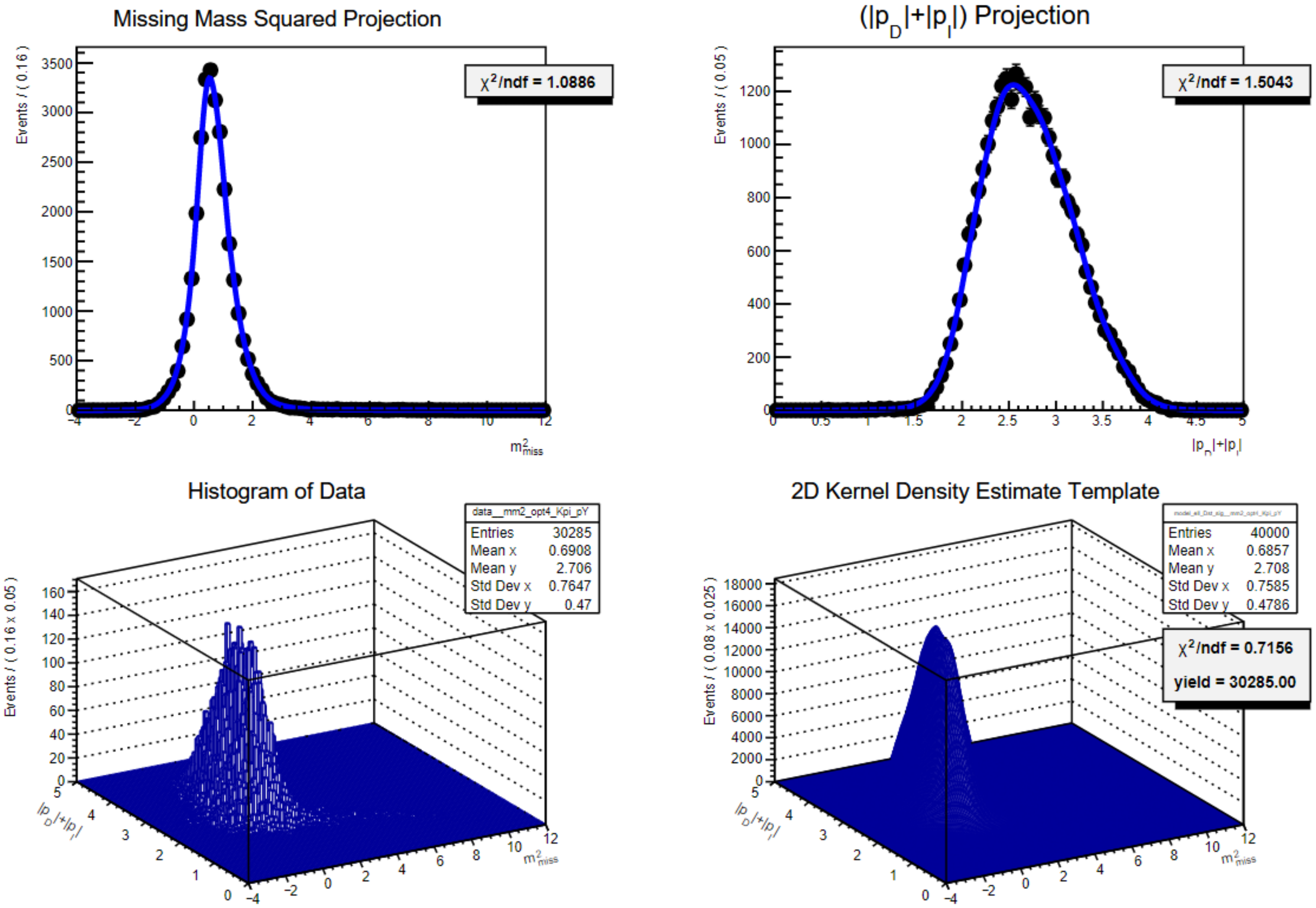
USED IN PRESENTATION: 50% of signal samples for PDF construction, 50% for composite fit and validation



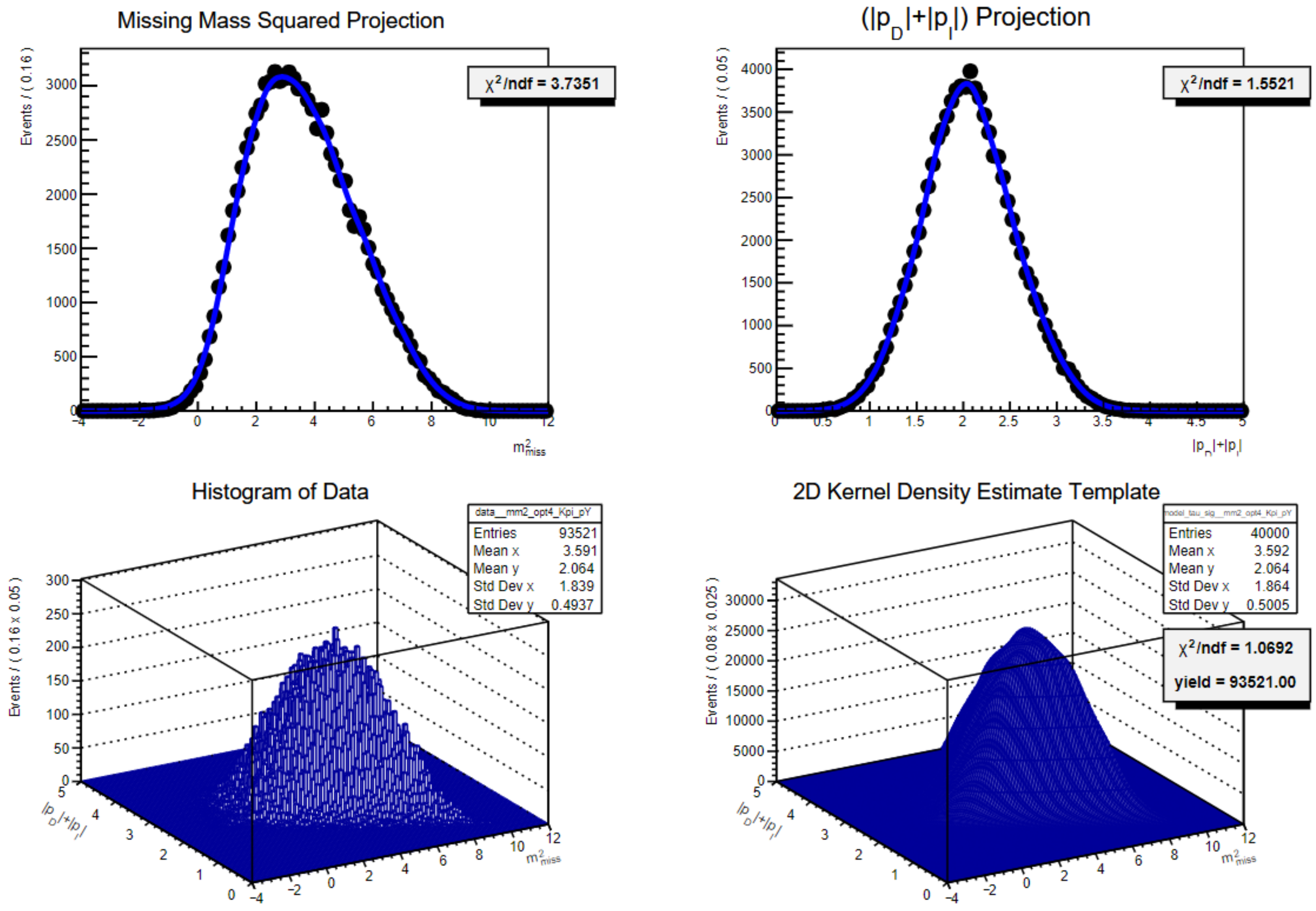
$B \to (D^0 \to K\pi)\tau\nu$ Train-Test Template



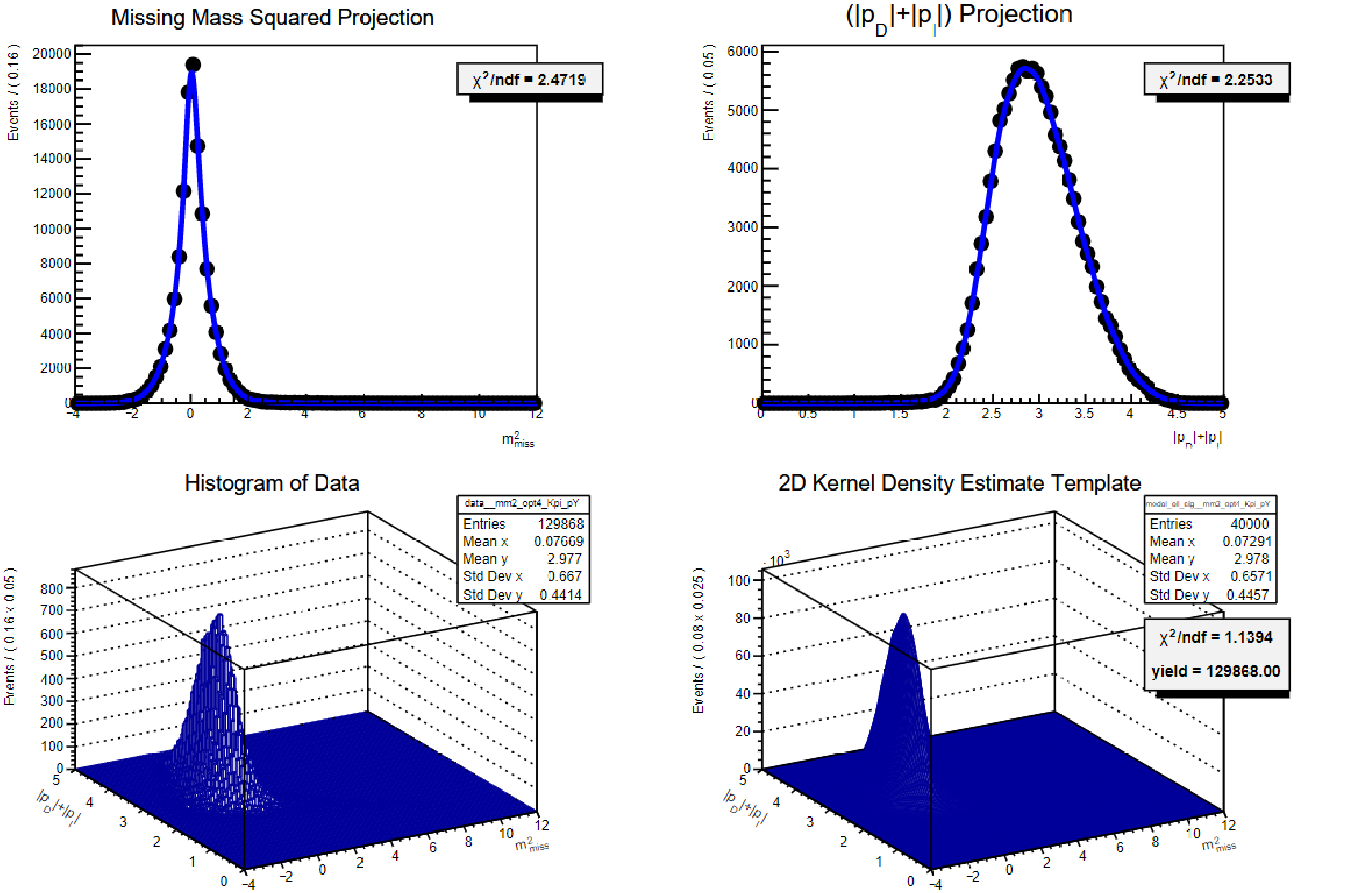
$B \to (D^* \to K\pi)e\nu$ Train-Test Template



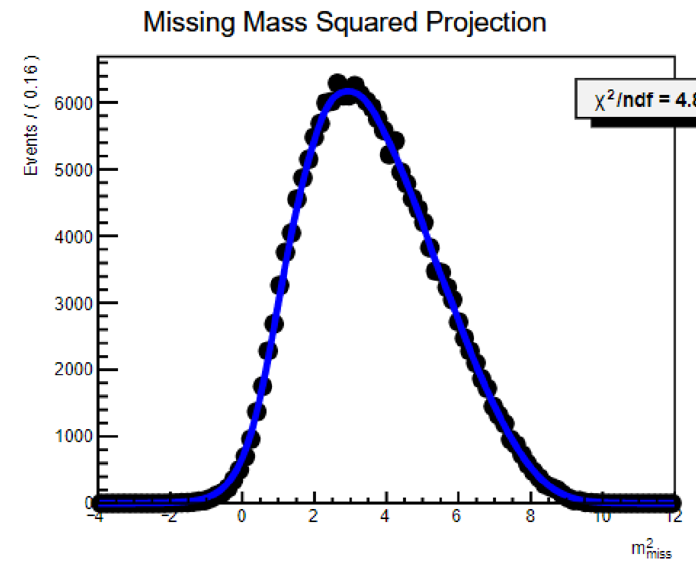
$B \to (D^* \to K\pi)\tau\nu$ Train-Test Template

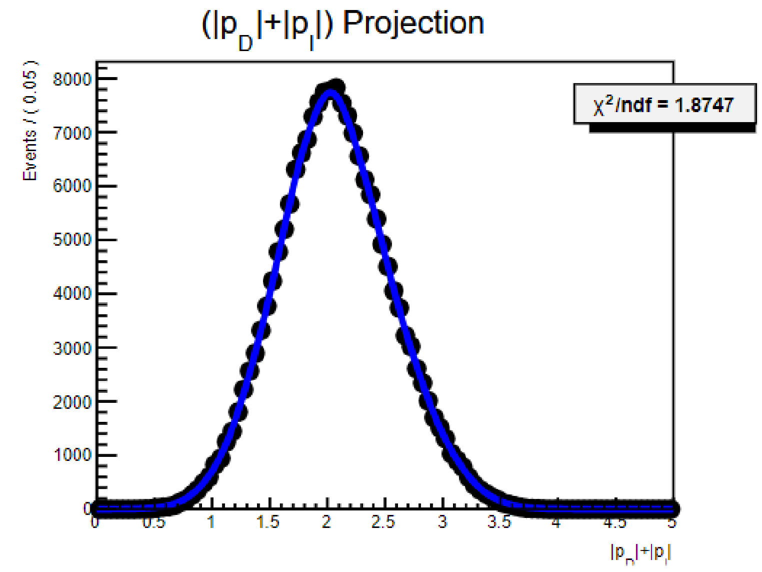


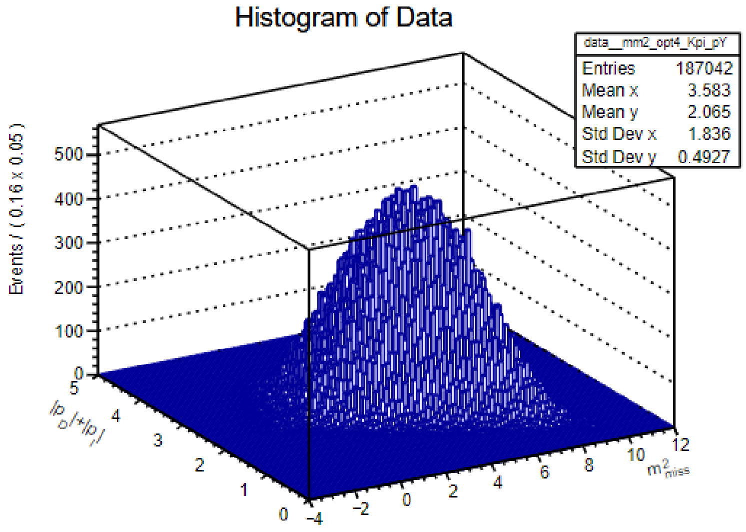
$B \to (D^0 \to K\pi) e\nu$ Template

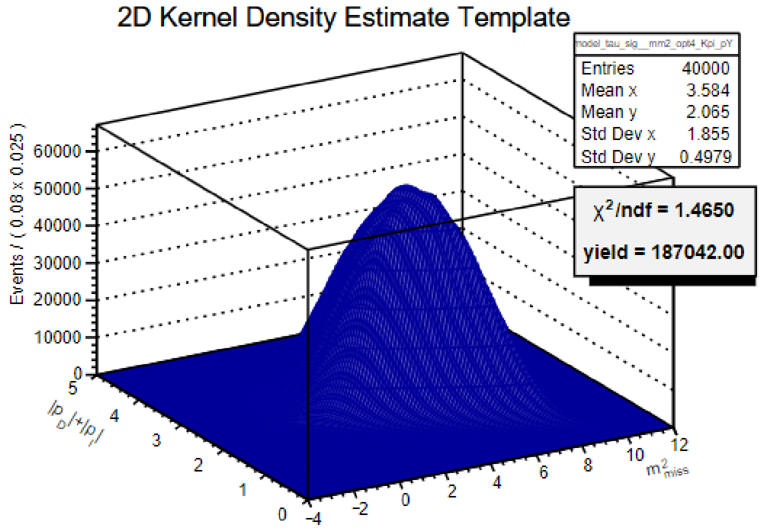


$B \to (D^0 \to K\pi)\tau\nu$ Template

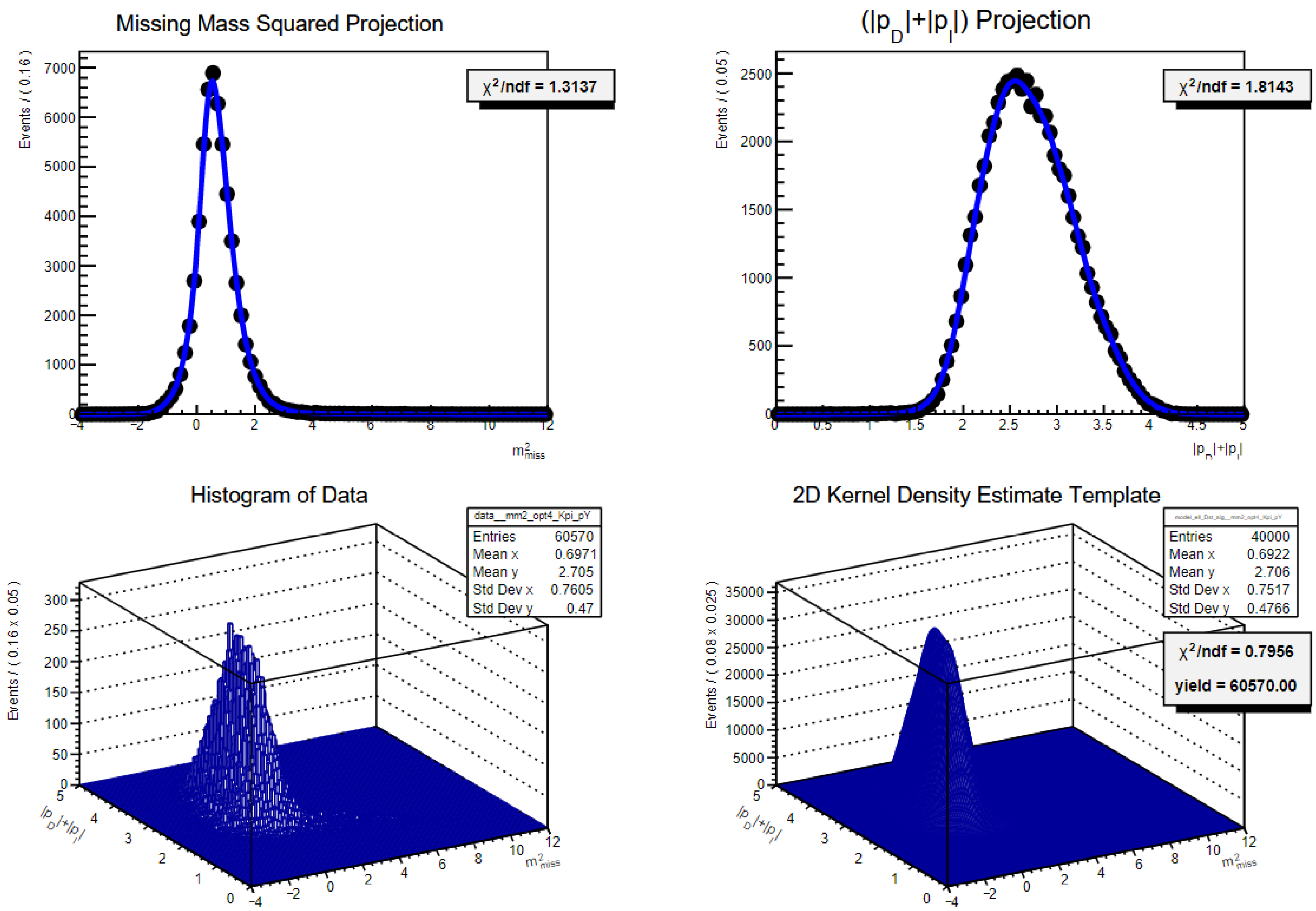




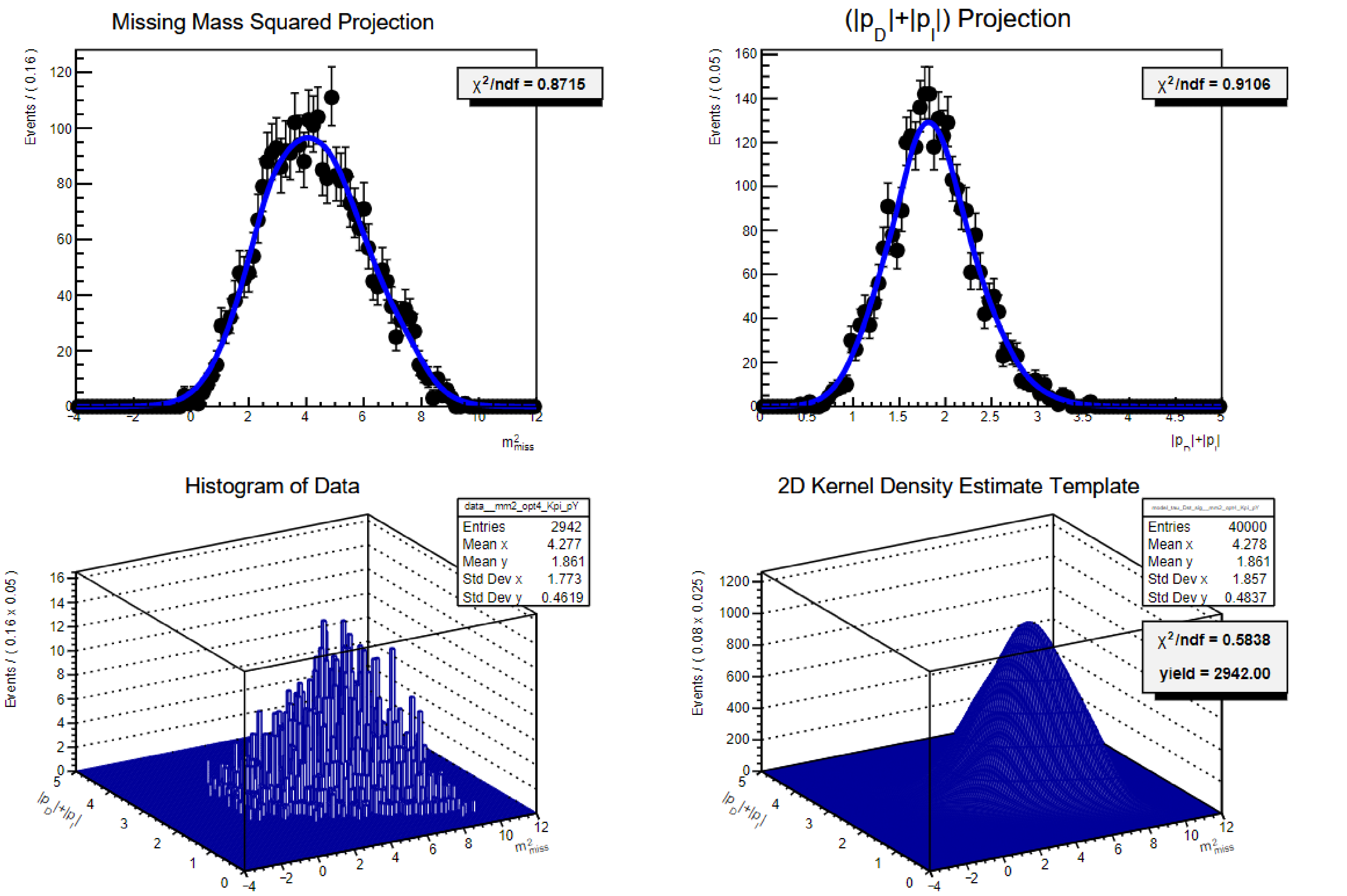




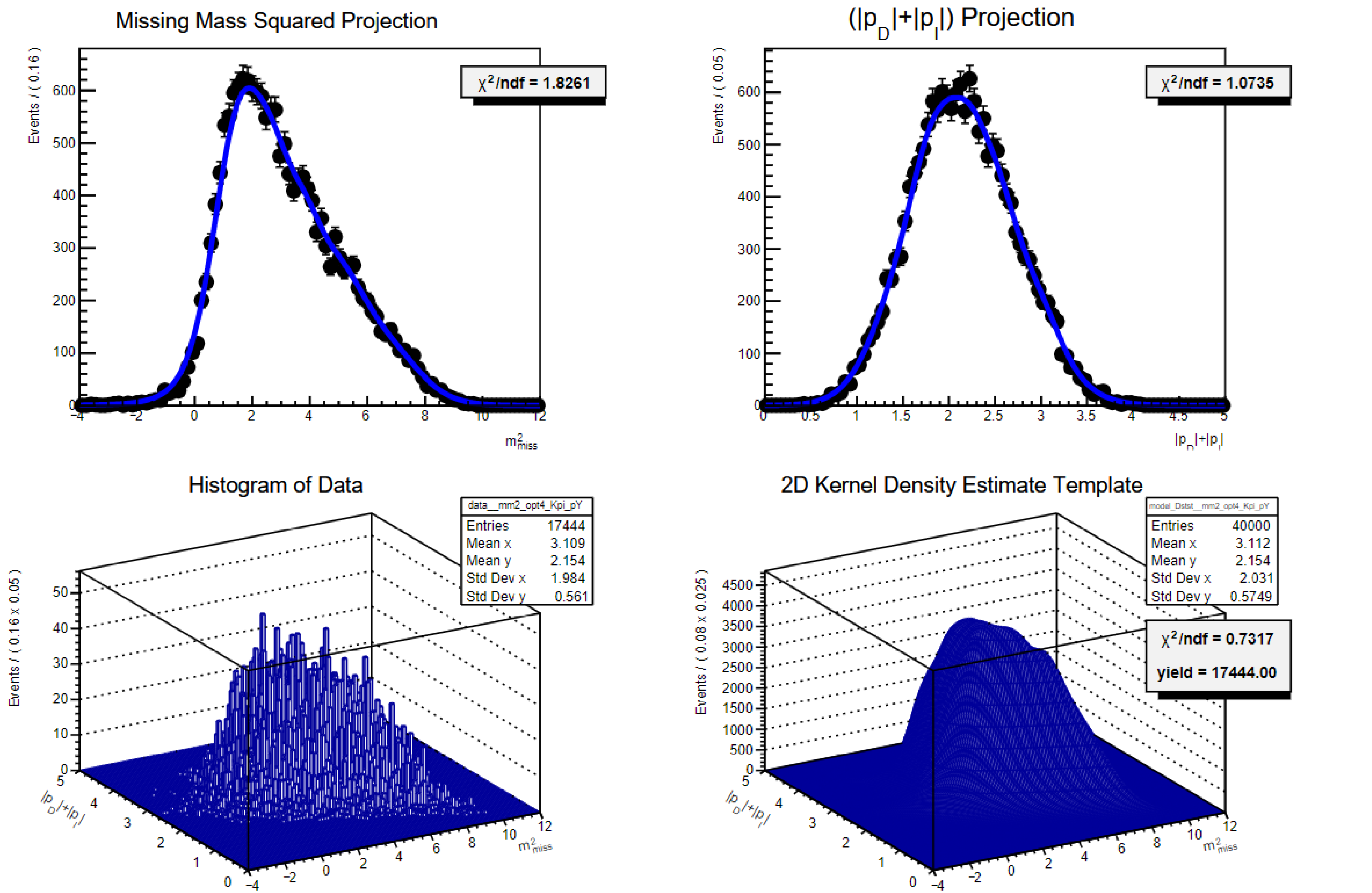
$B \to (D^* \to K\pi)e\nu$ Template



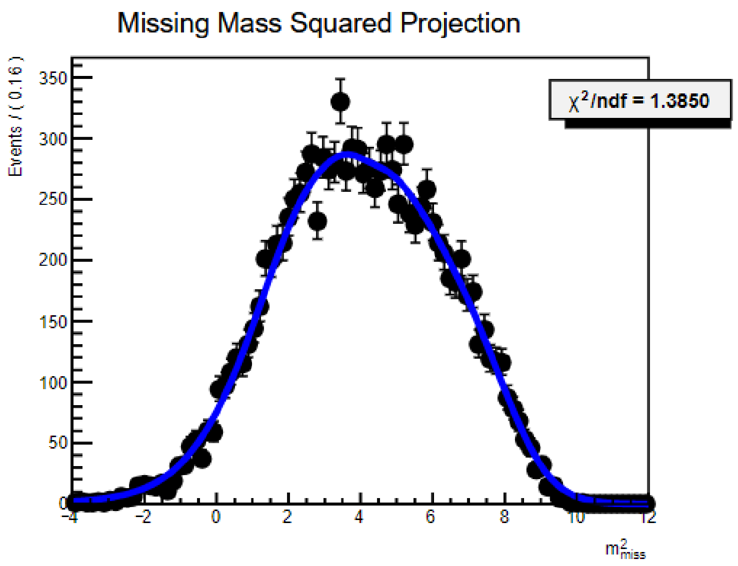
$B \to (D^* \to K\pi)\tau\nu$ Template

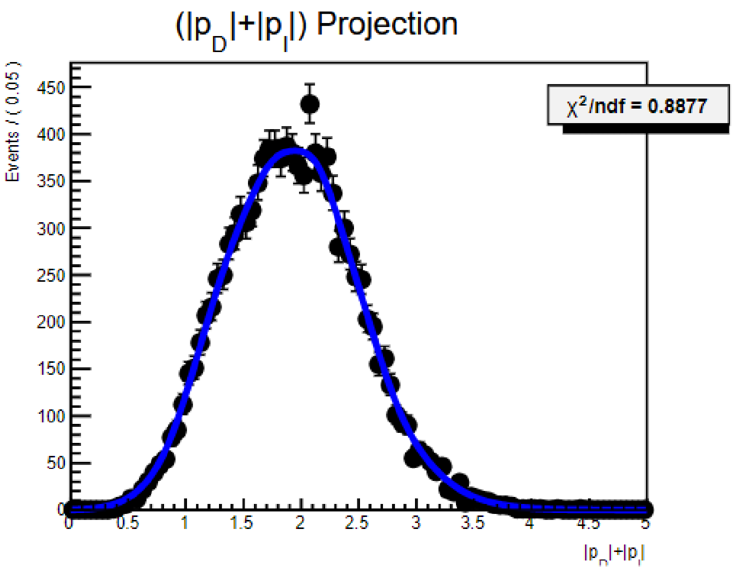


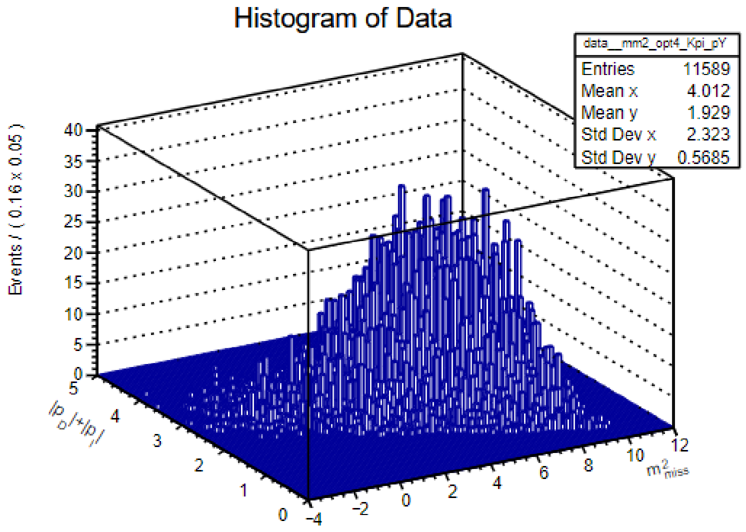
$B \to (D^{**} \dashrightarrow K\pi)\ell\nu$ Template

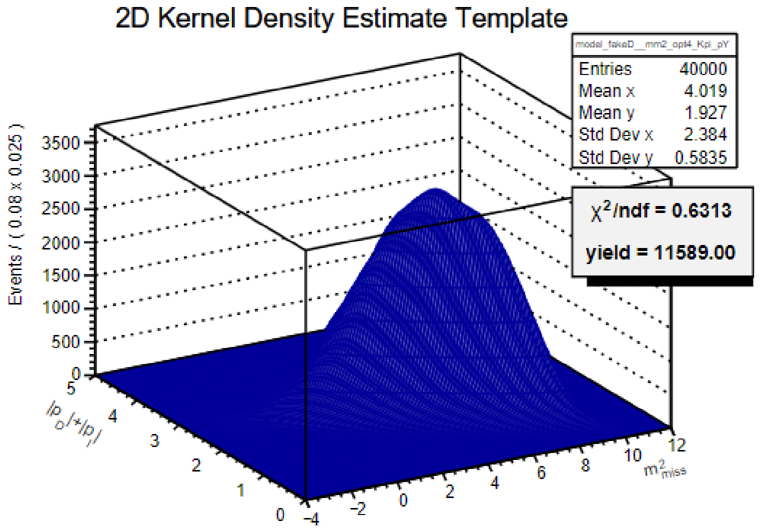


Fake D Template

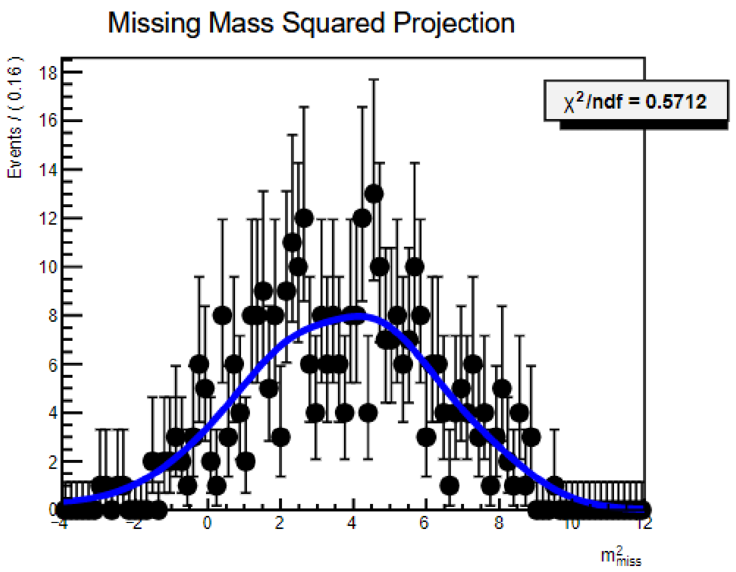


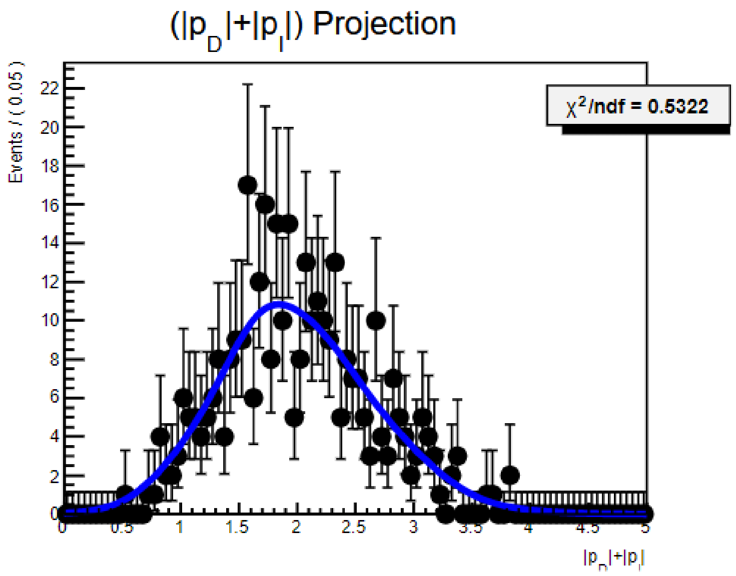


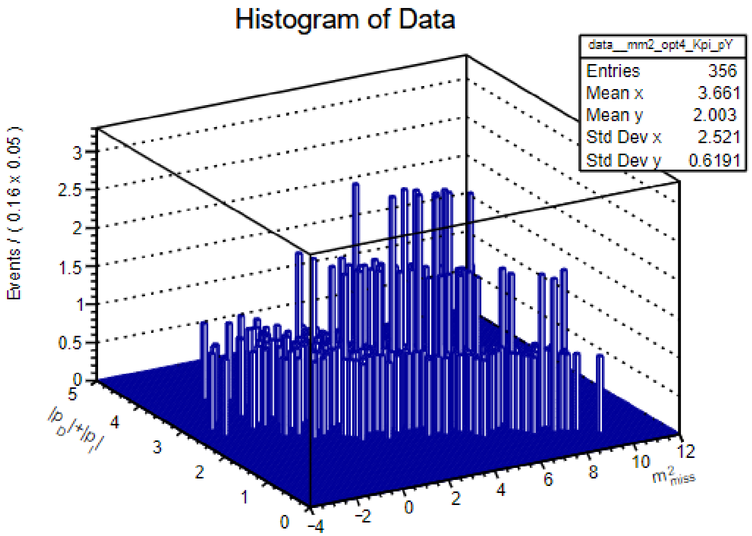


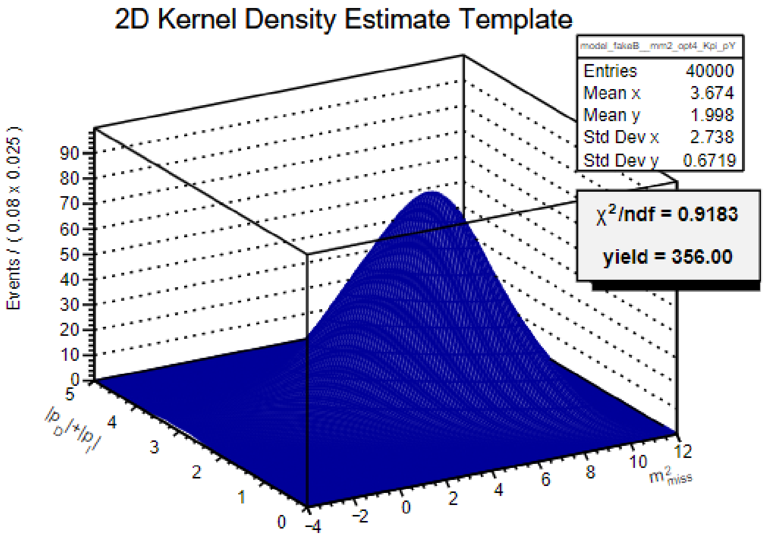


Fake B Template

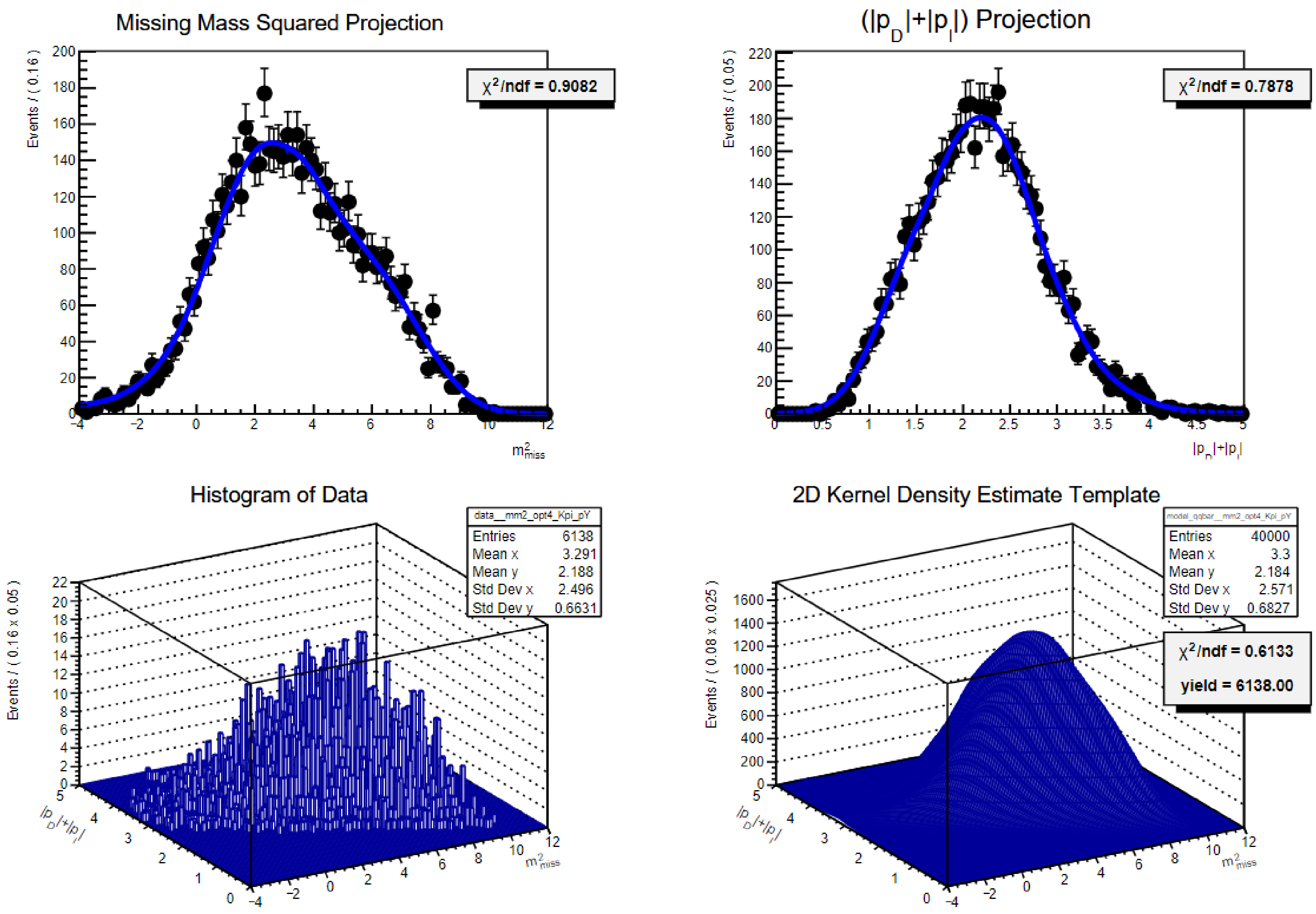








$q\bar{q}$ Template



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

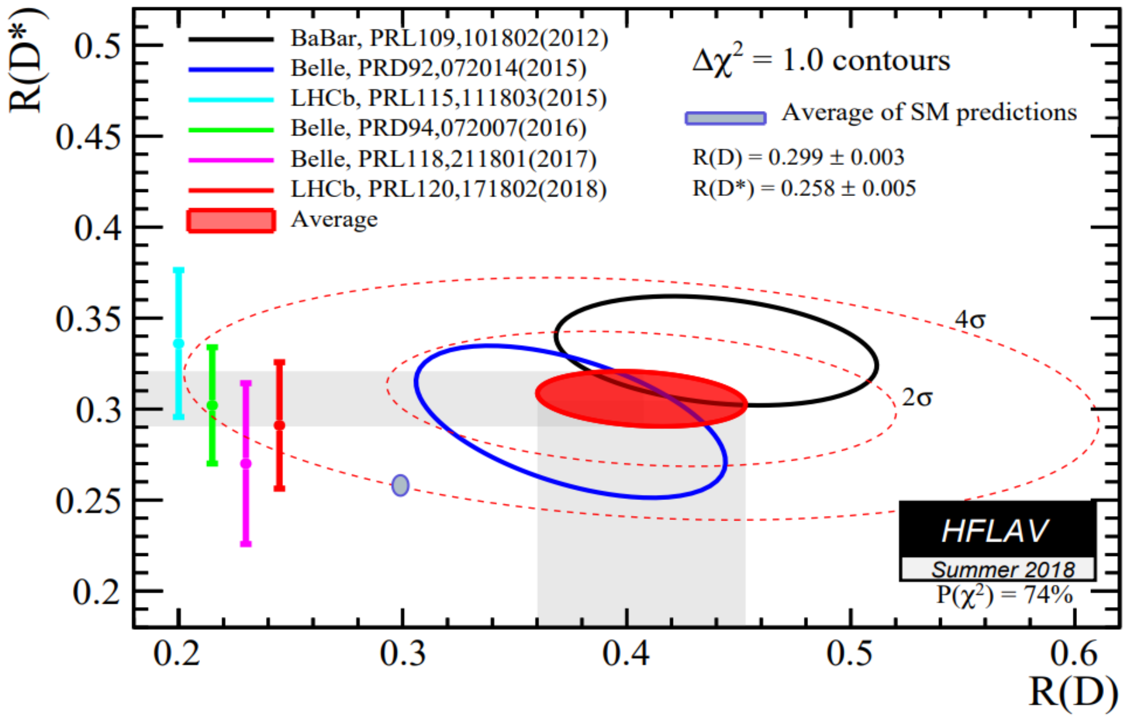
A test of lepton flavor universality…

$$\Gamma(B^- \to D^0 \ell^- \bar{\nu}_\ell) \propto \frac{g_\ell^2}{M_W^2}\frac{g^2}{M_W^2} m_B^5$$

$$\mathrm{R}(D) = \frac{\Gamma(B^- \to D^0 \tau^- \bar{\nu}_\tau)}{\Gamma(B^- \to D^0 \ell^- \bar{\nu}_\ell)} \propto \frac{g_\tau^2}{g_\ell^2}$$

Removes most systematic uncertainties

$$R(D^{(*)}) = \frac{N(D^{(*)}\tau\nu)}{N(D^{(*)}\ell\nu)} \frac{\varepsilon(D^{(*)}\ell\nu)}{\varepsilon(D^{(*)}\tau\nu)} \frac{1}{\mathcal{B}(\tau)}$$



HFLAV

Summer 2018: 3.62σ
$R(D) = 2.3\sigma$,
$R(D^*) = 3.0\sigma$

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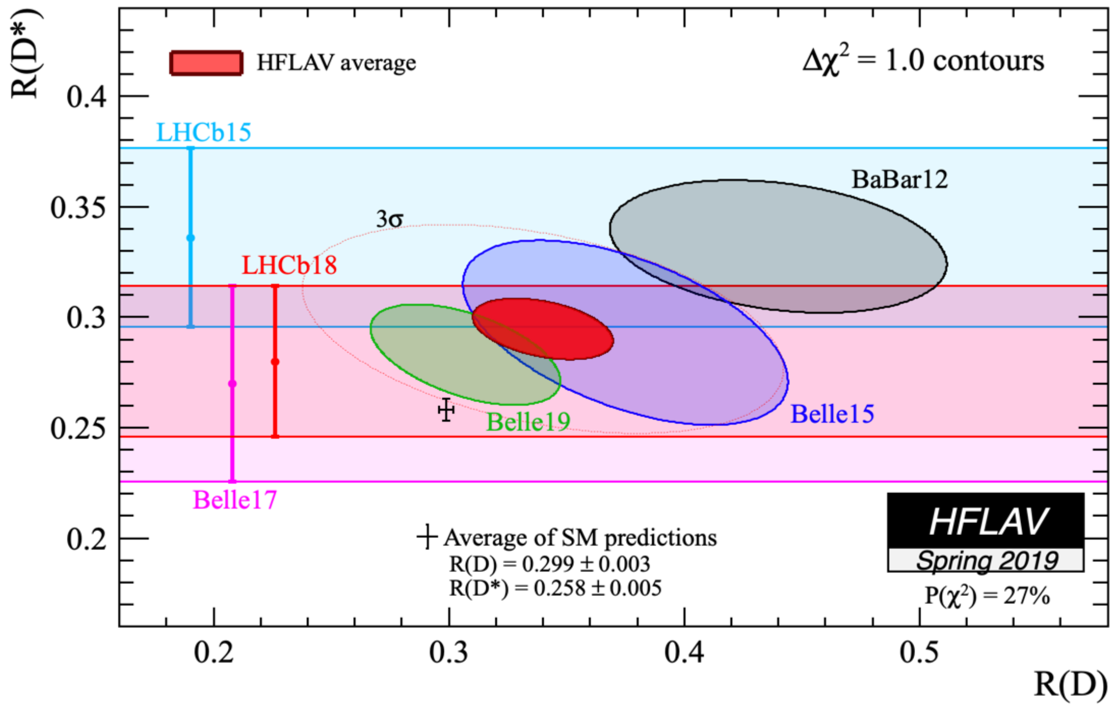

HFLAV

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***Spring* 2019: 3.08σ**
$R(D) = 1.4\sigma$,
$R(D^*) = 2.5\sigma$

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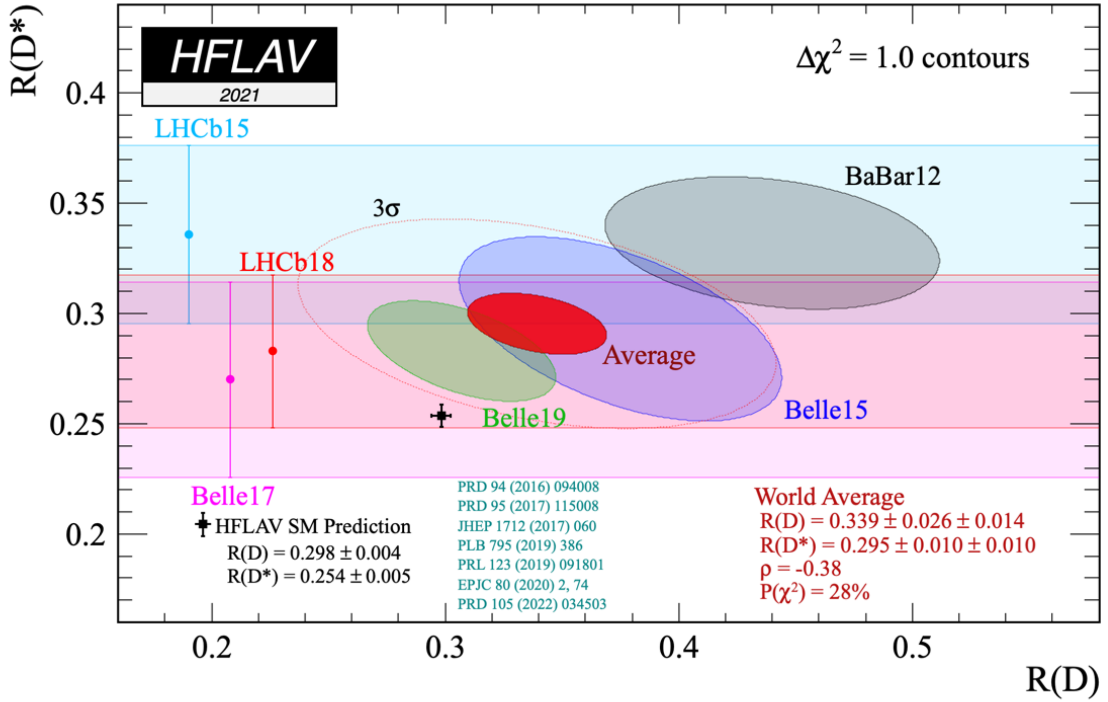

HFLAV

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

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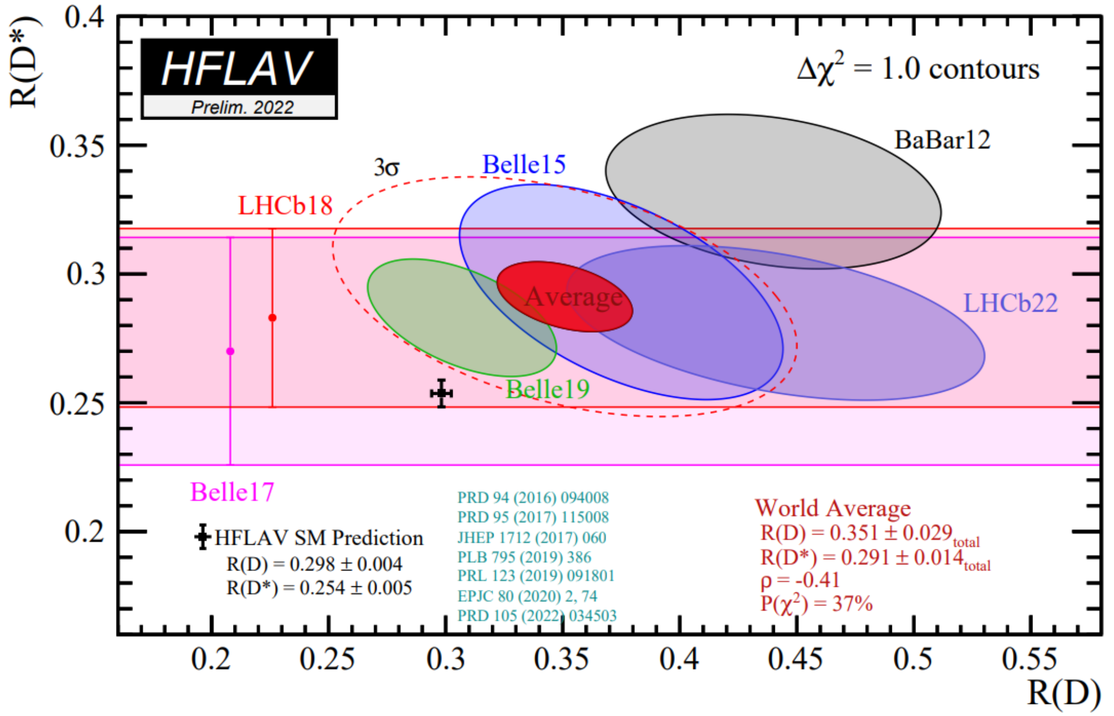

[HFLAV](#)

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***Spring 2021*: 3.3σ**
$R(D) = 1.4\sigma$,
$R(D^*) = 2.8\sigma$

***End of 2022*: 3.5σ**
$R(D) = 1.82\sigma$,
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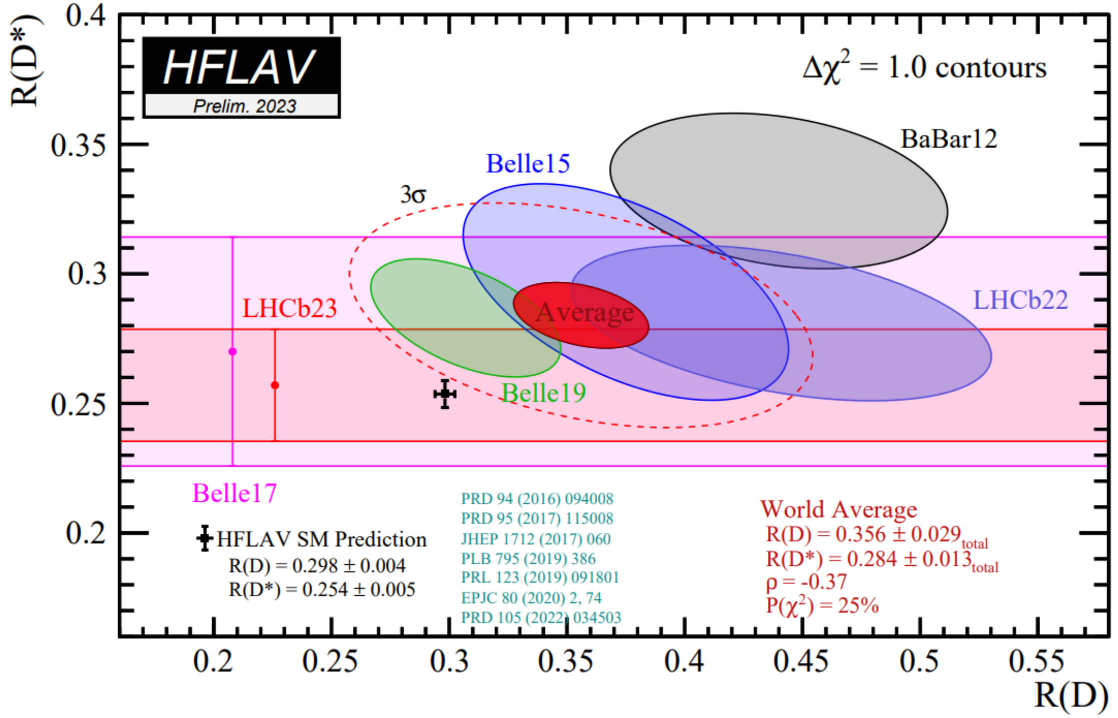

HFLAV

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***Spring 2021*: 3.3σ**
$R(D) = 1.4\sigma$,
$R(D^*) = 2.8\sigma$

***End of 2022*: 3.5σ**
$R(D) = 1.82\sigma$,
$R(D^*) = 2.49\sigma$

***Summer 2023*: 3.2σ**
$R(D) = 1.98\sigma$,
$R(D^*) = 2.15\sigma$

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

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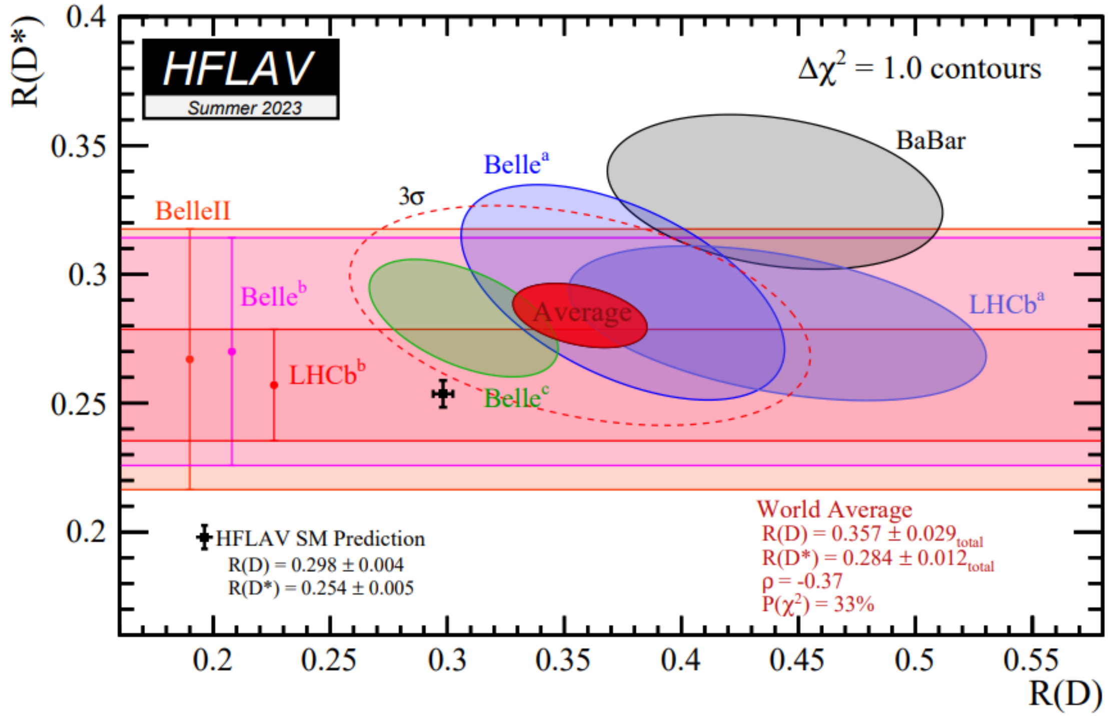
Removes most systematic uncertainties

$$R(D^{(*)}) = \frac{N(D^{(*)}\tau\nu)}{N(D^{(*)}\ell\nu)} \frac{\varepsilon(D^{(*)}\ell\nu)}{\varepsilon(D^{(*)}\tau\nu)} \frac{1}{\mathcal{B}(\tau)}$$



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+*Belle II Result*: 3.3σ
$R(D) = 2.0\sigma$,
$R(D^*) = 2.2\sigma$