# A simultaneous analysis of $B \to D\ell\nu$ and $B \to D^*\ell\nu$ decays

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SL WG meeting
July 2, 2024

# In a nutshell

- By reconstructing $D^0 l\nu$ and $D^- l\nu$ final states, perform a simultaneous analysis of $B \to Dl\nu$ and $B \to D^* l\nu$ where $D^*$ is partially reconstructed.
- Use isospin symmetry to assume equal SL decay width of $B^0$ and $B^-$ and reduce uncertainties. Can measure:
  1. $\mathscr{B}(B \to Dl\nu)$ and $\mathscr{B}(B \to D^* l\nu)$ and their ratio;
  2. model-independent observables: measure FF $\cdot |V_{cb}|$ in 5 bins of $w$.

     Method allows to reinterpret the measurement assuming any FF model.
  3. $f_{+-}/f_{00} = \mathscr{B}(\Upsilon(4S) \to B^+B^-)/\mathscr{B}(\Upsilon(4S) \to B^0\bar{B}^0)$ with 1% theoretical uncertainty.

     $\to$ input for any measurements of BR at Belle II, current theoretical uncertainty 4%!
- First simultaneous analysis at Belle II: an alternative approach to the ongoing measurements, affected by different sources of systematic uncertainties.

# Overview

Last talk [talk@SLmeeting]:

- Refine the selection of muon and electron channels.
- Apply missing corrections to MC: branching fractions and gap modes.
- Study of $X\ell\nu$ sample composition. Find a sideband enriched of these decays.

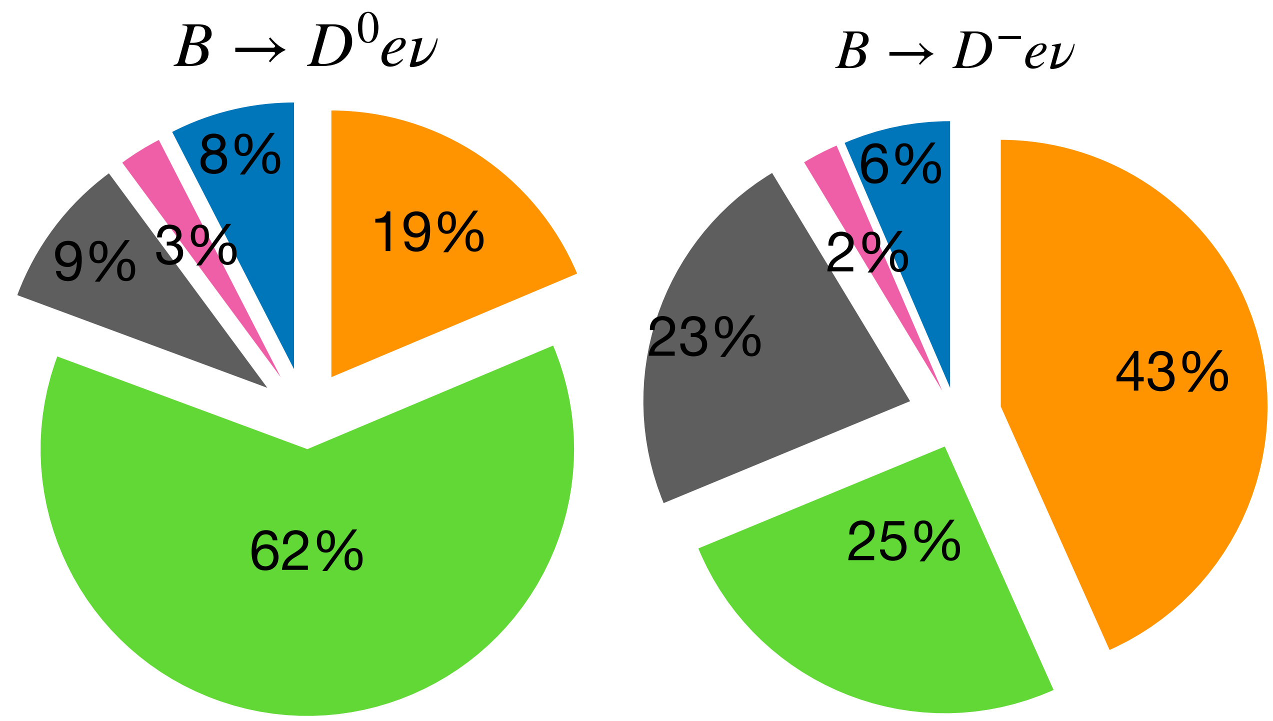
  Perform a 2D simultaneous fit between $D^0 e\nu$ and $D^- e\nu$ to constraint the $X\ell\nu$ component.

Today:

- Split the gap modes into $D^{(*)}\pi\pi\ell\nu$ and $D^{(*)}\eta\ell\nu$ templates.
- Split the real D to constrain better the sub-components (inclusive D decays, fake leptons, …).
- Test a simultaneous fit between the electron and muon samples in the sideband region to constrain the $X\ell\nu$ and real D components.

# Sample composition

Divide $B \to D\ell\nu$ samples in 6 components:




1. $B \to D\ell\nu$;
2. $B \to D^*\ell\nu$;

**signal**

3. $B \to X\ell\nu$ + gap modes, where $X$ is $D^{**}$, $D^{(*)}\tau\nu$ + lepton (real or fake);
4. Real D: real D + lepton (real or fake);

**Detailed composition study shown at talk@SLWG**

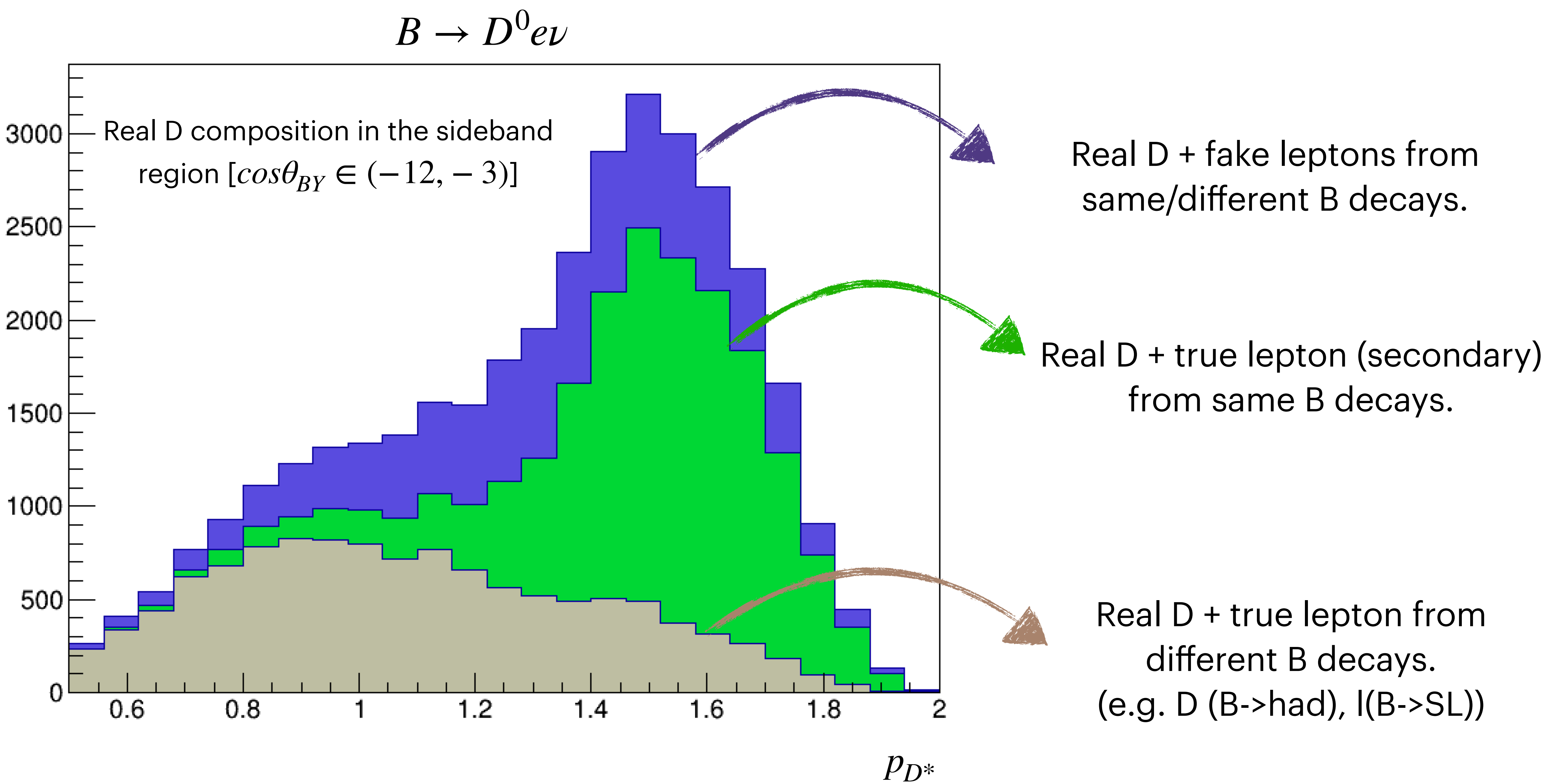
**Constrain using a $\cos\theta_{BY}$ sideband region**

5. Fake D: a random $K\pi/K\pi\pi$ combination + lepton (real or fake);
6. Continuum: background from $e^+e^- \to q\bar{q}$, $q \in [u, d, c, s]$.

**constrained from data: using D mass sideband + off-res**

# Real D validation

Detailed study of the real D composition at talk@SLWG.
Divided the real D component in three sub-components:




Use three different templates for the real D in the simultaneous fit.

# $X\ell\nu$ validation

Found a $cos\theta_{BY}$ sideband region [-12,-3] to validate these decays.

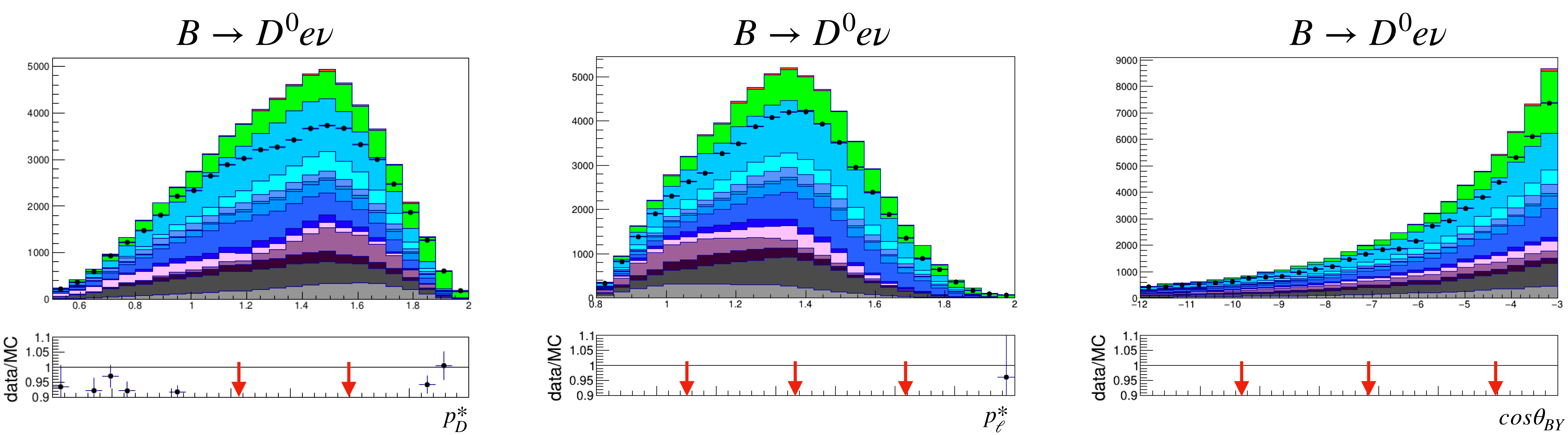
continuum
fake D

Take from off-res data and InvM(D) sideband.

$D\ell\nu$
$D^*\ell\nu$
$X\ell\nu(rest)$
$D_1\ell\nu$
$D_1'\ell\nu$
$D_0^*\ell\nu$
$D_2^*\ell\nu$
$D^{(*)}\pi\pi\ell\nu$
$D^{(*)}\eta\ell\nu$

enriched $X\ell\nu$ decays in the $cos\theta_{BY}$ sideband

$realD_{fake}, realD_{sec}, realD_{rest}$




Data/MC disagreement observed in the $cos\theta_{BY}$ sideband.

# Simultaneous fit

- Fit the $X\ell\nu$ and real D components in the $cos\theta_{BY}$ sideband region to constrain these decays.
- Perform a 2D simultaneous fit between electron and muon samples using $(p_D^*, p_\ell^*)$ variables.
- Free Real D components :

| | |
|---|---|
| $realD_{fake}(D^0\mu\nu), realD_{sec}(D^0 e\nu), realD_{rest}(D^0 e\nu)$<br>$realD_{fake}(D^-\mu\nu), realD_{sec}(D^- e\nu), realD_{rest}(D^- e\nu)$ | The other real D sub-components are determined from these parameters |

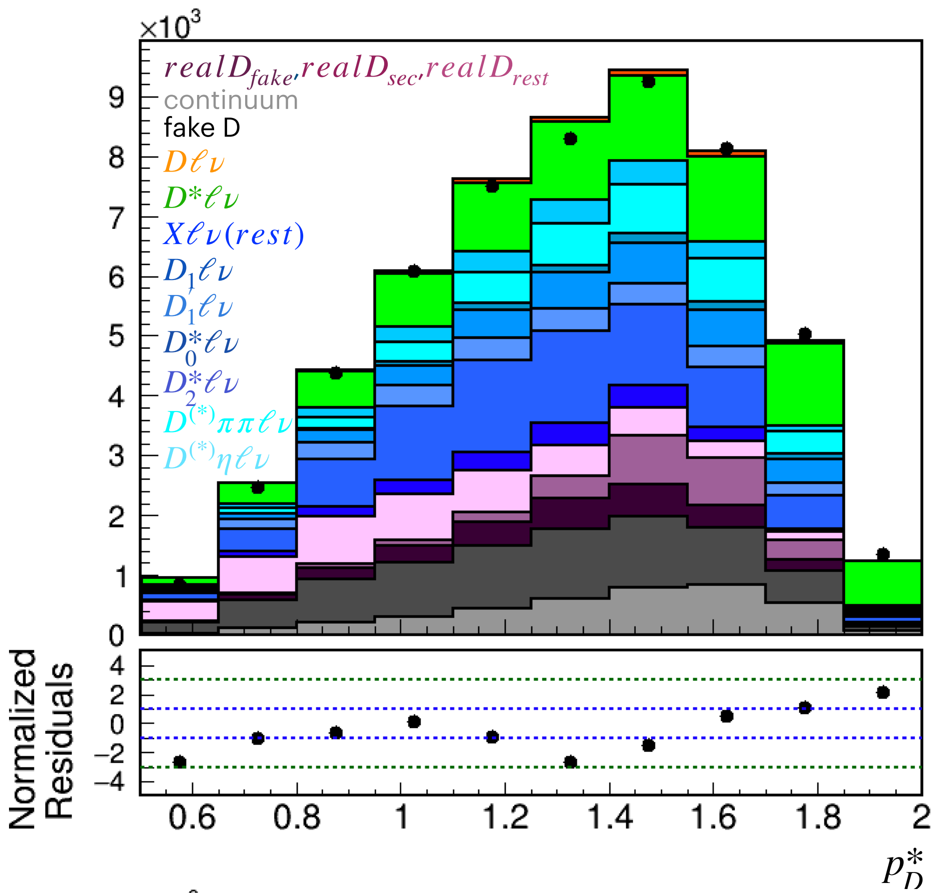
- Gaussian constraints on $D^{**}$ BR with the corresponding uncertainties:

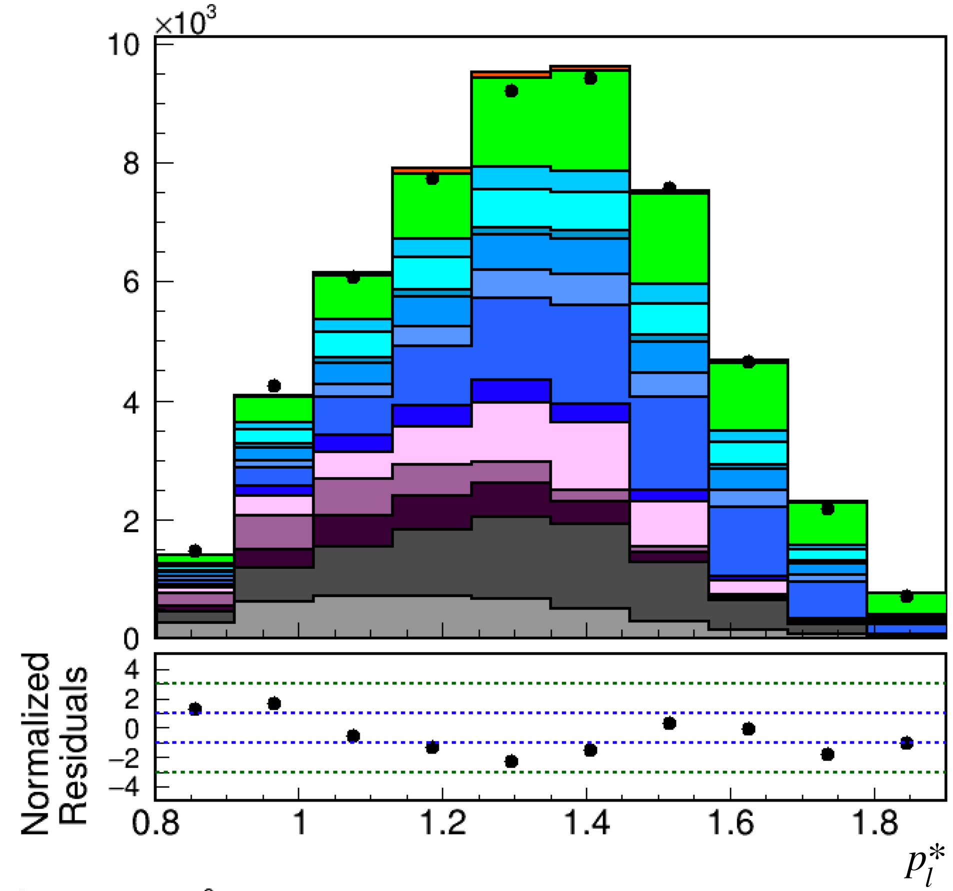
1. $D_1$ gaussian constraint (unc. 16%)
2. $D_0$ gaussian constraint (unc. 24%)
3. $D_1^{'}$ gaussian constraint (unc. 14%)
4. $D_2$ gaussian constraint (unc. 9%)
5. $D^{(*)}\pi\pi$ gaussian constraint (unc. 43%)
6. $D^{(*)}\eta$ gaussian constraint (unc. 100%)

- All the other components are fixed.
- Assume isospin symmetry to link the BR on the constraints between $D^0$ and $D^-$ samples.

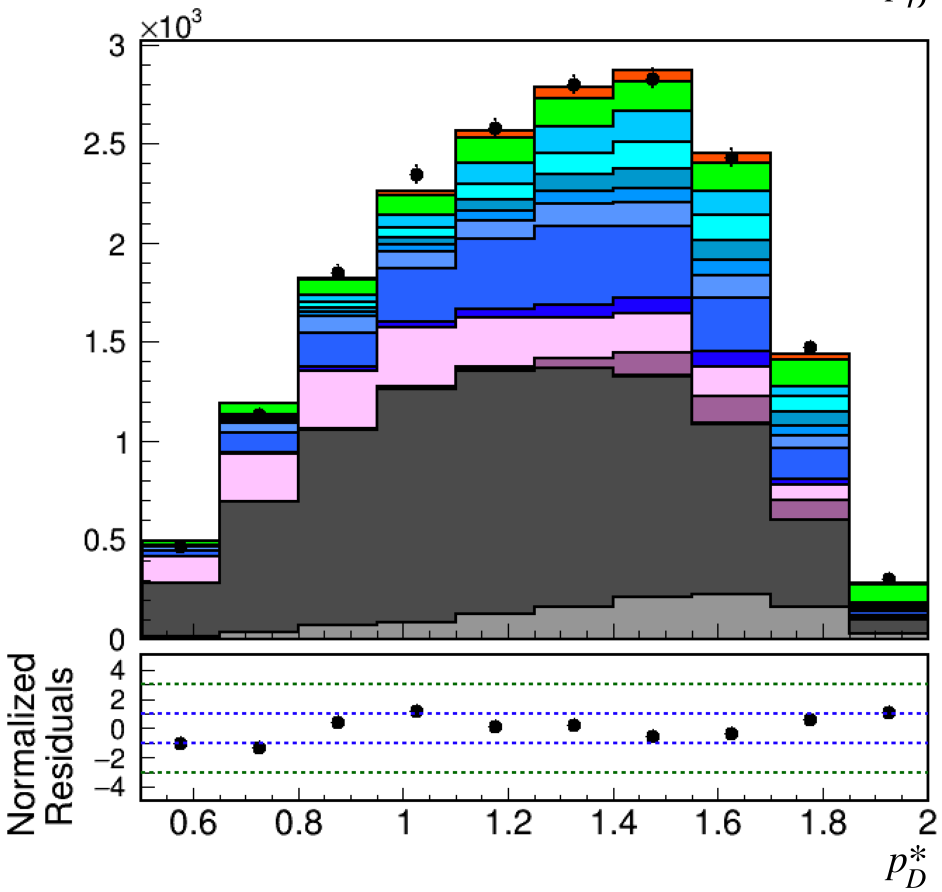
# Projections

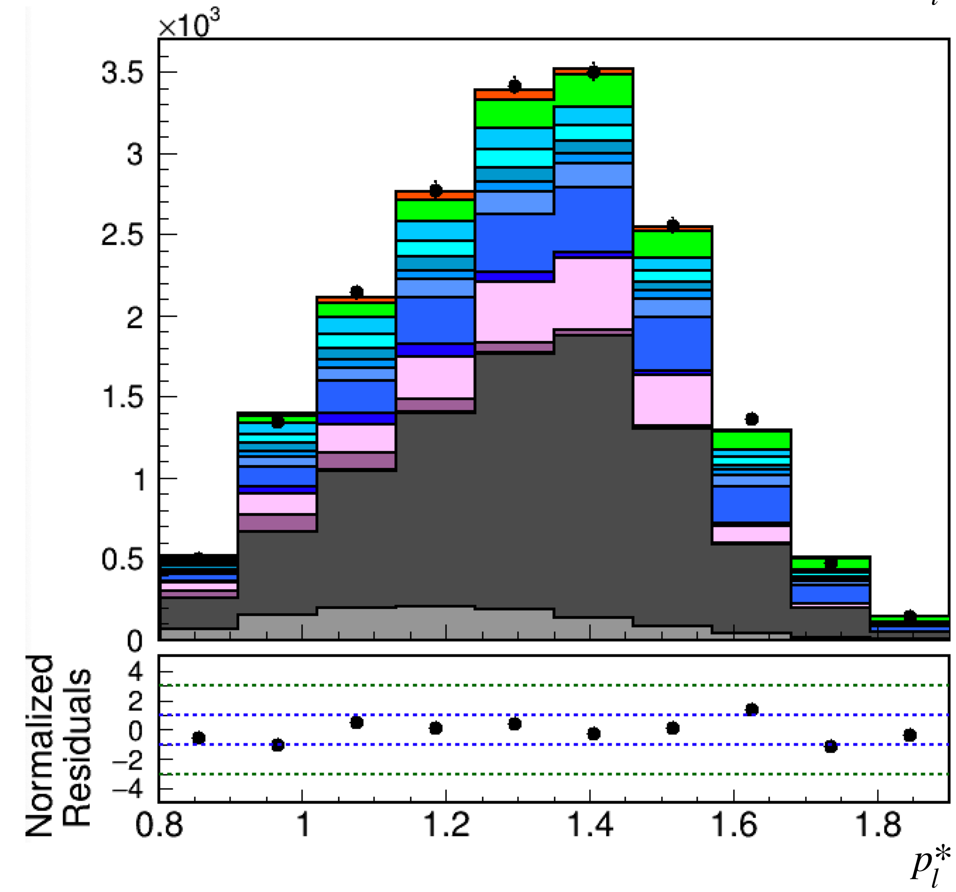
## $D^0 e\nu$



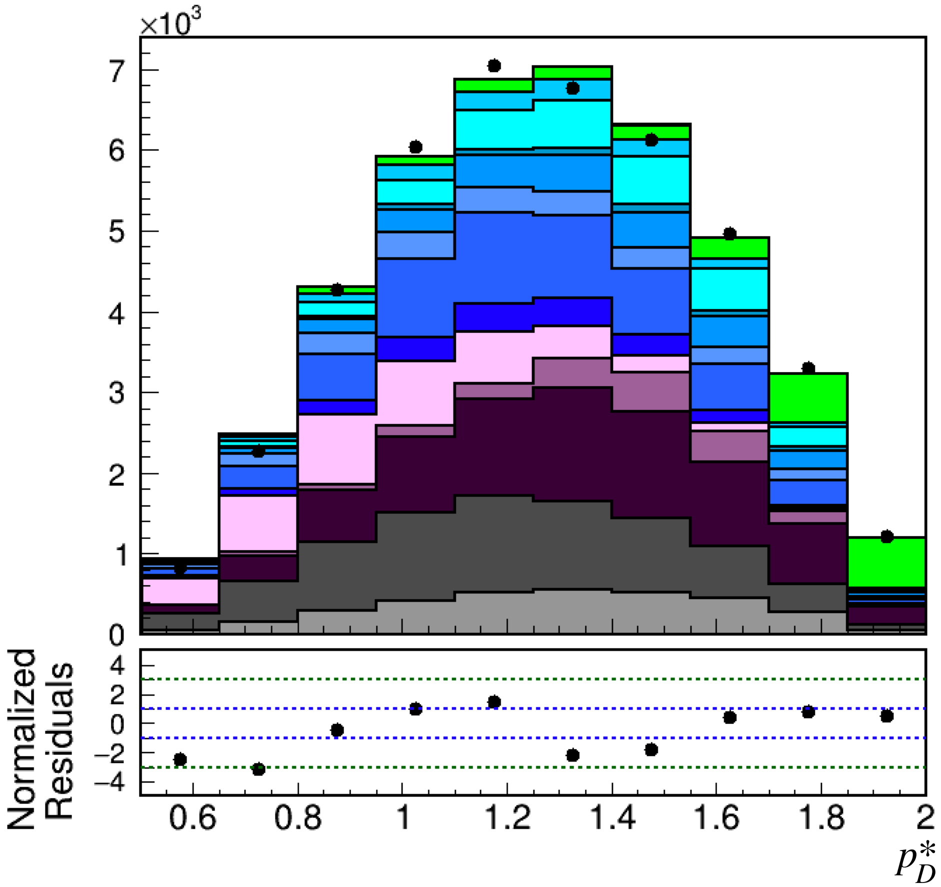

## $D^- e\nu$

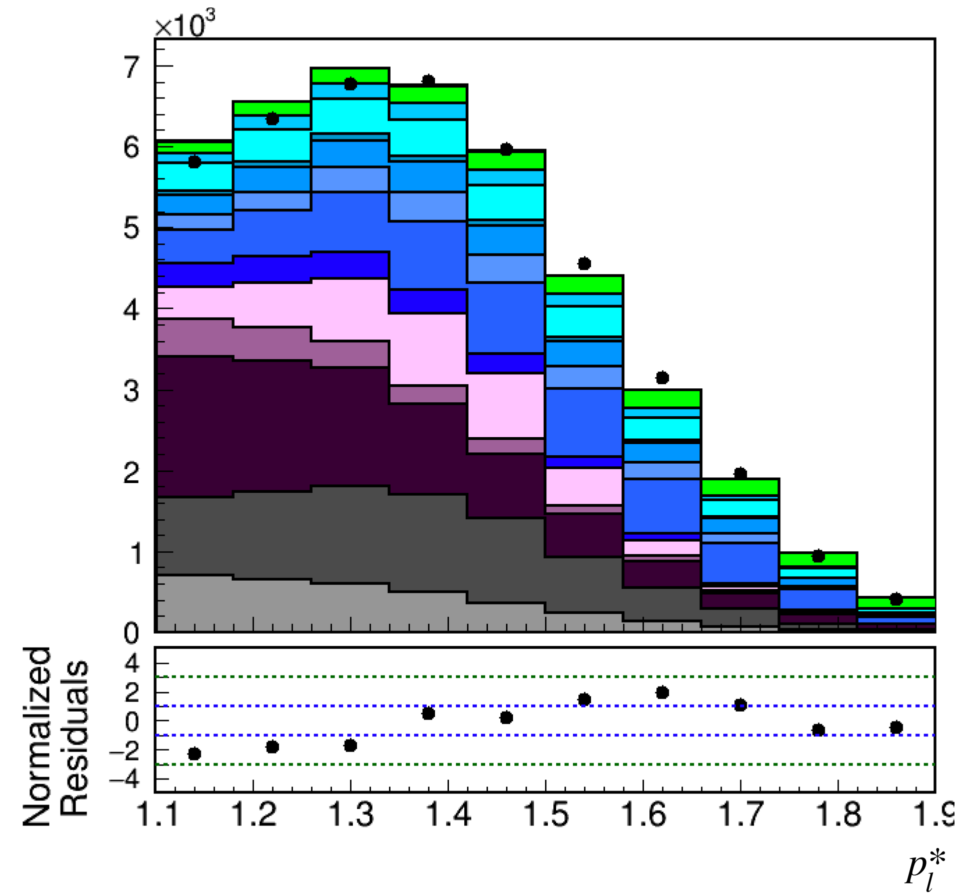


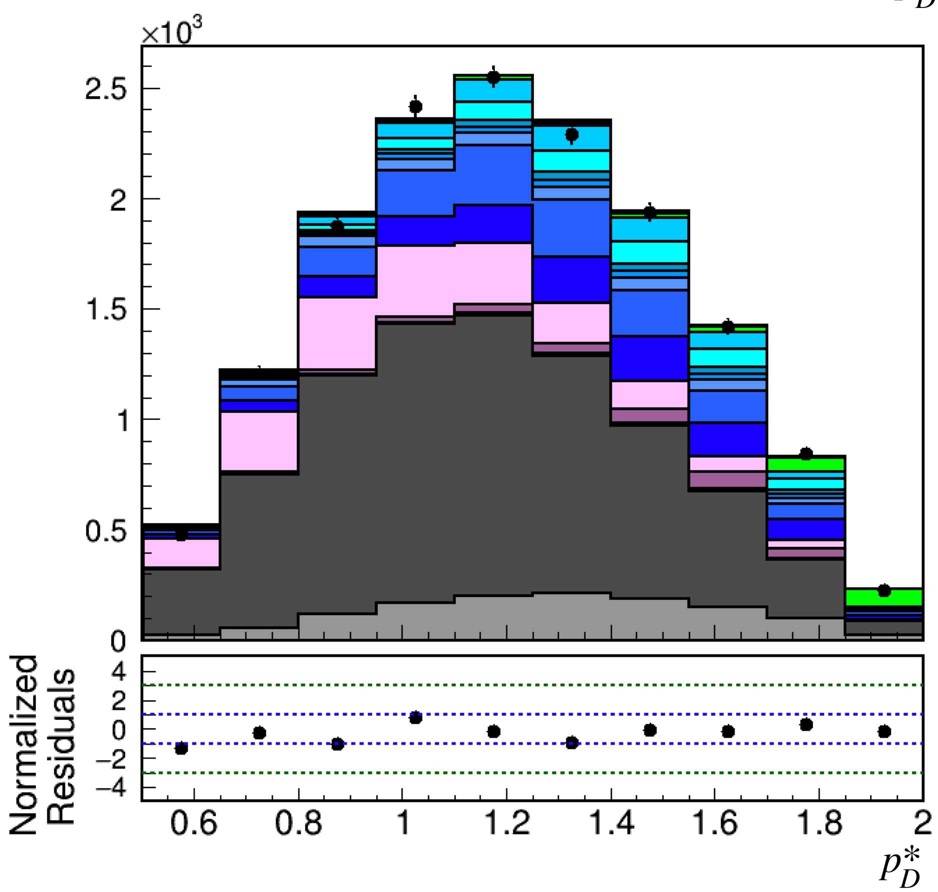
# Projections

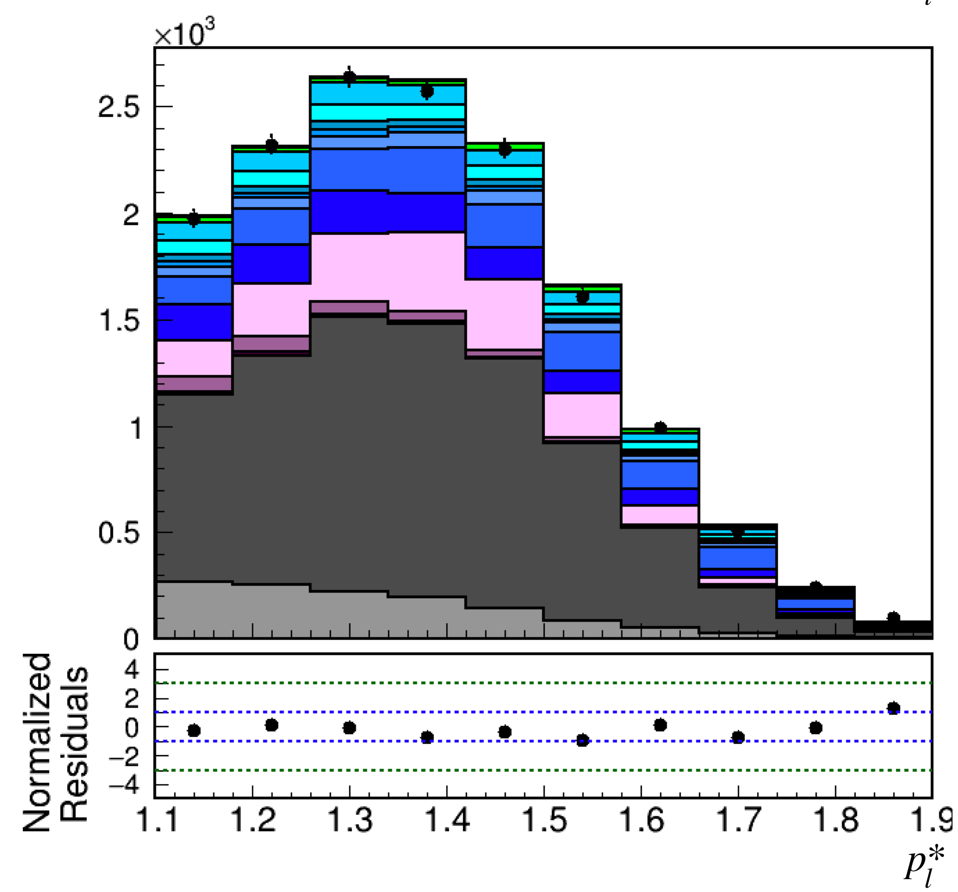
$D^0\mu\nu$




$D^-\mu\nu$



# Fit results

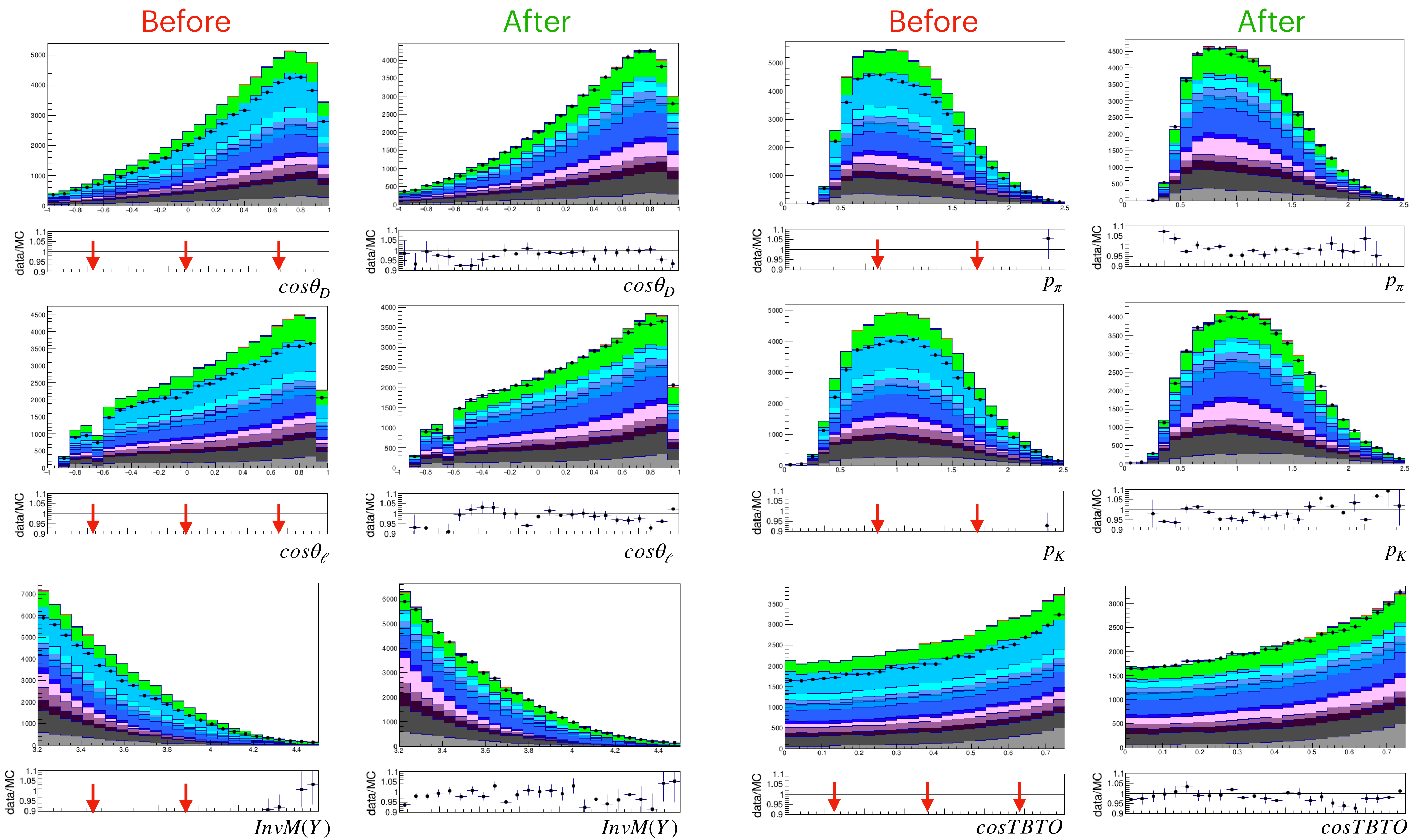
The simultaneous fit returns the following results:

| Fit parameters | Expected values | Fit results | relative unc. | Fitted/Expected |
|---|---|---|---|---|
| $\mathcal{B}(B \to D_1 \ell \nu)$ | 0.64% | (0.73 +- 0.08)% | 10.9% | 1.15 |
| $\mathcal{B}(B \to D_1^{'} \ell \nu)$ | 0.28% | (0.29 +- 0.04)% | 13.8% | 1.03 |
| $\mathcal{B}(B \to D_0^{*} \ell \nu)$ | 0.13% | (0.13 +- 0.03)% | 23.1% | 1.05 |
| $\mathcal{B}(B \to D_2 \ell \nu)$ | 0.32% | (0.33 +- 0.03)% | 9.1% | 1.03 |
| $\mathcal{B}(B \to D^{(*)} \pi\pi \ell \nu)$ | 0.30% | (0.25 +- 0.08)% | 31.3% | 0.85 |
| $\mathcal{B}(B \to D^{(*)} \eta \ell \nu)$ | 1.80% | (0.19 +- 0.12)% | 63.2% | 0.11 |
| $realD_{rest}(D^0 e \nu)$ | 2896 | 4607.4 +- 464.0 | 10.1% | 1.59 |
| $realD_{sec}(D^0 e \nu)$ | 3815 | 2684.8 +- 554.5 | 20.7% | 0.70 |
| $realD_{rest}(D^- e \nu)$ | 909 | 1846.7 +- 244.0 | 13.2% | 2.03 |
| $realD_{sec}(D^- e \nu)$ | 566 | 450.5 +- 257.5 | 57.2% | 0.80 |
| $realD_{fake}(D^0 \mu \nu)$ | 6673 | 7934.2 +- 850.9 | 10.7% | 1.19 |
| $realD_{fake}(D^- \mu \nu)$ | 879 | 79.6 +- 444.8 | 558.8% | 0.09 |

Use the fit results to scale the $D^{**}$ and real D components.

# Data/MC agreement: $D^0 e\nu$ sample

Check data/MC agreement after scaling $D^{**}$ and real D components according to the fit results.

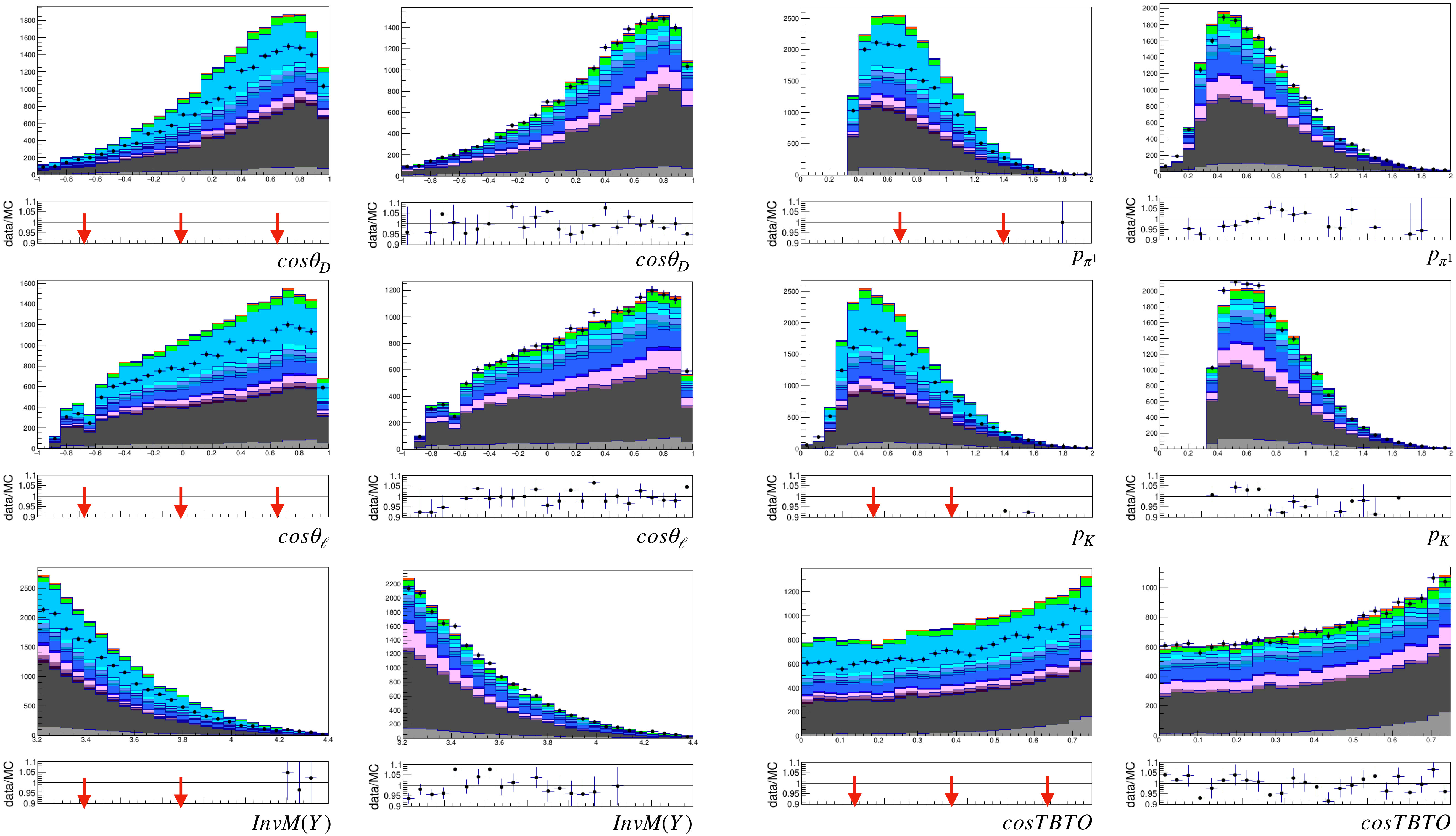



Data/MC agreement improves after scaling $D^{**}$ and real D components.

# Data/MC agreement: $D^{-}e\nu$ sample

Check data/MC agreement after scaling $D^{**}$ and real D components according to the fit results.

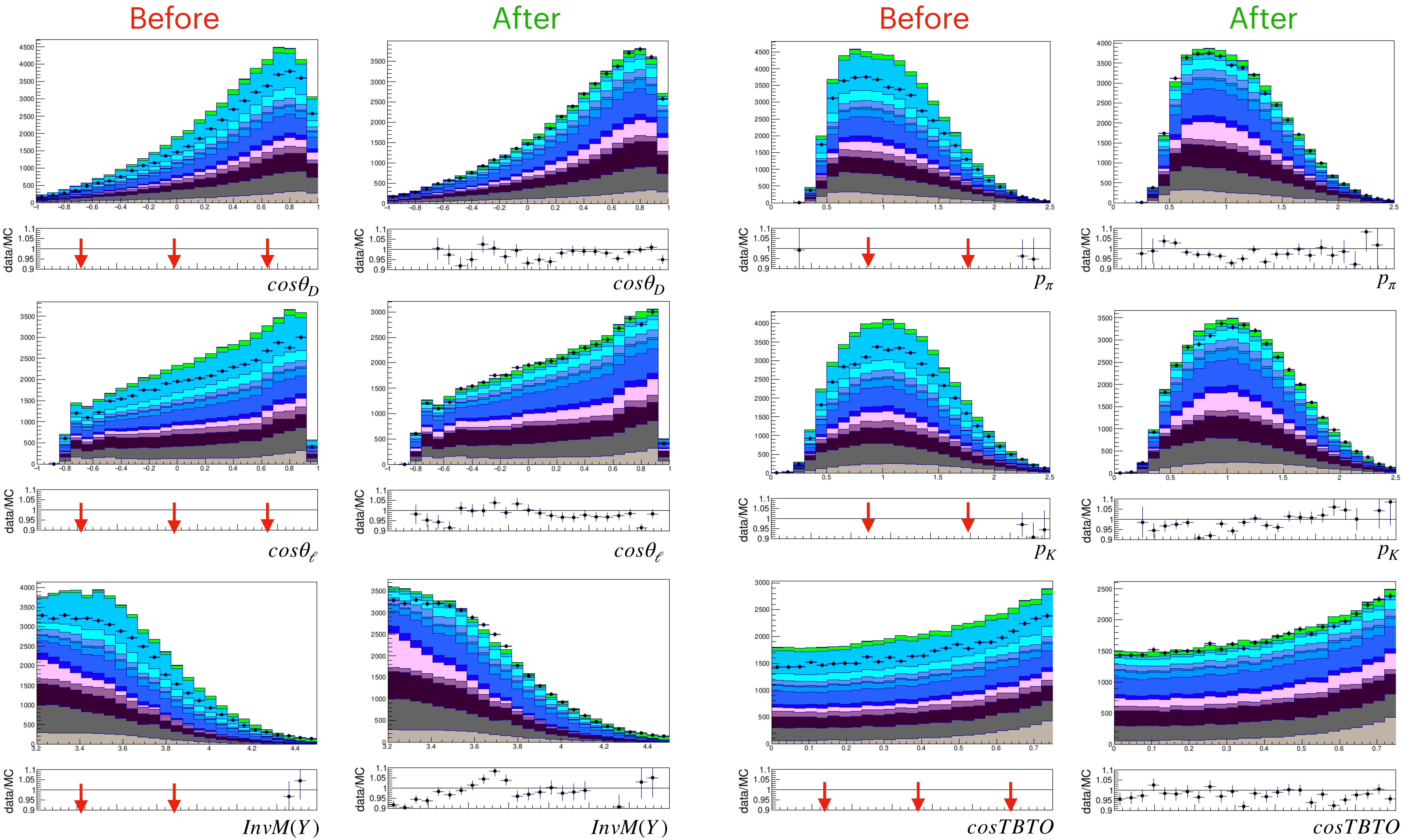
Before | After | Before | After




Data/MC agreement improves after scaling $D^{**}$ and real D components.

# Data/MC agreement: $D^0\mu\nu$ sample

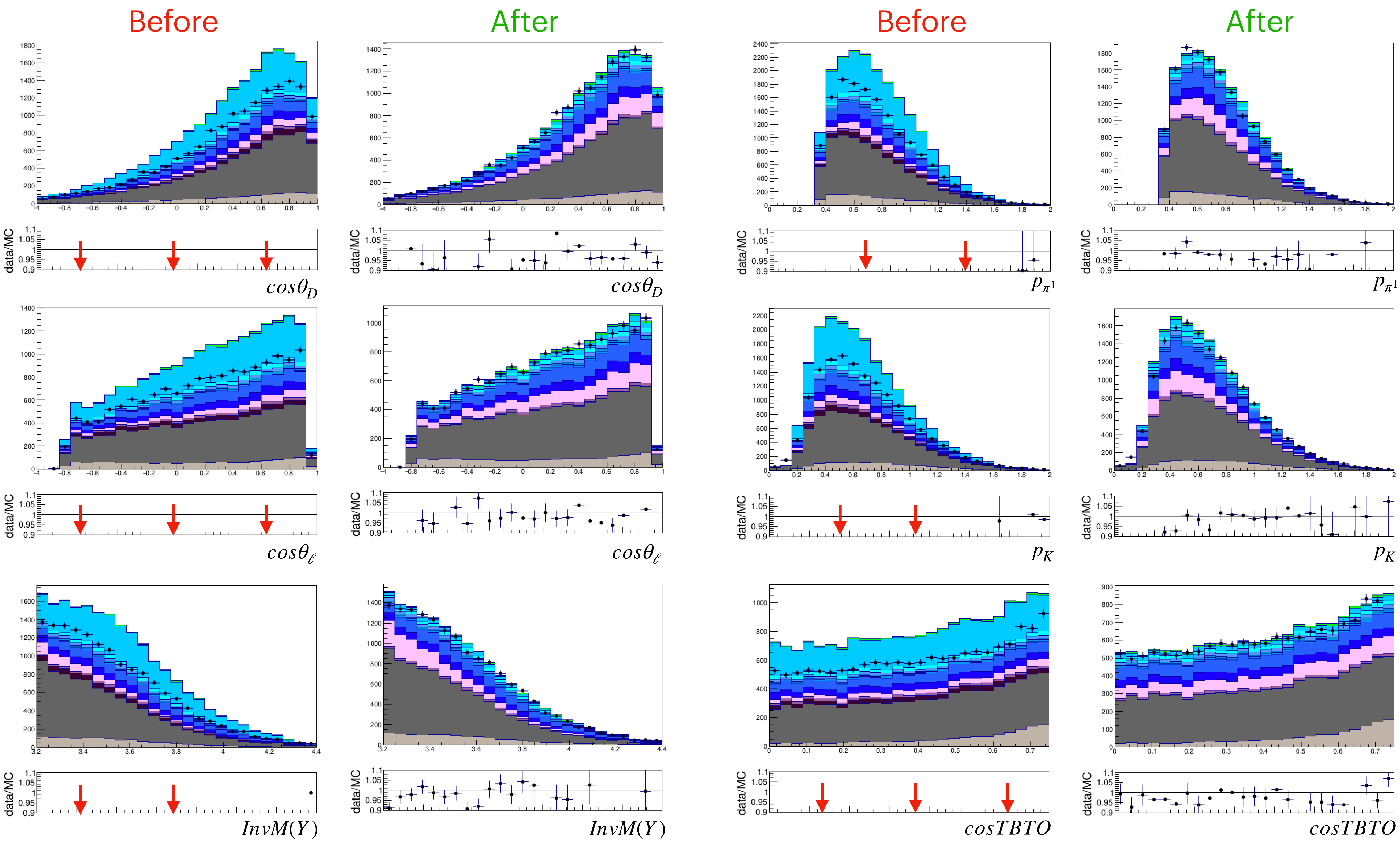
Check data/MC agreement after scaling $D^{**}$ and real D components according to the fit results.




Data/MC agreement improves after scaling $D^{**}$ and real D components.

# Data/MC agreement: $D^{-}\mu\nu$ sample

Check data/MC agreement after scaling $D^{**}$ and real D components according to the fit results.




Data/MC agreement improves after scaling $D^{**}$ and real D components.

# Summary

- Split the gap modes into e.g. split $D^{(*)}\pi\pi\ell\nu$ and $D^{(*)}\eta\ell\nu$ templates.

- Split the real D to constrain better the sub-components (inclusive D decays, fake leptons, …).

- Test a 2D simultaneous fit between the electron and muon samples in the sideband region to constrain the $X\ell\nu$ and real D components.

  Observed a good data/MC agreement after scaling $X\ell\nu$ and real D components according to the fit results.

# Next steps

- Perform a simultaneous fit between the signal and control region to constrain the $X\ell\nu$ decays and real D components.

# Backup

# Selection of $D\ell\nu$ samples

- |dr|<1 + |dz|<3 for all tracks
- binaryKaonID>0.6 (for $D^{-}\ell\nu$) + binaryKaonID>0.1 (for $D^{0}\ell\nu$)
- MuonID_noSVD>0.9, $PID_{BDT}(e)$ >0.9
- Treefit : $\chi^2 > 1\,\%$
- ROE mask: |dr|<1 + |dz|<3 + $p_{CMS} < 3.2$
- VisibleEnergyCMS>4 GeV, thetainCDCacceptance
- R2<0.4
- cosTBTO<0.75
- $p_{\ell}^{CMS} \in [0.8,2.2]$
- $p_{D}^{CMS} \in [0.5,2.5]$
- $InvM(D) \in [1.865,1.874]$ for $D^{-}\ell\nu$, $InvM(D) \in [1.86,1.87]$ for $D^{0}\ell\nu$
- $InvM(Y) > 3.2GeV$
- $cos\theta_{BY} \in [-2,1.1]$
- Cut on $p(\pi)$>0.35 (remove the systematics for slow tracks)
- KakunoFoxWolfram(h20)>0.18 (only for $D^{-}\ell\nu$ samples)
- $p_{ROE}^{CMS} < 2.8GeV$
- One candidate selection applied.

# New selection

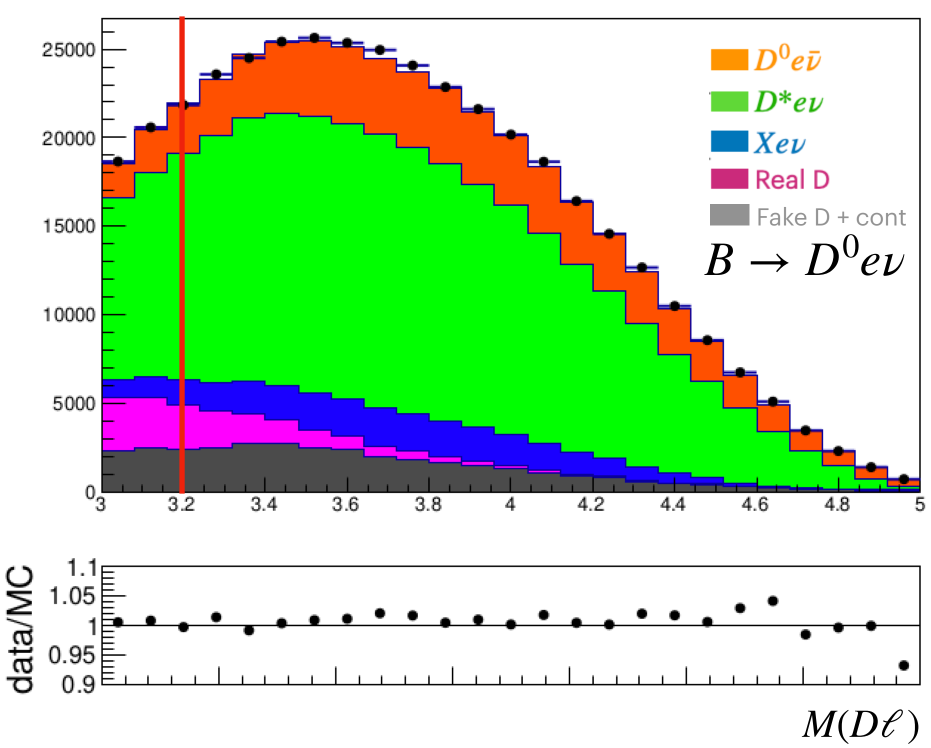
**Full selection in backup**

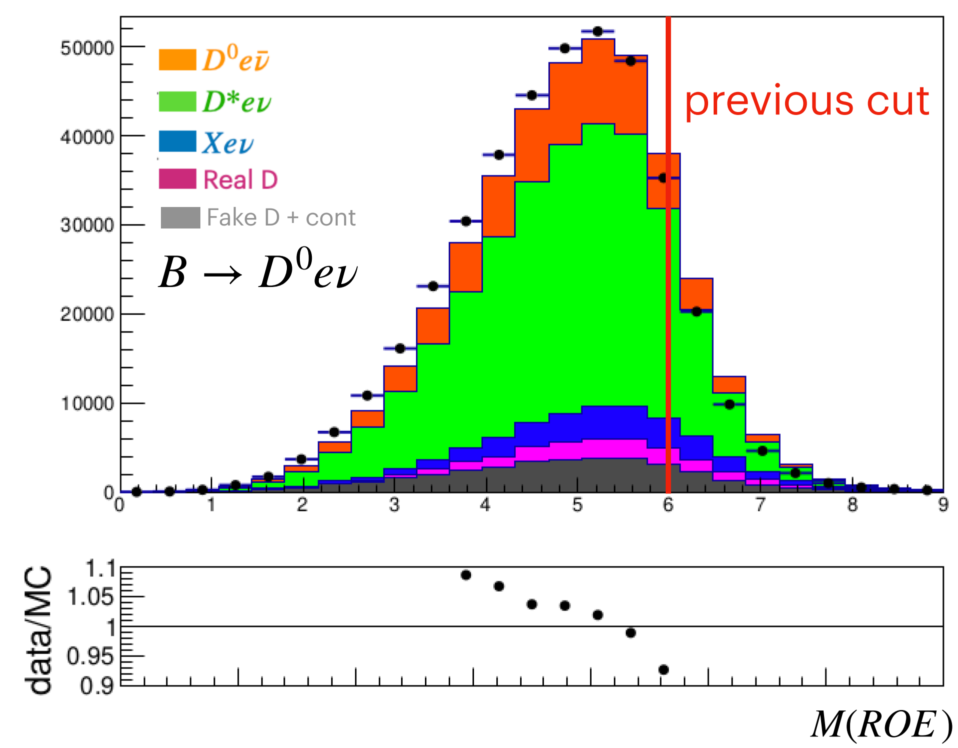
- Removed cuts on variables with a large data/MC disagreement:

   1. M(ROE)<5.2 GeV for $D^-\ell\nu$, M(ROE)<6 GeV for $D^0\ell\nu$.

   2. KakunoFoxWolfram(h20)>0.18 (removed only for $D^0\ell\nu$ sample).

- New cut on $M(D\ell)$>3.2 GeV to further reduce the real D component.
- Removed the tight cut on TreeFitter $\chi^2$ (> 5%) probability; replaced by $\chi^2$ > 1%.
- Cut on $p(\pi)$>0.35 GeV (only for $D^-\ell\nu$ sample) to remove the systematic due to slow tracks.
- Removed nCDCHits>20 cut for mesons ($K/\pi$): not required anymore for PID corrections.



# Branching fractions corrections

- Update the MC branching fractions according to the PDG:

| Decay | $\mathscr{B}(B^+)(MC)$ | $\mathscr{B}(B^+)(update)$ | $\mathscr{B}(B^0)(MC)$ | $\mathscr{B}(B^0)(update)$ | D** FF model |
|---|---|---|---|---|---|
| $B \to D_1 \ell \nu$ | 0.76% | (0.64 +- 0.10)% | 0.71% | (0.59 +- 0.10)% | BLR |
| $B \to D_0^* \ell \nu$ | 0.39% | (0.13 +- 0.03)% | 0.36% | (0.12 +- 0.03)% | BLR |
| $B \to D_1^{'} \ell \nu$ | 0.43% | (0.28 +- 0.04)% | 0.40% | (0.26 +- 0.04)% | BLR |
| $B \to D_2 \ell \nu$ | 0.37% | (0.32 +- 0.03)% | 0.35% | (0.30 +- 0.03)% | BLR |
| $B \to D\pi\pi \ell \nu$ | 0.53% | (0.07 +- 0.09)% | 0.49% | (0.07 +- 0.08)% | PHSP |
| $B \to D^*\pi\pi \ell \nu$ | 0.26% | (0.22 +- 0.10)% | 0.25% | (0.20 +- 0.10)% | PHSP |
| $B \to D\eta \ell \nu$ | 0.20% | (0.90 +- 0.90)% | 0.22% | (0.86 +- 0.86)% | PHSP |
| $B \to D^*\eta \ell \nu$ | 0.20% | (0.90 +- 0.90)% | 0.22% | (0.86 +- 0.86)% | PHSP |

The correction of the branching fractions leads to a modification of the form:

$$N_j^{new} = N_j^{MC} \frac{\mathscr{B}_j^{new}}{\mathscr{B}_j^{MC}}$$

$N_j^{MC}$ = # of events in MC for the j-component, $\mathscr{B}_j^{MC}$ = BR in MC, $\mathscr{B}_j^{new}$ = update BR.

# Gap modes

- In our MC, the gap modes $D^{(*)}\pi\pi\ell\nu$ and $D^{(*)}\eta\ell\nu$ have been generated with phase-space leading to a very soft lepton momentum.
- It seems physically less plausibile than a decay kinematic in which the hadronic particles are more correlated to each other.
- Remove these gap modes in our MC sample and replaced them by

$$B \to D^{**}[\to D^{(*)}\pi\pi]\ell\nu \qquad B \to D^{**}[\to D^{(*)}\eta]\ell\nu$$

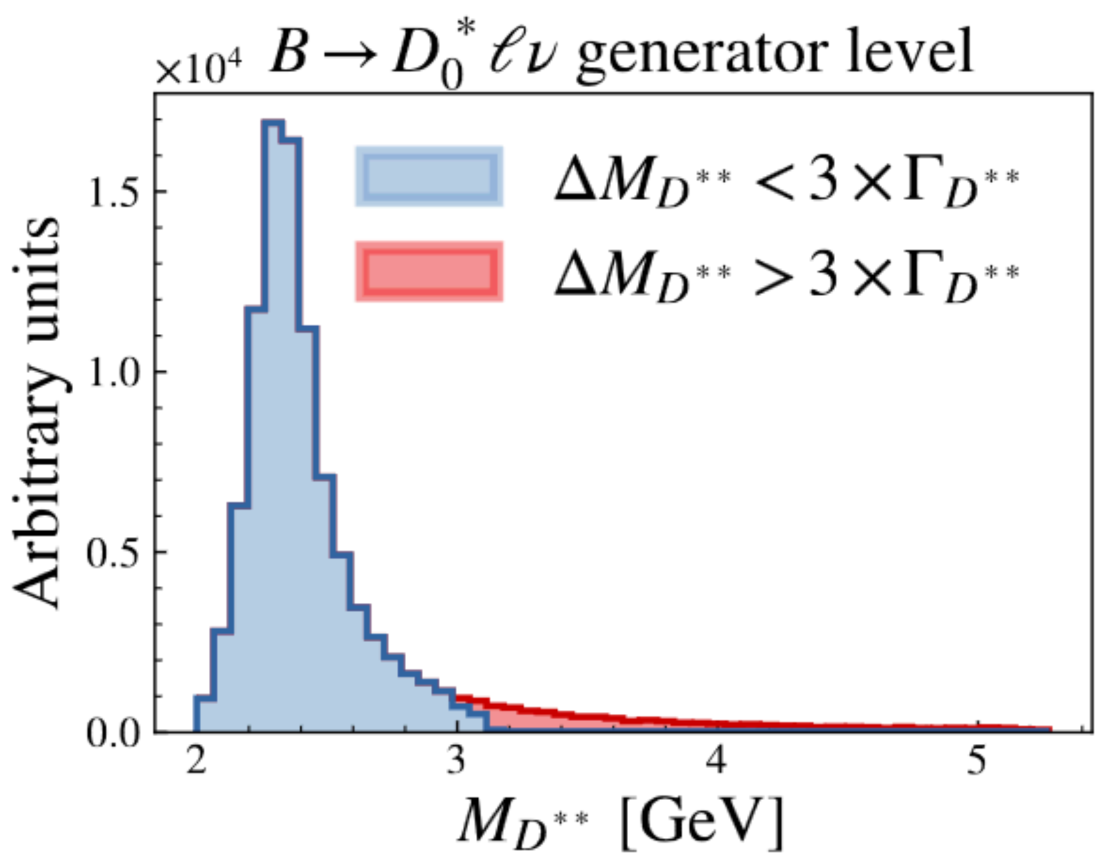
| Decay | Sim.events | Lumi (ab-1) | D** FF model |
|---|---|---|---|
| $B \to D_1^{'}[\to D\pi\pi]\ell\nu$ | $8 \cdot 10^6$ | B0: 16, B+: 14 | BLR |
| $B \to D_0^{*}[\to D\pi\pi]\ell\nu$ | $8 \cdot 10^6$ | B0: 16, B+: 14 | BLR |
| $B \to D_1^{'}[\to D^*\pi\pi]\ell\nu$ | $8 \cdot 10^6$ | B0: 3.2, B+: 2.8 | BLR |
| $B \to D_0^{*}[\to D^*\pi\pi]\ell\nu$ | $8 \cdot 10^6$ | B0: 3.2, B+: 2.8 | BLR |
| $B \to D_0^{*}[\to D\eta]\ell\nu$ | $8 \cdot 10^6$ | B0: 1.8, B+: 1.8 | BLR |
| $B \to D_1^{'}[\to D^*\eta]\ell\nu$ | $8 \cdot 10^6$ | B0: 1.8, B+: 1.8 | BLR |

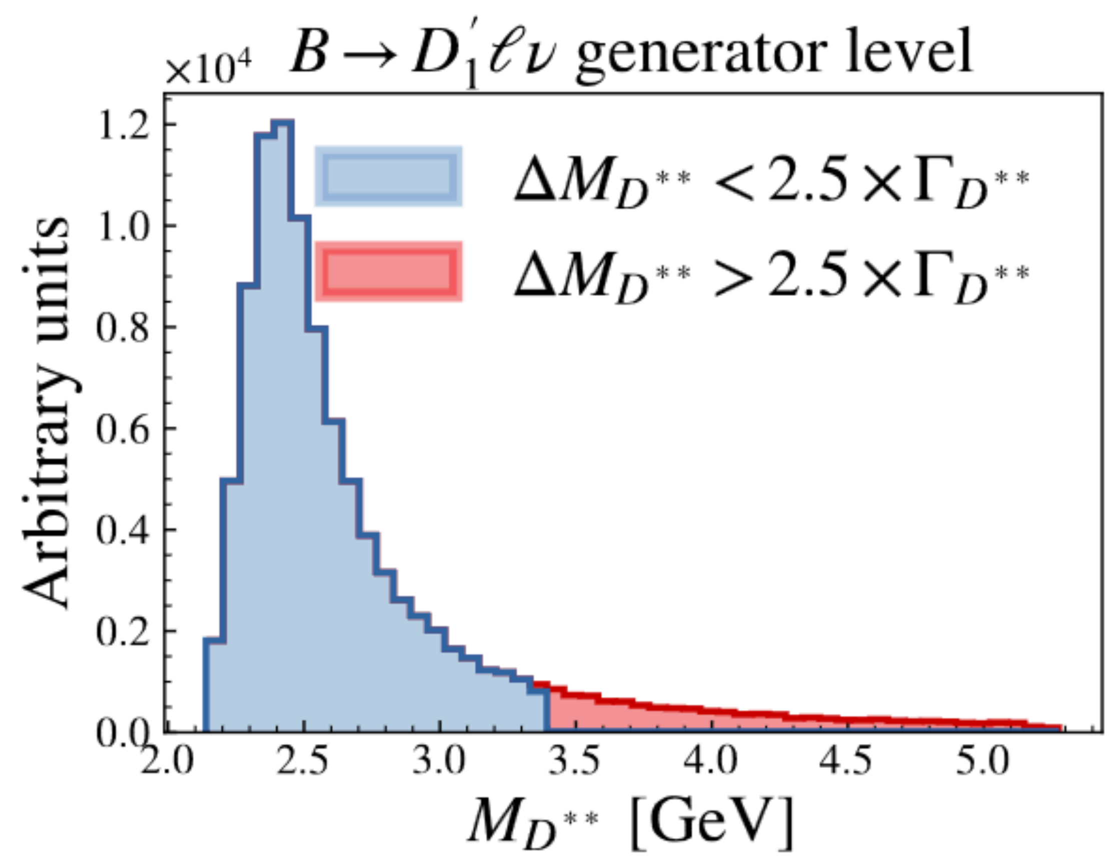
- $\mathscr{B}(B \to D^{(*)}\pi\ell\nu)$ set to 0; BR saturated by production via $D^{**}$ BR.

# $D^{**}$ resonances

- Issue is spotted with the modelling $D_0^*$ and $D_1^{'}$ resonances.
  First observation of this issue by Henrik.

- Due to their large width, some events are generated with $D^{**}$ mass larger than the nominal one leading to an unphysical enhancement in the $w \sim 1$ region.




Events that exceed 3 times the width of $D_0^*$ and 2.5 times of $D_1^{'}$ are rejected.

# $X\ell\nu$ composition

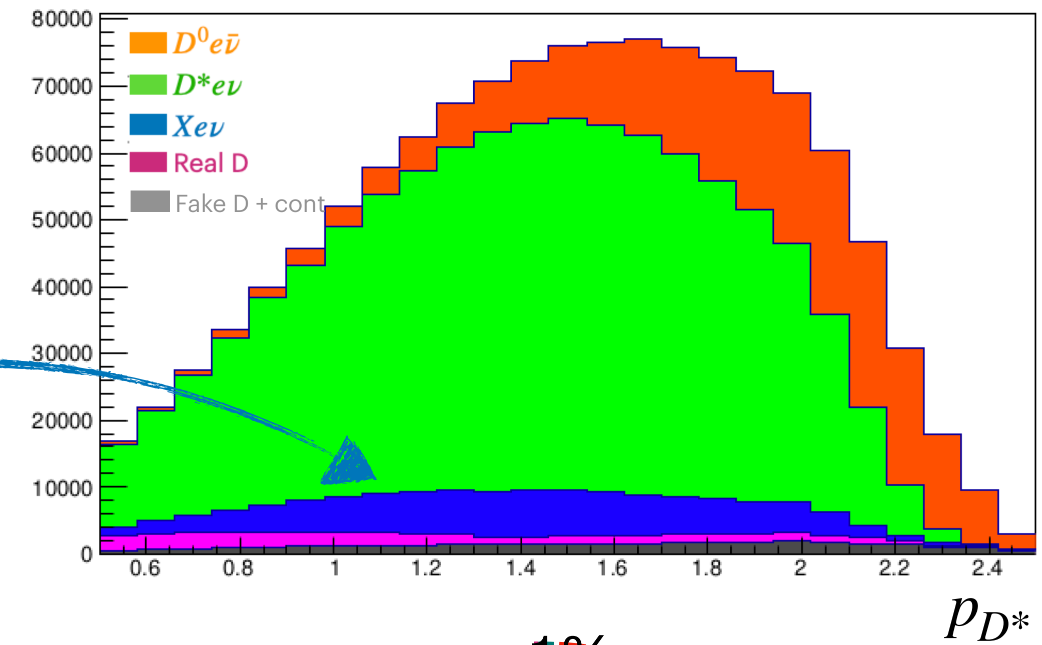
Studied the $X\ell\nu$ component after the BR and gap modes corrections.

Divided the $X\ell\nu$ component in different sub-components:

1. $D^{**}\ell\nu$
2. Gap modes
3. $D^{*}\tau\nu$
4. $D\tau\nu$
5. $D^{(*)}\ell\nu$, $\ell$ = misID lepton
6. $D^{**}\tau\nu$

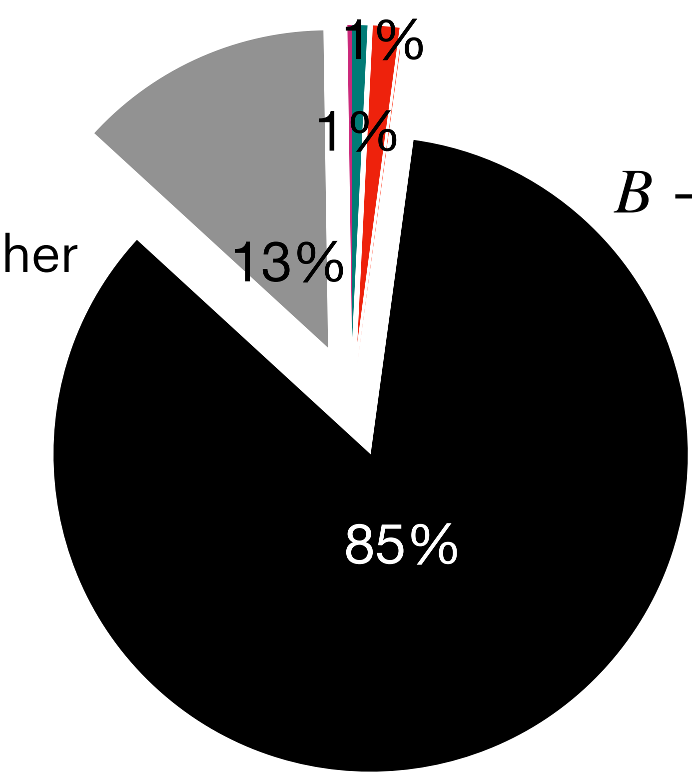
$X\ell\nu$ component

$B \to D^0 e\nu$




Similar proportions for the other samples (see backup)

$B \to D^0 e\nu$



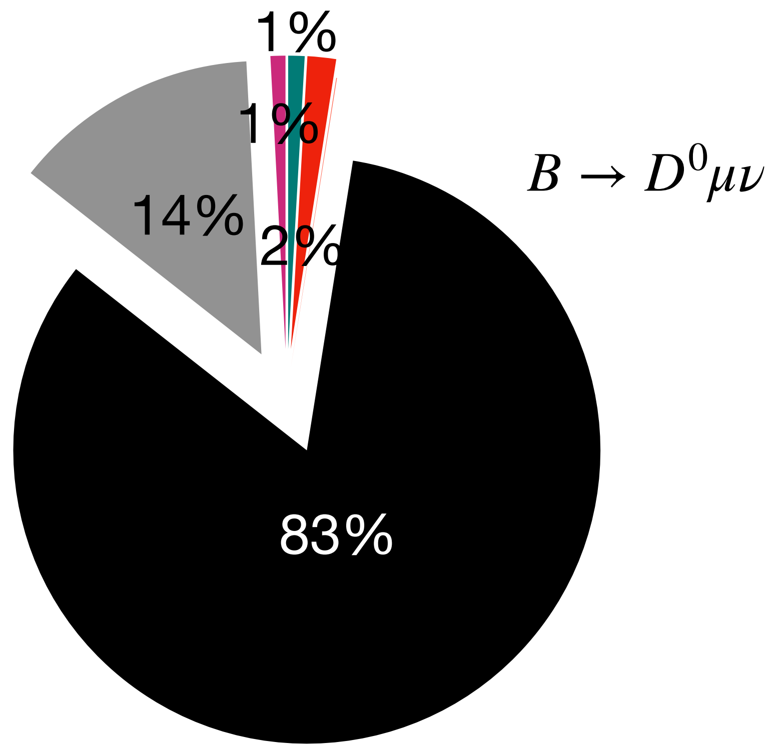

$X\ell\nu$ component dominated by $D^{**}\ell\nu$ and gap modes decays.

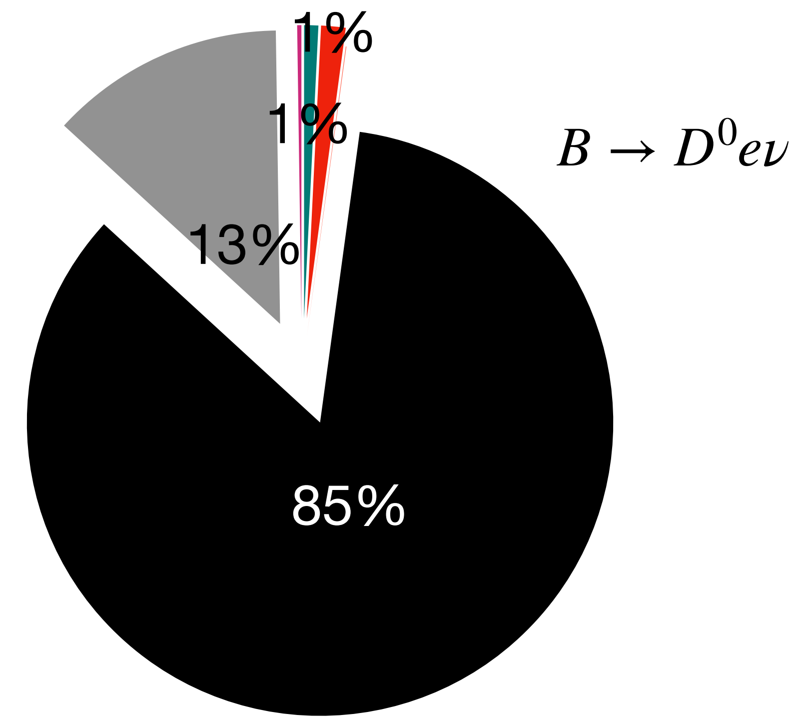
# $X\ell\nu$ composition

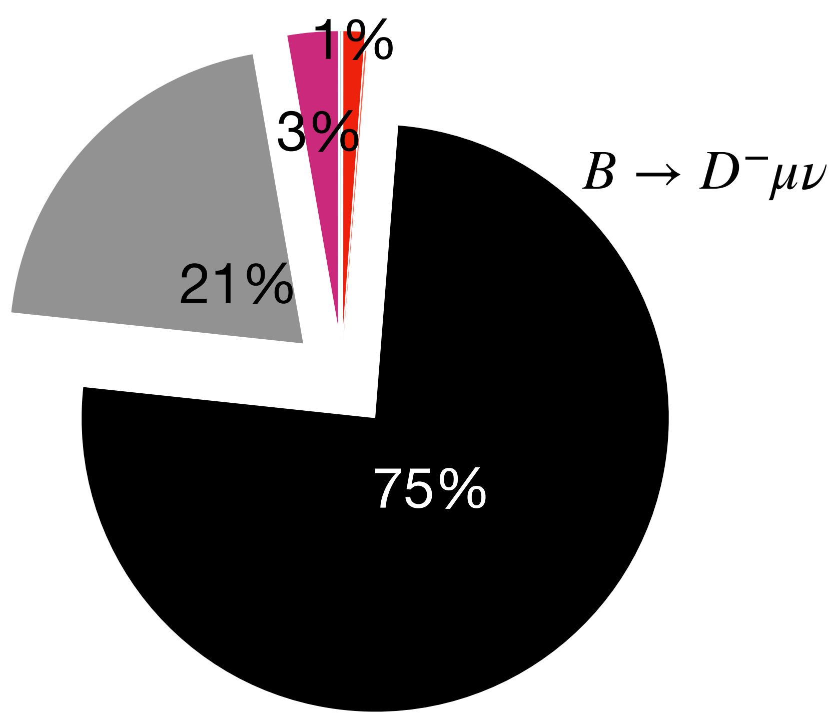
Studied the $X\ell\nu$ component after the BR and gap modes corrections.

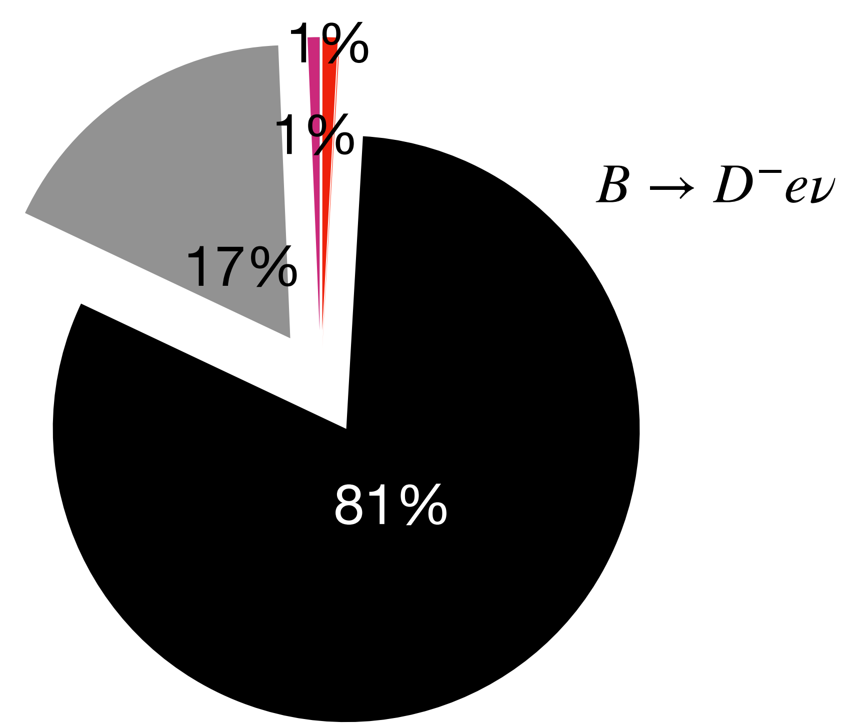
Divided the $X\ell\nu$ component in different sub-components:

1. $D\tau\nu$
2. $D^{*}\tau\nu$
3. $D^{**}\tau\nu$
4. Gap modes
5. $D^{(*)}\ell\nu$
6. $D^{**}\ell\nu$



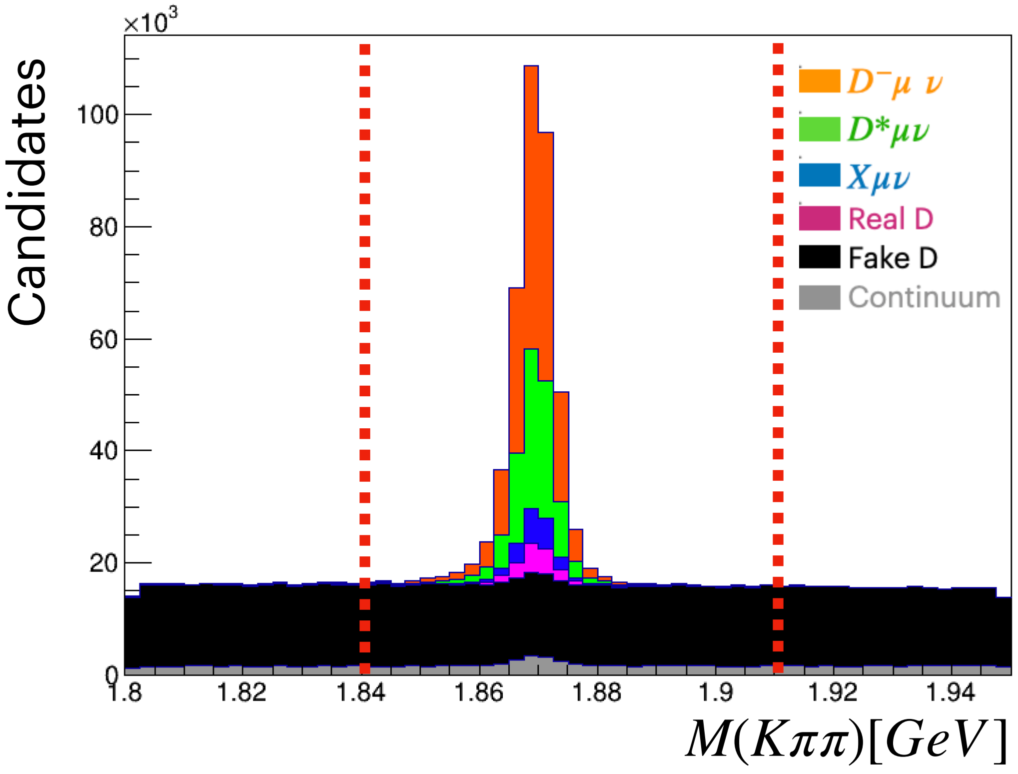
# Constraining fake D and continuum

- Can constrain from data **fake D** and **continuum** components using D mass sidebands.
Will use data to build one single template (fake D + continuum) and fix the normalisation.

Test the strategy using MC:

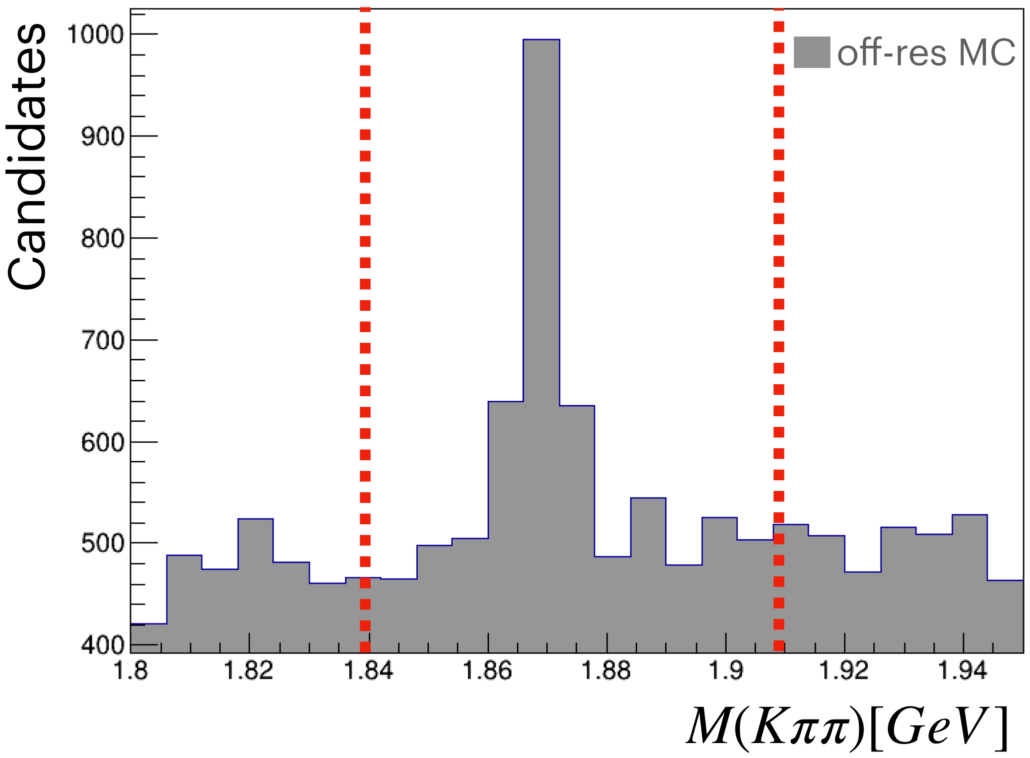
1. Build the template from D mass sidebands.

2. Take off-resonance MC sidebands, use it to extract the peak contribution in the signal region due to $e^+e^- \to c\bar{c}$.




3. Reweight the continuum peak due to the different cross section of $e^+e^- \to c\bar{c}$ between off-resonance and on-resonance in MC.

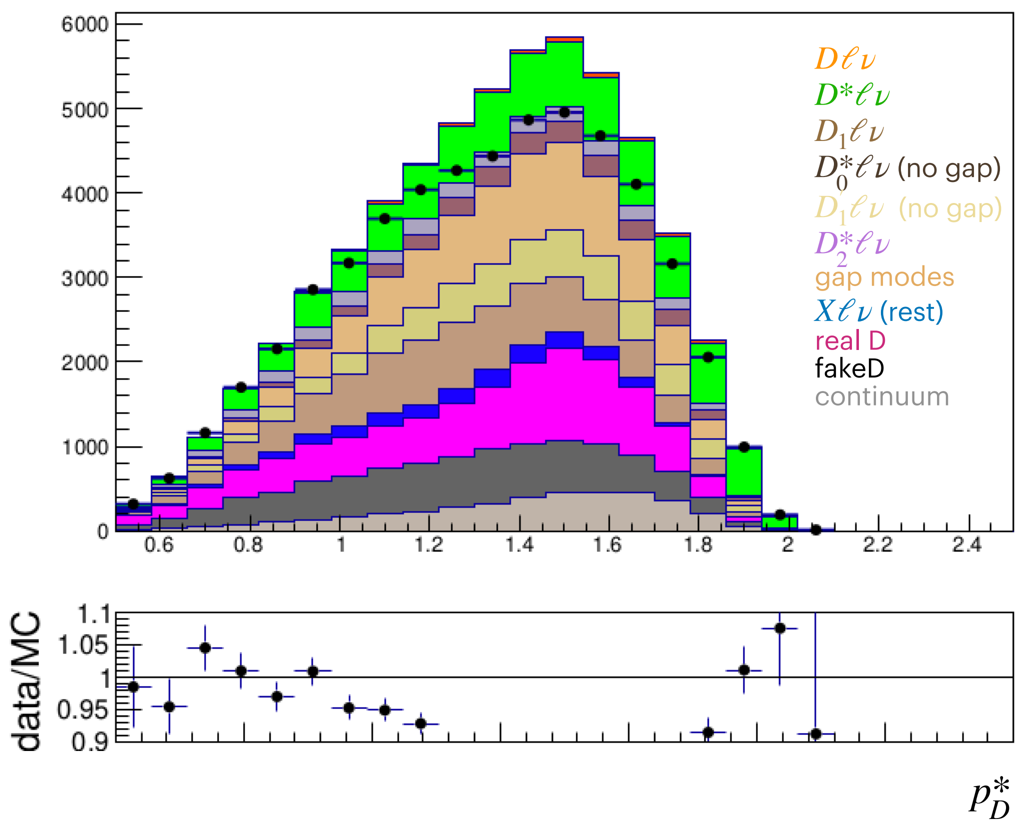
4. Scale to the same luminosity and add it to the final template.

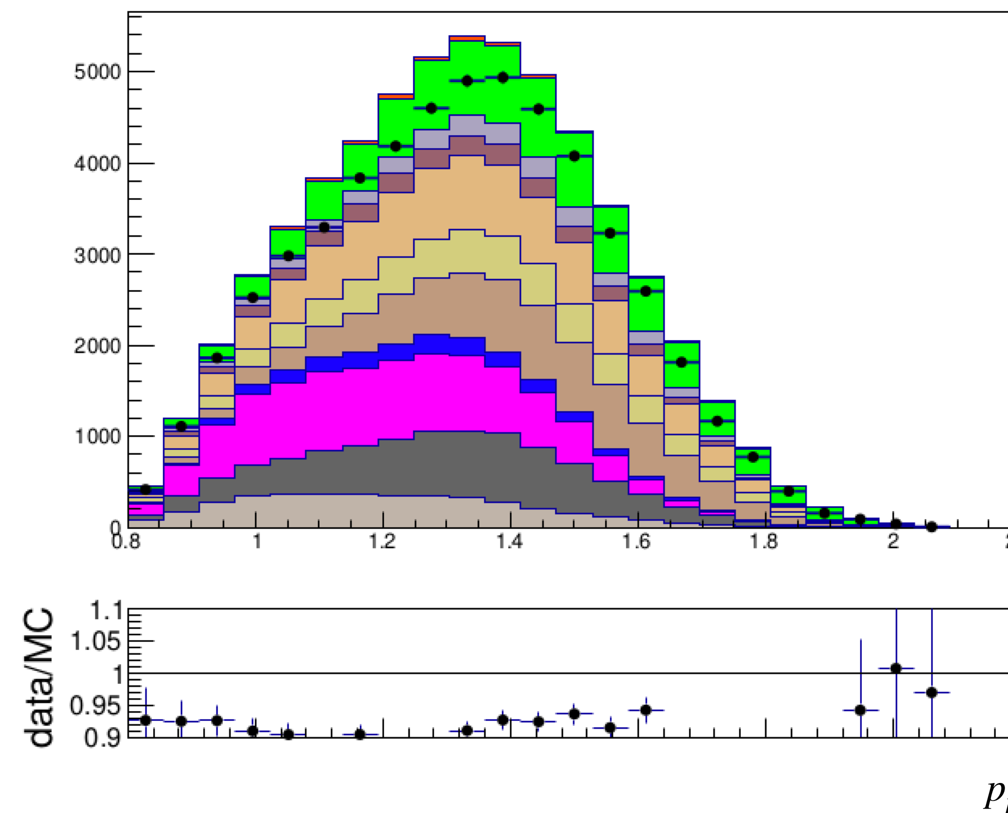



Will use same weights evaluated in 3) also in data.

# Projections (pre-fit)

## $D^0 e\nu$




## $D^- e\nu$