Search for invisible D^0 decays at Belle II

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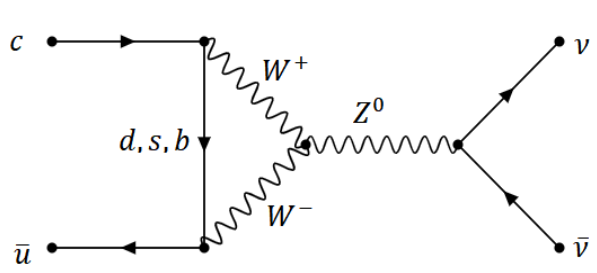
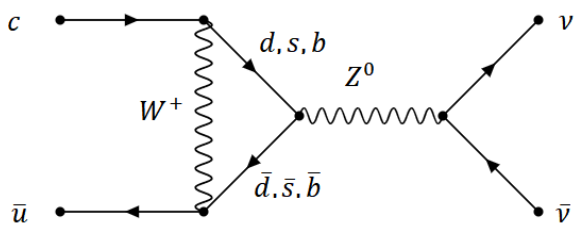
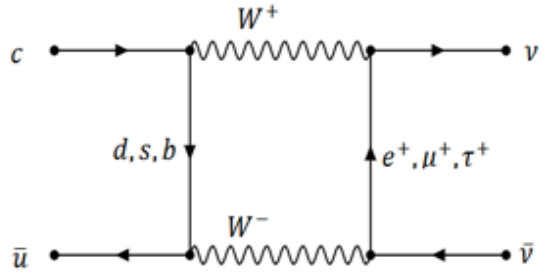
Introduction

- In SM, heavy (B or D) decays to $\nu\bar{\nu}$ is helicity suppressed with an expected BF of $\mathbf{Br}(D^0 \to \nu\bar{\nu}) = \mathbf{1.1 \times 10^{-30}}$, which is beyond the reach of experiment.







- But with several DM candidates, the BF can be enhanced to $O(10^{-15})$ [Phys. Rev. D **104**, 015014]
- The previous result is $BR_{UL} = 9.4 \times 10^{-5}$ at 90% CL at belle [Phys. Rev. D **102**, 012003 (2020)]

MC samples

- 6M Signal MC samples : produced and the decay is simulated by evtgen and detector simulation is done by Geant4

- Signal MC decay:
  - $e^+e^- \to c\bar{c} \to D_{tag}X_{frag}D^{*\pm}_{sig}$ (hadronization by PYTHIA)
  - $D^{*\pm}_{sig} \to D^0(\bar{D}^0)\pi^{\pm}_s$
  - $D^0(\bar{D}^0) \to \nu\bar{\nu}$ (PHSP)

- Background MC samples :
  - Official background MC samples ($1ab^{-1}$)
  - $e^+e^- \to \Upsilon(4S) \to B\bar{B}(charged, mixed)$, prompt production of $u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}, \tau\bar{\tau}(taupair)$
  - Skimming code is currently under writing and testing

Analysis Procedure : Charm tagging

D_{tag}, D^*_{tag}

1. Reconstruct D_{tag} using the chosen decay channels
2. Reconstruct D^*_{tag}

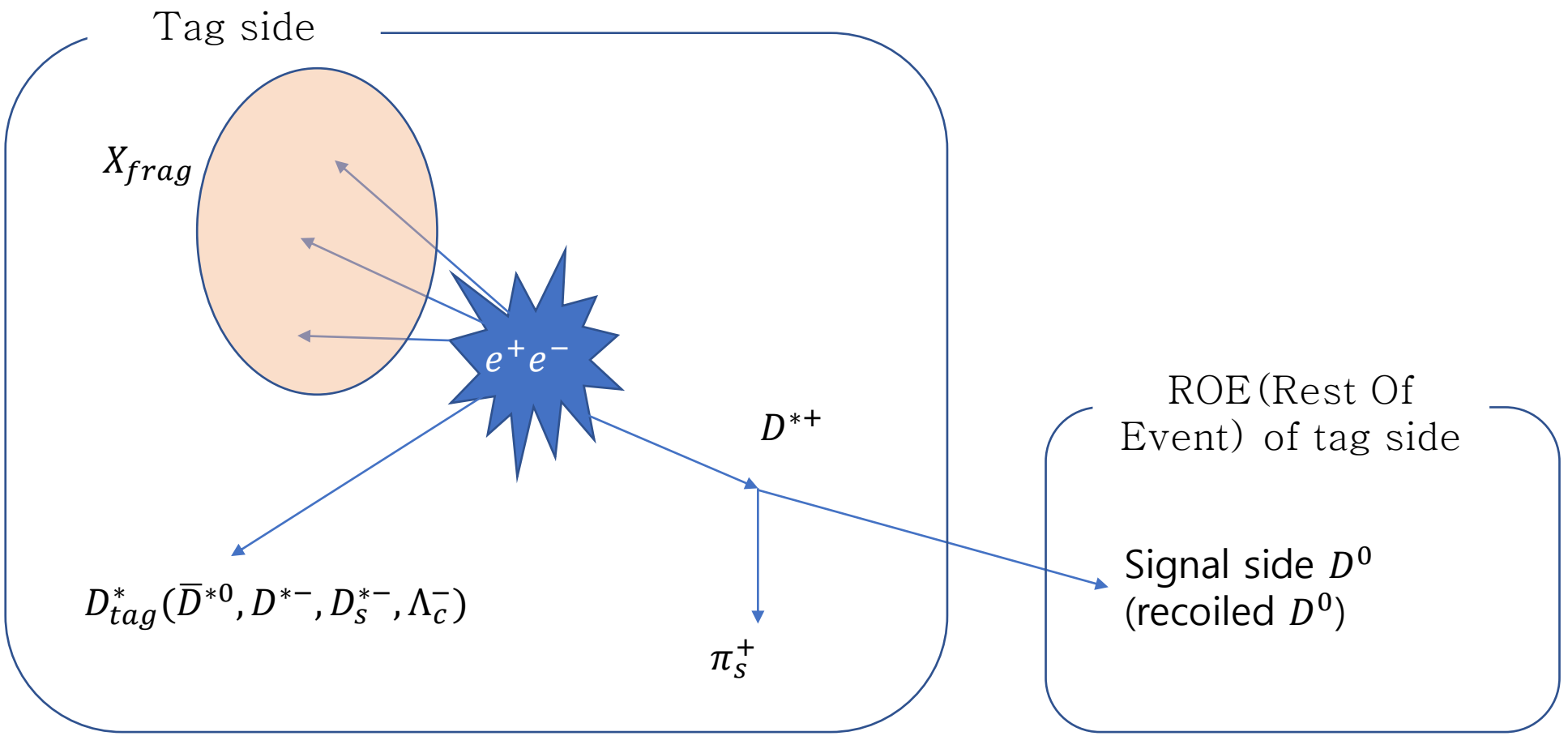
recoil part 1 (D^{*+})

1. With X_{frag} according to D^*_{tag}, calculate $M_{miss}(D^*_{tag}X_{frag})$ which is regarded as mass of D^{*+}_{sig}
2. Apply kinematic mass constrained Fit on $M_{miss}(D^*_{tag}X_{frag})$ to $m_{D^{*+}}$
3. BCS of D^{*+}_{sig} by using χ^2 from step 2

recoil part 2 (D^0)

5. Using slow pion, calculate $\mathrm{M_{miss}}(D^*_{tag}X_{frag}\pi^+_s)$
6. BCS of D^0 by using angle between D^0_{sig} and D^*_{tag} in cm frame

Schematics of $e^+e^- \to c\bar{c} \to D^*_{tag} X_{frag} D^{*+} \to D^*_{tag} X_{frag} \pi_s^+ D^0$



Final Particle selection criteria

Table 1: Final state particles selection criteria in tagging side

particles	selection critera
chargedtracks	$\|dr\| < 0.5,\ \|dz\| < 1.5,\ nCDCHits > 20$
K	$L_{K/\pi} > 0.1$
π	$L_{K/\pi} < 0.9$
p	$L_{K/p} < 0.9,\ L_{\pi/p} < 0.9$
$\pi_s^{\pm}$	$L_{K/\pi} < 0.9$ $\|dr\| < 0.5, \|dz\| < 1.5$ *noCut on nCDCHits*
regular π^0	π^0 reconstructed from 2γ $E_\gamma > 0.8$GeV for forward endcap $E_\gamma > 0.03$GeV for barrel region $E_\gamma > 0.06$GeV for backward endcap $0.115\text{GeV} < M < 0.150\text{GeV}$ Mass constrained Fit
strong π^0	with regular π^0, require $E_\gamma > 100$MeV for endcap region Mass constrained Fit $0.115\text{GeV} < M < 0.150\text{GeV}$
Λ^0	standard goodBelle Λ^0: flightlength in transverse plane > 0.1 cm $\cos(\Delta\theta) > 0.99$, $\Delta\theta$: azimuthal angle of between momentum and vertex vector $\chi^2 < 100$ $1.111GeV < M < 1.121GeV$
K_S^0	standard goodBelle K_S^0 $0.468GeV < M < 0.508GeV$
γ	$E_\gamma > 0.12$ GeV and π^0 veto

Decay channels and selections for charm tagger are based on the previous research

Table 2: Fragmentation particles selection criteria

particles	selection critera
charged tracks	$\|dr\| < 0.5,\ \|dz\| < 1.5$
$K^{\pm}$	$L_{K/\pi} > 0.6,\ L_e < 0.99$ $p > 0.1$GeV
$\pi^{\pm}$	$L_{K/\pi} < 0.9$ $p > 0.1$GeV
$p^+(\bar{p}^-)$	$L_{K/p} < 0.9,\ L_{\pi/p} < 0.9$ $p > 0.1$GeV
π^0	same with regular π^0 in tag side $p > 0.1$GeV
K_S^0	same with K_S^0 in tag side $p > 0.1$GeV

★ $L_{i/j} \equiv \frac{L_i}{L_i + L_j}$

Tag side decay channels

Table 3: D_{tag} decay channels

D^0 decay	$Br(\%)$	D^+ decay	$Br(\%)$	Λ_c^+ decay	$Br(\%)$	D_s^+ decay	$Br(\%)$
$K^-\pi^+$	3.9	$K^-\pi^+\pi^+$	9.4	$pK^-\pi^+$	5.0	$K^+K^-\pi^+$	5.5
$K^-\pi^+\pi^0$	13.9	$K^-\pi^+\pi^+\pi^0$	6.1	$pK^-\pi^+\pi^0$	3.4	$K_S^0K^+$	1.5
$K^-\pi^+\pi^+\pi^-$	8.1	$K_S^0\pi^+$	1.5	pK_s^0	1.1	$K_S^0K_S^0\pi^+$	5.4
$K^-\pi^+\pi^+\pi^-\pi^0$	4.2	$K_S^0\pi^+\pi^0$	6.9	$\Lambda^0\pi^+$	1.1	$K^+K^-\pi^+\pi^0$	5.6
$K_S^0\pi^+\pi^-$	2.9	$K_S^0\pi^+\pi^+\pi^-$	3.1	$\Lambda^0\pi^+\pi^0$	3.6	$K_S^0K^-\pi^+\pi^0$	7.2
$K_S^0\pi^+\pi^-\pi^0$	5.4	$K^+K^-\pi^+$	1.0	$\Lambda^0\pi^+\pi^+\pi^-$	2.6		
sum	38.4	sum	28.0	sum	16.8	sum	25.2

Table 6: D_{tag}^* decay channels

D^{*+} decay	Br(%)	D^{*0} decay	Br(%)	D_s^{*+} decay	Br(%)
$D^0\pi^0$	67.7	$D^0\pi^0$	61.9	$D_s^+\gamma$	93.5
$D^+\pi^0$	30.7	$D^0\gamma$	38.1		
sum	98.4	sum	100.0	sum	93.5

Preselection for tag side

Table 4: D_{tag} common selection criteria

particles	common selection criteria
D^0	treeVertex and Mass constrained Fit χ^2 <20 1.8 [GeV] < M < 1.9 [GeV]
D^+	treeVertex and Mass constrained Fit χ^2 <20 1.8 [GeV] < M < 1.9 [GeV],
D_s^+	treeVertex and Mass constrained Fit χ^2 <20 1.9 [GeV] < M < 2.0 [GeV]
Λ_c^+	treeVertex and Mass constrained Fit χ^2 <20 2.2 [GeV] < M < 2.4 [GeV]

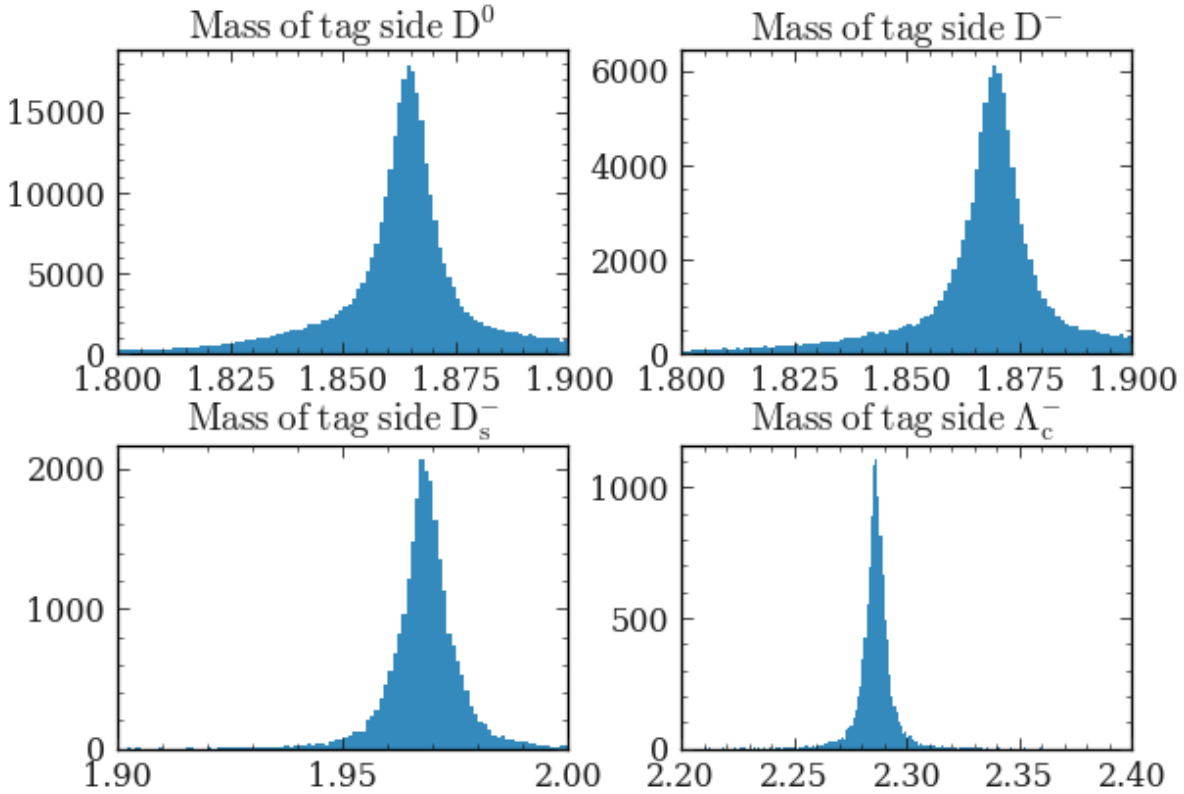
Table 7: ΔM Window and Mass selection range of D^*_{tag}

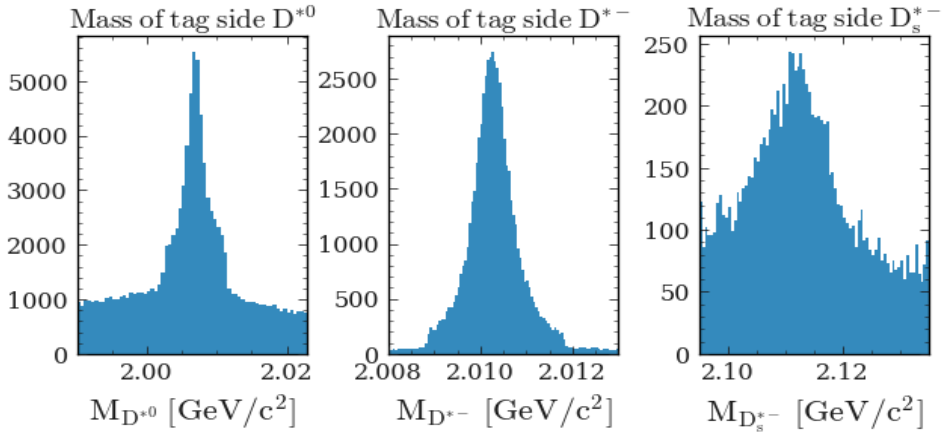
D^*_{tag}	Mass [GeV/c^2]	ΔM [GeV/c^2]
$D^{*+} \to D^0\pi^+$	1.975 ~ 2.045	0.144 ~ 0.147
$D^{*+} \to D^+\pi^0$	1.97 ~ 2.045	0.1375 ~ 0.1465
$D^{*0} \to D^0\pi^0$	1.97 ~ 2.045	0.1375 ~ 0.1465
$D^{*0} \to D^0\gamma$	1.96 ~ 2.05	0.125 ~ 0.159
$D_s^{*+} \to D_s^+\gamma$	2.07 ~ 2.15	0.125 ~ 0.17

Table 5: D_{tag} momentum selection

D^0 decay	p^* [GeV]	π^0 selection
$K^-\pi^+$	> 2.3	
$K^-\pi^+\pi^0$	> 2.5	regular
$K^-\pi^+\pi^-\pi^+$	> 2.3	
$K^-\pi^+\pi^-\pi^+\pi^0$	> 2.3]	strong
$K_s^0\pi^+\pi^-$	> 2.3	
$K_s^0\pi^+\pi^-\pi^0$	> 2.3	strong
D^+ decay	p^* [GeV]	π^0 selection
$K^-\pi^+\pi^+$	> 2.3	
$K^-\pi^+\pi^+\pi^0$	> 2.5	strong
$K_s^0\pi^+$	> 2.3	
$K_s^0\pi^+\pi^0$	> 2.4	regular
$K_s^0\pi^+\pi^+\pi^-$	> 2.3	
$K^+K^-\pi^+$	> 2.3	
D_s^+ decay	p^* [GeV]	π^0 selection
$K^+K^-\pi^+$	> 2.3	
$K_s^0K^+$	> 2.3	
$K_s^0K_s^0\pi^+$	> 2.3	
$K^+K^-\pi^+\pi^0$	> 2.5	strong
$K_s^0K^-\pi^+\pi^+$	> 2.4	
Λ_c^+ decay	p^* [GeV]	π^0 selection
$pK^-\pi^+$	> 2.3	
$pK^-\pi^+\pi^0$	> 2.5	strong
pK_s^0	> 2.3	
$\Lambda^0\pi^+$	> 2.3	
$\Lambda^0\pi^+\pi^0$	> 2.5	strong
$\Lambda^0\pi^+\pi^+\pi^-$	> 2.3	

$D_{tag}(\bar{D}^0, D^-, D_s^-, \Lambda_c^-)$ and $D^*_{tag}(\bar{D}^{*0}, D^{*-}, D_s^{*-})$ distribution





Fragmentation Table

Table 5: Fragmentation according to tag side

D^{*+}	D^{*0}	Λ_c^+	D_s^{*+}
nothing(K^+K^-)	$\pi^+(K^+K^-)$	$\pi^+\bar{p}$	K_S^0
$\pi^0(K^+K^-)$	$\pi^+\pi^0(K^+K^-)$	$\pi^+\pi^0\bar{p}$	$\pi^0K_S^0$
$\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^-\pi^+\bar{p}$	π^+K^-
$\pi^+\pi^-\pi^0(K^+K^-)$			$\pi^+\pi^+\pi^-K_S^0$
			$\pi^+\pi^-\pi^0K_S^0$
			π^+K^-
			$\pi^+\pi^0K^-$
			$\pi^+\pi^-\pi^+K^-$

Signal side recoiled D^{*+}, D^0 (in ROE of tag side)

Table 9: selection criteria of recoil part

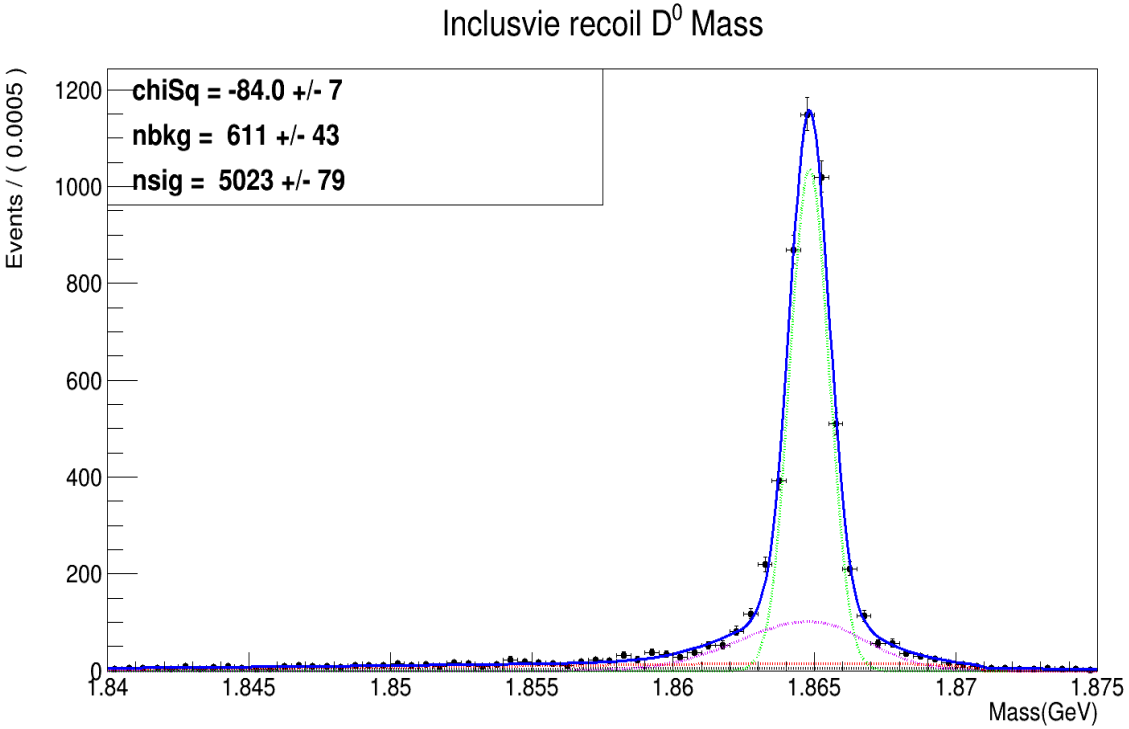
D_{sig}^{*+}	$1.86\,[\mathrm{GeV}] < M_{miss}(D_{tag}^* X_{frag}) < 2.16\,[\mathrm{GeV}]$
	kinematic mass constrained Fit : $M_{miss}(D_{tag}^* X_{frag}) = m_{D^{*+}}$
	require convergence of fit
	select best candidate with the highest *chiProb* calculated from mass constrained Fit
D_{sig}^0	select best candidates with largest angle
	between momentums of D_{tag}^* and $p_{miss}(D_{tag}X_{frag}\pi_s^+)$ in cm frame
	$p_{miss}^*(D_{tag}^* X_{frag}\pi_s^+) > 2.0\,[\mathrm{GeV}]$

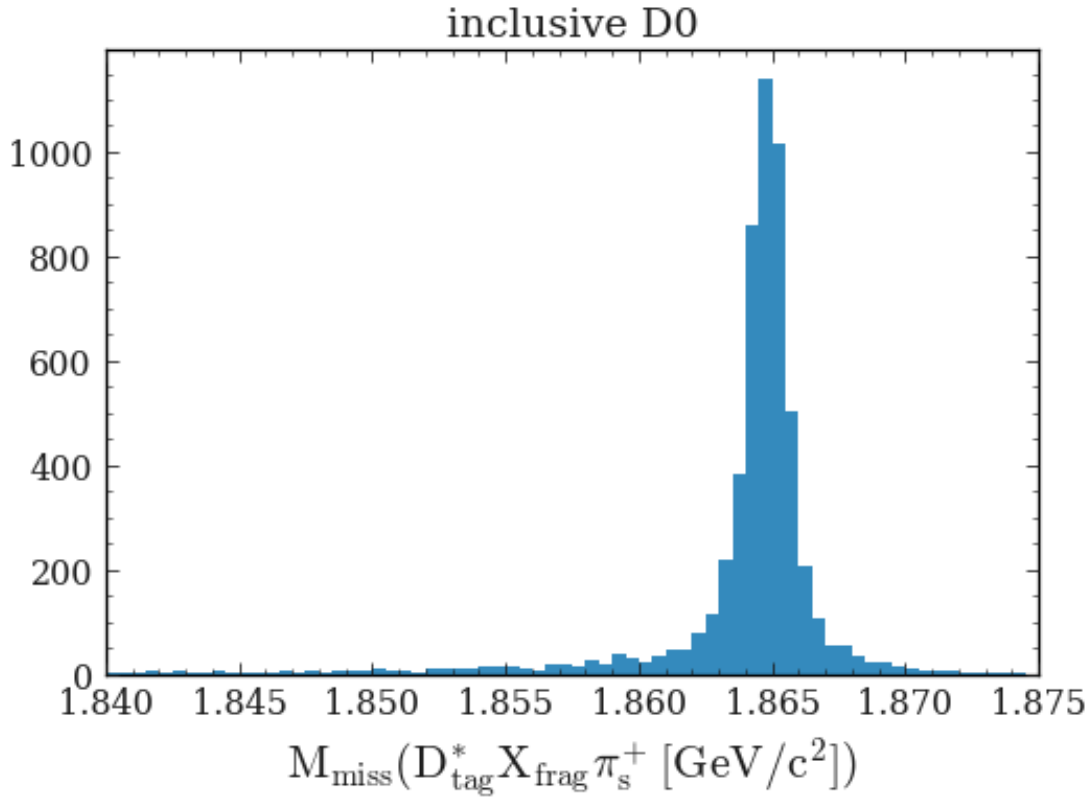
Definition of variables for checking recoil D

- Recoil mass $(M_{miss}(D^*_{tag}X_{frag}\pi^{\pm}_s)\ or\ M_{recoil}(D^0))$
  - $e^+e^- \rightarrow D^*_{tag}X_{frag}\pi^+_s D^0$
  - $p^\mu(e^+) + p^\mu(e^-) - \left(p^\mu\left(D^*_{tag}\right) + p^\mu\left(X_{frag}\right) + p^\mu(\pi^+_s)\right) = p^\mu(D^0_{sig})$
  - $M_{recoil}(D^0) = \sqrt{p^\mu(D^0) * p_\mu(D^0)}$
  - Inclusive D^0 : recoiled D^0 (no requirement on roe of tag side)

- E_{ECL} : sum of energies from roe of tag side remained in electromagnetic calorimeter(ECL) cluster
  - Exclusive D^0 : recoiled D^0 (requirement on roe of tag side)

Inclusive D^0 distribution of $D^0 \to \nu\bar{\nu}$ signal MC





yield of inclusive D = 5023 +/− 79

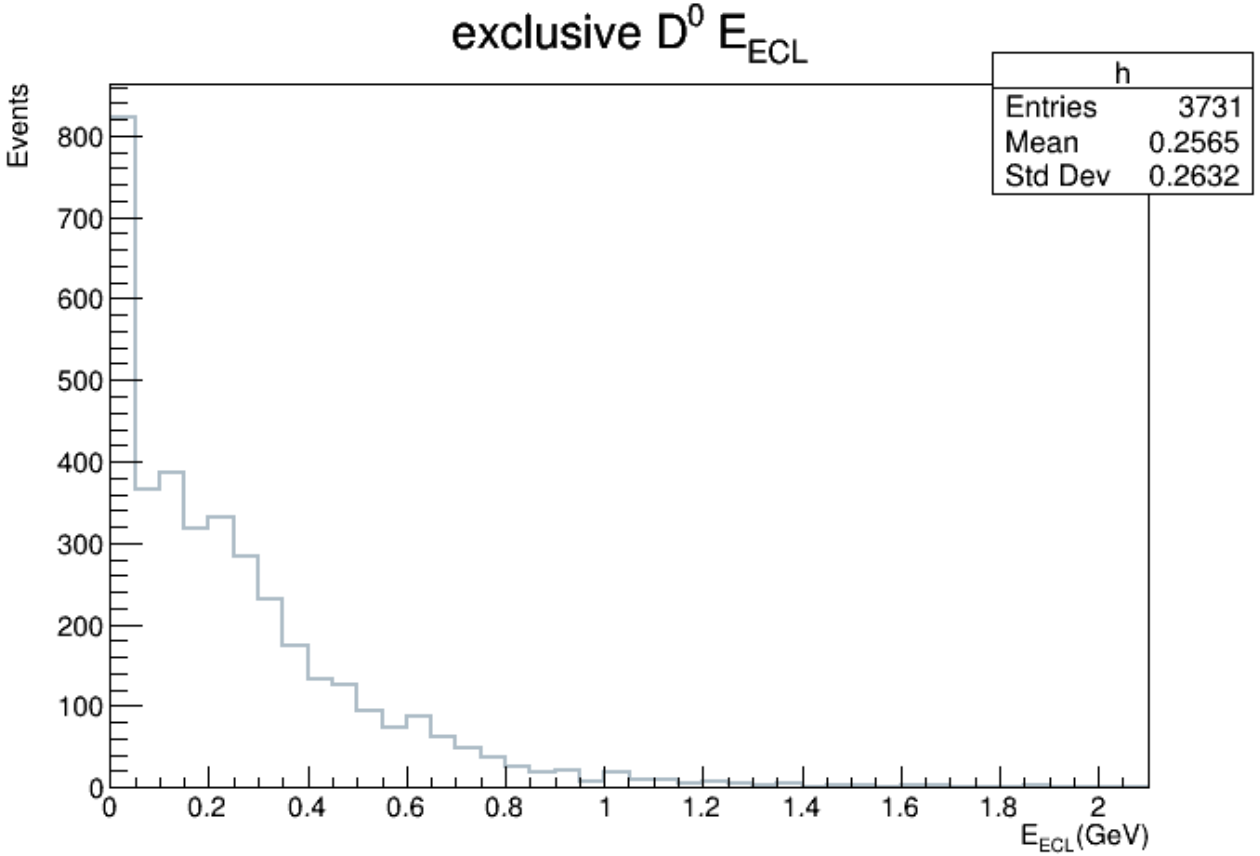
Extraction exclusive D^0 in $D^0 \rightarrow \nu\bar{\nu}$ signal MC

Selection for Exclusive D

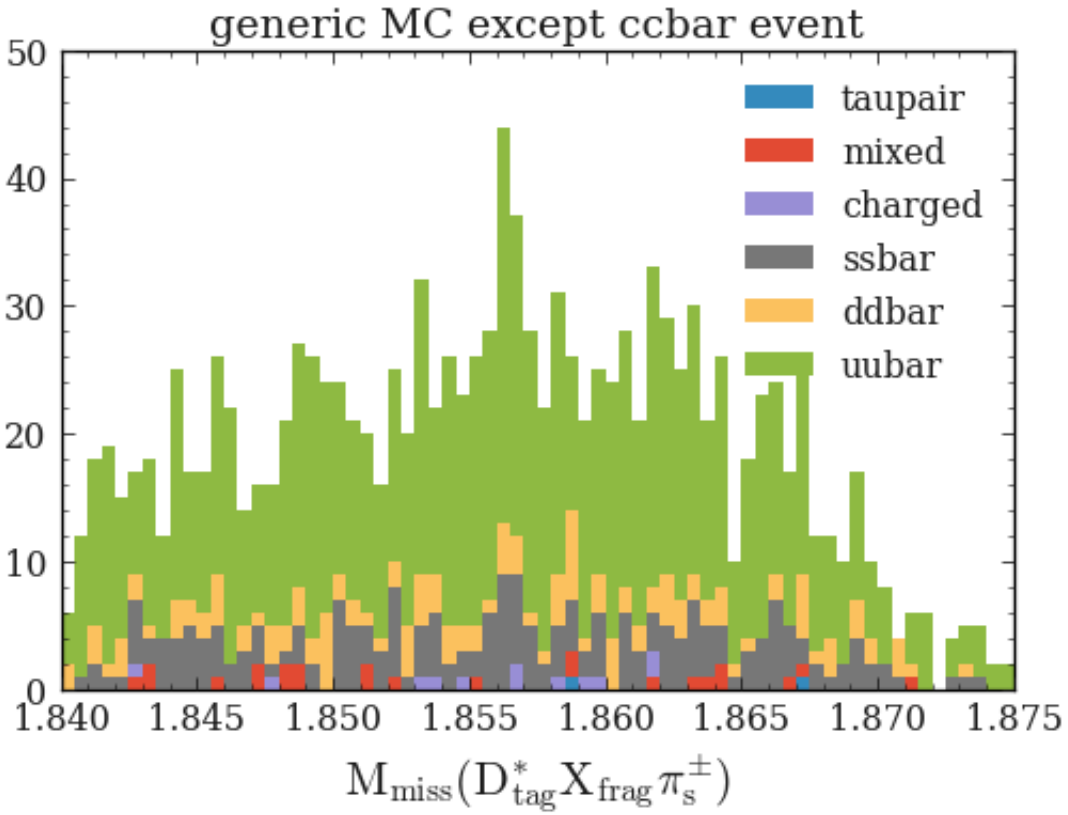
: No π^0, K_S^0, K_L^0, Λ^0, tracks in roe of tag side

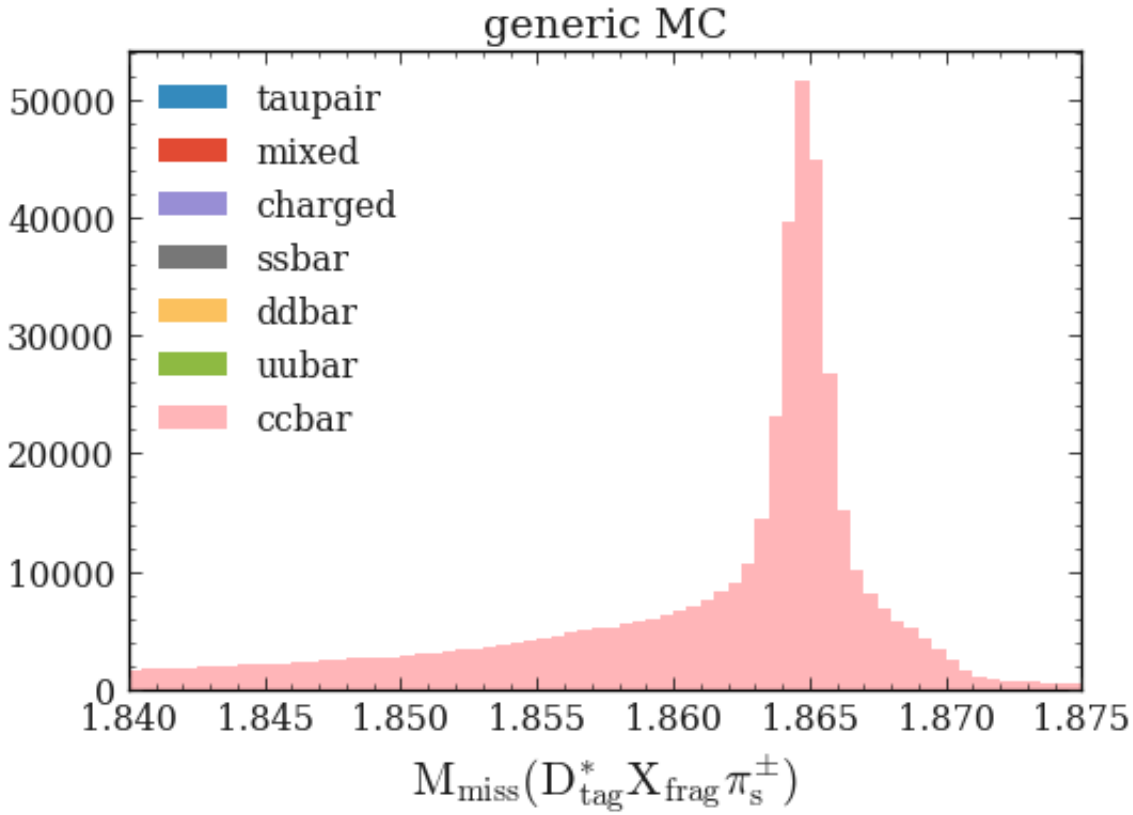
# of exclusive D = 3731 +/− 61 (counting)

$\varepsilon_{sig} = \frac{3731 \pm 61}{5023 \pm 79} \sim 0.7428$ +/− 0.0238 in $D^0 \rightarrow \nu\,\bar{\nu}$ signal MC



Applying D−tagging to generic MC





Study control sample $D^0 \to K^-\pi^+$ (ongoing)

- Check validation of charm tagger

  Study of $D^0 \to K^-\pi^+$ which has large branching fraction and clear final states

- 6M $D^0 \to K^-\pi^+$ Signal MC is produced

- Selection for exclusive D :

2 remaining tracks, π^0, K_S^0, K_L^0, and $\Lambda(\bar{\Lambda})$ at the signal side after the tagger's reconstruction.

- K PID: $\mathcal{L}_{K/\pi} > 0.6$, $\mathcal{L}_e < 0.95$, $\mathcal{L}_\mu < 0.95$
- π PID: $\mathcal{L}_{K/\pi} < 0.4$, $\mathcal{L}_e < 0.95$, $\mathcal{L}_\mu < 0.95$

Missing energy(recoil $D^0 - K^-\pi^+$) < 0.1 GeV: to reduce the semileptonic background.

Recoil $M_{D^0} > 1.84$ GeV/c^2(fitting region)

$E_{ECL} < 2.1$ GeV(fitting region)

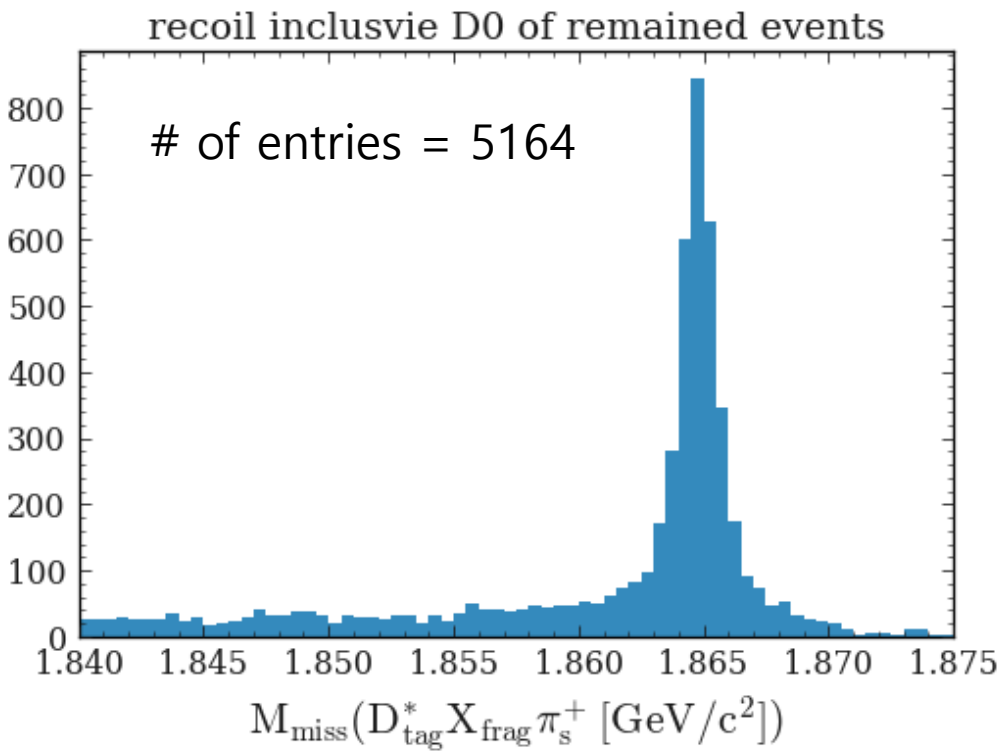
$1.80 <$ Reconstructed $M_{D^0} < 1.92$ GeV/c^2

Vertex fit is performed and the fit converges

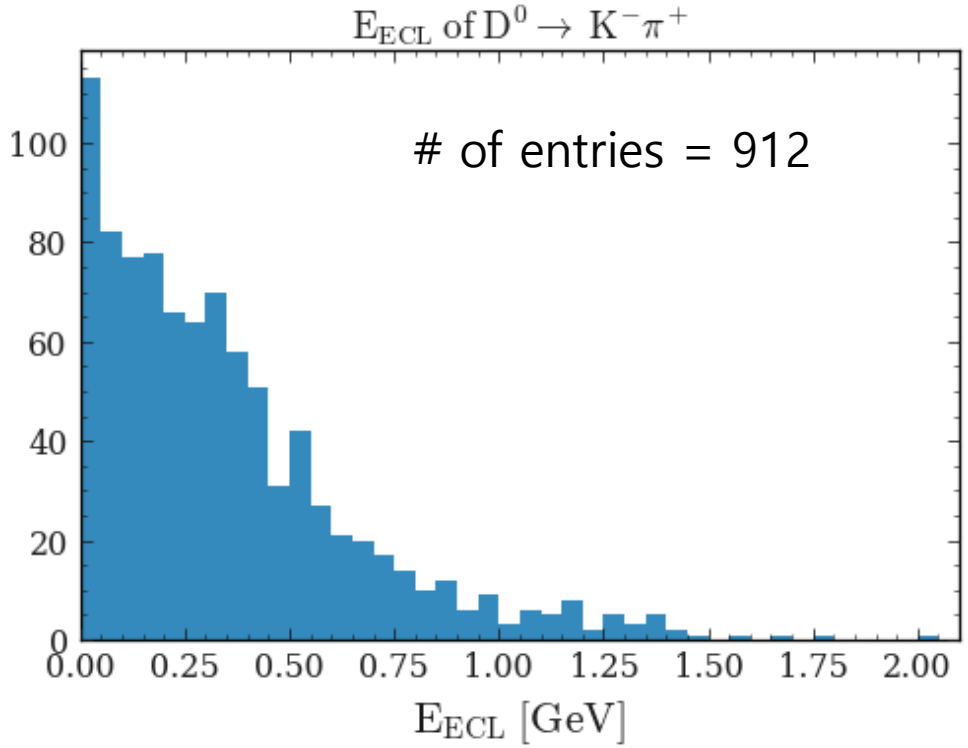
RS selection

Recoil D in $D^0 \to K^-\pi^+$ signal MC

M_{D^0} of Inclusive D



E_{ECL} of Exclusive D



Fitting result for $D^0 \to K^-\pi^+$ signal MC

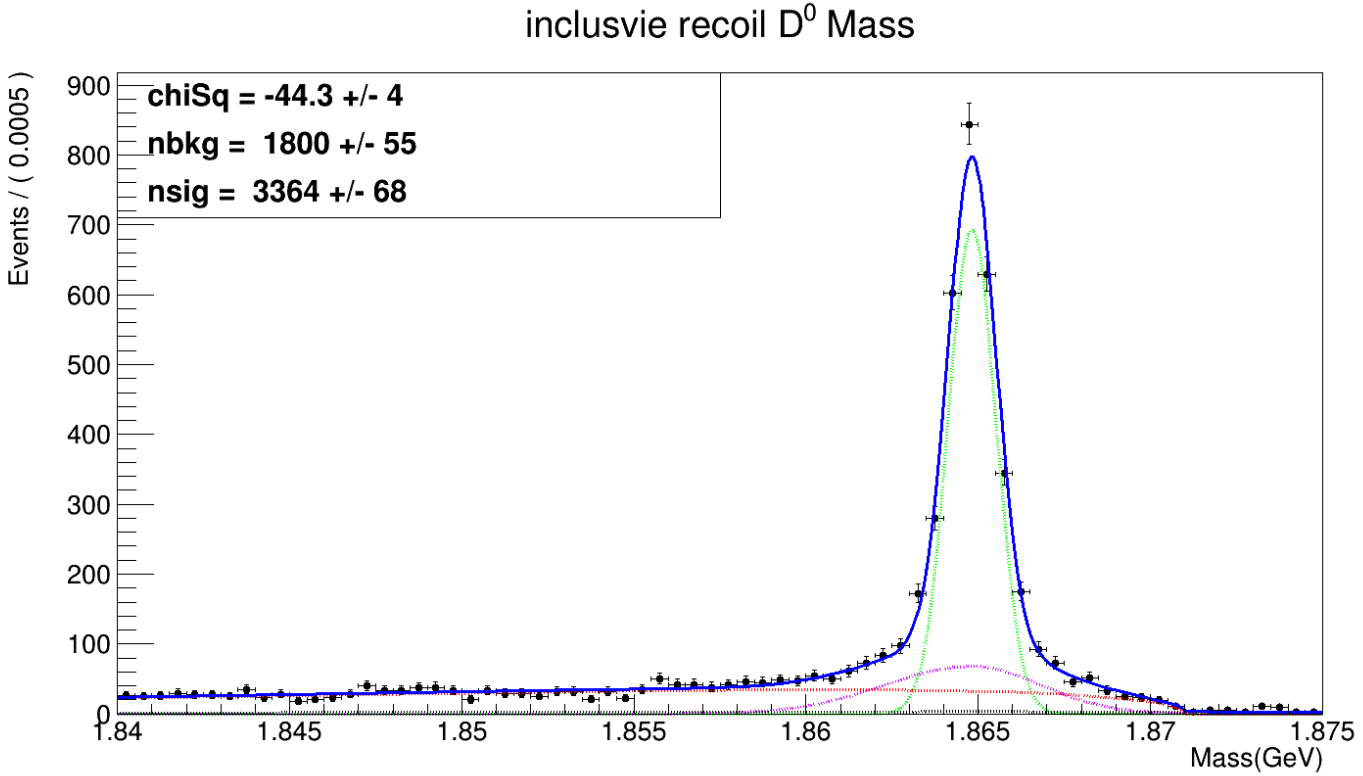
1D Extended unbinned Maximum Likelihood Fit for Inclusive D by roofit

N_{excl}^{recoil} : counted number for the exclusive D (plan to apply 2D fit, but not yet) ~ 912 +/− 30

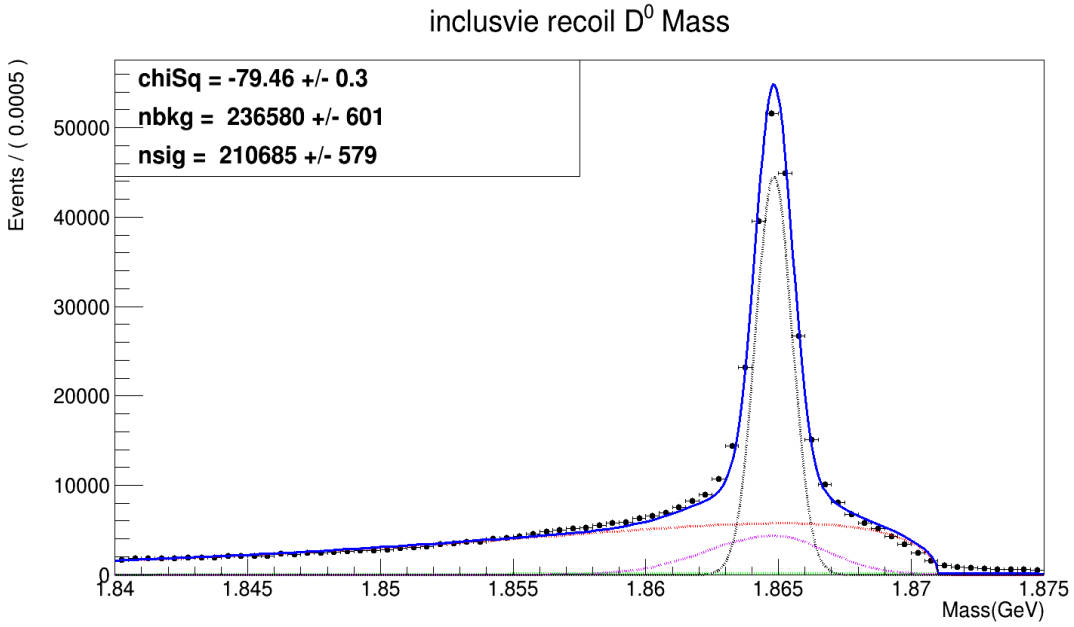
N_{incl}^{recoil} : the yield of inclusive D from fitting result ~ 3364 +/− 68

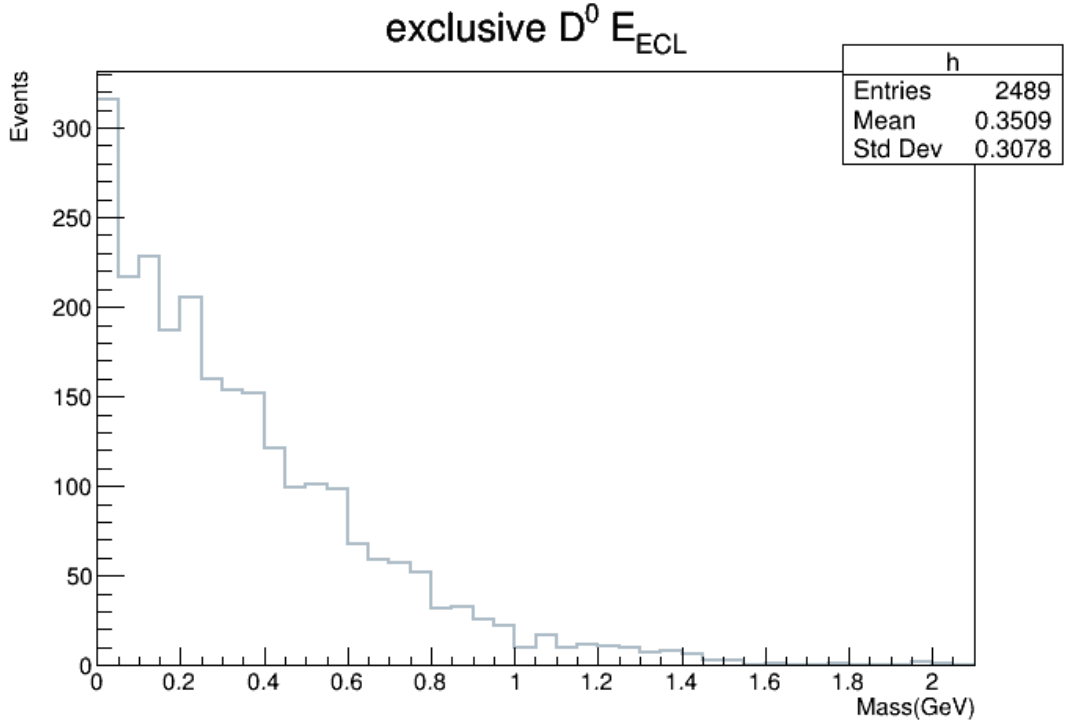
$$\varepsilon_{sig} = \frac{N_{excl}^{recoil}}{N_{incl}^{recoil}}$$

$$= 0.2711 \text{ +/− } 0.0144$$



Yield of inclusive D and # of exclusive D in official ccbar background MC about $D^0 \to K^-\pi^+$





Measurement of $\mathrm{Br}(D^0 \to K^-\pi^+)$ (ongoing)

- The BF is calculated by this formula :

$$Br(D^0 \to K^-\pi^+) = \frac{N^{recoil}_{exclusive}}{\varepsilon_{sig} * N^{recoil}_{inclusive}}$$

$\varepsilon_{sig} = 0.2711 +/- 0.0144$

$N^{recoil}_{inclusive} = 210685 +/- 579$

$N^{recoil}_{exclusive} = 2489 +/- 50$

(counted number, not yield from 2D fitting)

$\sqrt{2489} = 50$

(counting method, plan to apply 2D fit)

$Br(D^0 \to K^-\pi^+) = 0.0436 +/- 0.0033$

The uncertainty is calculated with assumption of maximally correlated

Summary & plan

- Summary
  - Analysis procedure was being performed by charm tagging method
  - Validation for charm tagger is ongoing
    - Study of $D^0 \to K^-\pi^+$ used as control sample

- Plan
  - Trial of 2D fit (M_{D^0}, E_{ECL}) for yield of exclusive D
  - Measurement of BF of $D^0 \to K^-\pi^+$ using official ccbar background MC