Study of D^0 decays to the invisible final states at Belle II

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Introduction to analysis

- In SM, heavy (B or D) decays to $\nu\bar{\nu}$ is helicity suppressed with an expected branching fraction of $\mathrm{Br}(\mathrm{D}^0 \rightarrow \nu\bar{\nu}) = 1.1 \cdot 10^{-30}$, which is beyond the reach of current collider experiments.

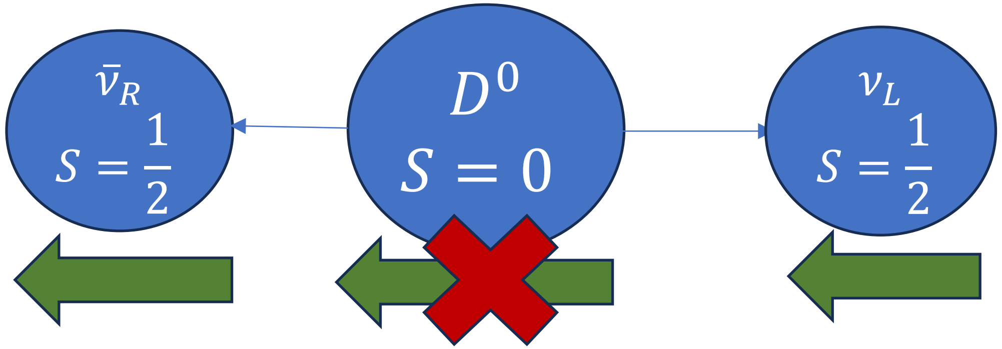


Figure1: Scheme of helicity suppresing

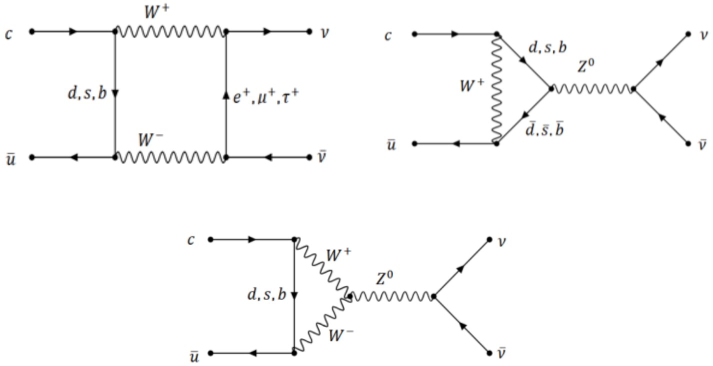


Figure2: Feynman diagram for $D^0 \rightarrow \nu\bar{\nu}$

- Therefore, search for D^0 → invisible final states is sensitive to new physics
- The previous result is $BR_{UL} = 9.4 \times 10^{-5}$ on 924 fb^{-1} data samples at 90% CL at belle [Phys. Rev. D 95, 011102(R)]

MC simulation samples

- 20M signal MC samples were used
- Signal Event used for simulation :

$$
\begin{aligned}
e^+e^- \to c\bar{c} \to D_{tag}X_{frag}D^{*+}_{sig} & \\
D^{*+}_{sig} \to D^0_{sig}\pi^+ & \\
D^0_{sig} \to \nu\bar{\nu} &
\end{aligned}
$$

- MC15ri generic MC($1ab^{-1}$) is used as generic background MC sample
- 20M Control sample ($D^0 \to K^-\pi^+$)
  - $D^0 \to K^+K^-, K^+\pi^-, K^-\pi^+\pi^0$ MC is also used as background for control sample study

Analysis Method : Charm Tagger

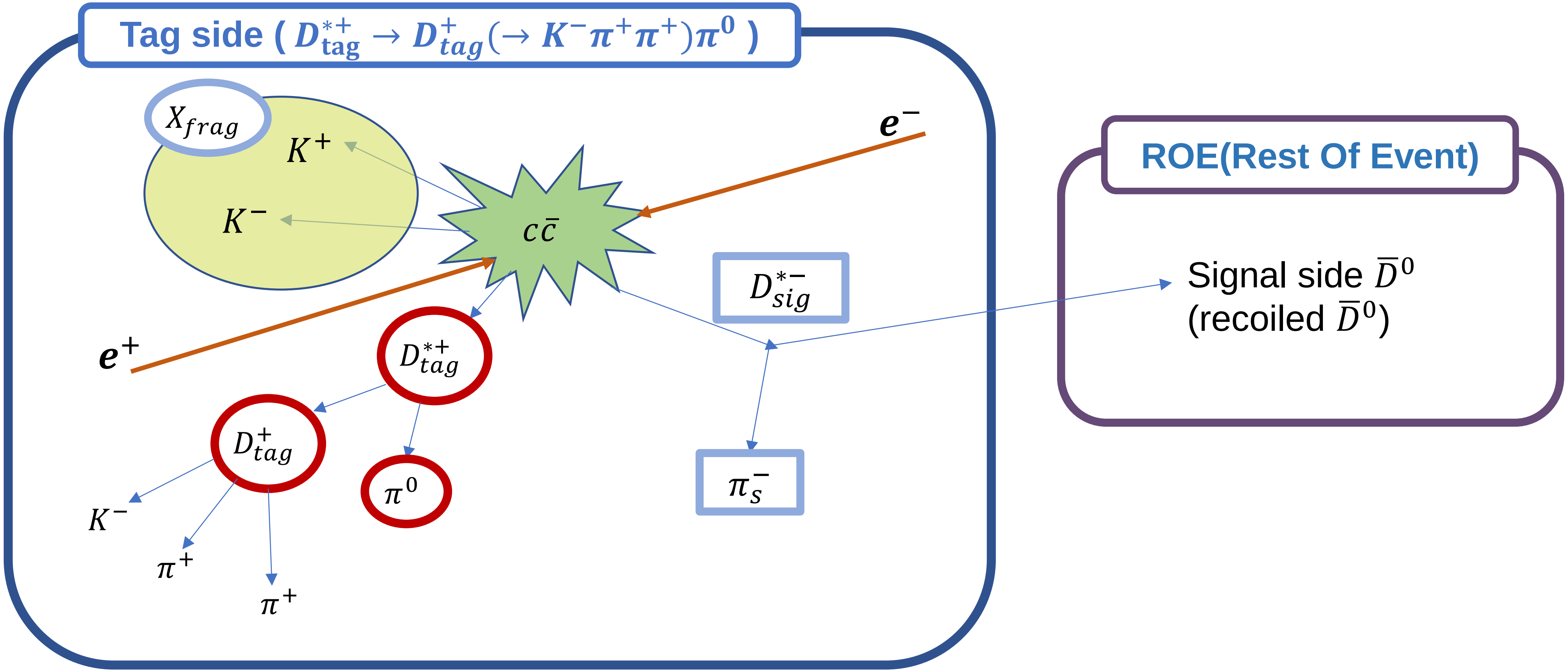


Figure3: schematics of signal event with tag side decay $D^{*+}_{tag} \rightarrow D^{+}_{tag}(\rightarrow K^{-}\pi^{+}\pi^{+})\pi^{0}$

Description of Charm tagging Procedure

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

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

Recoil part 1 (D^{*+})

1. 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 chiProb from step 2

Recoil part 2 (D^{0})

5. Using slow pion, calculate $\mathrm{M_{miss}}(D^{*}_{tag}X_{frag}\pi^{+}_{s})$ which is regarded as mass of signal side D^{0}
6. BCS of D^{0} by using angle between D^{0}_{sig} and tag side hadron in cm frame

Table1. Tag reconstruction 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	$K_S^0K^-\pi^+\pi^+$	1.5
$K_S^0\pi^+\pi^-\pi^0$	5.4	$K^+K^-\pi^+$	1.0	$\Lambda^0\pi^+\pi^+\pi^-$	2.6	$K^+\pi^-\pi^+K_S^0$	1.0
$K^-\pi^+\pi^0\pi^0$	8.9	$K^-K^+\pi^+\pi^0$	0.7	$p^+\pi^-\pi^+$	0.5	$\pi^+\pi^-\pi^+$	1.0
$\pi^-\pi^+$	0.1	$\pi^-\pi^+\pi^+$	0.3	$p^+K^-K^+$	0.1	$\pi^+K_S^0$	0.1
$\pi^-\pi^+\pi^-\pi^+$	0.8	$\pi^-\pi^+\pi^+\pi^0$	1.2	$p^+K^-\pi^+\pi^0\pi^0$	0.1	$\pi^+\pi^0K_S^0$	0.5
$\pi^-\pi^+\pi^0$	1.5	$K^+K_S^0K_S^0$	0.3	$p^+\pi^-\pi^+\pi^-\pi^+$	0.2	$K^-K^+\pi^+\pi^-\pi^+$	0.7
$\pi^-\pi^+\pi^0\pi^0$	1.0	$\pi^+\pi^0$	0.1	$p^+K_S^0\pi^0$	2.0		
K^-K^+	0.4			$p^+K_S^0\pi^+\pi^-$	1.6		
$K^-K^+\pi^0$	0.3			$\pi^+\pi^-\Sigma^+$	4.5		
$K^-K^+K_S^0$	0.4			$\pi^+\pi^-\pi^0\Sigma^+$	1.2		
$\pi^0K_S^0$	1.2			$\pi^0\Sigma^+$	1.2		
sum	53.1	sum	30.5	sum	28.2	sum	22.8

D^*_{tag} reconstruction channels and fragmentations for each tag particle

D^{*+} decay	Br(%)	D^{*0} decay	Br(%)	D^{*+}_s decay	Br(%)
$D^0\pi^+$	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

Table3: D^*_{tag} channel

D^{*+} *or* D^+	D^{*0} *or* D^0	Λ^+_c	D^{*+}_s *or* D^+_s
nothing(K^+K^-)	$\pi^+(K^+K^-)$	$\pi^+\bar{p}$	K^0_S
$\pi^0(K^+K^-)$	$\pi^+\pi^0(K^+K^-)$	$\pi^+\pi^0\bar{p}$	$\pi^0K^0_S$
$\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^+\pi^-(K^+K^-)$	$\pi^+\pi^-\pi^+\bar{p}$	π^+K^-
$\pi^+\pi^-\pi^0(K^+K^-)$			$\pi^+\pi^-\pi^0K^0_S$
			π^+K^-
			$\pi^+\pi^0K^-$
			$\pi^+\pi^-\pi^+K^-$

Table4: X_{frag} channel (total 24 channels)

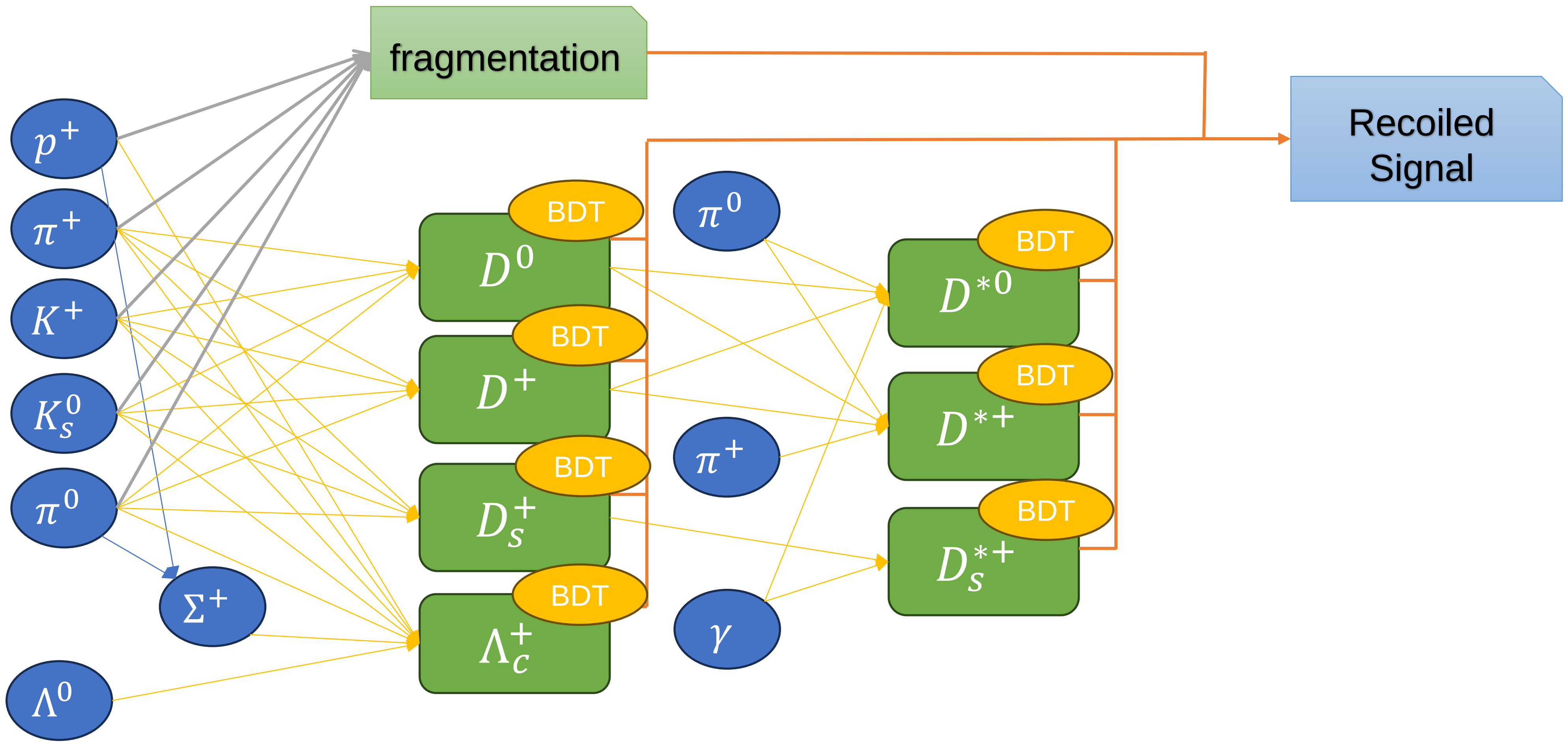
fastBDT training for Charm Tagging

- Input Variables of fastBDT
  (reduce # of input variables according to high correlation and low importance)
  - For D_{tag} training
    M, xp, dr(flight length), dz, chiProb, cosToThrustOfEvent,
    cosAngleBetweenMomentumAndVertexVectorInXYPlane,
    PID of daughters, cosHelicityAngle(2 body or 3 body decays),
    angle between 2 daughters of $\pi^0(\rightarrow \gamma\gamma), K_S^0(\rightarrow \pi^+\pi^-), \Lambda^0(\rightarrow p^+\pi^-), \Sigma^+(\rightarrow p^+\pi^0)$,
    $|\frac{E_{d_1}-E_{d_2}}{E_{d_1}+E_{d_2}}|$ of $\pi^0(\rightarrow \gamma\gamma), K_S^0(\rightarrow \pi^+\pi^-), \Lambda^0(\rightarrow p^+\pi^-), \Sigma^+(\rightarrow p^+\pi^0)$ etc…
  - For D^*_{tag} training
    $\Delta\mathrm{M}(= M_{D^*_{tag}} - M_{D_{tag}})$, momentum of $\pi_S^\pm, \gamma, \pi^0$,
    angle between D_{tag} and $\pi_S^\pm, \gamma, \pi^0$ etc…
- Hyper Parameters of BDT was optimized by applying grid search for each tag training

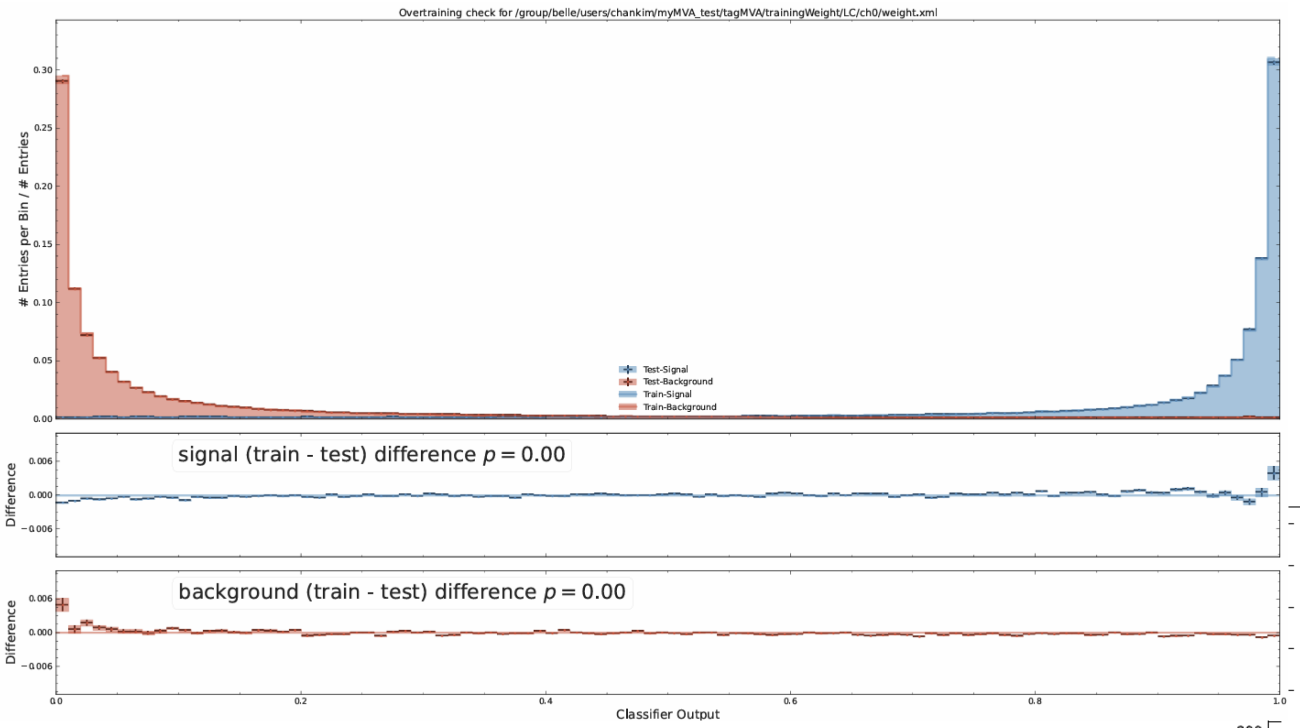
Preselection of Charm Tagger

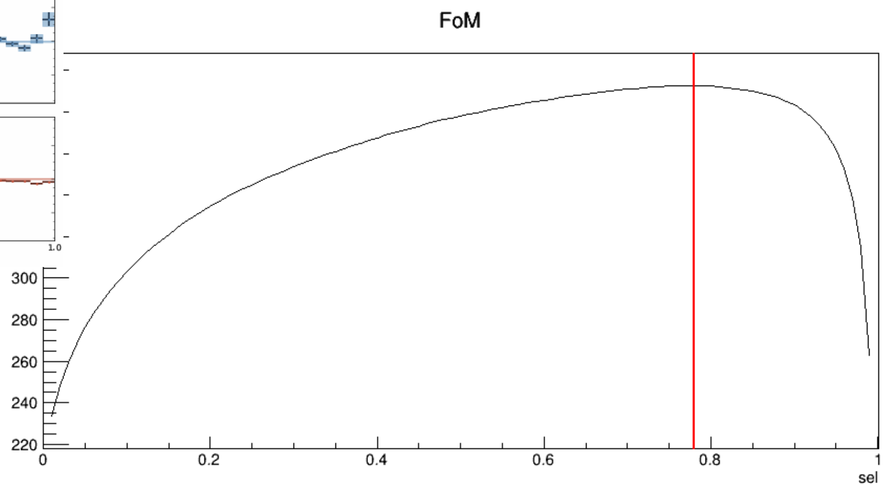
- For tracks : dr < 1.0 , |dz| < 3.0 and InCDCAcceptance
- $\pi^{\pm}$: 15 candidates with Highest pionID after pionID > 0.01
- $K^{\pm}$: 10 candidates with Highest kaonID after kaonID > 0.1
- $p^{\pm}$: 10 candidates with highest protonID after protonID > 0.1
- γ : beamBackgroundSuppression > 0.5 & fakePhotonSuppression > 0.1
  (E > 0.1 for γ in $D_s^{*+} \to D_s^+\gamma, D^{*0} \to D^0\gamma$)
- for fragmentations, PID selection of $\pi^{\pm}, K^{\pm}, p^{\pm}$ is on 0.1, 0.9, 0.9
  and additionally require p > 0.1 GeV
- K_S^0, Λ^0 :
  - mass and dr and χ^2 and angle between Momentum and Vertex Vector selection on Λ^0
  - goodBelleKshort for K_S^0 (similar selection to Λ^0)
- Σ^+ : reconstructed from $\Sigma^+ \to p^+\pi^0$ and mass cut (1.08 < M < 1.28)

Flow of Charm Tagger

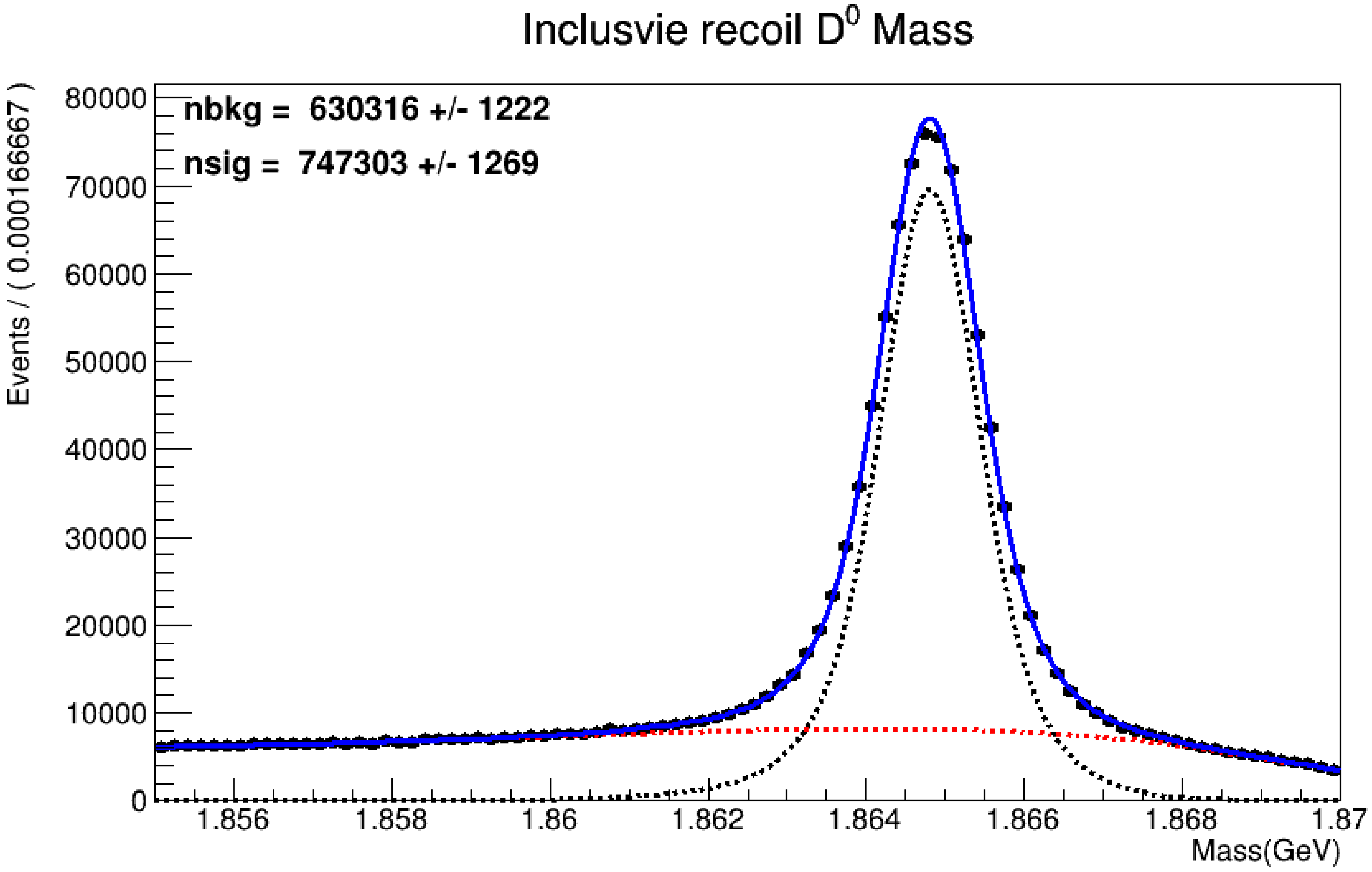


One example about training : $\Lambda_c^+ \to p^+ K^- \pi^+$





Reconstructed D^0 from charm tagger on generic MC



Variables for extracting signal side D

- Recoil mass ($M_{miss}\left(D^*_{tag}X_{frag}\pi_s^{\pm}\right)$ 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 signal side)
    => 1D fit on signal side recoil M_{D^0}
- E_{ECL} : sum of energies from roe of tag side remained in electromagnetic calorimeter(ECL) cluster
  - Exclusive D^0 : recoiled D^0 (requirement on signal side)
    => 2D fit on signal side (M_{D^0}, E_{ECL})

Fitting strategy

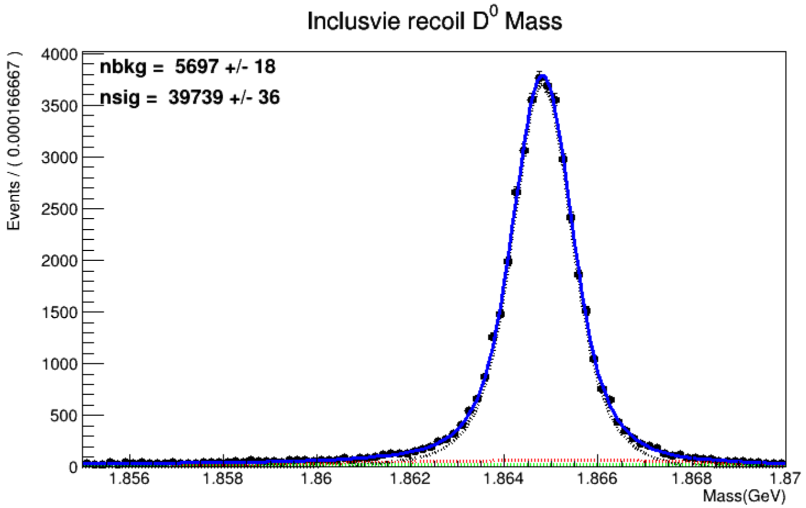
- Inclusive D fitting
  - 1D fitting : M_{D^0}
  - Signal pdf : 2 gaussians + 1 bifurcated gaussian
  - Background pdf : argus + linear

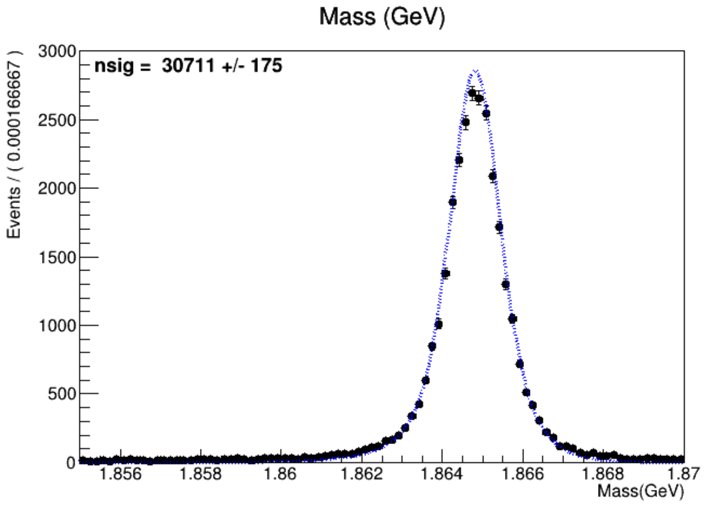
- Exclusive D fitting
  - 2D fitting : (M_{D^0}, E_{ECL})
  - Signal pdf : signal pdf from inclusive D fitting & histogram pdf from signal MC study
  - Background pdf :
    - Flat: Argus + linear & histogram PDF from MC study
    - Peak: 3 gaussians & histogram PDF from MC study

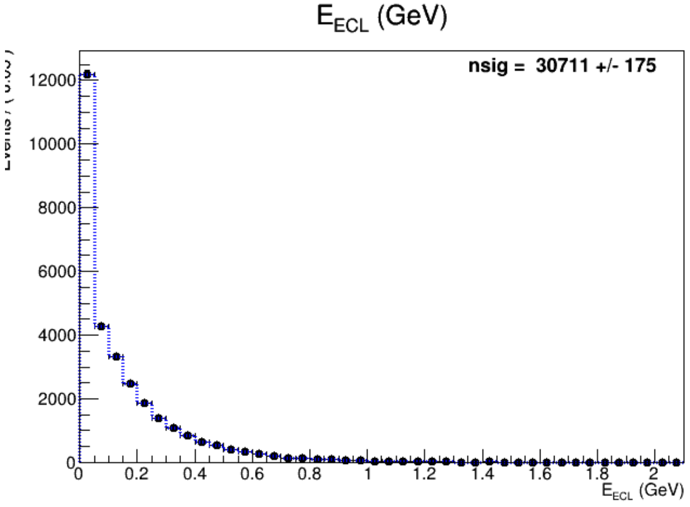
Exclusive D requirement (signal extraction)

- Exclusive : D^0 with selection on signal side
  fit on the 1.855 GeV < M_{D^0} < 1.870 GeV & E_{ECL} < 2.1 GeV
  - Selection for exclusive D^0 on Signal MC ($D^0 \rightarrow \nu\bar{\nu}$)
    - no remaining tracks, $\pi^0, K_L^0, K_S^0, \Lambda^0$
  - Selection for exclusive D^0 on Control sample ($D^0 \rightarrow K^-\pi^+$)
    - 2 remaining tracks and 1 reconstructed $D^0(K^-\pi^+)$
    - no $\pi^0, K_L^0, K_S^0, \Lambda^0$
    - $|\Delta E| < 0.1$ GeV ($\Delta E \equiv E$(recoil D^0) - $E_{K\pi}$)

Signal efficiency on signal MC

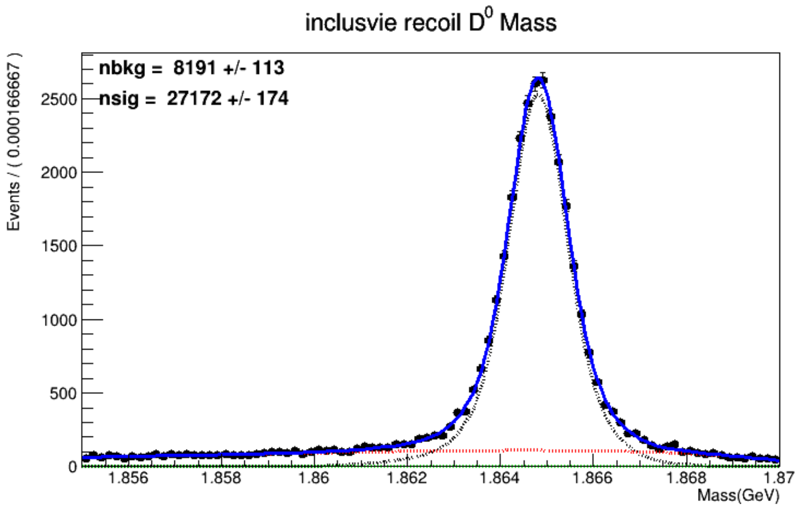


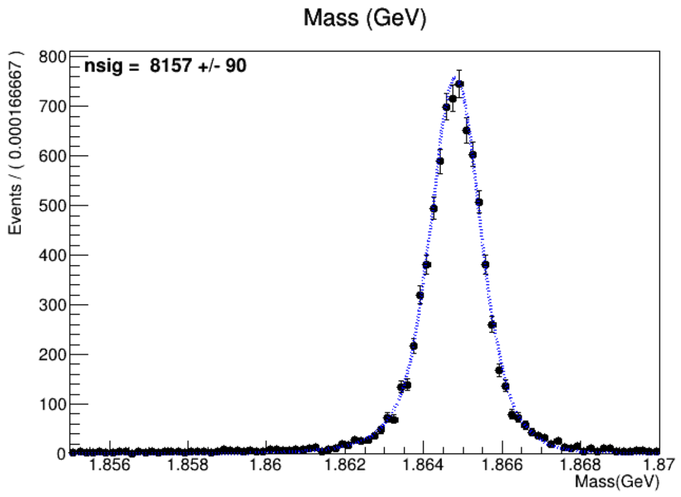


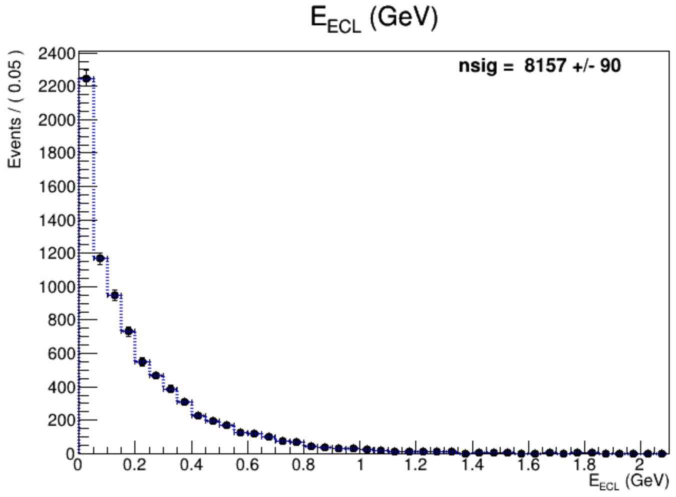


- Signal eff : $\frac{30711 \pm 175}{39739 \pm 36} = 0.77282 \pm 0.00446$

Signal efficiency on control sample

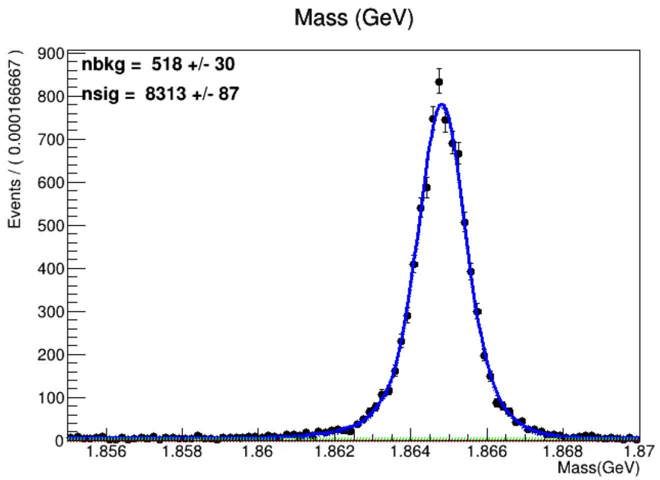


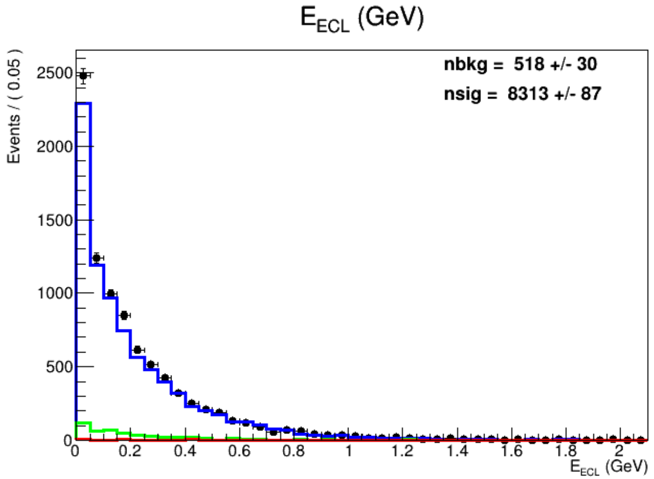




- Signal eff : $\frac{8157 \pm 90}{27172 \pm 174} = 0.30020 \pm 0.00383$

BR measurement on generic MC(uds/mixed/charged)



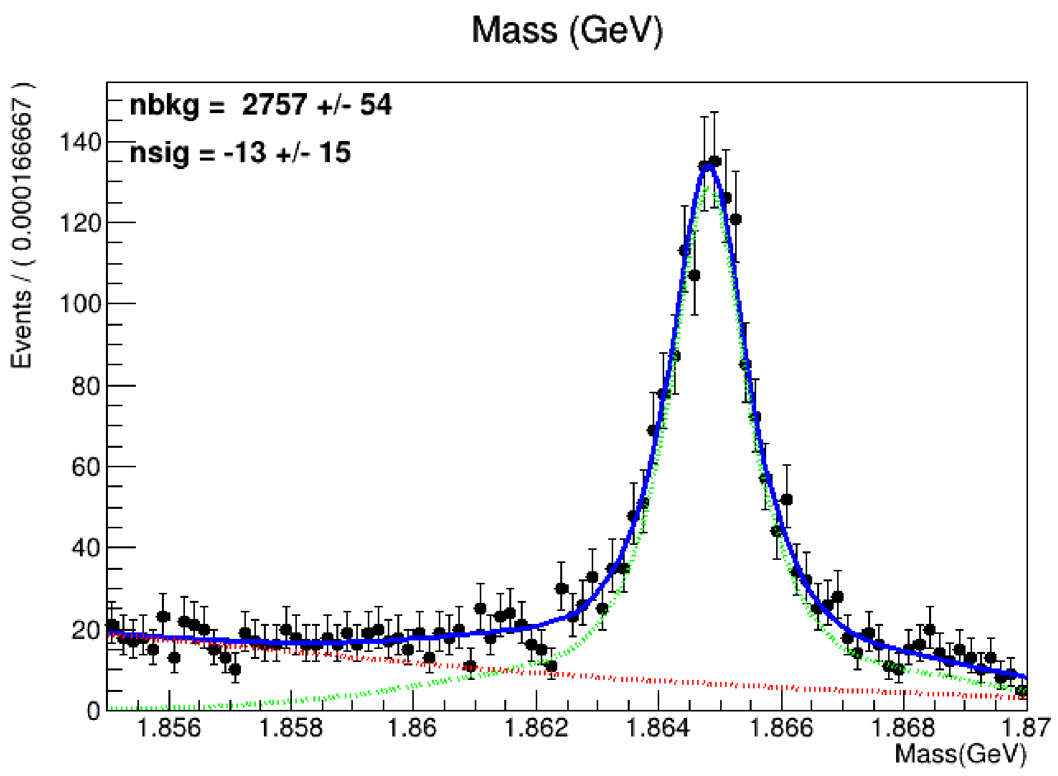


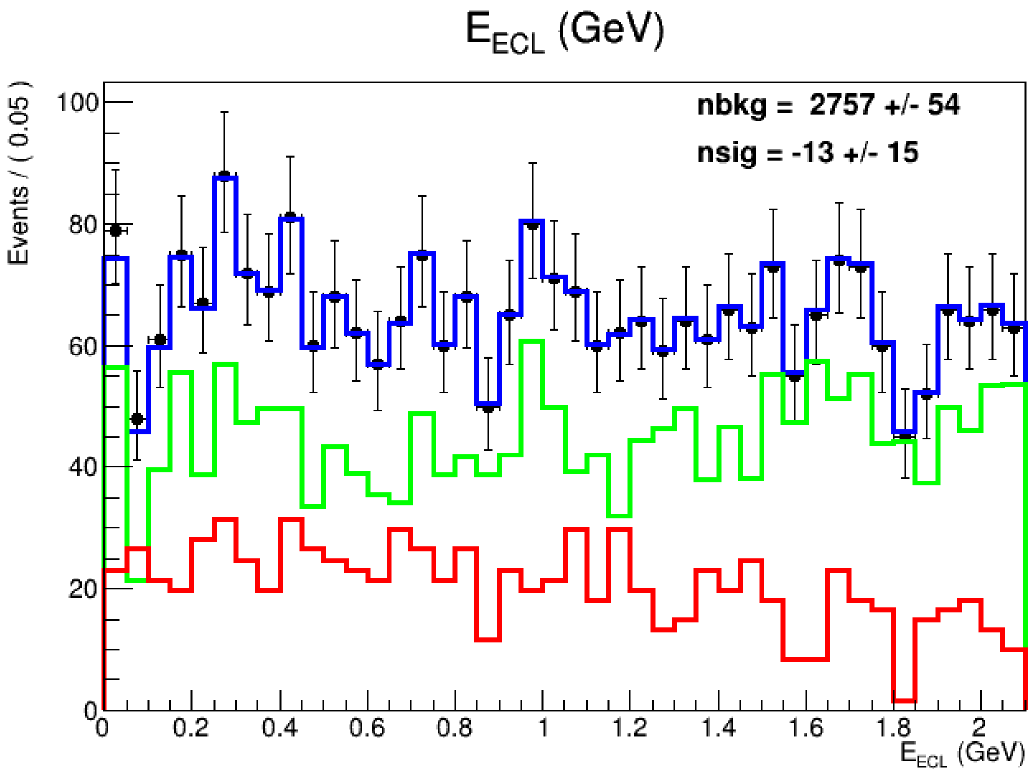
- $Br(D^0 \to K^-\pi^+) = \frac{N^{exclusive}}{N^{inclusive} * \epsilon_{sig}} = \frac{8313 \pm 87}{(747303 \pm 1269) * (0.30020 \pm 0.00383)} = 0.03706 \pm 0.00061$
  - Far from decfile BR value(0.0395) ~ 4σ
- The # of true signal event identified by TopoAna :

$$8757 \pm 94 \Rightarrow Br(D^0 \to K^-\pi^+) = 0.03903 \pm 0.00065$$

- This difference seems to be from similarity of E_{ECL} shape for the peaking background component
  - Main source is
    $D^0 \to K^+\pi^-,\ K^+K^-,\ K^-\pi^+\pi^0$ consists of 80% of background events
  - It seems to be irreducible error with current fitting strategy…
  - For validation of charm tagger, it is also possible to apply other fit strategy only for signal extraction about this control sample study

2D fit on generic MC for $D^0 \to$ invisibles





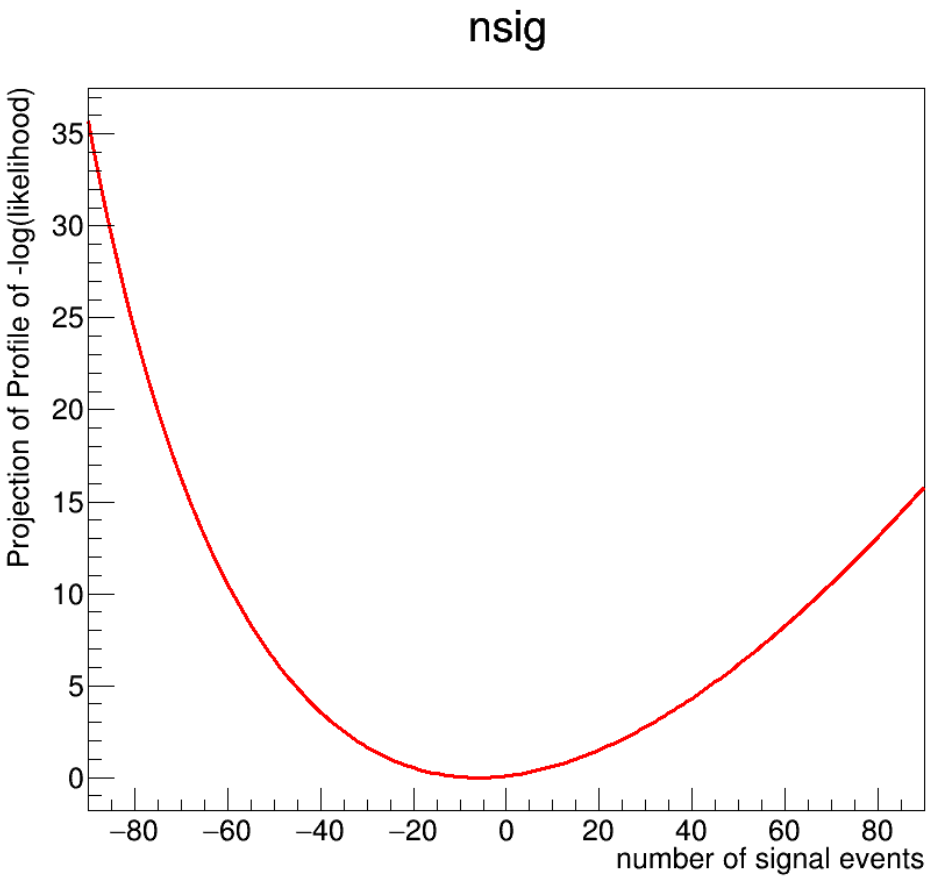
Upper limit estimation of $D^0 \to$ invisibles

- Way1) Upper Limit estimation by integration of likelihood function

$$\int_0^{N_{UL}} L(n)dn = 0.9 \int_0^{\infty} L(n)dn$$

$$N_{UL} = 11.4984$$

$$BR_{UL} = \frac{11.4984}{(747303 * 0.77282)} = 2.0 \times 10^{-5}$$

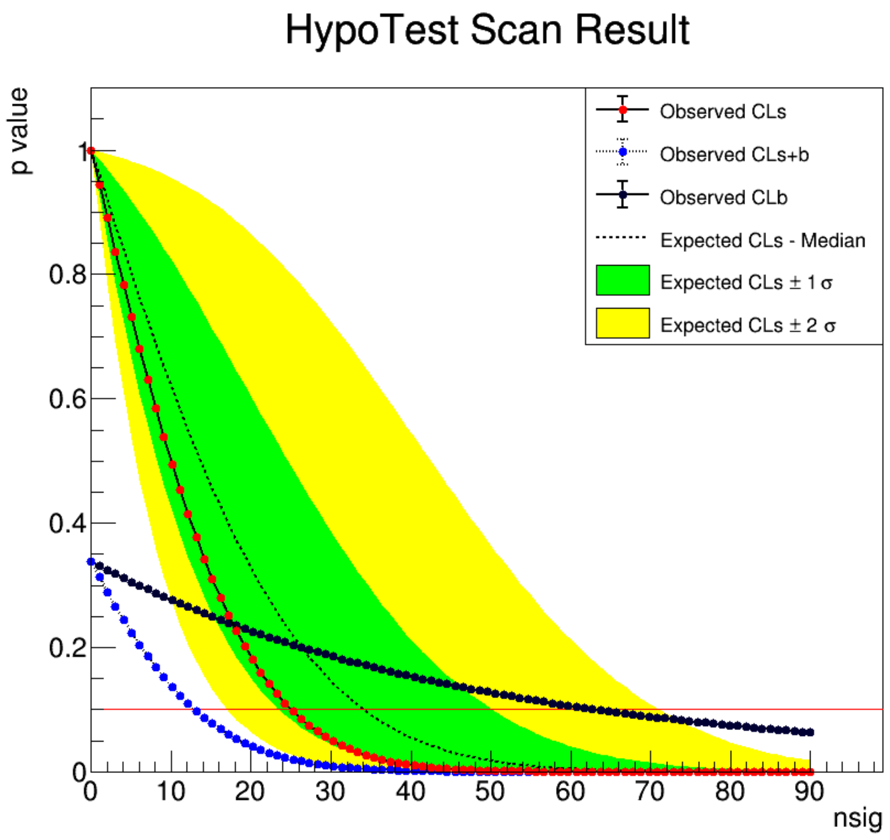


Upper limit estimation of $D^0 \to$ invisibles

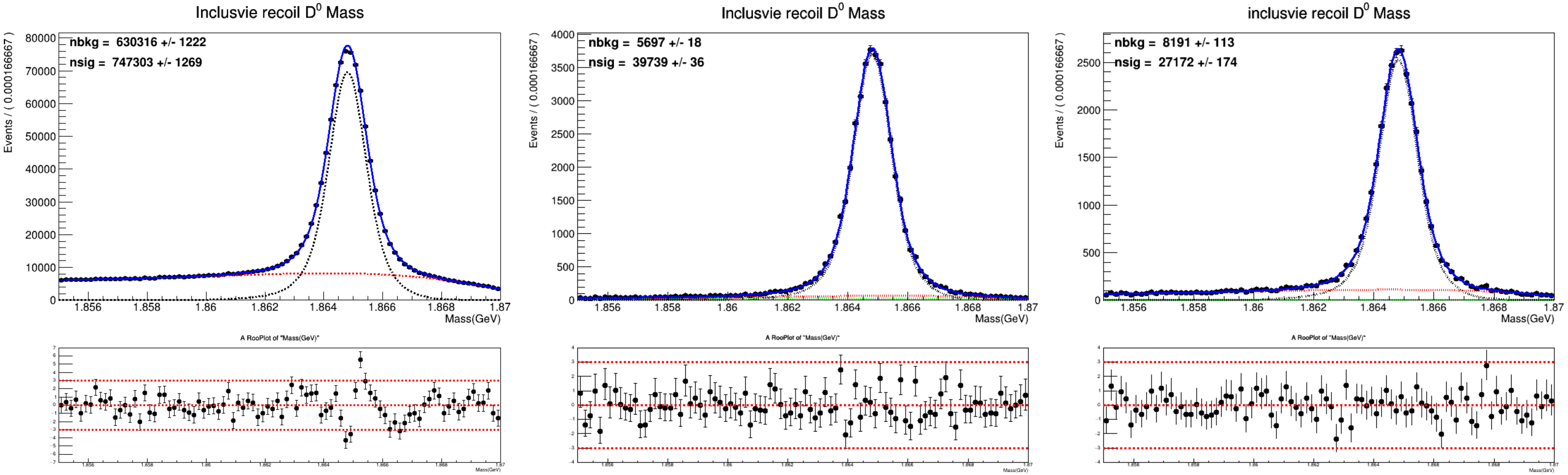
- Way2) Upper limit estimation by CLs method

$$N_{UL} = 22.0664$$

$$BR_{UL} = \frac{22.0664}{(747303*0.77282)} = 3.8 \times 10^{-5}$$

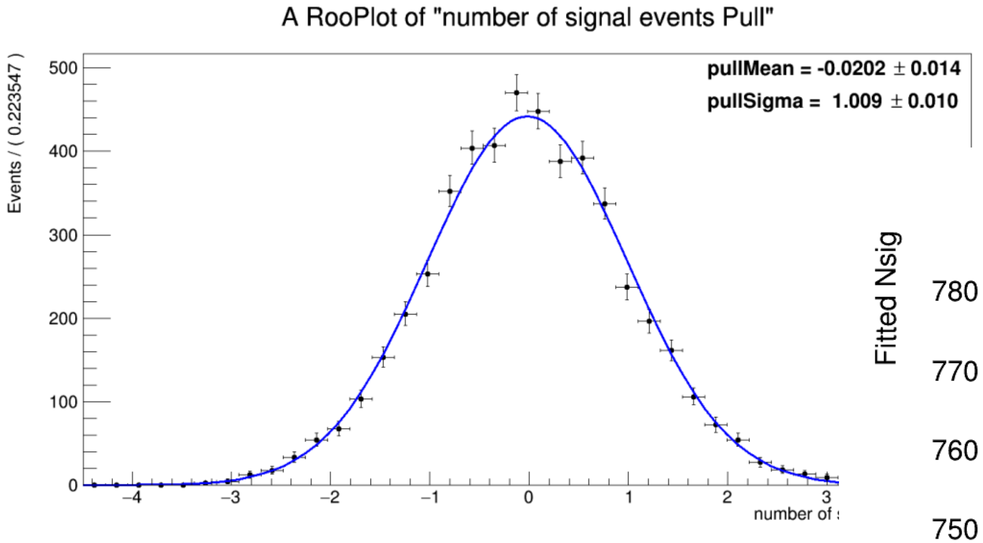


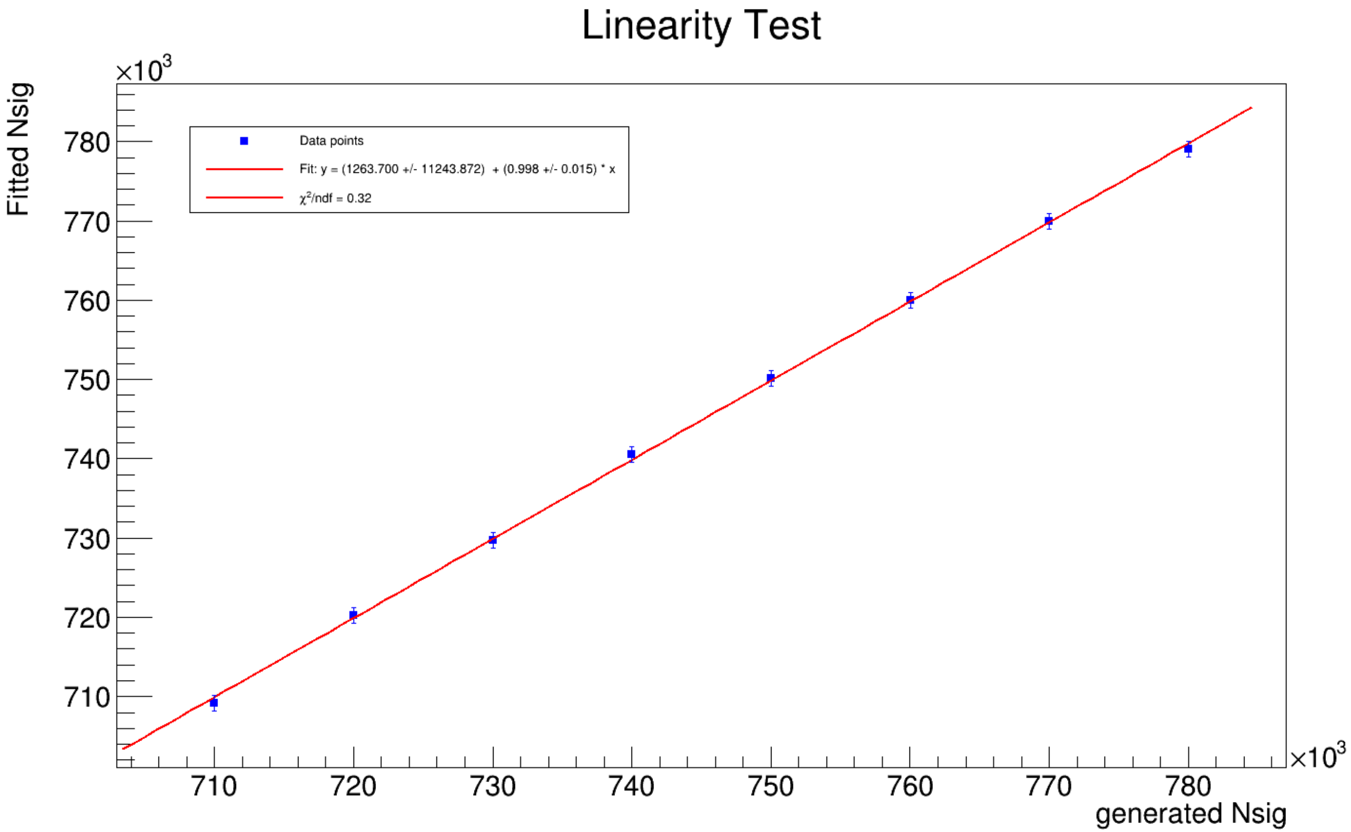
Check fit result with pull distribution for inclusive D



Left : generic MC, middle : signal MC, right : control sample

Inclusive D fit result check with ToyMC on generic MC





As next step

- Check control sample BR measurement result
  with other fit strategy using reconstructed D^0 mass and E_{ECL}
  (not using recoil mass and E_{ECL})
- Move on the run-dependent MC sample
- Study systematics
  => 1st priority : systematic uncertainty from charm tagger
  => PID, tracking, fitting strategy etc…

FYI) currently communicating with Kristof who is developing ccbarFEI
(comparison and some variables in BDT)

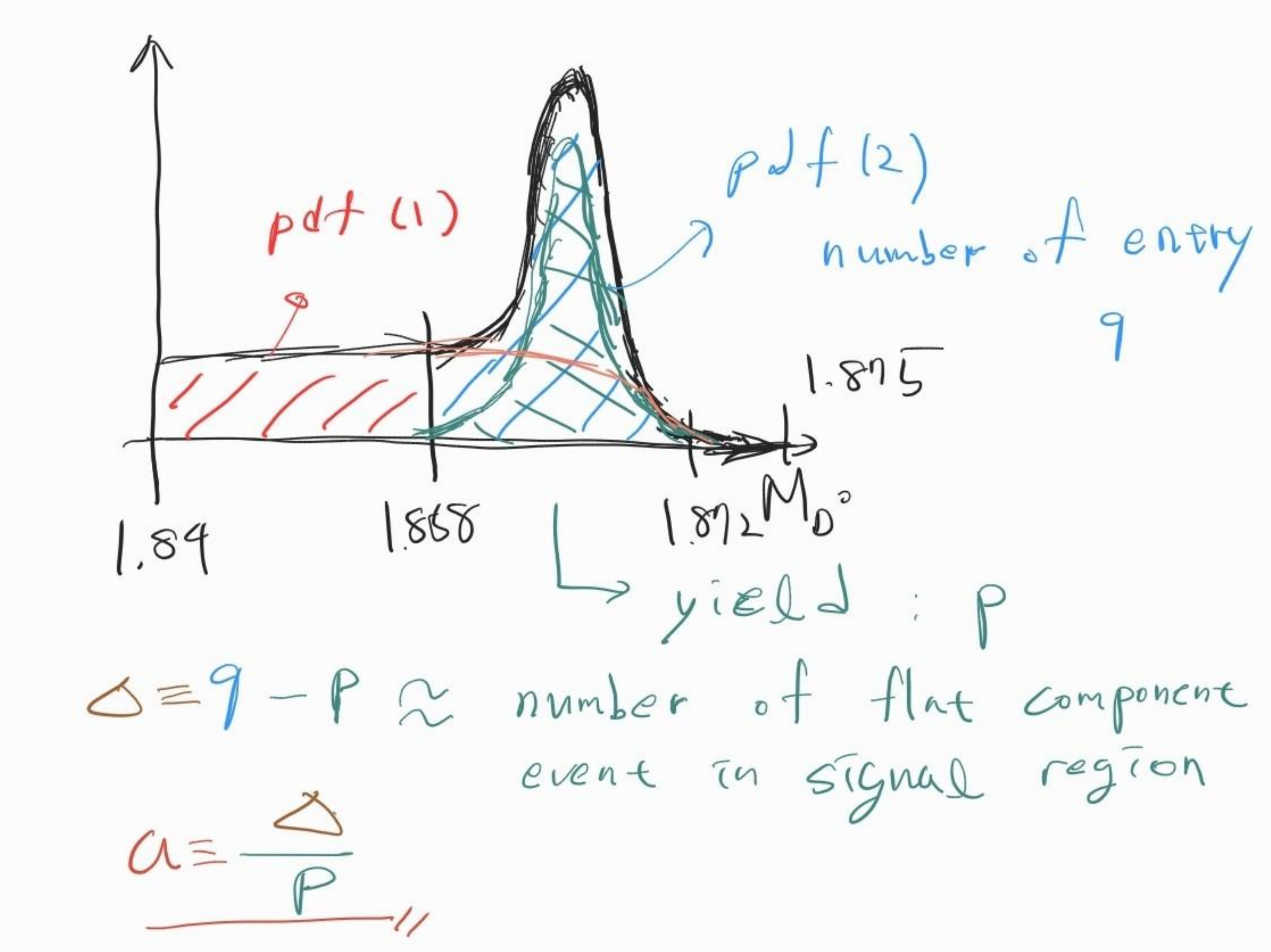
Backup : details of fit procedure

- Fit inclusive D0 on signal MC
- Fixed the signal PDF
- E_{ECL} histogram PDF
  - Signal PDF from signal MC
  - Background PDF is from E_{ECL} histogram on background events
    - Flat background PDF is from E_{ECL} on $1.855 < M_{D^0} < 1.860$ - - - (1)
    - Peak background PDF :
      histogram PDF from E_{ECL} on $1.860 < M_{D^0} < 1.870$ - - - (2)
      => peak background PDF : (2)*(1 + a) – (1)*a

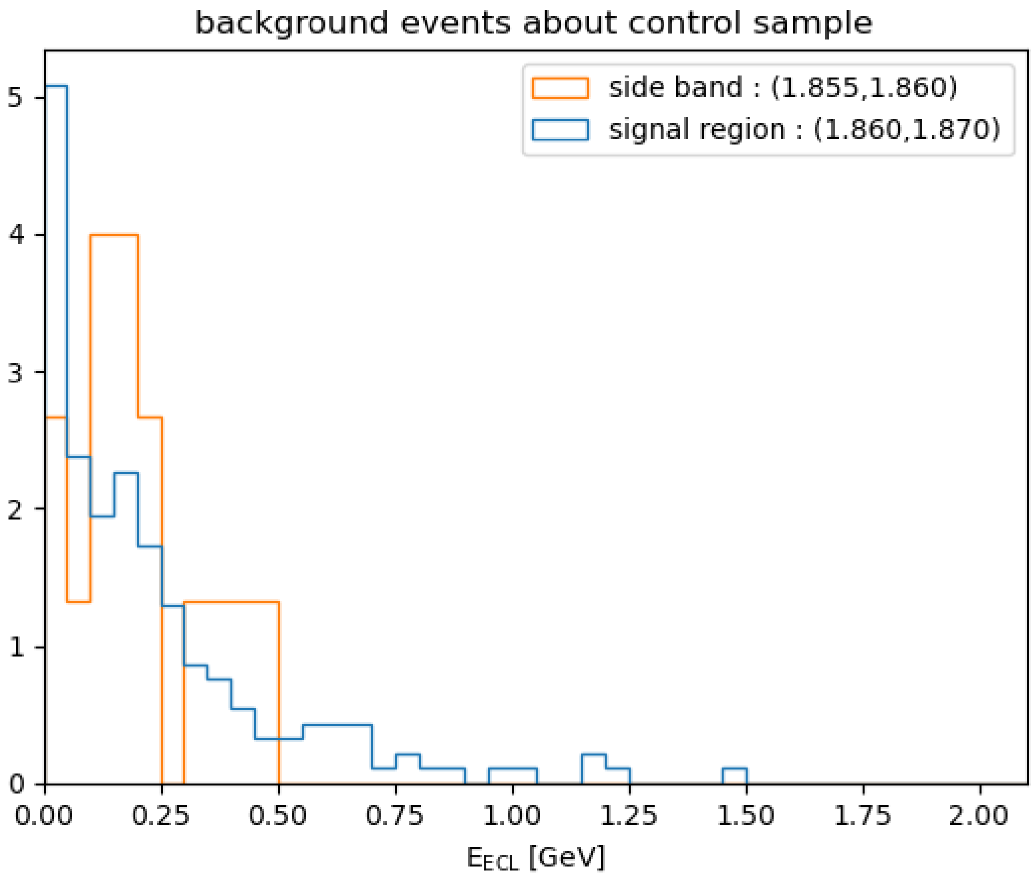
Backup : variable a

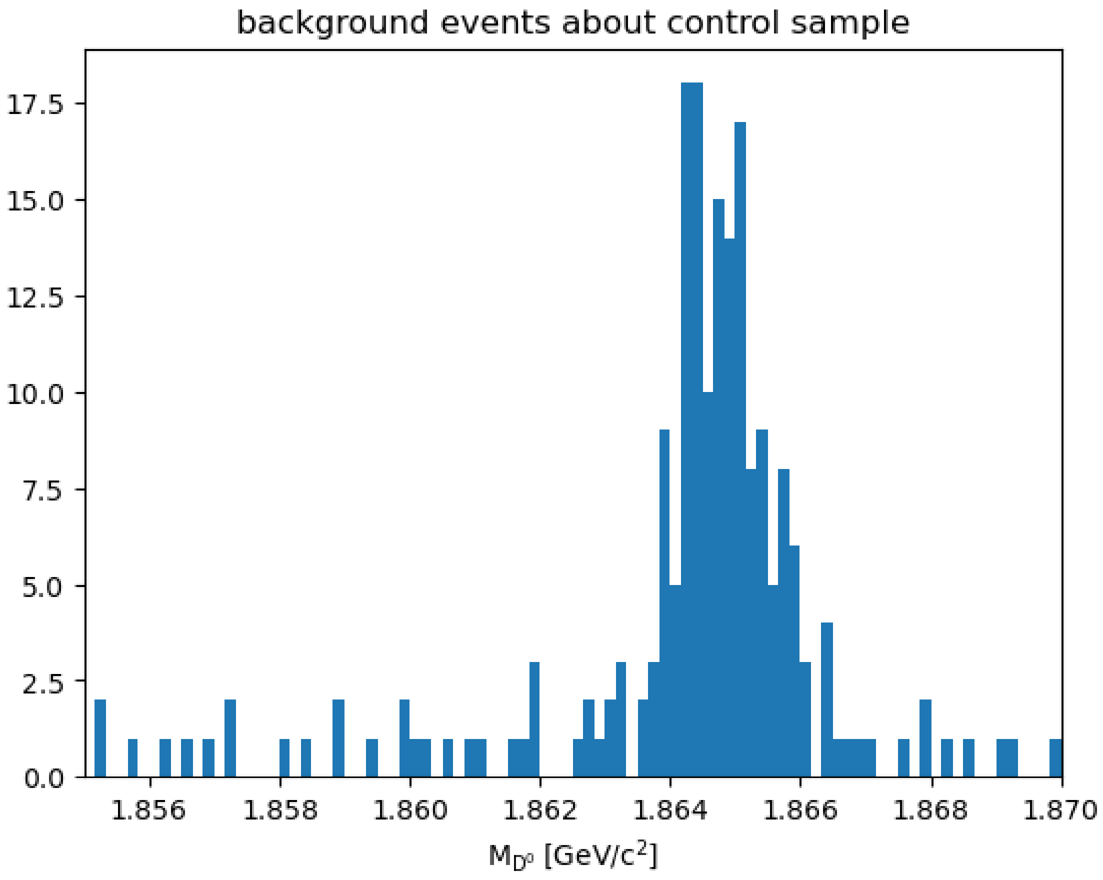
- The value of a can be roughly estimated

- a is floating number with small range around the estimated value



Backup : Check on background events ($D^0 \to K^+\pi^-, K^+K^-, K^-\pi^+\pi^0$) about control sample study





Backup : Check (M_{D^0}, E_{ECL}) on background events ($D^0 \to K^+\pi^-, K^+K^-, K^-\pi^+\pi^0$) about control sample study