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

Yonsei University
Chanho Kim

ckh424@yonsei.ac.kr

Introduction to analysis

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

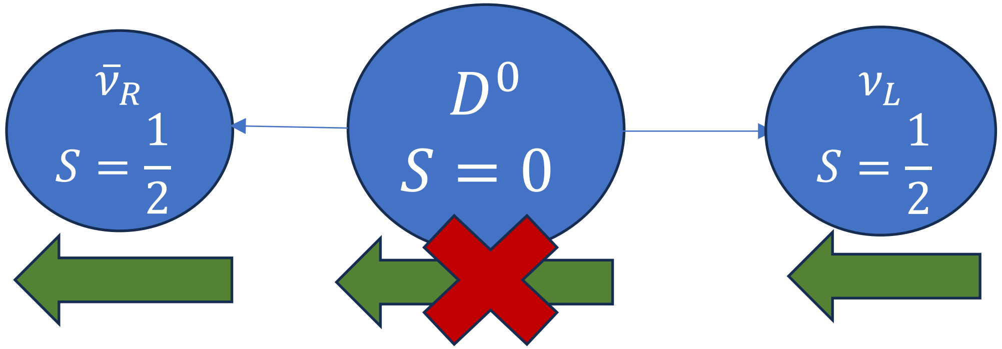


Figure1: Scheme of helicity suppresing

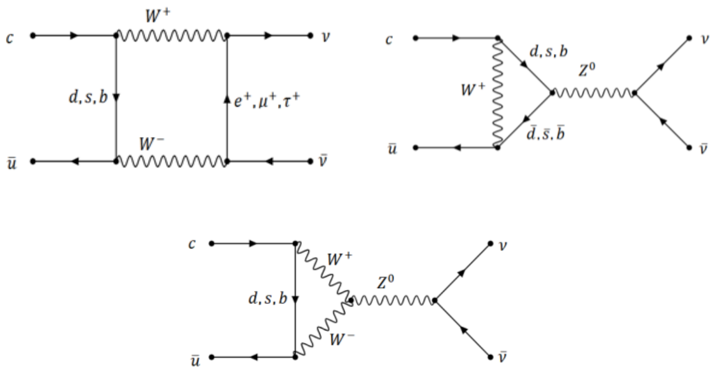


Figure2: Feynman diagram for $D^0 \to \nu\bar{\nu}$

- Therefore, search for $D^0 \to$ 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 ($D^0 \to K^-\pi^+$)

Analysis Method : Charm Tagger

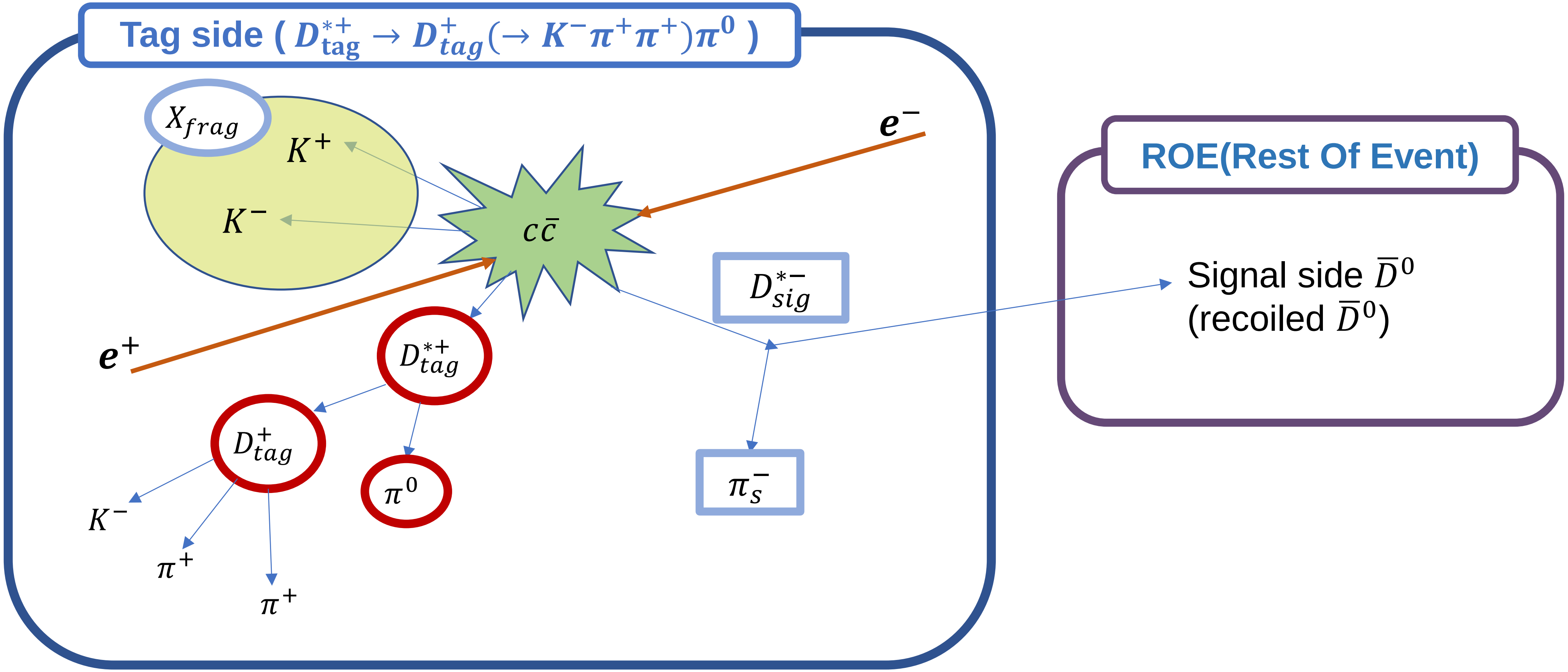


Figure3: schematics of signal event with tag side decay $\mathrm{D}^{*+}_{\mathrm{tag}} \to D^{+}_{tag}(\to K^{-}\pi^{+}\pi^{+})\pi^{0}$

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_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^-
			$\pi^+\pi^0K^-$
			$\pi^+\pi^-\pi^+K^-$

Table4: X_{frag} channel (total 25 channels)

fastBDT training for Charm Tagging

- Input Variables of fastBDT
  - For D_{tag} training

    M, p, dr(flight length), chiProb, Q, E, cosToThrustOfEvent,

    cosAngleBetweenMomentumAndVertexVectorInXYPlane, ImpactXY,

    xp, 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 $\pi_S^\pm, \gamma, \pi^0$,

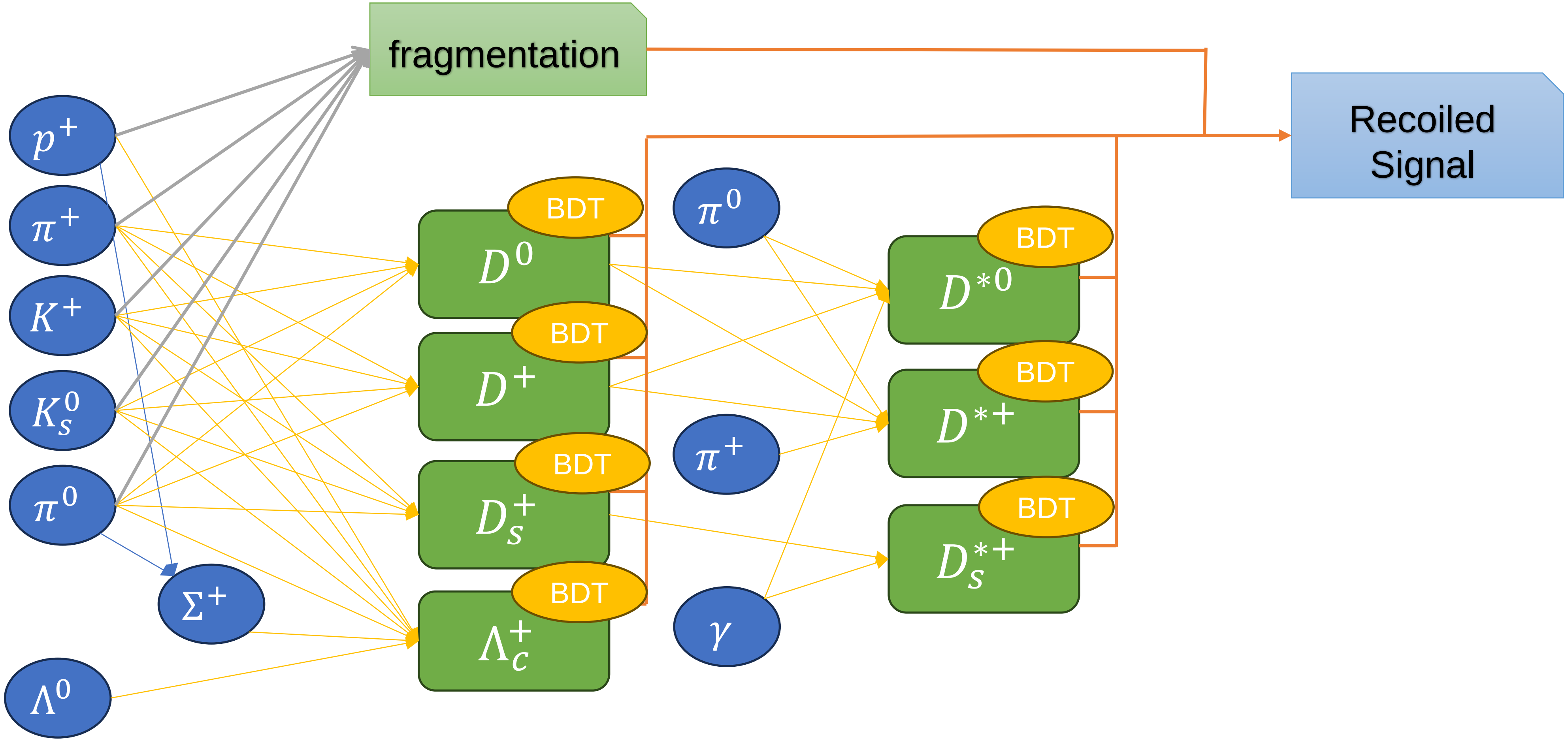
    angle between D_{tag} and $\pi_S^\pm, \gamma, \pi^0$ etc…
- Hyper Parameters of BDT was optimized by applying grid search for each tag training

Preselection of Charm Tagger

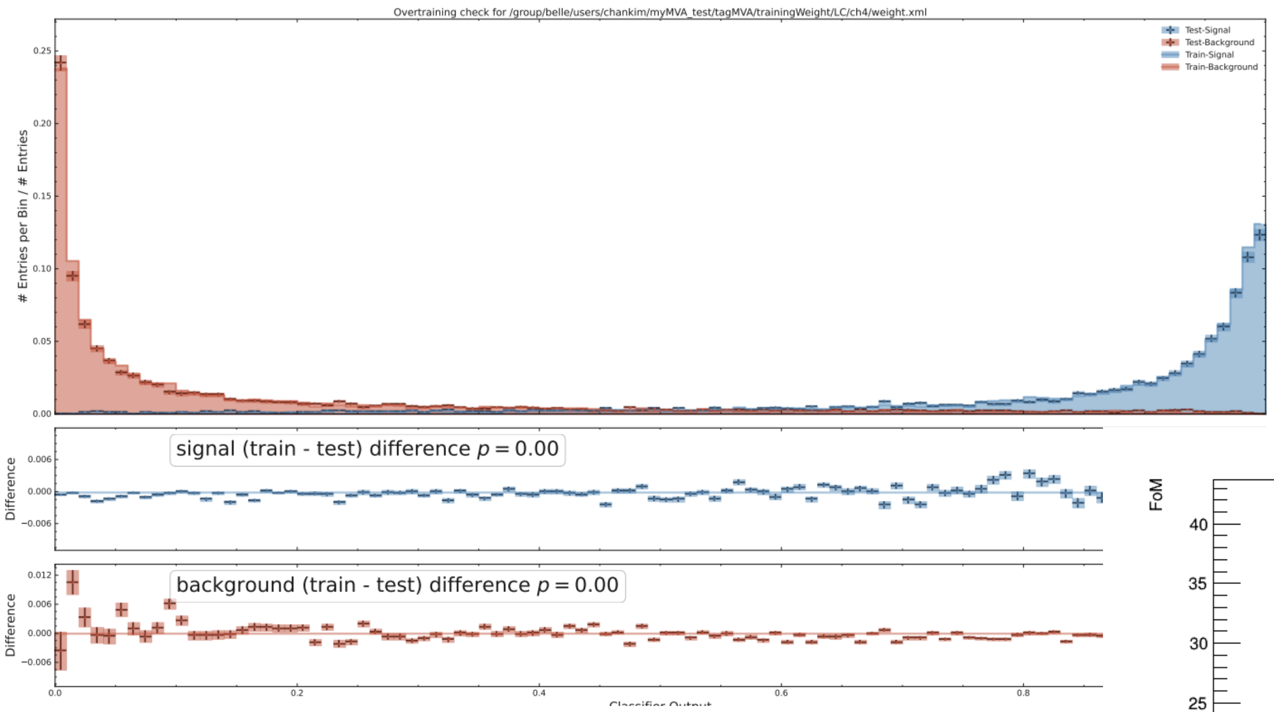
- For tracks : dr < 1.0 , |dz| < 3.0 and InCDCAcceptance
- $\pi^{\pm}$: 15 candidates with Highest pionID after pionID > 0.01
- $K^{\pm}$: 10 candidates with Highest kaonID after kaonID > 0.1
- $p^{\pm}$: 10 candidates with highest protonID after protonID > 0.1
- for fragmentations, PID selection of $\pi^{\pm}, K^{\pm},\ p^{\pm}$ is on 0.1, 0.9, 0.9 and additionally require p > 0.1 GeV

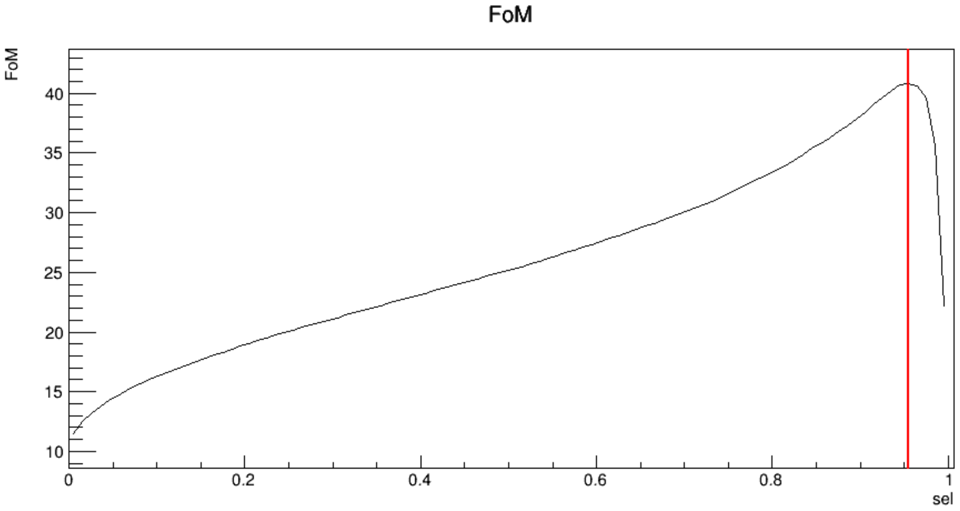
- K_S^0, Λ^0 :
  - mass and dr and χ^2 and angle between Momentum and Vertex Vector selection on Λ^0
  - goodBelleKshort for K_S^0 (similar selection to Λ^0)
- Σ^+ : reconstructed from $\Sigma^+ \to p^+\pi^0$ and mass cut (1.08 < M < 1.28)

Flow of Charm Tagger

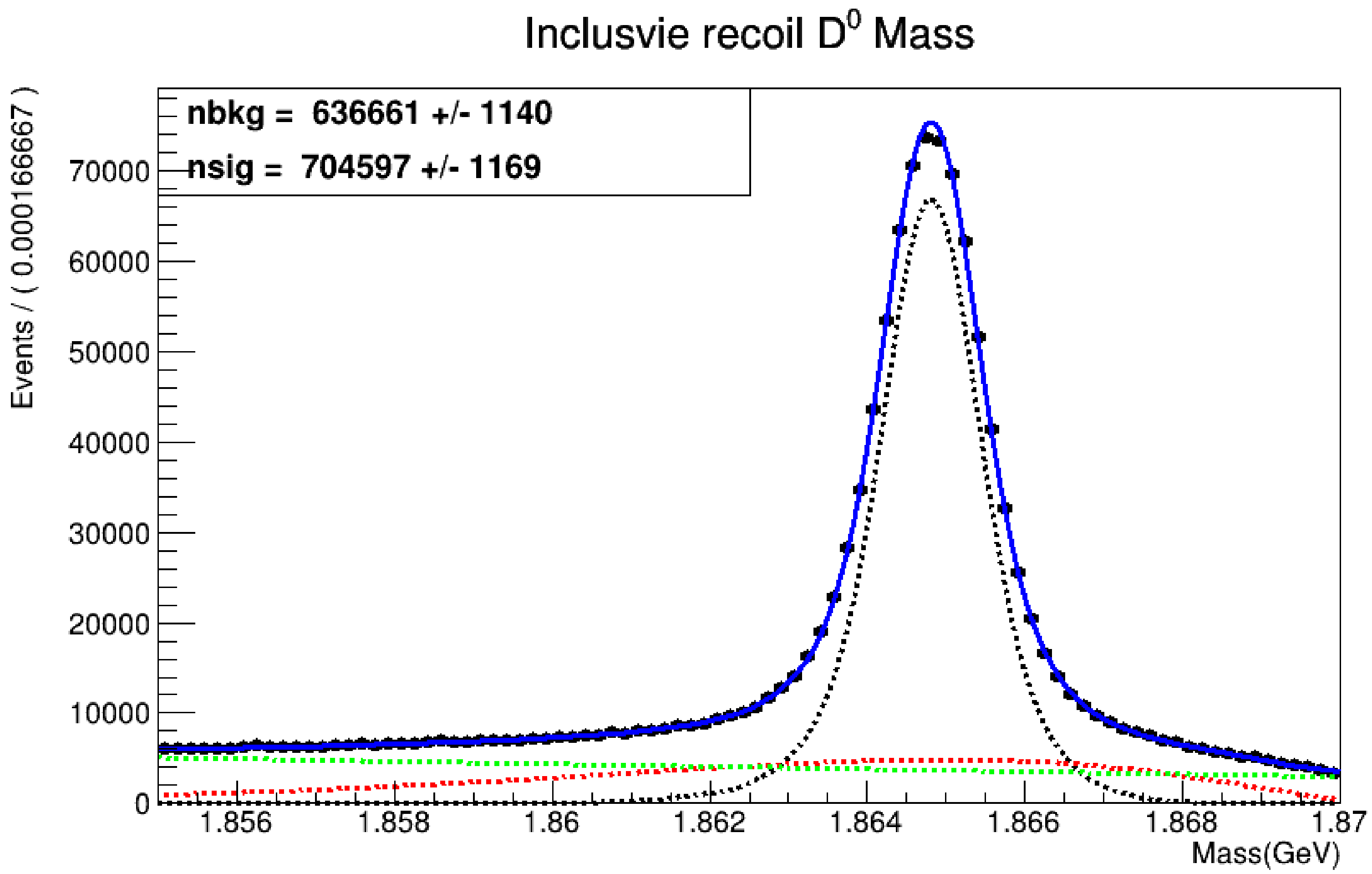


One example about training : $\Lambda_c^+ \rightarrow p^+K^-\pi^+\pi^0\pi^0$





Reconstructed D^0 from charm tagger on generic ccbar MC



Variables for extracting signal side D

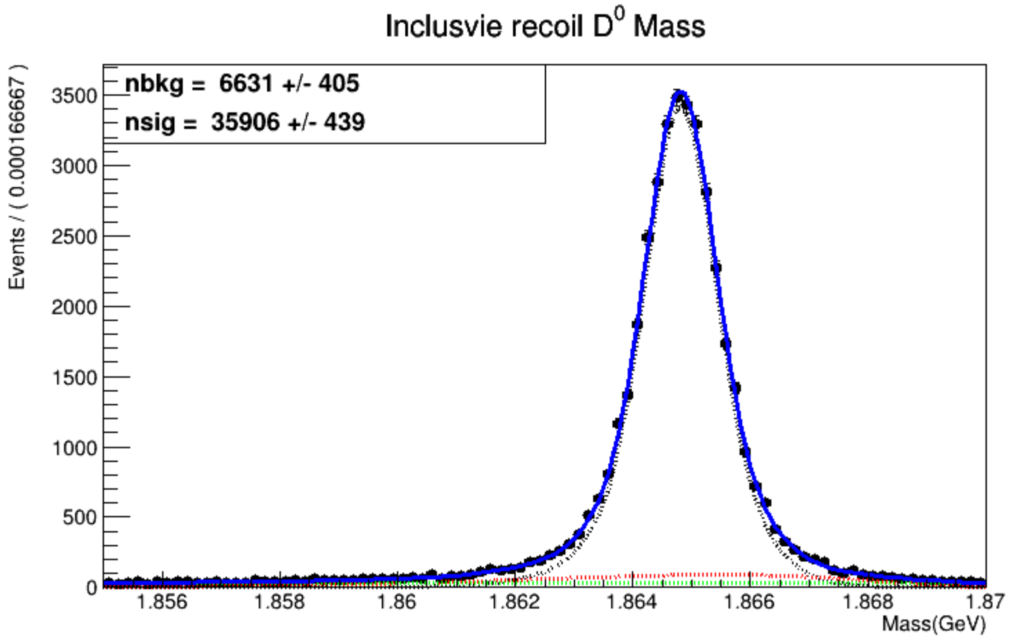
- Recoil mass ($M_{miss}\left(D^*_{tag} X_{frag} \pi^{\pm}_s\right)$ or $M_{recoil}(D^0)$)
  - $e^+e^- \rightarrow D^*_{tag} X_{frag} \pi^+_s D^0$
  - $p^\mu(e^+) + p^\mu(e^-) - \left(p^\mu\left(D^*_{tag}\right) + p^\mu\left(X_{frag}\right) + p^\mu(\pi^+_s)\right) = p^\mu(D^0_{sig})$
  - $M_{recoil}(D^0) = \sqrt{p^\mu(D^0) * p_\mu(D^0)}$
  - 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})

Exclusive D requirement for signal MC & control sample (signal extraction)

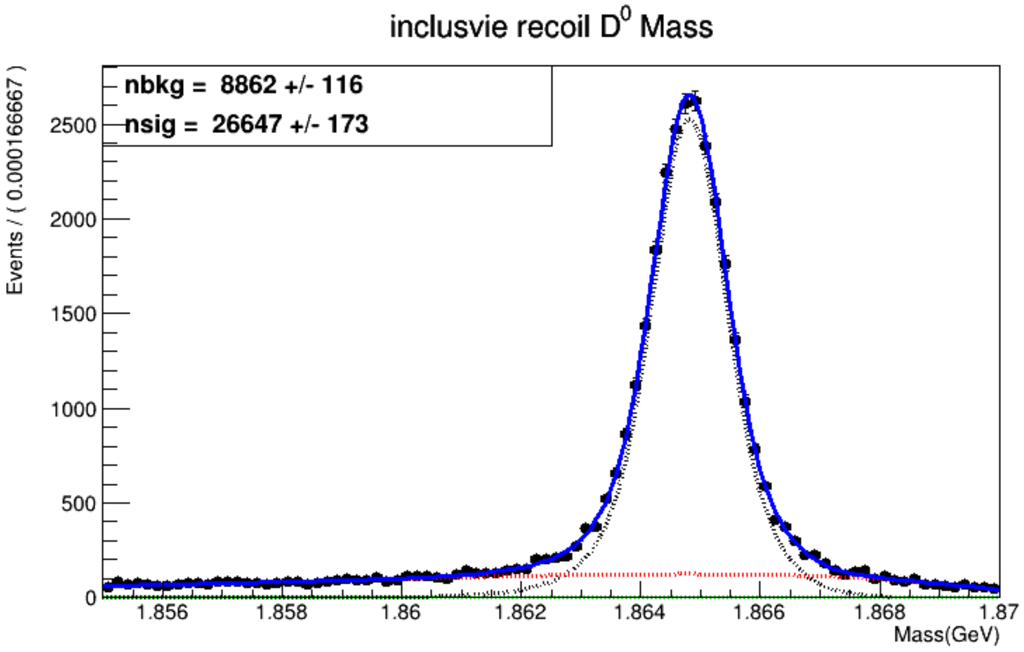
- Exclusive : D^0 with selection on signal side
  1.84 GeV < M_{D^0} < 1.875 GeV & E_{ECL} < 2.1 GeV
  - Signal MC ($D^0 \to \nu\bar{\nu}$) selection for exclusive D^0
    - no remaining tracks, $\pi^0, K_L^0, K_S^0, \Lambda^0$
  - Control sample ($D^0 \to K^-\pi^+$) selection for exclusive D^0
    (studying about this selection is on-going …)
    - 2 remaining tracks and 1 reconstructed $D^0(K^-\pi^+)$
    - no $\pi^0, K_L^0, K_S^0, \Lambda^0$
    - $|\Delta E| < 1.0\ \mathrm{GeV}$ ($\Delta E \equiv E$(recoil D^0) - $E_{K\pi}$)

Inclusive D fitting on signal MC / control sample

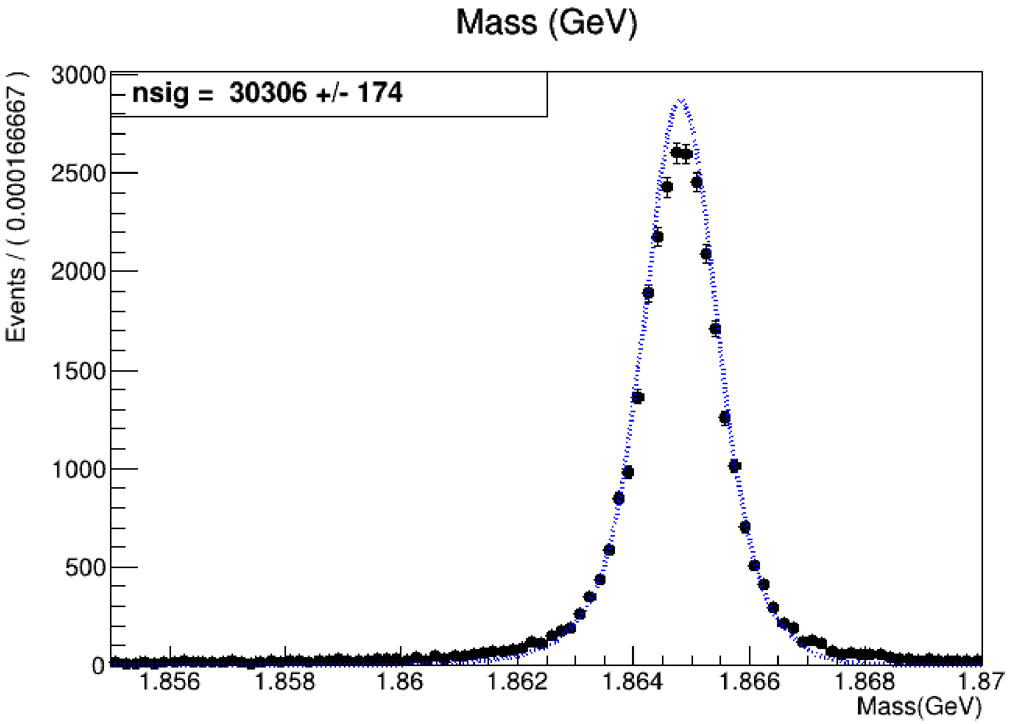
Signal MC

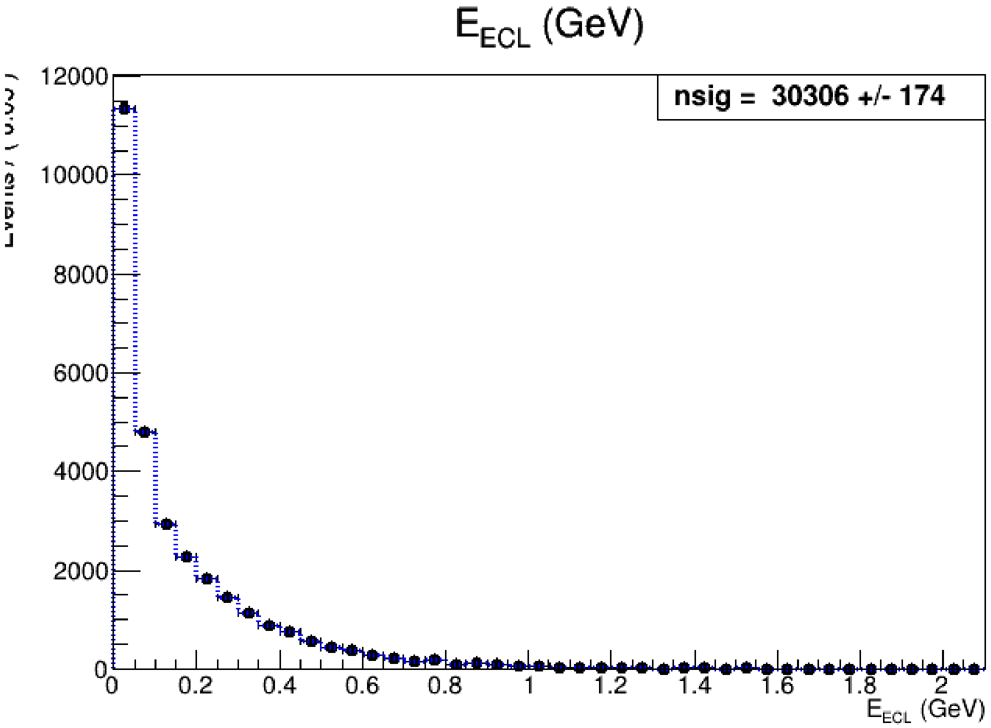


Control sample



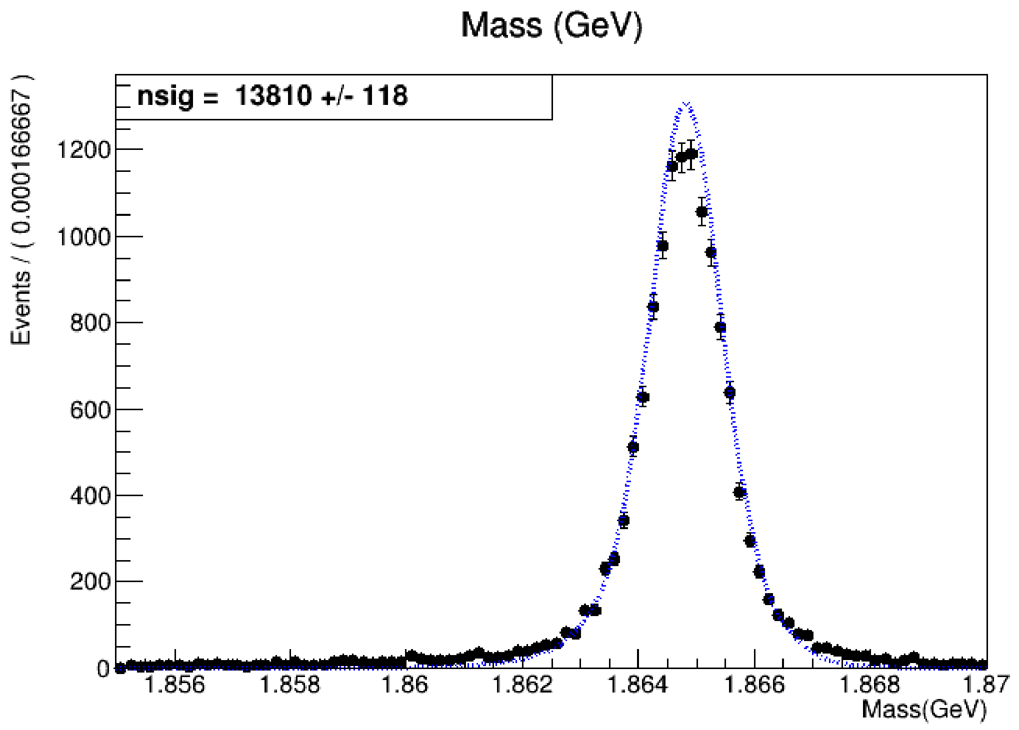
Extraction of exclusive D on signal MC

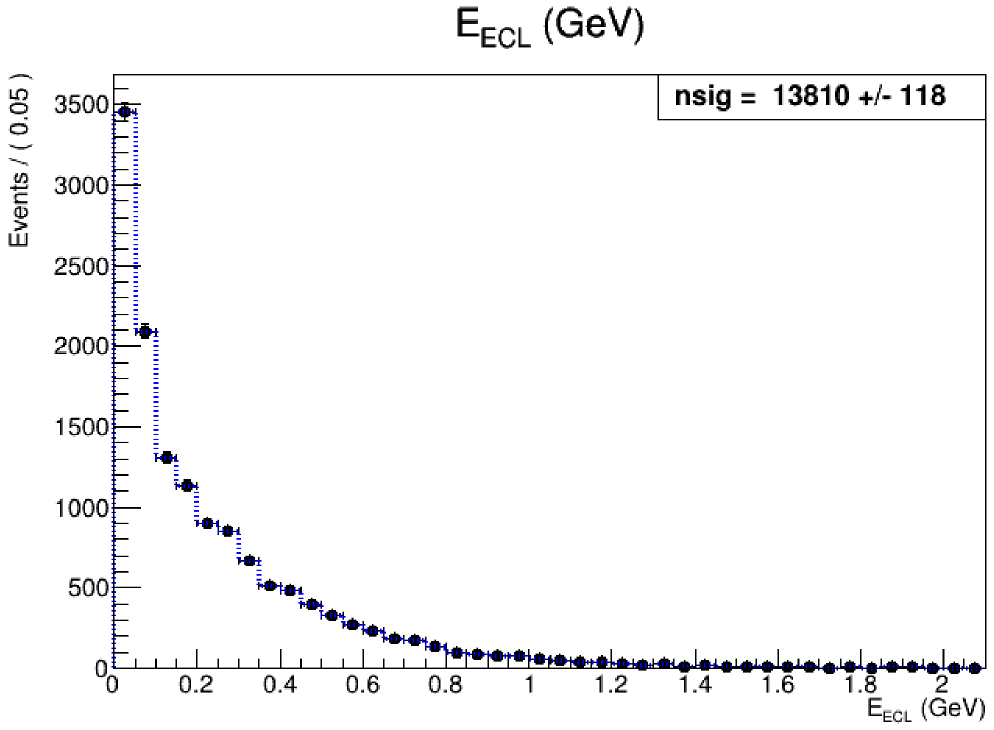




Signal efficiency = 0.84404 +/- 0.01140

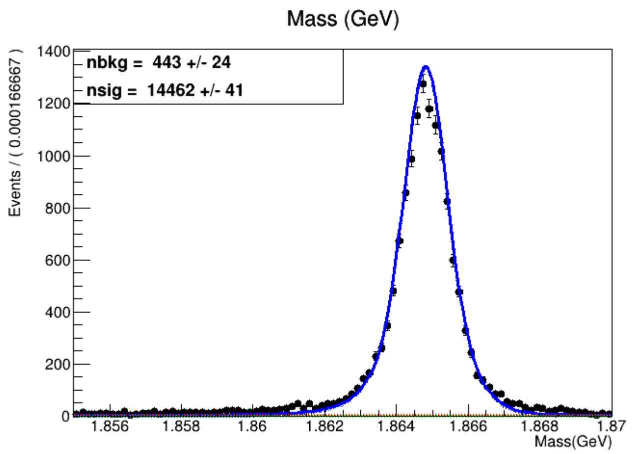
Extraction of exclusive D on control sample

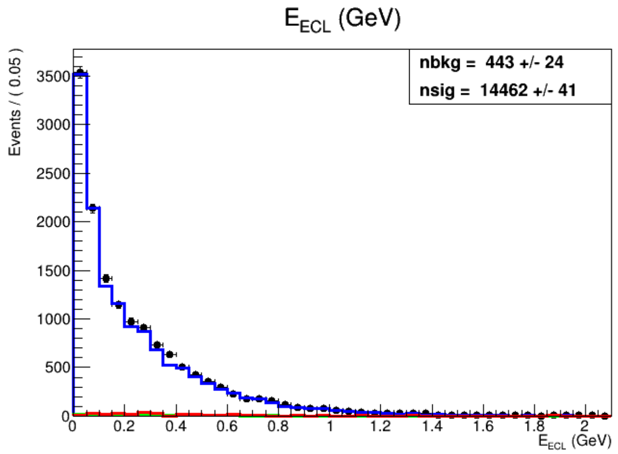




Signal efficiency = 0.51826 +/- 0.00556

Measurement of $Br(D^0 \to K^-\pi^+)$ on generic MC

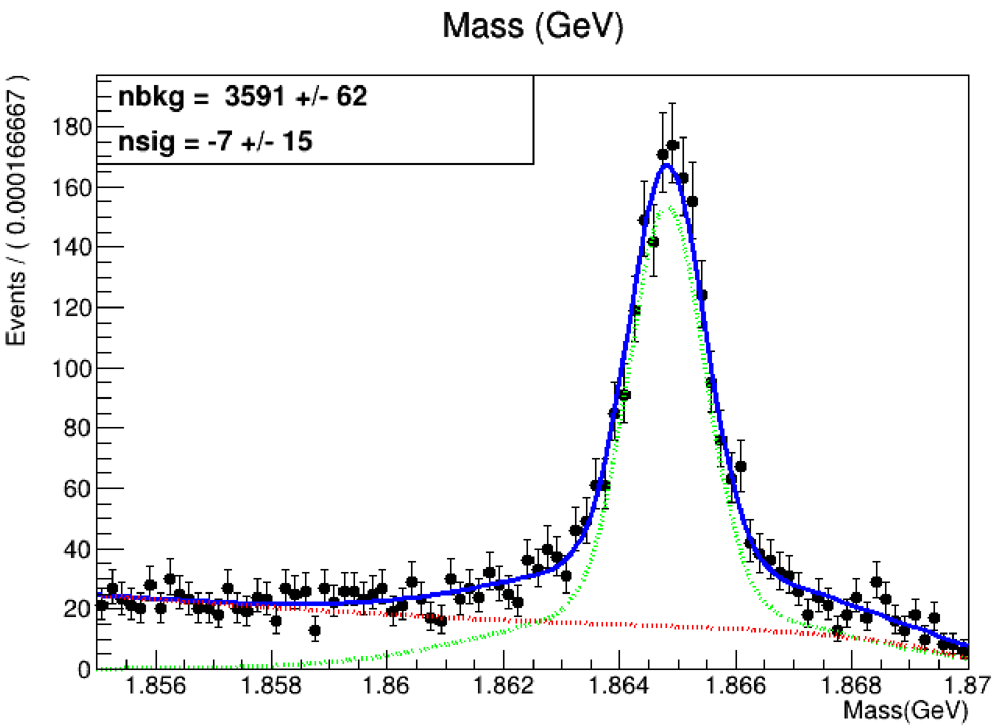


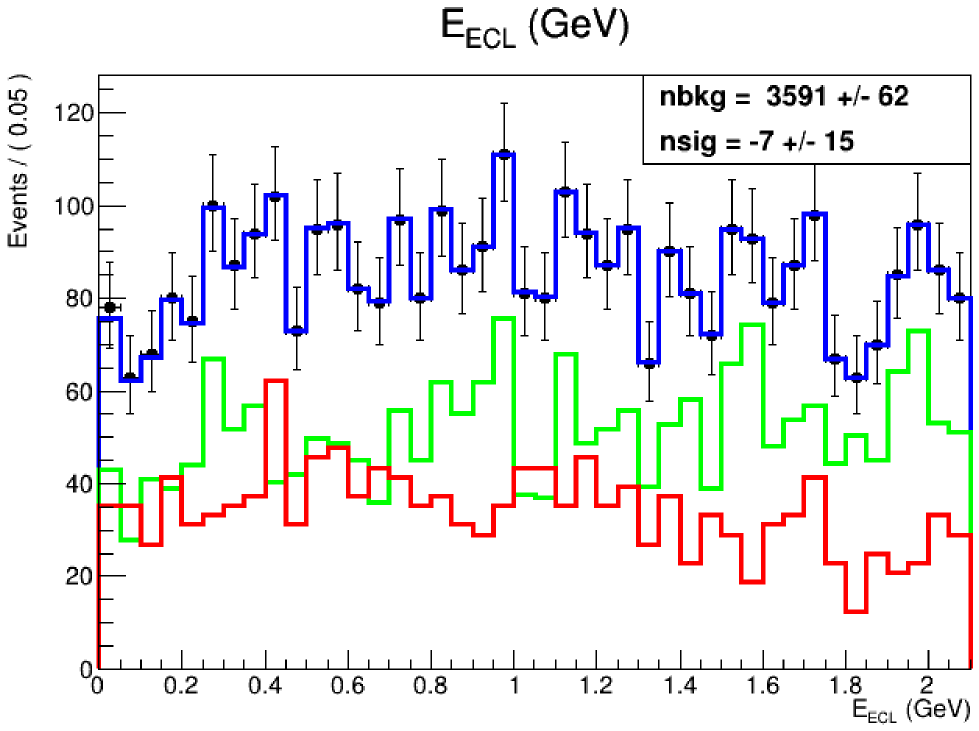


- BF formula : $Br(D^0 \to K^-\pi^+) = \frac{N_{exclusive}}{N_{inclusive} * \varepsilon_{sig}}$ (pdg value : 0.0395)
- Measurement of BF :

$$Br(D^0 \to K^-\pi^+) = \frac{14462 \pm 41}{(704597 \pm 1169) * (0.51826 \pm 0.00556)} = 0.039604 \pm 0.000444$$

Extraction of D^0 decays to invisible on generic ccbar MC

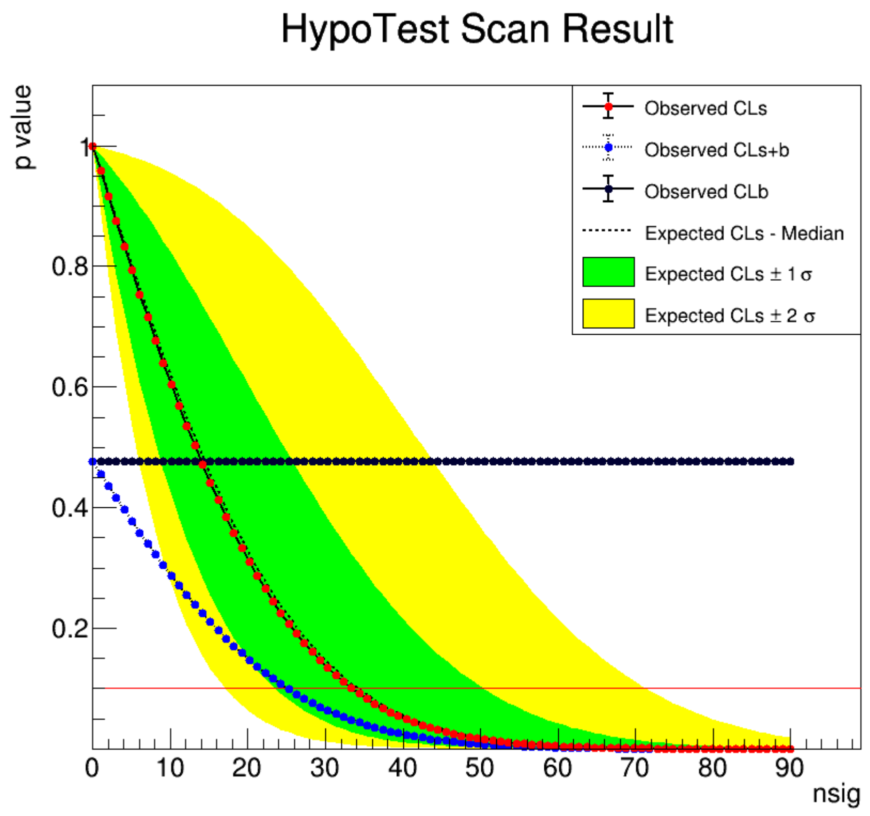




Trial to calculate Upper Limit of D^0 to invisible on $1\ ab^{-1}$ generic MC with CLs method

- Systematics are not considered yet…

- $N_{UL} = 34.4444$
- $BR_{UL} = \frac{34.4444}{(704597 * 0.84404)} = 5.62 \times 10^{-5}$

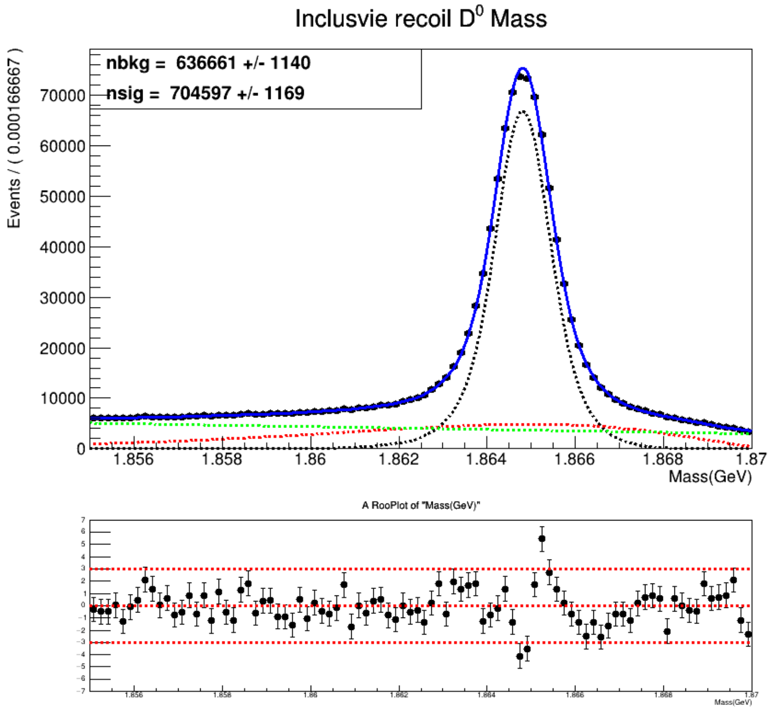


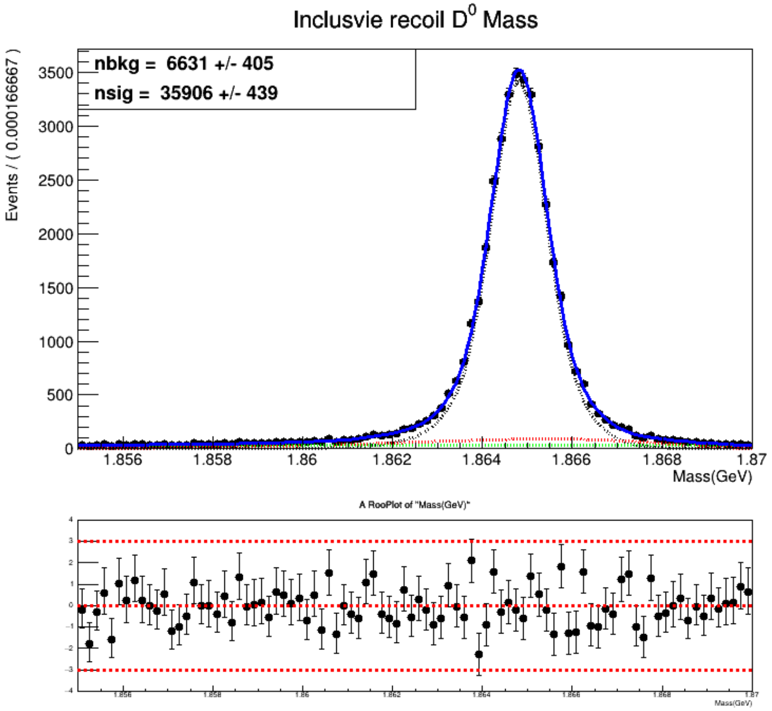
Fitting strategy & check with pull distribution

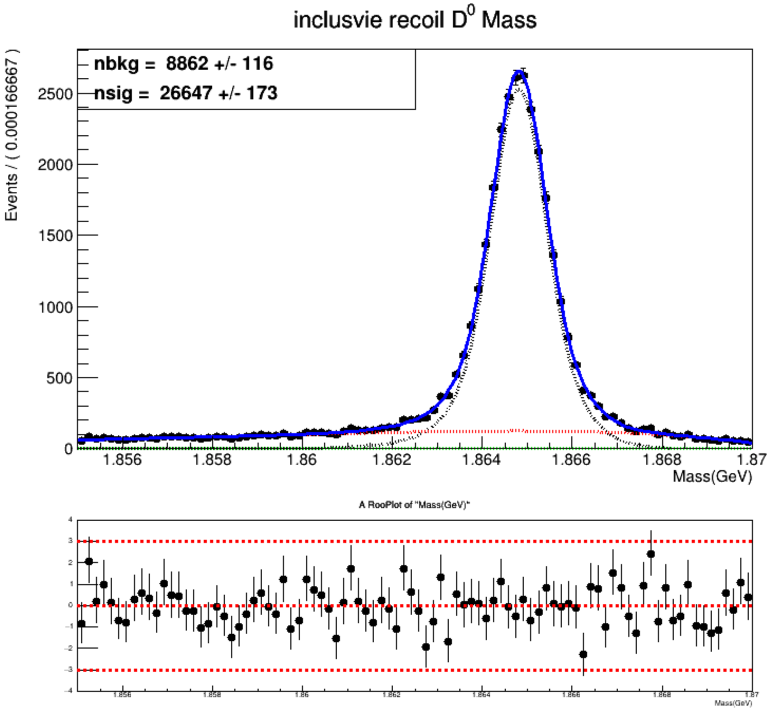
- Inclusive D fitting
  - 1D fitting : M_{D^0}
  - Signal pdf : 2 gaussians + 1 bifurcated gaussian
  - Background pdf : argus + linear

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

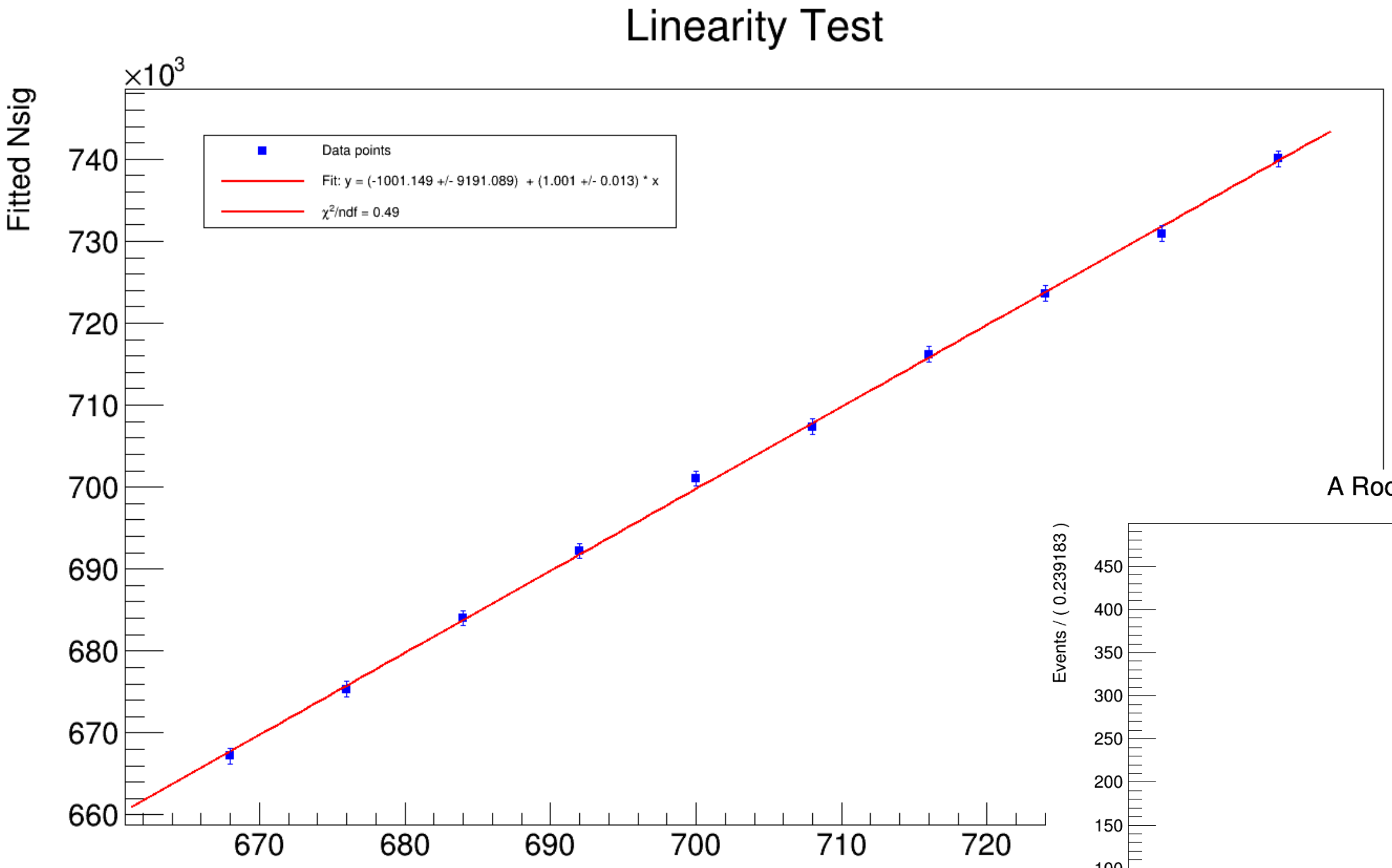
Fit result with Pull distribution for inclusive D

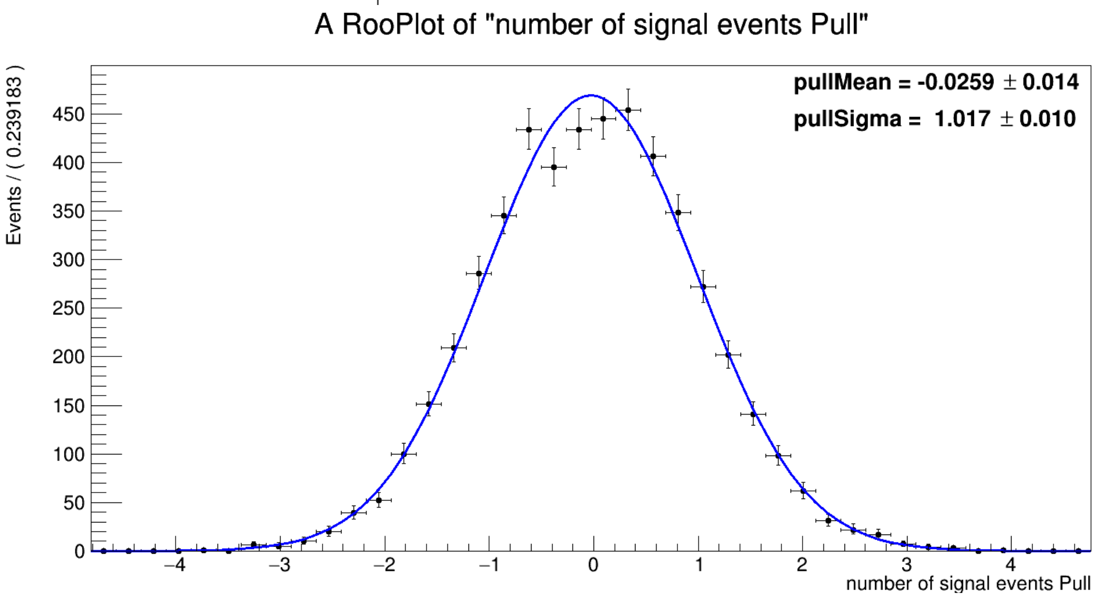






Inclusive D fit result check with ToyMC on generic MC





Backup : variable a

- The value of a can be roughly estimated

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