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 $\mathrm{Br}(\mathrm{D}^0 \to \nu\bar{\nu}) = 1.1 \cdot 10^{-30}$, which is beyond the reach of current collider experiments.

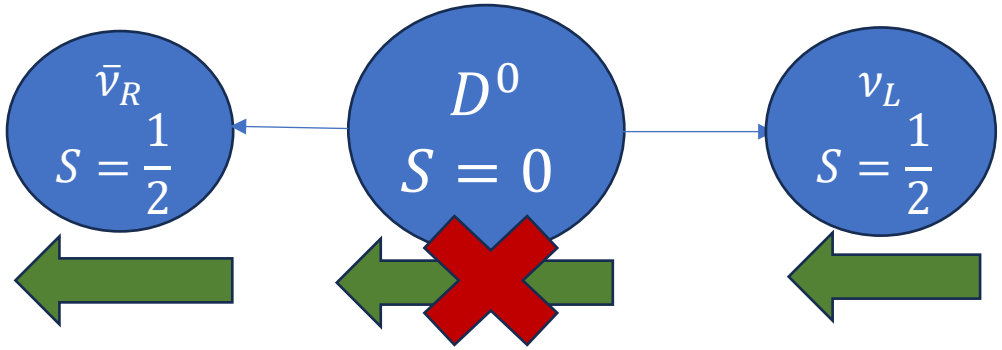


Figure1: Scheme of helicity suppressing

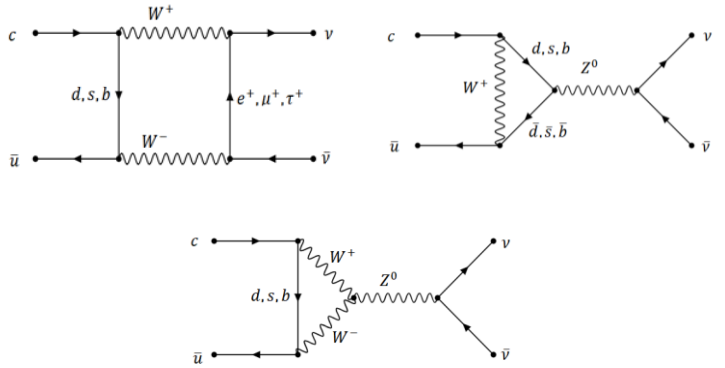


Figure2: Feynman diagram for $D^0 \to \nu\bar{\nu}$

- 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 :

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

- MC15ri generic MC($1ab^{-1}$) is used as generic background MC sample
  - Will move on run dependent MC soon
- 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

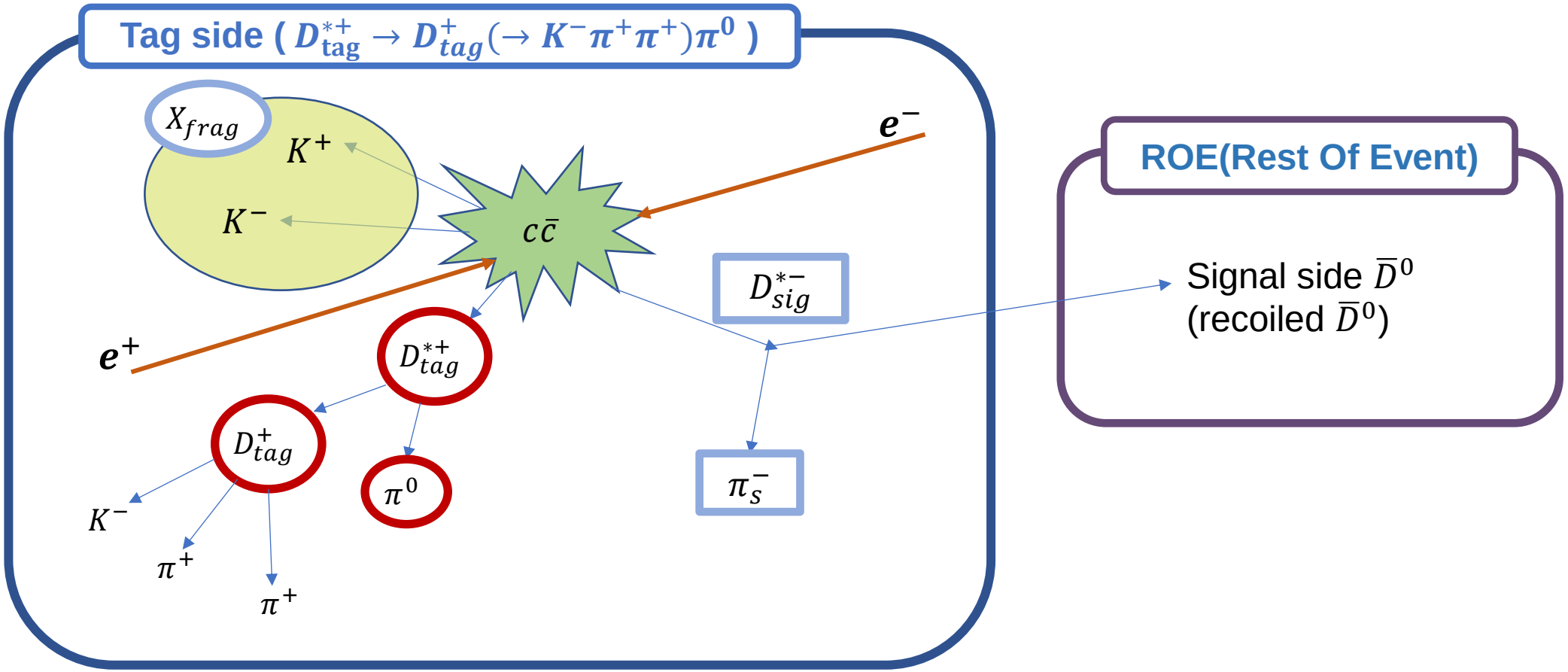


Figure3: schematics of signal event with tag side decay $D^{*+}_{tag} \to D^{+}_{tag}(\to K^-\pi^+\pi^+)\pi^0$

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 $\mathrm{M}_{\mathrm{miss}}(D^*_{tag}X_{frag}\pi^+_s)$ 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^-
$\pi^+\pi^-\pi^0(K^+K^-)$			$\pi^+\pi^-\pi^0K_S^0$
			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 $\pi^0(\to \gamma\gamma), K_S^0(\to \pi^+\pi^-), \Lambda^0(\to p^+\pi^-), \Sigma^+(\to p^+\pi^0)$,

    $|\frac{E_{d_1}-E_{d_2}}{E_{d_1}+E_{d_2}}|$ of $\pi^0(\to \gamma\gamma), K_S^0(\to \pi^+\pi^-), \Lambda^0(\to p^+\pi^-), \Sigma^+(\to p^+\pi^0)$ etc…
  - For D_{tag}^* training

    $\Delta M(= M_{D_{tag}^*} - M_{D_{tag}})$, momentum of $\pi_s^{\pm}, \gamma, \pi^0$,

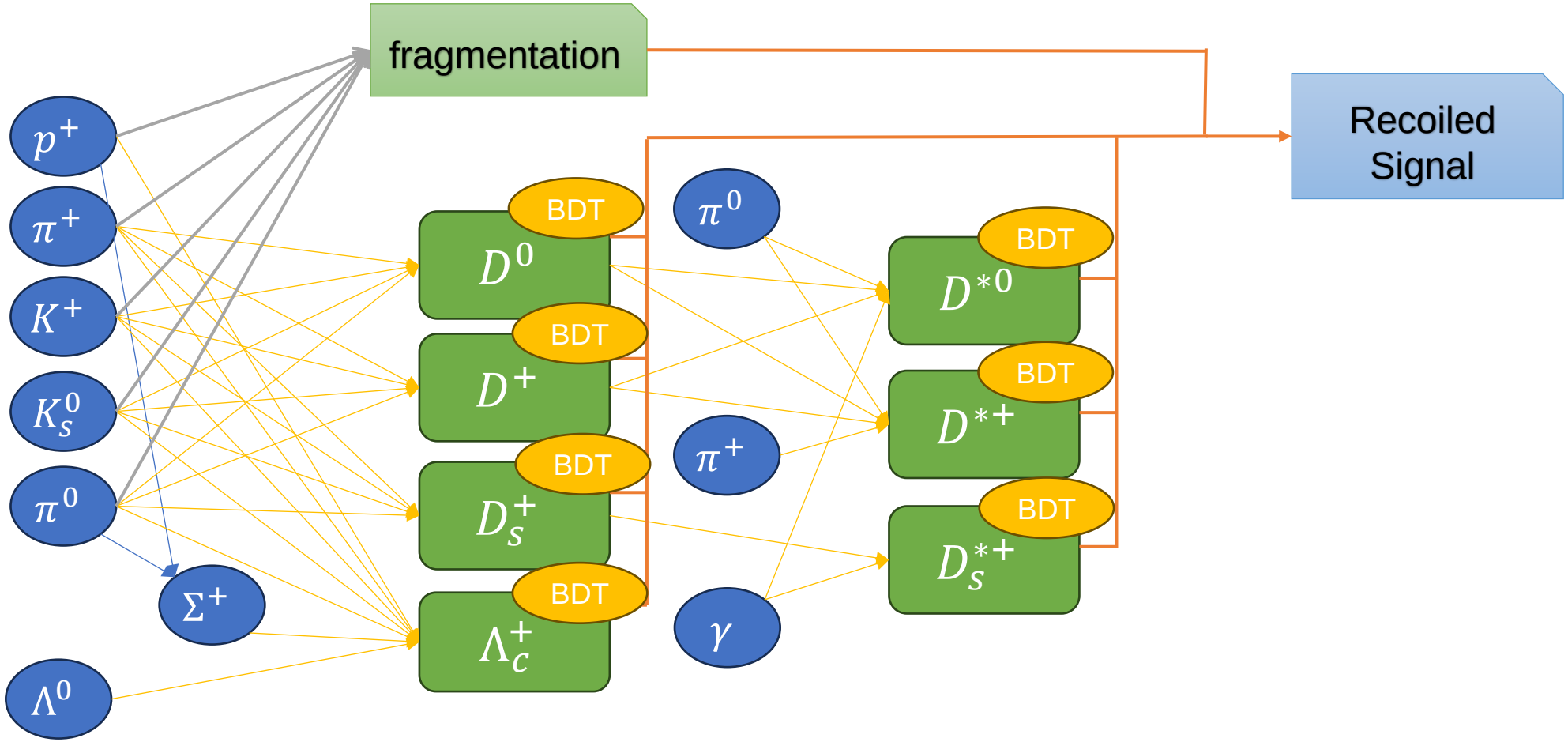
    angle between D_{tag} and $\pi_s^{\pm}, \gamma, \pi^0$ etc…
- Hyper Parameters of BDT was optimized by applying grid search for each tag training

Preselection of Charm Tagger

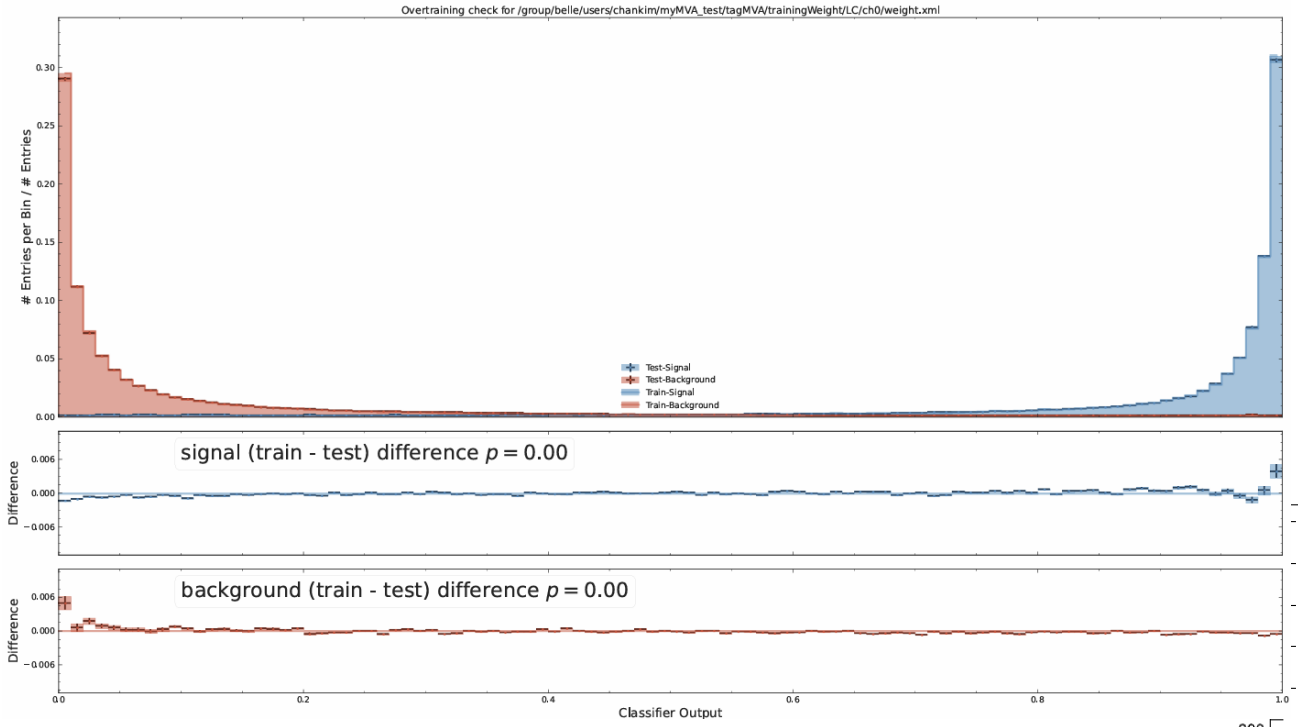
- For tracks : dr < 1.0 , |dz| < 3.0 and InCDCAcceptance
- $\pi^{\pm}$: 15 candidates with Highest pionID after pionID > 0.01
- $K^{\pm}$: 10 candidates with Highest kaonID after kaonID > 0.1
- $p^{\pm}$: 10 candidates with highest protonID after protonID > 0.1
- γ : beamBackgroundSuppression > 0.5 & 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

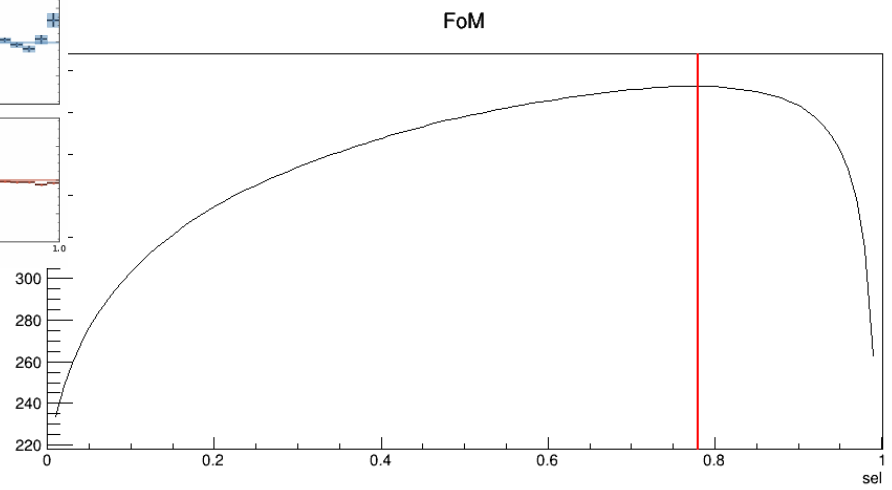
- K_S^0, Λ^0 :
  - mass and dr and χ^2 and angle between Momentum and Vertex Vector selection on Λ^0
  - goodBelleKshort for K_S^0 (similar selection to Λ^0)
- Σ^+ : reconstructed from $\Sigma^+ \to p^+\pi^0$ and mass cut (1.08 < M < 1.28)

Flow of Charm Tagger

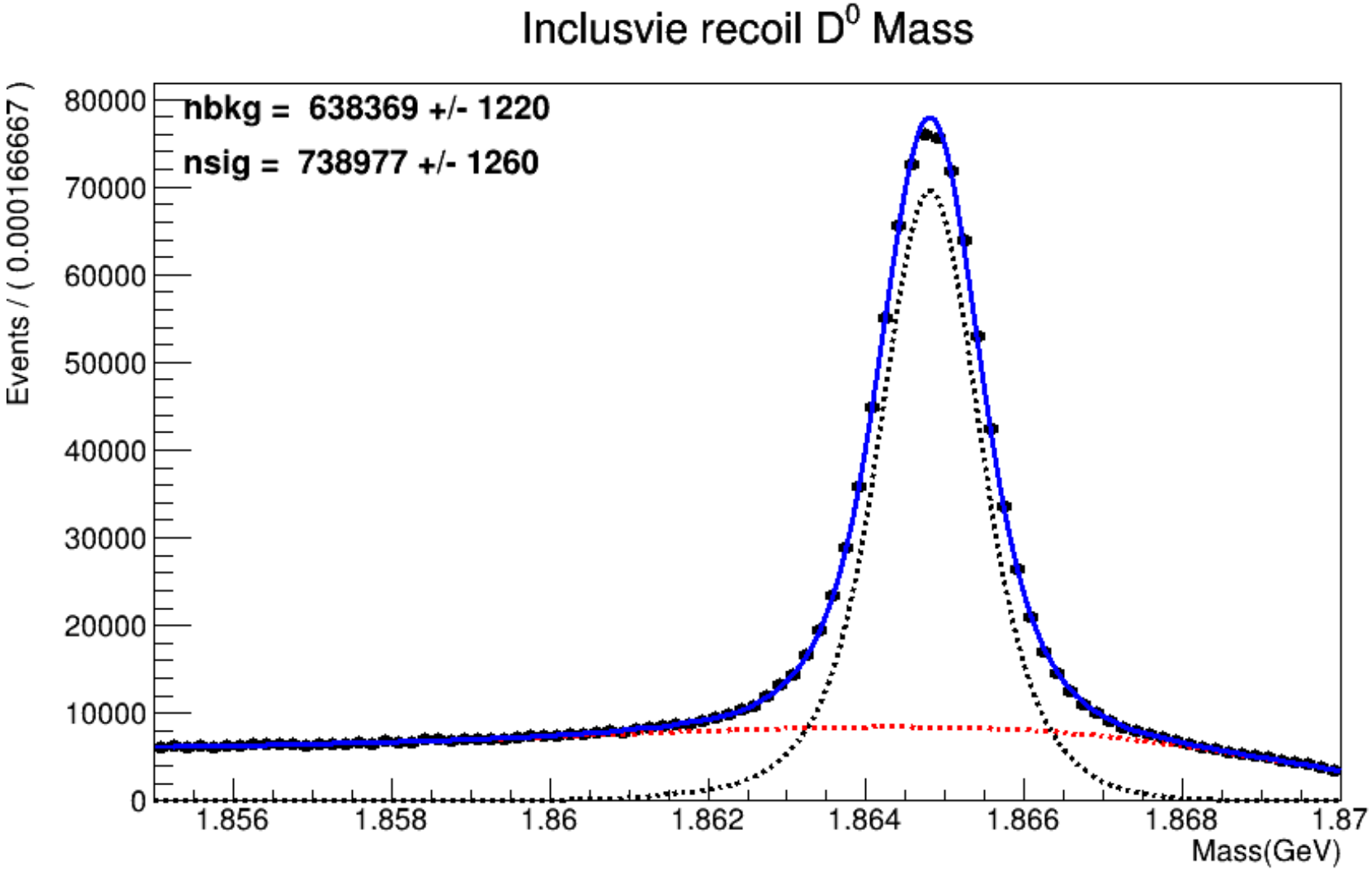


One example about training :
$\Lambda_c^+ \to p^+ K^- \pi^+$





Reconstructed D^0 from charm tagger on generic MC



Variables for extracting signal side D

- Recoil mass ($M_{miss}\left(D^*_{tag}X_{frag}\pi^{\pm}_s\right)$ 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})

Fitting strategy

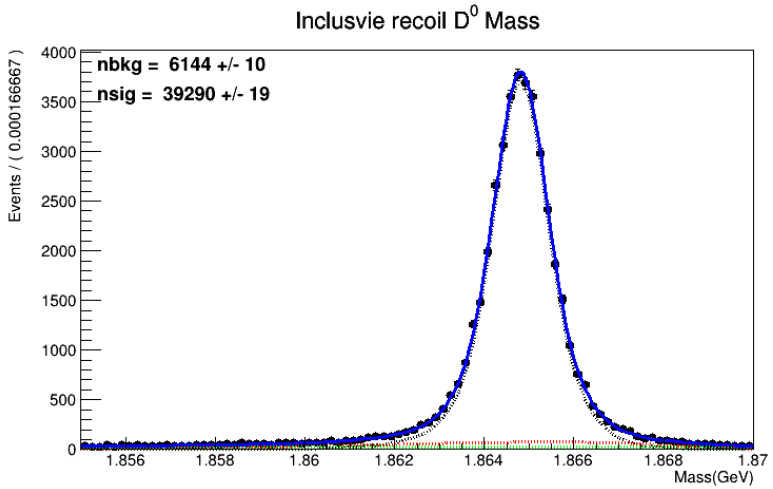
- Inclusive D fitting
  - 1D fitting : M_{D^0}
  - **Signal pdf : 2 gaussians + 1 bifurcated gaussian**
    - Shape fixed on inclusive D fit result of $D^0 \to \nu\bar{\nu}$ signal MC
  - **Background pdf :** argus + linear

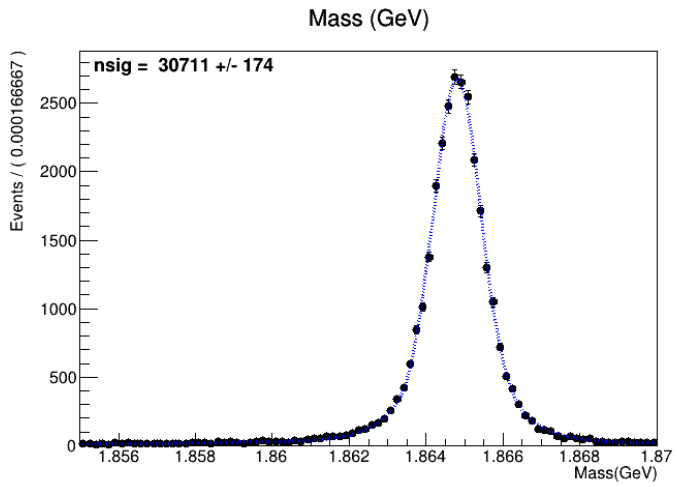
- Exclusive D fitting
  - 2D fitting : (M_{D^0}, E_{ECL})
  - **Signal pdf :**
    - **For M_{D^0}, signal pdf from exclusive D fitting**
    - For E_{ECL}, histogram pdf from signal MC study
  - **Background pdf :**
    - Flat: Argus + linear & histogram PDF from MC study
    - Peak: 3 gaussians & histogram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

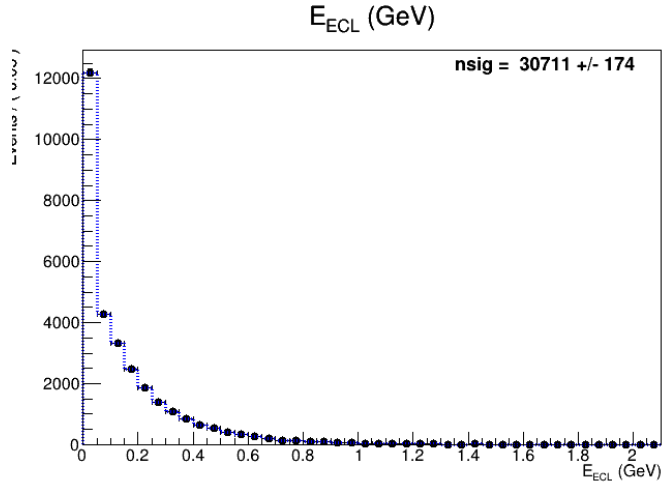
Exclusive D requirement (signal extraction)

- 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 ($D^0 \to \nu\bar{\nu}$)
    - no remaining tracks, $\pi^0, K_L^0, K_S^0, \Lambda^0$
  - Selection for exclusive D^0 on Control sample ($D^0 \to K^-\pi^+$)
    - 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

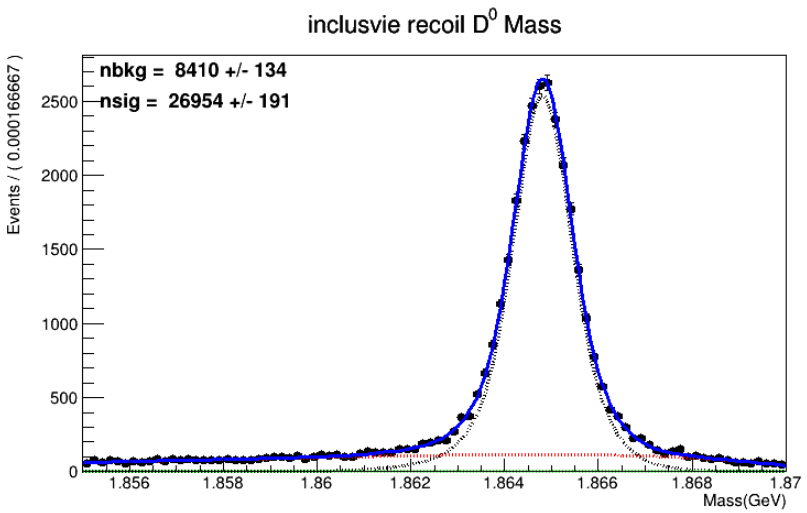


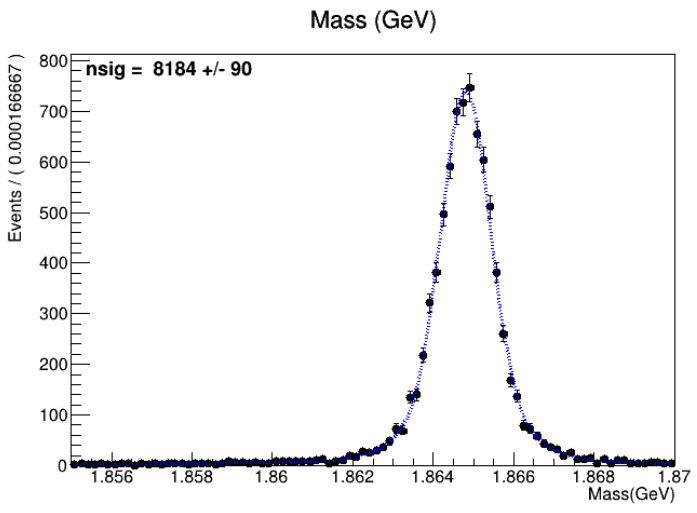


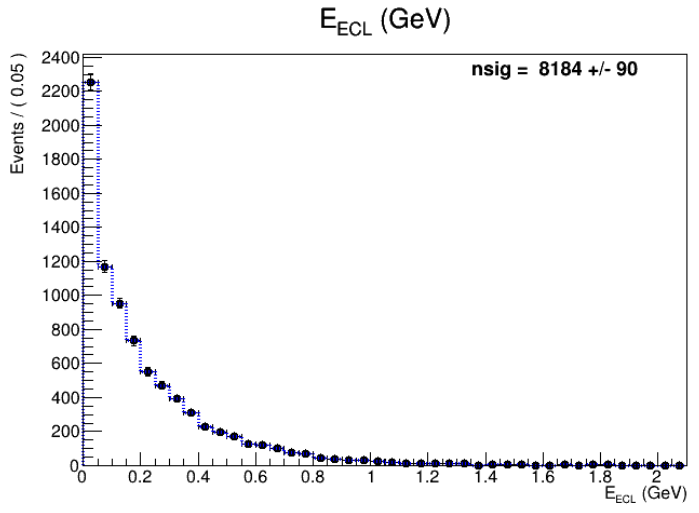


- Signal eff : $\frac{30711 \pm 174}{39290 \pm 19} = 0.78165 \pm 0.00444$

Signal efficiency on control sample

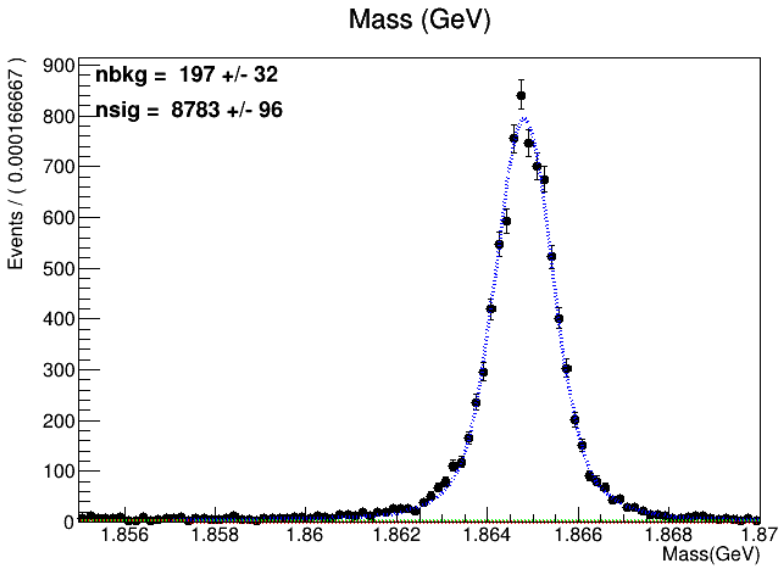


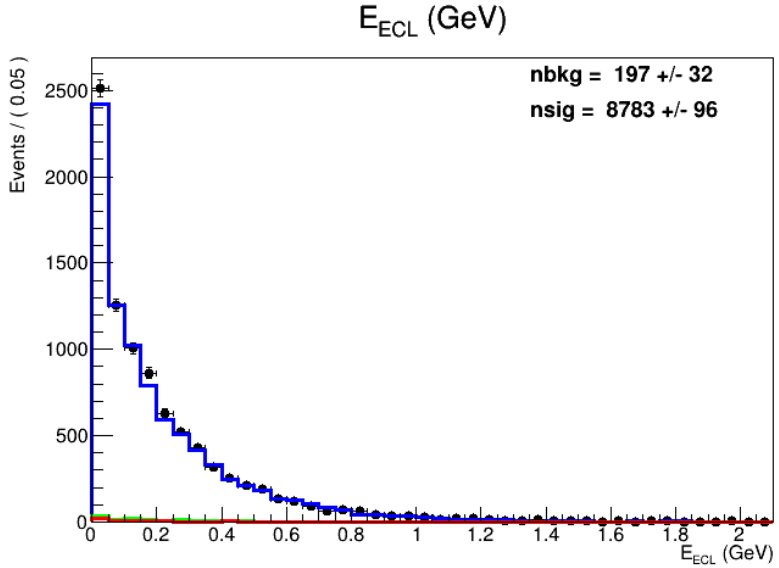




- Signal eff : $\frac{8184 \pm 90}{26954 \pm 191} = 0.30363 \pm 0.00397$

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

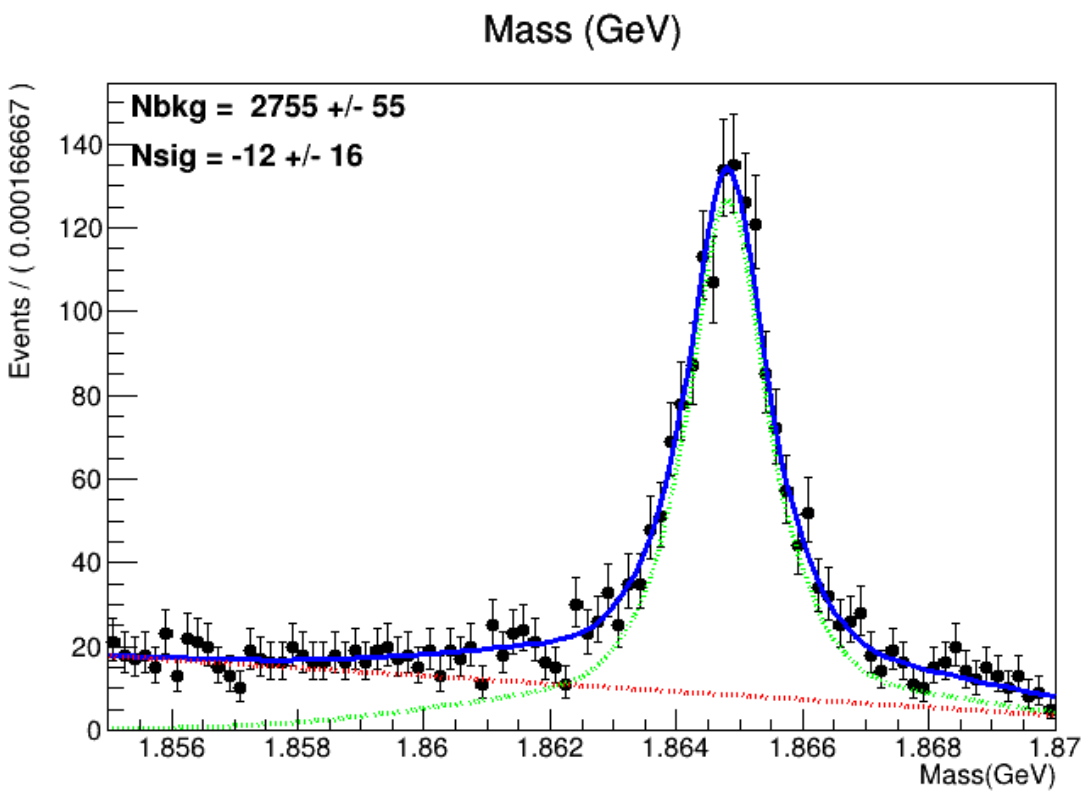


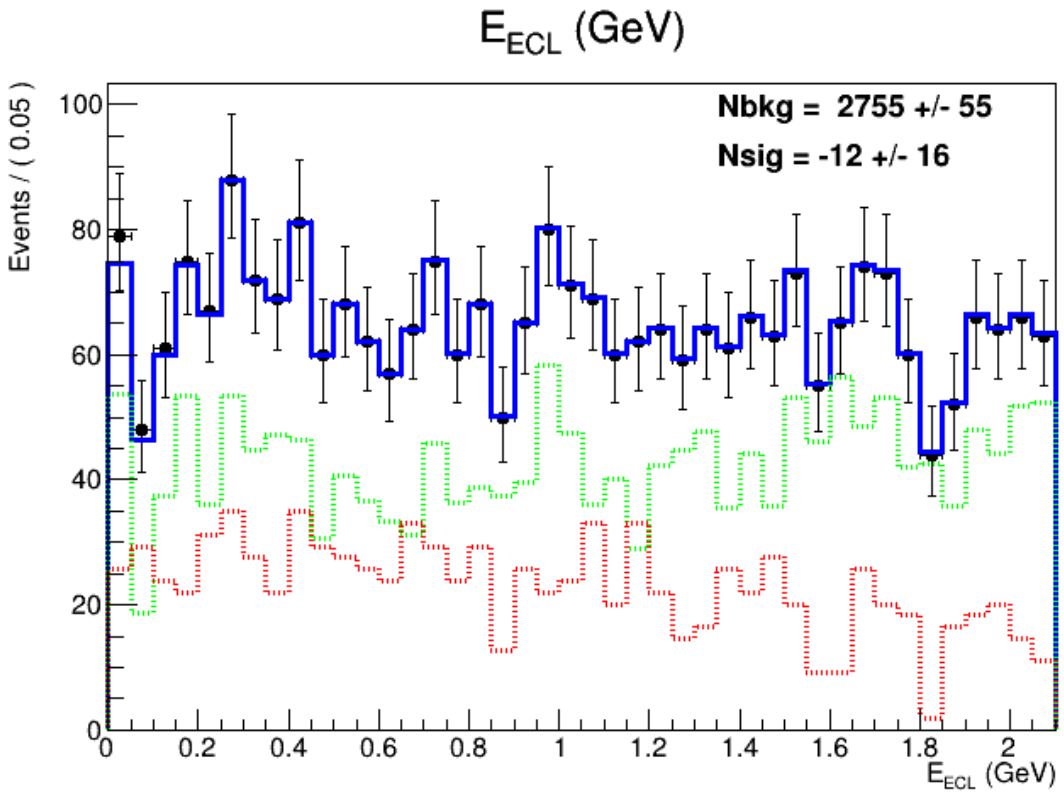


- $Br(D^0 \to K^-\pi^+) = \frac{N^{exclusive}}{N^{inclusive}{}_{*\epsilon_{sig}}} = \frac{8783 \pm 96}{(738977 \pm 1260)*(0.30363 \pm 0.00397)} = 0.039144 \pm 0.00067$
  - Far from decfile BR value(0.0395) ~ 0.5σ
- The # of true signal event identified by TopoAna :

$$8791 \pm 94 \Rightarrow Br(D^0 \to K^-\pi^+) = 0.039180 \pm 0.00067$$

2D fit on generic MC for $D^0 \rightarrow$ invisibles (no signals)





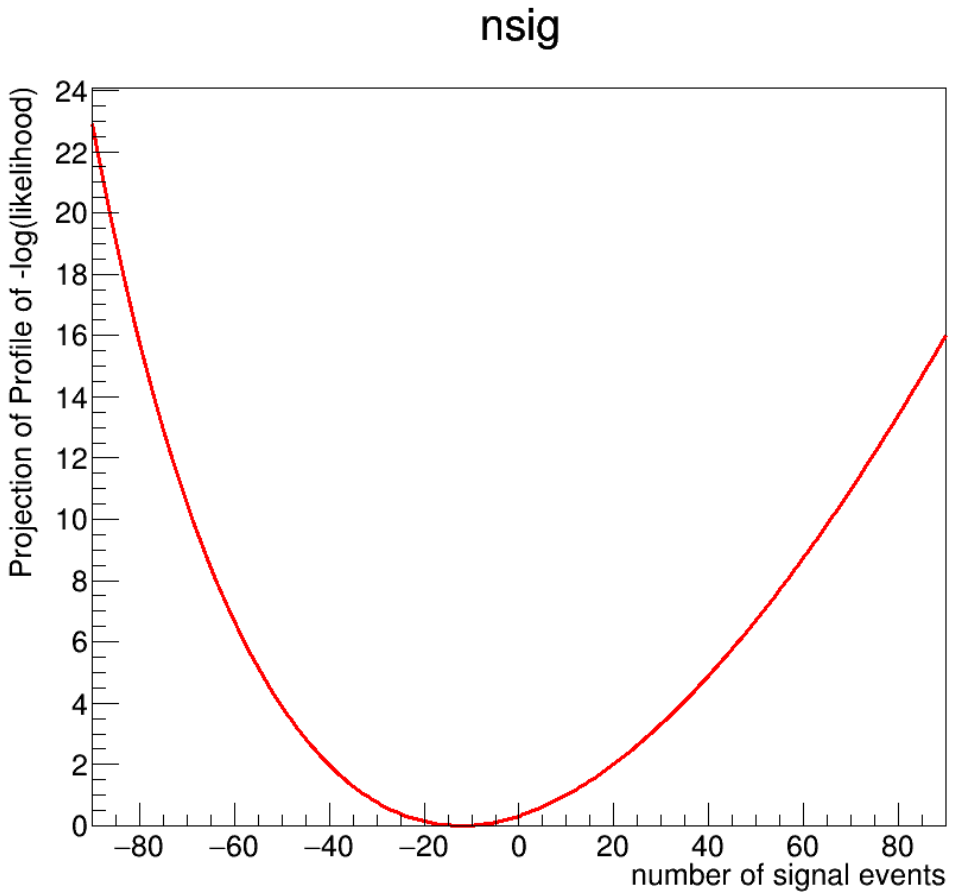
Upper limit estimation of $D^0 \rightarrow$ invisibles

- Way1) Upper Limit estimation by integration of likelihood function

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

$$N_{UL} = 13.9085$$

$$BR_{UL} = \frac{13.9085}{(738977 * 0.78165)} = 2.41 \times 10^{-5}$$

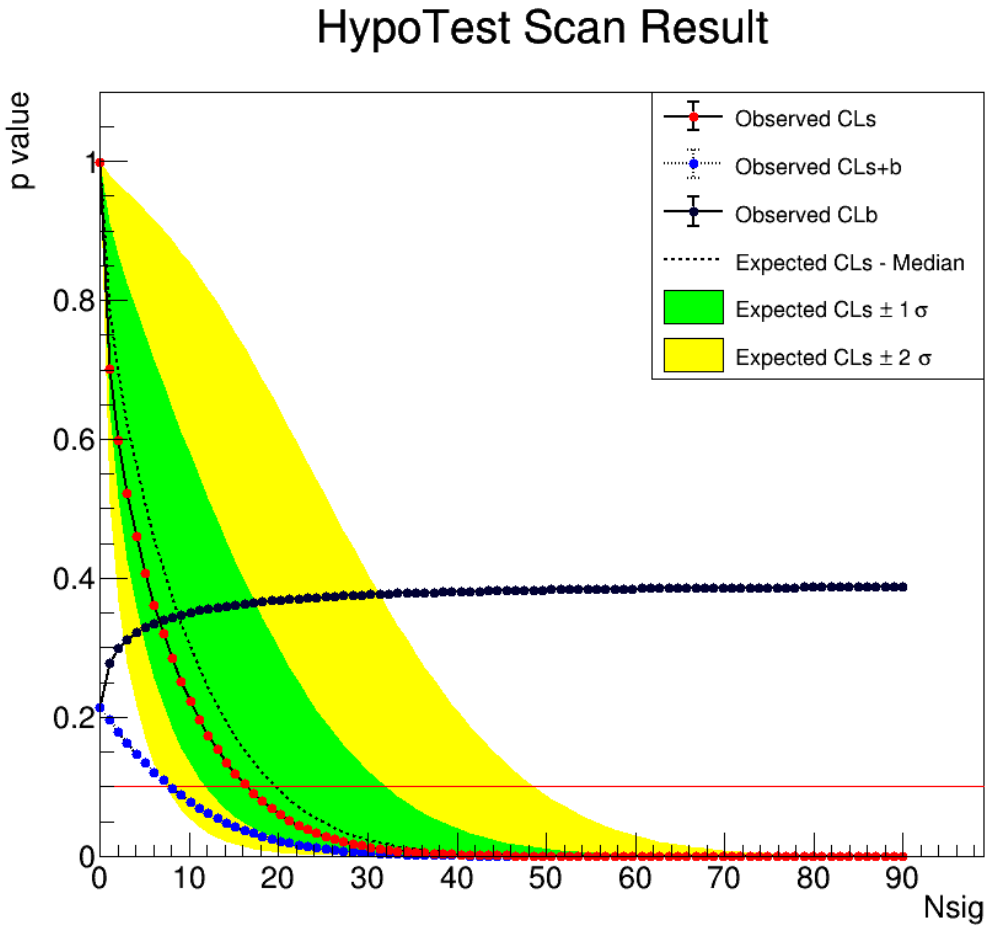


Upper limit estimation of $D^0 \rightarrow$ invisibles

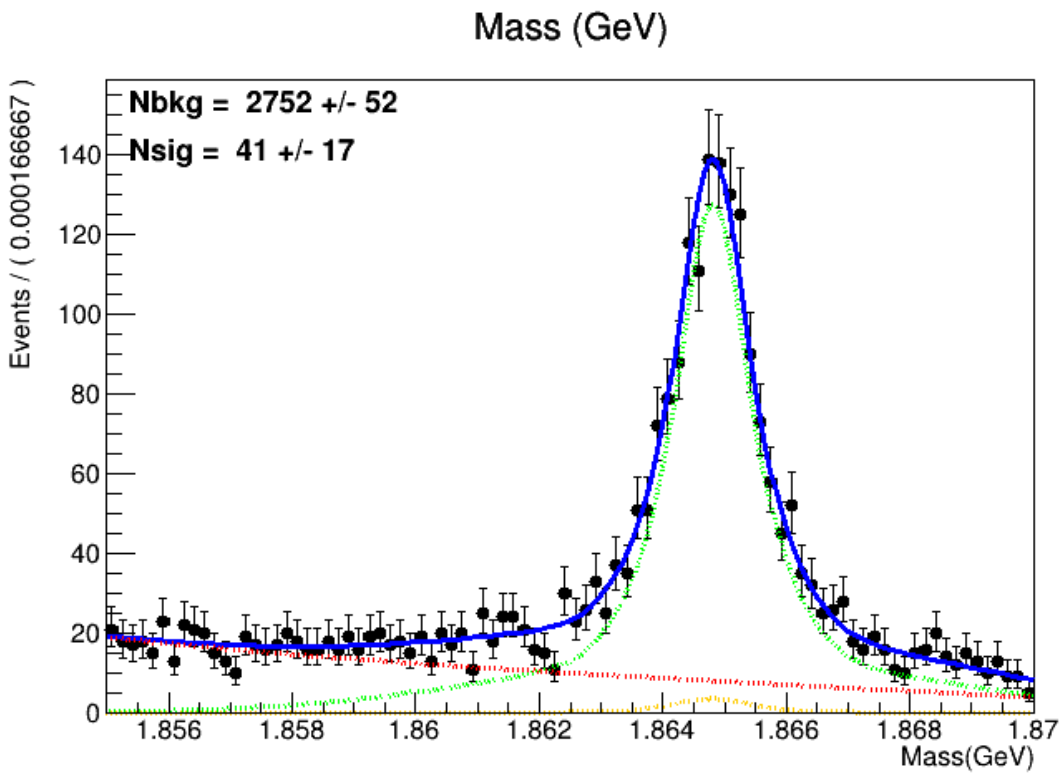
- Way2) Upper limit estimation by CLs method

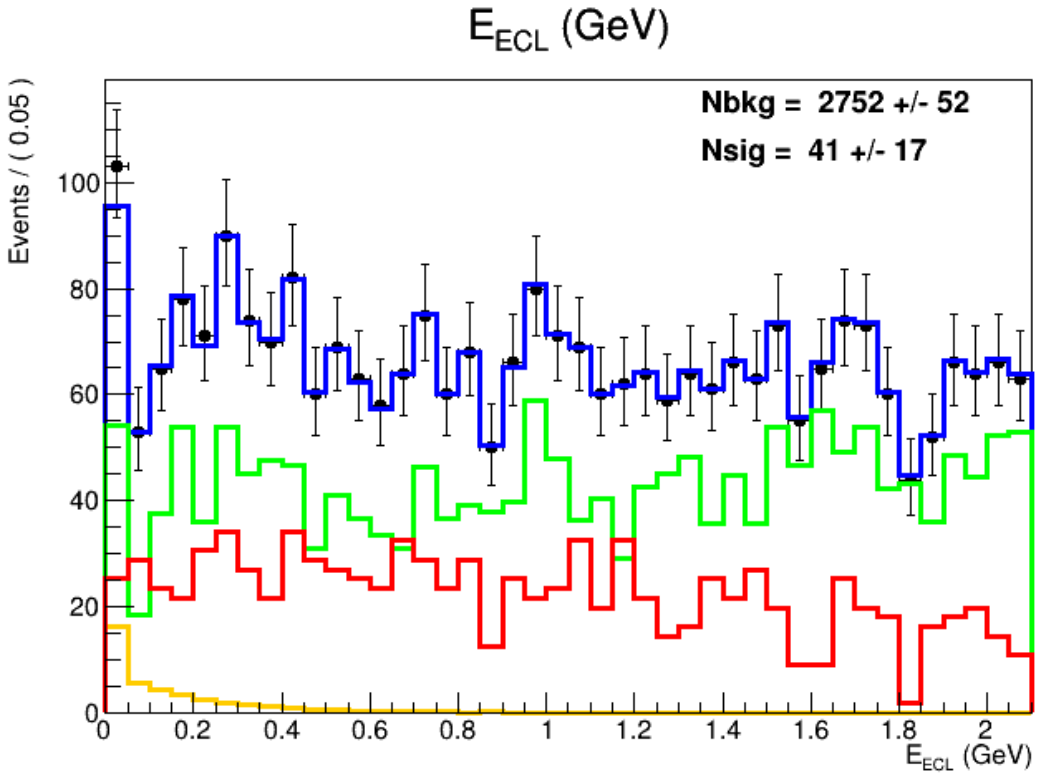
$$N_{UL} = 16.4465$$

$$BR_{UL} = \frac{16.4465}{(738977 * 0.78165)} = 2.85 \times 10^{-5}$$

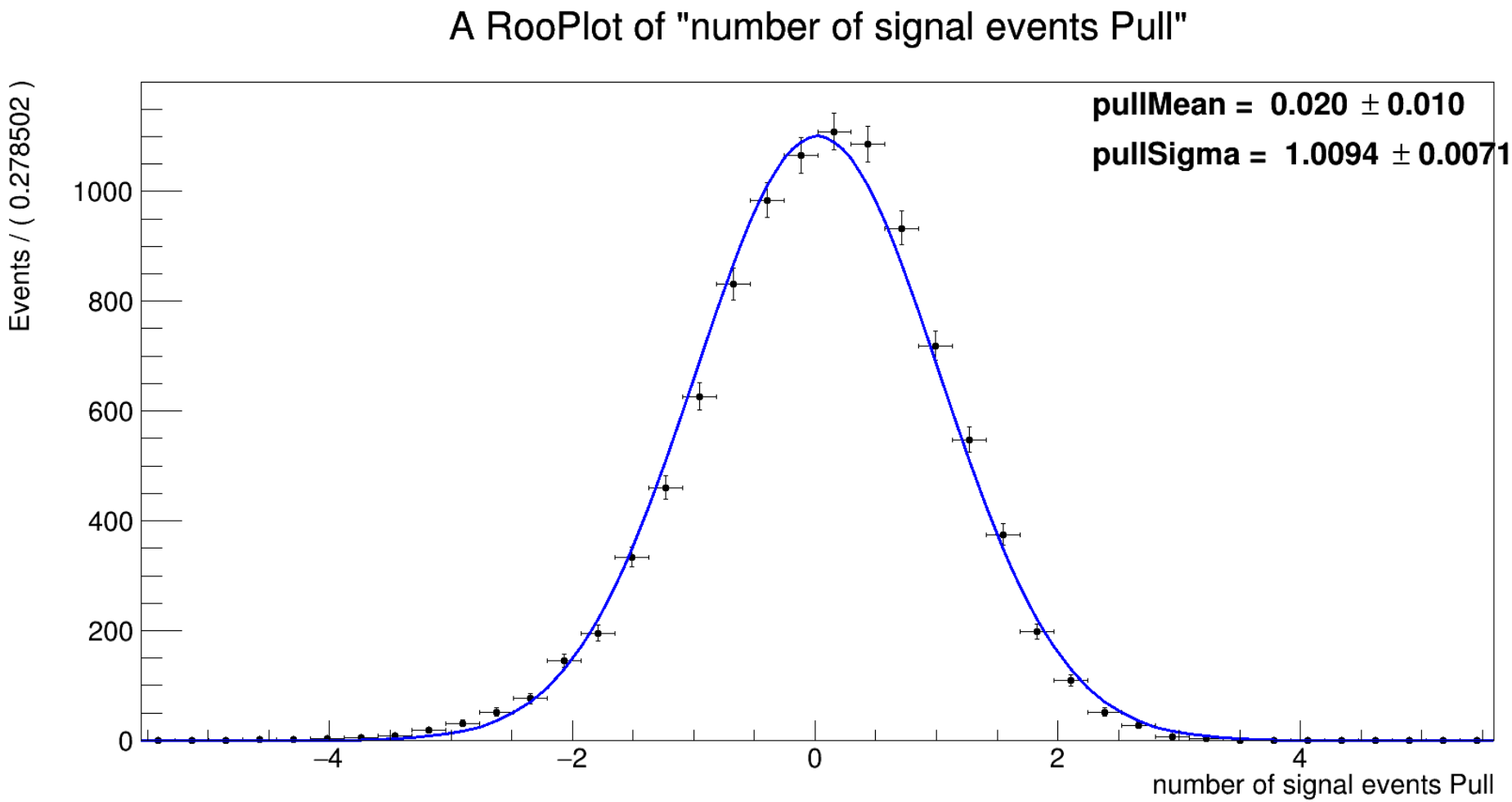


2D fit on generic MC for $D^0 \rightarrow$ invisibles (with signal embedding #($D^0 \rightarrow$invisibles) = 50)

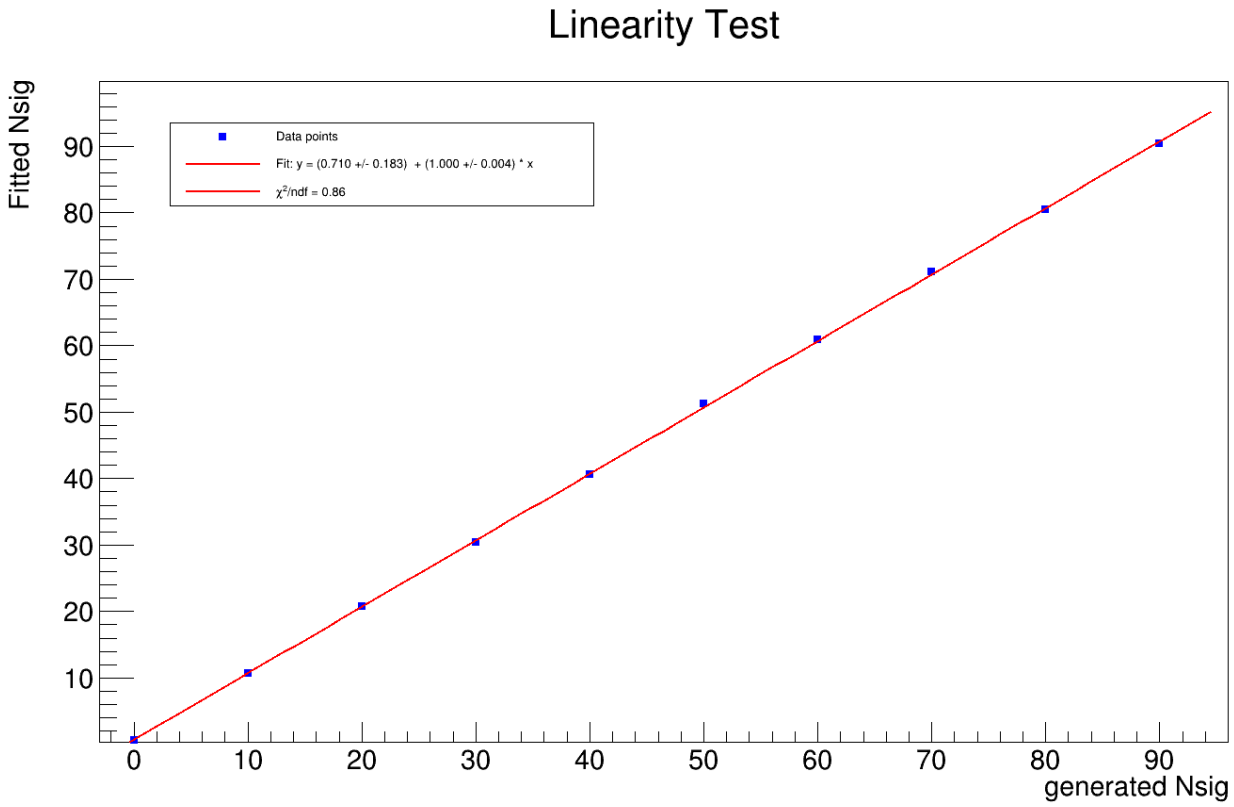


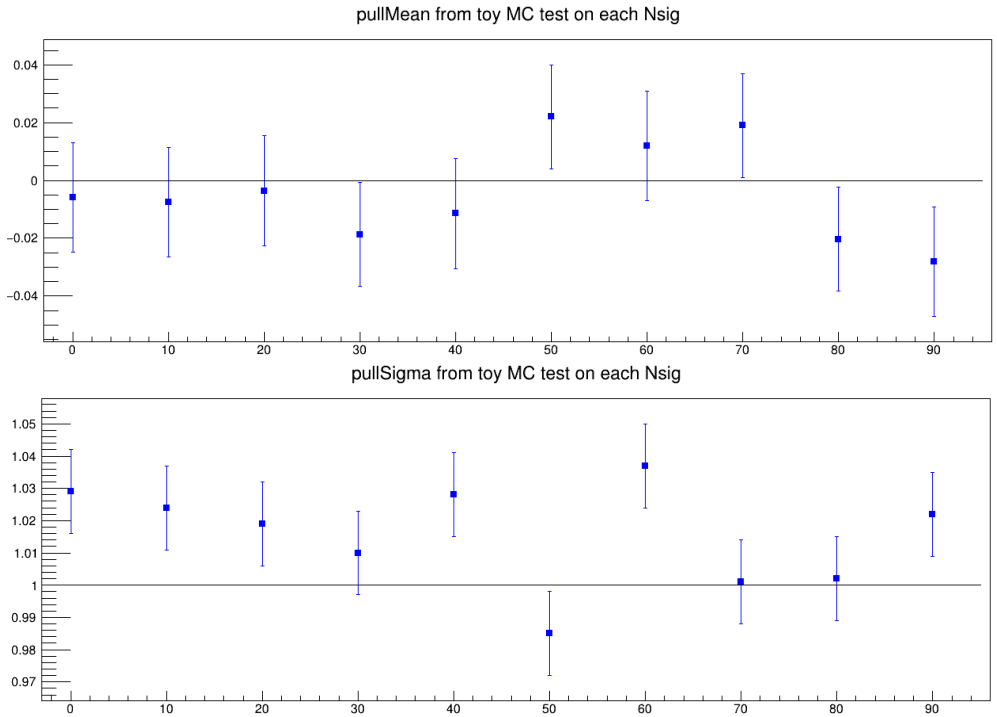


ToyMC test of 2D fit about exclusive $D^0 \rightarrow$ invisible

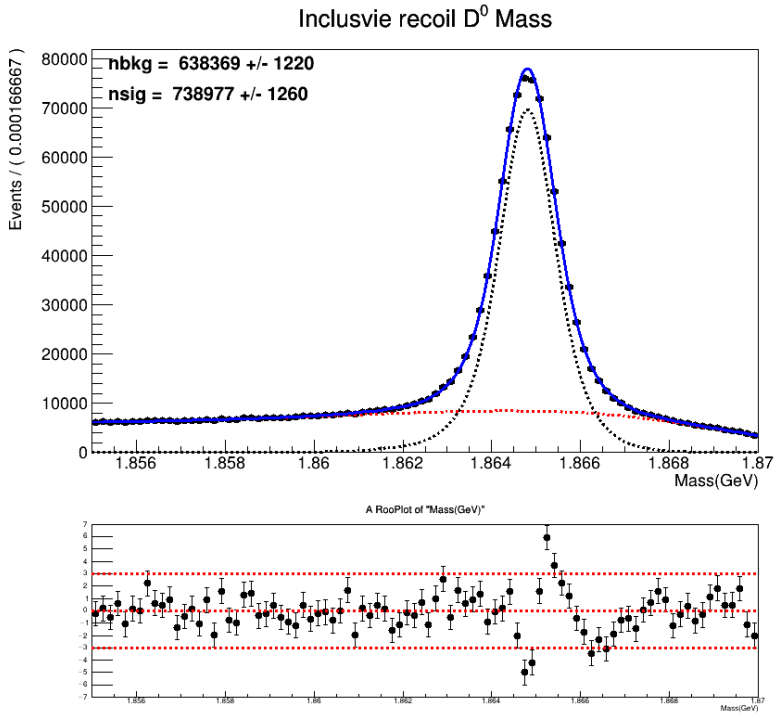


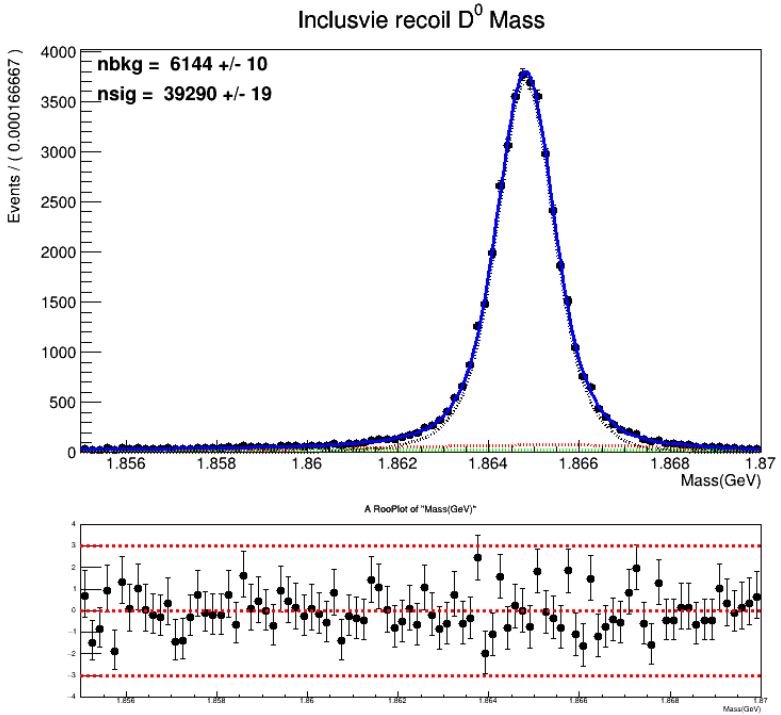
Linearity test of 2D fit about exclusive $D^0 \rightarrow$ invisible

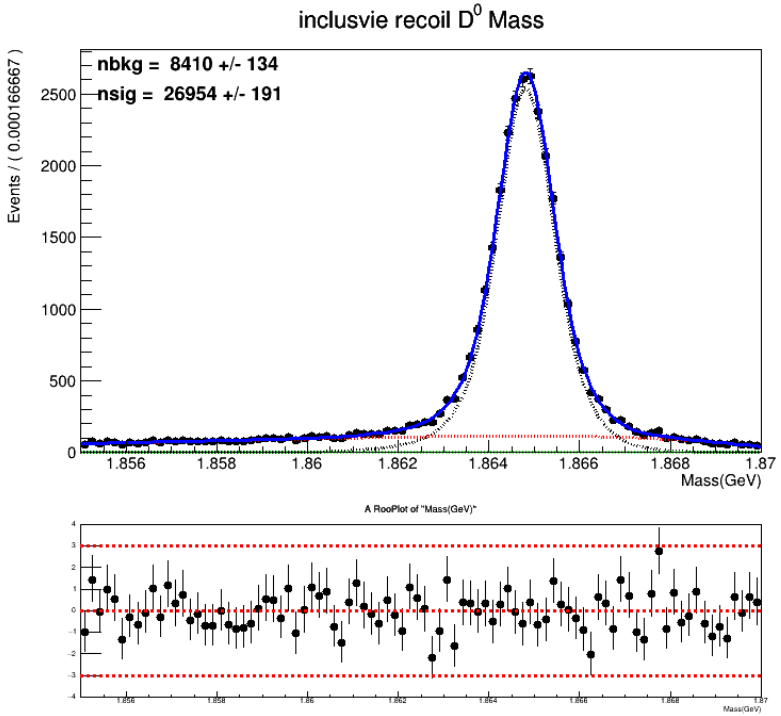




Check fit result with pull distribution for inclusive D

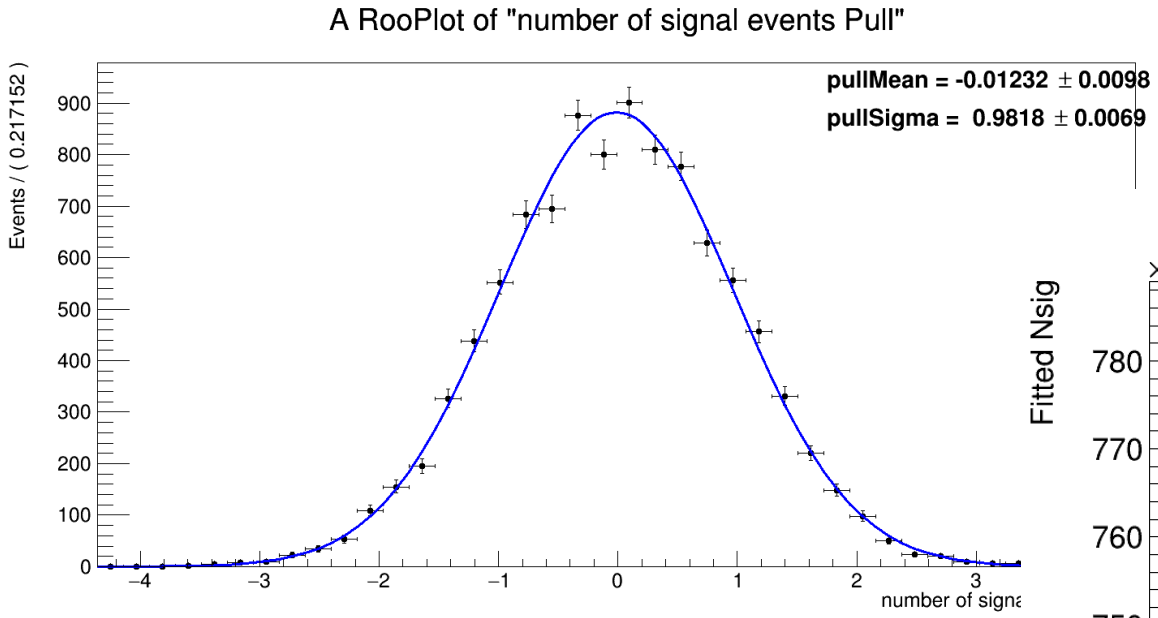


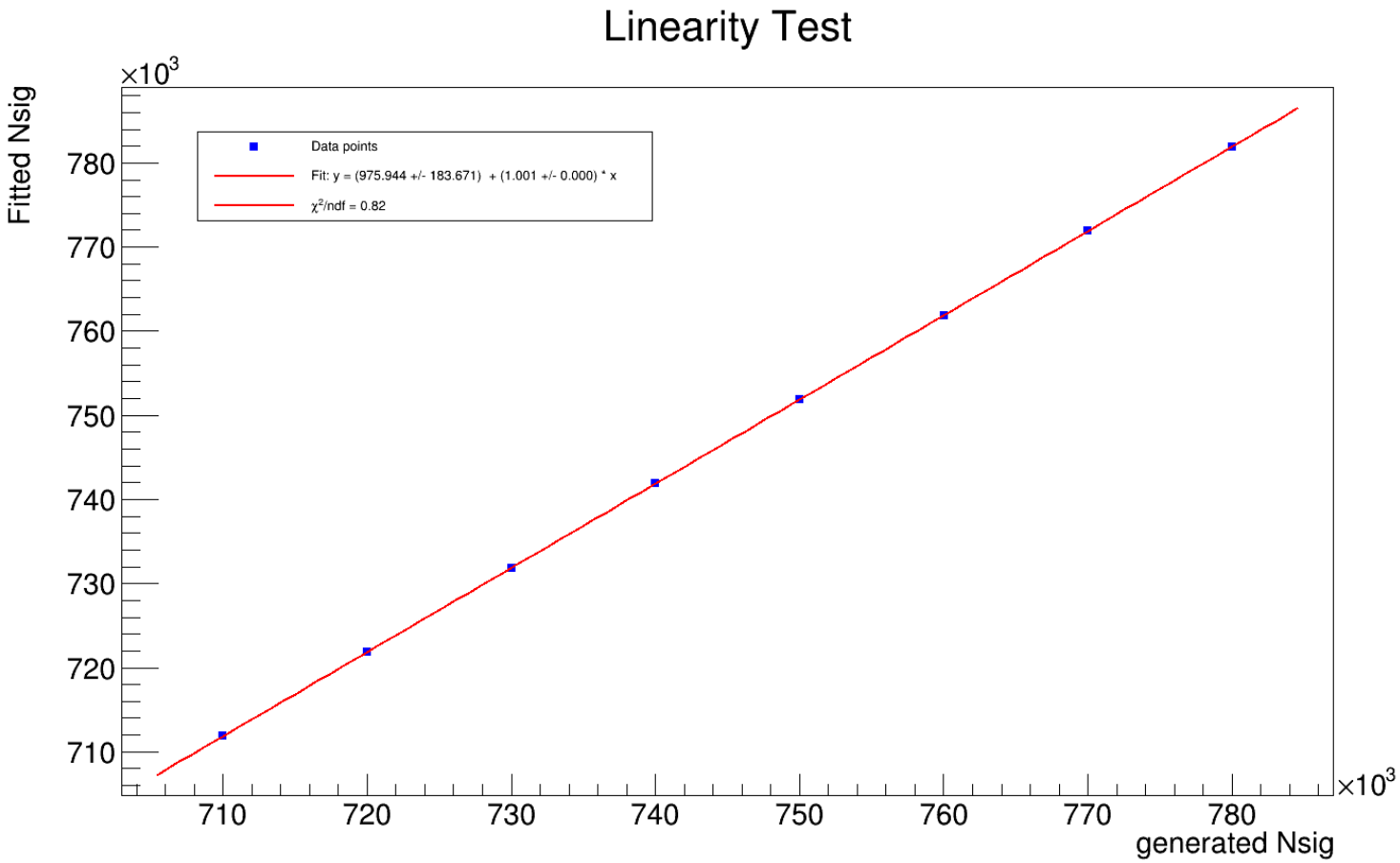




Left : generic MC, middle : signal MC, right : control sample

Inclusive D fit result check with ToyMC on generic MC





Next plan

- Study systematic uncertainty
  - Naively thinking, the 1st priority of systematics is systematic uncertainty from charm tagger
    ⇒ so, I would like to ask whether it is okay to see data for getting systematics

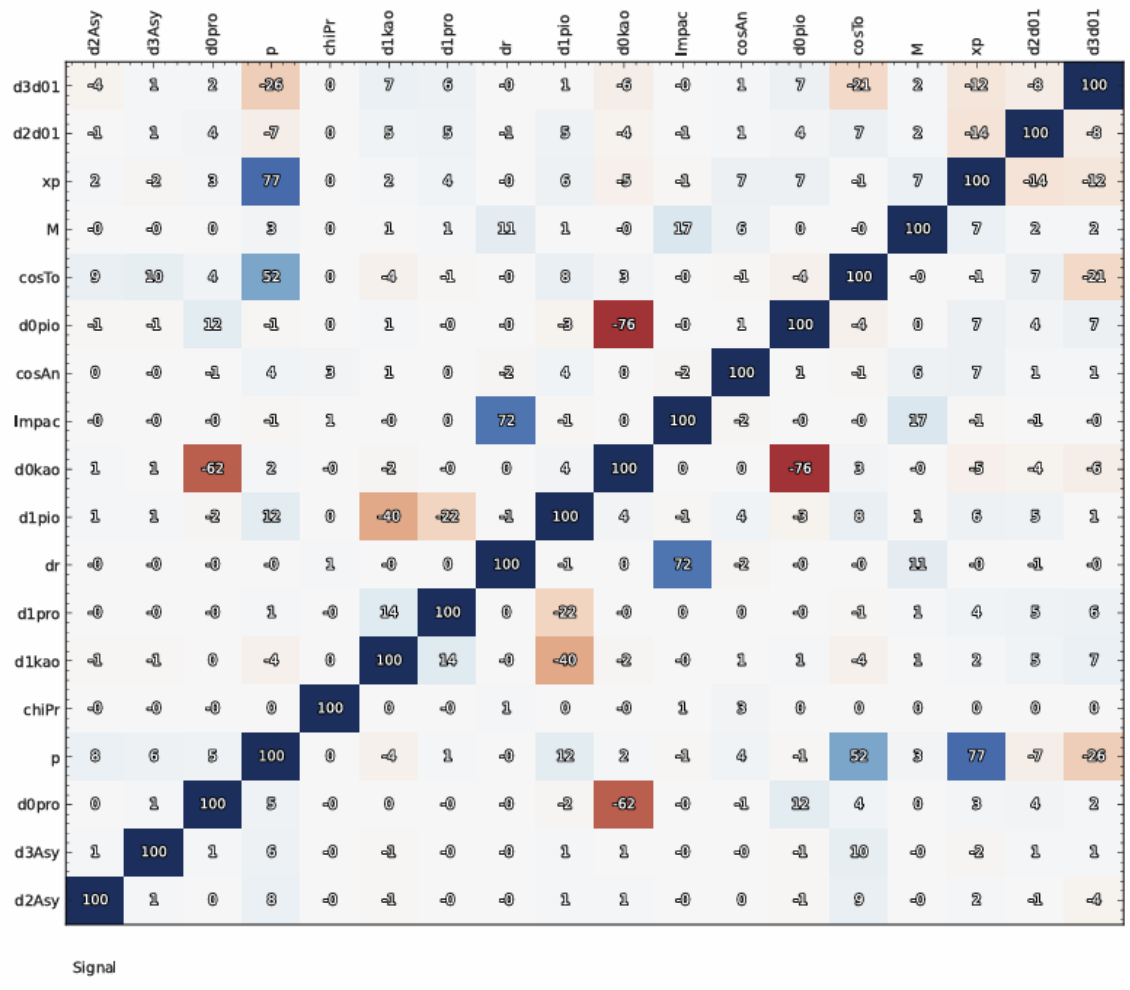
Decay	BF [%]
$D^0 \to K^-\pi^+$	3.948 %
$D^0 \to K^-\pi^+\pi^0$	14.4 %
$D^0 \to K^0_S\pi^+\pi^-$	2.80 %
$D^0 \to K^-\pi^+\pi^-\pi^+$	8.22 %
Total BF	29.368 %

Table: Decay channels to get systematic uncertainty about charm tagger

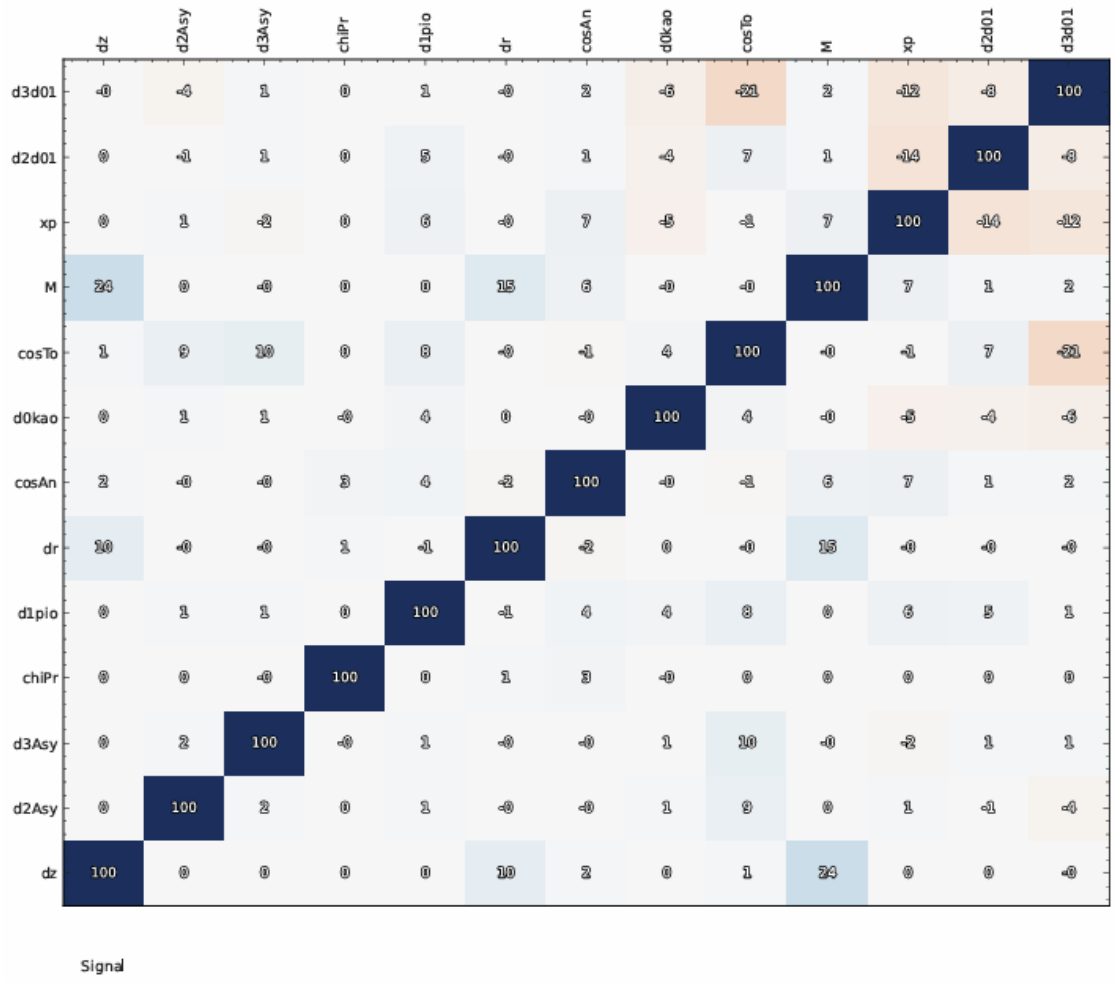
- Rough procedure:
  - Measure BF of each decays on Data(run-dependent) and MC
  - Check the Data/MC difference on measured BF of each decays
- May study semi-leptonic mode such as K l nu in future

  - Systematics from fit strategy, model and gamma selection and tracking efficiency and K^0_S, K^0_L and Λ^0 selection efficiency in exclusive veto conditions

Backup : check on correlation between previous BDT variables



Backup: Check on correlation between BDT variables

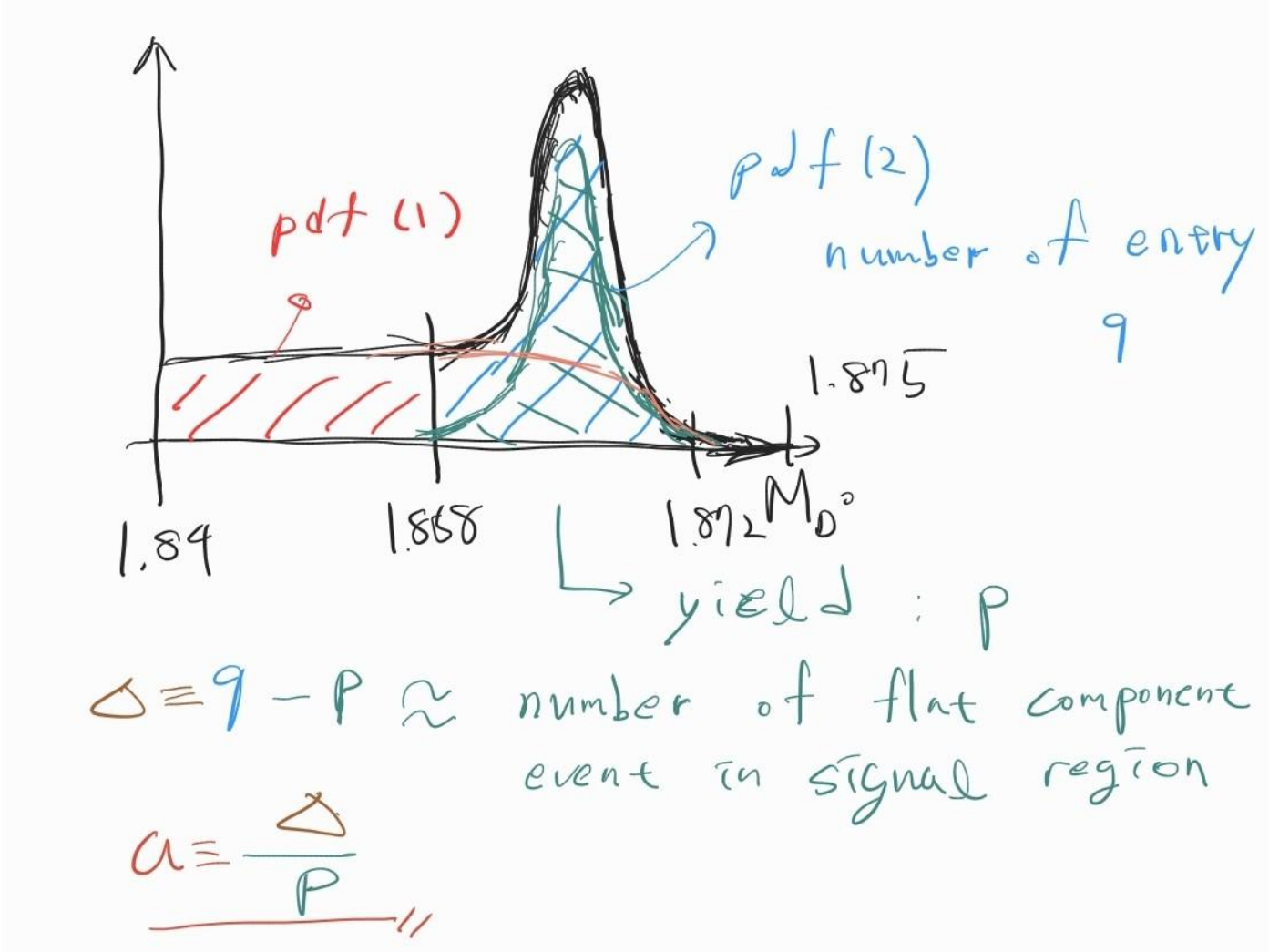


Backup : details of fit procedure

- 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

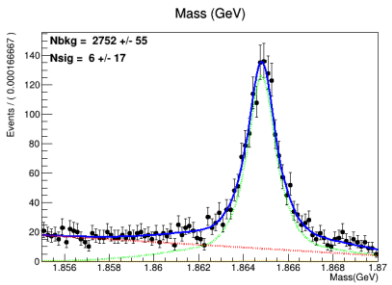
Backup : variable a

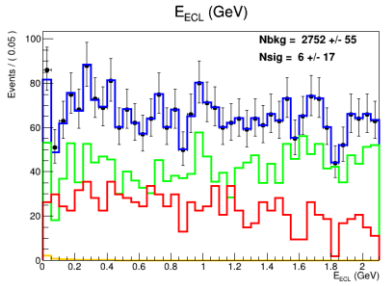
- The value of a can be roughly estimated
- a is floating number with small range around the estimated value



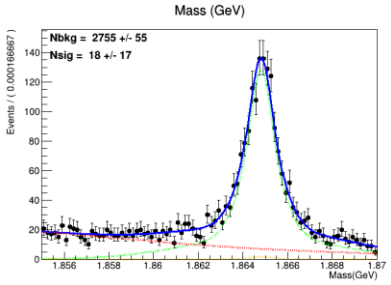
Backup : signal embedded fit result (15,30,69,75,150)

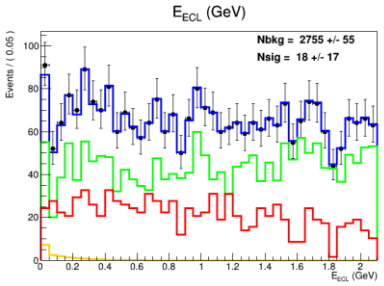
sig : 15



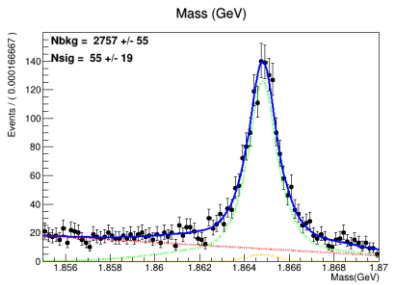


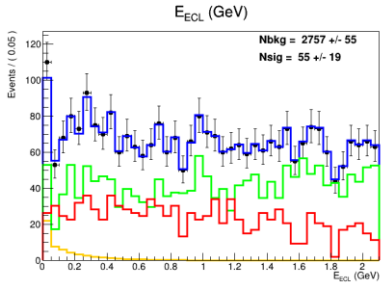
sig : 30



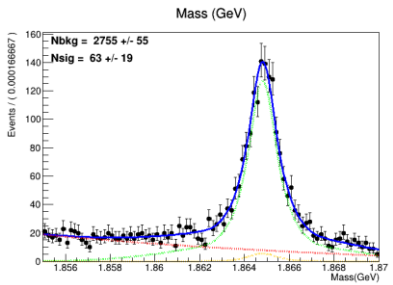


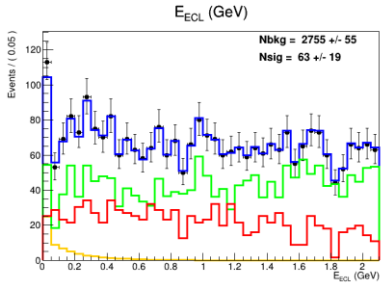
sig : 69



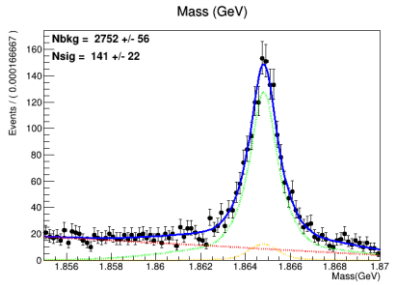


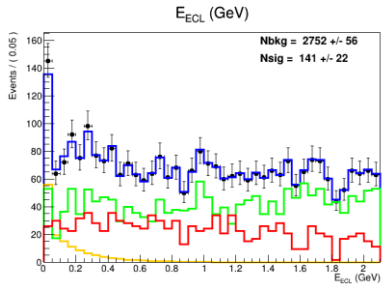
sig : 75



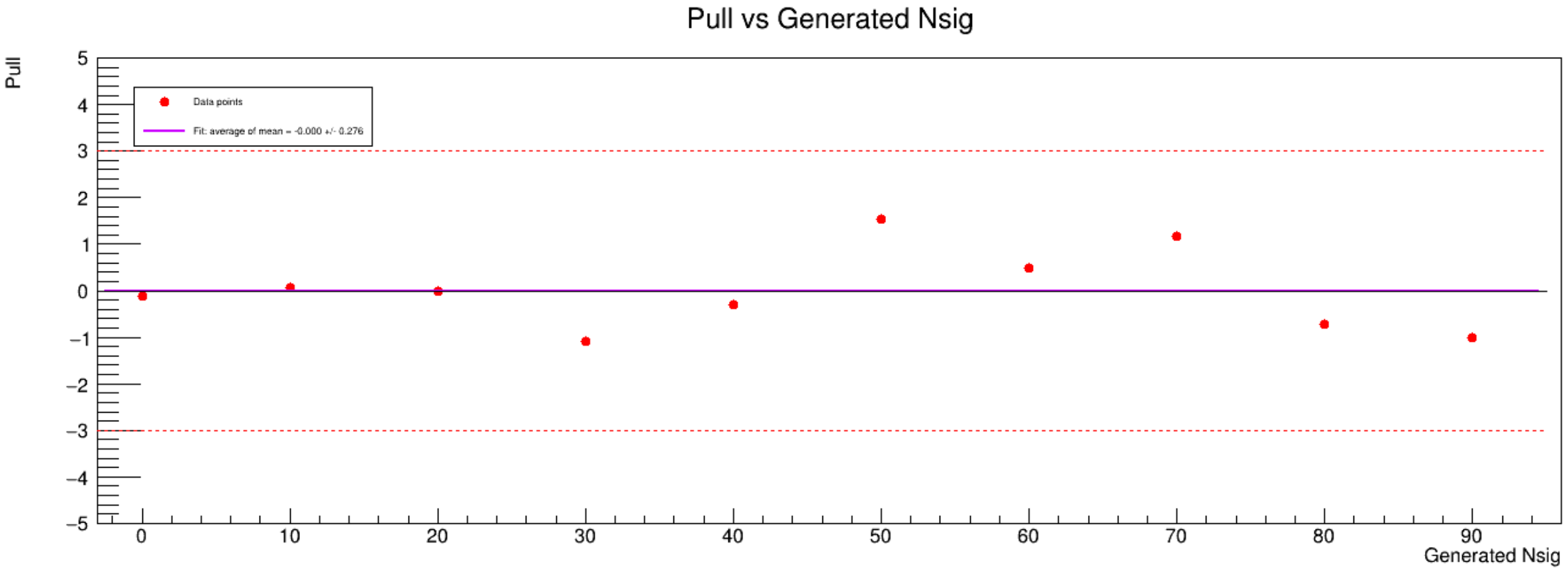


sig : 150





Backup: checking linearity test result about exclusive D fit with $Z(=\frac{N_{fitted}-N_{expected}}{\sigma})$



Backup: checking linearity test result about inclusive D fit with $Z(=\frac{N_{fitted}-N_{expected}}{\sigma})$