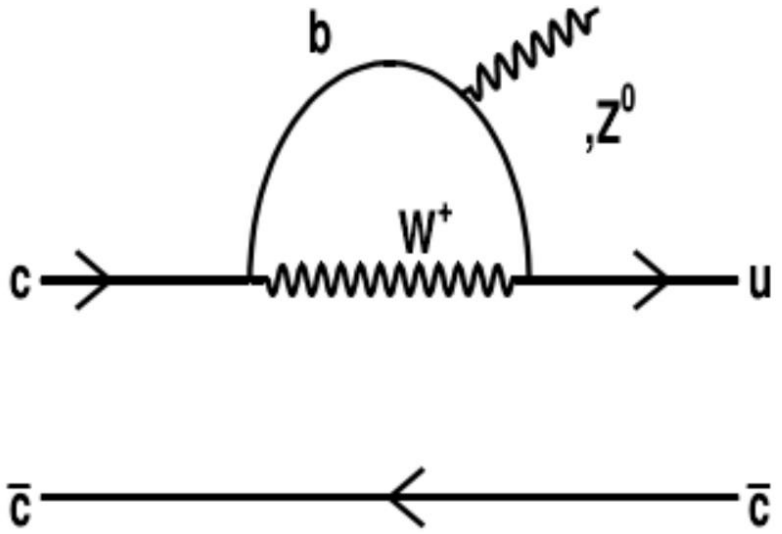
$$\textit{search for } J/\psi \rightarrow D^0 e^+ e^- \text{ +c.c}$$

Motivation

- In the SM, the branching fraction of FCNC process is expected to be very small and predicted to be about $10^{-10}\sim10^{-13}$.
- However, many new physic models predict that the branching fraction can be enhanced by 2 or 3 orders.
- Search for the FCNC process in the experiment provides an opportunity to study non-perturbative QCD effects and underlying dynamics.
- $J/\psi \to D^0 ee$ is an interesting process to study the FCNC process.



Data Sets

Boss version: 7.0.5

Data: $0.225 \times 10^9, 1.3 \times 10^9, 4.6 \times 10^9, 4.6 \times 10^9 J/\psi$ data collected in 2009, 2012, 2018 and 2019 respectively.

Inclusive MC: 224M, 1087M, 4600M and 4100M official inclusive samples generated in 2009, 2012, 2018 and 2019 Respectively.

Signal MC: 10^5MC events generated by generators shown below.

Process	Generator
$J/\psi \to D^0 e^+ e^- (J/\psi \to \bar{D}^0 e^+ e^-)$	DIYjsiD0EEpole
$D^0 \to K^- \pi^+ (\bar{D}^0 \to K^+ \pi^-)$	PHSP
$D^0 \to K^- \pi^+ \pi^0 (\bar{D}^0 \to K^+ \pi^- \pi^0)$	PHSP
$D^0 \to K^- \pi^+ \pi^- \pi^+ (\bar{D}^0 \to K^+ \pi^- \pi^+ \pi^-)$	PHSP

General Event Selection

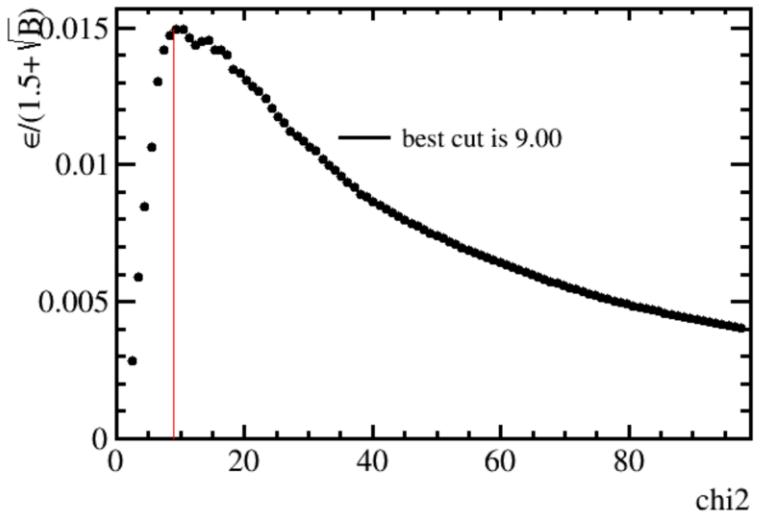
- Charged track
  - $|V_r| < 1\text{cm}\ |V_z| < 10\text{cm}, |cos\theta| < 0.93$
  - total charge is 0
- Good Gamma
  - $E_\gamma > 25\text{Mev}(EMC\ \text{Barrel})\ E_\gamma > 50\text{Mev}(\text{EMC Endcap})$
  - The angle between photon and the nearest charged tracks is required to be greater than 20°
  - $0 < TDC < 700ns$
- PID
  - For π: $Prob(\pi) > Prob(K), Prob(\pi) > Prob(e), Prob(\pi) > Prob(p)$
  - For K: $Prob(K) > Prob(\pi), Prob(K) > Prob(e), Prob(K) > Prob(p)$
  - For e: $Prob(e) > Prob(\pi), Prob(e) > Prob(K), Prob(e) > Prob(p)$

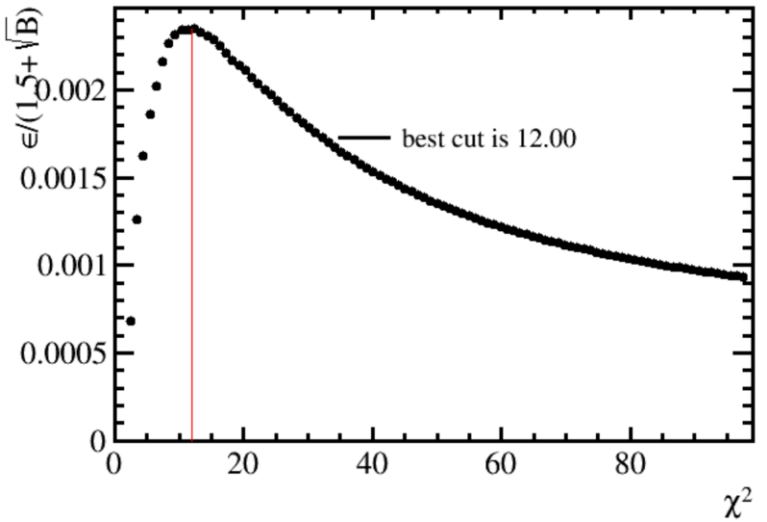
Event Selection

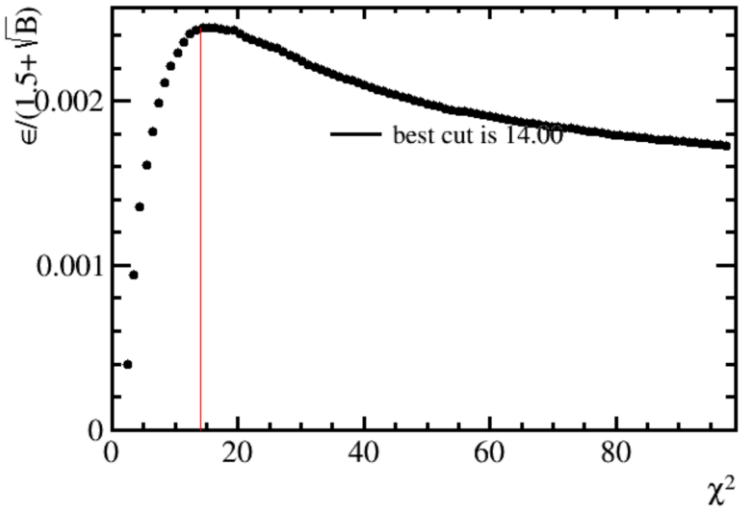
- $D^0 \to K^-\pi^+ mode:$
  - 4 charged tracks, K^-, π^+, e^- and e^+, are required and must come from the same vertex.
  - 4C fit is performed to select 4 charged tracks with hypothesis $J/\psi \to K^-\pi^+e^+e^-$, the corresponding χ^2 of the 4C fit is required to less than 60.
- $D^0 \to K^-\pi^+\pi^0$mode :
  - 4 charged tracks, K^-, π^+, e^-, e^+, and at least 2 photons are required. 4 charged tracks must come from the same vertex.
  - 5C fit is performed to select 4 charged tracks and 2 photons with hypothesis $J/\psi \to K^-\pi^+e^+e^-\gamma\gamma$ with addition constraining of the invariant mass of $\gamma\gamma$ to π^0. The corresponding χ^2 of the 5C fit is required to less than 60.
- $D^0 \to K^-\pi^+\pi^-\pi^+ mode:$
  - 6 charged tracks, K^-, π^+, π^-, π^+, e^- and e^+, are required and must come from the same vertex.
  - 4C fit is performed to select 4 charged tracks with hypothesis $J/\psi \to K^-\pi^+\pi^-\pi^+e^+e^-$, the corresponding χ^2 of the 4C fit is required to less than 60.

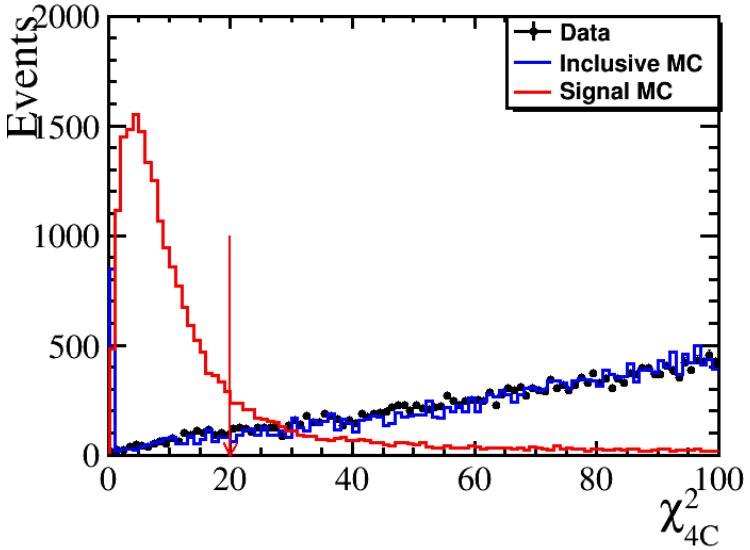
Event Selection

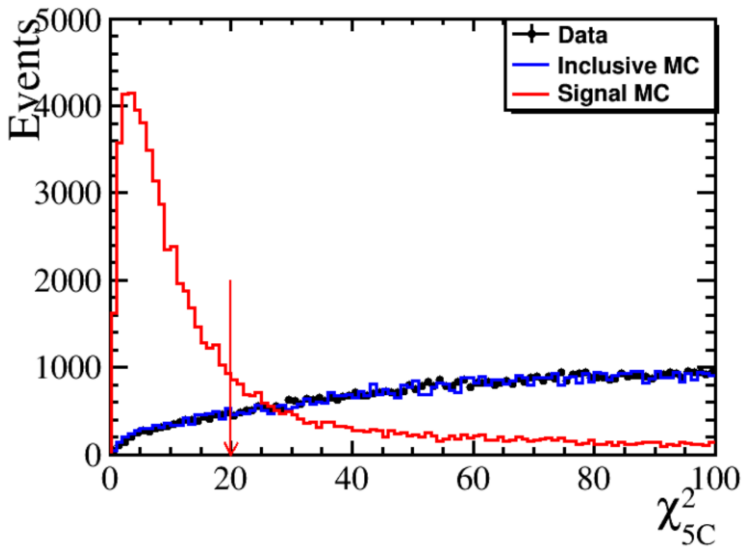
$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

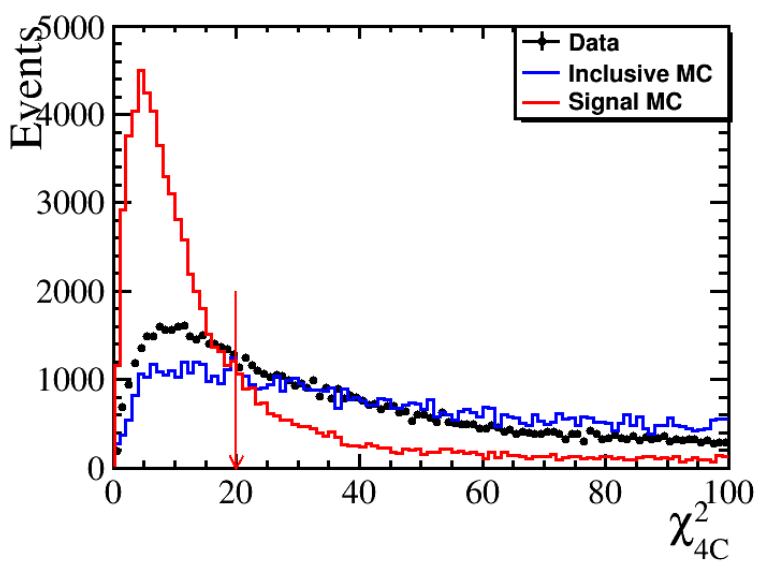








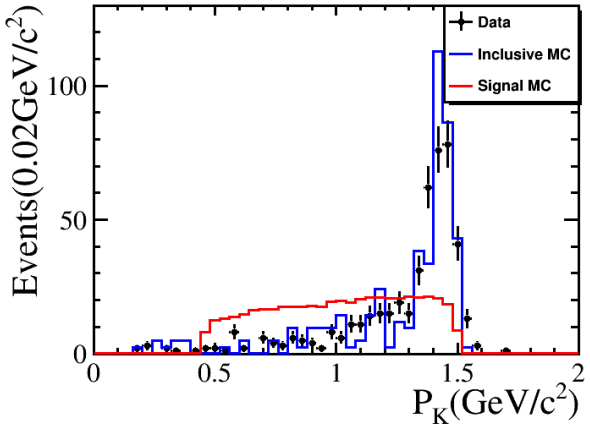


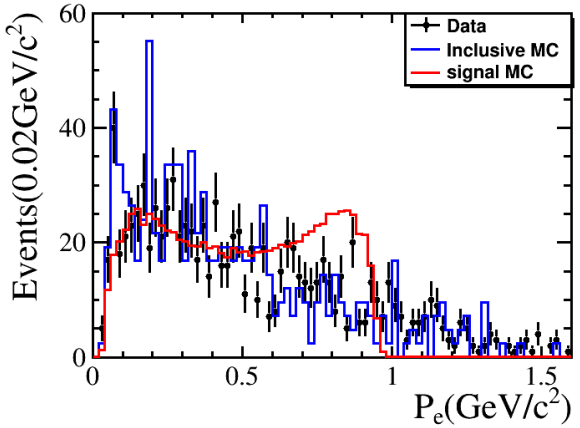


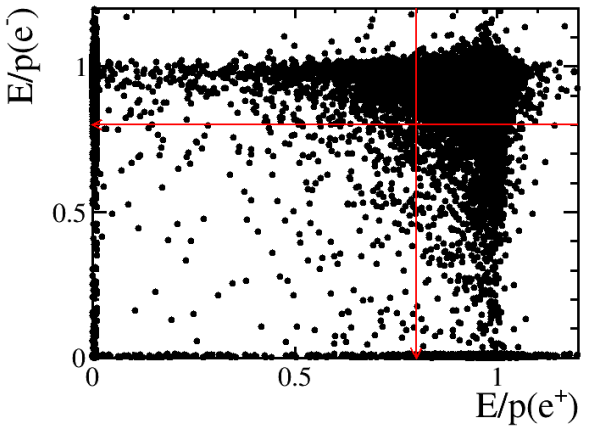
Backgrounds Analysis

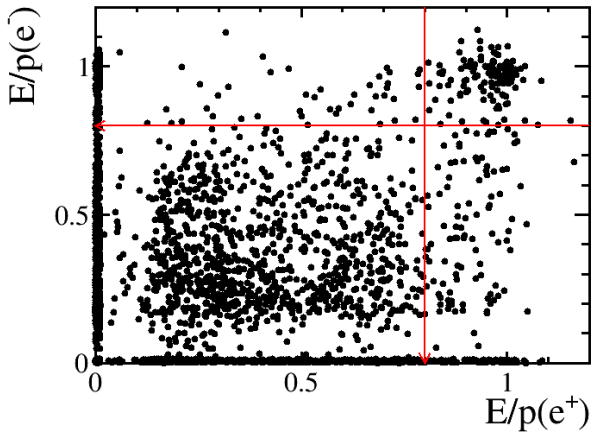
$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

- After all other selection addition.







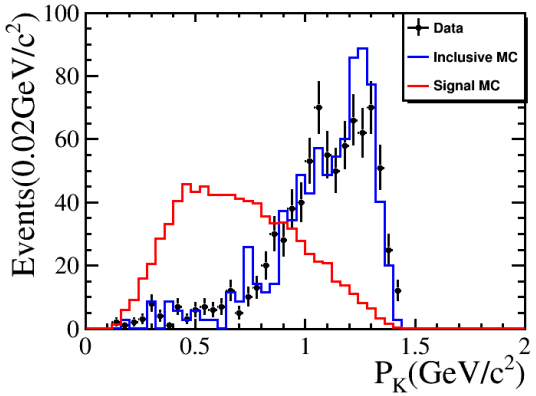


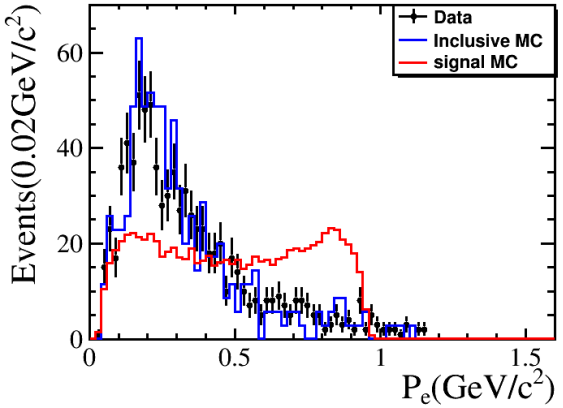
- Particle Misidentification
  - There are many events from e/π misidentification, due to the bad dE/dx resolution in this region, which is consistent with the topology analysis results.
  - K/π misidentification is the dominant background, since particles cannot be identified with dE/dx and TOF information in high momentum region.
  - To reject these events, cuts $\chi^2_{4C}(K^+\pi^-e^-e^+) < \chi^2_{4C}(\pi^+\pi^-e^-e^+)$, $\chi^2_{4C}(K^+\pi^-e^-e^+) < \chi^2_{4C}(\gamma\pi^+\pi^-e^-e^+)$ and $E/p > 0.8(e^+ \text{or} e^-)$ were applied correspondingly.

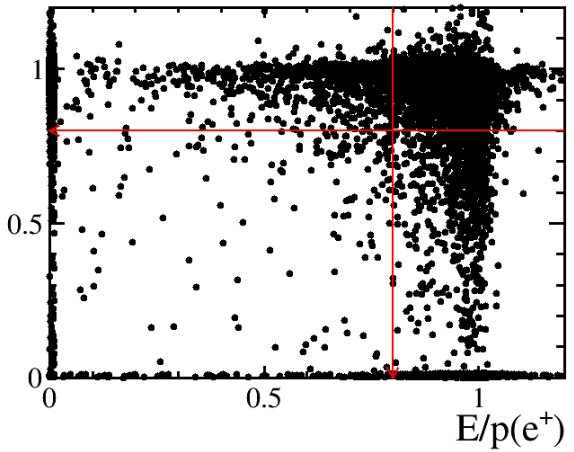
Backgrounds Analysis

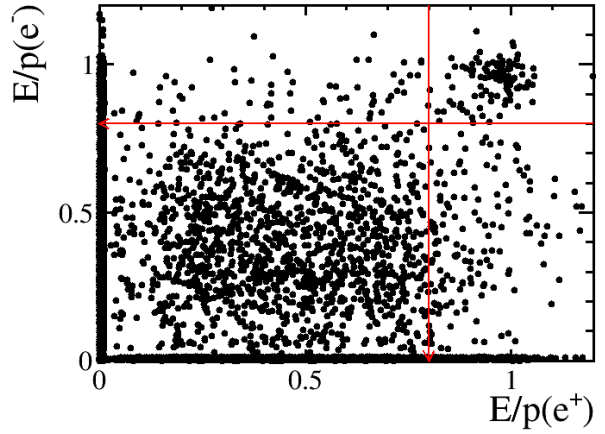
$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

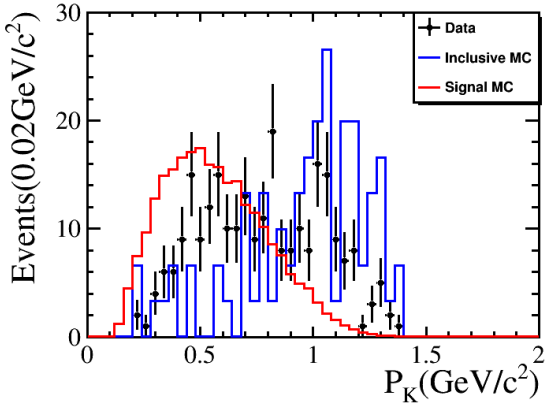
- After all other selection addition.

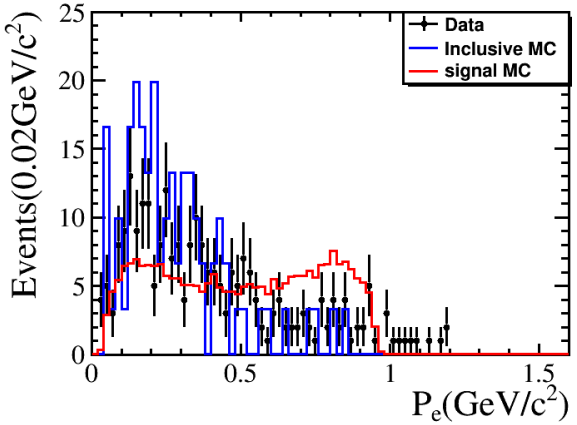


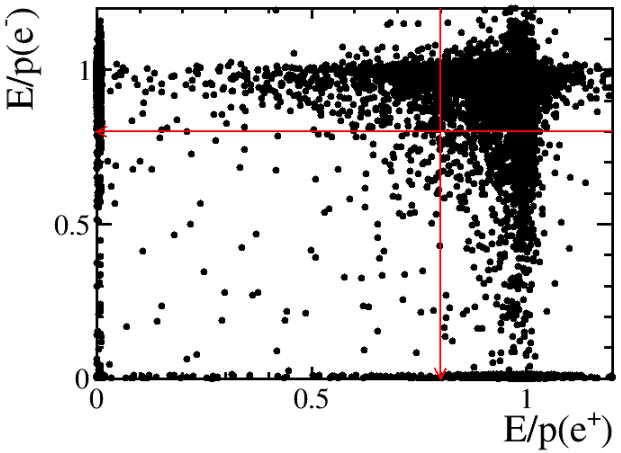


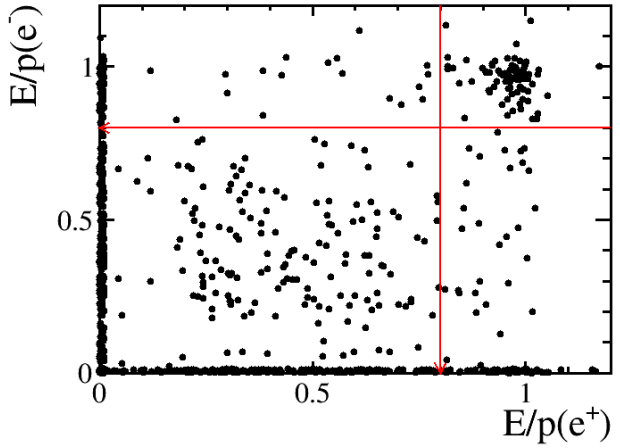






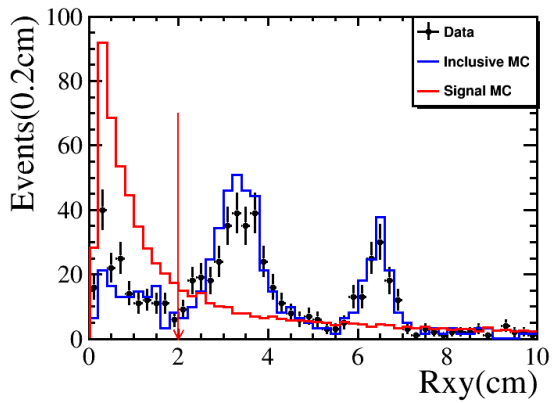


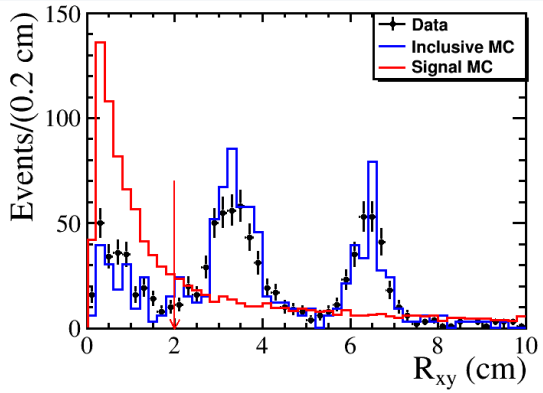


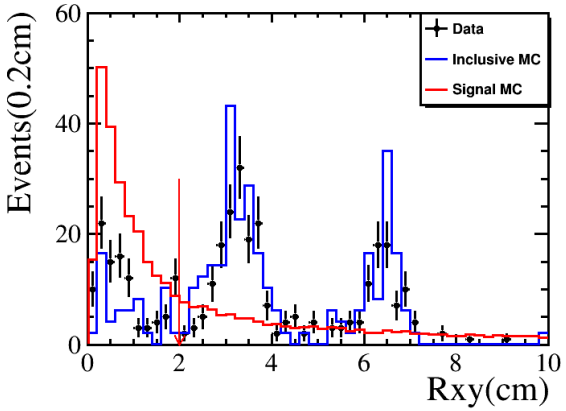


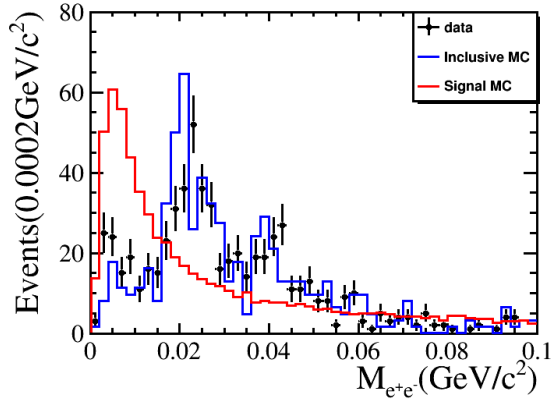
Backgrounds Analysis

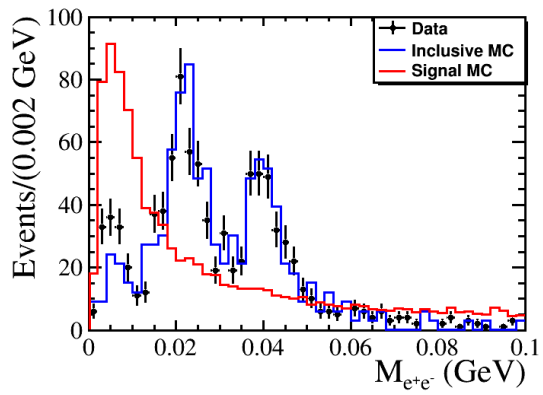
$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

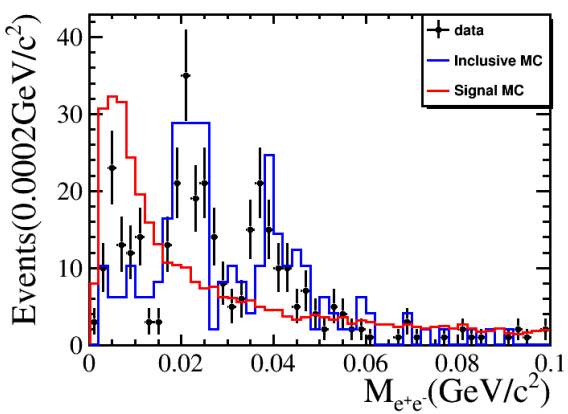








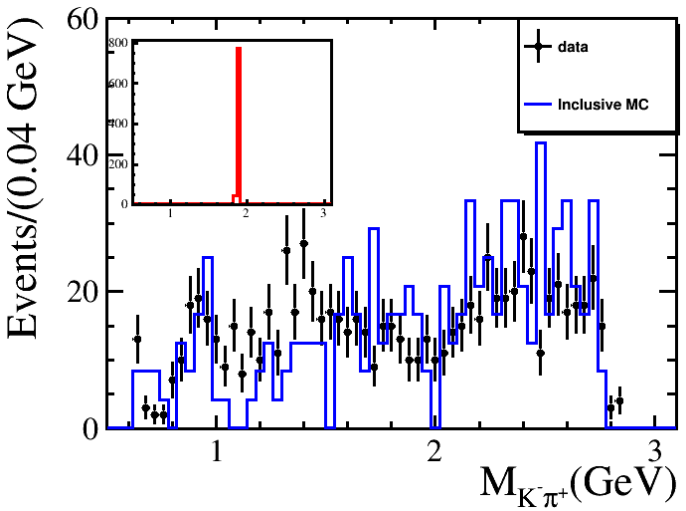


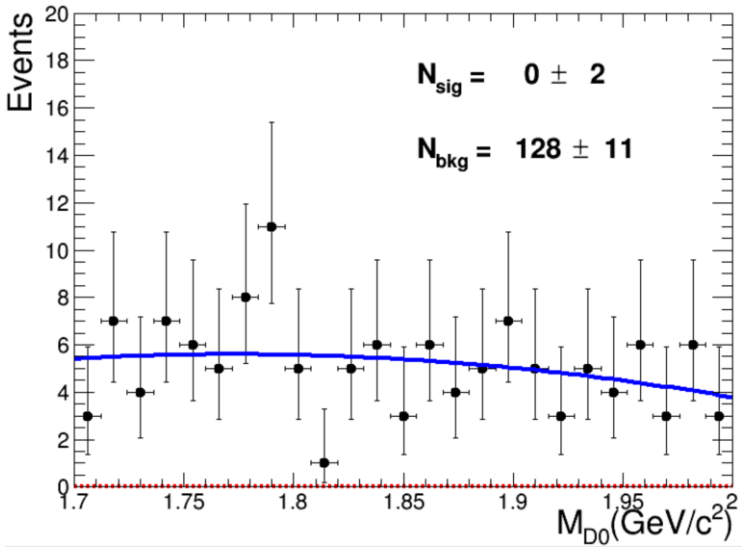


- Gamma Conversion
  - According to the distribution of R_{xy} and invariant mass of e^+e^-, gamma conversion events still survive in the backgrounds, which is consistent to the topology analysis results.
  - To reject these events, corresponding cuts $R_{xy} < 2, |L_{AB}| < 6\sigma$ and $cos\theta_{eg} < 0.99$were applied.

Fit to The Mass Spectrum

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$





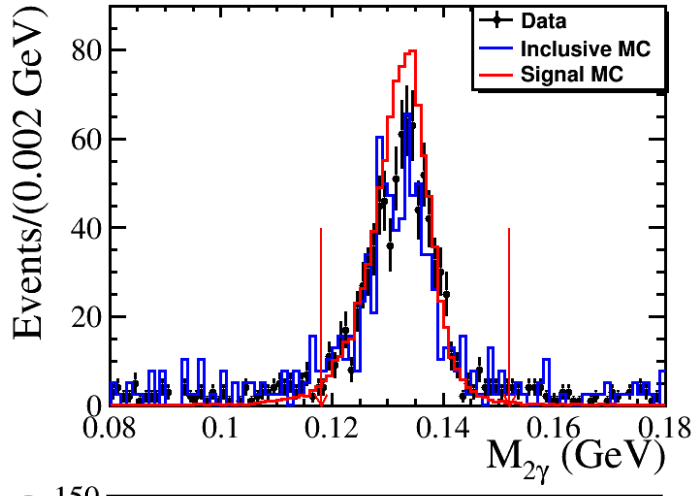
- Reconstruction D0 Mass
  - Invariant mass of kpi system was used to extract signal yields
  - Fit method: 1D binning maximum likelihood fit
  - Fit range: $1.7\ \mathrm{GeV}/c^2 < |E_\gamma| < 2.0\mathrm{GeV}/c^2$
  - Signal PDF: MC shape
  - BKG PDF: 2nd order Chebshev polynomial function

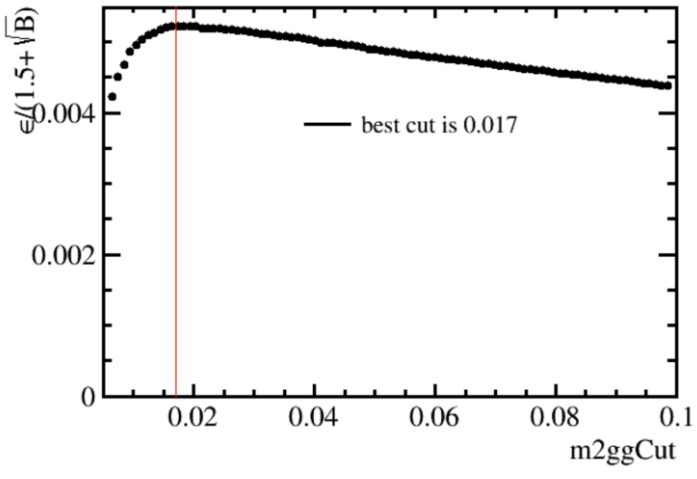
	$\bar{D}^0e^+e^-$		$D^0e^+e^-$	
	efficiency	Relative efficiency	efficiency	Reletive efficiency
Pass PID	44478		44963	
Pass 4C	33794	0.760	34173	0.760
χ^2_{4C}<20	25327	0.749	25725	0.753
$E/p(e^+)$>0.8 or $E/p(e^-)$>0.8	24745	0.977	25153	0.978
veto gamma conversion	23839	0.963	24250	0.964
χ^2cut	23838	0.999	24249	0.999

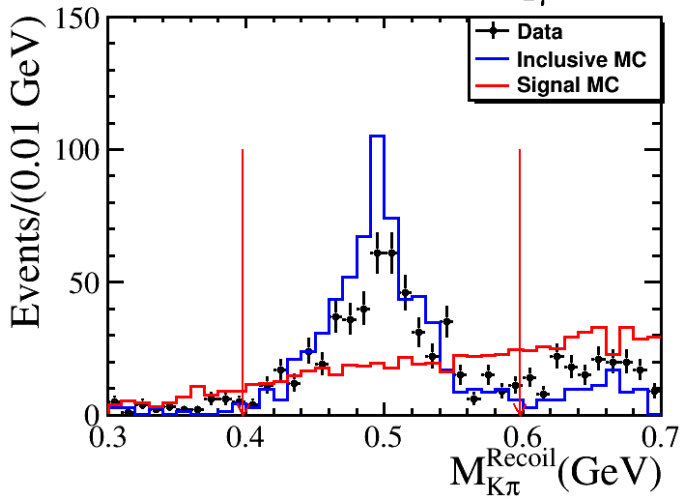
Backgrounds Analysis

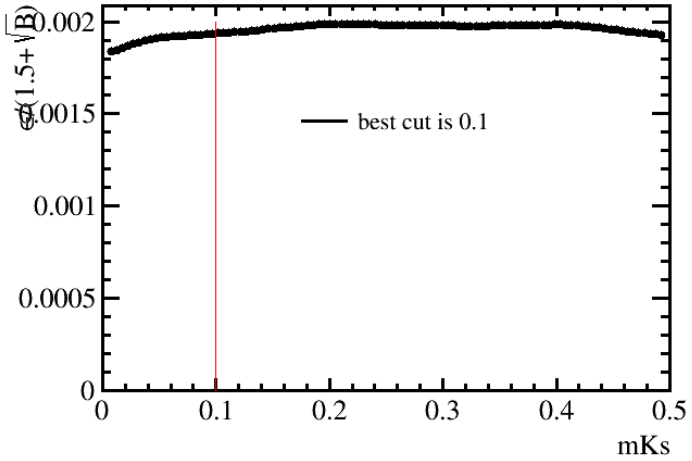
$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

- After all other selection addition.





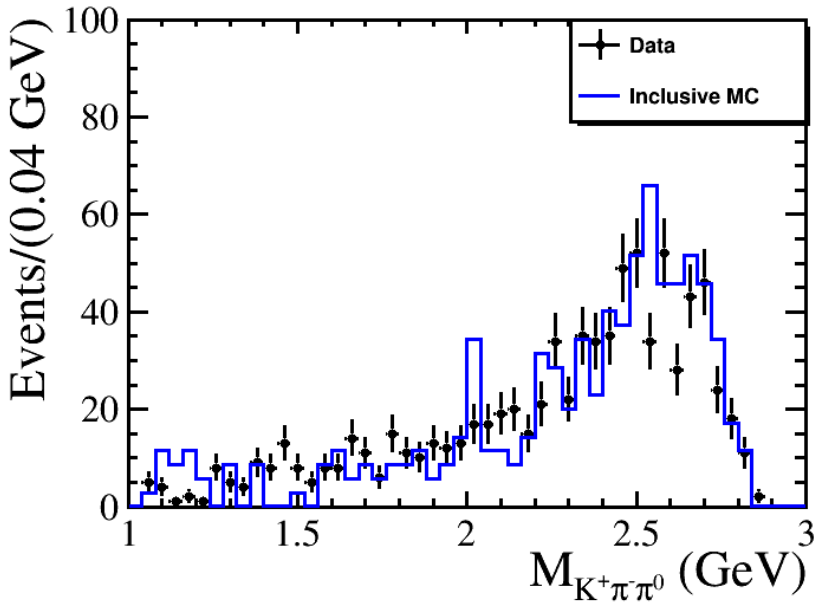


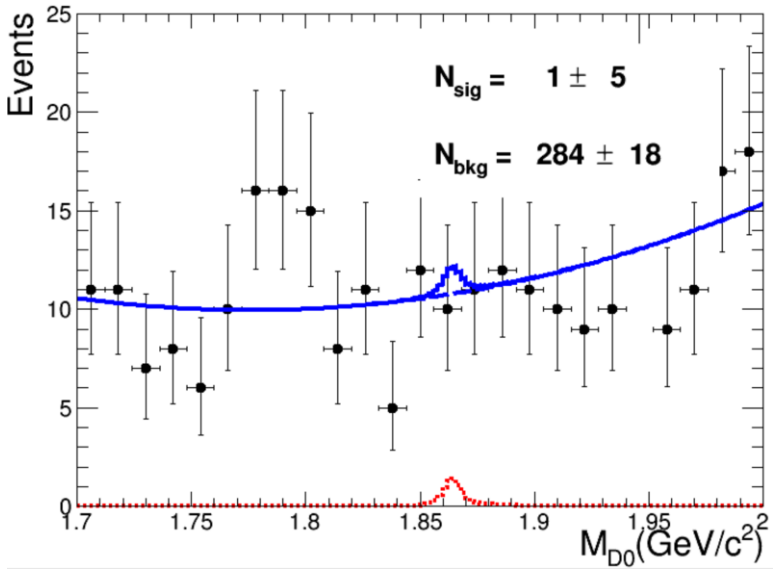


- π_0 selection
  - By using the Punzi Significance with the formula of $\epsilon/(1.5+\sqrt{B})$, we get the best cut region $|M_{\gamma\gamma}-0.135|<0.017\mathrm{GeV}/c^2$.
- Reject K_s events
  - The clear K_s signal is observed from the distribution of the recoil mass of the $K^{\mp}\pi^{\pm}$.
  - To the reject the K_s background, the mass window of K_s is required to be $0.1\ \mathrm{GeV}/c^2$, which is optimized by the Punzi Significance.

Fit to The Mass Spectrum

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$





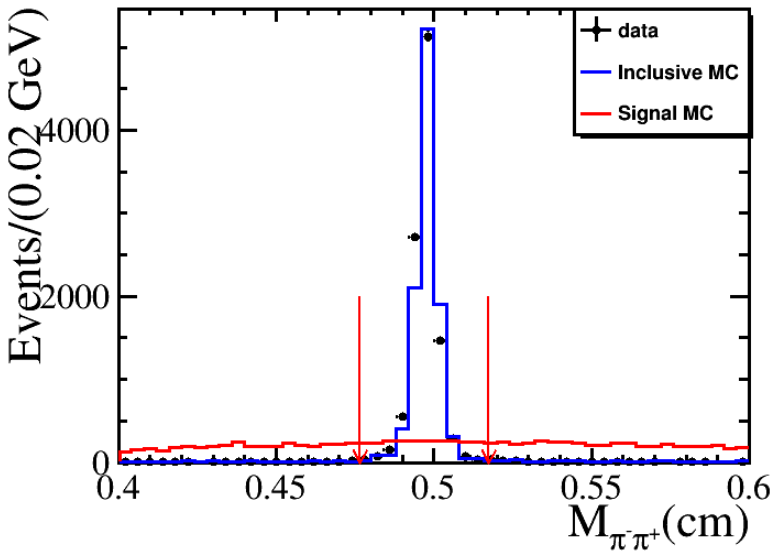
- Reconstruction D0 Mass
  - Invariant mass of kpi system was used to extract signal yields
  - Fit method: 1D binning maximum likelihood fit
  - Fit range: $1.7\ \mathrm{GeV}/c^2 < |E_\gamma| < 2.0\mathrm{GeV}/c^2$
  - Signal PDF: MC shape
  - BKG PDF: MC 2nd order Chebshev polynomial function

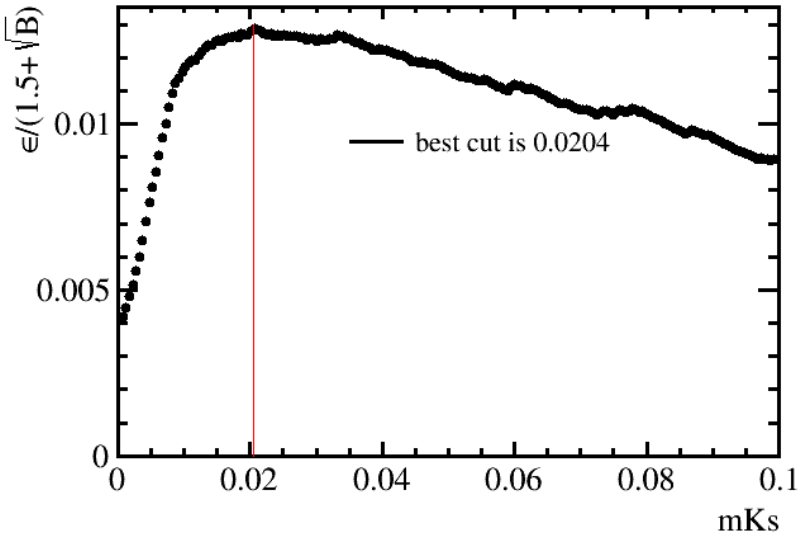
	$\bar{D}^0e^+e^-$		$D^0e^+e^-$	
	efficiency	Relative efficiency	efficiency	Reletive efficiency
Pass PID	36532		36677	
Pass 4C	25378	0.695	25642	0.699
χ^2_{4C}<20	16045	0.632	16330	0.637
$E/p(e^+)$>0.8 or $E/p(e^-)$>0.8	15355	0.957	15673	0.960
veto Ks	15355	1	15673	1
veto gamma conversion	14555	0.948	14810	0.945
χ^2cut	14555	1	14810	1

Backgrounds Analysis

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

- After all other selection addition.

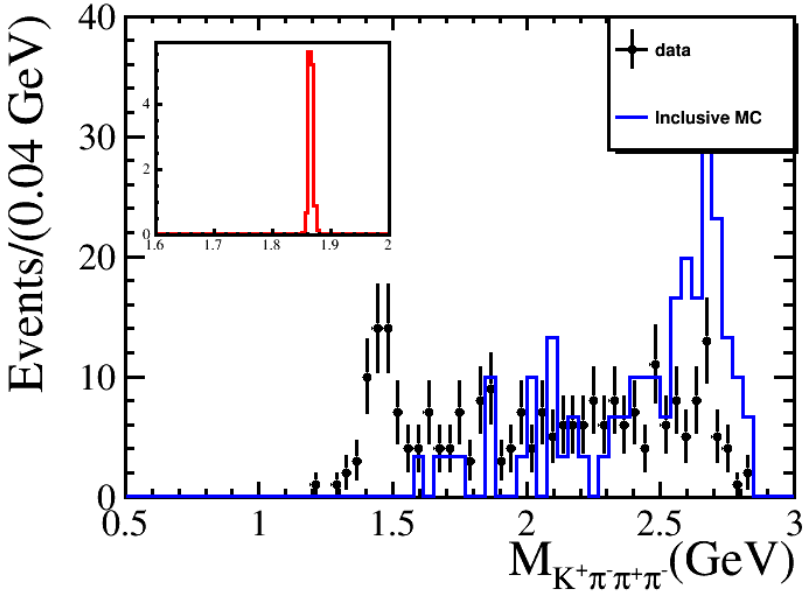


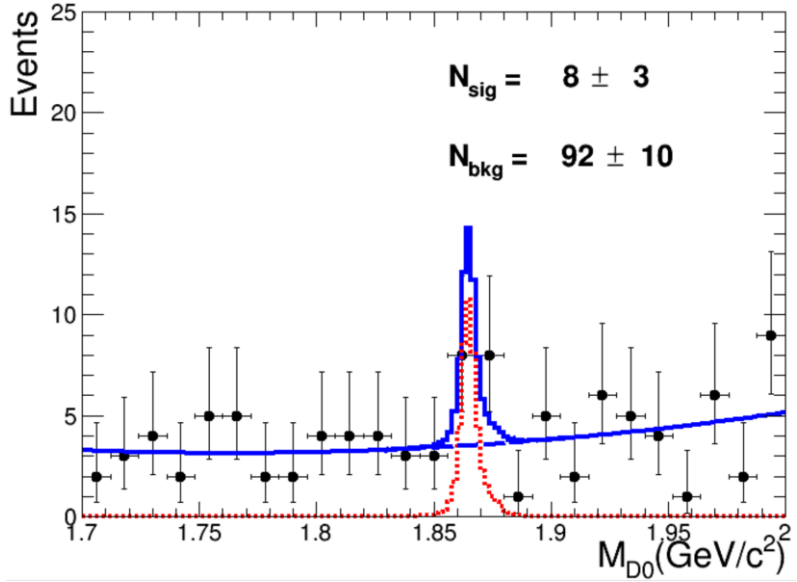


- Reject K_s events
  - $e^+e^- \to e^+e^-K_sK\pi$ was found to be the main background after above selections criteria applied.
  - By using the Punzi Significance with the formula of $\epsilon/(1.5+\sqrt{B})$, we get the best cut region $|M_{\pi\pi} - 0.497| < 0.0204\text{GeV}/c^2$.

Fit to The Mass Spectrum

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$





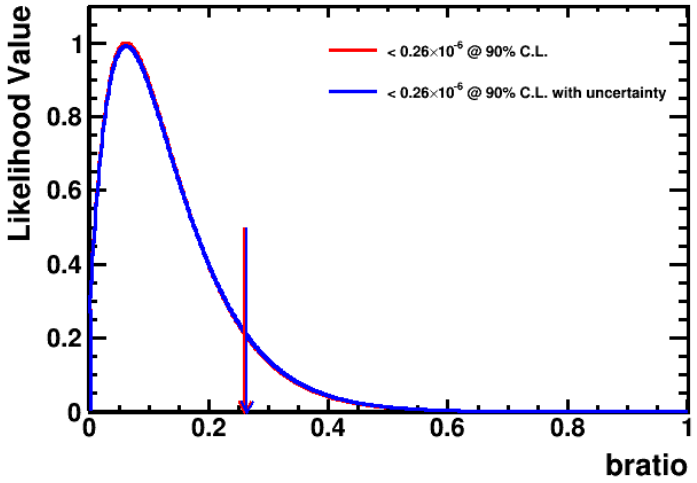
- Reconstruction D0 Mass
  - Invariant mass of kpi system was used to extract signal yields
  - Fit method: 1D binning maximum likelihood fit
  - Fit range: $1.7\ \mathrm{GeV}/c^2 < |E_\gamma| < 2.0\mathrm{GeV}/c^2$
  - Signal PDF: MC shape
  - BKG PDF: MC 2nd order Chebshev polynomial function

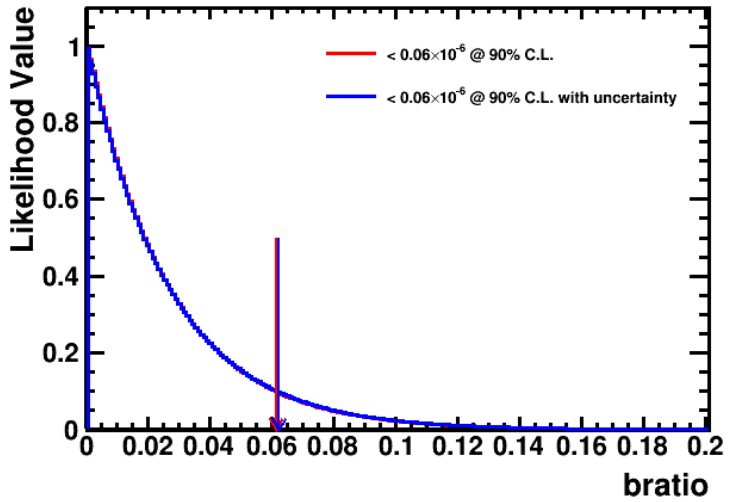
	$\bar{D}^0e^+e^-$		$D^0e^+e^-$	
	efficiency	Relative efficiency	efficiency	Reletive efficiency
Pass PID	29879		30208	
Pass 4C	21705	0.726	22044	0.730
χ^2_{4C}<20	14689	0.677	15140	0.687
$E/p(e^+)$>0.8 or $E/p(e^-)$>0.8	14396	0.980	14836	0.980
veto ks	12341	0.857	12680	0.855
veto gamma conversion	11731	0.951	11953	0.943

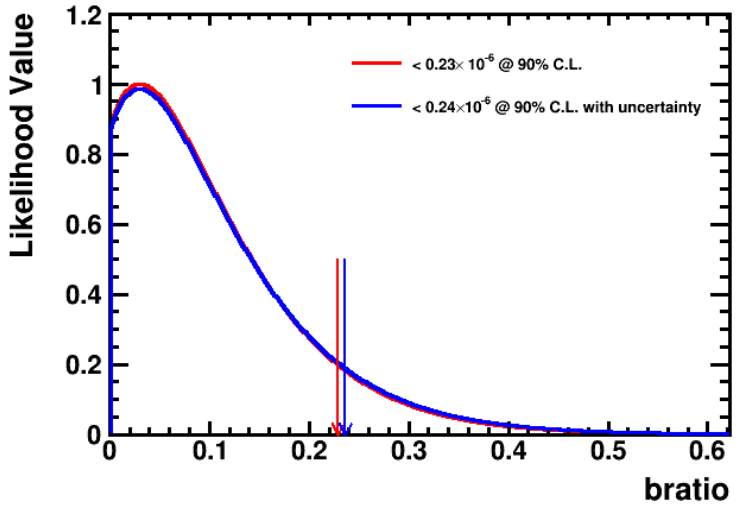
Upper Limits

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

- 09+12





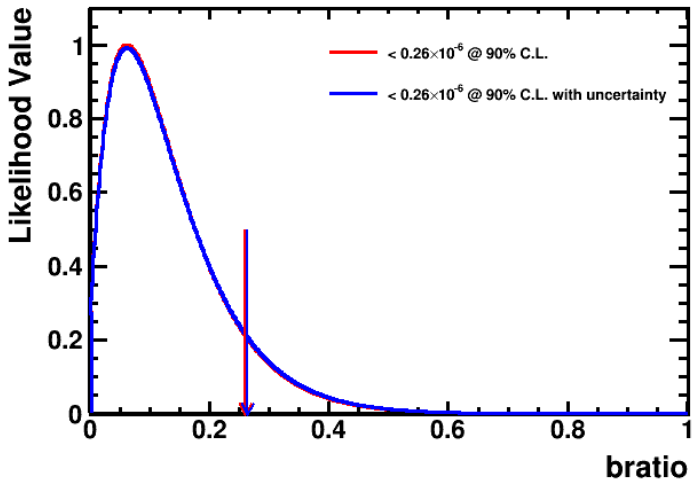


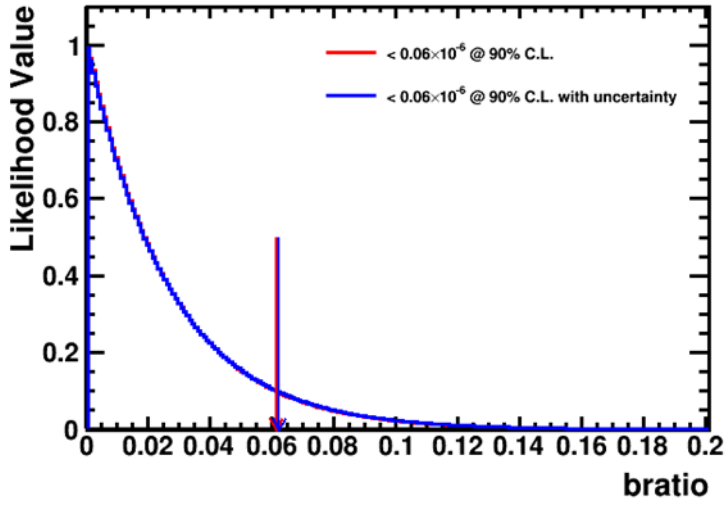
- Calculate the upper limit on the BF of $J/\psi \to D^0(\bar{D}^0)e^+e^-$based on the Bayesian method.
- A series of fits to the $M_{k\pi}$distribution were carried out by fixing the the BF of sigbal process at different values.
- The effect of systematic uncertainties was taken into account by convolved the distribution values of likelihood values with a Gaussian function which has a width given by the overall systematic uncertainty.
- The value that yields 90% of the likelihood integral over BF was taken as the upper limit of the BF.

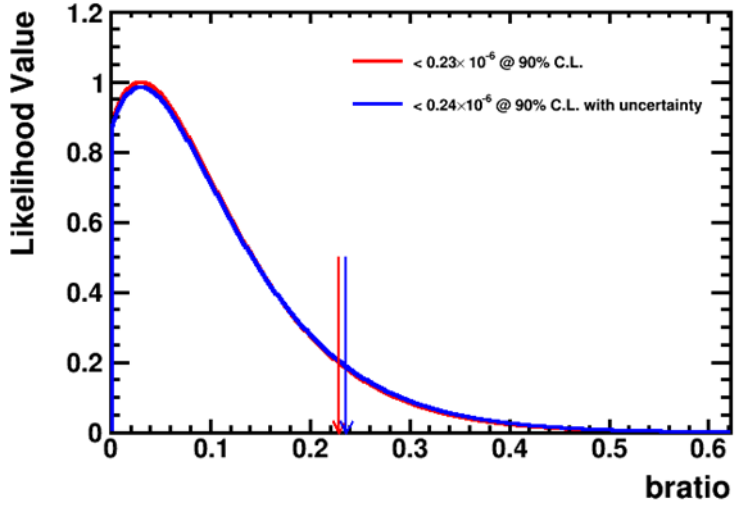
Upper Limits

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

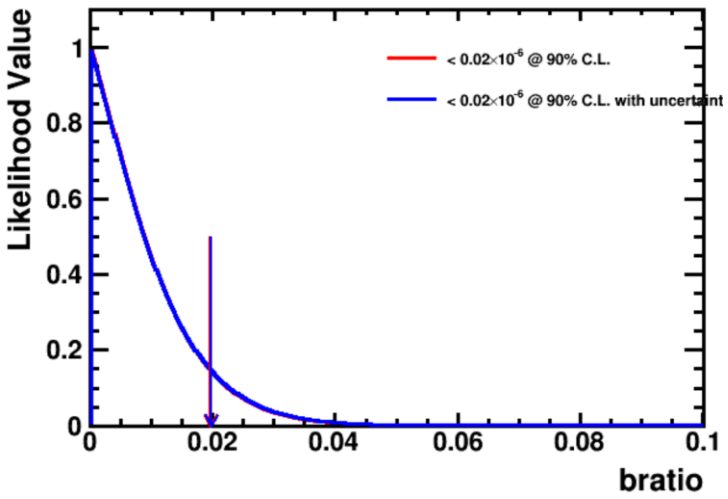
- 09+12

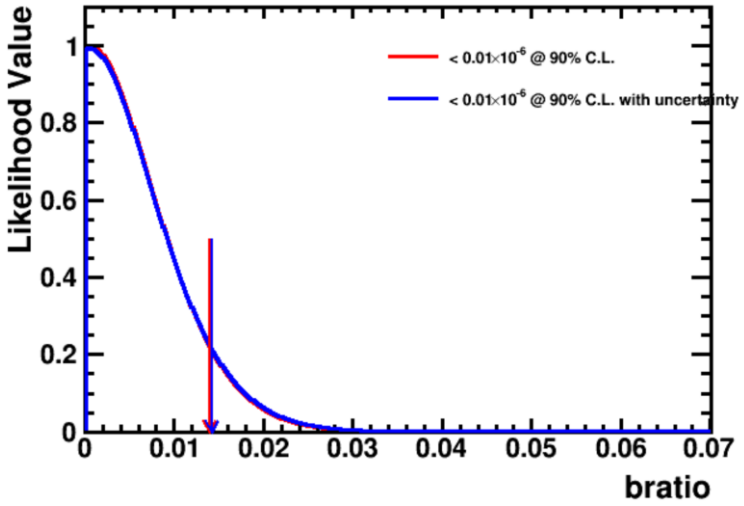


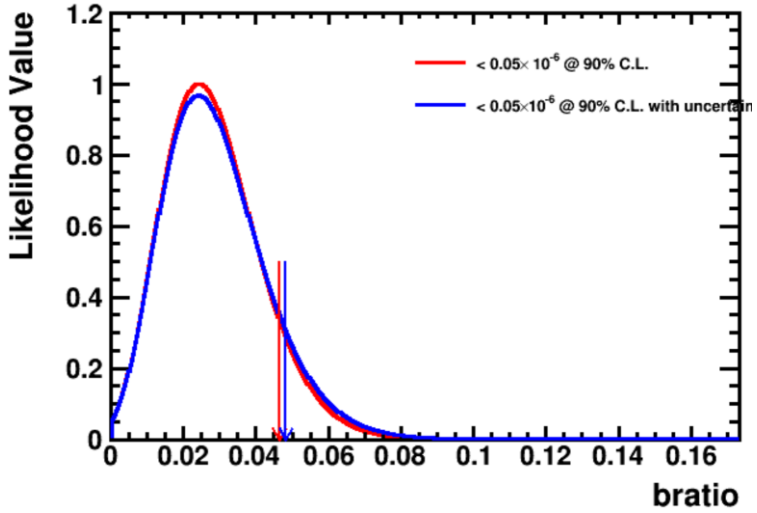




- 09+12+18+19



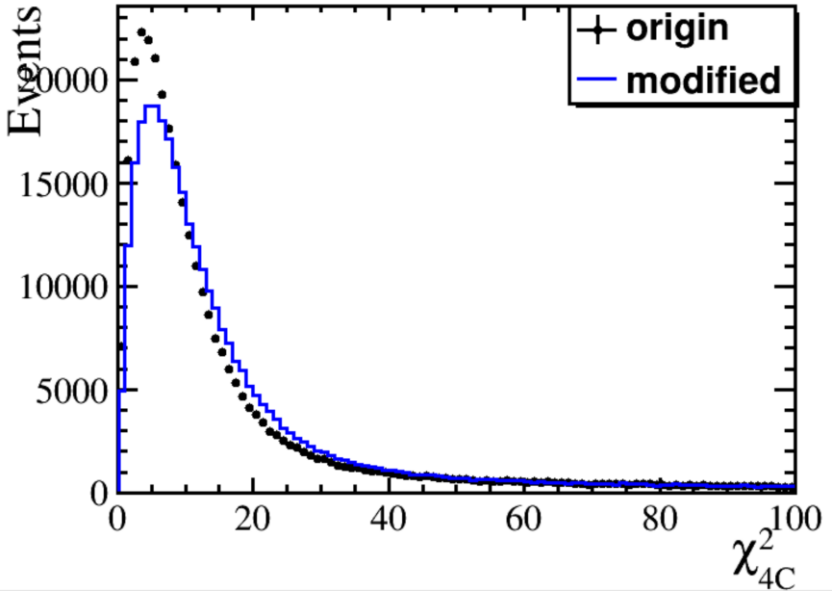




Systematic Error

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

- 4C kinematic fit
- Before modify:279943, After modify:278720, (279943-278720)/279943 = 0.044% is taken as systematic error.



The distribution difference of χ^2 of the kinematic fit between data and MC is mainly due to inconsistencies in the charged track parameters. The PULL distribution of charged track parameters of MC are corrected by smearing them to match the data using method in Ref. [23]. The difference in the detection efficiency between with and without making the correction to the MC is taken as the systematic uncertainty. The uncertainties associated with the requirements $\chi^2_{4C} < 60$. The uncertainty of the requirement is shown in Table. 10.

The correction factors are listed in Table.VIII. The correction factors depend weakly on the momentum of the track, the charge of the track and the type of the track. We adopted these correction factors in the MC simulation of $J/\psi \to \phi f_0(980)$ and compared the distributions of χ^2_{4C} and pull again, the plots are shown in Fig.44 and Fig.45.

Systematic Error

$D^0 \to k^-\pi^+$ $D^0 \to k^-\pi^+\pi^0$ $D^0 \to k^-\pi^+\pi^-\pi^+$

```
// Nils' parameters for J/psi 2009, BOSS 705
if(abs(runN)>=9947 && abs(runN)<=10878){
  if(!isVertexFitted)
      cerr << "ERROR: helix correction parameters for this dataset should be applied to WTrackParameter after vertex fit" << endl;

  if(firstCall)
    cerr << "WARNING: found no helix correction parameters for e, mu and p for this dataset" << endl;
  // pi+
  if (charge > 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = -0.008; track_calerr_d2[1] = 1.156; //phi0
    track_calmean_d2[2] = 0.0297; track_calerr_d2[2] = 1.090; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.242; track_calerr_d2[4] = 1.085; //lambda
  }
  // pi-
  else if (charge < 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.0314; track_calerr_d2[1] = 1.085; //phi0
    track_calmean_d2[2] = -0.0275; track_calerr_d2[2] = 1.000; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.244; track_calerr_d2[4] = 1.000; //lambda
  }
  // K+
  if (charge > 0 && n == 1){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.0087; track_calerr_d2[1] = 1.129; //phi0
    track_calmean_d2[2] = 0.0507; track_calerr_d2[2] = 1.137; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.322; track_calerr_d2[4] = 1.242; //lambda
  }
```

```
// Nils' parameters for J/psi 2012, BOSS 705
else if(abs(runN)>=27255 && abs(runN)<=28236){
  if(!isVertexFitted)
      cerr << "ERROR: helix correction parameters for this dataset should be applied to WTrackParameter after vertex fit" << endl;

  if(firstCall)
    cerr << "WARNING: found no helix correction parameters for e, mu and p for this dataset" << endl;
  // pi+
  if (charge > 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = -0.0152; track_calerr_d2[1] = 1.245; //phi0
    track_calmean_d2[2] = 0.128; track_calerr_d2[2] = 1.161; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.0114; track_calerr_d2[4] = 1.08; //lambda
  }
  // pi-
  else if (charge < 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.0105; track_calerr_d2[1] = 1.235; //phi0
    track_calmean_d2[2] = -0.126; track_calerr_d2[2] = 1.048; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = -0.002; track_calerr_d2[4] = 1.08; //lambda
  }
  // K+
  if (charge > 0 && n == 1){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.026; track_calerr_d2[1] = 1.262; //phi0
    track_calmean_d2[2] = 0.154; track_calerr_d2[2] = 1.210; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.009; track_calerr_d2[4] = 1.089; //lambda
  }
```

```
// Nils' correction factors for 2018 J/psi data
else if(abs(runN)>=52940 && abs(runN)<=56546){
  if(!isVertexFitted)
      cerr << "ERROR: helix correction parameters for this dataset should be applied to WTrackParameter after vertex fit" << endl;

  if(firstCall)
    cerr << "WARNING: found no helix correction parameters for e, mu and p for this dataset" << endl;
  // pi+
  if (charge > 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = -0.009; track_calerr_d2[1] = 1.195; //phi0
    track_calmean_d2[2] = 0.088; track_calerr_d2[2] = 1.1004; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.142; track_calerr_d2[4] = 1.1435; //lambda
  }
  // pi-
  else if (charge < 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.010; track_calerr_d2[1] = 1.195; //phi0
    track_calmean_d2[2] = -0.090; track_calerr_d2[2] = 1.0984; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.128; track_calerr_d2[4] = 1.1435; //lambda
  }
  // K+
  if (charge > 0 && n == 1){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.029; track_calerr_d2[1] = 1.295; //phi0
    track_calmean_d2[2] = 0.17; track_calerr_d2[2] = 1.195; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.176; track_calerr_d2[4] = 1.162; //lambda
  }
```

```
// Nils' correction factors for 2019 J/psi data
else if(abs(runN)>=56788 && abs(runN)<=59015){
  if(!isVertexFitted)
      cerr << "ERROR: helix correction parameters for this dataset should be applied to WTrackParameter after vertex fit" << endl;

  if(firstCall)
    cerr << "WARNING: found no helix correction parameters for e, mu and p for this dataset" << endl;
  // pi+
  if (charge > 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = -0.0054; track_calerr_d2[1] = 1.258;//phi0
    track_calmean_d2[2] = 0.07; track_calerr_d2[2] = 1.120; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.26; track_calerr_d2[4] = 1.175;//lambda
  }
  // pi-
  else if (charge < 0 && n == 0){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.014; track_calerr_d2[1] = 1.240; //phi0
    track_calmean_d2[2] = -0.08; track_calerr_d2[2] = 1.100; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.24; track_calerr_d2[4] = 1.175; //lambda
  }
  // K+
  if (charge > 0 && n == 1){
    track_calmean_d2[0] = 0; track_calerr_d2[0] = 1; //drho
    track_calmean_d2[1] = 0.04; track_calerr_d2[1] = 1.257; //phi0
    track_calmean_d2[2] = 0.17; track_calerr_d2[2] = 1.199; //kappa
    track_calmean_d2[3] = 0; track_calerr_d2[3] = 1; //dz
    track_calmean_d2[4] = 0.31; track_calerr_d2[4] = 1.165;//lambda
  }
```