Measurement of branching fraction of $D_s^{+*} \to e^+e^-D_s^+$

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Outline

- **Introduction**
- **Data Sample**
- **ST Selection**
- **ST yields and efficiencies (@4180)**
- **ST yields of D_s^+(@4180)**
- **e^+e^- Selection**
- **Signal Efficiencies**
- **Signal Fitting**
- **IO Check**
- **Summary and Next to do**

Introduction

- There are only two electromagnetic decays in $D_{(s)}^{*}$:
- ➢ 2012, CLEO-c: $\mathcal{B}(D_s^{+*} \to D_s^+ e^+ e^-) = (6.7^{+0.14}_{-0.12} \pm 0.09) \times 10^{-3}$
- ➢ 2021, BESIII : $\mathcal{B}(D^{*0} \to D^0 e^+ e^-) = (3.91 \pm 0.27 \pm 0.17 \pm 0.10) \times 10^{-3}$
- Studying $D_s^{+*} \to D_s^+ e^+ e^-$ with improved precision can provide more information about the EM interaction and the distribution of matter of D_s^{+*}.
- At 4.180 GeV, the data of BESIII are 5 times larger than CLEO-c, and can study the branching fraction of $D_s^{+*} \to D_s^+ e^+ e^-$ with improved precision.
- Consider more signal events, we can also try to extract the form factor of D_s^{+*} firstly.

Data Sample

- BOSS 703-1
- Data samples: 4180 (3189.0 pb^{-1})

Tag Modes
$D_s^+ \to K_S^0 K^+$
$D_s^+ \to K^+ K^- \pi^+$
$D_s^+ \to K_S^0 K^+ \pi^0$
$D_s^+ \to K^+ K^- \pi^+ \pi^0$
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$
$D_s^+ \to \pi^+ \pi^- \pi^+$
$D_s^+ \to \pi^+ \eta$
$D_s^+ \to \pi^+ \pi^0 \eta$
$D_s^+ \to \pi^+ \eta', \eta' \to \pi^+ \pi^- \eta$
$D_s^+ \to \pi^+ \eta', \eta' \to \gamma \rho^0, \rho^0 \to \pi^+ \pi^-$
$D_s^+ \to K^+ \pi^- \pi^+$

- Inclusive MC

Table 2: Components and Cross Section

	4180	4190	4200	4210	4220	4230
Components	Cross section (pb)					
$D^0\bar{D}^0$	179	159	148	139	133	130
D^+D^-	197	197	196	195	193	192
$D^{*0}\bar{D}^0$	1211	1187	1175	1159	1144	1133
$D^{*+}D^-$	1296	1270	1257	1241	1225	1212
$D^{*0}\bar{D}^{*0}$	2173	2112	1855	1491	1096	879
$D^{*+}D^{*-}$	2145	2085	1831	1472	1082	868
$D_s^+D_s^-$	34	42.7	38.5	32.3	22.4	18.4
$D_s^{*+}D_s^-$	961	925	921	853	750	629
$D_s^{*+}D_s^{*-}$	-	-	-	-	-	22
$DD^*\pi^+$	383	395	406	415	421	427
$DD^*\pi^0$	192	198	204	208	211	214
$DD\pi^+$	50	53	55	56	58	57
$DD\pi^0$	25	27	27	28	29	29
Components	Cross section (nb)					
$q\bar{q}$	13.8	13.7	13.6	13.6	13.5	13.5
$\gamma J/\psi$	0.40	0.39	0.39	0.38	0.37	0.37
$\gamma\psi(2S)$	0.42	0.40	0.39	0.38	0.37	0.37
$\gamma\psi(3770)$	0.06	0.06	0.06	0.06	0.06	0.06
$\tau\tau$	3.45	3.45	3.46	3.46	3.46	3.47
$\mu\mu$	5.24	5.22	5.19	5.16	5.14	5.13
ee	423.99	422.55	420.47	418.43	416.61	415.20
$\gamma\gamma$	1.7	1.7	1.7	1.7	1.5	1.5
HCT	0.10178	0.12331	0.14525	0.16555	0.18486	0.19660

Data Sample

- Signal MC:

The sample is produced by a DIY generator.

- I, $e^+e^- \to D_s^* D_s + c.c.$ is generated by ConExc model in the BesEvtGen incorporating both radiative correction and vacuum polarization, the corresponding angular distribution is $1 + cos^2\theta$.
- II, $D_s^{\pm *} \to D_s^{\pm}\gamma^* \to D_s^{\pm}e^+e^-$ is modelled (arXiv:2111.04932v2) with

$$\frac{d\Gamma}{dq^2 dcos\theta_1^*} \sim C\frac{|f(q^2)|^2}{q^2}(1-\frac{4m_l^2}{q^2})^{1/2}[(m_{D_s^{*\pm}}^2 - m_{D_s^{\pm}}^2 + q^2)^2 - 4m_{D_s^{*\pm}}^2 q^2]^{\frac{3}{2}} \times [(1+\frac{4m_l^2}{q^2}) + (1-\frac{4m_l^2}{q^2})\cos^2\theta_1^*]$$

C contains all the constants, q^2 is transfer momentum squre, θ^* is the polar angle of electron in γ^* rest frame, $m_{D_s^{\pm *}}$, $m_{D_s^{\pm}}$ and m_l are the invariant mass of $D_s^{\pm *}$, $D_s^{\pm}$ and electron.

- III, One of $D_s^{\pm}$ decay into ST mode according to the PWA results from Prof. Dong and another $D_s^{\pm}$ decay inclusively.

Data Sample

$$e^+e^- \to D_s^{*+}D_s^-,\ D_s^{*+} \to D_s^+e^+e^-,\ D_s^+ \to tag\ modes \qquad \boldsymbol{\epsilon_{i,j}^{+,dau}}$$

$$e^+e^- \to D_s^{*+}D_s^-,\ D_s^{*+} \to D_s^+e^+e^-,\ D_s^- \to tag\ modes \qquad \boldsymbol{\epsilon_{i,j}^{-,bac}}$$

$$e^+e^- \to D_s^+D_s^{*-},\ D_s^{*-} \to D_s^-e^+e^-,\ D_s^- \to tag\ modes \qquad \boldsymbol{\epsilon_{i,j}^{-,dau}}$$

$$e^+e^- \to D_s^+D_s^{*-},\ D_s^{*-} \to D_s^-e^+e^-,\ D_s^+ \to tag\ modes \qquad \boldsymbol{\epsilon_{i,j}^{+,bac}}$$

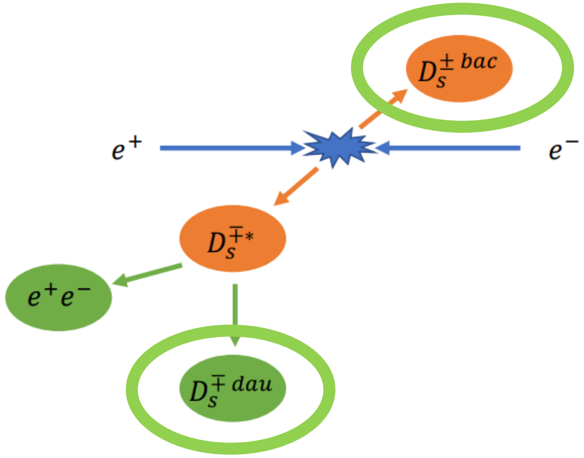
$$\mathcal{B}_s = \frac{2 \times \sum_i N(DT)_i^{\pm,dau/bac}}{\sum_i N(ST)_i^{\pm} \times \epsilon(DT)_i^{\pm,dau/bac} / \epsilon(ST)_i^{\pm}}$$

$$\Downarrow$$

$$\sum_i N(DT)_i^{\pm,dau/bac} = \frac{\sum_i N(ST)_i^{\pm} \times \mathcal{B}_s \times \epsilon(DT)_i^{\pm,dau/bac} / \epsilon(ST)_i^{\pm}}{2}$$

ST Selections

DTAG Package: DTagAlg-00-01-09



Good tracks:

- $V_{xy} = \sqrt{V_x^2 + V_y^2} < 1.0$ cm, $|V_z| < 10.0$ cm, $|cos\theta| < 0.93$

PID:

- Use dE/dx in MDC and time-of-flight in TOF.
- $Prob(K) > 0$ and $Prob(K) > Prob(\pi)$ for K.
- $Prob(\pi) > 0$ and $Prob(\pi) > Prob(K)$ for π.

Good photons:

- The showers time is required to be within 700 ns of the event start time to suppress the electronic noise.
- $|cos\theta| < 0.8$ and $E_{min} > 25$MeV .
- $0.86 < |cos\theta| < 0.92$ and $E_{min} > 50$MeV .
- 10° isolation from any charged tracks.

π^0 Selection:

Reconstructed through $\pi^0 \to \gamma\gamma$ with Pi0EtaToGGRecAlg Package.

- γ satisfying the requirements of photon selection.

Perform a constrained fit on the photon pairs to the nominal π^0 mass:

- The unconstrained invariant mass for π^0 : $0.115 < M_{\gamma\gamma} < 0.150$ GeV$/c^2$
- Mass fit: $\chi^2_{1C} < 30$

ST Selections

η Selection:

Reconstructed through $\eta \rightarrow \gamma\gamma$ with Pi0EtaToGGRecAlg Package.

- γ satisfying the requirements of photon selection.

Perform a constrained fit on the photon pairs to the nominal η mass:

- The unconstrained invariant mass for η : $490 < M_{\gamma\gamma} < 580\ \mathrm{MeV}/c^2$.
- Mass fit: $\chi^2_{1C} < 30$

η' Selection:

Reconstructed through $\eta' \rightarrow \pi^+\pi^-\eta$ and $\eta' \rightarrow \rho^0\gamma$.

For $\eta' \rightarrow \pi^+\pi^-\eta$: we require:

- $943 < M_{\pi^+\pi^-\eta} < 973\ \mathrm{MeV}/c^2$

For $\eta' \rightarrow \rho^0\gamma$: we require:

- $946 < M_{\pi^+\pi^-\eta} < 970\ \mathrm{MeV}/c^2$
- $570 < M_{\pi^+\pi^-} < 970\ \mathrm{MeV}/c^2$

K^0_S Selection:

Reconstructed with VeeVertexAlg Package.

- $|V_z| < 20.0$ cm, $|cos\theta| < 0.93$.

A constrained vertex fit is performed:

- $\chi^2_{1VF} < 100$
- $487 < M_{\pi^+\pi^-} < 511\ \mathrm{MeV}/c^2$

A second constrained vertex fit is performed:

- $\chi^2_{2VF} < 100$
- $L/\sigma_L > 2$

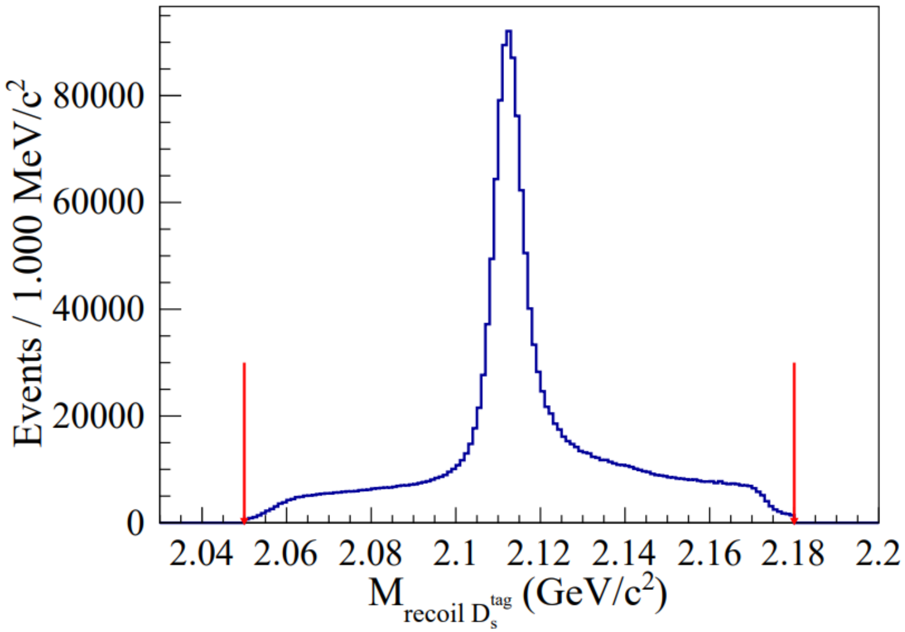
L is the distance between the vertex and the IP and σ_L is the uncertainty of L.

- $\pi^{\pm 0}$ from $D_s^{\pm}$ directly require: $P_{\pi^{\pm 0}} > 100$ MeV/c

For $D_s^+ \rightarrow \pi^+\pi^+\pi^-$ and $D_s^+ \rightarrow K^+\pi^+\pi^-$:

- Veto events with $M_{\pi^+\pi^-} \in (0.468, 0.528)\ \mathrm{GeV}/c^2$

ST Selections



- $M_{recoil\ D_s^{tag}} = \sqrt{(E_{cm} - E_{D_s^{tag}})^2 - p^2_{D_s^{tag}}}$

Where $E_{D_s^{tag}} = \sqrt{p^2_{D_s^{tag}} + M^2_{D_s\ PDG}}$

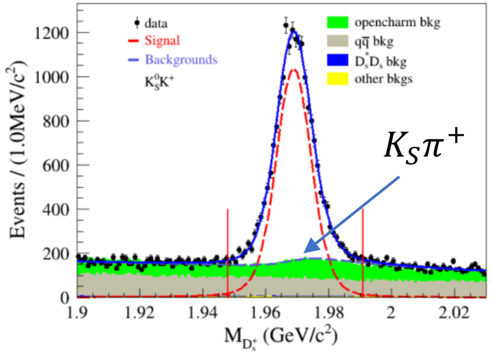
- Best $M_{recoil\ D_s^{tag}}$ in each tag mode.
- $2.05 < M_{recoil\ D_s^{tag}} < 2.18\ \mathrm{GeV}/c^2$

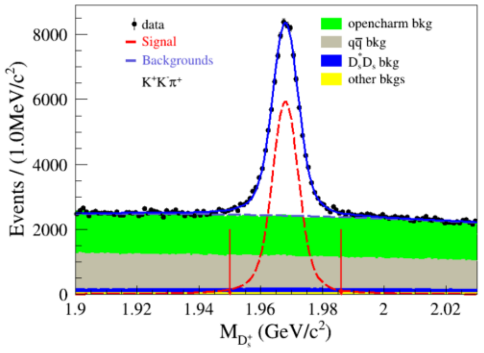
Tag Modes	Mass Window (GeV)
$D_s^+ \to K_S^0 K^+$	(1.948, 1.991)
$D_s^+ \to K^+ K^- \pi^+$	(1.950, 1.986)
$D_s^+ \to K_S^0 K^+ \pi^0$	(1.946, 1.987)
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	(1.947, 1.982)
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	(1.953, 1.983)
$D_s^+ \to \pi^+ \pi^- \pi^+$	(1.952, 1.984)
$D_s^+ \to \pi^+ \eta$	(1.930, 2.000)
$D_s^+ \to \pi^+ \pi^0 \eta$	(1.920, 2.000)
$D_s^+ \to \pi^+ \eta', \eta' \to \pi^+ \pi^- \eta$	(1.938, 1.997)
$D_s^+ \to \pi^+ \eta', \eta' \to \gamma \rho^0, \rho^0 \to \pi^+ \pi^-$	(1.938, 2.006)
$D_s^+ \to K^+ \pi^- \pi^+$	(1.953, 1.983)

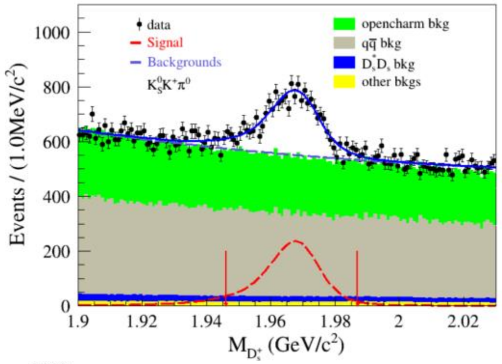
ST yields and efficiencies (@4180)

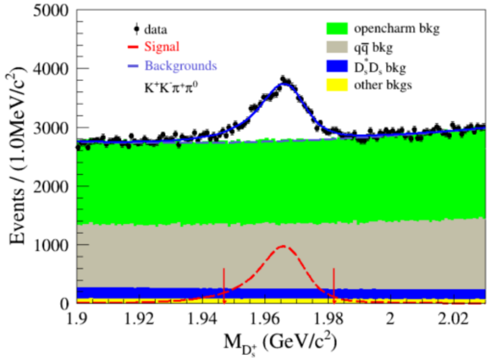
Tag Modes	Yields tag D_s^+	Eff tag D_s^+(%)	Yields tag D_s^-	Eff tag D_s^-(%)
$D_s^+ \to K_S^0 K^+$	15221 ± 186	47.79	15637 ± 192	47.26
$D_s^+ \to K^+ K^- \pi^+$	68315 ± 436	40.71	69052 ± 442	41.04
$D_s^+ \to K_S^0 K^+ \pi^0$	4881 ± 278	14.71	4790 ± 264	14.51
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	18558 ± 557	11.04	20011 ± 596	10.79
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	7110 ± 160	19.91	7158 ± 163	20.48
$D_s^+ \to \pi^+ \pi^- \pi^+$	18142 ± 678	54.34	18569 ± 629	55.26
$D_s^+ \to \pi^+ \eta$	8922 ± 313	45.64	9263 ± 318	45.17
$D_s^+ \to \pi^+ \pi^0 \eta$	20919 ± 1093	18.35	21213 ± 1039	18.90
$D_s^+ \to \pi^+ \eta', \eta' \to \pi^+ \pi^- \eta$	4701 ± 130	23.49	4521 ± 120	23.72
$D_s^+ \to \pi^+ \eta', \eta' \to \gamma \rho^0, \rho^0 \to \pi^+ \pi^-$	10998 ± 427	29.32	11141 ± 413	29.65
$D_s^+ \to K^+ \pi^- \pi^+$	8332 ± 467	46.65	8124 ± 537	46.09
Sum	186100 ± 1675		189478 ± 1654	

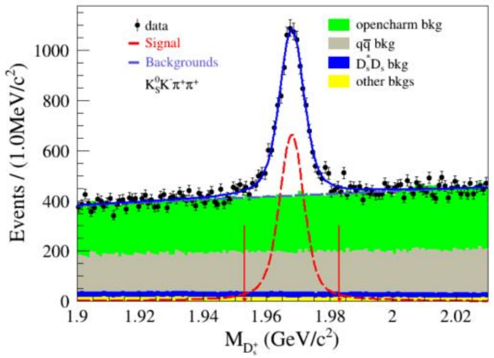
ST yields of D_s^+(@4180)

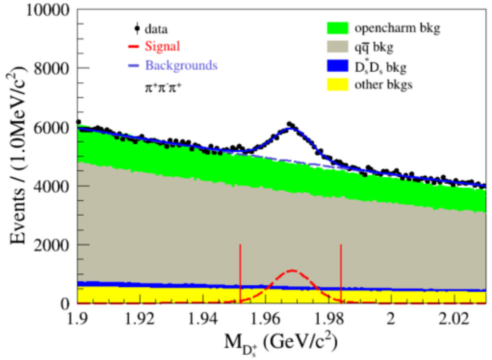


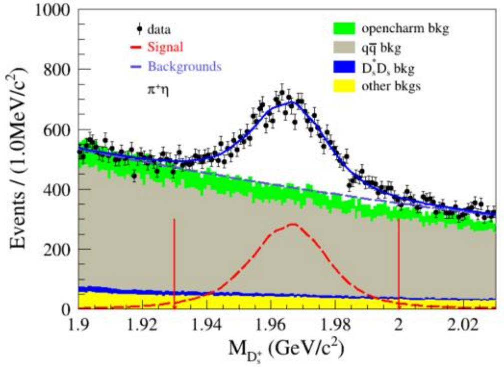


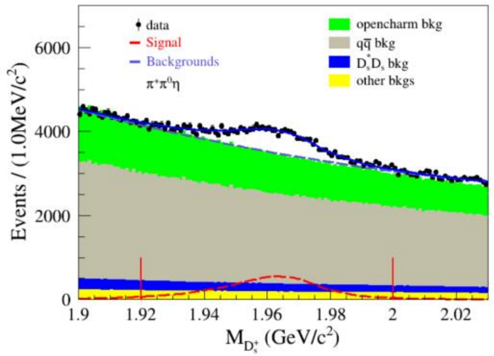


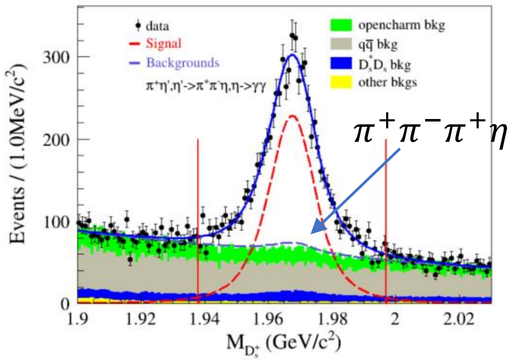


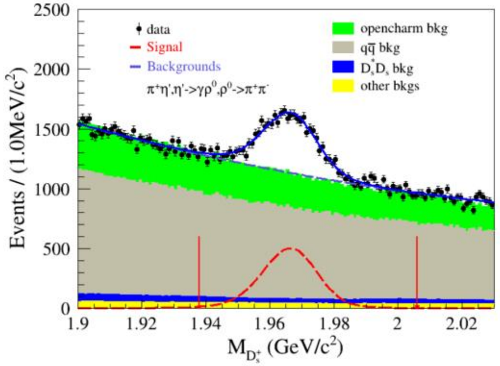


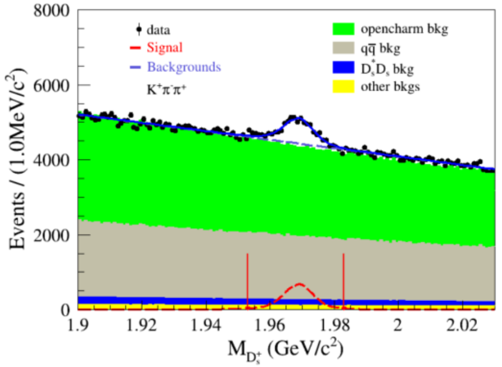






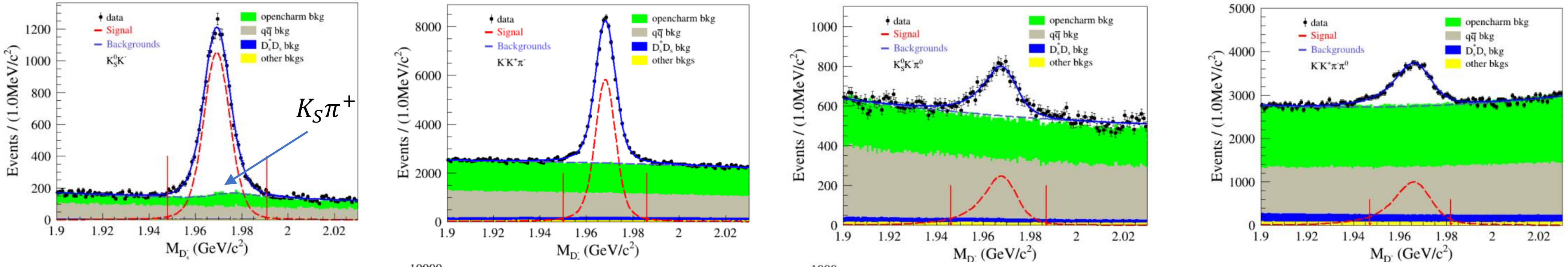


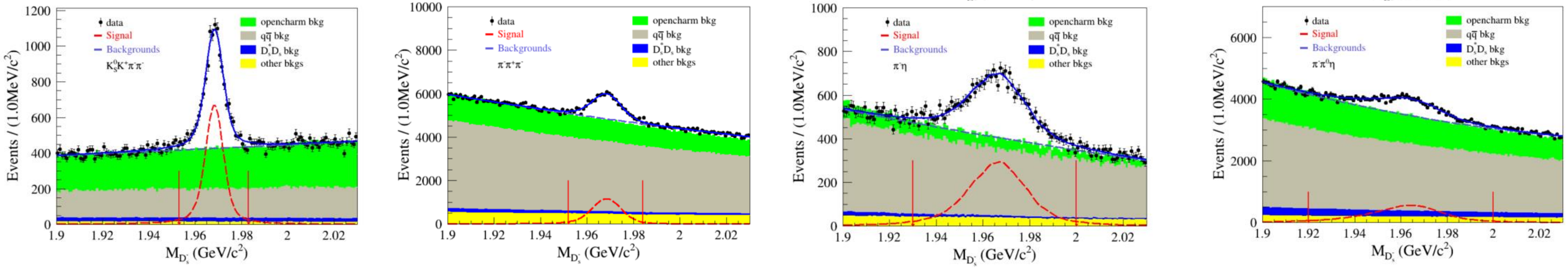


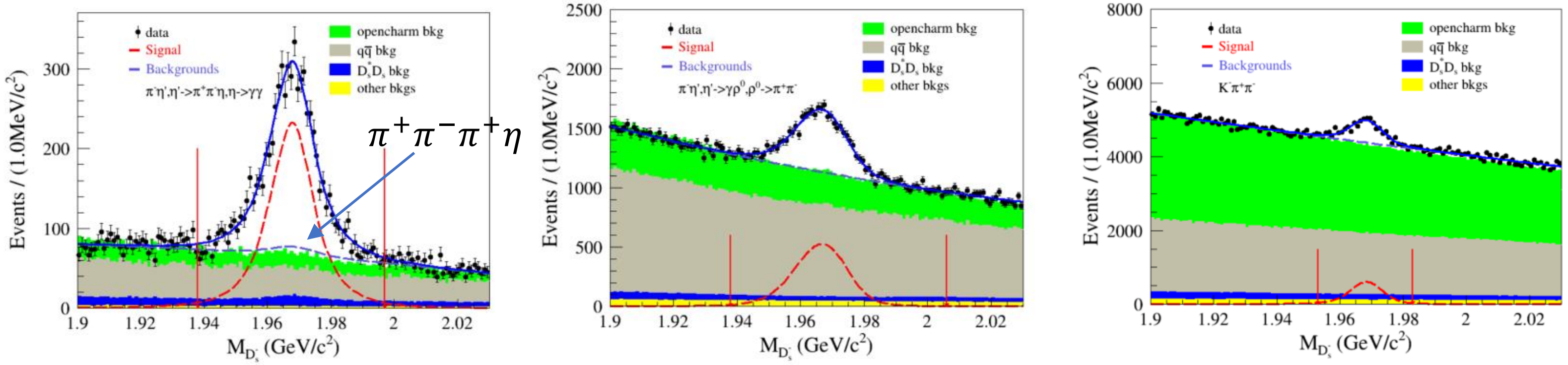


Shape$\otimes$Gauss+ Chebyshev

ST yields of D_s^-(@4180)



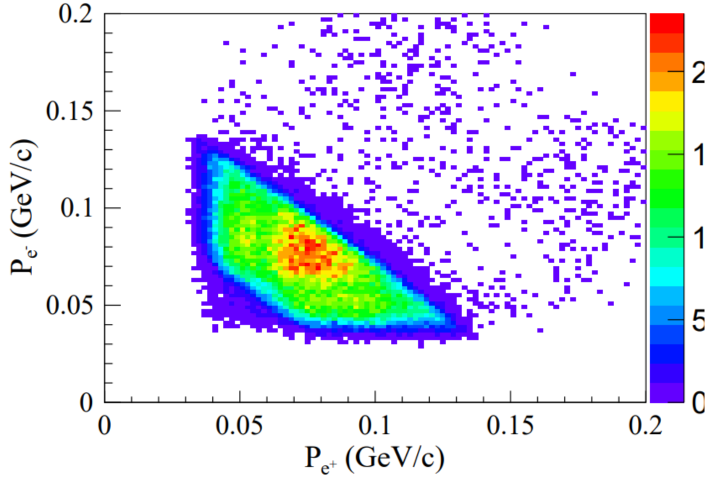


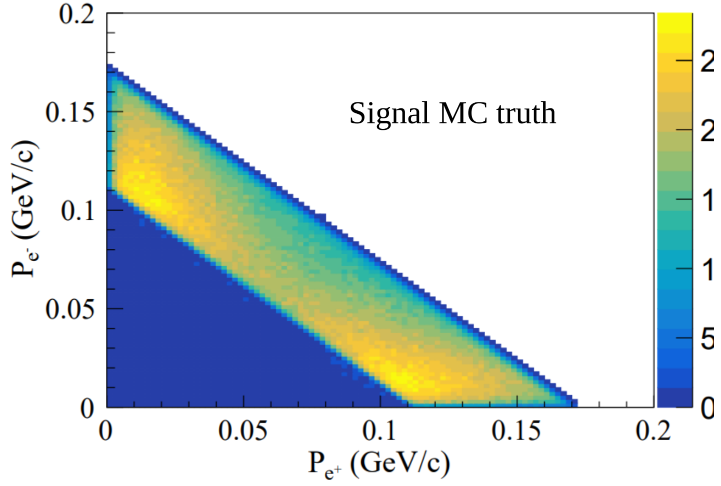


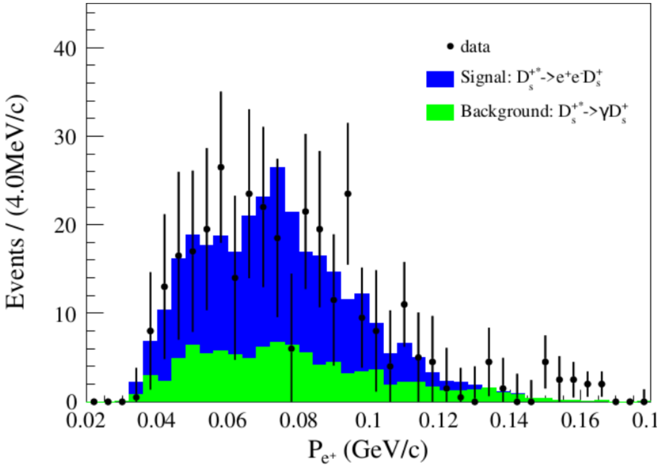
Shape⊗Gauss+ Chebyshev

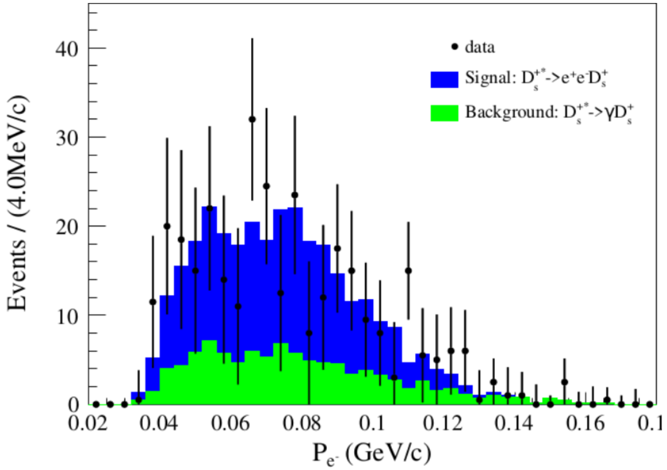
e^+e^- Selections

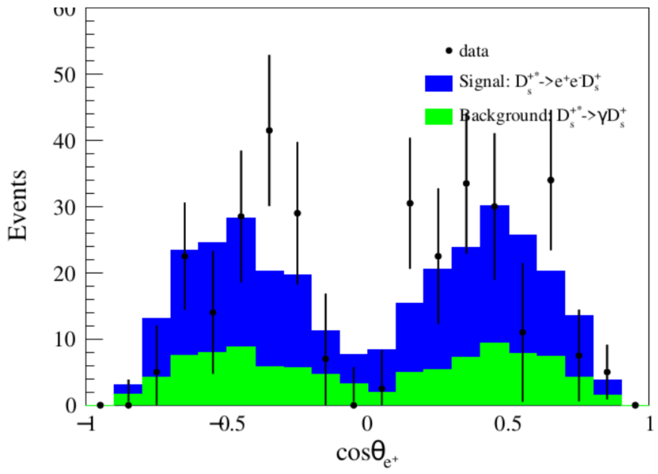
- $P_{e^+} < 0.2$ GeV/c and $P_{e^-} < 0.2$ GeV/c.
- PID with dE/dx in MDC: $Prob(e) > 0, Prob(e) > Prob(\pi)$

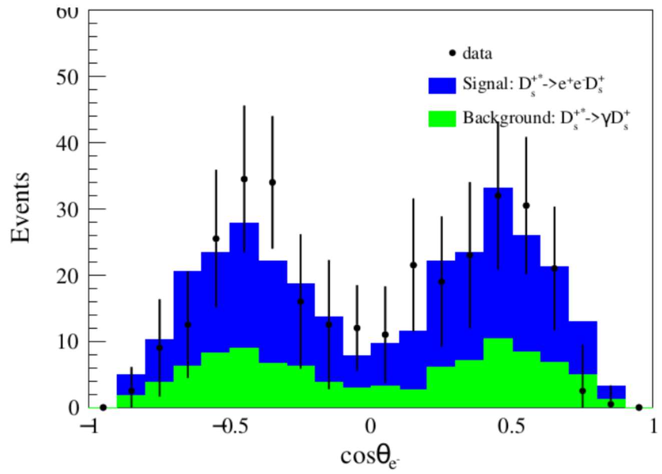












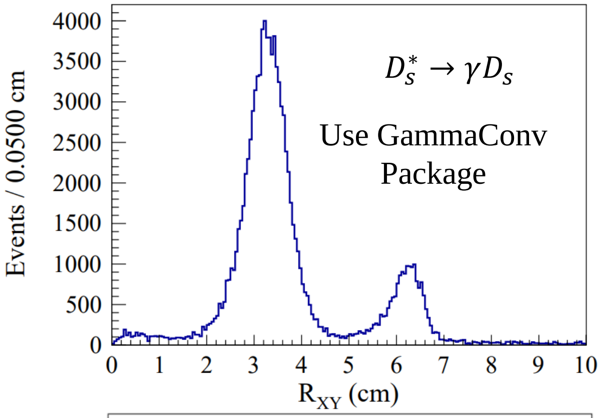
e^+e^- Selections

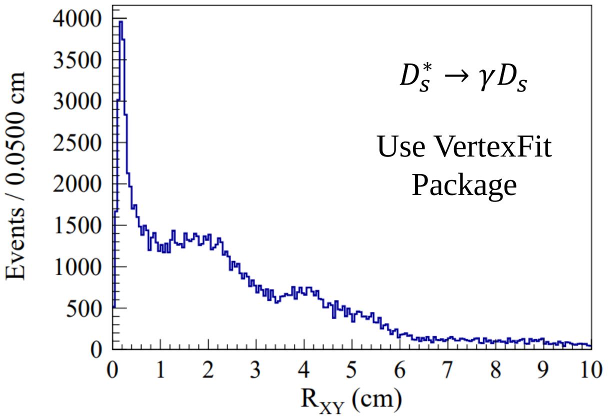
For $cos\theta_{e^+e^-} > 0.92$:

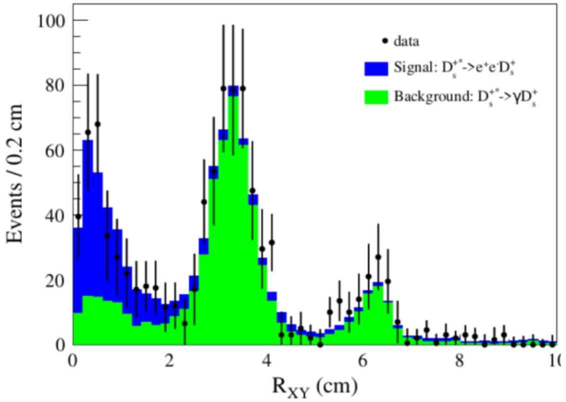
- Use GammaConv Package, $R_{XY} = \sqrt{V_x^2 + V_y^2} < 2$ cm

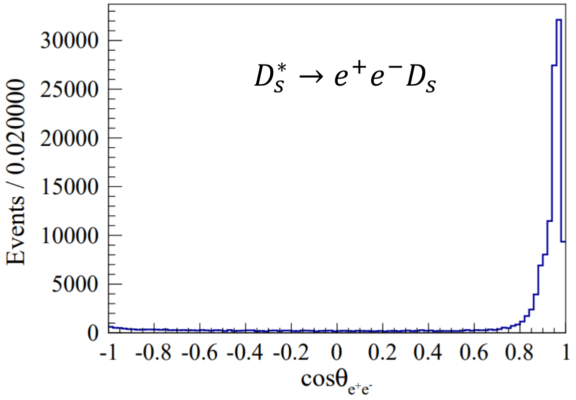
For $cos\theta_{e^+e^-} < 0.92$:

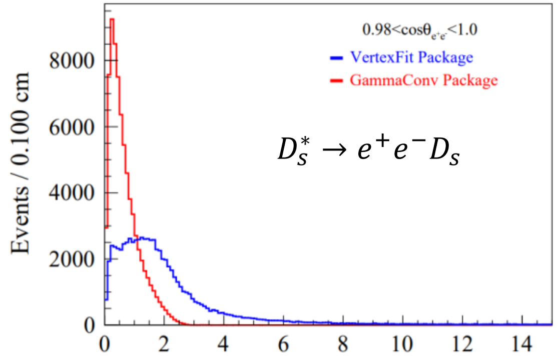
- Use Vertex Fitting Package, $R_{XY} = \sqrt{V_x^2 + V_y^2} < 2$ cm

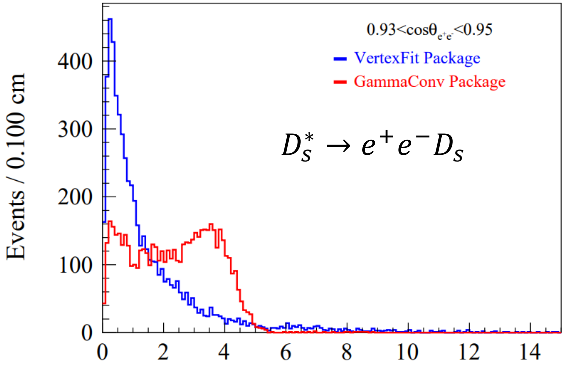


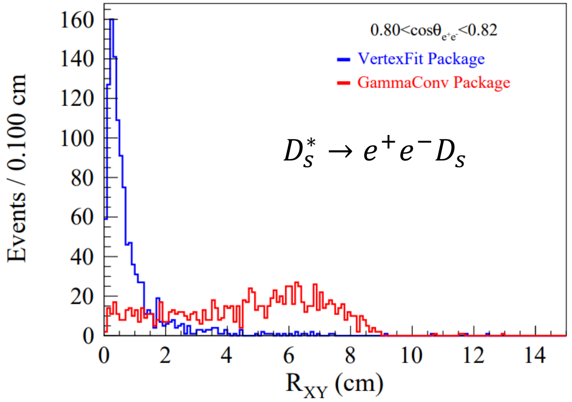




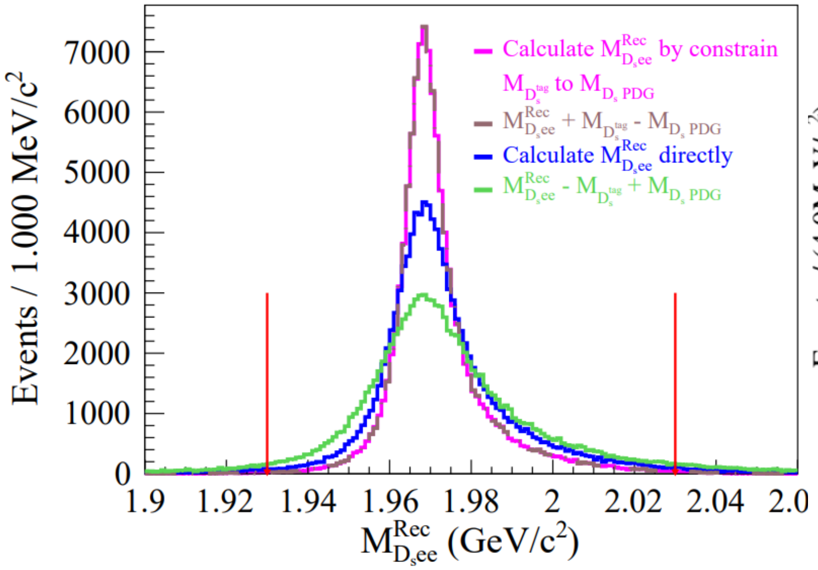


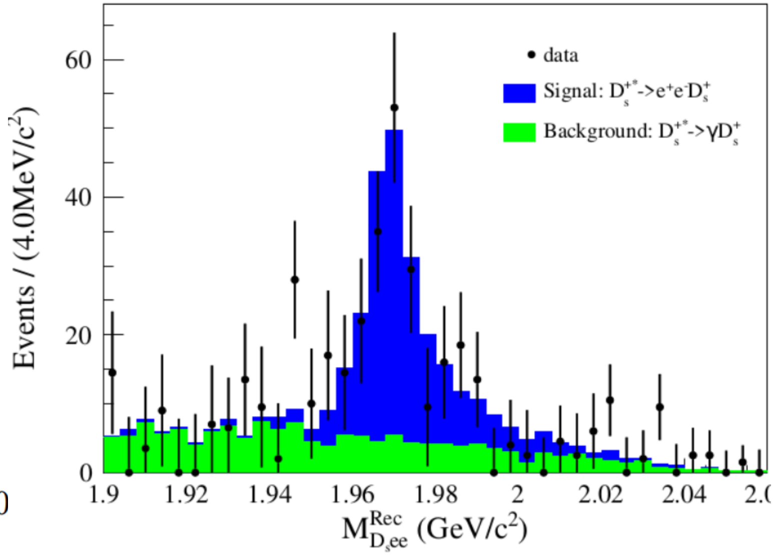


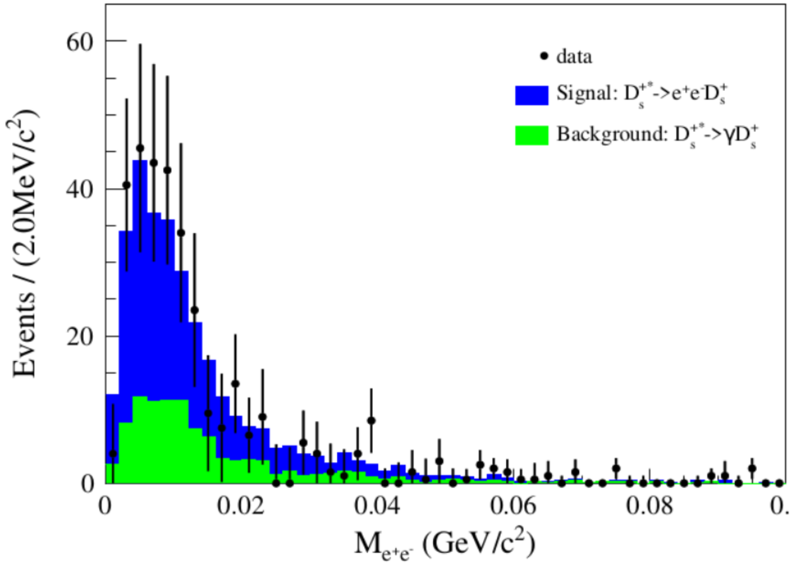




e^+e^- Selections







- $M^{Rec}_{D_s e^+ e^-} = \sqrt{(E^{Rec}_{D_s e^+ e^-})^2 - (P^{Rec}_{D_s e^+ e^-})^2}$

Where $P^{Rec}_{D_s e^+ e^-} = P_{cms} - P_{D_s} - P_{e^+ e^-}$ and $E^{Rec}_{D_s e^+ e^-} = E_{cms} - \sqrt{P^2_{D_s} + M^2_{D_s\ PDG}} - E_{e^+ e^-}$

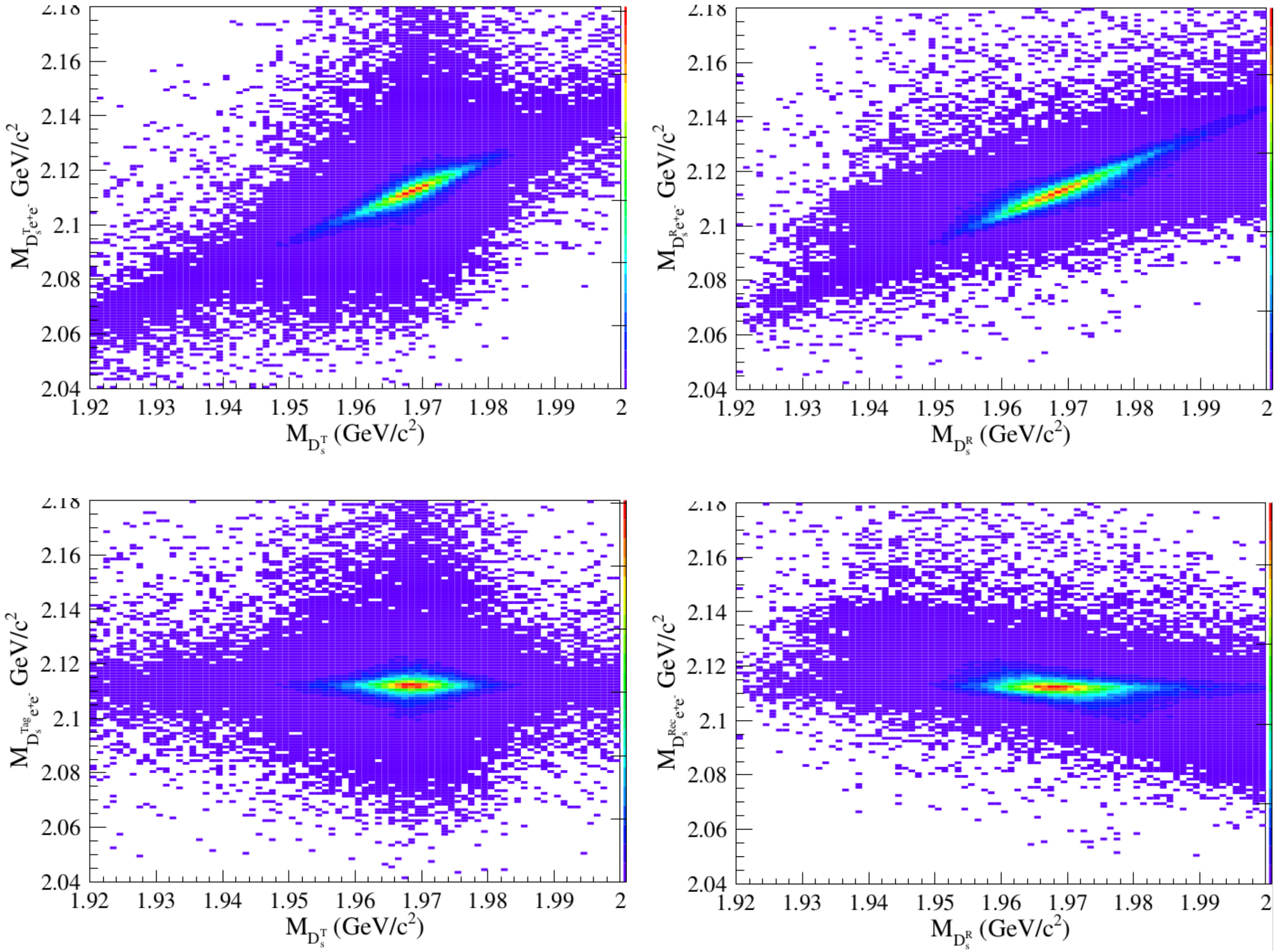
- Select $M^{Rec}_{D_s e^+ e^-}$ closest $m_{D_s\ PDG}$.
- $1.93 < M^{Rec}_{D_s e^+ e^-} < 2.03\ \mathrm{GeV}/c^2$

Signal Efficiencies

Tag Modes	$\epsilon_{i,j}^{+,dau}$(%)	$\epsilon_{i,j}^{-,bac}$(%)	$\epsilon_{i,j}^{-,dau}$(%)	$\epsilon_{i,j}^{+,bac}$(%)
$D_s^+ \to K_S^0 K^+$	3.90	4.14	3.91	4.04
$D_s^+ \to K^+ K^- \pi^+$	3.28	3.52	3.30	3.54
$D_s^+ \to K_S^0 K^+ \pi^0$	1.25	1.49	1.24	1.56
$D_s^+ \to K^+ K^- \pi^+ \pi^0$	0.78	1.06	0.81	1.07
$D_s^+ \to K_S^0 K^- \pi^+ \pi^+$	1.42	1.63	1.45	1.63
$D_s^+ \to \pi^+ \pi^- \pi^+$	4.56	4.98	4.46	4.97
$D_s^+ \to \pi^+ \eta$	4.19	4.40	4.12	4.42
$D_s^+ \to \pi^+ \pi^0 \eta$	1.83	2.10	1.83	2.19
$D_s^+ \to \pi^+ \eta', \eta' \to \pi^+ \pi^- \eta$	1.81	1.98	1.77	1.97
$D_s^+ \to \pi^+ \eta', \eta' \to \gamma \rho^0, \rho^0 \to \pi^+ \pi^-$	2.64	2.70	2.65	2.79
$D_s^+ \to K^+ \pi^- \pi^+$	3.88	4.24	3.93	4.31

✓ The momentum of e^+ and e^- are very low, so the tracking efficiencies are very low, it's the main reason that the signal efficiencies are very limited.

Signal Fitting



Have:

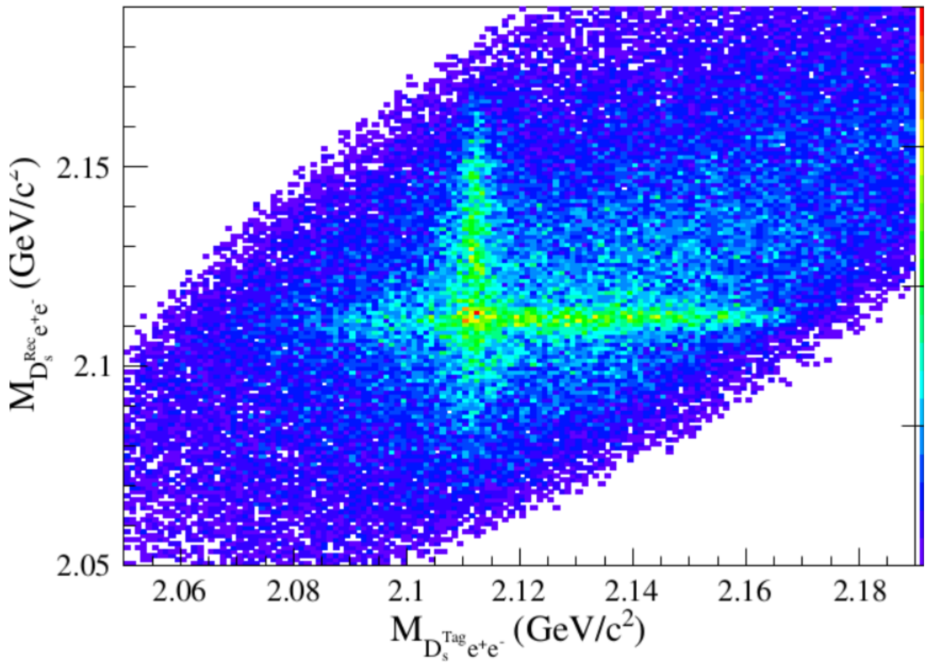
$$p_{D_s^T e^+e^-} = p_{D_s^T} + p_{e^+e^-}$$
$$p_{D_s^R e^+e^-} = p_{cms} - p_{D_s^T}$$
$$p_{D_s^R} = p_{cms} - p_{D_s^T} - p_{e^+e^-}$$

Cancel the correlation

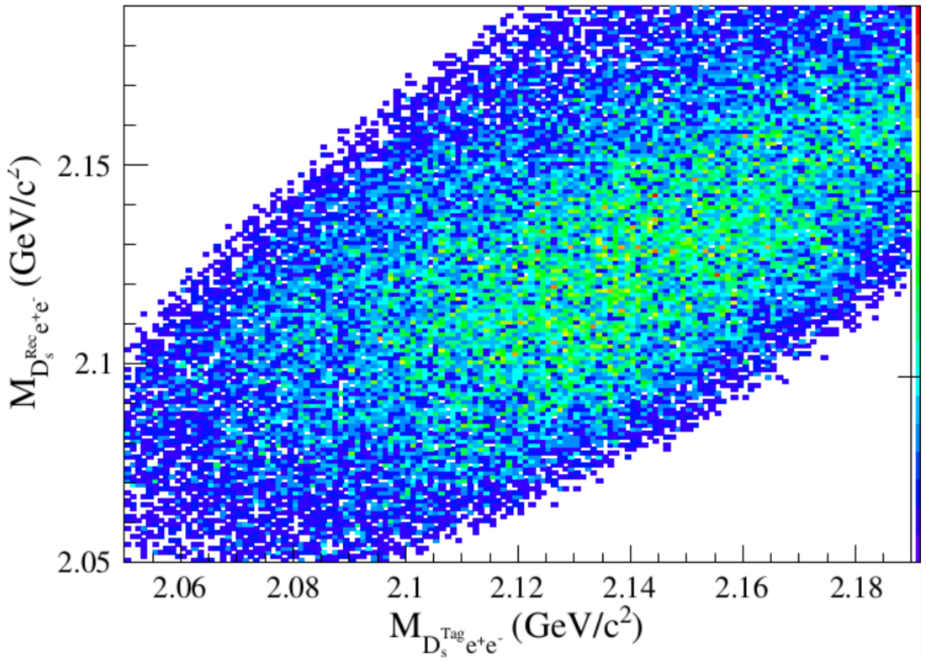
Use these two signal parameters:

$$M_{D_s^{Tag} e^+e^-} = M_{D_s^T e^+e^-} - M_{D_s^T} + M_{D_s\,PDG}$$
$$M_{D_s^{Rec} e^+e^-} = M_{D_s^R e^+e^-} - M_{D_s^R} + M_{D_s\,PDG}$$

Signal Fitting

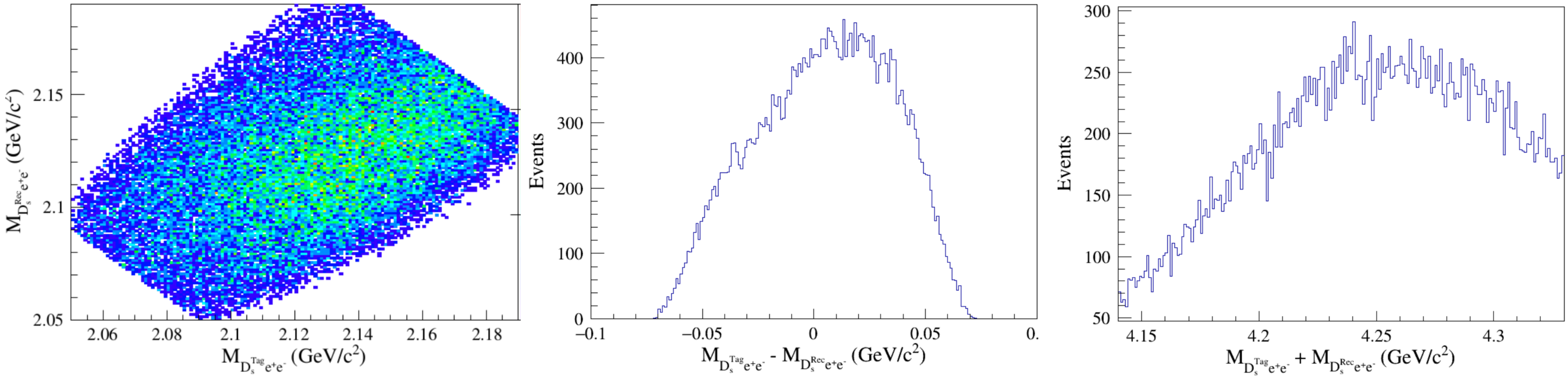


Inclusive MC

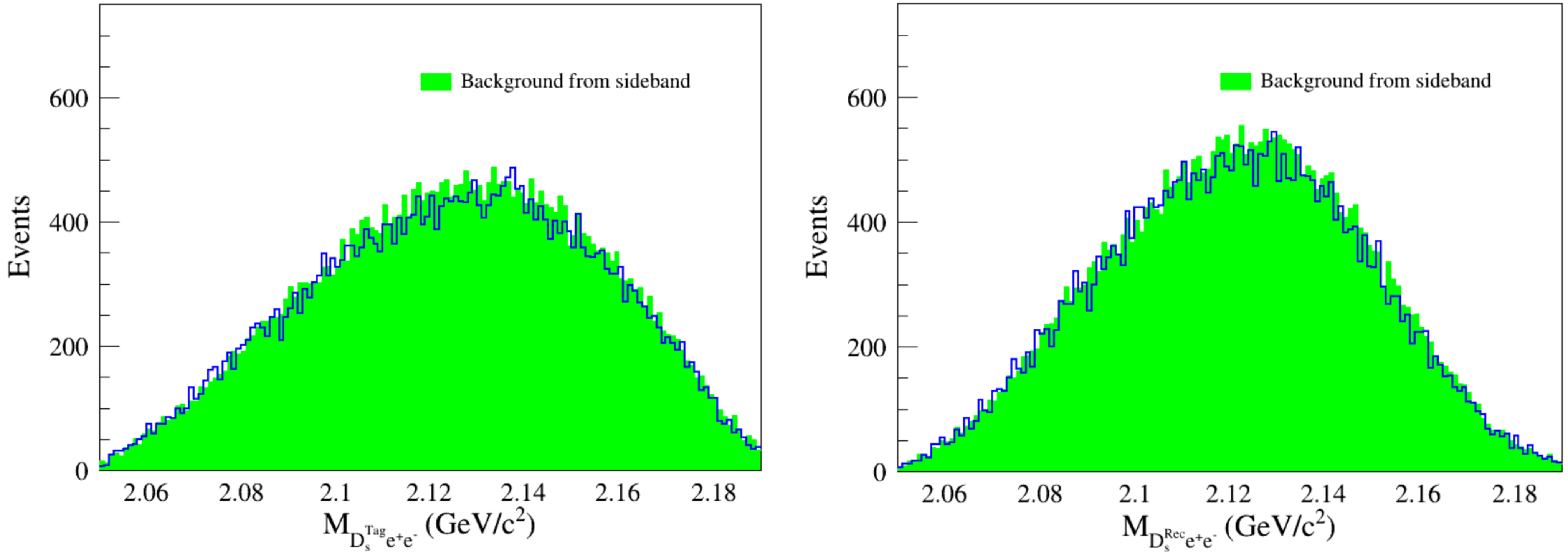


Background from inclusive MC

Signal Fitting



Signal Fitting



Background from inclusive MC

Signal Fitting

$$\begin{cases} PDF_{i\,D_s^{dau}} = N_{iD_s^{dau}} PDF_{i\,D_s^{dau}} + N_{bkg\,i\,D_s^{bac}} PDF_{i\,bac} + N_{bkg\,i\,D_s^{dau}} PDF_{i\,BKGD_s^{dau}} \\ PDF_{i\,D_s^{bac}} = N_{iD_s^{bac}} PDF_{i\,D_s^{bac}} + N_{bkg\,i\,D_s^{dau}} PDF_{i\,dau} + N_{bkg\,i\,D_s^{bac}} PDF_{i\,BKGD_s^{bac}} \end{cases}$$

$$\begin{cases} N_{bkg\,i\,D_s^{bac}} = Scale_{dau} \times N_{iD_s^{bac}} \\ N_{bkg\,i\,D_s^{dau}} = Scale_{bac} \times N_{iD_s^{dau}} \end{cases}$$

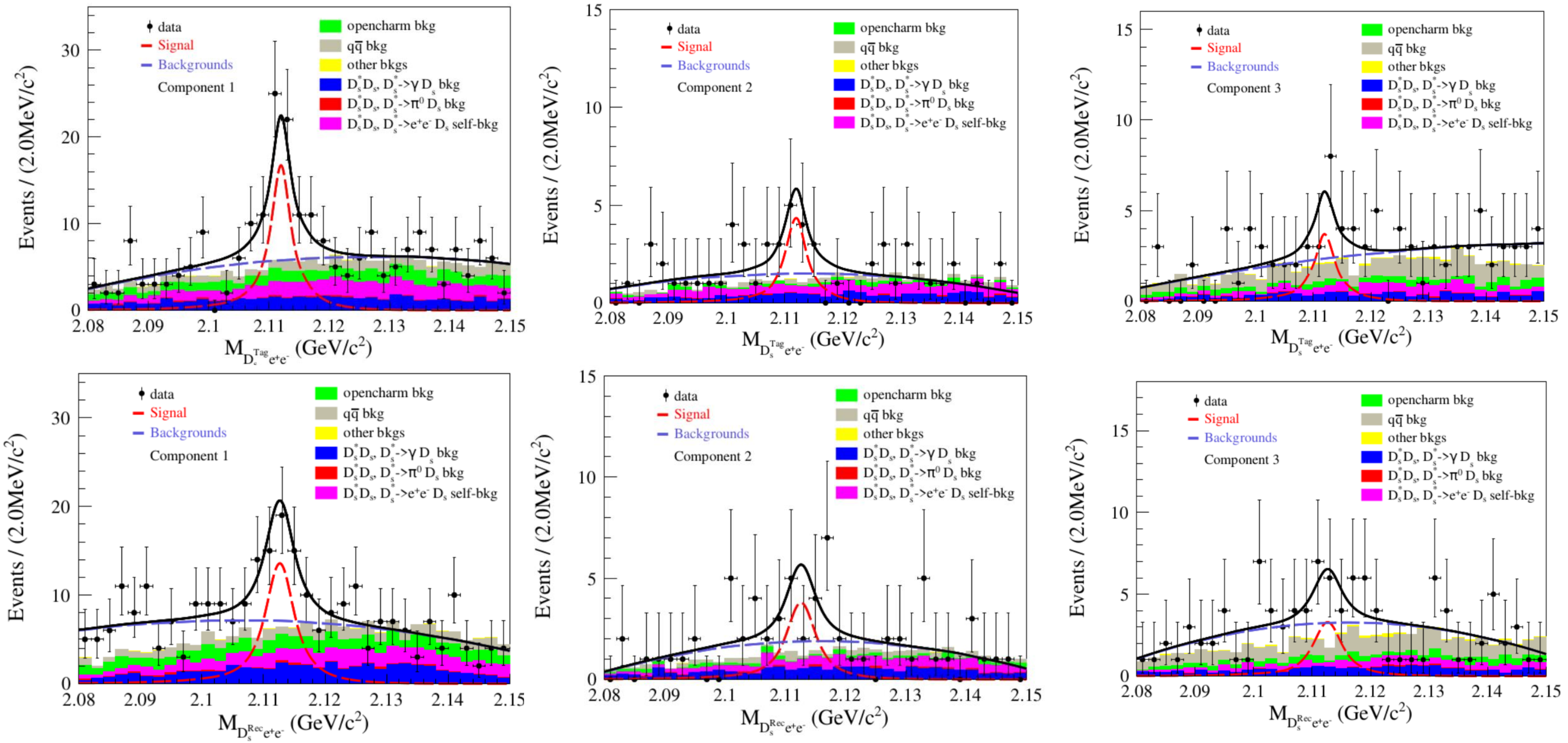
$$\begin{cases} PDF_{i\,BKGD_s^{dau}}: 2^{nd}\text{ Chebyshev ploynomial} \\ PDF_{i\,BKGD_s^{bac}}: 2^{nd}\text{ Chebyshev ploynomial} \end{cases}$$

$$\begin{cases} PDF_{i\,D_s^{dau}} = Shape_{i\,D_s^{dau}} \otimes Gauss(\mu_1, \sigma_1) \\ PDF_{i\,D_s^{bac}} = Shape_{i\,D_s^{bac}} \otimes Gauss(\mu_2, \sigma_2) \end{cases}$$

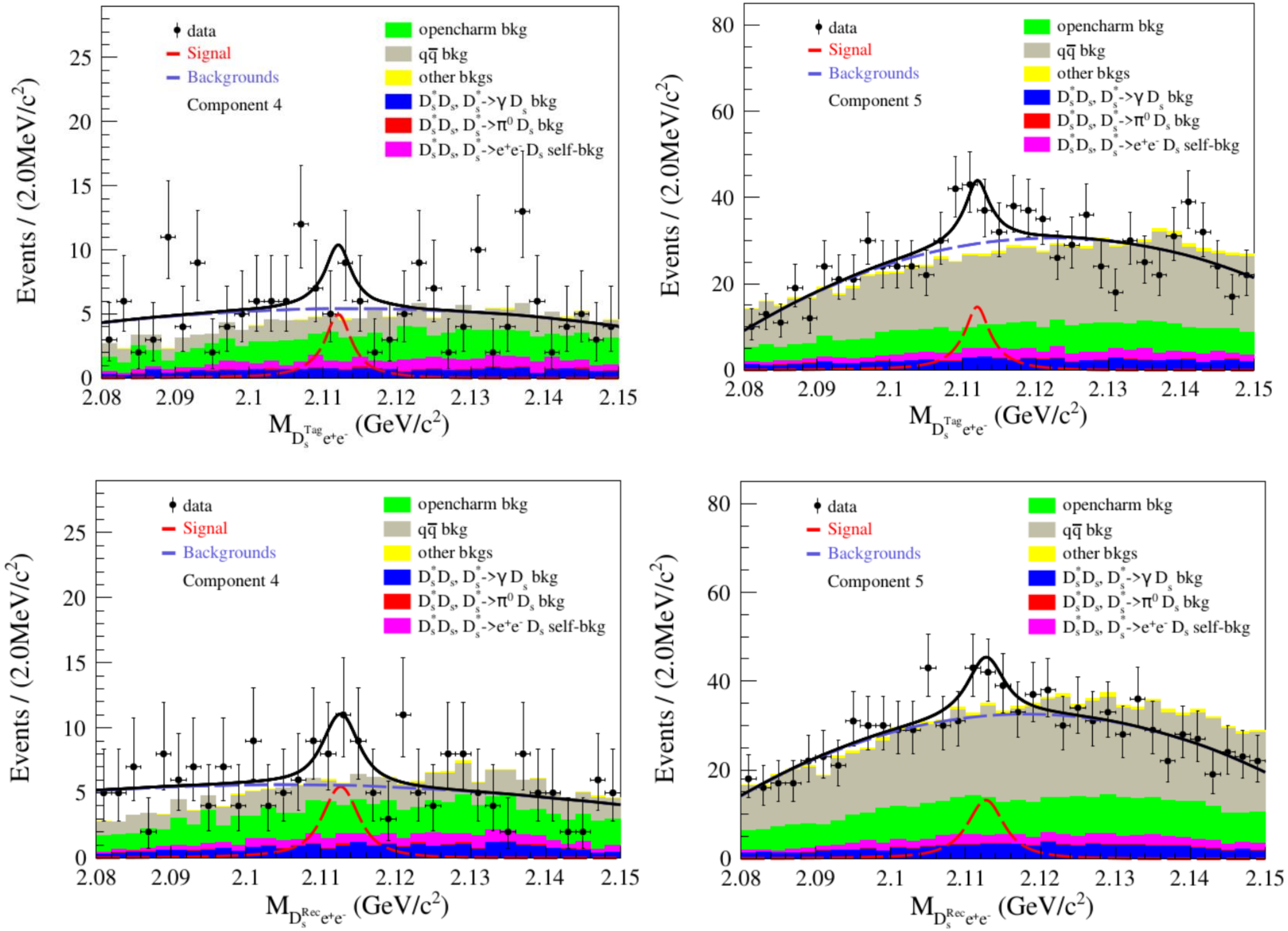
$$\boldsymbol{Likelihood} = \prod_{\boldsymbol{i}} \boldsymbol{L_{iD_s^{dau}} L_{iD_s^{bac}}}$$

Component 1	**Component 3**	**Component 5**
$D_s^+ \to K^+K^-\pi^+$	$D_s^+ \to K_S^0 K^-\pi^+\pi^+$	$D_s^+ \to \pi^+\pi^-\pi^+$
Component 2	$D_s^+ \to \pi^+\eta$	$D_s^+ \to \pi^+\pi^0\eta$
$D_s^+ \to K_S^0 K^+$	**Component 4**	$D_s^+ \to \pi^+\eta', \eta' \to \gamma\rho^0, \rho^0 \to \pi^+\pi^-$
$D_s^+ \to \pi^+\eta', \eta' \to \pi^+\pi^-\eta$	$D_s^+ \to K_S^0 K^+\pi^0$	$D_s^+ \to K^+\pi^-\pi^+$
	$D_s^+ \to K^+K^-\pi^+\pi^0$	Sum

Signal Fitting



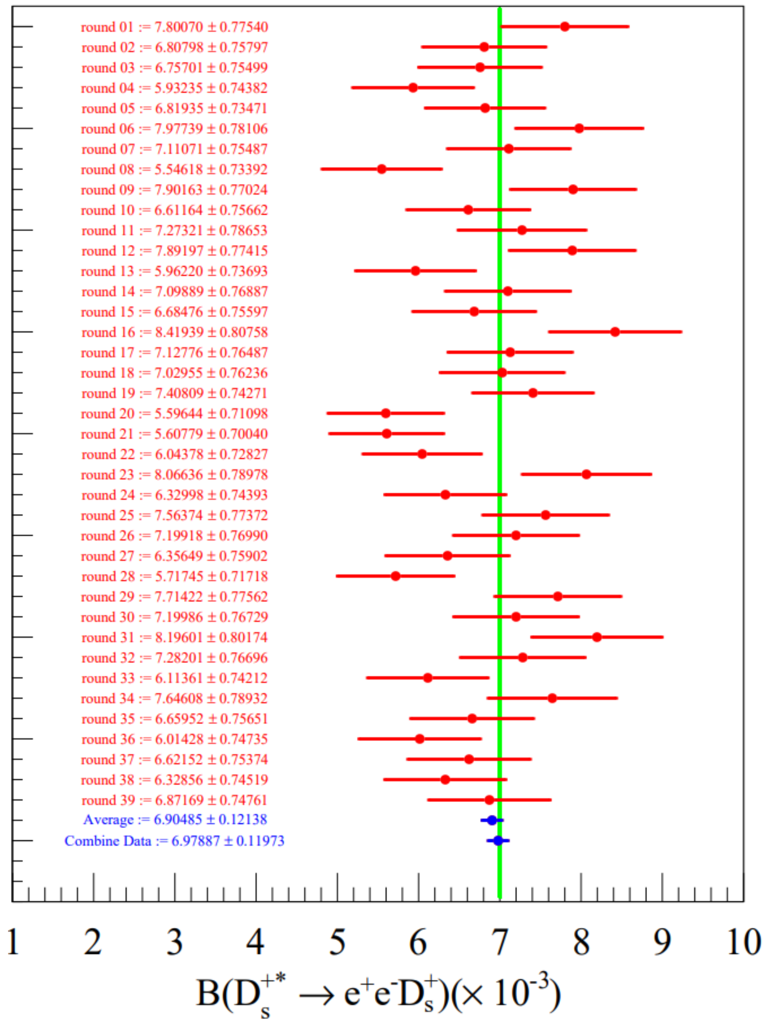
Signal Fitting

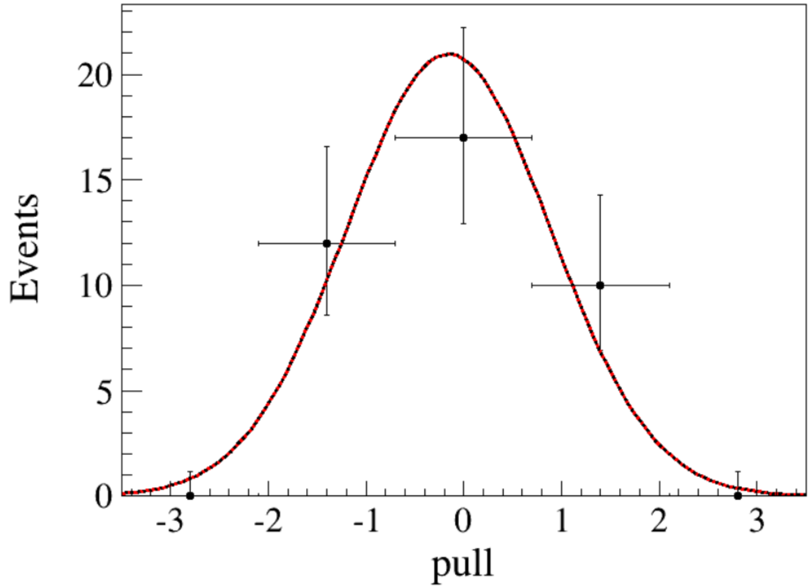


	Results
This work	$(\mathbf{8.89 \pm 1.15}) \times \mathbf{10^{-3}}$
CLEO-c	$\left(\mathbf{6.7^{+1.4}_{-1.2} \pm 0.9}\right) \times \mathbf{10^{-3}}$

	Statistical Uncertainty(%)
This work	**12.94**
CLEO-c	**18~21**

IO Check





	Result
mean	-0.1555 ± 0.1666
sigma	1.0401 ± 0.1212

Summary and Next to do

- ✓ We have a preliminary result about $\mathcal{B}(D_s^{+*} \to D_s^+ e^+ e^-) = (8.89 \pm 1.15) \times 10^{-3}$ using data at 4.180 GeV.
- ✓ IO Check of branching fraction has been finished.

	Results
This work	$(\mathbf{8.89 \pm 1.15}) \times \mathbf{10^{-3}}$
CLEO-c	$(\mathbf{6.7^{+1.4}_{-1.2} \pm 0.9}) \times \mathbf{10^{-3}}$

	Statistical Uncertainty(%)
This work	**12.94**
CLEO-c	**18~21**

- Next to do:
- Using 2D fitting to get a correct statistical uncertainty (almost done).
- Try the method to extract the form factor (almost done).
- Add more data at 4.190 4.200, 4.210, 4.220, 4.230.
- Systematic uncertainty

Thanks!