Measurement of branching fractions of $D^+ \to K^+K^-\pi^+\pi^+\pi^-$ and $K^0_S K^+\pi^+\pi^-\pi^0$

Physics & Software Meeting

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Introduction

- Since the discovery of D mesons in 1976, their decays have been extensively studied. However, many hadronic D decays remain unmeasured.
- The BFs of hadronic D decays provide important information for testing lepton flavor universality in B physics [PLB781,368].
- Combining measured BFs with partial wave analysis results helps study quark SU(3) symmetry and its breaking effects.
- CP violation in charm decays is crucial for understanding the universe's asymmetry. CP violation was observed in D decays at the LHCb in 2019 [PRL122,211803].
- Our goal is to measure the BFs of unknown hadronic D decays.

Single tag

$$N^{obs}_{tag} = 2N_{D^+D^-}\mathcal{B}_{tag}\epsilon_{tag}$$
$$N^{obs}_{sig} = 2N_{D^+D^-}\mathcal{B}_{tag}\mathcal{B}_{sig}\epsilon_{tag,sig}$$
$$\mathcal{B}_{sig} = \frac{N^{obs,\alpha}_{sig}}{\Sigma_\alpha N^{obs,\alpha}_{tag}\epsilon^{\alpha}_{tag,sig}/\epsilon^{\alpha}_{tag}}$$

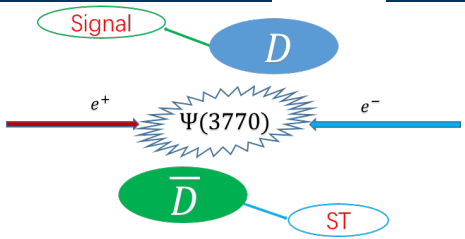
N^{obs}_{sig} : *Signal yields*

N^{obs}_{tag} : *Single tag yields*

$\epsilon_{tag,sig}$: *Double tag efficiency*

ϵ_{tag} : *Single tag efficiency*

α : *Six single tag modes*



Event selection

Charge track : $|V_{xy}| < 1cm$ $\quad |V_z| < 10cm$ $\quad |\cos\theta| < 0.93$

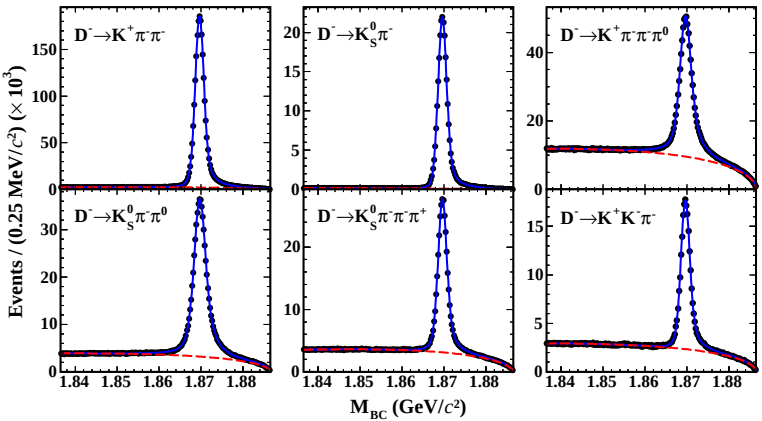
$K^0_S \to \pi^+\pi^-$: no PID performed on π $\quad |\cos\theta| < 0.93$
$M_{\pi^+\pi^-} \in (0.4857, 0.5097) GeV/c^2$ $\quad |R_z| < 20.0cm$
Vertex fit: $\chi^2 < 100$ $\quad 2^{\text{nd}}$vertex fit: $L/\sigma > 2$

PID : $K : \mathrm{CL}_K > \mathrm{CL}_\pi, \mathrm{CL}_K > 0$ $\quad dE/dx + TOF$
$\pi : \mathrm{CL}_\pi > \mathrm{CL}_K, \mathrm{CL}_\pi > 0$

Photon : $0 \le t_{TDC} \le 14 (\times 50\,\text{ns})$
Barrel : $|\cos\theta| < 0.8, E^{Barrel}_{\gamma,EMC} > 25MeV$
Endcap : $0.86 < |\cos\theta| < 0.92, E^{Endcap}_{\gamma,EMC} > 25MeV$

π^0 : Mass constraint fit on $\quad \pi^0(\gamma\gamma) : \chi^2 < 50$
$\pi^0 \in (0.115, 0.150) GeV/c^2$

$Double - Gaussian(signal) + ARGUS(BKG)$



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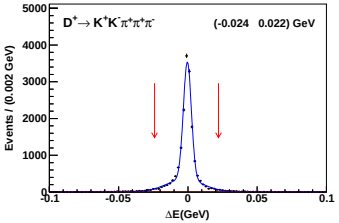
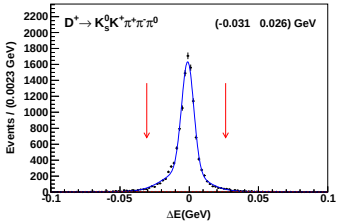
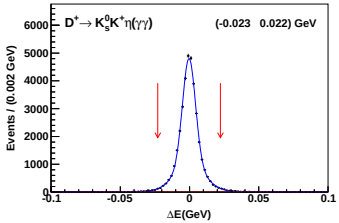
Cut for Fitting

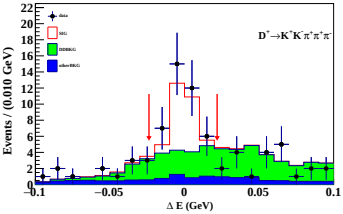
- common cut
  - $|\Delta E_{tag}| \in 3.5\sigma$
  - $|M^{sig}_{\pi^+\pi^-} - 0.4977| > 0.02 GeV/c^2$
  - $|M_{K^0_S} - 0.4977| < 0.012 GeV/c^2$
  - $\theta_{D\overline{D}} > 160^\circ$
- additional cut for fitting ΔE_{sig}
  - $1.863 GeV/c^2 < M^{tag(sig)}_{BC} < 1.877 GeV/c^2$
- additional cut for fitting M^{sig}_{BC}
  - $\Delta E_{sig} \in 3\sigma$
- additional cut for fitting others
  - $\Delta E_{sig} \in 3\sigma$
  - $1.863 GeV/c^2 < M^{tag(sig)}_{BC} < 1.877 GeV/c^2$

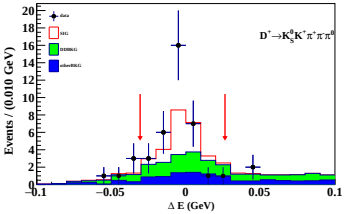
Fitting ΔE_{sig} at 3σ signal region

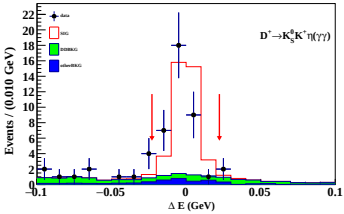




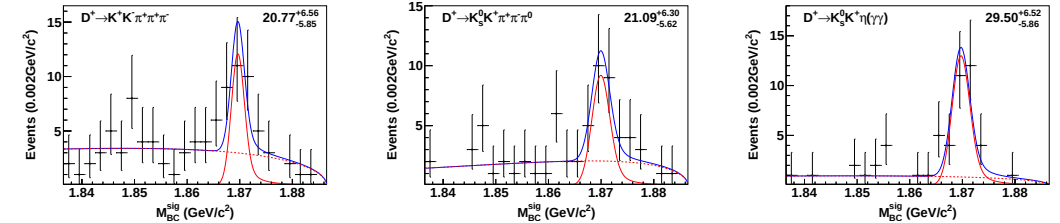






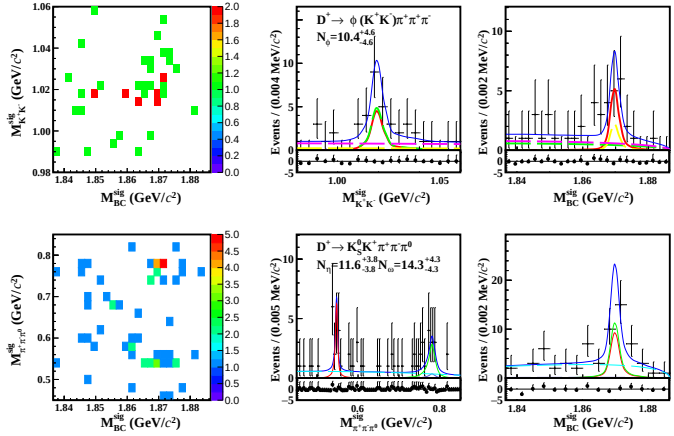


Fitting M_{BC}^{sig}

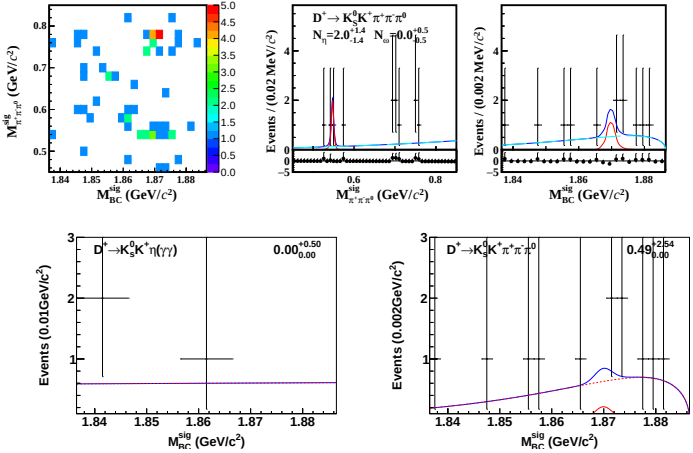


$$\textit{Truth shape} \otimes \textit{Gaussian}(\textit{signal}) + \textit{ARGUS}(\textit{background})$$

FITTING M_{BC}^{sig}



SigMC shape(signal) + ARGUS(background)


$M^{sig}_{\pi^+\pi^-\pi^0}$ (GeV/c^2)
M^{sig}_{BC} (GeV/c^2)
$D^+ \to K^0_S K^+\pi^+\pi^-\pi^0$
$N_\eta = 2.0^{+1.4}_{-1.4}$ $N_{\omega} = 0.0^{+0.5}_{0.5}$
Events / (0.02 MeV/c^2)
$M^{sig}_{\pi^+\pi^-\pi^0}$ (GeV/c^2)
Events / (0.002 MeV/c^2)
M^{sig}_{BC} (GeV/c^2)
$D^+ \to K^0_S K^+\eta(\gamma\gamma)$
$0.00^{+0.50}_{0.00}$
Events (0.01GeV/c^2)
M^{sig}_{BC} (GeV/c^2)
$D^+ \to K^0_S K^+\pi^+\pi^-\pi^0$
$0.49^{+2.54}_{0.00}$
Events (0.002GeV/c^2)
M^{sig}_{BC} (GeV/c^2)

Decay modes of $D^+ \to K^+K^-\pi^+\pi^+\pi^-$

$$
\begin{aligned}
D^+ &\to K^+K^-\pi^+\pi^+\pi^- \\
&\to \phi\pi^+\pi^+\pi^-, \phi \to K^+K^- && (62\%) \\
&\to K^+K^-\pi^+\pi^+\pi^- && (38\%)
\end{aligned}
$$

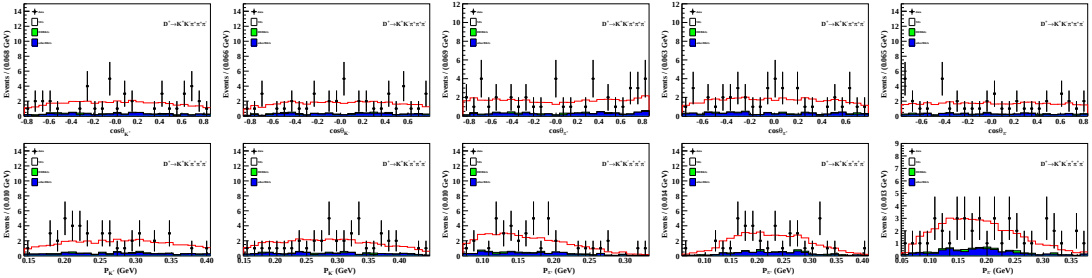
$$
\begin{aligned}
D^+ &\to K^0_S K^+\pi^+\pi^-\pi^0 \\
&\to \overline{K'}{}^0_1 K^+,\ \overline{K'}{}^0_1 \to \omega\overline{K}^0, \overline{K}^0 \to K^0_S, \omega \to \pi^-\pi^+\pi^0 && (41.0\%) \\
&\to \overline{K'}{}^+_1 K^0_S,\ \overline{K'}{}^+_1 \to \omega K^+, \omega \to \pi^-\pi^+\pi^0 && (32.1\%) \\
&\to K^0_S K^+\eta, \eta \to \pi^-\pi^+\pi^0 && (26.9\%)
\end{aligned}
$$

$D^+ \to K^+K^-\pi^+\pi^+\pi^-$

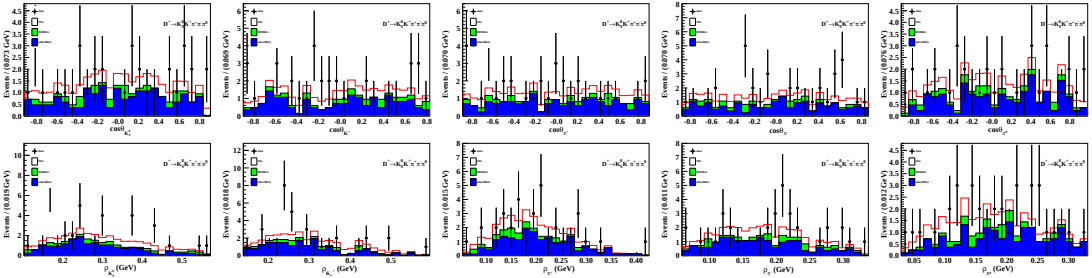
Tag modes	$N_{\rm gen}$	$N_{\rm obs}^{\rm sig}$	$\epsilon_{\rm tag}(\%)$	$\epsilon_{\rm tag,sig}(\%)$	$\epsilon_{\rm sig}(\%)$	Weight
$K^+\pi^-\pi^-$	100000	4403 ± 68	52.44 ± 0.01	4.40 ± 0.09	8.40 ± 0.17	7.74 ± 0.11
$K^0_S\pi^-$	100000	4174 ± 67	51.89 ± 0.02	4.17 ± 0.09	8.04 ± 0.17	
$K^+\pi^-\pi^-\pi^0$	100000	1769 ± 45	27.19 ± 0.01	1.77 ± 0.08	6.51 ± 0.29	
$K^0_S\pi^-\pi^0$	100000	1906 ± 45	27.57 ± 0.01	1.91 ± 0.08	6.91 ± 0.29	
$K^0_S\pi^-\pi^-\pi^+$	100000	2093 ± 48	29.68 ± 0.01	2.09 ± 0.08	7.05 ± 0.27	
$K^+K^-\pi^-$	100000	3380 ± 61	42.05 ± 0.02	3.38 ± 0.09	8.04 ± 0.20	

In the case of the decay mentioned above,
the final efficiency is obtained by weighting through single-tag channels,
other decay channels can be found in the backup slides.

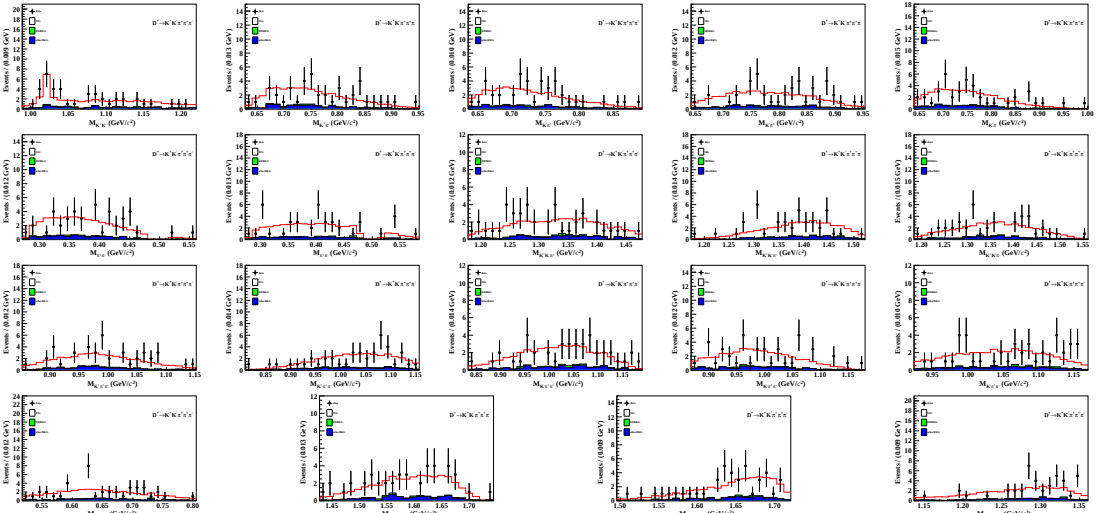
Angle and Momentum of $D^+ \to K^+K^-\pi^+\pi^+\pi^-$



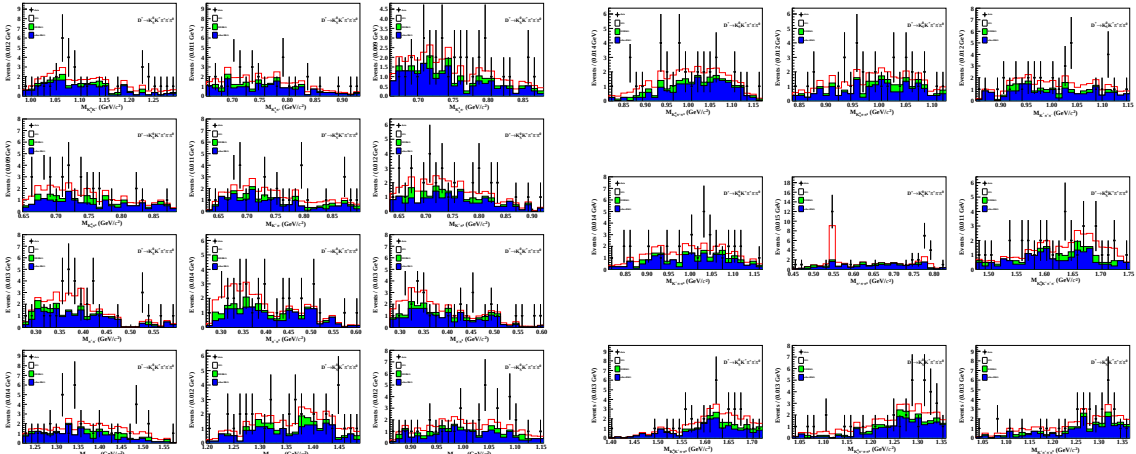
Angle and Momentum of $D^+ \to K^0_S K^+ \pi^+ \pi^- \pi^0$



Invariant mass of $D^+ \to K^+K^-\pi^+\pi^+\pi^-$



Invariant mass of $D^+ \to K^0_S K^+ \pi^+ \pi^- \pi^0$



Results of Branching Fractions

Decay mode	$N_{\rm data,net}$	$N_{\rm tag}$	$\epsilon_{\rm sig}(\%)$	$\mathcal{B}_{\rm sig}(\times 10^{-4})$	Significance
$K^+K^-\pi^+\pi^+\pi^-$	$20.8^{+6.6}_{-5.9}$	4296647 ± 2438	7.74 ± 0.11	$0.62^{+0.20}_{-0.18}$	4.0
$K^0_S K^+\pi^+\pi^-\pi^0$	$21.1^{+6.3}_{-5.6}$		3.90 ± 0.08	$1.84^{+0.55}_{-0.49}$	4.4
$K^0_S K^+\eta(\gamma\gamma)$	$29.5^{+6.5}_{-5.9}$		15.10 ± 0.15	$1.68^{+0.37}_{-0.33}$	6.8
$K^0_S K^+\eta(\pi^+\pi^-\pi^0)$	$10.5^{+3.9}_{-3.9}$		6.49 ± 0.10	$2.41^{+0.87}_{-0.87}$	4.0
$K^0_S K^+\omega(\pi^+\pi^-\pi^0)$	$14.3^{+4.3}_{-4.3}$		3.23 ± 0.07	$1.69^{+0.51}_{-0.51}$	3.8
$\phi(K^+K^-)\pi^+\pi^+\pi^-$	$10.4^{+4.6}_{-4.6}$		6.34 ± 0.10	$0.77^{+0.35}_{-0.35}$	2.1

Decay mode	$\mathcal{B}(\times 10^{-4})$	$\mathcal{B}_{PDG}(\times 10^{-4})$
$D^+ \to K^+K^-\pi^+\pi^+\pi^-$	$0.62^{+0.20}_{-0.18}$	2.3 ± 1.2
$D^+ \to K^0_S K^+\eta(\gamma\gamma)$	$1.68^{+0.37}_{-0.33}$	1.8 ± 0.5
$D^+ \to K^0_S K^+\eta(\pi^+\pi^-\pi^0)$	$2.41^{+0.87}_{-0.87}$	

The top table shows the final results, the left table displaying the comparison between the results and the PDG values.

Systematic uncertainties

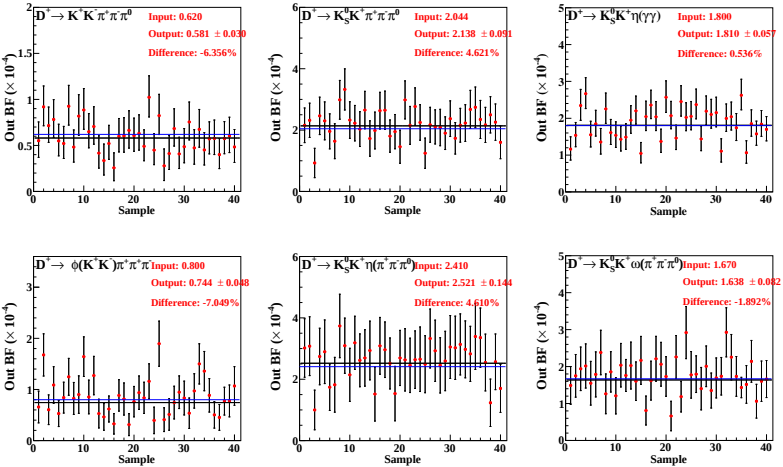
Decay modes	1	2	3	4	5	6
$N_{\rm tag}$	0.1	0.1	0.1	0.1	0.1	0.1
$(K/\pi)^{\pm}$ tracking	3.0	5.0	1.0	3.0	3.0	5.0
$(K/\pi)^{\pm}$ PID	3.0	5.0	1.0	3.0	3.0	5.0
K^0_S reconstruction	2.0	-	2.0	2.0	2.0	-
$\eta\&\pi^0$ reconstruction	3.3	-	-	3.3	3.3	-
K^0_S rejection	0.0	0.0	-	0.0	0.0	0.0
$\mathcal{B}_{\rm sub-decay}$	0.08	-	0.5	1.2	0.8	1.0
$\Delta E_{\rm sig}$ cut	1.6	0.2	0.0	1.6	1.6	0.2
Mass fit	6.3	1.6	9.0	3.8	3.7	4.0
MC generator	6.2	2.6	-	6.2	6.2	2.6
MC statistics	1.8	1.3	1.7	2.0	3.6	1.6
Total	10.6	7.8	9.5	9.5	9.7	8.6

Relative systematic uncertainties (%) in the measurements of the BFs of $D^+ \to$

(1) $K^0_S K^+\pi^+\pi^-\pi^0$,
(2) $K^+K^-\pi^+\pi^+\pi^-$,
(3) $K^0_S K^+\eta(\gamma\gamma)$,
(4) $K^0_S K^+\eta(\pi^+\pi^-\pi^0)$,
(5) $K^0_S K^+\omega(\pi^+\pi^-\pi^0)$,
(6) $\phi(K^+K^-)\pi^+\pi^+\pi^-$

The leftmost column in the table displays all the considered items.

IO CHECK



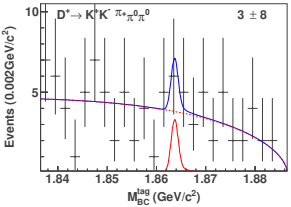
The left displays the difference of the BFs between the input and output in the 40$\times$MC sample.

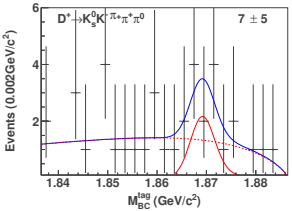
Summary

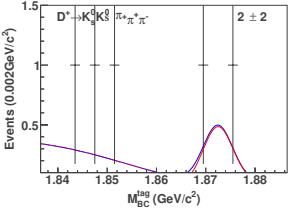
- By analyzing an e^+e^- annihilation data of 7.9 fb^{-1} collected at $\sqrt{s} = 3.773$ GeV with the BESIII detector:
  - improved precision:
    - $D^+ \to K^+K^-\pi^+\pi^+\pi^-$
    - $D^+ \to K^0_S K^+ \eta$
  - measured for the first time:
    - $D^+ \to K^0_S K^+\pi^+\pi^-\pi^0$
    - $D^+ \to \phi\pi^+\pi^+\pi^-$
    - $D^+ \to K^0_S K^+ \omega$

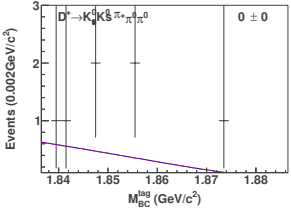
Thank You!

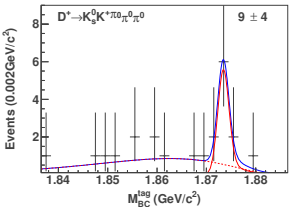
Backup slides











$D^+ \to K^0_S K^+ \pi^+ \pi^- \pi^0$

Tag modes	$N_{\rm gen}$	$N^{\rm sig}_{\rm obs}$	$\epsilon_{\rm tag}(\%)$	$\epsilon_{\rm tag,sig}(\%)$	$\epsilon_{\rm sig}(\%)$	Weight
$K^+\pi^-\pi^-$	100000	2286 ± 51	52.44 ± 0.01	2.29 ± 0.06	4.36 ± 0.12	3.90 ± 0.08
$K^0_S\pi^-$	100000	2322 ± 51	51.89 ± 0.02	2.32 ± 0.07	4.47 ± 0.13	
$K^+\pi^-\pi^-\pi^0$	100000	788 ± 31	27.19 ± 0.01	0.79 ± 0.05	2.90 ± 0.20	
$K^0_S\pi^-\pi^0$	100000	939 ± 33	27.57 ± 0.01	0.94 ± 0.06	3.40 ± 0.21	
$K^0_S\pi^-\pi^-\pi^+$	100000	979 ± 34	29.68 ± 0.01	0.98 ± 0.06	3.30 ± 0.19	
$K^+K^-\pi^-$	100000	1737 ± 44	42.05 ± 0.02	1.74 ± 0.06	4.13 ± 0.15	

$D^+ \to K^0_S K^+ \omega(\pi^+\pi^-\pi^0)$

Tag modes	$N_{\rm gen}$	$N^{\rm sig}_{\rm obs}$	$\epsilon_{\rm tag}(\%)$	$\epsilon_{\rm tag,sig}(\%)$	$\epsilon_{\rm sig}(\%)$	Weight
$K^+\pi^-\pi^-$	100000	1924 ± 45	52.44 ± 0.01	1.92 ± 0.06	3.67 ± 0.11	3.23 ± 0.07
$K^0_S\pi^-$	100000	1854 ± 44	51.89 ± 0.02	1.85 ± 0.06	3.57 ± 0.11	
$K^+\pi^-\pi^-\pi^0$	100000	638 ± 27	27.19 ± 0.01	0.64 ± 0.05	2.34 ± 0.18	
$K^0_S\pi^-\pi^0$	100000	751 ± 21	27.57 ± 0.01	0.75 ± 0.05	2.72 ± 0.19	
$K^0_S\pi^-\pi^-\pi^+$	100000	781 ± 29	29.68 ± 0.01	0.78 ± 0.05	2.63 ± 0.17	
$K^+K^-\pi^-$	100000	1507 ± 40	42.05 ± 0.02	1.51 ± 0.06	3.58 ± 0.14	

$D^+ \to K^0_S K^+ \eta(\pi^+\pi^-\pi^0)$

Tag modes	$N_{\rm gen}$	$N^{\rm sig}_{\rm obs}$	$\epsilon_{\rm tag}(\%)$	$\epsilon_{\rm tag,sig}(\%)$	$\epsilon_{\rm sig}(\%)$	Weight
$K^+\pi^-\pi^-$	100000	3768 ± 63	52.44 ± 0.01	3.77 ± 0.08	7.19 ± 0.16	6.49 ± 0.10
$K^0_S\pi^-$	100000	3870 ± 64	51.89 ± 0.02	3.87 ± 0.08	7.46 ± 0.16	
$K^+\pi^-\pi^-\pi^0$	100000	1374 ± 39	27.19 ± 0.01	1.37 ± 0.07	5.05 ± 0.25	
$K^0_S\pi^-\pi^0$	100000	1539 ± 40	27.57 ± 0.01	1.54 ± 0.07	5.58 ± 0.26	
$K^0_S\pi^-\pi^-\pi^+$	100000	1622 ± 42	29.68 ± 0.01	1.62 ± 0.07	5.46 ± 0.24	
$K^+K^-\pi^-$	100000	2980 ± 56	42.05 ± 0.02	2.98 ± 0.08	7.09 ± 0.19	

$D^+ \to K^0_S K^+ \eta(\gamma\gamma)$

Tag modes	$N_{\rm gen}$	$N^{\rm sig}_{\rm obs}$	$\epsilon_{\rm tag}(\%)$	$\epsilon_{\rm tag,sig}(\%)$	$\epsilon_{\rm sig}(\%)$	Weight
$K^+\pi^-\pi^-$	100000	8497 ± 100	52.44 ± 0.01	8.50 ± 0.12	16.20 ± 0.22	15.10 ± 0.15
$K^0_S\pi^-$	100000	8426 ± 100	51.89 ± 0.02	8.43 ± 0.12	16.24 ± 0.22	
$K^+\pi^-\pi^-\pi^0$	100000	3422 ± 63	27.19 ± 0.01	3.42 ± 0.10	12.59 ± 0.39	
$K^0_S\pi^-\pi^0$	100000	3802 ± 68	27.57 ± 0.01	3.80 ± 0.11	13.79 ± 0.40	
$K^0_S\pi^-\pi^-\pi^+$	100000	4233 ± 71	29.68 ± 0.01	4.23 ± 0.11	14.26 ± 0.37	
$K^+K^-\pi^-$	100000	6700 ± 90	42.05 ± 0.02	6.70 ± 0.12	15.93 ± 0.28	

$D^+ \to \phi(K^+K^-)\pi^+\pi^+\pi^-$

Tag modes	$N_{\rm gen}$	$N_{\rm obs}^{\rm sig}$	$\epsilon_{\rm tag}(\%)$	$\epsilon_{\rm tag,sig}(\%)$	$\epsilon_{\rm sig}(\%)$	Weight
$K^+\pi^-\pi^-$	100000	3556 ± 62	52.44 ± 0.01	3.56 ± 0.08	6.78 ± 0.15	6.34 ± 0.10
$K^0_S\pi^-$	100000	3472 ± 60	51.89 ± 0.02	3.47 ± 0.08	6.69 ± 0.15	
$K^+\pi^-\pi^-\pi^0$	100000	1438 ± 40	27.19 ± 0.01	1.44 ± 0.07	5.29 ± 0.26	
$K^0_S\pi^-\pi^0$	100000	1606 ± 206	27.57 ± 0.01	1.61 ± 0.07	5.83 ± 0.27	
$K^0_S\pi^-\pi^-\pi^+$	100000	1835 ± 20	29.68 ± 0.01	1.83 ± 0.08	6.18 ± 0.26	
$K^+K^-\pi^-$	100000	2796 ± 53	42.05 ± 0.02	2.80 ± 0.08	6.65 ± 0.19	