Study of $D^+ \to \mu^+ \nu_\mu$ in STCF

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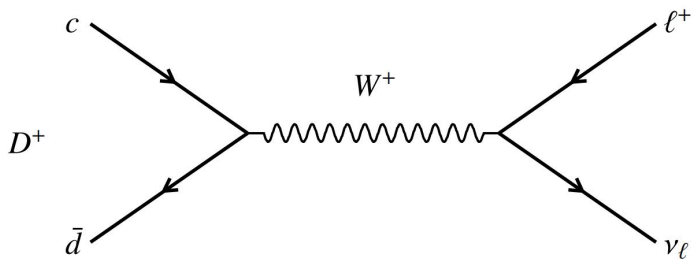
Outline

Motivation

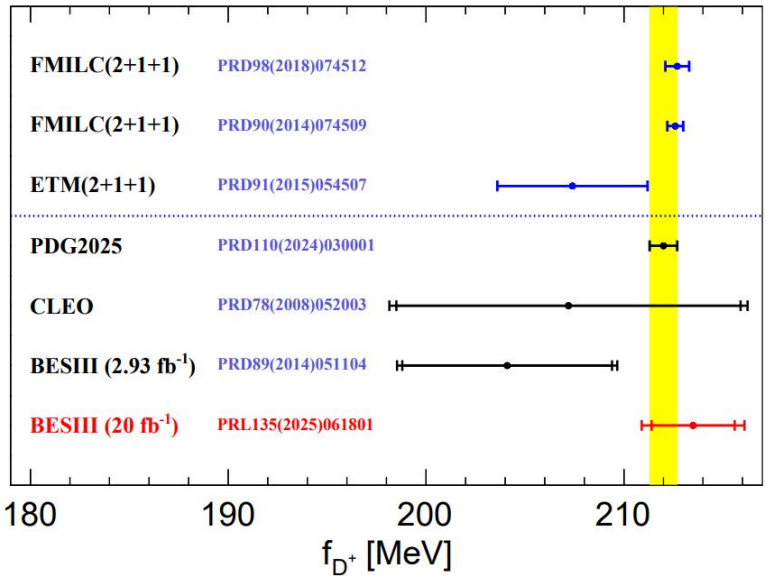


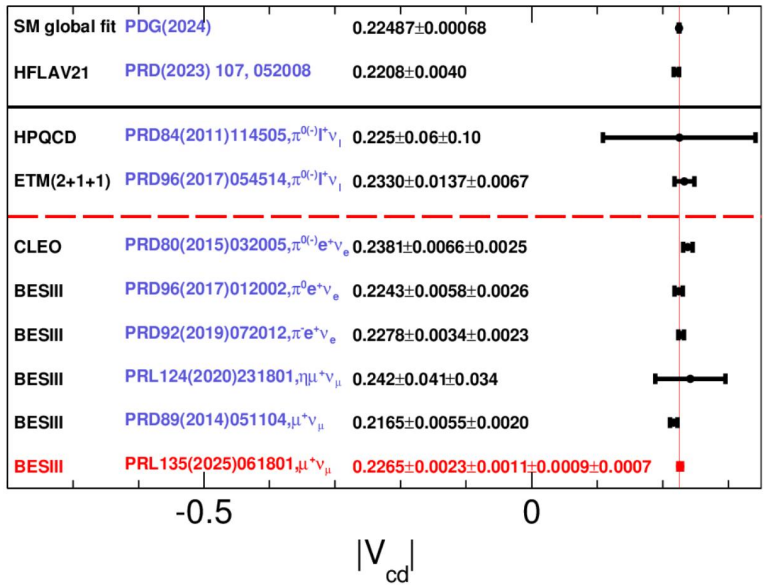
$$\Gamma(D^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{cd}|^2 f_{D^+}^2 m_{\ell^+}^2 m_{D^+}(1 - \frac{m_{\ell^+}^2}{m_{D^+}^2})^2$$

Fig. 1: The Feynman diagram of the leptonic decay $D^+ \to \ell^+\nu_\ell$.

- Measurement of the bf of $D^+ \to l^+\nu_l$ is important to determine f_{D^+} to validate the calculation in LQCD,and better $|V_{cd}|$ to test the unitarity of the CKM matrix.
- Test on τ - μ lepton flavor universality in charm sector.
- With the predicted $f_{D^+} : f_{D_s^+} : f_B$, the measured f_{D^+} and $f_{D_s^+}$ are crucial to test different theoretical calculations of the decay constants and help discriminate different models and indirectly improve f_B.

Motivation





Experiment	$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$ $(\times 10^{-4})$
MARK-III [26]	< 7.2
BESI [27]	8^{+16+5}_{-5-2}
BESII [29]	$12.2^{+11.1}_{-5.3} \pm 1.0$
CLEO [30]	$3.5 \pm 1.4 \pm 0.6$
CLEO [31]	$4.40 \pm 0.66^{+0.09}_{-0.12}$
CLEO [32]	$3.82 \pm 0.32 \pm 0.09$
BESIII [33]	$3.71 \pm 0.19 \pm 0.06$
BESIII [34]	$3.74 \pm 0.17 \pm 0.06$

Experiment	Decay chain	$\mathcal{B}$ (%)
CLEO-c [13]	$D_s^+ \to \mu^+\nu_\mu$	$0.594 \pm 0.066 \pm 0.031$
CLEO-c [14]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to \rho^+\bar{\nu}_\tau)$	$0.552 \pm 0.057 \pm 0.021$
CLEO-c [15]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$	$0.530 \pm 0.047 \pm 0.022$
Babar [16]	$D_s^+ \to e^+\nu_e$	< 0.023
Babar [16]	$D_s^+ \to \mu^+\nu_\mu$	$0.602 \pm 0.038 \pm 0.034$
Babar [16]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$	$0.507 \pm 0.052 \pm 0.068$
Babar [16]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau)$	$0.491 \pm 0.047 \pm 0.054$
Belle [17]	$D_s^+ \to \mu^+\nu_\mu$	$0.644 \pm 0.076 \pm 0.057$
Belle [18]	$D_s^+ \to e^+\nu_e$	< 0.01
Belle [18]	$D_s^+ \to \mu^+\nu_\mu$	$0.531 \pm 0.028 \pm 0.020$
Belle [18]	$D_s^+ \to \tau^+\nu_\tau$	$0.570 \pm 0.021^{-0.031}_{-0.030}$
BESIII [19]	$D_s^+ \to \mu^+\nu_\mu$	$0.495 \pm 0.067 \pm 0.026$
BESIII [20]	$D_s^+ \to \mu^+\nu_\mu$	$0.549 \pm 0.016 \pm 0.015$
BESIII [21]	$D_s^+ \to \mu^+\nu_\mu$	$0.535 \pm 0.013 \pm 0.016$
BESIII [21]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to \pi^+\bar{\nu}_\tau)$	$0.521 \pm 0.025 \pm 0.017$
BESIII [22]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau)$	$0.529 \pm 0.025 \pm 0.020$
BESIII [23]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to e^+\nu_e\bar{\nu}_\tau)$	$0.527 \pm 0.010 \pm 0.012$
BESIII [25]	$D_s^+ \to \tau^+\nu_\tau\,(\tau^+ \to \pi^+\bar{\nu}_\tau)$	$0.541 \pm 0.017 \pm 0.013$

MC samples

- OSCAR version : 2.6.2
- Ecm=3.773GeV
- $D^+ \to \mu^+\nu_\mu$ Signal MC

- Double tag method

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

$D^- \to K_S^0\pi^-$

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

$D^- \to K_S^0\pi^-\pi^0$

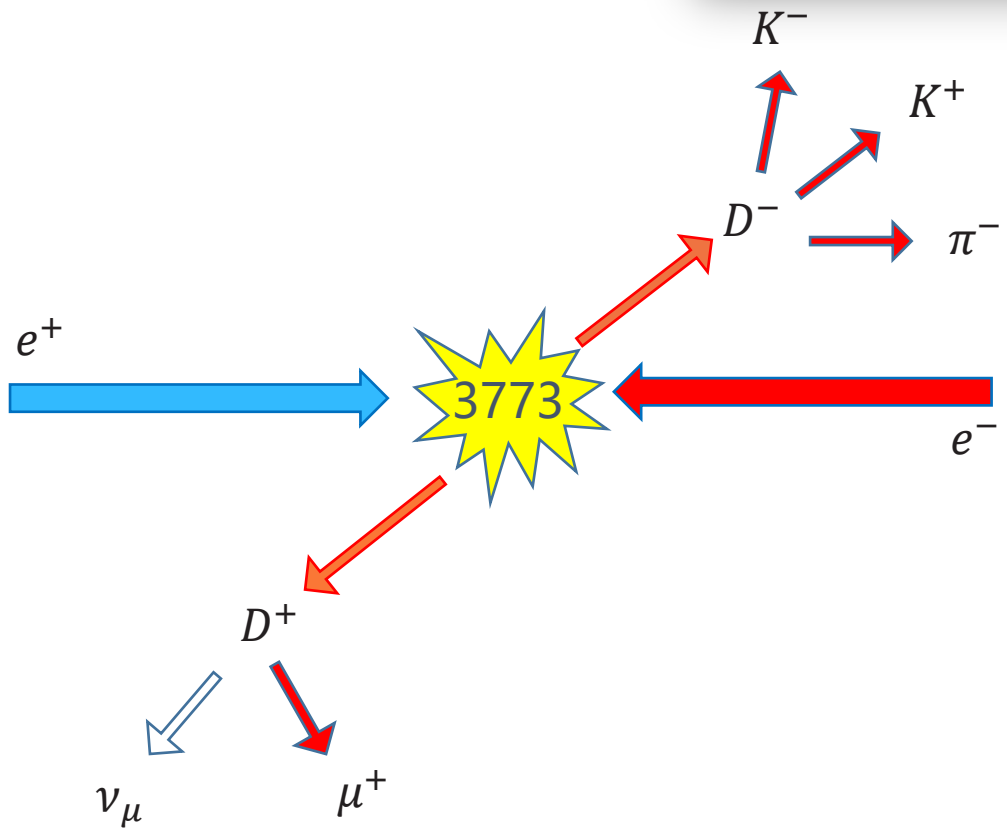
$D^- \to K^+\pi^-\pi^-\pi^0$

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

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

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

Double tag method



- For the i-th tag mode:

$$N^i_{\rm ST} = 2N_{D\bar{D}}\mathcal{B}^i_{\rm ST}\epsilon^i_{\rm ST}$$

$$N^i_{\rm DT} = 2N_{D^+D^-}\mathcal{B}^i_{\rm ST}\mathcal{B}_{\rm sig}\epsilon^i_{\rm ST,sig}$$

- Measured branching fraction:

$$\mathcal{B}_{\rm sig} = \frac{\sum_i N^i_{\rm DT}}{\sum_i N^i_{\rm ST}\cdot\epsilon^i_{\rm sig}}$$

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

where , $\epsilon^i_{\rm sig} = \dfrac{\epsilon^i_{\rm ST,sig}}{\epsilon^i_{\rm ST}}$

Good charged tracks (not form K^0_S)

- |Vz| < 10 cm
- |Vxy| < 1 cm
- |cosθ| < 0.93

PID (GlobalPID)

μ , π , K

maximum probility

Good photon

- Barrel E ≥ 25MeV, Endcap E ≥ 50 MeV
- $\theta_{\gamma-\text{charged}} > 10°$
- 0 ≤ TDC ≤ 14 (x50ns)

K^0_S

- |Vz| < 20 cm ,|cosθ| < 0.93
- M ($\pi^+\pi^-$) ∈ (0.487, 0.511) GeV/c^2
- $\chi^2_{vtx} < 100$

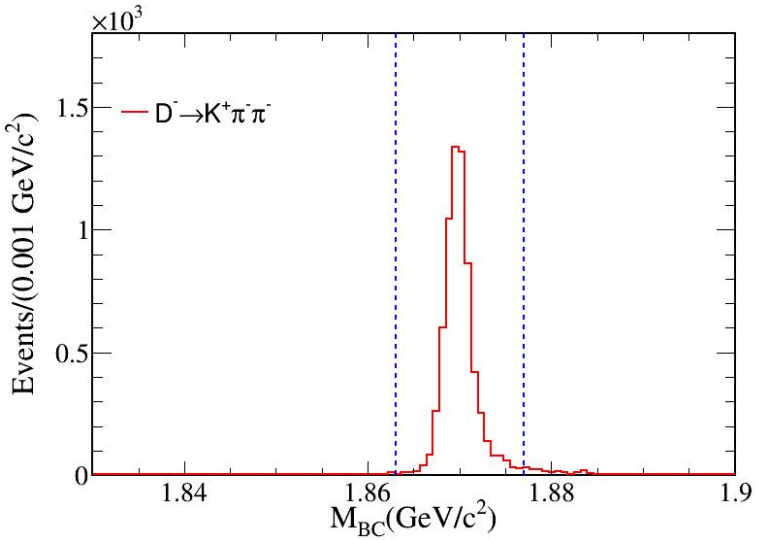
π^0

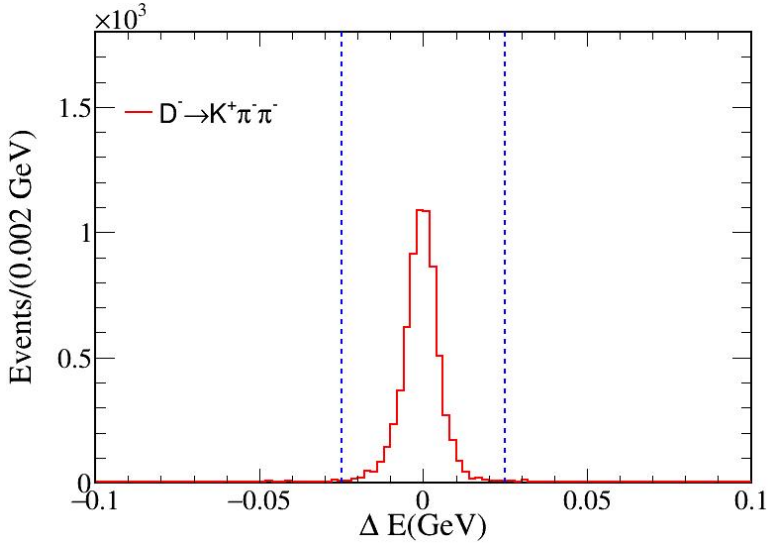
- π^0 : M ($\gamma\gamma$) ∈ (0.115, 0.150) GeV/c^2
- $\chi^2_{1C} < 50$

D^+

$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_{\bar{D}}|^2}$$

$$\Delta E = E_{\bar{D}} - E_{\mathrm{beam}}$$

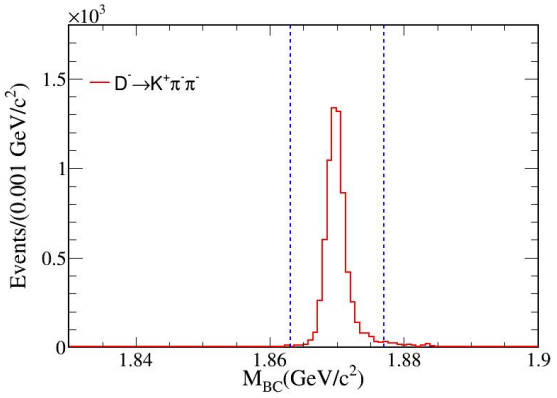


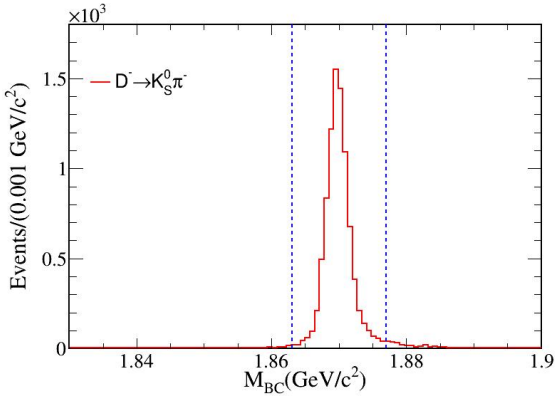


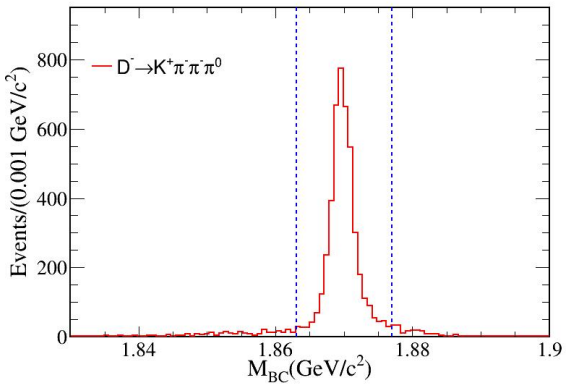
D^+

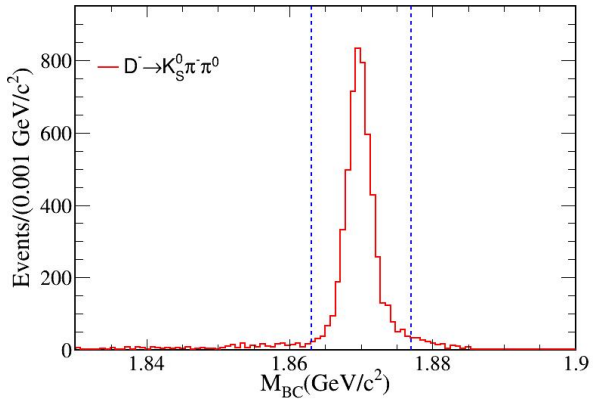
Tag mode	ΔE (GeV)	$M_{\rm BC}$ (GeV/c^2)
$D^- \to K^+\pi^-\pi^-$	(-0.025,0.024)	(1.865,1.875)
$D^- \to K^0_S\pi^-$	(-0.025,0.026)	(1.865,1.875)
$D^- \to K^+\pi^-\pi^-\pi^0$	(-0.057,0.046)	(1.865,1.875)
$D^- \to K^0_S\pi^-\pi^0$	(-0.062,0.049)	(1.865,1.875)
$D^- \to K^0_S\pi^-\pi^-\pi^+$	(-0.028,0.027)	(1.865,1.875)
$D^- \to K^+K^-\pi^-$	(-0.024,0.023)	(1.865,1.875)
$D^- \to \pi^+\pi^-\pi^-$	(-0.030,0.029)	(1.865,1.875)
$D^- \to K^+\pi^-\pi^-\pi^-\pi^+$	(-0.029,0.027)	(1.865,1.875)

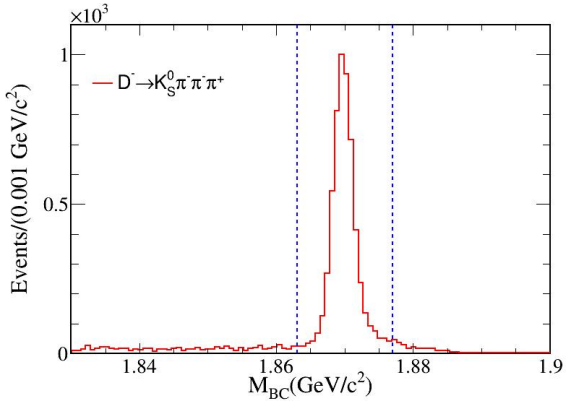
mBC

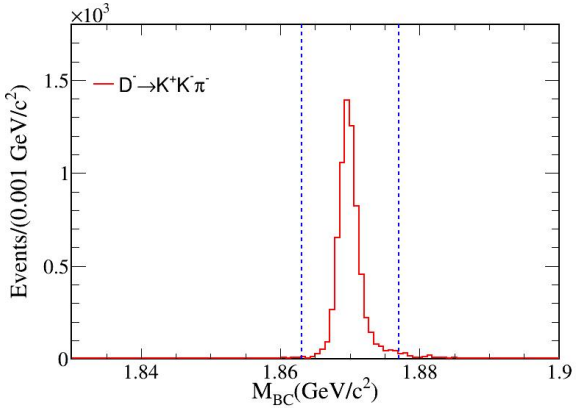

×10³
D⁻→K⁺π⁻π⁻
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

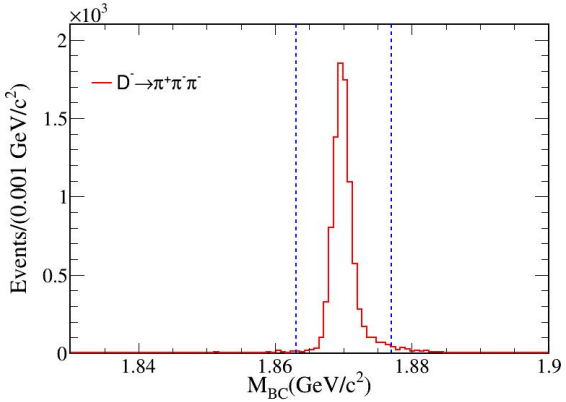

×10³
D⁻→K⁰Sπ⁻
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

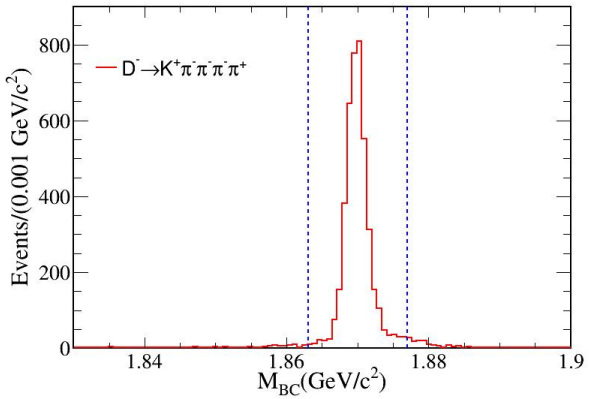

D⁻→K⁺π⁻π⁻π⁰
Events/(0.001 GeV/c²)
M_BC(GeV/c²)


D⁻→K⁰Sπ⁻π⁰
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

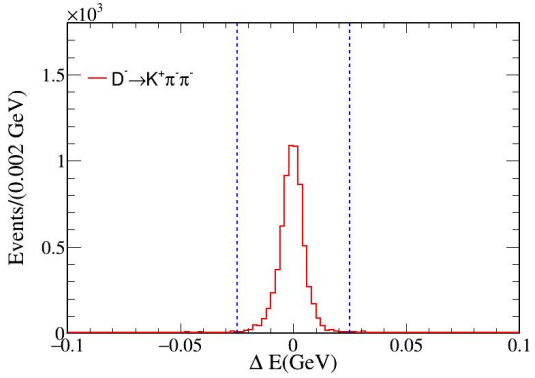

×10³
D⁻→K⁰Sπ⁻π⁻π⁺
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

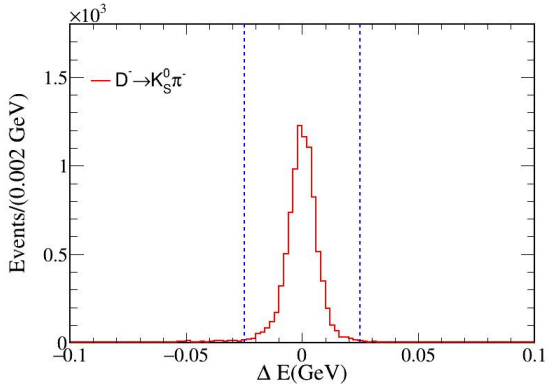

×10³
D⁻→K⁺K⁻π⁻
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

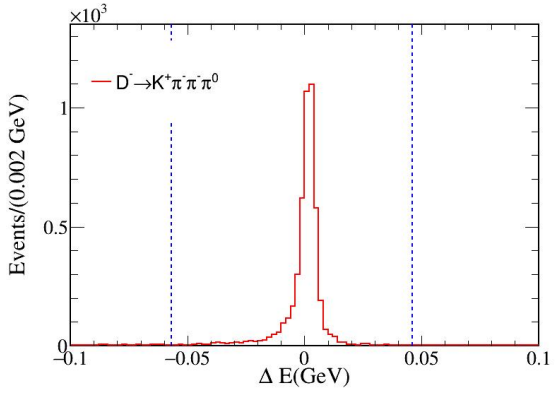

×10³
D⁻→π⁺π⁻π⁻
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

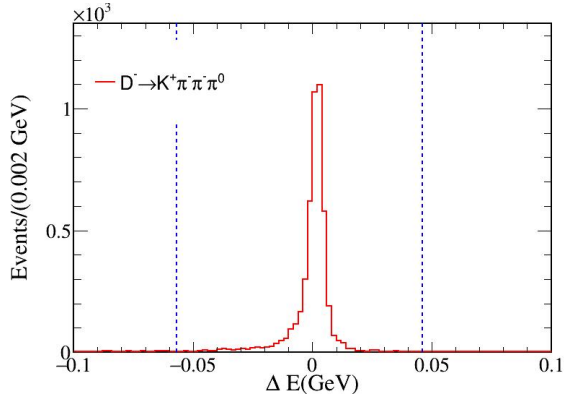

D⁻→K⁺π⁻π⁻π⁻π⁺
Events/(0.001 GeV/c²)
M_BC(GeV/c²)

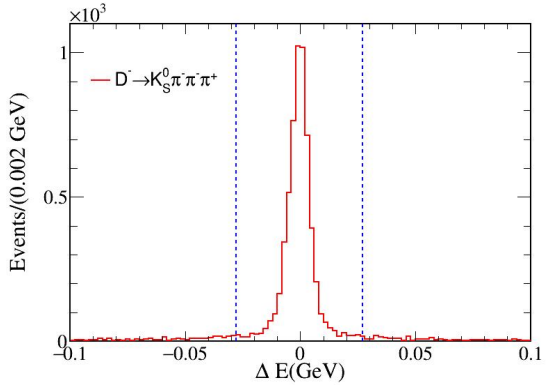
ΔE

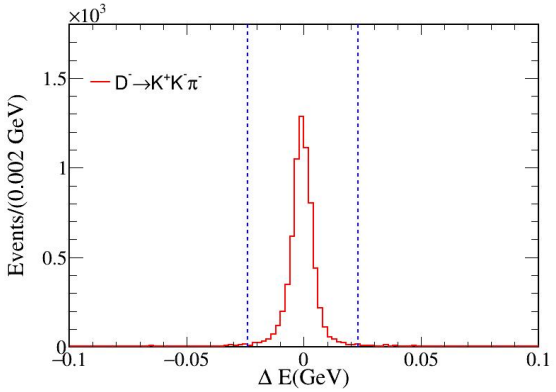

×10³
D⁻→K⁺π⁻π⁻
Events/(0.002 GeV)
Δ E(GeV)

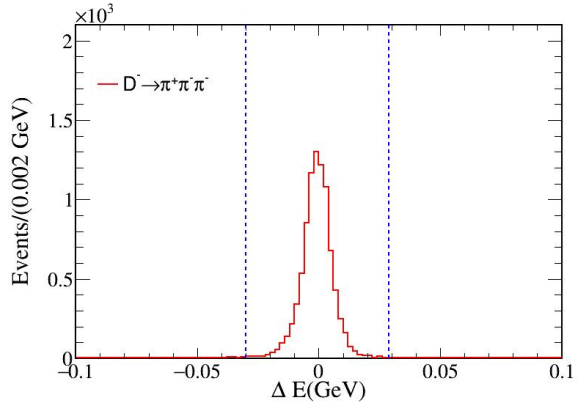

×10³
D⁻→K⁰Sπ⁻
Events/(0.002 GeV)
Δ E(GeV)

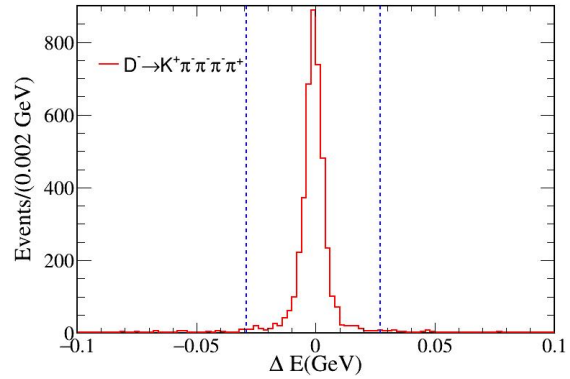

×10³
D⁻→K⁺π⁻π⁻π⁰
Events/(0.002 GeV)
Δ E(GeV)


×10³
D⁻→K⁺π⁻π⁻π⁰
Events/(0.002 GeV)
Δ E(GeV)


×10³
D⁻→K⁰Sπ⁻π⁻π⁺
Events/(0.002 GeV)
Δ E(GeV)


×10³
D⁻→K⁺K⁻π⁻
Events/(0.002 GeV)
Δ E(GeV)


×10³
D⁻→π⁺π⁻π⁻
Events/(0.002 GeV)
Δ E(GeV)


D⁻→K⁺π⁻π⁻π⁻π⁺
Events/(0.002 GeV)
Δ E(GeV)

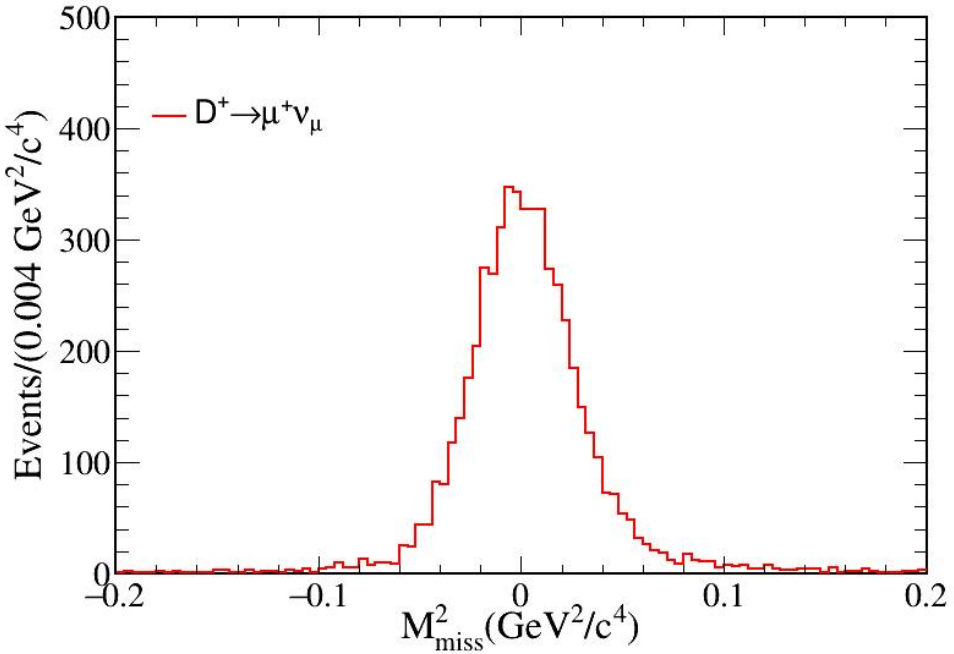
ST efficiency

tagmode	ST_eff	ST_eff BESIII
$D^- \to K^-\pi^+\pi^-$	51.32	51.08
$D^- \to K_S^0\pi^-$	55.21	51.42
$D^- \to K^+\pi^-\pi^-\pi^0$	26.29	24.53
$D^- \to K_S^0\pi^-\pi^0$	28.09	26.45
$D^- \to K_S^0\pi^-\pi^-\pi^+$	34.92	29.68
$D^- \to K^+K^-\pi^-$	40.35	40.91
$D^- \to \pi^+\pi^-\pi^-$	54.24	54.10
$D^- \to K^+\pi^-\pi^-\pi^-\pi^+$	23.20	23.29

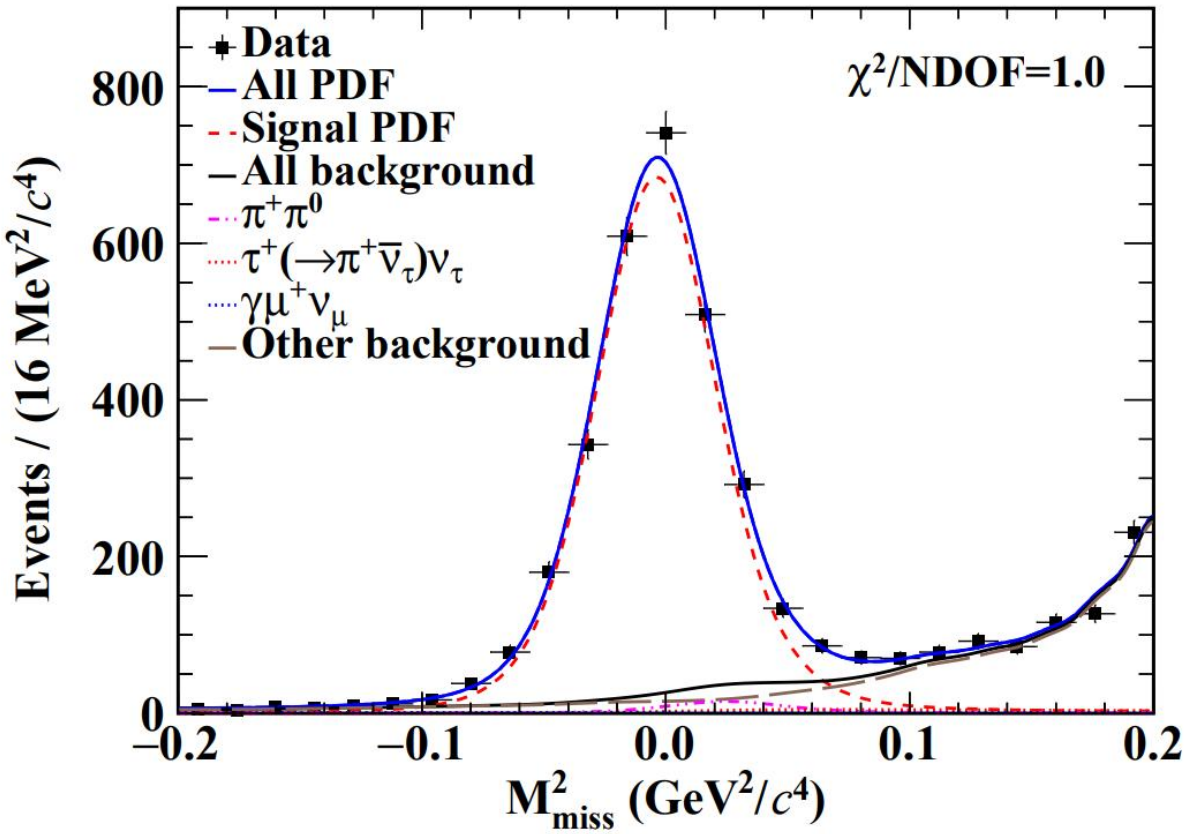
DT analysis

$D^+ \to \mu^+ \nu_\mu$

- Only one good charged track
- PID μ



$$M^2_{\text{miss}} = (E_{\text{cm}} - E_{\text{tag}} - E_{\mu^+})^2 - |-\vec{p}_{\text{tag}} - \vec{p}_{\mu^+}|^2$$


Data
All PDF
Signal PDF
All background
$\pi^+\pi^0$
$\tau^+(\to\pi^+\bar{\nu}_\tau)\nu_\tau$
$\gamma\mu^+\nu_\mu$
Other background
χ^2/NDOF=1.0
Events / (16 MeV^2/c^4)
M^2_{miss} (GeV^2/c^4)
800
600
400
200
0
−0.2
−0.1
0.0
0.1
0.2

DT efficiencies

tagmode	DT_eff	DT_eff BESIII
$D^- \to K^-\pi^+\pi^-$	39.53	35.81
$D^- \to K_S^0\pi^-$	42.36	36.25
$D^- \to K^+\pi^-\pi^-\pi^0$	22.46	18.24
$D^- \to K_S^0\pi^-\pi^0$	23.53	19.33
$D^- \to K_S^0\pi^-\pi^-\pi^+$	25.72	21.37
$D^- \to K^+K^-\pi^-$	32.24	28.88
$D^- \to \pi^+\pi^-\pi^-$	42.67	37.77
$D^- \to K^+\pi^-\pi^-\pi^-\pi^+$	18.95	16.69

- Estimate the measurement precision

$$\mathcal{L} = 1ab^{-1} \text{ at } \sqrt{s} = 3.773 \text{ GeV}$$

$$N_{D^+D^-} = \mathcal{L} \bullet \sigma_{e^+e^-\to D^+D^-} \approx 2.8\times 10^9$$

$$\sum i\, N^i_{\rm ST} = 2N_{D\bar{D}}\mathcal{B}^i_{\rm ST}\epsilon^i_{\rm ST} \approx 6.4\times 10^8$$

$$\sum i N^i_{\rm DT} = 2N_{D^+D^-}\mathcal{B}^i_{\rm ST}\mathcal{B}_{\rm sig}\epsilon^i_{\rm ST,sig} \approx 5.4\times 10^5$$

$$\sigma_{stat} = \sqrt{\left(\frac{\sqrt{N_{DT}}}{N_{DT}}\right)^2 + \left(\frac{\sqrt{N_{ST}}}{N_{ST}}\right)^2}$$

$$\frac{\Delta f_{D^+}}{f_{D^+}} = \sqrt{\left(\frac{1}{2}\frac{\Delta\tau_{D^+}}{\tau_{D^+}}\right)^2 + \left(\frac{1}{2}\frac{\Delta\mathcal{B}}{\mathcal{B}}\right)^2 + \left(\frac{\Delta|V_{cd}|}{|V_{cd}|}\right)^2}$$

$$\frac{\Delta|V_{cd}|}{|V_{cd}|} = \sqrt{\left(\frac{1}{2}\frac{\Delta\tau_{D^+}}{\tau_{D^+}}\right)^2 + \left(\frac{1}{2}\frac{\Delta\mathcal{B}}{\mathcal{B}}\right)^2 + \left(\frac{\Delta f_{D^+}}{f_{D^+}}\right)^2}$$

	STCF(%)	BESIII(%)
BF	0.14	2.0
f_{D^+}	0.07	1.0
$\|V_{cd}\|$	0.07	1.0

M. Ablikim *et al.*, (BESIII Collaboration), Phys. Rev. Lett **135**, 061801 (2025).

Table 14: Systematic uncertainties in the measurement of the BF of $D^+ \to \mu^+\nu_\mu$.

Source	Uncertaintiy (%)
$M_{\rm BC}$ fit	0.30
μ^+ tracking	0.06
μ^+ PID	0.10
$E_{\rm max}^{\rm extra\ \gamma}$ && $N_{\rm charge}^{\rm extra}$	0.08
$M^2_{\rm miss}$ fit	0.90
Effect of $D^+ \to \gamma\mu^+\nu_\mu$	0.17
Tag bias	0.14
MC statistic	0.16
Total	0.99

- Based on the signal MC samples, the ST efficiencies and DT efficiencies for 8 tag modes are obtained.

- The predicted result shows a 15-times enhancement in statistical precision compared to the world's current most accurate result (BESIII).

Thank you for attention

Back up