Prospects of measuring $D^0 \to K_1(\to K\pi\pi)^- l^+ \nu_l$ @ STCF & LHCb

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Outline

- Motivation
- Angular distribution in $D \to K_1(\to K\pi\pi)l^+\nu_l$
- $D \to K_1(\to K\pi\pi)e^+\nu_e$ at BESIII
- Prospect of $D^0 \to K_1(\to K\pi\pi)^- e^+\nu_e$ at STCF
- Prospect of $D^0 \to K_1(\to K\pi\pi)^- \mu^+\nu_\mu$ at LHCb
- Summary

Motivation:Photon Polarization In $B \to K_1\gamma$

- Photon Polarization in $b \to s\gamma$ is sensitive to BSM
- A noval method is provided to combine the $B \to K_1\gamma$ and $D \to K_1 e^+\nu_e$ to determine the photon helicity [PRL 125, 051802 (2020)]

$$\mathcal{A}'_{\rm UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_K}}{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_l \frac{d\Gamma_{K_1 e\nu_e}}{d\cos\theta_l}}$$

$$\mathcal{A}'_{\rm UD} = \frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}.$$

$D \to K_1(\to K\pi\pi)e^+\nu$

$$\mathcal{A}_{UD} \equiv \frac{\left[\int_0^1 - \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}}{\left[\int_0^1 + \int_{-1}^0\right] d\cos\theta_K \frac{d\hat{\Gamma}_{K_1\gamma}}{d\cos\theta_K}} = \lambda_\gamma \frac{3}{4}\frac{{\rm Im}[\vec{n}\cdot(\vec{J}\times\vec{J}^*)]}{|\vec{J}|^2}$$

$B \to K_1(\to K\pi\pi)\gamma$

$$\lambda_\gamma = \frac{4}{3}\frac{\mathcal{A}_{UD}}{\mathcal{A}'_{\rm UD}}$$ **In SM,** $\lambda_\gamma \simeq 1$

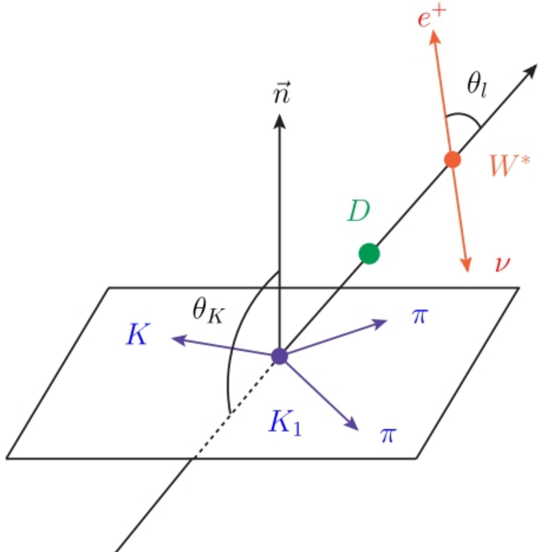
[1.1-1.3]GeV:

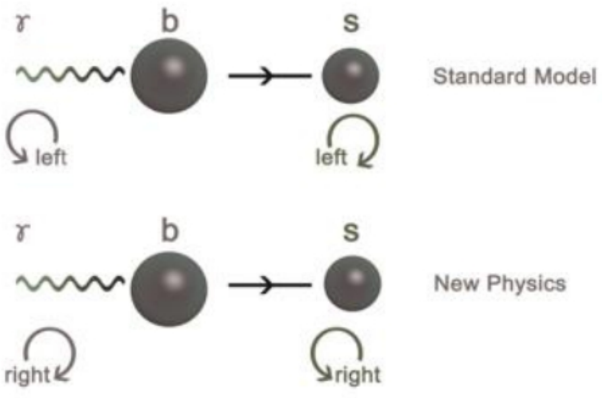
LHCb: PRL112.161801(2014)

$$\mathcal{A}_{UD} = (6.9 \pm 1.7)\times 10^{-2}$$

If SM

$$A'_{UD} = (9.2 \pm 2.3)\times 10^{-2}$$

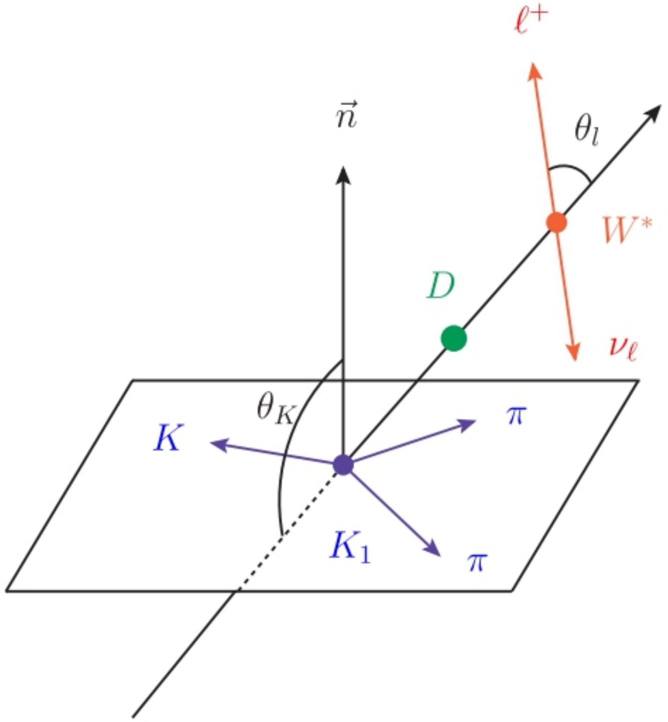




Picture taken from report of Fu-Sheng Yu

Angular distribution in $D \to K_1(\to K\pi\pi)l^+\nu_l$ [PRD 104, 053003 (2021)]

$$\frac{d\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_K} = \frac{G_F^2|V_{cs}|^2 q^2\sqrt{\lambda(m_D^2, m_{K_1}^2, q^2)}}{512\pi^3 m_D^3}(1-\hat{m}_\ell^2)^2 \times \frac{3}{8}(d_1 + d_1'[\cos^2\theta_K\cos^2\theta_\ell] + d_2\cos\theta_\ell + d_2'\cos^2\theta_K\cos\theta_\ell$$
$$+ d_3\cos\theta_K + d_3'\cos\theta_K\cos^2\theta_\ell + d_4\cos\theta_K\cos\theta_\ell + d_5\cos^2\theta_K + d_5'\cos^2\theta_\ell). \quad (28)$$



Angular distribution in $D \to K_1(\to K\pi\pi)l^+\nu_l$

$$H_{K_1} = \frac{d_3 + d_3'}{d_2 + d_2'} = \frac{\mathrm{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]}{|J|^2}.$$

$$\mathcal{A}'_{\mathrm{UD}} \equiv \frac{\frac{d\Gamma}{dq^2}[\cos\theta_K > 0] - \frac{d\Gamma}{dq^2}[\cos\theta_K < 0]}{\frac{d\Gamma}{dq^2}[\cos\theta_\ell > 0] - \frac{d\Gamma}{dq^2}[\cos\theta_\ell < 0]}$$
$$= \frac{3d_3 + d_3'}{3d_2 + d_2'}$$
$$= H_{K_1} \boxed{\frac{(2 + \hat{m}_\ell^2)(|c_-|^2 - |c_+|^2)}{2[(|c_-|^2 - |c_+|^2) + 2\mathrm{Re}[c_0 c_t^*]\hat{m}_\ell^2]}}.$$

e: $H_{K_1} = A'_{UD}$

$$\mathcal{A}_{\mathrm{UD}} \equiv \frac{\Gamma_{K_1\gamma}[\cos\theta_K > 0] - \Gamma_{K_1\gamma}[\cos\theta_K < 0]}{\Gamma_{K_1\gamma}[\cos\theta_K > 0] + \Gamma_{K_1\gamma}[\cos\theta_K < 0]}$$
$$= \lambda_\gamma \frac{3}{4} \boxed{\frac{\mathrm{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]}{|\vec{J}|^2}}$$

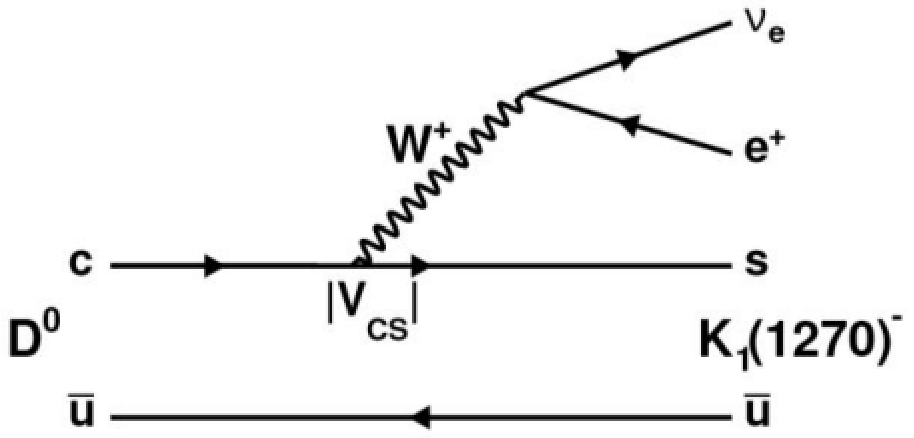
$B \to K_1\gamma$

$$d_1 = (1 + \hat{m}_\ell^2)(|c_-|^2 + |c_+|^2) + 4|c_0|^2 + 4\hat{m}_\ell^2|c_t|^2,$$
$$d_1' = (1 - \hat{m}_\ell^2)(4|c_0|^2 + |c_-|^2 + |c_+|^2),$$
$$d_2 = -2[|c_-|^2 - |c_+|^2 + 4\mathrm{Re}[c_0 c_t^*]\hat{m}_\ell^2],$$
$$d_2' = -2[|c_-|^2 - |c_+|^2 - 4\mathrm{Re}[c_0 c_t^*]\hat{m}_\ell^2],$$
$$d_3 = 2\frac{\mathrm{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]}{|J|^2}[(1 + \hat{m}_\ell^2)(|c_+|^2 - |c_-|^2)],$$
$$d_3' = 2\frac{\mathrm{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]}{|J|^2}[(1 - \hat{m}_\ell^2)(|c_+|^2 - |c_-|^2)]$$
$$d_4 = 4\frac{\mathrm{Im}[\vec{n} \cdot (\vec{J} \times \vec{J}^*)]}{|J|^2}(|c_-|^2 + |c_+|^2),$$
$$d_5 = -[(1 + \hat{m}_\ell^2)(-|c_-|^2 - |c_+|^2) + 4|c_0|^2 + 4\hat{m}_\ell^2|c_t|^2],$$
$$d_5' = -[(1 - \hat{m}_\ell^2)(4|c_0|^2 - |c_-|^2 - |c_+|^2)].$$

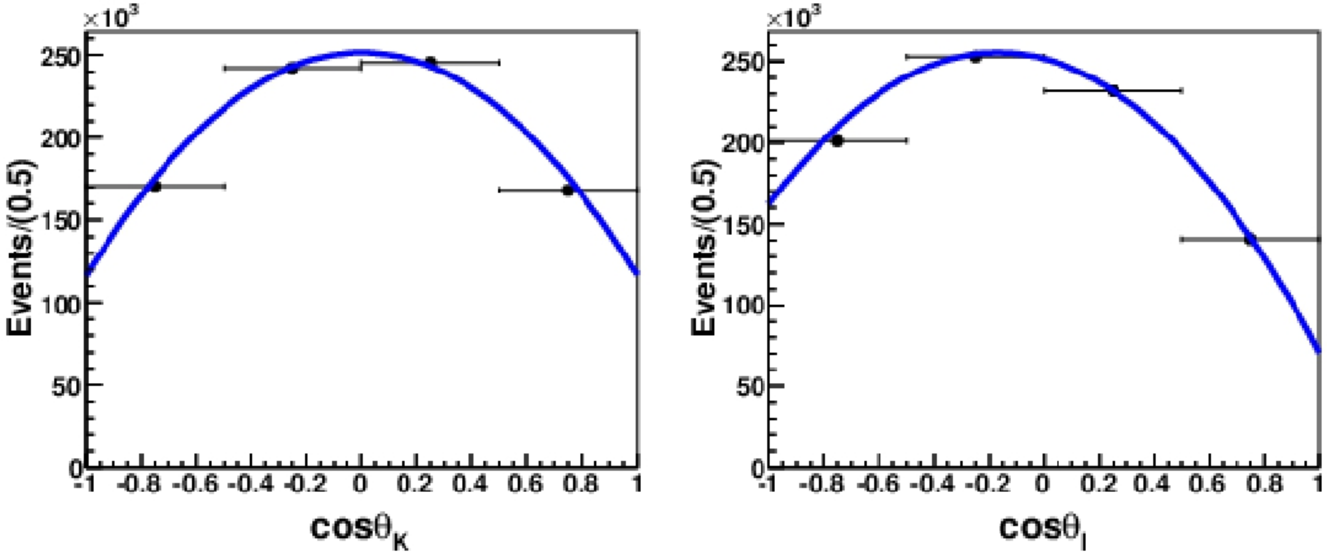
$D \to K_1(\to K\pi\pi)e^+\nu_e$ at BESIII

- Using 2.93 fb^{-1} of e^+e^- collision data at BESIII , first observation of $D^0 \to K_1(1270)^- e^+\nu_e$ and $D^+ \to K_1(1270)^0 e^+\nu_e$ have been both published with ~100 signals [PRL 127, 131801 (2021)] , [PRL 123, 231801 (2019)].
  - $B(D^0 \to K_1(1270)^- e^+\nu_e) = (1.09 \pm 0.13^{+0.09}_{-0.16} \pm 0.12) \times 10^{-3}$
  - $B(D^+ \to K_1(1270)^0 e^+\nu_e) = (2.30 \pm 0.26^{+0.18}_{-0.21} \pm 0.25) \times 10^{-3}$

The yield is too small for angular analysis and A'_{UD} measurement



Prospect of $D^0 \to K_1(\to K\pi\pi)^- e^+\nu_e$ at STCF

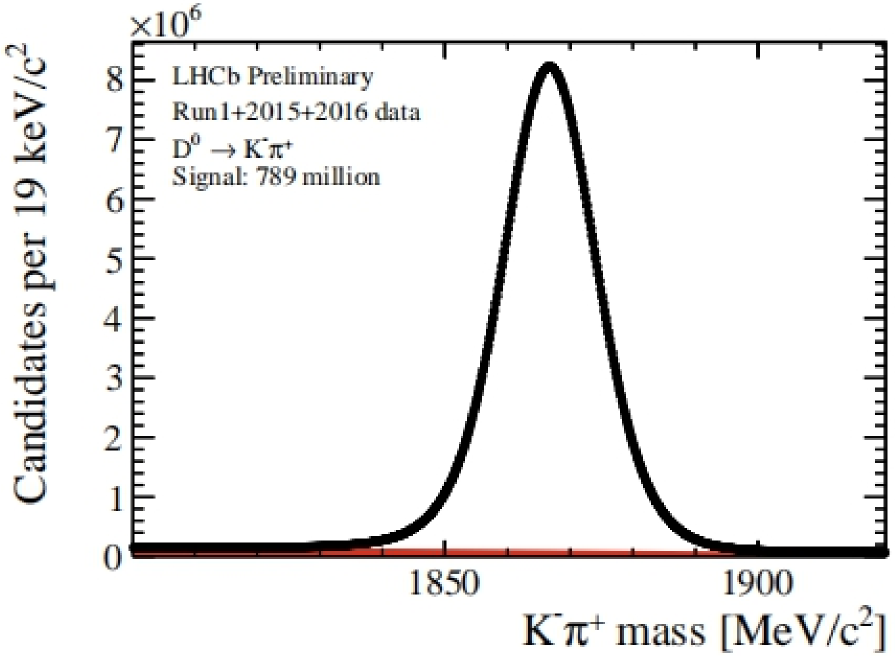


- $1\ ab^{-1}$ at $\sqrt{s} = 3.773$ GeV
- Fast simulation tool for STCF [JINST 16 P03029 (2021)]
- Statistical sensitivity of $\boldsymbol{H_{K_1}}$ (A'_{UD}): 1.5% [arXiv:2107.06118, accepted by EPJC]

Prospect of $D^0 \to K_1(\to K\pi\pi)^- \mu^+ \nu_\mu$ at LHCb

LHCb: the world's largest charm factory

- At LHC, the production cross-section of charm is ~20 times larger than the beauty one.
- More than 1 billion $D^0 \to K^-\pi^+$ reconstructed with full LHCb data samples
- Software trigger for charm has both exclusive selections and inclusive based on MVA trainings

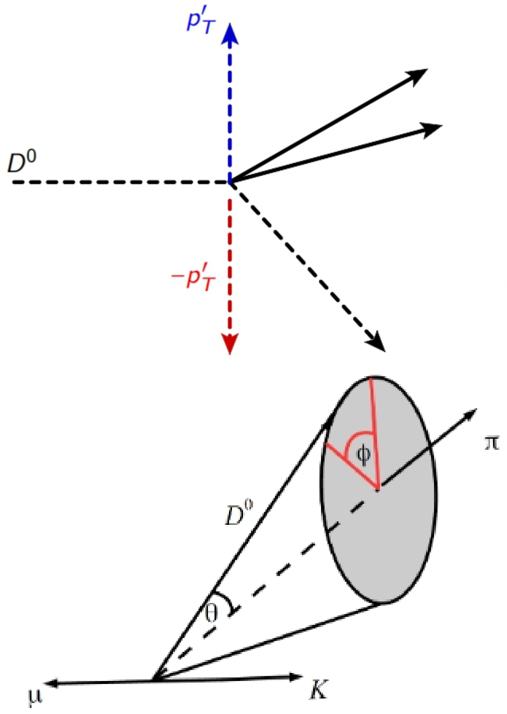


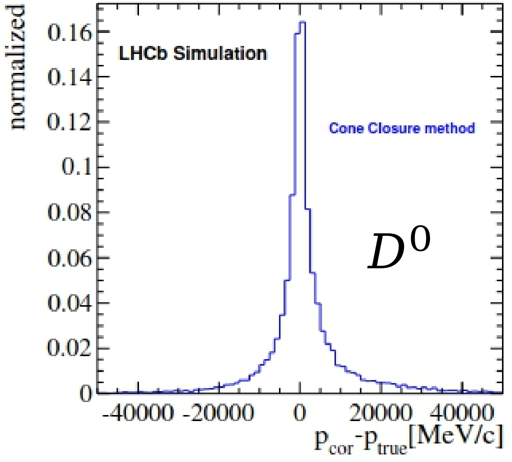
LHCb-CONF-2016-005

Prospect of $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ at LHCb

Charm semileptonic decays at LHCb

- Muons are good, electrons are a bit more difficult
- Challenge: only partially reconstructed final state
  1. neutrino transverse momentum can be constrained by the D flight direction
  2. Total neutrino momentum can be solved by the cone-closure method with D^0 and D^{*+} mass constraints [FERMILAB-THESIS-1995-05]

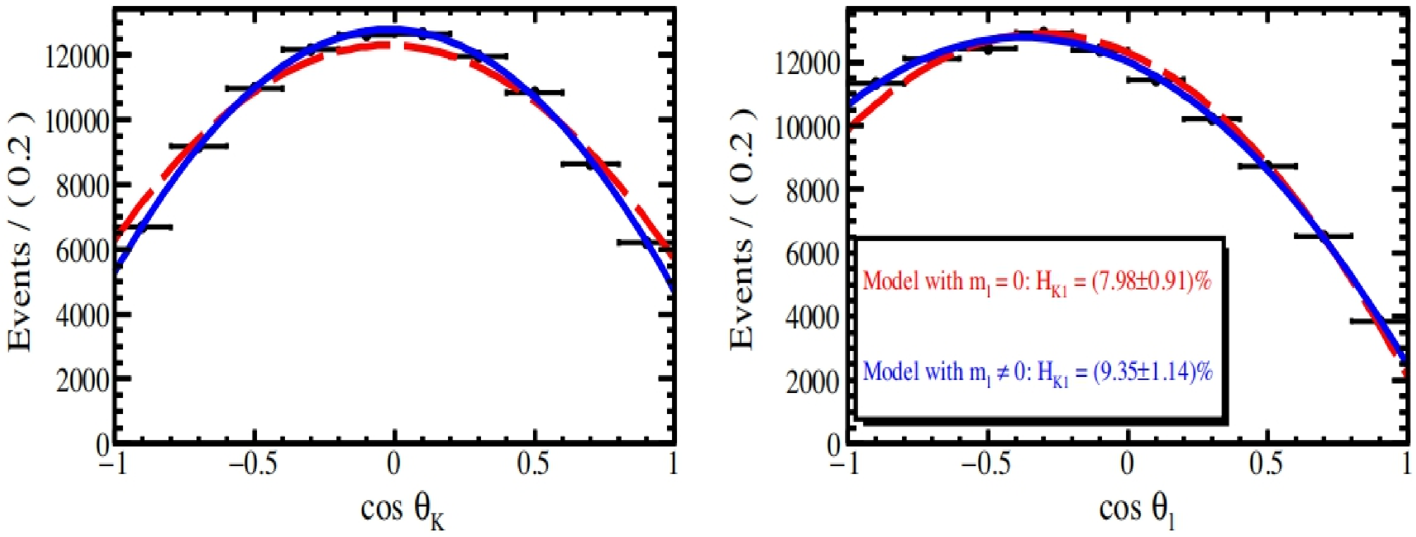




Taken from Mitze's master thesis

Prospect of $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ at LHCb

- About 2000 $D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+\mu^+\mu^-$ candidates at LHCb, 2 fb^{-1}at 8 TeV [PRL 119,181805 (2017)]
- $B(D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu)$ two orders of magnitude higher than B$(D^0 \to K^-\pi^+\mu^+\mu^-)$
- Conservatively estimation: 10^5 $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ candidates based on 9 fb^{-1} at LHCb



- $\sim 10^5$ $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$ signals generated by RapidSim [Comput.Phys. Commun. 214, 239 (2017).]
- Muon mass can not be neglected
- Statistical sensitivity of H_{K_1}:1.1% [PRD 104, 053003 (2021)]

Summary

- A'_{UD} in $D \to K_1(\to K\pi\pi)e^+\nu_e$ and H_{K_1} in $D \to K_1(\to K\pi\pi)l^+\nu_l$ can help to determine the photon helicity in $B \to K_1(\to K\pi\pi)\gamma$
- LHCb is a promising place to measure $D^0 \to K_1(\to K\pi\pi)^-\mu^+\nu_\mu$, thanks to its large production cross-section of charm and good detection performance. Statistical sensitivity of H_{K_1} is expected to be 1.1%
- STCF can give ~300 times $D^0 \to K_1(\to K\pi\pi)^-e^+\nu_e$ candidates more than BESIII, enough for angular analysis and A'_{UD} measurement. Statistical sensitivity of $H_{K_1}(A'_{UD})$ is expected to be 1.5%

BackUp

Cone Closure

In the Kμ rest frame

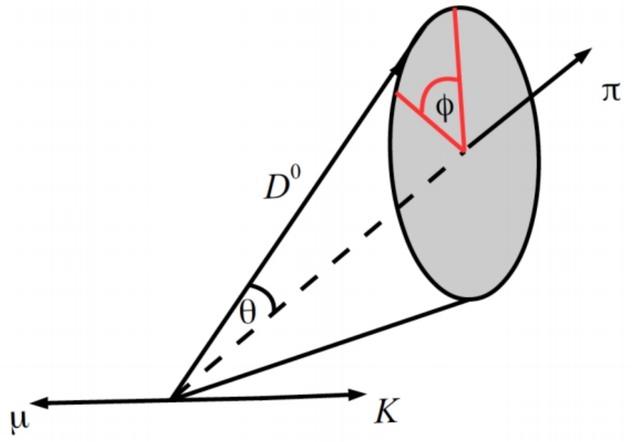
$$\vec{p}(K\mu) = 0, \quad \vec{p}(D^0) = \vec{p}(\nu) \quad \text{and} \quad E(D^0) = m(K\mu) + p(D^0).$$

Using the D^0 mass constraint allows, in this reference frame, to determine the magnitude of the D^0 momentum:

$$m_{D^0}^2 = E^2(D^0) - p^2(D^0) = m^2(K\mu) + 2\, m(K\mu)\, p(D^0)$$
$$\Longrightarrow \quad p(D^0) = \frac{m_{D^0}^2 - m^2(K\mu)}{2\, m(Kmu)}. \tag{16}$$

Additionally, using the D^{*+} mass constraint restricts the D^0 momentum vector to lie on a cone with respect to the momentum of the pion (see Figure 19 for a visual representation), whose opening angle θ is determined as

$$m_{D^{*+}}^2 = \left[E(D^0) + E(\pi)\right]^2 - \left[\vec{p}(D^0) + \vec{p}(\pi)\right]^2$$
$$= m_{D^0}^2 + m_{\pi^+}^2 + 2\, E(D^0)\, E(\pi) - 2\, p(D^0)\, p(\pi) \cos\theta$$
$$\Longrightarrow \quad \cos\theta = \frac{2E(D^0)E(\pi) - (m_{D^{*+}}^2 - m_{D^0}^2 - m_{\pi^+}^2)}{2p(D^0)p(\pi)}. \tag{17}$$



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