D 介子四体末态振幅分析

"粲强子衰变和标准模型的精确测量"2025夏季年会　　贵州民族大学

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2025.8.14

研究背景和目的

利用振幅分析研究粲介子多体强子衰变，有助于理解其强、弱衰变动力学机制，检验及刻度非微扰QCD理论模型

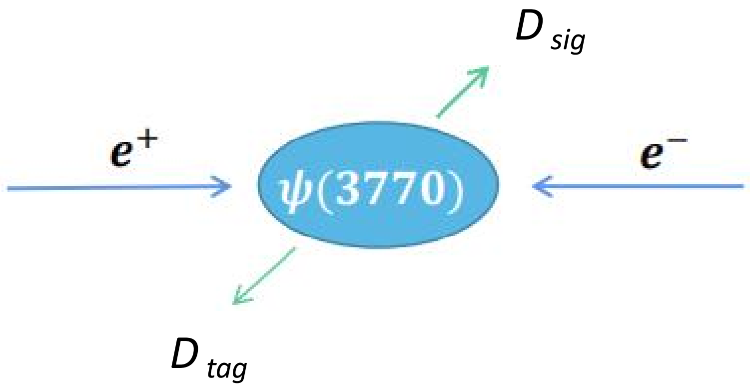
相较于三体衰变，四体衰变通常分支比更小，数据统计量低，同时中间过程复杂，振幅分析难度更大，相关研究较为匮乏

通过振幅分析，提供衰变中间共振态信息，针对特定过程进行研究：

- $D \to VV$：粲介子重要强子衰变过程，分支比大，同时包含三种角动量态，为解决重介子极化疑难提供关键信息
- $D \to AP$： 研究轴矢量介子的重要途径，如$K_1(1270)$, $a_1(1260)$, $K_1(1400)$等
- $D \to VS$： 研究标量介子如$a_0(980)$，结合理论模型判断其夸克组成
- $D \to PP$： 研究激发态赝标量介子$\eta(1405)$，$\eta(1475)$等
- $D \to VP$： 研究含ω /ϕ ($\to \pi^+\pi^-\pi^0$)的过程

研究方法

利用双标记法重建D介子



构造振幅模型，通过最大似然拟合寻找最佳解

- **Total amplitude**: The sum over all the partial wave amplitudes $\mathcal{M}_{D^0}(p_j) = \sum_n c_n \mathcal{A}_n(p_j)$, $\mathcal{A}_n(p_j) = P_n^1 P_n^2 S_n F_n^1 F_n^2 F_n^{D^0}$
  - $c_n = \rho_n e^{i\phi_n}$: complex coefficient
  - $\mathcal{A}_n(p)$: the n^{th} intermediate process amplitude
  - $P_n^{1,2}(m)$: propagator
  - $S_n(p_j)$: spin factor
  - $F_n^{1,2}(F_n^{D^0})$: the Blatt-Weisskopf barriers of the intermediate resonance and D_0 meson.
- **PDF** is calculated by following formula

$$\mathrm{PDF}(p_j) = \omega_{\mathrm{sig}} \frac{\varepsilon(p_j)|\mathcal{M}(p_j)|^2 R_4(p_j)}{\int \varepsilon(p_j)|\mathcal{M}(p_j)|^2 R_4(p_j)\mathrm{d}p_j} + (1-\omega_{\mathrm{sig}}) \frac{B(p_j)R_4(p_j)}{\int B(p_j)R_4(p_j)\mathrm{d}p_j}$$

- $B(p_j)$: background shape
- $\mathcal{M}(p_j)$: total amplitude
- ω_{sig}: fraction of signal
- $R_4(p_j)$: phase space

研究方法

helicity振幅$D \to VV \to (P_1P_2)(P_3P_4)$

$$H_{\lambda_{V_1},\lambda_{V_2}} = F^{J_D}_{\lambda_{V_1},\lambda_{V_2}} D^{J_D}_{\lambda_D,\lambda_{V_1}-\lambda_{V_2}}(\phi_{V_1},\theta_{V_1},0)\cdot P_{V_1} F^{J_{V_1}}_{\lambda_{P_1},\lambda_{P_2}} D^{J_{V_1}}_{\lambda_{V_1},\lambda_{P_1}-\lambda_{P_2}}(\phi_{P_1},\theta_{P_1},0)\cdot P_{V_2} F^{J_{V_2}}_{\lambda_{P_3},\lambda_{P_4}} D^{J_{V_2}}_{\lambda_{V_2},\lambda_{P_3}-\lambda_{P_4}}(\phi_{P_3},\theta_{P_3},0).$$

$$J_D = 0 \implies \lambda_{V_1} = \lambda_{V_2} \quad \therefore |A|^2 = \left|\sum_{\lambda_{V_1}\lambda_{V_2}} H_{\lambda_{V_1}\lambda_{V_2}}\right|^2 = |H_{11} + H_{-1-1} + H_{00}|^2$$

$$F^{J_D}_{\pm1\pm1} = \sqrt{\frac{1}{3}}g_{00} \pm \sqrt{\frac{1}{2}}Wrg_{11} + \sqrt{\frac{1}{6}}r^2g_{22} \quad , \quad F^{J_D}_{00} = \gamma_1\gamma_2(-\sqrt{\frac{1}{3}}g_{00} + \sqrt{\frac{2}{3}}r^2g_{22}) \qquad r = 2|q|$$

$|q|$: momentum of V in D rest frame $\quad$ γ: Lorentz factor of V in D rest frame $\quad$ W: mass of D (m)

$$f_L = \frac{|H_{00}|^2}{|H_{11}+H_{-1-1}+H_{00}|^2}$$

The transformation is based on the references JHEP06(2023)039 and Phys.Rev.D 57 (1998) 431-442 .

研究现状

$D^0 \to K_S^0\pi^+\pi^-\pi^0$ (Feng Yutong)
$D^0 \to K_S^0\pi^0\pi^0\pi^0$ (Rong Shaoshi)

$D^0 \to K_S^0K^+\pi^-\pi^0$ (Li Zhenxuan)
$D^0 \to K_S^0K^-\pi^+\pi^0$ (Li Zhenxuan)
$D^0 \to K^+K^-\pi^0\pi^0$ (Wang Jiahao)
$D^+ \to K_S^0K^-\pi^+\pi^+$ (Wang Jiahao)
$D^+ \to K^+K^-\pi^+\pi^0$ (Lu Yu)

$D^0 \to K^-K^-K^+\pi^+$ (Shi Jialei)

$D^0 \to K_L^0\pi^+\pi^-\pi^0$ (Feng Yutong)
$D^+ \to K_S^0K^+\pi^+\pi^-$ (Li Shuo)
$D^0 \to K^-\pi^+\pi^+\eta$ (Zeng Xin)
$D^0 \to K^-\pi^+\pi^0\eta$ (Zhou Shuai)
$D^0 \to K_S^0\pi^+\pi^-\eta$ (Liu Xinghan)
$D^+ \to \pi^+\pi^+\pi^-\pi^0$ (Li Xu)
$D^0 \to \pi^+\pi^-\pi^0\pi^0$ (Shan Xinyu)
$D^0 \to \pi^+\pi^-\pi^+\pi^-$ (Shan Xinyu)

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

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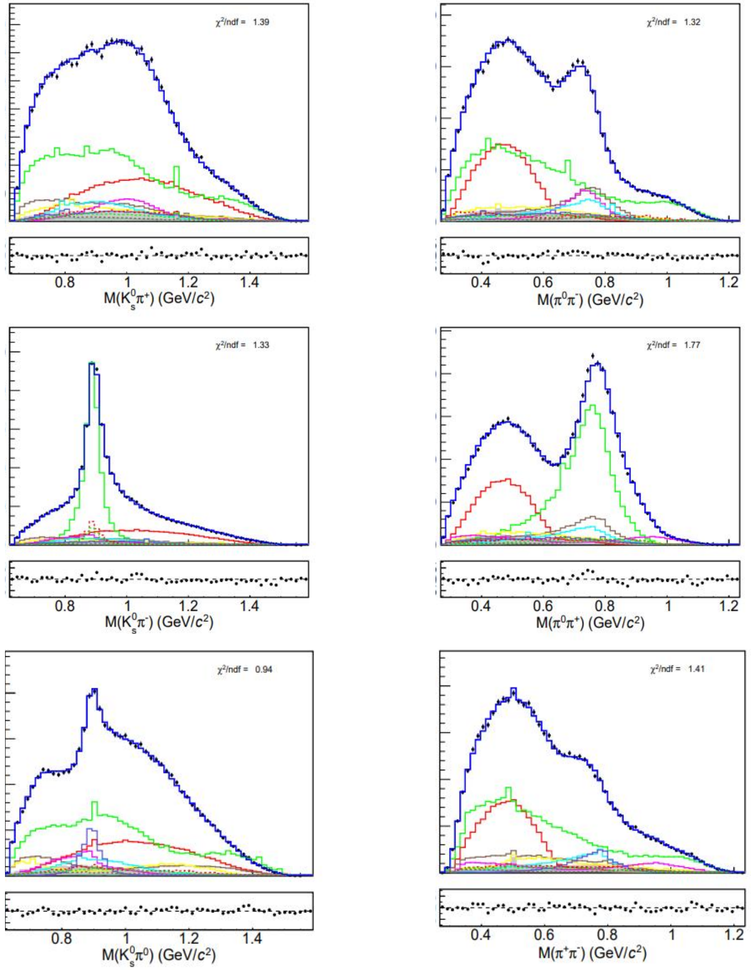
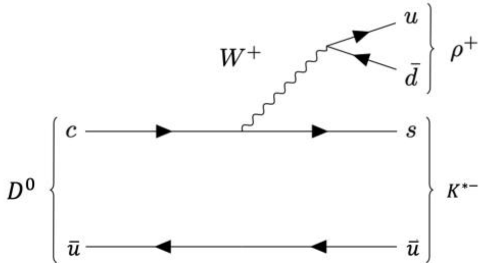




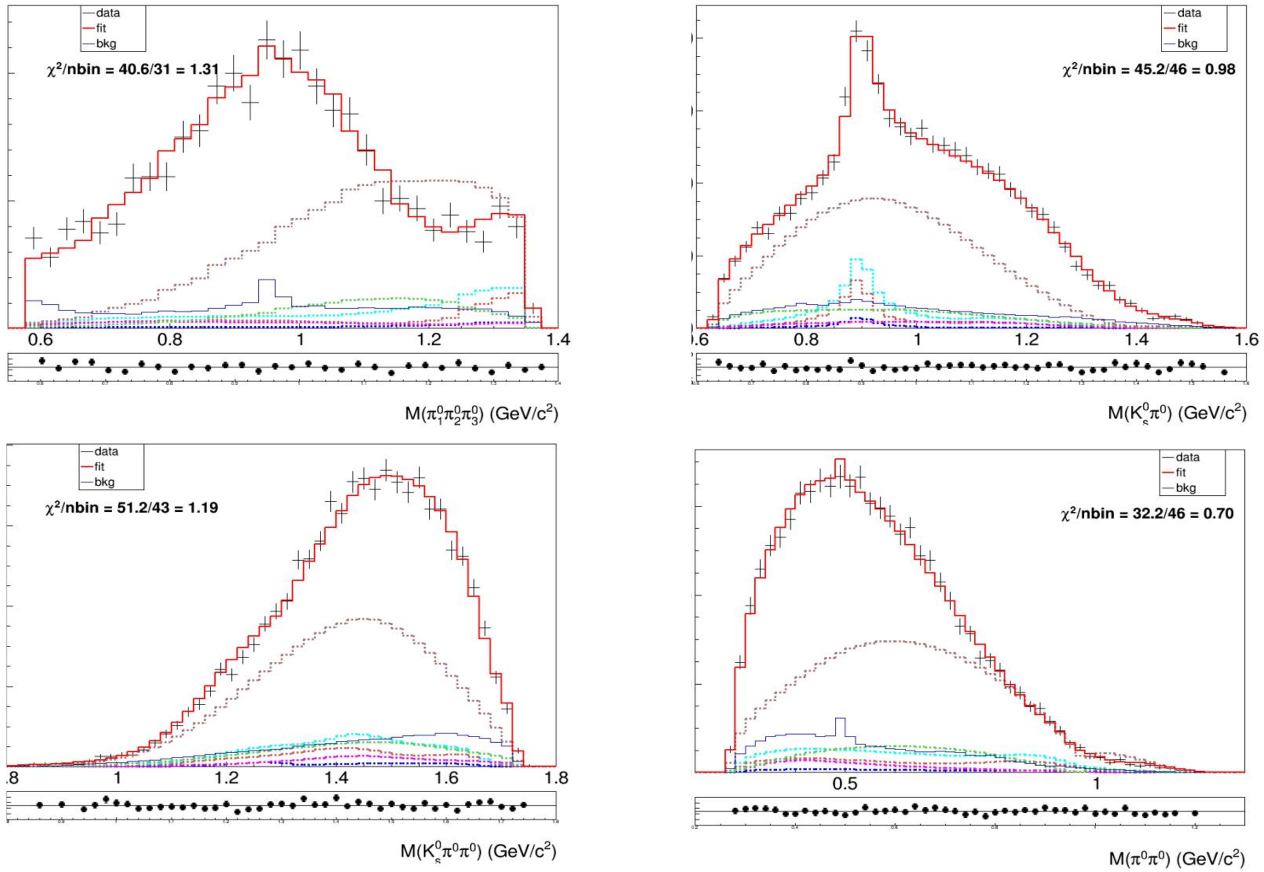
Amplitude
ωK_S^0
ϕK_S^0
$\omega(1420)$
$\omega(1650)$
$K(1410)^-\pi^+$ [$K(1410) \to K_S^0\rho(770)$]
$\bar{K}^*(1680)^0\pi^0$
$K^*(1680)^-\pi^+$
$K^*(1680)^+\pi^-$
$\pi(1300)K_S^0$
$\bar{K}(1460)^0\pi^0$
$K(1460)^-\pi^+$
$h_1(1170)K_S^0$
$a_1(1260)K_S^0$
$a_1(1640)K_S^0$
$K_1(1270)^-\pi^+$
$\bar{K}_1(1270)^0\pi^0$
$\bar{K}_1(1400)^0\pi^0$
$K_1(1400)^-\pi^+$
$\bar{K}_1(1650)^0\pi^0$
$K_1(1650)^-\pi^+$
$a_2(1320)K_S^0$
$K_2^*(1430)^-\pi^+$
$\bar{K}_2^*(1430)^0\pi^0$
$K^*(892)^-\rho(770)^+$
$\bar{K}^*(892)^0\rho(770)^0$
$K^*(892)^-\rho(1450)^+$
$\bar{K}^*(892)^0\rho(1450)^0$ [D]
$K^*(1680)^-\rho(770)^+$ [S]
$\rho(1450)^0(K_S^0\pi^0)^{L=1}$
$\bar{K}^*(892)^0 f_2(1270)$

- CP-even fractions
- longitudinal polarization fraction of $D^0 \to K^{*-}\rho^+$and $D^0 \to \bar{K}^{*0}\rho^0$.
- $D^0 \to K^{*-}\rho^+$纵向极化0.5左右
- $D^0 \to \bar{K}^{*0}\rho^0$ 横向极化主导

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

- 末态包含三个全同π^0，振幅分析难度较大
- 不含ρ，中间态较少

Amplitude
$D^0 \to \bar{K}_1(1400)^0\pi^0, \bar{K}_1(1400)^0 \to \bar{K}^*(892)^0\pi^0$
$D^0 \to \bar{K}_1(1270)^0\pi^0, \bar{K}_1(1270)^0 \to \bar{K}^*(892)^0\pi^0$
$D^0 \to \bar{K}(1460)\pi^0, \bar{K}(1460) \to \bar{K}^*(892)^0\pi^0$
$D^0 \to \bar{K}(1460)\pi^0, \bar{K}(1460) \to \bar{K}^0(\pi^0\pi^0)_{S-\mathrm{wave}}$
f_{KK}
β_0
β_1
$D^0 \to \bar{K}_S^0\pi(1300), \pi(1300) \to (\pi^0\pi^0)_{S-\mathrm{wave}}\pi^0$
$f_{\pi\pi}$
β_0
β_1
$D^0 \to (K_S^0\pi^0)_{S-\mathrm{wave}}(\pi^0\pi^0)_{S-\mathrm{wave}}$
$\alpha_{3/2}$
$\alpha_{K\eta'}$
β_1
$f_{\pi\pi}$



- 为$K_1(1270)/K_1(1400)$混合角的确定提供实验测量

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

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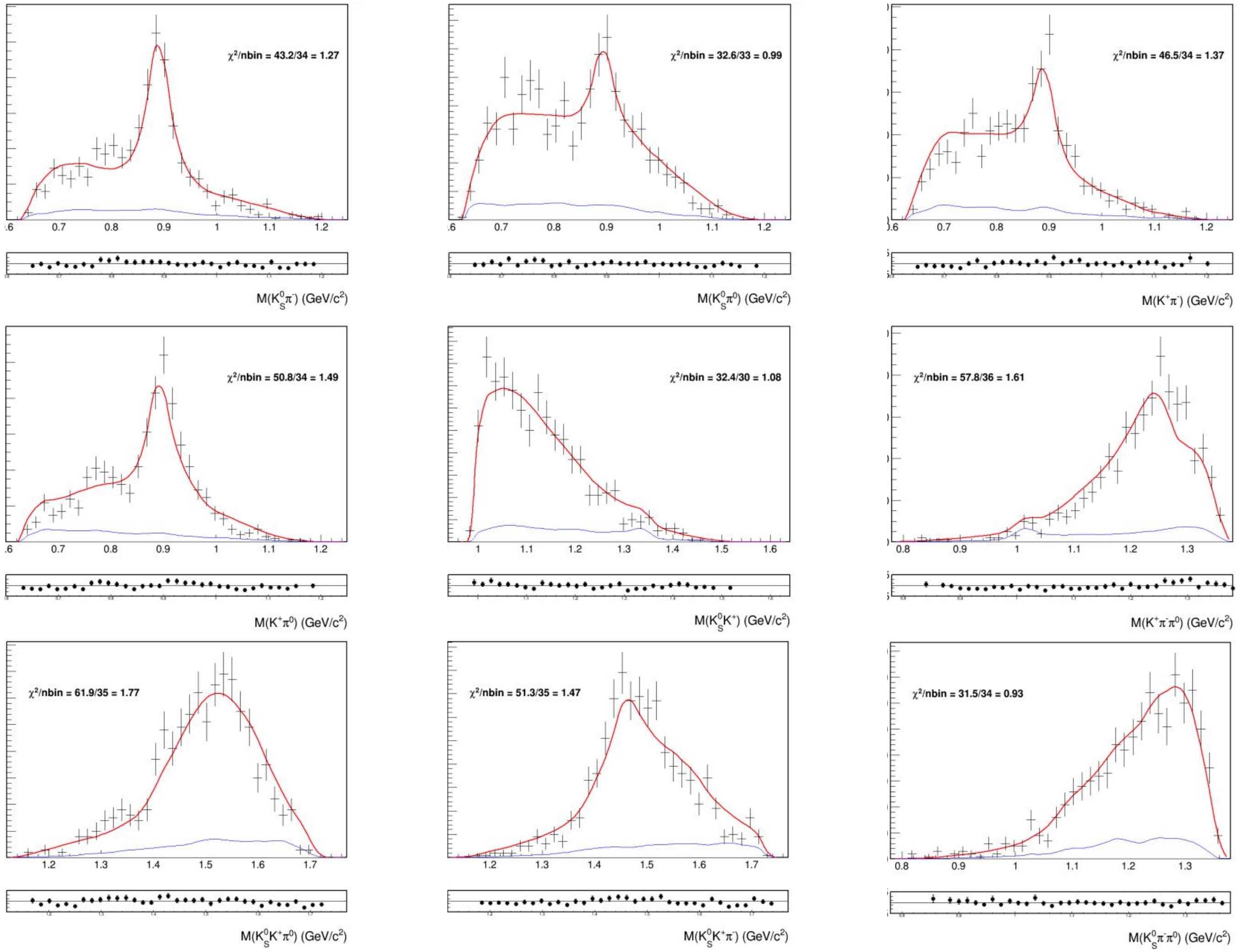
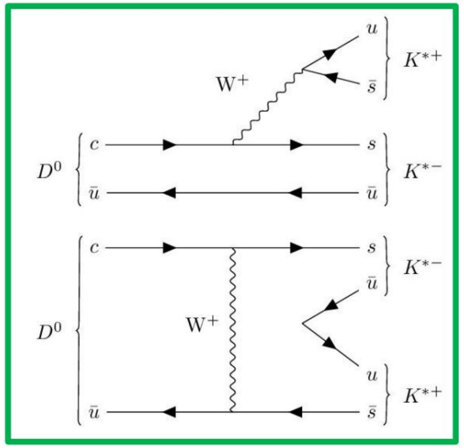
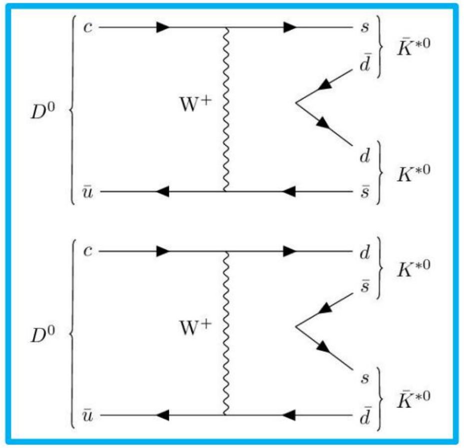


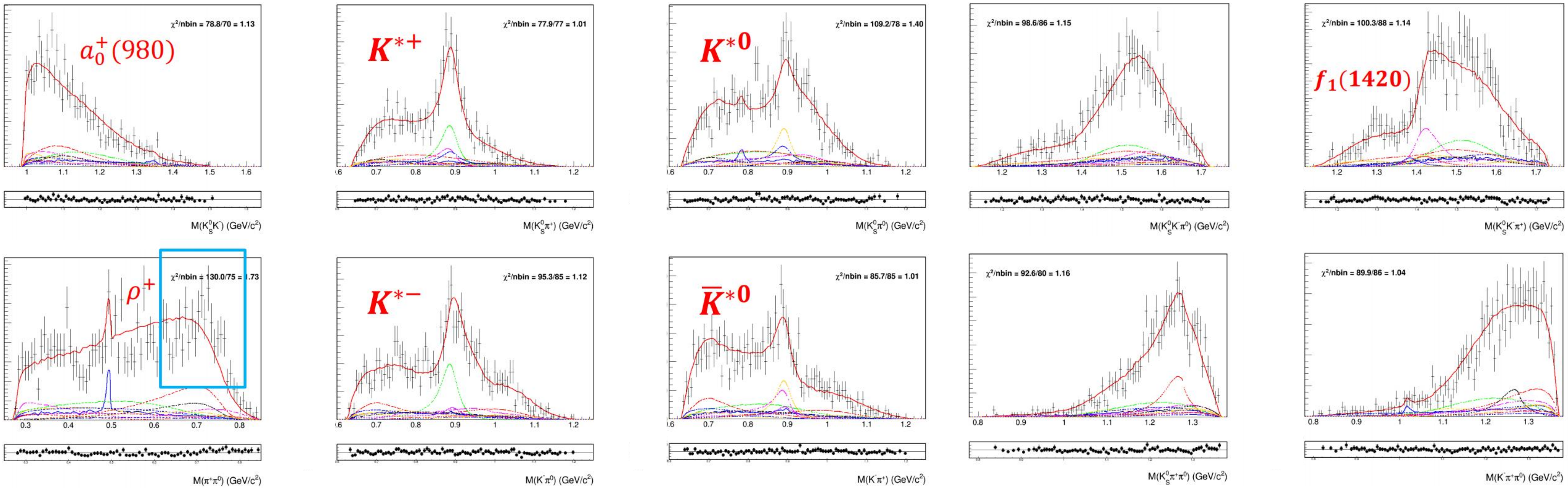
Amplitude
$D^0[S] \to K^{*+}K^{*-}$
$D^0[P] \to K^{*+}K^{*-}$
$D^0 \to K^{*+}K^{*-}$
$D^0[S] \to \bar{K}^{*0}K^{*0}$
$D^0[D] \to \bar{K}^{*0}K^{*0}$
$D^0 \to K^{*0}K^{*0}$
$D^0 \to K_1^-(1400)[S](\to K^*\pi)K^+$
$D^0 \to K_1^0(1270)[S](\to K^+\rho^-)K_S^0$
$D^0 \to \eta(1475)(\to K^*K)\pi^0$
$D^0 \to a_0^+(980)\rho^-$





同时测量到$D^0 \to K^{*-}K^{*+}$，$D^0 \to \bar{K}^{*0}K^{*0}$的极化

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

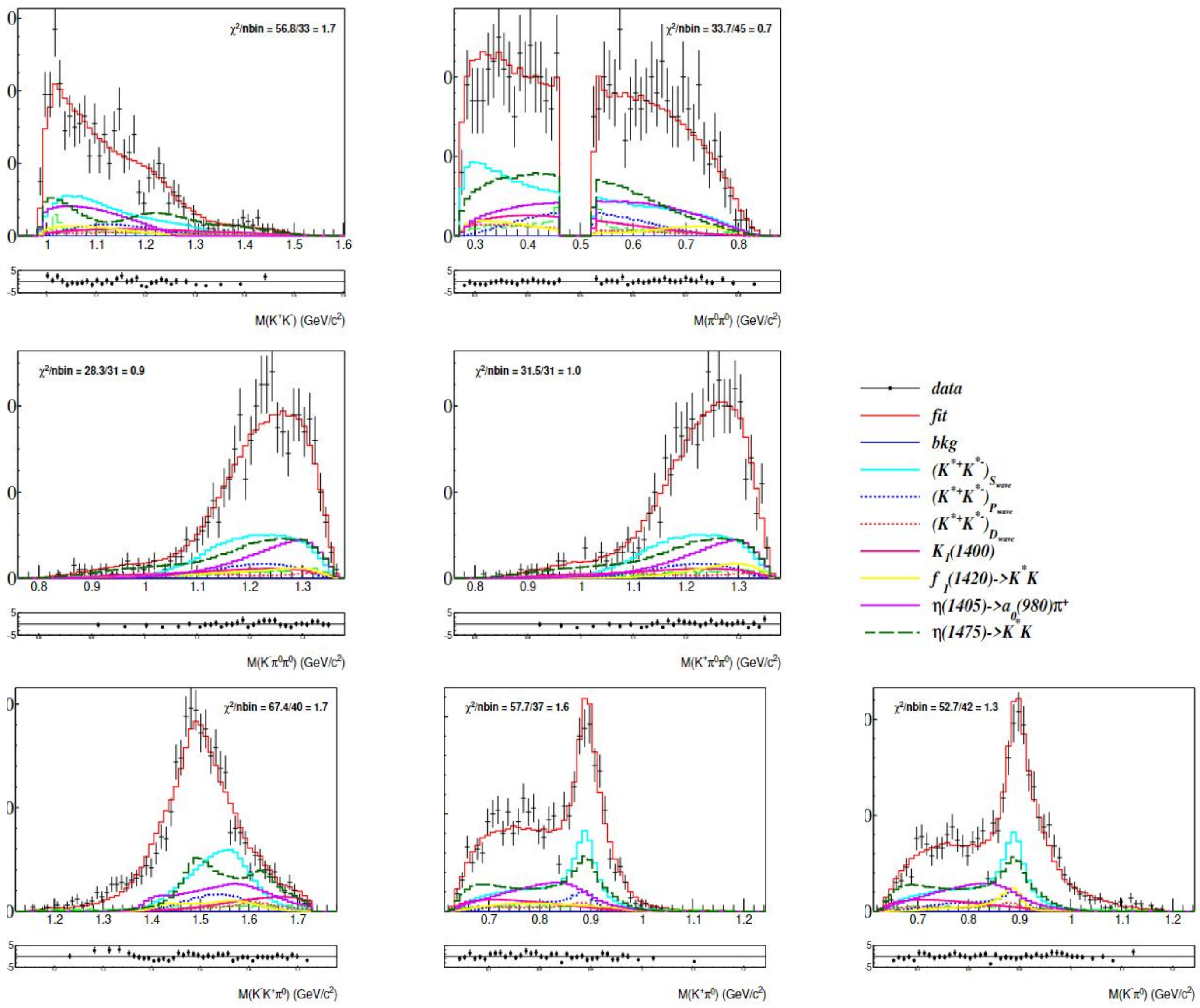


Amplitude	
$D^0[S] \to K^{*+}K^{*-}$	$D^0 \to K_1^+(1270)[S](\to K_S^0\rho^+)K^-$
$D^0[P] \to K^{*+}K^{*-}$	$D^0 \to K_1^+(1400)[S](\to K^*\pi)K^-$
$D^0[D] \to K^{*+}K^{*-}$	$D^0 \to \bar{K}_1^0(1270)[S](\to K^-\rho^+)K_S^0$
$D^0 \to K^{*+}K^{*-}$	$D^0 \to \bar{K}_1^0(1400)[S](\to K^*\pi)K_S^0$
$D^0[S] \to \bar{K}^{*0}K^{*0}$	$D^0 \to f_1(1420)[S](\to K^*K)\pi^0$
$D^0[P] \to \bar{K}^{*0}K^{*0}$	$D^0 \to f_1(1420)(\to a_0^-(980)\pi^+)\pi^0$
$D^0[D] \to \bar{K}^{*0}K^{*0}$	$D^0 \to \eta(1405)(\to a_0^-(980)\pi^+)\pi^0$
$D^0 \to \bar{K}^{*0}K^{*0}$	$D^0 \to a_0^-(980)\rho^+$

- 同时测量$D^0 \to K^{*-}K^{*+}$，$D^0 \to \bar{K}^{*0}K^{*0}$的极化
- 结合上个分析，可以测 $r_{+/-} = \frac{\mathcal{B}(D^0 \to a_0^+\rho^-)}{\mathcal{B}(D^0 \to a_0^-\rho^+)}$

  为确定a_0结构提供信息

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



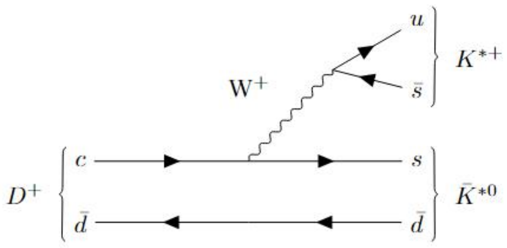
Amplitude
$D^0[S] \to K^{*+}(892)K^{*-}(892)$
$D^0[P] \to K^{*+}(892)K^{*-}(892)$
$D^0[D] \to K^{*+}(892)K^{*-}(892)$
$D^0 \to K^{*+}(892)K^{*-}(892)$
$D^0 \to K_1(1400)^+(\to K^*(892)^+\pi^0)K^-$
$D^0 \to f_1(1420)(\to K^*(892)^+K^-)\pi^0$
$D^0 \to f_1(1420)(\to K^*(892)^-K^+)\pi^0$
$D^0 \to f_1(1420)\pi^0$
$D^0 \to \eta(1405)(\to a_0(980)\pi^0)\pi^0$
$D^0 \to \eta(1475)(\to K^{*-}(892)K^+)\pi^0$
$D^0 \to \eta(1475)(\to K^{*+}(892)K^-)\pi^0$
$D^0 \to \eta(1475)\pi^0$

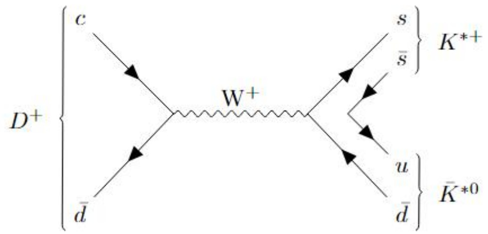
- 主要过程：$D \to VV$
- 横向极化主导
- $D^0 \to K^{*+}K^{*-}$分支比测量

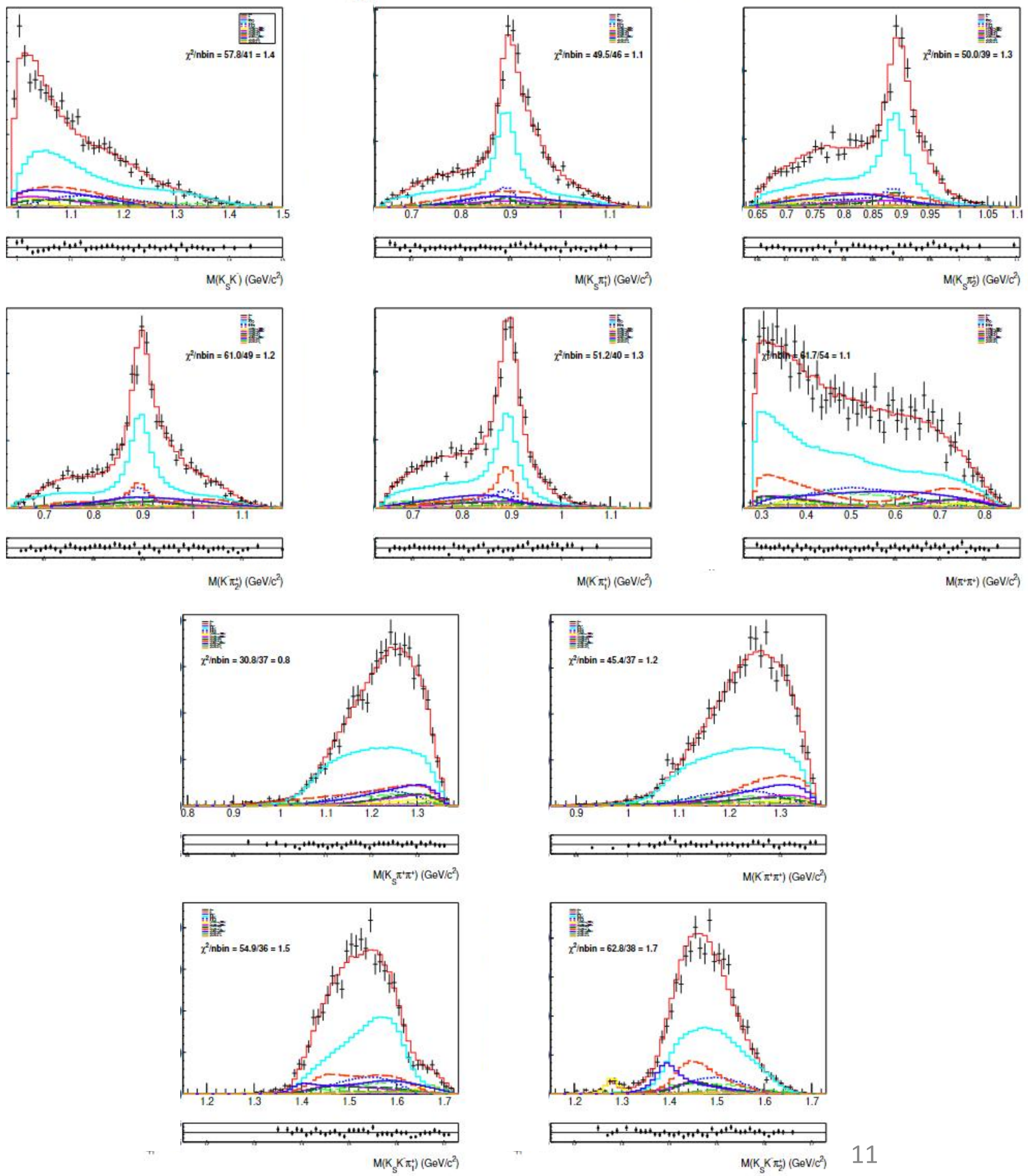
Amplitude	$\mathcal{B}(D^0 \to K^*(892)^+K^*(892)^-)$ $(\times 10^{-3})$
NRCQM with FSIs [13]	9.92±0.34
NRCQM without FSIs [13]	5.86
flavor SU(3) symmetry model [9]	2.4
factorization approach [41]	7.3

$D^+ \to K_S^0 K^- \pi^+ \pi^+$ BAM-01017

Amplitude
$D^+[S] \to \bar{K}^*(892)^0 K^*(892)^-$
$D^+[P] \to \bar{K}^*(892)^0 K^*(892)^-$
$D^+[D] \to \bar{K}^*(892)^0 K^*(892)^-$
$D^+ \to f_1(1285)\pi^+, f_1(1285) \to a_0(980)\pi^+$
$D^+ \to f_1(1420)\pi^+, f_1(1420) \to K^*(892)^+ K^-$
$D^+ \to f_1(1420)\pi^+, f_1(1420) \to K^*(892)^0 K_S$
$D^+ \to f_1(1420)\pi^+, f_1(1420) \to a_0(980)\pi^+$
$D^+ \to \eta(1405)\pi^+, \eta(1405) \to a_0(980)\pi^+$
$D^+ \to \eta(1475)\pi^+, \eta(1475) \to K^*(892)^+ K^-$
$D^+ \to \eta(1475)\pi^+, \eta(1475) \to K^*(892)^0 K_S$



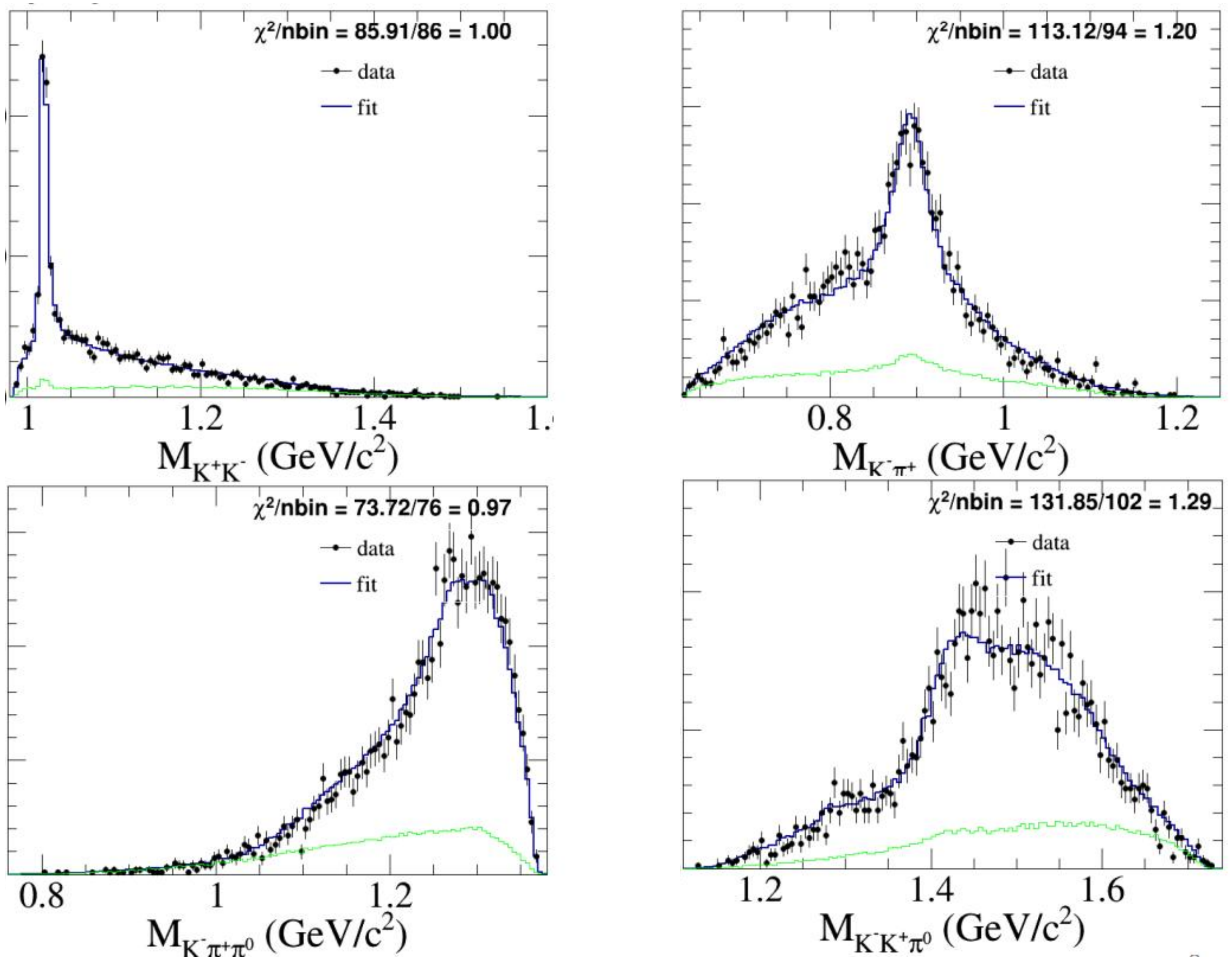




- 主要过程：$D \to VV$
- 横向极化主导
- $D^+ \to K^{*0} K^{*+}$分支比首次测量

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

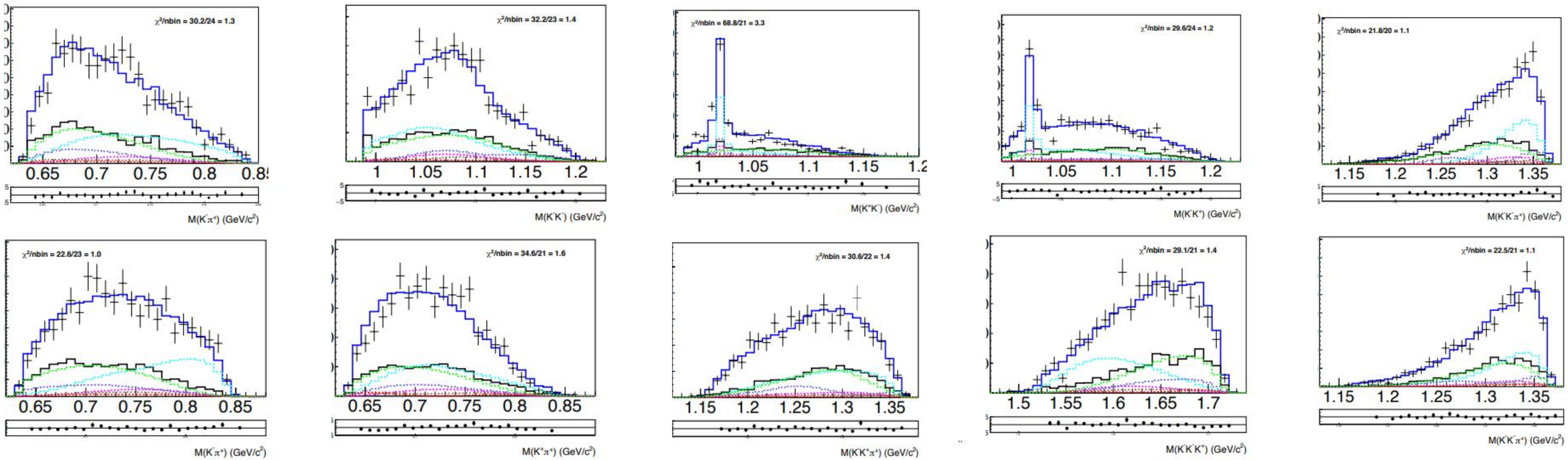
已过组内审核



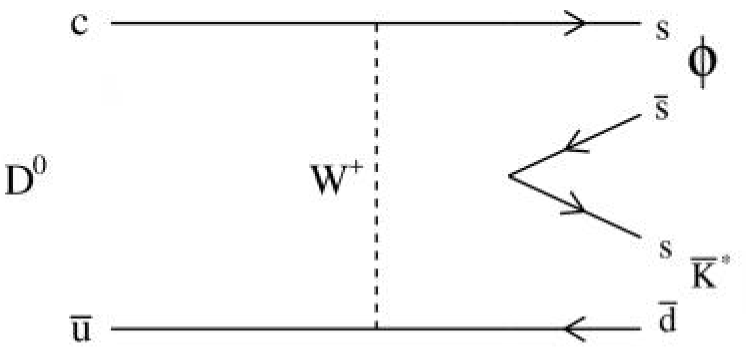
同时测量$D^+ \to K^{*0}K^{*+}$，$D^+ \to \phi\rho^+$的极化

$D^+ \to \phi\rho^+$	S
	P
	D
$D^+ \to \bar{K}^{*0}K^+$	S
	P
	D
$D^+ \to \bar{K}_1(1270)^0(\rho^+K^-)K^+$	S
$D^+ \to \bar{K}_1(1400)^0(\bar{K}^*\pi)K^+$	S
$D^+ \to a_0(980)^0\rho^+$	
$D^+ \to f_1(1420)(K^*K)\pi^+$	S
$D^+ \to f_1(1285)(K^*K)\pi^+$	S
$D^+ \to \eta(1405)(a_0(980)\pi^0)\pi^+$	
$D^+ \to \eta(1405)(K^*K)\pi^+$	

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



$D^0[S] \to \phi \bar{K}^{*0}$
$D^0[P] \to \phi \bar{K}^{*0}$
$D^0[D] \to \phi \bar{K}^{*0}$
$D^0 \to \phi \bar{K}^{*0}$
$D^0 \to (K^- \pi^+)_S \phi$
$D^0 \to (K^- K^+)_S \bar{K}^{*0}$



Other ongoing analysis....

$D^0 \to K_L^0\pi^+\pi^-\pi^0$	(Feng Yutong)	初步结果
$D^+ \to K_S^0K^+\pi^+\pi^-$	(Li Shuo)	2024.12 合作组会分会报告
$D^+ \to K^-\pi^+\pi^+\eta$	(Zeng Xin)	初步结果
$D^0 \to K^-\pi^+\pi^0\eta$	(Zhou Shuai)	初步结果
$D^0 \to K_S^0\pi^+\pi^-\eta$	(Liu Xinghan)	2025.4 Workshop分会报告
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	(Li Xu)	2023.12 合作组会分会报告
$D^0 \to \pi^+\pi^-\pi^0\pi^0$	(Shan Xinyu)	2.93fb^{-1}已发表
$D^0 \to \pi^+\pi^-\pi^+\pi^-$	(Shan Xinyu)	2.93fb^{-1}已发表 在更新20.3fb^{-1}中

总结

对D介子四体衰变的振幅分析研究积累了丰富的成果

- 对$D \to VV$过程有了更深入的了解，包括$D^0 \to K^{*-}K^{*+}$，$D^0 \to \overline{K}^{*0}K^{*0}, D^0 \to K^{*-}\rho^+, D^0 \to \overline{K}^{*0}\rho^+, D^+ \to K^{*0}K^{*+}$，$D^+ \to \phi\rho^+$等
- 测量到大量$D \to AP$过程，为研究轴矢量介子性质及衰变方式提供重要信息
- 在部分衰变道的研究中，观测到实验值与理论预期不符的情况，如$D^0 \to \overline{K}^{*0}\rho^0$的极化情况、$D^0 \to K^{*-}K^{*+}$的分支比、$D \to a_0\rho$系统中的$r_{+/-}$、$r_{+/0}$值等

谢谢！