Amplitude Analysis and Branching Fraction Measurement of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$ at BESIII

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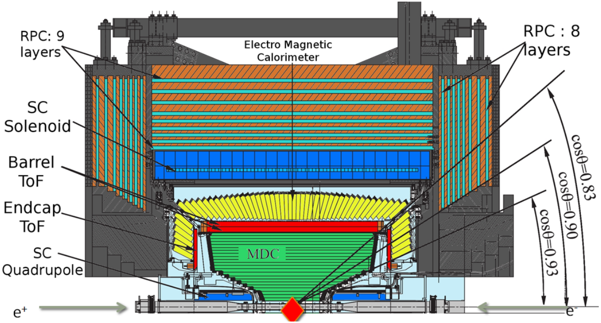
Outline

Outline

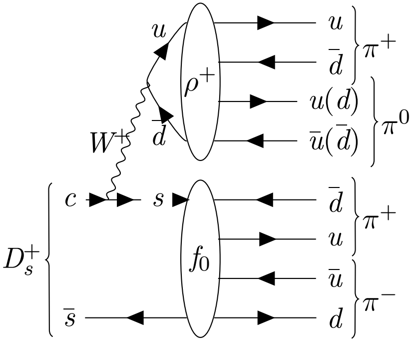
Introduction to BESIII

- BESIII is a large magnetic spectrometer operating on BEPCII
- Accumulated huge electron-positron colliding data at tau-charm energy region(2-5 GeV)
- Analysis of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$ is performed based on 7.33 fb^{-1} data taken by BESIII at $\sqrt{s} = 4.13 - 4.23$ GeV



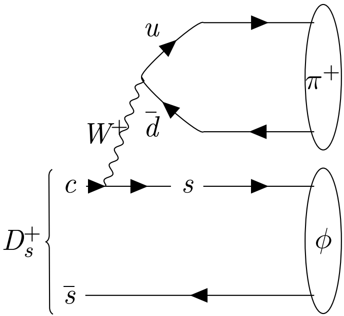
Motivation

- D_s^+ decays contain rich information of QCD in low-energy domain
- $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$ decay is never studied before, and can be used to study $f_0(980)\rho^+$, $f_0(500)\rho^+$, $\phi\pi^+$, $\omega\pi^+$ and $\rho^+\rho^0$
- Study of $D_s^+ \to f_0(980)\rho^+$ can be **combined** with $D_s^+ \to a_0(980)\rho$ to study $f_0(980) - a_0(980)$ **mixing**
- Study of $D_s^+ \to f_0(500)\rho^+$ serves to distinguish **long-distance interaction** prediction on whether $f_0(500)$ is **tetraquark** or conventional meson



Motivation

- $D_s^+ \to \phi\pi^+$ is a **key reference channel** in D_s^+ study. In $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$ it can be studied via $\phi \to \pi^+\pi^-\pi^0$
- Studies of ϕ meson are mainly conducted in e^+e^- annihilation(KLOE/CMD/SND) and $K-p$ scattering(HBC) experiments, which face challenges from **complicated background** and **continuum interference**
- BESIII accumulates huge data containing ϕ mesons from charm meson decays, which provides a novel method to study ϕ meson
- In comparing different channels of ϕ in charm decays, one can measure **relative BF** of ϕ decay



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Selection Method

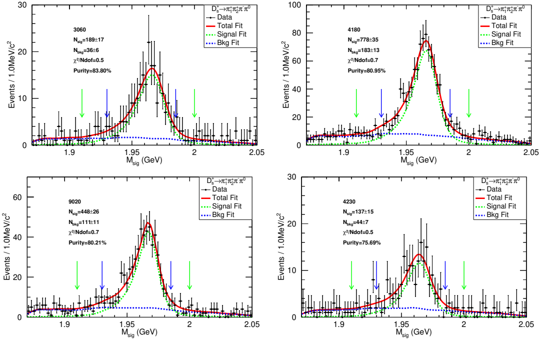
- Signals are extracted from $e^+e^- \to D_s^{*+}D_s^- \to (\gamma D_s^+)D_s^- + c.c.$
- D_s mesons are produced **in pair**. Reconstruct seven single tag D_s channels firstly, then find signal $\pi^+\pi^+\pi^-\pi^0$ in recoiling side
- Veto $M_{\pi^+\pi^-}$ within (0.46,0.52) GeV$/c^2$ to reject $K_S^0\pi^+\pi^0$

Single-Tag Channel	**Mass Window** (GeV$/c^2$)
$D_s^- \to K_S^0K^-$	$(1.948, 1.991)$
$D_s^- \to K^+K^-\pi^-$	$(1.950, 1.986)$
$D_s^- \to K^+K^-\pi^-\pi^0$	$(1.947, 1.982)$
$D_s^- \to K_S^0K^+\pi^-\pi^-$	$(1.953, 1.983)$
$D_s^- \to \pi^-\eta$	$(1.958, 2.000)$
$D_s^- \to \pi^-\eta'$	$(1.940, 1.996)$
$D_s^- \to K^-\pi^-\pi^+$	$(1.953, 1.986)$

Outline

Amplitude Analysis: Selection and Purity

- Divide into four sub-samples according to c.m. energy, to cover the differences of detection efficiency. Perform simultaneous fit
- Strict selection to reduce background



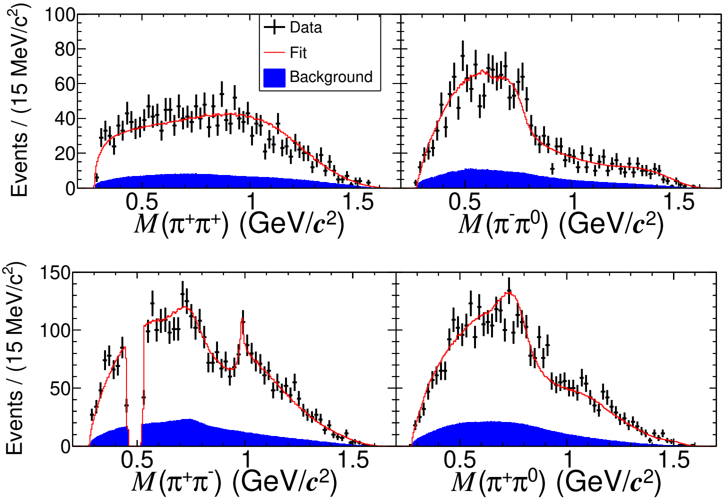
Sub-Sample	Purity(%)
(4.128-4.157)	83.80 ± 1.11
(4.178)	80.95 ± 0.71
(4.189-4.219)	80.21 ± 1.04
(4.226)	75.69 ± 2.20

Amplitude Analysis: Methodology and Summary

- Construct amplitude model through **covariant tensor** method, considering interferences among components
- Fit Fraction(FF) is the fraction of a component to whole process
- $f_0(500)\rho^+$, $f_0(1500)\rho^+$ and $a_2(1320)^+\pi^0$ are excluded because of **limited significance**

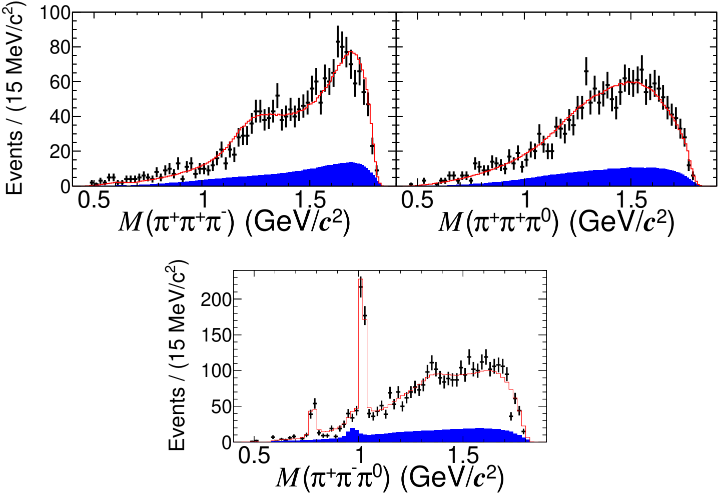
Component	Coupling magnitude	Phase	Fit Fraction(FF)(%)
$D_s^+ \to f_0(1370)\rho^+$	1.0(fixed)	0.0(fixed)	$24.9 \pm 3.8 \pm 2.1$
$D_s^+ \to f_0(980)\rho^+$	$0.40 \pm 0.04 \pm 0.03$	$3.99 \pm 0.13 \pm 0.07$	$12.6 \pm 2.1 \pm 1.0$
$D_s^+ \to f_2(1270)\rho^+$	$0.77 \pm 0.10 \pm 0.03$	$1.11 \pm 0.10 \pm 0.10$	$9.5 \pm 1.7 \pm 0.6$
$D_s^+[S] \to \rho^+\rho^0$	$0.12 \pm 0.02 \pm 0.01$	$1.10 \pm 0.18 \pm 0.10$	$3.5 \pm 1.2 \pm 0.6$
$D_s^+[S] \to \rho^+(1450)\rho^0$	$1.15 \pm 0.19 \pm 0.08$	$0.43 \pm 0.18 \pm 0.17$	$4.6 \pm 1.3 \pm 0.8$
$D_s^+[P] \to \rho^+\rho^0(1450)$	$0.57 \pm 0.06 \pm 0.01$	$4.58 \pm 0.16 \pm 0.09$	$8.6 \pm 1.3 \pm 0.4$
$D_s^+ \to \phi\pi^+, \phi \to \rho\pi$	$0.075 \pm 0.006 \pm 0.004$	$2.90 \pm 0.15 \pm 0.18$	$24.9 \pm 1.2 \pm 0.4$
$D_s^+ \to \omega\pi^+, \omega \to \rho\pi$	$0.20 \pm 0.02 \pm 0.03$	$3.22 \pm 0.21 \pm 0.09$	$6.9 \pm 0.8 \pm 0.3$
$D_s^+ \to a_1^+\pi^0$, $a_1^+[S] \to \rho^0\pi^+$	$0.57 \pm 0.06 \pm 0.05$	$3.78 \pm 0.16 \pm 0.12$	$12.5 \pm 1.6 \pm 1.0$
$D_s^+ \to a_1^0\pi^+$, $a_1^0[S] \to \rho\pi$	$0.31 \pm 0.06 \pm 0.04$	$4.82 \pm 0.15 \pm 0.12$	$6.3 \pm 1.9 \pm 1.2$
$D_s^+ \to \pi^0(1300)\pi^+ \to ([P]\rho\pi)\pi^+$	$0.28 \pm 0.04 \pm 0.07$	$2.22 \pm 0.14 \pm 0.08$	$11.7 \pm 2.3 \pm 2.2$

Ampitude Analysis: Fit Projection



- In $M_{\pi^+\pi^-}$ spectrum, veto K_S at (0.46,0.52) GeV$/c^2$ and clear $f_0(980)$ signal can be observed

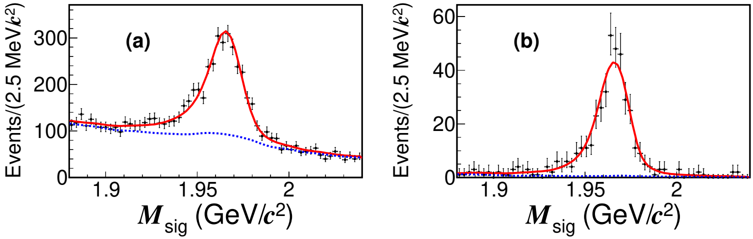
Amplitude Analysis: Fit Projection



- In $M_{\pi^+\pi^-\pi^0}$ spectrum, clear ϕ and ω signal can be observed and precisely measured. Fit result and data is **consistent**

Outline

Branching Fraction Measurement



- Because of high purity of $D_s^+ \to \eta(\to \pi^+\pi^-\pi^0)\pi^+$, $\eta\pi^+$ is measured separately from non-η process
- For $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$(non-$\eta$), we get 2489 ± 91 signals and BF is measured to be $(2.04 \pm 0.08)\%$
- For $D_s^+ \to \eta(\to \pi^+\pi^-\pi^0)\pi^+$, we get 392 ± 22 signals and BF is measured to be $(3.58 \pm 0.21) \times 10^{-3}$

Outline

Relative BF R_ϕ Measurement

- Based on fit fraction(FF$_i$), total BF(BF($D_s^+ \to 4\pi|$non-η)) and BF of sub-decays, one can calculate the BF of a component in the amplitude model: BF$_i$ = FF$_i$ $\times$ BF($D_s^+ \to 4\pi|$non-η) $\div$ BF$_{\text{sub}}$

Component	BF (10^{-3})(PDG)	BF (10^{-3})(This work)
$D_s^+ \to \phi\pi^+$	$44.9 \pm 1.0 \pm 1.4$	$33.0 \pm 2.1 \pm 0.9$
$D_s^+ \to \omega\pi^+$	$1.77 \pm 0.32 \pm 0.13$	$1.58 \pm 0.19 \pm 0.08$
$D_s^+ \to \eta\pi^+$	$16.7 \pm 0.8 \pm 0.6$	$15.6 \pm 0.9 \pm 0.4$

- **Combining** the BESIII measurement of $D_s^+ \to \phi(\to K^+K^-)\pi^+$, one can calculate $R_\phi = \frac{\mathcal{B}(\phi\to\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi\to K^+K^-)} = 0.230 \pm 0.014 \pm 0.010$, which **differs by $> 4\sigma$ and by $\sim 30\%$ relatively** from the world average value $R_\phi^{\text{PDG}} = \frac{\mathcal{B}(\phi(1020)\to\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi(1020)\to K^+K^-)} = 0.313 \pm 0.010$

Outline

Summary & Outlook

- Summary
  - Report of Amplitude Analysis and BF Measurement of $D_s^+ \to \pi^+\pi^+\pi^-\pi^0$
  - $D_s^+ \to f_0(980)\rho^+$ is precisely measured, providing valuable information to $f_0 - a_0$ **mixing** study
  - $D_s^+ \to f_0(500)\rho^+$ is excluded due to limited significance, suggesting its tetraquark configuration according to **long-distance interaction** prediction
  - $D_s^+ \to \phi\pi^+$ is precisely measured, and get $R_\phi = \frac{\mathcal{B}(\phi\to\pi^+\pi^-\pi^0)}{\mathcal{B}(\phi\to K^+K^-)} = 0.230 \pm 0.014 \pm 0.010$, which **differs by** $> 4\sigma$ **and by** $\sim 30\%$ **relatively** from PDG value. Expect theory explain
- Outlook
  - Based on huge $\psi(3770)$ data accumulated by BESIII, Studies of f_0 in charm sector such as $D \to a_0/f_0\pi$、$D \to a_0/f_0\rho$ **are ongoing**
  - Regarding the anomaly in R_ϕ, **Cross Checks** are being performed at BESIII in $D_{(s)}^+ \to \pi^+\pi^+\pi^-\pi^0\pi^0$、$D_{(s)}^+ \to K_SK_L\pi^+$

Thanks for Listening!
Suggestions are Welcomed!

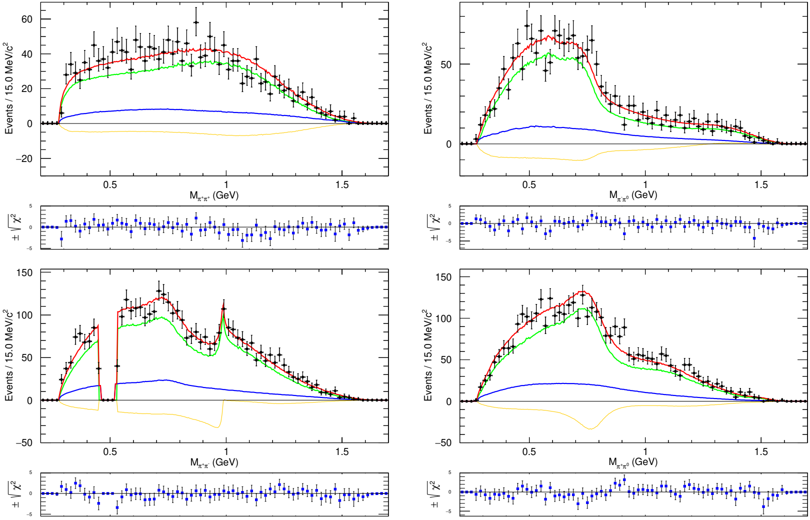
BackUp

数据样本

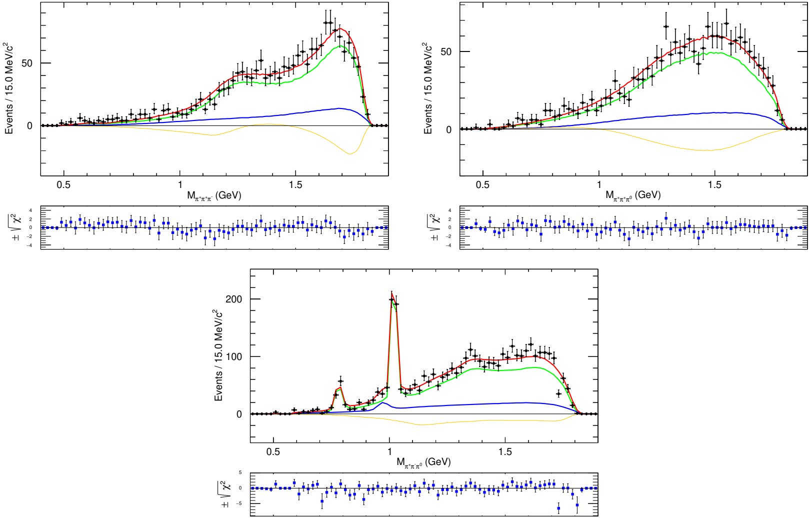
- 分析基于的数据样本详细信息见下表

样本	年份	亮度 (pb^{-1})	E_{cm} (MeV)
4130	2019	401.5	4128.48 ± 0.44
4160	2019	408.7	4157.44 ± 0.44
4180	2016	$3189.0 \pm 0.2 \pm 31.9$	平均 4178
4180	2016		
4190	2017	$526.7 \pm 0.1 \pm 2.2$	$4188.99 \pm 0.06 \pm 0.41$
4190	2012	$43.33 \pm 0.03 \pm 0.29$	$4188.59 \pm 0.15 \pm 0.68$
4200	2017	$526.0 \pm 0.1 \pm 2.1$	$4199.03 \pm 0.05 \pm 0.41$
4210	2017	$517.1 \pm 0.1 \pm 1.8$	$4209.25 \pm 0.06 \pm 0.42$
4210	2013	$54.95 \pm 0.03 \pm 0.36$	$4207.13 \pm 0.14 \pm 0.61$
4220	2017	$514.6 \pm 0.1 \pm 1.8$	$4218.84 \pm 0.05 \pm 0.40$
4220	2013	$54.60 \pm 0.03 \pm 0.36$	$4217.13 \pm 0.14 \pm 0.67$
4230	2013	$1047.34 \pm 0.14 \pm 10.16$	$4320.34 - 2.87 \times 10^{-3} \times N_{run} \pm 0.05$
4230	2013		$4225.54 \pm 0.05 \pm 0.65$
4230	2012	$44.54 \pm 0.03 \pm 0.29$	$4226.26 \pm 0.04 \pm 0.65$

振幅分析：拟合结果投影图



振幅分析：拟合结果投影图



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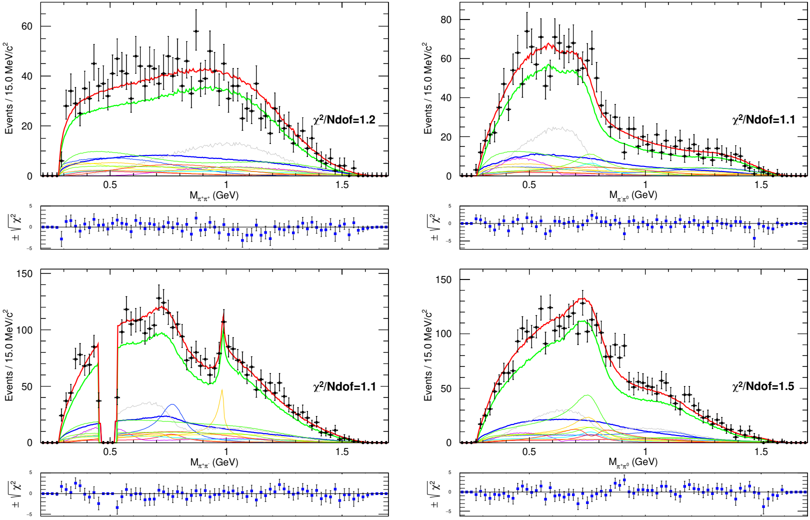
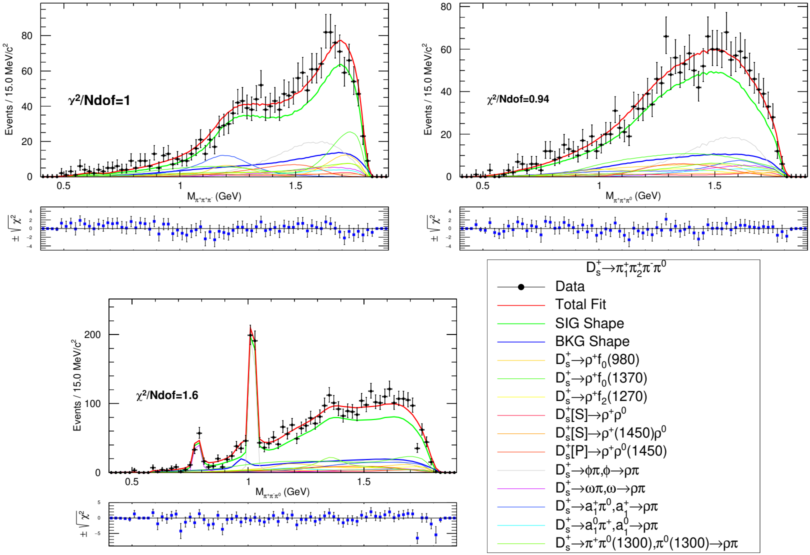


振幅分析：拟合结果投影图



事例挑选

- 带电径迹挑选
  - $|\cos\theta|<0.93$;
  - 与对撞点沿 XY 平面距离 $R_{xy} < 1.0$cm
  - 与对撞点沿 Z 轴距离 $|R_z| < 10.0$cm
- $K^+(K^-)$ 粒子鉴别
  - $CL_K > 0$; $CL_K > CL_\pi$
- $\pi^+(\pi^-)$ 粒子鉴别
  - $CL_\pi > 0$; $CL_\pi > CL_K$
- 好光子 γ 挑选
  - $\theta>10^\circ$
  - $E > 0.025$GeV, $|\cos\theta| <0.8$
  - $E > 0.05$GeV, $0.86< |\cos\theta| <0.92$
  - 飞行时间 $0 < t_{TDC} < 700$ns

事例挑选

- K_S^0 重建
  - 通过一对带电径迹重建
  - 顶点拟合: $\chi^2 < 100$
  - 要求不变质量满足 0.487< $M_{\pi^+\pi^-}$ <0.511GeV/c^2
- π^0 重建
  - 用一对好光子 γ 重建，且至少一个来自 BESIII 桶部
  - π^0 质量运动学拟合: $\chi^2 < 30$
  - 要求不变质量满足:0.115< $M_{\gamma\gamma}$ <0.150GeV/c^2
- η 重建
  - 用一对好光子 γ 重建，且至少一个来自 BESIII 桶部
  - η 质量运动学拟合: $\chi^2 < 30$
  - 要求不变质量满足:0.500< $M_{\gamma\gamma}$ <0.570GeV/c^2
- $\eta^{'}$ 重建
  - 用 $\pi^+\pi^-\eta_{\gamma\gamma}$ 重建
  - 要求不变质量满足:0.946< $M_{\pi^+\pi^-\eta_{\gamma\gamma}}$ <0.970GeV/c^2

事例挑选

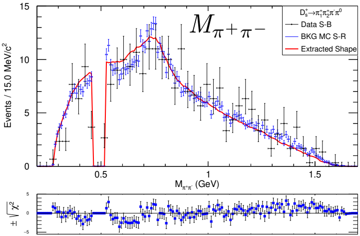
- 定义观测量 $M_{rec}=\sqrt{(E_{cm}-\sqrt{p_{D_s}^2+m_{D_s}^2})^2-|\vec{p}_{cm}-\vec{p}_{D_s}|^2}$，并要求至少事例中挑出的一对 D_s 介子，至少有一个满足 2.100< M_{rec} <2.125GeV/c^2，以**反冲得到** D_s^*
- 定义观测量 $M_{rec0}=\sqrt{(E_{cm}-\sqrt{|p_{D_s^2\gamma}|^2+m_{D_s^*}^2})^2-|\vec{p}_{D_s^1}|^2}$，要求选出的 D_s^* 满足 1.958< M_{rec0} <1.986GeV/c^2，**选出** D_s^*
- 要求不变质量 $M_{\pi^+\pi^-}$ 在 (0.46,0.52)GeV/c^2 区间外，**排除** $K_S^0\pi^+\pi^0$
- 要求不变质量 $M_{\pi^+\pi^-\pi^0}$ 在 (0.52,0.58)GeV/c^2 区间外，**排除** $\pi^+\eta$
- 在振幅分析中，同时重建单标记道与信号道 D_s，加入标记侧 D_s 质量、信号侧 D_s 质量、D_s^* 质量和总四动量约束，进行**运动学拟合**，提高末态动量分辨率

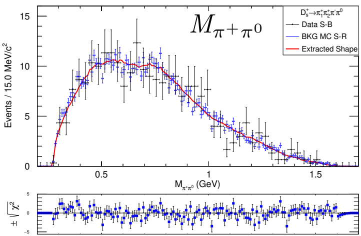
振幅分析：拟合公式与本底形状

- 振幅分析通过如下公式对数据进行拟合

$$\begin{aligned}
\text{PDF}(p_i) &= \omega_{sig} f_S(p_i) + (1-\omega_{sig}) f_B(p_i) \\
&= \omega_{sig} \frac{\epsilon(p_j)|M(p_j)|^2}{\int \epsilon(p_j)|M(p_j)|^2 \, d\Omega_4} + (1-\omega_{sig}) \frac{B(p_j)}{\int B(p_j) \, d\Omega_4} \\
&= \epsilon(p_j)[\omega_{sig} \frac{|M(p_j)|^2}{\int \epsilon(p_j)|M(p_j)|^2 \, d\Omega_4} + (1-\omega_{sig}) \frac{B(p_j)/\epsilon_{5D}}{\int B(p_j) \, d\Omega_4}]
\end{aligned}$$

- **信号 PDF** 由振幅公式构造，**本底 PDF** 通过 MC 样本估计





振幅分析：系统误差

振幅分析中的**系统误差**总结为**五个来源**

- (I) 共振态模型：通过改变质量或者宽度 $\pm 1\sigma$ 误差后结果的变化评估；对于 Flatté 传播子则改变其参数;
- (II) 势垒因子：通过在 $[2.0,4.0] GeV^{-1}$ 范围内改变势垒因子后，拟合结果的变化评估
- (III) 拟合偏差：通过对信号 MC 进行拟合，并对结果进行 Pull 分布分析，以其对标准正态分布的偏离作为该项误差评估
- (IV) 本底形状：通过在误差范围内调节样本纯度以及改变本底形状抽取方式后，拟合结果的变化来评估
- (V) 数据 MC 效率差异：通过控制样本得到修正因子，并修正数据中各个 π 介子的效率后，拟合结果的变化来评估

振幅分析：系统误差

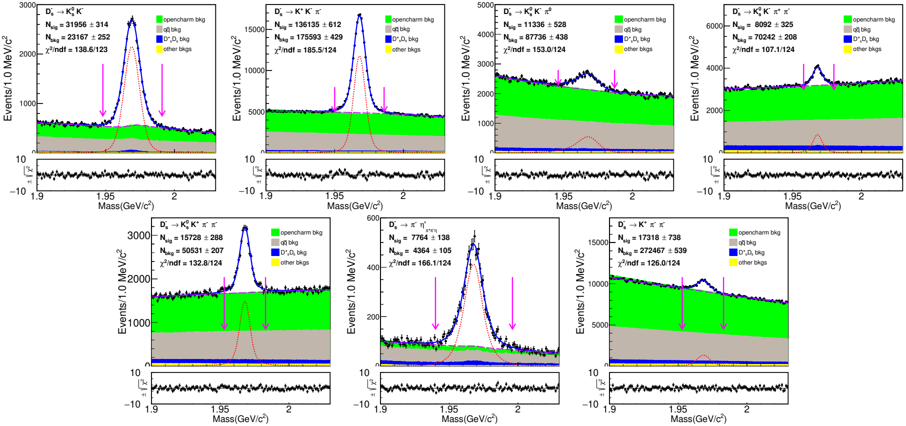
Component	Parameter	Source					Total
		I	II	III	IV	V	
$D_s \to \rho^+ f_0(1370)$	FF	1.3	1.3	0.7	0.5	0.4	2.1
$D_s \to \rho^+ f_0(980)$	FF	1.0	0.1	0.2	0.2	0.1	1.0
	Phase	0.06	0.02	0.03	0.00	0.00	0.07
	Magnitude	0.03	0.01	0.01	0.01	0.00	0.03
$D_s \to \rho^+ f_2(1270)$	FF	0.3	0.5	0.1	0.1	0.1	0.6
	Phase	0.09	0.03	0.00	0.01	0.00	0.10
	Magnitude	0.01	0.02	0.01	0.01	0.01	0.03
$D_s[S] \to \rho^+ \rho^0$	FF	0.3	0.5	0.2	0.0	0.0	0.6
	Phase	0.09	0.02	0.03	0.01	0.01	0.10
	Magnitude	0.01	0.01	0.00	0.00	0.00	0.01
$D_s[S] \to \rho^+(1450) \rho^0$	FF	0.3	0.6	0.0	0.2	0.3	0.8
	Phase	0.11	0.12	0.03	0.02	0.04	0.17
	Magnitude	0.03	0.04	0.03	0.03	0.04	0.08
$D_s[S] \to \rho^+ \rho^0(1450)$	FF	0.2	0.3	0.1	0.0	0.0	0.4
	Phase	0.03	0.07	0.04	0.02	0.02	0.09
	Magnitude	0.01	0.01	0.00	0.00	0.00	0.01

振幅分析：系统误差

Component	Parameter	Source I	II	III	IV	V	Total
$D_s \to \phi\pi^+, \phi \to \rho\pi$	FF	0.1	0.1	0.3	0.2	0.0	0.4
	Phase	0.10	0.13	0.07	0.01	0.02	0.18
	Magnitude	0.002	0.002	0.002	0.002	0.001	0.004
$D_s \to \omega\pi^+, \omega \to \rho\pi$	FF	0.0	0.2	0.2	0.0	0.0	0.3
	Phase	0.07	0.03	0.05	0.01	0.02	0.09
	Magnitude	0.00	0.02	0.01	0.01	0.01	0.03
$D_s \to a_1^+\pi^0, a_1^+[S] \to \rho\pi$	FF	0.7	0.7	0.1	0.1	0.1	1.0
	Phase	0.11	0.02	0.00	0.02	0.02	0.12
	Magnitude	0.03	0.03	0.02	0.01	0.01	0.05
$D_s \to a_1^0\pi^+, a_1^0[S] \to \rho\pi$	FF	0.9	0.5	0.0	0.5	0.4	1.2
	Phase	0.11	0.03	0.04	0.02	0.02	0.12
	Magnitude	0.03	0.02	0.01	0.01	0.01	0.04
$D_s[S] \to \pi^0(1300)\pi^+$	FF	1.1	1.7	0.0	0.6	0.7	2.2
	Phase	0.03	0.07	0.01	0.02	0.02	0.08
	Magnitude	0.04	0.05	0.01	0.01	0.01	0.07

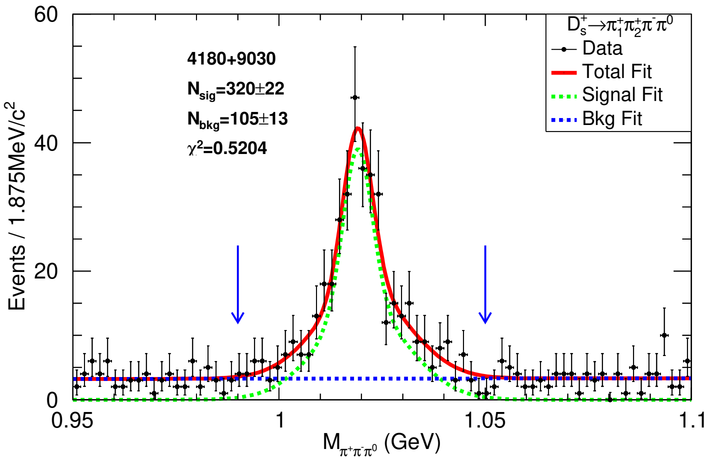
分支比测量：单标记产额

- 分为四个数据集，合并得到最终结果
- (I)(4.13-4.16) 样本 (II)(4.18) 样本 (III) (4.19-4.22) 样本 (IV) (4.23) 样本。下图展示 (II) 样本上的单标记拟合结果

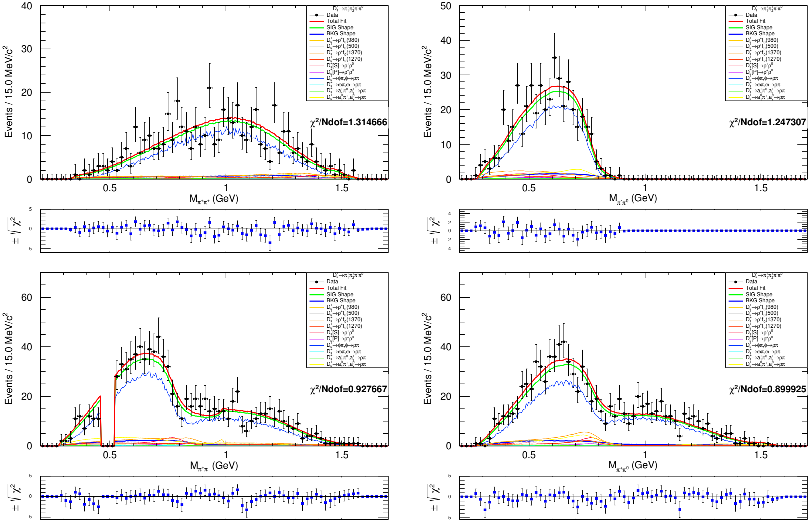


ϕ 检查

- 对 ϕ 的峰直接拟合
- 简单计算得比分为 $(23.4 \pm 1.6)\%$，与振幅分析结果 $(24.9 \pm 1.2 \pm 0.4)\%$ 误差内一致



振幅分析：拟合结果投影图



振幅分析：拟合结果投影图