# *D* Decay Models from BESIII

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2023 Belle II Physics Week
30th Nov - 3rd Dec, 2023

# Outline

- **Introduction**
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  - *D* Meson Decays at EvtGen
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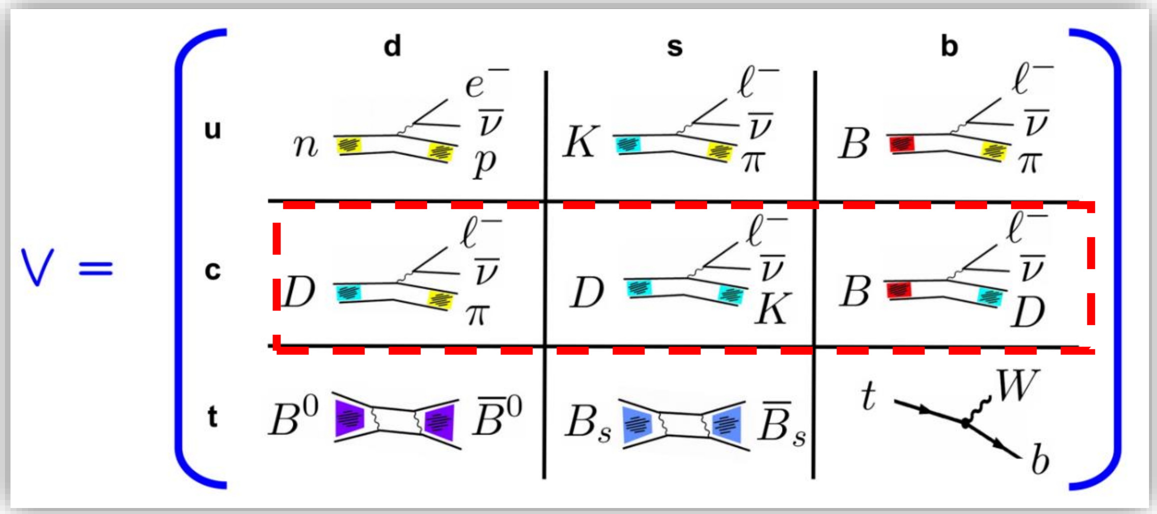
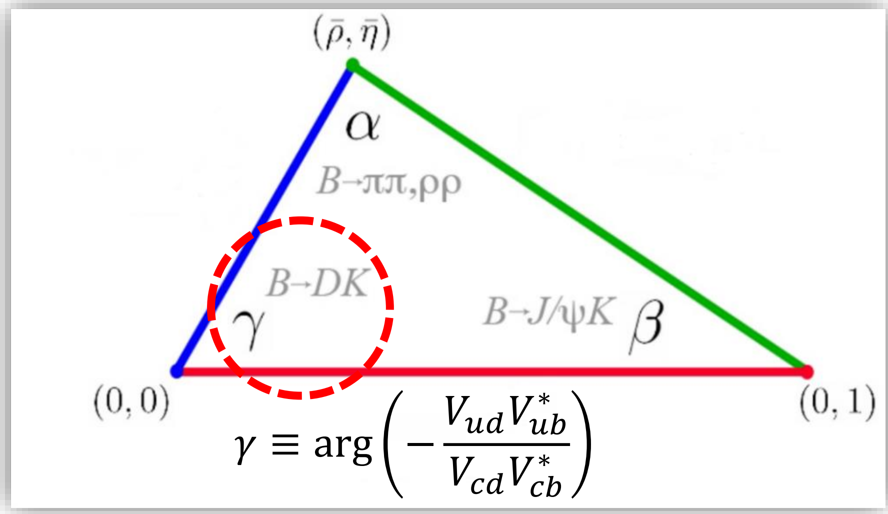
  - Data Set of *D* Meson at BESIII
- **Amplitude Analysis of *D* meson Decays**
  - Framework of amplitude analysis
  - An example of hadronic decay: $D^0 \to K^-\pi^+\pi^0\pi^0$
  - An example of semi-leptonic decay: $D \to \pi\pi e^+\nu$
- ***D* meson decays in BESIII-EvtGen**
- **Summary**

# Contribution of Charm in CKM Measurement

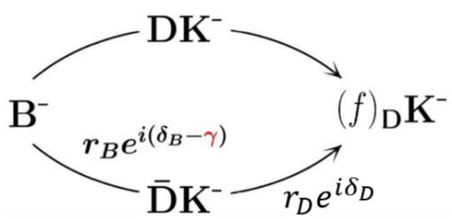



- $V_{cd}$ & $V_{cs}$: **Measured in (semi-)leptonic $D_{(s)}$ meson decays**

- $\gamma$ : **Interference between $B \to D^0 K$ and $B \to \bar{D}^0 K$**

  **Input from charm: Strong phase differences of $D^0$ decays**




- $V_{cb}$ : **Measured in semi-leptonic decay of $B \to D^{(*)} l^- \bar{\nu}$**

  **What can charm provide? *D* Decay models may be helpful !**

# *D* Meson Decays at EvtGen

***D* decay card in EvtGen-02-02-01** ⟹

- **BFs: out of date**
  - => update to new PDG value
- **Decay models (final states: $\pi, K, \eta$ …)**
  - **2-body decays (fine)**

    => No changes are required
  - **3-body decays**

    **D_DALITZ & PHSP (need update)**

    => i. Model from Dalitz analysis

    ii. Interpolation on Dalitz plane
  - **>= 4-body decays**

    **No specific model (need update)**

    **Direct sum of intermediate processes**

    => i. Model from amplitude analysis

    ii. Model from ML

```
0.038900000 K-      pi+                        PHSP; #[Reconstructed PDG2011]
#
0.012200000 K_S0    pi0                        PHSP; #[Reconstructed PDG2011]
0.010000000 K_L0    pi0                        PHSP; #[Reconstructed PDG2011]
0.000000000 anti-K0 pi0                        PHSP; #[Reconstructed PDG2011]
#
0.004290000 K_S0    eta                        PHSP; #[Reconstructed PDG2011]
0.003802795 K_L0    eta                        PHSP; #[Reconstructed PDG2011]
0.000000000 anti-K0 eta                        PHSP; #[Reconstructed PDG2011]
#
0.009300000 K_S0    eta'                       PHSP; #[Reconstructed PDG2011]
0.008980094 K_L0    eta'                       PHSP; #[Reconstructed PDG2011]
0.000000000 anti-K0 eta'                       PHSP; #[Reconstructed PDG2011]
#
0.011100000 omega   K_S0                       SVS; #[Reconstructed PDG2011]
0.010904400 omega   K_L0                       SVS; #[Reconstructed PDG2011]
0.000000000 omega   anti-K0                    SVS; #[Reconstructed PDG2011]
#
0.001603588 anti-K*0 eta                       SVS; #[Reconstructed PDG2011]
0.000916336 anti-K*0 eta'                      SVS; #[Reconstructed PDG2011]
0.078000000 a_1+    K-                         SVS; #[Reconstructed PDG2011]
0.067625607 K*-     rho+                       SVV_HELAMP  1.0 0.0 1.0 0.0 1.0 0.0; #[Reconstructed PDG2011]
0.015800000 anti-K*0 rho0                      SVV_HELAMP  1.0 0.0 1.0 0.0 1.0 0.0; #[Reconstructed PDG2011]
0.011000000 anti-K*0 omega                     SVV_HELAMP  1.0 0.0 1.0 0.0 1.0 0.0; #[Reconstructed PDG2011]
# the Dalitz mode below includes K*bar(892)0 pi0,
# K*(892)- pi+, and K- rho(770)+ resonances
0.139000000 K-      pi+     pi0                D_DALITZ; #[Reconstructed PDG2011]
0.006634274 K*BR    pi0                        SVS; #[Reconstructed PDG2011]
0.016000000 K_1-    pi+                        SVS; #[Reconstructed PDG2011]
0.006505987 anti-K_10 pi0                      SVS; #[Reconstructed PDG2011]
#
# the Dalitz mode below includes K*(892)- pi+ and Kbar0 rho(770)0 resonances
# LHCb PR 09 Apr 2004 split into KS/KL
0.029400000 K_S0    pi+     pi-                D_DALITZ; #[Reconstructed PDG2011]
0.027856619 K_L0    pi+     pi-                D_DALITZ; #[Reconstructed PDG2011]
0.000000000 anti-K0 pi+     pi-                D_DALITZ; #[Reconstructed PDG2011]
#
0.008300000 K_S0    pi0     pi0                PHSP; #[Reconstructed PDG2011]
0.004425904 K_L0    pi0     pi0                PHSP; #[Reconstructed PDG2011]
0.000000000 anti-K0 pi0     pi0                PHSP; #[Reconstructed PDG2011]
#
0.024000000 anti-K*0 pi+     pi-               PHSP; #[Reconstructed PDG2011]
0.010629499 anti-K*0 pi0     pi0               PHSP; #[Reconstructed PDG2011]
0.009163361 K*-     pi+     pi0                PHSP; #[Reconstructed PDG2011]
0.006231086 K-      rho+    pi0                PHSP; #[Reconstructed PDG2011]
0.005305586 K-      pi+     rho0               PHSP; #[Reconstructed PDG2011]
```

# *D* Meson Decays at EvtGen

### *D* decay card in EvtGen-02-02-01

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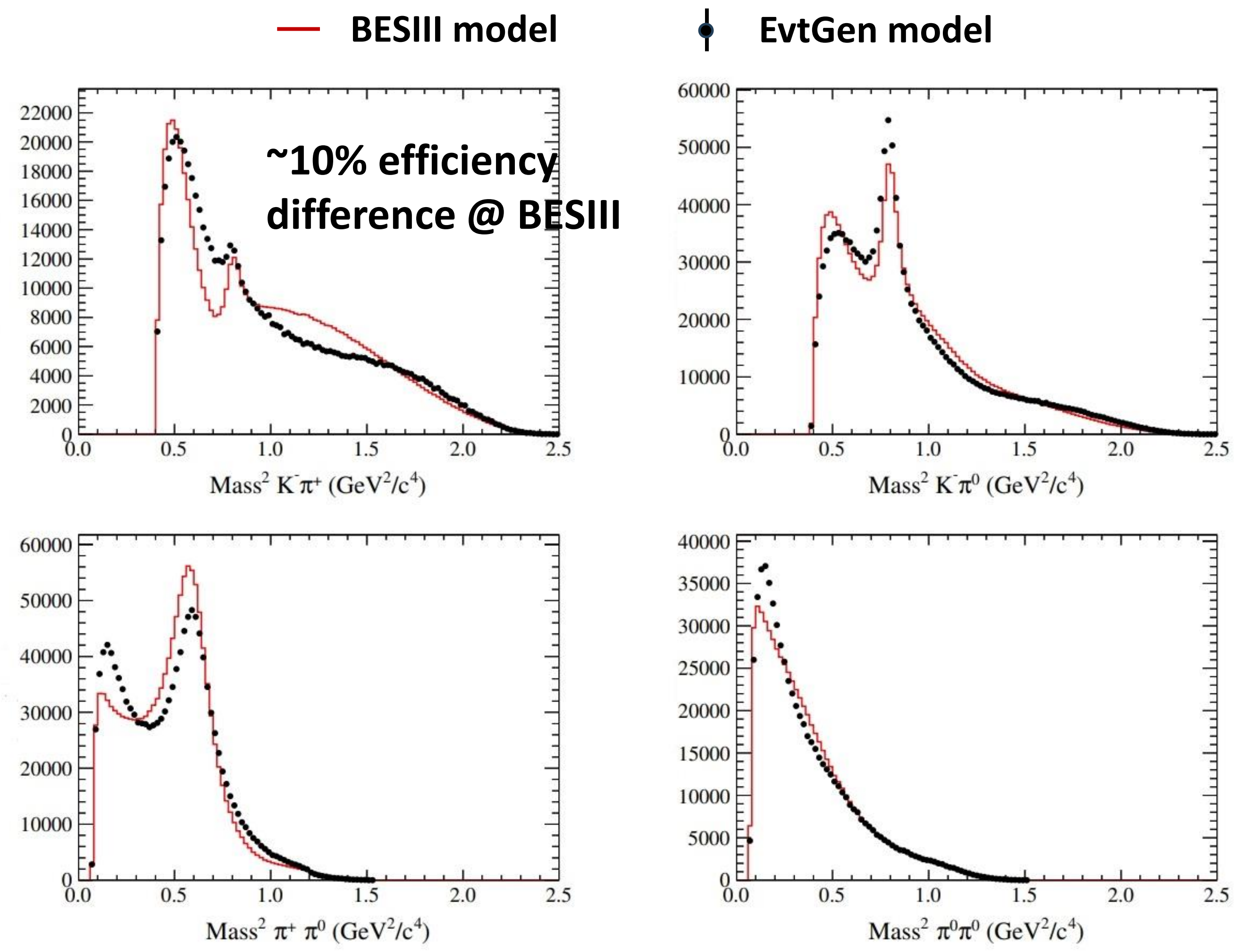
    **No specific model (need update)**

    **Direct sum of intermediate processes**

  **=> i. Model from amplitude analysis**

  **ii. Model from ML**

### Example: $D^0 \to K^- \pi^+ \pi^0 \pi^0$



# BEPCII & BESIII

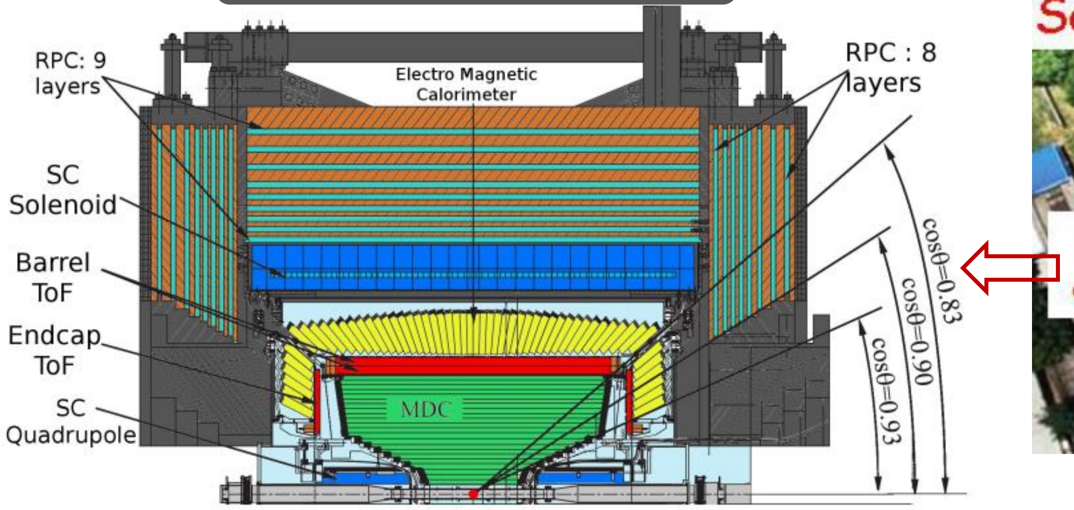
MDC: small cell & Gas: $He/C_3H_8(60/40)$, 43 layers
$\sigma_p/p = 0.5\%@1GeV$,
$\sigma_{dE/dx} = 6\%$

TOF: Barrel: $\sigma_T = 100ps$
endcap: $\sigma_T = 110ps$
(60ps for endcap after upgraded to MRPC in 2015)

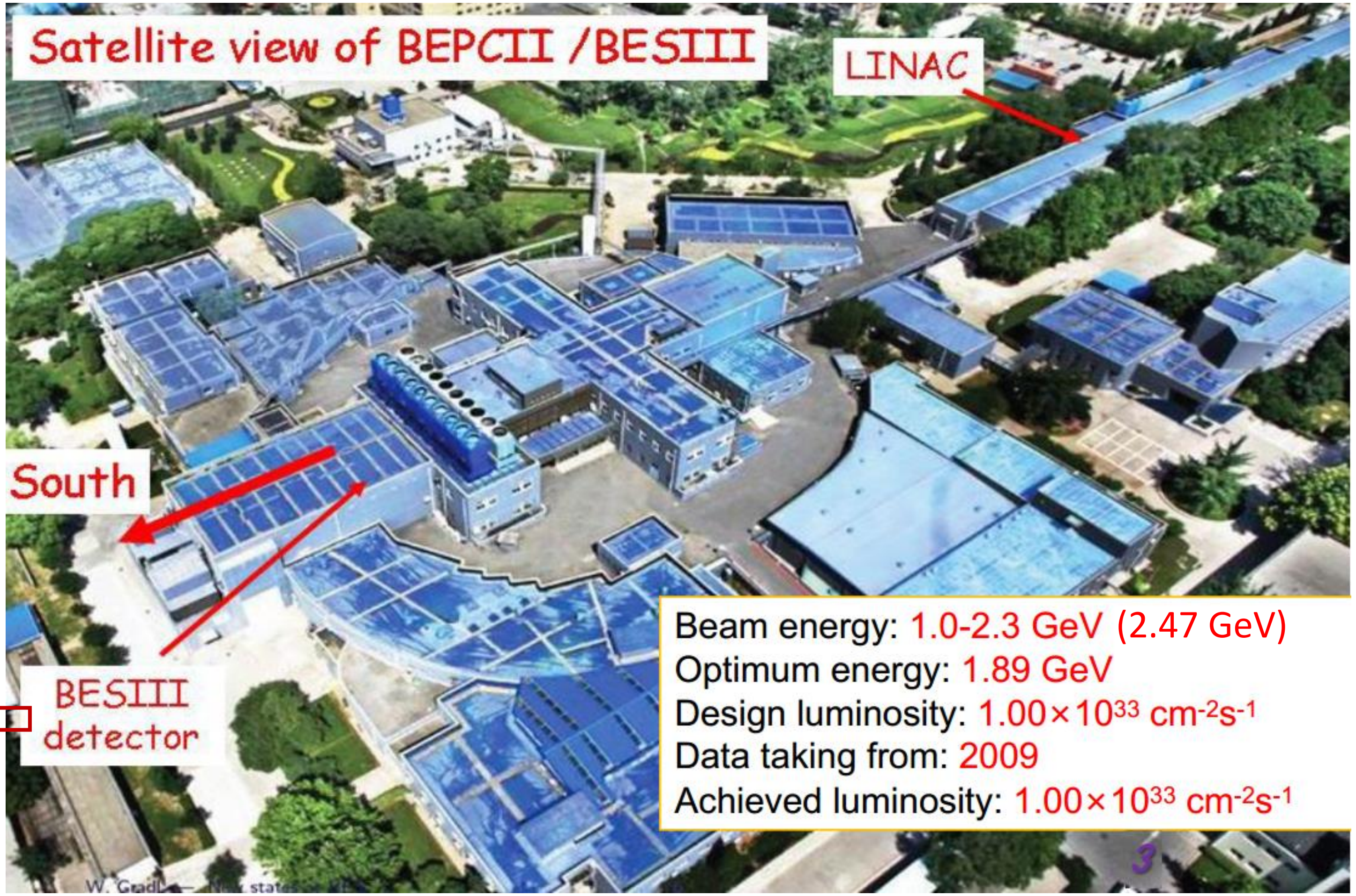
EMC: CsI crystal. 28cm
$\Delta E/E = 2.5\%@1GeV$,
$\sigma_z = 0.6cm/\sqrt{E}$

MUC: 9layers RPC
(8 layers in Endcap)
$\sigma_{R\phi} = 1.4\sim1.7cm$

Magnet: 1T Super conducting




[Nucl. Instr. Meth. A614, 345(2010)]



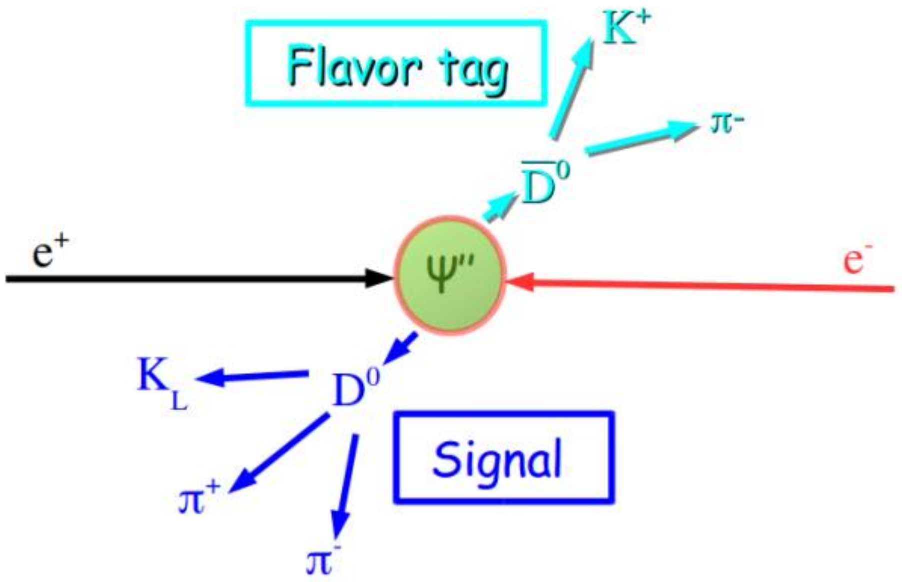
# Data Set of *D* Meson @ BESIII

- ***D* meson pair production near threshold @ BESIII**

| $E_{cm}$ (GeV) | Data taking year | Pair Production | ST *D* Yields | L (fb[-1]) |
|---|---|---|---|---|
| 3.773 | 2011,2012 (2022-2024) | $D^0\overline{D}^0, D^+D^-$ | 2.5M $D^0$, 1.7M $D^\pm$ (×6.8) | 2.93 (-> 20) |

- **Advantage**
  - Extremely clean environment
  - Full kinematic constraint (recoil $\nu, K_L^0$ …)
  - Absolute branching fraction measurement
  - Quantum correlated $D^0\overline{D}^0$ analysis
- **Disadvantage**
  - No time-dependent analysis for $D^0$
  - Smaller *D* yields (2-3 orders lower) compared with Belle /BelleII and LHCb

Double tag (DT): Reconstruct both *D*

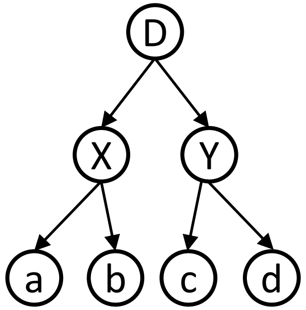


# Amplitude analysis of $D$ Meson Decays

[PRD **48**, 1225, PRD **57**, 431, EPJA **16**, 537, JHEP05(2017)143]

- **Amplitude of hadronic decay $D \to f$ (4-body as example)**: Covariant tensor formula

Isobar model




$$M_D = \sum_{spin} \left| \sum_i \Lambda_i S_i(p) B_{L_D}(p) T_X(m_X) B_{L_X}(p) T_Y(m_Y) B_{L_Y}(p) \right|^2$$

- $\Lambda_i$: Complex factor of partial wave
- $S_i(p)$: Spin factor (covariant tensor)
- $B_L(p)$: Blatt-Weisskopf barrier factor
- $T(m)$: Propagator (Relative Breit-Wigner, Flatte, K-Matrix …)

- **Amplitude of semi-leptonic decay $D \to X_q l^+ \nu_l$** :

$$M_D = \sum_{spin} \left| \sum_{X,\lambda_X} \frac{G_F}{\sqrt{2}} V_{cq} A_X T_X(m_X) \langle X | \bar{q} \gamma^\mu (1-\gamma_5) c | D \rangle \times \bar{u}(p_\nu) \gamma^\mu (1-\gamma_5) v(p_l) \right|^2$$

- $A_X$: Amplitude of X->final states
- $T_X(m_X)$: Propagator
- $\langle X | \bar{q} \gamma^\mu (1-\gamma_5) c | D \rangle$: D->X transition matrix (contain form factors)

[PRD **46**, 5040, PRD **69**, 074025]

# Amplitude analysis of *D* Meson Decays

- **Signal PDF:** $P_s(p) = \frac{\epsilon_s(p) M_D(p)}{\int \epsilon_s(p) M_D(p) \mathrm{d}\Phi}$
  - $\epsilon_s$: signal efficiency
  - Integration in denominator: MC integration $\frac{1}{N_{sel}} \sum_{i=1}^{N_{sel}} \frac{M_D(p_i^{rec})}{M_{MC}(p_i^{tru})}$ with toy MC

- **Likelihood Fit:**
  - **General formula:**

$$\ln L = \sum_i \ln \left[ f \frac{M_D(p_i)}{\int \epsilon_s(p) M_D(p) \mathrm{d}\Phi} + (1-f) \frac{B(p_i)/\epsilon_s(p_i)}{\int \epsilon_s(p) B(p)/\epsilon_s(p) \mathrm{d}\Phi} \right] + \sum_i \ln \epsilon_s(p_i)$$

signal fraction

observed BKG PDF

const. & omitted

  - **Likelihood deduction (low background):**

$$\ln L = \sum_{i \in Data} \ln P_s(p_i) - \sum_{j \in BKG} w_j \ln P_s(p_j)$$

A data set of BKG events

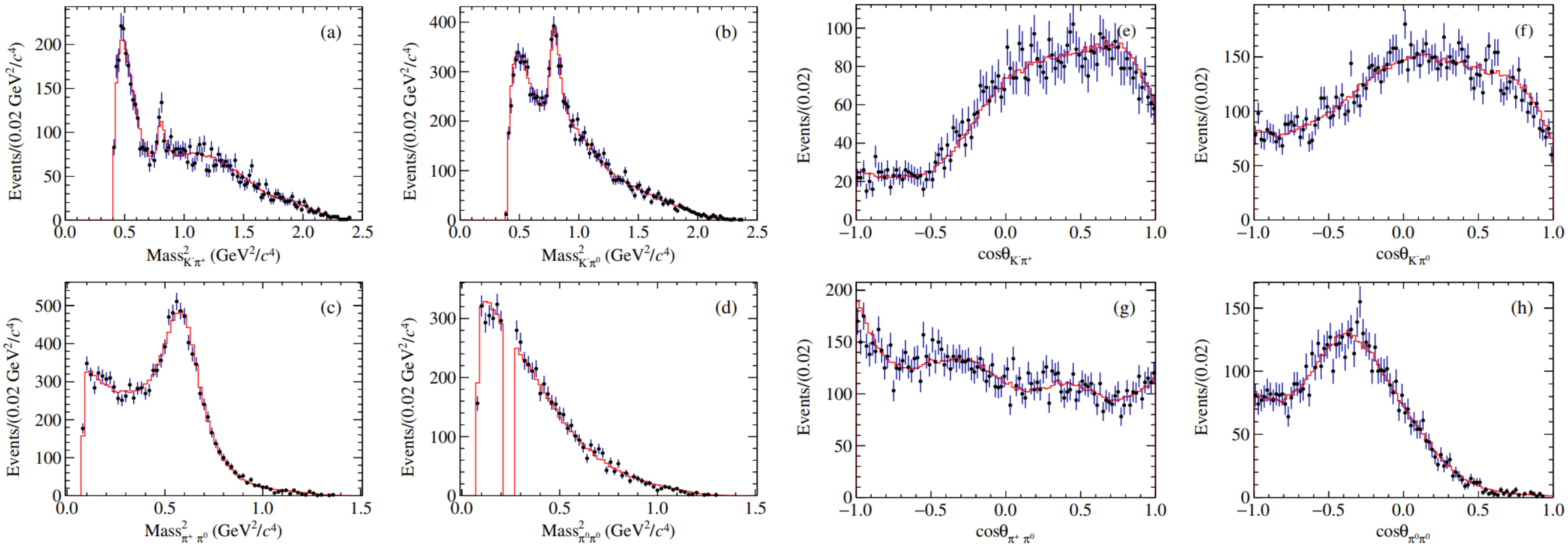
weight to normalize the number of BKG events

# Amplitude analysis of *D* Meson Decays

**A hadronic example: $D^0 \to K^-\pi^+\pi^0\pi^0$ (2.93 fb$^{-1}$)**

[PRD **99**, 092008]

**Total event: 5950** **Purity: 99%**



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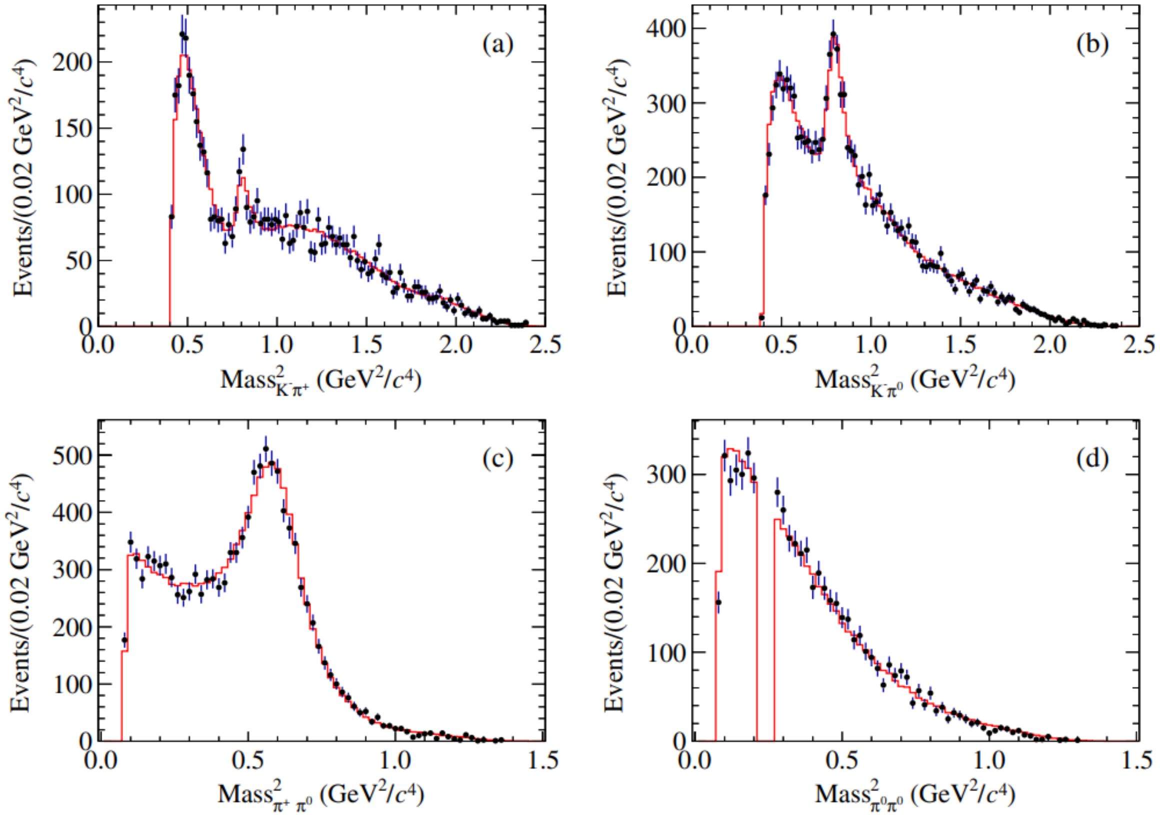



| Amplitude mode | FF [%] | Phase [$\phi$] | Significance [$\sigma$] |
|---|---|---|---|
| $D \to SS$ | | | |
| $D \to (K^-\pi^+)_{S\text{-wave}}(\pi^0\pi^0)_S$ | $6.92 \pm 1.44 \pm 2.86$ | $-0.75 \pm 0.15 \pm 0.47$ | >10 |
| $D \to (K^-\pi^0)_{S\text{-wave}}(\pi^+\pi^0)_S$ | $4.18 \pm 1.02 \pm 1.77$ | $-2.90 \pm 0.19 \pm 0.47$ | 6.0 |
| $D \to AP, A \to VP$ | | | |
| $D \to K^-a_1(1260)^+, \rho^+\pi^0[S]$ | $28.36 \pm 2.50 \pm 3.53$ | 0 (fixed) | >10 |
| $D \to K^-a_1(1260)^+, \rho^+\pi^0[D]$ | $0.68 \pm 0.29 \pm 0.30$ | $-2.05 \pm 0.17 \pm 0.25$ | 6.1 |
| $D \to K_1(1270)^-\pi^+, K^{*-}\pi^0[S]$ | $0.15 \pm 0.09 \pm 0.15$ | $1.84 \pm 0.34 \pm 0.43$ | 4.9 |
| $D \to K_1(1270)^0\pi^0, K^{*0}\pi^0[S]$ | $0.39 \pm 0.18 \pm 0.30$ | $-1.55 \pm 0.20 \pm 0.26$ | 4.8 |
| $D \to K_1(1270)^0\pi^0, K^{*0}\pi^0[D]$ | $0.11 \pm 0.11 \pm 0.11$ | $-1.35 \pm 0.43 \pm 0.48$ | 4.0 |
| $D \to K_1(1270)^0\pi^0, K^-\rho^+[S]$ | $2.71 \pm 0.38 \pm 0.29$ | $-2.07 \pm 0.09 \pm 0.20$ | >10 |
| $D \to (K^{*-}\pi^0)_A\pi^+, K^{*-}\pi^0[S]$ | $1.85 \pm 0.62 \pm 1.11$ | $1.93 \pm 0.10 \pm 0.15$ | 7.8 |
| $D \to (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[S]$ | $3.13 \pm 0.45 \pm 0.58$ | $0.44 \pm 0.12 \pm 0.21$ | >10 |
| $D \to (K^{*0}\pi^0)_A\pi^0, K^{*0}\pi^0[D]$ | $0.46 \pm 0.17 \pm 0.29$ | $-1.84 \pm 0.26 \pm 0.42$ | 5.9 |
| $D \to (\rho^+K^-)_A\pi^0, K^-\rho^+[D]$ | $0.75 \pm 0.40 \pm 0.60$ | $0.64 \pm 0.36 \pm 0.53$ | 5.1 |
| $D \to AP, A \to SP$ | | | |
| $D \to ((K^-\pi^+)_{S\text{-wave}}\pi^0)_A\pi^0$ | $1.99 \pm 1.08 \pm 1.55$ | $-0.02 \pm 0.25 \pm 0.53$ | 7.0 |
| $D \to VS$ | | | |
| $D \to (K^-\pi^0)_{S\text{-wave}}\rho^+$ | $14.63 \pm 1.70 \pm 2.41$ | $-2.39 \pm 0.11 \pm 0.35$ | >10 |
| $D \to K^{*-}(\pi^+\pi^0)_S$ | $0.80 \pm 0.38 \pm 0.26$ | $1.59 \pm 0.19 \pm 0.24$ | 4.1 |
| $D \to K^{*0}(\pi^0\pi^0)_S$ | $0.12 \pm 0.12 \pm 0.12$ | $1.45 \pm 0.48 \pm 0.51$ | 4.1 |
| $D \to VP, V \to VP$ | | | |
| $D \to (K^{*-}\pi^+)_V\pi^0$ | $2.25 \pm 0.43 \pm 0.45$ | $0.52 \pm 0.12 \pm 0.17$ | >10 |
| $D \to VV$ | | | |
| $D \to K^{*-}\rho^+[S]$ | $5.15 \pm 0.75 \pm 1.28$ | $1.24 \pm 0.11 \pm 0.23$ | >10 |
| $D \to K^{*-}\rho^+[P]$ | $3.25 \pm 0.55 \pm 0.41$ | $-2.89 \pm 0.10 \pm 0.18$ | >10 |
| $D \to K^{*-}\rho^+[D]$ | $10.90 \pm 1.53 \pm 2.36$ | $2.41 \pm 0.08 \pm 0.16$ | >10 |
| $D \to (K^-\pi^0)_V\rho^+[P]$ | $0.36 \pm 0.19 \pm 0.27$ | $-0.94 \pm 0.19 \pm 0.28$ | 5.7 |
| $D \to (K^-\pi^0)_V\rho^+[D]$ | $2.13 \pm 0.56 \pm 0.92$ | $-1.93 \pm 0.22 \pm 0.25$ | >10 |
| $D \to K^{*-}(\pi^+\pi^0)_V[D]$ | $1.66 \pm 0.52 \pm 0.61$ | $-1.17 \pm 0.20 \pm 0.39$ | 7.6 |
| $D \to (K^-\pi^0)_V(\pi^+\pi^0)_V[S]$ | $5.17 \pm 1.91 \pm 1.82$ | $-1.74 \pm 0.20 \pm 0.31$ | 7.6 |
| $D \to TS$ | | | |
| $D \to (K^-\pi^+)_{S\text{-wave}}(\pi^0\pi^0)_T$ | $0.30 \pm 0.21 \pm 0.30$ | $-2.93 \pm 0.31 \pm 0.82$ | 5.8 |
| $D \to (K^-\pi^0)_{S\text{-wave}}(\pi^+\pi^0)_T$ | $0.14 \pm 0.12 \pm 0.10$ | $2.23 \pm 0.38 \pm 0.65$ | 4.0 |
| TOTAL | 98.54 | | |

# Amplitude analysis of *D* Meson Decays

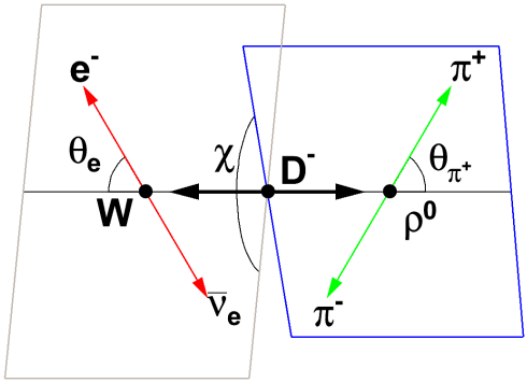
**A semi-leptonic example**

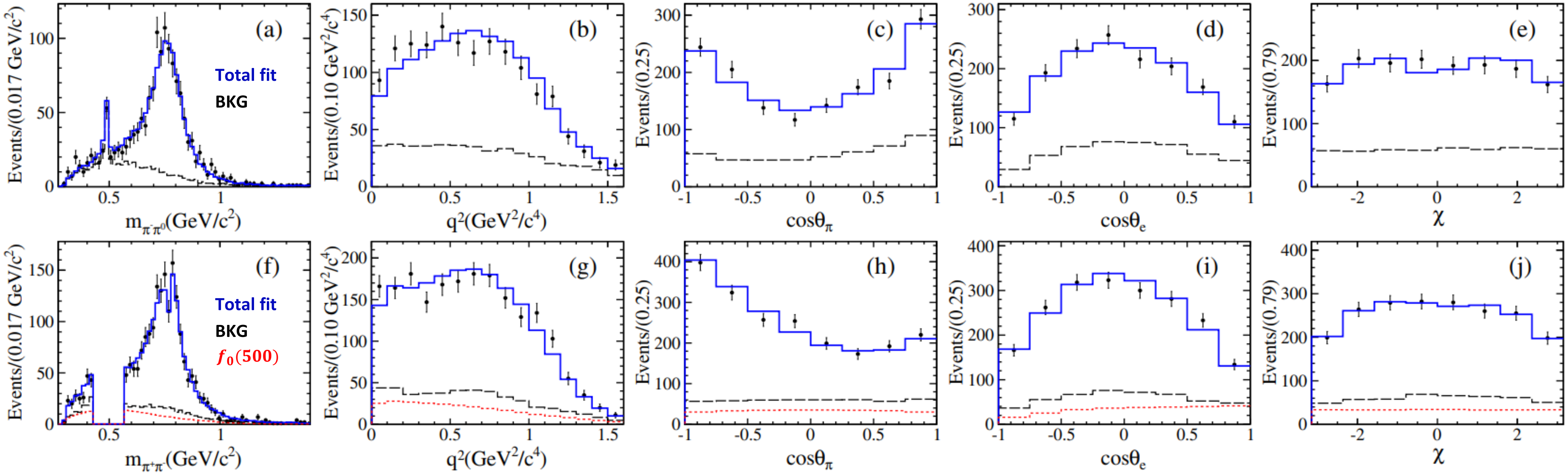
**$D \to \pi\pi e^+\nu_e$ (2.93 fb$^{-1}$)**

[PRL 122, 062001]

| channel | $N_{obs}$ | Purity |
|---|---|---|
| $D^0$ | 1498 | 67% |
| $D^+$ | 2017 | 76% |

| Signal mode | This analysis ($\times 10^{-3}$) |
|---|---|
| $D^0 \to \pi^-\pi^0 e^+\nu_e$ | $1.445 \pm 0.058 \pm 0.039$ |
| $D^0 \to \rho^- e^+\nu_e$ | $1.445 \pm 0.058 \pm 0.039$ |
| $D^+ \to \pi^-\pi^+ e^+\nu_e$ | $2.449 \pm 0.074 \pm 0.073$ |
| $D^+ \to \rho^0 e^+\nu_e$ | $1.860 \pm 0.070 \pm 0.061$ |
| $D^+ \to \omega e^+\nu_e$ | $2.05 \pm 0.66 \pm 0.30$ |
| $D^+ \to f_0(500) e^+\nu_e$, $f_0(500) \to \pi^+\pi^-$ | $0.630 \pm 0.043 \pm 0.032$ |
| $D^+ \to f_0(980) e^+\nu_e$, $f_0(980) \to \pi^+\pi^-$ | $<0.028$ |



# *D* Meson Decays at BESIII-EvtGen

**It is very convenient to add a new decay model under the framework of EvtGen**

1. Add a script in “src/EvtGen/EvtGenModels”

```
class EvtD0ToKpipi0pi0:public EvtDecayProb  {

public:

   EvtD0ToKpipi0pi0() {}
   virtual ~EvtD0ToKpipi0pi0();
   void getName(std::string& name);
   EvtDecayBase* clone();
   void init();
   void initProbMax();
   void decay(EvtParticle *p);
```

`void getName(std::string& name);` → Define the model name used in Decay Card

```
void EvtD0ToKpipi0pi0::getName(std::string& model_name){
   model_name="D0ToKpipi0pi0";
}
```

`void initProbMax();` → Set maximum probability of decay amplitude

`void decay(EvtParticle *p);` → Provide the probability of the amplitude model over the PHSP

2. Register the model in “src/EvtGen/EvtGenModels/EvtModelReg.cpp”

```
modelist.Register(new EvtD0ToKpipi0pi0);
```

3. Use this decay model in Decay Card

```
0.08835        K-      pi+     pi0     pi0     D0ToKpipi0pi0;
```

# Summary

- The $D\overline{D}$ data near threshold taken by BESIII provides a clean environment to perform amplitude analyses for multi-body *D* meson decays.

- Using 2.93 $\mathrm{fb}^{-1}$ $\psi(3770)$ data, a series of amplitude analyses has been done by BESIII.

| | | | |
|---|---|---|---|
| $D^0 \to K^-\pi^+\pi^+\pi^-$ | [PRD **95**, 072010] | $D \to K\pi e^+ v_e$ | [PRD 94, 032001, PRD 99, 011103] |
| $D^0 \to K^-\pi^+\pi^0\pi^0$ | [PRD **99**, 092008] | $D \to \pi\pi e^+ v_e$ | [PRL 122, 062001] |
| $D^+ \to K_S^0\pi^+\pi^+\pi^-$ | [PRD **100**, 072008] | $D \to \pi\eta e^+ v_e$ | [PRL 121, 081802] |
| **The analyses of other $K3\pi$ modes and most of SCS modes are on going at BESIII** | | | |

- The 20 $\mathrm{fb}^{-1}$ data are expected to be achieved in the next year. More accurate results and more *D* decay models will be come in the near future.

- We hope that these results can help us to improve the modeling of *D* decays and benefit the Vcb measurement

*Thank you!*