Charm Physics at BESIII

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On behalf of the BESIII Collaboration

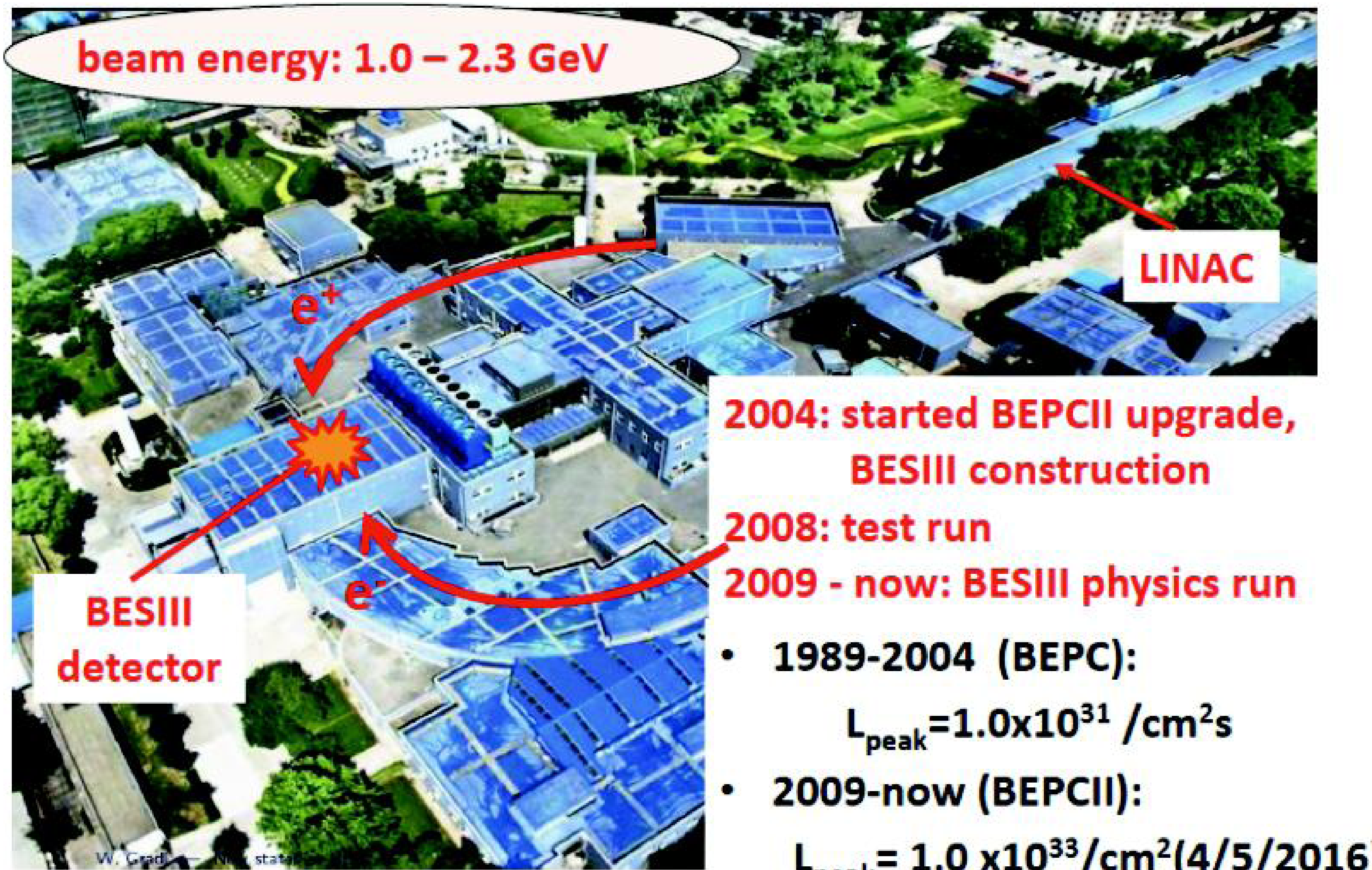
XIIIth Rencontres du Vietnam, Flavour Physics Conference

ICISE, Quy Nhon, Vietnam 13-19 August 2017

Outline

- BESIII experiment
- Datasets / analysis techniques
- Highlights of recent results on
  - (Semi-)leptonic $D_{(s)}$ decays
  - Hadronic $D_{(s)}$ decays
  - Λ_c decays

Beijing Electron Positron Collider (BEPCII)

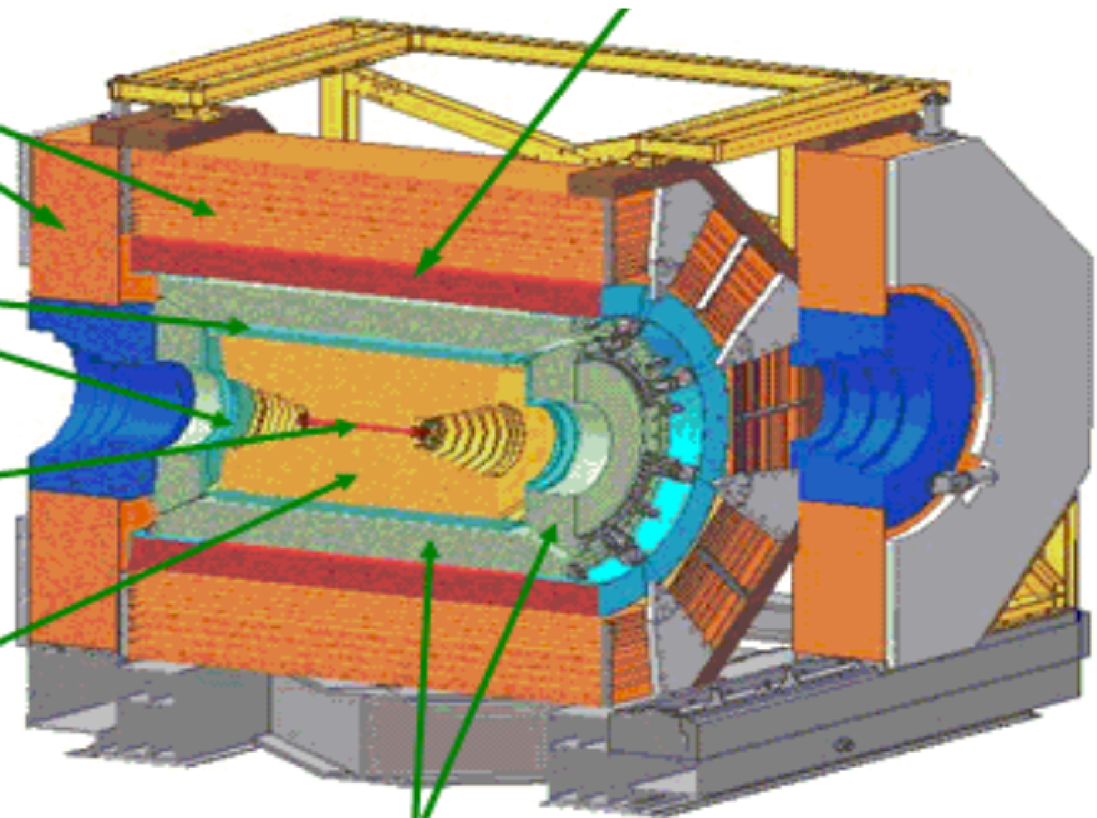


BESIII Detector

Muon Counter
8-9 layers RPC
$\Delta R\varphi = 1.4$ cm ~ 1.7 cm

Super-conducting magnet
1.0 Tesla

Time of Flight (TOF)
σ_T: 90 ps Barrel
110 ps Endcap



Beryllium beam pipe

Drift Chamber (MDC)
$\sigma_p/p = 0.5\%$ (1 GeV)
$\sigma_{dE/dx} = 6\%$

EMC (CsI)
$\sigma_E/\sqrt{E} = 2.5\%$ (1 GeV)
$\sigma_{Z,\varphi} = 0.5 - 0.7$ cm/$\sqrt{E}$

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

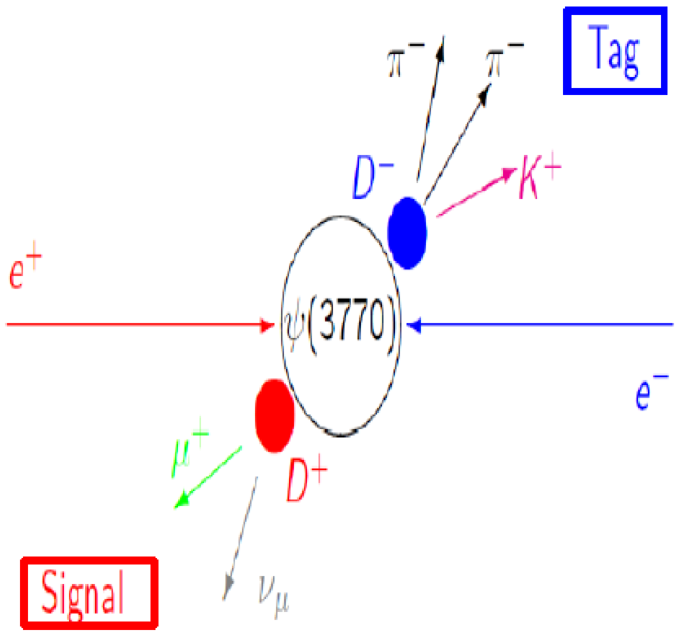
Charm data sets at BESIII

- $D^{0(+)}$ data
  - Taken @ E_{cm} = 3.773 GeV, L_{int} = 2.93 fb^{-1}
  - $e^+e^- \rightarrow D^0\bar{D}^0/D^+D^-$: 21 M D^0 and 16 M D^+ produced
- D_s^+ data
  - Taken @ E_{cm} = 4.009 GeV, L_{int} = 0.482 fb^{-1}
    - $e^+e^- \rightarrow D_s^+D_s^-$: 0.3 M D_s^+ produced
  - Taken @ E_{cm} = 4.178 GeV, L_{int} = 3.19 fb^{-1}
    - $e^+e^- \rightarrow D_s^*D_s$: 6 M D_s^+ produced
    - Accumulated in 2016
- Λ_c data
  - Taken @ E_{cm} = 4.599 GeV, L_{int} = 0.567 fb^{-1}
  - $e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$: 0.2 M Λ_c produced

Tagging method

$e^+ e^- \to \psi(3770) \to D^+ D^-$
2.93 fb^{-1} @3.773 GeV

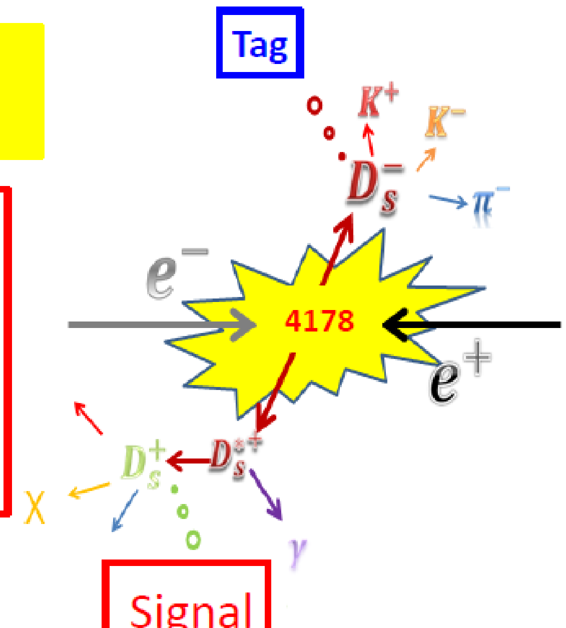
$e^+ e^- \to D_s^{*+} D_s^-$
3.19 fb^{-1} @4.178 GeV



Charge conjugated processes are implied

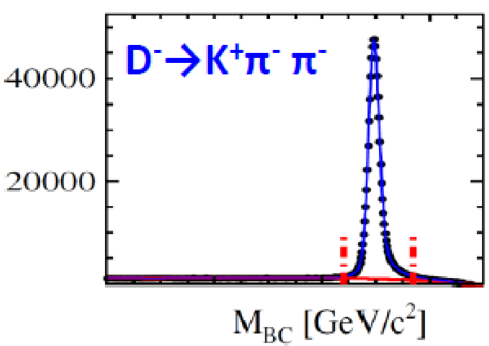
The signal branching fraction:

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm sig}}{N_{D_{(s)}^{\rm tag}} \times \epsilon}$$



For Tag side(reconstructed from $K^+\pi^-\pi^-$):

$$\Delta E = E_{D^-} - E_{\rm beam}$$
$$M_{\rm BC} = \sqrt{E_{\rm beam}^2 - |\vec{p}_{D^-}|^2}$$

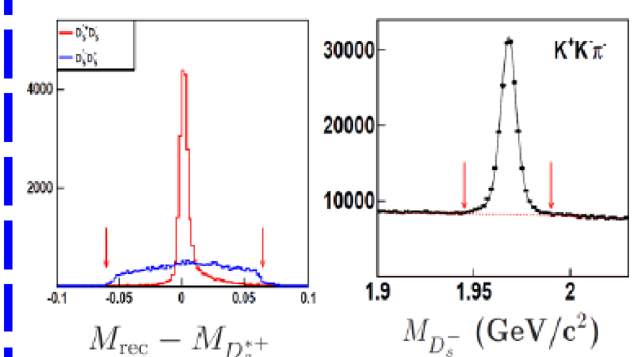


For Signal side(reconstruct μ^+):

$$E_{\rm miss} = E_{\rm beam} - E_{\mu^+}$$
$$\vec{p}_{\rm miss} = -\vec{p}_{D^-} - \vec{p}_{\mu^+}$$
$$M^2_{\rm miss} = E^2_{\rm miss} - |\vec{p}_{\rm miss}|^2$$
$$U_{\rm miss} = E_{\rm miss} - |\vec{p}_{\rm miss}|$$

For Tag side(reconstructed from $K^+K^-\pi^-$):

$$M_{\rm rec} = \sqrt{(E_{\rm cm} - \sqrt{|\vec{p}_{D_s^-}|^2 + m^2_{D_s^-}})^2 - |-\vec{p}_{D_s^-}|^2}$$

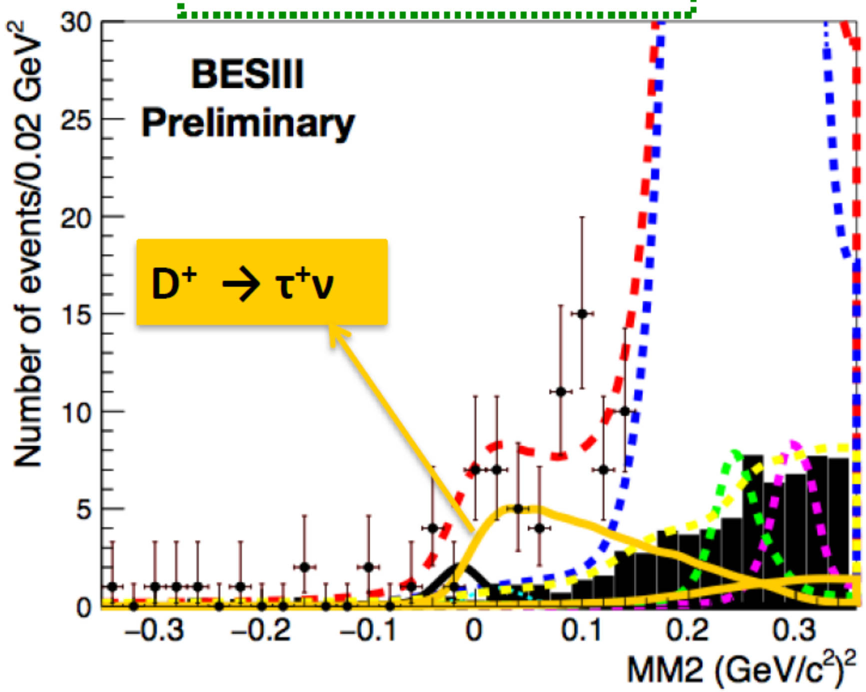


2.93/fb data @ 3.773 GeV

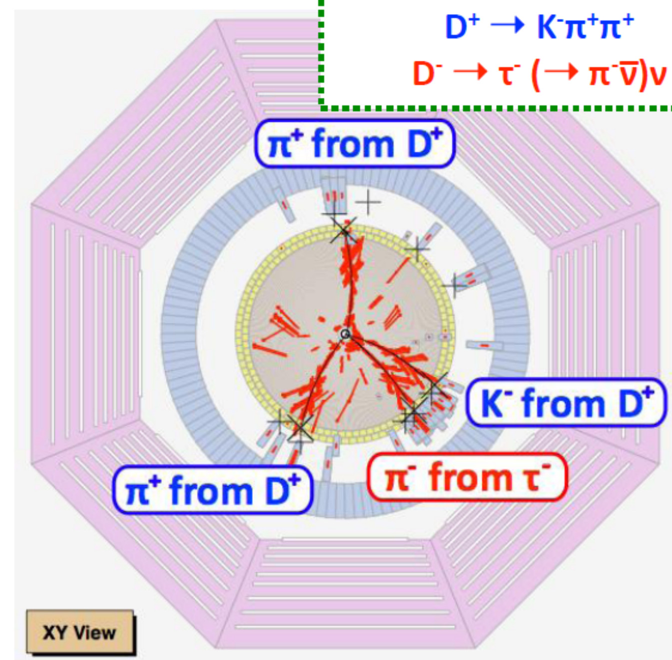
$D^+ \to \tau^+\nu$ via $\tau^+ \to \pi^+\nu$ (> 4σ, first evidence!)

- Split sample into TWO (μ dominant & π dominant)
- Simultaneous un-binned maximum likelihood fit

The π dominant sample

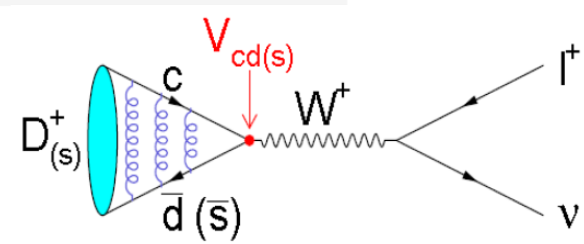


A single candidate event:
$D^+ \to K^-\pi^+\pi^+$
$D^- \to \tau^- (\to \pi^-\bar{\nu})\nu$



B($D^+ \to \tau^+ \nu$)
= $(1.20 \pm 0.24_{stat}) \times 10^{-3}$

$$R \equiv \frac{\Gamma(D^+ \to \tau^+\nu)}{\Gamma(D^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2\left(1-\frac{m_{\tau^+}^2}{M_{D^+}^2}\right)^2}{m_{\mu^+}^2\left(1-\frac{m_{\mu^+}^2}{M_{D^+}^2}\right)^2}$$



= 3.21 ± 0.64 (BESIII)

= 2.66 ± 0.01 (SM prediction)

2.93/fb data @ 3.773 GeV

Search for $D^{0(+)} \rightarrow a_0(980)^{-(0)} e^+ \nu_e$

- Nontrivial internal structure of light hadron mesons.
- With chiral unitarity approach in the coupled channels, BF is predicted to be ~5 x 10^{-5}.

- Improve understanding of classification of light scalar mesons

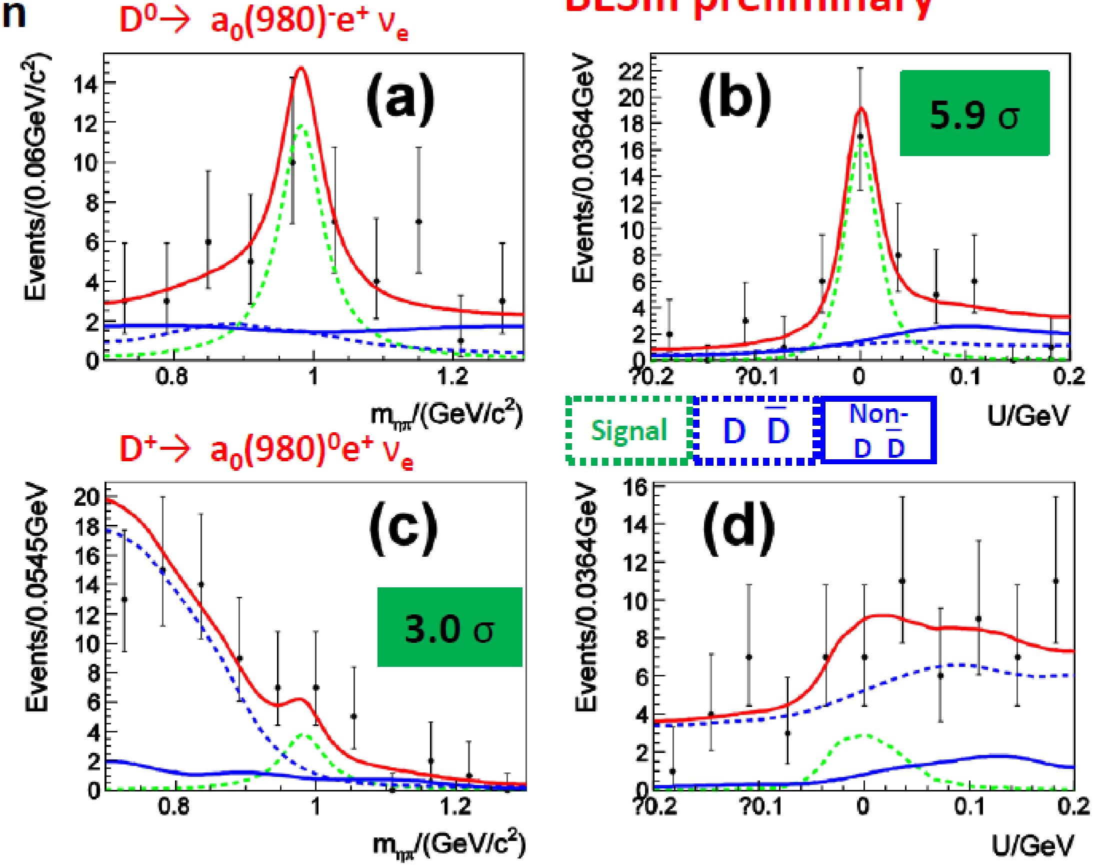
$$R \equiv \frac{\mathcal{B}(D^+ \to f_0 l^+ \nu) + \mathcal{B}(D^+ \to \sigma l^+ \nu)}{\mathcal{B}(D^+ \to a_0 l^+ \nu)}$$

R= 1(3) if traditional qqbar (tetra quark) system

(W. Wang and C-D. Lu, PRD 82 034016 (2010)

2-dimentional fit

BESIII preliminary



$B(D^0 \to a_0(980)^- e^+ \nu_e) \times B(a_0(980)^- \to \eta\pi^-)$

$$= (1.12 \pm 0.29(\mathrm{stat}) \pm 0.10(\mathrm{syst})) \times 10^{-4}$$

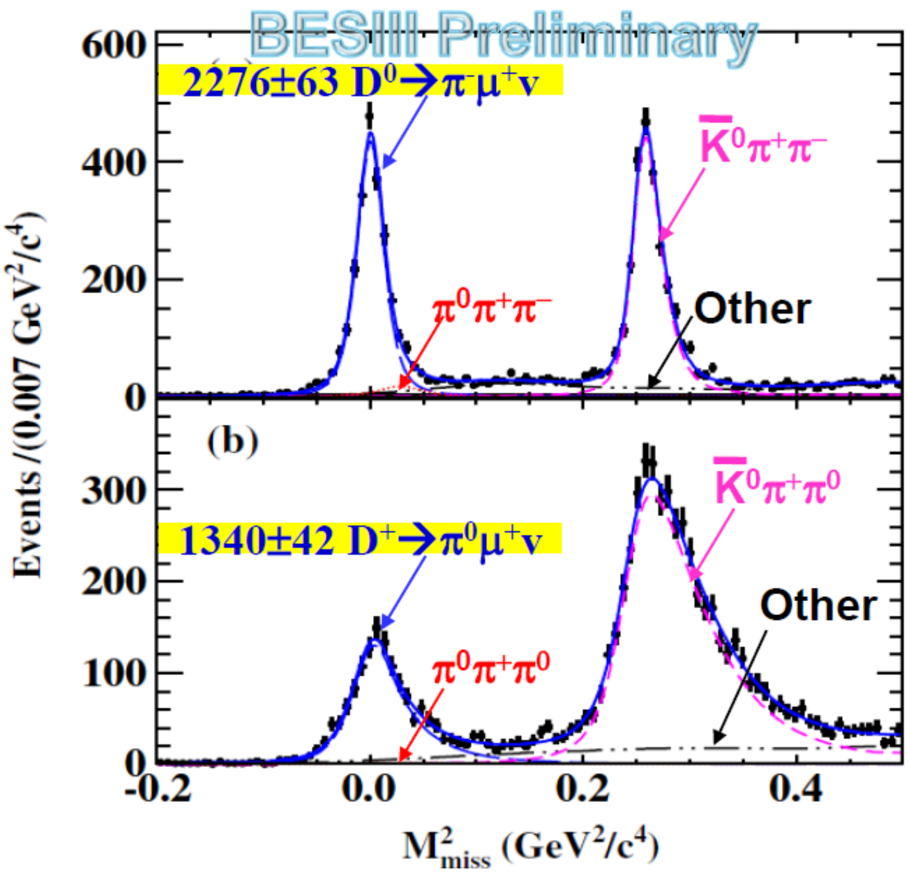
$B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta\pi^0) =$

$$= (1.47 \pm 0.66(\mathrm{stat}) \pm 0.14(\mathrm{syst})) \times 10^{-4}$$

$B(D^+ \to a_0(980)^0 e^+ \nu_e) \times B(a_0(980)^0 \to \eta\pi^0)$
< (2.7 x 10^{-4}) at 90% C.L.

2.93/fb data @ 3.773 GeV

$D^0 \to \pi^-\mu^+\nu$ and $D^+ \to \pi^0\mu^+\nu$ decays



- Branching fractions Preliminary

$B(D^0 \to \pi^-\mu^+\nu) = (0.267 \pm 0.007 \pm 0.007)\%$

Measured with much improved precision

$B(D^+ \to \pi^0\mu^+\nu) = (0.342 \pm 0.011 \pm 0.010)\%$

Measured for the first time

- Isospin conservation: consistent

$$\frac{\Gamma(D^0 \to \pi^-\mu^+\nu)}{2\Gamma(D^+ \to \pi^0\mu^+\nu)} = 0.990 \pm 0.054$$

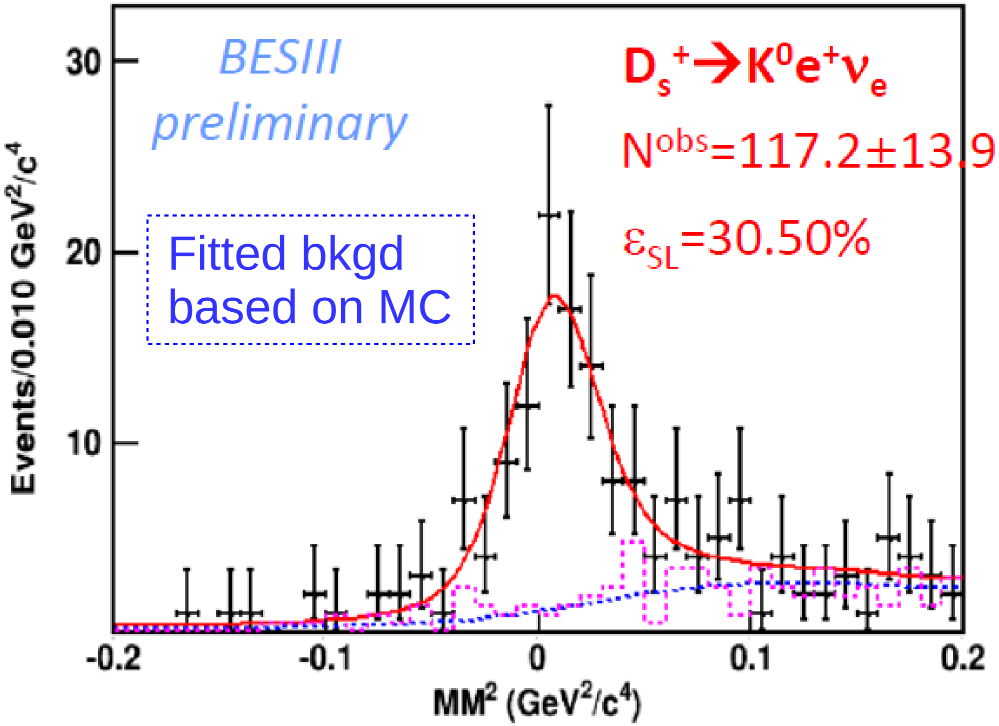
- **Ratio for LU test in $D^{0(+)} \to \pi l^+\nu$ by combing $B^{PDG}[D^{0(+)} \to \pi e^+\nu]$ and $B^{BESIII}[D^{0(+)} \to \pi e^+\nu]$**

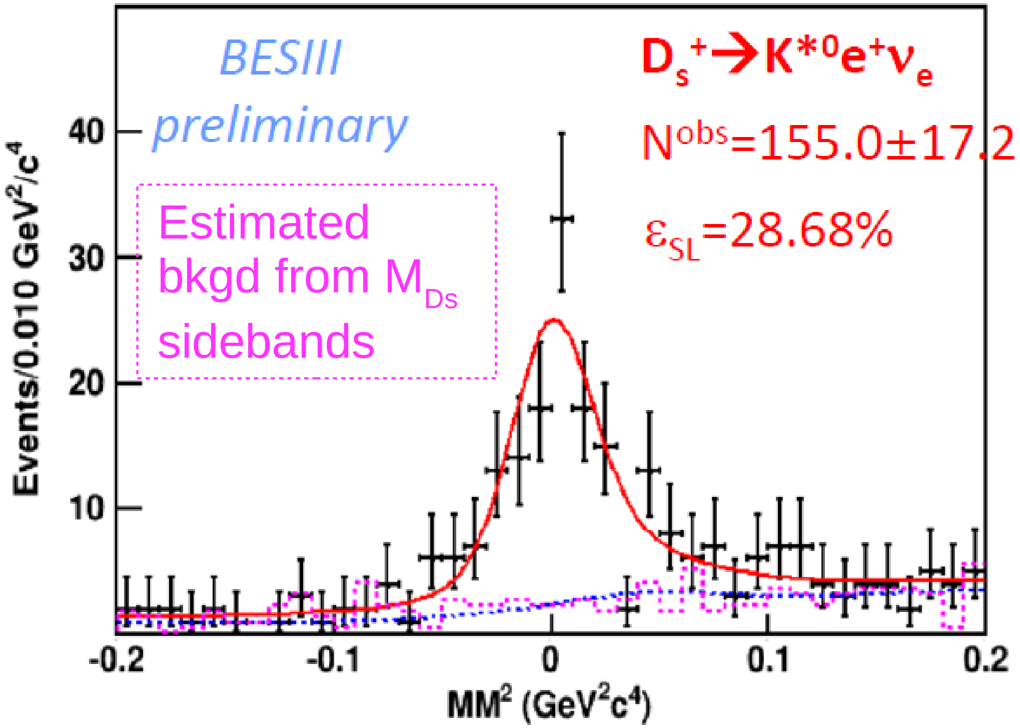
$R^0_{LU}=0.918 \pm 0.036$ $R^+_{LU}=0.921 \pm 0.045$

agree with expectation based on LU within 1.5 and 1.1 σ

3.19/fb data @ 4.178 GeV

$D_s^+ \to (K^0/K^{*0})\, e^+\nu_e$ decays





- Branching fractions Preliminary

$Br[D_s^+ \to K^0e^+\nu_e] = (3.25 \pm 0.38_{[stat]} \pm 0.16_{[syst]}) \times 10^{-3}$ $(3.9 \pm 0.9) \times 10^{-3}$ [PDG2017]

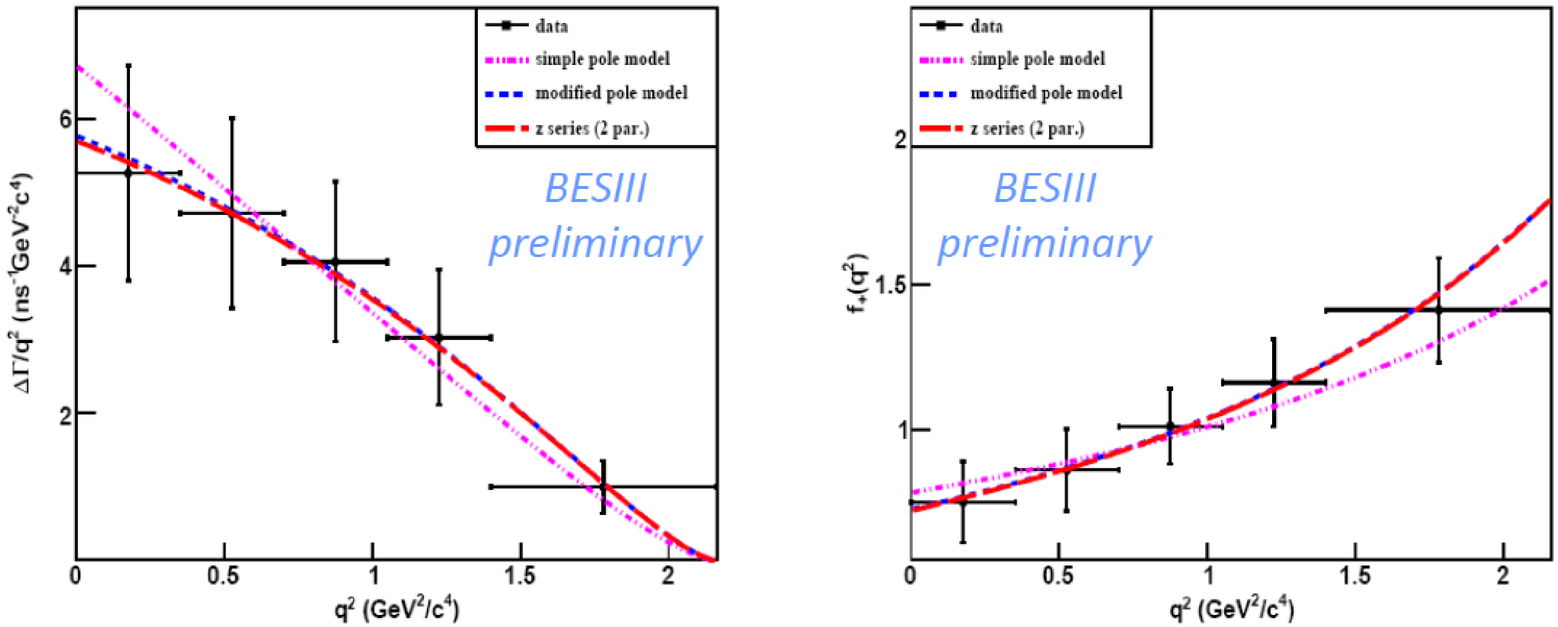
$Br[D_s^+ \to K^{*0}e^+\nu_e] = (2.38 \pm 0.26_{[stat]} \pm 0.13_{[syst]}) \times 10^{-3}$ $(1.8 \pm 0.4) \times 10^{-3}$ [PDG2017]

Much improved precision

Form factor measurement from $D_s^+ \to K^0 e^+ \nu_e$

Fit to partial decay rates:

$$\frac{d\Gamma(D_s^+ \to K^0 e^+ \nu_e)}{dq^2} = \frac{G_F^2 |V_{cd}|^2}{24\pi^3} p_{K^0}^3 |f_+(q^2)|^2$$



- The preliminary results for form factors:

Model	Parameter	Value	$f_+(0)$
Simple pole	$f_+(0)\|V_{cd}\|$	$0.175 \pm 0.010 \pm 0.001$	$0.778 \pm 0.044 \pm 0.004$
Modified pole model	$f_+(0)\|V_{cd}\|$	$0.163 \pm 0.017 \pm 0.003$	$0.725 \pm 0.076 \pm 0.013$
	α	$0.45 \pm 0.44 \pm 0.02$	
Series two parameters	$f_+(0)\|V_{cd}\|$	$0.162 \pm 0.019 \pm 0.003$	$0.720 \pm 0.084 \pm 0.013$
	r_1	$-2.94 \pm 2.32 \pm 0.14$	

$f_+(0)$ obtained by inserting $|V_{cd}| = 0.22492 \pm 0.00050$ from **CKMfitter**

2.93/fb data @ 3.773 GeV

Amplitude analysis of $D^+ \to K_S\pi^+\pi^+\pi^-$

Doubly tagged sample: $D^- \to K^+\pi^-\pi^-$ vs. $D^+ \to K_S\pi^+\pi^+\pi^-$

New results!

In total: 4559 events with very high purity ~99%

An unbinned likelihood fit is performed using the signal PDF given by

$$f_S(p_j) = \frac{\epsilon(p_j)|M(p_j)|^2 R_4(p_j)}{\int \epsilon(p_j)|M(p_j)|^2 R_4(p_j)dp_j}$$

Four-body phase-space: R_4

Measurement efficiency: ε

Amplitude	ϕ	fit fraction
$D^+ \to K^0_S a_1(1260)^+, a_1(1260)^+ \to \rho^0\pi^+[S]$	0.000(fixed)	$0.567 \pm 0.020 \pm 0.044$
$D^+ \to K^0_S a_1(1260)^+, a_1(1260)^+ \to f_0(500)\pi^+$	$-2.023 \pm 0.068 \pm 0.113$	$0.050 \pm 0.006 \pm 0.007$
$D^+ \to \bar{K}_1(1400)^0\pi^+, \bar{K}_1(1400)^0 \to K^{*-}\pi^+[S]$	$-2.714 \pm 0.038 \pm 0.051$	$0.380 \pm 0.013 \pm 0.014$
$D^+ \to \bar{K}_1(1400)^0\pi^+, \bar{K}_1(1400)^0 \to K^{*-}\pi^+[D]$	$3.431 \pm 0.137 \pm 0.117$	$0.015 \pm 0.004 \pm 0.005$
$D^+ \to \bar{K}_1(1270)^0\pi^+, \bar{K}_1(1270)^0 \to K^0_S\rho^0[S]$	$-0.418 \pm 0.070 \pm 0.087$	$0.036 \pm 0.004 \pm 0.002$
$D^+ \to \bar{K}(1460)^0\pi^+, \bar{K}(1460)^0 \to K^0_S\rho^0$	$-1.850 \pm 0.120 \pm 0.223$	$0.014 \pm 0.004 \pm 0.003$
$D^+ \to (K^0_S\rho^0)_A[D]\pi^+$	$2.328 \pm 0.097 \pm 0.068$	$0.011 \pm 0.003 \pm 0.002$
$D^+ \to K^0_S(\rho^0\pi^+)_P$	$1.656 \pm 0.083 \pm 0.056$	$0.031 \pm 0.004 \pm 0.010$
$D^+ \to (K^{*-}\pi^+)_A[S]\pi^+$	$-4.321 \pm 0.047 \pm 0.073$	$0.132 \pm 0.011 \pm 0.011$
$D^+ \to (K^{*-}\pi^+)_A[D]\pi^+$	$0.989 \pm 0.158 \pm 0.229$	$0.013 \pm 0.004 \pm 0.004$
$D^+ \to (K^0_S(\pi^+\pi^-)_S)_A\pi^+$	$-2.935 \pm 0.060 \pm 0.125$	$0.051 \pm 0.004 \pm 0.003$
$D^+ \to ((K^0_S\pi^-)_S\pi^+)_P\pi^+$	$1.864 \pm 0.069 \pm 0.288$	$0.022 \pm 0.003 \pm 0.003$

Fit Fraction: $FF(n) = \frac{\sum_{k=1}^{N_{\rm gen}} |\tilde{A}_{\mathbf{n}}(p_j^k)|^2}{\sum_{k=1}^{N_{\rm gen}} |M(p_j^k)|^2}$

Total amplitude: $M(p_j) = \sum_n c_n A_n(p_j)$

$$A_n(p_j) = P_n^1(m_1)P_n^2(m_2)S_n(p_j)F_n^1(p_j)F_n^2(p_j)F_n^D(p_j)$$

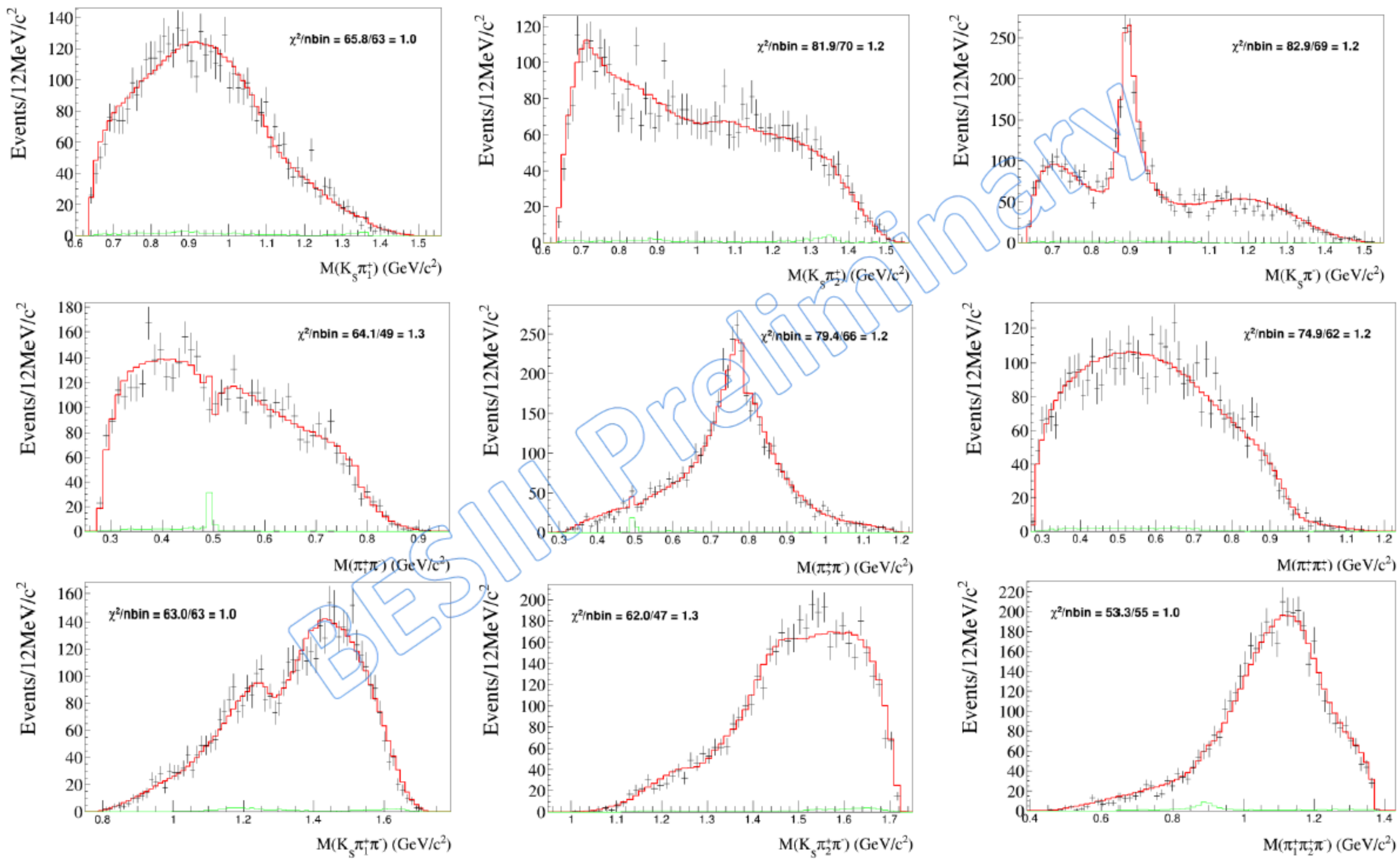
Propagator

Spin factor

Blatt-Weisskoft barrier factor

Projections of invariant mass.

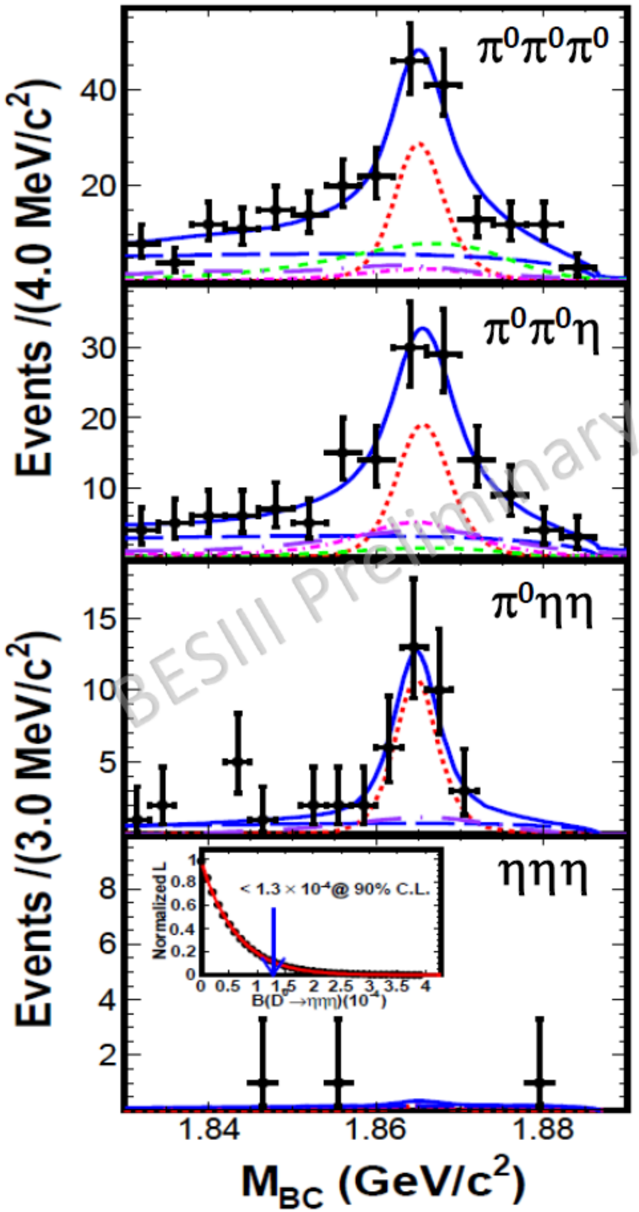
For the two identical pions, they are sorted with the invariant mass of $\pi^+\pi^-$ pair:
lower one is denoted as π_1, and the other one is denoted as π_2.
Points with error bars: data, red histograms: fit, green histograms: background estimated from MC.



Fit fractions(FF) for different components

Component	BESIII	Mark III	E691
$D^+ \to K_S^0 a_1(1260)^+(\rho^0\pi^+)$	$0.567 \pm 0.020 \pm 0.044$	$0.539 \pm 0.057 \pm 0.070$	$0.830 \pm 0.140 \pm 0.200$
$D^+ \to K_S^0 a_1(1260)^+(f_0(500)\pi^+)$	$0.050 \pm 0.006 \pm 0.007$		
$D^+ \to \bar{K}_1(1400)^0\pi^+$	$0.372 \pm 0.015 \pm 0.016$	$0.277 \pm 0.047 \pm 0.080$	
$D^+ \to \bar{K}_1(1270)^0\pi^+$	$0.036 \pm 0.004 \pm 0.002$		
$D^+ \to \bar{K}(1460)^0\pi^+$	$0.014 \pm 0.004 \pm 0.003$		
$D^+ \to K_S^0\pi^+\rho^0$	$0.044 \pm 0.005 \pm 0.005$		$0.070 \pm 0.040 \pm 0.060$
$D^+ \to K^{*-}\pi^+\pi^+$	$0.139 \pm 0.012 \pm 0.020$		$0.330 \pm 0.060 \pm 0.140$
$D^+ \to K_S^0\pi^+\pi^+\pi^-$ nonresonant	$0.074 \pm 0.005 \pm 0.008$	$0.170 \pm 0.056 \pm 0.100$	$0.100 \pm 0.040 \pm 0.060$

Measurement of SCS Decays $D^0 \to \pi^0\pi^0\pi^0, \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $\eta\eta\eta$



Signal

CF decay with K_S

$D^0 \to 4\pi^0$

Cross-feeds

Combinatorial

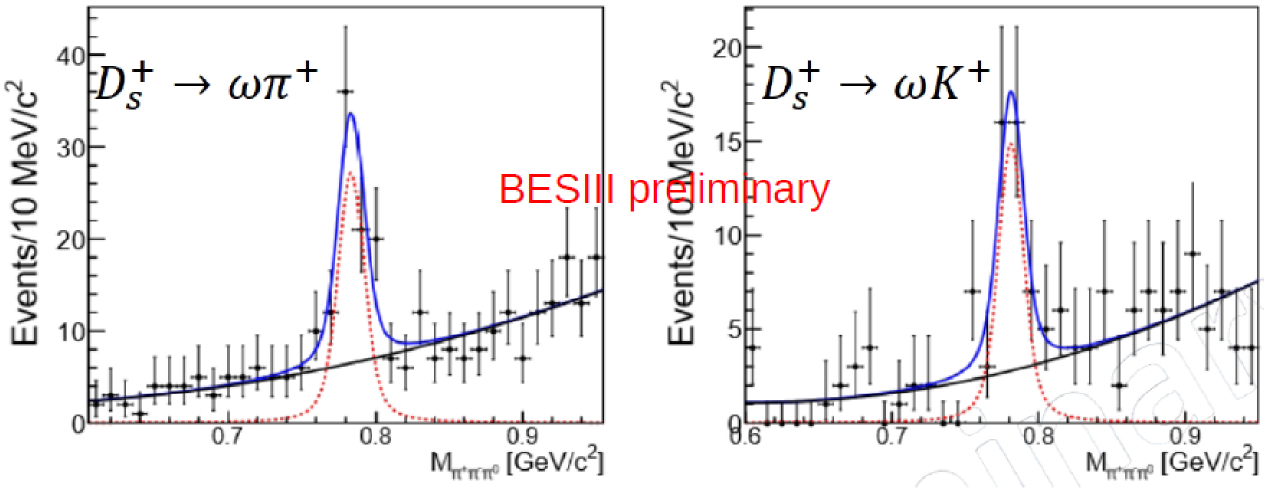
New results!

- First measurement (observation) of SCS decay $D^0 \to \pi^0\eta\eta$
- First evidences for SCS decays $D^0 \to \pi^0\pi^0\pi^0$ and $D^0 \to \pi^0\pi^0\eta$
- Upper limit at 90% CL is set for $Br(D^0 \to \eta\eta\eta)$

Mode	N_{DT}^{sig}	Significance	$\mathcal{B}$ ($\times 10^{-4}$)	$\mathcal{B}_{PDG}$ ($\times 10^{-4}$)
$\pi^0\pi^0\pi^0$	60 ± 13	4.8σ	$2.0 \pm 0.4 \pm 0.3$	< 3.5
$\pi^0\pi^0\eta$	42 ± 12	3.8σ	$3.8 \pm 1.1 \pm 0.7$	–
$\pi^0\eta\eta$	27 ± 6	5.5σ	$7.3 \pm 1.6 \pm 1.5$	–
$\eta\eta\eta$	–	–	< 1.3	–

3.19/fb data @ 4.178 GeV

First observations of $D_s^+ \to \omega\pi^+$ and $D_s^+ \to \omega K^+$



Signal mode	Branching fraction (10^{-3})	Statistical significance (σ)
$D_s^+ \to \omega\pi^+$	$1.85 \pm 0.30(stat.) \pm 0.19(sys.)$	7.7
$D_s^+ \to \omega K^+$	$1.13 \pm 0.24(stat.) \pm 0.14(sys.)$	6.2

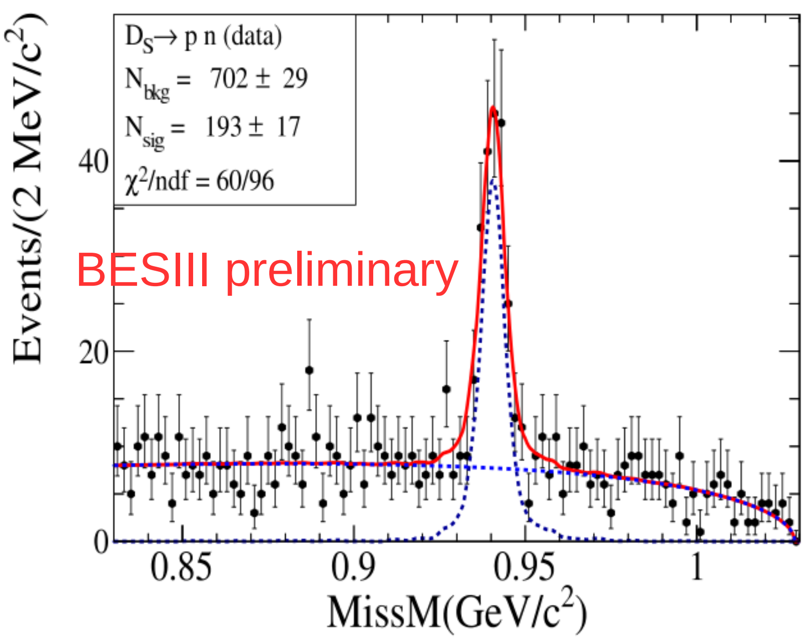
BESIII preliminary

3.19/fb data @ 4.178 GeV

$$\boxed{\mathcal{B}_{D_s^+ \to p\bar{n}} = (1.22 \pm 0.10 \pm 0.05) \times 10^{-3}}$$

BESIII preliminary

- Greatly improved accuracy over CLEO-c measurement of $(1.30 \pm 0.36^{+0.12}_{-0.16}) \times 10^{-3}$
- Consistent with the prediction of the enhanced BR due to long-distance effect via hadronic loop

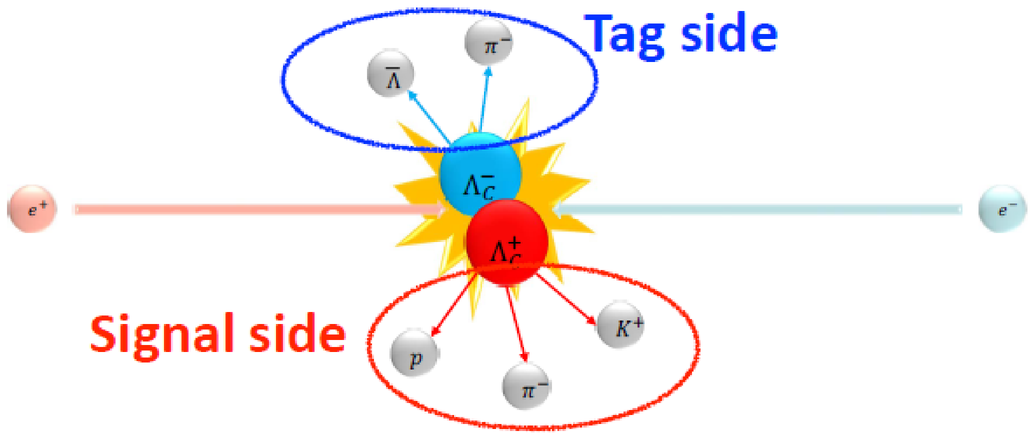


Signal: MC shape ⊗Gaussian
Background:Argus function

Recent results based on Λ_c pair production @ mass threshold

Around E_{cm} ~ 4.6 GeV ,
they are produced in pair.

$e^+e^- \rightarrow \gamma^* \rightarrow \Lambda_c^{\pm}\overline{\Lambda}_c^{\mp}$.



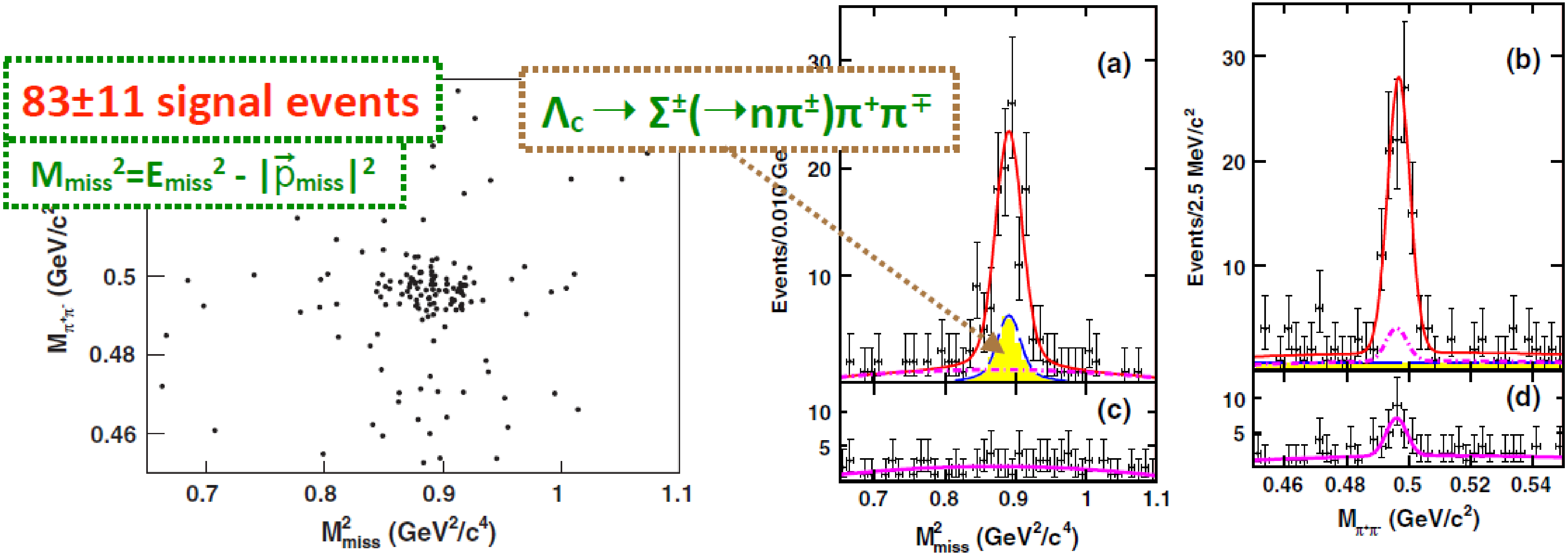
The integrated luminosity = 567 pb^{-1} (CPC 39, 093001 (2015))
Number of Λ_c produced ~ 0.2M (PRL 116, 052001 (2016))

Observation of $\Lambda_c^+ \to n K_S^0 \pi^+$

PRL 118, 112001 (2017)

0.57/fb data @ 4.599 GeV

- First direct measurement Λ_c decay involving the neutron in the final state.
- A test of the isospin symmetry.



$BF(\Lambda_c^+ \to nK_S^0\pi^+) = (1.82 \pm 0.23 \pm 0.11)\%$

$BF(\Lambda_c^+ \to nK^0\pi^+)/BF(\Lambda_c^+ \to pK^-\pi^+) = (0.62 \pm 0.09)\%$ (w/ BESIII's meas.*)

$BF(\Lambda_c^+ \to nK^0\pi^+)/BF(\Lambda_c^+ \to pK^0\pi^0) = (0.97 \pm 0.16)\%$ (w/ BESIII's meas.*)

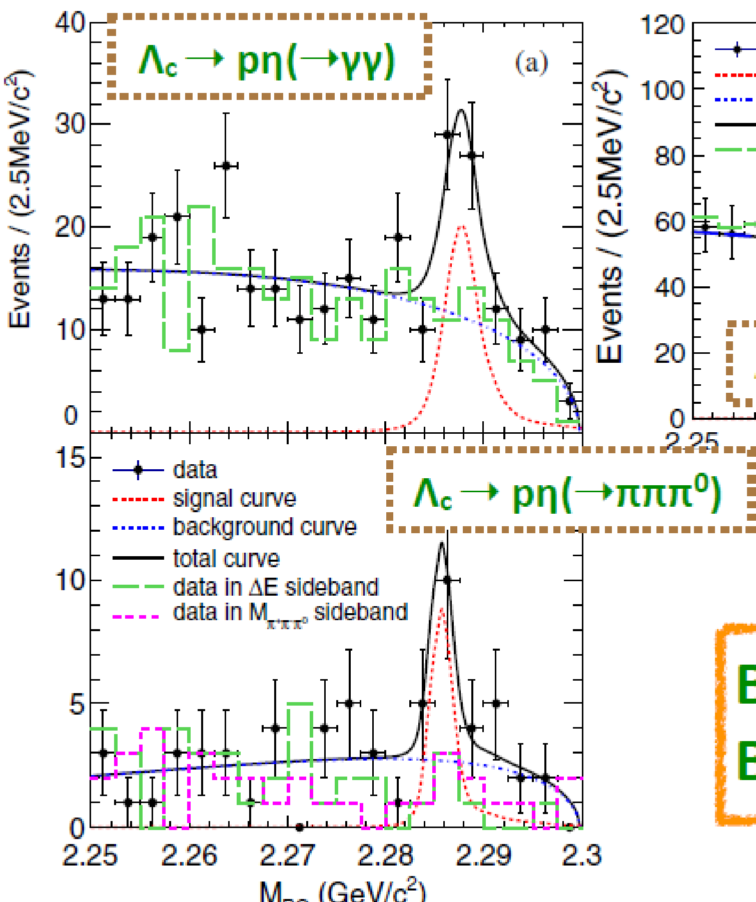
* PRL 116, 052001 (2016)

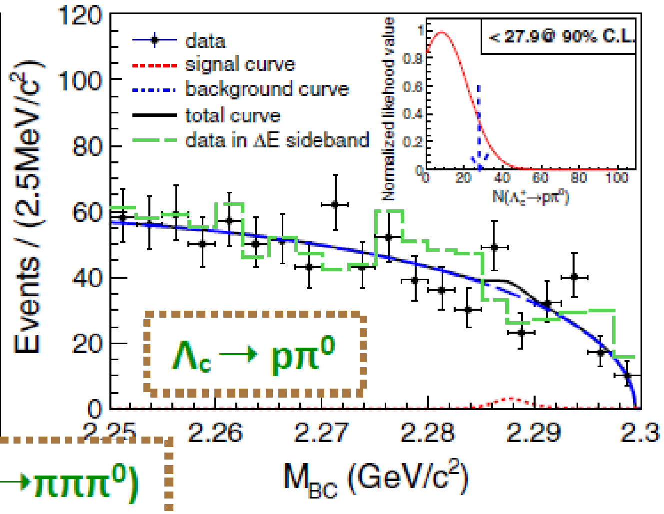
0.57/fb data @ 4.599 GeV

$\Lambda_c^+ \to p\,\eta$ and $p\,\pi^0$

PRD 95, 111102(R) (2017)

- First evidence of the SCS decay, $\Lambda_c^+ \to p\,\eta$ (4.2σ stat. significance).
- No signals seen in $\Lambda_c^+ \to p\,\pi^0$.
- Predicted BFs vary under different theoretical models (SU(3) symmetry and FSI).





	$\Lambda_c^+ \to p\eta$	$\Lambda_c^+ \to p\pi^0$	$\frac{\mathcal{B}_{\Lambda_c^+ \to p\pi^0}}{\mathcal{B}_{\Lambda_c^+ \to p\eta}}$
BESIII	1.24 ± 0.29	< 0.27	< 0.24
Sharma *et al.* [3]	$0.2^{a}(1.7^{b})$	0.2	$1.0^{a}(0.1^{b})$
Uppal *et al.* [4]	0.3	0.1–0.2	0.3–0.7
S. L. Chen *et al.* [12]	...	$0.11–0.36^{c}$	...
Cai-Dian Lü *et al.* [13]	...	0.45	...

[a] Assumed to have a positive sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[b] Assumed to have a negative sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.
[c] Calculated relying on different values of parameters b and α.

$\mathrm{BF}(\Lambda_c^+ \to p\,\eta) = (1.24 \pm 0.28 \pm 0.10) \times 10^{-3}$

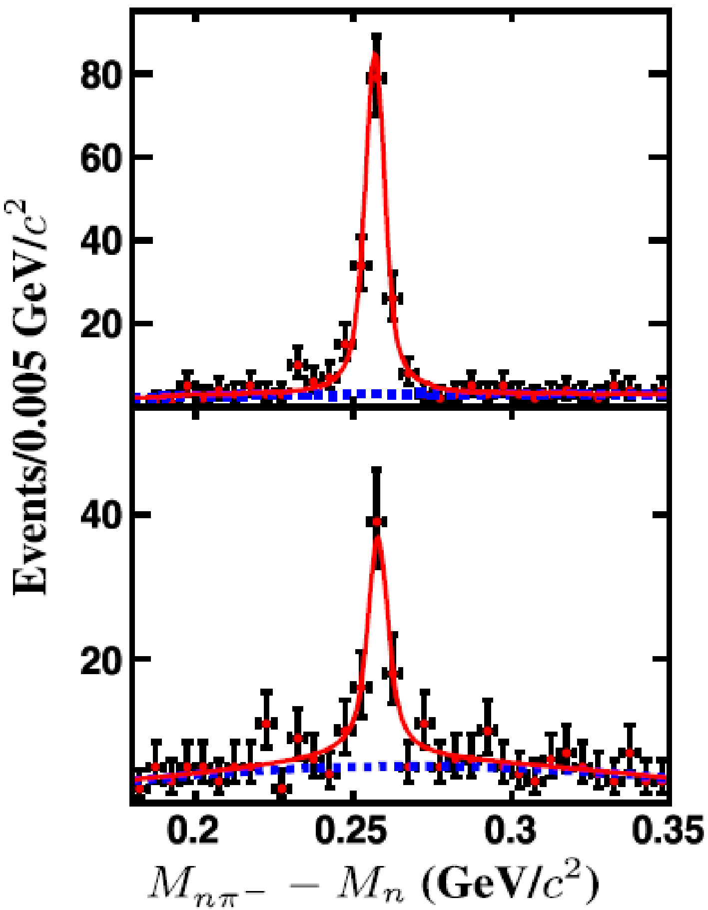
$\mathrm{BF}(\Lambda_c^+ \to p\,\pi^0) < 2.7 \times 10^{-4}$ @ 90% C.L.

0.57/fb data @ 4.599 GeV

Observation of $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$

Recently accepted to PLB

- First observation of CF decay, $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$.
- and improved BF on $\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$.
- $\Sigma^- \to n\pi^-$ is reconstructed .



- Fit to $M_{n\pi-}$ - M_n to extract the signal yields.

$$M_{n\pi^-} = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^+(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+(\pi^0)}|^2}$$

$$M_n = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^+\pi^-(\pi^0)})^2 - |\vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+\pi^-(\pi^0)}|^2}$$

BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$) = (2.11±0.33±0.14)%

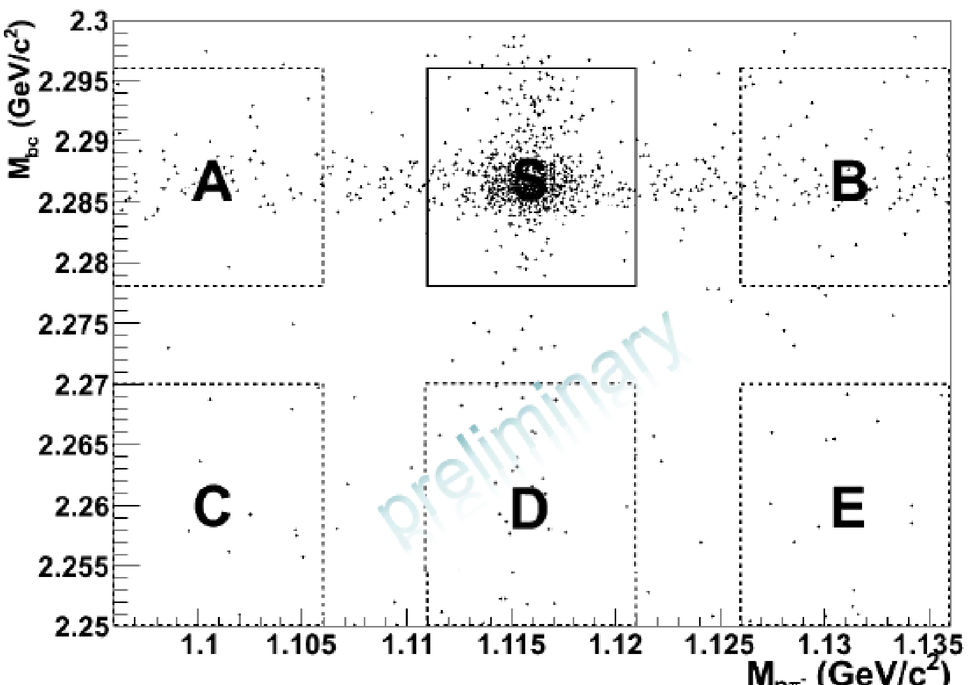
BF($\Lambda_c^+ \to \Sigma^-\pi^+\pi^+$) = (1.81±0.17±0.09)%

0.57/fb data @ 4.599 GeV

$\Lambda_c^+ \rightarrow \Lambda + X$

~preliminary result~

- Current PDG : BF($\Lambda_c^+ \rightarrow \Lambda + X$) = (35±11)%
  Large rate, but also with large uncertainty…
- Double tag method: Tagged with two modes; $pK\pi$ and pK_S.
- Extract yields from 2D distributions in bins of $p_{p\pi}$ and |cosθ|, where θ is the polar angle w.r.t. the beam pipe.



- BF($\Lambda_c^+ \rightarrow \Lambda + X$) = (36.98±2.18)%
- Also, looked for;

$$\mathcal{A}_{CP} = \frac{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) - \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}{\mathcal{B}(\Lambda_c^+ \to \Lambda + X) + \mathcal{B}(\bar{\Lambda}_c^- \to \bar{\Lambda} + X)}.$$

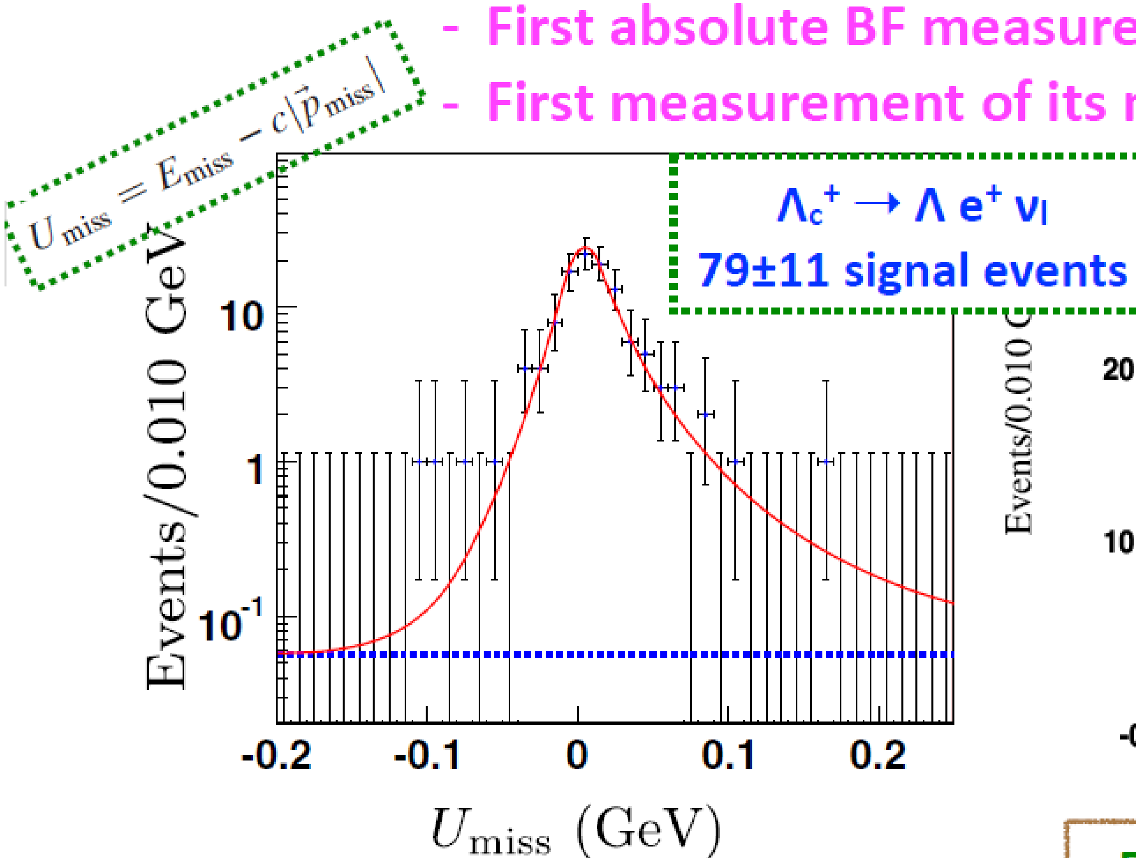
- A_{CP} = +0.02±0.06.

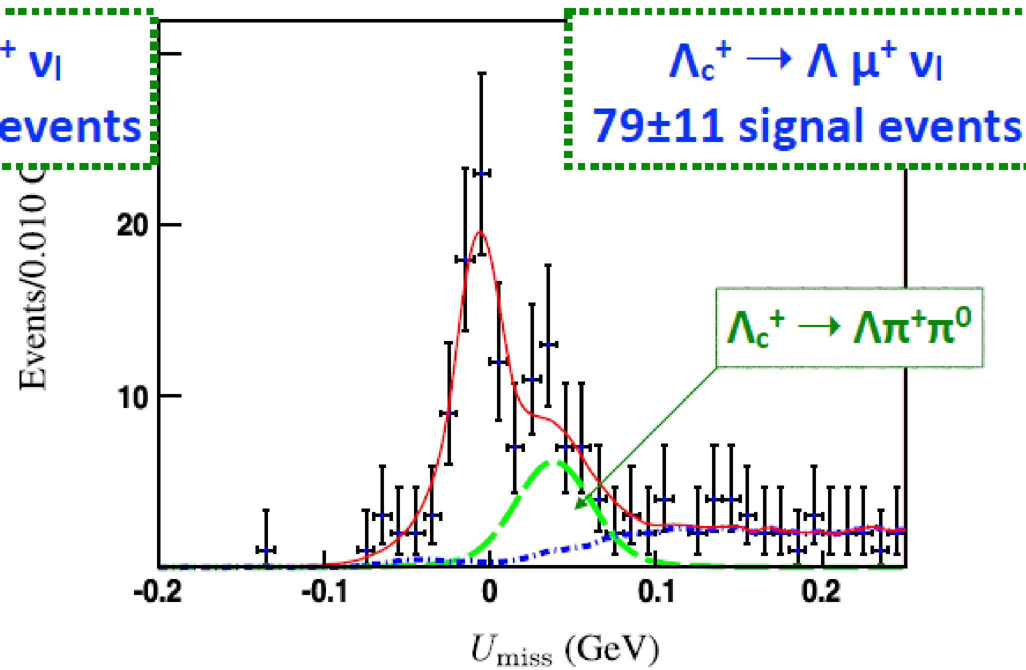
0.57/fb data @ 4.599 GeV

BF($\Lambda_c^+ \to \Lambda\ \ell^+ \nu_l$)

PRL 115, 221805 (2015) and PLB 767, 42 (2017)

- Large rate via the CF transition, $c \to s\ l^+ \nu_l$.
- First absolute BF measurement!
- First measurement of its muonic mode!





BF($\Lambda_c^+ \to \Lambda\ e^+ \nu_e$) = (3.63±0.38±0.20)%

- BF($\Lambda_c^+ \to \Lambda\ \mu^+ \nu_\mu$) = (3.49±0.46±0.27)%
- $\Gamma(\Lambda_c^+ \to \Lambda\ \mu^+ \nu_\mu)/\Gamma(\Lambda_c^+ \to \Lambda\ e^+ \nu_e)$ = 0.96±0.16±0.04

Summary

- $D_{(s)}$ and Λ_c data produced at mass threshold allow us to perform inclusive and exclusive branching fraction measurements with accuracy
- Double tag method provides clean samples for amplitude analyses
- A large range of recent (< 1 year) studies on $D_{(s)}$ and Λ_c decays are covered, more in the backup
- Stay tuned for more charm results from BESIII in the coming months, esp. on D_s and Λ_c decays
- BESIII will keep collecting data in the next ~ decade

Backup

2.93/fb data @ 3.773 GeV

Amplitude analysis of $D^0 \to K^-\pi^+\pi^+\pi^-$

PHYSICAL REVIEW D **95**, 072010 (2017)

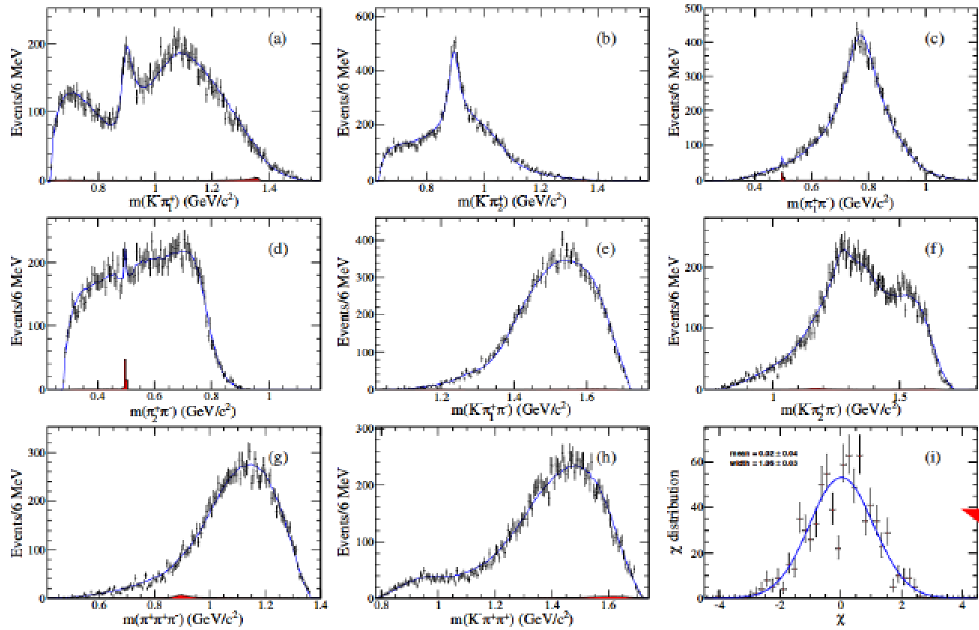
Amplitude	ϕ_i	Fit fraction (%)
$D^0[S] \to \bar{K}^*\rho^0$	$2.35 \pm 0.06 \pm 0.18$	$6.5 \pm 0.5 \pm 0.8$
$D^0[P] \to \bar{K}^*\rho^0$	$-2.25 \pm 0.08 \pm 0.15$	$2.3 \pm 0.2 \pm 0.1$
$D^0[D] \to \bar{K}^*\rho^0$	$2.49 \pm 0.06 \pm 0.11$	$7.9 \pm 0.4 \pm 0.7$
$D^0 \to K^-a_1^+(1260),\ a_1^+(1260)[S] \to \rho^0\pi^+$	0(fixed)	$53.2 \pm 2.8 \pm 4.0$
$D^0 \to K^-a_1^+(1260),\ a_1^+(1260)[D] \to \rho^0\pi^+$	$-2.11 \pm 0.15 \pm 0.21$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[S] \to \bar{K}^{*0}\pi^-$	$1.48 \pm 0.21 \pm 0.24$	$0.1 \pm 0.1 \pm 0.1$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270)[D] \to \bar{K}^{*0}\pi^-$	$3.00 \pm 0.09 \pm 0.15$	$0.7 \pm 0.2 \pm 0.2$
$D^0 \to K_1^-(1270)\pi^+,\ K_1^-(1270) \to K^-\rho^0$	$-2.46 \pm 0.06 \pm 0.21$	$3.4 \pm 0.3 \pm 0.5$
$D^0 \to (\rho^0K^-)_A\pi^+,\ (\rho^0K^-)_A[D] \to K^-\rho^0$	$-0.43 \pm 0.09 \pm 0.12$	$1.1 \pm 0.2 \pm 0.3$
$D^0 \to (K^-\rho^0)_P\pi^+$	$-0.14 \pm 0.11 \pm 0.10$	$7.4 \pm 1.6 \pm 5.7$
$D^0 \to (K^-\pi^+)_{\text{S-wave}}\rho^0$	$-2.45 \pm 0.19 \pm 0.47$	$2.0 \pm 0.7 \pm 1.9$
$D^0 \to (K^-\rho^0)_V\pi^+$	$-1.34 \pm 0.12 \pm 0.09$	$0.4 \pm 0.1 \pm 0.1$
$D^0 \to (\bar{K}^{*0}\pi^-)_P\pi^+$	$-2.09 \pm 0.12 \pm 0.22$	$2.4 \pm 0.5 \pm 0.5$
$D^0 \to \bar{K}^{*0}(\pi^+\pi^-)_S$	$-0.17 \pm 0.11 \pm 0.12$	$2.6 \pm 0.6 \pm 0.6$
$D^0 \to (\bar{K}^{*0}\pi^-)_V\pi^+$	$-2.13 \pm 0.10 \pm 0.11$	$0.8 \pm 0.1 \pm 0.1$
$D^0 \to ((K^-\pi^+)_{\text{S-wave}}\pi^-)_A\pi^+$	$-1.36 \pm 0.08 \pm 0.37$	$5.6 \pm 0.9 \pm 2.7$
$D^0 \to K^-((\pi^+\pi^-)_S\pi^+)_A$	$-2.23 \pm 0.08 \pm 0.22$	$13.1 \pm 1.9 \pm 2.2$
$D^0 \to (K^-\pi^+)_{\text{S-wave}}(\pi^+\pi^-)_S$	$-1.40 \pm 0.04 \pm 0.22$	$16.3 \pm 0.5 \pm 0.6$
$D^0[S] \to (K^-\pi^+)_V(\pi^+\pi^-)_V$	$1.59 \pm 0.13 \pm 0.41$	$5.4 \pm 1.2 \pm 1.9$
$D^0 \to (K^-\pi^+)_{\text{S-wave}}(\pi^+\pi^-)_V$	$-0.16 \pm 0.17 \pm 0.43$	$1.9 \pm 0.6 \pm 1.2$
$D^0 \to (K^-\pi^+)_V(\pi^+\pi^-)_S$	$2.58 \pm 0.08 \pm 0.25$	$2.9 \pm 0.5 \pm 1.7$
$D^0 \to (K^-\pi^+)_T(\pi^+\pi^-)_S$	$-2.92 \pm 0.14 \pm 0.12$	$0.3 \pm 0.1 \pm 0.1$
$D^0 \to (K^-\pi^+)_{\text{S-wave}}(\pi^+\pi^-)_T$	$2.45 \pm 0.12 \pm 0.37$	$0.5 \pm 0.1 \pm 0.1$

2.93/fb data @ 3.773 GeV

Amplitude analysis of $D^0 \to K^-\pi^+\pi^+\pi^-$

PHYSICAL REVIEW D **95,** 072010 (2017)

Four-body decay is in a five-dimensional phase-space.
Here are 1D projections onto two- or three-body system.

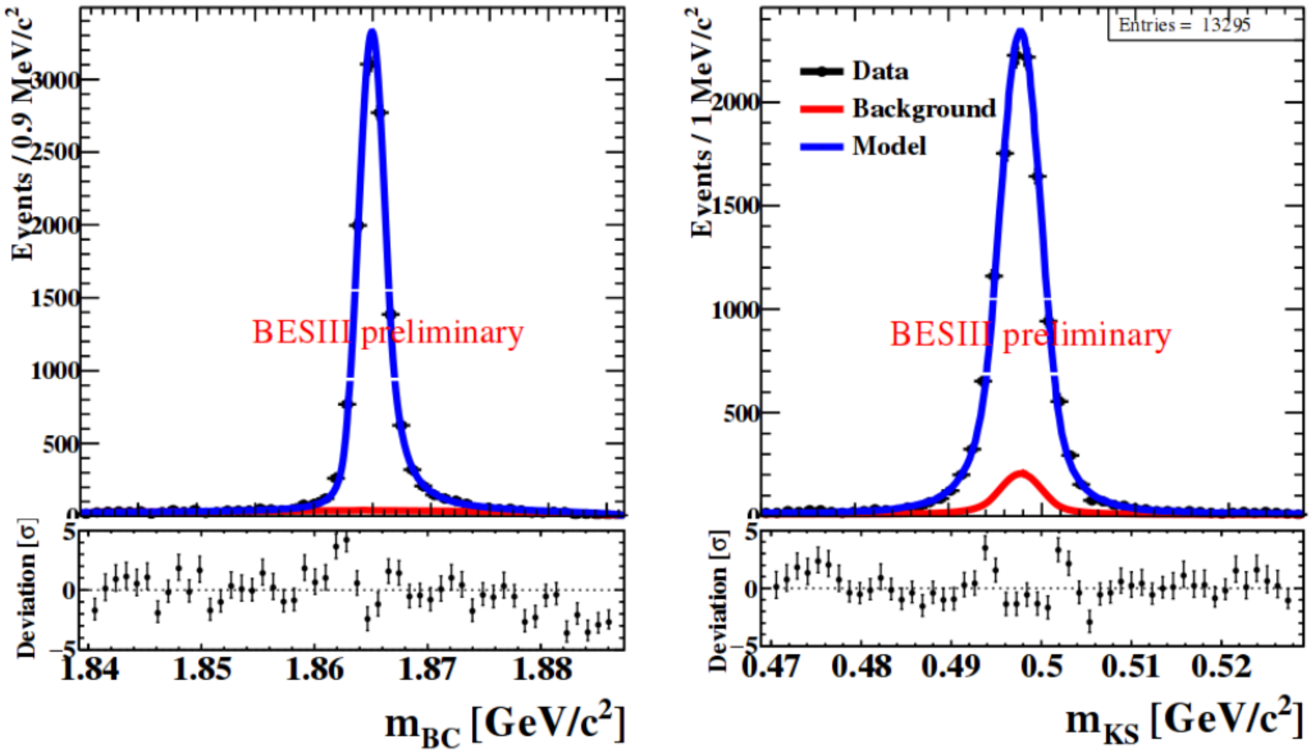


X value distribution of bins in five-dimension for goodness-of-fit

Component	Fit fraction (%)	Mark III's result	E691's result
$D^0 \to \bar{K}^{*0}\rho^0$	$12.3 \pm 0.4 \pm 0.5$	$14.2 \pm 1.6 \pm 5$	$13 \pm 2 \pm 2$
$D^0 \to K^- a_1^+(1260)(\rho^0\pi^+)$	$54.6 \pm 2.8 \pm 3.7$	$49.2 \pm 2.4 \pm 8$	$47 \pm 5 \pm 10$
$D^0 \to K_1^-(1270)(\bar{K}^{*0}\pi^-)\pi^+$	$0.8 \pm 0.2 \pm 0.2$	$6.6 \pm 1.9 \pm 3$	...
$D^0 \to K_1^-(1270)(K^-\rho^0)\pi^+$	$3.4 \pm 0.3 \pm 0.5$		
$D^0 \to K^-\pi^+\rho^0$	$8.4 \pm 1.1 \pm 2.5$	$8.4 \pm 2.2 \pm 4$	$5 \pm 3 \pm 2$
$D^0 \to \bar{K}^{*0}\pi^+\pi^-$	$7.0 \pm 0.4 \pm 0.5$	$14.0 \pm 1.8 \pm 4$	$11 \pm 2 \pm 3$
$D^0 \to K^-\pi^+\pi^+\pi^-$	$21.9 \pm 0.6 \pm 0.6$	$24.2 \pm 2.5 \pm 6$	$23 \pm 2 \pm 3$

Branching-fraction measurement of $D^0 \rightarrow K_S K^+ K^-$

2.93/fb data @ 3.773 GeV



$$N_{sig} = 11743 \pm 113$$

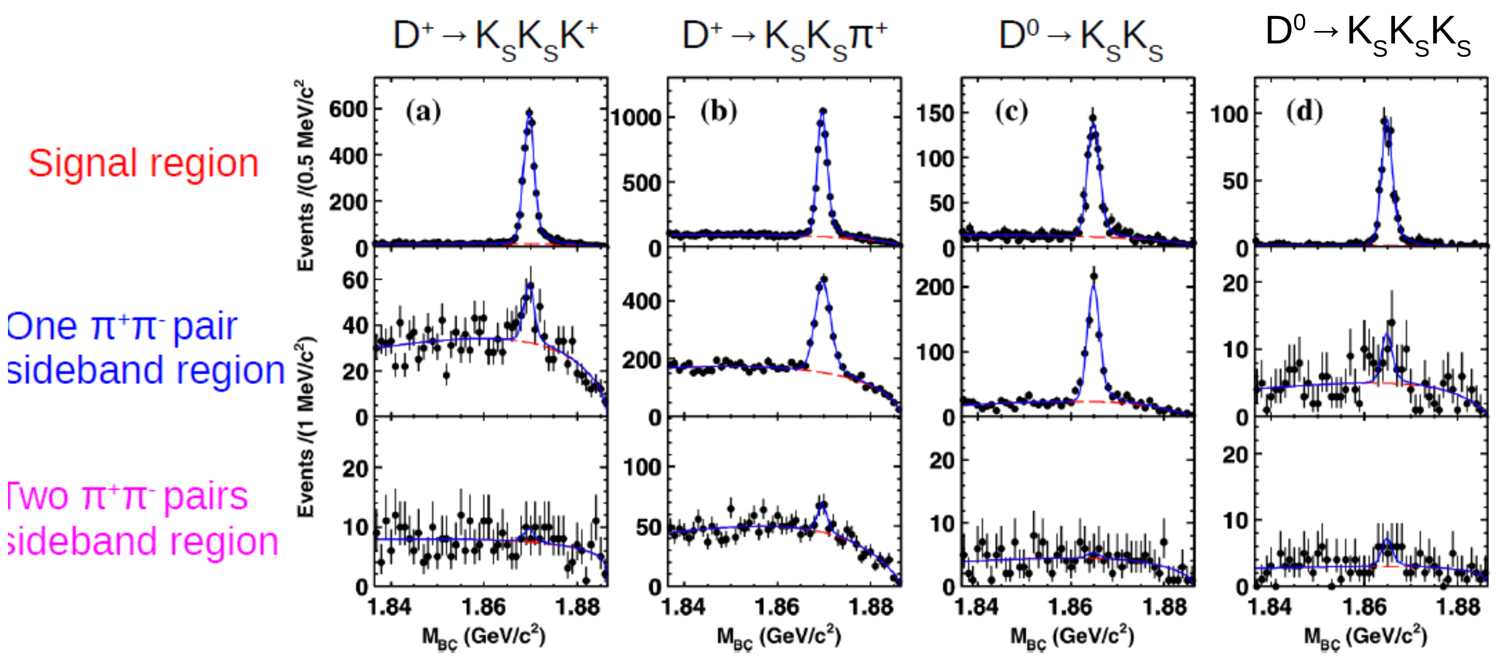
$$BF_{data}(D^0 \rightarrow K_s^0 K^+ K^-) = (4.622 \pm 0.045\,(\text{stat.}) \pm 0.181\,(\text{sys.})) \times 10^{-3}$$

- Relative uncertainty: 4.0 %
- PDG(2014) value: $(4.47 \pm 0.34) \times 10^{-3} \rightarrow$ Deviation 0.81 σ
- Ongoing Dalitz plot analysis

2.93/fb data @ 3.773 GeV

Measurements of the branching fractions for $D^+ \to K_S K_S K^+$, $K_S K_S \pi^+$ and $D^0 \to K_S K_S (K_S)$

Physics Letters B 765 (2017) 231–237



For modes with two K_S: $N_{\rm net} = N_{K_S^0 {\rm sig}} - \frac{1}{2} N_{\rm sb1} + \frac{1}{4} N_{\rm sb2} - N^{\rm b}_{\rm other}$

For mode with three K_S: $N_{\rm net} = N_{K_S^0 {\rm sig}} - \frac{1}{2} N_{\rm sb1} + \frac{1}{4} N_{\rm sb2} - \frac{1}{8} N_{\rm sb3} - N^{\rm b}_{\rm other}$

Decay modes	$N_{K_S^0 {\rm sig}}$	$N_{\rm sb1}$	$N_{\rm sb2}$	$N_{\rm sb3}$	$N^{\rm b}_{\rm other}$	$N_{\rm net}$	ϵ (%)	$\mathcal{B}$ ($\times 10^{-4}$)
$D^+ \to K_S^0 K_S^0 K^+$	3616 ± 66	97 ± 19	6 ± 8	–	18 ± 2	3551 ± 67	8.27 ± 0.04	25.4 ± 0.5
$D^+ \to K_S^0 K_S^0 \pi^+$	5643 ± 88	1464 ± 68	69 ± 19	–	31 ± 3	4897 ± 94	10.72 ± 0.04	27.0 ± 0.5
$D^0 \to K_S^0 K_S^0$	888 ± 36	626 ± 31	3 ± 6	–	0	576 ± 39	16.28 ± 0.30	1.67 ± 0.11
$D^0 \to K_S^0 K_S^0 K_S^0$	622 ± 27	24 ± 8	14 ± 6	0	16 ± 3	597 ± 27	3.92 ± 0.05	7.21 ± 0.33

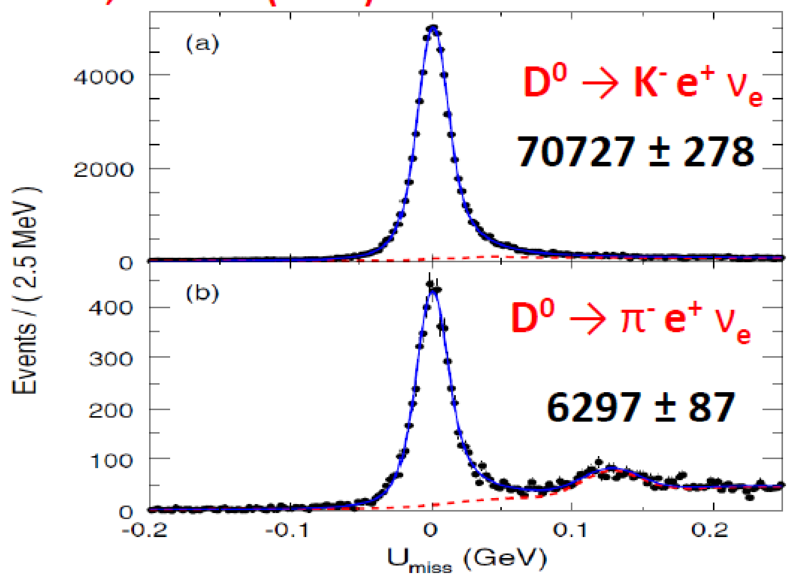
2.93/fb data @ 3.773 GeV

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

$B(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$

$B(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%$

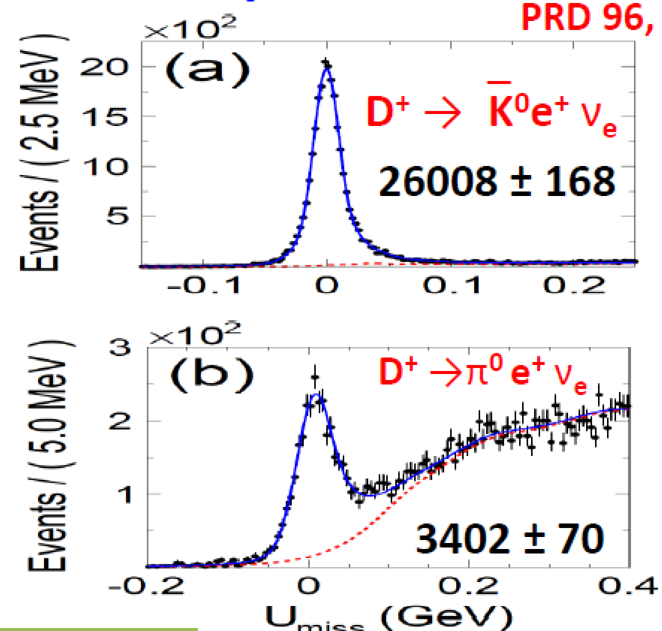
PRD 92, 072012 (2015)



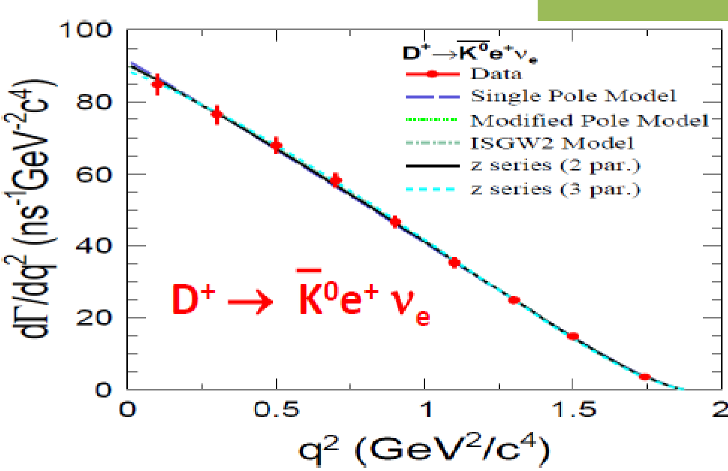
$B(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.60 \pm 0.06 \pm 0.15)\%$

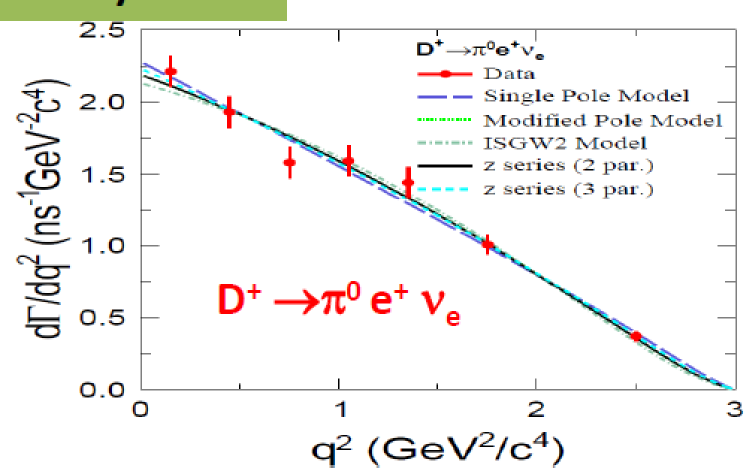
$B(D^+ \to \pi^0 e^+ \nu_e) = (0.363 \pm 0.008 \pm 0.005)\%$

PRD 96, 012002 (2017)



Differential decay rates



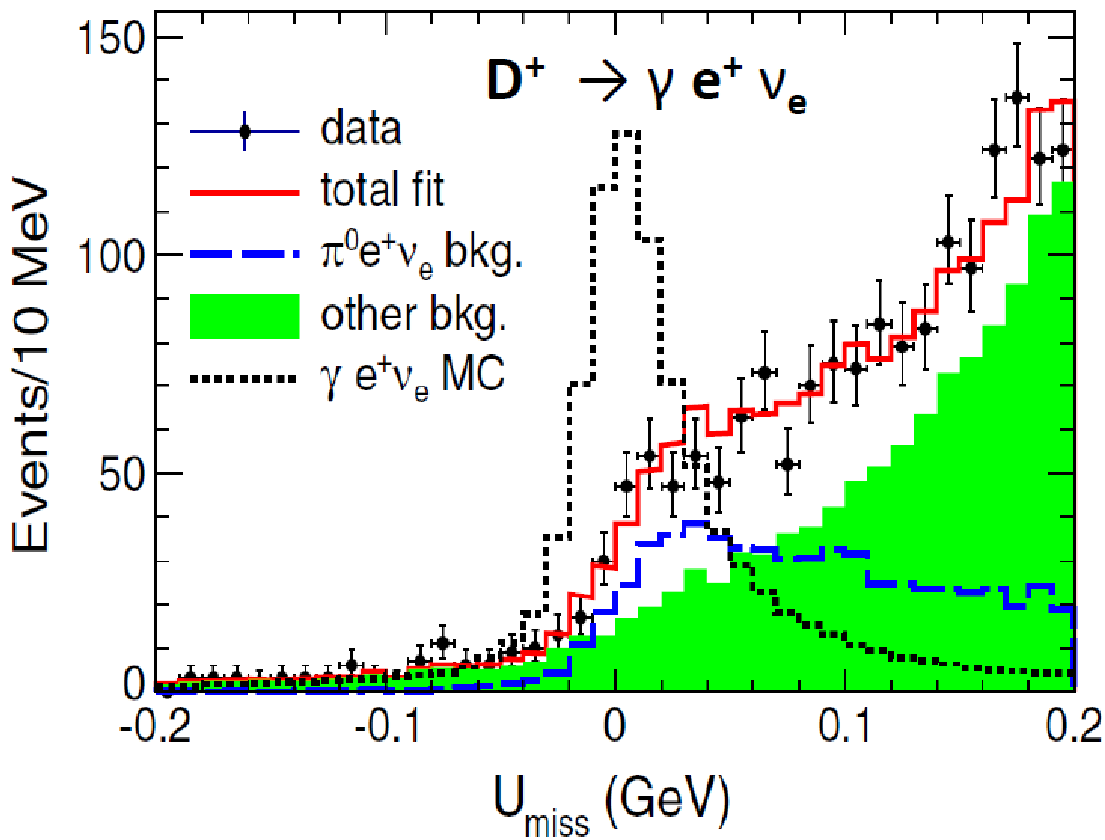


2.93/fb data @ 3.773 GeV

Search for the rare decay $D^+ \to \gamma e^+ \nu_e$

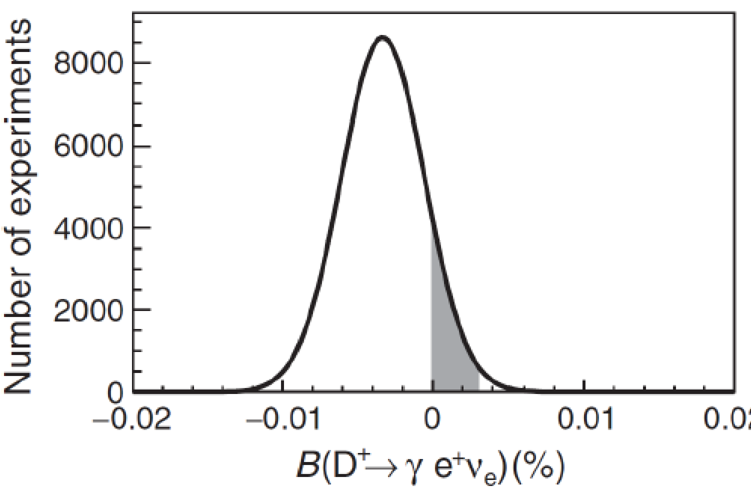
- **Not subject to the helicity suppression rule due to the presence of a radiative photon.**
- **Predicted rates are reachable range :**

  e.g., J.-C. Yang and M.-Z. Yang predict $B(D^+ \to \gamma e^+ \nu_e) \sim 2\times10^{-5}$ via Factorization.



PRD 95, 071102(R) (2017)

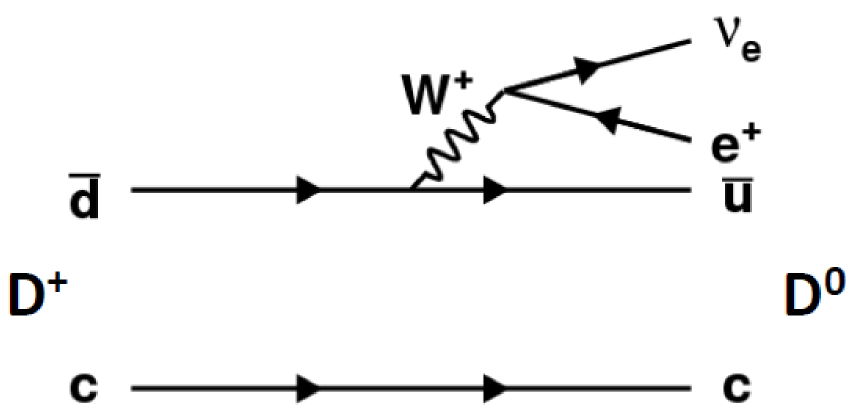
- **Only $E_\gamma > 10$ MeV considered.**
- **(-21 ± 23) signal events.**



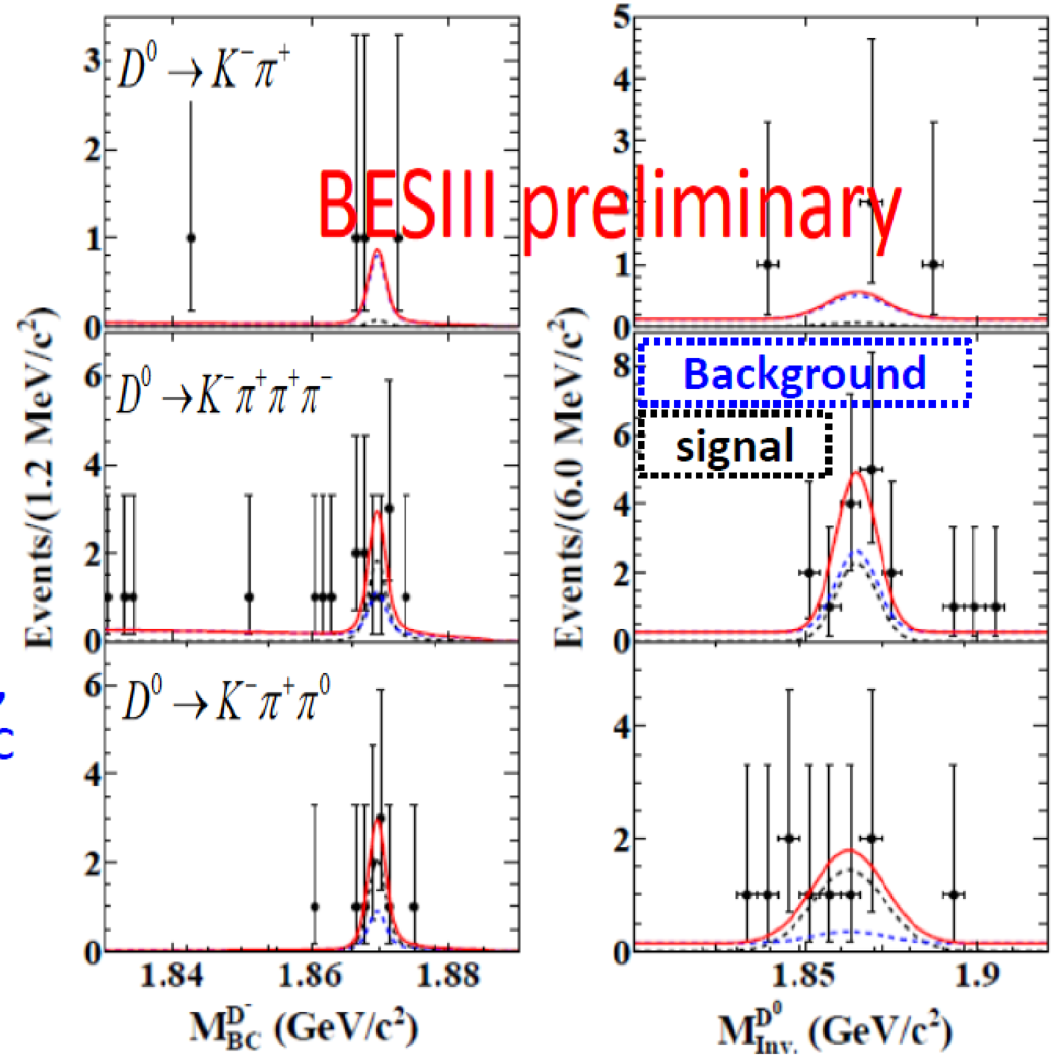
$B(D^+ \to \gamma e^+ \nu_e) < 3.0 \times 10^{-5}$ at 90% C.L.

Search for the radiative leptonic decay $D^+ \to D^0 e^+ \nu_e$

2.93/fb data @ 3.773 GeV



Applying the SU(3) symmetry for the light quarks, this rare decay branching fraction can be predicted by theoretical calculation, and its theoretical value is 2.78 x 10^{-13} [EPJC 59, 841 (2009)]



$B(D^+ \to D^0 e^+ \nu_e) < 8.7 \times 10^{-5}$ at 90% C.L..