Semileptonic D-decays at BESIII

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On behalf of the BESIII collaboration

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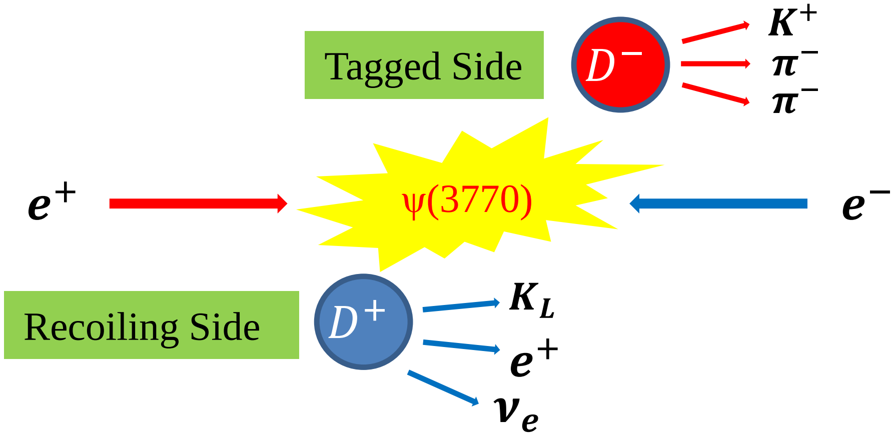
Outline

- Measurement Technique
- Study of $D^+ \rightarrow K^-\pi^+e^+\upsilon_e$
- Study of $D^+ \rightarrow \omega(\phi)e^+\upsilon_e$
- Study of $D^+ \rightarrow K_L e^+\upsilon_e$

Measurement Technique

- About 2.92 fb^{-1} of data is collected at $\psi(3770)$, which ensures a pure $D\bar{D}$ final state with no additional final state hadrons. In events where one D is fully reconstructed, semileptonic signals are searched at the recoiling side.



- Branching fractions can be obtained using:

$$\mathrm{Br}(D^+ \to X\, e^+\nu_e) = \frac{\mathrm{N_{sig}}}{\sum_\alpha \mathrm{N}_{\mathrm{tag}}^{\mathrm{obs},\alpha}\epsilon_{\mathrm{tag,sig}}^{\alpha}/\epsilon_{\mathrm{tag}}^{\alpha}}$$

N_{sig} is the number of semileptonic candidates, $N_{tag}^{obs,\alpha}$ the number of observed tagged mode α, while $\epsilon_{\mathrm{tag}}^{\alpha}$ and $\epsilon_{\mathrm{tag,sig}}^{\alpha}$ the reconstruction efficiencies of tagged mode α and both the tagged and semileptonic mode.

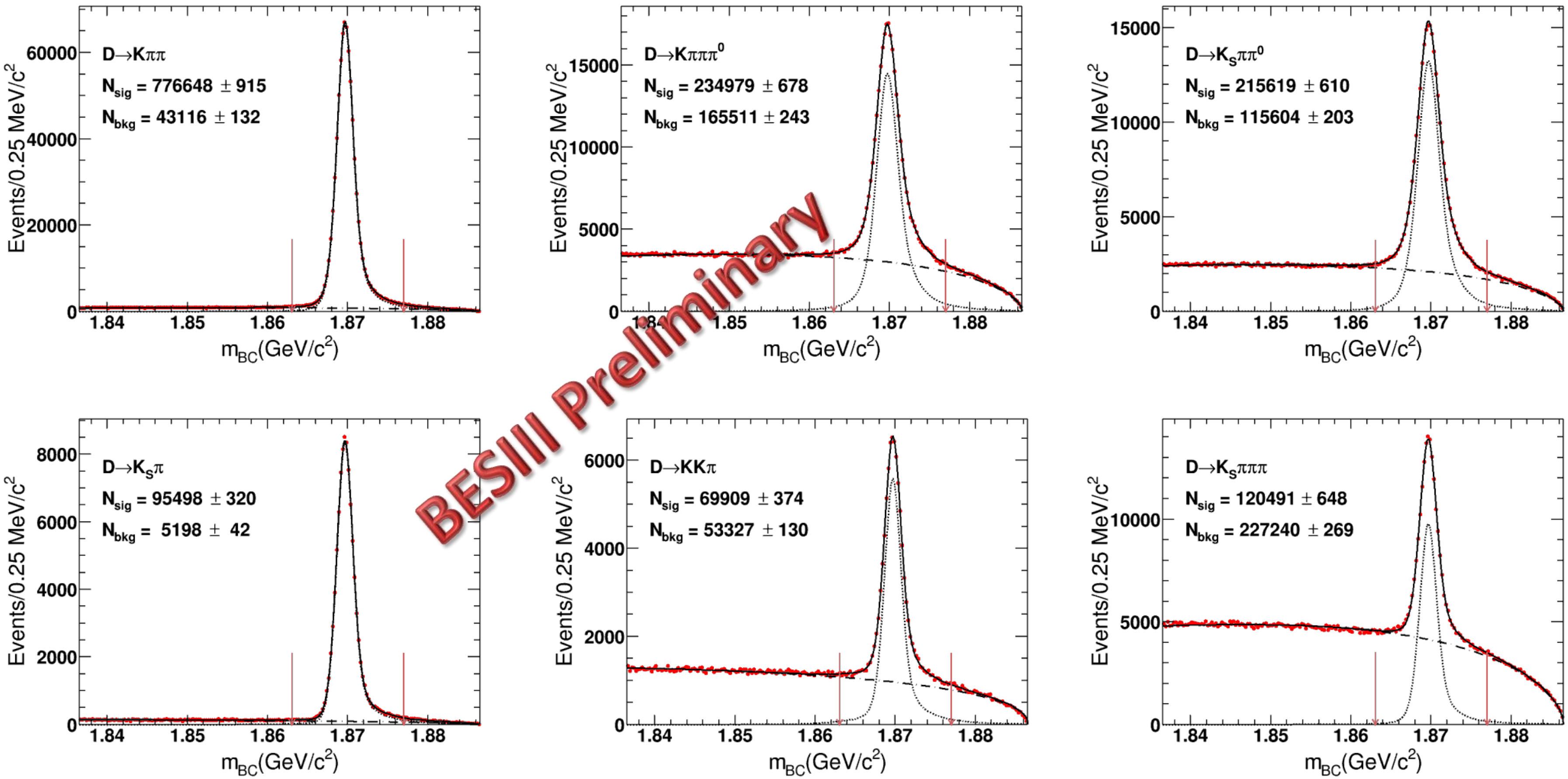
- Six hadronic decay modes are chosen as tags:
$D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^-\pi^+\pi^+\pi^0$, $D^+ \to K_S{}^0\,\pi^+$
$D^+ \to K_S{}^0\,\pi^+\pi^0$, $D^+ \to K_S{}^0\,\pi^+\pi^+\pi^-$, $D^+ \to K^+K^-\pi^+$

- Tags are selected based on two variables, and tag yield is obtained by fitting m_{BC}.

$$\Delta E = E_D - E_{beam},\ \ m_{BC} = \sqrt{E_{beam}^2 - |\vec{p}_D|^2}$$

m_{BC} Distribution

Tag yield is obtained by fitting m_{BC}. In the case of $D^+ \to K^-\pi^+e^+\upsilon_e$ study, the fits are illustrated as below.



Signal: MC shape convoluting a double Gaussion; Background : Argus Function

Study of $D^+ \to K^-\pi^+e^+\upsilon_e$

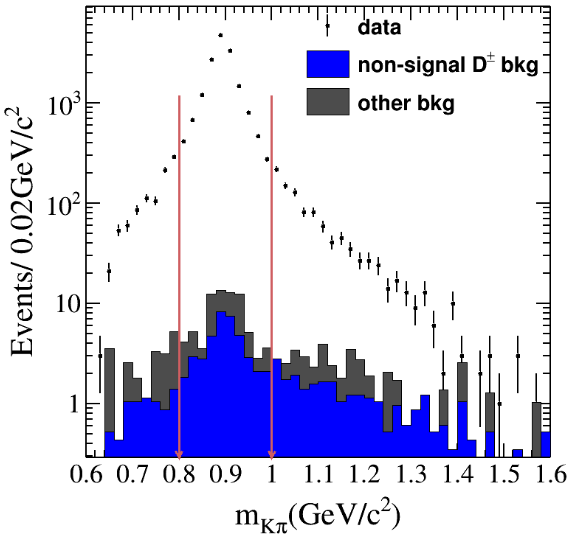
In the $D^+ \to K^-\pi^+e^+\upsilon_e$ decay, we can measure:

- Branching fractions
- The fractions and properties of different $K\pi$ (non-)resonant amplitudes
  - S: non-resonant, $K_0^*(1430)$
  - P: $K^*(892)$, $K^*(1410)$
  - D: $K_2^*(1430)$
- q^2 dependent transition form factors in $D^+ \to \bar{K}^{*0}(892)e^+\upsilon_e$ (q^2 is the invariant mass of $e^+\upsilon_e$)
  - The $D^+ \to \bar{K}^{*0}(892)e^+\upsilon_e$ decay can be described in terms of 3 helicity basis form factors: $H_{\pm,0}(q^2)$ (Any dependence on the lepton mass is neglected), which are measured in a model-independent way
  - $H_{\pm,0}(q^2)$ are generally written as linear combinations of a vector ($V(q^2)$) and two axial-vector ($A_{1,2}(q^2)$) form factors, which are measured based on SPD (Spectroscopic Pole Dominance) model in the amplitude analysis

These measurements are important to compare with theoretical calculations and previous experiments

Branching Fraction

- A nearly background-free (~0.7%) sample of more than 18000 candidates is selected. The $m_{K\pi}$ distribution is shown on the right.



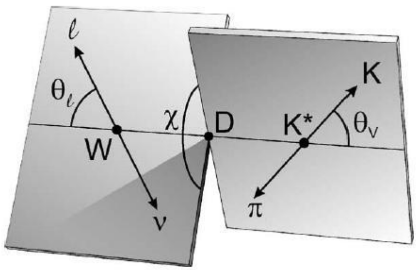
- Branching fractions over the whole $m_{K\pi}$ range and in the $K^{*0}(892)$ dominated window [0.8, 1] GeV/c^2 are calculated:

$$Br(\mathrm{D^+ \to K^- \pi^+ e^+ \nu_e}) = (3.71 \pm 0.03 \pm 0.09)\%$$

$$Br(\mathrm{D^+ \to K^- \pi^+ e^+ \nu_e})_{[0.8,1]} = (3.33 \pm 0.03 \pm 0.08)\%$$

- Amplitude analysis is performed based on this sample (see next page).
The differential decay width of the $\mathrm{D^+ \to K^- \pi^+ e^+ \nu_e}$ decay can be fully described using:
[citation: N. Cabibbo and A. Maksymowicz, Phys. Rev. 137, B438 (1965)]

  - $\mathrm{m_{K\pi}}$ - inv. mass squared of $K\pi$
  - q^2 - inv. mass of $e^+\nu_e$
  - θ_K, θ_e, χ angles



Amplitude Analysis

PDF Parameterization

(citation: BABAR Collaboration, Phys. Rev. D 83, 072001 (2011))

- Unbinned Maximum likelihood fit (background considered)

- Non-resonant S-wave amplitude:
  Magnitude: polynomial variation with $m_{K\pi}$
  Phase δ_S: same as in LASS scattering experiment [Nucl. Phys. B296, 493 (1988)]

- Other amplitudes: Breit-Wigner function with mass-dependent width

- Form factors are parameterized based on SPD model:

$$V(q^2) = \frac{V(0)}{1-q^2/m_V^2}, \quad A_{1,2}(q^2) = \frac{A_{1,2}(0)}{1-q^2/m_A^2}$$

Fit Results with S+P (preliminary)

- The fractions of the components can be extracted

$$f(D^+ \to (K^-\pi^+)_{K^{*0}(892)}\, e^+\nu_e) = (93.93 \pm 0.22 \pm 0.18)\%$$

$$f(D^+ \to (K^-\pi^+)_{S-wave}\, e^+\nu_e) = (6.05 \pm 0.22 \pm 0.18)\%$$

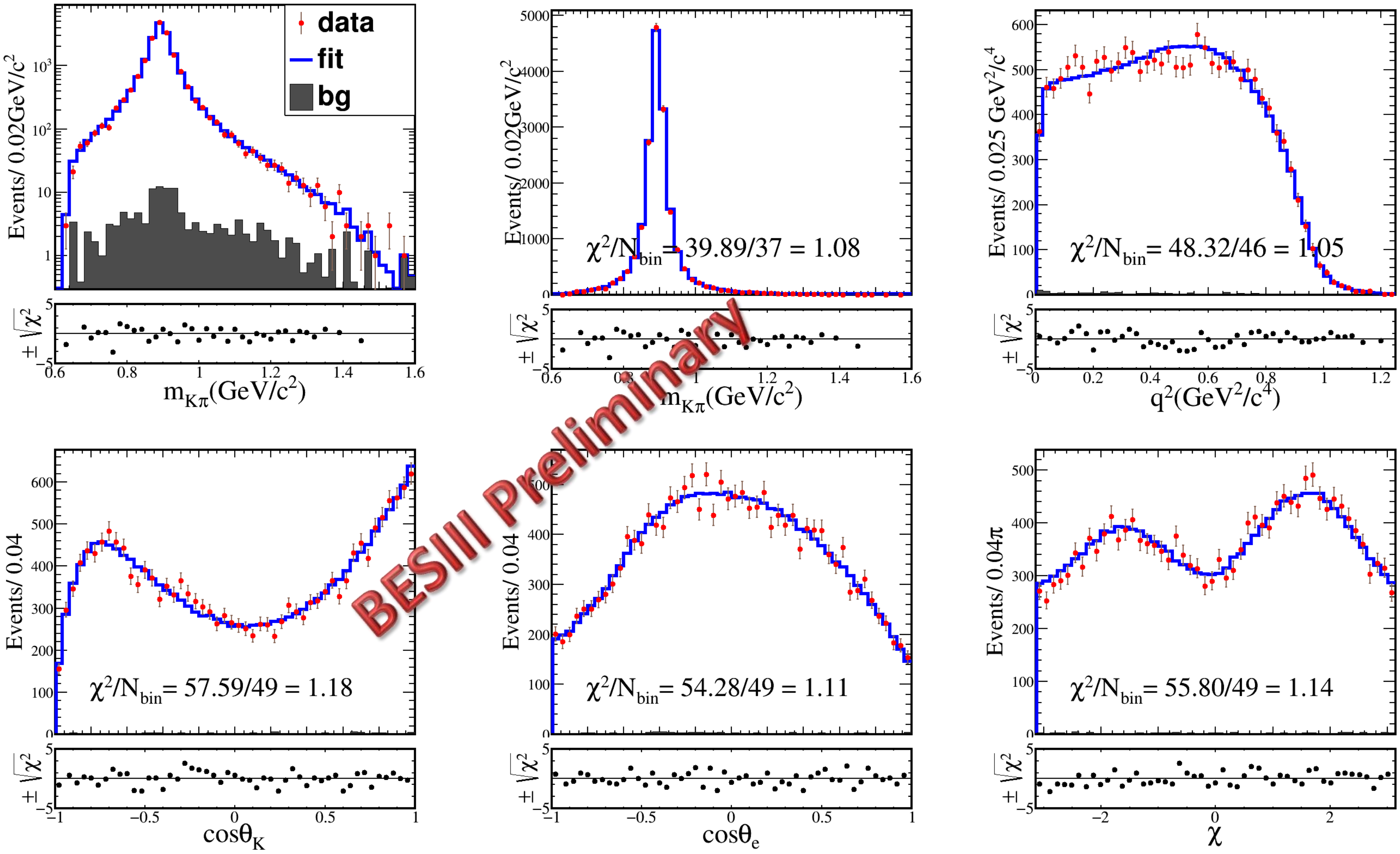
other components have significances less than 5σ and correspond to fractions below 1%

- The S-wave phase measured from amplitude analysis is illustrated in the following pages

- $m_{K^{*0}(892)} = (894.60 \pm 0.25 \pm 0.08)\ \mathrm{MeV}/c^2$
  $\Gamma_{K^{*0}(892)} = (46.42 \pm 0.56 \pm 0.15)\ \mathrm{MeV}/c^2$
  $r_{BW} = (3.07 \pm 0.26 \pm 0.11)\ (\mathrm{GeV}/c)^{-1}$

- $m_V = (1.81^{+0.25}_{-0.17} \pm 0.02)\ \mathrm{GeV}/c^2$ (first measurement)
  $m_A = (2.61^{+0.22}_{-0.17} \pm 0.03)\ \mathrm{GeV}/c^2$
  $A_1(0) = 0.573 \pm 0.011 \pm 0.020$
  $r_V = V(0)/A_1(0) = 1.411 \pm 0.058 \pm 0.007$
  $r_2 = A_2(0)/A_1(0) = 0.788 \pm 0.042 \pm 0.008$

Projections of data and fitted MC distribution



The signal contains S-wave and $K^{*0}(892)$ components.

In the lower histograms, χ of the (combined) bins of the upper histograms are provided.

S-wave Phase Measurement

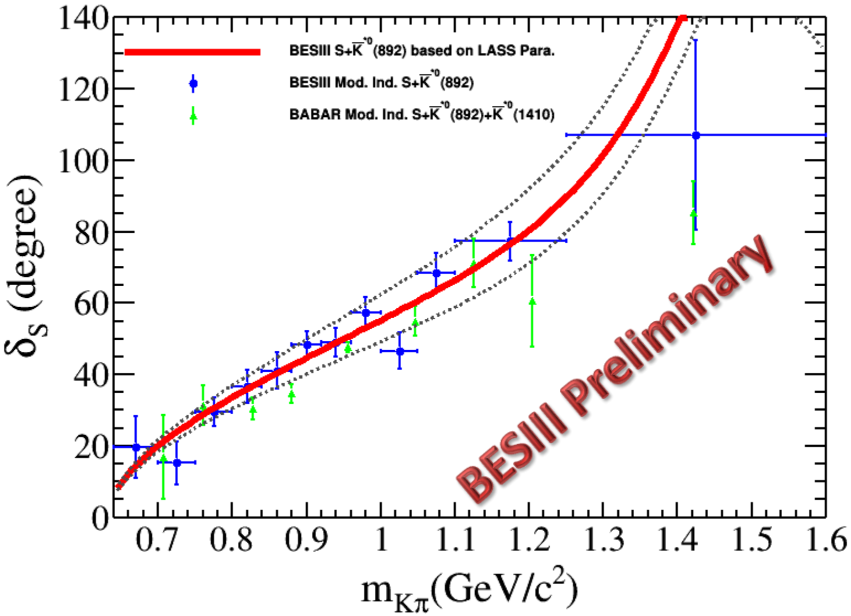
Instead of using the LASS parameterization for δ_S, we fit the phase in different $m_{K\pi}$ intervals, assuming δ_S remains constant within each interval.

- Bin division: similar size for each bin, wider for the last two due to low population
- $K^{*0}(892)$ related parameters are also set free
- Blue dots: BESIII Model-independent measurement

Red or dotted lines: predicted by fit based on LASS parameterization

Green dots: BABAR Model-independent measurement with S+$\overline{K}^{*0}(892) + \overline{K}^{*0}(1410)$

[citation: BABAR Collaboration, Phys. Rev. D 83, 072001 (2011)]



Model-independent measurement of BESIII are consistent with its result from amplitude analysis within 1σ.

Model-Independent Measurement of Form Factors

- Events located in the $K^{*0}(892)$ window $[0.8,1]$ GeV/c^2, are used to measure the form factors by a Projective Weighting Technique [citation: CLEO collaboration, Phys. Rev. D 81, 112001 (2010)].

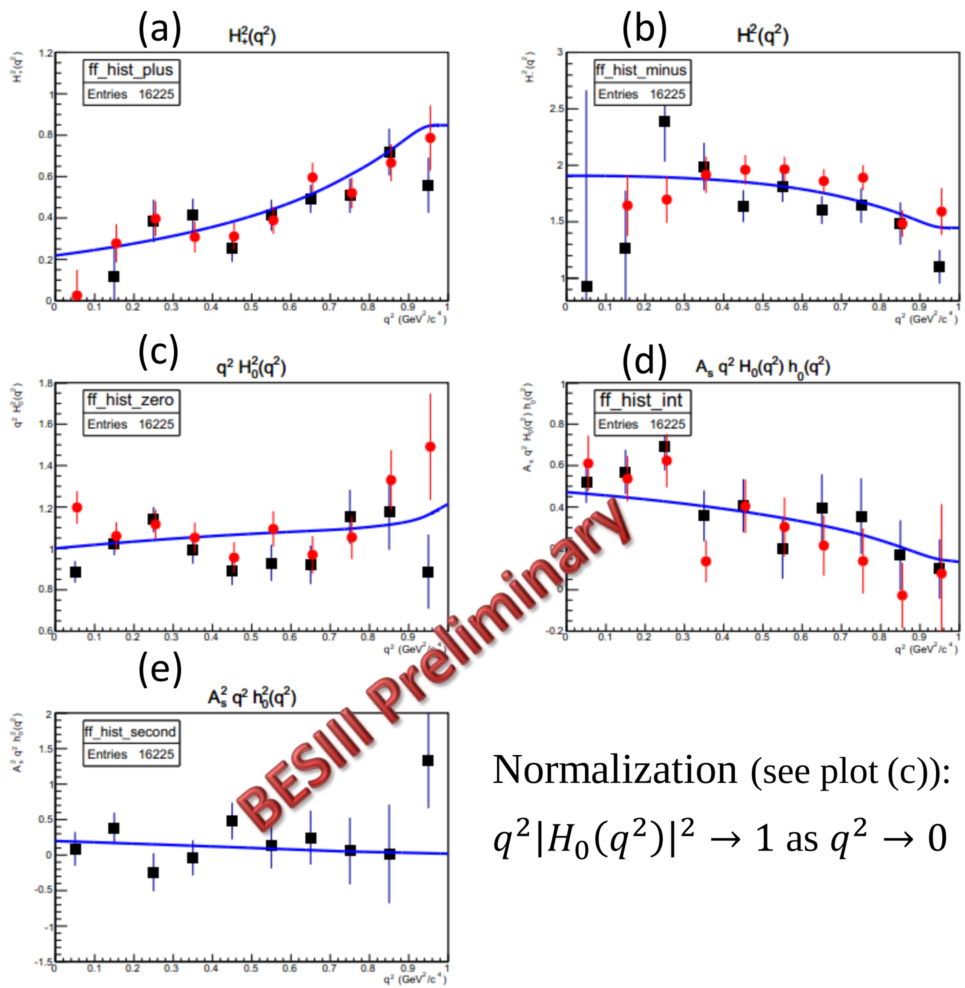
- Signal is assumed to be composed of $K^{*0}(892)$ and a non-resonant S-wave.

- Helicity basis form factors include:
  P-wave related: $H_{\pm,0}(q^2)$
  S-wave related: $h_0(q^2)$

- Five weighted q^2 histograms are built.
  Weight is assigned to each event based on $(q^2, cos\theta_K, cos\theta_e)$.

- Form factors are independently computed in each q^2 bin.

- The model-independent measurements are generally consistent with CLEO's report and the predicted trend based on the SPD model from amplitude analysis.



Normalization (see plot (c)):

$q^2|H_0(q^2)|^2 \to 1$ as $q^2 \to 0$

Red dots : BESIII model-independent measurement
Black dots : CLEO model-independent measurement
Blue Line : BESIII result from amplitude analysis, which is based on SPD model and mass-dependent S-wave

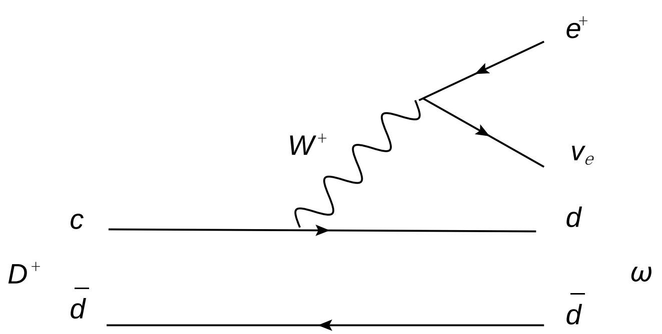
Notice: The lines are not simple fits of these dots!

Study of $D^+ \to \omega(\phi) e^+ \upsilon_e$

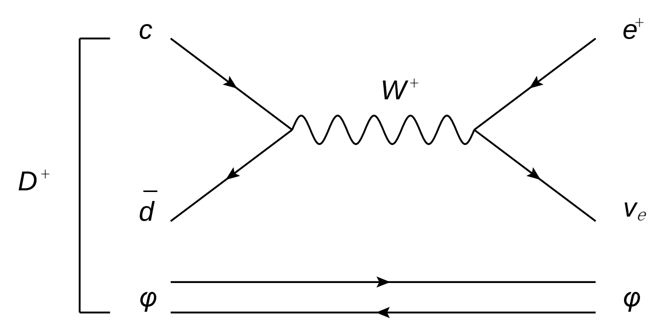
- Current status of $D^+ \to \omega(\phi) e^+ \upsilon_e$

D^+ Decay Modes	Fraction	Confidence level
$D^+ \to \omega e^+ \nu_e$	$(1.82 \pm 0.18 \pm 0.07) \times 10^{-3}$	
$D^+ \to \phi e^+ \nu_e$	$< 9.0 \times 10^{-5}$	CL=90%

- Form factors of $D^+ \to \omega e^+ \upsilon_e$ have never been measured before
- No significant excess of $D^+ \to \phi e^+ \upsilon_e$ is observed
- $D^+ \to \phi e^+ \upsilon_e$ decay proceeds only through $\omega - \phi$ mixing or non-perturbative "Weak Annihilation" (WA) process (see Fig (b)). Measurement of its branching ratio can help to judge the dominant process.



(a) Feynman diagram representing the charged current process $D^+ \to \omega e^+ \upsilon_e$



(b) Feynman diagram representing the WA process $D^+ \to \phi e^+ \upsilon_e$

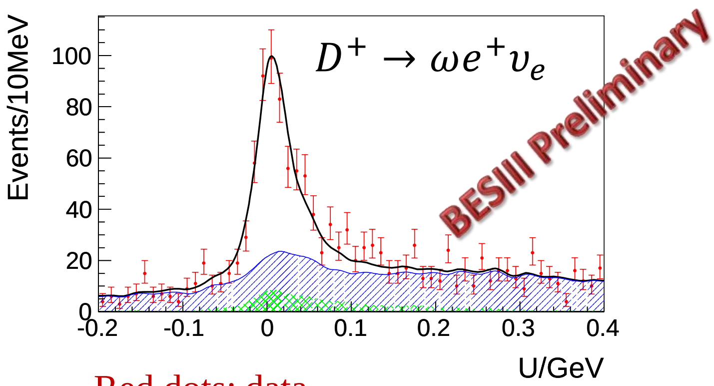
Branching Fraction

- Semileptonic decays are identified using the variable U:

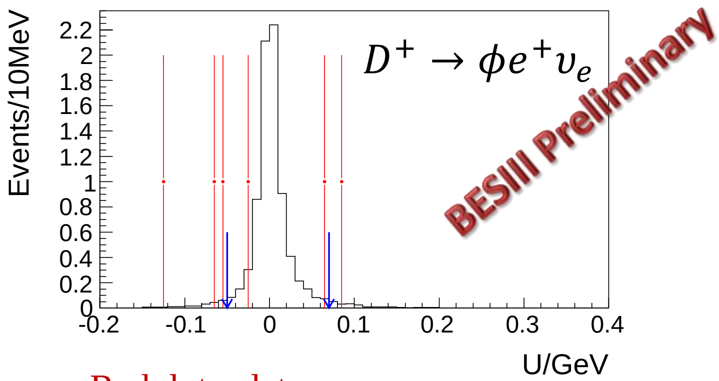
$$U = E_{miss} - |\vec{p}_{miss}|, \quad E_{miss} = E_{beam} - E_{\omega(\phi)} - E_e$$

$$\vec{P}_{miss} = -\overrightarrow{P'}_{tag} - \vec{P}_{\omega(\phi)} - \vec{P}_e\ , \qquad \overrightarrow{P'}_{tag} = \vec{P}_{tag}\sqrt{E_{beam}^2 - m_D^2}$$

- U distribution for the $D^+ \to \omega(\phi)e^+\upsilon_e$ decay:



Red dots: data
Black line: fit result
Blue area: total background
Green area: peaking background



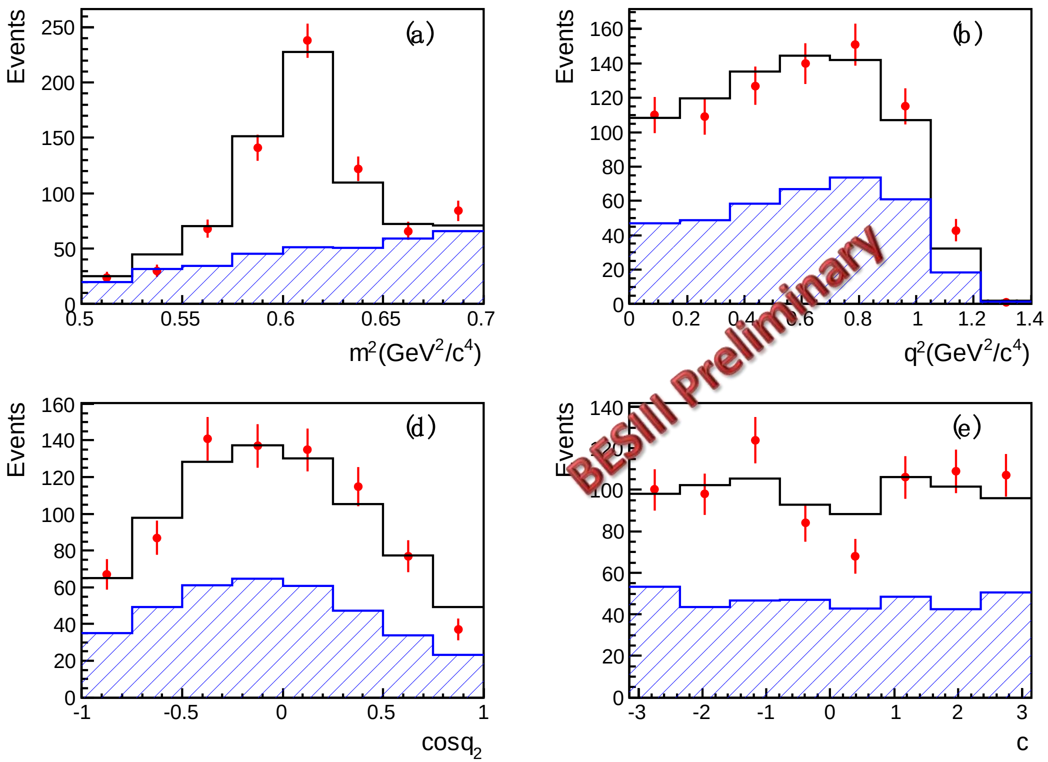
Red dots: data
Black histogram: signal MC simulation
Arrows: signal region

- Branching fractions are compared with the world average value [citation: Particle Data Group, Chin. Phys. C, 527 38, 090001 (2014)].

Mode	This work	Previous
$\omega e^+ \nu_e$	$(1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$	$(1.82 \pm 0.18 \pm 0.07) \times 10^{-3}$
$\phi e^+ \nu_e$	$< 1.3 \times 10^{-5}$ $(@90\%C.L.)$	$< 9.0 \times 10^{-5}$ $(@90\%C.L.)$

Form Factors in $D^+ \to \omega e^+ \upsilon_e$

Form factors for $D^+ \to \omega e^+ \upsilon_e$ decay can be parameterized similarly as in the $D^+ \to K^- \pi^+ e^+ \upsilon_e$ decay. The projections and the form factor parameters are shown below:



Red dots: data

Black Line: fit results

Blue area: Background

$$r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$$

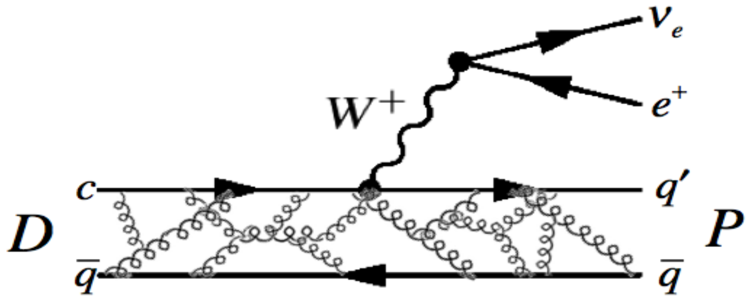
$$r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$$

Study of $D^+ \to K_L e^+ \upsilon_e$ (first measurement)

- Branching fraction of $D^+ \to K_L e^+ \upsilon_e$ has never been measured before

- $K^0 - \bar{K}^0$mixing is expected to give rise to CP asymmetry with magnitude of about -3.3$\times 10^{-3}$ in $D^+ \to K_L e^+ \nu_e$ decay [citation: Z.Z.Xing, Phys. Lett. B 353(1995)31; 363 (1995) 266]

- The differential decay width of $D^+ \to K_L e^+ \nu_e$ can be parameterized based on the transition form factor $f_+^K(q^2)$ and the CKM matrix element $|V_{cs}|$:



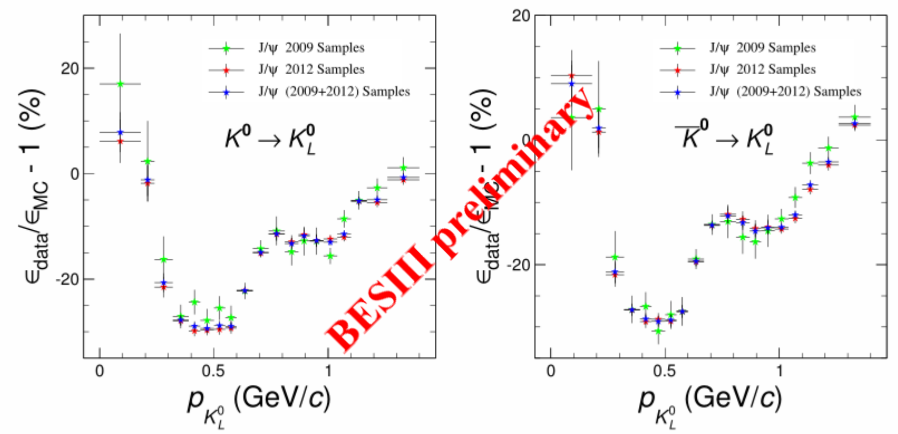
$$\frac{d\Gamma(D \to P e \nu)}{dq^2} = X \frac{G_F^2 |V_{cs(d)}|^2 p_{K(\pi)}^3}{24\pi^3} |f_+(q^2)|^2$$

For *P* = *K* case, *X* = 1

- Experimental study of $D^+ \to K_L e^+ \nu_e$ is important to test the theoretical prediction of $A_{CP}^{D^+ \to K_L e^+ \nu_e}$, the LQCD calculation on $f_+^K(0)$ and the unitarity of the CKM matrix.

Branching Fraction and $A_{CP}^{D^+ \to K_L e^+ \nu_e}$

- K_L reconstruction:
  - The direction of K_L momentum can be determined from the induced shower in EMC.
  - K_L momentum can be inferred by constraining the neutrino $U = 0$ (for U definition see page 12).
  - Because nuclear interaction is different for K^0 and $\bar{K}^0$, and $K^0 - \bar{K}^0$ coherent oscillation is not considered in simulation, reconstruction efficiencies are corrected separately for K_L from K^0 and $\bar{K}^0$



- Branching fraction:
  - Signal yields are obtained by fitting m_{BC} of the tag side (see next page).
  - In this analysis, branching fraction is calculated separately for each charm and tag mode using:

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}(1 - f_{\rm bkg}^{\rm peak})}{\epsilon N_{\rm ST}}$$

  - CP asymmetry is determined using:

$$A_{CP} \equiv \frac{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) - \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) + \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}$$

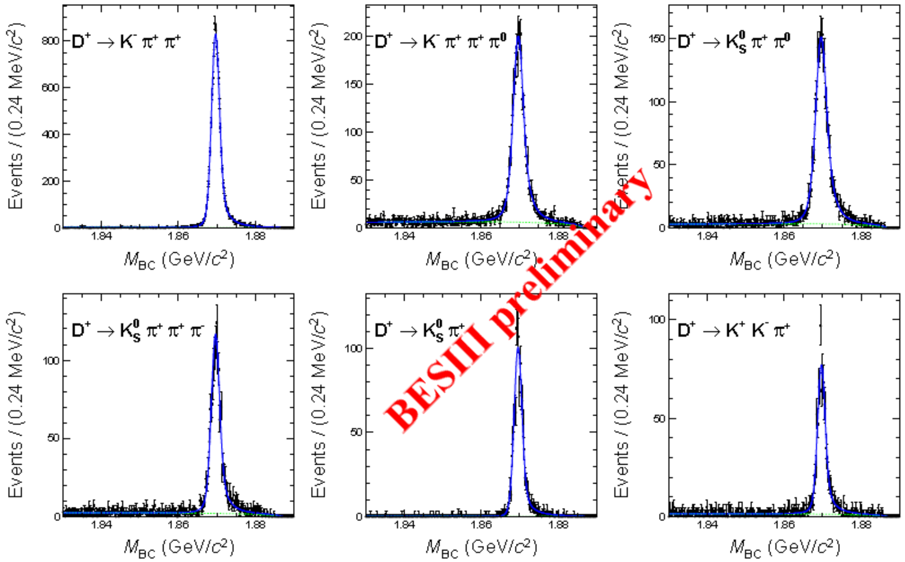
$D^+ \to K_L^0 e^+ \nu_e$					
Tag Mode	$N_{\rm ST}$	$N_{\rm DT}$	$f_{\rm bkg}^{\rm peak}(\%)$	$\epsilon(\%)$	$\mathcal{B}_{\rm sig}(\%)$
$D^- \to K^+\pi^-\pi^-$	410200 ± 670	10492 ± 103	41.83 ± 0.28	33.96 ± 0.10	4.381 ± 0.050
$D^- \to K^+\pi^-\pi^-\pi^0$	120060 ± 457	3324 ± 64	44.78 ± 0.49	33.14 ± 0.19	4.613 ± 0.103
$D^- \to K_S^0\pi^-\pi^0$	102136 ± 378	2658 ± 56	38.93 ± 0.58	35.67 ± 0.21	4.456 ± 0.108
$D^- \to K_S^0\pi^-\pi^-\pi^+$	59158 ± 303	1459 ± 41	40.84 ± 0.76	32.51 ± 0.27	4.488 ± 0.145
$D^- \to K_S^0\pi^-$	47921 ± 225	1287 ± 36	38.90 ± 0.88	35.07 ± 0.32	4.679 ± 0.155
$D^- \to K^+K^-\pi^-$	35349 ± 239	905 ± 32	44.64 ± 0.97	30.98 ± 0.35	4.575 ± 0.190
Averaged					4.455 ± 0.038

$D^- \to K_L^0 e^- \bar{\nu}_e$					
Tag Mode	$N_{\rm ST}$	$N_{\rm DT}$	$f_{\rm bkg}^{\rm peak}(\%)$	$\epsilon(\%)$	$\mathcal{B}_{\rm sig}(\%)$
$D^+ \to K^-\pi^+\pi^+$	407666 ± 668	10354 ± 103	40.44 ± 0.29	34.02 ± 0.11	4.447 ± 0.051
$D^+ \to K^-\pi^+\pi^+\pi^0$	117555 ± 450	3264 ± 63	42.28 ± 0.52	33.19 ± 0.19	4.829 ± 0.107
$D^+ \to K_S^0\pi^+\pi^0$	101824 ± 378	2642 ± 55	39.06 ± 0.58	35.92 ± 0.21	4.402 ± 0.104
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	59046 ± 303	1533 ± 42	39.68 ± 0.77	33.44 ± 0.27	4.683 ± 0.147
$D^+ \to K_S^0\pi^+$	48240 ± 226	1217 ± 35	38.50 ± 0.88	35.20 ± 0.32	4.408 ± 0.147
$D^+ \to K^+K^-\pi^+$	35742 ± 240	942 ± 32	44.04 ± 0.95	32.40 ± 0.36	4.552 ± 0.181
Averaged					4.508 ± 0.038

Branching Fraction and $A_{CP}^{D^+\to K_L e^+\nu_e}$

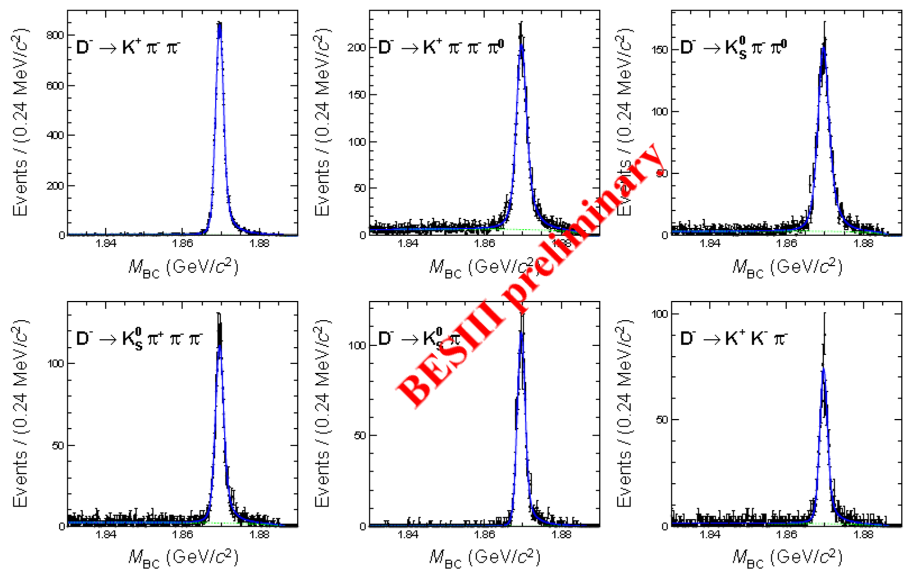
The fraction of peaking backgrounds are estimated by MC.

Black dots: data;
Blue: Fit result;
Green Line: combinatorial background



Branching fraction:
$\bar{\mathcal{B}}(D^+\to K_L e^+\nu_e) = (4.482 \pm 0.027 \pm 0.103)\%$

CP asymmetry:
$A_{CP}^{D^+\to K_L e^+\nu_e} = (-0.59 \pm 0.60 \pm 1.50)\%$



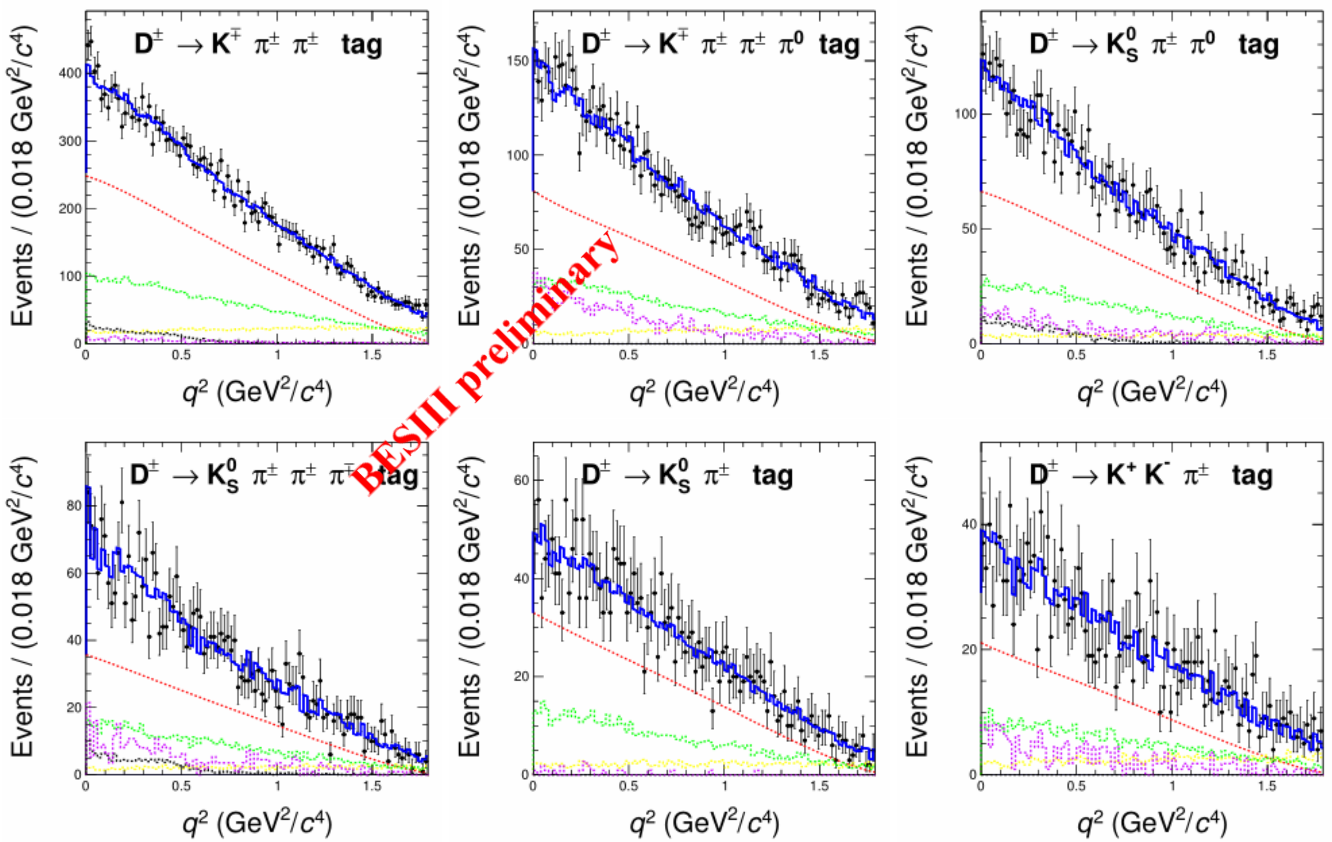
Form Factor measurement

Signal shape of q^2 distribution can be described using $\frac{dn_{\rm observed}}{dq^2} = AN_{\rm tag}p^3(q'^2)|f_+(q'^2)|^2\epsilon(q'^2)\otimes\sigma(q'^2,q^2)$

2-par. Series Expansion is performed for form factor $f_+(q^2)$: $f_+(q^2)=\frac{1}{P(q^2)\phi(q^2,t_0)}\sum_{k=0}^{\infty}a_k(t_0)\left[z(q^2,t_0)\right]^k$

[cite: Becher and Hill, Phys. Lett. B 633, 61 (2006)]

Simultaneous fits are performed:



$f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$, $r_1 \equiv a_1/a_0 = 1.91 \pm 0.33 \pm 0.24$

Summary

- In the study of $D^+ \to K^-\pi^+e^+\upsilon_e$:
  - Branching fractions are measured:

    $\mathrm{Br}(D^+ \to K^-\pi^+e^+\nu_e) = (3.71 \pm 0.03 \pm 0.09)\%$

    $\mathrm{Br}(D^+ \to K^-\pi^+e^+\nu_e)_{[0.8,1]} = (3.33 \pm 0.03 \pm 0.08)\%$
  - Amplitude analysis is applied:
    - Fractions of the $K\pi$ components are analyzed. S-wave contribution is observed to be $(6.05 \pm 0.22 \pm 0.18)\%$.
    - $K^{*0}(892)$ properties and the form factors based on the SPD model are provided.
  - Model-independent measurement of S-wave phase and the $K^{*0}(892)$ helicity basis form factors are performed. They are generally consistent with previous reports and the amplitude analysis results.

- In the study of $D^+ \to \omega(\phi)e^+\upsilon_e$:
  - Branching fractions or upper limits are provided:

    $\mathrm{Br}(D^+ \to \omega e^+\nu_e) = (1.63 \pm 0.11 \pm 0.08) \times 10^{-3}$

    $\mathrm{Br}(D^+ \to \phi e^+\nu_e) < 1.3 \times 10^{-5}$ (@90% C.L.)
  - Form factor parameters in $D^+ \to \omega e^+\upsilon_e$ are first measured:

    $r_V = V(0)/A_1(0) = 1.24 \pm 0.09 \pm 0.06$; $r_2 = A_2(0)/A_1(0) = 1.06 \pm 0.15 \pm 0.05$

- In the study of $D^+ \to K_L e^+\upsilon_e$:
  - Branching fractions and CP assymetry are measured:

    $\bar{B}(D^+ \to K_L e^+\nu_e) = (4.482 \pm 0.027 \pm 0.103)\%$, $A_{CP}^{D^+\to K_L e^+\nu_e} = (-0.59 \pm 0.60 \pm 1.50)$
  - Form factor related parameters are also measured:

    $f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$, $r_1 \equiv a_1/a_0 = 1.91 \pm 0.33 \pm 0.24$

Backup

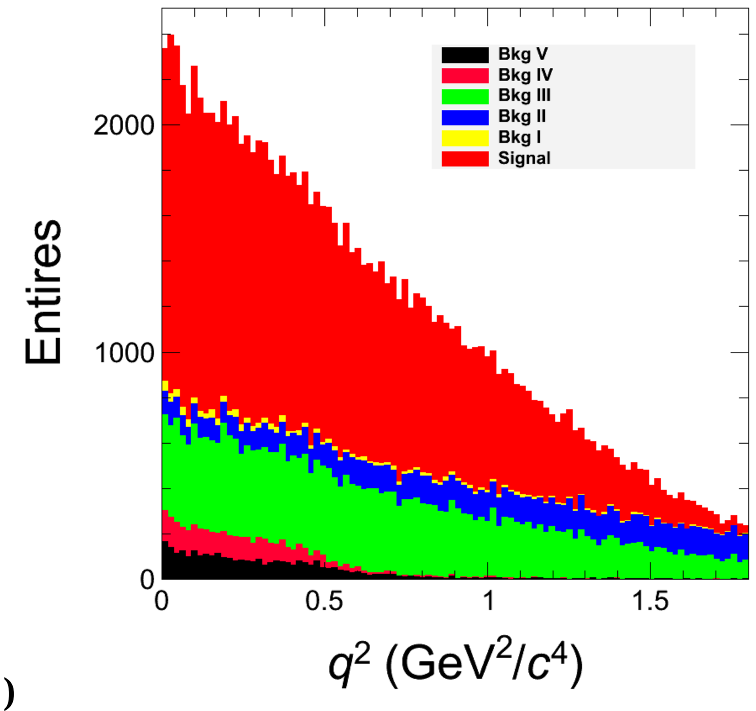
Estimation of Backgrounds in the Double Tag

By using MC-truth information of the K_L efficiency corrected $D\bar{D}$ MC samples, the double-tag D candidates can be divided into the following categories:

- **Signal: tag-side matched and signal-side matched signal events**
- **Background:**

- **Bkg I: $D\bar{D}$ decays of which hadronic tag D is mis-reconstructed and non-$D\bar{D}$ processes. Its proportion varies from 1% to 12% according to the specific hadronic tag mode**
- **Bkg II: (~10%) $D^+ \to K_L e^+ \nu_e$ events of which K_L shower is mis-reconstructed.**
- **Bkg III: $D^+ \to X e \upsilon_e$ non-signal events (~24%), which are from $D^+ \to \bar{K}^*(892)^0 e^+ \upsilon_e$ (41.9%), $D^+ \to K_S e^+ \upsilon_e$ (41.2%), $D^+ \to \pi^0 e^+ \upsilon_e$ (10.2%), $D^+ \to \eta e^+ \upsilon_e$(6.0%) and $D^+ \to \omega e^+ \upsilon_e$ (0.7%)**
- **Bkg IV: $D^+ \to X \mu \upsilon_\mu$ events (~3%), consist of $D^+ \to K_L \mu^+ \upsilon_\mu$ (65.2%), $D^+ \to \bar{K}^*(892)^0 \mu^+ \upsilon_\mu$ (23.3%) and $D^+ \to K_S \mu^+ \upsilon_\mu$ (11.5%)**
- **Bkg V: Non-leptonic D decay events (~3%), which are from $D^+ \to \bar{K}^0 \pi^+ \pi^0$ (78%) and $D^+ \to \bar{K}^0 K^*(892)^+$ (22%)**

Composition of double-tag D candidates



In the determination of $B(D^+ \to K_L e^+ \nu_e)$, the peaking backgrounds consist of Bkg II~Bkg V. This estimation brings in 1.6% systematic uncertainty.