

$|V_{cs}|$, $f_+^K(0)$ and $f_{D_S^+}$ measurements in $D_{(s)}^+$
and Lepton universality test in $D \rightarrow \pi l \nu$
at BESIII

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Outline

➤ Introduction

➤ Pure leptonic decay: $D_s^+ \rightarrow \mu^+ \nu_\mu$

➤ Semi-leptonic decay: $D \rightarrow K(\pi)l^+ \nu_l$

$$D^{0(+)} \rightarrow \pi^{-(0)} \mu^+ \nu_\mu$$

$$D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu$$

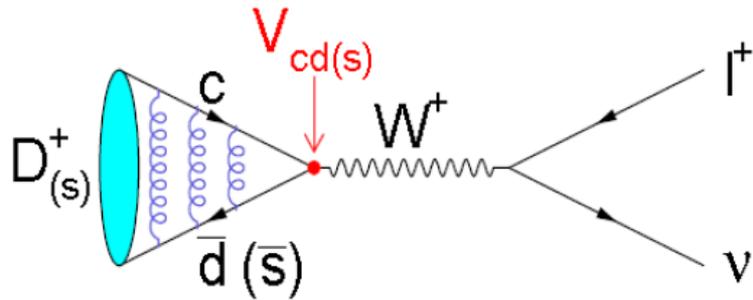
$$D^+ \rightarrow \bar{K}^0 e^+ \nu_e; \pi^0 e^+ \nu_e$$

$$D_s^+ \rightarrow K^0 e^+ \nu_e; K^{*0} e^+ \nu_e$$

➤ Summary

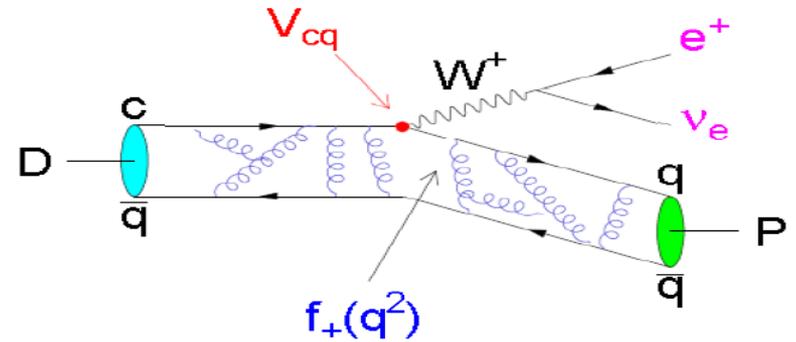
Main goals

$D_{(s)}$ pure leptonic decay



$$\Gamma(D_{(s)}^+ \rightarrow l^+ \nu_l) \propto |f_{D_{(s)}^+}|^2 \cdot |V_{cd(s)}|^2$$

$D_{(s)}$ semi-leptonic decay

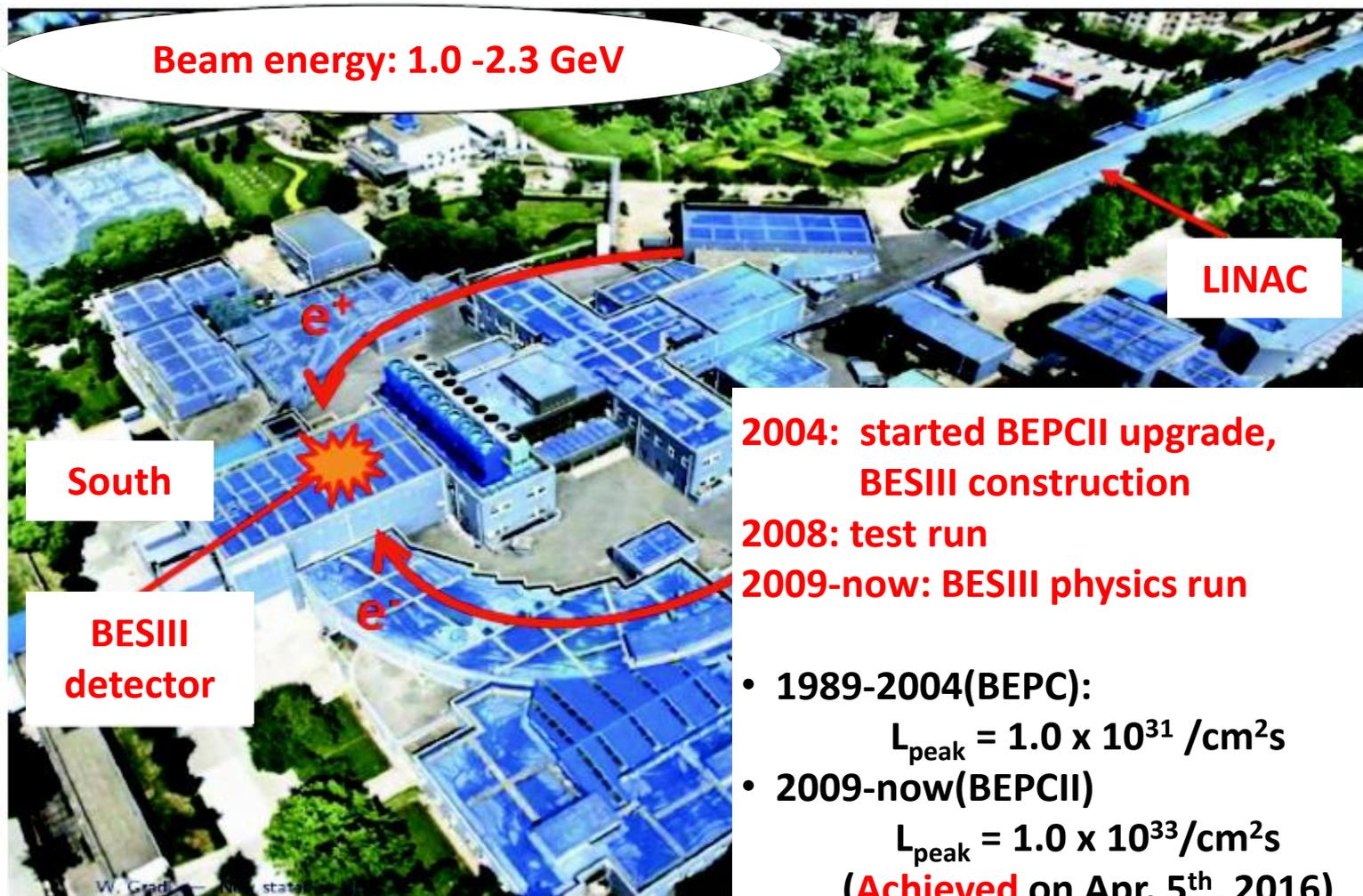


$$\Gamma(D_s^+ \rightarrow P l^+ \nu_l) \propto |f_+^{K(\pi)}(q^2)|^2 \cdot |V_{cd(s)}|^2$$

- ❖ Decay constant $f_{D_s^+}$, form factor $f_+^K(0)$: better calibrate Lattice QCD;
- ❖ CKM matrix element $|V_{cs}|$: better test the unitarity of the CKM matrix;
- ❖ Lepton universality test.

Beijing Electron Positron Collider (BEPCII) in China

A double-ring collider with high luminosity



2004: started BEPCII upgrade,
BESIII construction

2008: test run

2009-now: BESIII physics run

- 1989-2004(BEPC):

$$L_{\text{peak}} = 1.0 \times 10^{31} / \text{cm}^2\text{s}$$

- 2009-now(BEPCII)

$$L_{\text{peak}} = 1.0 \times 10^{33} / \text{cm}^2\text{s}$$

(**Achieved** on Apr. 5th, 2016)

BESIII detector

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

From inner to outside:

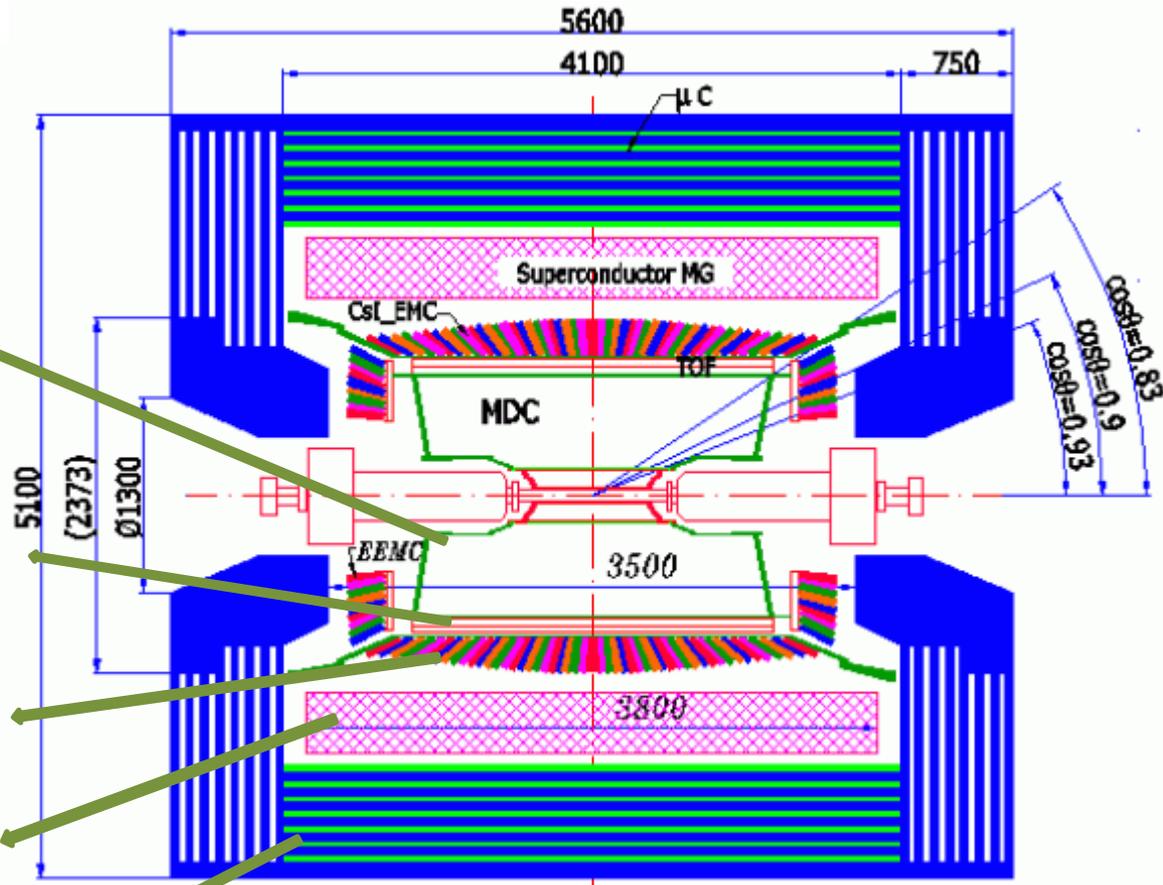
MDC: small cell & Gas:He/C₃H₈(60/40), 43 layers; $\sigma_{xy} = 130 \mu\text{m}$; $\sigma_p/p = 0.5\%$ @1 GeV; $dE/dx = 6\%$

TOF: $\sigma_T = 100$ ps Barrel, 110 ps Endcap

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

Magnet: 1T Super conducting

MUC: 9 layers RPC, 8 layers for endcaps



Data Acquisition:
Event rate = 4k Hz
Total data volume ~ 50 MB/s

$D^{0(+)}$ and D_s^+ data set at BESIII

➤ $D^{0(+)}$ data:

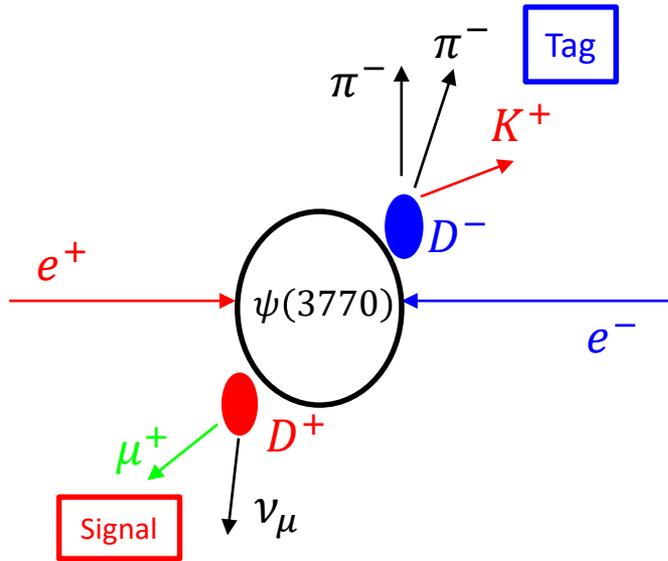
- Taken @ $E_{cm} = 3.773 \text{ GeV}$.
- Integrated luminosity = 2.93 fb^{-1}
(The **world's largest** e^+e^- annihilation sample taken at the mass-threshold).
- cross section: $\sigma(e^+e^- \rightarrow D^0\bar{D}^0) \sim 3.6 \text{ nb} \Rightarrow 21 \text{ M } D^0 \text{ produced!}$
- cross section: $\sigma(e^+e^- \rightarrow D^+D^-) \sim 2.9 \text{ nb} \Rightarrow 16 \text{ M } D^+ \text{ produced!}$

➤ D_s^+ data:

- @ $E_{cm} = 4.178 \text{ GeV}$.
 - Based on the data accumulated in 2016!
 - Integrated luminosity = 3.19 fb^{-1}
 - $\sigma(e^+e^- \rightarrow D_s^* D_s) \sim 1 \text{ nb} \Rightarrow \sim 6 \text{ M } D_s \text{ produced!!}$

Tagging method

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

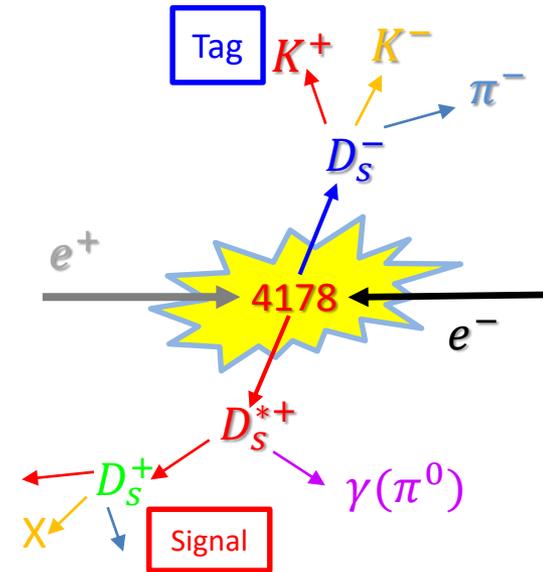


Charge conjugated processes are implied

The **signal** branching fraction:

$$B_{sig} = \frac{N_{sig}}{N_{D(s)}^{tag} \times \epsilon}$$

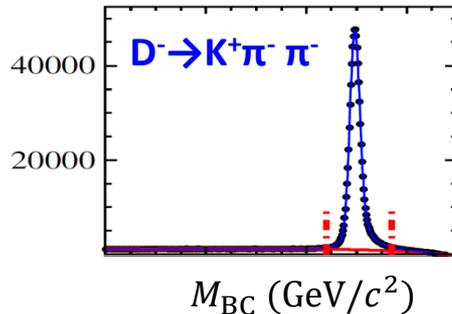
$e^+ e^- \rightarrow D_s^{*+} D_s^-$
 $3.19 \text{ fb}^{-1} @ 4.178 \text{ GeV}$



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

$$\Delta E = E_{D^-} - E_{beam}$$

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



For Signal side (reconstruct μ^+):

$$E_{miss} = E_{beam} - E_{\mu^+}$$

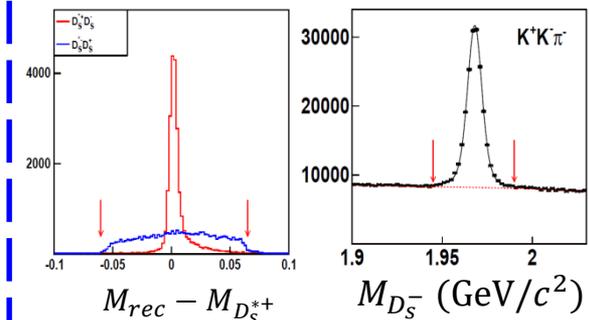
$$\vec{p}_{miss} = -\vec{p}_{D^-} - \vec{p}_{\mu^+}$$

$$M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}|^2$$

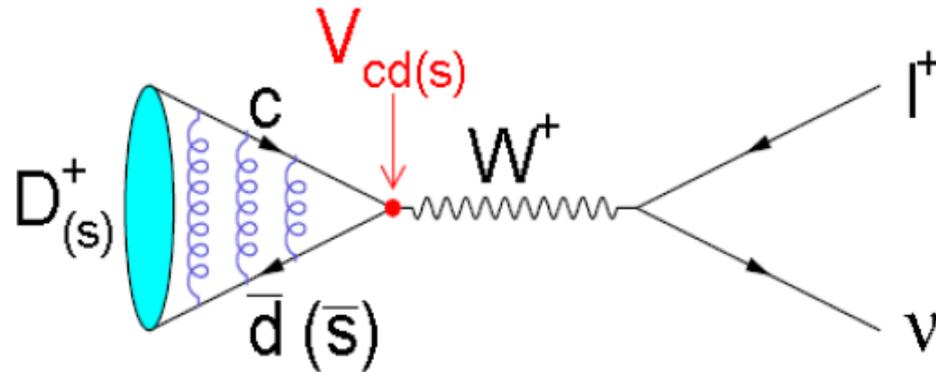
$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$

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

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



D_s^+ pure leptonic decay



In the SM:
$$\Gamma(D_{(s)}^+ \rightarrow l^+ \nu) = \frac{G_F^2 f_{D_{(s)}^+}^2}{8\pi} |V_{cd(s)}|^2 m_l^2 m_{D_{(s)}^+} \left(1 - \frac{m_l^2}{m_{D_{(s)}^+}^2}\right)^2$$

Measure the product of $f_{D_s^+}$ and $|V_{cs}|$ directly

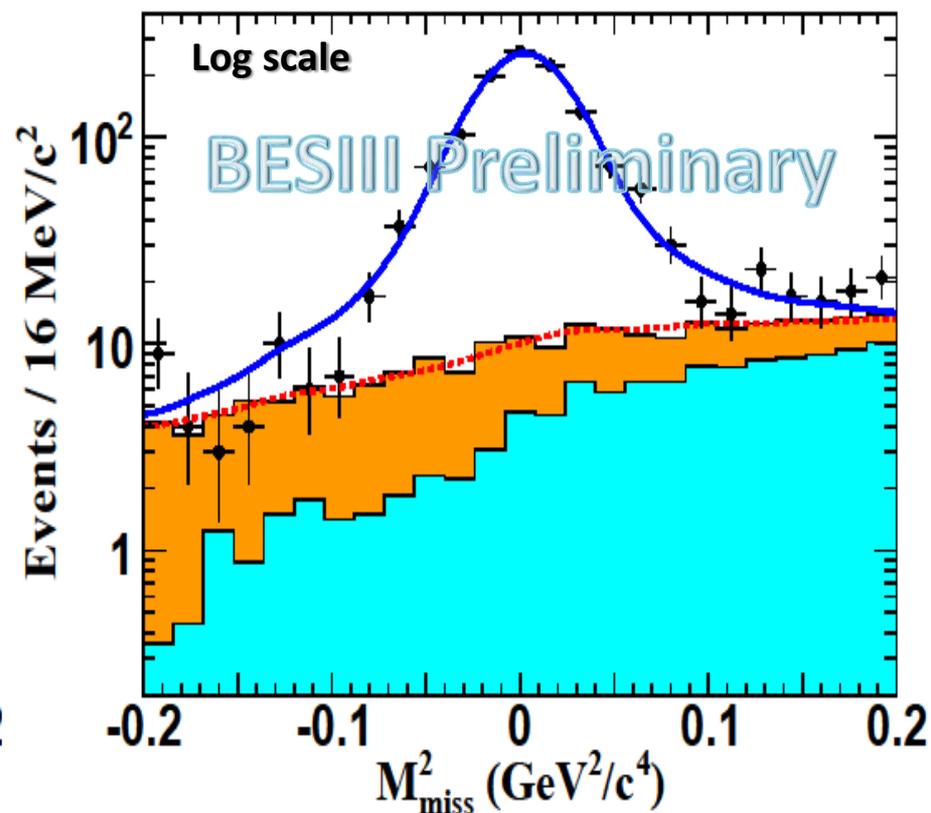
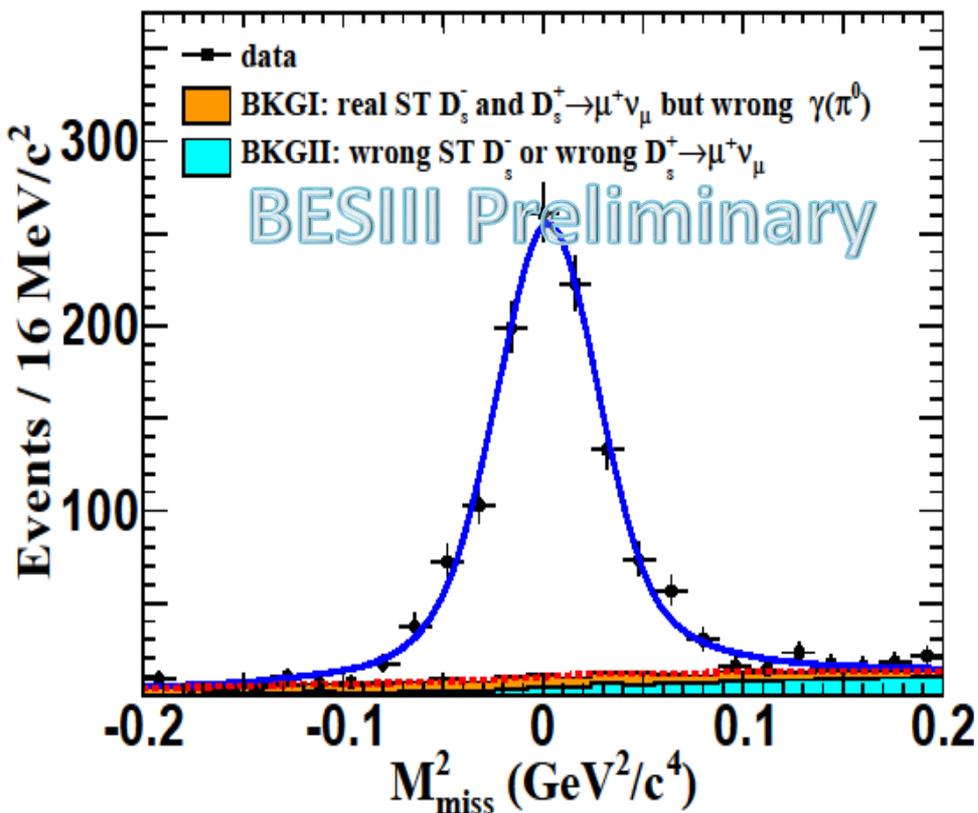
Bridge to precisely measure

- Decay constant $f_{D_s^+}$ with input $|V_{cs}|^{\text{CKMfitter}}$
- CKM matrix element $|V_{cs}|$ with input $f_{D_s^+}^{\text{LQCD}}$

$D_s^+ \rightarrow \mu^+ \nu_\mu$

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

NEW result based on the 4178 MeV data!



• M_{miss}^2 fit:

1. Constraining signal/BKGI ratio via signal MC
2. Fixing BKGII via inclusive MC

$$N(D_s^+ \rightarrow \mu^+ \nu) = 1135.0 \pm 33.1$$

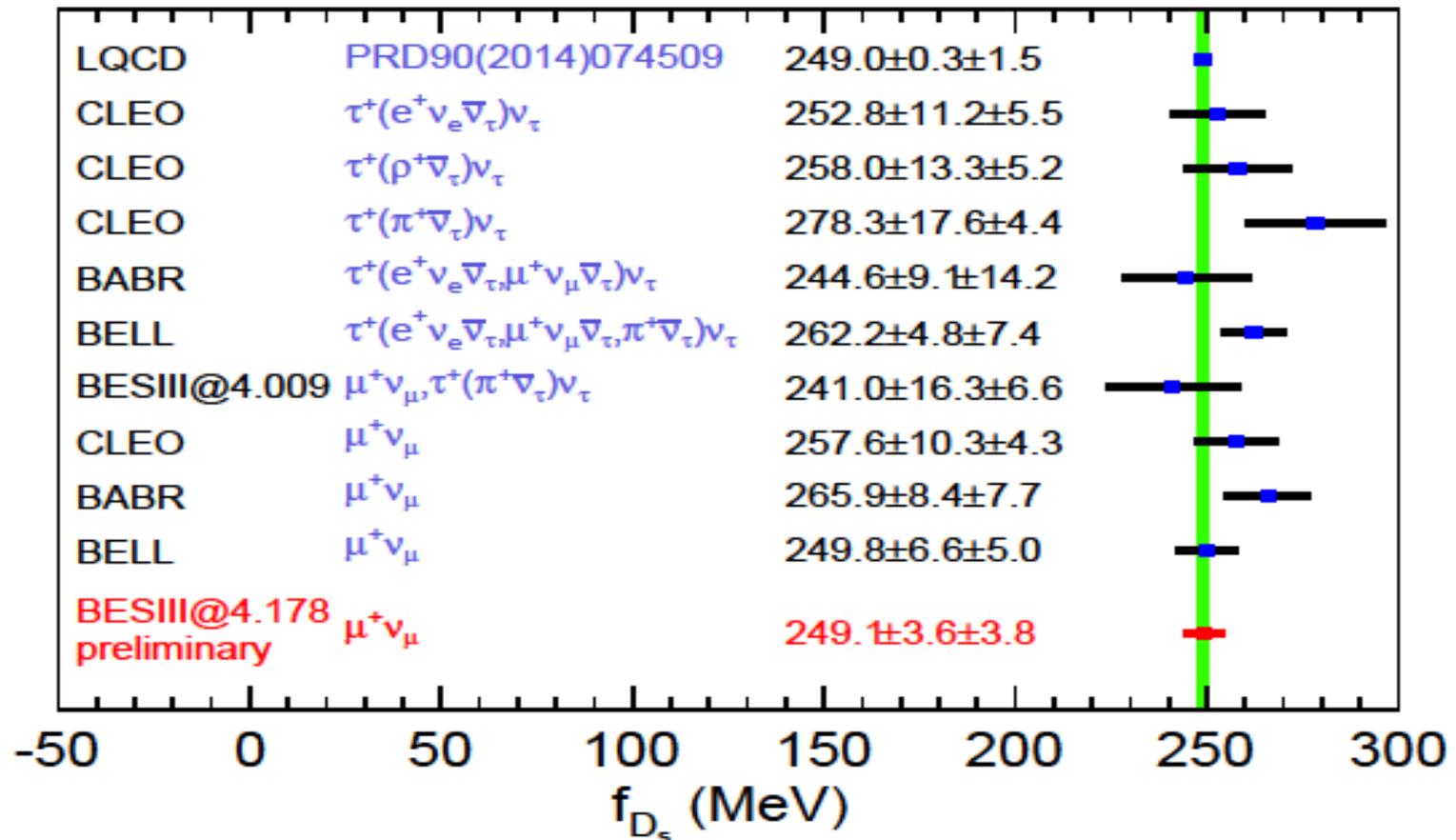
$$B(D_s^+ \rightarrow \mu^+ \nu) = (5.28 \pm 0.15 \pm 0.14) \times 10^{-3}$$

Comparison of $f_{D_s^+}$

$$f_{D_s^+} |V_{cs}| = 242.5 \pm 3.5_{\text{stat.}} \pm 3.7_{\text{syst.}} \text{ MeV}$$

- Taking $|V_{cs}|^{\text{CKMfitter}}$ as input, we obtain

$$f_{D_s^+} = 249.1 \pm 3.6_{\text{stat.}} \pm 3.8_{\text{syst.}} \text{ MeV}$$

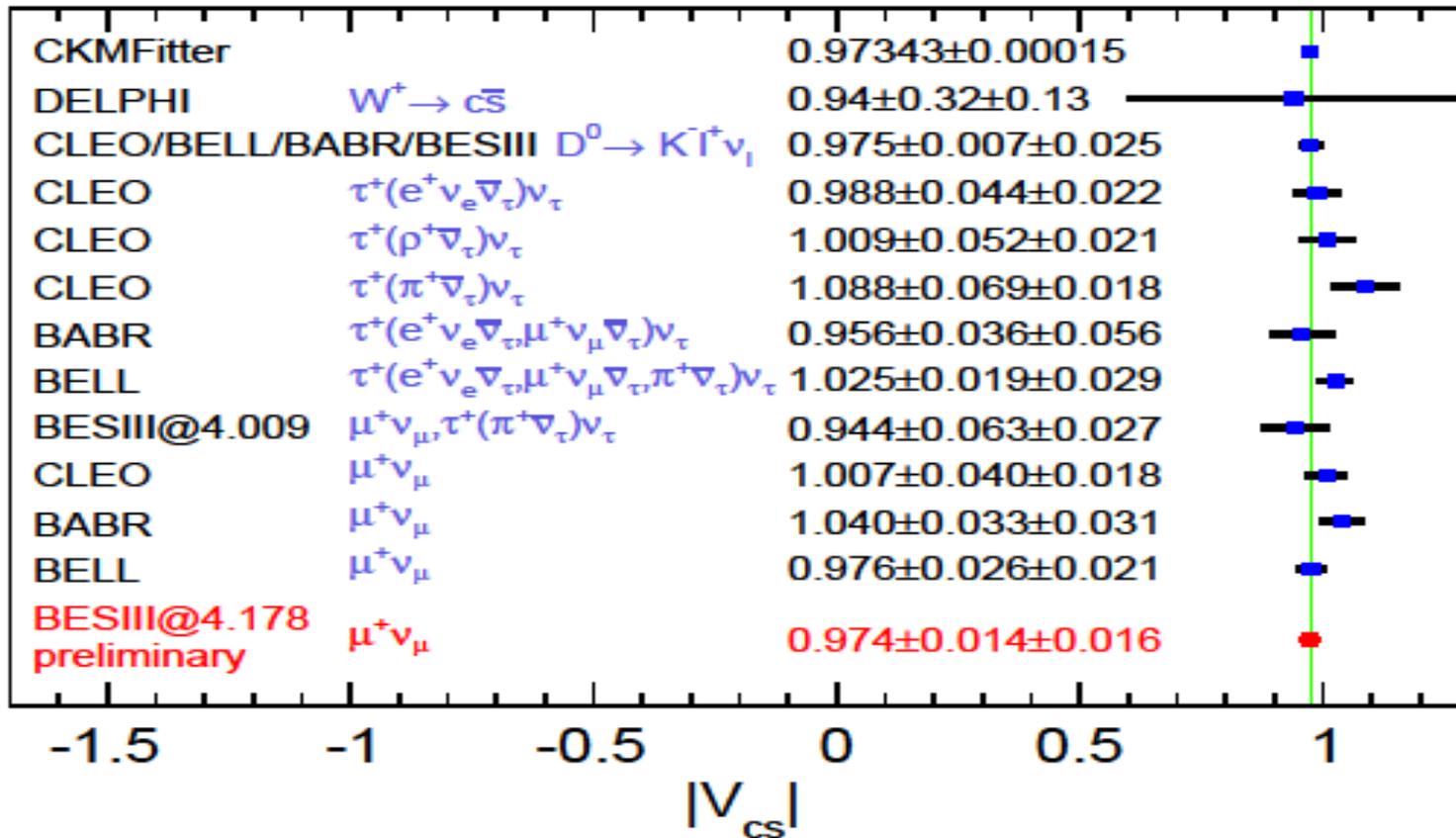


Comparison of $|V_{cs}|$

$$f_{D_s^+} |V_{cs}| = 242.5 \pm 3.5_{\text{stat.}} \pm 3.7_{\text{syst.}} \text{ MeV}$$

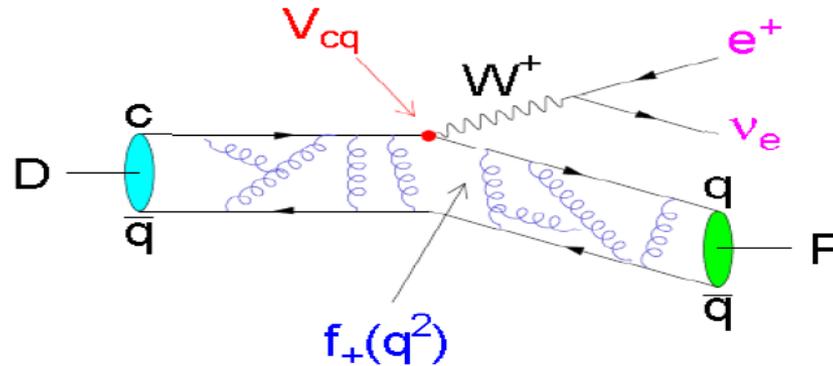
- Taking $f_{D_s^+}^{\text{LQCD}}[\text{PRD } 90(2014)074509]$ as input, we obtain

$$|V_{cs}| = 0.974 \pm 0.014_{\text{stat.}} \pm 0.016_{\text{syst.}}$$



$D_{(s)}$ semi-leptonic decay

$D \rightarrow P e^+ \nu$ ($P=K, \pi$)



Differential rates: $\frac{d\Gamma}{dq^2} = X \frac{G_F^2 p^3}{24\pi^3} |f_+(q^2)|^2 |V_{cd(s)}|^2$ ($X = 1$ for K^-, π^-, \bar{K}^0 ; $X = \frac{1}{2}$ for π^0)

Bridge to precisely measure

- **Form factor $f_+^{D \rightarrow K}(0)$ with input $|V_{cs}|$ CKMfitter**

-- Single pole model

$$f_+(q^2) = \frac{f_+(0)}{1 - q^2/M_{pole}^2}$$

-- ISGW2 model

$$f_+(q^2) = f_+(q_{max}^2) \left(1 + \frac{r^2}{12} (q_{max}^2 - q^2) \right)^{-2}$$

-- Modified pole model

$$f_+(q^2) = \frac{f_+(0)}{\left(1 - \frac{q^2}{M_{pole}^2}\right) \left(1 - \alpha \frac{q^2}{M_{pole}^2}\right)}$$

-- Series expansion

$$f_+(t) = \frac{1}{P(t)\Phi(t, t_0)} a_0(t_0) \left(1 + \sum_{k=1}^{\infty} r_k(t_0) [z(t, t_0)]^k \right)$$

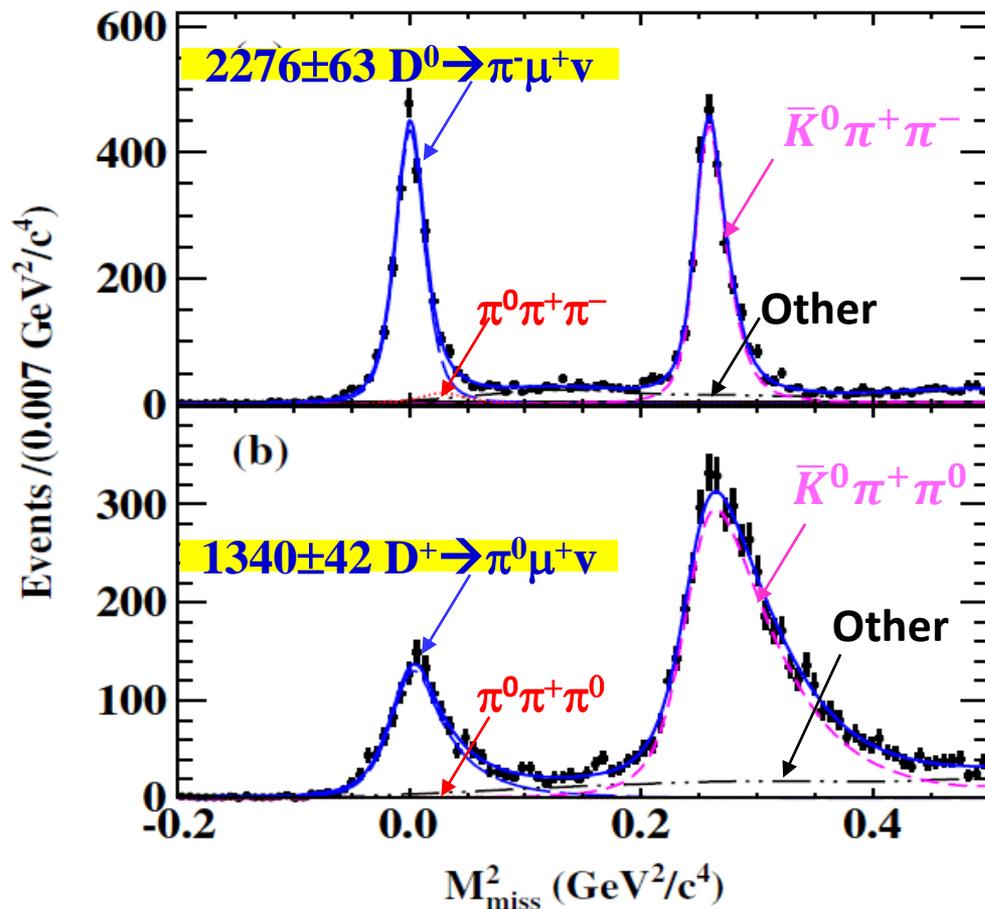
- **CKM matrix element $|V_{cs}|$ with input $f_+^{LQCD, D \rightarrow K}(0)$**

$D^{0(+)} \rightarrow \pi^{-(0)} \mu^+ \nu_\mu$

$e^+ e^- \rightarrow \psi(3770) \rightarrow D^+ D^-$

2.93 fb⁻¹ @3.773 GeV

arXiv:1802.05492 [hep-ex]



Lepton universality:

(Based on ZPC 46, 93 (1990); PRD 69, 074025 (2004); PLB 633, 61 (2006); PDG2016, the predicted value is 0.97)

Agree within

$$\frac{\Gamma(D^+ \rightarrow \pi^0 \mu^+ \nu_\mu)}{\Gamma(D^+ \rightarrow \pi^0 e^+ \nu_e)} = 0.942 \pm 0.037 \pm 0.027 \quad 0.6\sigma$$

$$\frac{\Gamma(D^0 \rightarrow \pi^- \mu^+ \nu_\mu)}{\Gamma(D^0 \rightarrow \pi^- e^+ \nu_e)} = 0.905 \pm 0.027 \pm 0.023 \quad 1.9\sigma$$

$B(D^{0(+)} \rightarrow \pi^{-(0)} e^+ \nu_e)$ is from BESIII

Isospin conversation:

(predicted value is 1)

Consistent within uncertainty

$$\frac{\Gamma(D^0 \rightarrow \pi^- \mu^+ \nu_\mu)}{2\Gamma(D^+ \rightarrow \pi^0 \mu^+ \nu_\mu)} = 0.990 \pm 0.041 \pm 0.035$$

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

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

$D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu$

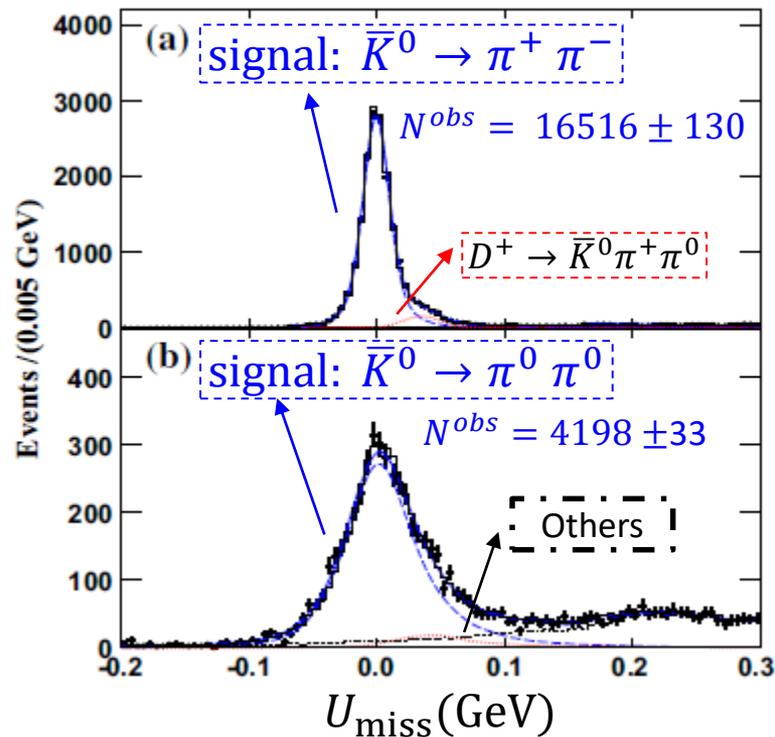
$e^+ e^- \rightarrow \psi(3770) \rightarrow D^+ D^-$

2.93 fb⁻¹ @3.773 GeV

EPJC 76, 369(2016)

Simultaneous fit: The double tag production yield has been constrained to be same for the two modes, which is corrected by the detector efficiency and daughter decay branching fractions:

$$N_{DT}^{\text{prd}} = 132712 \pm 1041$$



Lepton universality:

$$\frac{\Gamma(D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu)}{\Gamma(D^+ \rightarrow \bar{K}^0 e^+ \nu_e)} = 0.988 \pm 0.033 \quad \text{consistent}$$

$B(D^+ \rightarrow \bar{K}^0 e^+ \nu_e)$ is from PDG

Isospin conversation:

$B(D^+ \rightarrow K^- \mu^+ \nu_\mu)$ is from PDG

$$\frac{\Gamma(D^0 \rightarrow K^- \mu^+ \nu_\mu)}{\Gamma(D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu)} = 0.963 \pm 0.044 \quad \text{consistent}$$

$$B(D^+ \rightarrow \bar{K}^0 \mu^+ \nu) = (8.72 \pm 0.07 \pm 0.18)\%$$

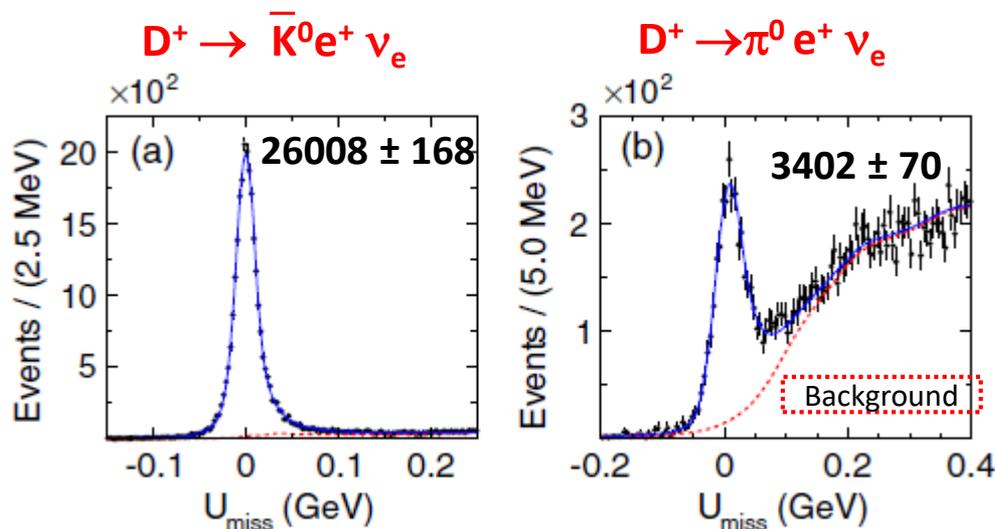
$D^+ \rightarrow \bar{K}^0(\pi^0)e^+\nu_e$

PRD 96, 012002 (2017)

$e^+ e^- \rightarrow \psi(3770) \rightarrow D^+ D^-$

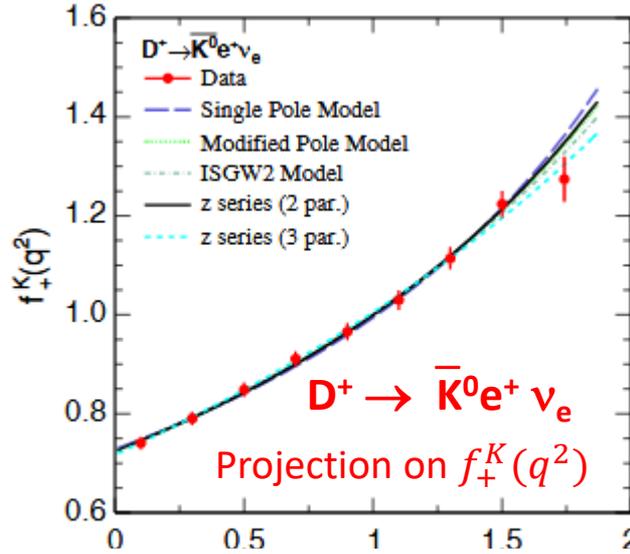
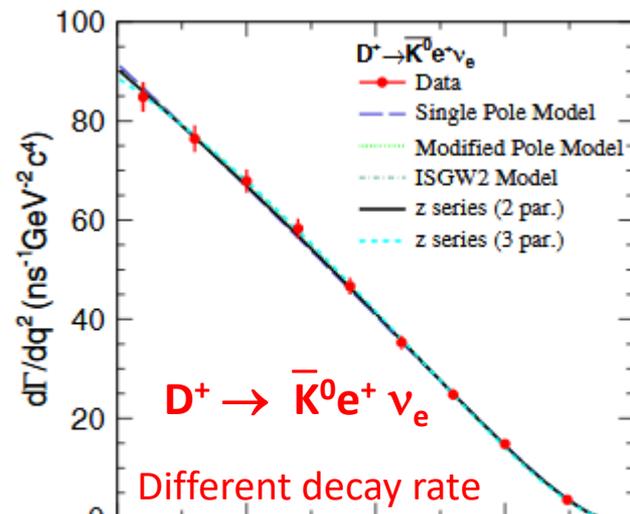
$2.93 \text{ fb}^{-1} @ 3.773 \text{ GeV}$

A binned extended maximum likelihood fit



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

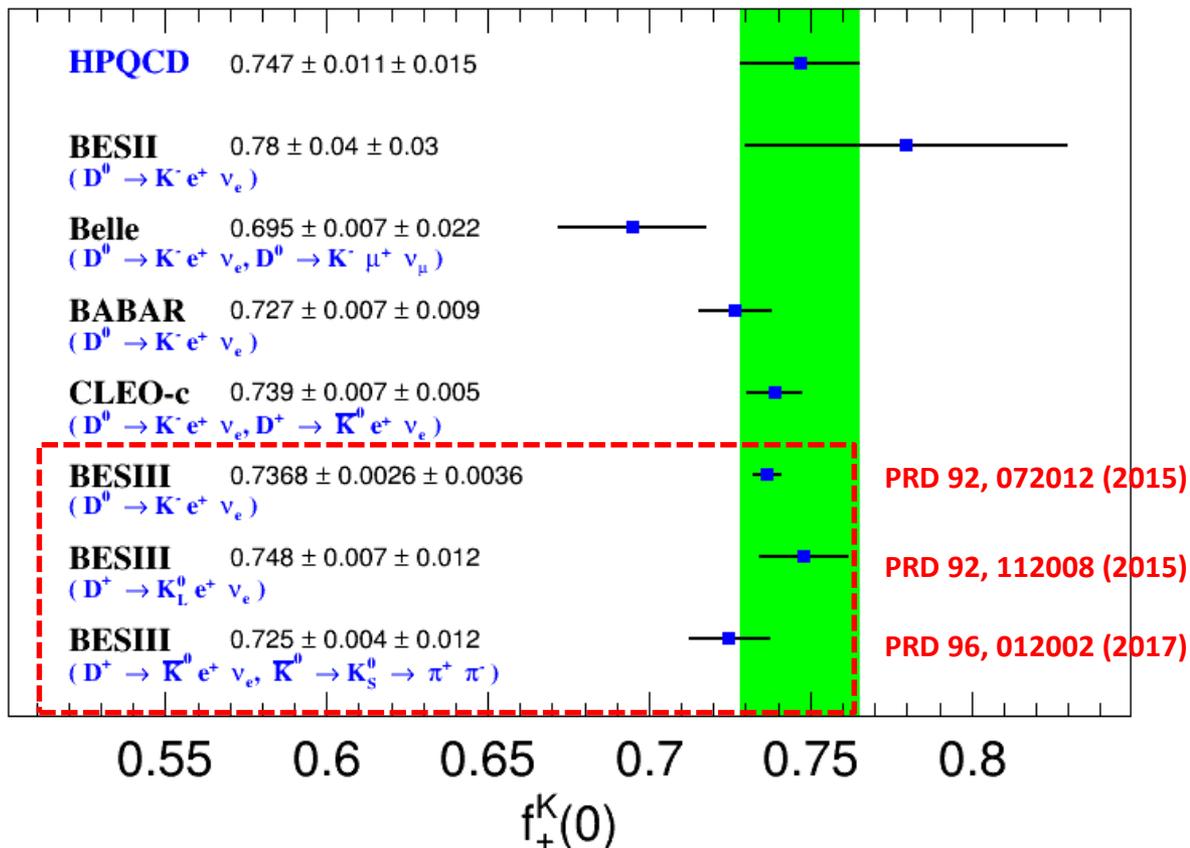
$$B(D^+ \rightarrow \pi^0 e^+ \nu_e) = (0.363 \pm 0.008 \pm 0.005)\%$$



$$q^2 = (E_{e^+} + E_{\nu_e})^2/c^4 - (\vec{p}_{e^+} + \vec{p}_{\nu_e})^2/c^2$$

Comparisons of $f_+^K(0)$ for $D \rightarrow K e^+ \nu_e$

BESIII: more precise; consistent with others.

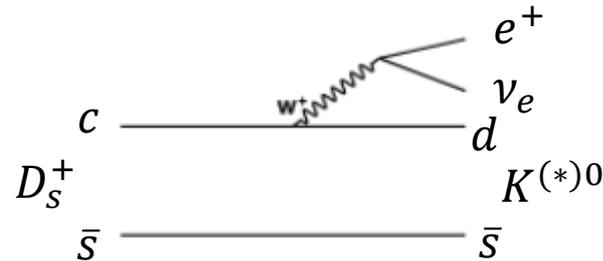


$$D_s^+ \rightarrow K^{(*)0} e^+ \nu_e$$

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

NEW result based on the 4178 MeV data!

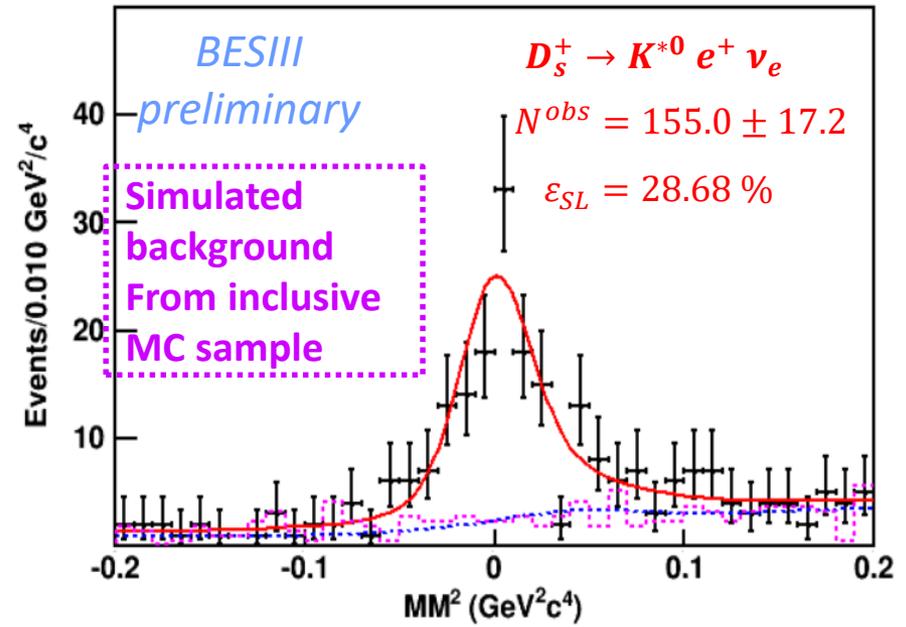
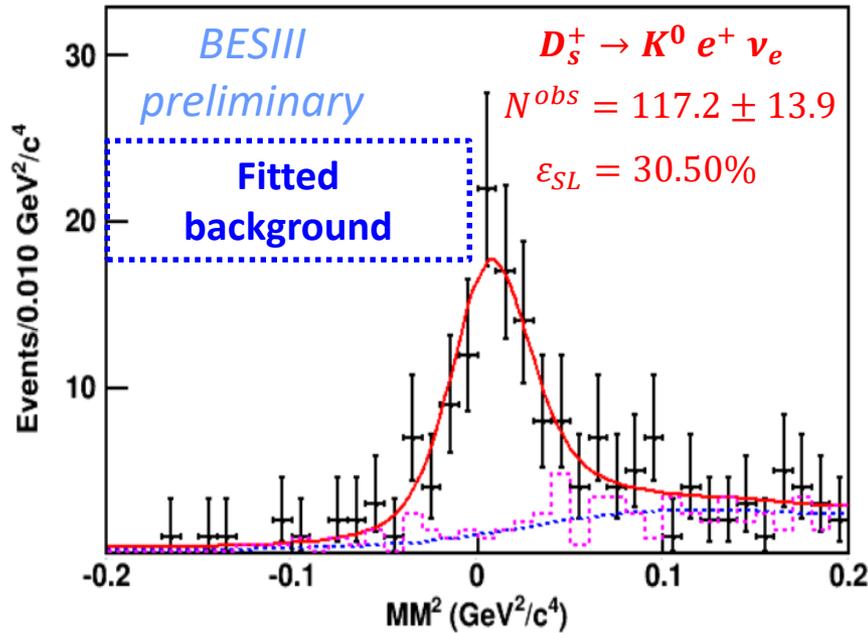
Cabibbo-suppressed



Currently measurements are only from one single experiment

| $\Gamma(D_s^+ \rightarrow K^{*}(892)^0 e^+ \nu_e) / \Gamma_{\text{total}}$ | | | | | Γ_{29} / Γ |
|--|------|--------------|------|------------------|------------------------|
| VALUE (10 ⁻²) | EVTS | DOCUMENT ID | TECN | COMMENT | |
| 0.18 ± 0.04 ± 0.01 | 32 | HIETALA 2015 | | Uses CLEO data | |
| ••• We do not use the following data for averages, fits, limits, etc. ••• | | | | | |
| 0.18 ± 0.07 ± 0.01 | 7.5 | YELTON 2009 | CLEO | See HIETALA 2015 | |
| $\Gamma(D_s^+ \rightarrow K^0 e^+ \nu_e) / \Gamma_{\text{total}}$ | | | | | Γ_{28} / Γ |
| VALUE (10 ⁻²) | EVTS | DOCUMENT ID | TECN | COMMENT | |
| 0.39 ± 0.08 ± 0.03 | 42 | HIETALA 2015 | | Uses CLEO data | |
| ••• We do not use the following data for averages, fits, limits, etc. ••• | | | | | |
| 0.37 ± 0.10 ± 0.02 | 14 | YELTON 2009 | CLEO | See HIETALA 2015 | |

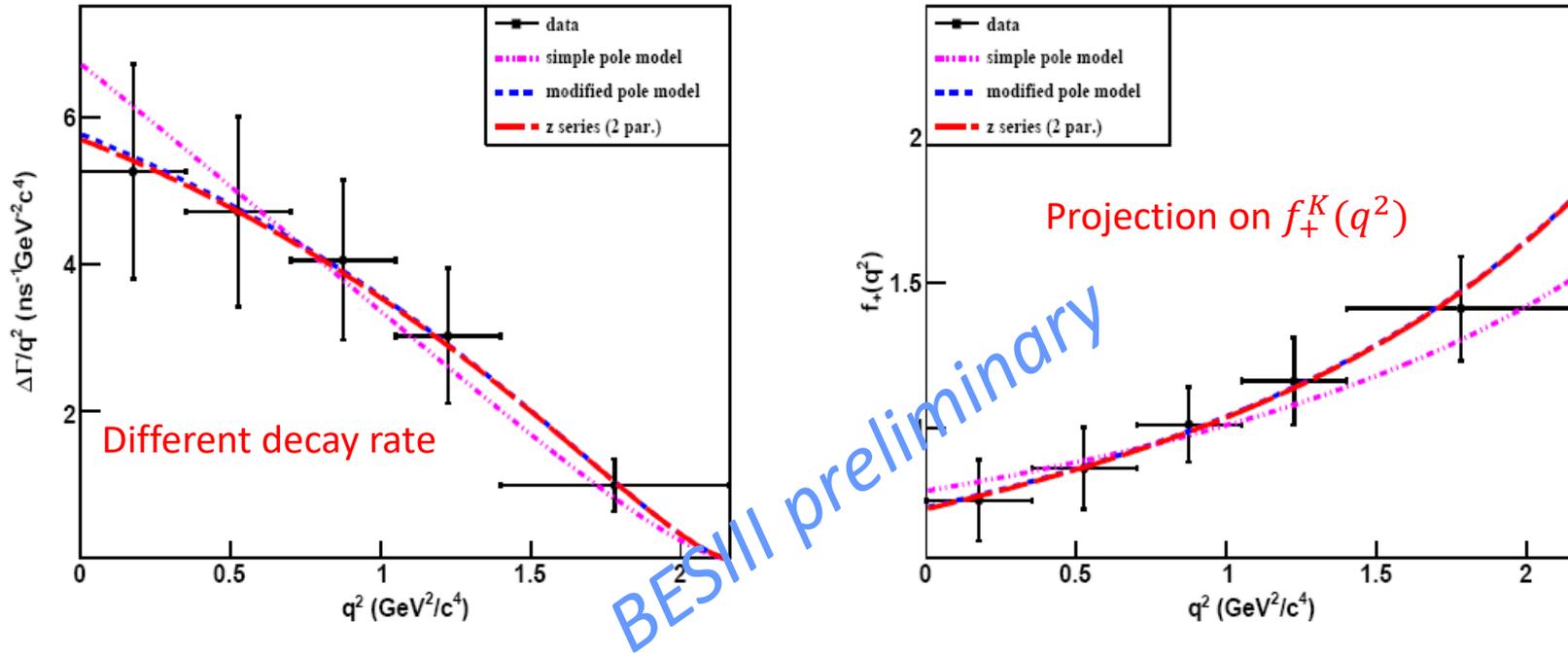
Branching fraction of $D_s^+ \rightarrow K^{(*)0} e^+ \nu_e$



| Channel | Measured BFs [$\times 10^{-3}$] | Predicted BFs [$\times 10^{-3}$] |
|--------------------------------------|---|------------------------------------|
| $D_s^+ \rightarrow K^0 e^+ \nu_e$ | 3.9 ± 0.9 [PDG2017] | 2.0 [1] |
| | $3.25 \pm 0.38 \pm 0.14$ [BESIII preliminary] | 3.2 [2] |
| | | $3.90^{+0.74}_{-0.57}$ [3] |
| | | 2.9 [4] |
| $D_s^+ \rightarrow K^{*0} e^+ \nu_e$ | 1.8 ± 0.4 [PDG2017] | 2.2 [5] |
| | $2.38 \pm 0.26 \pm 0.12$ [BESIII preliminary] | 1.9 [2] |
| | | $2.33^{+0.29}_{-0.30}$ [3] |
| | | 1.7 [4] |

- Consistent with the PDG.
- Still, statistically limited.
- Fitting error dominates systematics.

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



□ 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 | $-2.94 \pm 2.32 \pm 0.14$ | |

Inserting $|V_{cd}| = 0.22492 \pm 0.00050$ obtained by CKMfitter, the $f_+(0)$ can be obtained.

Summary

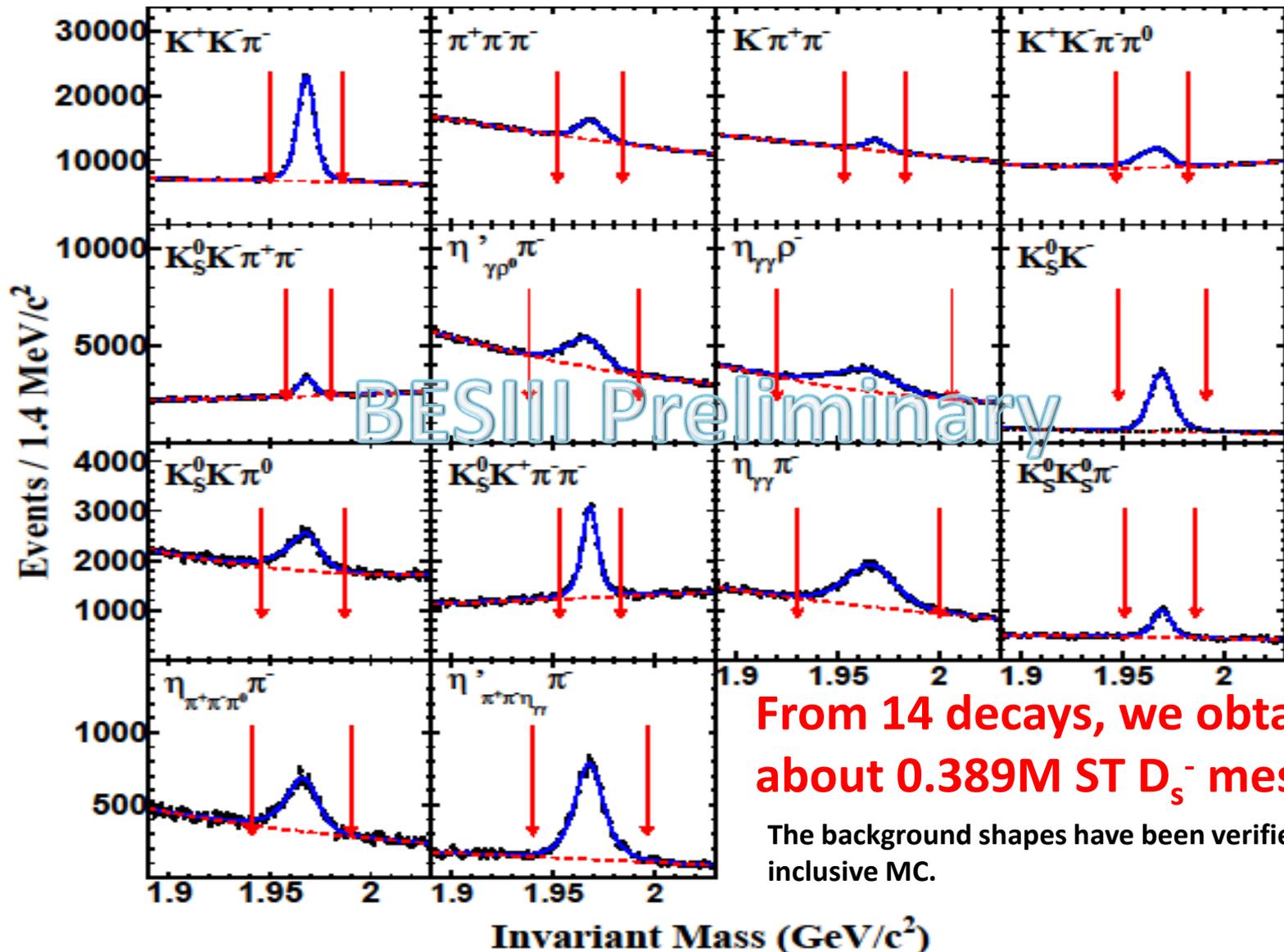
- ❖ With 2.93 and 3.19 fb⁻¹ data taken at 3.773 and 4.18 GeV, BESIII have studied $D_s^+ \rightarrow l^+ \nu_l$, $D \rightarrow K(\pi)l \nu_l$ decays to measure their branching fractions, decay constant $f_{D_s^+}$, form factor $f_+^K(0)$, and the CKM matrix element $|V_{cs}|$, as well as the lepton universality test;
- ❖ Improved measurements of decay constant $f_{D_s^+}$ and form factor $f_+^{D \rightarrow K}(q^2)$, which are important to test and calibrate LQCD calculations.
- ❖ Improved measurements of CKM matrix element $|V_{cs}|$, which are important to test the CKM matrix unitarity.
- ❖ Based on 3.19 fb⁻¹ data at 4.178 GeV accumulated in 2016, the measurements of $f_{D_s^+}$ and $|V_{cs}|$, by other D_s^+ decays, the form factor studies of $D_s^+ \rightarrow \eta^{(\prime)} e^+ \nu_e \dots$ can be expected in the near future.

Thanks for your attention!

Back up

Single tag candidates

3.19 fb⁻¹ data taken at 4.178 GeV in 2016



$$D_s^+ \rightarrow K^0 e^+ \nu_e$$

The correlation matrix including both statistical and systematic Uncertainties. [preliminary]

| | $0.00 < q^2 \leq 0.35$ | $0.35 < q^2 \leq 0.70$ | $0.70 < q^2 \leq 1.05$ | $1.05 < q^2 \leq 1.40$ | $1.40 < q^2 \leq q_{\max}^2$ |
|-----------------------------|------------------------|------------------------|------------------------|------------------------|------------------------------|
| $\rho_i^{\text{stat+syst}}$ | 1.000 | -0.154 | 0.016 | -0.000 | 0.001 |
| | -0.154 | 1.000 | -0.117 | 0.011 | -0.001 |
| | 0.016 | -0.117 | 1.000 | -0.102 | 0.008 |
| | -0.000 | 0.011 | -0.102 | 1.000 | -0.075 |
| | 0.001 | -0.001 | 0.008 | -0.075 | 1.000 |

In the calculation of the systematic covariance matrix, we have considered the systematic uncertainties arising from the uncertainties in the number of D_s^- tags, D_s^+ lifetime, MC statistics, $E_{\gamma_{\max}}$ cut, $M_{K_S^0 e^+}$ cut, fits to MM^2 distribution, tracking and PID efficiencies.

$D_s^+ \rightarrow K^{*0} e^+ \nu_e$

The differential decay rate for $D_s^+ \rightarrow K^{*0} e^+ \nu_e$ can be expressed in terms of three helicity amplitudes ($H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$)

$$\begin{aligned} \frac{d^5\Gamma}{dm_{K\pi} dq^2 d\cos\theta_K d\cos\theta_e d\chi} &= \frac{3}{8(4\pi)^4} G_F^2 |V_{cd}|^2 \frac{p_{K\pi} q^2}{M_{D_s}^2} \mathcal{B}(K^{*0} \rightarrow K^+ \pi^-) |\mathcal{BW}(m_{K\pi})|^2 \\ &\times [(1 + \cos\theta_e)^2 \sin^2\theta_K |H_+(q^2, m_{K\pi})|^2 \\ &+ (1 - \cos\theta_e)^2 \sin^2\theta_K |H_-(q^2, m_{K\pi})|^2 \\ &+ 4\sin^2\theta_e \cos^2\theta_K |H_0(q^2, m_{K\pi})|^2 \\ &+ 4\sin\theta_e(1 + \cos\theta_e) \sin\theta_K \cos\theta_K \cos\chi H_+(q^2, m_{K\pi}) H_0(q^2, m_{K\pi}) \\ &- 4\sin\theta_e(1 - \cos\theta_e) \sin\theta_K \cos\theta_K \cos\chi H_-(q^2, m_{K\pi}) H_0(q^2, m_{K\pi}) \\ &- 2\sin^2\theta_e \sin^2\theta_K \cos 2\chi H_+(q^2, m_{K\pi}) H_-(q^2, m_{K\pi})]. \end{aligned}$$

The helicity amplitudes of $H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$ take the form of

$$H_{\pm}(q^2) = (M_{D_s} + m_{K\pi}) A_1(q^2) \mp \frac{2M_{D_s} p_{K\pi}}{M_{D_s} + M_{K\pi}} V(q^2) \text{ and}$$

$$H_0(q^2) = \frac{1}{2m_{K\pi} q} [(M_{D_s}^2 - m_{K\pi}^2 - q^2)(M_{D_s} + m_{K\pi}) A_1(q^2) - \frac{4M_{D_s}^2 p_{K\pi}^2}{M_{D_s} + M_{K\pi}} A_2(q^2)],$$

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/M_A^2} \text{ and } V(q^2) = \frac{V(0)}{1 - q^2/M_V^2}, \quad r_V = \frac{V(0)}{A_1(0)} \text{ and } r_2 = \frac{A_2(0)}{A_1(0)}.$$

The Breit-Wigner function of K^{*0} line shape takes the form as

$$\mathcal{BW}(M_{K\pi}) = \frac{\sqrt{m_0 \Gamma_0} (p/p_0)}{m_0^2 - m_{K\pi}^2 - i m_0 \Gamma(m_{K\pi})} \frac{B(p)}{B(p_0)}$$

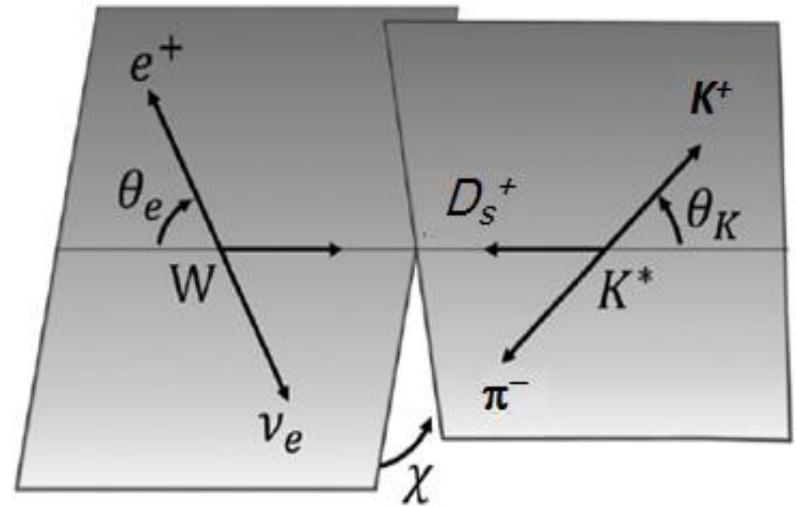
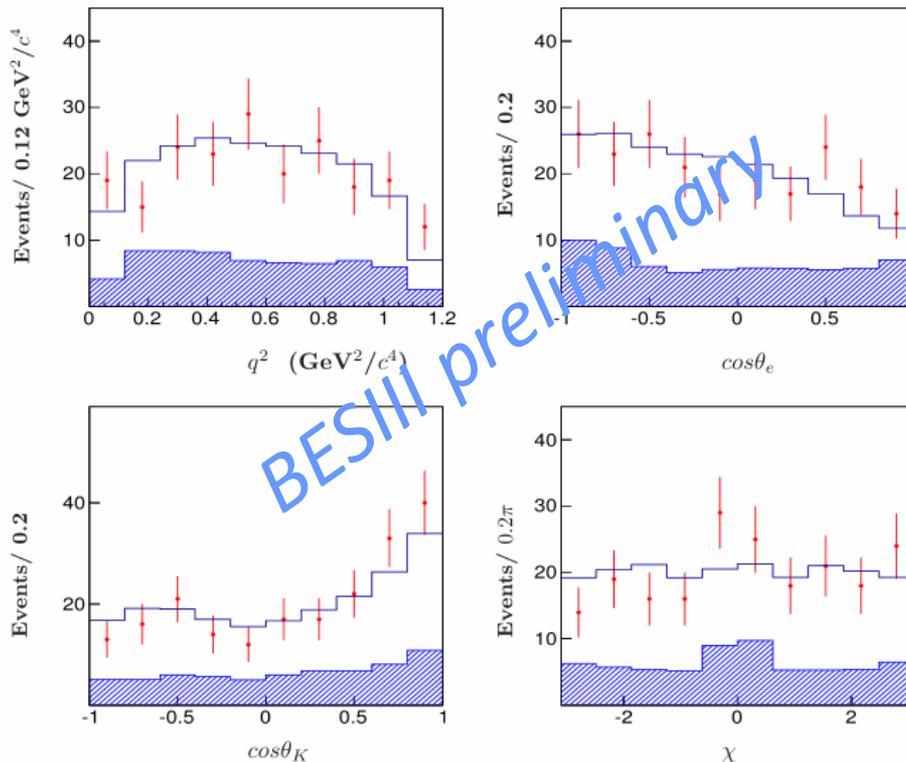
$$\text{where } B(p) = \frac{1}{\sqrt{1 + R^2 p^2}} \text{ with } R = 3 \text{ GeV}^{-1} \text{ and } \Gamma(m_{K\pi}) = \Gamma_0 \left(\frac{p}{p_0}\right)^3 \frac{m_0}{m_{K\pi}} \left(\frac{B(p)}{B(p_0)}\right)^2.$$

$D_s^+ \rightarrow K^{*0} e^+ \nu_e$

Following the same parametrization used in;

[1] BESIII Collaboration, M. Ablikim, *et al.*, Phys. Rev. D 94, 032001 (2016).

[1] CLEO Collaboration, S. Dobbs, *et al.*, Phys. Rev. Lett. 110, 131802 (2013).



□ The preliminary results for form factors:

$$r_V = 1.67 \pm 0.34 \pm 0.16 \text{ and } r_2 = 0.77 \pm 0.28 \pm 0.07$$

The first errors are statistical and the second are systematic.