南開大學
Nankai University

Charm meson leptonic and semi-leptonic decays at BESIII

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全国第十六届重味物理和CP破坏研讨会
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Outline

01 Introduction: BESIII experiment

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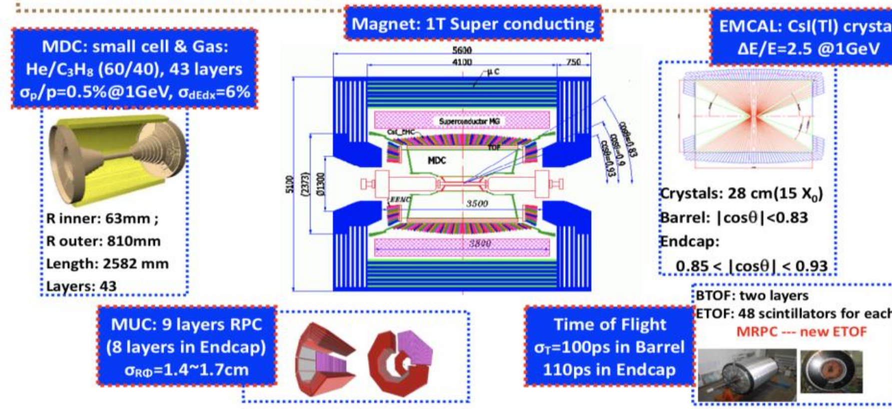
- A powerful general purpose detector.
- Excellent neutral/charged particle detection/identification with a large coverage.
  - ✓ Precision tracking
  - ✓ CsI calorimeter
  - ✓ PID via dE/dx & Time of Flight



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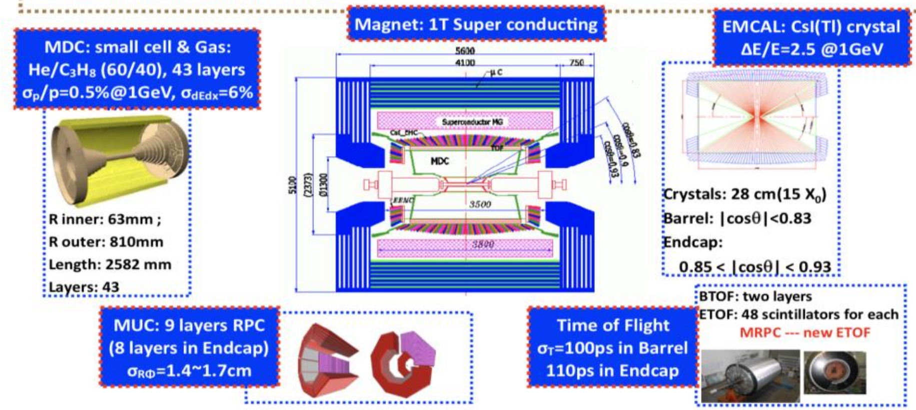

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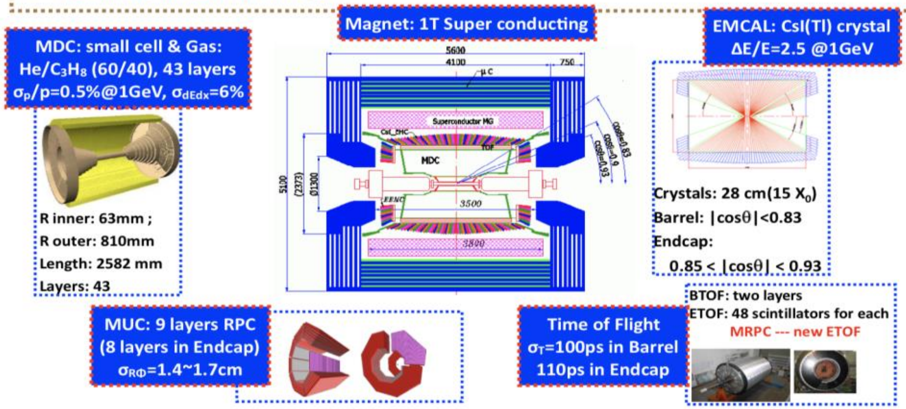
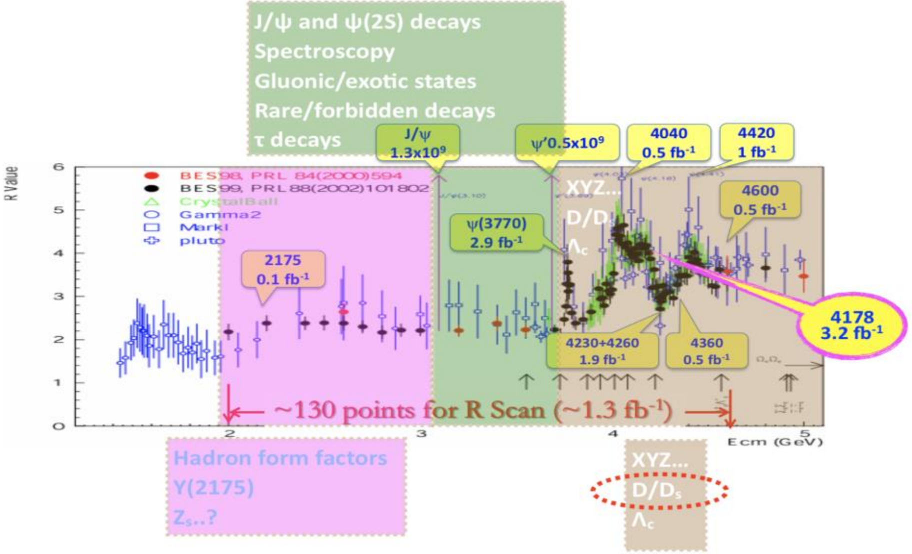
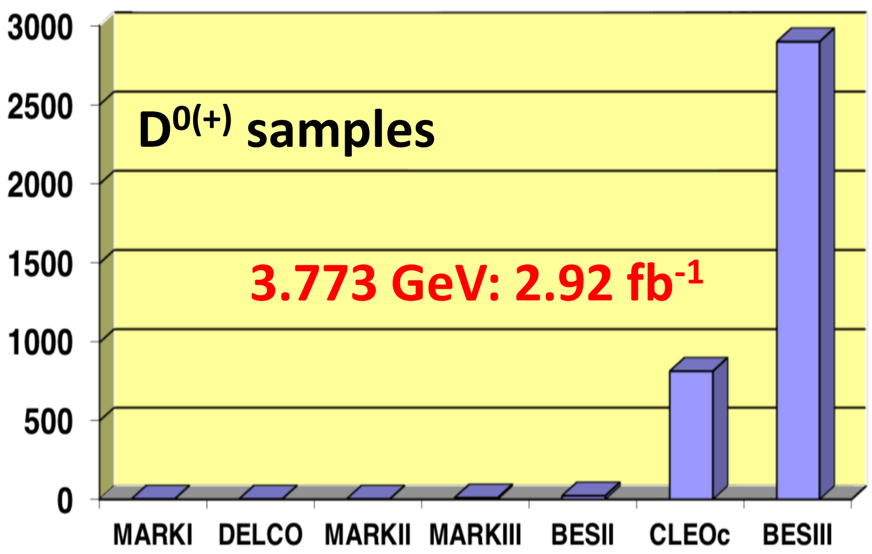
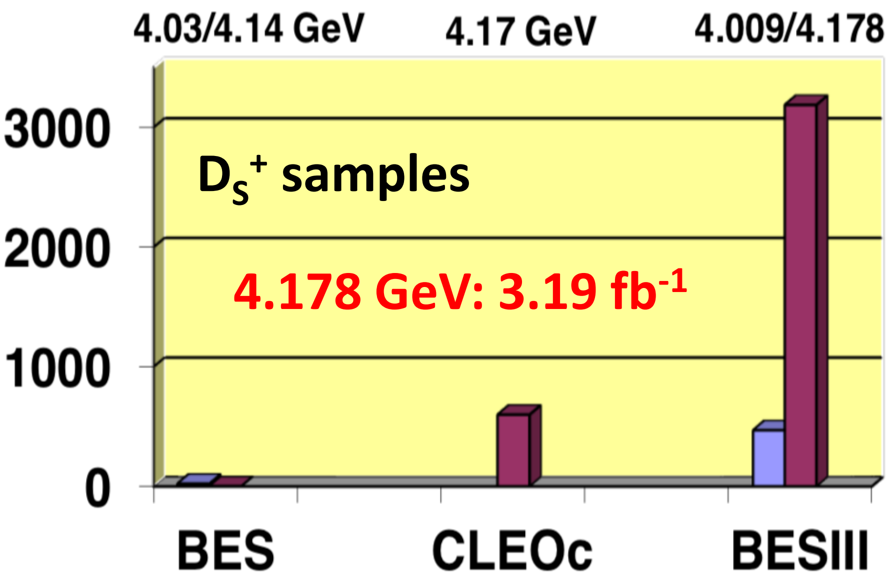




01 Introduction: data samples & method





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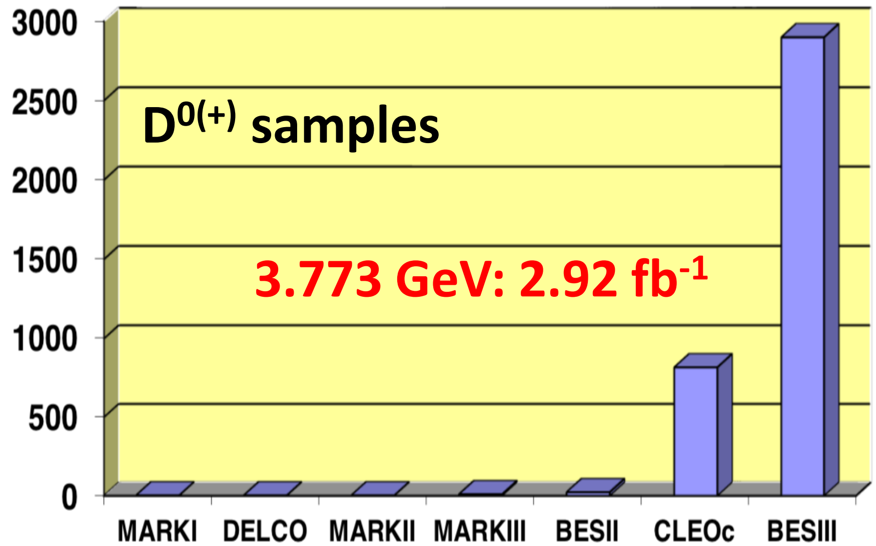

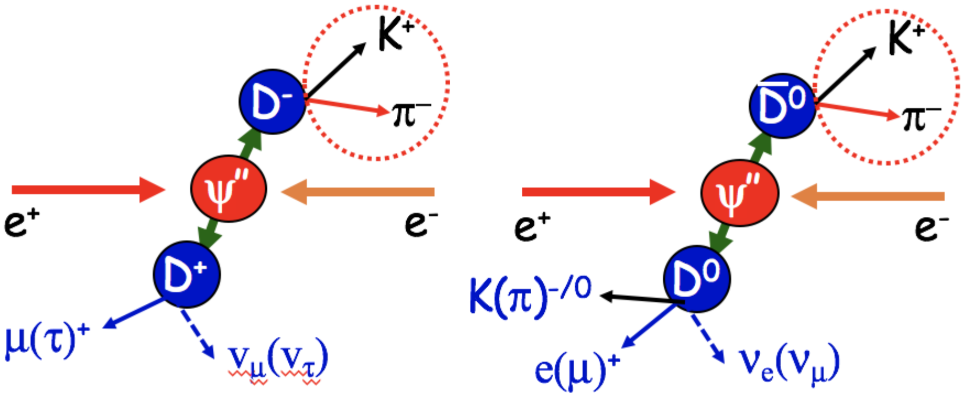

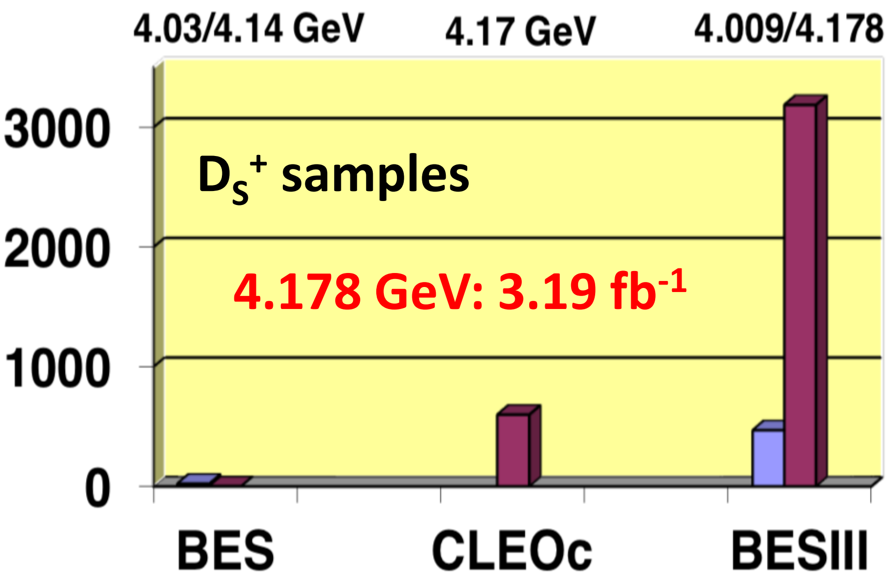

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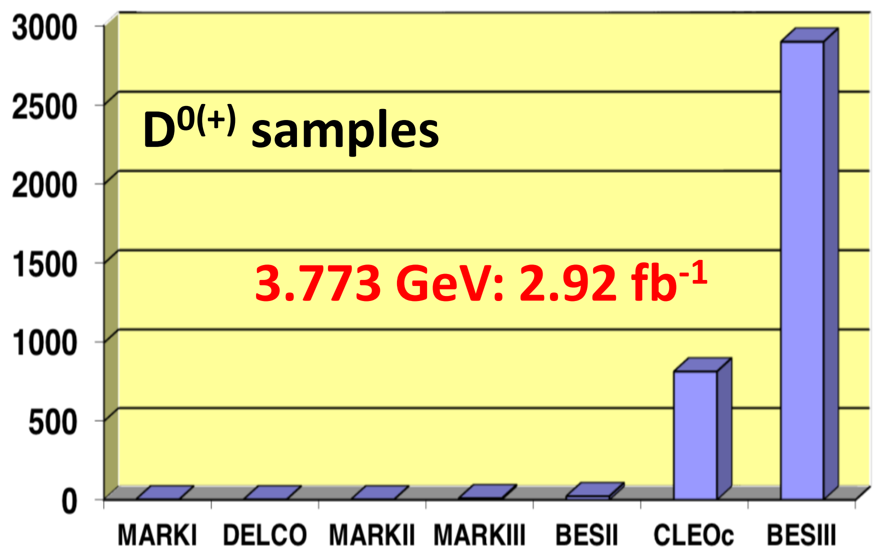
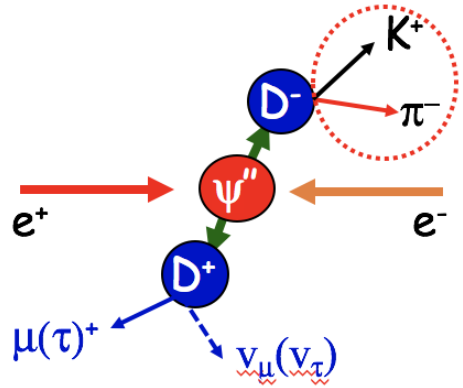
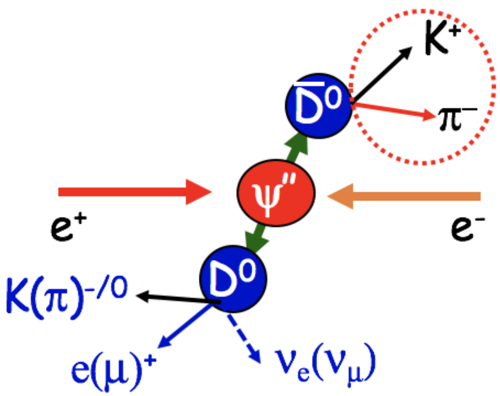
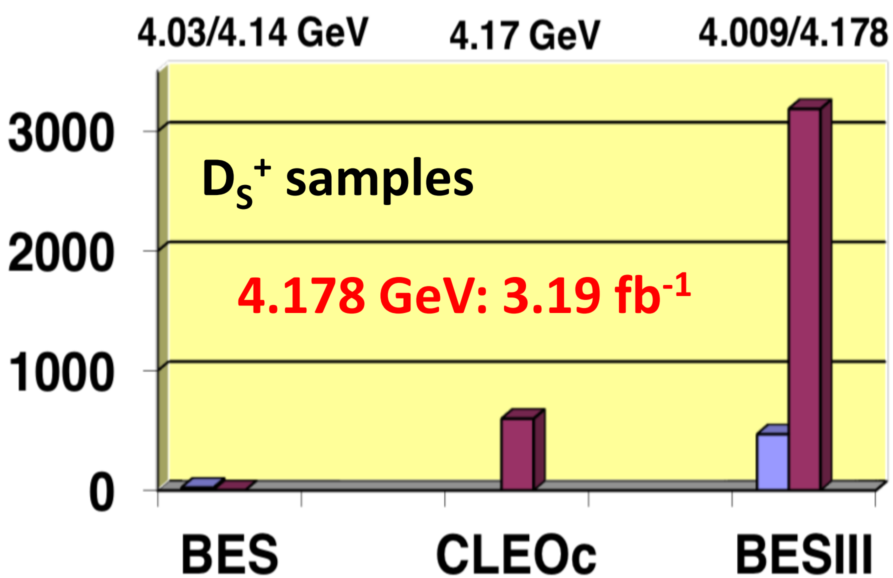








$$N_{\rm ST}^{i} = 2 \times N_{D\bar{D}} \times B_{ST}^{i} \times \epsilon_{ST}^{i}$$

$$N_{\rm DT}^{i} = 2 \times N_{D\bar{D}} \times B_{ST}^{i} \times B_{sig} \times \epsilon_{ST\ vs\ sig}^{i}$$

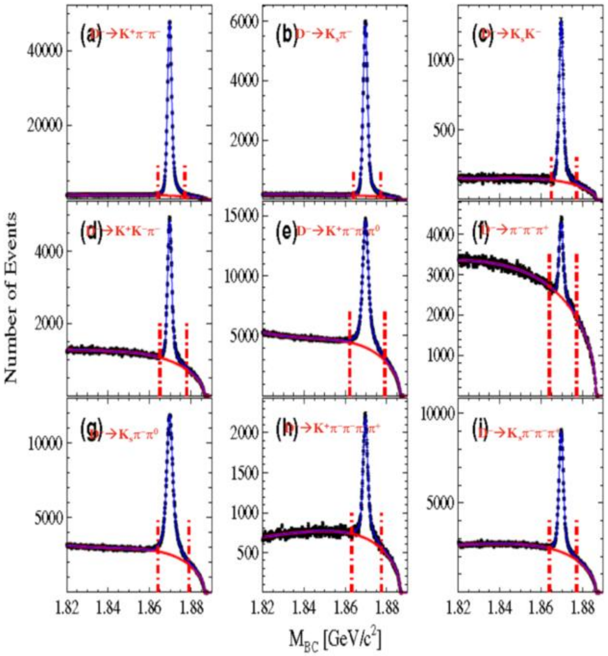
$$B_{sig} = \frac{\Sigma N_{DT}^{i}}{\Sigma N_{ST}^{i} \times \bar{\epsilon}_{sig}} = \frac{N_{DT}^{tot}}{N_{ST}^{tot} \times \bar{\epsilon}_{sig}}$$

$$\bar{\epsilon}_{sig} = \Sigma(N_{ST}^{i} \times \epsilon_{ST\ vs\ sig}^{i} / \epsilon_{ST}^{i}) / \Sigma N_{ST}^{i}$$

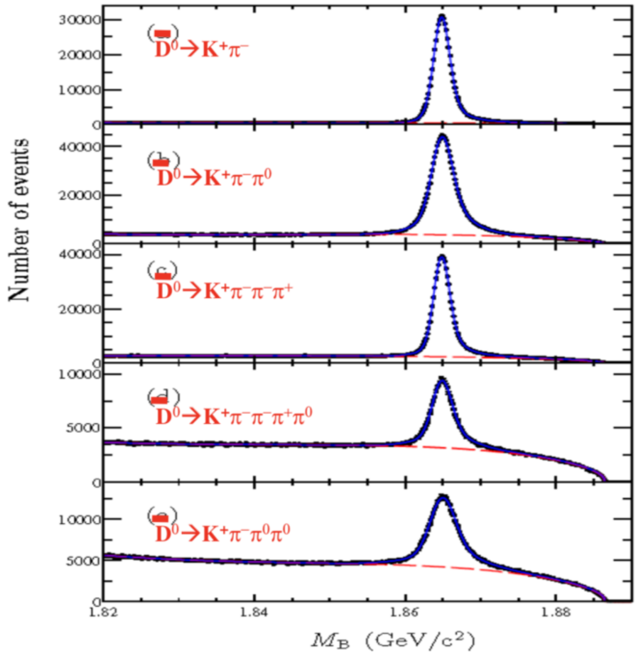
01 Introduction: single tags

Charge conjugations included

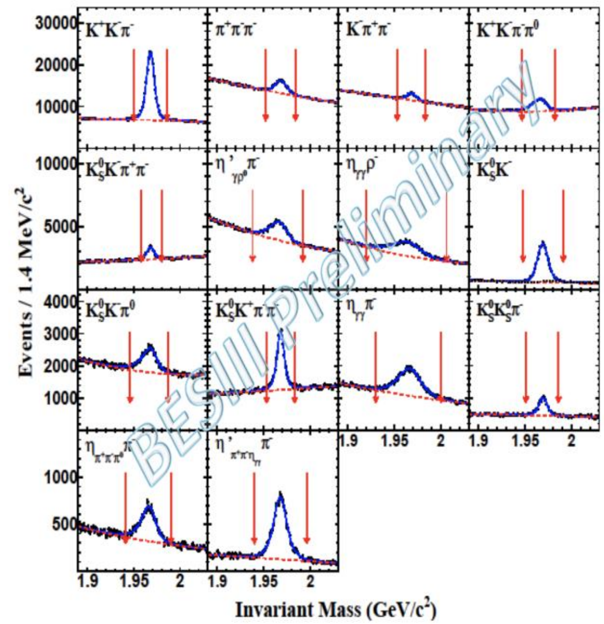
$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$ [1]



$N_{\bar{D}^0_{tag}} = (279.33 \pm 0.37) \times 10^4$ [2]



$N_{D_S^+ tag} = 0.389$ Million



6 largest tag modes give 1.5 million D^- tags

3 largest tag modes give 2.3 million D^0 tags

[1] Phys. Rev. D89, 051104(R) (2014) ; [2] Phys. Rev. D92, 072012 (2015);

02

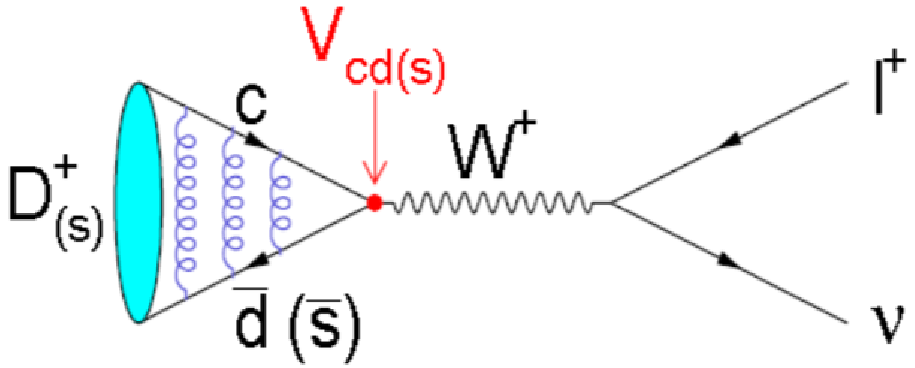
Leptonic Decays

① $D^+ \to \mu^+ \nu_\mu$

② $D^+ \to \tau^+ \nu_\mu$

③ $D_S^+ \to \mu^+ \nu_\mu$

02 Leptonic Decays



In the SM: $$\Gamma(D^+_{(s)} \to \ell^+ \nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}} \left(1 - \frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

Bridge to precisely measure

- **Decay constant $f_{D(s)+}$ with input $|V_{cd(s)}|^{CKMfitter}$**
- **CKM matrix element $|V_{cd(s)}|$ with input $f^{LQCD}_{D(s)+}$**

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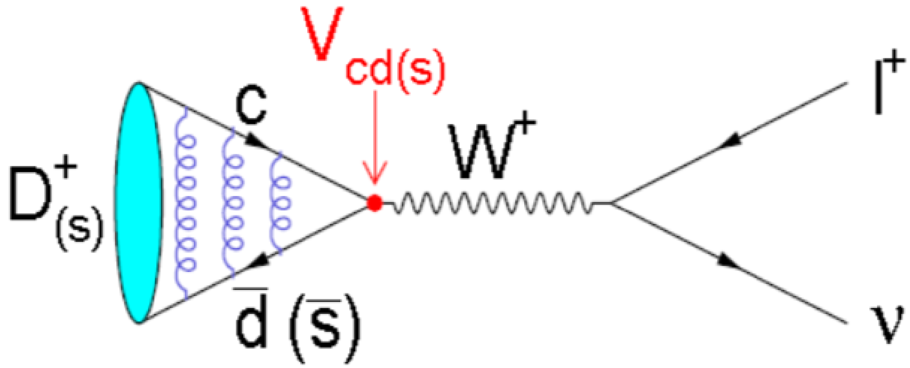

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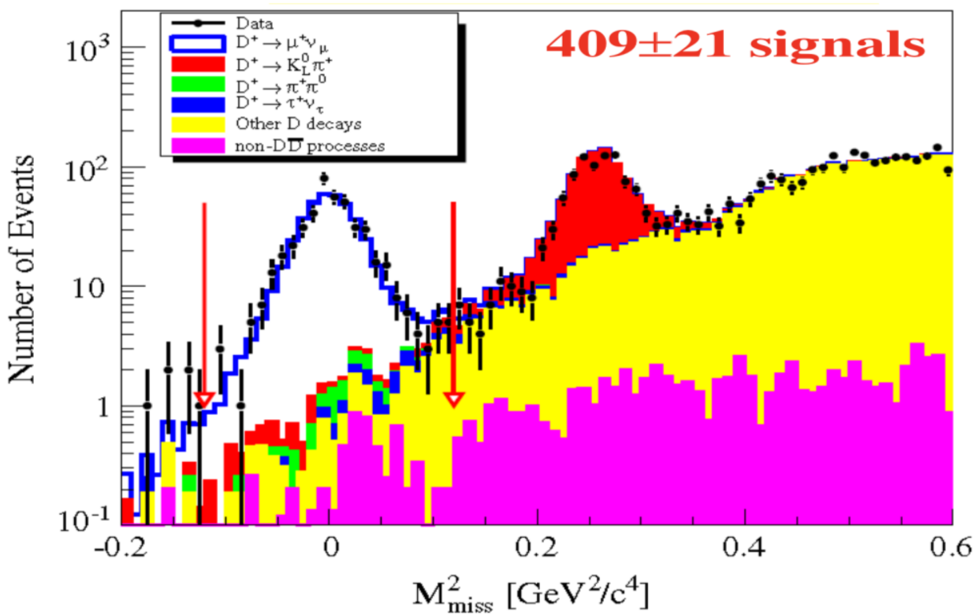

$$B\left(D^+ \to \mu^+\nu_\mu\right) = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

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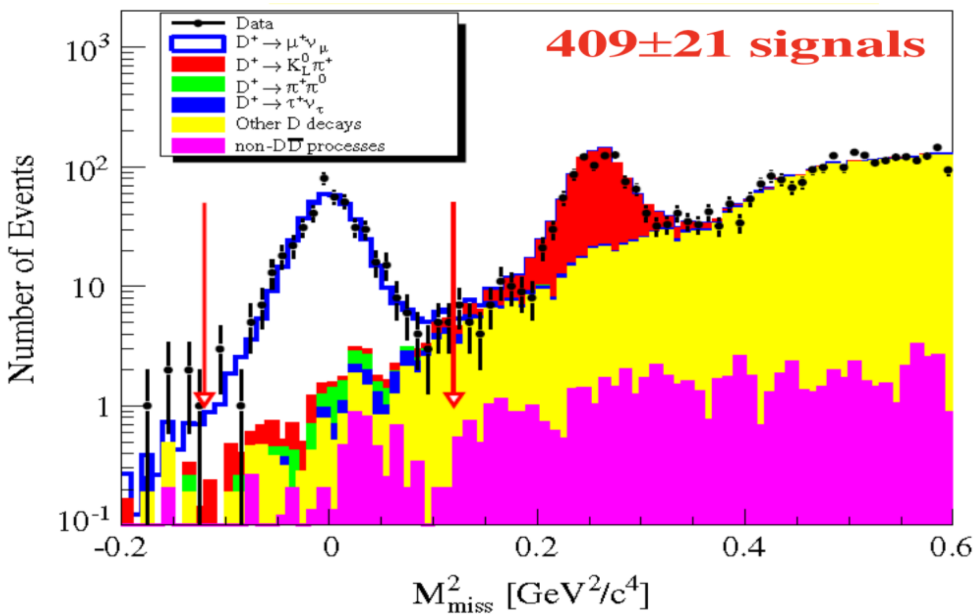

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$$f_{D^+}|V_{cd}| = (45.75 \pm 1.20 \pm 0.39)\ MeV$$

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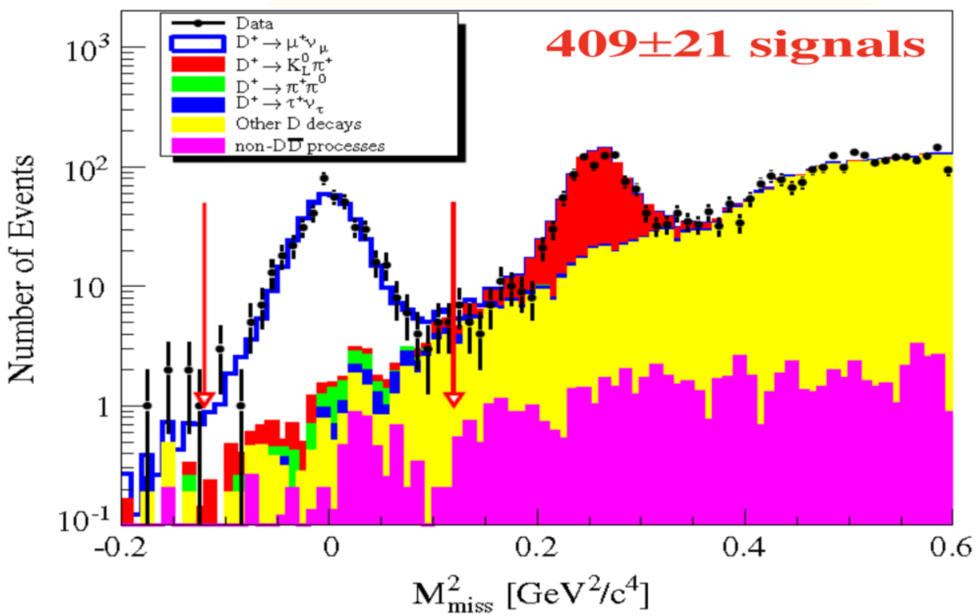

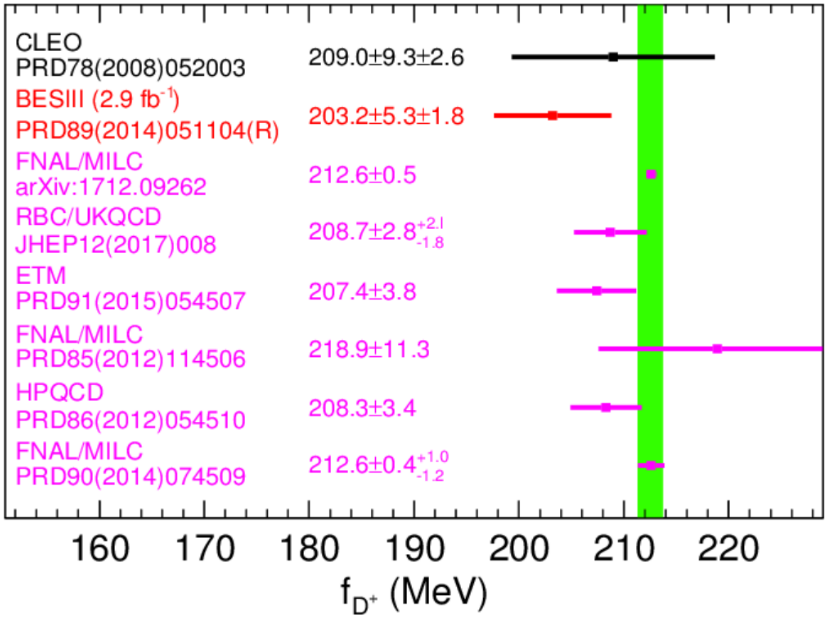

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$$f_{D^+}|V_{cd}| = (45.75 \pm 1.20 \pm 0.39)\ MeV$$

input $|V_{cd}|^{CKMfitter}$

$$f_{D^+} = (203.2 \pm 5.3 \pm 1.8)\ MeV$$

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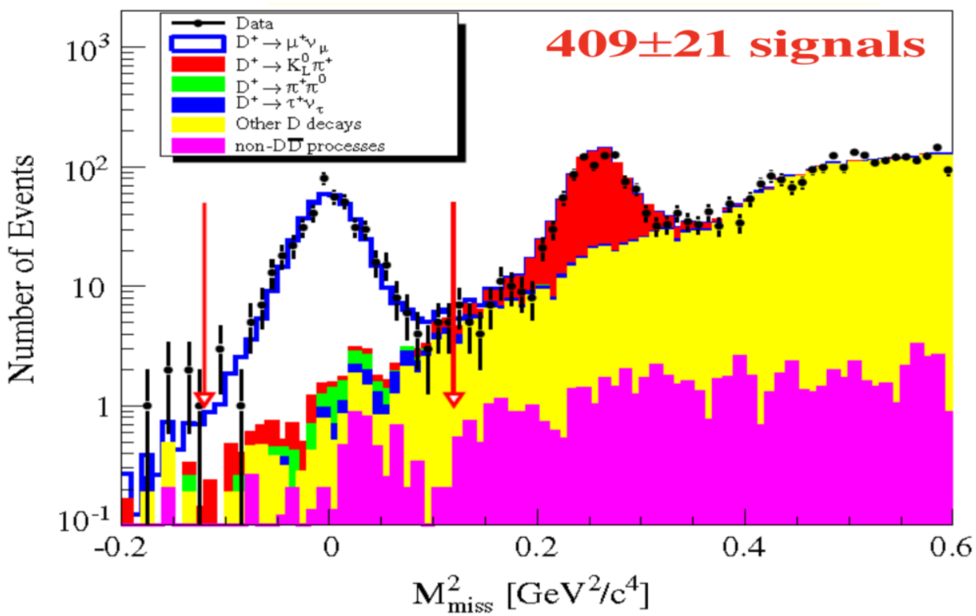
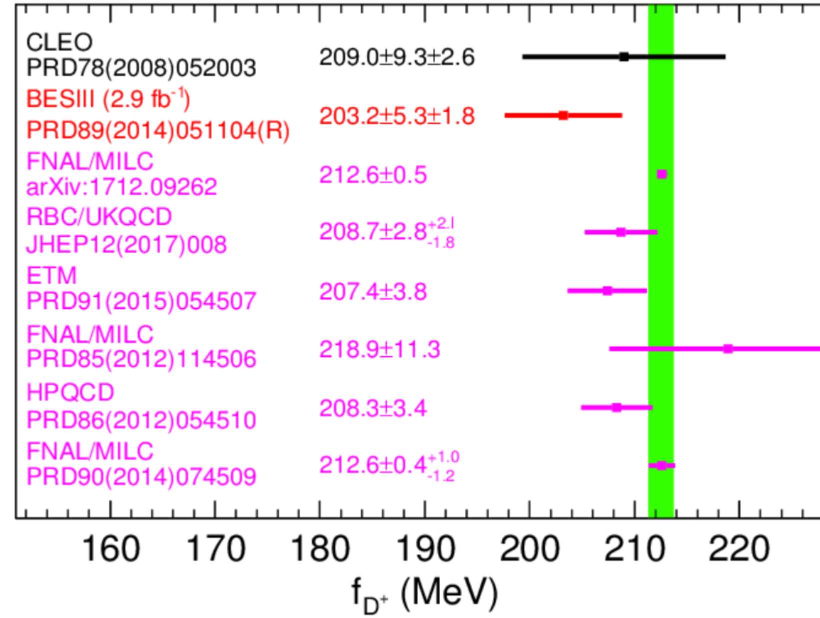
02 Leptonic Decays: $D^+ \to \mu^+ \nu_\mu$





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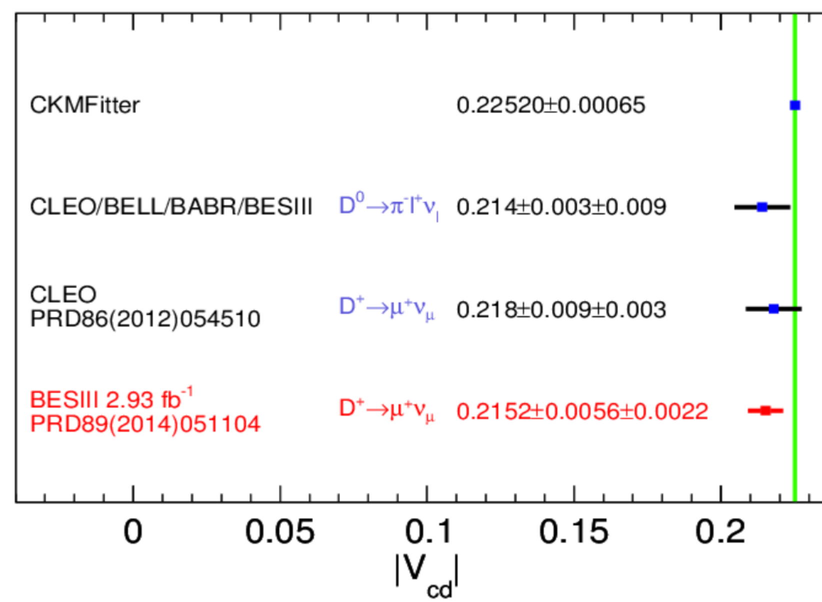
input $|V_{cd}|^{CKMfitter}$

input f_{D+}^{LQCD}

$$f_{D^+} = (203.2 \pm 5.3 \pm 1.8)\ MeV$$

$$|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047$$



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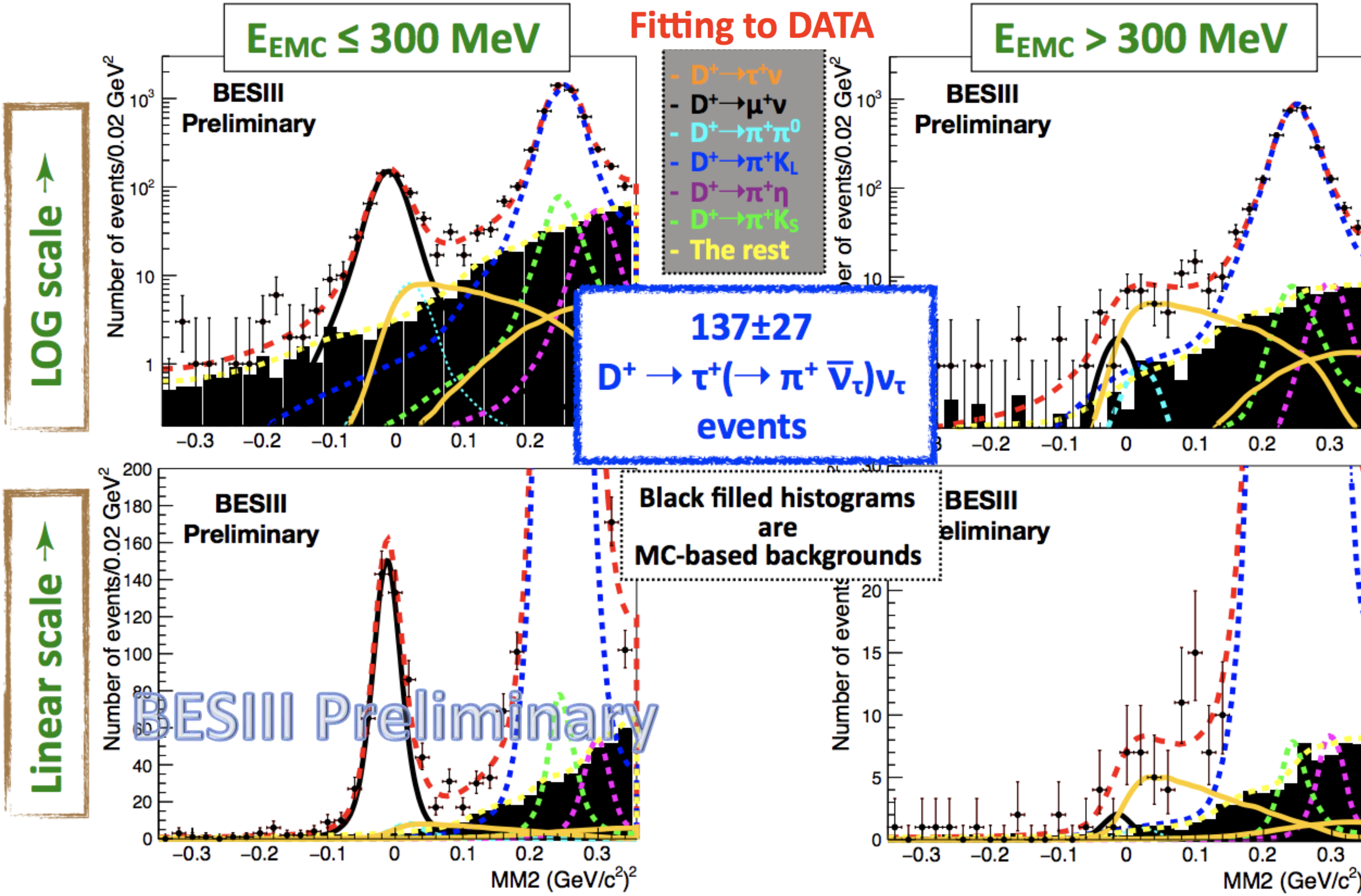
02 Leptonic Decays: $D^+ \to \tau^+ \nu_\tau$



$$B(D^+ \to \tau^+ \nu_\tau) = (0.120 \pm 0.024_{stat})\%$$

> 4σ : statistical significance

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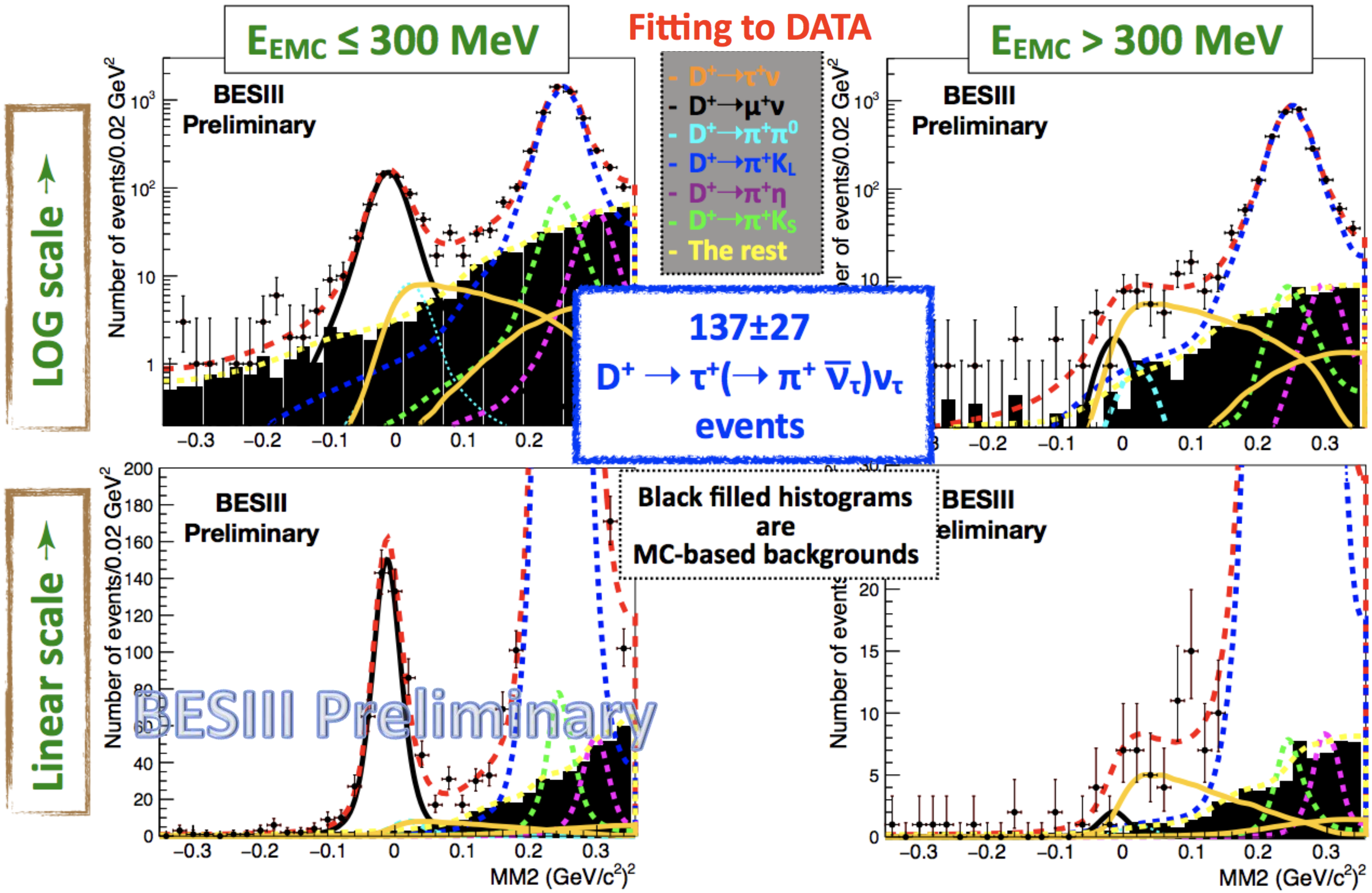


$\mathrm{B}(\mathrm{D}^+ \to \tau^+ \nu_\tau) = (0.120 \pm 0.024_{\mathrm{stat}})\%$

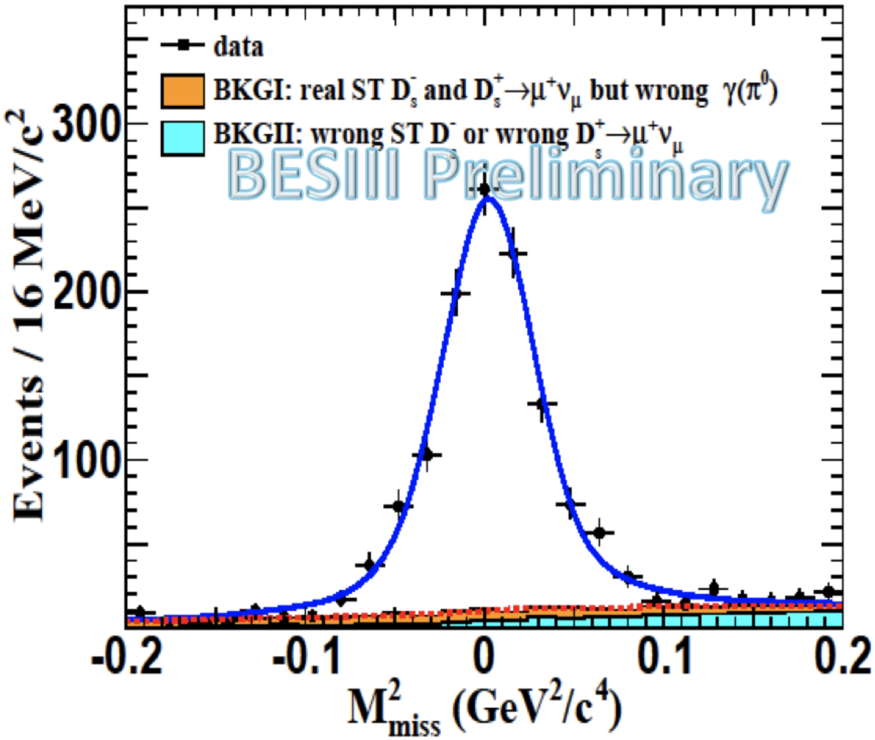
> 4σ : statistical significance

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

SM prediction: R = 2.66 ± 0.01

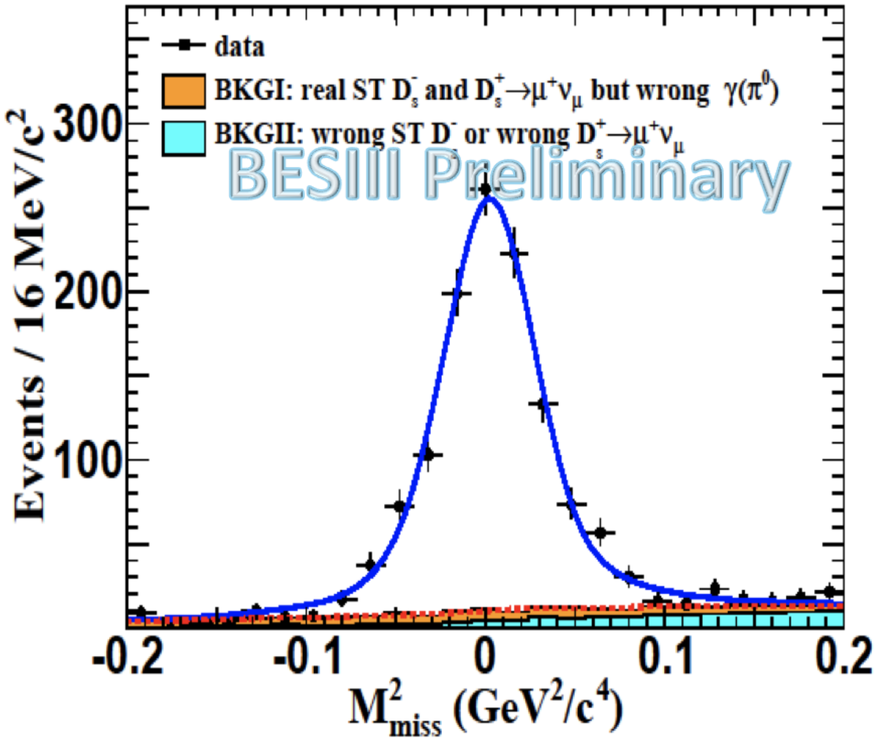
BESIII result: R = 3.21 ± 0.64

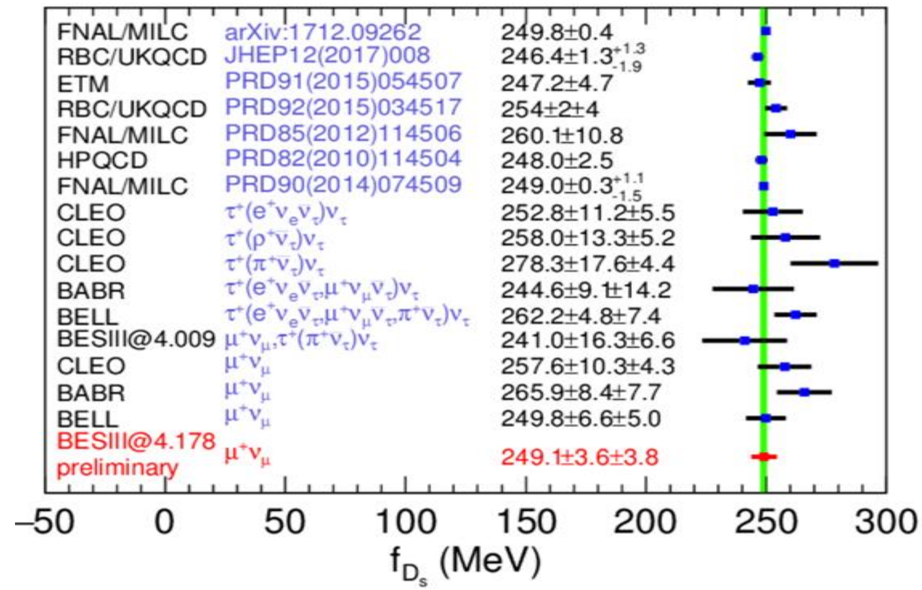
02 Leptonic Decays: $D_S^+ \to \mu^+ \nu_\mu$



$B\left(D_S^+ \to \mu^+ \nu_\mu\right) = (0.528 \pm 0.015 \pm 0.014)\%$

02 Leptonic Decays: $D_S^+ \to \mu^+ \nu_\mu$





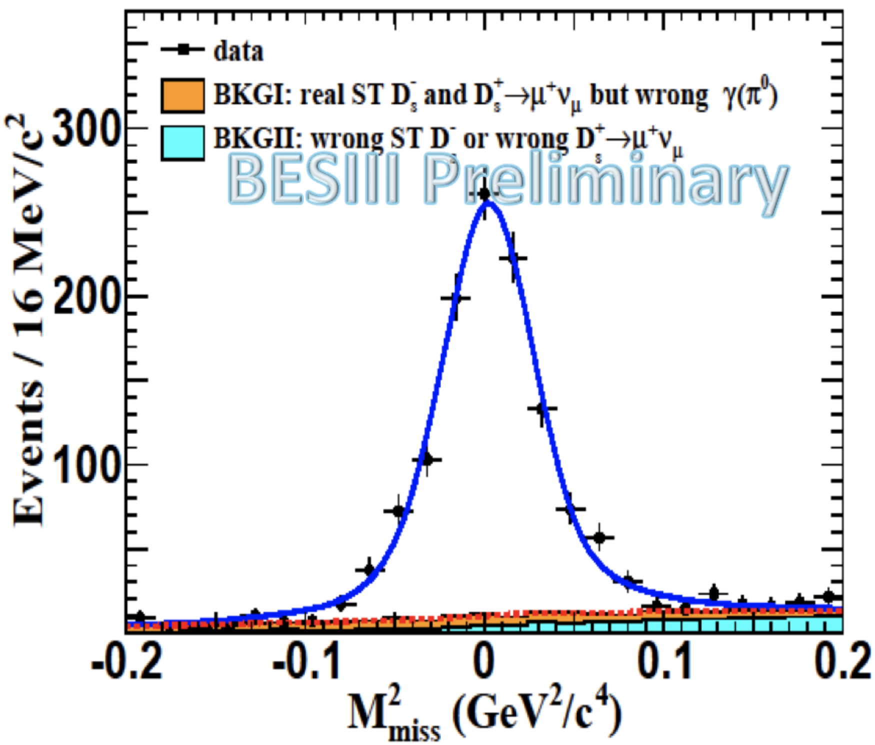
$$B\left(D_S^+ \to \mu^+\nu_\mu\right) = (0.528 \pm 0.015 \pm 0.014)\%$$

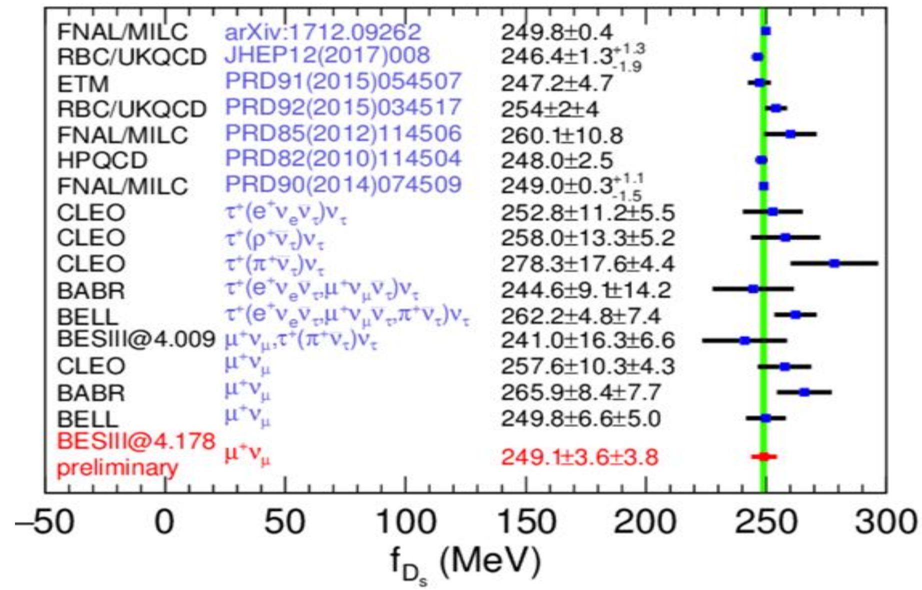
$$\mathbf{f_{D_S^+}|V_{cs}| = (242.5 \pm 3.5 \pm 3.7)\ MeV}$$

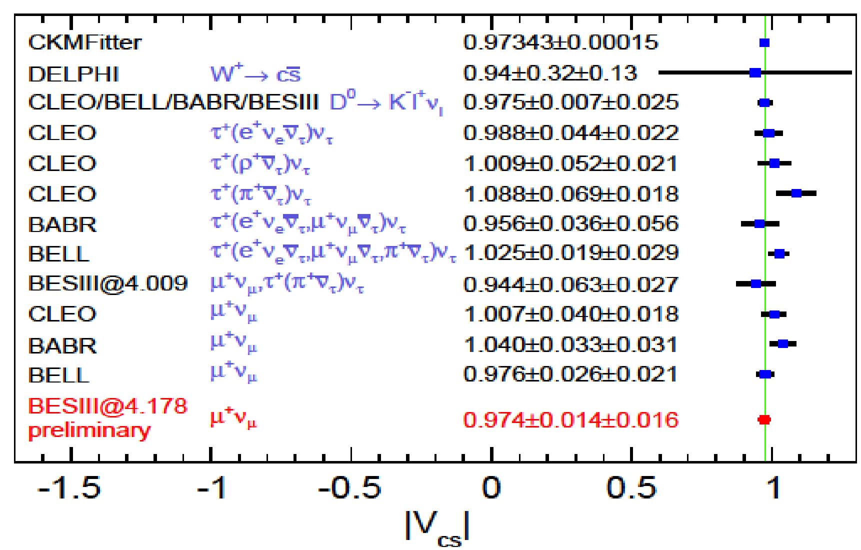
input $|V_{cs}|^{CKMfitter}$

$$f_{D_S^+} = (249.1 \pm 3.6 \pm 3.8)\ MeV$$

02 Leptonic Decays: $D_S^+ \to \mu^+\nu_\mu$







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$$\mathbf{f_{D_S^+}|V_{cs}| = (242.5 \pm 3.5 \pm 3.7)\ MeV}$$

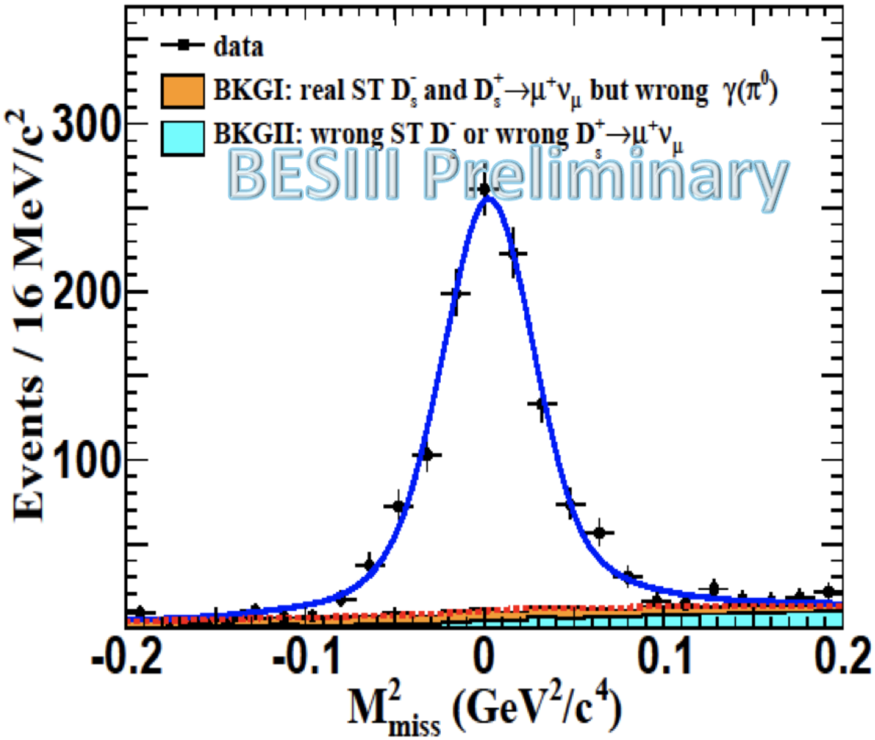
input $|V_{cs}|^{CKMfitter}$

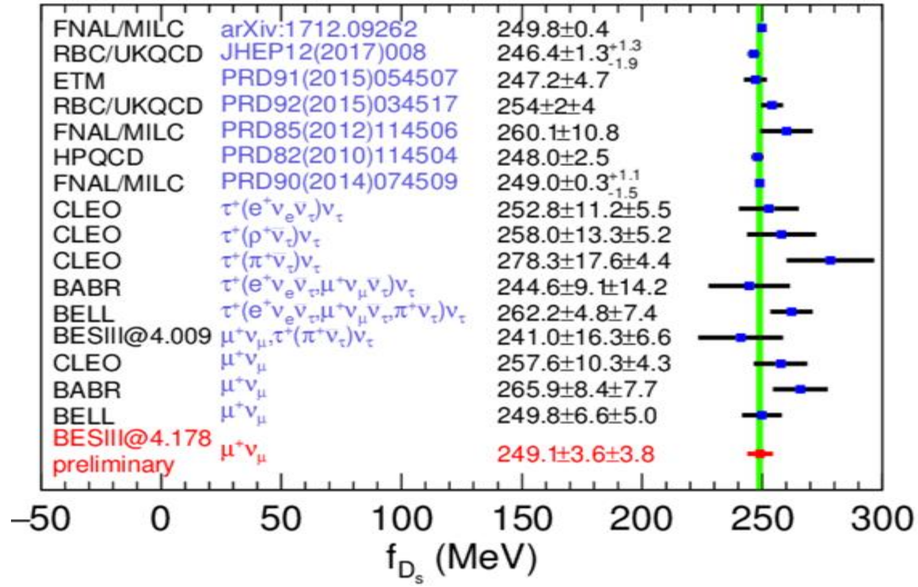
input $f_{D_s}^{LQCD}$ (PRD90(2014)074509)

$$|V_{cs}| = 0.974 \pm 0.014 \pm 0.016$$

$$f_{D_S^+} = (249.1 \pm 3.6 \pm 3.8)\ MeV$$

02 Leptonic Decays: $D_S^+ \to \mu^+ \nu_\mu$





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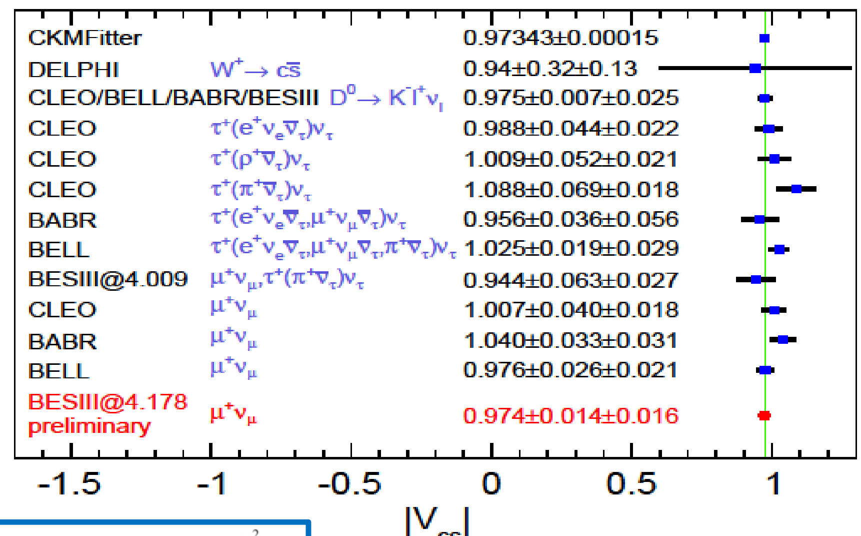


$$R \equiv \frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} = \frac{m_{\tau^+}^2\left(1-\frac{m_{\tau^+}^2}{M_{D_s^+}^2}\right)^2}{m_{\mu^+}^2\left(1-\frac{m_{\mu^+}^2}{M_{D_s^+}^2}\right)^2}$$

SM prediction: R = 9.74 ± 0.01

BESIII result: R = 10.2 ± 0.5

03

Semi-Leptonic Decays

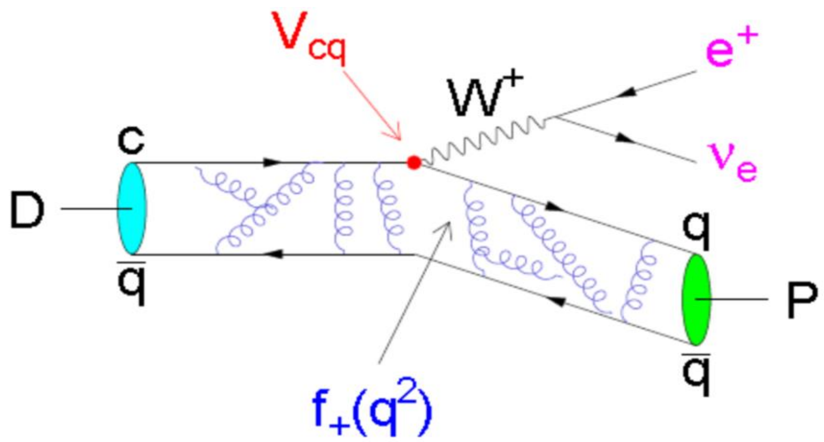
① $D^{0/+} \to K(\pi)^{-/0} e^+ \nu_e$

② $D^{0/+} \to K(\pi)^{-/0} \mu^+ \nu_\mu$

③ $D_S^+ \to K^{(*)0} e^+ \nu_e$

④ $D^{0/+} \to \pi^+ \pi^{-/0} e^+ \nu_e$

03 Semi-leptonic Decays: $D^{0/+} \to K(\pi)^{-/0} e^+ \nu_e$



– **Single pole form**

$$f_+(q^2) = \frac{f_+(0)}{1 - \frac{q^2}{M^2_{\rm pole}}}$$

– **ISGW2 model**

$$f_+(q^2) = f_+(q^2_{\rm max}) \left(1 + \frac{r^2_{\rm ISGW2}}{12}(q^2_{\rm max} - q^2)\right)^{-2}$$

– **Modified pole model**

$$f_+(q^2) = \frac{f_+(0)}{(1 - \frac{q^2}{M^2_{\rm pole}})(1 - \alpha \frac{q^2}{M^2_{\rm pole}})}$$

– **Series expansion model**

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

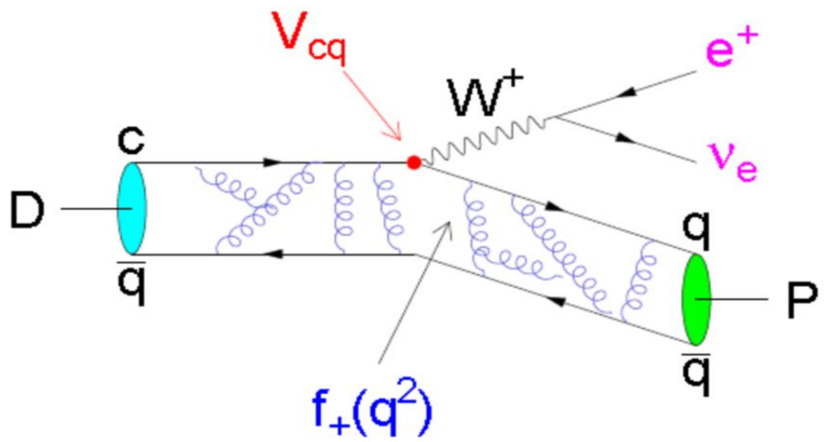
- partial decay width

$$\frac{d\Gamma_{P\ell^+\nu_\ell}}{dq^2} = \frac{G_F^2|V_{cq}|^2}{8\pi^3 m_D} |\vec{p}_P| |f_+^P(q^2)|^2 (\frac{W_0 - E_P}{F_0})^2 \times \left[\frac{1}{3} m_D |\vec{p}_P|^2 + \mathcal{O}(m_\ell^2)\right]$$

$$W_0 = (m_D^2 + m_P^2 - m_\ell^2)/2m_D,\ F_0 = W_0 - E_P + m_\ell^2/2m_D$$

- measure $V_{cd(s)}$ to test the unitary of CKM matrix
- measure the form factors $f_+^P(0)$ to calibrate the Lattice QCD calculation
- test lepton universality via $\mathcal{R} = \Gamma_\mu/\Gamma_e$

03 Semi-leptonic Decays: $D^{0/+} \to K(\pi)^{-/0} e^+ \nu_e$



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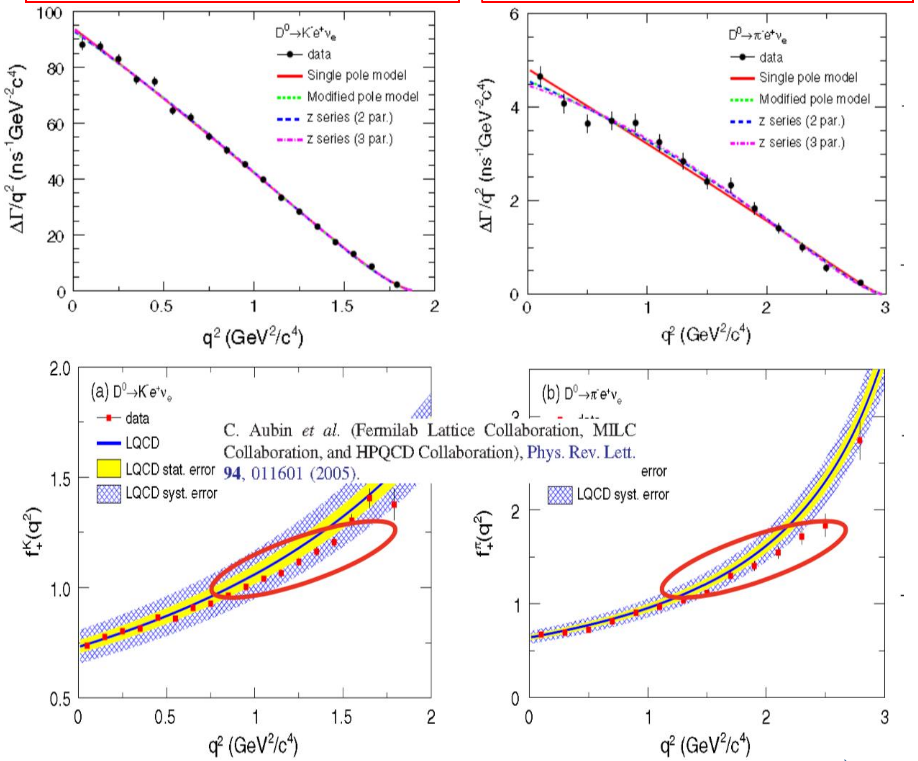
$B(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014 \pm 0.033)\%$

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



C. Aubin *et al.* (Fermilab Lattice Collaboration, MILC Collaboration, and HPQCD Collaboration), Phys. Rev. Lett. **94**, 011601 (2005).

$$f_+^{\pi}(0)|V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$
$$f_+^{K}(0)|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

with $|V_{cd}|/|V_{cs}|$ →

$$f_+^{\pi}(0) = 0.6372 \pm 0.0080 \pm 0.0044$$
$$f_+^{K}(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

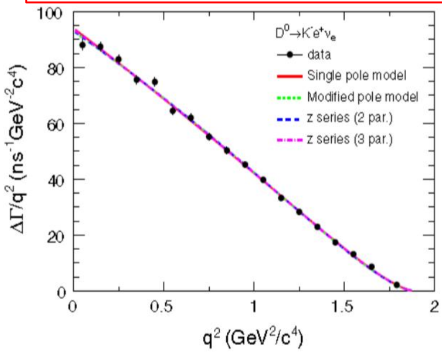
with $f_+^{\pi}(0)/f_+^{K}(0)$ →

$$|V_{cd}| = 0.2155 \pm 0.0027(\text{stat}) \pm 0.0014(\text{sys}) \pm 0.0094(\text{LQCD})$$
$$|V_{cs}| = 0.9601 \pm 0.0033(\text{stat}) \pm 0.0047(\text{sys}) \pm 0.0239(\text{LQCD})$$

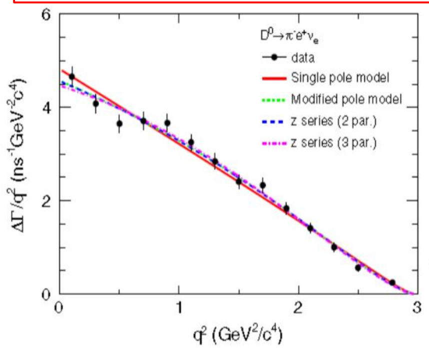
[1] Phys. Rev. D92, 072012 (2015); [2] Phys. Rev. D96, 012002 (2017)

03 Semi-leptonic Decays: $D^{0/+} \to K(\pi)^{-/0} e^+ \nu_e$

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

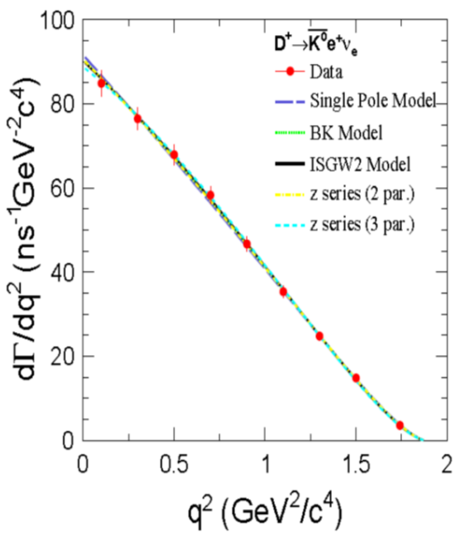


$B(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004 \pm 0.003)\%$



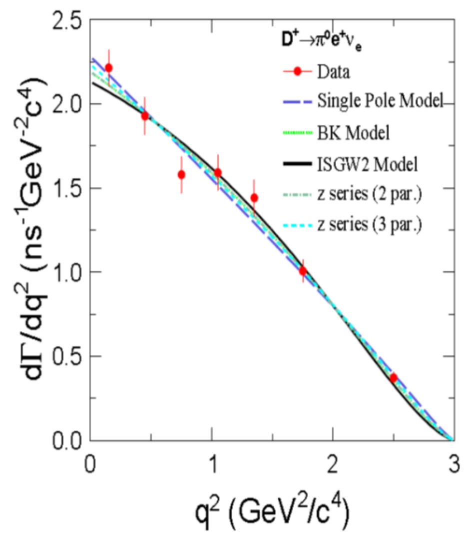
$B(D^0 \to \bar{K}^0 e^+ \nu_e) = (8.604 \pm 0.056 \pm 0.151)\%$

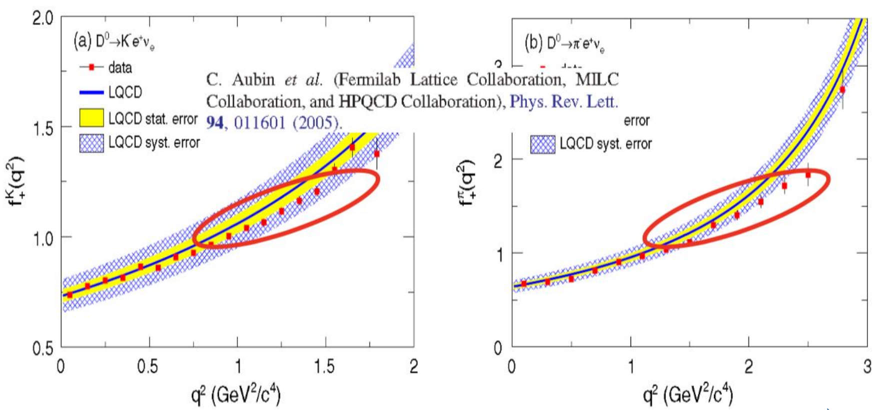
$$I_K \equiv \frac{\Gamma(D^0 \to K^- e^+ \nu_e)}{\Gamma(D^+ \to \bar{K}^0 e^+ \nu_e)} = 1.03 \pm 0.01 \pm 0.02$$



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

$$I_\pi \equiv \frac{\Gamma(D^0 \to \pi^- e^+ \nu_e)}{2\Gamma(D^+ \to \pi^0 e^+ \nu_e)} = 1.03 \pm 0.03 \pm 0.02$$





C. Aubin *et al.* (Fermilab Lattice Collaboration, MILC Collaboration, and HPQCD Collaboration), Phys. Rev. Lett. **94**, 011601 (2005).

$$f_+^\pi(0)|V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$
$$f_+^K(0)|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

with $|V_{cd}|/|V_{cs}|$ →

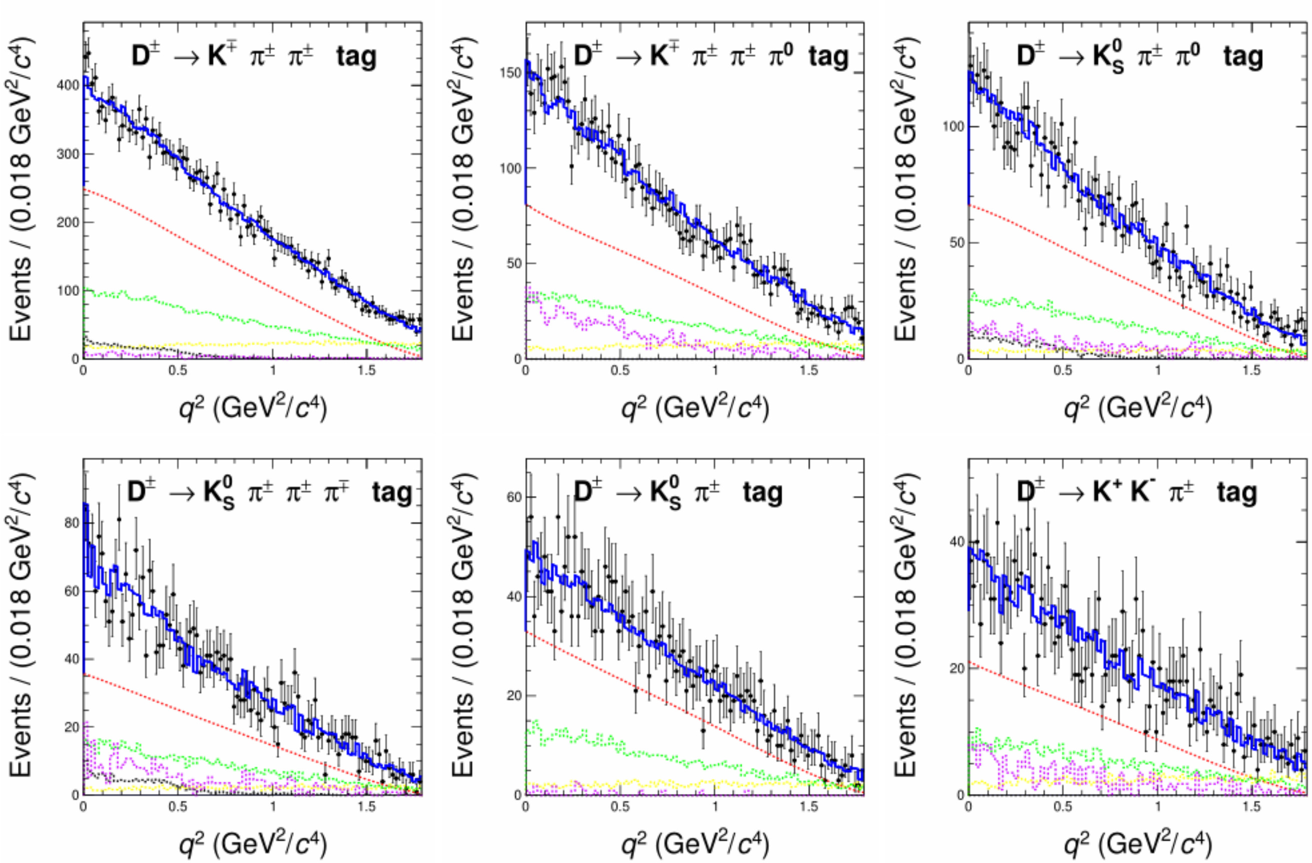
$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$
$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

with $f_+^\pi(0)/f_+^K(0)$ →

$$|V_{cd}| = 0.2155 \pm 0.0027(\text{stat}) \pm 0.0014(\text{sys}) \pm 0.0094(\text{LQCD})$$
$$|V_{cs}| = 0.9601 \pm 0.0033(\text{stat}) \pm 0.0047(\text{sys}) \pm 0.0239(\text{LQCD})$$

[1] Phys. Rev. D92, 072012 (2015); [2] Phys. Rev. D96, 012002 (2017)

03 Semi-leptonic Decays: $D^+ \to K_L^0 e^+ \nu_e$



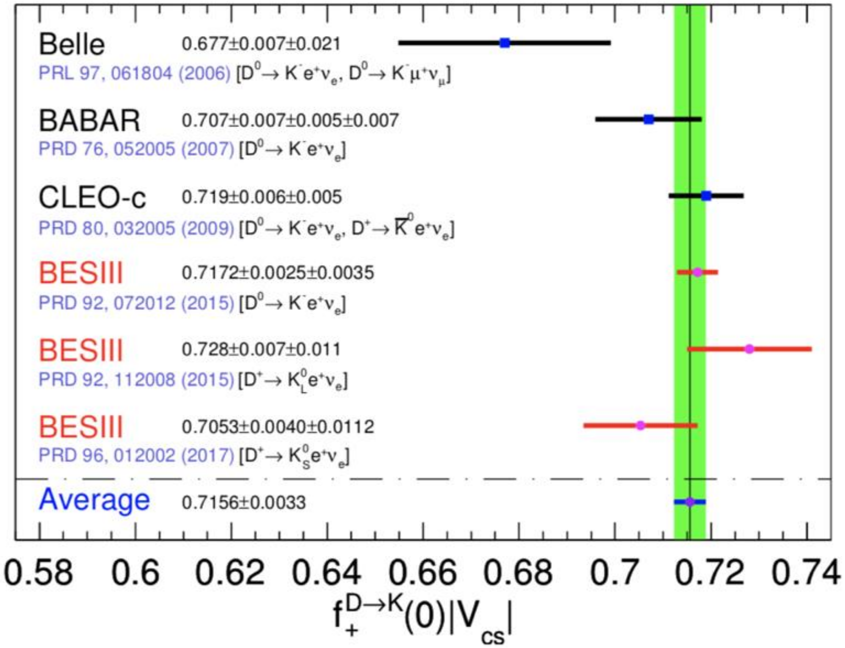
$$\overline{B}(D^+ \to K_L e^+ \nu_e) = (4.482 \pm 0.027 \pm 0.103)\%$$

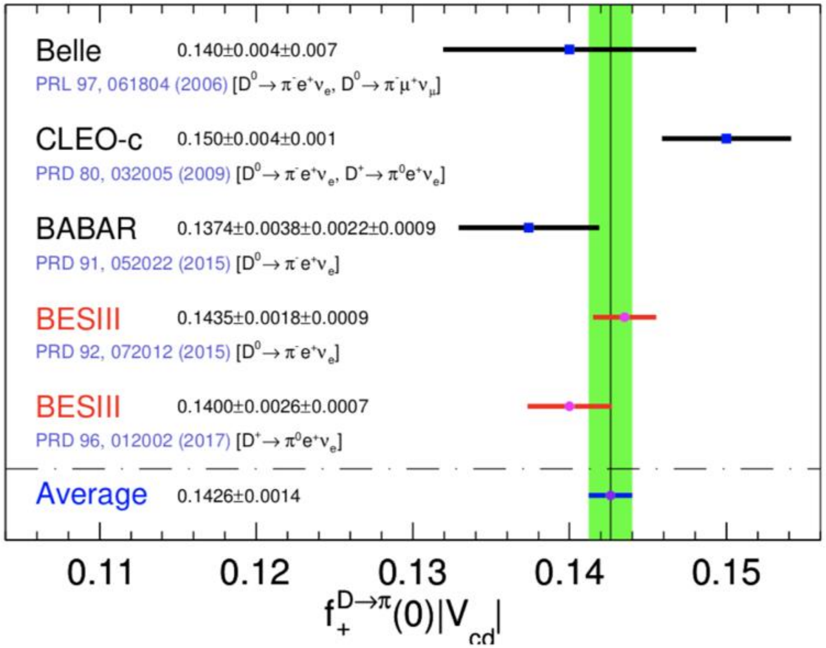
$$A_{CP} \equiv \frac{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) - \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}{\mathcal{B}(D^+ \to K_L^0 e^+ \nu_e) + \mathcal{B}(D^- \to K_L^0 e^- \bar{\nu}_e)}$$

$$f_+^K(0)|V_{cs}| = 0.728 \pm 0.006 \pm 0.011$$

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

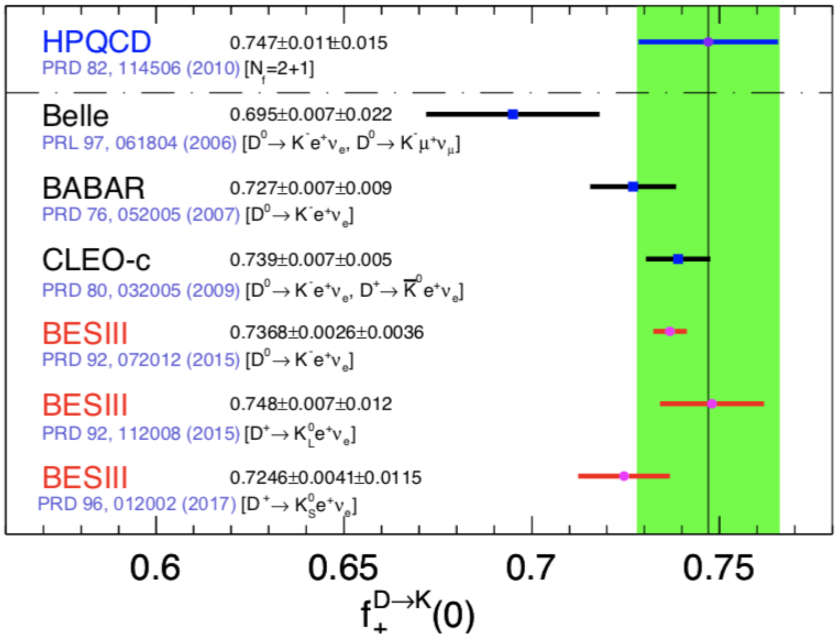
03 Semi-leptonic Decays: $|V_{cs}|$ and $|V_{cd}|$

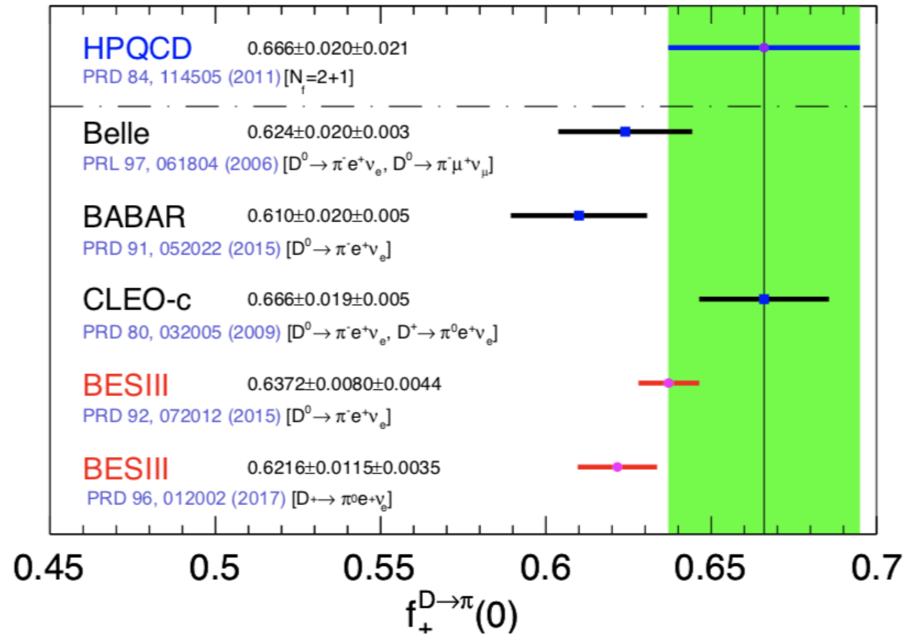




- BESIII contribute to the $|V_{cd(s)}|$ determination dominantly
- $|V_{cd}| = 0.214 \pm 0.002_{\rm exp.} \pm 0.009_{\rm LQCD}$, $|V_{cs}| = 0.958 \pm 0.004_{\rm exp.} \pm 0.024_{\rm LQCD}$ with LQCD calculations for $f_+^{D\to K/\pi}(0)$ [PRD 82, 114506 (2010); 84, 114505 (2011)]
- CKM matrix elements determination suffers from large LQCD uncertainties

03 Semi-leptonic Decays: $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$

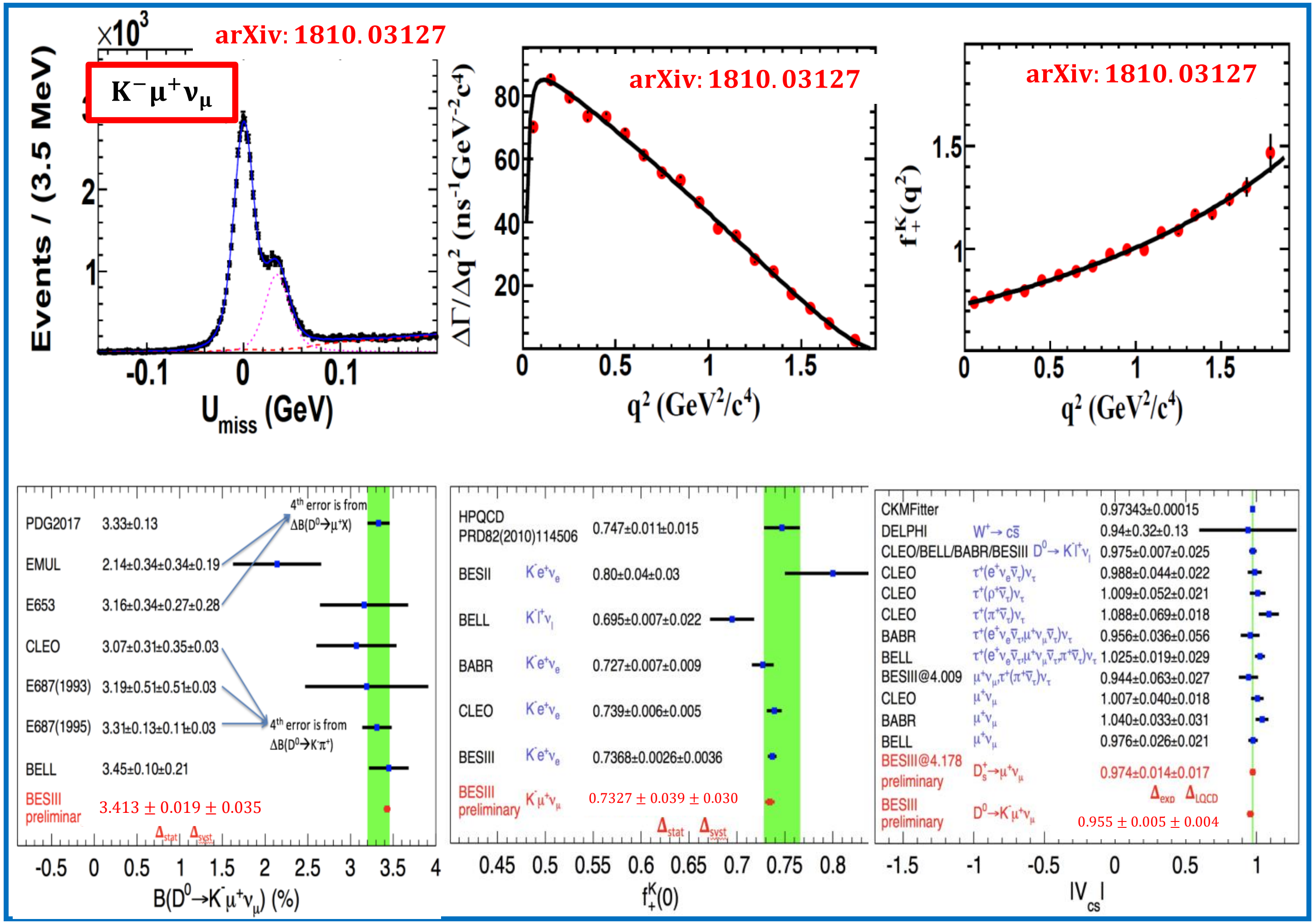




- assuming the CKM matrix is unitary, BESIII contribute to the $f_+^{D\to K/\pi}(0)$ determination dominantly

03 Semi-leptonic Decays: $D^{0/+} \to K(\pi)^{-/0}\mu^+\nu_\mu$

$B(D^0 \to K^-\mu^+\nu_\mu) = (3.413 \pm 0.019 \pm 0.035)\%$

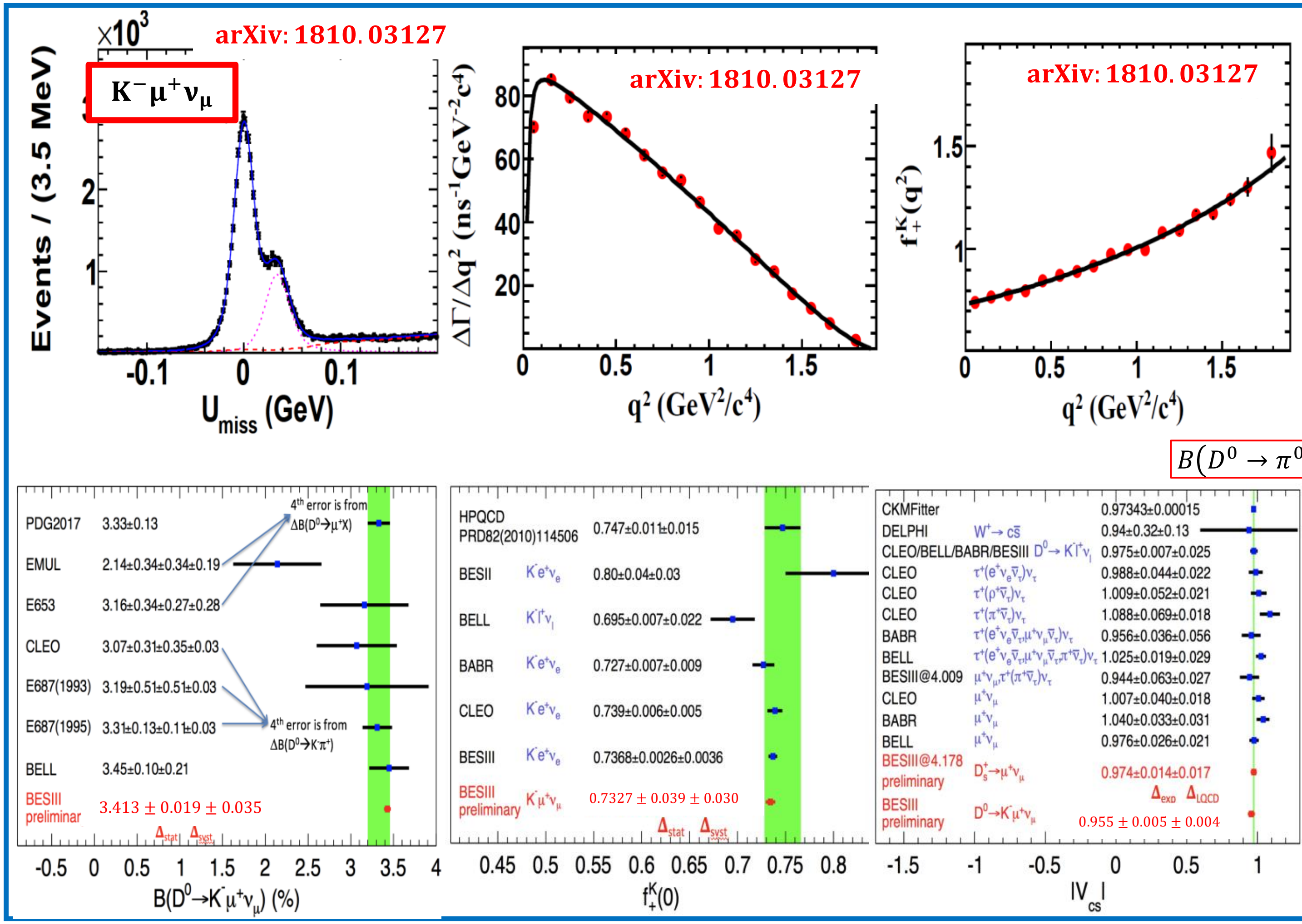


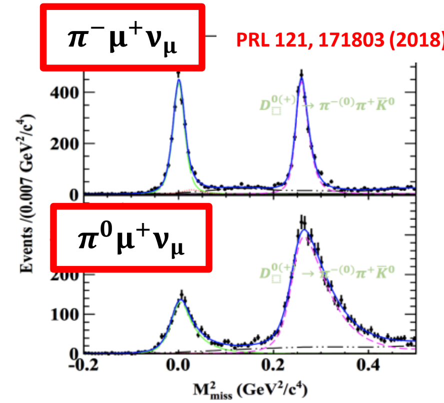
[1] Phys. Rev. Lett. 121, 171803 (2018); [2] Eur. Phys. J. C76, 369 (2016);

03 Semi-leptonic Decays: $D^{0/+} \to K(\pi)^{-/0}\mu^+\nu_\mu$

$B(D^0 \to K^-\mu^+\nu_\mu) = (3.413 \pm 0.019 \pm 0.035)\%$

$B(D^0 \to \pi^-\mu^+\nu_\mu) = (0.272 \pm 0.008 \pm 0.006)\%$





measured for the first time

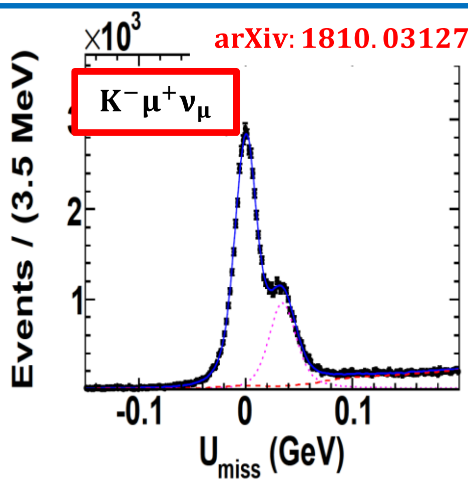
$B(D^0 \to \pi^0\mu^+\nu_\mu) = (0.350 \pm 0.011 \pm 0.010)\%$

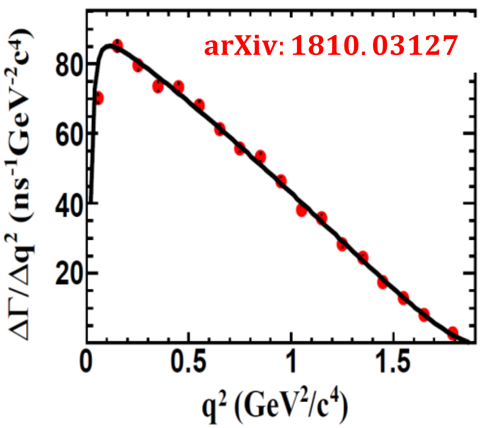
[1] Phys. Rev. Lett. 121, 171803 (2018); [2] Eur. Phys. J. C76, 369 (2016);

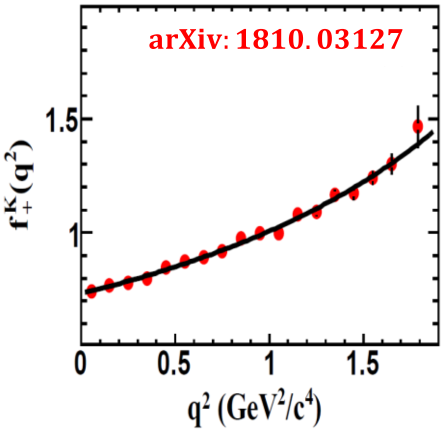
03 Semi-leptonic Decays: $D^{0/+} \to K(\pi)^{-/0}\mu^+\nu_\mu$

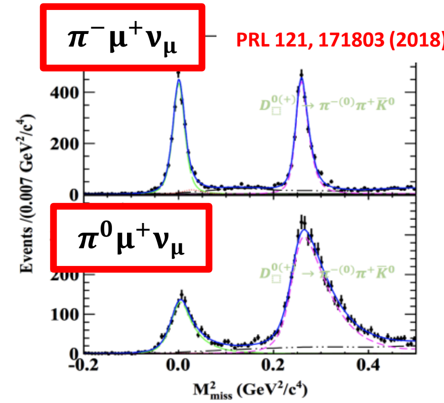
$B(D^0 \to K^-\mu^+\nu_\mu) = (3.413 \pm 0.019 \pm 0.035)\%$

$B(D^0 \to \pi^-\mu^+\nu_\mu) = (0.272 \pm 0.008 \pm 0.006)\%$



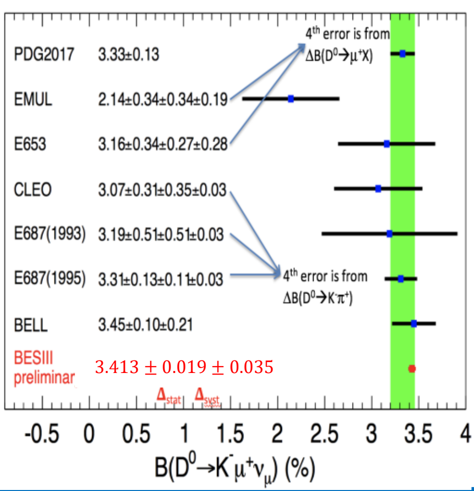


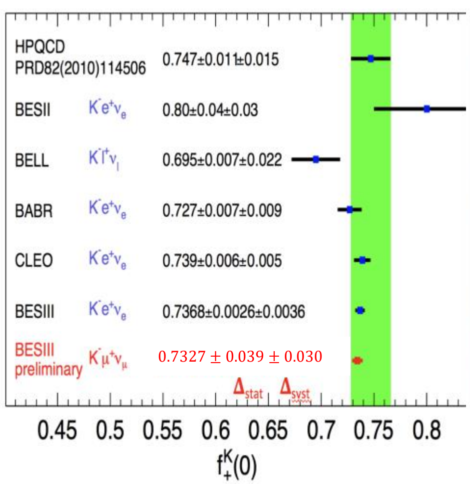


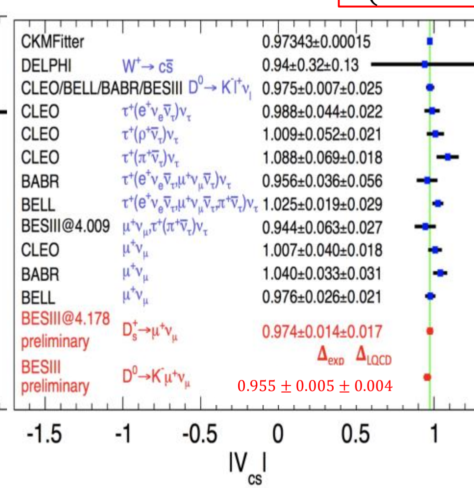


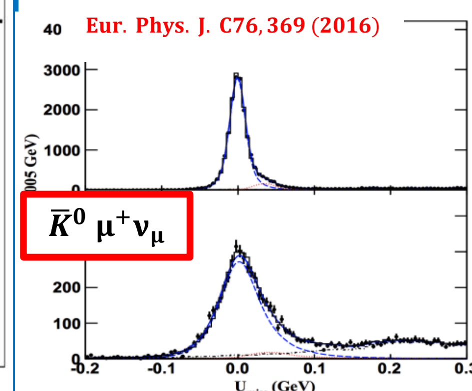
measured for the first time

$B(D^0 \to \pi^0\mu^+\nu_\mu) = (0.350 \pm 0.011 \pm 0.010)\%$





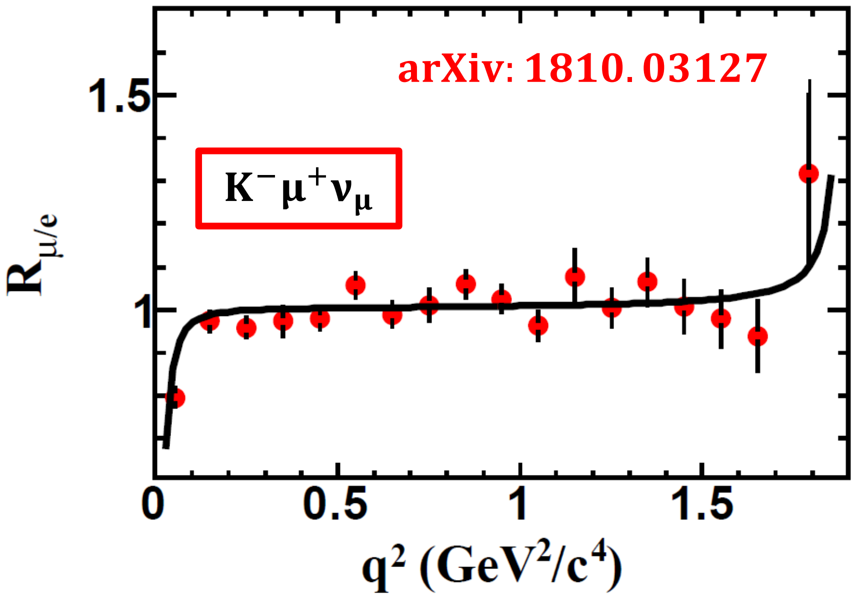




$B(D^0 \to \bar{K}^0\mu^+\nu_\mu) = (8.72 \pm 0.07 \pm 0.18)\%$

[1] Phys. Rev. Lett. 121, 171803 (2018); [2] Eur. Phys. J. C76, 369 (2016);

03 Semi-leptonic Decays: test of LFU

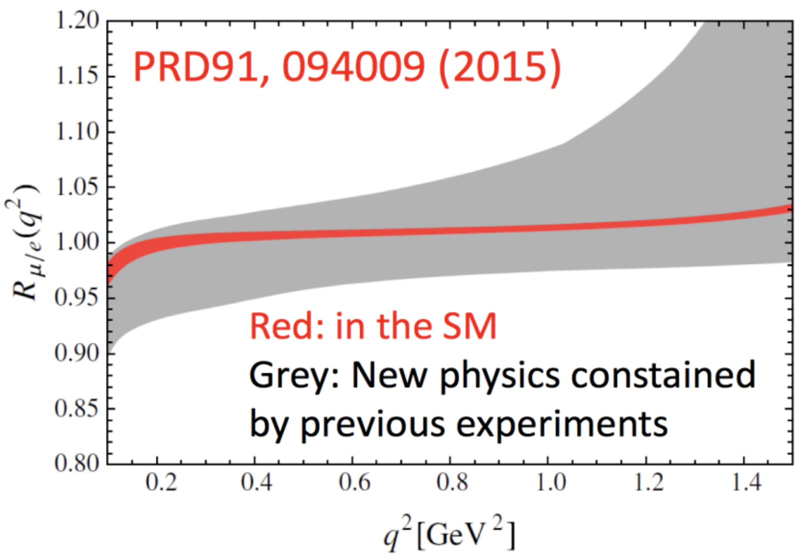


In full q^2 interval:

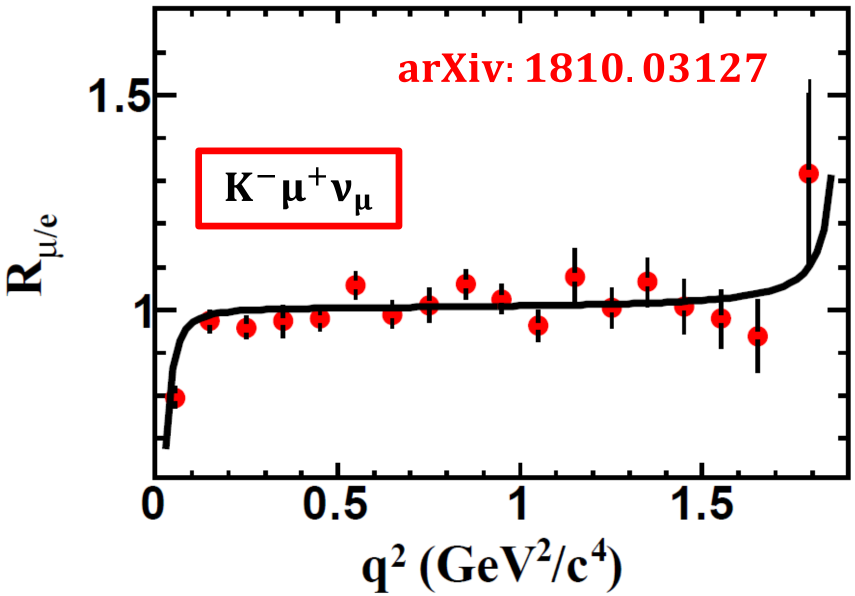
$$R^{K}_{\mu/e} = \frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)[\text{arXiv: 1810.03127}]}{\Gamma(D^0 \to K^-e^+\nu_e)[\text{PRD92, 072012(2017)}]}$$

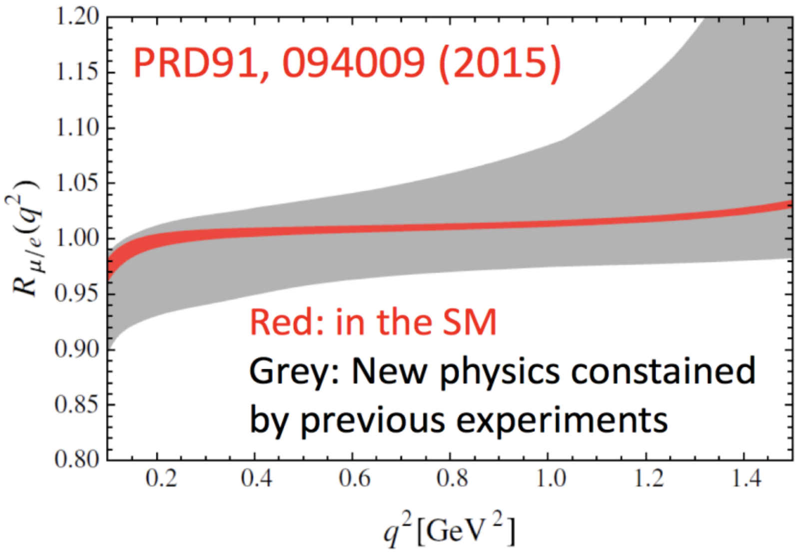
$$= 0.974 \pm 0.007 \pm 0.012$$

$$R^{K^0}_{\mu/e} = \frac{\Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)[\text{EPJC76, 369 (2016)}]}{\Gamma(D^+ \to \bar{K}^0 e^+\nu_e)[\text{PRD96,012002(2017)}]} = 1.013 \pm 0.011 \pm 0.027$$



03 Semi-leptonic Decays: test of LFU

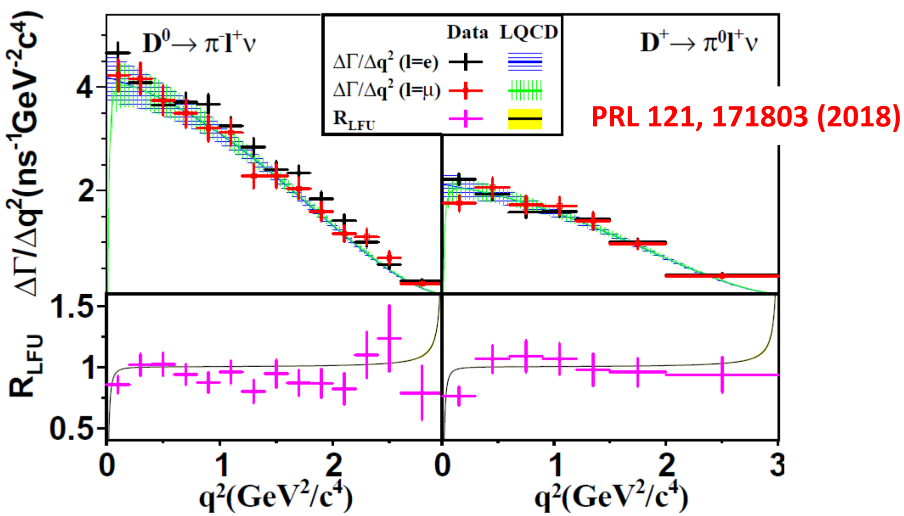




In full q^2 interval:

$$R^{K}_{\mu/e} = \frac{\Gamma(D^0 \to K^-\mu^+\nu_\mu)[\text{arXiv: 1810.03127}]}{\Gamma(D^0 \to K^-e^+\nu_e)[\text{PRD92, 072012(2017)}]} = 0.974 \pm 0.007 \pm 0.012$$

$$R^{K^0}_{\mu/e} = \frac{\Gamma(D^+ \to \bar{K}^0\mu^+\nu_\mu)[\text{EPJC76, 369 (2016)}]}{\Gamma(D^+ \to \bar{K}^0 e^+\nu_e)[\text{PRD96,012002(2017)}]} = 1.013 \pm 0.011 \pm 0.027$$

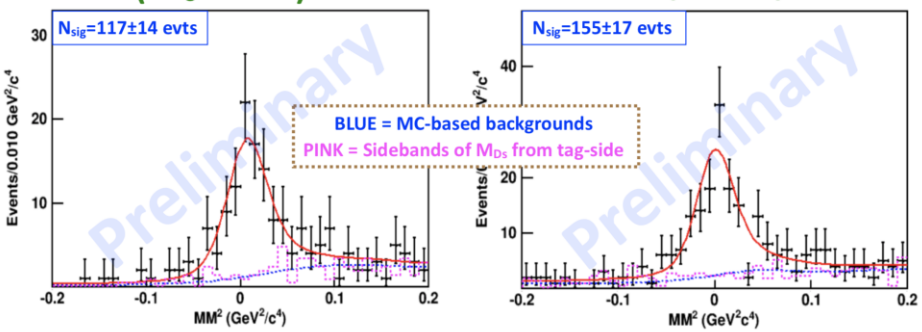


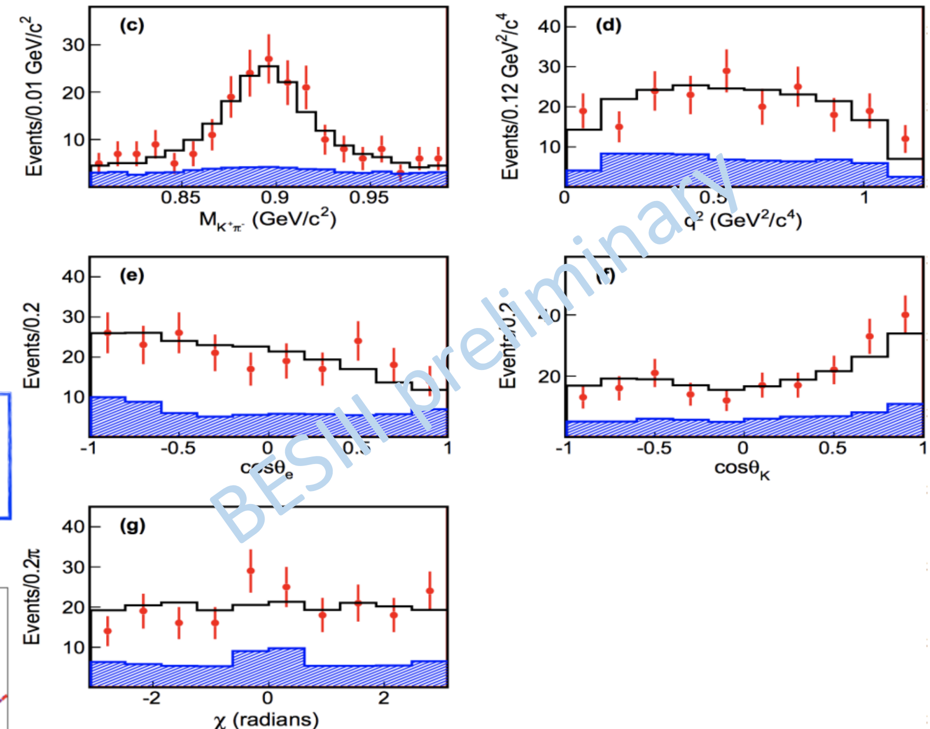
$$R^{\pi}_{\mu/e} = \frac{\Gamma(D^0 \to \pi^-\mu^+\nu_\mu)[\text{PRL 121, 171803 (2018)}]}{\Gamma(D^0 \to \pi^- e^+\nu_e)[\text{PRD92,072012(2017)}]} = 0.922 \pm 0.030 \pm 0.022$$

$$R^{\pi^0}_{\mu/e} = \frac{\Gamma(D^+ \to \pi^0\mu^+\nu_\mu)[\text{PRL 121, 171803 (2018)}]}{\Gamma(D^+ \to \pi^0 e^+\nu_e)[\text{PRD96,012002(2017)}]} = 0.964 \pm 0.037 \pm 0.026$$

03 Semi-leptonic Decays: $D_S^+ \to K^{(*)0} e^+ \nu_e$

$K^0(=K_S \to \pi^+\pi^-)e\nu$ $K^{*0}(\to K^+\pi^-)e\nu$

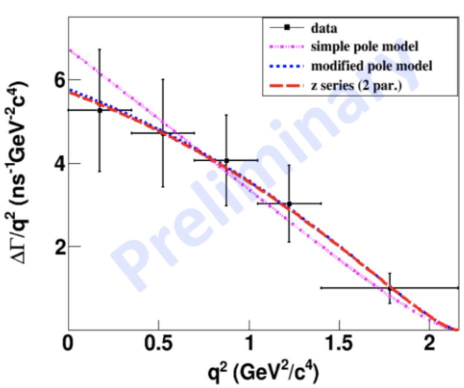


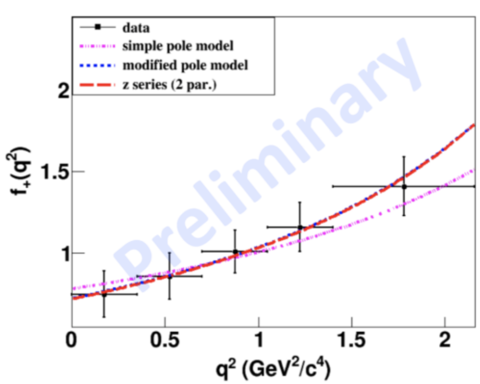


Preliminary results

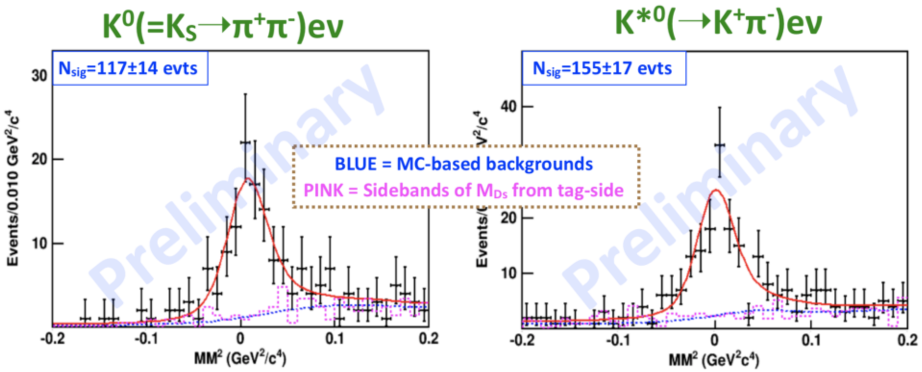
BF($D_s \to K^0$ e ν) = (3.25±0.38±0.14)×10^{-3} : (3.9±0.9)×10^{-3} [PDG2017]

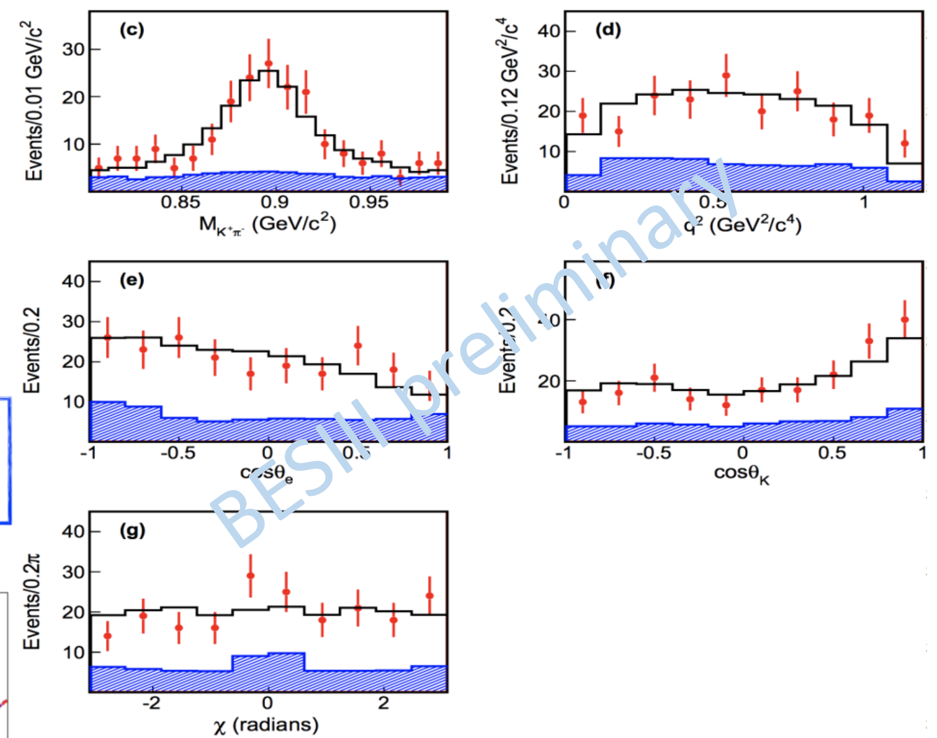
BF($D_s \to K^{*0}$ e ν) = (2.38±0.26±0.12)×10^{-3} : (1.8±0.4)×10^{-3} [PDG2017]





03 Semi-leptonic Decays: $D_S^+ \to K^{(*)0} e^+ \nu_e$

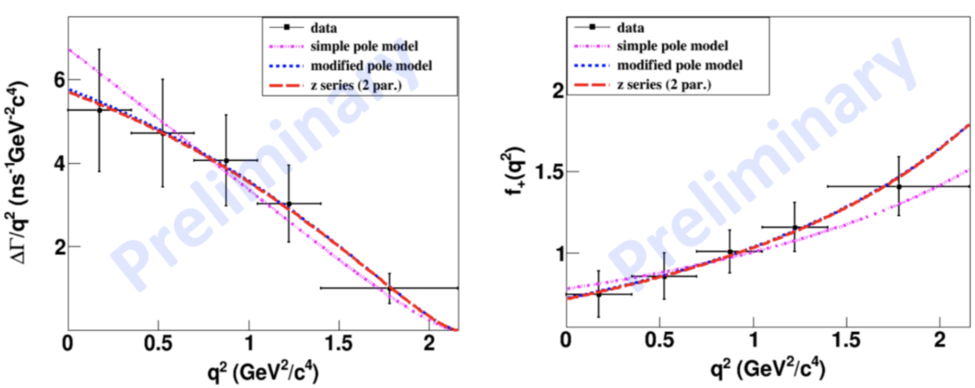




Preliminary results

BF($D_s \to K^0$ e ν) = $(3.25\pm0.38\pm0.14)\times10^{-3}$: $(3.9\pm0.9)\times10^{-3}$ [PDG2017]

BF($D_s \to K^{*0}$ e ν) = $(2.38\pm0.26\pm0.12)\times10^{-3}$: $(1.8\pm0.4)\times10^{-3}$ [PDG2017]



The FFs in $D_S^+ \to K^0 e^+ \nu_e$ are extracted for the first time:

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

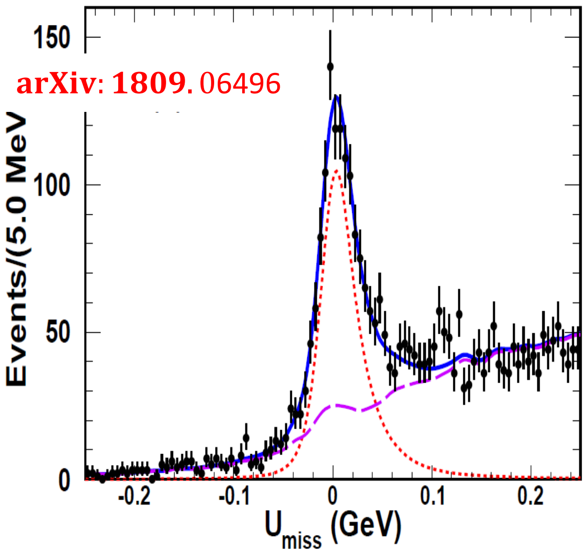
The form factor ratios in $D_S^+ \to K^{*0} e^+ \nu_e$ are extracted for the first time:

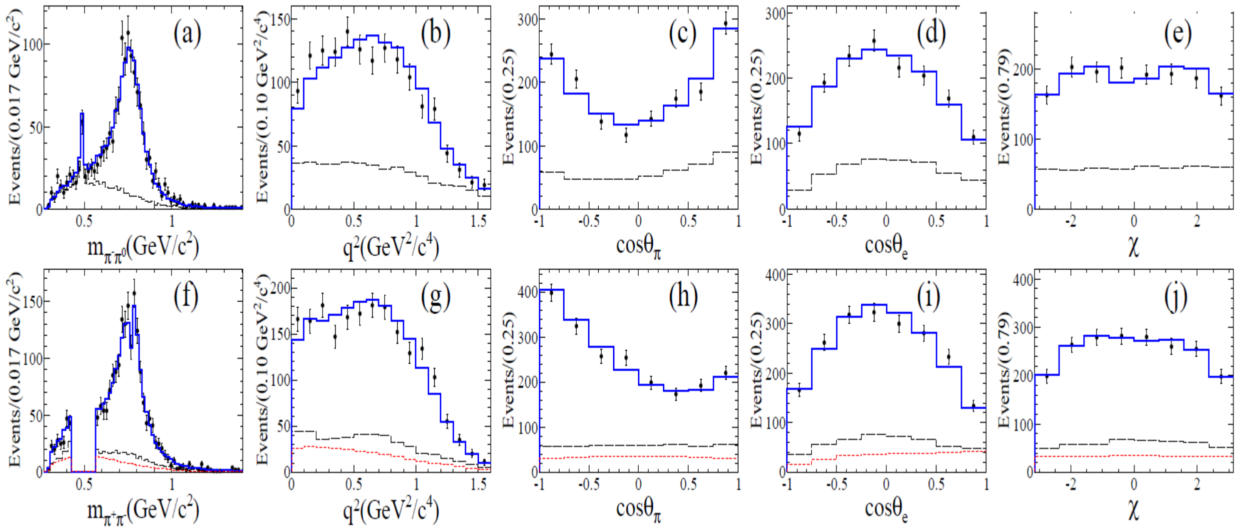
$$r_V = \frac{V(0)}{A_1(0)} = 1.67 \pm 0.34 \pm 0.16$$

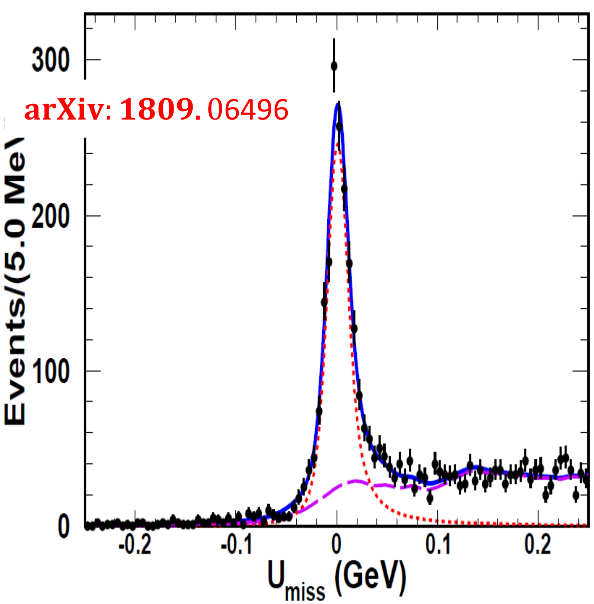
$$r_2 = \frac{A_2(0)}{A_1(0)} = 0.77 \pm 0.28 \pm 0.07$$

03 Semi-leptonic Decays: $D^{0/+} \to \pi^+\pi^{-/0}e^+\nu_e$

arXiv: 1809.06496



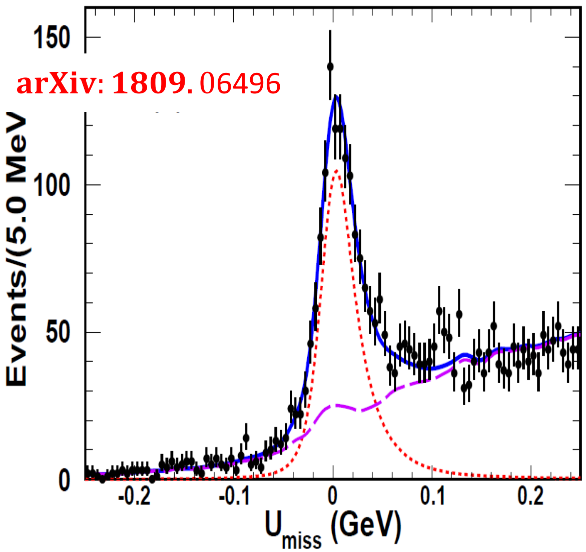




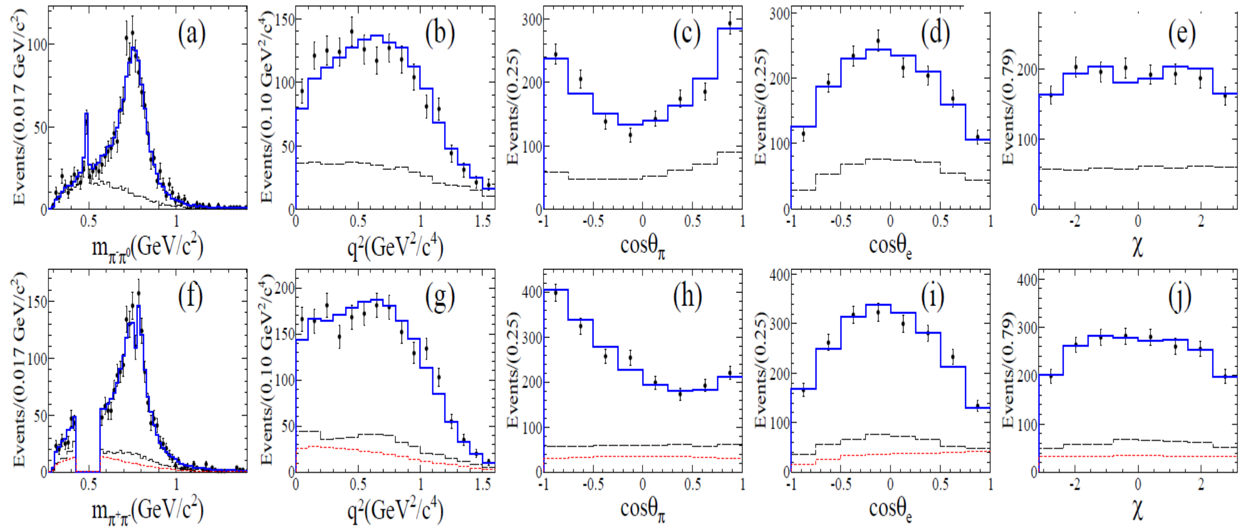
arXiv: 1809.06496

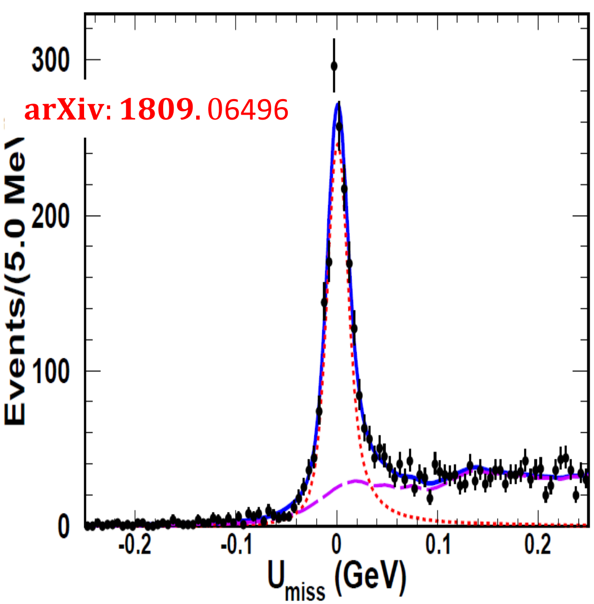
Signal mode	this analysis ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)
$D^0 \to \pi^-\pi^0 e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$	–
$D^0 \to \rho^- e^+\nu_e$	$1.445 \pm 0.058 \pm 0.039$	1.77 ± 0.16
$D^+ \to \pi^-\pi^+ e^+\nu_e$	$2.449 \pm 0.074 \pm 0.073$	–
$D^+ \to \rho^0 e^+\nu_e$	$1.860 \pm 0.070 \pm 0.061$	$2.18^{+0.17}_{-0.25}$
$D^+ \to \omega e^+\nu_e$	$2.05 \pm 0.66 \pm 0.30$	1.69 ± 0.11
$D^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-$	$0.630 \pm 0.043 \pm 0.032$	–
$D^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^+\pi^-$	< 0.028	–

03 Semi-leptonic Decays: $D^{0/+} \to \pi^+\pi^{-/0}e^+\nu_e$



arXiv: 1809.06496





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$D^+ \to \pi^-\pi^+ e^+\nu_e$	$2.449 \pm 0.074 \pm 0.073$	–
$D^+ \to \rho^0 e^+\nu_e$	$1.860 \pm 0.070 \pm 0.061$	$2.18^{+0.17}_{-0.25}$
$D^+ \to \omega e^+\nu_e$	$2.05 \pm 0.66 \pm 0.30$	1.69 ± 0.11
$D^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-$	$0.630 \pm 0.043 \pm 0.032$	–
$D^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^+\pi^-$	< 0.028	–

- The $\pi^+\pi^-$ S-Wave contribution is observed for the first time;
- Hadronic FF ratios $D \to \rho e^+\nu_e$ at q^2=0 are obtained:

$$r_V = \frac{V(0)}{A_1(0)} = 1.695 \pm 0.083 \pm 0.051 \qquad r_2 = \frac{A_2(0)}{A_1(0)} = 0.845 \pm 0.056 \pm 0.039$$

04 Summary

- Measurements of $D^+ \to \mu^+\nu_\mu$; $D^+ \to \tau^+\nu_\mu$; $D_S^+ \to \mu^+\nu_\mu$, $f_{D_{(S)}^+}$ and CKM elements:

$$\mathbf{f_{D^+}|V_{cd}| = (45.75 \pm 1.20 \pm 0.39)\ MeV}$$

$$\mathbf{f_{D_S^+}|V_{cs}| = (242.5 \pm 3.5 \pm 3.7)\ MeV}$$

$\mathbf{f_{D^+} = (203.2 \pm 5.3 \pm 1.8)\ MeV}$

$\mathbf{f_{D_S^+} = (249.1 \pm 3.6 \pm 3.8)\ MeV}$

← with $|V_{cd}|/|V_{cs}|$

with $f_{D^+}/f_{D_S^+}$ →

$\mathbf{|V_{cd}| = 0.2210 \pm 0.0058 \pm 0.0047}$

$\mathbf{|V_{cs}| = 0.974 \pm 0.014 \pm 0.016}$

04 Summary

- Measurements of $D^+ \to \mu^+\nu_\mu$; $D^+ \to \tau^+\nu_\mu$; $D_S^+ \to \mu^+\nu_\mu$, $f_{D_{(S)}^+}$ and CKM elements:

$$\mathbf{f_{D^+}|V_{cd}| = (45.75 \pm 1.20 \pm 0.39)\ MeV}$$

$$\mathbf{f_{D_S^+}|V_{cs}| = (242.5 \pm 3.5 \pm 3.7)\ MeV}$$

$$\mathbf{f_{D^+} = (203.2 \pm 5.3 \pm 1.8)\ MeV}$$

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$$f_+^\pi(0)|V_{cd}| = 0.1435 \pm 0.0018 \pm 0.0009$$

$$f_+^K(0)|V_{cs}| = 0.7172 \pm 0.0025 \pm 0.0035$$

← with $|V_{cd}|/|V_{cs}|$ | with $f_+^\pi(0)/f_+^K(0)$ →

$$f_+^\pi(0) = 0.6372 \pm 0.0080 \pm 0.0044$$

$$f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$$

$$|V_{cd}| = 0.2155 \pm 0.0027(\text{stat}) \pm 0.0014(\text{sys}) \pm 0.0094(\text{LQCD})$$

$$|V_{cs}| = 0.9601 \pm 0.0033(\text{stat}) \pm 0.0047(\text{sys}) \pm 0.0239(\text{LQCD})$$

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- Measurements of $D^+ \to K^0_{(L)}(\pi^0)e^+\nu_e(\mu^+\nu_\mu)$ and test of LFU:

	$R(D_s^+)$	$R(D^+)$	$R(K^-)$	$R(\bar{K}^0)$	$R(\pi^-)$	$R(\pi^0)$
SM	9.74(1)	2.66(1)	0.975(1)	0.975(1)	0.985(2)	0.985(2)
BESIII	10.19(52)	3.21(64)	0.974(14)	1.013(29)	0.922(37)	0.964(45)

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- Measurements of $\boldsymbol{D_S^+ \to K^{(*)0}e^+\nu_e}$ and $\boldsymbol{D^{0/+} \to \pi^+\pi^{-/0}e^+\nu_e}$

THANKS

谢谢！

Study of the form factors in $D_s^+ \to K^0 e^+ \nu_e$

The differential decay width for $D_s^+ \to K^0 e^+ \nu_e$ is given by

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

where p_{K^0} is the momentum in the rest frame of the D_s^+ meson.

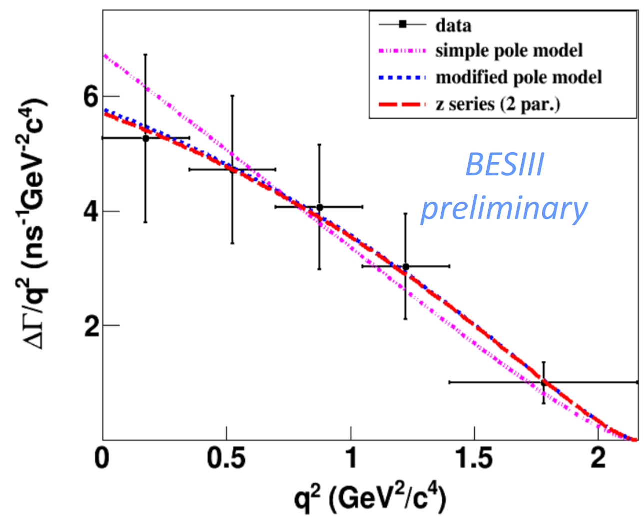
$$q^2 = (E_{\rm cm} - E_{D_s^-} - E_\gamma - E_{K^0})^2 - (|-\vec{p}_{D_s^-} - \vec{p}_\gamma - \vec{p}_{K^0}|)^2.$$

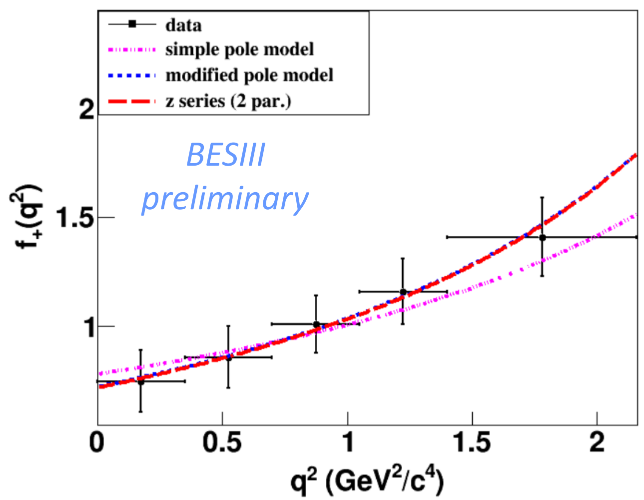
The parametrization of form factors:

- Simple pole model:
  $f_+(q^2) = \frac{f_+(0)}{1 - q^2/M^2_{\rm pole}}$, where $m_{\rm pole} = m_{D_s^{*+}} = 2112.1 \pm 0.4$ MeV/c^2.
- Modified pole model:
  $f_+(q^2) = \frac{f_+(0)}{(1 - q^2/M^2_{\rm pole})(1 - \alpha q^2/M^2_{\rm pole})}$.
- Series expansion [two parameters]:
  $f_+(t) = \frac{1}{P(t)\Phi(t,t_0)} a_0(t_0)(1 + \sum_{k=1}^{\infty} r_k(t_0)[z(t,t_0)]^k)$.

Fit to partial decay rates in $D_s^+ \to K^0 e^+ \nu_e$

$$\chi^2 = \sum_{ij} (\Delta\Gamma_i^{\rm measured} - \Delta\Gamma_i^{\rm expected}) \mathcal{C}_{ij}^{-1} (\Delta\Gamma_j^{\rm measured} - \Delta\Gamma_j^{\rm expected})$$

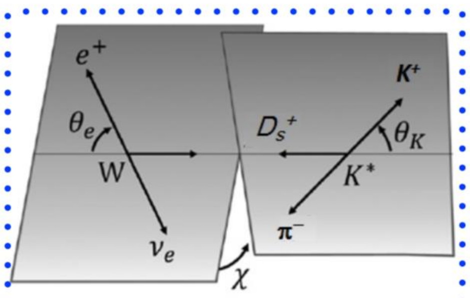




Extracting FF for $D_s \rightarrow K^{*0} e \nu$

- **The differential decay rate depends on 5 variables (PRL 110,131802) and cab be expressed in terms of 3 helicity amplitudes:**

$$\frac{d^5\Gamma}{dm_{K\pi}dq^2 dcos\theta_K dcos\theta_e d\chi} = \frac{3}{8(4\pi)^4}G_F^2|V_{cd}|^2\frac{p_{K\pi}q^2}{M_{D_s}^2}\mathcal{B}(K^{*0}\to K^+\pi^-)|\mathcal{BW}(m_{K\pi})|^2$$



$$\begin{aligned}
&\times\ [(1+cos\theta_e)^2 sin^2\theta_K|H_+(q^2,m_{K\pi})|^2 \\
&+\ (1-cos\theta_e)^2 sin^2\theta_K|H_-(q^2,m_{K\pi})|^2 \\
&+\ 4sin^2\theta_e cos^2\theta_K|H_0(q^2,m_{K\pi})|^2 \\
&+\ 4sin\theta_e(1+cos\theta_e)sin\theta_K cos\theta_K cos\chi H_+(q^2,m_{K\pi})H_0(q^2,m_{K\pi}) \\
&-\ 4sin\theta_e(1-cos\theta_e)sin\theta_K cos\theta_K cos\chi H_-(q^2,m_{K\pi})H_0(q^2,m_{K\pi}) \\
&-\ 2sin^2\theta_e sin^2\theta_K cos2\chi H_+(q^2,m_{K\pi})H_-(q^2,m_{K\pi})].
\end{aligned}$$

The helicity amplitudes of $H_+(q^2)$, $H_-(q^2)$ and $H_0(q^2)$ take the form of $H_\pm(q^2) = (M_{D_s}+m_{K\pi})A_1(q^2) \mp \frac{2M_{D_s}P_{K\pi}}{M_{D_s}+M_{K\pi}}V(q^2)$ and

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

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

- **We perform 5 dimensional fit to extract the form factor ratios, *r_V* and *r_2*.**