(Semi-)leptonic charm decays at BESIII

报告人：马海龙

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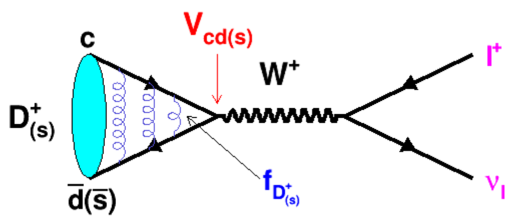
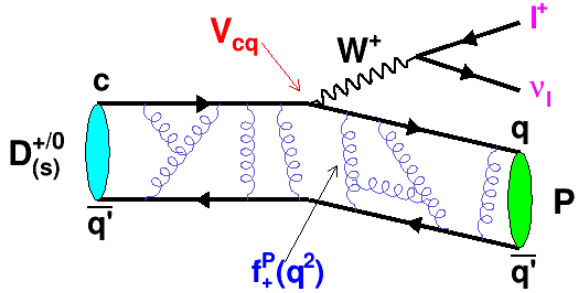
Introduction

c→s/de⁺v跃迁中强、弱作用能够很好分离





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

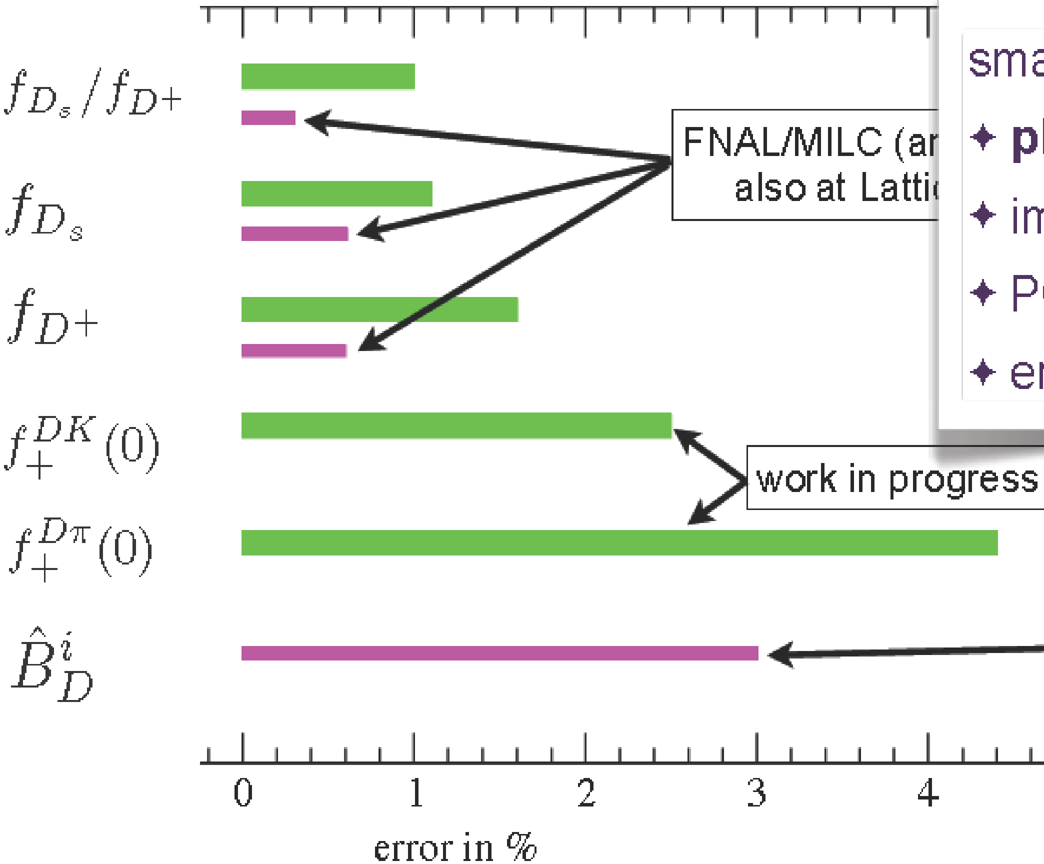
$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$$

状态:2001年，$|V_{cs(d)}|$精度7(16)%。人们寄望D半轻衰变精密测量$|V_{cs(d)}|$。至2012年，精度大约2.5(4.8)%。但长期以来，半轻测量受制于LQCD对形状因子计算精度。

- 测定CKM矩阵元$|V_{cs}|$和$|V_{cd}|$→检验CKM矩阵幺正性
- 测定衰变常数$f_{D(s)+}$, 形状因子$f_+^{D\to h}(0)$…→检验LQCD计算
- 测定(微分)衰变率→检验e–μ和μ–τ轻子普适性
- 寻找D→Sev或Aev→探讨标量介子S和轴矢量介子A性质

Progress of LQCD before BESIII

errors (in %) comparison: FLAG-2 averages vs. new results



small errors due to

- ✦ **physical light quark masses**
- ✦ improved charm-quark action (HISQ)
- ✦ PCAC (no renormalization)
- ✦ ensembles with small lattice spacings

- **First results for D mixing bag parameters** (all five) with local operators only by ETM (2013, 2014) $n_f = 2, 2+1+1$
- work in progress: FNAL/MILC (Lattice 2014)

review by C. Bouchard @ Lattice 2014

- **2018年，FNAL/MILC对$f_{D(s)}$计算精度达到0.2%**

Recent $D^{0(+)}$, D_s^+ and Λ_c^+ samples

Taking from Longke Li's talk at joint workshop of BESIII/Belle/LHCb at Nankai

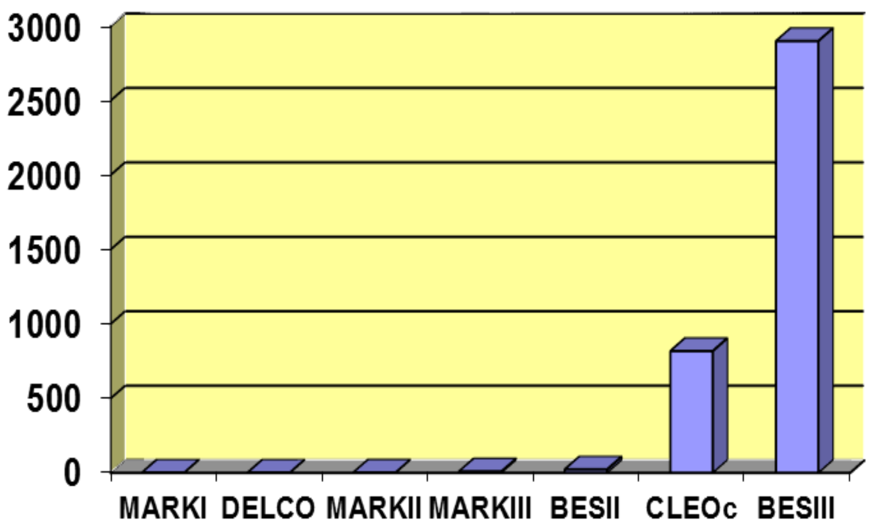
Experiment	Machine	C.M	Lumin.	N(D)	efficiency	advantage/disadvantage
CLEO	CESR (e^+e^-)	3.77 GeV	0.8 fb^{-1}	2.9×10^6 $2.3 \times 10^6 (D^\pm)$	~10-30%	☺ extremely clean enviroment ☺ pure D-beam, almost no bkg ☺ quantum coherence ☹ no CM boost, no T-dep analyses
		4.17 GeV	0.6 fb^{-1}	0.6×10^6		
BESIII	BEPC-II (e^+e^-)	3.77 GeV	2.92 fb^{-1}	10.5×10^6 8.4×10^6 $D^{0(+)}$		
		4.18 GeV	3 fb^{-1} D_s^+	3×10^6		
		4.6 GeV	**0.567 fb^{-1}** Λ_c^+	★	★★★	
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	1.3×10^9	~5-10%	☺ clear event environment ☺ high trigger efficiency ☺ high-efficiency detection of neutrals ☺ many high-statistics control samples ☺ time-dependent analysis ☹ smaller cross-section than pp colliders
	PEP-II (e^+e^-)	10.58 GeV	0.5 ab^{-1}	6.5×10^8 ★★	★★	
CDF	Tevatron ($p\bar{p}$)	1.96 TeV	9.6 fb^{-1}	1.3×10^{11}	<0.5%	☺ large production cross-section ☺ large boost: excellent time resolution ☹ dedicated trigger required ☹ hard to do neutrals and neutrinos
LHCb	LHC (pp)	7 TeV 8 TeV	1.0 fb^{-1} 2.0 fb^{-1}	5.0×10^{12} ★★★	★	

- **CLEOc, Belle和BaBar实验开展了粲介子纯轻半轻衰变测量**

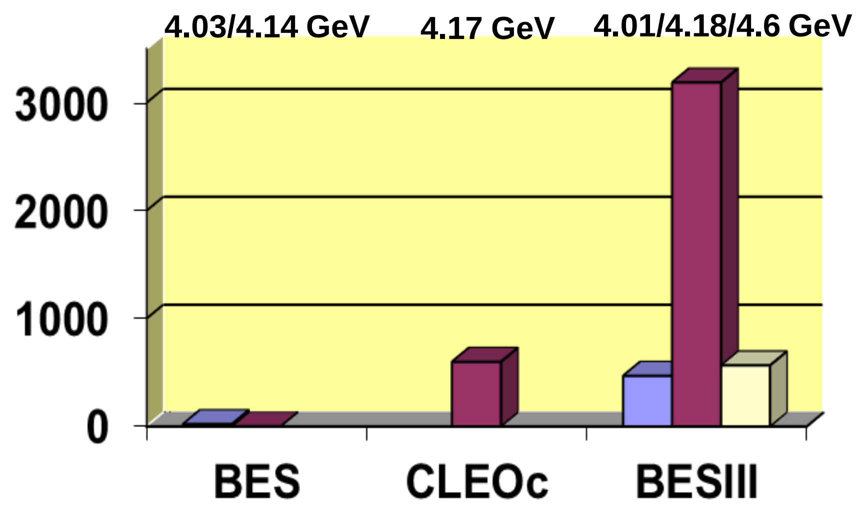
世界上最大的近阈粲强子样本

- 2010-2011年: 2.9 fb^{-1}@3.773 GeV

D^0、D^+ 约11月

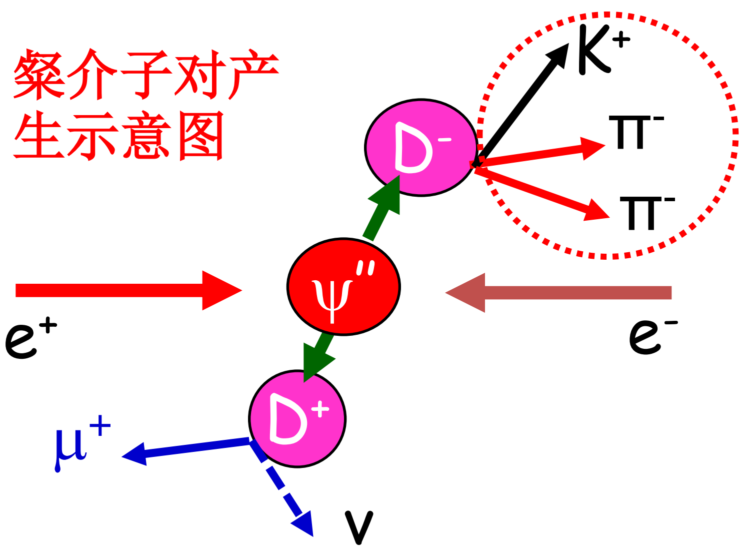


- 2014年: 0.6 fb^{-1}@4.6 GeV Λ_c^+
- 2016年: 3.2 fb^{-1}@4.18 GeV D_s^+



约1/5/1月

粲介子对产生示意图



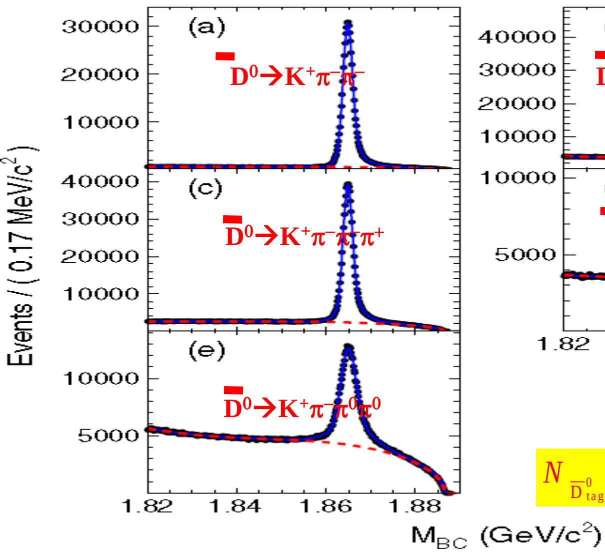
优势：产额大、背景低、系统误差小，可测量绝对分支比

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

- BESIII实验研究需增加统计量、发挥近阈优势、改进系统误差

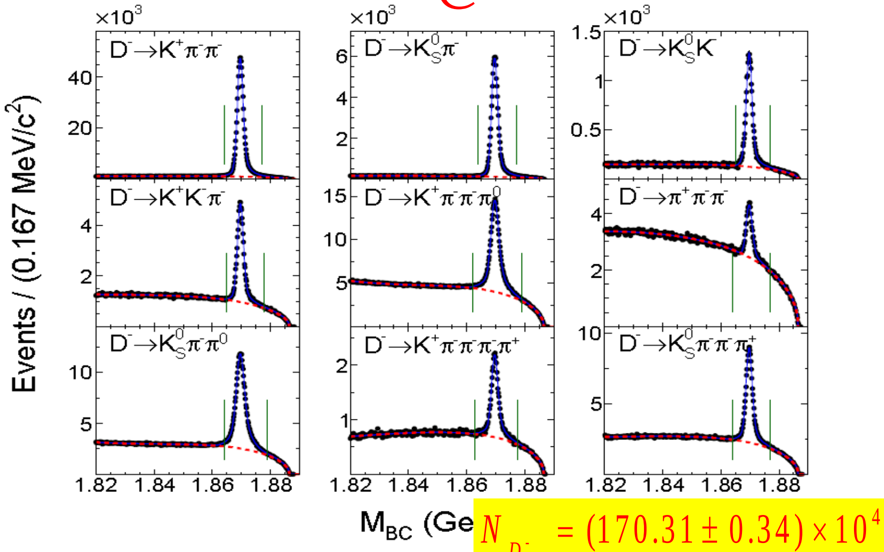
单标记$D^{0(+)}$、D_s^+和Λ_c^+样本

$e^+e^- \rightarrow D^0\bar{D}^0$ @3.773 GeV



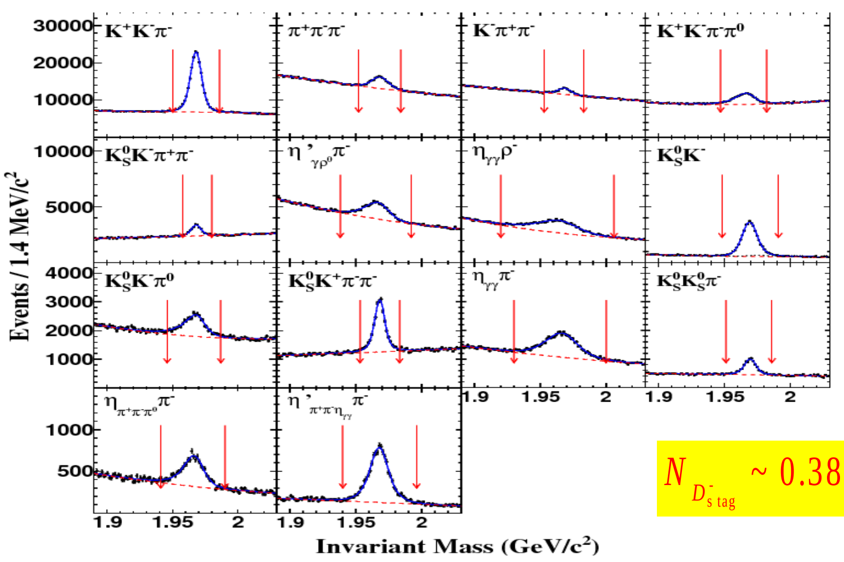
$N_{\bar{D}^0_{tag}} = (279.33 \pm 0.37) \times 10^4$

$e^+e^- \rightarrow D^+D^-$ @3.773 GeV



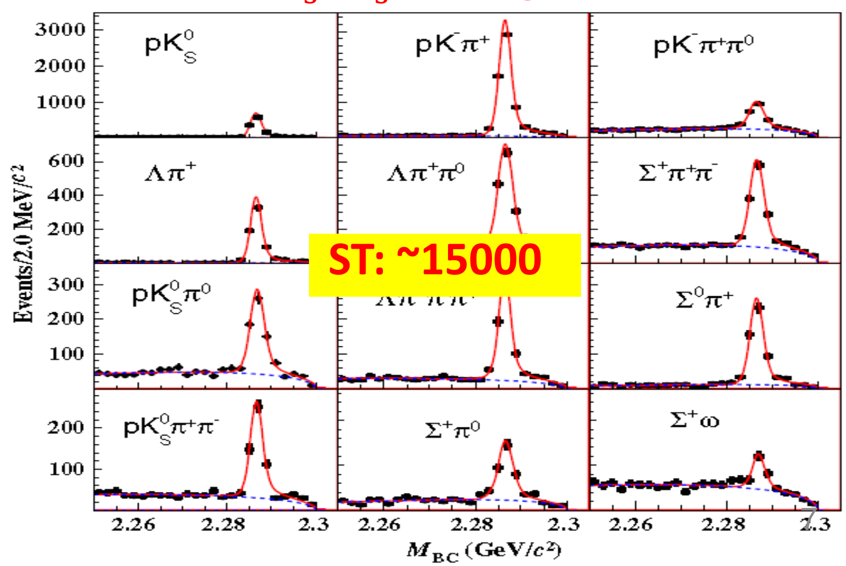
$N_{D^-_{tag}} = (170.31 \pm 0.34) \times 10^4$

$e^+e^- \rightarrow D_s^{*+}D_s^- + c.c.$@4.18 GeV



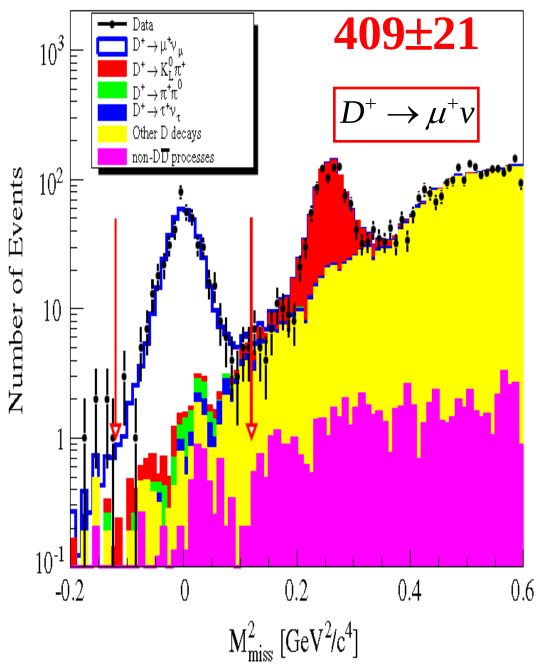
$N_{D^-_{s\ tag}} \sim 0.389$M

$e^+e^- \rightarrow \Lambda_s^+\Lambda_s^- + c.c.$@4.18 GeV



纯轻衰变$D^+\to l^+\nu$研究

PRD89(2014)051104

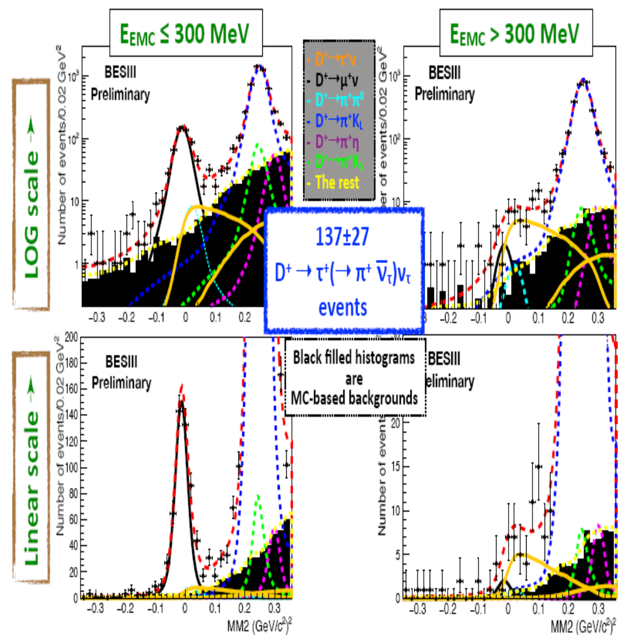


$$B[D^+\to\mu^+\nu]=(3.71\pm0.19\pm0.06)\times10^{-4}$$

$$\boxed{f_{D^+}|V_{cd}|=46.7\pm1.2\pm0.4\,\mathrm{MeV}}$$

BESIII初步结果

$\boxed{D^+\to\tau^+\nu}$ Fitting to DATA >5σ



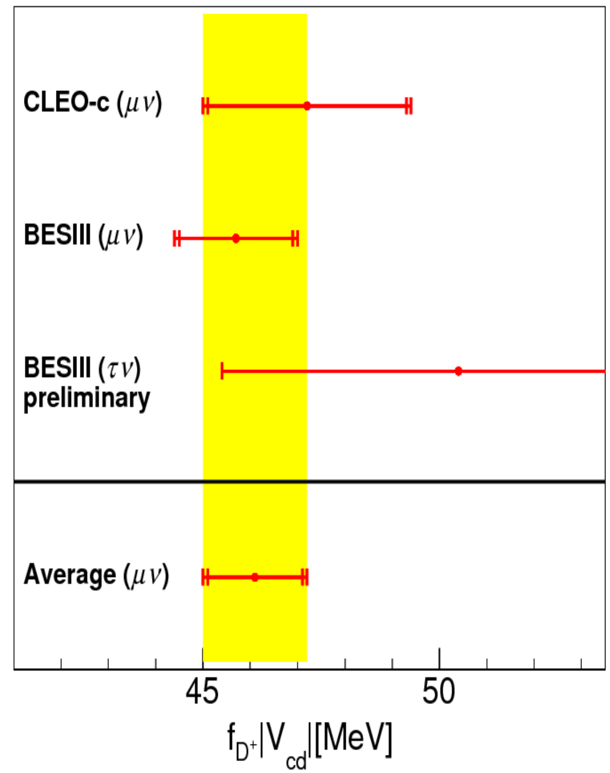
$$B[D^+\to\tau^+\nu]=(1.20\pm0.24_{stat})\times10^{-3}$$

$$\boxed{f_{D^+}|V_{cd}|=50.4\pm5.0_{stat}\,\mathrm{MeV}}$$

统计误差主导

New inputs from PDG2018:

	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
m_{D^+}	1.86965(5) GeV
τ_{D^+}	1.040(7) ps
G_F	$1.1663787(6)\times10^{-5}$ GeV^{-2}

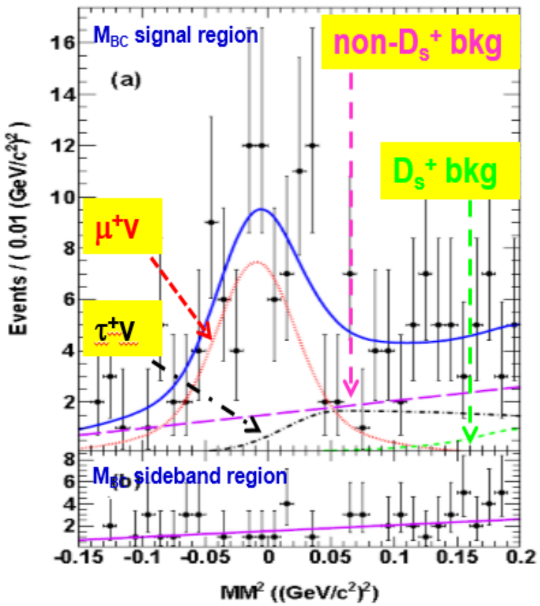


BESIII首次提出使用D^+纯轻衰变测量$|V_{cd}|$

纯轻衰变$D_s^+ \to l^+ \nu$研究

0.48 fb^{-1} data@4.01 GeV

PRD94(2016)072004



$$B[D_s^+ \to \mu^+ \nu] = (5.17 \pm 0.75 \pm 0.21) \times 10^{-3}$$

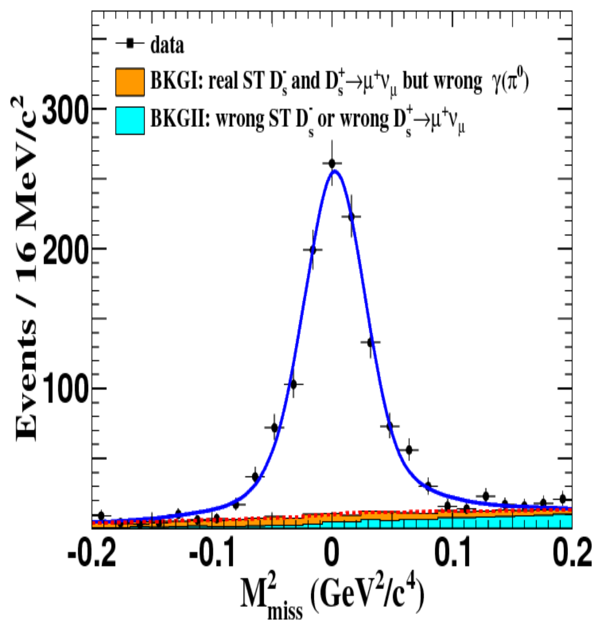
$$B[D_s^+ \to \tau^+ \nu] = (3.28 \pm 1.83 \pm 0.37)\%$$

$$\boxed{f_{D_s^+} | V_{cs} | = 239 \pm 17 \pm 5 \, \text{MeV}[\mu]}$$

$$\boxed{f_{D_s^+} | V_{cs} | = 193 \pm 54 \pm 11 \, \text{MeV}[\tau]}$$

3.19 fb^{-1} data@4.178 GeV

PRL122(2019)071802

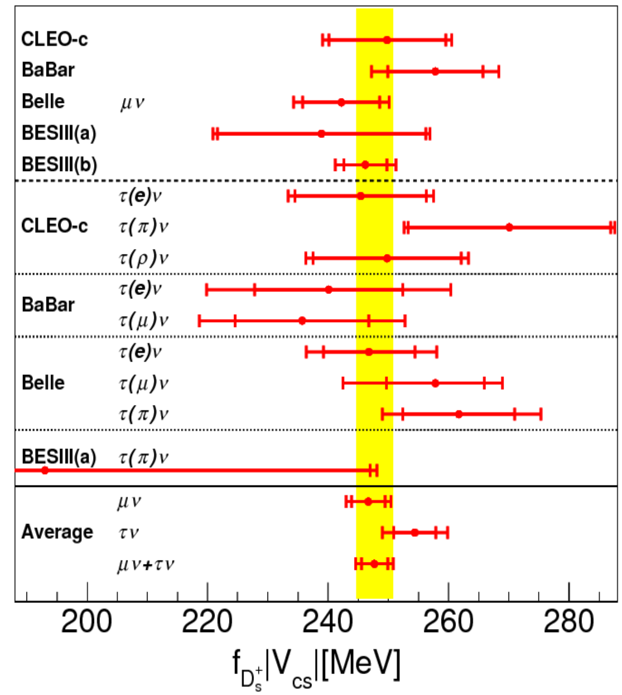


$$B[D_s^+ \to \mu^+ \nu] = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

$$\boxed{f_{D_s^+} | V_{cs} | = 242.5 \pm 3.5 \pm 3.7 \, \text{MeV}[\mu]}$$

New inputs from PDG2018:

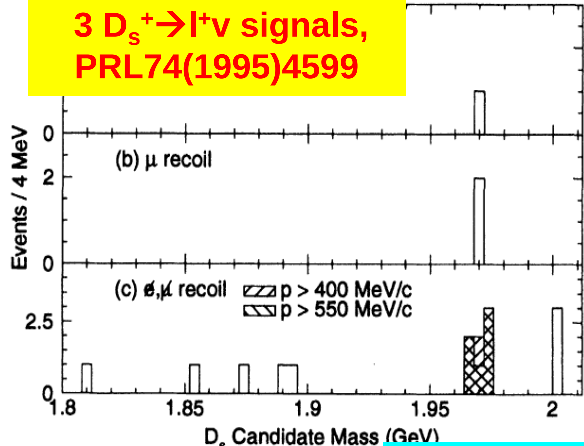
	value
m_μ	0.1056583745(24) GeV
m_τ	1.77686(12) GeV
$m_{D_s^+}$	1.96834(7) GeV
$\tau_{D_s^+}$	504(4) ps
G_F	$1.1663787(6) \times 10^{-5}$ GeV^{-2}



30年来，北京谱仪$D_{(s)}$纯轻衰变研究

- **BESI, 22.3 pb^{-1}@4.03GeV**

3 $D_s^+\to l^+\nu$ signals, PRL74(1995)4599



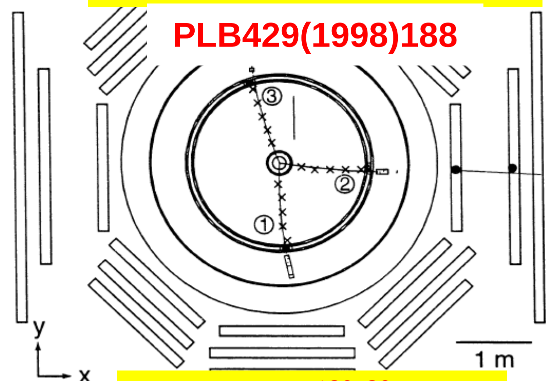
$f_{D_s^+} = (430^{+150+40}_{-130-40})$ MeV

First absolute measurement

- **BESI, 22.3 pb^{-1}@4.03GeV**

1st signal of $D^+\to\mu^+\nu$

PLB429(1998)188

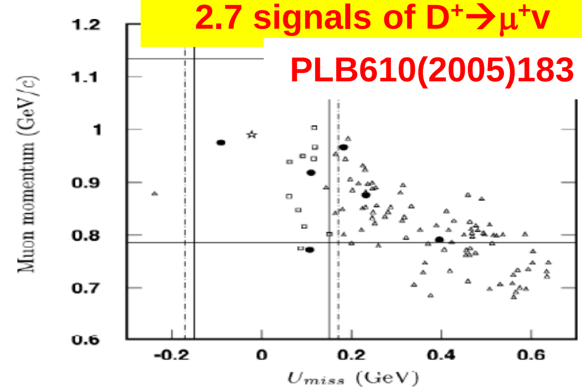


$f_{D^+} = (300^{+180+80}_{-150-40})$ MeV

- **BESII, 33 pb^{-1}@ψ''**

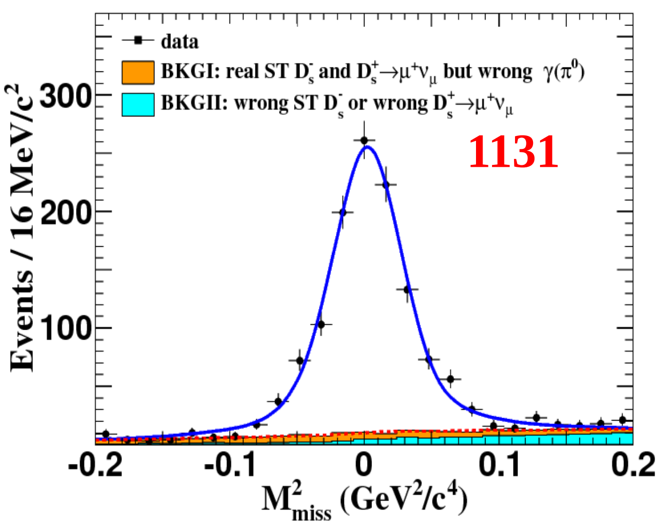
2.7 signals of $D^+\to\mu^+\nu$

PLB610(2005)183

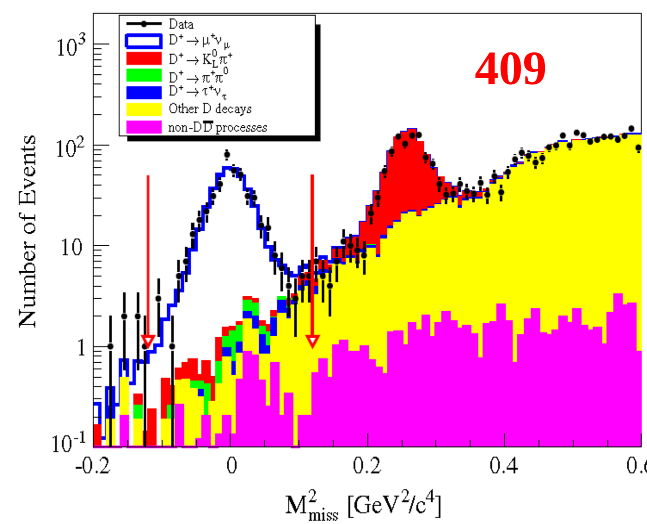


$f_{D^+} = (371^{+129}_{-119} \pm 25)$ MeV

BESIII: 3.19 fb^{-1}@4.178GeV

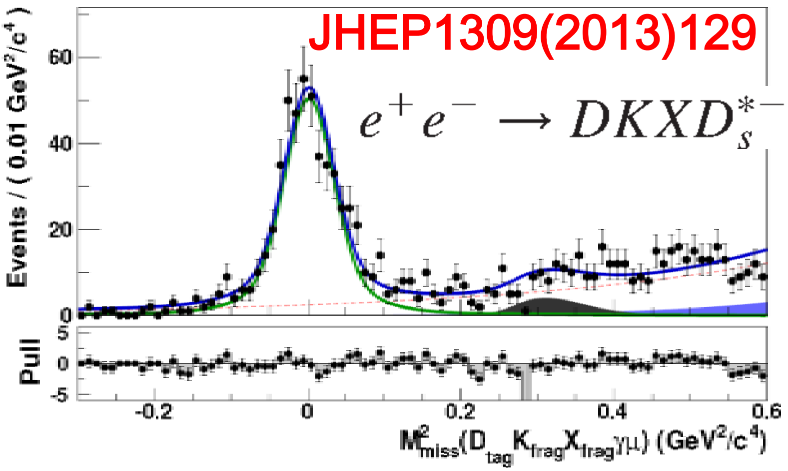


BESIII: 2.93 fb^{-1}@3.773GeV

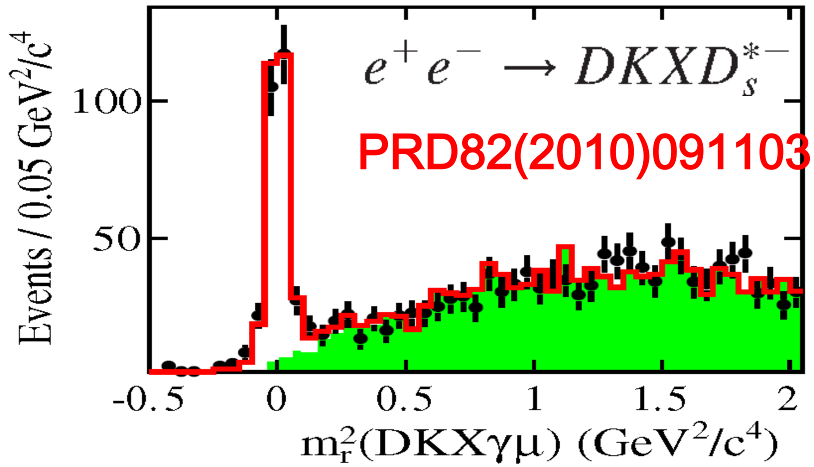


近20年，不同实验对$D_s \to \mu^+\nu$纯轻的研究

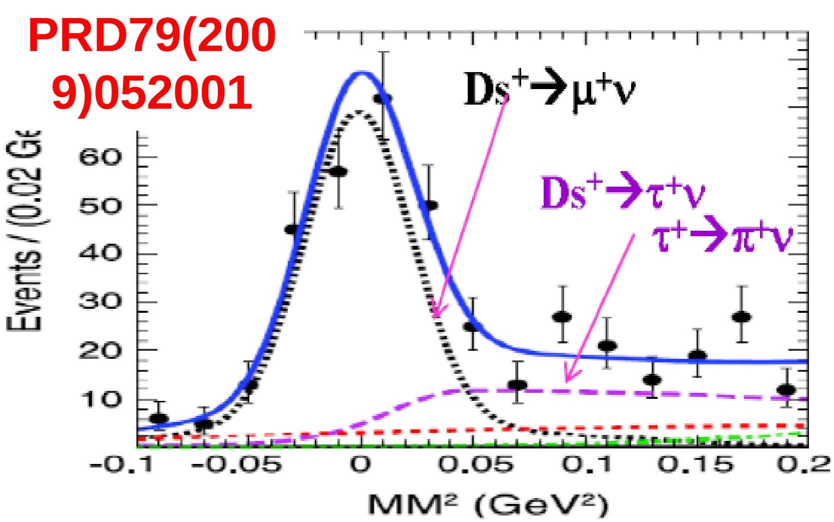
- Belle, 913 fb^{-1} at 10.58 GeV



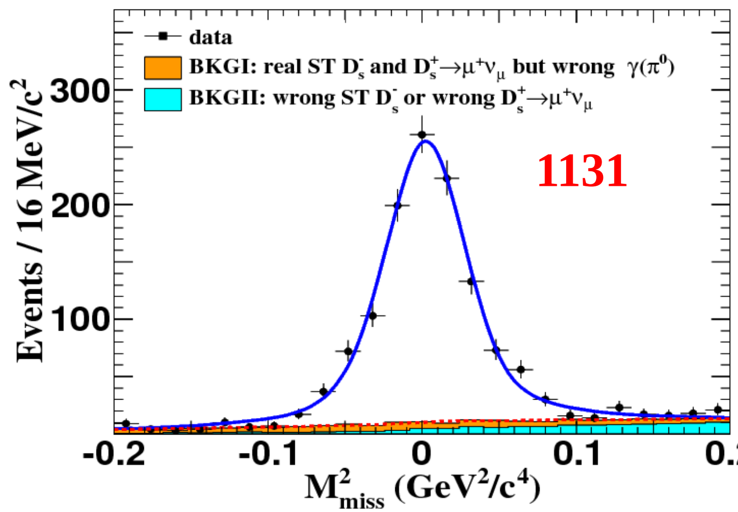
- Babar, 521 fb^{-1} at 10.58 GeV



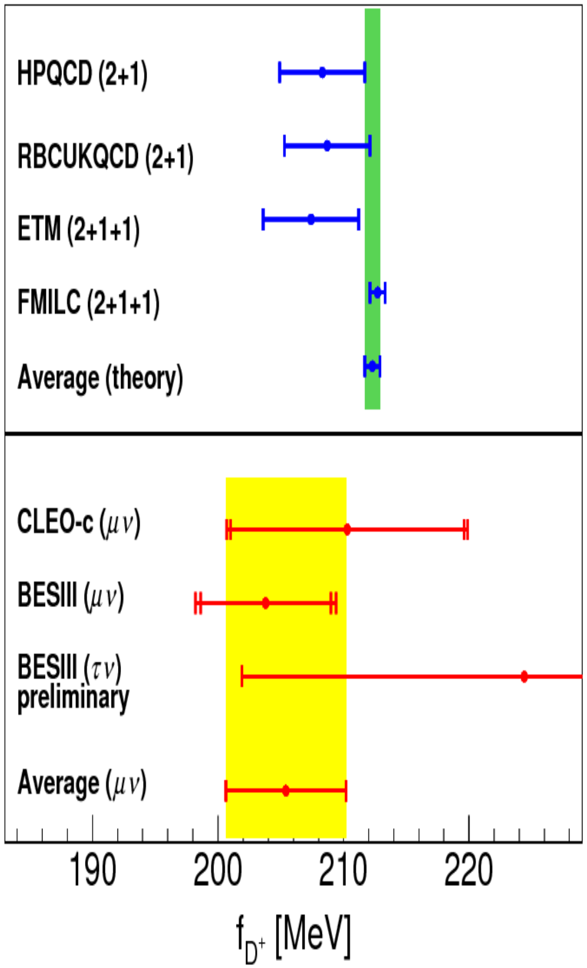
- CLEOc: 600 pb^{-1}@ 4.17GeV



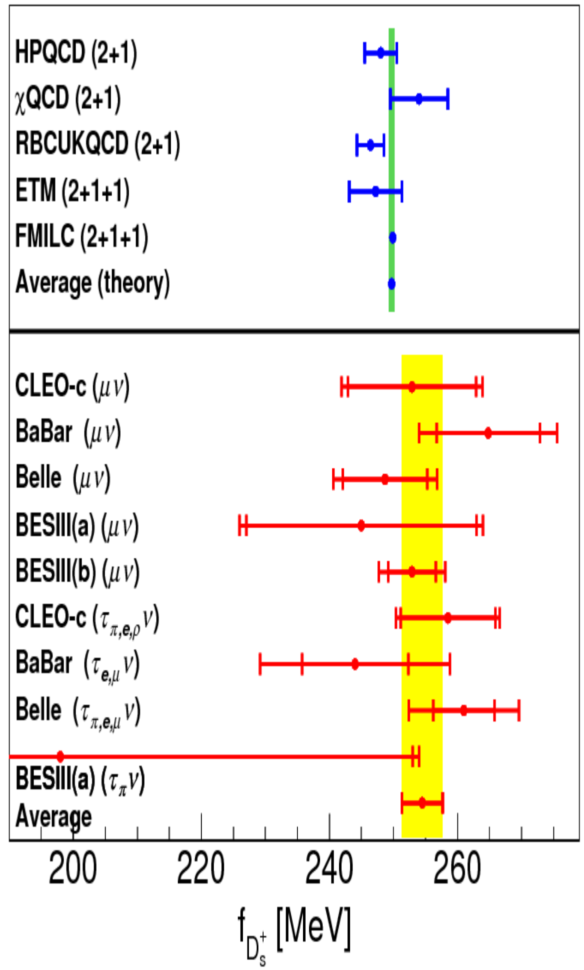
BESIII: 3.19 fb^{-1}@4.178GeV



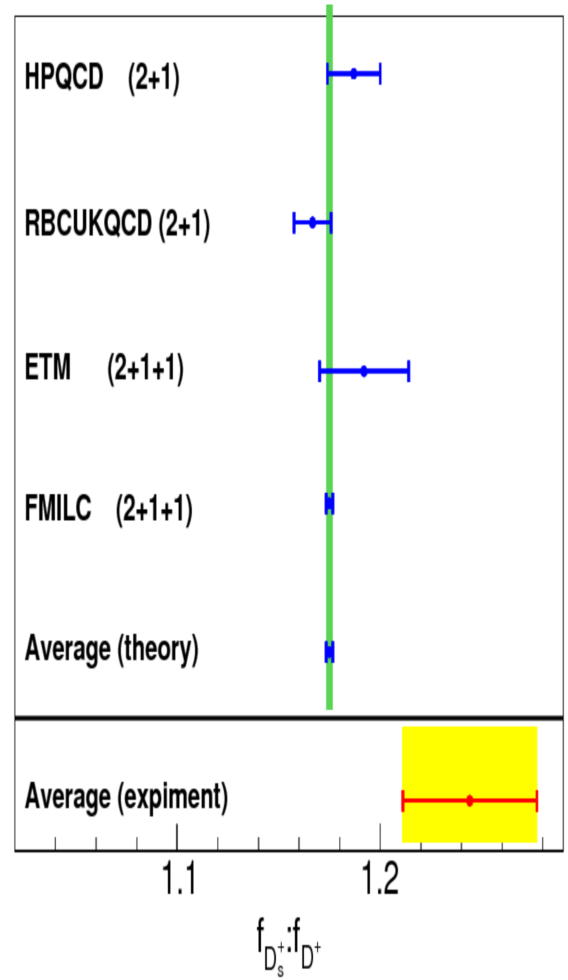
f_{D+}、f_{Ds+}、$f_{Ds+}:f_{D+}$实验和理论比较



-1.4σ差异



+1.5σ差异



2σ差异

半轻衰变D→Pev动力学研究

Form factor parameterization

– **Single pole form**

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

free

– **Modified pole**

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

fixed at $m_{D(s)^*}$

– **ISGW2**

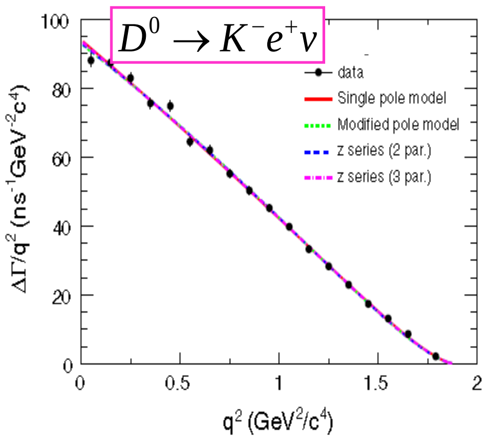
$$f_+(q^2) = f_+(q^2_{\max})\left(1+\frac{r^2_{\rm ISGW2}}{12}(q^2_{\max}-q^2)\right)^{-2}$$

– **Series expansion**

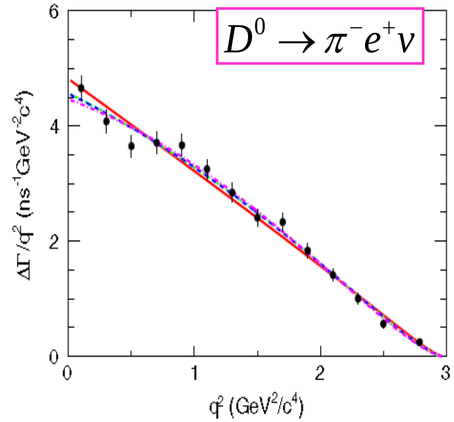
$$f_+(t) = \frac{1}{P(t)\Phi(t,t_0)}a_0(t_0)\left(1+\sum_{k=1}^{\infty}r_k(t_0)[z(t,t_0)]^k\right)$$

The shown results are based on 2nd order series expansion

PRD92(2015)072012

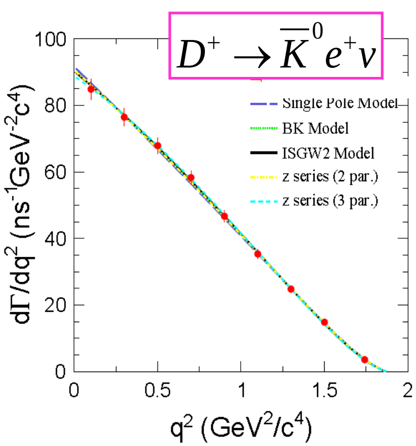


$f_+^K(0)|V_{cs}| = 0.717(03)(04)$

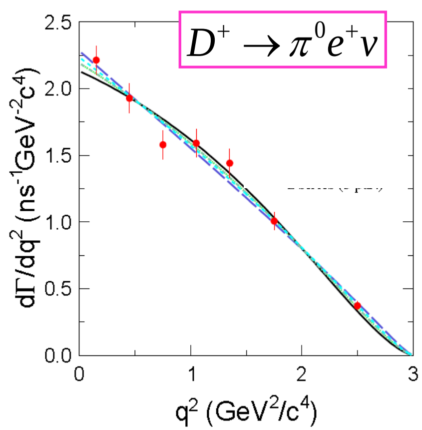


$f_+^\pi(0)|V_{cd}| = 0.144(02)(01)$

PRD96(2017)012002



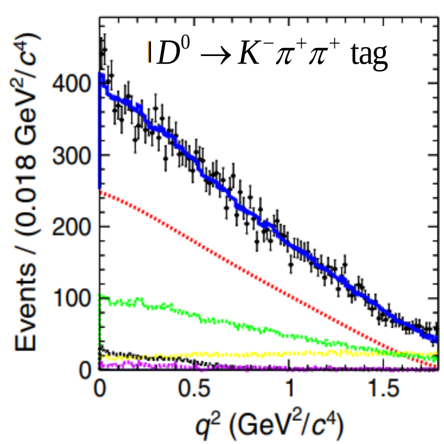
$f_+^K(0)|V_{cs}| = 0.705(04)(11)$

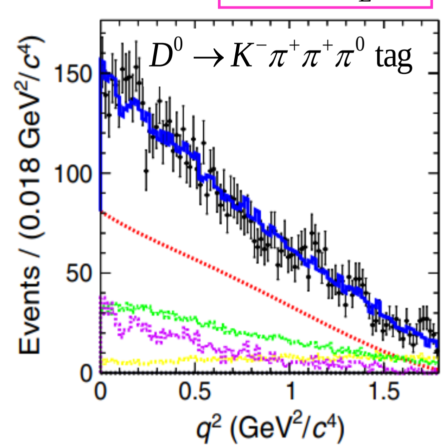


$f_+^\pi(0)|V_{cd}| = 0.140(03)(01)$

PRD92(2015)112008

$D^+ \to K_L^0 e^+ \nu$





$f_+^K(0)|V_{cs}| = 0.728(06)(11)$

半轻衰变$D^0 \rightarrow K^-\mu^+\nu$动力学研究

Differential partial widths

$$
\begin{aligned}
\frac{d\Gamma}{dq^2} = & \frac{G_F^2|V_{cs}|^2}{8\pi^3 m_D}|\vec{p}_K||f_+^K(q^2)|^2\left(\frac{W_0 - E_K}{F_0}\right)^2 \\
& \times \Big[\frac{1}{3}m_D|\vec{p}_K|^2 + \frac{m_\ell^2}{8m_D}(m_D^2 + m_K^2 + 2m_D E_K) \\
& + \frac{1}{3}m_\ell^2\frac{|\vec{p}_K|^2}{F_0} + \frac{1}{4}m_\ell^2\frac{m_D^2 - m_K^2}{m_D}\mathrm{Re}\left(\frac{f_-^K(q^2)}{f_+^K(q^2)}\right) \\
& + \frac{1}{4}m_\ell^2 F_0\left|\frac{f_-^K(q^2)}{f_+^K(q^2)}\right|^2\Big]
\end{aligned}
$$

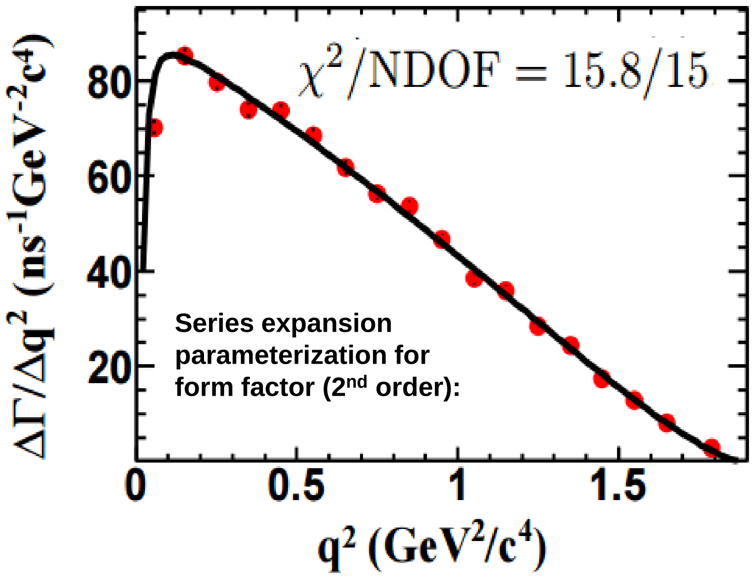
Assumed to be independent of q^2 following FOCUS's treatment (PLB607(2005)233)

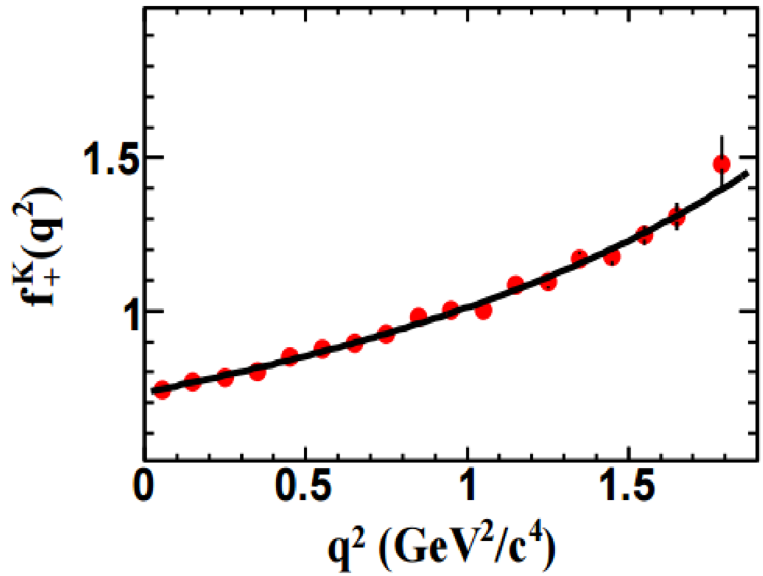
$$q = p_\mu + p_\nu$$

$$W_0 = (m_D^2 + m_K^2 - m_\ell^2)/2m_D$$

$$F_0 = W_0 - E_K + m_\ell^2/2m_D$$

PRL122(2019)011804





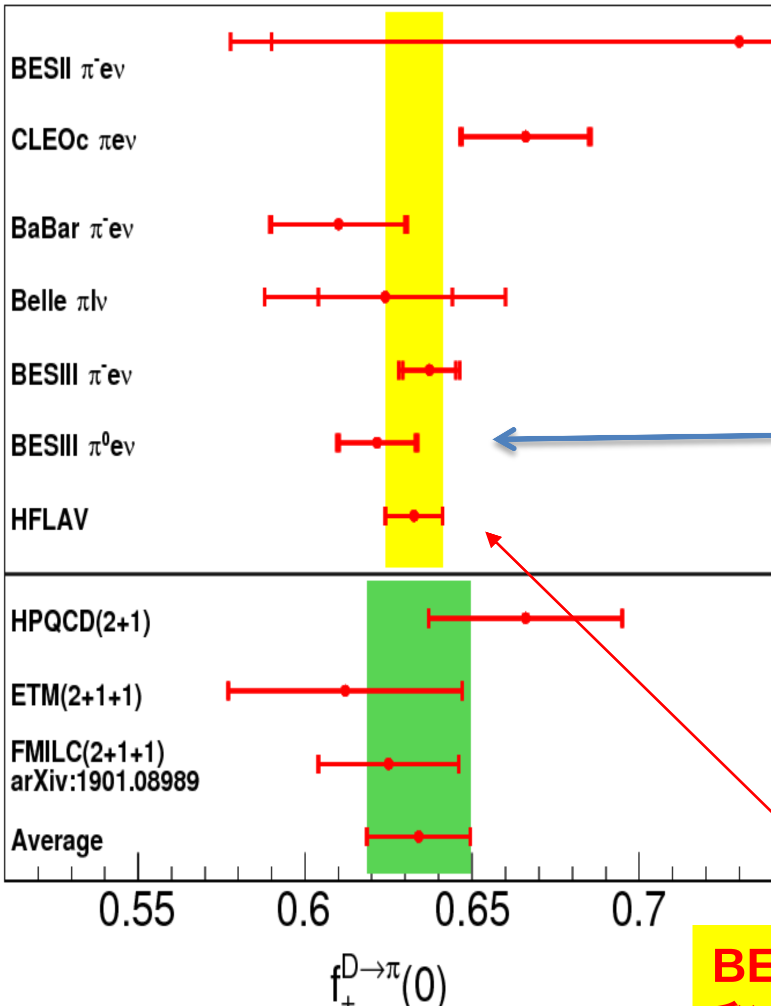
$$\boxed{f_+^K(0)|V_{cs}| = 0.7148(38)(29)}$$

形状因子$f_+^{K(\pi)}(0)$实验和理论比较

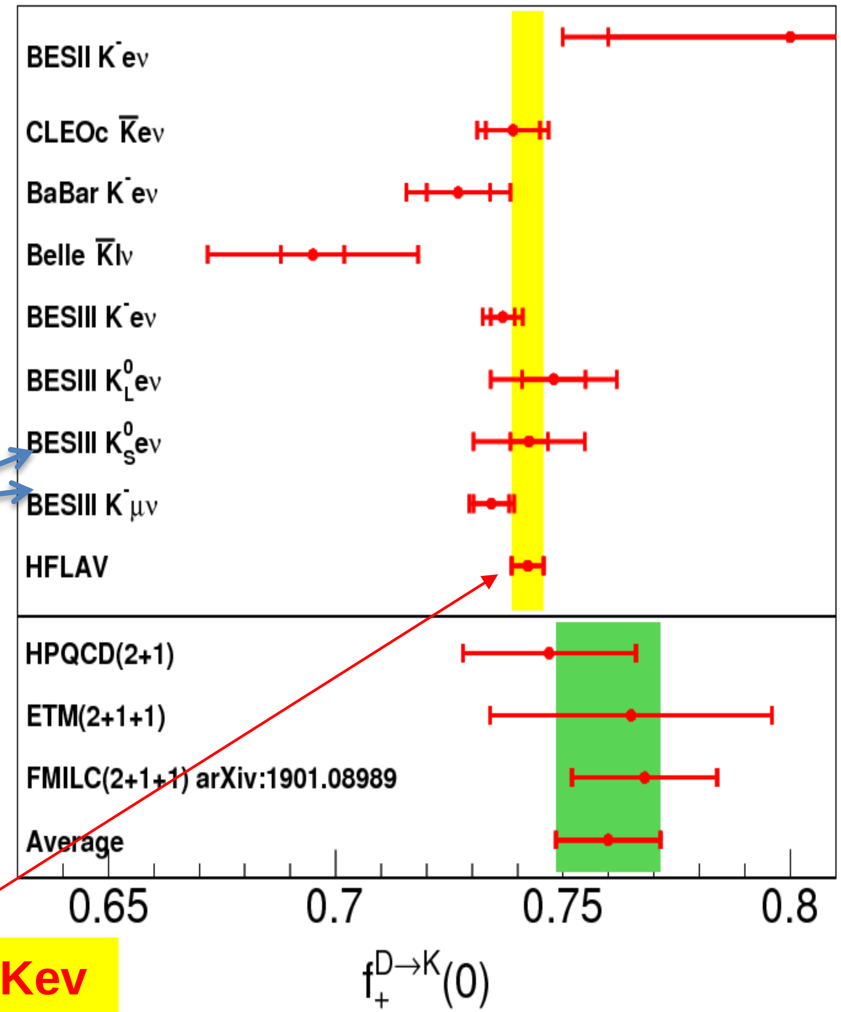
HFLAV16 averages based on a combined analysis of all D→K(π)lν measurements before 2016 using series expansion

$f_+^K(0)|V_{cs}|=0.7226(22)(26)$

$f_+^\pi(0)|V_{cd}|=0.1426(17)(08)$



Not included for averages



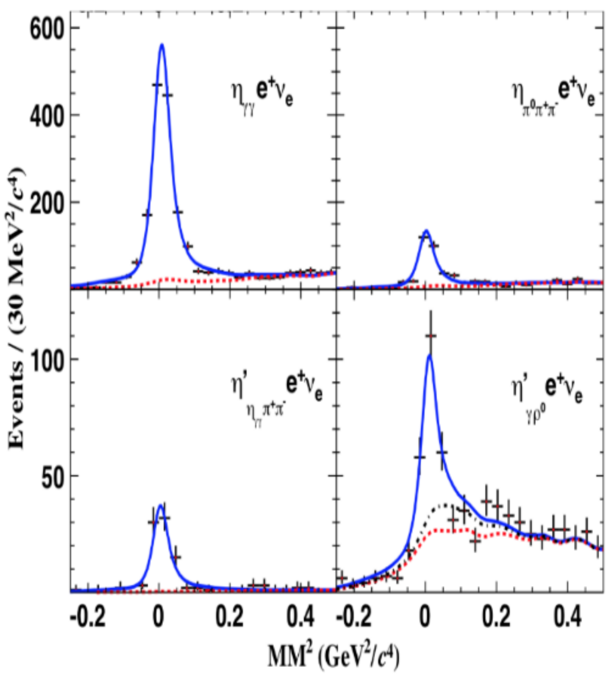
BESIII D^0→Keν 和πeν结果主导

半轻衰变D→η(')e+v动力学研究

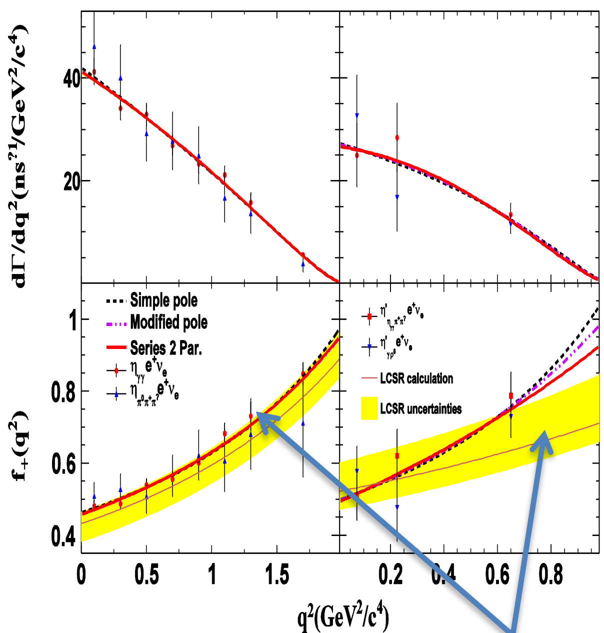
改进$D_s^+ \to \eta^{(\prime)} e^+ \nu$分支比，首次测定形状因子

3.19 fb^{-1} data@4.178 GeV

PRL122(2019)121801



微分跃迁率拟合



PRD88, 034023

$$B[D_s^+ \to \eta e^+ \nu] = (2.32 \pm 0.06 \pm 0.06)\%$$

$$B[D_s^+ \to \eta' e^+ \nu] = (0.82 \pm 0.07 \pm 0.03)\%$$

$$f_+^{D_s \to \eta}(0) = 0.446 \pm 0.005 \pm 0.004$$

$$f_+^{D_s \to \eta'}(0) = 0.477 \pm 0.049 \pm 0.011$$

$D^+ \to \eta^{(\prime)} e^+ \nu$衰变研究

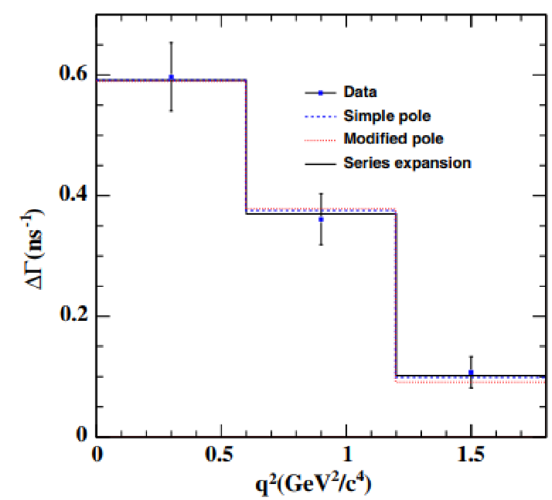
PRD97(2018)092009

分支比测量:

$$B[D^+ \to \eta e^+ \nu] = (10.74 \pm 0.81 \pm 0.51) \times 10^{-4}$$

$$B[D^+ \to \eta' e^+ \nu] = (1.91 \pm 0.51 \pm 0.13) \times 10^{-4}$$

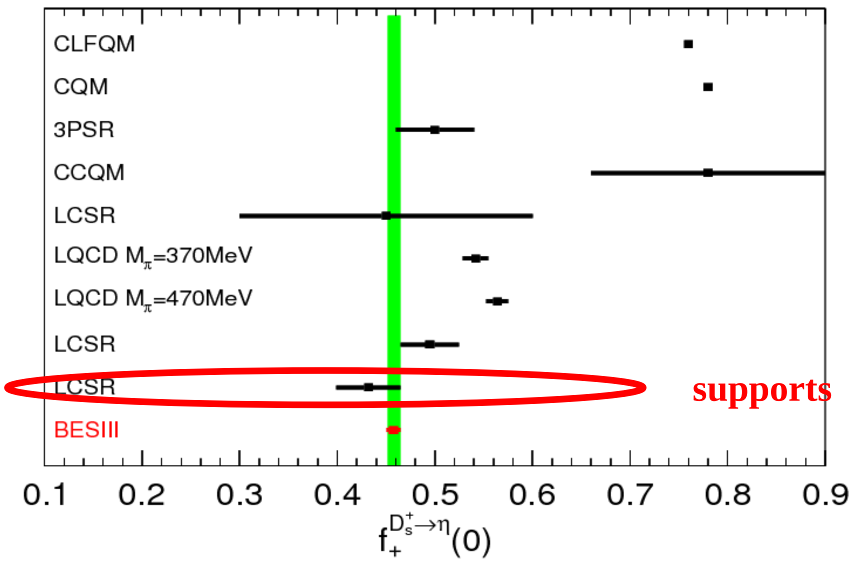
$D^+ \to \eta e^+ \nu$跃迁率拟合:

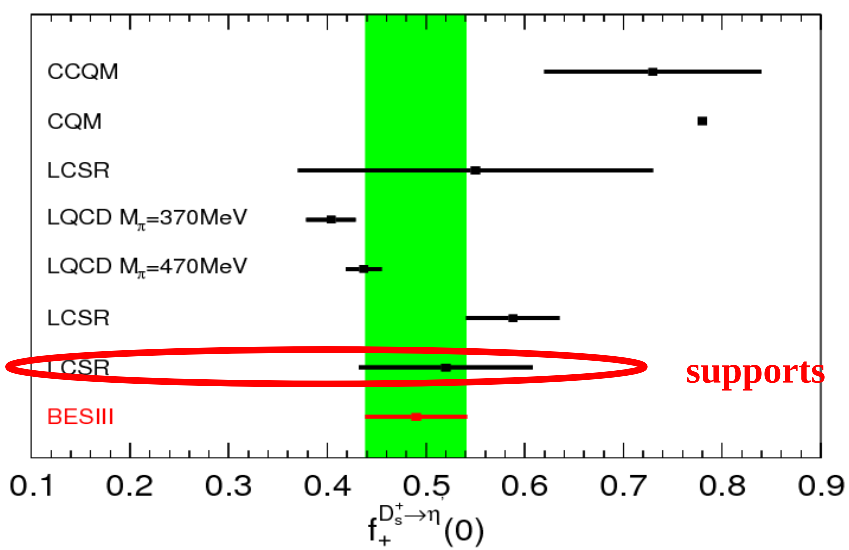


$$f_+^{D^+ \to \eta}(0)|V_{cd}| = (7.84 \pm 0.64 \pm 0.21)\%$$

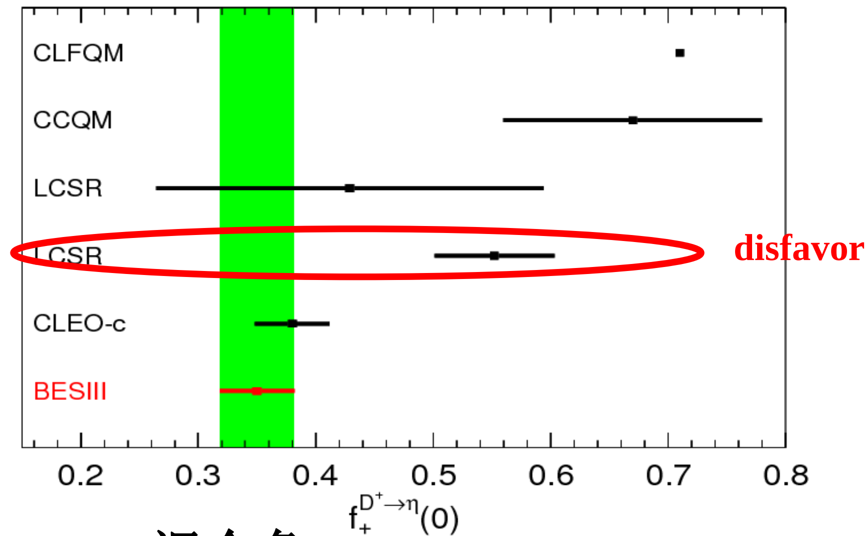
形状因子和η–η'混合角比较

$f^{D_s\to\eta^{(\prime)}}_+(0)$实验和理论比较





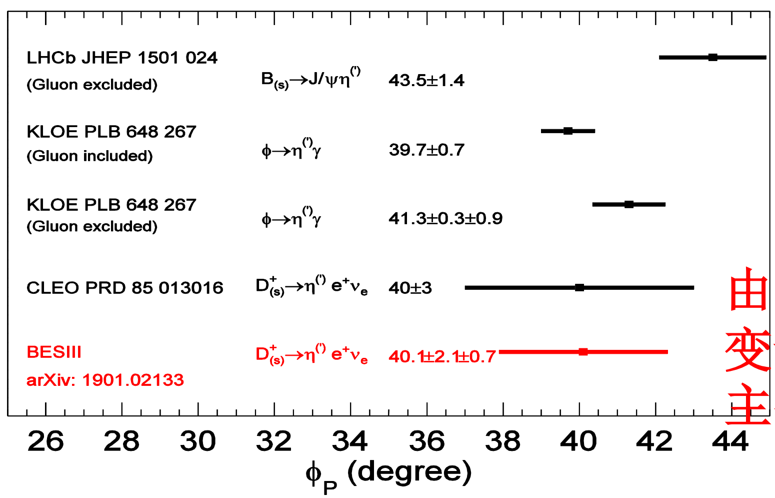
$f^{D^+\to\eta}_+(0)$实验和理论比较



η-η'混合角:

$$\frac{\Gamma(D_s^+\to\eta' e^+\nu)/\Gamma(D_s^+\to\eta e^+\nu)}{\Gamma(D^+\to\eta' e^+\nu)/\Gamma(D^+\to\eta e^+\nu)} \simeq \cot^4\phi_P$$

With the BFs in PRD97, 092009 & arXiv:1901.02133



由D^+衰变误差主导

CKM矩阵元|V$_{cs}$|和|V$_{cd}$|比较

Averages of published measurements

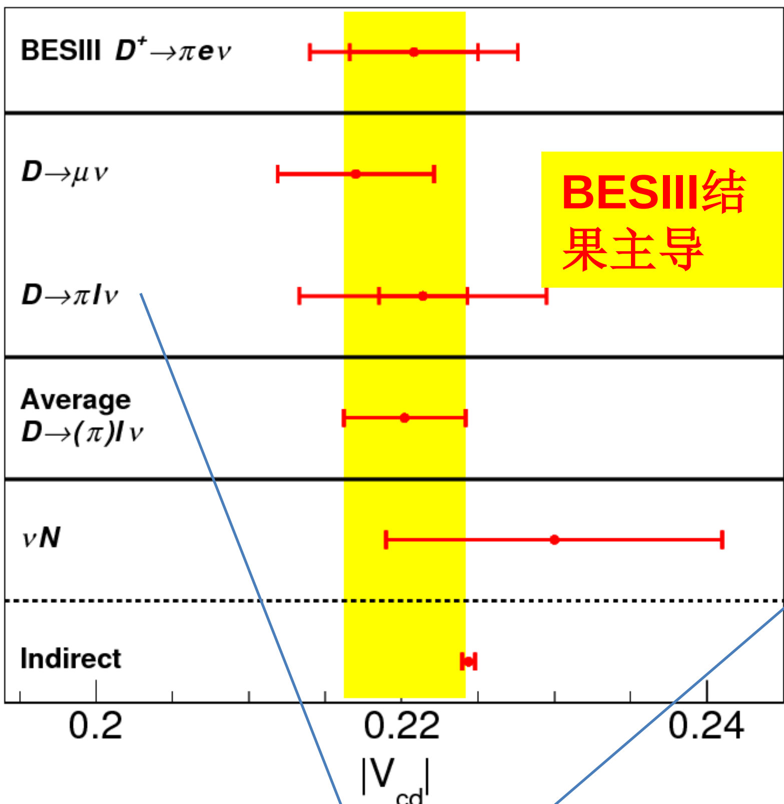
$f_{D_s^+}|V_{cs}| = 247.7(22)(22)$ MeV

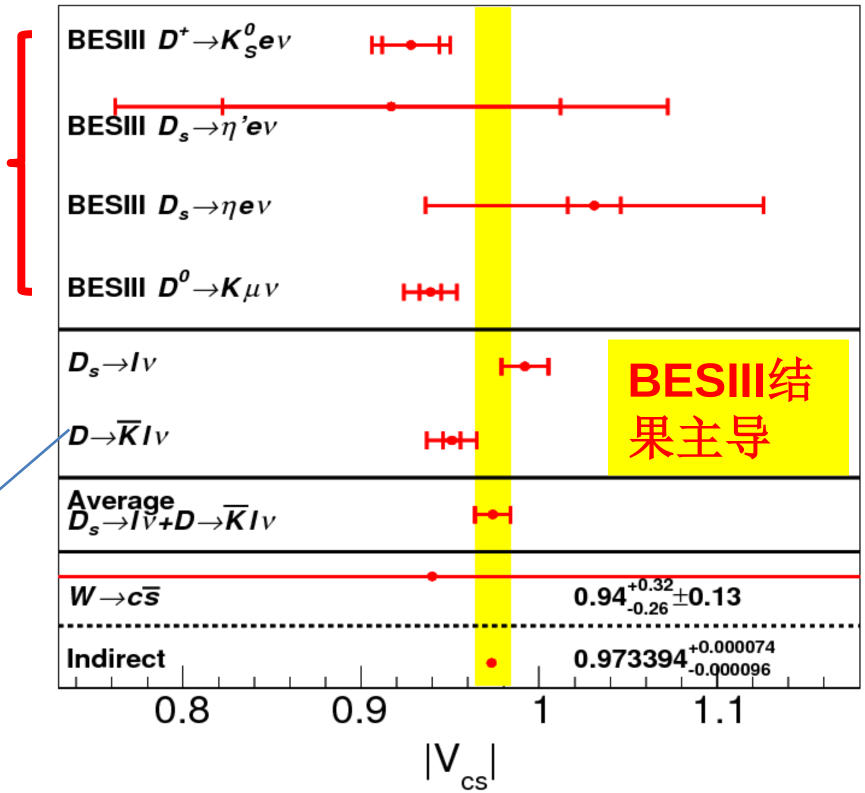
$f_{D^+}|V_{cd}| = 46.1(10)(04)$ MeV

Averages of theoretical calculations

$f_{D_s^+}^{LQCD} = 249.7(04)$ MeV

$f_{D^+}^{LQCD}$ 212.3(06) MeV





HFLAV16 gave a combined analysis of all D→K(π)lv measurements before 2016 using series expansion

$f_+^K(0)|V_{cs}| = 0.7226(22)(26)$

$f_+^\pi(0)|V_{cd}| = 0.1426(17)(08)$

Averages of f(0) based on HPQCD /ETM/FMILC

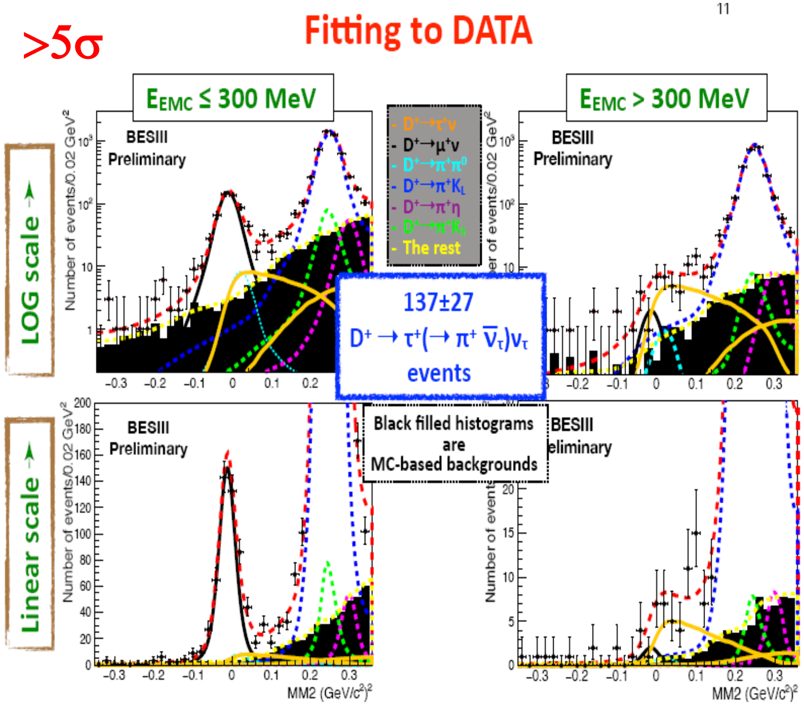
$f_+^K(0)^{LQCD} = 0.760(11)$

$f_+^\pi(0)^{LQCD} = 0.634(15)$

|V$_{cs(d)}$| results shown above

$D_{(s)}^+ \to l^+ \nu$衰变检验轻子普适性

>5σ



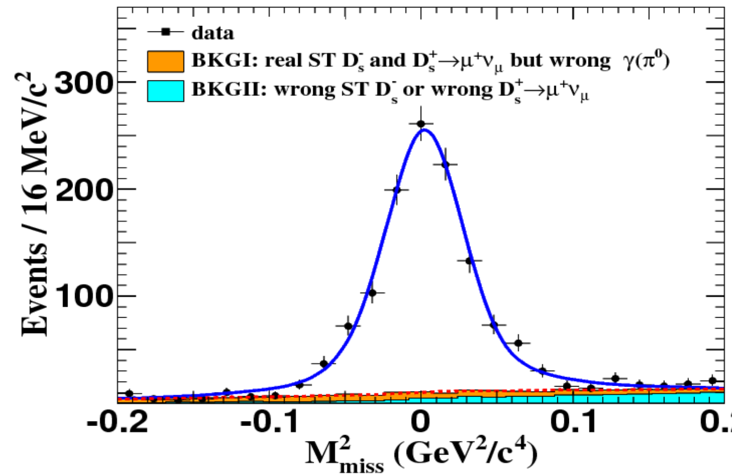
$$B[D^+ \to \mu^+\nu] = (3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$$

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

$$\frac{B[D^+ \to \tau^+\nu]}{B[D^+ \to \mu^+\nu]} = 3.21 \pm 0.64_{\mathrm{stat}}$$

SM预期: 2.66

PRL122(2019)071802



$$B[D_s^+ \to \mu^+\nu] = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

Combined results:

$$\overline{B}[D_s^+ \to \mu^+\nu] = (5.49 \pm 0.17) \times 10^{-3}$$

$$B^{PDG}[D_s^+ \to \tau^+\nu] = (5.49 \pm 0.17) \times 10^{-3}$$

$$\frac{B[D_s^+ \to \tau^+\nu]}{B[D_s^+ \to \mu^+\nu]} = 9.98 \pm 0.52$$

SM预期: 9.74

$D^{0(+)} \to \pi l^+ \nu$衰变检验轻子普适性

B物理研究中：

$$R(D^{(*)}) = \frac{B(B \to D^{(*)}\tau\nu)}{B(B \to D^{(*)} l \nu)}$$

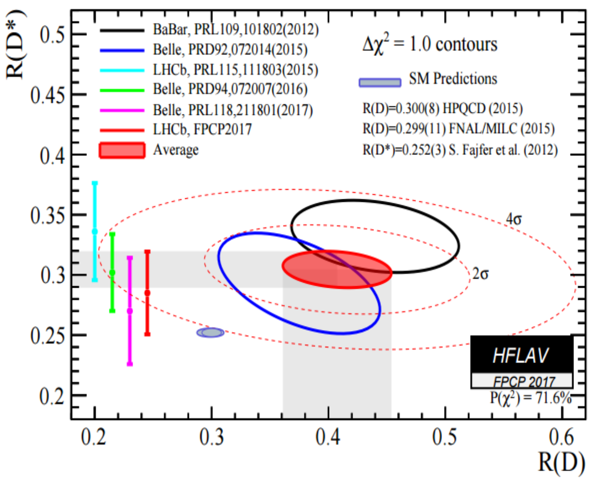
与LFU预期有3.9σ偏离

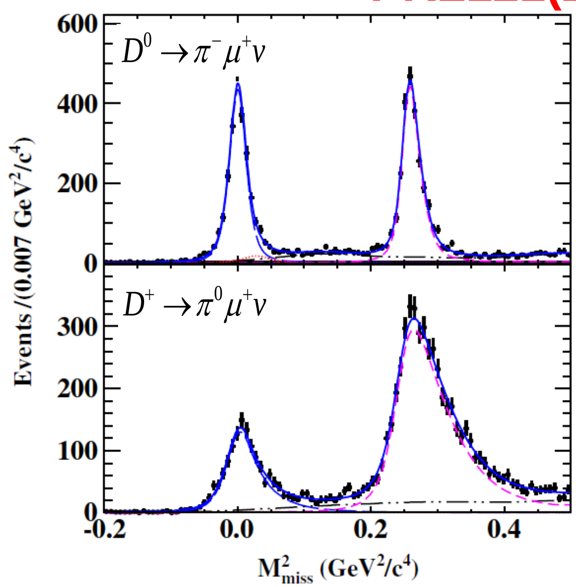
SM预期: 0.985

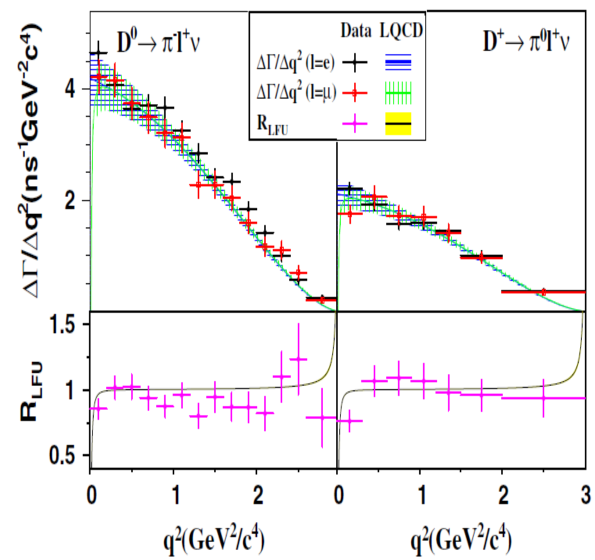
$$\frac{\Gamma^{PDG}[D^0 \to \pi^- \mu^+ \nu]}{\Gamma^{PDG}[D^0 \to \pi^- e^+ \nu]} = 0.82 \pm 0.08 \qquad \textbf{(2.1σ)}$$

$$B^{PDG}[D^+ \to \pi^0 \mu^+ \nu] = (0.272 \pm 0.024)\%$$

PRL121(2018)171803







BESIII:

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

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

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

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

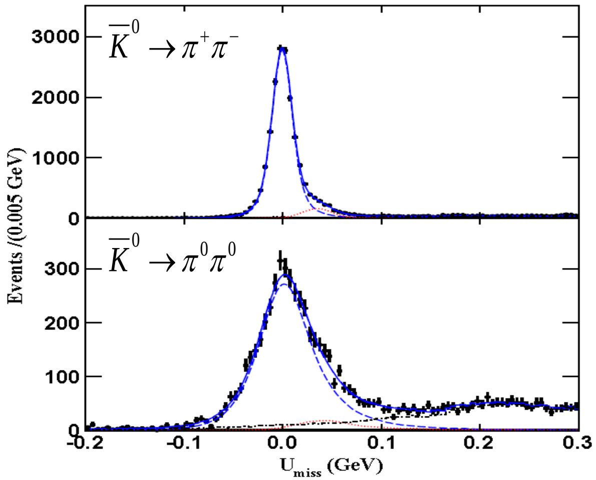
$$\boxed{\frac{\Gamma[D^0 \to \pi^- \mu^+ \nu]}{\Gamma[D^0 \to \pi^- e^+ \nu]} = 0.922 \pm 0.030 \pm 0.022} \qquad \textbf{(1.7σ)}$$

$$\boxed{\frac{\Gamma[D^+ \to \pi^0 \mu^+ \nu]}{\Gamma[D^+ \to \pi^0 e^+ \nu]} = 0.964 \pm 0.037 \pm 0.026} \qquad \textbf{(0.5σ)}$$

$D\to\bar{K}l^{+}\nu$衰变检验轻子普适性

EPJC76(2016)369

SM预期: 0.97



$$B[D^+\to\overline{K}^0\mu^+\nu]=(8.72\pm0.07\pm0.18)\%$$

$$B^{PDG}[D^+\to\overline{K}^0e^+\nu]=(8.74\pm0.19)\%$$

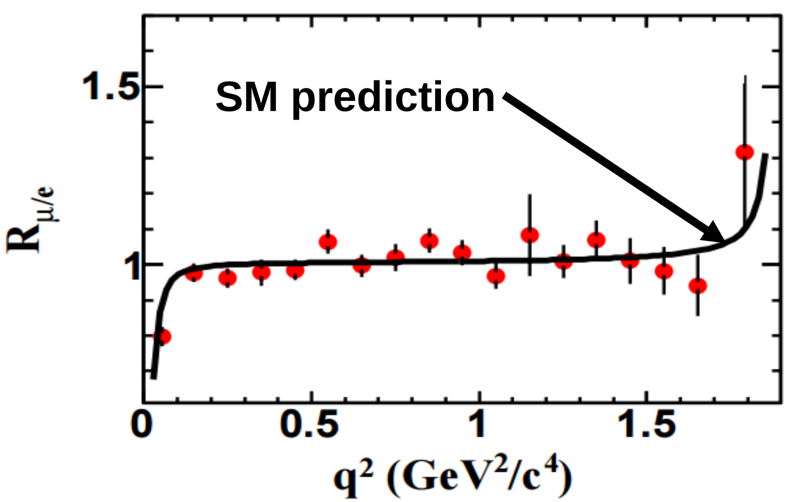
$$\boxed{\frac{\Gamma[D^+\to\overline{K}^0\mu^+\nu]}{\Gamma[D^+\to\overline{K}^0e^+\nu]}=1.00\pm0.03}$$

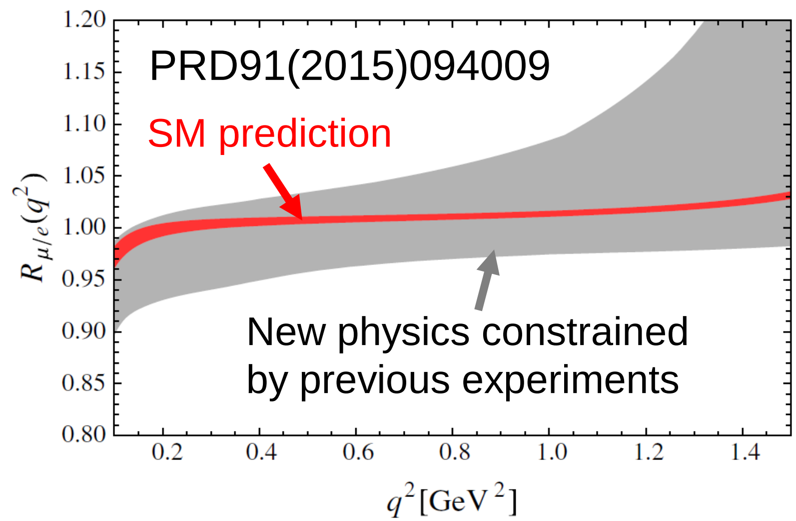
$$B[D^0\to K^-\mu^+\nu]=(3.413\pm0.019\pm0.035)\%$$

$$B^{BESIII}[D^0\to K^-e^+\nu]=(3.505\pm0.014\pm0.033)\%$$

PRL122(2019)011804

$$\boxed{\frac{\Gamma[D^0\to K^-\mu^+\nu]}{\Gamma[D^0\to K^-e^+\nu]}=0.978\pm0.007\pm0.012}$$

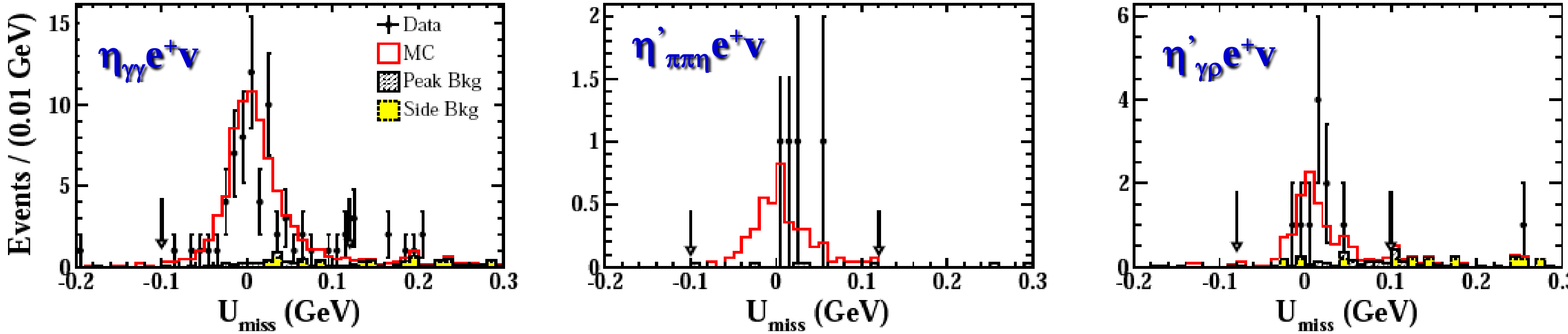




LFU test with $D_s^+ \to \phi/\eta^{(')} l^+ \nu$ decays

PRD94(2016)112003

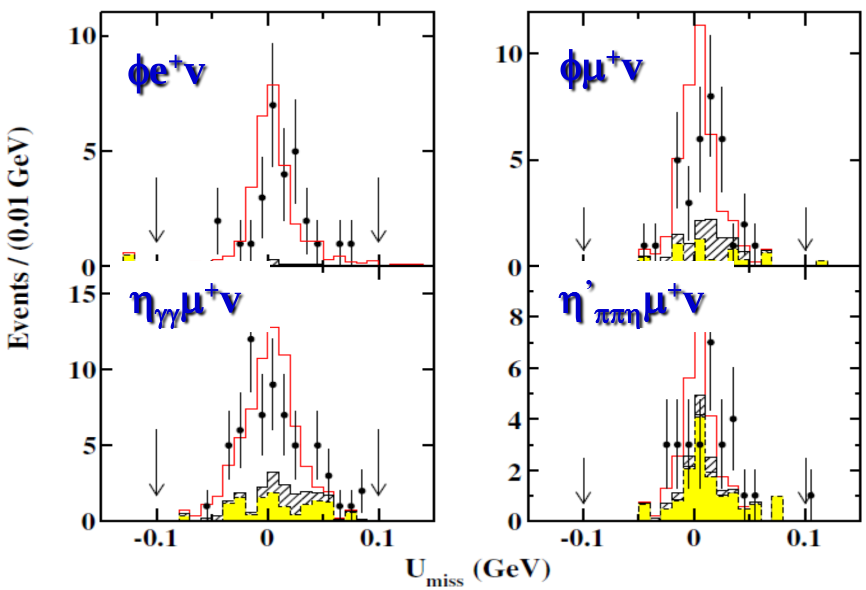
0.48 fb^{-1} data@4.01 GeV



$B[D_s^+ \to \eta e^+ \nu] = (2.30 \pm 0.31 \pm 0.08)\%$

$B[D_s^+ \to \eta' e^+ \nu] = (0.93 \pm 0.30 \pm 0.05)\%$

PRD97(2018)012006



$B[D_s^+ \to \phi e^+ \nu] = (2.26 \pm 0.45 \pm 0.09)\%$

$B[D_s^+ \to \phi \mu^+ \nu] = (1.94 \pm 0.53 \pm 0.09)\%$

$B[D_s^+ \to \eta \mu^+ \nu] = (2.42 \pm 0.46 \pm 0.11)\%$

$B[D_s^+ \to \eta' \mu^+ \nu] = (1.06 \pm 0.54 \pm 0.07)\%$

First measurements

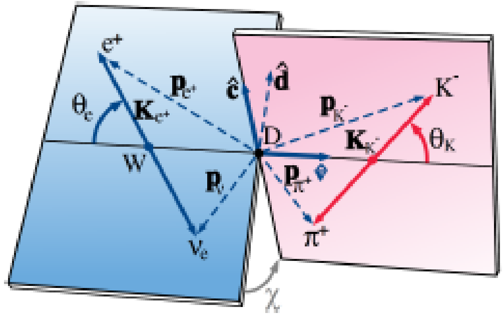
$$\boxed{\frac{\Gamma[D_s^+ \to \phi \mu^+ \nu]}{\Gamma[D_s^+ \to \phi e^+ \nu]} = 0.86 \pm 0.29}$$

$$\boxed{\frac{\Gamma[D_s^+ \to \eta \mu^+ \nu]}{\Gamma[D_s^+ \to \eta e^+ \nu]} = 1.05 \pm 0.24}$$

$$\boxed{\frac{\Gamma[D_s^+ \to \eta' \mu^+ \nu]}{\Gamma[D_s^+ \to \eta' e^+ \nu]} = 1.14 \pm 0.68}$$

半轻衰变D→Ve⁺ν形状因子测量

因D→Vμν形状因子和背景更加复杂，目前完成了一些D→Veν研究



- $m^2 = (p_{\pi^+} + p_{K^-})^2$
- $\cos(\theta_K) = \frac{\hat{v}\cdot \mathbf{K}_{K^-}}{|\mathbf{K}_{K^-}|}$
- $\cos(\chi) = \hat{c}\cdot\hat{d}$
- $q^2 = (p_{e^+} + p_{\nu_e})^2$
- $\cos(\theta_e) = -\frac{\hat{v}\cdot \mathbf{K}_{e^+}}{|\mathbf{K}_{e^+}|}$
- $\sin(\chi) = (\hat{c}\times\hat{v})\cdot\hat{d}$

Decay rate depend on 5 variables and 3 form factors

$$d^5\Gamma = \frac{G_F^2|V_{cs}|^2}{(4\pi)^6 m_D^2} X\beta\mathcal{I}(m^2, q^2, \theta_K, \theta_e, \chi)dm^2dq^2d\cos(\theta_K)d\cos(\theta_e)d\chi$$

- $X = p_{K\pi}m_D$, $p_{K\pi}$ is the momentum of the $K\pi$ system in the D rest frame
- $\beta = 2p^*/m$, p^* is the breakup momentum of the $K\pi$ system in its rest frame
- $\mathcal{I}$ can be expressed in terms of helicity amplitudes $H_{0,\pm}$:

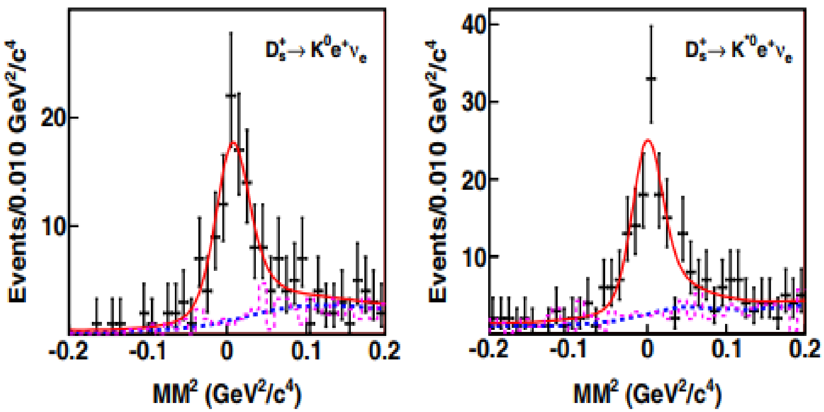
$$H_0(q^2) = \frac{1}{2mq}\left[(m_D^2 - m^2 - q^2)(m_D + m)A_1(q^2) - 4\frac{m_D^2 p_{K\pi}^2}{m_D + m}A_2(q^2)\right]$$

$$H_\pm(q^2) = (m_D + m)A_1(q^2) \mp \frac{2m_D p_{K\pi}}{m_D + m}V(q^2)$$

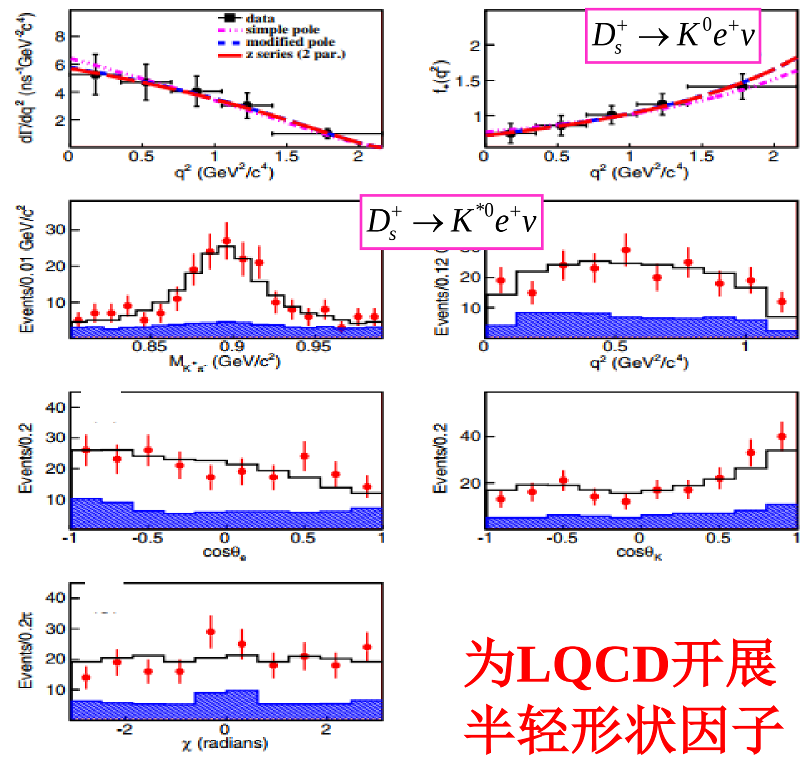
- Vector form factor: $V(q^2) = \frac{V(0)}{1-q^2/m_V^2}$; or: FF ratio $r_V = V(0)/A_1(0)$
- Axial-vector form factor: $A_1(q^2) = \frac{A_1(0)}{1-q^2/m_A^2}$, $A_2(q^2) = \frac{A_2(0)}{1-q^2/m_A^2}$; or: FF ratio $r_2 = A_2(0)/A_1(0)$

$D_s^+ \to K^{(*)0} e^+ \nu$ 衰变的研究

PRL122(2019)061801



微分跃迁率拟合投影



改进测定分支比:

$$B_{D_s^+ \to K^0 e^+ \nu} = (3.25 \pm 0.38 \pm 0.16) \times 10^{-3}$$ 理论: **2.0-3.9×10⁻³**

$$B_{D_s^+ \to K^{*0} e^+ \nu} = (2.37 \pm 0.26 \pm 0.20) \times 10^{-3}$$ 理论: **1.7-2.3×10⁻³**

为LQCD开展半轻形状因子计算提供了重要参照依据

首次测定形状因子:

$D_s^+ \to K^0 e^+ \nu$ $\quad f_+^{D_s \to K}(0) = 0.720 \pm 0.084 \pm 0.013$

$D_s^+ \to K^{*0} e^+ \nu$

$$r_V = 1.67 \pm 0.34 \pm 0.16$$

$$r_2 = 0.77 \pm 0.28 \pm 0.07$$

形状因子比值:

$$f_+^{D_s \to K}(0) / f_+^{D^+ \to \pi}(0) = 1.16 \pm 0.14 \pm 0.02$$

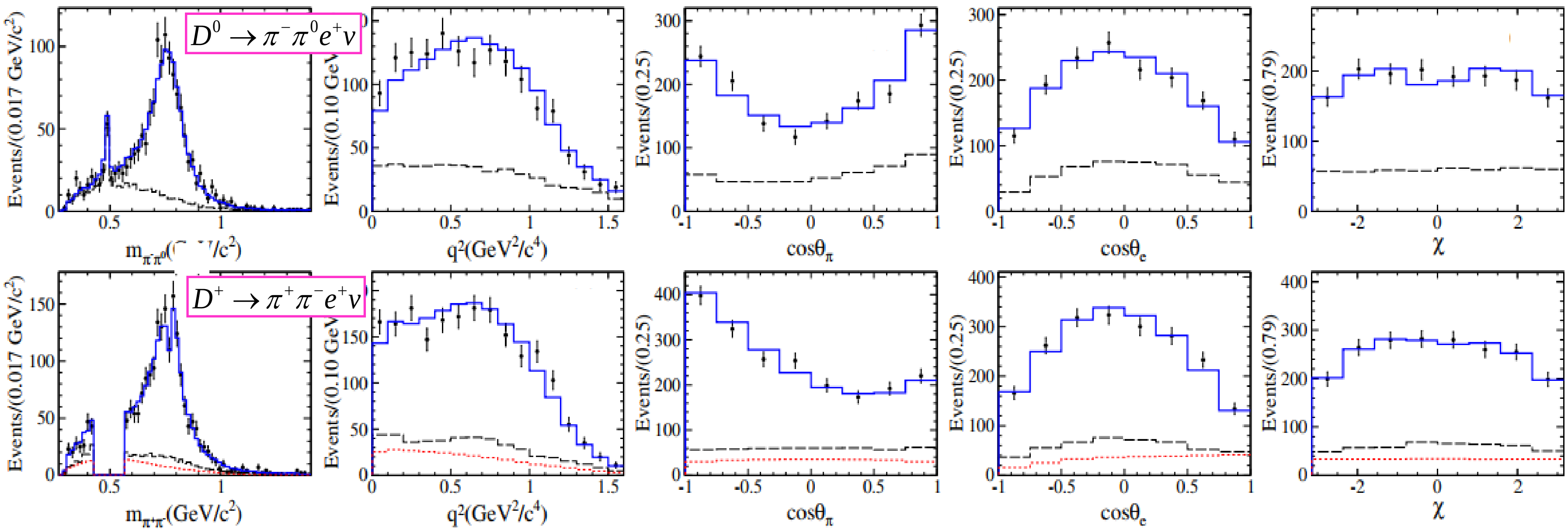
$$r_V^{D_s \to K^{*0}} / r_V^{D^+ \to \rho^0} = 1.13 \pm 0.26 \pm 0.11$$

$$r_2^{D_s \to K^{*0}} / r_2^{D^+ \to \rho^0} = 0.93 \pm 0.36 \pm 0.10$$

$D^{0(+)} \to \pi\pi e^+ \nu$衰变的研究

PRL122(2019)062001

微分跃迁率拟合投影



结果显示，该过程由$D \to \rho e v$主导，
并首次观测到$D^+ \to f_0(500)e^+v$ (>10σ)

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

改进测定形状因子

$r_V = 1.695 \pm 0.083 \pm 0.051$　　$r_2 = 0.845 \pm 0.056 \pm 0.039$

理论预期: 如果轻标量介子是两(四)夸克态，则R=1(3)，有助于探讨其夸克成分

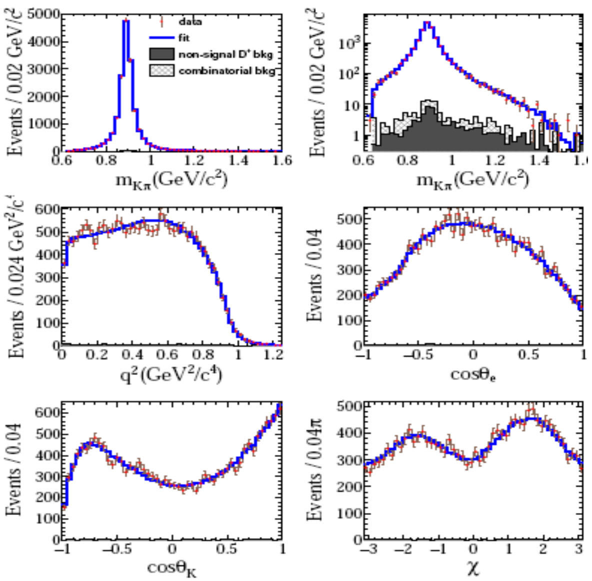
$$R = [B_{D^+ \to f_0(980)^0 e^+ v} + B_{D^+ \to f_0(500)^0 e^+ v}] / B_{D^+ \to a_0(980)^0 e^+ v}$$

BESIII测得R>2.7，倾向支持四夸克态

D→K̄πe⁺ν和ωe⁺ν衰变的研究

PRD94(2016)032001

改进测量$D^+ \to K^-\pi^+e^+\nu$



$$B_{D^+\to K^-\pi^+e^+\nu} = (3.77\pm0.03\pm0.08)\%$$

$$f_{\text{S-wave}} = (6.05\pm0.22\pm0.18)\%$$

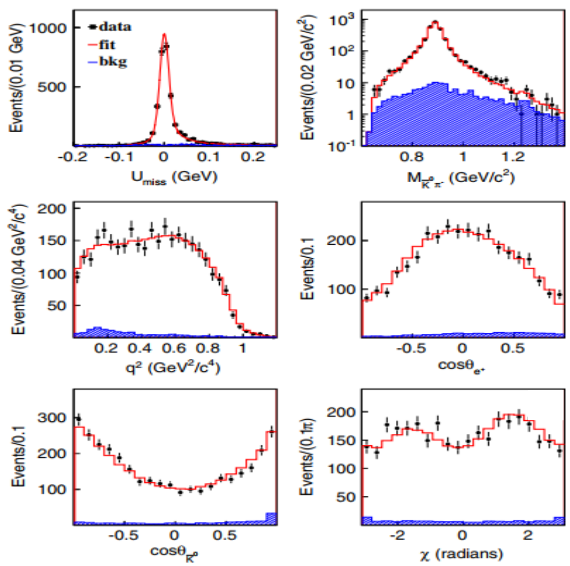
$$r_V = 1.411\pm0.058\pm0.007$$

$$r_2 = 0.788\pm0.042\pm0.008$$

$$A_1(0) = 0.589\pm0.010\pm0.012$$

PRD99(2018)011103

$D^0 \to K_S^0\pi^-e^+\nu$



精密测量分支比，并首次测量形状因子

$$B_{D^0\to \overline{K}^0\pi^-e^+\nu} = (1.43\pm0.03\pm0.03)\%$$

原分支比测量来自**BESII**

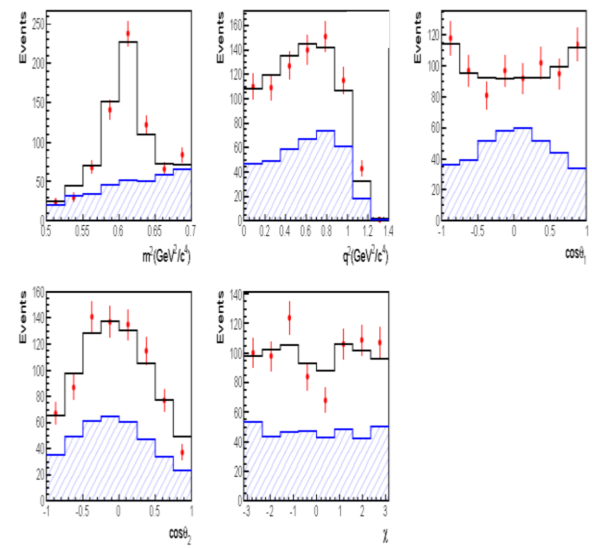
$$f_{\text{S-wave}} = (5.51\pm0.97\pm0.62)\%$$

$$r_V = 1.46\pm0.07\pm0.02$$

$$r_2 = 0.67\pm0.06\pm0.01$$

PRD92(2015)071101

$D^+ \to \omega e^+\nu$



精密测量分支比，并首次测量形状因子

$$B_{D^+\to \omega e^+\nu} = (1.63\pm0.11\pm0.08)\times10^{-3}$$

$$r_V = 1.24\pm0.09\pm0.06$$

$$r_2 = 1.06\pm0.15\pm0.05$$

半轻衰变$D^{0(+)} \to a_0(980)e^+\nu$首次观测

- Explore the nontrivial internal structure of light hadron mesons, traditional $q\bar{q}$ states, tetra quark system

- With chiral unitarity approach in the coupled channels, BF is predicted to be order of $5(6)\times10^{-5}$ for $D^{0(+)}$ decays

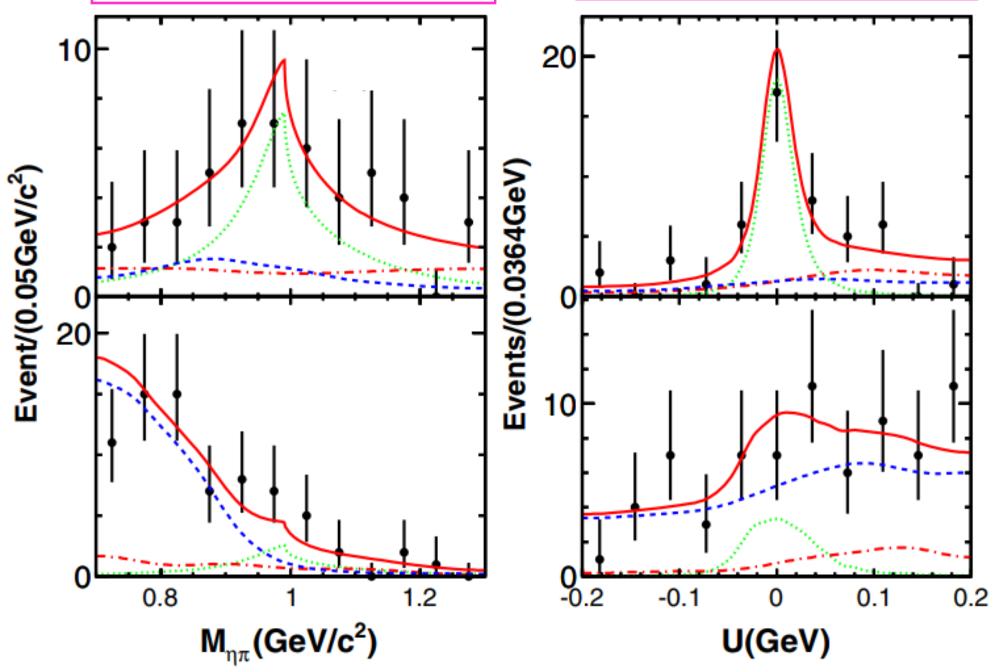
PRL121(2018)081802

- Improve understanding of classification of light scalar mesons

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

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

$D^+ \to a_0(980)^0 e^+\nu[3.0\sigma]$ $D^0 \to a_0(980)^- e^+\nu[6.5\sigma]$



首次测出联合分支比

$$B_{D^+\to a_0(980)^0 e^+\nu} B_{a_0(980)^0\to\eta\pi^0} = (1.66^{+0.81}_{-0.66}\pm0.11)\times10^{-4}$$

$$B_{D^0\to a_0(980)^- e^+\nu} B_{a_0(980)^-\to\eta\pi^-} = (1.33^{+0.33}_{-0.29}\pm0.09)\times10^{-4}$$

$$\frac{\Gamma_{D^0\to a_0(980)^- e^+\nu}}{\Gamma_{D^+\to a_0(980)^0 e^+\nu}} = 2.05\pm0.95\pm0.06$$

与同位旋守恒预期一致

半轻衰变$D^+\to\bar{K}_1(1270)^0e^+\nu$首次观测

粲介子P波半轻跃迁已预期30年[PRD52, 2783]，但仍无实验确认

在忽略K1[K_1(1270)-K_1(1400)]混合时，夸克模型暗示B_{D0}约0.12%/B_{D+}约0.34%

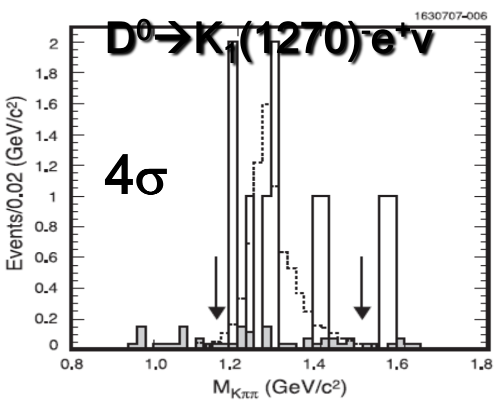
从τ/D强子/B衰变，理论提取K_1混合角:33^0–35^0或57^0–55^0、45^0、60^0、35^0–65^0有很大争议

粲介子半轻衰变探讨K_1混合及粒子参数理想窗口

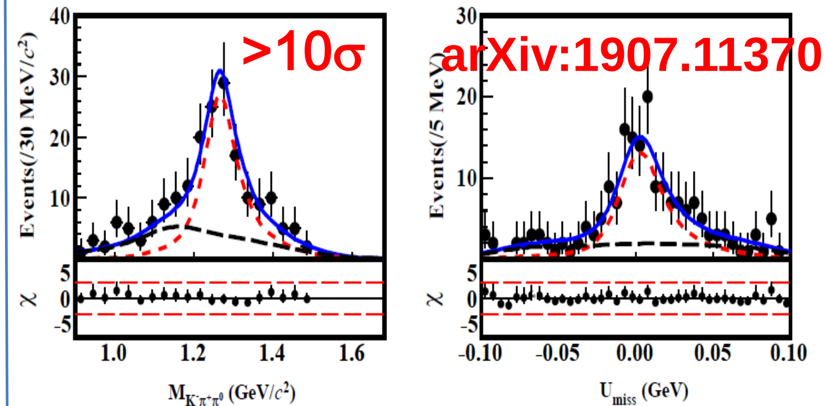
近期理论计算BFs强烈依赖K_1混合角

CLEOc, PRL99(2007)91801

Evidence wtth 281 pb[-1]

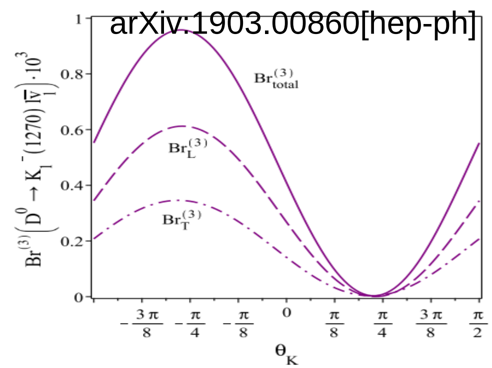


$$B_{D^0\to K_1(1270)^-e^+\nu}=(7.6^{+4.1}_{-3.0}\pm0.6\pm0.7)\times10^{-4}$$



BESIII首次观测到$D^+\to Ae\nu$

$$B_{D^+\to K_1(1270)^-e^+\nu}=(2.30\pm0.26\pm0.18\pm0.25)\times10^{-4}$$

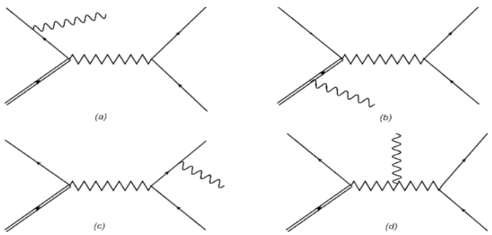


B与K_1混合角依赖示意图

支持混合角约33^0或57^0的计算

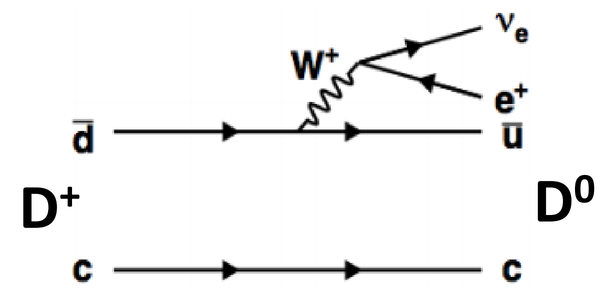
更大样本→形状因子；轴矢量粒子性质；寻找夸克模型预期的BF更小的其它衰变

寻找D辐射半轻衰变或β衰变



BF expected to be less than 10^{-3}

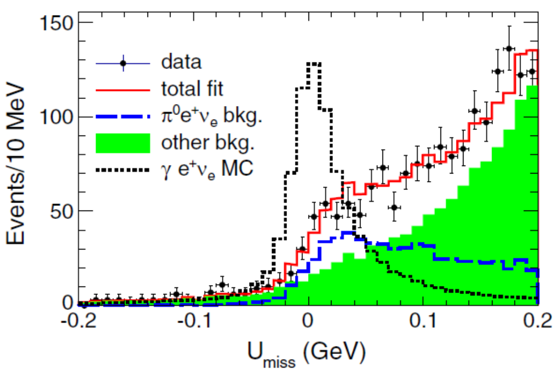
Detectable if BF at level of 10^{-4}

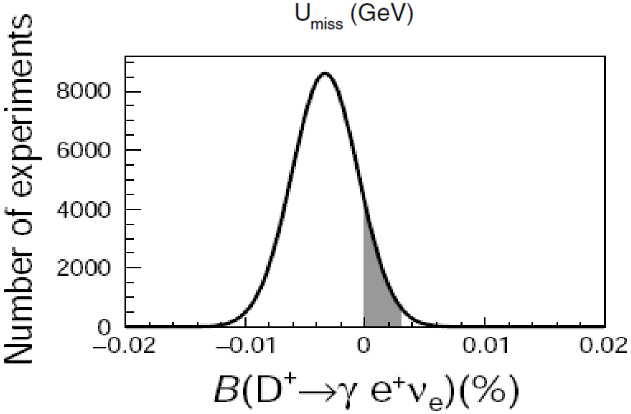


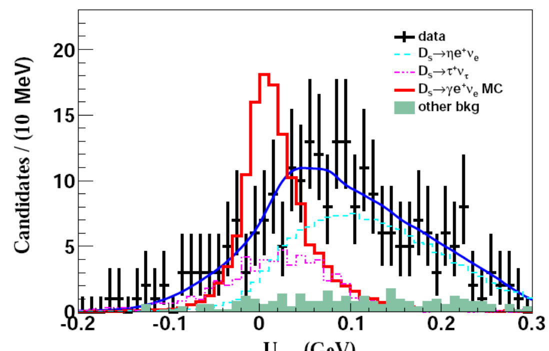
PRD95(2017)071102

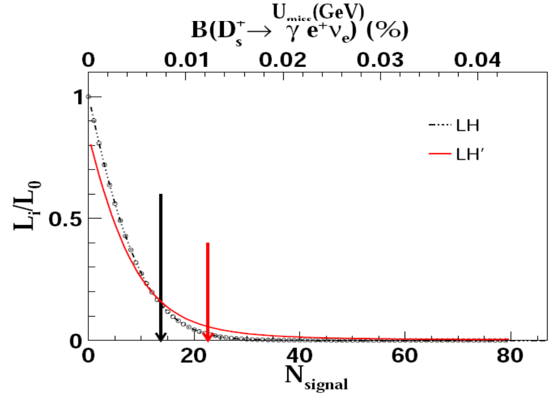
PRD99(2019)072002

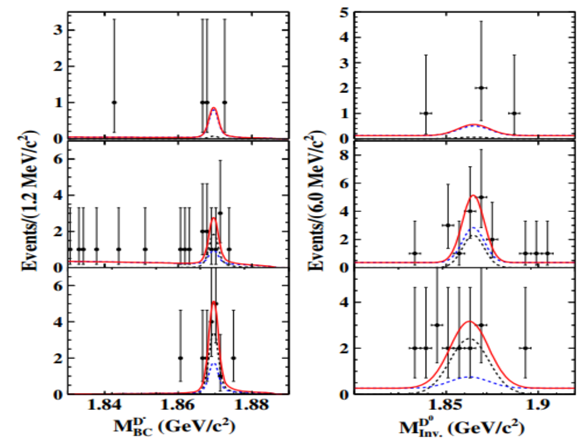
PRD96(2017)092002











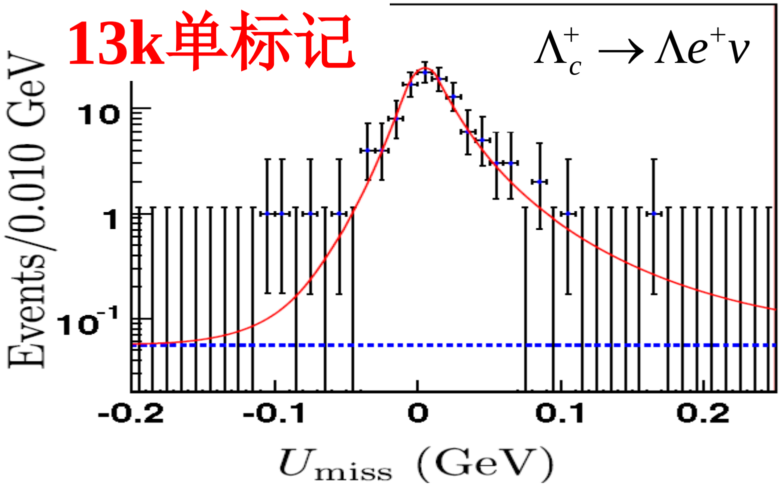
$B[D^+ \to D^0 e^+ \nu] < 1\times10^{-4}$ @90%C.L.

$B[D^+ \to \gamma e^+ \nu]|_{E\gamma>10\ MeV} < 3.0\times10^{-4}$ @90%C.L.

$B[D_s \to \gamma e^+ \nu]|_{E\gamma>10\ MeV} < 1.2\times10^{-4}$ @90%C.L.

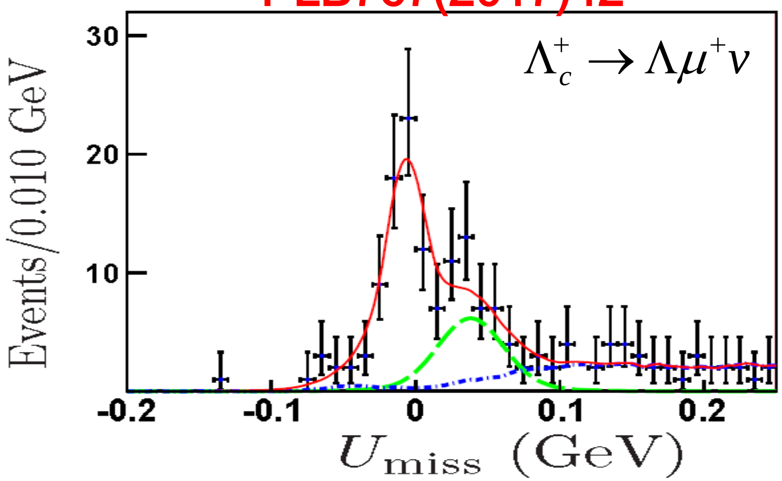
粲重子$\Lambda_c^+ \to \Lambda l^+ \nu$绝对分支比

PRL115(2015)221805



$$B[\Lambda_c^+ \to \Lambda e^+ \nu] = (3.63 \pm 0.38 \pm 0.20)\%$$

PLB767(2017)42



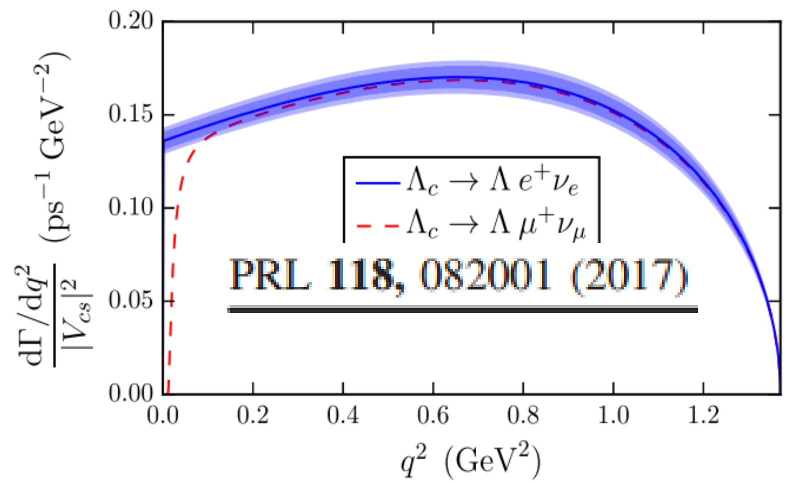
$$B[\Lambda_c^+ \to \Lambda \mu^+ \nu] = (3.49 \pm 0.46 \pm 0.26)\%$$

大大限定理论计算：原有理论计算(1.4-9.2)%较大范围内

轻子谱适性检验：

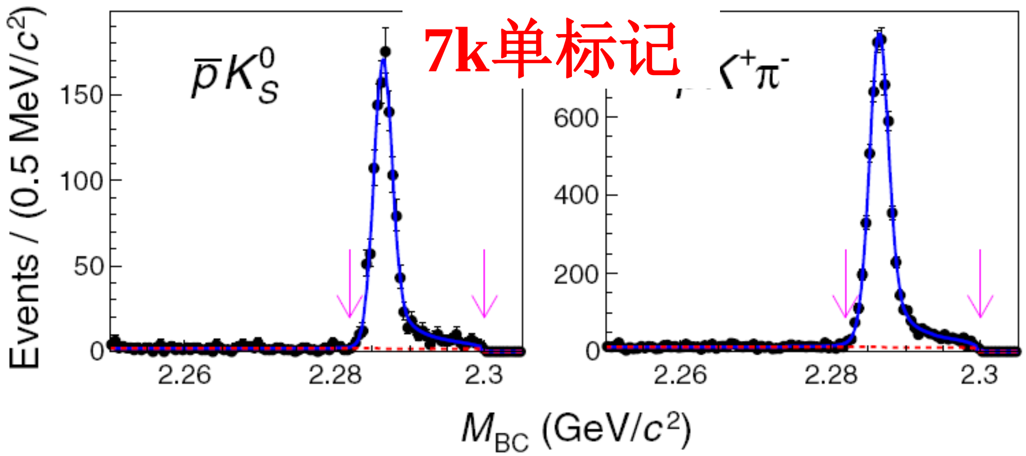
$$\frac{\Gamma[\Lambda_c^+ \to \Lambda \mu^+ \nu]}{\Gamma[\Lambda_c^+ \to \Lambda e^+ \nu]} = 0.96 \pm 0.16 \pm 0.04$$

引发LQCD计算: BF与BESIII一致

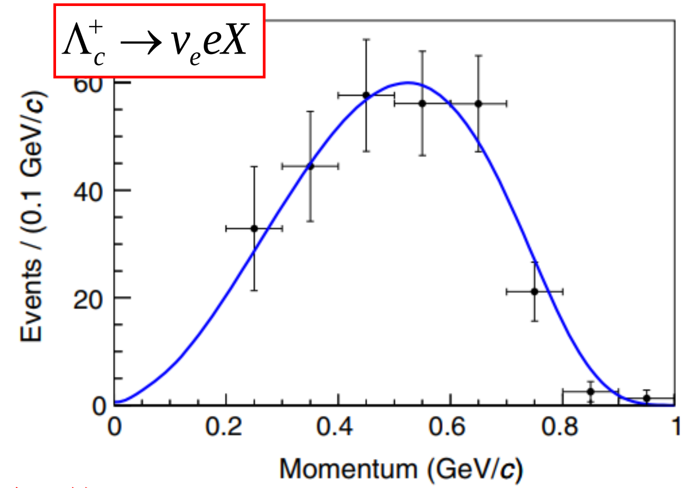


更多数据有望开展形状因子研究

粲重子$\Lambda_c^+ \to e\nu_e X$绝对分支比



PRL121(2018)251801



$B_{\Lambda_c^+ \to \nu_e eX} = (3.95 \pm 0.34 \pm 0.09)\%$ 精度显著改进

Result	$\Lambda_c^+ \to Xe^+\nu_e$	$[\Gamma(\Lambda_c^+ \to Xe^+\nu_e)/\Gamma(D \to Xe^+\nu_e)]$
BESIII	3.95 ± 0.35	1.26 ± 0.12
MARK II [11]	4.5 ± 1.7	1.44 ± 0.54
Effective-quark method [8,9]		1.67
Heavy-quark expansion [10]		1.2

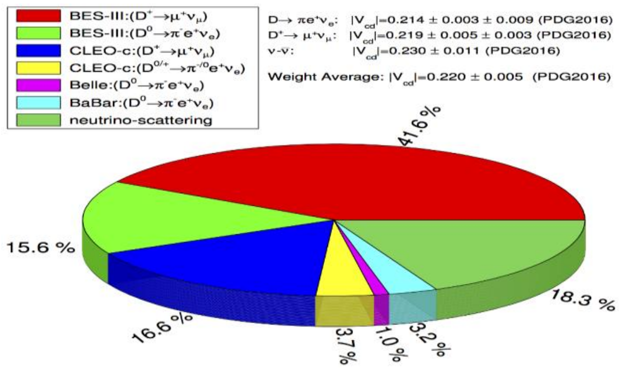
与单举粲介子分宽度之比，能够精密刻度理论预期

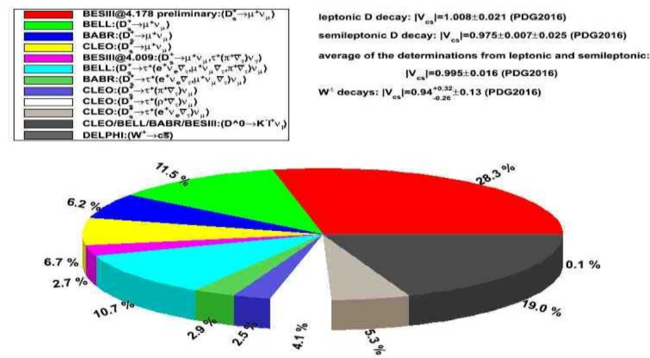
Decay channel	$\mathcal{B}$ (%)	Model
$\Lambda_c^+ \to \Lambda e^+\nu_e$	3.63 ± 0.43 [5]	$F_1^V(q^2) = 2.52/5.09 - q^2$ [28]
$\Lambda_c^+ \to \Lambda(1405)e^+\nu_e$	0.38 ± 0.38 [30]	PYTHIA [29]
$\Lambda_c^+ \to ne^+\nu_e$	0.27 ± 0.27 [31]	PYTHIA [29]

结果表明，没有其他大的遍举电子半轻衰变

Summary and prospect

BESIII实验在粲介子衰变常数、半轻形状因子、轻子普适性检验、$|V_{cs(d)}|$测量和Λ_c^+绝对分支比测量等方面取得重要成果。





$|V_{cd}|$: 4.8→2.3%

$|V_{cs}|$: 2.5→1.5%

-- 半轻测量$|V_{cs(d)}|$寄望LQCD大幅改进计算精度

-- 现有4.13-4.23 GeV数据，增加约1倍D_s

$|V_{cs}|$→1%

-- 未来10 fb^{-1} $\psi(3770)$数据: Sev, Aev形状因子研究

$|V_{cd}|$→~1.2%

-- 2020年，3-5 fb^{-1} Λ_c^+ @4.6-4.7 GeV: $\Lambda l\nu$形状因子，新衰变

谢谢！