Studies of charmed hadrons at BESIII

马海龙 (高能所)

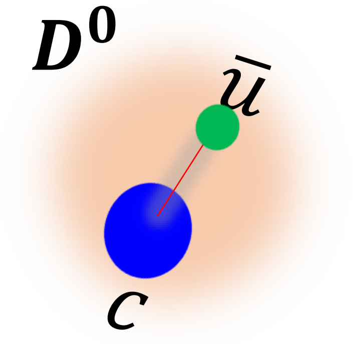
BESIII

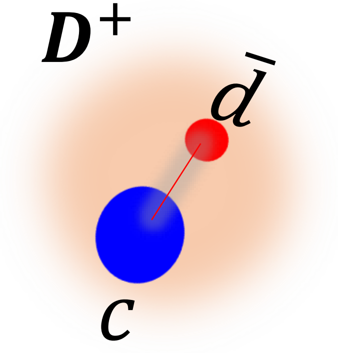
中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

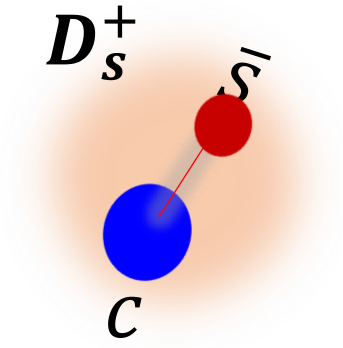
第四届重味物理和量子色动力学研讨会
2022年6月27-30日，湖南长沙

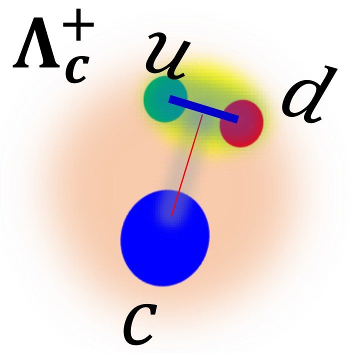
Contents

- Motivation
- Data samples
- (Semi)leptonic D decays
- Hadronic D decays
- Charmed baryon Λ_c^+ decays
- Summary



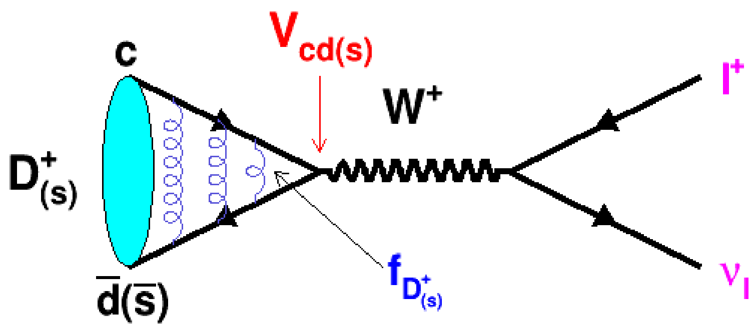


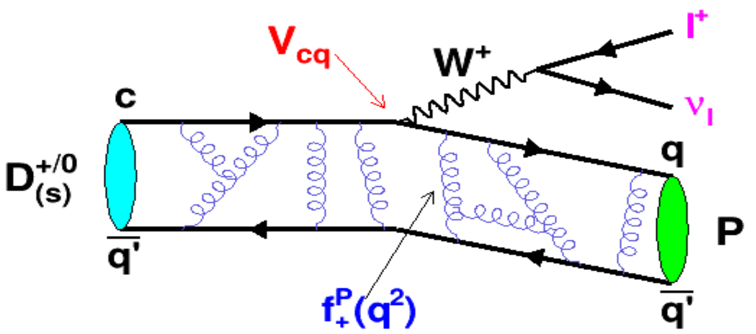




(Semi)leptonic *D* decays

探讨夸克和轻子相互作用的理想桥梁，检验标准模型的理想探针之一



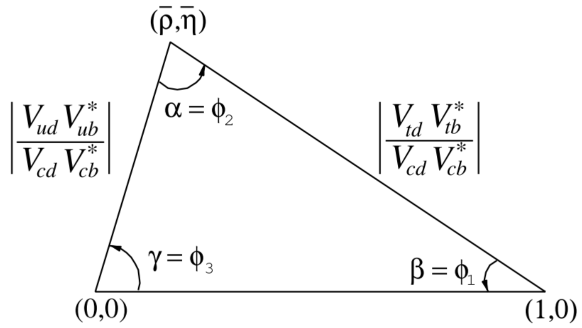


$$\Gamma(D^+_{(s)} \to \ell^+\nu_\ell) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi}|V_{cd(s)}|^2 m_\ell^2 m_{D^+_{(s)}}\left(1-\frac{m_\ell^2}{m^2_{D^+_{(s)}}}\right)^2$$

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

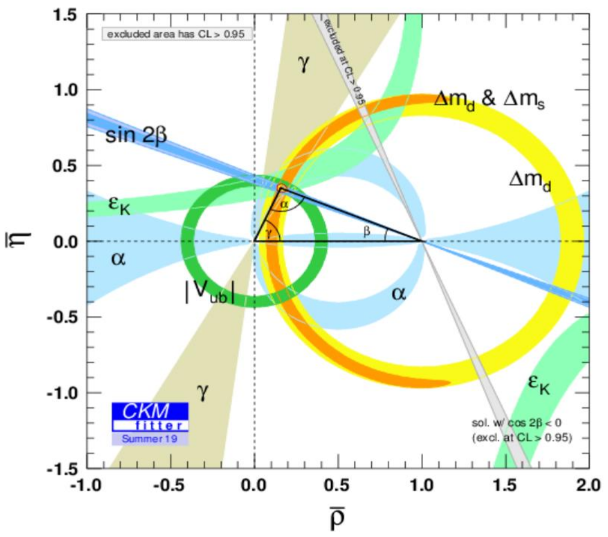
- 衰变常数、半轻衰变形状因子 →精密刻度格点QCD等计算
- CKM矩阵元$|V_{cs}|$、$|V_{cd}|$ →在更高精密下检验CKM矩阵的幺正性
- 分支比之比$B_{\mu/e}$、 $B_{\tau/\mu}$ →精确检验轻子普适性
- 稀有含轻衰变 →寻找超出标准模型的新物理效应

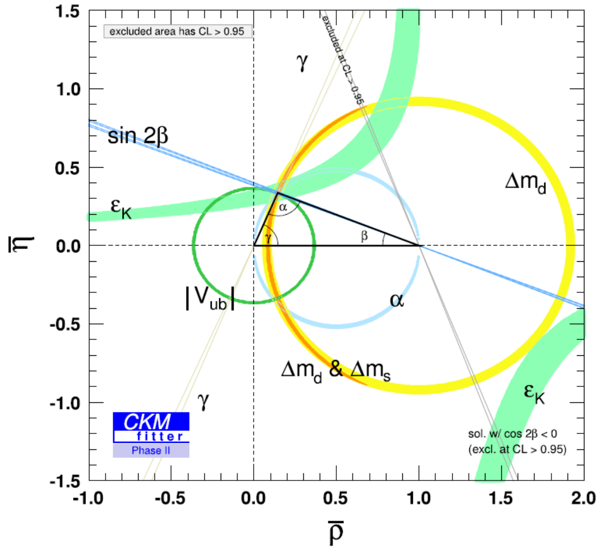
Hadronic D decays



In B physics, precision measurements of CP violation phase angles α, β and γ offer powerful tests on the EW theories. Among them, the γ precision is the most urgent

Precision measurements of γ at LHCb and Belle II need input the strong phase differences of neutral D decays





Quantum-correlated $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ pairs at BESIII offer an ideal opportunity to extract the strong phase differences between D^0 and $\bar{D}^0$

In the future 10-15 years, the statistical uncertainties of measuring will reach at ~1.5° and 0.4° at Belle II and LHCb upgrade

The constraint on the γ measurement before BESIII is only 2°, improved measurements of strong phase differences are highly desirable

Charmed baryon Λ_c^+ decays

- Λ_c^+ 是粲重子家族研究的基石；
- BESIII之前，几乎所有实验结果都是相对$\Lambda_c^+ \to pK^-\pi^+$的测量，相对精度>25%；
- 无近阈实验测量；
- >50%的遍举衰变丢失；
- 无末态含中子衰变的测量。

BESIII近阈数据为系统研究Λ_c^+衰变弱衰变机制提供了难得的历史机遇

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes with a p: $S = -1$ final states				
$p\overline{K}^0$		(2.3 ± 0.6) %		873
$pK^-\pi^+$	[a]	(5.0 ± 1.3) %		823
$p\overline{K}^*(892)^0$	[b]	(1.6 ± 0.5) %		685
$\Delta(1232)^{++}K^-$		(8.6 ± 3.0) $\times 10^{-3}$		710
$\Lambda(1520)\pi^+$	[b]	(1.8 ± 0.6) %		627
$pK^-\pi^+$ nonresonant		(2.8 ± 0.8) %		823
$p\overline{K}^0\pi^0$		(3.3 ± 1.0) %		823
$p\overline{K}^0\eta$		(1.2 ± 0.4) %		568
Hadronic modes with a hyperon: $S = -1$ final states				
$\Lambda\pi^+$		(1.07 ± 0.28) %		864
$\Lambda\pi^+\pi^0$		(3.6 ± 1.3) %		844
$\Lambda\rho^+$		< 5 %	CL=95%	636
$\Lambda\pi^+\pi^+\pi^-$		(2.6 ± 0.7) %		807
$\Sigma(1385)^+\pi^+\pi^-$, $\Sigma^{*+} \to \Lambda\pi^+$		(7 ± 4) $\times 10^{-3}$		688
$\Sigma(1385)^-\pi^+\pi^+$, $\Sigma^{*-} \to \Lambda\pi^-$		(5.5 ± 1.7) $\times 10^{-3}$		688
$\Lambda\pi^+\rho^0$		(1.1 ± 0.5) %		524
$\Sigma(1385)^+\rho^0$, $\Sigma^{*+} \to \Lambda\pi^+$		(3.7 ± 3.1) $\times 10^{-3}$		363
$\Lambda\pi^+\pi^+\pi^-$ nonresonant		< 8 $\times 10^{-3}$	CL=90%	807
$\Lambda\pi^+\pi^+\pi^-\pi^0$ total		(1.8 ± 0.8) %		757
$\Lambda\pi^+\eta$	[b]	(1.8 ± 0.6) %		691
$\Sigma(1385)^+\eta$	[b]	(8.5 ± 3.3) $\times 10^{-3}$		570
$\Lambda\pi^+\omega$	[b]	(1.2 ± 0.5) %		517
$\Lambda\pi^+\pi^+\pi^-\pi^0$, no η or ω		< 7 $\times 10^{-3}$	CL=90%	757
$\Lambda K^+\overline{K}^0$		(4.7 ± 1.5) $\times 10^{-3}$	S=1.2	443
$\Xi(1690)^0K^+$, $\Xi^{*0} \to \Lambda\overline{K}^0$		(1.3 ± 0.5) $\times 10^{-3}$		286
$\Sigma^0\pi^+$		(1.05 ± 0.28) %		825
$\Sigma^+\pi^0$		(1.00 ± 0.34) %		827
$\Sigma^+\eta$		(5.5 ± 2.3) $\times 10^{-3}$		713
$\Sigma^+\pi^+\pi^-$		(3.6 ± 1.0) %		804
$\Sigma^+\rho^0$		< 1.4 %	CL=95%	575
$\Sigma^-\pi^+\pi^+$		(1.7 ± 0.5) %		799
$\Sigma^0\pi^+\pi^0$		(1.8 ± 0.8) %		803
$\Sigma^0\pi^+\pi^+\pi^-$		(8.3 ± 3.1) $\times 10^{-3}$		763
$\Sigma^+\pi^+\pi^-\pi^0$		—		767
$\Sigma^+\omega$	[b]	(2.7 ± 1.0) %		569
Semileptonic modes				
$\Lambda\ell^+\nu_\ell$	[c]	(2.0 ± 0.6) %		871
$\Lambda e^+\nu_e$		(2.1 ± 0.6) %		871
$\Lambda\mu^+\nu_\mu$		(2.0 ± 0.7) %		867
Inclusive modes				
e^+ anything		(4.5 ± 1.7) %		–
pe^+ anything		(1.8 ± 0.9) %		–
p anything		(50 ±16) %		–

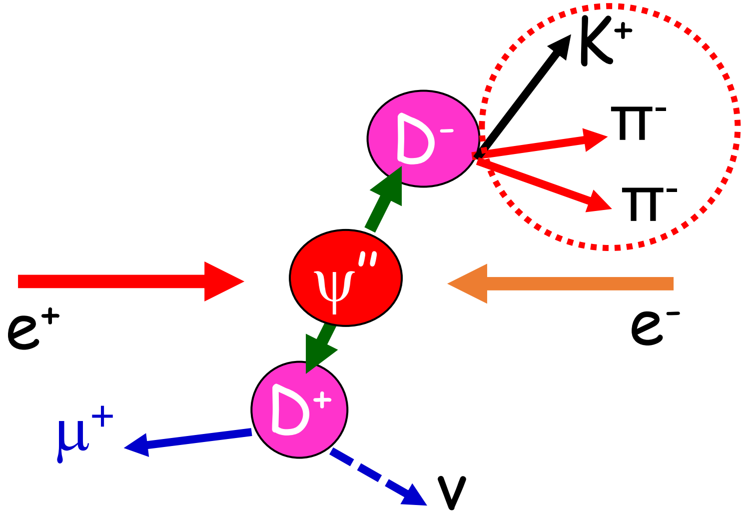
Data samples at BESIII

2009: 106M $\psi(3686)$
225M J/ψ
2010: 0.98 fb^{-1} $\psi(3770)$
2011: 2.93 fb^{-1} $\psi(3770)$ ($D^{0(+)}$)
0.48 fb^{-1} @4.01 GeV
2012: 0.45B $\psi(3686)$ (total)
1.30B J/ψ (total)
2013: 1.09 fb^{-1} @4.23 GeV (XYZ&D_s^+)
0.83 fb^{-1} @4.26 GeV
0.54 fb^{-1} @4.36 GeV
10×0.05 fb^{-1} XYZ scan@3.81-4.42 GeV
2014: 1.03 fb^{-1} @4.42 GeV
0.11 fb^{-1} @4.47 GeV
0.11 fb^{-1} @4.53 GeV
0.05 fb^{-1} @4.575 GeV
0.57 fb^{-1} @4.60 GeV (XYZ&Λ_c^+)
0.80 fb^{-1} R scan @3.85-4.59 GeV

2009: 106M $\psi(3686)$
2015: R-scan 2-3 GeV+2.175 GeV
2016: 3.20 fb^{-1} @4.178 GeV (XYZ&D_s^+)
2017: 7×0.50 fb^{-1} @4.19-4.22 GeV (XYZ&D_s^+),
@4.24-4.27 (XYZ)
2018: More J/ψ+tuning new RF cavity
2019: 10B J/ψ (total)
8×0.50 fb^{-1} XYZ scan@4.13, 4.16 (XYZ&D_s^+),
4.29-4.44 GeV
2020： 3.8 fb^{-1} @ 4.61-4.7 GeV (XYZ&Λ_c^+)
2021： 2.0 fb^{-1} @ 4.74-4.946 GeV
2.7B $\psi(3686)$ (total)
2022: 0.4 fb^{-1} @3.650 GeV
0.4 fb^{-1} @3.682 GeV
2.9→8 fb^{-1} $\psi(3770)$ ($D^{0(+)}$, total)
2023-2024: 8→20 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$)

Totally about 38 fb^{-1} at E_{cm} between 2 and 4.95 GeV in 13 year running

World largest threshold charmed hadron samples at BESIII



世界上最大的近阈数据

对产生→双标记方法

背景低→系统误差小

中性*D*介子量子关联

与Belle和LHCb优势互补

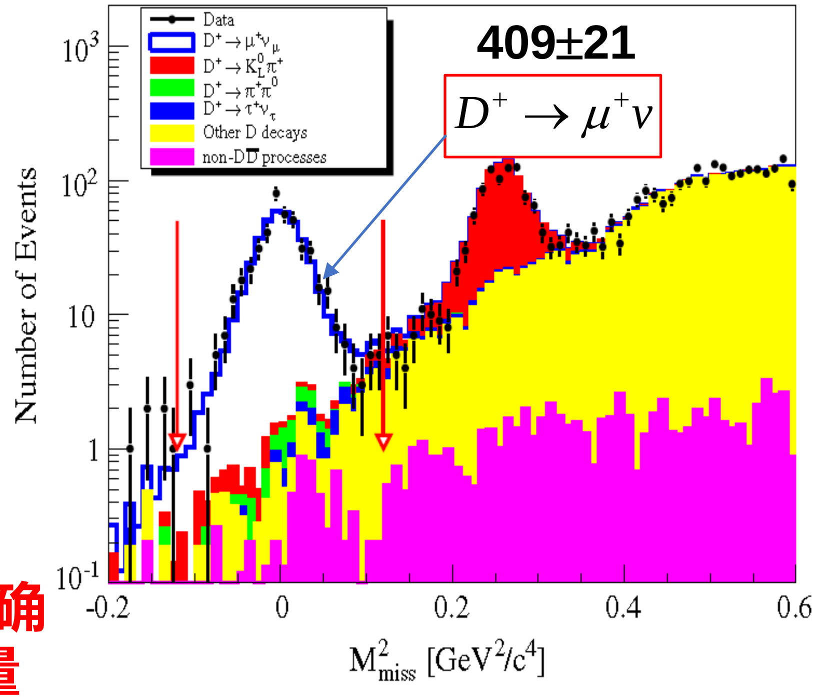
质心能量 (GeV)	采集年份	亮度 (fb^{-1})	D^0 产额	D^+ 产额	D_s^+ 产额	Λ_c^+ 产额
3.773	2010-2011(+2022)	2.93→8	2.5M (2.7×)	1.7M(2.7×)		
4.009	2011	0.5			13K	
4.18-4.23	2016,2017,2014,2019	7.3			1.5M	
4.6 (4.61-4.7)	2014(+2020)	0.6→4.5				15K (8×)

(Semi)leptonic D decays

Studies of $D^+ \to l^+ \nu_l$

2.93 fb^{-1} data@ 3.773 GeV

PRD89(2014)051104

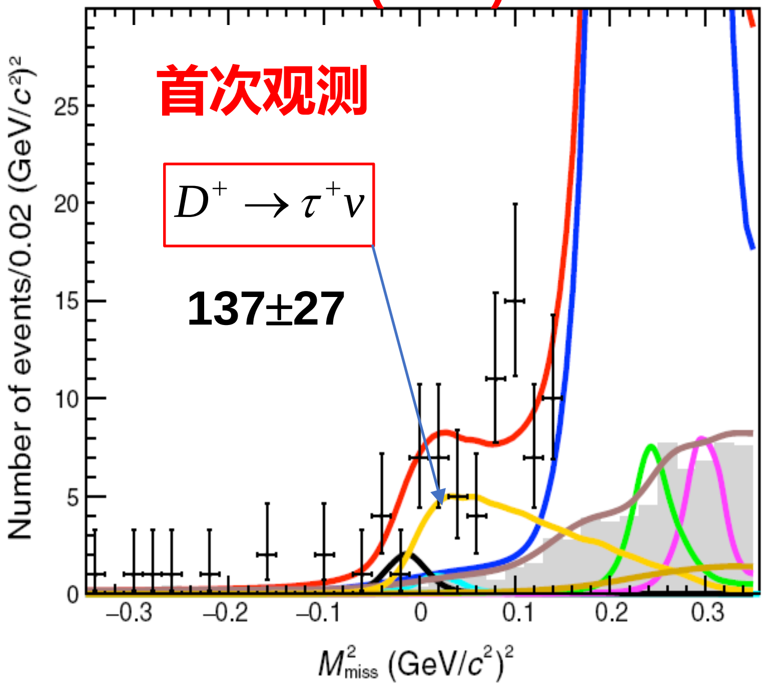


最精确测量

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

$$f_{D^+}|V_{cd}| = 46.7 \pm 1.2 \pm 0.4 \text{ MeV}$$

PRL123(2019)211802



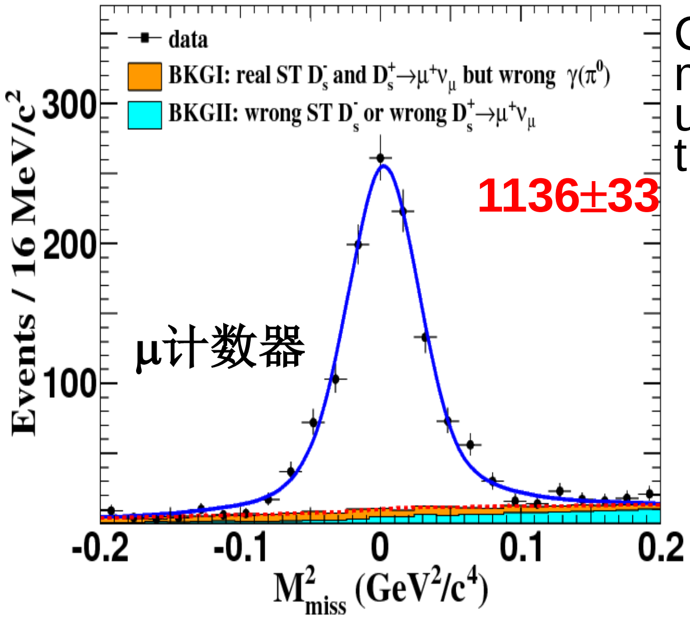
$$B[D^+ \to \tau^+ v] = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

$$f_{D^+}|V_{cd}| = 50.4 \pm 5.0 \pm 2.5 \text{ MeV}$$

Studies of $D_s^+ \to \mu^+\nu_\mu$

3.19 fb^{-1}@4.18 GeV

PRL122(2019)071802



Constrained fit to matched and un-matched transition $\gamma(\pi^0)$

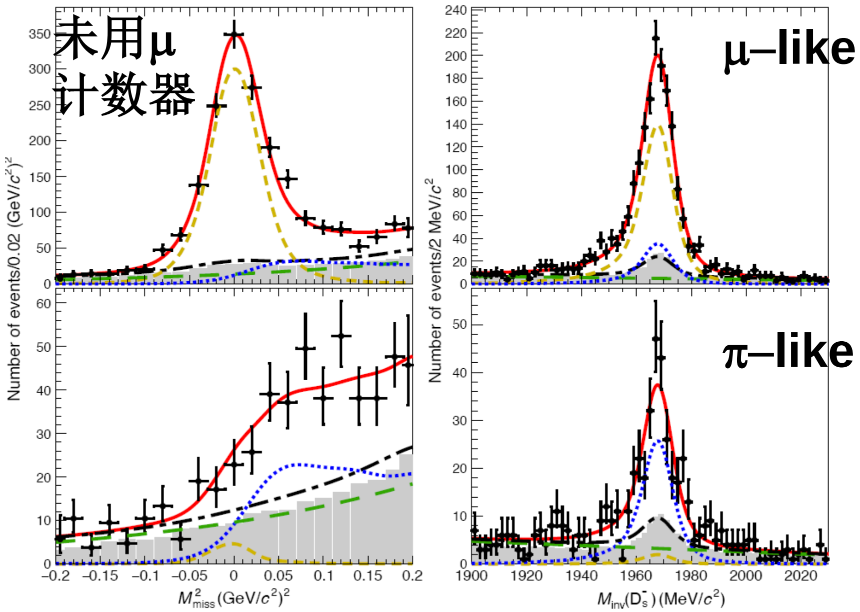
$$B[D_s^+ \to \mu^+ v] = (5.49 \pm 0.16 \pm 0.15) \times 10^{-3}$$

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

精度~2.1%

6.3 fb^{-1}@4.18-4.23GeV

PRD104(2021)052009



2198±55

$$B[D_s^+ \to \mu^+ v] = (5.35 \pm 0.13 \pm 0.16) \times 10^{-3}$$

$$f_{D_s^+}|V_{cs}| = (243.1 \pm 3.0 \pm 3.7)\ \text{MeV}$$

精度~2.0%

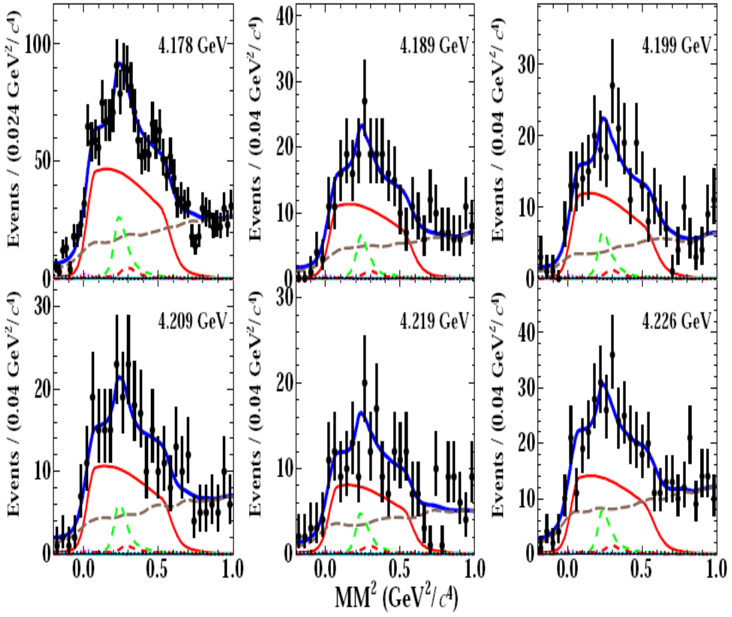
Studies of $D_s^+ \to \tau^+\nu_\tau$

PRD104(2021)032001

$D_s^+ \to \tau^+(\rho^+\nu)\nu$

6.3 fb^{-1}

1745±84



$f_{D_s^+}|V_{cs}| = (244.8 \pm 5.8 \pm 4.8)$ MeV

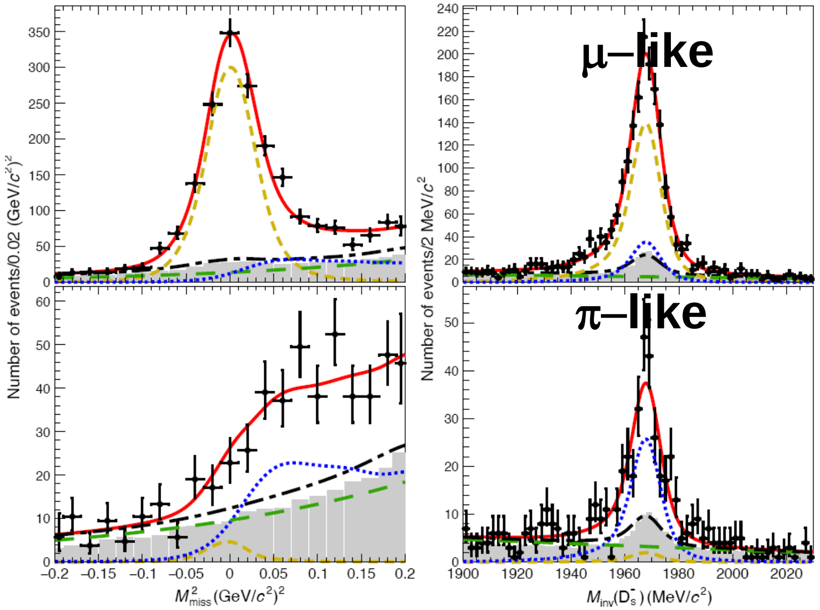
精度~3.1%

PRD104(2021)052009

$D_s^+ \to \tau^+(\pi^+\nu)\nu$

6.3 fb^{-1}

946±46



$f_{D_s^+}|V_{cs}| = (243.0 \pm 5.8 \pm 4.0)$ MeV

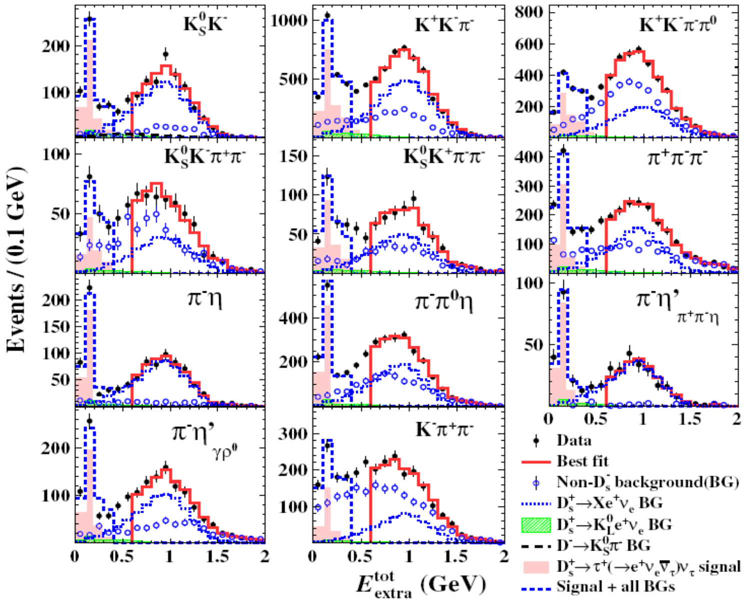
精度~2.9%

PRL127(2021)171801

$D_s^+ \to \tau^+(e^+\nu\nu)\nu$

6.3 fb^{-1}

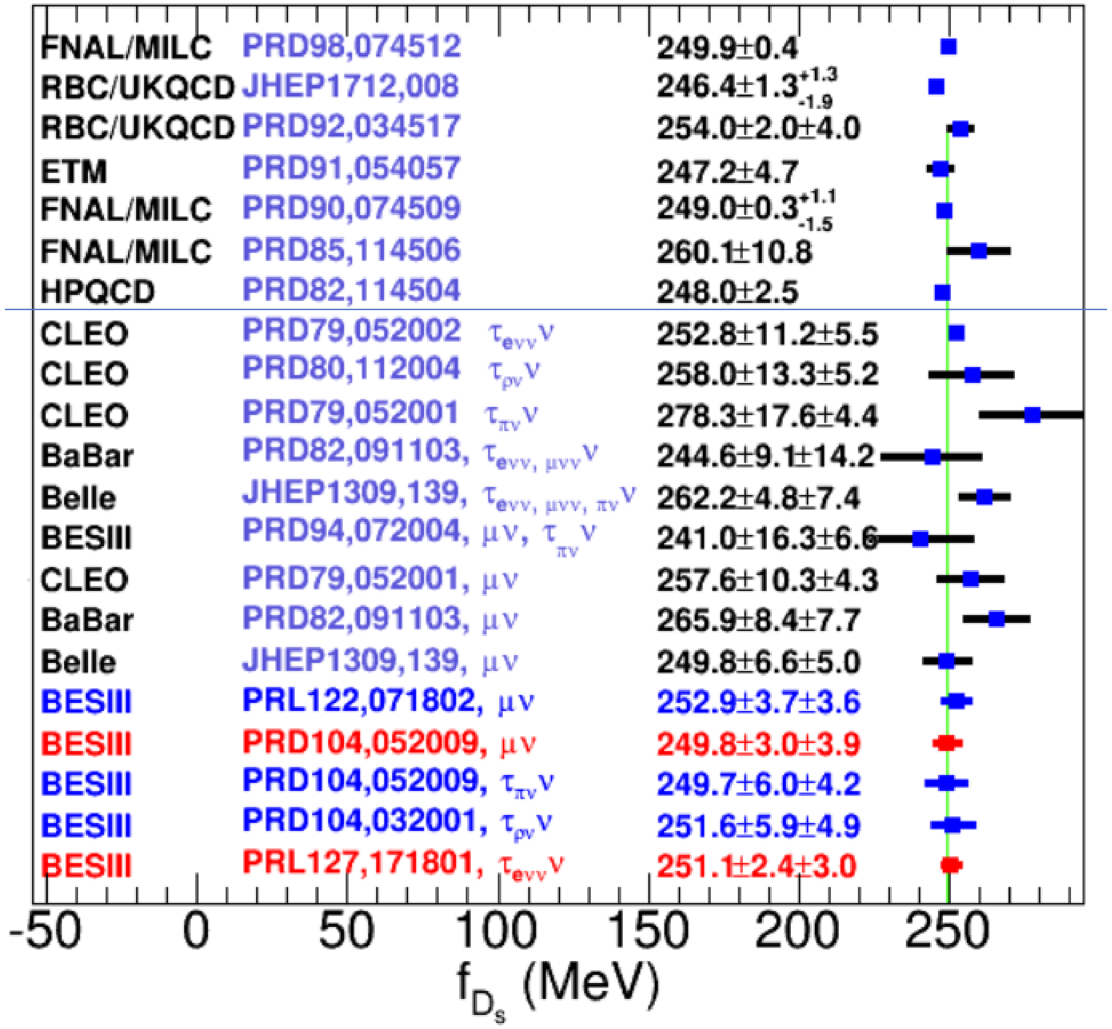
4940±97

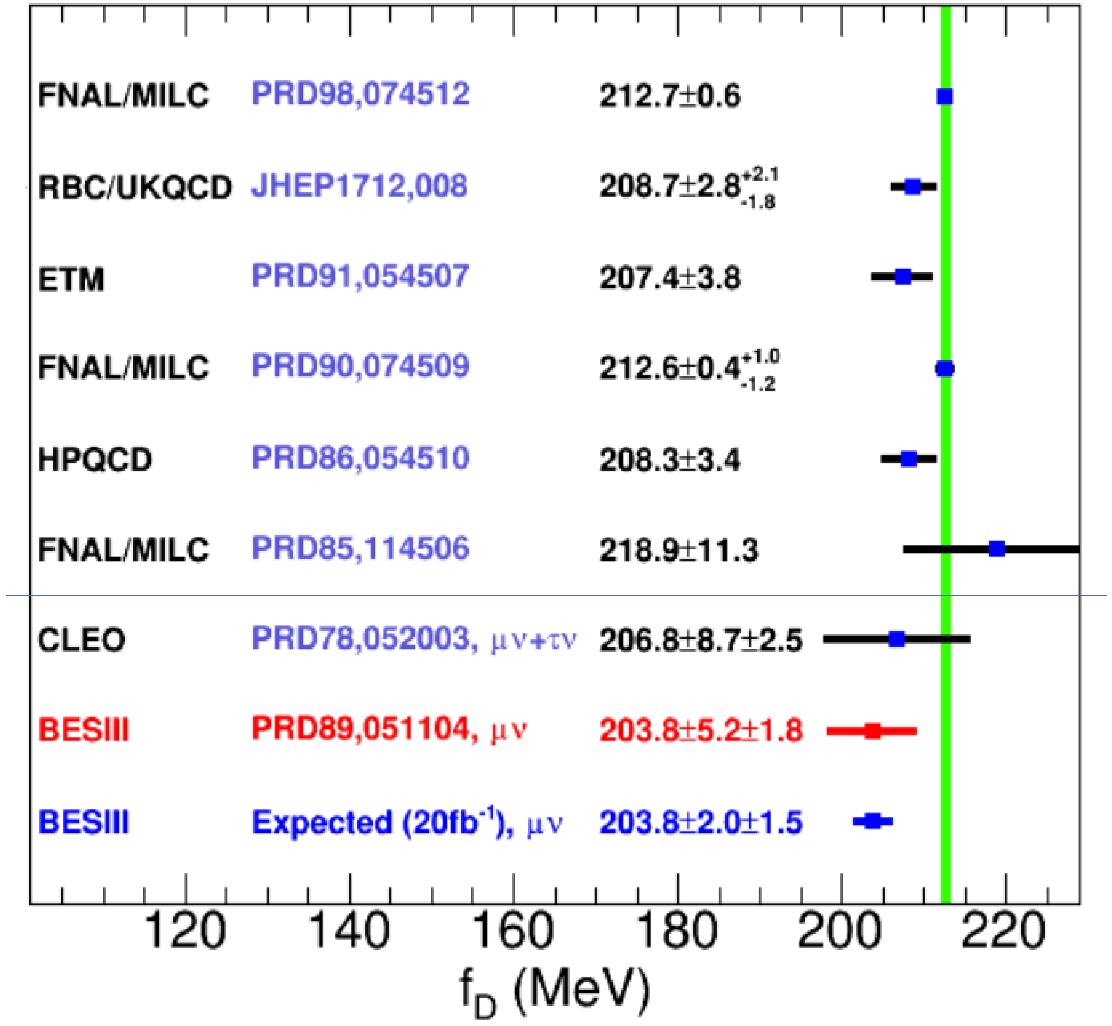


$f_{D_s^+}|V_{cs}| = (244.4 \pm 2.3 \pm 2.9)$ MeV

精度~1.5%

Comparisons of f_{D^+} and $f_{D_s^+}$





Studies of $D \to P e^+ \nu_e$ dynamics

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

动力学研究 → $f_+^{D\to P}(0)|V_{cs(d)}|$

形状因子参数化形式

– **Single pole form** $$f_+(q^2) = \frac{f_+(0)}{1-\frac{q^2}{M_{\rm pole}^2}}$$

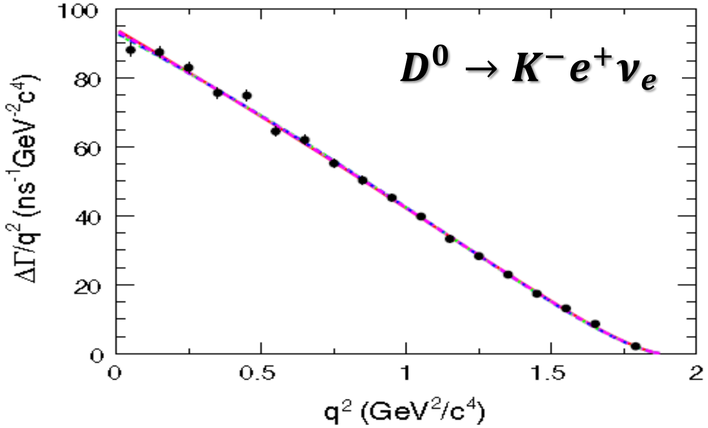
– **Modified pole** $$f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M_{\rm pole}^2})(1-\alpha\frac{q^2}{M_{\rm pole}^2})}$$

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

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

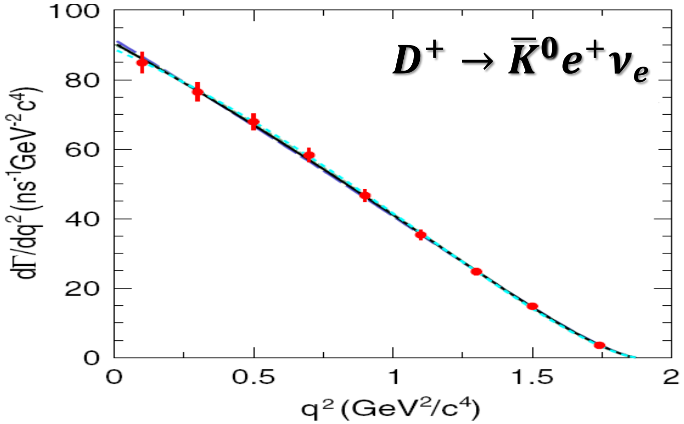
Studies of $c \to s l^+ \nu_l$ semileptonic decays

PRD92(2015)072012



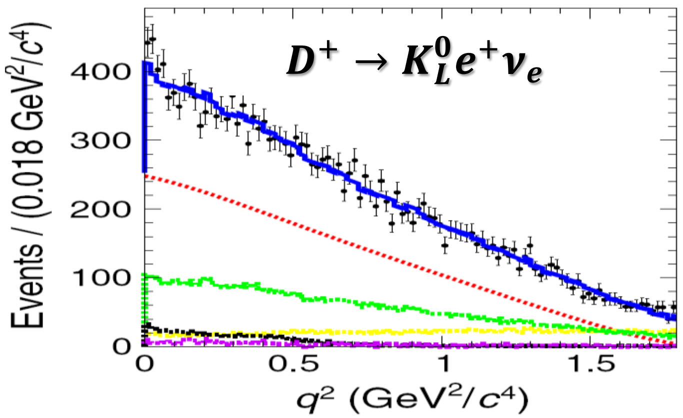
$f_+^{D\to K}(0)|V_{cs}| = 0.717(03)(04)$

PRD96(2017)012002



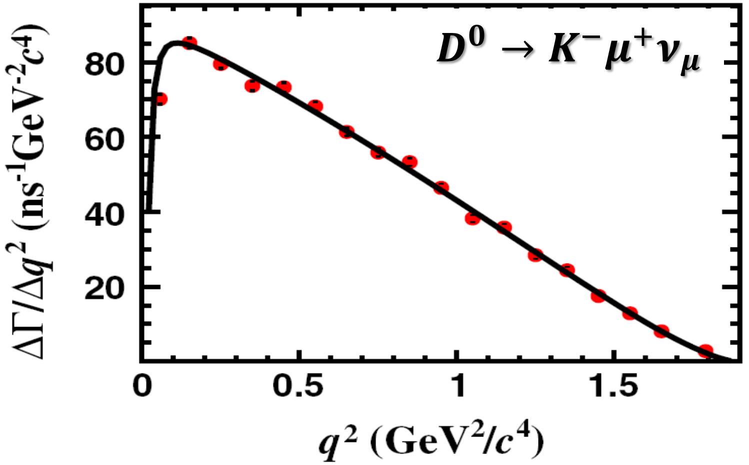
$f_+^{D\to K}(0)|V_{cs}| = 0.705(04)(11)$

PRD92(2015)112008



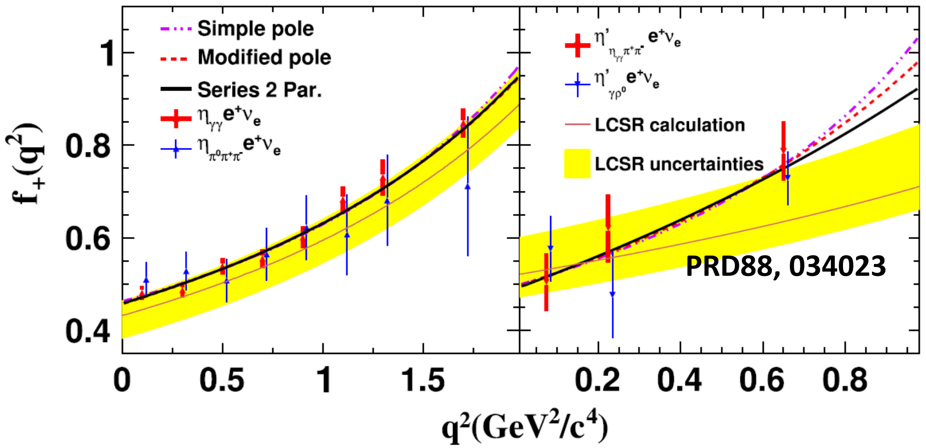
$f_+^{D\to K}(0)|V_{cs}| = 0.728(06)(11)$

PRL122(2019)011804



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

$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ **PRL123(2019)121801**

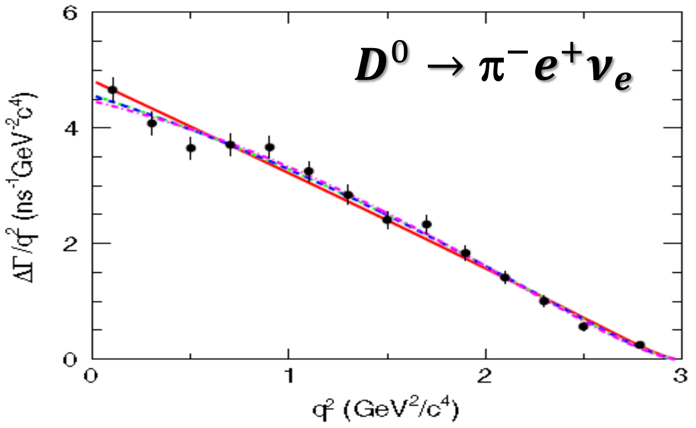


首次提取

$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.446(05)(04)$ $f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.477(49)(11)$

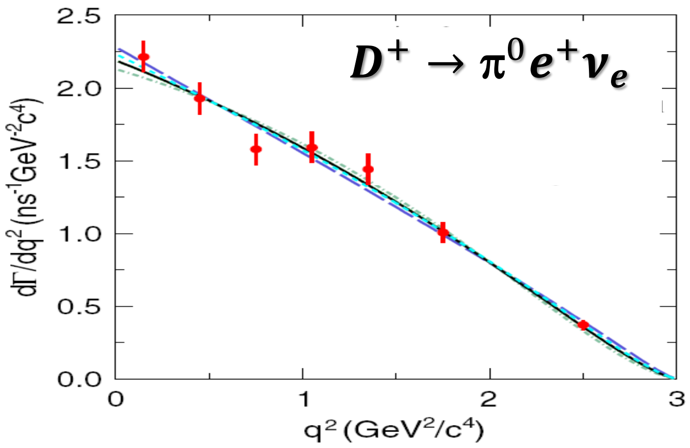
Studies of $c \to d l^+ \nu_l$ semileptonic decays

PRD92(2015)072012



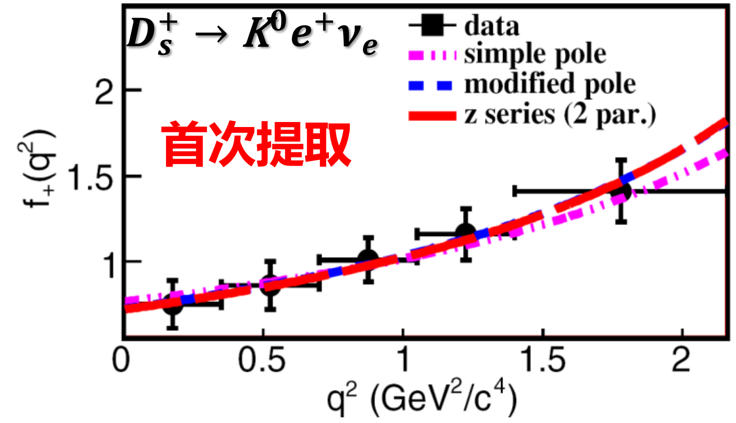
$f_+^{D\to\pi}(0)|V_{cd}| = 0.144(02)(01)$

PRD96(2017)012002



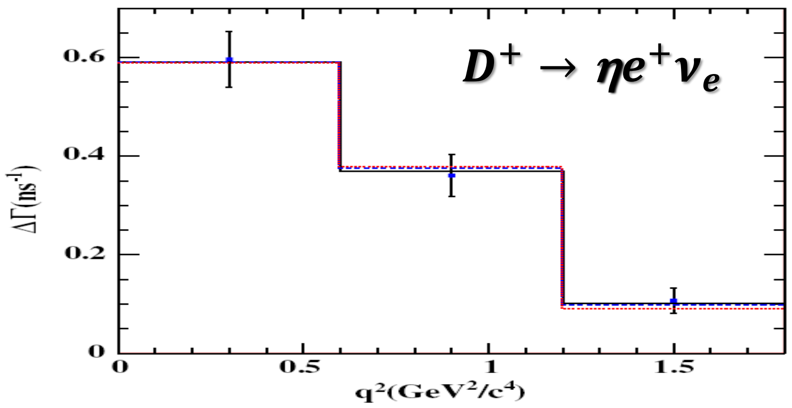
$f_+^{D\to\pi}(0)|V_{cd}| = 0.140(03)(01)$

PRL122(2019)061801



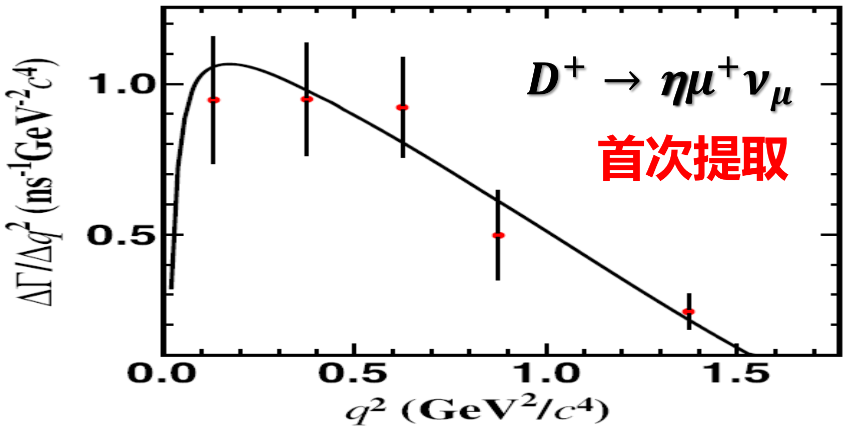
$f_+^{D_s\to K}(0)|V_{cd}| = 0.162(19)(03)$

PRD97(2018)092009



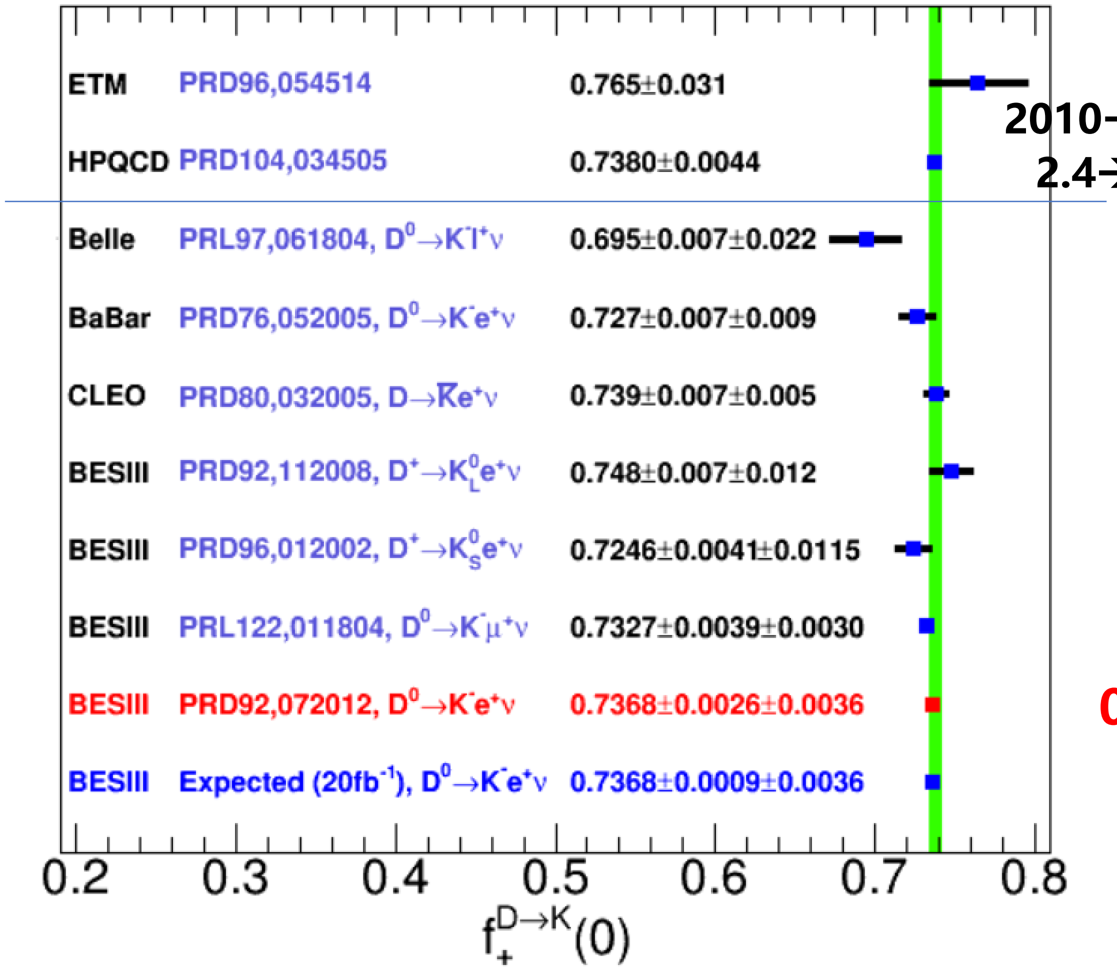
$f_+^{D\to\eta}(0)|V_{cd}| = 0.079(06)(02)$

PRL124(2020)231801



$f_+^{D\to\eta}(0)|V_{cd}| = 0.087(08)(02)$

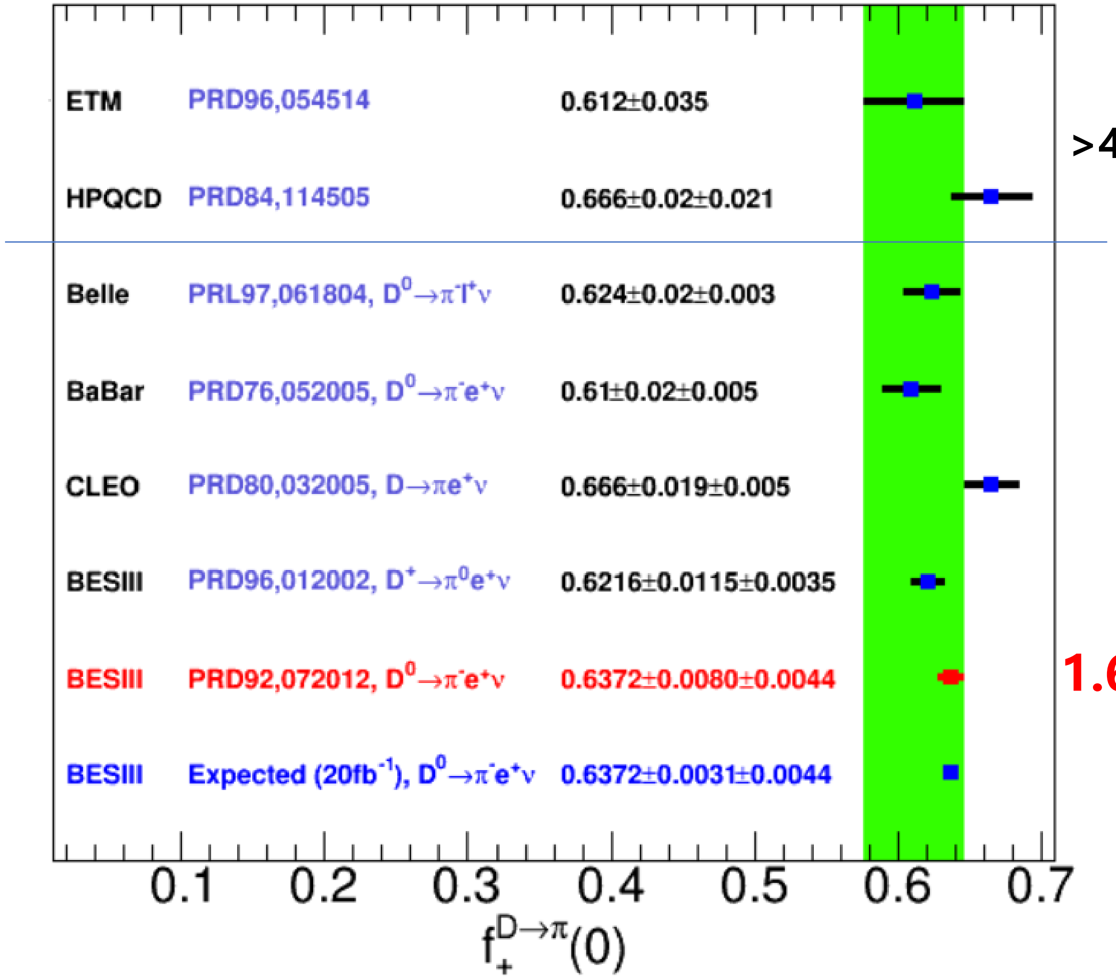
Comparisons of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$



2010→2021
2.4→0.6%

0.7%

Experimental precision is comparable to the latest LQCD result

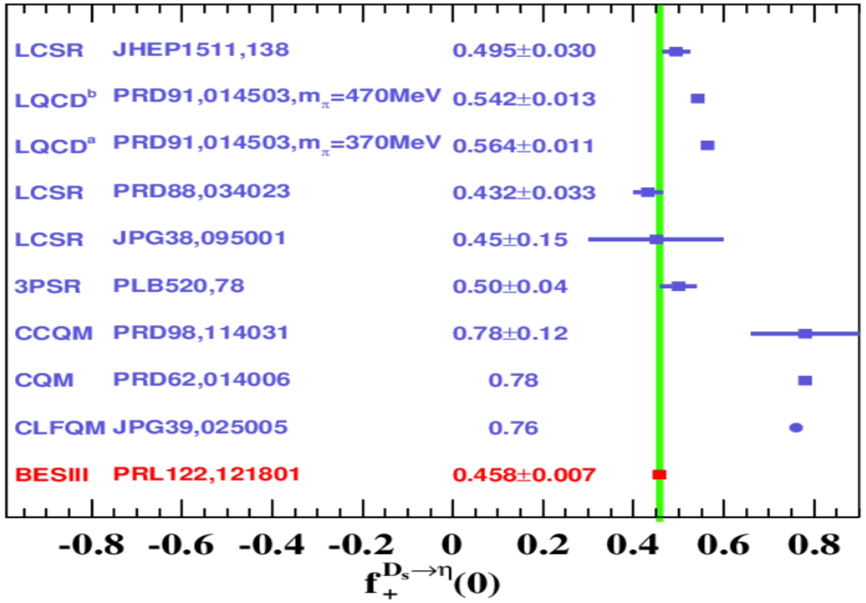


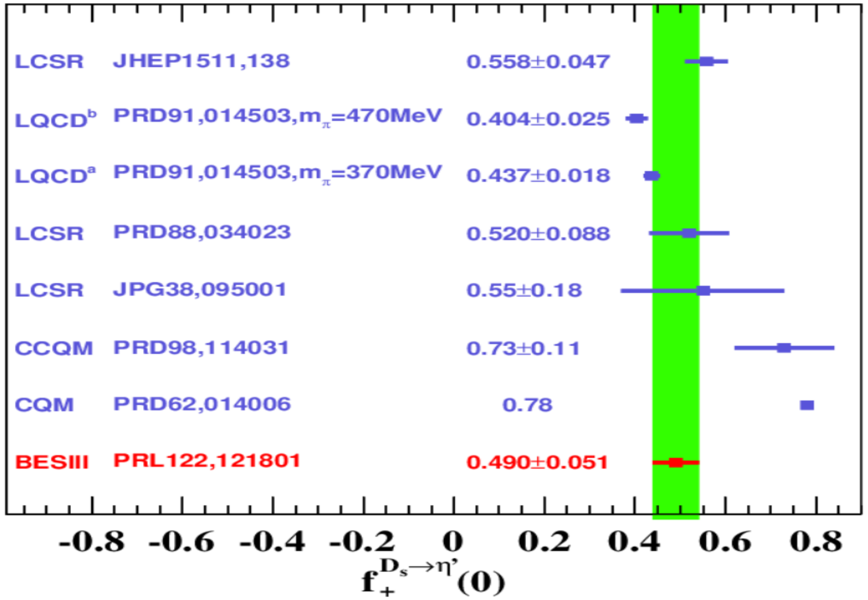
>4%

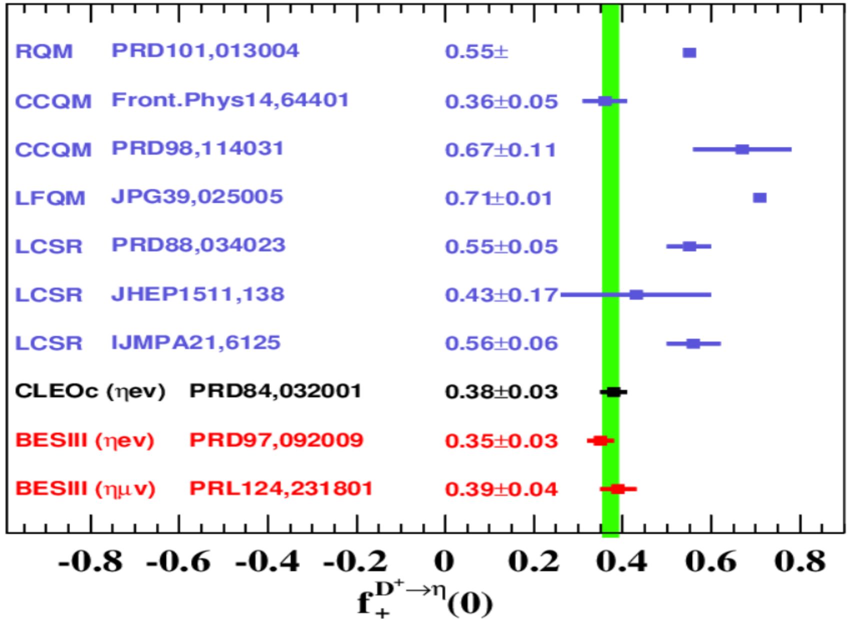
1.6%

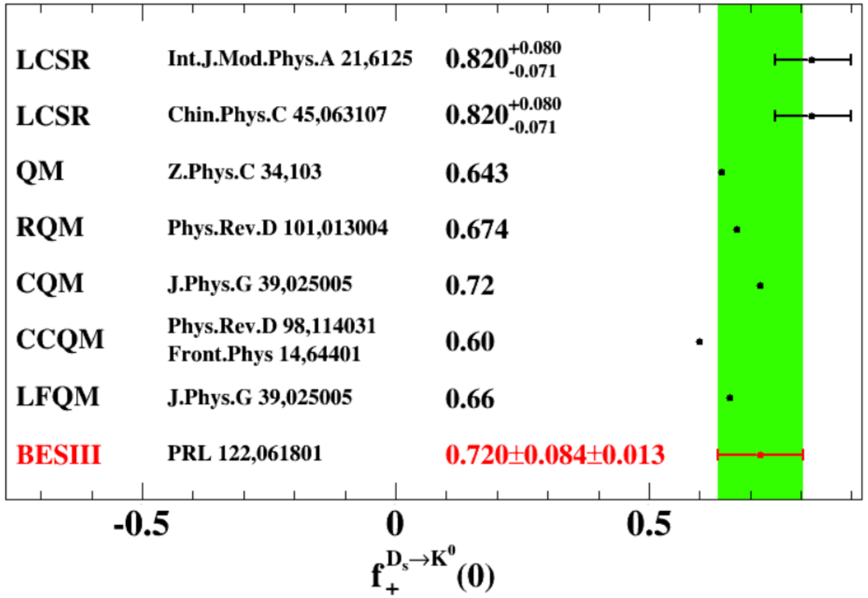
The measurements of the Cabibbo-suppressed decays are still dominated by statistical uncertainties

Comparisons of other form factors

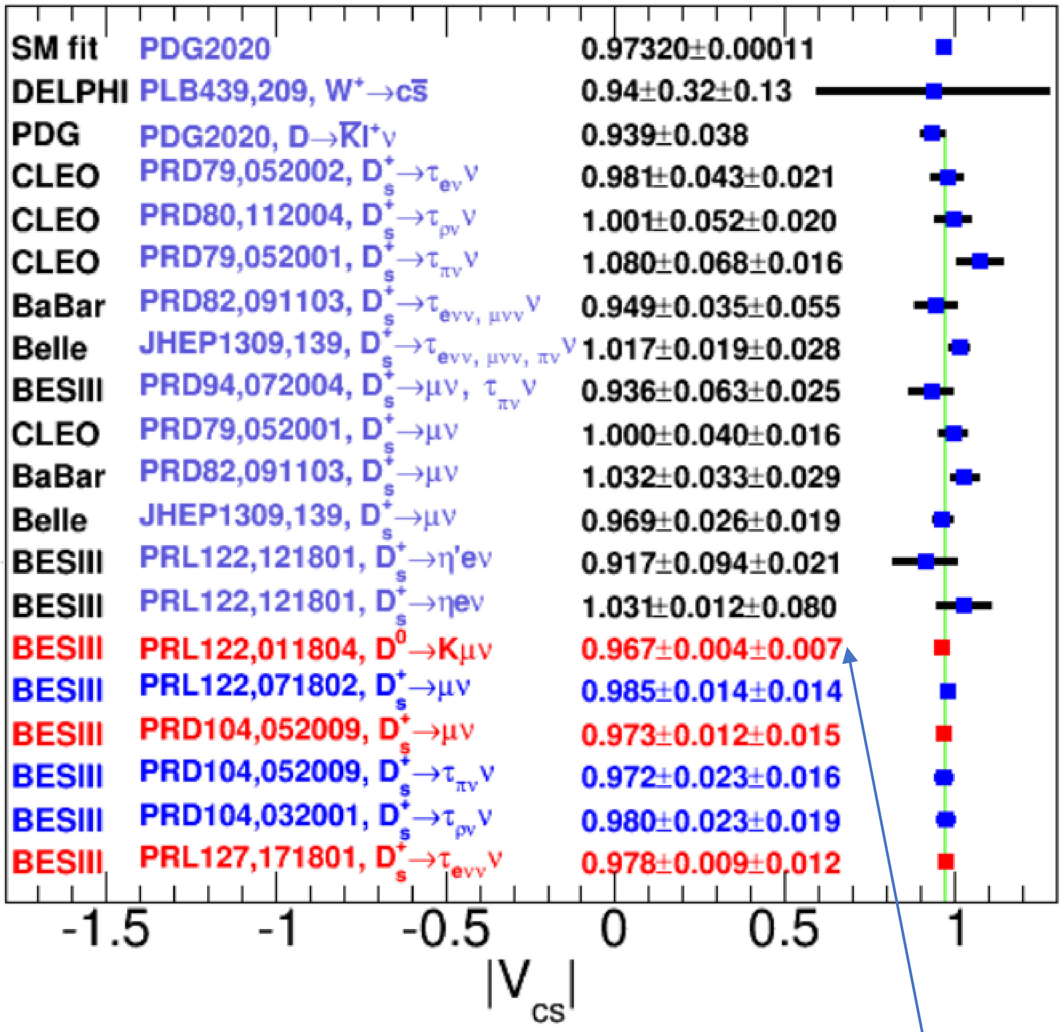


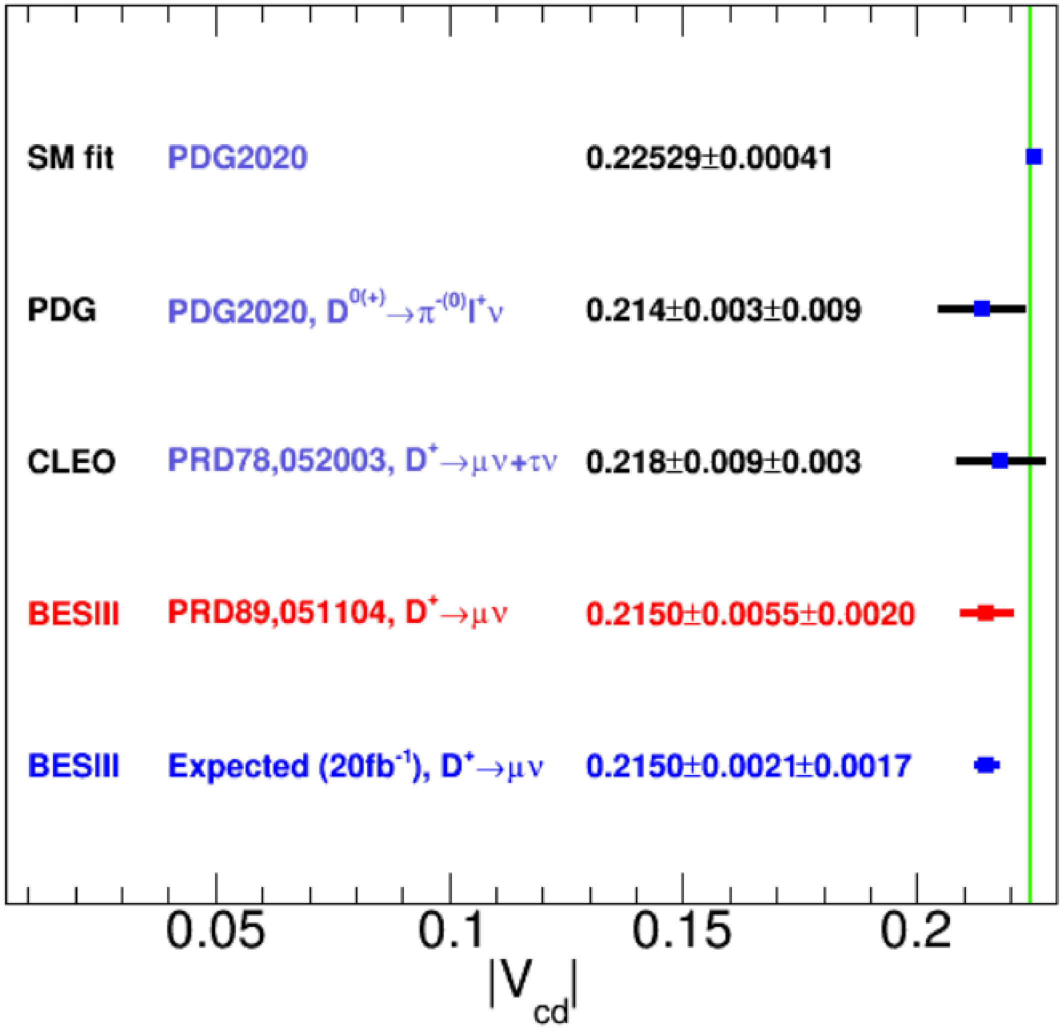






Comparisons of $|V_{cs}|$ and $|V_{cd}|$



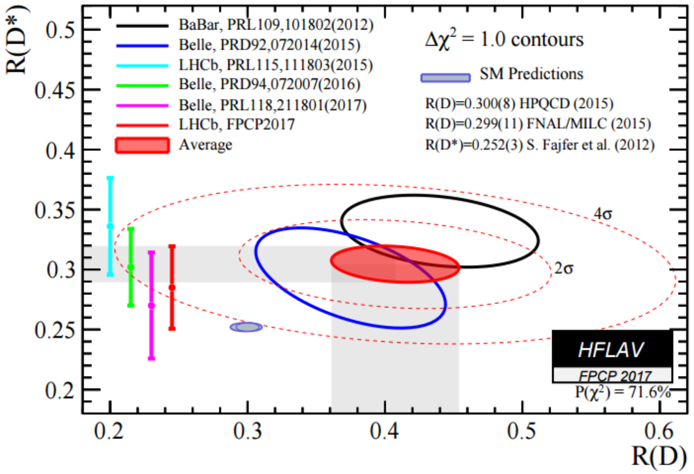


$f^K_+(0)$@HPQCD精度:2.4%→0.6%

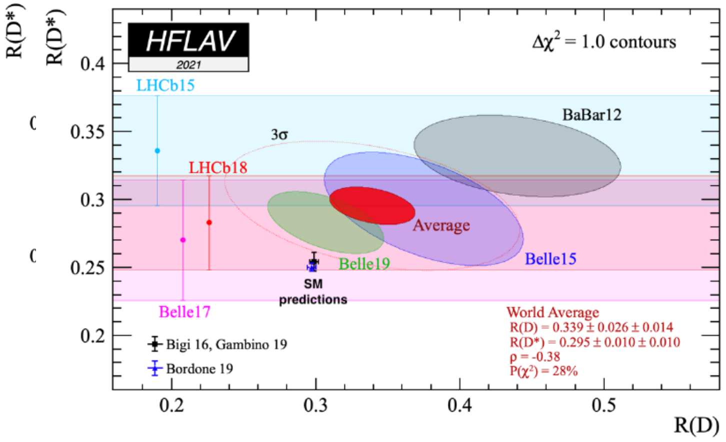
LFU tests in charm decays before BESIII

Tension in B physics

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\,\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\,l\,\nu_l)}$$



3.9σ



3.3σ

Tension in D physics

$$\mathrm{B}^{\mathrm{PDG18}}[D^0 \to \pi^-\mu^+\nu] = (0.237 \pm 0.024)\%$$ **(2.1σ)**

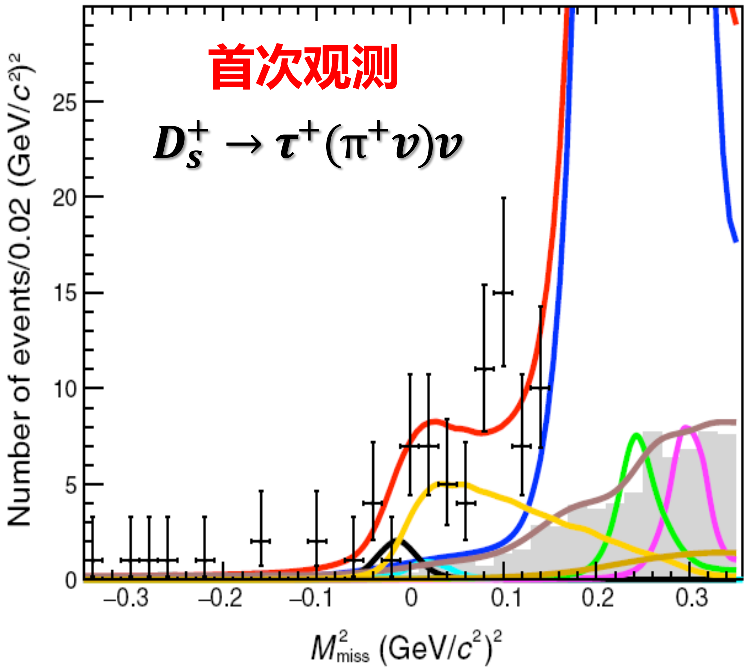
$$\frac{\Gamma^{\mathrm{PDG18}}[D^0 \to \pi^-\mu^+\nu]}{\Gamma^{\mathrm{PDG18}}[D^0 \to \pi^-e^+\nu]} = 0.82 \pm 0.08$$ **SM prediction: 0.985**

粲强子遍举μ半轻衰变大量研究空白!

	D^0		D^+		D_s^+	
$c \to s l^+\nu$	K^-	$4\%^{\text{Belle}}$	$\bar{K}^0$	$7\%^{\text{FOCUS}}$	η	NA
	K^{*-}	$13\%^{\text{FOCUS}}$	$\bar{K}^{*0}$	$3\%^{\text{CLEOc}}$	η’	NA
					ϕ	NA
					f_0	NA
$c \to d l^+\nu$	π^-	$10\%^{\text{Belle}}$	π^0	NA	K^0	NA
	ρ^-	NA	ρ^0	$17\%^{\text{FOCUS}}$	K^{*0}	NA
			ω	NA		
			η	NA		
			η’	NA		

Tests of LFU in $D^+_{(s)} \to l^+\nu_l$

PRL123(2019)211802



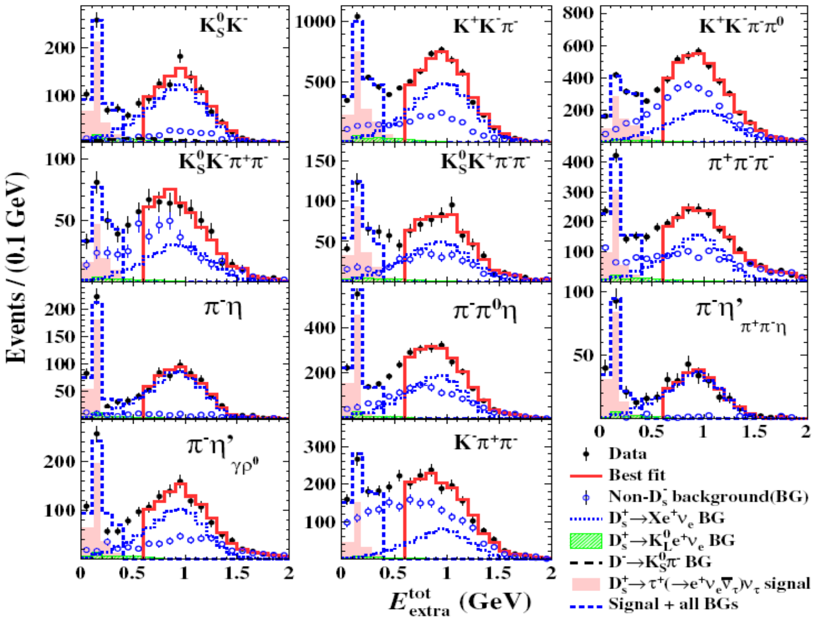
$$B[D^+ \to \tau^+ v] = (1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$$

$$B^{PDG}[D^+ \to \mu^+ v] = (3.74 \pm 0.17) \times 10^{-4}$$

$$R_D = \frac{B[D^+ \to \tau^+ v]}{B[D^+ \to \mu^+ v]} = 3.21 \pm 0.64 \pm 0.43$$

SM prediction: 2.67

PRL127(2021)171801 $D_s^+ \to \tau^+(e^+ vv)v$



Combined results:

$$B[D_s^+ \to \mu^+ v] = (5.43 \pm 0.16) \times 10^{-3}$$

$$B[D_s^+ \to \tau^+ v] = (5.33 \pm 0.12)\%$$

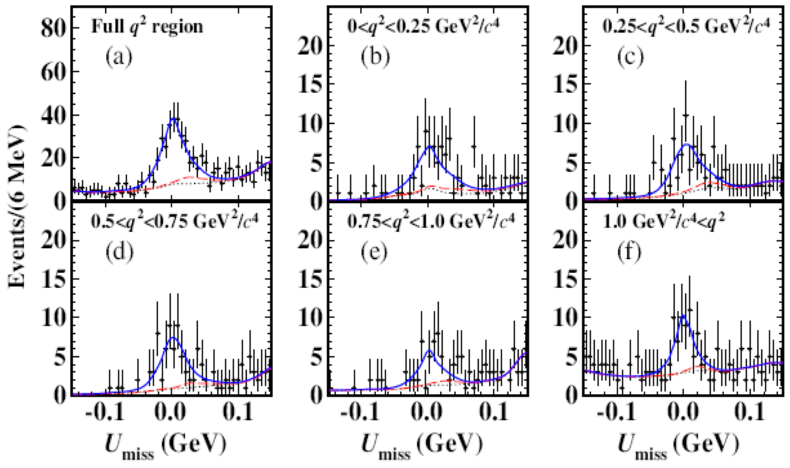
$$R_{Ds} = \frac{B[D_s^+ \to \tau^+ v]}{B[D_s^+ \to \mu^+ v]} = 9.82 \pm 0.36$$

SM prediction: 9.75

Tests of LFU in $D \to (P,V)l^+\nu_l$

首次观测 $D^+ \to \eta\mu^+v$

PRL124(2020)231801

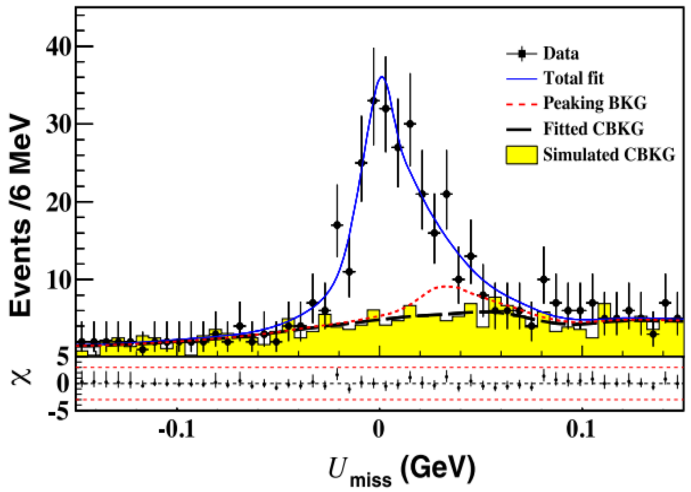


$\mathrm{B}[D^+ \to \eta\mu^+v] = (0.104 \pm 0.010 \pm 0.005)\%$

$$R_{D\eta} = \frac{\Gamma[D^+ \to \eta\mu^+v]}{\Gamma[D^+ \to \eta e^+v]} = 0.91 \pm 0.13$$

首次观测 $D^+ \to \omega\mu^+v$

PRD101(2020)072005

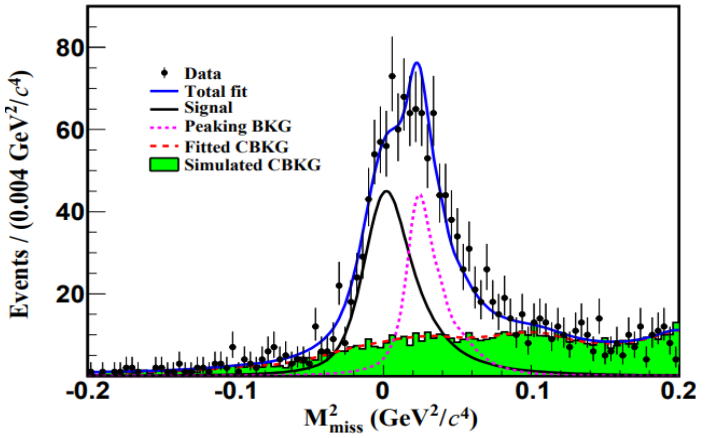


$\mathrm{B}[D^+ \to \omega\mu^+v] = (0.177 \pm 0.018 \pm 0.011)\%$

$$R_{D\omega} = \frac{\Gamma[D^+ \to \omega\mu^+v]}{\Gamma[D^+ \to \omega e^+v]} = 1.05 \pm 0.14$$

首次观测 $D^0 \to \rho^-\mu^+v$

PRD104(2021)L091103



$\mathrm{B}[D^0 \to \rho^-\mu^+v] = (0.135 \pm 0.009 \pm 0.009)\%$

$$R_{D\rho} = \frac{\Gamma[D^+ \to \omega\mu^+v]}{\Gamma[D^+ \to \omega e^+v]} = 0.90 \pm 0.11$$

SM prediction: 0.93-0.96

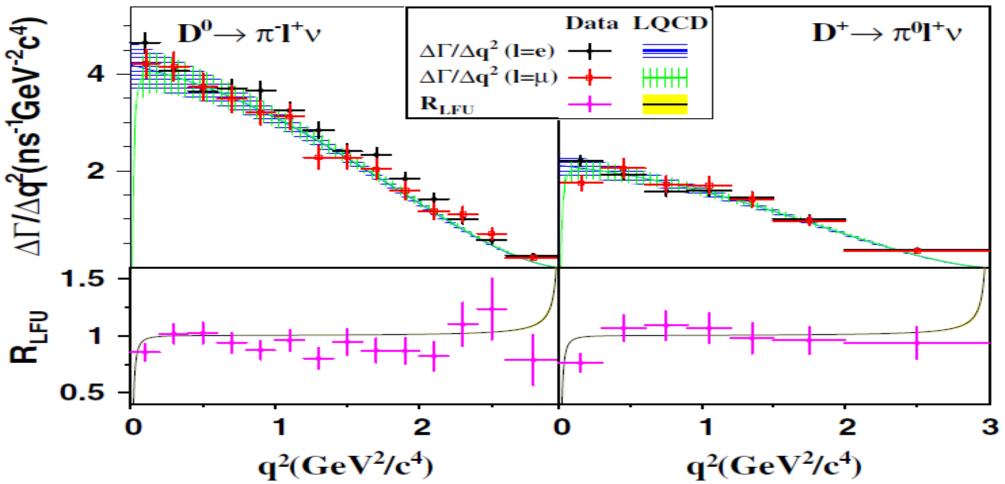
Summary of LFU tests at BESIII

The $D^+ \to \tau^+\nu$ and six semimuonic D decays are observed for the first time. **Five semimuonic charm decays are measured with higher precision**

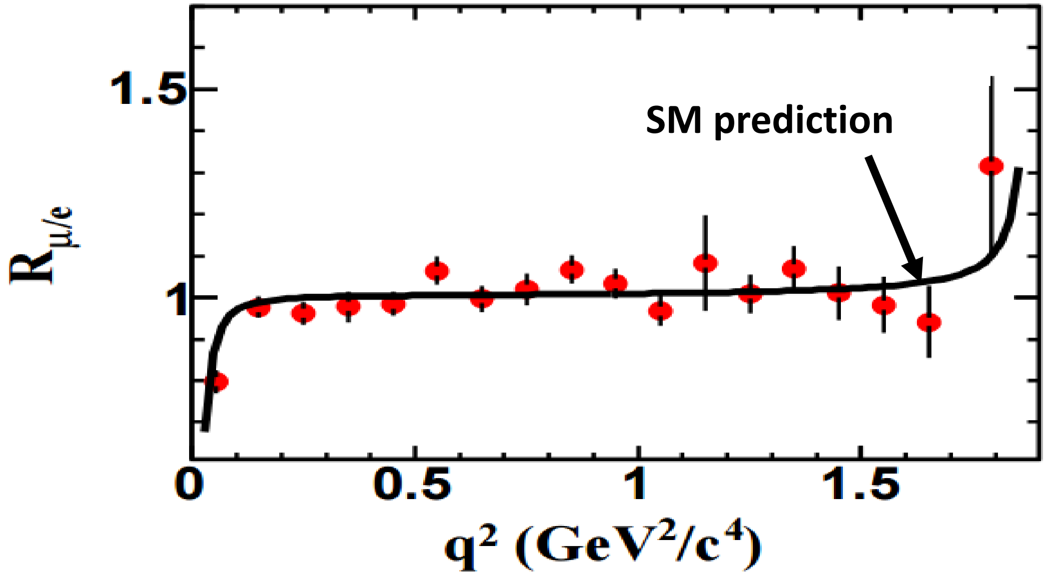
	BF ratios		References
μ/e	$D^0 \to K^-$	$0.978 \pm 0.007 \pm 0.012$	PRL122(2019)011804
	$D^0 \to \pi^-$	$0.922 \pm 0.030 \pm 0.022$	PRL121(2018)171803
	$D^0 \to \rho^-$	0.90 ± 0.11	PRD104(2021)L091003
	$D^+ \to \bar{K}^0$	1.00 ± 0.03	EPJC76(2016)369
	$D^+ \to \pi^0$	$0.964 \pm 0.037 \pm 0.026$	PRL121(2018)171803
	$D^+ \to \omega$	1.05 ± 0.14	PRD101(2020)072005
	$D^+ \to \eta$	0.91 ± 0.13	PRL124(2020)231801
	$D_s^+ \to \eta$	0.86 ± 0.29	PRD97(2018)012006
	$D_s^+ \to \eta'$	1.14 ± 0.68	
	$D_s^+ \to \phi$	1.05 ± 0.24	
	$\Lambda_c^+ \to \Lambda$	$0.96 \pm 0.16 \pm 0.04$	PLB767(2017)42
τ/μ	$D^+ \to \tau^+\nu$	$3.21 \pm 0.64 \pm 0.43$	PRL123(2019)211802
	$D_s^+ \to \tau^+\nu$	9.67 ± 0.36	PRL127(2021)171801

No deviation greater than 1.7σ was found!

PRL121(2018)171803



PRL122(2019)011804

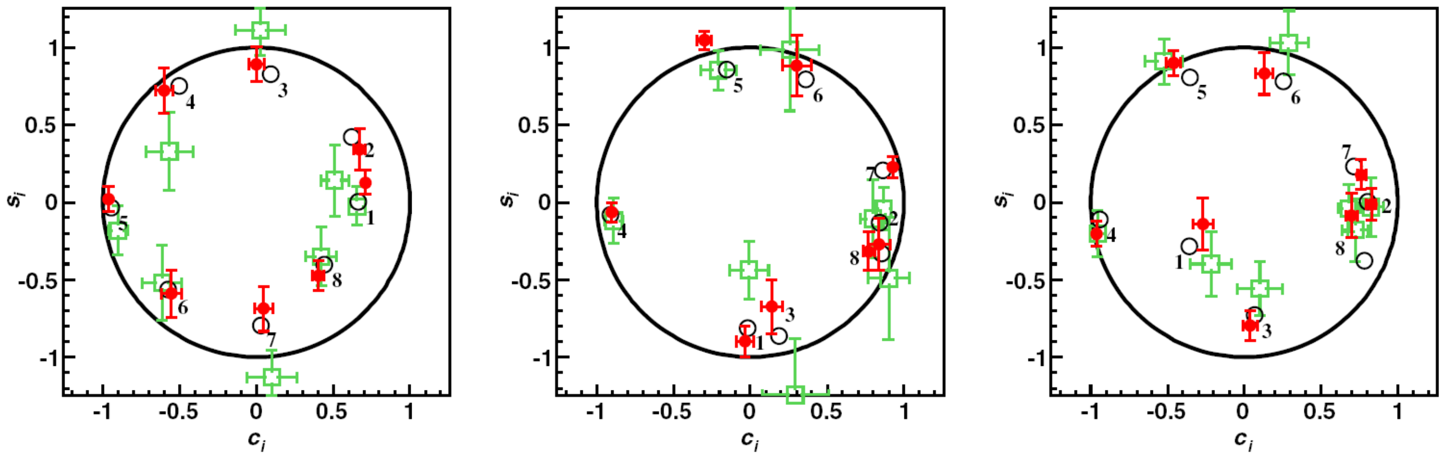


Hadronic D decays

Strong phase differences between D^0 and $\bar{D}^0$

$D \to K^0_{S/L}\pi^+\pi^-$

PRL124(2020)241802

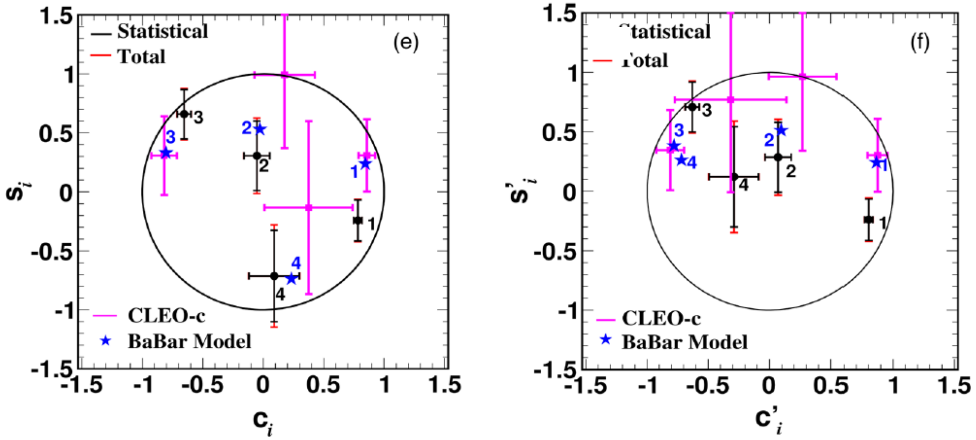


$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ at 3.773 GeV

Constraint on γ measurement ~ 0.9°

$D \to K^0_{S/L}K^+K^-$

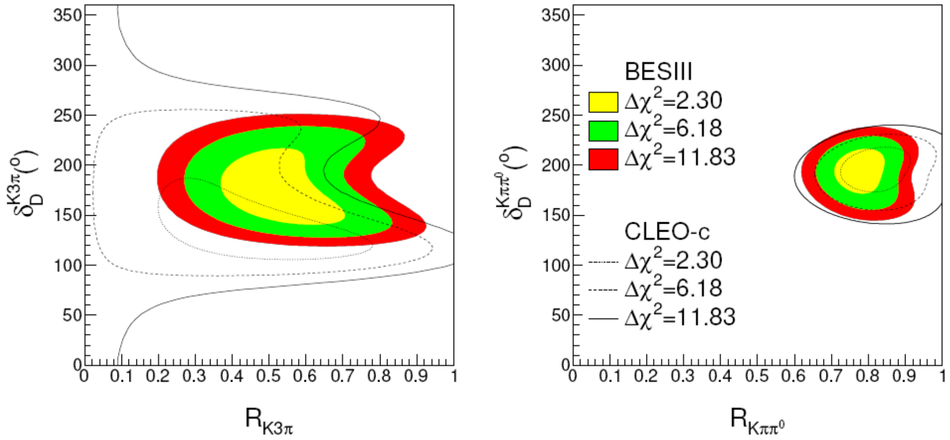
PRD102(2020)052008



Constraint on γ measurement ~ 1.3°

$D \to K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^0$

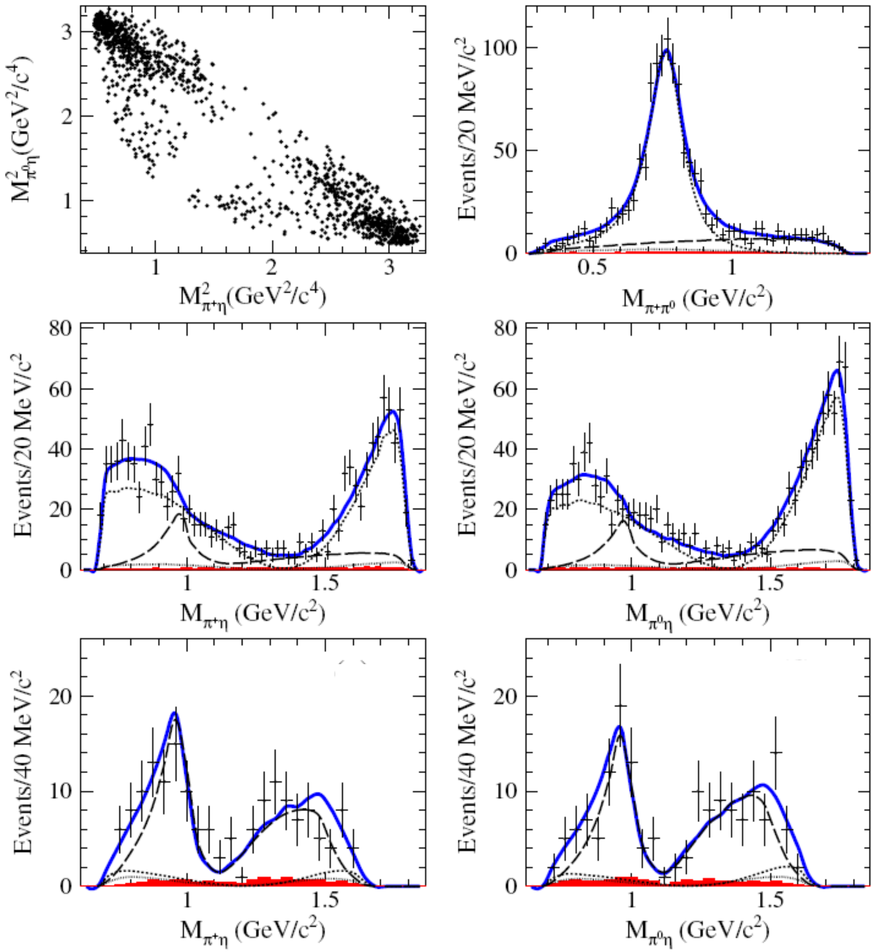
JHEP05(2021)164



Constraint on γ measurement ~ 6°

Amplitude analysis of $D_s^+ \to \eta\pi^+\pi^0$

PRL123(2020)112001



Amplitude	ϕ_n (rad)	FF_n
$D_s^+ \to \rho^+\eta$	0.0 (fixed)	$0.783 \pm 0.050 \pm 0.021$
$D_s^+ \to (\pi^+\pi^0)_V\eta$	$0.612 \pm 0.172 \pm 0.342$	$0.054 \pm 0.021 \pm 0.025$
$D_s^+ \to a_0(980)\pi$	$2.794 \pm 0.087 \pm 0.044$	$0.232 \pm 0.023 \pm 0.033$

$$B_{D_s^+ \to \pi^+\pi^0\eta} = (9.50 \pm 0.28 \pm 0.41)\%$$

$$B^{\mathrm{PDG18}}_{D_s^+ \to \pi^+\pi^0\eta} = (9.2 \pm 1.2)\%$$

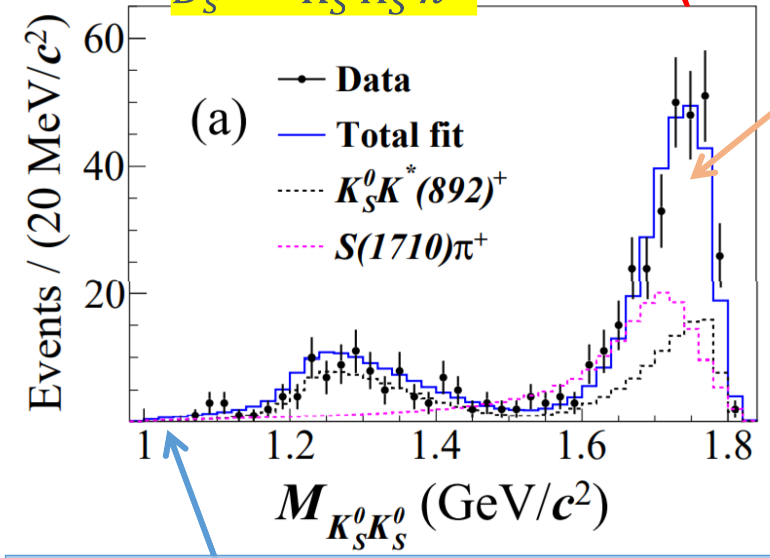
$$B_{D_s^+ \to \rho^+\eta} = (7.44 \pm 0.48 \pm 0.44)\%$$

$$B_{D_s^+ \to a_0(980)\pi} = (2.20 \pm 0.22 \pm 0.34)\%$$

Observation of abnormally large branching fraction for annihilation process, which is greater than that of the known D annihilation decay by two order of magnitude

Observation of $a_0(1817)$ in $D_s^+ \to KK\pi$

$D_s^+ \to K_S^0 K_S^0 \pi^+$ PRD105(2022)L051103



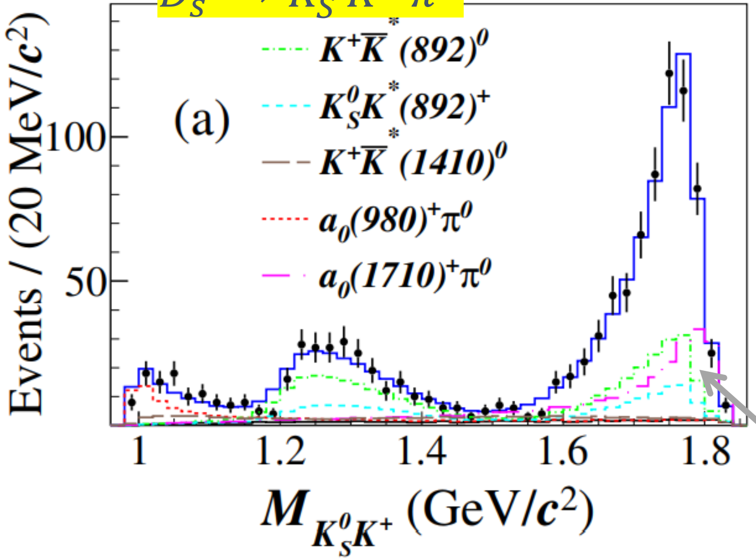
constructive interference: $a_0(1817)$ and $f_0(1710)$

destructive interference: $a_0(980)$ and $f_0(980)$

- The isovector partner of $f_0(1710)$ or $X(1812)$?
- Same resonance observed in η_c to $\pi\pi\eta$ by BaBar?

PRD104(2021)072002

$D_s^+ \to K_S^0 K^+ \pi^0$ arXiv:2204.09614



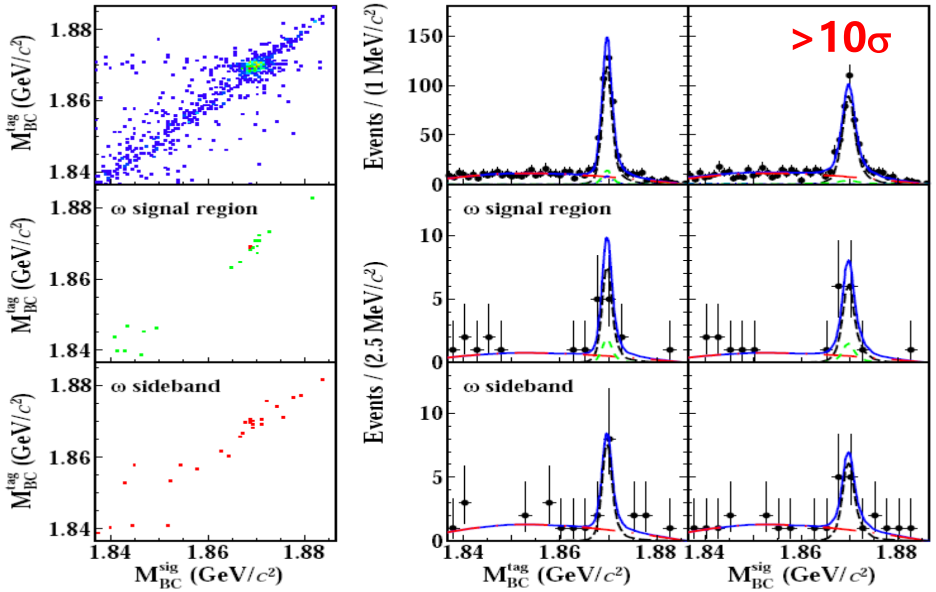
- M=$1.817 \pm 0.008 \pm 0.020$ GeV/c^2
- Γ= $0.097 \pm 0.022 \pm 0.015$ GeV/c^2
- $\mathcal{B}(D_s^+ \to a_0(1817)^+\pi^0)$ $= (3.44 \pm 0.52 \pm 0.32) \times 10^{-3}$
- Significance $> 10\sigma$

$a_0(1817)^+$ in $K_S^0 K^+$ mass spectrum

Abnormal phenomena in hadronic D decays

首次观测到双卡比玻压制衰变$D^+ \to K^+\pi^+\pi^-\pi^0$

PRL125(2020)241802



实验:

$B_{D^+\to K^+\pi^+\pi^-\pi^0} = (1.13\pm0.08)\times10^{-3}$

$B_{DCS}/B_{CF} = (6.3\pm0.5)\tan^4\theta_C$

得到BESIII半轻标记 PRD104(2021)072005 和Belle实验结果arXiv: 2205.02018的确认

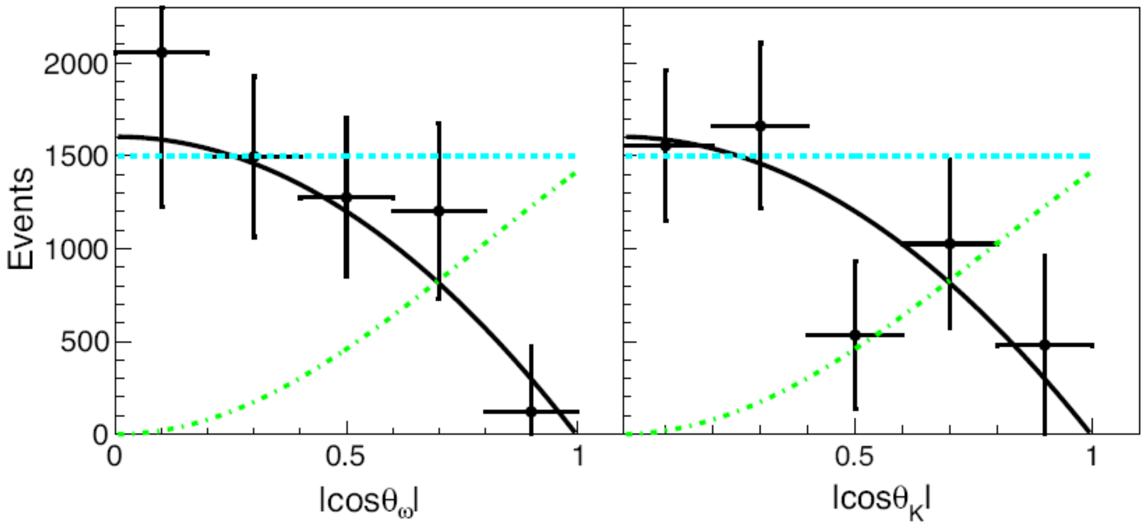
理论预言:

$B_{DCS}/B_{CF}\sim(0.5-2.0)\tan^4\theta_C$

θ_C为卡比玻混合角

首次观测到$D^+ \to \omega\phi$

PRL128(2022)011803

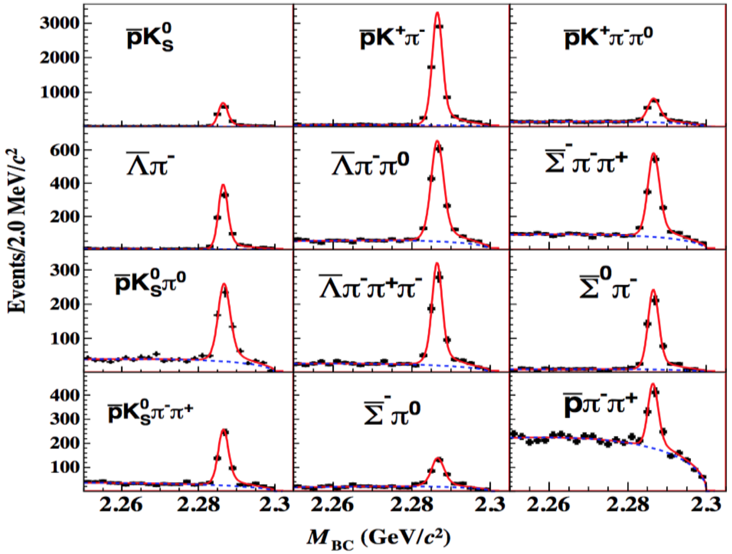


发现$D^+ \to VV$衰变横向极化与理论显著差异:有助于深入探讨D^0-$\bar{D}^0$混合和CP破坏机制

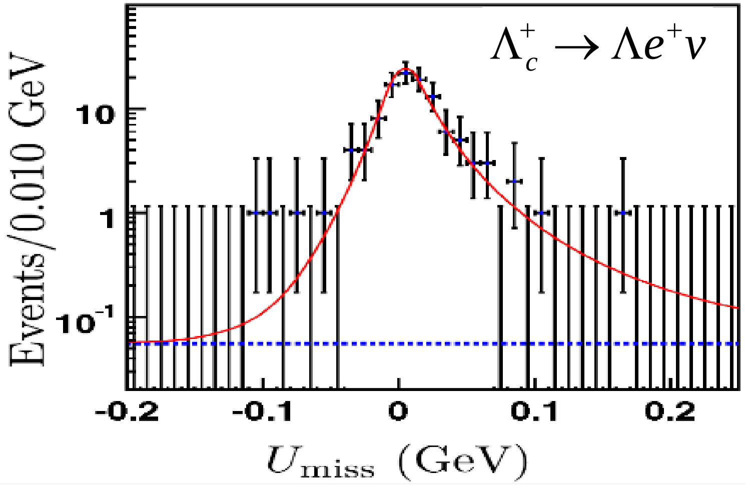
Charmed baryon Λ_c^+ decays

Absolute branching fractions of Λ_c^+ decays

PRL116(2016)052001



PRL115(2015)221805



16 papers with 0.57 fb^{-1}@4.6 GeV:

Hadronic decay

$\Lambda_c^+ \to pK^-\pi^+$ + 11 CF modes	PRL116(2016)052001
$\Lambda_c^+ \to$ pK$^+$K$^-$, p$\pi^+\pi^-$	PRL117(2017)232002
$\Lambda_c^+ \to$ n$K_S^0\pi^+$	PRL118(2017)112001
$\Lambda_c^+ \to$ pη, pπ^0	PRD95(2017)111102(R)
$\Lambda_c^+ \to \Sigma^-\pi^+\pi^+\pi^0$	PLB772(2017)388
$\Lambda_c^+ \to \Xi^{0(*)}K^+$	PLB783(2018)200
$\Lambda_c^+ \to \Lambda\eta\pi^+$	PRD99(2019)032010
$\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta'$	CPC43(2019)083002
$\Lambda_c^+ \to$ BP decay asymmetries	PRD100(2019)07200
$\Lambda_c^+ \to pK_s\eta$	PLB817(2021)136327

Semi-leptonic decay

$\Lambda_c^+ \to \Lambda e^+\nu_e$	PRL115(2015)221805
$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$	PLB767(2017)42

Inclusive decay

$\Lambda_c^+ \to \Lambda$X	PRL121(2018)062003
$\Lambda_c^+ \to e^+$X	PRL121(2018)251801
$\Lambda_c^+ \to K_S^0$X	EPJC80(2020)935

Production

$\Lambda_c^+\Lambda_c^-$ cross section	PRL120(2018)132001

Very productive for the data taken in 35 days!

Impact on the world data of Λ_c^+

PDG2014

Λ_c^+ DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
Hadronic modes with a p: $S = -1$ final states				
$p\overline{K}^0$		(2.3 ± 0.6) %		873
$pK^-\pi^+$	[a]	(5.0 ± 1.3) %		823
$p\overline{K}^*(892)^0$	[b]	(1.6 ± 0.5) %		685
$\Delta(1232)^{++}K^-$		(8.6 ± 3.0) $\times 10^{-3}$		710
$\Lambda(1520)\pi^+$	[b]	(1.8 ± 0.6) %		627
$pK^-\pi^+$ nonresonant		(2.8 ± 0.8) %		823
$p\overline{K}^0\pi^0$		(3.3 ± 1.0) %		823
$p\overline{K}^0\eta$		(1.2 ± 0.4) %		568

Citation: P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

Λ_c^+ REFERENCES

We have omitted some papers that have been superseded by later experiments. The omitted papers may be found in our 1992 edition (Physical Review **D45**, 1 June, Part II) or in earlier editions.

AAIJ	19AG	PR D100 032001	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	19AX	PR D100 072004	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	19X	CP C43 083002	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	19Y	PR D99 032010	M. Ablikim *et al.*	(BESIII Collab.) ★
AAIJ	18N	PR D97 091101	R. Aaij *et al.*	(LHCb Collab.)
AAIJ	18R	JHEP 1803 182	R. Aaij *et al.*	(LHCb Collab.)
AAIJ	18V	JHEP 1803 043	R. Aaij *et al.*	(LHCb Collab.)
ABLIKIM	18AF	PRL 121 251801	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	18E	PRL 121 062003	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	18Y	PL B783 200	M. Ablikim *et al.*	(BESIII Collab.) ★
BERGER	18	PR D98 112006	M. Berger *et al.*	(BELLE Collab.)
ABLIKIM	17D	PL B767 42	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17H	PRL 118 112001	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17Q	PR D95 111102	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	17Y	PL B772 388	M. Ablikim *et al.*	(BESIII Collab.) ★
PAL	17	PR D96 051102	B. Pal *et al.*	(BELLE Collab.)
ABLIKIM	16	PRL 116 052001	M. Ablikim *et al.*	(BESIII Collab.) ★
ABLIKIM	16U	PRL 117 232002	M. Ablikim *et al.*	(BESIII Collab.) ★
YANG	16	PRL 117 011801	S.B. Yang *et al.*	(BELLE Collab.)
ABLIKIM	15Y	PRL 115 221805	M. Ablikim *et al.*	(BESIII Collab.) ★
ZUPANC	14	PRL 113 042002	A. Zupanc *et al.*	(BELLE Collab.)
LEES	11G	PR D84 072006	J.P. Lees *et al.*	(BABAR Collab.)

For example

PDG2020

Hadronic modes with a p or n: $S = -1$ final states

	Mode		Fraction	Scale factor
Γ_1	pK^0_S		(1.59 ± 0.08) %	S=1.1
Γ_2	$pK^-\pi^+$		(6.28 ± 0.32) %	S=1.4
Γ_3	$p\overline{K}^*(892)^0$	[a]	(1.96 ± 0.27) %	
Γ_4	$\Delta(1232)^{++}K^-$		(1.08 ± 0.25) %	
Γ_5	$\Lambda(1520)\pi^+$	[a]	(2.2 ± 0.5) %	
Γ_6	$pK^-\pi^+$ nonresonant		(3.5 ± 0.4) %	
Γ_7	$pK^0_S\pi^0$		(1.97 ± 0.13) %	S=1.1
Γ_8	$nK^0_S\pi^+$		(1.82 ± 0.25) %	
Γ_9	$p\overline{K}^0\eta$		(1.6 ± 0.4) %	
Γ_{10}	$pK^0_S\pi^+\pi^-$		(1.60 ± 0.12) %	S=1.1
Γ_{11}	$pK^-\pi^+\pi^0$		(4.46 ± 0.30) %	S=1.5
Γ_{12}	$pK^*(892)^-\pi^+$	[a]	(1.4 ± 0.5) %	
Γ_{13}	$p(K^-\pi^+)_{\text{nonresonant}}\pi^0$		(4.6 ± 0.8) %	
Γ_{14}	$\Delta(1232)\overline{K}^*(892)$		seen	
Γ_{15}	$pK^-2\pi^+\pi^-$		(1.4 ± 0.9) $\times 10^{-3}$	
Γ_{16}	$pK^-\pi^+2\pi^0$		(1.0 ± 0.5) %	

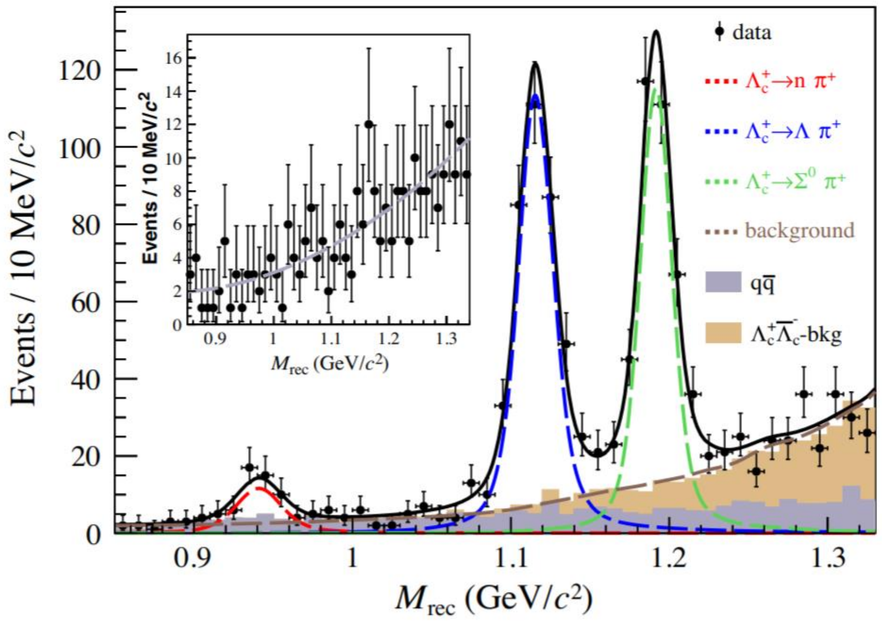
With 0.567 fb^{-1} data at 4.6 GeV, BESIII significantly contributed to the Λ_c^+ decay field, with much improved precision and new decay modes

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

首次发现$\Lambda_c^+ \to n\pi^+$

PRL128(2022)142001

3.9 fb^{-1}数据



结果有助于检验、完善基于夸克SU(3)对称性的理论计算

Decay	Yields	Branching fraction
$\Lambda_c^+ \to n\pi^+$	50 ± 9	$(6.6 \pm 1.2_{stat} \pm 0.4_{syst})\times 10^{-4}$
$\Lambda_c^+ \to \Lambda\pi^+$	376 ± 22	$(1.31 \pm 0.08_{stat} \pm 0.05_{syst})\times 10^{-2}$
$\Lambda_c^+ \to \Sigma^0\pi^+$	343 ± 22	$(1.22 \pm 0.08_{stat} \pm 0.07_{syst})\times 10^{-2}$

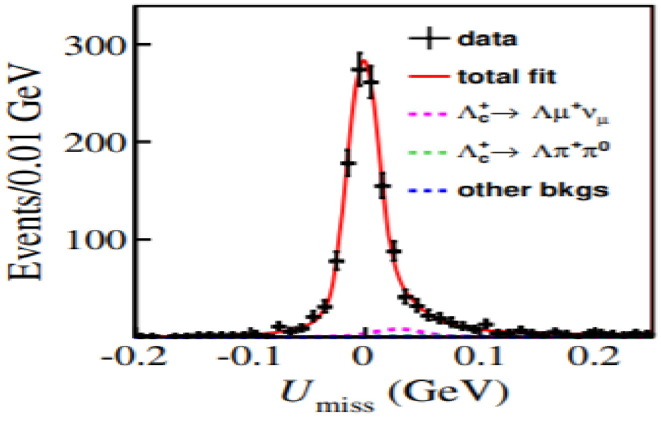
$R=B[\Lambda_c^+ \to n\pi^+]/B[\Lambda_c^+ \to p\pi^0]>7.2$@90% C.L.

$\mathcal{B}(\Lambda_c^+ \to n\pi^+)\times 10^{-4}$	R	Reference
4	2	PRD 55, 7067 (1997)
9	2	PRD 93, 056008 (2016)
11.3 ± 2.9	2	PRD 97, 073006 (2018)
8 or 9	4.5 or 8.0	PRD 49, 3417 (1994)
2.66	3.5	PRD 97, 074028 (2018)
6.1 ± 2.0	4.7	PLB 790, 225 (2019)
7.7 ± 2.0	9.6	JHEP 02 (2020) 165

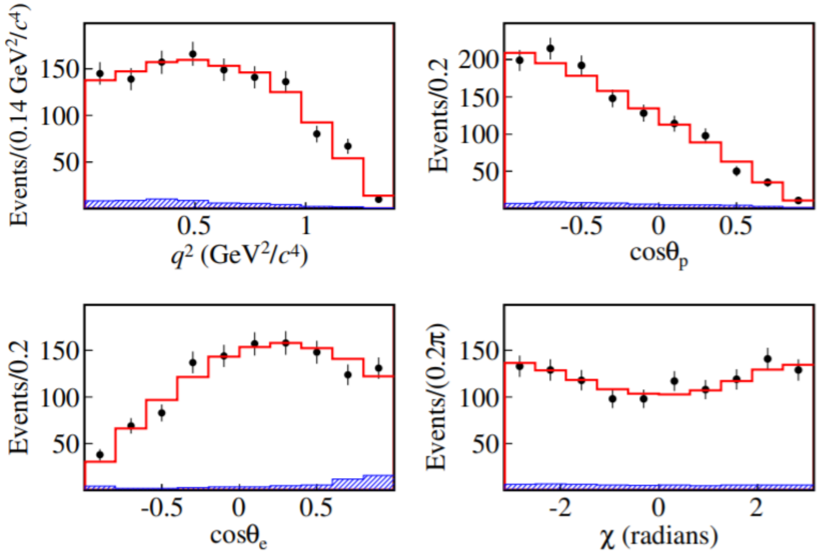
Study of $\Lambda_c^+ \to \Lambda e^+ \nu_e$

本周最新结果, arXiv:2207.14149, submitted to PRL

4.5 fb^{-1}数据

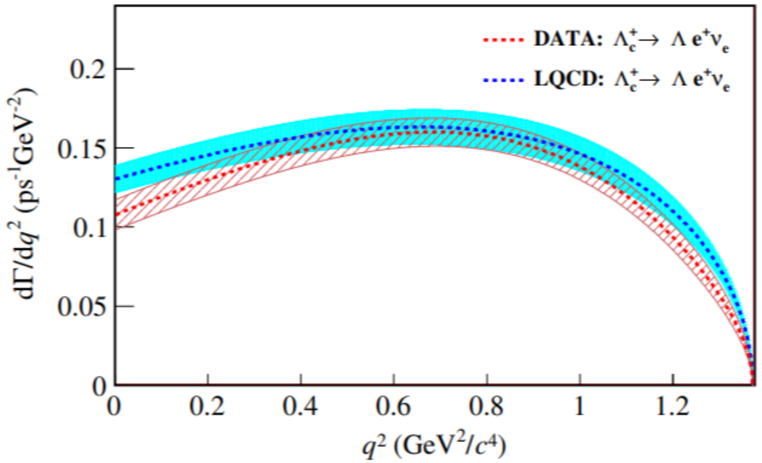


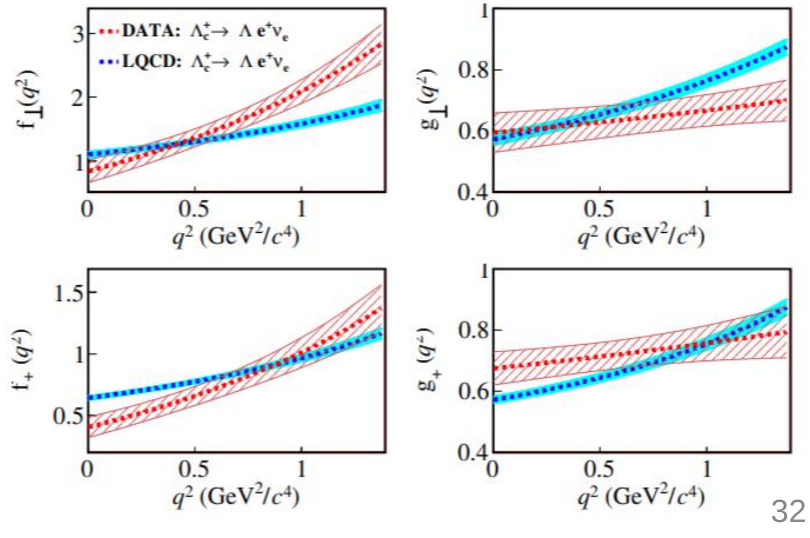
$$\frac{d^4\Gamma}{dq^2 d\cos\theta_e d\cos\theta_p d\chi} = \frac{G_F^2|V_{cs}|^2}{2(2\pi)^4} \cdot \frac{Pq^2}{24M_{\Lambda_c}^2} \times$$
$$\Big\{ \frac{3}{8}(1-\cos\theta_e)^2 |H_{\frac{1}{2}1}|^2 (1+\alpha_\Lambda\cos\theta_p)$$
$$+ \frac{3}{8}(1+\cos\theta_e)^2 |H_{-\frac{1}{2}-1}|^2 (1-\alpha_\Lambda\cos\theta_p)$$
$$+ \frac{3}{4}\sin^2\theta_e [|H_{\frac{1}{2}0}|^2 (1+\alpha_\Lambda\cos\theta_p) + |H_{-\frac{1}{2}0}|^2 (1-\alpha_\Lambda\cos\theta_p)]$$
$$+ \frac{3}{2\sqrt{2}}\alpha_\Lambda \cos\chi \sin\theta_e \sin\theta_p \times$$
$$[(1-\cos\theta_e)H_{-\frac{1}{2}0}H_{\frac{1}{2}1} + (1+\cos\theta_e)H_{\frac{1}{2}0}H_{-\frac{1}{2}-1}]\Big\}$$



$B[\Lambda_c^+ \to \Lambda e^+\nu_e] = (3.56 \pm 0.11 \pm 0.07)\%$

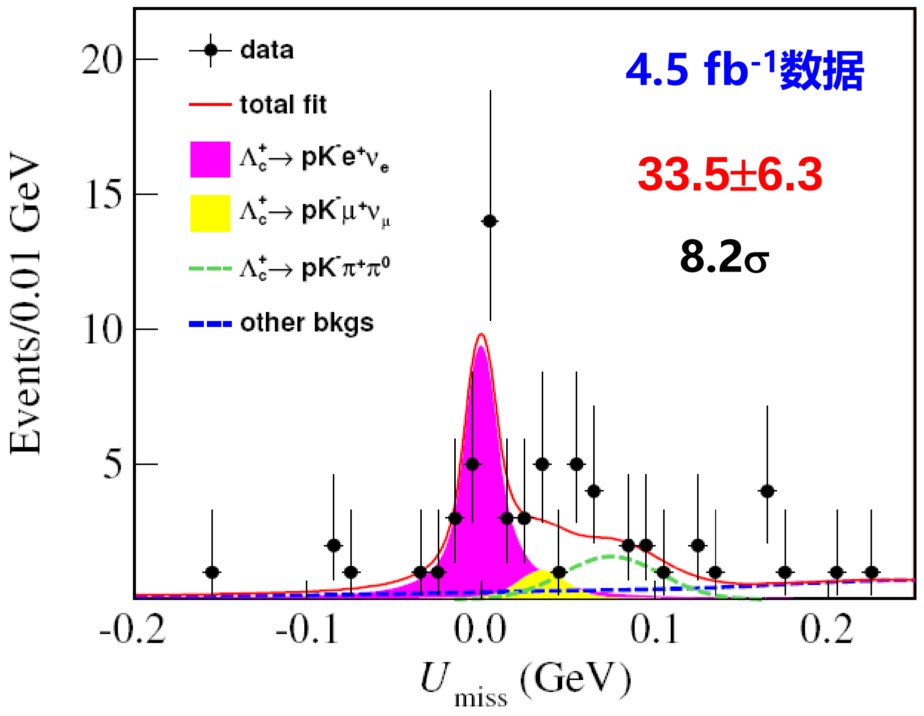
	$\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$ [%]
Constituent quark model (HONR) [8]	4.25
Light-front approach [9]	1.63
Covariant quark model [10]	2.78
Relativistic quark model [11]	3.25
Non-relativistic quark model [12]	3.84
Light-cone sum rule [13]	3.0 ± 0.3
Lattice QCD [14]	3.80 ± 0.22
$SU(3)$ [15]	3.6 ± 0.4
Light-front constituent quark model [16]	3.36 ± 0.87
MIT bag model [16]	3.48
Light-front quark model [17]	4.04 ± 0.75
This work	$3.56 \pm 0.11 \pm 0.07$

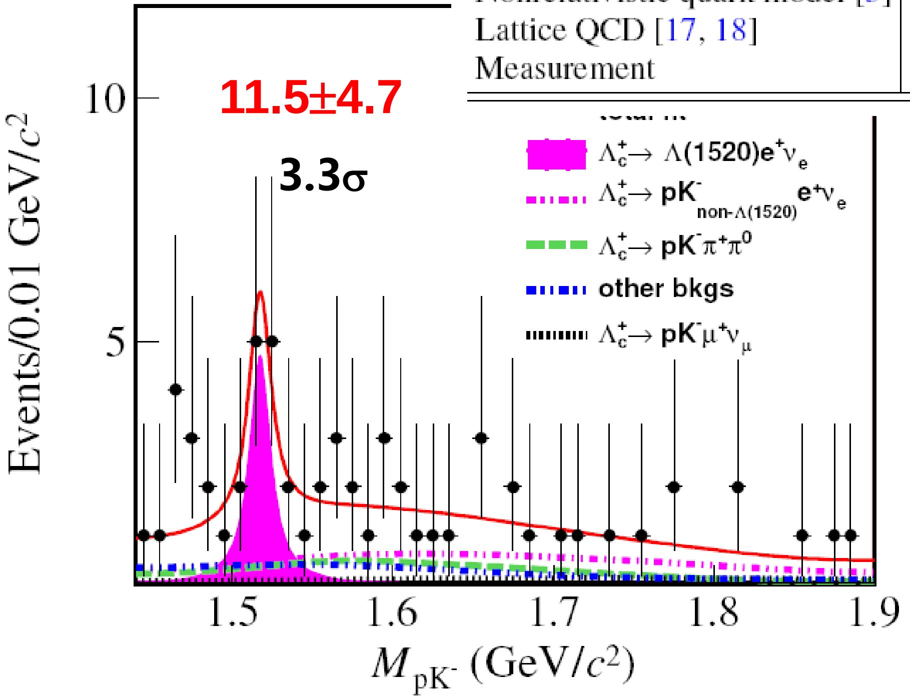




First observation of $\Lambda_c^+ \to pK^- e^+ \nu_e$

本周最新结果, arXiv:2207.11483, submitted to PRL





	$\mathcal{B}(\Lambda_c^+ \to \Lambda(1520)e^+\nu_e)$ $[\times 10^{-3}]$
Constituent quark model [4]	1.01
Nonrelativistic quark model [5]	0.60
Lattice QCD [17, 18]	$0.512 \pm 0.082 \pm 0.008$
Measurement	$1.36 \pm 0.56 \pm 0.14$

$\mathrm{B}[\Lambda_c^+ \to pK^- e^+\nu_e] = (8.2 \pm 1.5 \pm 0.6) \times 10^{-4}$

$\mathrm{B}[\Lambda_c^+ \to \Lambda(1520) e^+\nu_e] = (1.36 \pm 0.56 \pm 0.14) \times 10^{-3}$

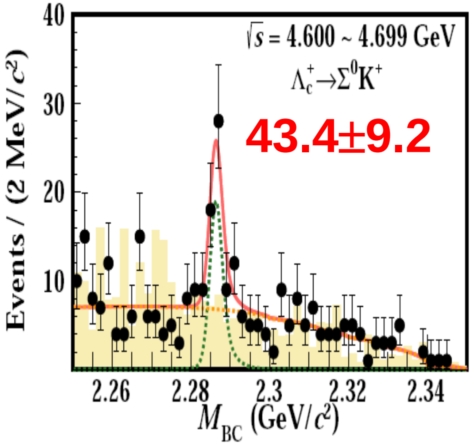
$$\frac{\mathrm{B}[\Lambda_c^+ \to pK^- e^+\nu_e]}{\mathrm{B}[\Lambda_c^+ \to X e^+\nu_e]} = (2.1 \pm 0.4 \pm 0.1)\%$$

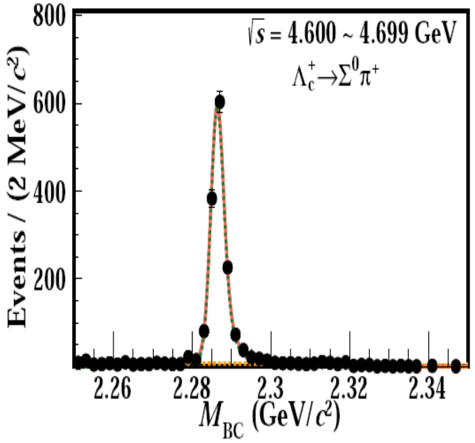
$$\frac{\mathrm{B}[\Lambda_c^+ \to \Lambda(1520) e^+\nu_e]}{\mathrm{B}[\Lambda_c^+ \to X e^+\nu_e]} = (3.4 \pm 1.4 \pm 0.4)\%$$

Larger data set helps to determine form factors in $\Lambda_c^+ \to \Lambda(1520)e^+\nu_e$, which is important to explore the internal structure of $\Lambda(1520)$

Measurement of BFs of $\Lambda_c^+ \to \Sigma^0 K^+$ and $\Lambda_c^+ \to \Sigma^+ K_s^0$

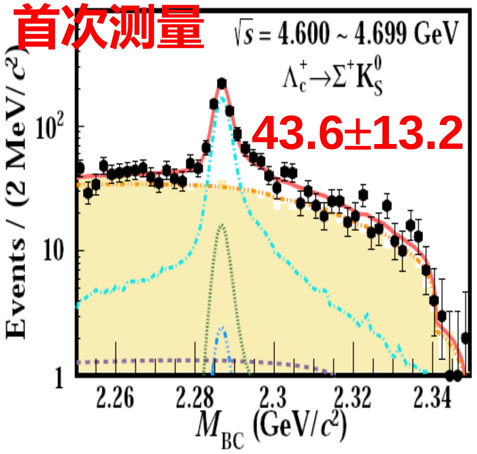
本周最新结果, arXiv:2207.10906, submitted to PRD

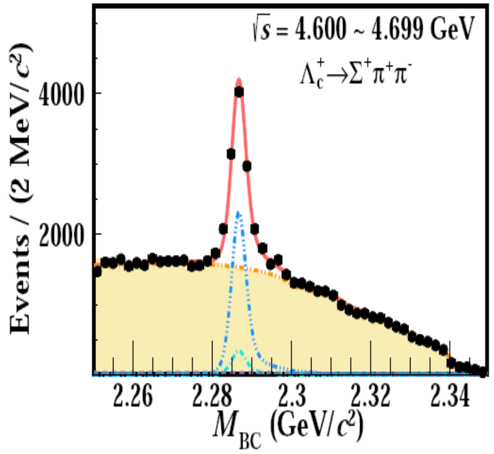




4.5 fb[-1]数据

首次测量





$B[\Lambda_c^+ \to \Sigma^0 K^+]/B[\Lambda_c^+ \to \Sigma^0 \pi^+] = (3.61 \pm 0.73 \pm 0.05)\%$

$B[\Lambda_c^+ \to \Sigma^+ K_S^0]/B[\Lambda_c^+ \to \Sigma^+ \pi^+ \pi^-] = (1.06 \pm 0.31 \pm 0.04)\%$

联合参考道PDG分支比:

$B[\Lambda_c^+ \to \Sigma^0 K^+] = (4.7 \pm 0.9 \pm 0.1 \pm 0.3) \times 10^{-4}$

$B[\Lambda_c^+ \to \Sigma^+ K_S^0] = (4.8 \pm 1.4 \pm 0.02 \pm 0.03) \times 10^{-4}$

	$\mathcal{B}(\Lambda_c^+ \to \Sigma^0 K^+)$	$\mathcal{B}(\Lambda_c^+ \to \Sigma^+ K_S^0)$
QCD corrections [2]	2(8)	2(4)
MIT bag model [3]	7.2 ± 1.8	7.2 ± 1.8
Diagrammatic analysis [4]	5.5 ± 1.6	9.6 ± 2.4
$SU(3)_F$ flavor symmetry [5]	5.4 ± 0.7	5.4 ± 0.7
IRA method [6]	5.0 ± 0.6	1.0 ± 0.4
PDG 2020 [28]	5.2 ± 0.8	/

$B[\Lambda_c^+ \to \Sigma^0 K^+]/B[\Lambda_c^+ \to \Sigma^+ K_S^0] = 0.98 \pm 0.36$

Summary

- 近年来：BESIII基于已有数据，在粲强子含轻和强子等各类衰变研究中取得了重要进展 (发表文章100余篇，其中24篇PRL)

- 2022年以来：基于4.5 fb^{-1}的Λ_c^+样本@4.6-4.7 GeV，已推出首批成果

- 2022年：新增~5fb^{-1}的$D^{0(+)}$样本@3.773 GeV；2023-2024年：→ 20 fb^{-1} @3.773 GeV

- 未来3-5年，期待更丰富的粲强子物理成果：

  $f_+^{D\to K}(0) \to 0.4\%$, $f_+^{D\to\pi}(0) \to 0.5\%$；$f_{D^+} \to 1.0\%$, $f_{D_s^+} \to 0.8\%$

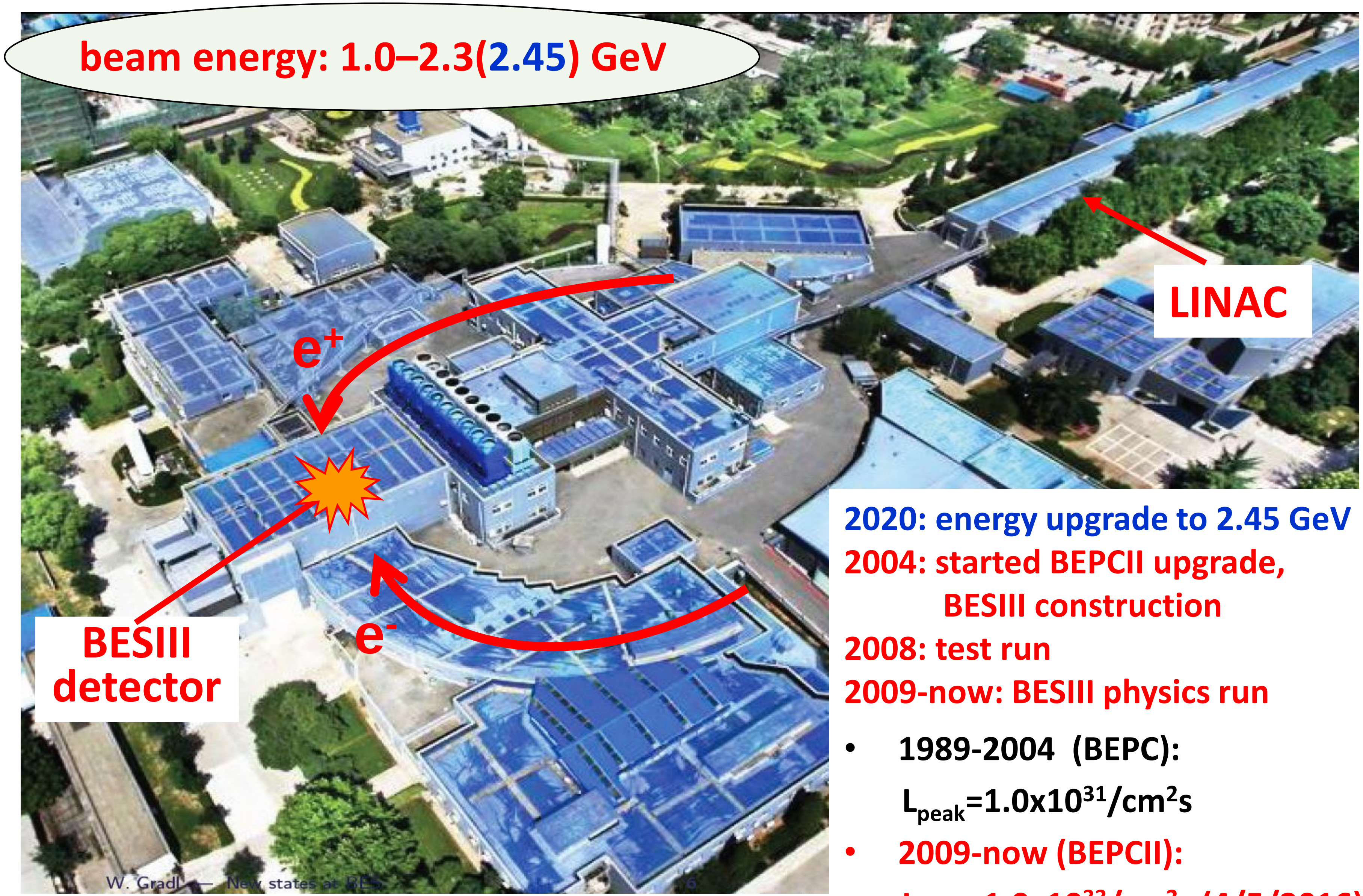
  $|V_{cs}| \to 0.5\%$, $|V_{cd}| \to 1.0\%$

  ……

Thank you!

Back slides

Beijing Electron Positron Collider (BEPCII)



2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade,
BESIII construction

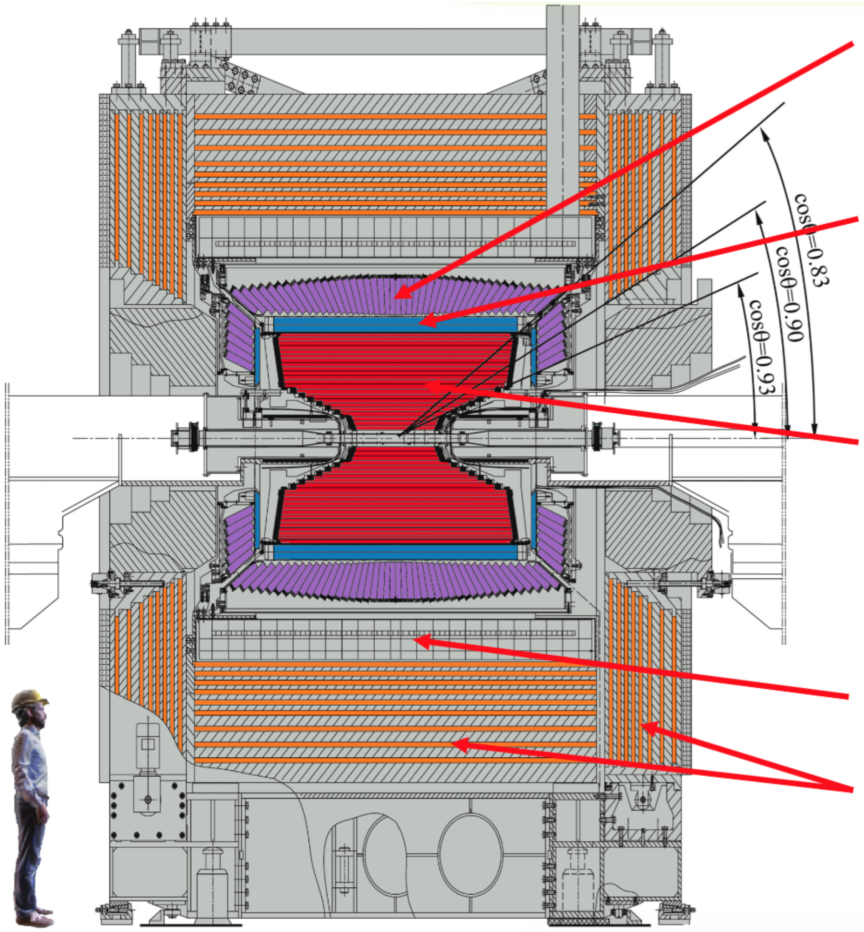
2008: test run

2009-now: BESIII physics run

- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31}/cm^{2}s
- 2009-now (BEPCII):
  L_{peak}=1.0x10^{33}/cm^{2}s (4/5/2016)

BESIII detector

NIMA614(2010)345



EMC: CsI crystals
$\Delta E/E$ = 2.5% @ 1 GeV - Barrel
$\Delta E/E$ = 5.0% @ 1 GeV - Endcaps

TOF:
σ_T = 80 ps Barrel
σ_T = 110 (60) ps Endcap

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Magnet: 1T Super conducting

Muon ID: 9 layer RPC

Trigger: Tracks & Showers

Excellent resolution, particle identification, and large coverage for neutral and charged particles

BESIII collaboration

Europe (17/115)

Germany (6): Bochum University, GSI Darmstadt, Helmholtz Institute Mainz, Johannes Gutenberg University of Mainz, Universitaet Giessen, University of Münster
Italy (3): Ferrara University, INFN, University of Torino
Netherlands (1): KVI/University of Groningen
Russia (2): Budker Institute of Nuclear Physics, Dubna JINR
Sweden (1): Uppsala University
Turkey (1): Turkish Accelerator Center Particle Factory Group
UK (2): University of Manchester, University of Oxford
Poland (1) National Centre for Nuclear Research

USA (4/8)

Carnegie Mellon University
Indiana University
University of Hawaii
University of Minnesota

South America (1/1)

Chile: University of Tarapaca

China (48/367)

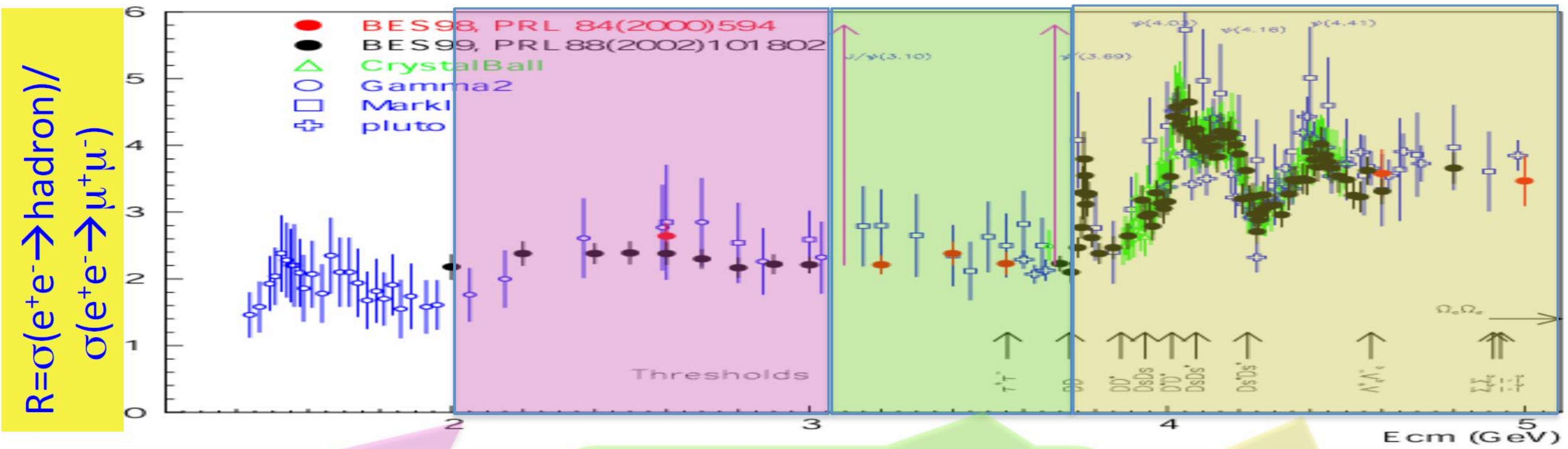
Institute of High Energy Physics (146), other units(221): Beijing Institute of Petro-chemical Technology, Beihang University, China Center of Advanced Science and Technology, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Henan Normal University, Henan University of Science and Technology, Huazhong Normal University, Huangshan College, Hunan University, Hunan Normal University, Henan University of Technology Institute of modern physics, Jilin University, Lanzhou University, Liaoning Normal University, Liaoning University, Nanjing Normal University, Nanjing University, Nankai University, North China Electric Power University, Peking University, Qufu normal university, Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shanghai Jiaotong Univeristy, Soochow University, South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Sciences, University of Jinan, University of Science and Technology of China, University of Science and Technology Liaoning, University of South China, Wuhan University, Xinyang Normal University, Zhejiang University, Zhengzhou University, YunNan University , China University of Geosciences

Asia (6/10)

Pakistan (2): COMSATS Institute of Information Technology
University of the Punjab, University of Lahore
Mongolia (1): Institute of Physics and Technology
Korea (1): Chung-Ang University
India (1): Indian Institute of Technology madras
Thailand (1): Suranaree University of Technology

~500 members from 76 institutes in 16 countries

Physics at BESIII



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

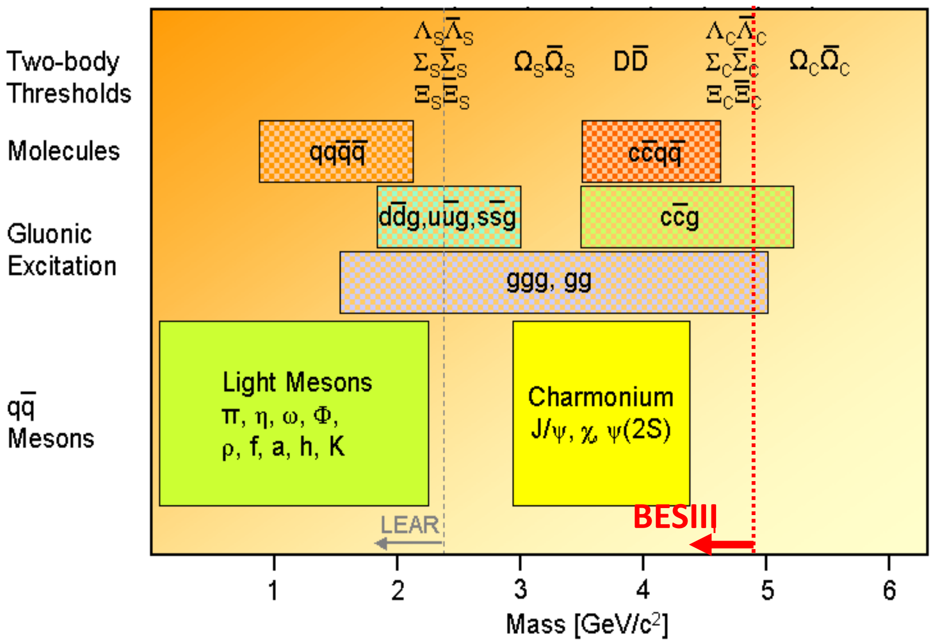
- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

- XYZ particles
- D mesons
- f_D and f_{Ds}
- D_0-D_0 mixing
- Charm baryons

World largest J/ψ, ψ(3686), ψ(3770),… data samples

More than 370 papers and 71 in Phys. Rev. Lett.

Unique hadrons at BESIII



Charmed hadrons:

- Produced in pair
- Quantum correlated $D^0\bar{D}^0$

$2.93\ \text{fb}^{-1}$@3.773 GeV: $D\bar{D}$
$0.48\ \text{fb}^{-1}$@4.009 GeV: $D_s\bar{D}_s$
$6.32\ \text{fb}^{-1}$@4.18-4.23 GeV: $D_s\bar{D}_s^*$
$4.4\ \text{fb}^{-1}$@4.6-4.7 GeV: $\Lambda_c\bar{\Lambda}_c$

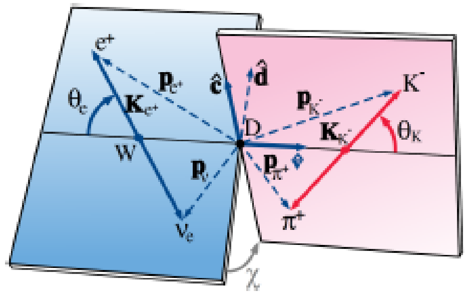
Hadron-physics challenges:

- Understanding of established states: precision spectroscopy
- Nature of exotic states: search and spectroscopy of unexpected states

At BESIII, two golden ways to study hadron spectroscopy:

- **Light hadrons**: charmonium decays (10B J/ψ and 2.7 B $\psi(2S)$)
- **Heavy hadrons (XYZ)**: direct production, radiative and hadronic transitions (23 fb^{-1} data above 3.8 GeV)

$D \to V e^+ \nu_e$形状因子测量



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

Decay rate depend on 5 variables and 3 form factors

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

- $X = p_{K\pi} m_D$, $p_{K\pi}$ 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 $H_{0,\pm}$:

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

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

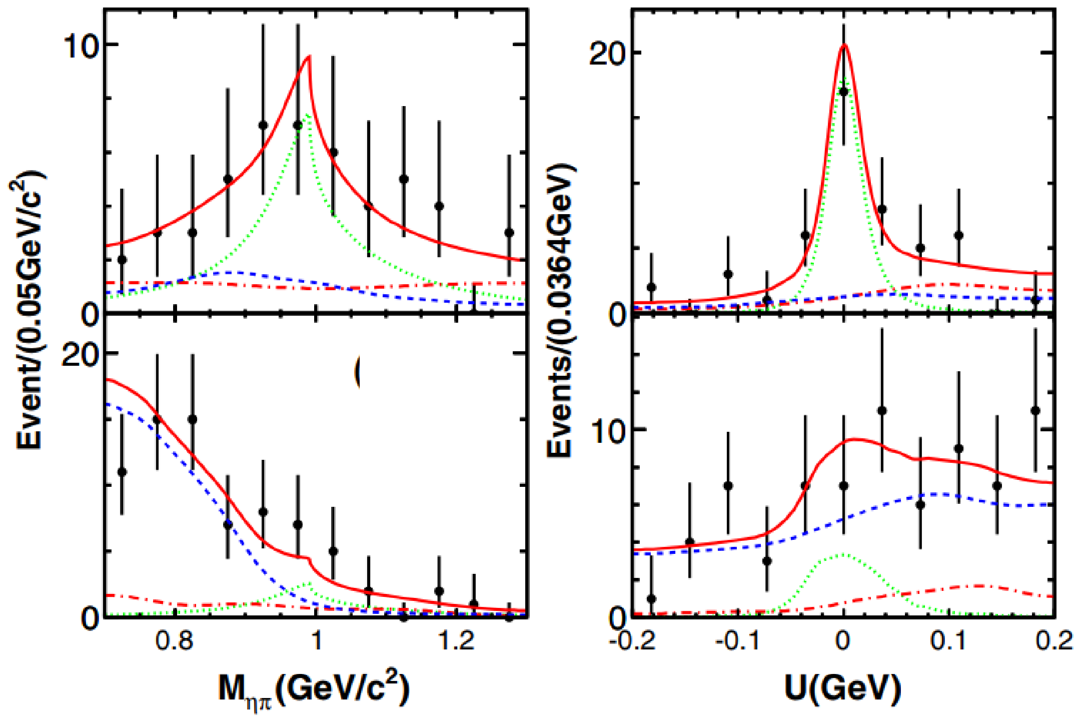
- Vector form factor: $V(q^2) = \frac{V(0)}{1 - q^2/m_V^2}$; or: FF ratio $r_V = V(0)/A_1(0)$
- Axial-vector form factor: $A_1(q^2) = \frac{A_1(0)}{1 - q^2/m_A^2}$, $A_2(q^2) = \frac{A_2(0)}{1 - q^2/m_A^2}$; or: FF ratio $r_2 = A_2(0)/A_1(0)$

相关研究详见本节张书磊报告

首次观测到$D \to (S,A)e^+\nu_e$型半轻衰变

PRL121(2018)081802

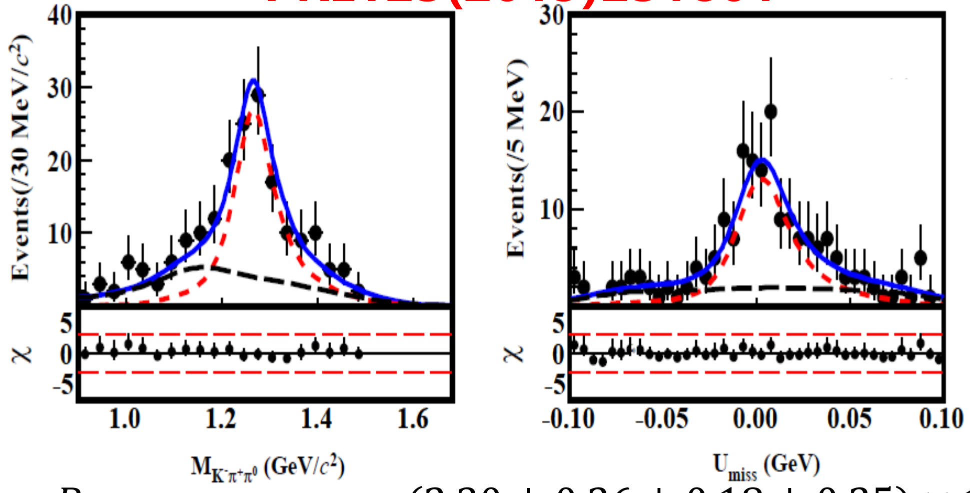
$D^+ \to a_0(980)^0 e^+ \nu [3.0\sigma]$ $\quad D^0 \to a_0(980)^- e^+ \nu [6.5\sigma]$



$$B_{D^+ \to a_0(980)^0 e^+ \nu} B_{a_0(980)^0 \to \eta\pi^0} = (1.66^{+0.81}_{-0.66} \pm 0.11) \times 10^{-4}$$

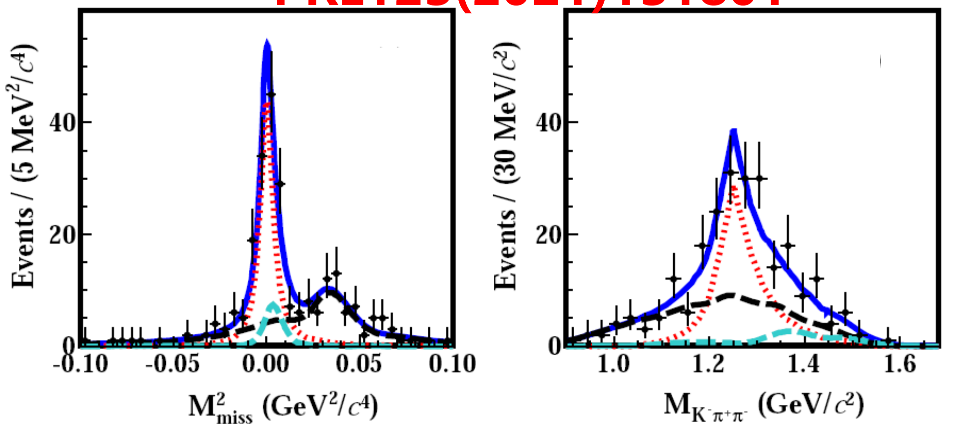
$$B_{D^0 \to a_0(980)^- e^+ \nu} B_{a_0(980)^- \to \eta\pi^-} = (1.33^{+0.33}_{-0.29} \pm 0.09) \times 10^{-4}$$

PRL123(2019)231801



$$B_{D^+ \to \bar{K}_1^0(1270) e^+ \nu} = (2.30 \pm 0.26 \pm 0.18 \pm 0.25) \times 10^{-3}$$

PRL123(2021)131801



$$B_{D^0 \to K_1(1270)^- e^+ \nu} = (1.09 \pm 0.13 \pm 0.13 \pm 0.12) \times 10^{-3}$$

PRL125,051802

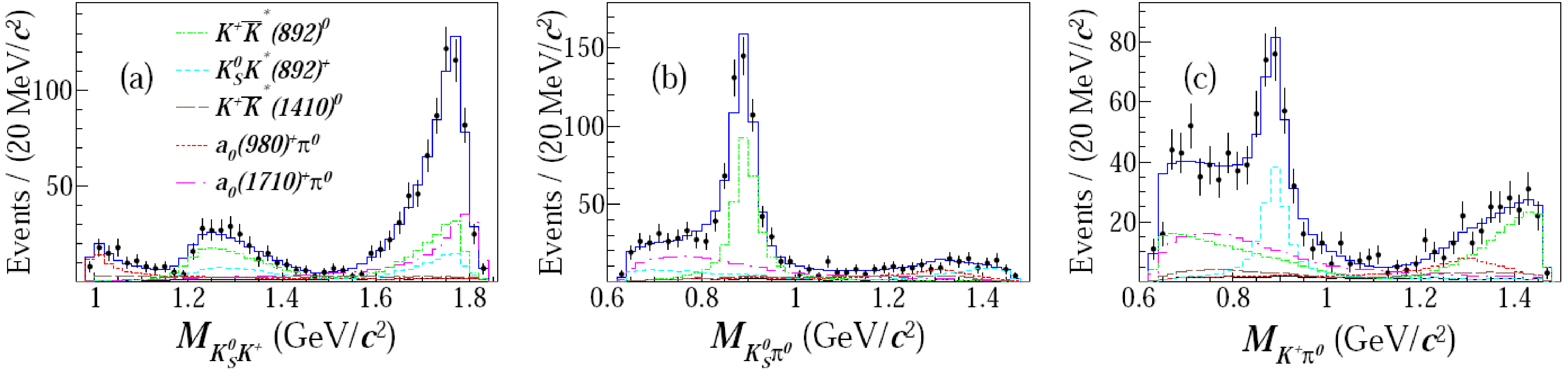
Combined analysis of $D \to \bar{K}_1\ e^+ \nu$ and B→gK$_1$ helps better access photon polarization in b→sg

Other semileptonic D decays

■$D_s^+ \to \pi^0 e^+ \nu_e$	arXiv:2206.13870
■$D_s^+ \to f_0 e^+ \nu_e$	PRD105(2022)L031101
■$D^{0(+)} \to \bar{K} e^+ \nu_e$	PRD104(2021)052008
■$D_s^+ \to \nu_e e X$	PRD104(2021)012003
■$D_s^+ \to a_0(980)^0 e^+ \nu$	PRD104(2021)092004
■$D^0 \to b_1(1235)^- e^+ \nu$	PRD101(2020)112005
■$D_s^+ \to p\bar{p} e^+ \nu_e$	PRD100(2019)112008
■$D_s^+ \to \gamma e^+ \nu_e$	PRD99(2019)072002
■$D_s^+ \to \eta^{(\prime)} \mu^+ \nu$ and $\phi \mu^+ \nu$	PRD97(2018)012006
■$D^+ \to \gamma e^+ \nu_e$	PRD95(2017)071102
■$D^+ \to D^0 e^+ \nu_e$	PRD96(2016)092002
■$D^+ \to \bar{K}^0 e^+ \nu_e$ via $\bar{K}^0 \to \pi^0 \pi^0$	CPC40(2016)113001
■$D_s^+ \to l^+ \nu_l$ @ 4.009 GeV	PRD94(2016)072004
■$D_s^+ \to \eta^{(\prime)} e^+ \nu_e$ @ 4.009 GeV	PRD94(2016)112003

Amplitude analysis of $D_s^+ \to K_S K^+ \pi^0$

arXiv:2204.09614, submitted to PRL



Amplitude	Phase (rad)	FF (%)	BF (10^{-3})	σ
$D_s^+ \to \bar{K}^*(892)^0 K^+$	0.0(fixed)	$32.7 \pm 2.2 \pm 1.9$	$4.77 \pm 0.38 \pm 0.32$	> 10
$D_s^+ \to K^*(892)^+ K_S^0$	$-0.16 \pm 0.12 \pm 0.11$	$13.9 \pm 1.7 \pm 1.3$	$2.03 \pm 0.26 \pm 0.20$	> 10
$D_s^+ \to a_0(980)^+ \pi^0$	$-0.97 \pm 0.27 \pm 0.25$	$7.7 \pm 1.7 \pm 1.8$	$1.12 \pm 0.25 \pm 0.27$	6.7
$D_s^+ \to \bar{K}^*(1410)^0 K^+$	$0.17 \pm 0.15 \pm 0.08$	$6.0 \pm 1.4 \pm 1.3$	$0.88 \pm 0.21 \pm 0.19$	7.6
$D_s^+ \to a_0(1710)^+ \pi^0$	$-2.55 \pm 0.21 \pm 0.07$	$23.6 \pm 3.4 \pm 2.0$	$3.44 \pm 0.52 \pm 0.32$	> 10

Observation of $a_0(1812)^+$, which is the isovector partner of the $f_0(1710)$ and $f_0(1770)$

$M = (1.817 \pm 0.008 \pm 0.020)\mathrm{GeV}/c^2$

$\Gamma = (97 \pm 22 \pm 15)\mathrm{MeV}$

$$\frac{B[D_s^+ \to \bar{K}^{*0} K^+]}{B[D_s^+ \to \bar{K}^0 K^{*+}]} = 2.35^{+0.42}_{-0.23} \pm 0.10$$

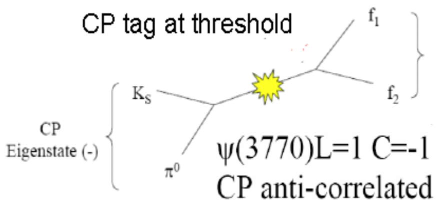
$$\frac{B[a_0^+(980) \to \bar{K}^0 K^+]}{B[a_0^+(980) \to \eta\pi^+]} = (13.7 \pm 3.6 \pm 4.2)\%$$

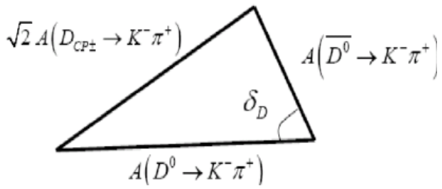
Amplitude analyses of other hadronic D decays

$D_s^+ \to K^+\pi^+\pi^-\pi^0$	arXiv:2205.13759
$D_s^+ \to K^+\pi^+\pi^-$	arXiv:2205.08844, accepted by JHEP
$D_s^+ \to K^+K^-\pi^+\pi^+\pi^-$	JHEP07(2022)051
$D_s^+ \to \eta\pi^+\pi^+\pi^-$	JHEP04(2022)058
$D_s^+ \to K_S^0K_S^0\pi^+$	PRD105(2022)L051103
$D_s^+ \to \pi^+\pi^0\pi^0$	JHEP01(2022)052
$D_s^+ \to \pi^+\pi^+\pi^-$	arXiv:2108.10050, under PRD review
$D_s^+ \to \eta\pi^+\pi^+\pi^-$	PRD104(2021)L071101
$D^+ \to K_S^0K^+\pi^0$	PRD104(2021)012006
$D_s^+ \to K_S^0\pi^+\pi^0$	JHEP06(2021)181
$D_s^+ \to K^+K^-\pi^+\pi^0$	PRD104(2021)032011
$D_s^+ \to K_S^0K^-\pi^+\pi^+$	PRD103(2021)092006
$D_s^+ \to K^+K^-\pi^+$	PRD104(2021)012016
$D^0 \to K_S^0K^+K^-$	arXiv:2006.02800
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	PRD100(2019)072008
$D^0 \to K^-\pi^+\pi^0\pi^0$	PRD99(2019)092008
$D^0 \to K^-\pi^+\pi^+\pi^-$	PRD95(2017)072010
$D^+ \to K_S^0\pi^+\pi^0$	PRD89(2014)052001

Strong phase parameters of neutral D decays

PLB734(2014)227



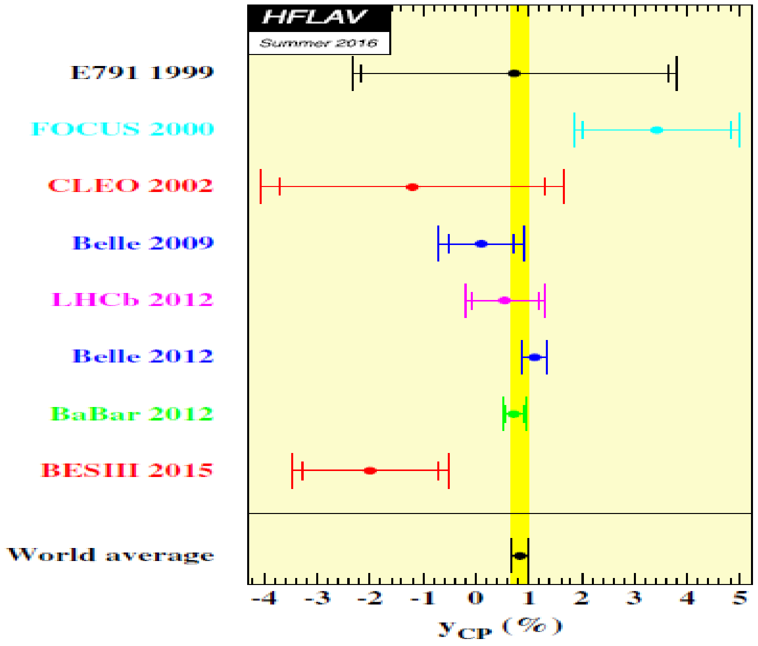


$$\mathcal{A}_{CP\to K\pi} = \frac{\mathcal{B}_{D_2\to K^-\pi^+} - \mathcal{B}_{D_1\to K^-\pi^+}}{\mathcal{B}_{D_2\to K^-\pi^+} + \mathcal{B}_{D_1\to K^-\pi^+}}.$$

$$2r\boxed{\cos\delta_{K\pi}} + y = (1 + R_{\mathrm{WS}}) \cdot \mathcal{A}_{CP\to K\pi},$$

$$|D_1\rangle \equiv \frac{|D^0\rangle + |\overline{D}^0\rangle}{\sqrt{2}} \quad |D_2\rangle \equiv \frac{|D^0\rangle - |\overline{D}^0\rangle}{\sqrt{2}}.$$

PLB744(2015)339



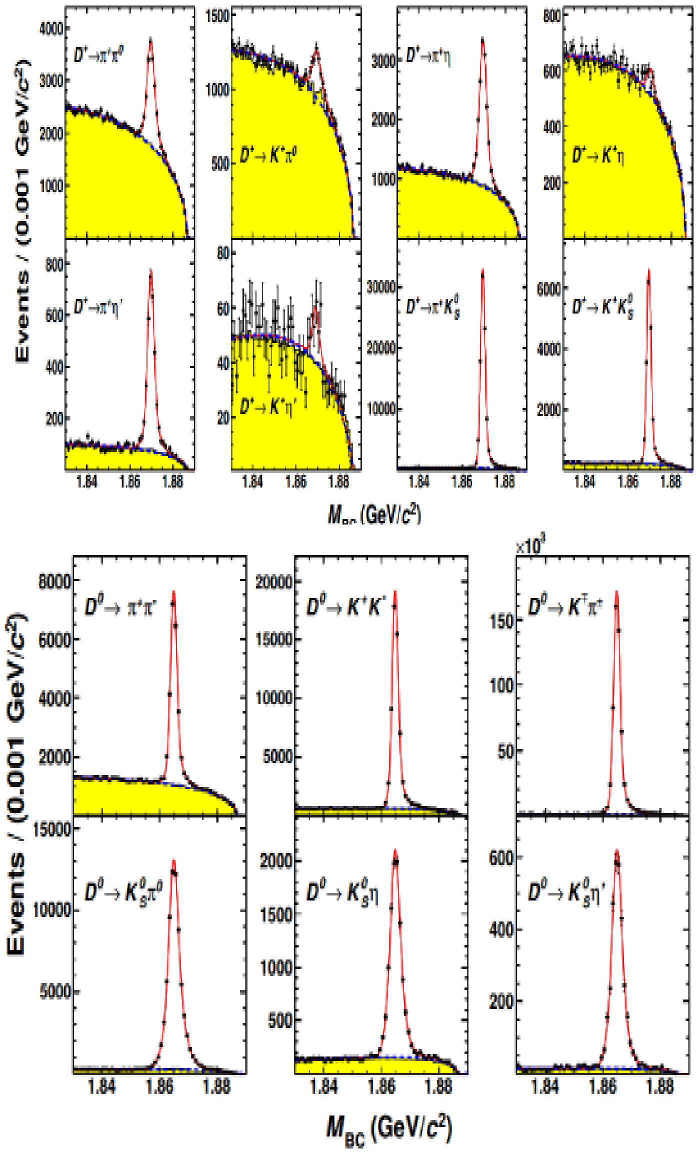
$A^{K\pi}_{CP}$=(12.7±1.3±0.7)%

$\cos\delta_{K\pi}$=1.02±0.11±0.06±0.01

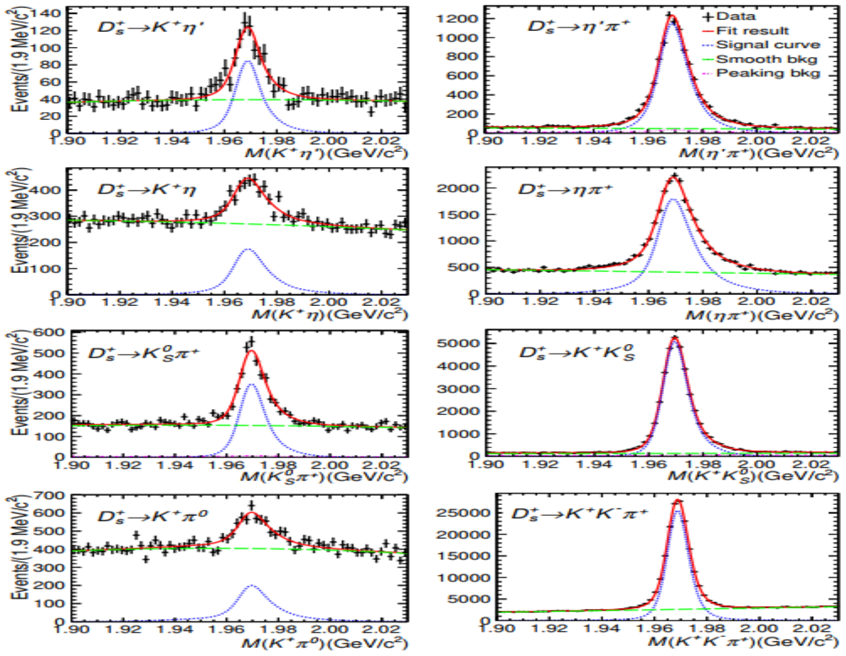
The most precise result to date

Branching fractions of $D \to PP$

PRD97(2018)072004

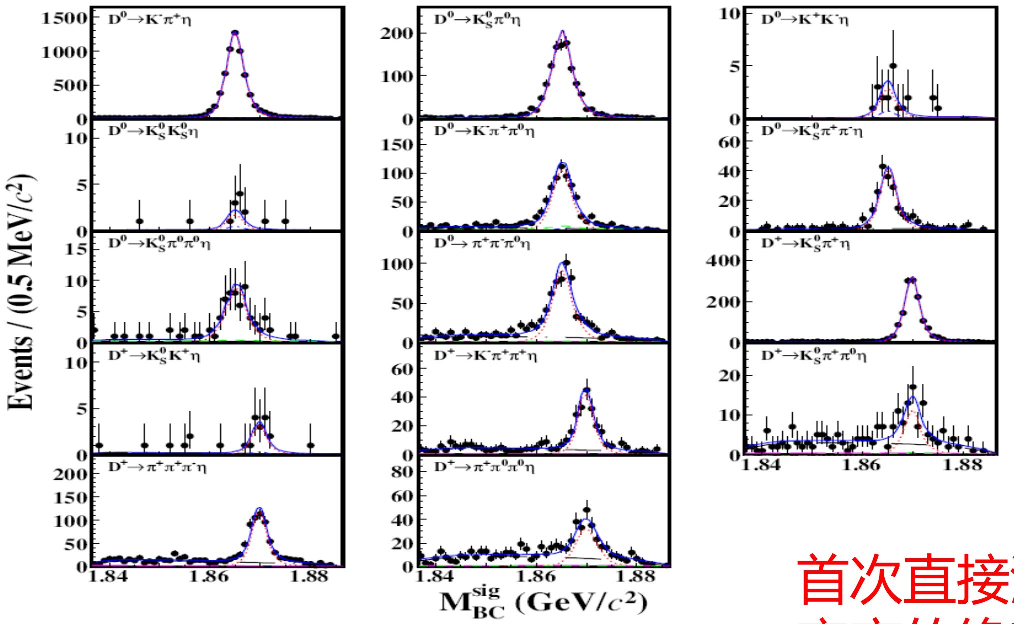


JHEP08(2020)146

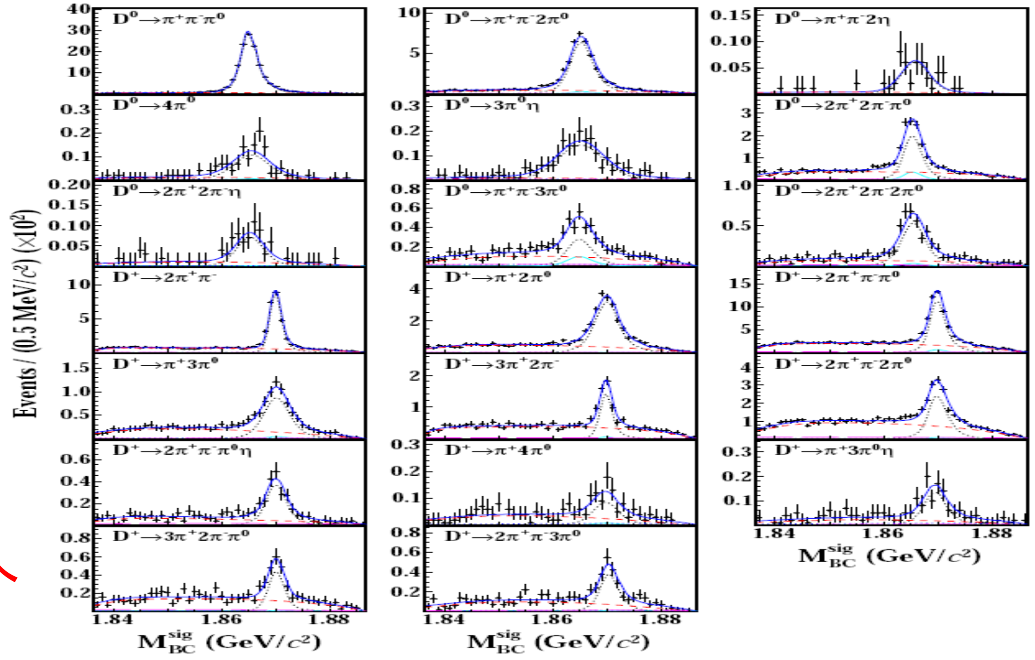


Absolute branching fractions of hadronic D decays

PRL124(2020)241803



arXiv:2206.13864



首次直接测量三十多个衰变的绝对分支比

Decay	ΔE_{sig} (MeV)	N_{DT}	ϵ_{sig} (%)	$\mathcal{B}_{sig}$ ($\times 10^{-4}$)
$D^0 \to K^-\pi^+\eta$	(−37, 36)	6116.2 ± 81.8	14.22	185.3(25)(31)
$D^0 \to K^0_S\pi^0\eta$	(−57, 45)	1092.7 ± 35.2	4.66	100.6(34)(30)
$D^0 \to K^+K^-\eta$	(−27, 27)	13.1 ± 4.0	9.53	0.59(18)(05)
$D^0 \to K^0_S K^0_S\eta$	(−29, 28)	7.3 ± 3.2	2.36	1.33(59)(18)
$D^0 \to K^-\pi^+\pi^0\eta$	(−44, 36)	576.5 ± 28.8	5.53	44.9(22)(15)
$D^0 \to K^0_S\pi^+\pi^-\eta$	(−33, 32)	248.2 ± 18.0	3.80	28.0(19)(10)
$D^0 \to K^0_S\pi^0\pi^0\eta$	(−56, 41)	64.7 ± 9.2	1.58	17.6(23)(13)
$D^0 \to \pi^+\pi^-\pi^0\eta$	(−57, 45)	508.6 ± 26.0	6.76	32.3(17)(14)
$D^+ \to K^0_S\pi^+\eta$	(−36, 36)	1328.2 ± 37.8	6.51	130.9(37)(31)
$D^+ \to K^0_S K^+\eta$	(−27, 27)	13.6 ± 3.9	4.72	1.85(52)(08)
$D^+ \to K^-\pi^+\pi^+\eta$	(−33, 33)	188.0 ± 15.3	8.94	13.5(11)(04)
$D^+ \to K^0_S\pi^+\pi^0\eta$	(−49, 41)	48.7 ± 9.7	2.57	12.2(24)(06)
$D^+ \to \pi^+\pi^+\pi^-\eta$	(−40, 38)	514.6 ± 25.7	9.67	34.1(17)(10)
$D^+ \to \pi^+\pi^0\pi^0\eta$	(−70, 49)	192.5 ± 17.1	3.86	32.0(28)(17)

Decay	ΔE_{sig} (MeV)	N_{DT}	ϵ_{sig} (%)	$\mathcal{B}_{sig}$ ($\times 10^{-4}$)
$\pi^+\pi^-\pi^0$	(−62, 36)	12792.6(120.1)	40.91	134.3(13)(16)
$\pi^+\pi^-2\pi^0$	(−75, 37)	3783.7(70.5)	16.29	99.8(19)(24)
$\pi^+\pi^-2\eta$	(−37, 29)	42.5(6.7)	2.14	8.5(13)(04)
$4\pi^0$	(−105, 41)	96.0(11.5)	5.41	7.6(09)(07)
$3\pi^0\eta$	(−82, 40)	155.3(14.7)	2.83	23.6(22)(17)
$2\pi^+2\pi^-\pi^0$	(−52, 33)	942.4(40.0)	11.70	34.6(15)(15)
$2\pi^+2\pi^-\eta$	(−36, 28)	48.5(7.8)	3.46	6.0(10)(06)
$\pi^+\pi^-3\pi^0$	(−76, 39)	182.7(20.9)	5.13	15.3(17)(13)
$2\pi^+2\pi^-2\pi^0$	(−64, 36)	350.0(22.9)	3.15	47.7(31)(21)
$2\pi^+\pi^-$	(−30, 28)	2614.3(58.0)	50.63	33.1(07)(05)
$\pi^+2\pi^0$	(−96, 44)	1968.0(51.7)	27.33	46.2(12)(09)
$2\pi^+\pi^-\pi^0$	(−59, 35)	4649.5(83.5)	25.42	117.4(21)(21)
$\pi^+3\pi^0$	(−86, 39)	573.7(30.2)	8.83	41.7(22)(13)
$3\pi^+2\pi^-$	(−37, 33)	462.1(28.7)	16.26	18.2(11)(10)
$2\pi^+\pi^-2\pi^0$	(−74, 39)	1207.1(45.4)	7.21	107.4(40)(30)
$2\pi^+\pi^-\pi^0\eta$	(−51, 33)	191.4(15.9)	3.17	38.8(32)(12)
$\pi^+4\pi^0$	(−90, 41)	56.7(10.4)	1.87	19.5(36)(23)
$\pi^+3\pi^0\eta$	(−66, 37)	79.7(10.9)	1.77	28.9(40)(22)
$3\pi^+2\pi^-\pi^0$	(−49, 34)	182.8(17.3)	5.02	23.4(22)(15)
$2\pi^+\pi^-3\pi^0$	(−66, 37)	185.9(17.0)	3.49	34.2(31)(16)

Absolute BFs of other hadronic D decays

▪BFs of $D^{0(+)} \to$ K3pi and K4pi	arXiv:2205.14031, accepted by PRD
▪DCS decays $D^0 \to K^-\pi^+\pi^0$ and $K^-\pi^+\pi^0\pi^0$	PRD105(2022)112001
▪$D^{0(+)} \to K_L\,(\omega, \phi, \eta, \eta')$	PRD105(2022)092010
▪$D^{0(+)} \to K\pi\omega$	PRD105(2022)032009
▪DCS decays $D^+ \to K^+\pi^0\pi^0$ and $K^+\pi^0\eta$	arXiv:2110.10999, submitted to JHEP
▪DCS decay $D^+ \to K^+\pi^+\pi^-\pi^0$ *via SL method*	PRD104(2021)072005
▪$D^{0(+)} \to KK\pi\pi$	PRD102(2020)052006
▪$D^{0(+)} \to \omega\pi\pi$	PRD102(2020)052003
▪$D^+ \to \eta\eta\pi^+$	PRD101(2020)052009
▪$D^{0(+)} \to \phi X$	PRD100(2019)072006
▪Two-body $D^{0(+)} \to \phi P$ decays	PLB798(2019)135017
▪$D_s^+ \to \omega K^+$ and $\omega\pi^+$	PRD99(2019)091101
▪$D_s^+ \to K^0_{S/L}K^+$	PRD99(2019)032002
▪$D_s^+ \to p\bar{n}$	PRD99(2019)031101
▪$D^+ \to K^0_{S/L}K^+(\pi^0)$	PRD99(2019)112005
▪$D^{0(+)} \to \bar{K}\pi\eta'$	PRD98(2018)092009
▪$D^0 \to \omega\eta$	PRD97(2018)052005
▪$D^0 \to 3\pi^0, 2\pi^0\eta, 2\eta\pi^0$	PLB781(2018)781
▪$D^{0(+)} \to K^0_S X$	PLB765(2017)231
▪$D_s^+ \to \eta' X$ and $\eta'\rho^+$@4.009 GeV	PLB750(2016)466

Rare D decays

- $D^0 \to \pi^0 \nu\nu$ — PRD105(2022)L071102
- $D^0 \to pe$ — PRD105(2022)032006
- $D^+ \to \Lambda e^+$、Σe^+ — PRD101(2020)031102
- $D^0 \to hhe^+e^+$ — PRD99(2019)112002
- $D^+ \to h^+h^0e^+e^-$ — PRD97(2018)072015
- $D^0 \to \gamma\gamma$ — PRD91(2015)112015