BESIII上粲介子含轻衰变的研究

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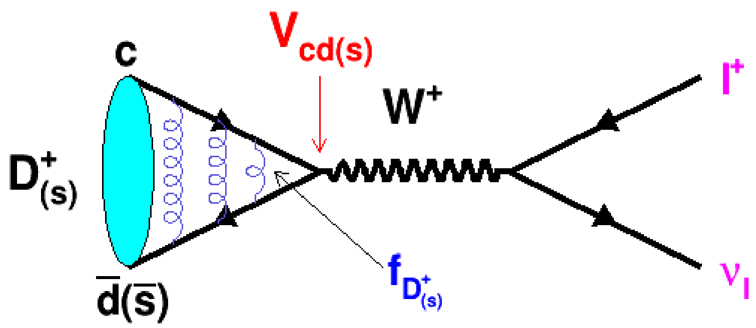
第四届中国格点量子色动力学会议，湖南省长沙市，
2024年10月11-15日

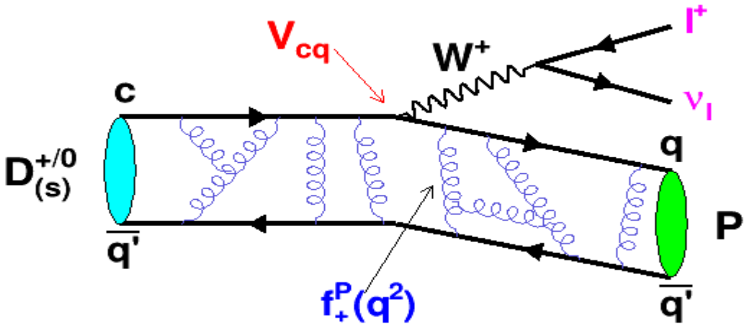
主要内容

- 物理动机
- 数据样本
- 粲介子纯轻衰变研究
- 粲介子半轻衰变研究
- 总结

(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





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

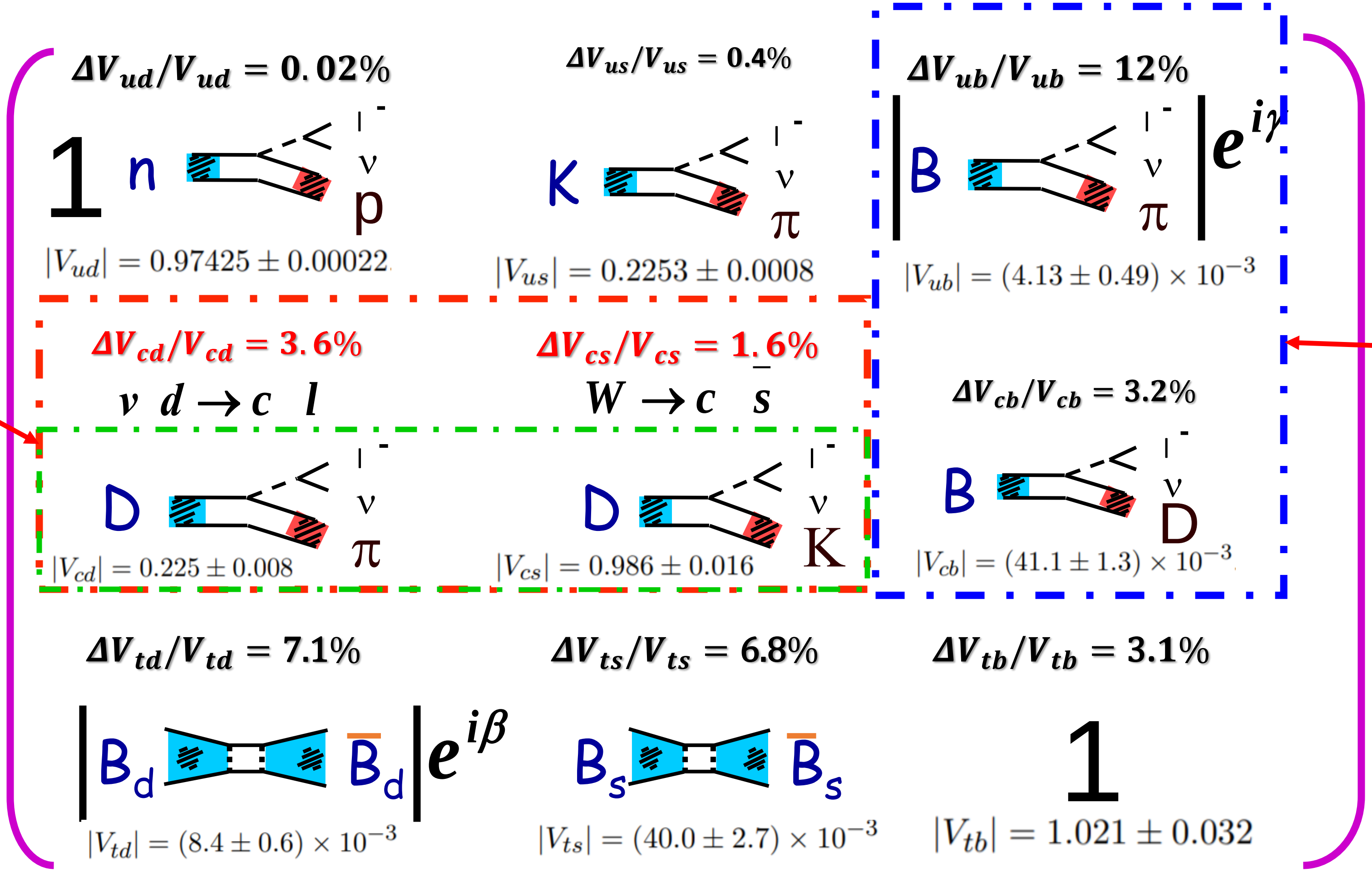
$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2$$

- 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$|V_{cs}|$、$|V_{cd}|$ →在更高精度下检验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

BESIII之前$|V_{cs(d)}|$的测量状态

PDG2014

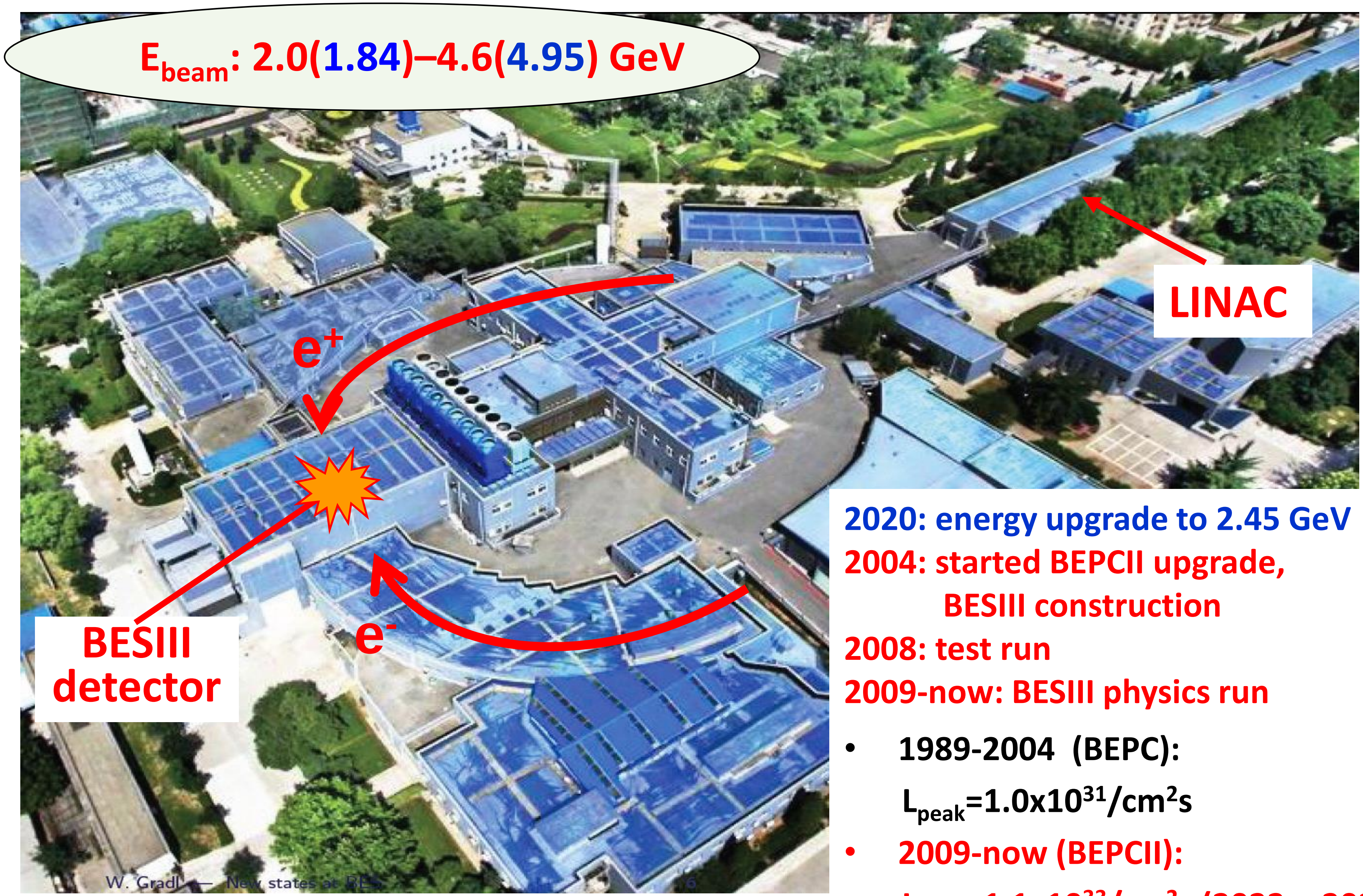
Direct measurement: (semi)leptonic D decays



Indirect constraint: Hadronic D decays

V_{ud}, V_{us} and V_{cb} are the best determined due to flavor symmetries: I, SU(3), HQS. Charm (V_{cd} & V_{cs}) and rest of the beauty sector (V_{ub}, V_{td}, V_{ts}) are poorly determined. Theoretical errors on hadronic matrix element dominate.

北京正负电子对接机II (BEPCII)



2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade,
BESIII construction

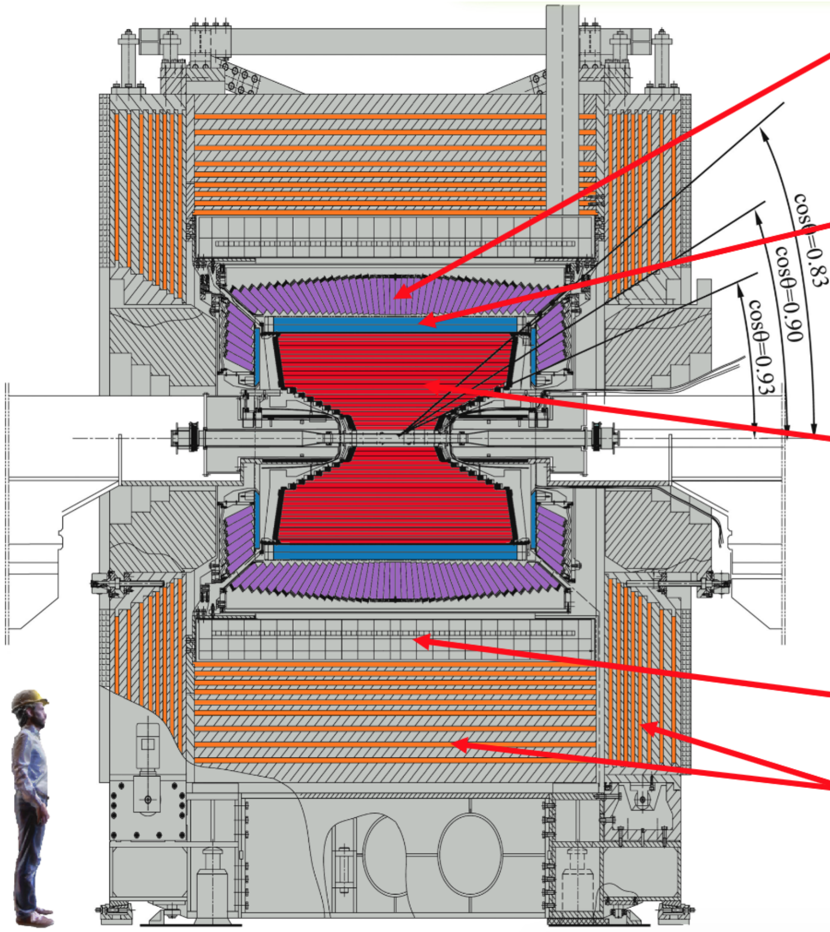
2008: test run

2009-now: BESIII physics run

- 1989-2004 (BEPC):
  $L_{peak}=1.0\text{x}10^{31}/cm^2s$
- 2009-now (BEPCII):
  $L_{peak}=1.1\text{x}10^{33}/cm^2s$ (2022、2023)

北京谱仪III (BESIII)

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国际合作组

ed or

Europe (18)

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 Turin,

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(3): University of Manchester, University of Oxford, University of Bristol

Poland(1): National Centre for Nuclear Research

Pakistan(2)

COMSATS Institute of Information Technology

University of the Punjab

India(1)

Indian Institute of Technology madras

Mongolia(1)

Institute of Physics and Technology

Korea(1)

Chung-Ang University

Thailand(1)

Suranaree University of Technology

USA(3)

Carnegie Mellon University

Indiana University

University of Hawaii

Chile(1)

University of Tarapaca

China (54)

Beihang University, Central China Normal University, Central South University, China Center of Advanced Science and Technology, China University of Geosciences, Fudan University, Guangxi Normal University, Guangxi University, Hangzhou Normal University, Hebei University, Henan University, Henan Normal University, Henan University of Science and Technology, Henan University of Technology, Huangshan College, Hunan University, Hunan Normal University, Inner Mongolia University, Institute of High Energy Physics, 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, Renmin University of China， Shanxi University, Shanxi Normal University, Sichuan University, Shandong Normal University, Shandong University, Shandong University of Technology, Shanghai Jiao Tong University, Soochow University,South China Normal University, Southeast University, Sun Yat-sen University, Tsinghua University, University of Chinese Academy of Scienc[es], 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, Yantai University , Yunnan University , Zhejiang University, Zhengzhou University

> 600 members
From 82 institutions
in 16 countries

Data samples at BESIII

2009: 106M $\psi(3686)$
225M J/ψ
2010: 0.98 fb^{-1} **$\psi(3770)$**
2011: 2.93 fb^{-1} $\psi(3770)$ ($D^{0(+)}$, total)
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

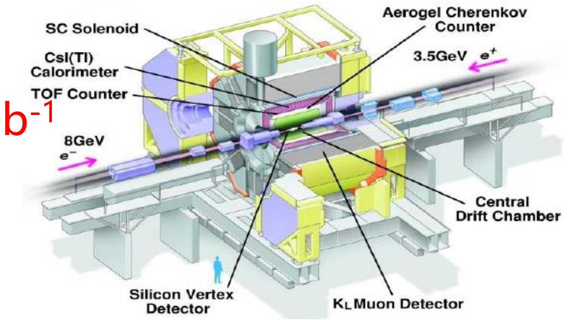
2016: 3.20 fb^{-1} @4.178 GeV (XYZ&D_s^+)
2017: 7×0.50 fb^{-1} @4.19-4.22 GeV (XYZ&D_s^+),
@4.24-4.27 (XYZ)
2018: More J/ψ+tuning new RF cavity
2019: 10B J/ψ (total)
8×0.50 fb^{-1} XYZ scan@4.13, 4.16 (XYZ&D_s^+),
4.29-4.44 GeV
2020: 3.8 fb^{-1} @ 4.61-4.7 GeV (XYZ&Λ_c^+)
2021: 2.0 fb^{-1} @ 4.74-4.946 GeV
2.7B $\psi(3686)$ (total)
2022: 0.4 fb^{-1} @3.650 GeV
0.4 fb^{-1} @3.682 GeV
2.9→7.9 fb^{-1} $\psi(3770)$ ($D^{0(+)}$, total)
2023-2024: 7.9→20.3 fb^{-1} $\psi(3770)$ (for $D^{0(+)}$, total)
2×0.42 fb^{-1} $\psi(3770)$ scan
0.14 fb^{-1} @3.800-3.885 GeV
0.13 fb^{-1} @3.554 GeV
0.025 fb^{-1} @1.84-2.00 GeV

>50 fb^{-1} at E_{cm} between 1.84 and 4.95 GeV in 15 year running

近年来开展粲强子研究的实验

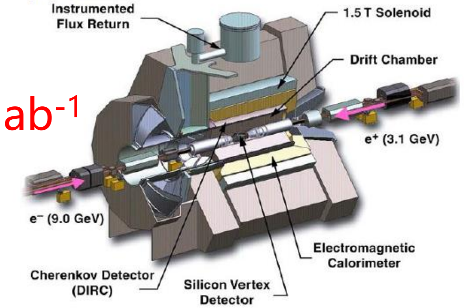
Belle @ KEKB
e^+e^- : ~10.6 GeV ($\Upsilon(4S)$)
$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb
$L_{peak} = 2 \times 10^{34}\ cm^{-2}\ s^{-1}$

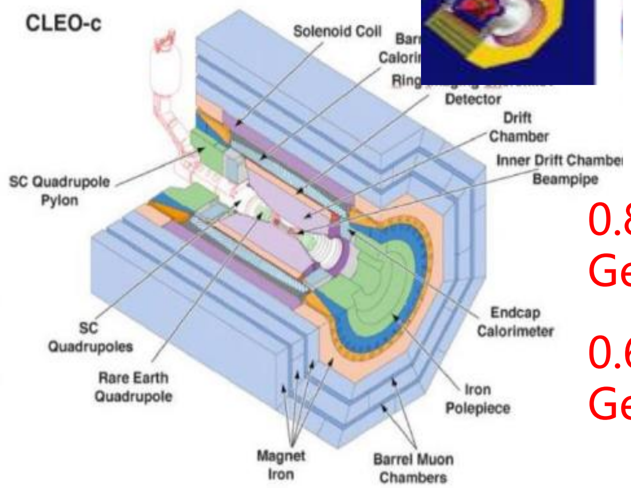
0.98 ab^{-1}



BaBar @ PEP-II
e^+e^- : ~10.6 GeV ($\Upsilon(4S)$)
$\sigma(e^+e^- \to c\bar{c}) = 1.3$ nb
$L_{peak} = 1 \times 10^{34}\ cm^{-2}\ s^{-1}$

0.54 ab^{-1}





0.8 fb^{-1}@3.774 GeV

0.6 fb^{-1}@4.170 GeV

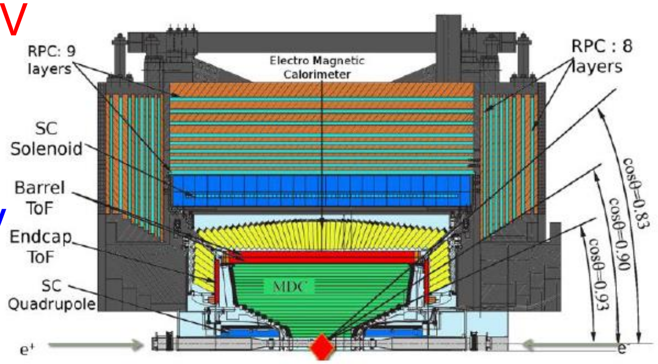
BESIII @ BEPC II
e^+e^- : 2-4.6 GeV
$\sigma(e^+e^- \to c\bar{c}) = 3$ nb
$L_{peak} = 1 \times 10^{33}\ cm^{-2}\ s^{-1}$

2.9→20.3 fb^{-1}@3.773 GeV

7.33 fb^{-1}@4.13-4.23 GeV

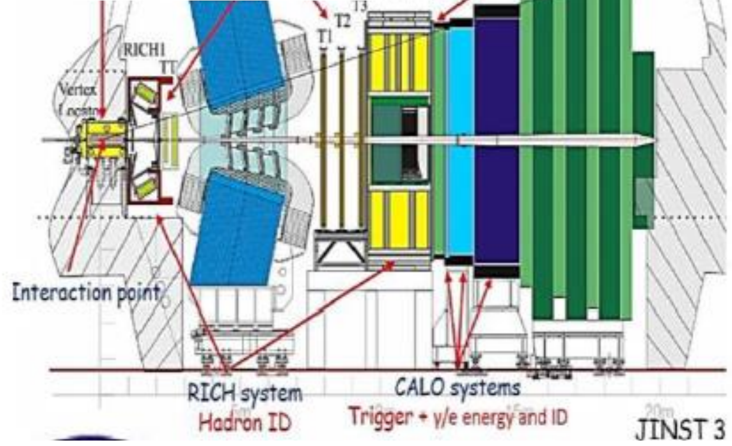
4.50 fb^{-1}@4.6-4.7 GeV

10.6 fb^{-1}@4.23-4.7 GeV

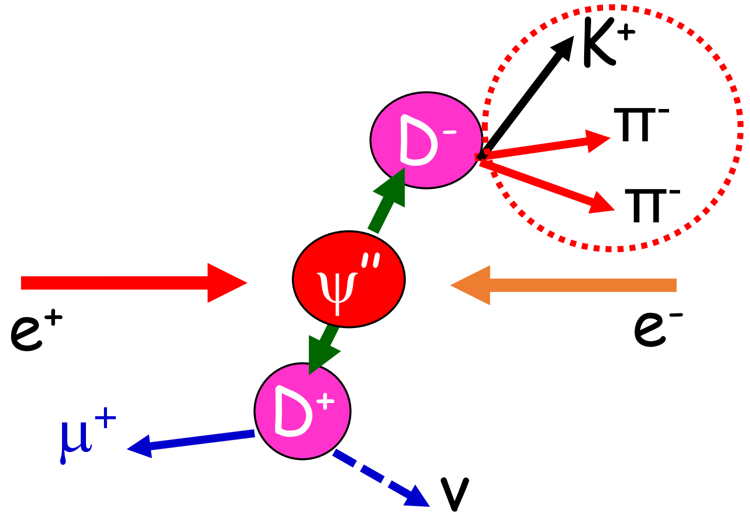


LHCb @ LHC
pp : 7-13 TeV
$\sigma(c\bar{c}) = 1.4\text{-}2.6$ mb
$L_{peak} = 4 \times 10^{32}\ cm^{-2}\ s^{-1}$
(luminosity leveling)

9 fb^{-1}



The world largest threshold charmed hadrons at BESIII



Produced in pair → Double tag method
Low background → low systematic uncertainties
Quantum correlation for $\psi(3770) \to D^0\bar{D}^0$ pairs

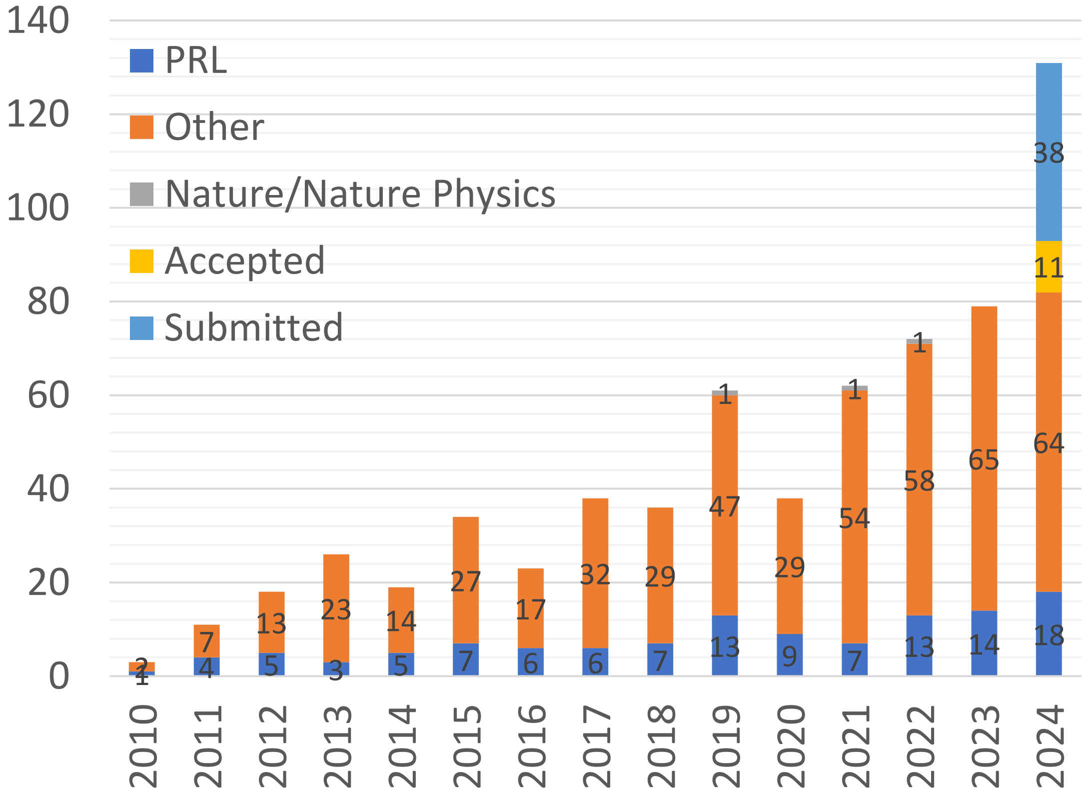
Yields of Singly Tagged (ST) charmed hadrons

E_{cm} (GeV)	Data taking year	L (fb^{-1})	ST D^0 yield	ST D^+ Yield	ST D_s^+ yield	ST Λ_c^+ yield
3.773	2010-11 (→2022-24)	2.93 → 20.3	2.7M (~7×)	1.7M (~7×)		
4.009	2011	0.48			13K	
4.13-4.23	2016,2017,2012,2019	7.33			0.8M	
4.6-4.7	2014, 2020	4.5				0.12M

Total yields of various charmed hadrons at BESIII are lower than Belle and LHCb by 2-3 orders.
However, BESIII, Belle and LHCb have complimentary advantages in various charm physics

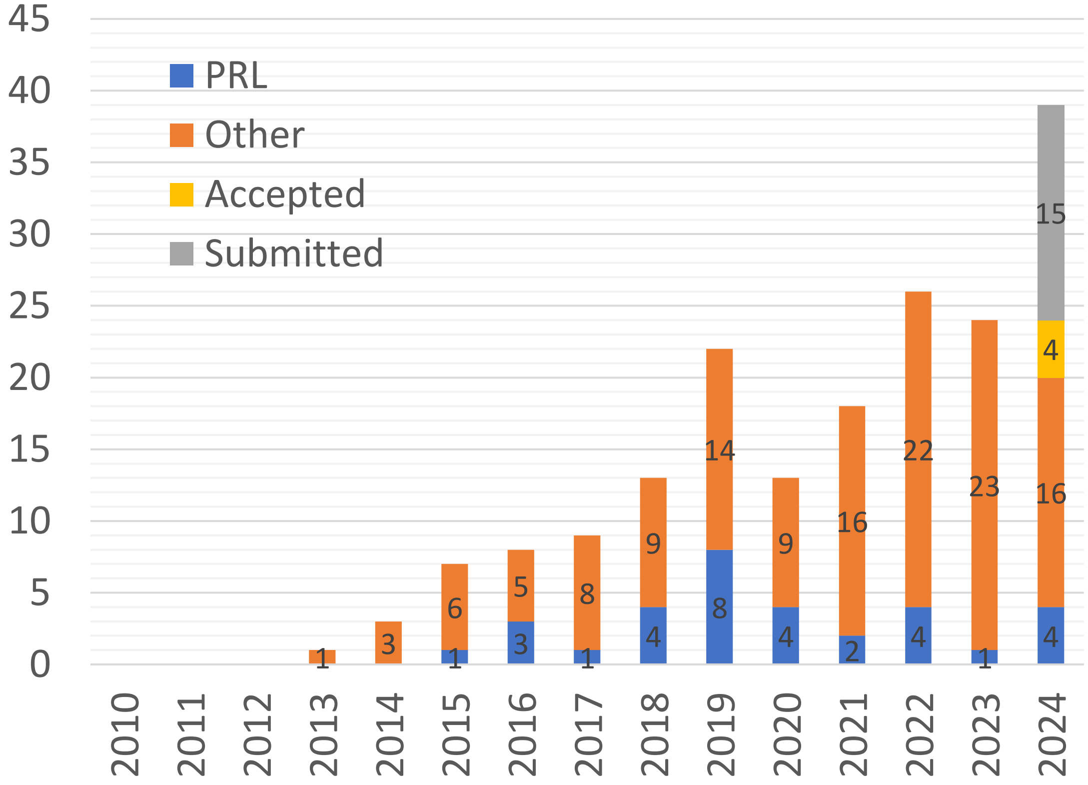
Publications of BESIII

BESIII physics



602 papers and 121 in PRL

Charm physics at BESIII



164 papers and 32 in PRL

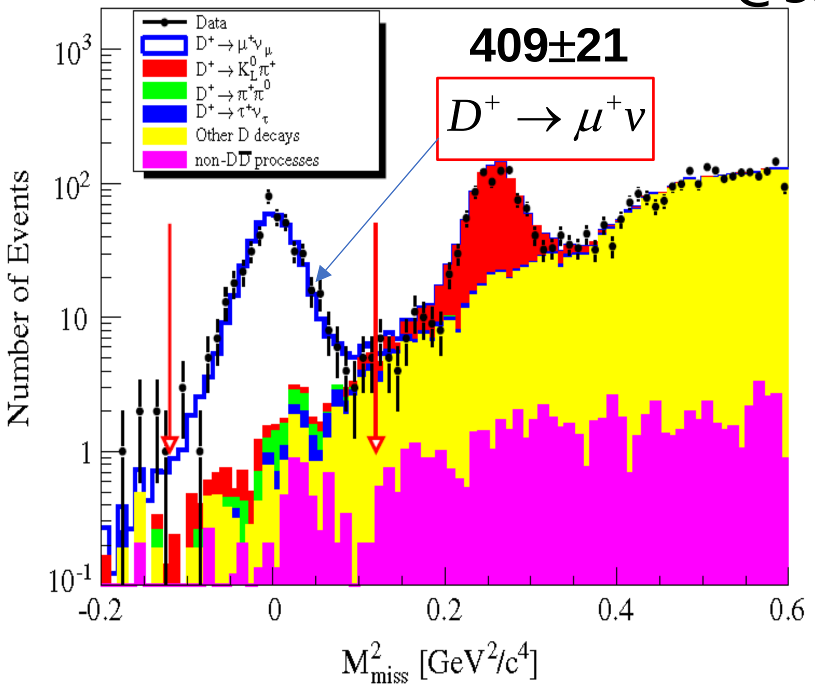
粲介子含轻衰变: >50篇文章 (15篇PRL)

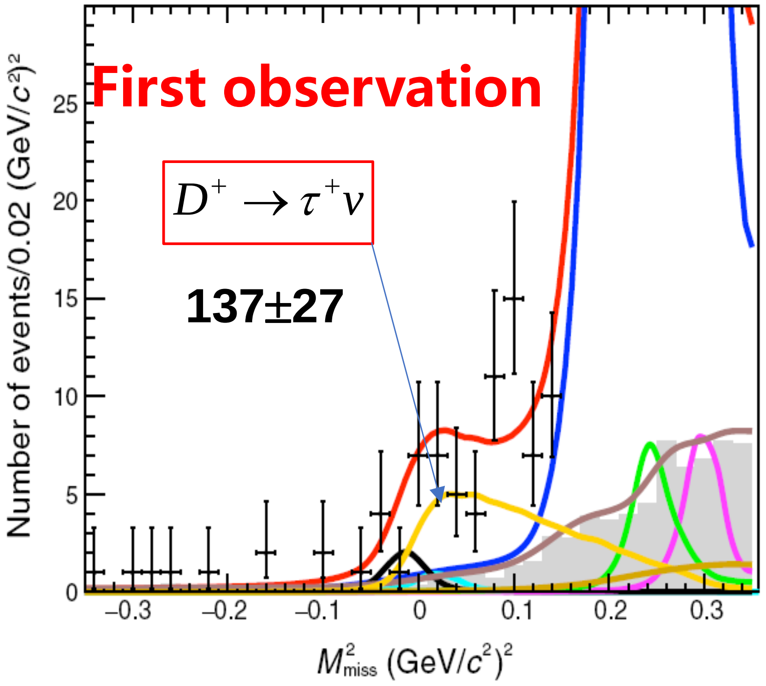
粲介子纯轻衰变

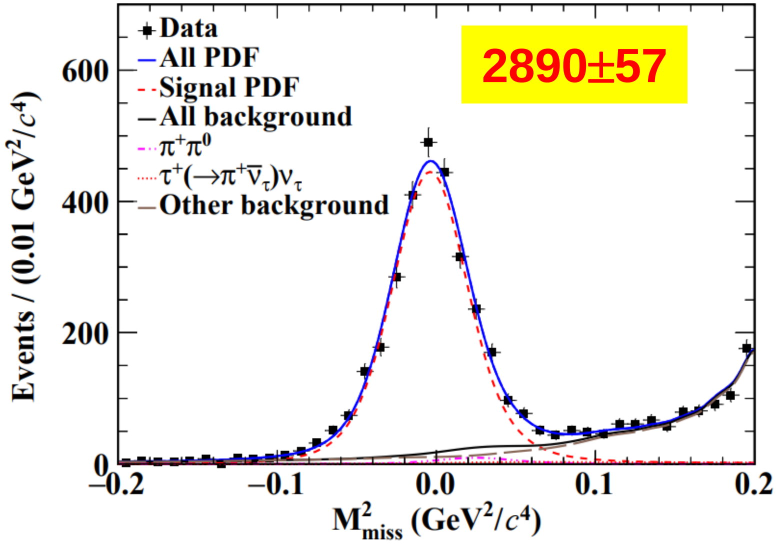
Studies of $D^+ \to l^+\nu_l$

PRD89(2014)051104 **2.93 fb^{-1} @3.773 GeV** **PRL123(2019)211802** **arXiv:2410.07626，最新结果**

20.3 fb^{-1}@3.773 GeV







The most precise to date

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

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

Precision~2.7%

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

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

Precision~11%

$B[D^+ \to \mu^+ v] = (3.98 \pm 0.08 \pm 0.04) \times 10^{-4}$

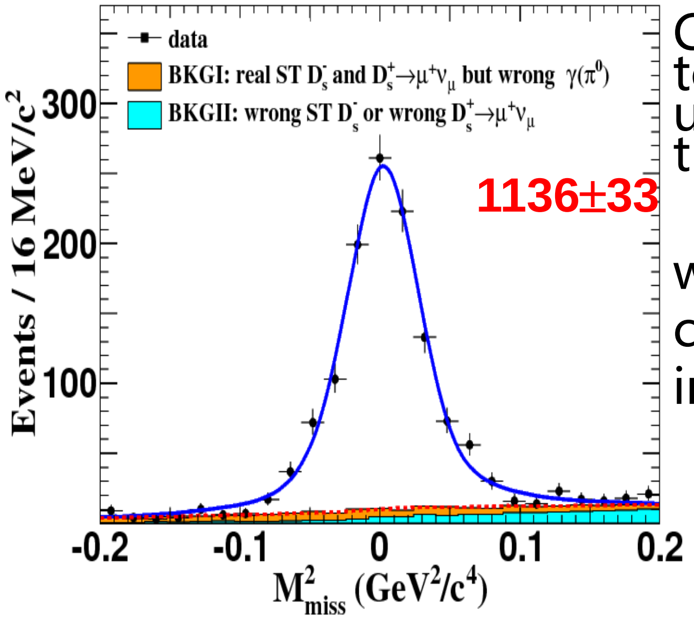
$f_{D^+}|V_{cd}| = 47.53 \pm 0.48 \pm 0.27$ MeV

Precision~1.2%

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 $\gamma(\pi^0)$

with μ counter information

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

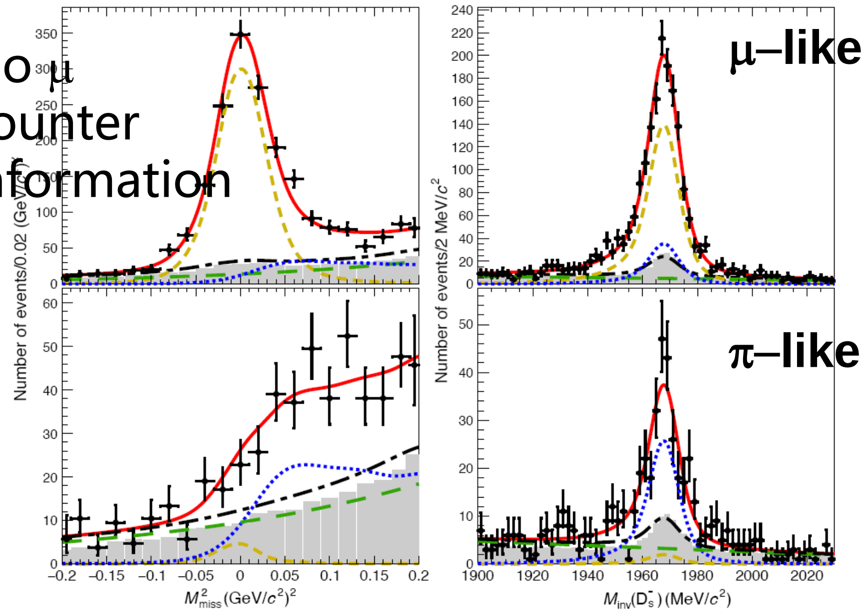
$$\mathbf{f_{D_s^+}|V_{cs}| = (246.2 \pm 3.6 \pm 3.5)\ MeV}$$

Precision~2.1%

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

PRD104(2021)052009

No μ counter information



2198±55

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

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

Precision~2.0%

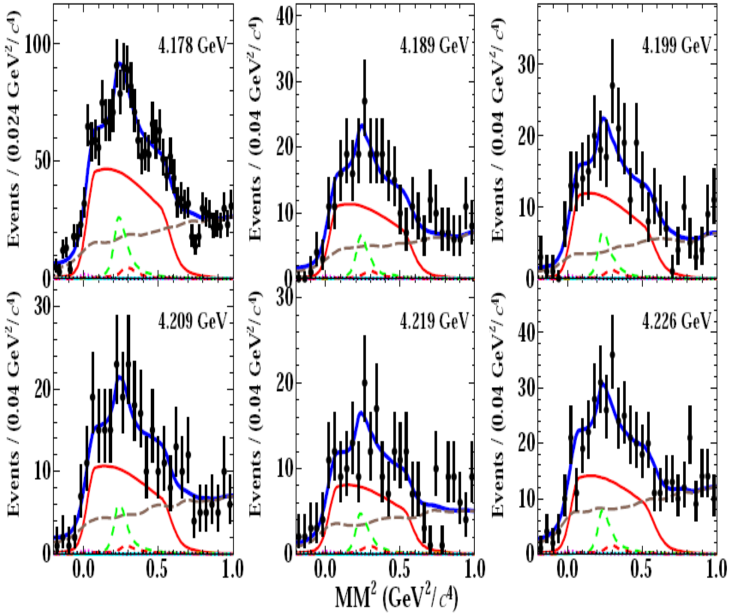
Studies of $D_s^+ \to \tau^+\nu_\tau$

PRD104(2021)032001

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

6.3 fb^{-1}

1745±84



$B[D_s^+ \to \tau^+ v] = (5.29 \pm 0.25 \pm 0.20)\%$

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

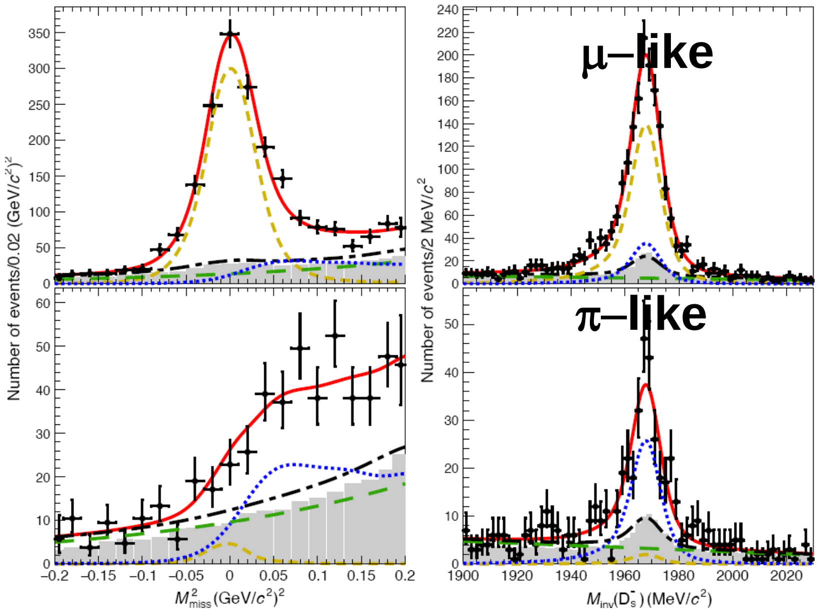
Precision~3.1%

PRD104(2021)052009

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

6.3 fb^{-1}

946±46



$B[D_s^+ \to \tau^+ v] = (5.21 \pm 0.25 \pm 0.17)\%$

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

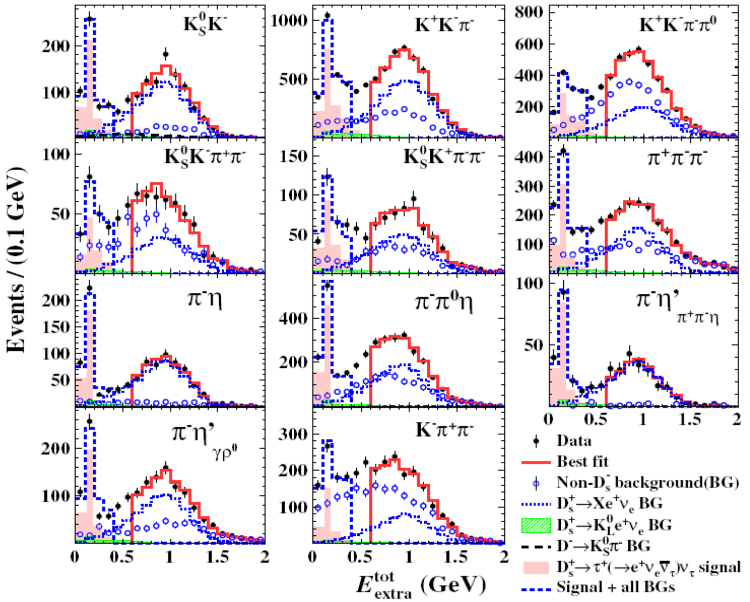
Precision~2.9%

PRL127(2021)171801

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

6.3 fb^{-1}

4940±97



$B[D_s^+ \to \tau^+ v] = (5.27 \pm 0.10 \pm 0.12)\%$

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

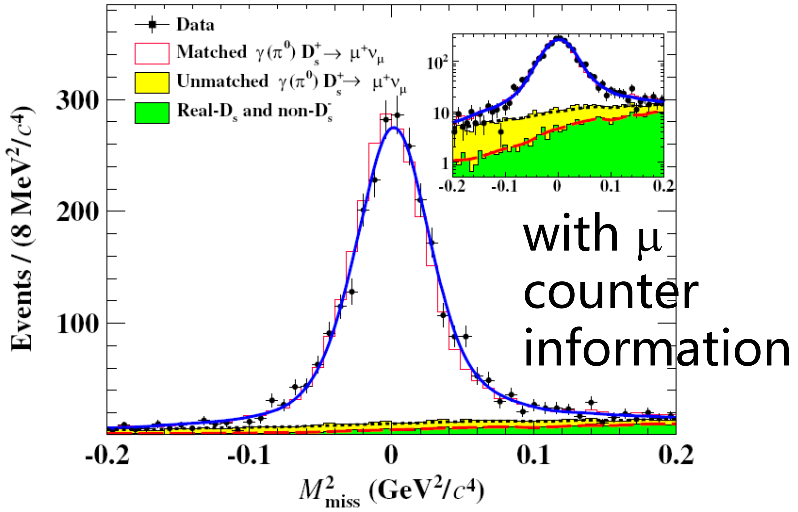
Precision~1.5%

More measurements of $D_s^+ \to l^+\nu_l$

PRD108(2023)112001

$D_s^+ \to \mu^+ v$

7.33 fb^{-1} **2515±52**



$$B[D_s^+ \to \mu^+ v] = (5.29 \pm 0.11 \pm 0.09) \times 10^{-3}$$

$$f_{D_s^+}|V_{cs}| = (241.8 \pm 2.5 \pm 2.2)\ \mathrm{MeV}$$

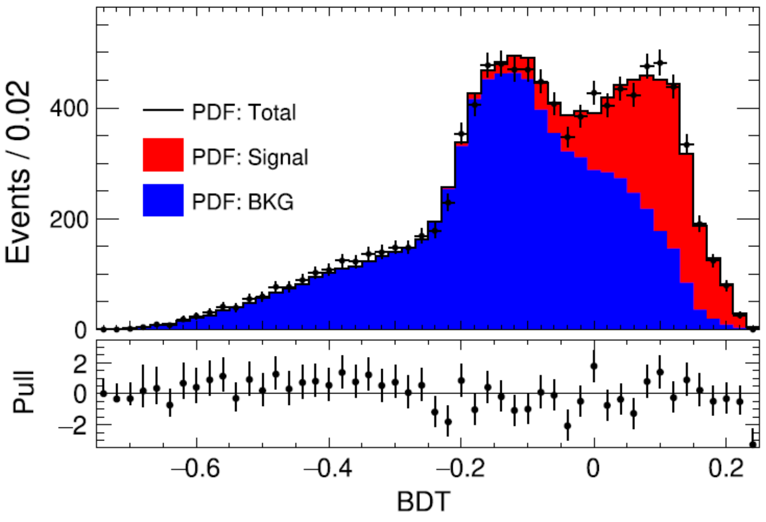
Precision~1.4%

The most precise to date

PRD108(2023)092014

$D_s^+ \to \tau^+(\pi^+ v)v$ **BDT**

7.33 fb^{-1} **2411±75**



$$B[D_s^+ \to \tau^+ v] = (5.44 \pm 0.17 \pm 0.13)\%$$

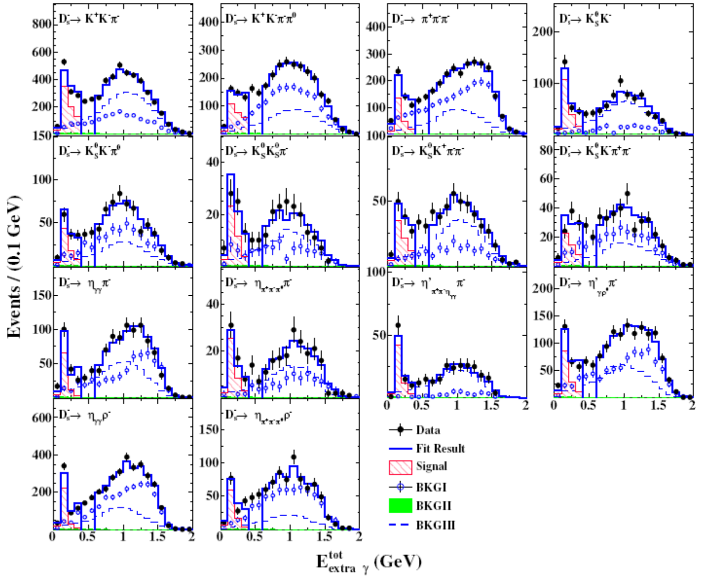
$$f_{D_s^+}|V_{cs}| = (248.3 \pm 3.9 \pm 3.2)\ \mathrm{MeV}$$

Precision~2.0%

JHEP09(2023)124

$D_s^+ \to \tau^+(\mu^+ vv)v$

7.33 fb^{-1} **2281±73**



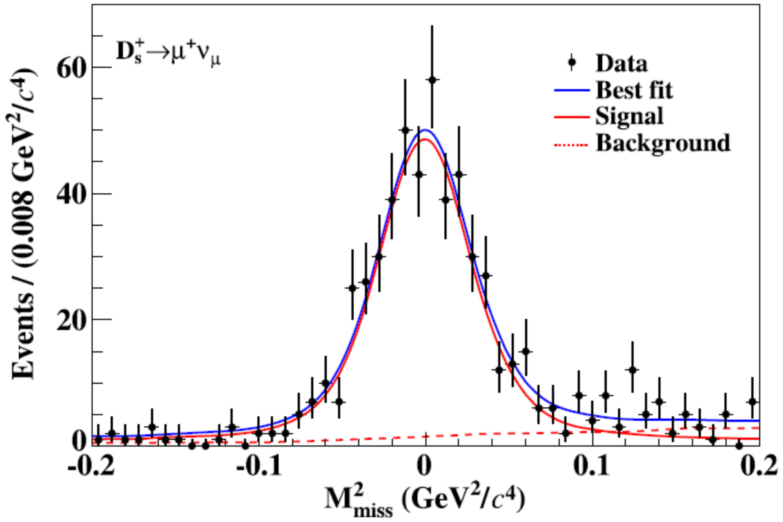
$$B[D_s^+ \to \tau^+ v] = (5.37 \pm 0.17 \pm 0.15)\%$$

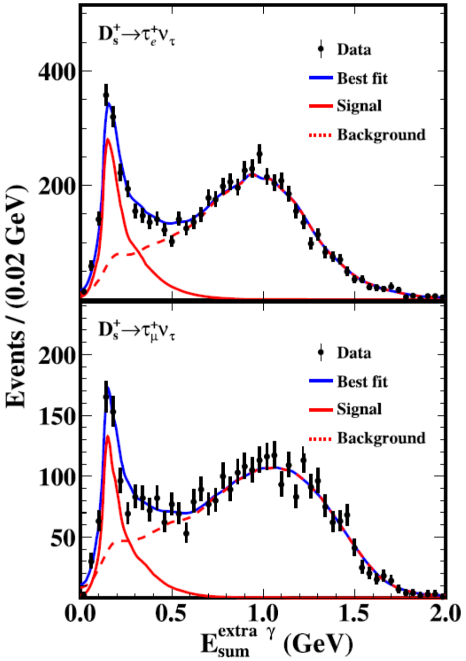
$$f_{D_s^+}|V_{cs}| = (246.7 \pm 3.9 \pm 3.6)\ \mathrm{MeV}$$

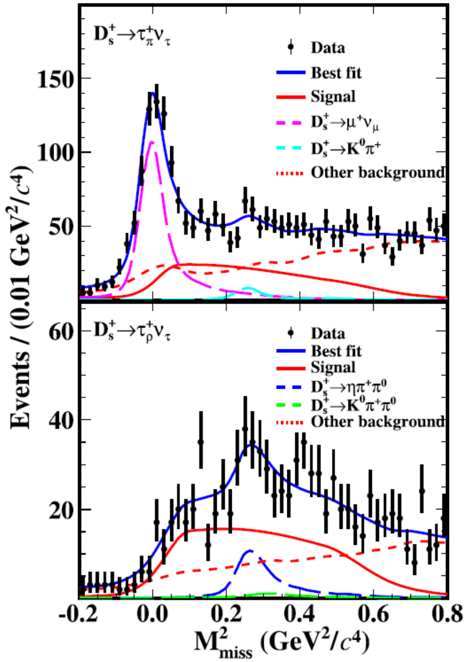
Precision~2.2%

基于$e^+e^- \to D_s^{*+}D_s^{*-}$研究$D_s^+$纯轻衰变

PRD110 (2024) 052002



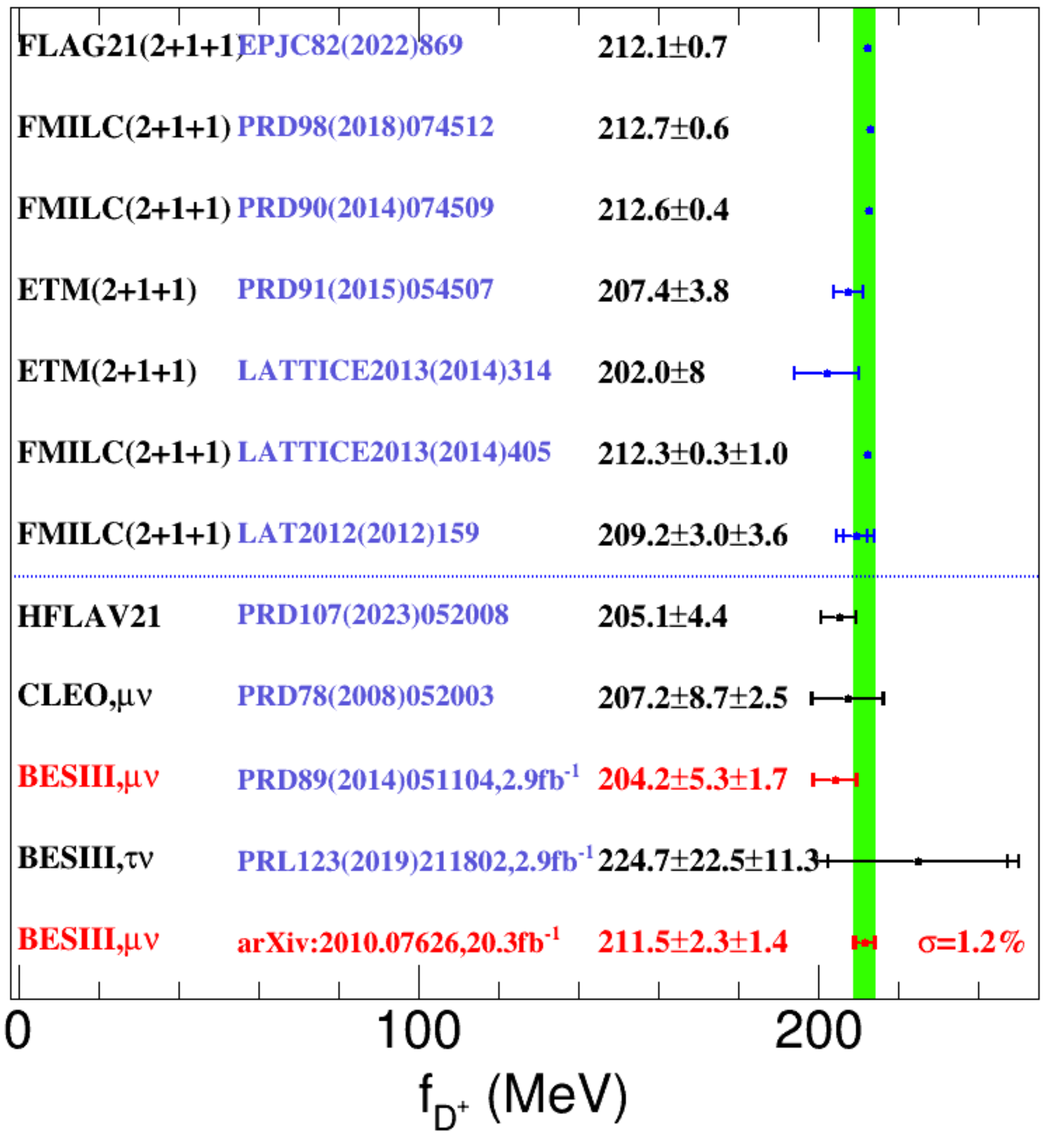


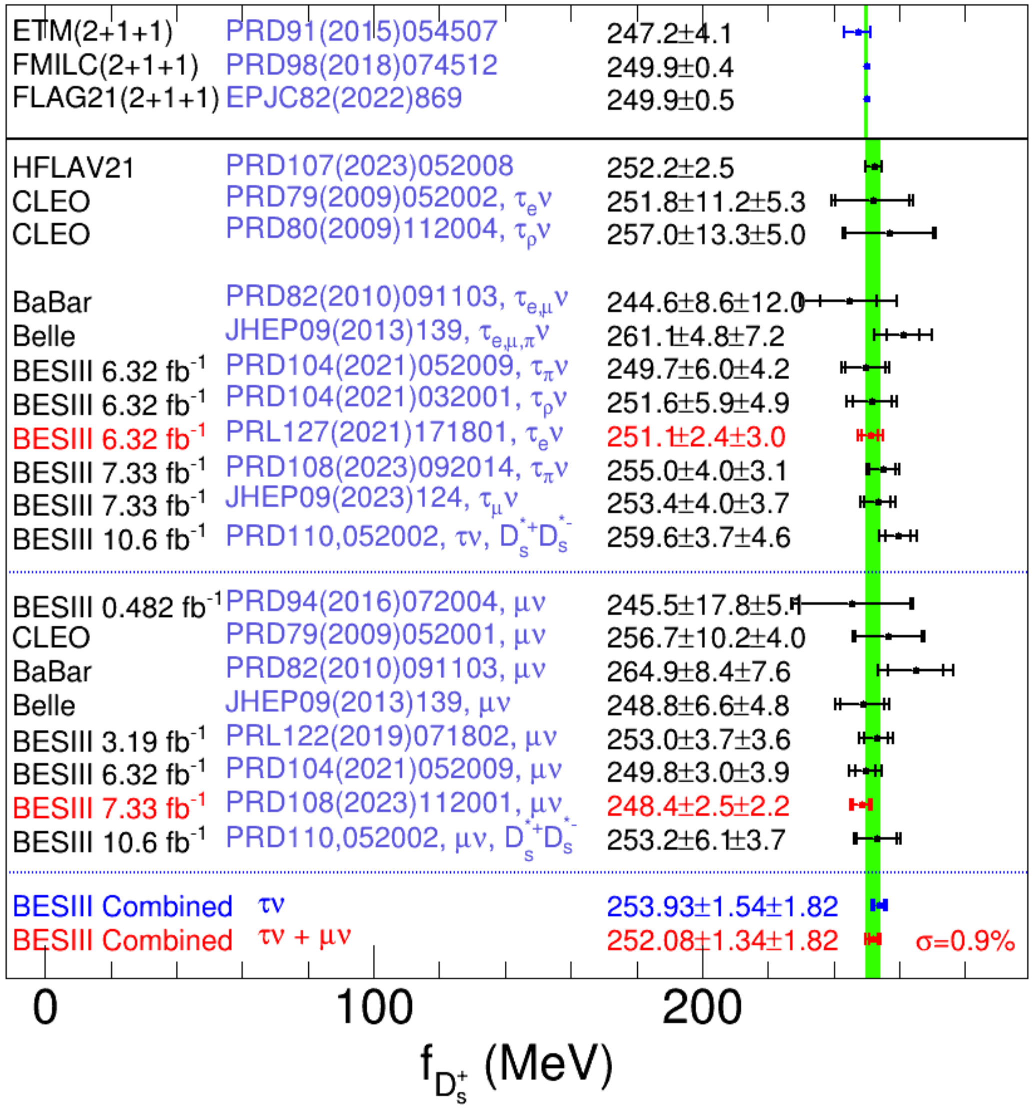


基于4.23-4.7 GeV 10.6 fb^{-1}数据，挖掘现有及未来BESIII数据潜力

		No lepton universality constraint		Lepton universality constraint	
Signal decay	$\bar{\epsilon}_{sig}$ (%)	N_{DT}	$\mathcal{B}$ (%)	N_{DT}^{SM}	$\mathcal{B}^{SM}$ (%)
$D_s^+\to\tau_e^+\nu_\tau$	7.81 ± 0.02	2845 ± 83	$5.60\pm0.16\pm0.20$	2754 ± 69	$5.39\pm0.14\pm0.20$
$D_s^+\to\tau_\mu^+\nu_\tau$	18.57 ± 0.04				
$D_s^+\to\tau_\pi^+\nu_\tau$	8.93 ± 0.02				
$D_s^+\to\tau_\rho^+\nu_\tau$	6.11 ± 0.02				
$D_s^+\to\mu_b^+\nu_\mu$	94.76 ± 0.20	579 ± 34	$0.491\pm0.029\pm0.020$	641 ± 16	$0.553\pm0.014\pm0.021$
$D_s^+\to\mu_a^+\nu_\mu$	74.67 ± 0.16	507 ± 26	$0.547\pm0.026\pm0.016$	...	...

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

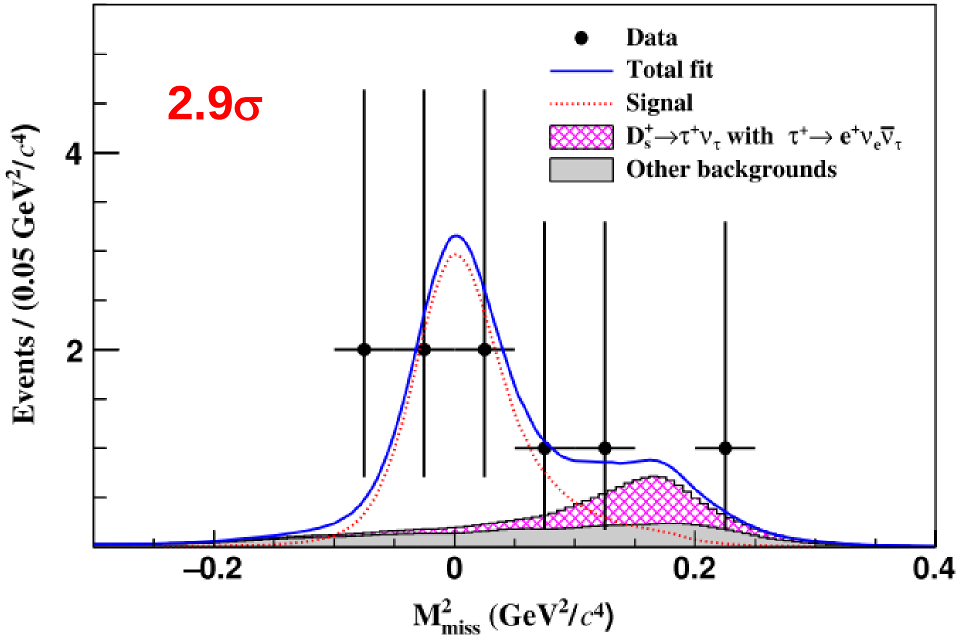




First experimental study of $D_s^{*+} \to e^+\nu_e$

PRL131 (2023) 141802

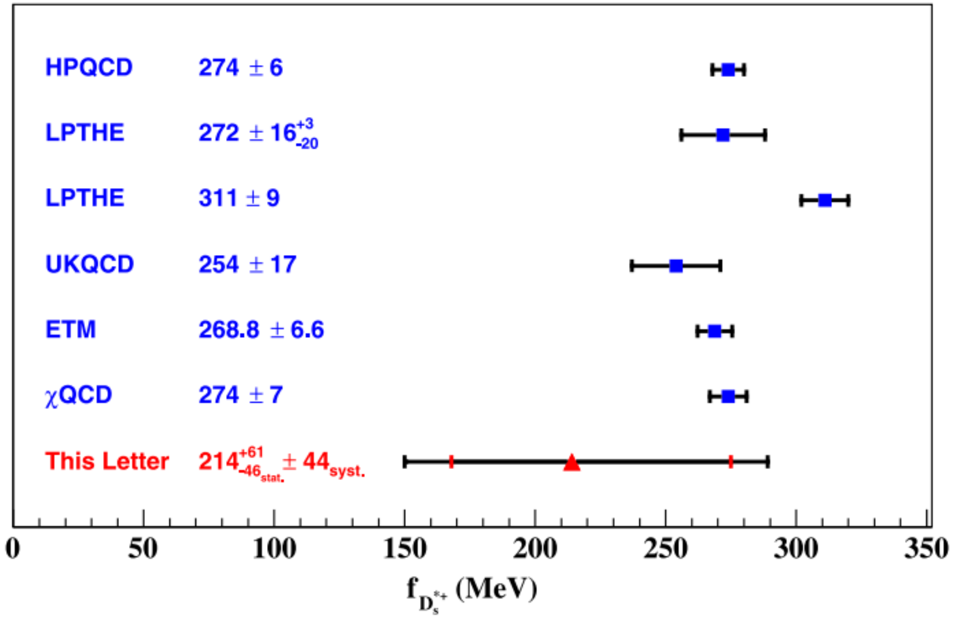
7.33 fb^{-1}@4.13-4.23 GeV



$$\mathcal{B}(D_s^{*+} \to e^+\nu_e) = (2.1^{+1.2}_{-0.9\,\text{stat}} \pm 0.2_{\text{syst}}) \times 10^{-5}$$

$$\Gamma(D_s^{*+} \to \ell^+\nu_\ell) = \frac{G_F^2}{12\pi}|V_{cs}|^2 f^2_{D_s^{*+}} m^3_{D_s^{*+}}\left(1 - \frac{m^2_{\ell^+}}{m^2_{D_s^{*+}}}\right)^2 \times \left(1 + \frac{m^2_{\ell^+}}{2m^2_{D_s^{*+}}}\right),$$

联合格点QCD计算的D_s^{*+}总宽度，首次抽取D_s^{*+}衰变常数



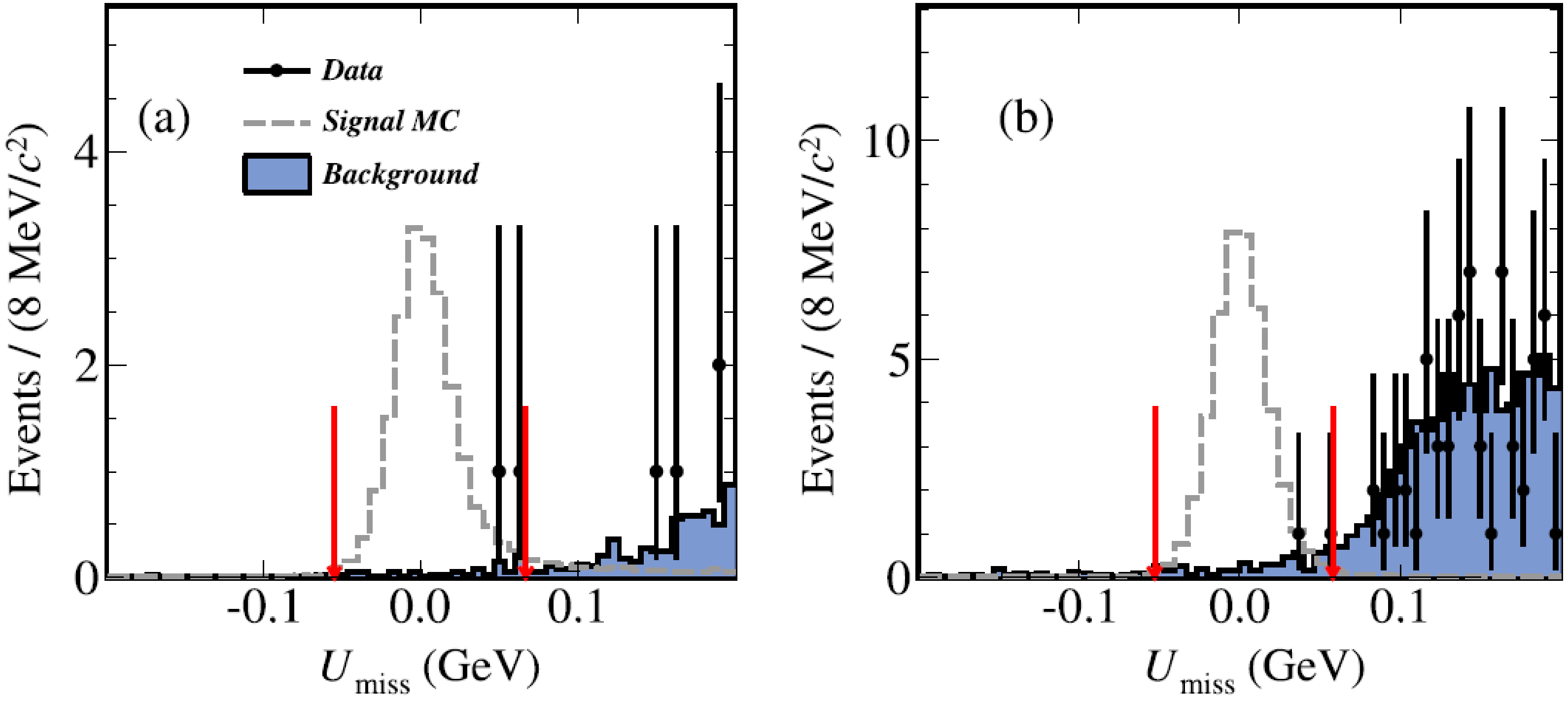
→ 为约束格点QCD计算的D_s^{*+}衰变常数首次提供实验依据

→ 对D_s^{*+}宽度上限的约束改进3个量级

Search for $D^{*+} \to l^+\nu_l$

PRD110 (2024) 012003

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



Signal mode	N_{ST}^{tot}	N_{SR}^{data}	N_{SB}^{data}	N_{SR}^{MC}	N_{SB}^{MC}	$\bar{\epsilon}_{D^{*+}\to\ell^+\nu_\ell}(\%)$	N_{UL}	$\mathcal{B}_{UL}$
$D^{*+} \to e^+\nu_e$	516256 ± 1870	2	4	34	239	80.90 ± 1.46	5.9	1.1×10^{-5}
$D^{*+} \to \mu^+\nu_\mu$		1	61	182	2872	68.86 ± 1.23	2.2	4.3×10^{-6}

分支比上限比标准模型预期高3个量级

粲介子半轻衰变

- $D \to Pe^{+}\nu_e$
- $D \to Ve^{+}\nu_e$
- $D \to Se^{+}\nu_e$
- $D \to Ae^{+}\nu_e$
- 其它衰变

} 见本次会议张书磊的报告

$D \to Pl^+\nu_l$型半轻衰变

微分跃迁率测量

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2|V_{cd(s)}|^2}{24\pi^3}p^3|f_+(q^2)|^2 \longrightarrow \mathbf{f}_+^{D\to P}(0)|V_{cs(d)}|$$

Form factor parameterizations:

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

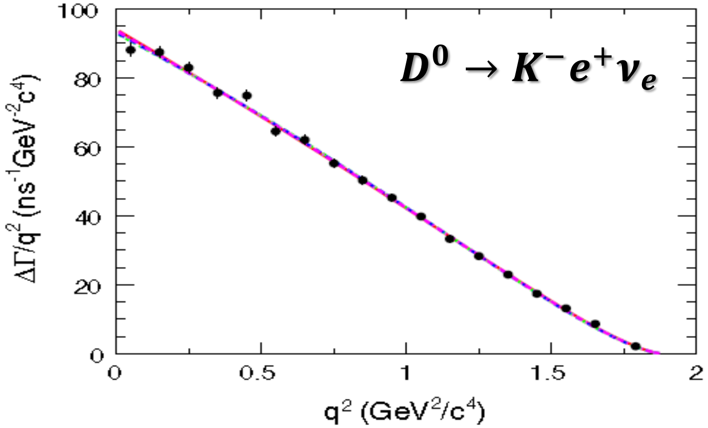
– Modified pole $$f_+(q^2) = \frac{f_+(0)}{(1-\frac{q^2}{M_{\rm pole}^2})(1-\alpha\frac{q^2}{M_{\rm pole}^2})}$$

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

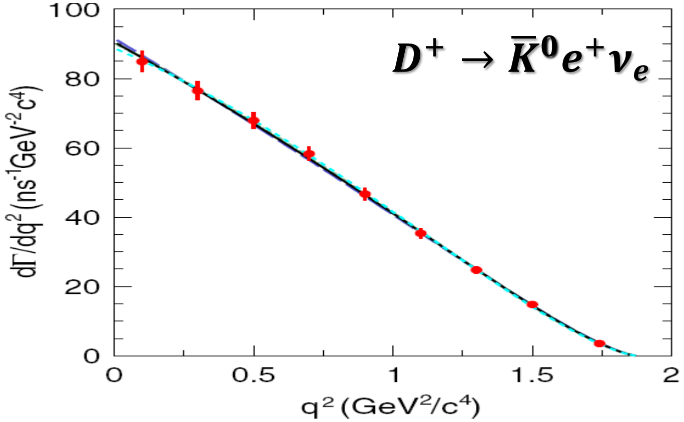
$c \to s l^+ \nu_l$ 型半轻衰变

PRD92(2015)072012



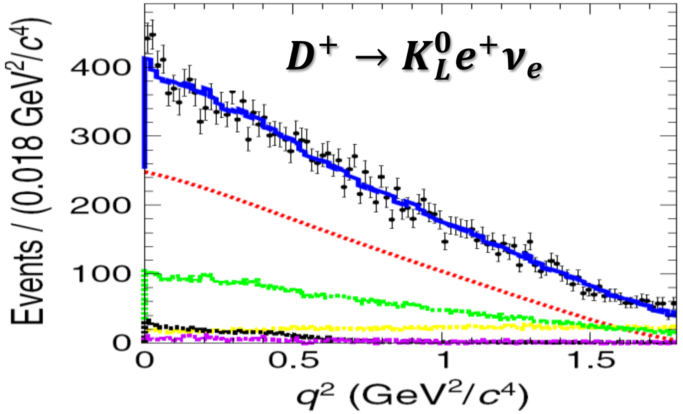
$f_+^{D\to K}(0)|V_{cs}| = 0.717(03)(04)$

PRD96(2017)012002



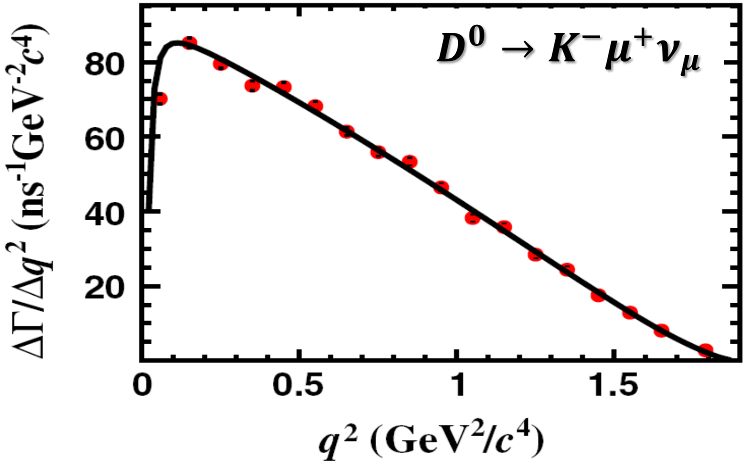
$f_+^{D\to K}(0)|V_{cs}| = 0.705(04)(11)$

PRD92(2015)112008



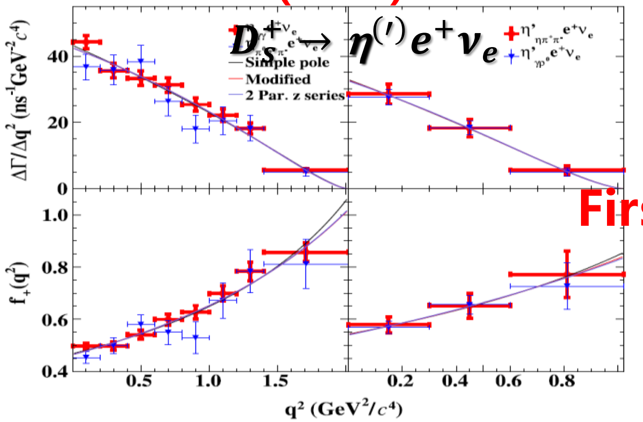
$f_+^{D\to K}(0)|V_{cs}| = 0.728(06)(11)$

PRL122(2019)011804



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

PRL123(2019)121801→
PRD108(2023)092003

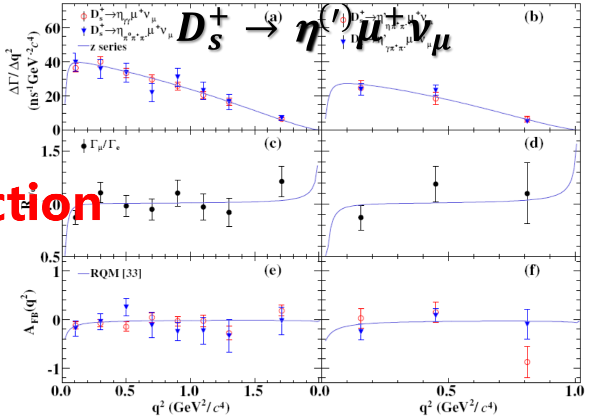


$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.452(07)(07)$

$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.525(24)(09)$

First extraction

PRL132(2024)091802

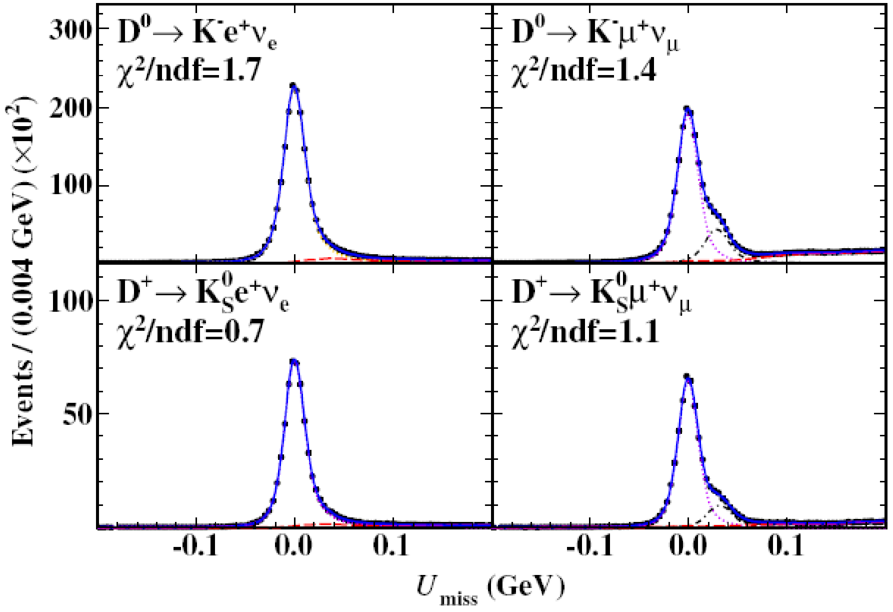


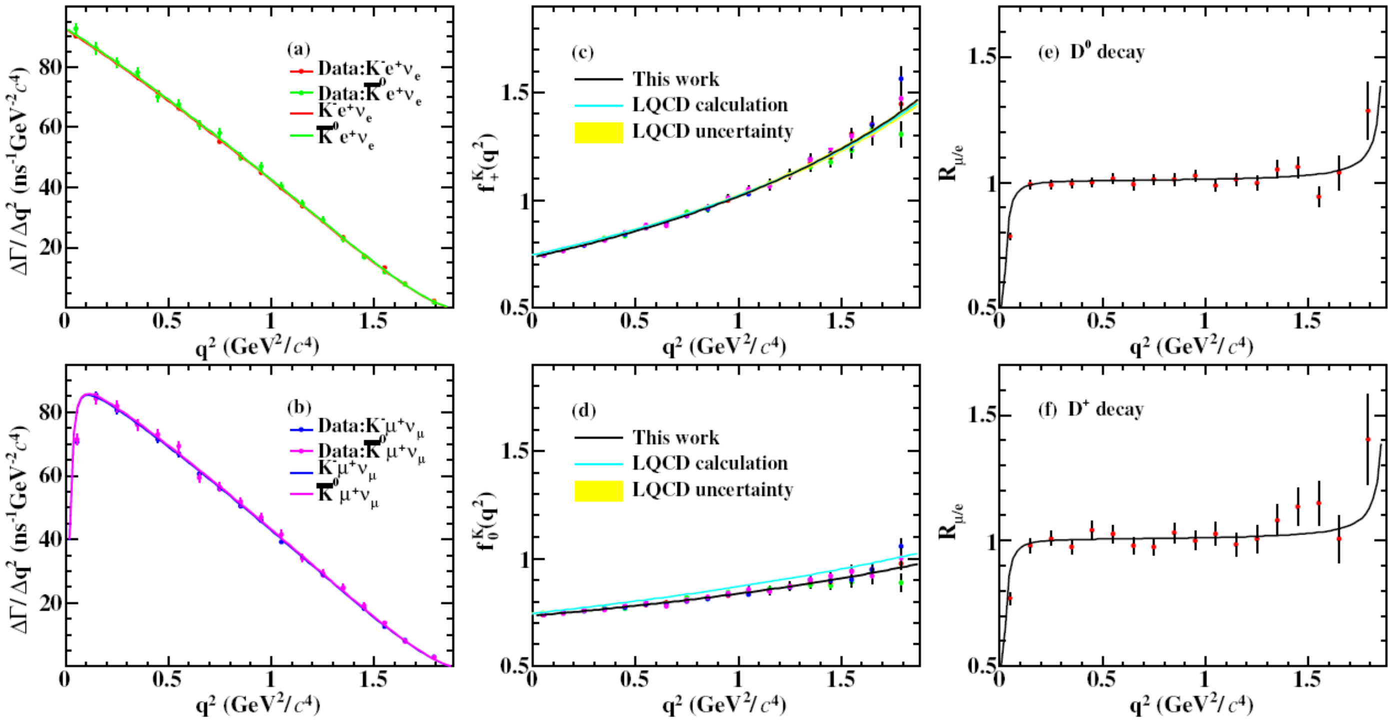
$f_+^{D_s\to\eta}(0)|V_{cs}| = 0.451(10)(08)$

$f_+^{D_s\to\eta'}(0)|V_{cs}| = 0.506(37)(11)$

Recent results of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ ($\ell = e$ or μ)

7.9 fb^{-1} @3.773 GeV **arXiv:2408.09087**



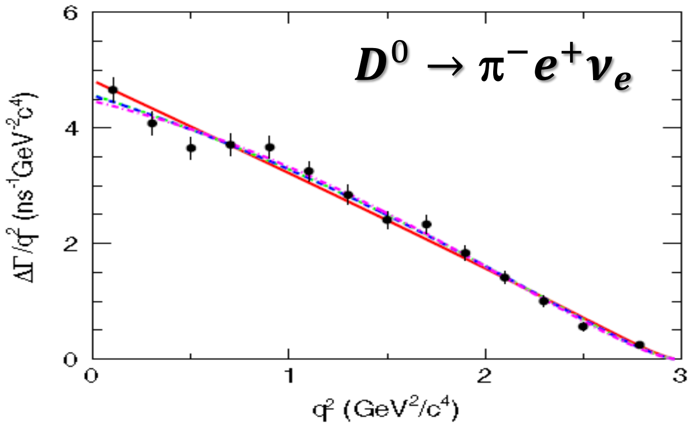


Decay	$N_{\rm DT}$	$\bar{\varepsilon}_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$ (%)
$D^0 \to K^- e^+ \nu_e$	190605 ± 471	68.79 ± 0.03	$3.509 \pm 0.009 \pm 0.013$
$D^0 \to K^- \mu^+ \nu_\mu$	147596 ± 488	54.85 ± 0.03	$3.408 \pm 0.011 \pm 0.013$
$D^+ \to \bar{K}^0 e^+ \nu_e$	57846 ± 256	15.74 ± 0.01	$8.856 \pm 0.039 \pm 0.078$
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	47229 ± 248	13.14 ± 0.01	$8.661 \pm 0.046 \pm 0.080$

Case	Decay	$f_+^K(0)\|V_{cs}\|$	$r_1(t_0)$	$\rho_{2\rm par}$	χ^2/ndf
Individual fit	$D^0 \to K^- e^+ \nu_e$	$0.7168 \pm 0.0016 \pm 0.0014$	$-2.30 \pm 0.05 \pm 0.03$	0.53	16.3/16
	$D^0 \to K^- \mu^+ \nu_\mu$	$0.7150 \pm 0.0022 \pm 0.0016$	$-2.28 \pm 0.08 \pm 0.02$	0.67	17.2/16
	$D^+ \to \bar{K}^0 e^+ \nu_e$	$0.7204 \pm 0.0027 \pm 0.0033$	$-2.13 \pm 0.10 \pm 0.07$	0.30	13.1/16
	$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	$0.7122 \pm 0.0035 \pm 0.0030$	$-2.41 \pm 0.12 \pm 0.08$	0.46	10.4/16
Simultaneous fit	$D \to \bar{K}\ell^+\nu_\ell$	$0.7162 \pm 0.0011 \pm 0.0012$	$-2.28 \pm 0.04 \pm 0.02$	0.48	61.2/70

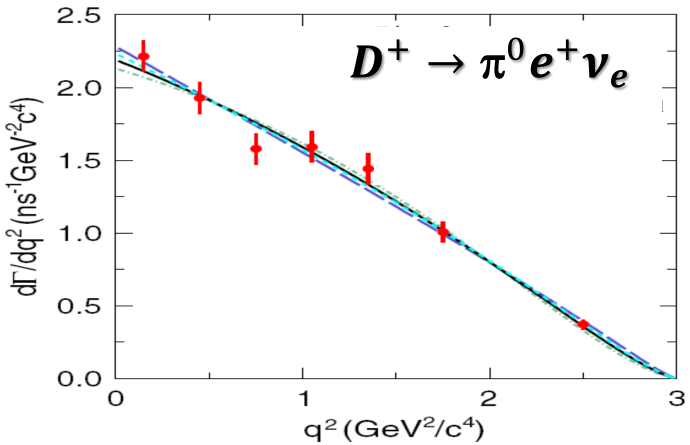
$c \to d l^+ \nu_l$ 型半轻衰变

PRD92(2015)072012



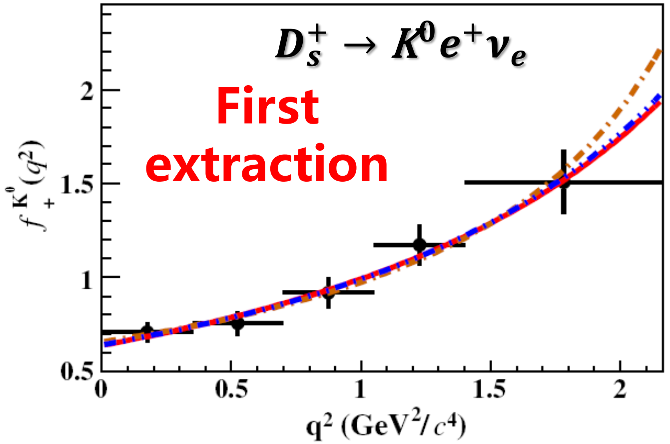
$f_+^{D\to\pi}(0)|V_{cd}| = 0.144(02)(01)$

PRD96(2017)012002



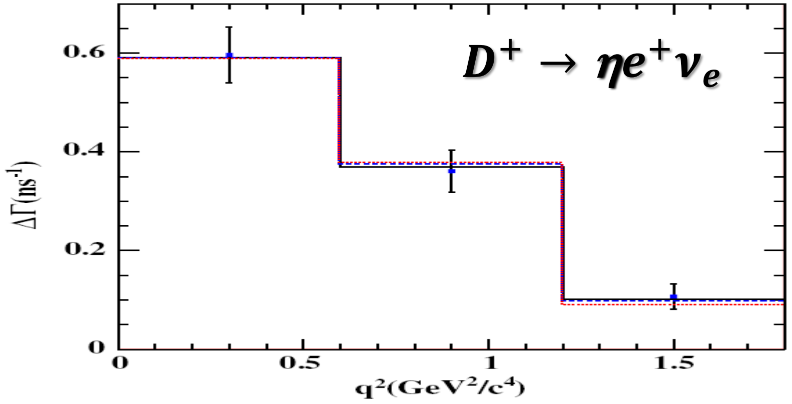
$f_+^{D\to\pi}(0)|V_{cd}| = 0.140(03)(01)$

PRL122(2019)061801
→arXiv:2406.19190



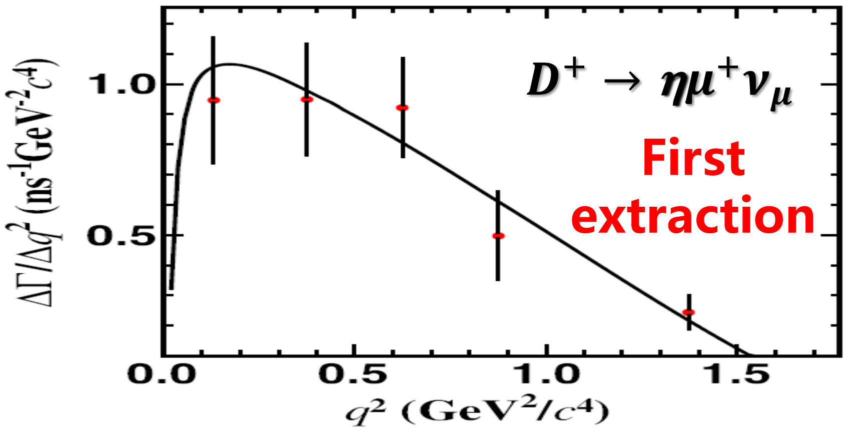
$f_+^{D_s\to K}(0)|V_{cd}| = 0.143(11)(03)$

PRD97(2018)092009



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

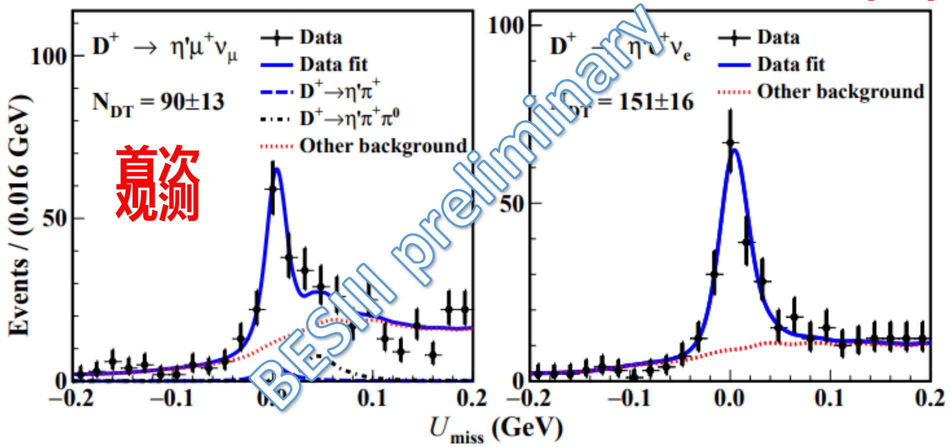
PRL124(2020)231801



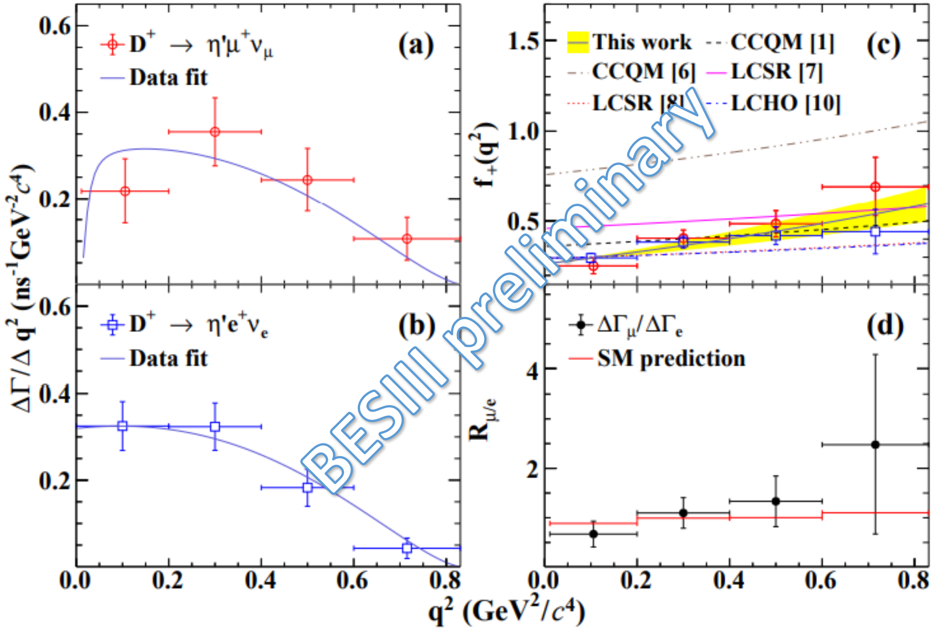
$f_+^{D\to\eta}(0)|V_{cd}| = 0.087(08)(02)$

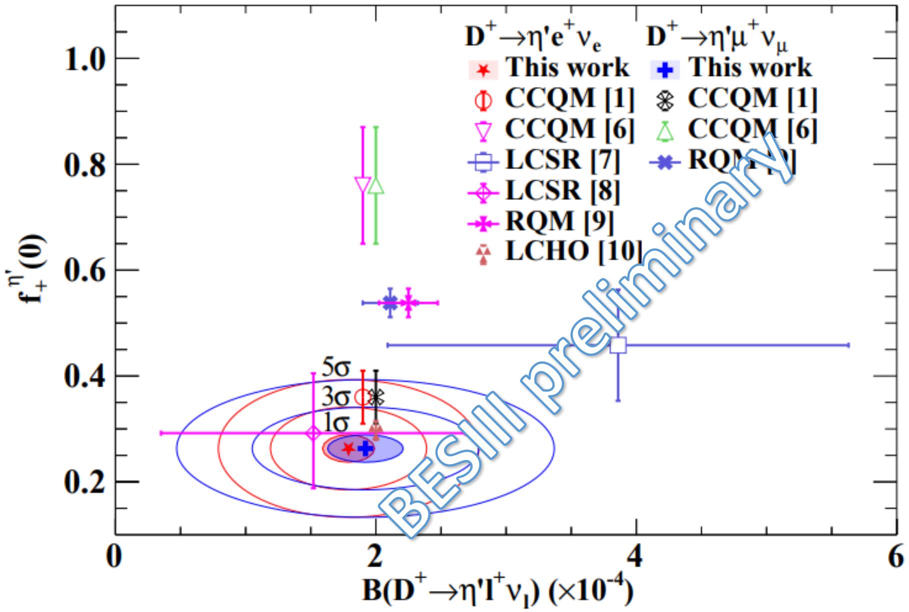
Recent results of $D^+ \to \eta'\ell^+\nu_\ell$ ($\ell = e$ or μ)

20.3 fb^{-1} @3.773 GeV，最新结果, submitted to arXiv, no No. yet



Decay	$\eta'\mu^+\nu_\mu$		$\eta' e^+\nu_e$	
η' decay	$\eta\pi^+\pi^-$	$\gamma\pi^+\pi^-$	$\eta\pi^+\pi^-$	$\gamma\pi^+\pi^-$
$\epsilon_{\rm sig}$ (%)	1.77±0.01	2.77±0.01	2.70±0.01	5.50±0.01
$N_{\rm DT}$	90±13		151±16	
Significance	8.6σ		12.9σ	
$\mathcal{B}$ ($\times 10^{-4}$)	$1.92 \pm 0.28 \pm 0.08$		$1.79 \pm 0.19 \pm 0.07$	

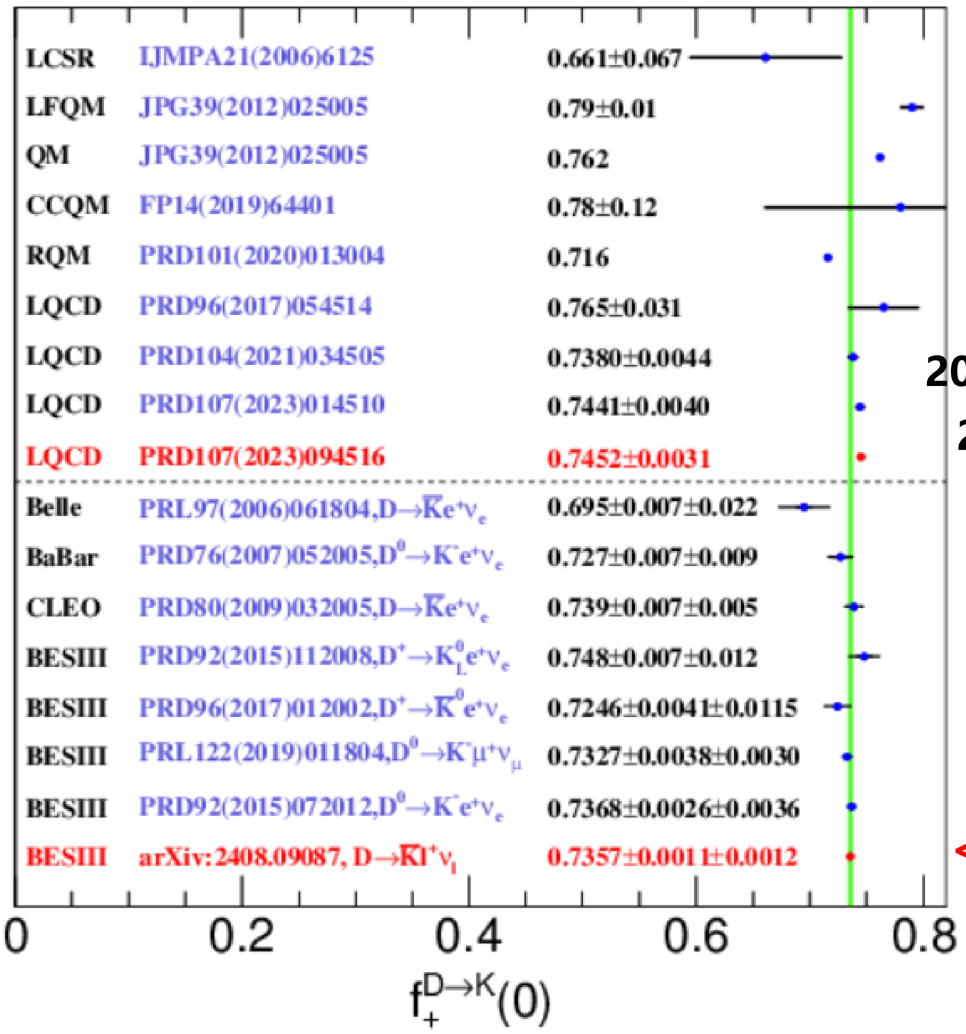




$f_+^{D\to\eta'}(0)|V_{cd}| = (5.92 \pm 0.56 \pm 0.13)\%$

首次抽取$D^+ \to \eta'$形状因子，为检验理论计算提供了重要依据

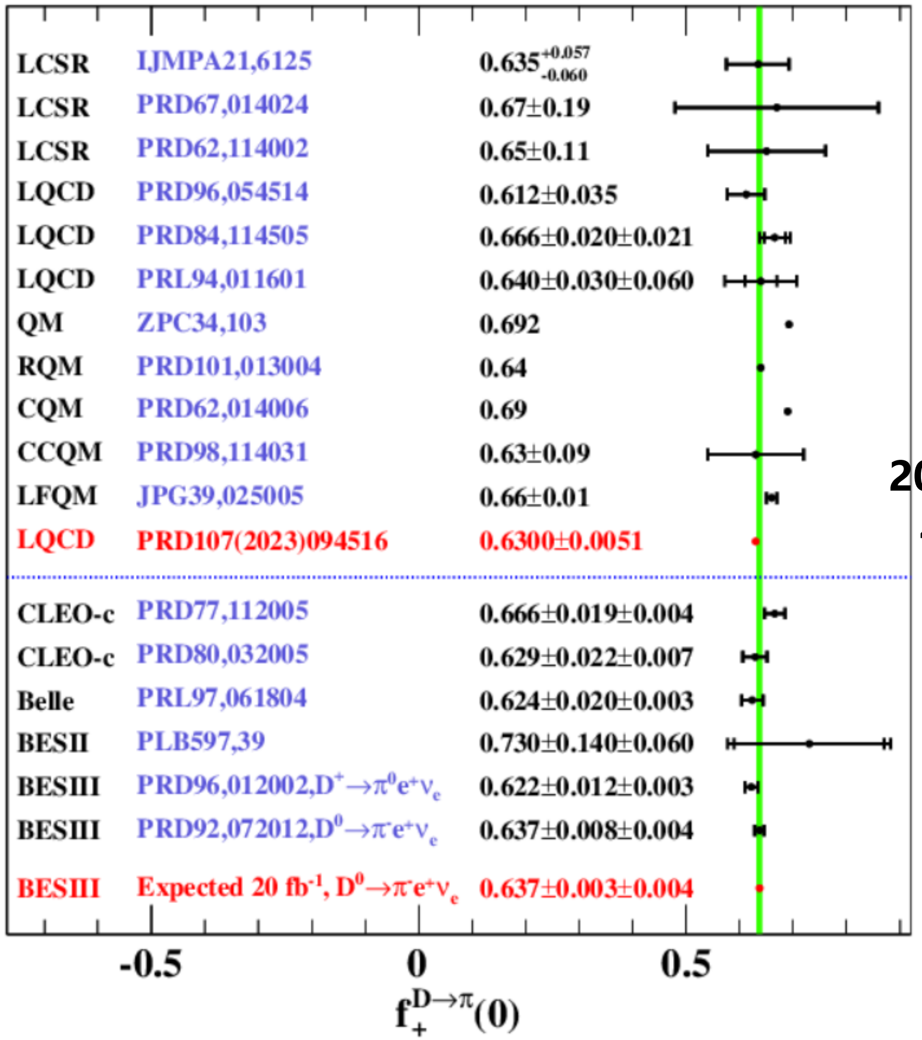
Comparisons of $f_+^{D\to K}(0)$ and $f_+^{D\to\pi}(0)$



2010→2023

2.4→0.4%

<0.3%



2011→2023

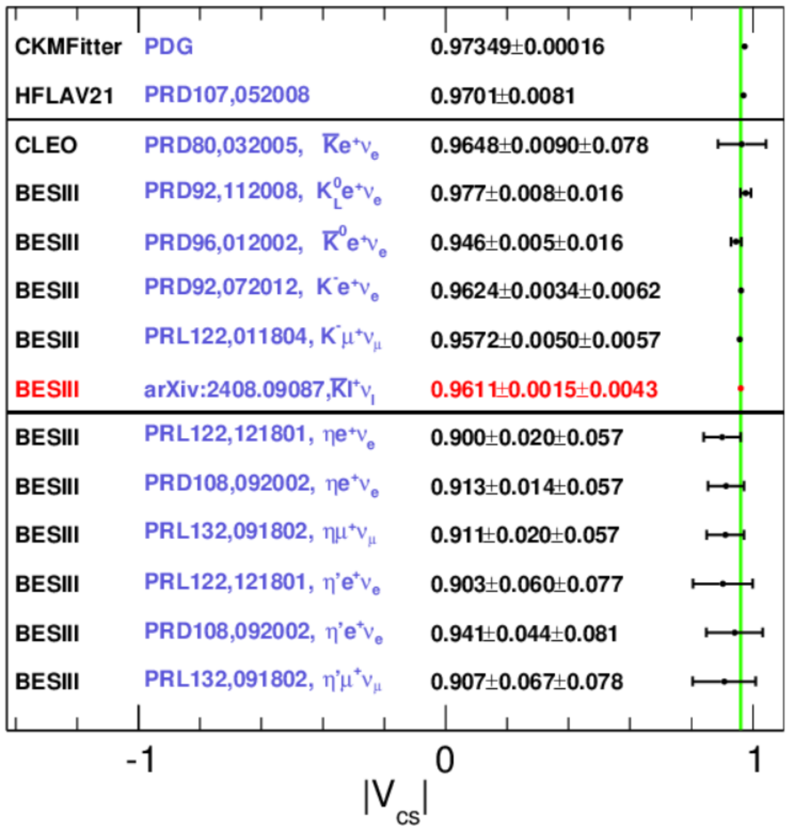
4.4→0.8%

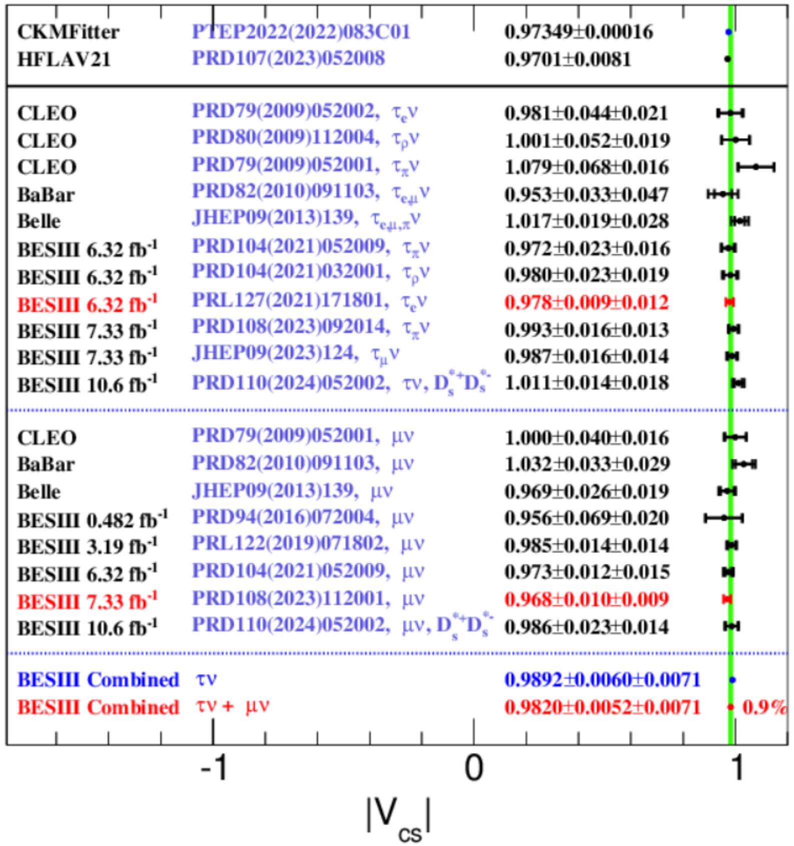
1.6%

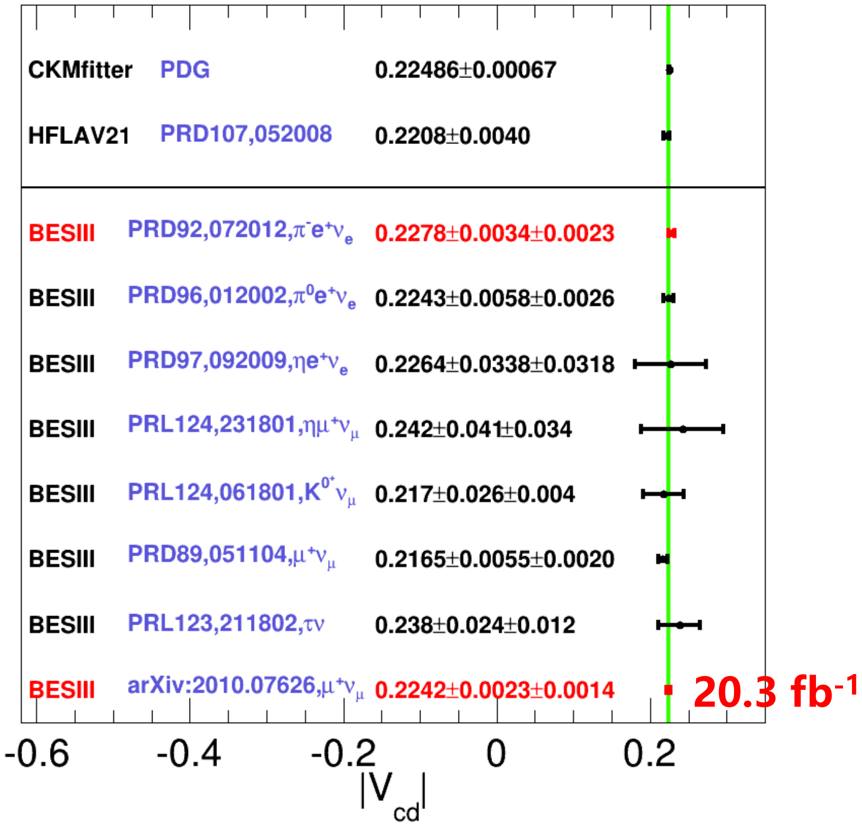
Experimental precision of $f_+^{D\to K}(0)$ is comparable to the latest LQCD precision

Experimental precision of $f_+^{D\to\pi}(0)$ is still dominated by statistical uncertainties

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



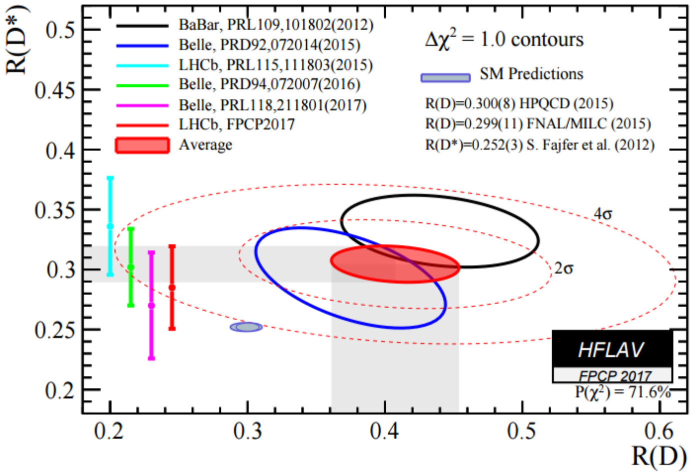




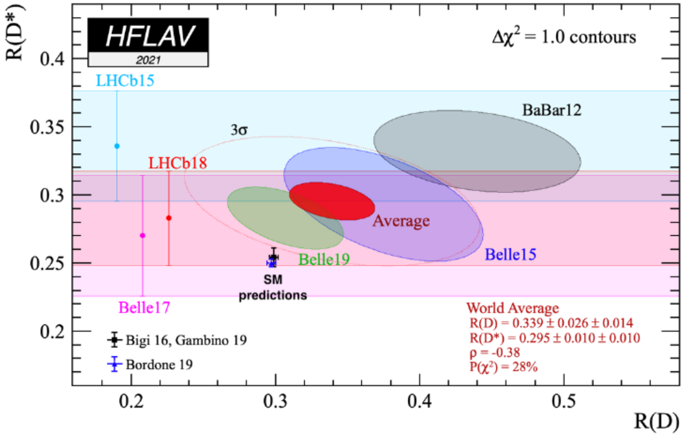
LFU tests in (semi)leptonic D decays before BESIII

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

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

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

(2.1σ)

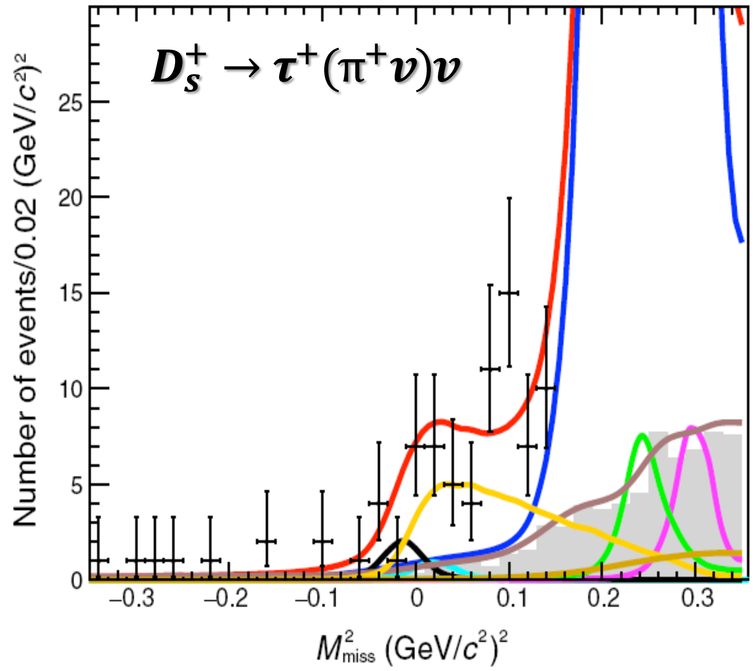
SM prediction: 0.985

The knowledge of semimuonoic charm meson decays is very poor

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

Tests of LFU in leptonic charm decays

PRL123(2019)211802



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

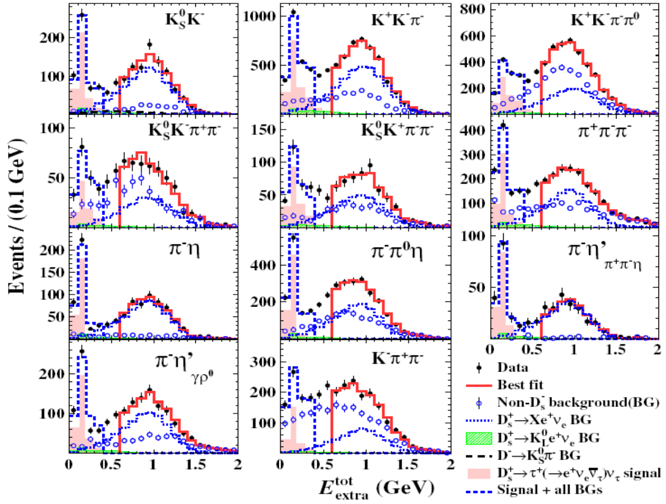
$$\mathrm{B}^{\mathrm{PDG}}[D^+ \to \mu^+ v] = (3.74 \pm 0.17) \times 10^{-4}$$

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

SM prediction: 2.67

PRD108(2023)112001 $D_s^+ \to \mu^+ v$

PRL127(2021)171801, $D_s^+ \to \tau^+(e^+ v v)v$,
PRD108(2023)092014, $D_s^+ \to \tau^+(\pi^+ v)v$,
PRD104(2021)032001, $D_s^+ \to \tau^+(\rho^+ v)v$,
JHEP09(2023)124 $D_s^+ \to \tau^+(\mu^+ v v)v$



$$\mathrm{B}^{\mathrm{BESIII}}[D_s^+ \to \mu^+ v] = (5.294 \pm 0.108 \pm 0.085) \times 10^{-3}$$

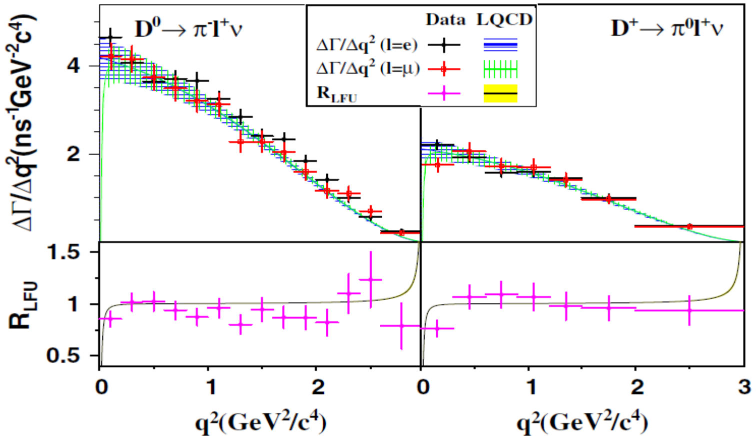
$$\mathrm{B}^{\mathrm{BESIII}}[D_s^+ \to \tau^+ v] = (5.32 \pm 0.07 \pm 0.07)\%$$

$$\mathrm{R}_{Ds} = \frac{\mathrm{B}[D_s^+ \to \tau^+ v]}{\mathrm{B}[D_s^+ \to \mu^+ v]} = 10.05 \pm 0.35$$

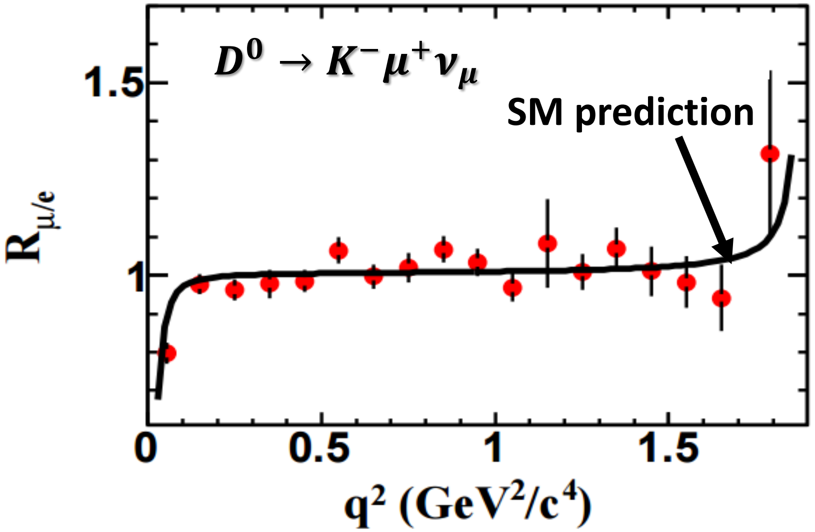
SM prediction: 9.75

Tests of LFU in semileptonic charm decays

PRL121(2018)171803



PRL122(2019)011804



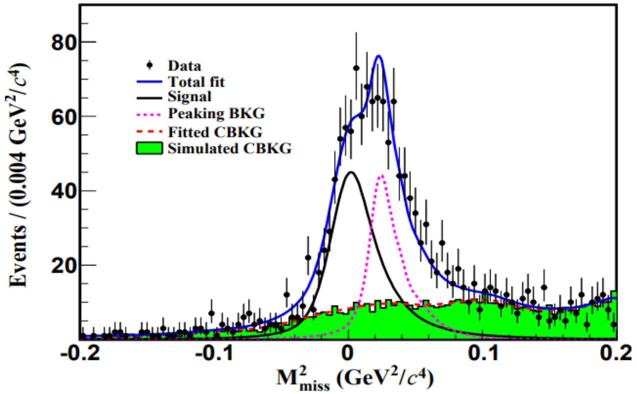
SM predictions: 0.93-0.99

$D^+ \to \eta\mu^+\nu$ **PRL124(2020)231801**

$D^+ \to \omega\mu^+\nu$ **PRD101(2020)072005**

$D^0 \to \rho^-\mu^+\nu$ **PRD104(2021)L091103**

$D^+ \to \rho^0\mu^+\nu$ **arXiv:2401.13225**



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

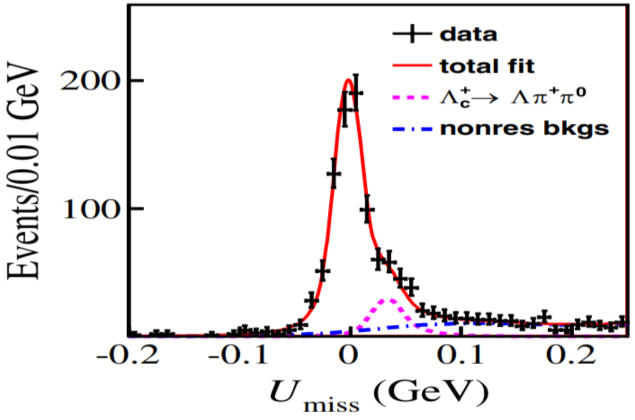
$$R_{D^+\omega} = \frac{\Gamma[D^+ \to \omega\mu^+\nu]}{\Gamma[D^+ \to \omega e^+\nu]} = 1.05 \pm 0.14$$

$$R_{D^0\rho} = \frac{\Gamma[D^0 \to \rho^-\mu^+\nu]}{\Gamma[D^0 \to \rho^- e^+\nu]} = 0.90 \pm 0.11$$

$$R_{D^+\rho} = \frac{\Gamma[D^+ \to \rho^0\mu^+\nu]}{\Gamma[D^+ \to \rho^0 e^+\nu]} = 0.88 \pm 0.10$$

$\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$

PLB767(2017)42→
PRD108(2023)L031105



$$R_{\Lambda_c^+\Lambda} = \frac{\Gamma[\Lambda_c^+ \to \Lambda\mu^+\nu]}{\Gamma[\Lambda_c^+ \to \Lambda e^+\nu]} = 0.98 \pm 0.06$$

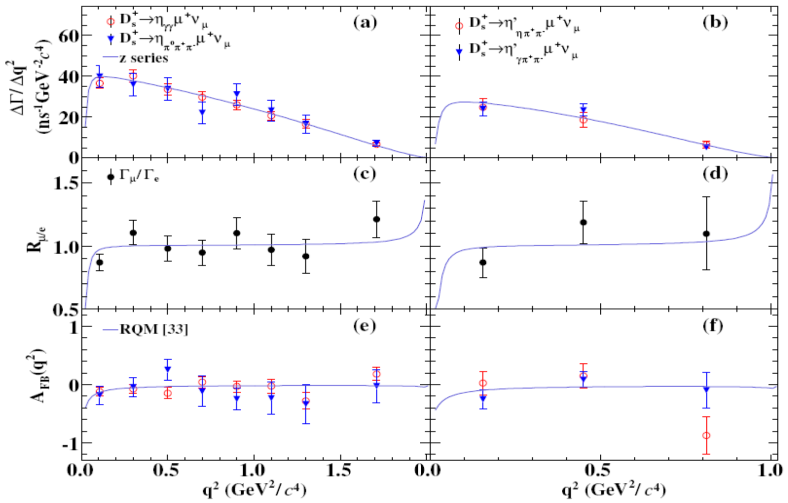
$D^0 \to K^{*-}\mu^+\nu$ **arXiv:2401.12927**

$$R_{D^0K^{*-}} = \frac{\Gamma[D^0 \to K^{*-}\mu^+\nu]}{\Gamma[D^0 \to K^{*-}e^+\nu]} = 0.96 \pm 0.08$$

Summary of LFU tests at BESIII

PRD97(2018)012006 →

$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$ PRL132(2024)091802



$$R_{D_s^+\eta} = \frac{\Gamma[D_s^+ \to \eta\mu^+ v]}{\Gamma[D_s^+ \to \eta e^+ v]} = 0.984 \pm 0.032$$

$$R_{D_s^+\eta'} = \frac{\Gamma[D_s^+ \to \eta'\mu^+ v]}{\Gamma[D_s^+ \to \eta' e^+ v]} = 0.989 \pm 0.089$$

$D_s^+ \to \phi\mu^+\nu_\mu$ JHEP12(2023)072

$$R_{D_s^+\phi} = \frac{\Gamma[D_s^+ \to \phi\mu^+ v]}{\Gamma[D_s^+ \to \phi e^+ v]} = 0.94 \pm 0.08$$

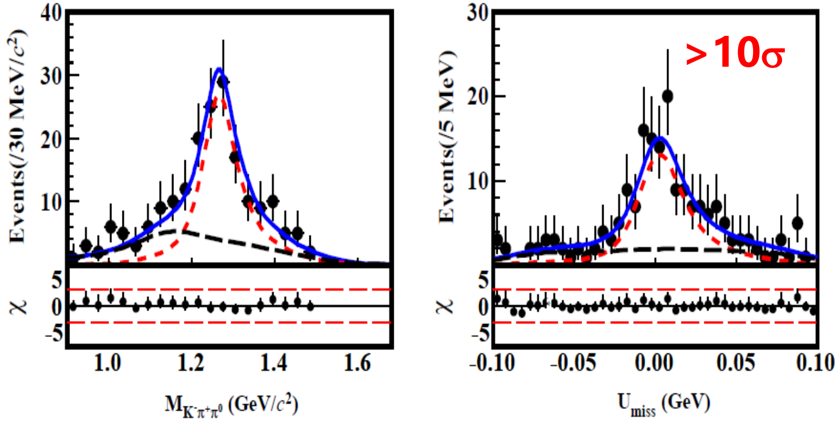
No deviation greater than 1.7σ is found!

Eleven decays are observed for the first time, all other decays are measured with better precision

	BF ratios		References
μ/e	$D^0 \to K^-$	$0.971 \pm 0.004 \pm 0.005$	arXiv:2408.090987
	$D^0 \to \pi^-$	$0.922 \pm 0.030 \pm 0.022$	PRL121(2018)171803
	$D^0 \to \rho^-$	0.90 ± 0.11	PRD104(2021)L091003
	$D^+ \to \bar{K}^0$	$0.978 \pm 0.007 \pm 0.012$	arXiv:2408.090987
	$D^+ \to \pi^0$	$0.964 \pm 0.037 \pm 0.026$	PRL121(2018)171803
	$D^+ \to \eta$	0.91 ± 0.13	PRL124(2020)231801
	$D^+ \to \eta'$	$1.07 \pm 0.19 \pm 0.03$	Submitted, no arXiv No.
	$D^0 \to K^{*-}$	0.96 ± 0.08	arXiv:2403.12927
	$D^+ \to \omega$	1.05 ± 0.14	PRD101(2020)072005
	$D^+ \to f_0$	1.14 ± 0.28	arXiv:2401.13225
	$D^+ \to \rho^0$	0.88 ± 0.10	arXiv:2401.13225
	$D_s^+ \to \eta$	$0.984 \pm 0.028 \pm 0.016$	PRL132(2024)091802
	$D_s^+ \to \eta'$	$0.989 \pm 0.082 \pm 0.034$	
	$D_s^+ \to \phi$	0.94 ± 0.08	JHEP12(2023)072
	$\Lambda_c^+ \to \Lambda$	$0.98 \pm 0.05 \pm 0.03$	PRD108(2023)L031105
τ/μ	$D^+ \to \tau^+\nu$	3.02 ± 0.68	BESIII arXiv
	$D_s^+ \to \tau^+\nu$	10.05 ± 0.35	PRL127(2021)171801

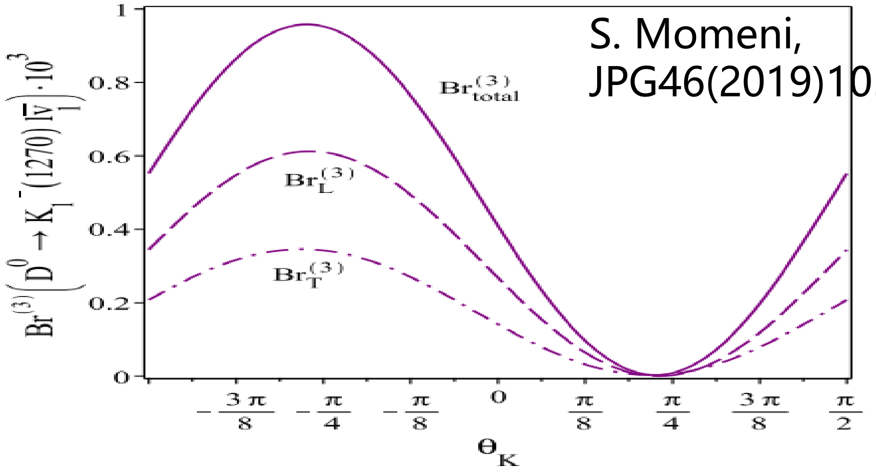
$D \to Ae^+\nu_e$半轻衰变的研究

$D^+ \to \bar{K}_1^0(1270)e^+\nu_e$ PRL123(2019)231801



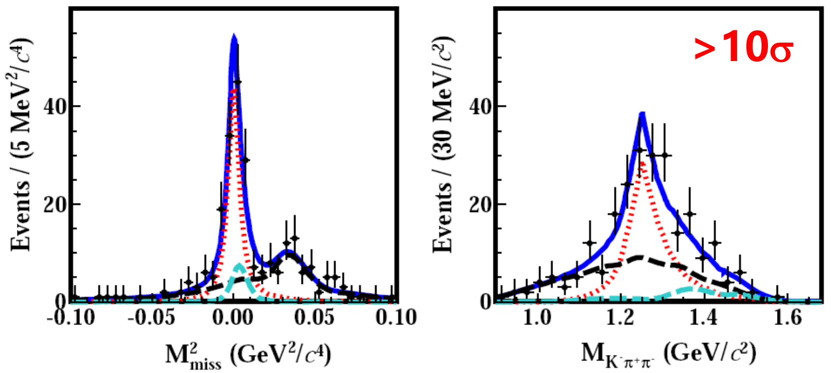
$$B_{D^+\to\bar{K}_1^0(1270)e^+\nu_e} = (2.30\pm0.26\pm0.18\pm0.25)\times10^{-3}$$

Helps to test various theoretical calculations which are sensitive to K_1 mixing angle



S. Momeni, JPG46(2019)105006

$D^0 \to K_1(1270)^-e^+\nu_e$ PRL127(2021)131801



$$B_{D^0\to K_1(1270)^-e^+\nu_e} = (1.09\pm0.13\pm0.13\pm0.12)\times10^{-3}$$

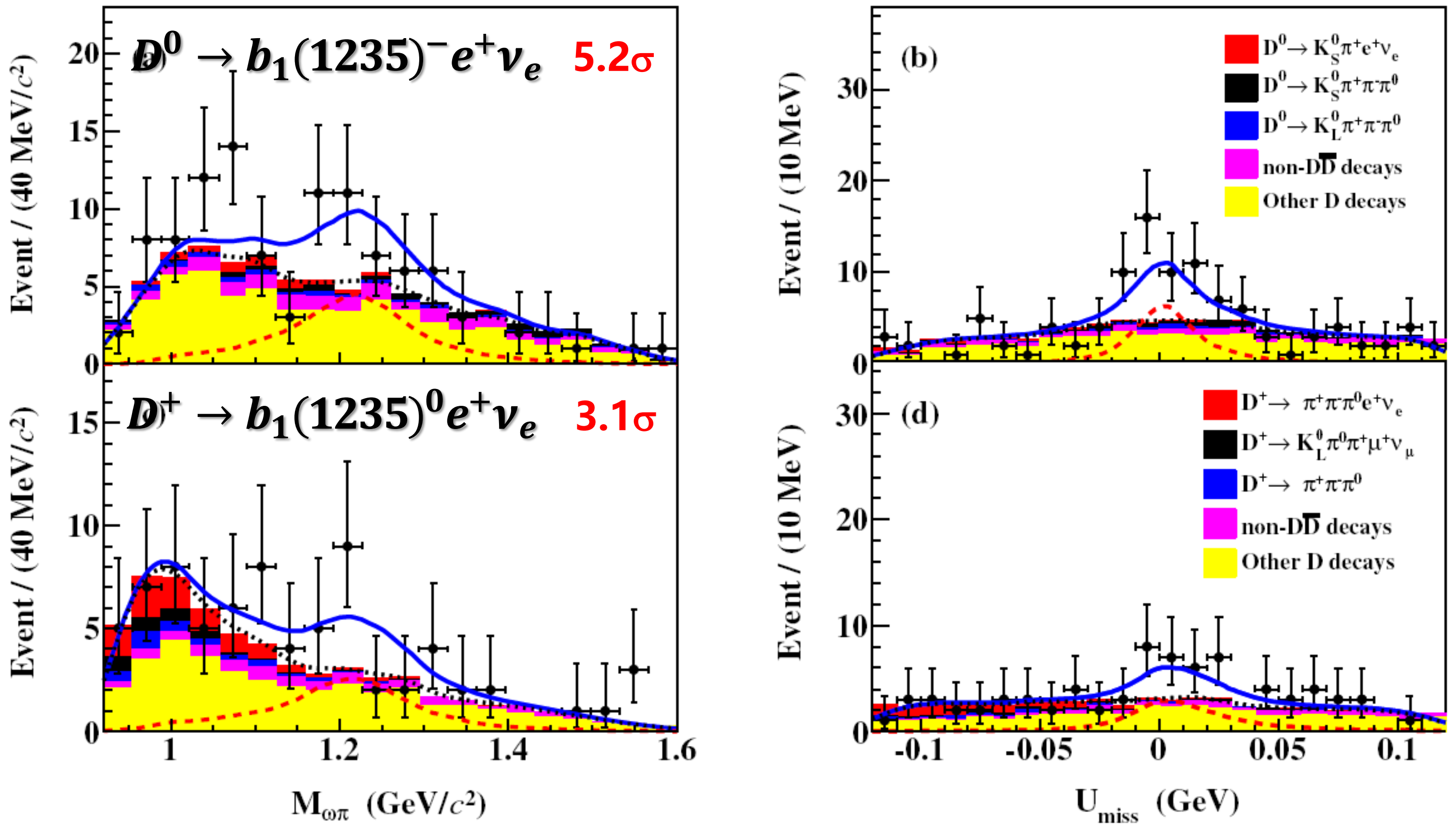
New window to explore the property and nature of K_1 and K_1 mixing angle

Combined analysis of $D \to \bar{K}_1 e^+\nu$ and $B \to \gamma\bar{K}_1$ helps to constrain new physics effect in the studies of photon polarization in $b \to s\gamma$ process

Wei Wang et al. PRL125(2020)051802

Observation of $D \to Ae^+\nu_e$

arXiv:2407.20551



$$\mathcal{B}(D^0 \to b_1(1235)^- e^+\nu_e) \times \mathcal{B}(b_1(1235)^- \to \omega\pi^-) = (0.72 \pm 0.18^{+0.06}_{-0.08}) \times 10^{-4}$$

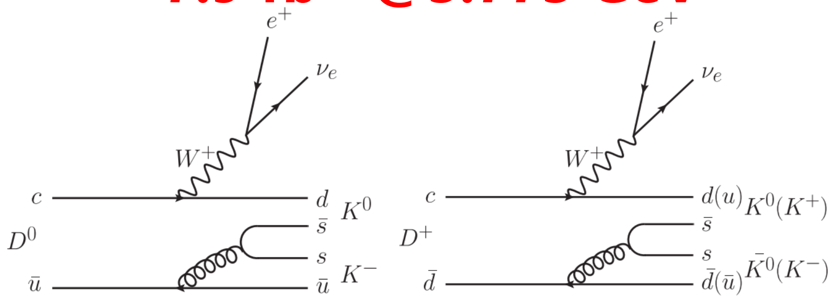
$$\mathcal{B}(D^+ \to b_1(1235)^0 e^+\nu_e) \times \mathcal{B}(b_1(1235)^0 \to \omega\pi^0) = (1.16 \pm 0.44 \pm 0.16) \times 10^{-4}$$

支持ωπ是b_1主导衰变模式

$$\frac{\Gamma(D^0 \to b_1^- e^+\nu_e)}{2\Gamma(D^+ \to b_1^0 e^+\nu_e)} = 0.78 \pm 0.19^{+0.04}_{-0.05}$$

$D \to KKe^+\nu_e$半轻衰变的寻找

7.9 fb^{-1} @3.773 GeV

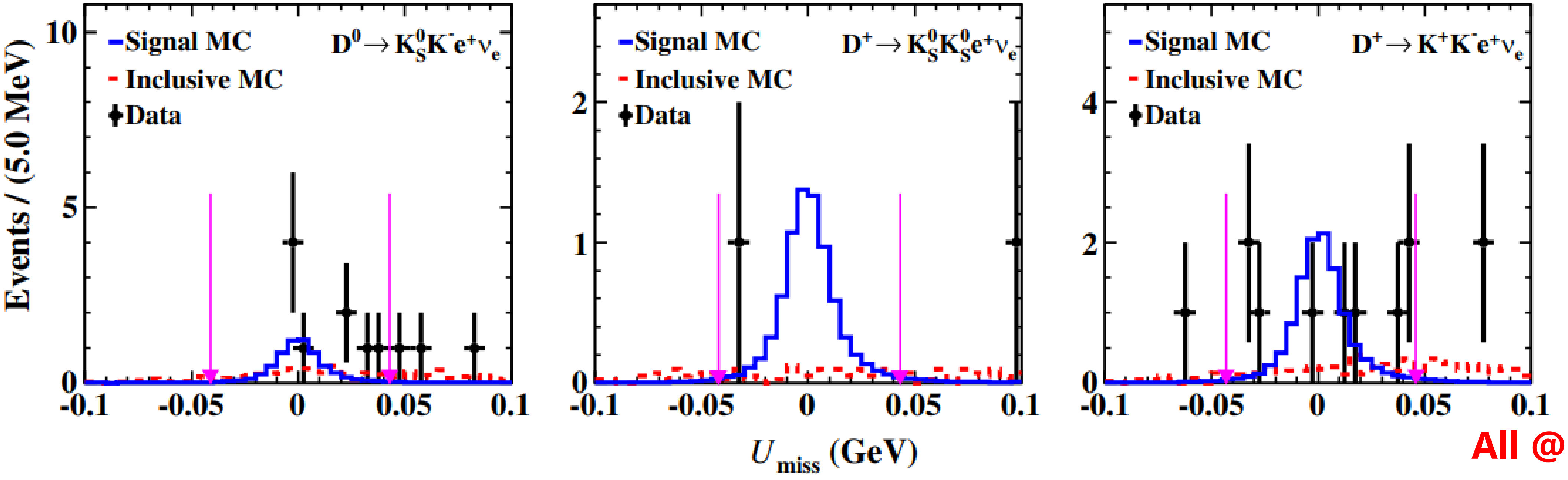


(a) (b)

PRL121(2018)081802

BFs	$a_0(980)[\to \pi\eta]e^+\nu_e$ [7] ($\times 10^{-4}$)	$a_0(980)[\to K^0_S K^-]e^+\nu_e$ ($\times 10^{-5}$)	$a_0(980)[\to K^0_S K^0_S]e^+\nu_e$ ($\times 10^{-5}$)	$a_0(980)[\to K^+ K^-]e^+\nu_e$ ($\times 10^{-5}$)
D^0	$1.33^{+0.33}_{-0.29} \pm 0.09$	$1.14^{+0.28}_{-0.24} \pm 0.07$	...	...
D^+	$1.66^{+0.81}_{-0.66} \pm 0.11$	...	$0.71^{+0.34}_{-0.28} \pm 0.05$	$2.86^{+1.39}_{-1.13} \pm 0.19$

PRD109(2024)070032



All @90% CL

$B_{D^0 \to K^0_s K^- e^+ \nu_e} < 2.13 \times 10^{-4}$ $B_{D^+ \to K^0_s K^0_s e^+ \nu_e} < 1.53 \times 10^{-4}$ $B_{D^+ \to K^+ K^- e^+ \nu_e} < 2.10 \times 10^{-4}$

$D \to K\eta e^+\nu_e$和$D \to \eta\eta e^+\nu_e$的寻找

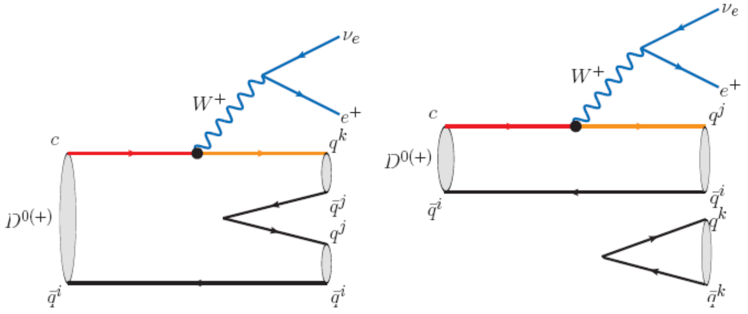
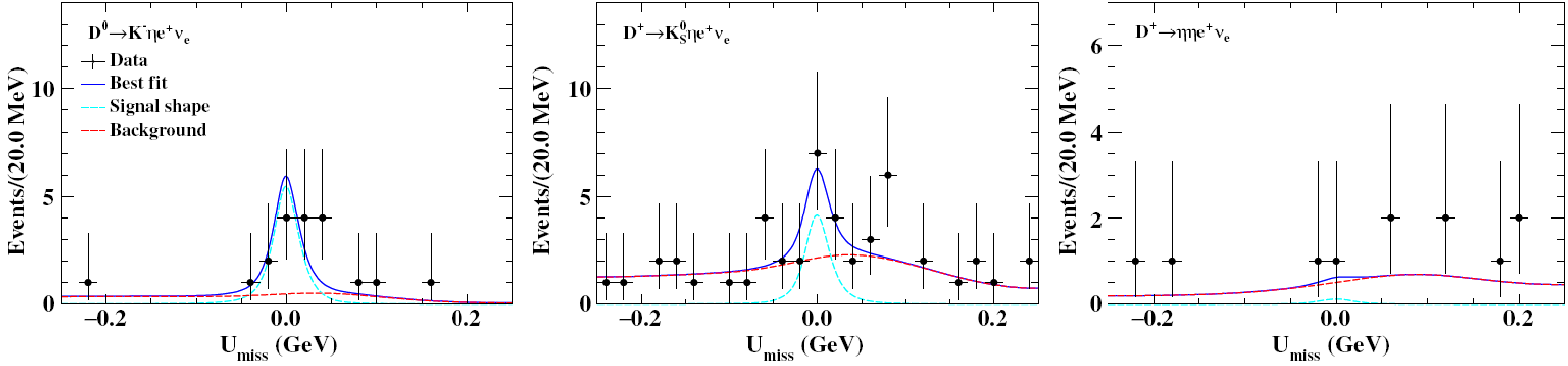


Table 1. The branching fractions of $D^0 \to K^-\eta e^+\nu_e$, $D^+ \to \bar{K}^0\eta e^+\nu_e$ and $D^+ \to \eta\eta e^+\nu_e$ predicted using SU(3) flavor symmetry [5].

Decay	$D^0 \to K^-\eta e^+\nu_e$	$D^+ \to \bar{K}^0\eta e^+\nu_e$	$D^+ \to \eta\eta e^+\nu_e$
Value ($\times 10^{-6}$)	3.51 ± 3.51	8.9 ± 8.9	3.16 ± 2.26

7.9 fb^{-1} @3.773 GeV

arXiv:2409.15044



Decay	N^{fit}_{sig}	Significance (σ)	N^{up}_{sig}	$\bar{\varepsilon}_{SL}$ (%)	$\mathcal{B}$ ($\times 10^{-4}$)	$\mathcal{B}^{up}$ ($\times 10^{-4}$)
$D^0 \to K^-\eta e^+\nu_e$	$11.1^{+4.5}_{-3.8}$	3.3	...	5.29 ± 0.05	$0.84^{+0.34}_{-0.29} \pm 0.22$	...
$D^+ \to K^0_S\eta e^+\nu_e$	$8.4^{+4.7}_{-3.9}$	1.9	17.8	7.79 ± 0.05	...	< 2.0
$D^+ \to \eta\eta e^+\nu_e$	$0.3^{+1.9}_{-1.2}$	0.0	4.8	7.52 ± 0.05	...	< 1.0

All @90% CL

总结

- 基于前期数据，BESIII粲介子含轻衰变的研究取得了一系列重要成果。

- BESIII上粲介子衰变常数、形状因子、$|V_{cs}|$和$|V_{cd}|$测量精度达到(0.3-1)%。

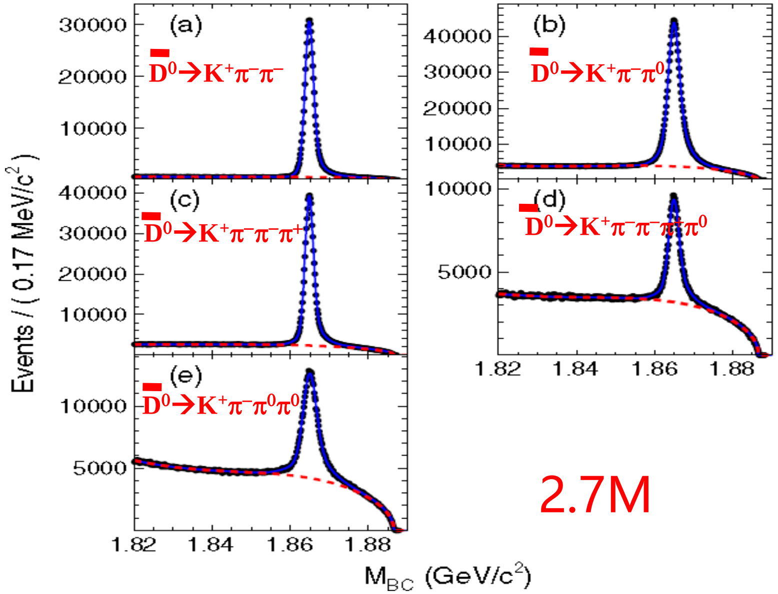
- 基于最新的、20.3 fb^{-1}@3.773 GeV数据，第一批粲介子$D^{0(+)}$重要的物理成果已于本周发布，更多结果将随后陆续推出。

谢谢!

Backup slides

Single-tag charmed hadrons at BESIII

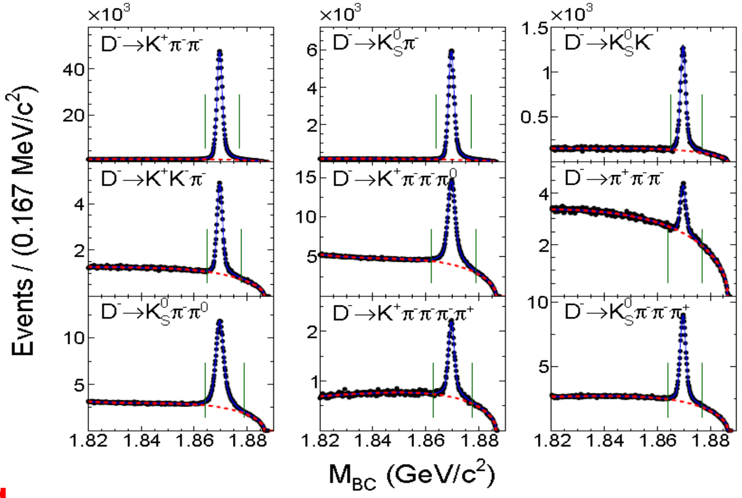
$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$



2.93→20.3 fb^{-1}
@3.773 GeV

2.7M

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

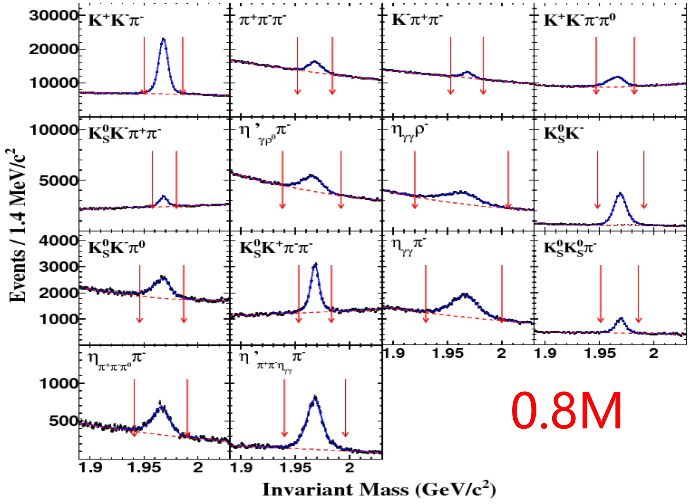


2.93→20.3 fb^{-1}
@3.773 GeV

1.7M

The single-tag yields of $\bar{D}^0$, D^-, and D_s^- are 3.6, 3.6, and 9 times CLEO-c, respectively

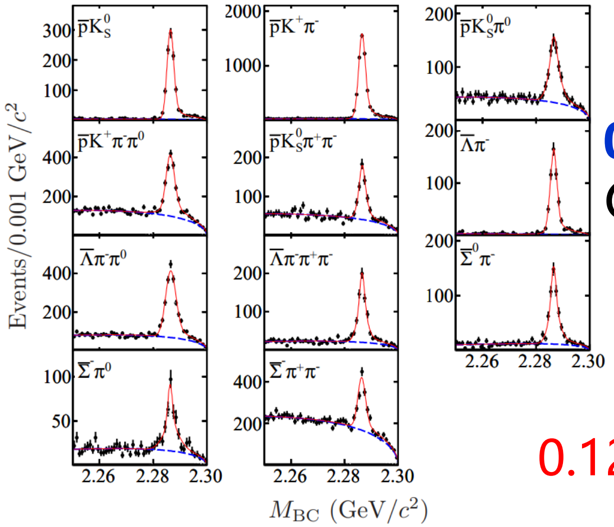
$e^+e^- \to \psi(4160) \to D_s^+D_s^{*-} + c.c.$



7.33 fb^{-1}
@4.13-4.23 GeV

0.8M

$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^- + c.c.$

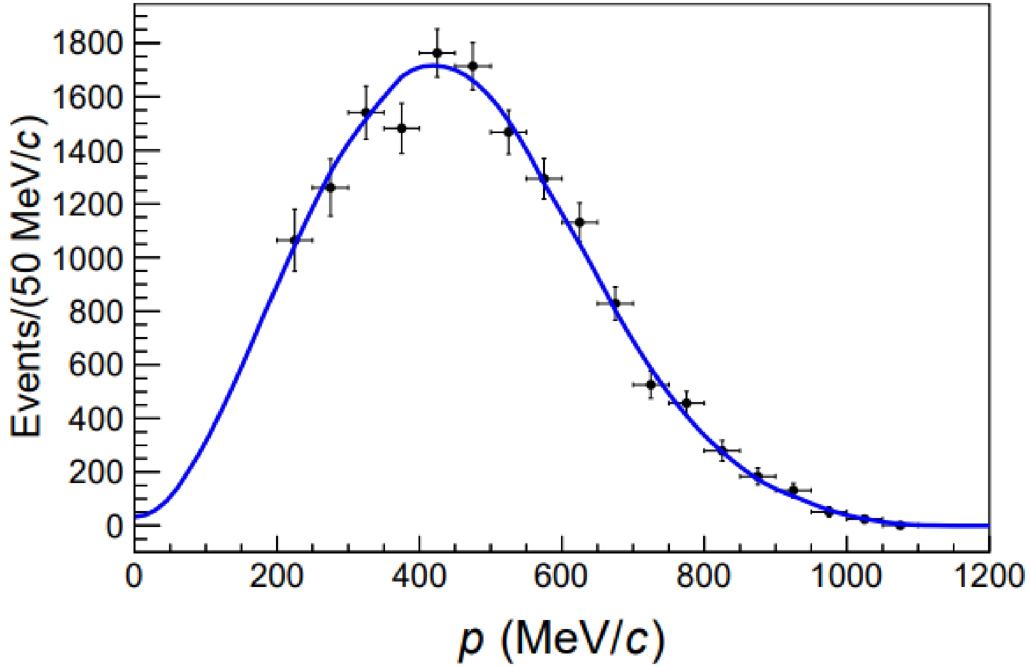


0.57→4.5 fb^{-1}
@4.6-4.7 GeV

0.12M

粲介子单举半轻衰变$D_s^+ \to \nu_e e X$

PRD104(2021)012003



$$B_{D_s^+ \to \nu_e e X} = (6.30 \pm 0.13 \pm 0.10)\%$$

与此前最好精度的CLEO结果比，统计误差改进3倍，系统误差改进1.5倍

$$\Gamma_{D_s^+ \to \nu_e e X} / \Gamma_{D^0 \to \nu_e e X} = 0.790 \pm 0.016 \pm 0.020$$

与理论预期0.813 [J. L. Rosner PRD83(2011)034025]一致

已知遍举电子半轻衰变道的分支比[PDG2020]

$D_s^+ \to \phi e^+ \nu_e$	$(2.37 \pm 0.11)\%$
$D_s^+ \to \eta e^+ \nu_e$	$(2.32 \pm 0.08)\%$
$D_s^+ \to \eta' e^+ \nu_e$	$(0.80 \pm 0.07)\%$
$D_s^+ \to K^0 e^+ \nu_e$	$(0.34 \pm 0.04)\%$
$D_s^+ \to K^*(892)^0 e^+ \nu_e$	$(0.21 \pm 0.03)\%$
$D_s^+ \to f_0(980) e^+ \nu_e, f_0(980) \to \pi\pi$	$(0.30 \pm 0.05)\%$
Sum of semielectronic modes	$(6.34 \pm 0.17)\%$
$\mathcal{B}(D_s^+ \to X e^+ \nu_e)$	$(6.52 \pm 0.42)\%$
$D_s^+ \to \tau^+ \nu_\tau \to e^+ \bar{\nu}_\tau \nu_e \nu_\tau$	$(0.96 \pm 0.04)\%$

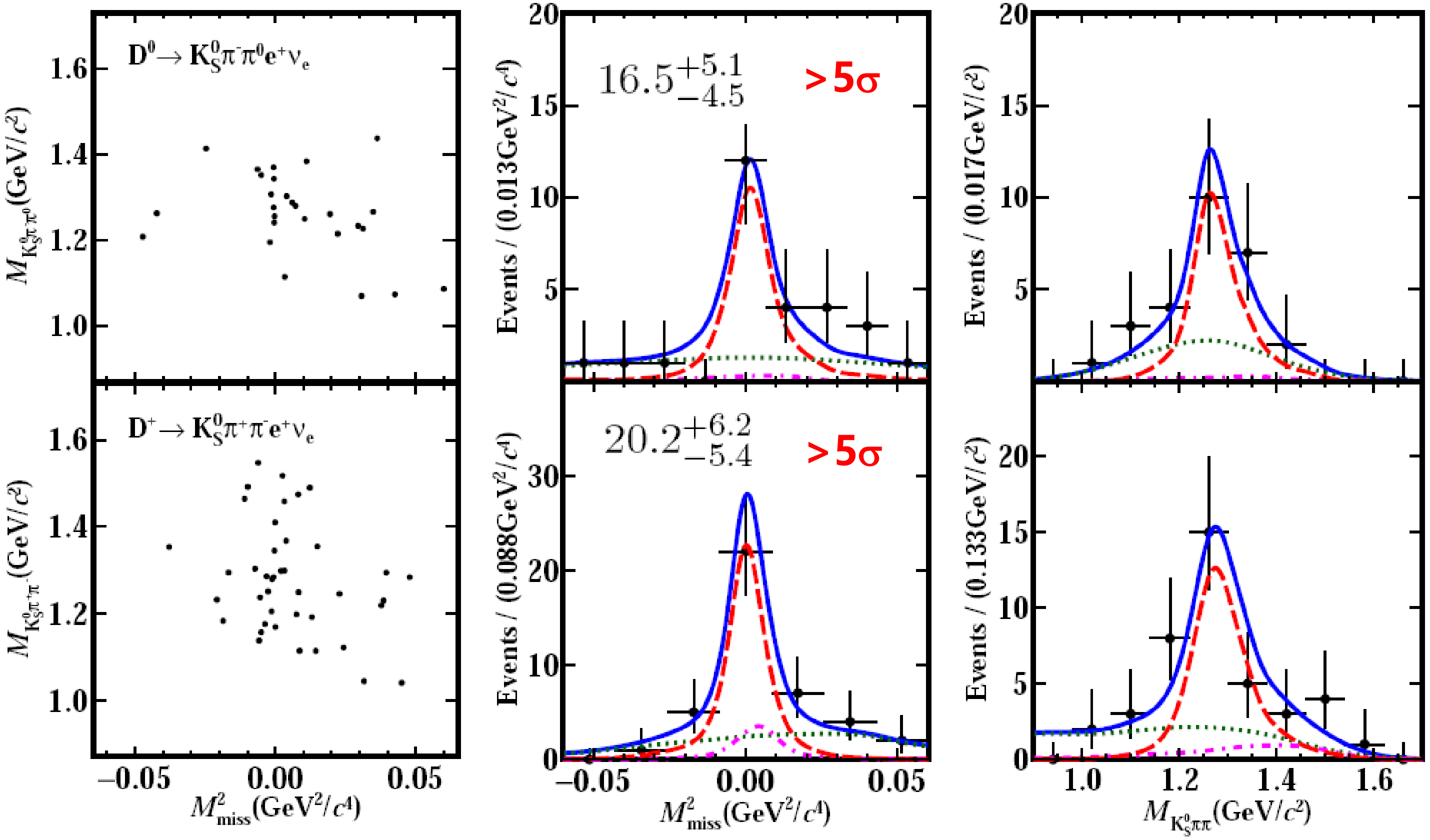
单举和遍举电子半轻衰变分支比之差:

$$\triangle B = (-0.04 \pm 0.23)\%$$

表明没有更多D_s^+遍举电子半轻衰变

$D \to Ae^+\nu_e$半轻衰变的研究

arXiv:2403.19091

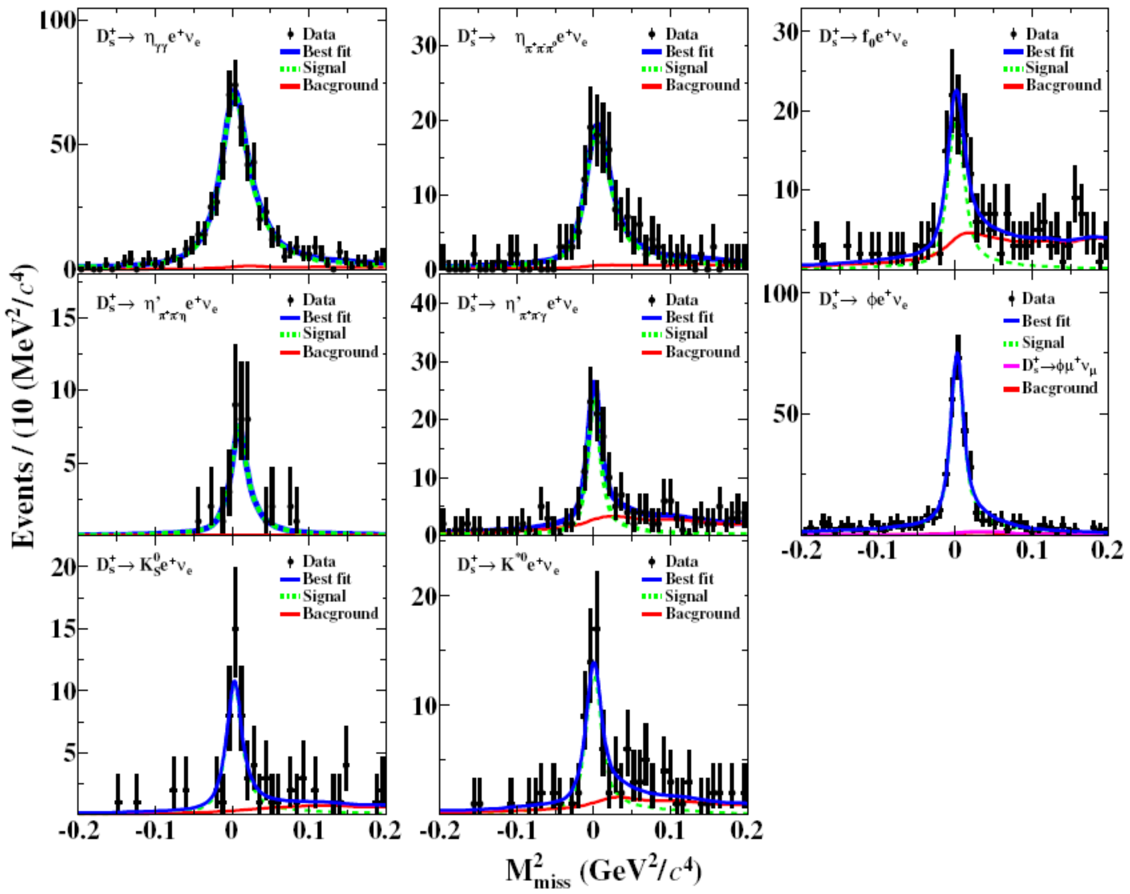


Decay mode	$\mathcal{B}_{\rm sig}$ $(\times 10^{-4})$	$\mathcal{B}_{\rm com}$ $(\times 10^{-4})$
$D^0 \to K_S^0\pi^-\pi^0 e^+\nu_e$	$(1.69^{+0.53}_{-0.46} \pm 0.18)$	/
$D^+ \to K_S^0\pi^+\pi^- e^+\nu_e$	$(1.47^{+0.45}_{-0.40} \pm 0.20)$	/
$D^0 \to K_1(1270)^- e^+\nu_e$	$(10.5^{+3.3}_{-2.8} \pm 1.2 \pm 1.2)$	$(10.8^{+1.3+0.8}_{-1.2-1.1} \pm 1.2)$
$D^+ \to \bar{K}_1(1270)^0 e^+\nu_e$	$(12.9^{+4.0}_{-3.5} \pm 1.8 \pm 1.5)$	$(18.6^{+2.3}_{-2.2} \pm 1.3 \pm 2.1)$

基于$e^+e^- \to D_s^{*+}D_s^{*-}$的$D_s^+$半轻衰变的研究

基于4.23-4.7 GeV 10.6 fb^{-1}数据，挖掘现有及未来BESIII数据潜力

arXiv:2406.01332, accepted by PRD



Decay	ϵ_{sig} (%)	N_{DT}	$\mathcal{B}$ (%)
$D_s^+ \to \eta_{\gamma\gamma} e^+\nu_e$	50.78 ± 0.12	716.2 ± 33.8	$2.35 \pm 0.11 \pm 0.10$
$D_s^+ \to \eta_{\pi^+\pi^-\pi^0} e^+\nu_e$	20.42 ± 0.08		
$D_s^+ \to \eta'_{\pi^+\pi^-\eta} e^+\nu_e$	22.35 ± 0.07	133.7 ± 14.5	$0.82 \pm 0.09 \pm 0.04$
$D_s^+ \to \eta'_{\pi^+\pi^-\gamma} e^+\nu_e$	32.48 ± 0.09		
$D_s^+ \to \phi_{K^+K^-} e^+\nu_e$	25.48 ± 0.07	350.2 ± 24.5	$2.21 \pm 0.16 \pm 0.11$
$D_s^+ \to f_{0\,\pi^+\pi^-} e^+\nu_e$	46.24 ± 0.11	91.0 ± 14.1	$0.15 \pm 0.02 \pm 0.01$
$D_s^+ \to K^0 e^+\nu_e$	46.21 ± 0.11	50.5 ± 8.4	$0.24 \pm 0.04 \pm 0.01$
$D_s^+ \to K^{0\star} e^+\nu_e$	41.78 ± 0.10	65.4 ± 10.9	$0.19 \pm 0.03 \pm 0.01$