Scalars in Charmed Meson Decays at BESIII

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湖南大學
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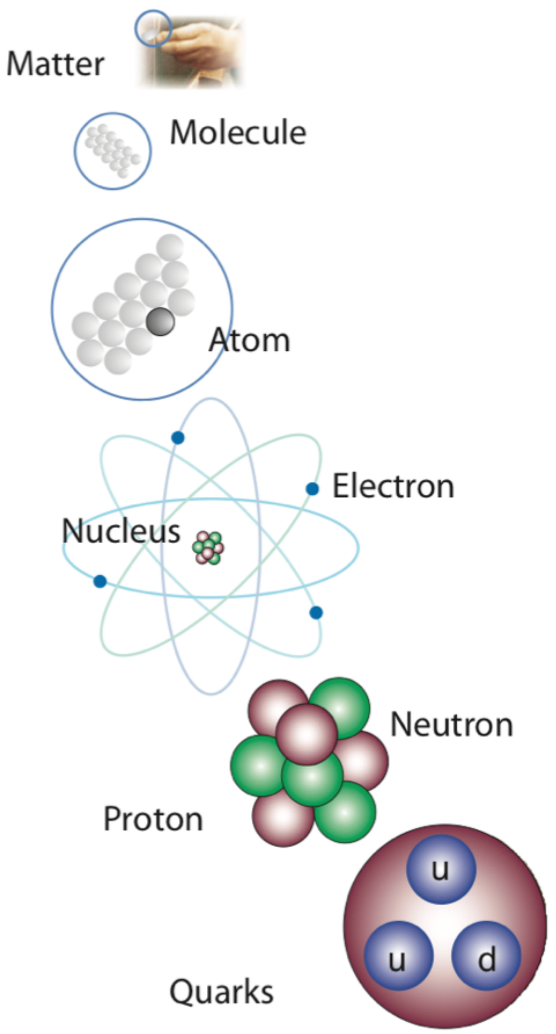
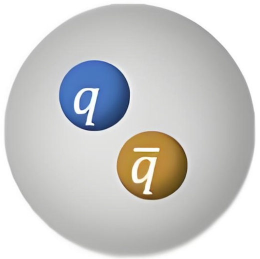
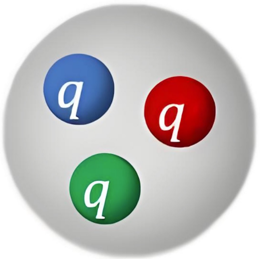
Content

Physics motivation

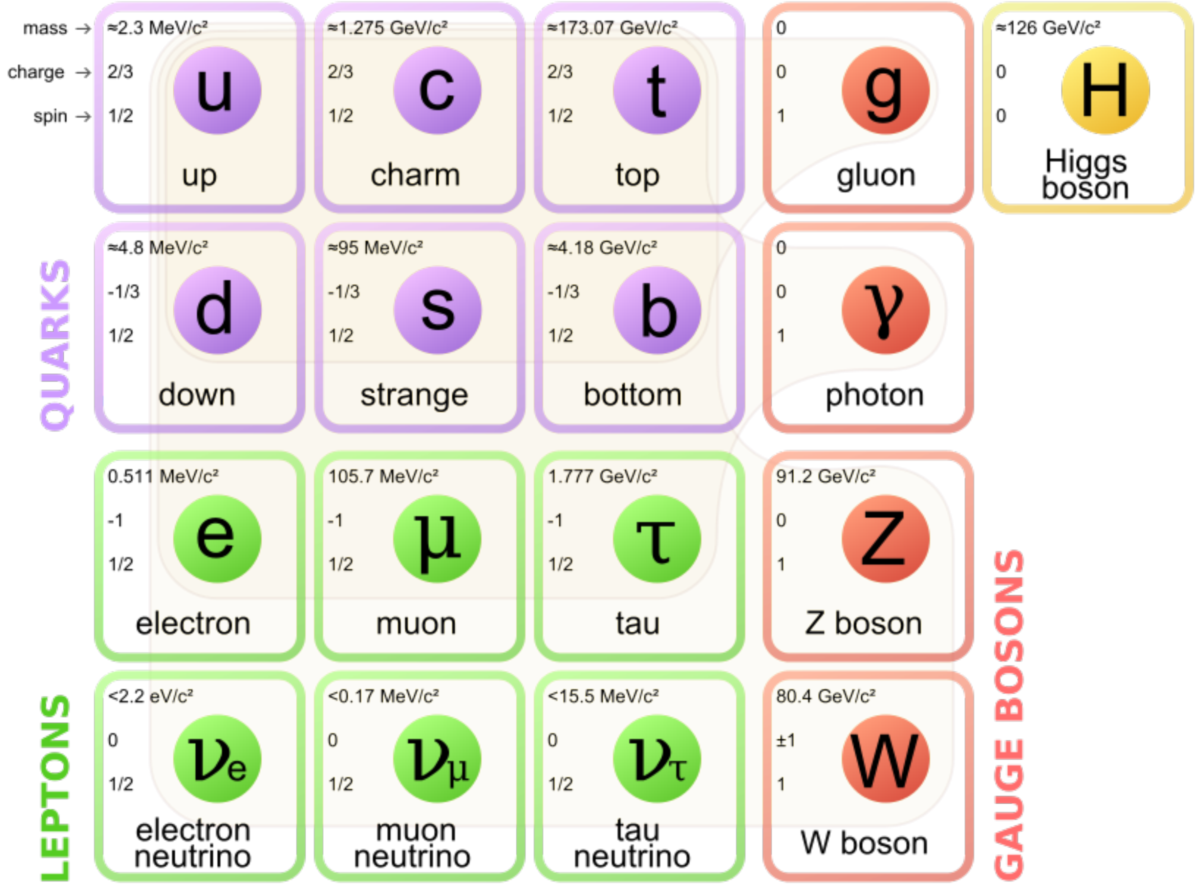




Meson

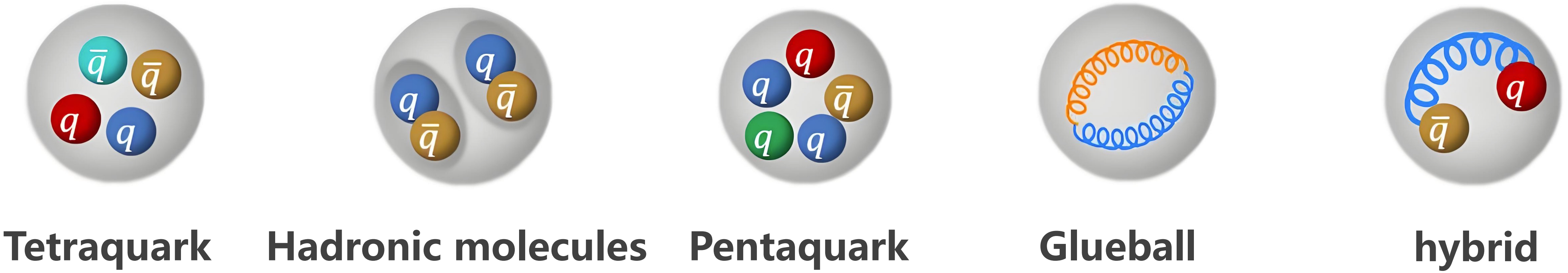


Baryon



- **All matters are made out of quarks and leptons.**
- **Ordinary hadrons: Meson and Baryon.**

Physics motivation



- **Quark model allows for them.**
- **How about scalar mesons:**

  $f_0(500), K^*(700), f_0(980)$ **and** $a_0(980)$, etc

➔ $q\bar{q}$ mixture, tetraquark, hadronic molecule or hybrid?

Physics motivation

Jose R. Pelaez, *Physics Reports 658 (2016) 1*,
"From controversy to precision on the sigma meson:
a review on the status of the non-ordinary $f_0(500)$ resonance"

For researchers outside the field, it may be surprising that despite having established Quantum Chromodynamics (QCD) as the fundamental theory of the Strong Interaction 40 years ago, the spectrum of lowest mass states, and particularly that of scalar mesons, may be still under debate. Actually, light scalar mesons have been a puzzle in our understanding of the Strong Interaction for almost six decades. This may be even more amazing given the fact that they play a very relevant role within nuclear and hadron physics, as in the nucleon-nucleon attraction and in the spontaneous breaking of chiral symmetry, both of them fundamental features of the Strong Interaction. The relatively poor theoretical understanding of hadrons at low energies causes little surprise since it is textbook knowledge that QCD becomes non-perturbative at low energies and does not allow for precise calculations of the light hadron spectrum. However, young and not so young people outside the field are often unaware of the fact that even basic empirical properties such as the existence of many of the lightest mesons and resonances are still actively discussed, even if they were suggested much before QCD was proposed. Moreover, it is often the case that

Physics motivation

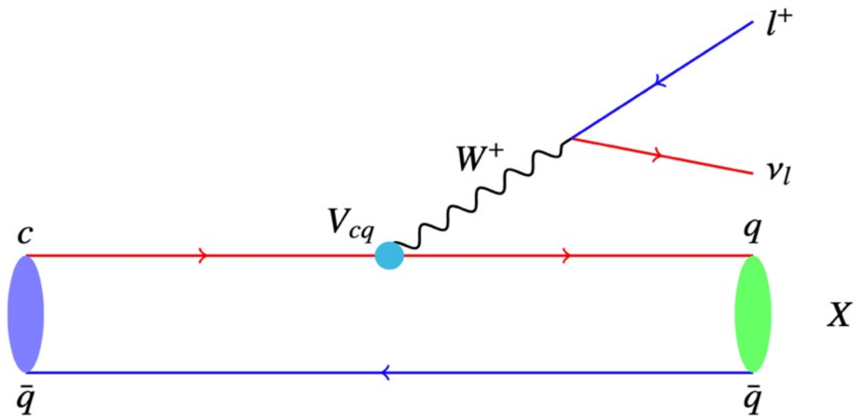
Scalar mesons $f_0(500), K^*(700), f_0(980)$ and $a_0(980)$

- Their nontrivial quark structure has remained controversial for many years!
- Many interpretations: $q\bar{q}$ mixture, tetraquark, molecule, and hybrid etc.
- They play a important role in the dynamics of the spontaneous breaking of QCD chiral symmetry and in the origin of pseudoscalar meson masses.
- They can help to understand the confinement of quarks.

★ Semi-leptonic decay of charmed meson is an ideal probe for their nature!

Physics motivation

??? ➠ Why is semi-leptonic decay of charmed meson?



$$\Gamma(D_{(s)} \to S\, \ell^+ \nu_\ell) \propto |V_{cd(s)}|^2 |f_+(q^2)|^2\, dq^2$$

- **Clean environment:** hadrons ***X*** can be separated from leptons pair.
- **High statistics** of charmed meson at experiments.
- Besides, the branching fraction (BF) measurement of semi-leptonic decay can be used to achieve:
  - Hadronic Form factor (FF) measurement ➔ **Test different QCD models (LQCD/QCDSR)**
  - $\mathcal{R}_{\mu/e} = \mathcal{B}(D_{(s)} \to X\mu^+\nu_\mu)/\mathcal{B}(D_{(s)} \to Xe^+\nu_e)$ measurement ➔ **Test lepton flavor universality (LFU)**

Content

Data sample

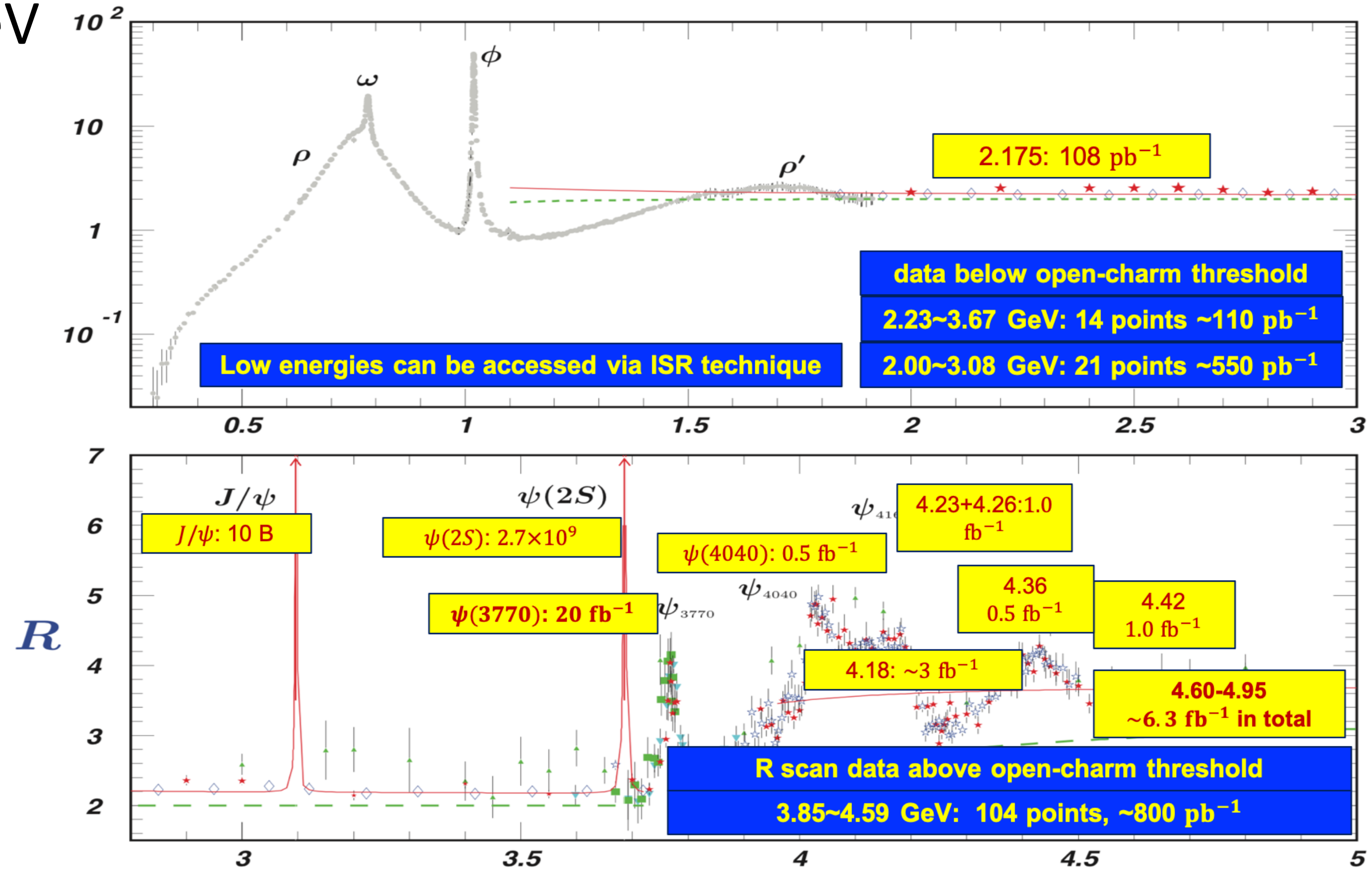
- Symmetric e^+e^- collider @2 – 5GeV
- Pair-production near threshold
- $D\bar{D}$@3.773GeV

  2.93 fb^{-1} 2010-2011

  4.99 fb^{-1} 2021-2022

  8.16 fb^{-1} 2021-2022

  4.19 fb^{-1} 2022-2024

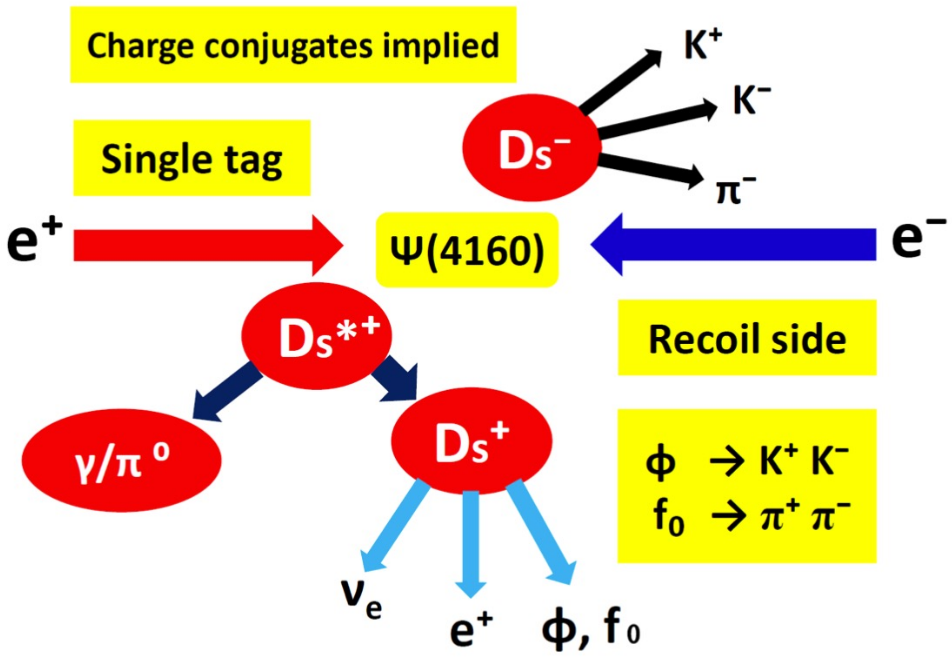


~20 fb^{-1} on the $\psi(3770)$ had been collected!

- $D_sD_s^*$ @4.13-4.23GeV: 7.33 fb^{-1}

Analysis method: Double Tag

Take Ds decay as an example (complicated case)



$\mathcal{B}_{\gamma}(D_S^{*}\to\gamma D_S)$

$$N_{tag} = 2N_{D_S^{\pm}D_S^{\mp}}\mathcal{B}_{tag}\,\epsilon_{tag}$$
$$N_{sig} = 2N_{D_S^{\pm}D_S^{\mp}}\mathcal{B}_{tag}\mathcal{B}_{sig}\mathcal{B}_{\gamma}\epsilon_{sig}$$

$$\mathcal{B}_{sig} = \frac{N_{sig}}{\mathcal{B}_{\gamma}N_{tag}\epsilon_{sig}/\epsilon_{tag}}$$

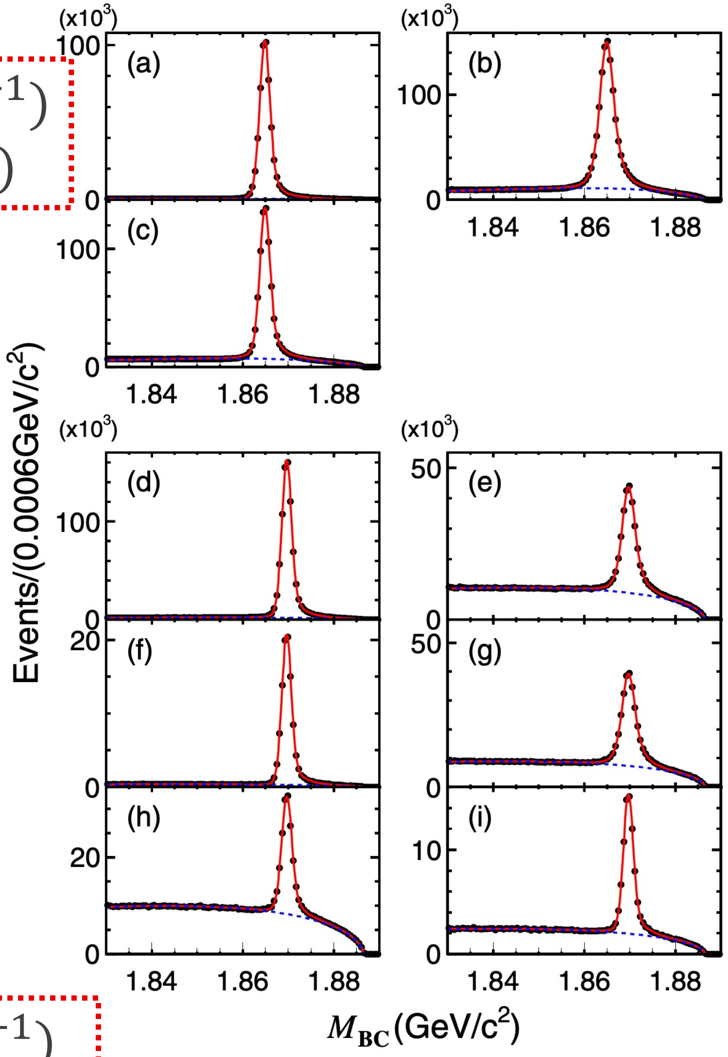
$$\mathcal{B}_{sig} = \frac{N_{sig}}{\mathcal{B}_{\gamma}\sum_{\alpha}N_{tag}^{\alpha}\epsilon_{sig}^{\alpha}/\epsilon_{tag}^{\alpha}}$$

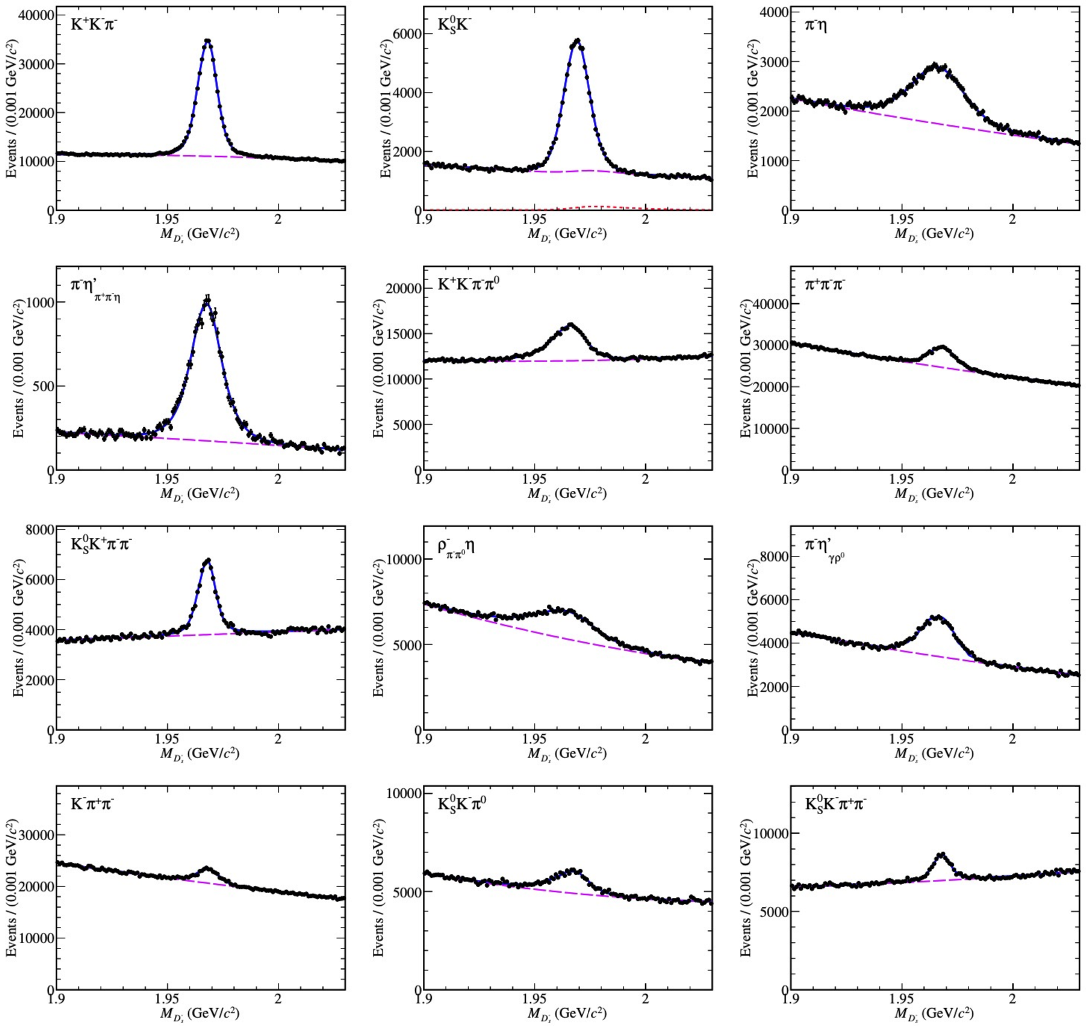
- Mature method
- Absolute BF measurement
- Low background
- Systematic cancellation (tag)

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

Analysis method: Single Tag sample

D^0: ~2.76 M (2.93 fb^{-1})
D^0: ~6.31 M (7.9 fb^{-1})





D^+: ~1.57 M (2.93 fb^{-1})
D^+: ~4.15 M (7.9 fb^{-1})

D_s: 0.77 M

The differential decay rate of $D_{(s)}$ -> $S\,\ell\nu_\ell$

$$\Gamma(D_{(s)} \to S\ell^+\nu_\ell)/dq^2 \propto |V_{cd(s)}|^2|f_+(q^2)|^2$$

$$S: a_0(980), f_0(500), f_0(980)$$

- Use least χ^2 method to fit the measured partial decay width in different $\boldsymbol{q^2}$ bin.
- Taking the correlations among $\boldsymbol{q^2}$ bins into account.
- FF in different form (The width needs to be considered ?)

– **Single pole form**

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

– **Modified pole model**

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

– **ISGW2 model**

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

– **Series expansion model**

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

The differential decay rate of $D_{(s)}$ -> $S\,\ell\nu_\ell$

- Point-like differential decay rate:

$$\frac{d\Gamma(D_{(s)}\to S\ell^+\nu_\ell)}{dq^2} = \frac{G_F^2|V_{cd(s)}|^2}{24\pi^3} p_{f_0}^3 |f_+(q^2)|^2$$

- Double differential decay rate:

(N.N.Achasov *et al.*, PRD102,016022(2020); W. Wang, PLB759,501(2016))

$$\frac{d^2\Gamma(D_{(s)}\to S\ell^+\nu_\ell)}{ds\,dq^2} = \frac{G_F^2|V_{cd(s)}|^2}{192\pi^4 m_{D_{(s)}}^3} \lambda^{\frac{3}{2}}\left(m_{D_{(s)}}^2, s, q^2\right) |f_+(q^2)|^2 P(s)$$

$$P(s) = \begin{cases} \dfrac{g_1\rho_{\pi\pi/\pi\eta}}{|m_0^2 - s - i(g_1\rho_{\pi\pi/\pi\eta} + g_1\rho_{KK})|^2}, & \text{Flatte: } f_0(980)/a_0(980) \\ \dfrac{m_{f_0}\Gamma(s)}{(s-m_{f_0}^2)^2 + m_{f_0}^2\Gamma^2(s)}, & \text{RBW: } f_0(500) \\ \dfrac{m_r\Gamma_{tot}(s)}{(m_r^2 - s - g_1^2\frac{s-s_A}{m_r^2-s_A}z(s))^2 + m_r^2\Gamma_{tot}^2(s)}, & \text{Bugg: } f_0(500) \end{cases}$$

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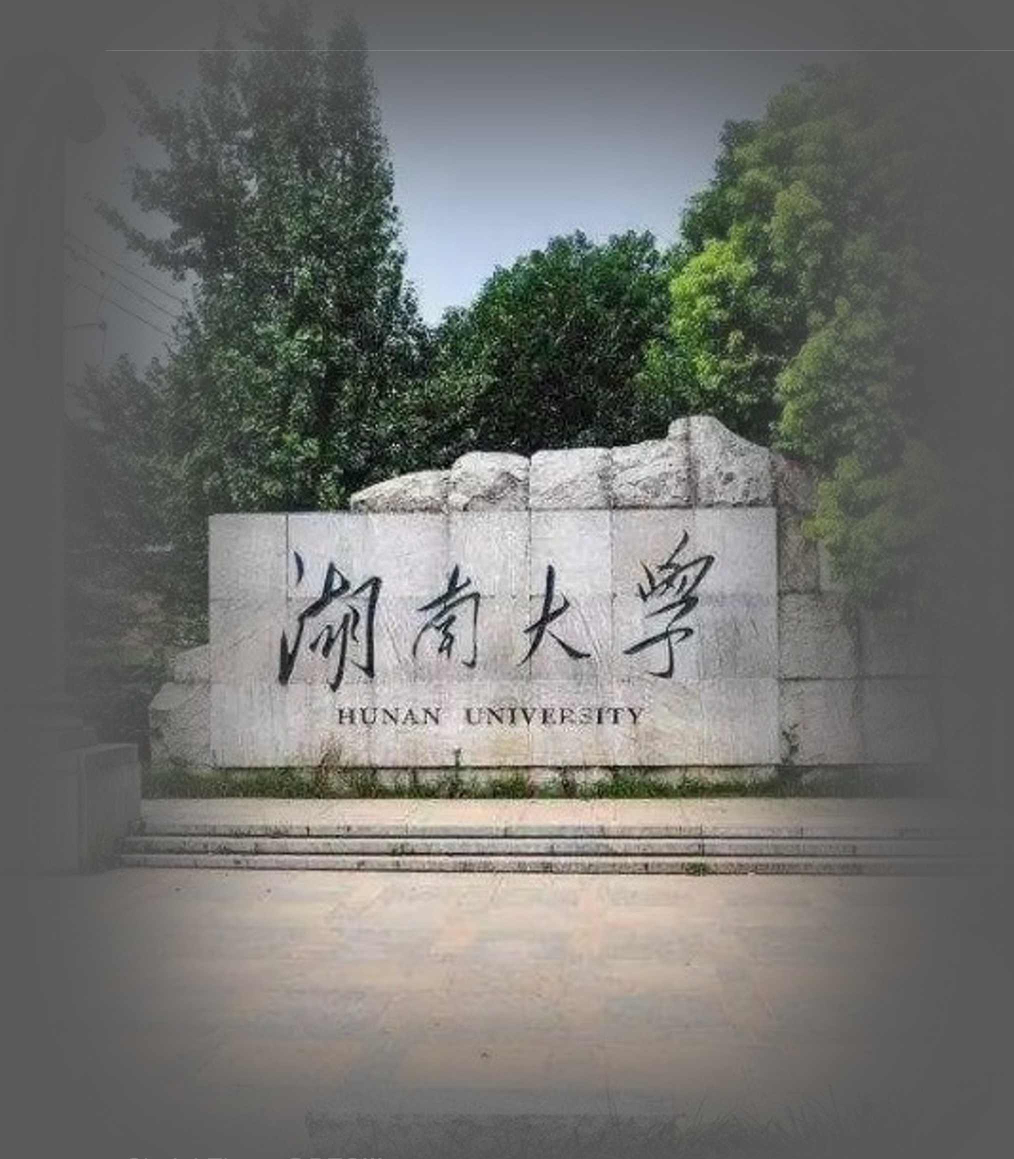
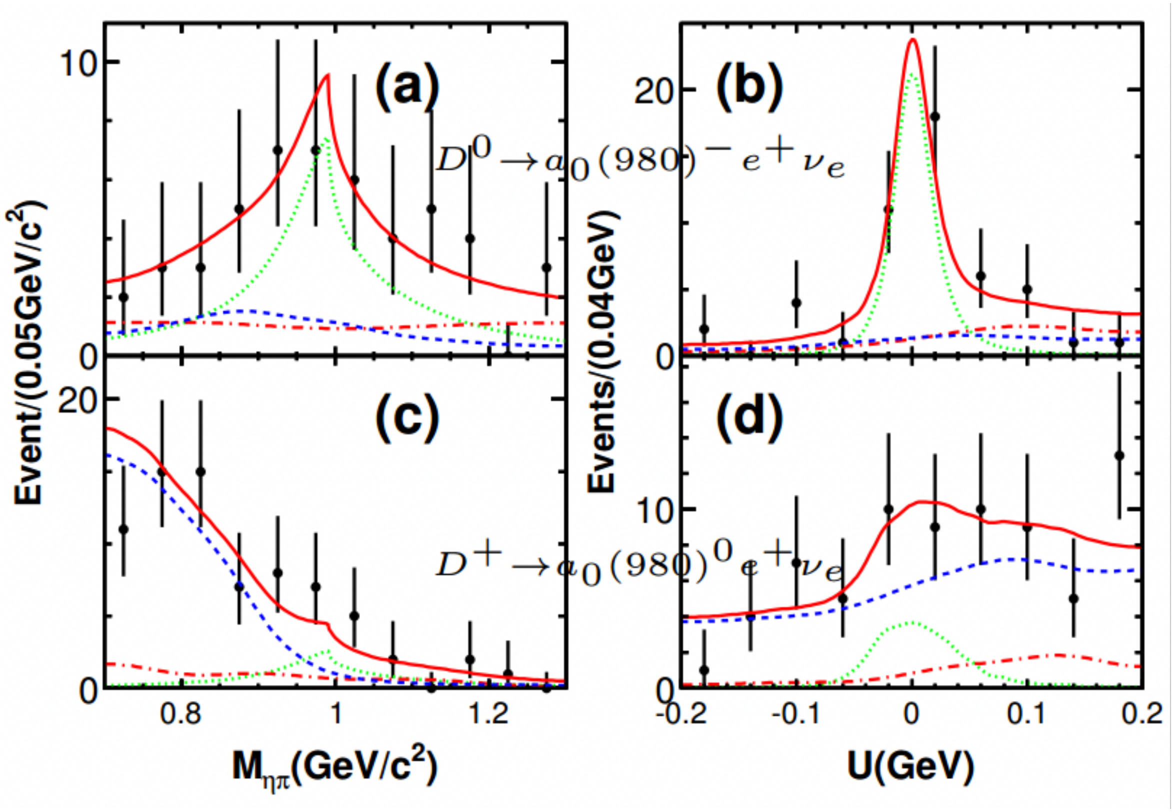


- 01 **Physics motivation ✓**
- 02 **Data and analysis method ✓**
- 03 **Results in review ✓**
- 04 **Summary and prospect**

First observation of $D^0 \to a_0(980)^- e^+ \nu_e$

Phys. Rev. Lett. 121, 081802 (2018)

- 2.93 fb^{-1} data @ 3.773 GeV
- $N_{\mathrm{sig}}^{D^0} = 25.7^{+6.4}_{-5.7}$
- $N_{\mathrm{sig}}^{D^+} = 10.2^{+5.0}_{-4.1}$
- Branching fraction (BF) help to understand the nature of the $\boldsymbol{a_0(980)}$



Decay	BF ($\times 10^{-4}$)	Significance
$D^0 \to a_0(980)^- e^+ \nu_e,\ a_0(980)^- \to \eta\pi^-$	$1.33^{+0.33}_{-0.29} \pm 0.09$	6.4σ
$D^+ \to a_0(980)^0 e^+ \nu_e,\ a_0(980)^0 \to \eta\pi^0$	$1.66^{+0.81}_{-0.66} \pm 0.11$ < 3.0 (90% C.L.)	2.9σ

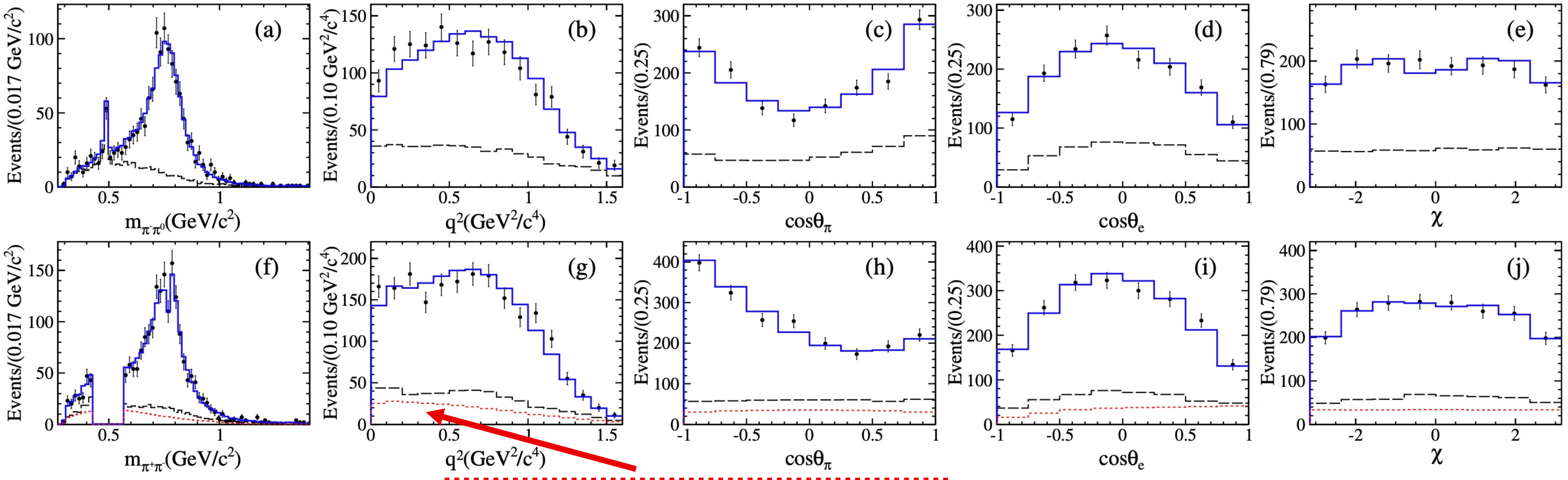
First observation of $D^+ \to f_0(500)e^+\nu_e$

Phys. Rev. Lett. 122, 062001 (2019)

$|U_{\text{miss}}| < 0.06$ GeV → $N_{\text{Event}}^{D^0} = 1498$, Bkg: $(33.28 \pm 0.87)\%$
$N_{\text{Event}}^{D^+} = 2017$, Bkg: $(23.82 \pm 0.69)\%$

D^0

D^+



- 2.93 fb^{-1} data @ 3.773 GeV

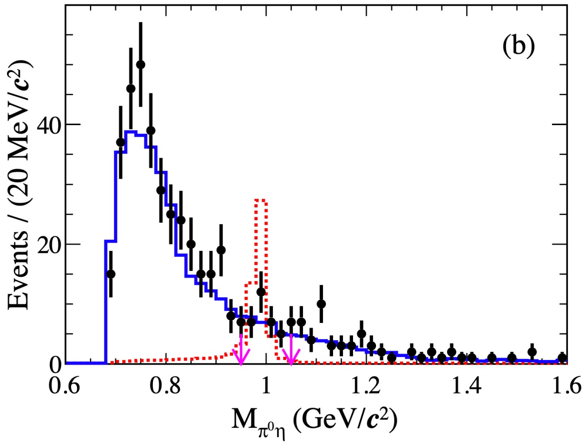
$f_{f_0(500)} = (25.7 \pm 1.6 \pm 1.1)\%$

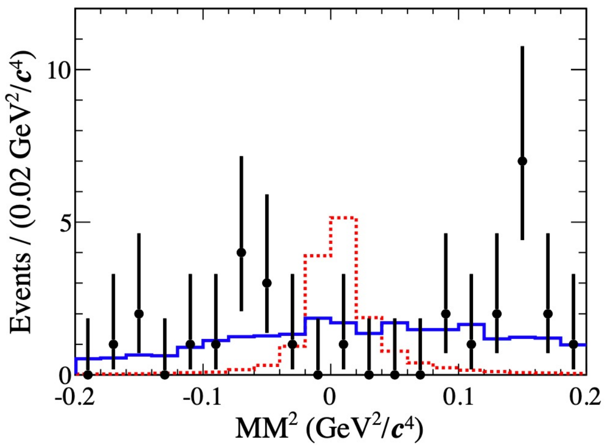
- $R = \frac{\mathcal{B}(D^+\to f_0(500)e^+\nu_e)+\mathcal{B}(D^+\to f_0(980)e^+\nu_e)}{\mathcal{B}(D^+\to a_0(980)e^+\nu_e)} > 2.7@90\%CL$
- Favor tetraquark (R=3, PRD82, 034016(2010)) for f_0 and a_0

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

Search for the decay $D_s^+ \to a_0(980)\, e^+\nu_e$

Phys. Rev. D. 103, 092004 (2021)





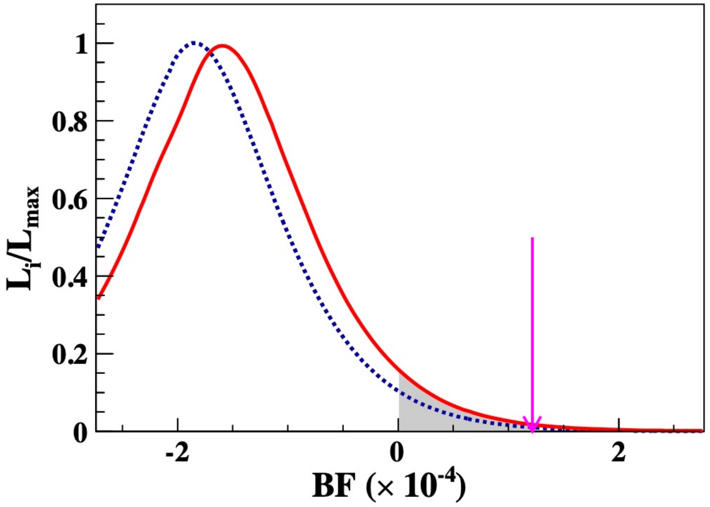
- 6.33 fb^{-1} data @ 4.178-4.226 GeV
- No significant signal is observed.

  An upper limit is determined at 90% confidence level (CL):

$$\mathcal{B}(D_s^+ \to a_0(980)e^+\nu_e, f_0(980) \to \pi^0\eta) < 1.2\times10^{-4}$$

- First study of $a_0(980) - f_0(980)$ mixing in the charm sector.

  No obvious isospin violation is observed.



Study of the decays $D_s^+ \to \pi^0\pi^0 e^+\nu_e$ and $D_s^+ \to K_S^0 K_S^0 e^+\nu_e$

Phys. Rev. D. 105, L031101 (2022)

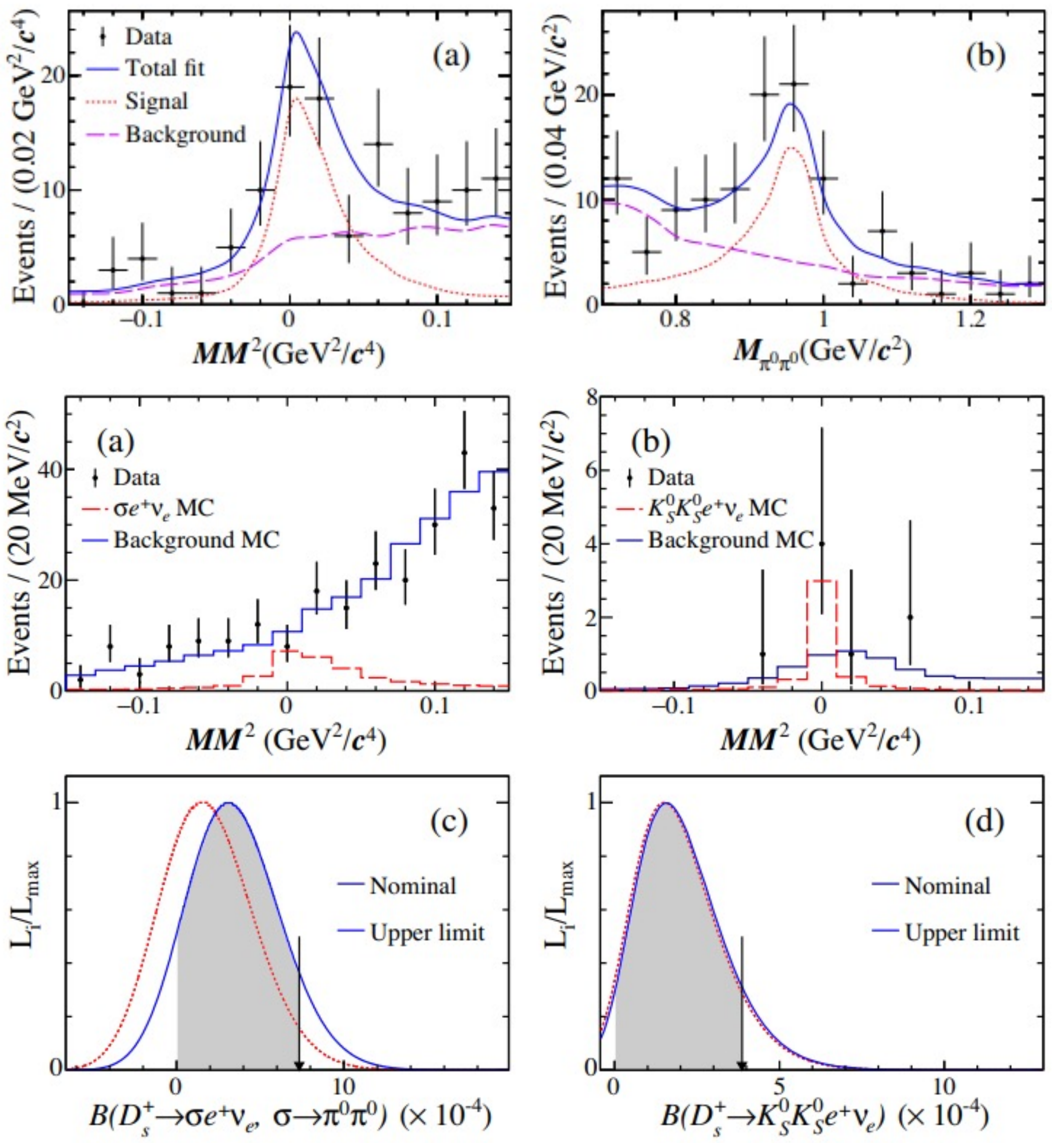
- 6.32 fb^{-1} data @ 4.178-4.226 GeV
- $N_{\mathrm{sig}}^{f_0(980)} = 54.8 \pm 10.1$ (7.8 σ significance)
- First BFs Measurement:

$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^0\pi^0)$$
$$= (7.9 \pm 1.4 \pm 0.4)\times 10^{-4}$$

- No significant signal:

$$\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^0\pi^0) < 7.3\times 10^{-4}$$
$$\mathcal{B}\left(D_s^+ \to K_S^0 K_S^0 e^+\nu_e\right) < 3.8\times 10^{-4}$$

- BFs help to understand the nature of the $f_0(500)$ and $f_0(980)$, and test different theoretical calculations.



Study of the $f_0(980)$ through the decay $D_s^+ \to K^+K^-\mu^+\nu_\mu$

JHEP12(2023)072

- 7.33 fb^{-1} data @ 4.128-4.226 GeV
- $N_{\text{sig}} = 1725 \pm 68$ for BF measurement

$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu) = (2.25 \pm 0.09 \pm 0.07)\times10^{-2}$

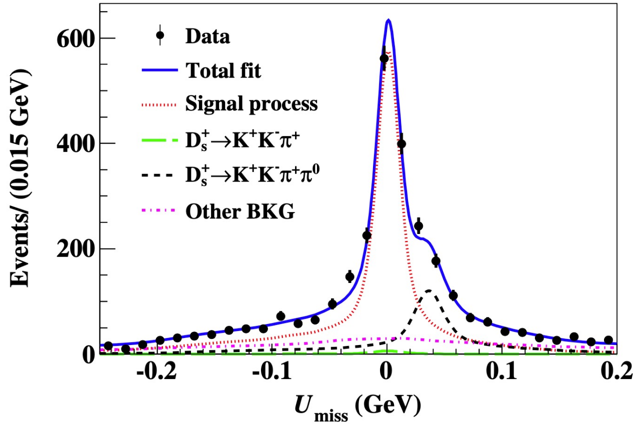
$\mathcal{B}(D_s^+ \to \phi\mu^+\nu_\mu)/\mathcal{B}(D_s^+ \to \phi e^+\nu_e) = 0.94 \pm 0.08$ ➔ No **LFU** violation

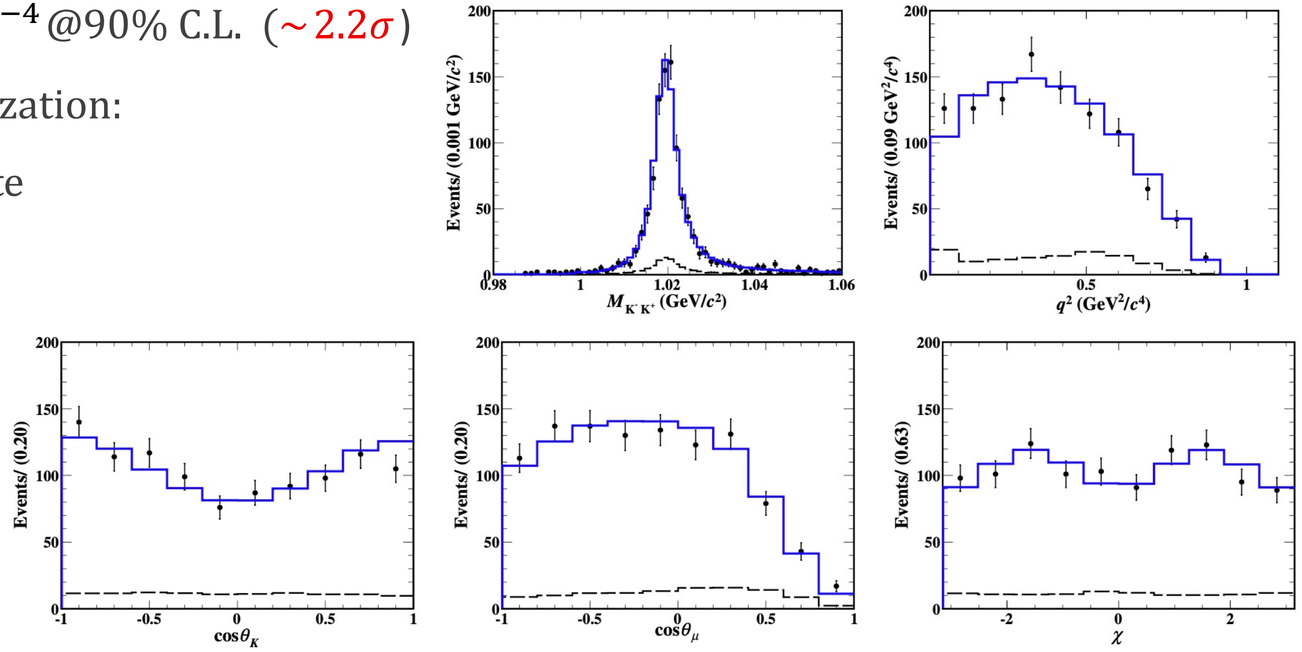
$\mathcal{B}(D_s^+ \to f_0(980)\mu^+\nu_\mu)\cdot\mathcal{B}(f_0(980) \to K^+K^-) < 5.45\times10^{-4}$ @90% C.L. ($\sim2.2\sigma$)

- **First FF measurement** based on single pole parameterization:
  - **Partial wave analysis** is performed ➔ ϕ dominate
  - **μ mass** is considered in the formula

Table 5. Measured FF ratios and comparison with previous measurements.

Experiments	r_V	r_2
PDG [42]	1.80±0.08	0.84±0.11
This analysis	1.58±0.17±0.02	0.71±0.14±0.02
BABAR [25]	1.807±0.046±0.065	0.816±0.036±0.030
FOCUS [58]	1.549±0.250±0.148	0.713±0.202±0.284
Theory	r_V	r_2
CCQM [5]	1.34±0.27	0.99±0.20
CQM [6]	1.72	0.73
LFQM [7]	1.42	0.86
LQCD [3]	1.72±0.21	0.74±0.12
HMχT [8]	1.80	0.52





$|U_{\text{miss}}| < 0.02$ GeV

$N_{\text{Event}}^{D_s^+} = 939$, Bkg: $(9.8 \pm 0.7)\%$

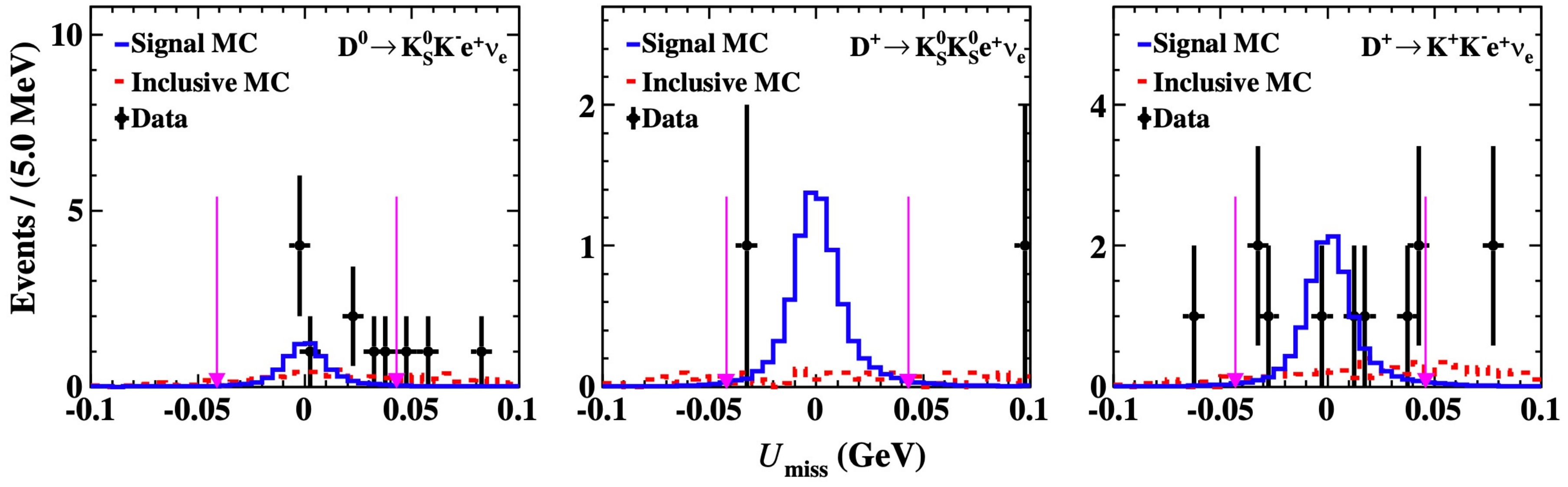
Search for the decay $D \to K\bar{K}e^+\nu_e$

Phys. Rev. D. 109, 072003 (2024)

- 7.9 fb^{-1} data @ 3.773 GeV [2010,2011,2021]
- No significant signal is observed, upper limits are determined at 90%CL assuming $a_0(980)$ contribution:

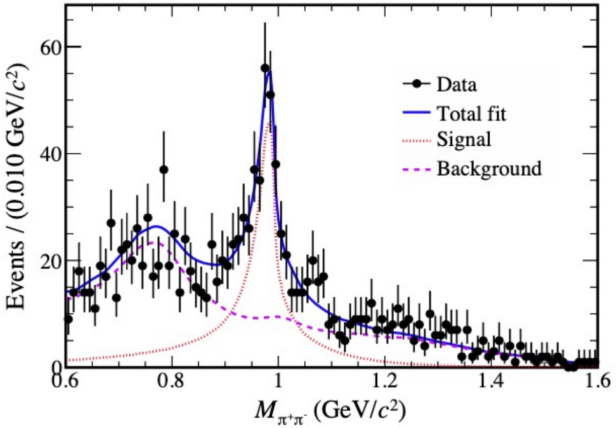
$$\mathcal{B}(D^0 \to K_S^0 K^- e^+ \nu_e) < 2.13\times10^{-5}$$

$$\mathcal{B}(D^+ \to K_S^0 K_S^0 e^+ \nu_e) < 1.54\times10^{-5}, \mathcal{B}(D^+ \to K^+ K^- e^+ \nu_e) < 2.10\times10^{-5}$$



Study of the $f_0(980)$ and $f_0(500)$ through the decay $D_s^+ \to \pi^+\pi^- e^+\nu_e$

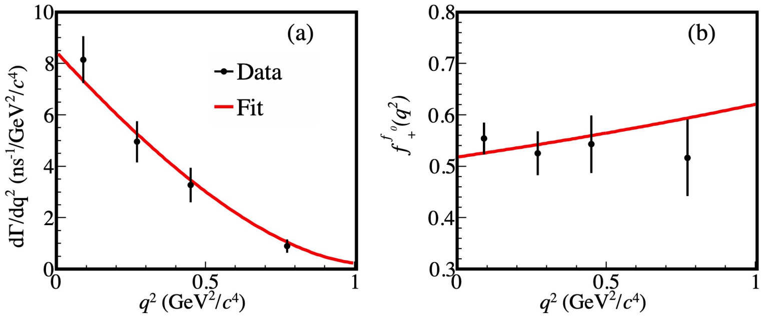
Phys. Rev. Lett. 132, 141901 (2024)



- $7.33\ \text{fb}^{-1}$ data @ 4.128-4.226 GeV ➔ $N_{\text{sig}} = 439 \pm 33$
- $\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^+\pi^-) = (1.72 \pm 0.13 \pm 0.10)\times 10^{-3}$

  ➔ **$s\bar{s}$ is dominant** based on $|f_0(980)\rangle = \sin\phi|\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\rangle + \cos\phi\,|s\bar{s}\rangle$

  $\phi = (19.7 \pm 12.8)^\circ$

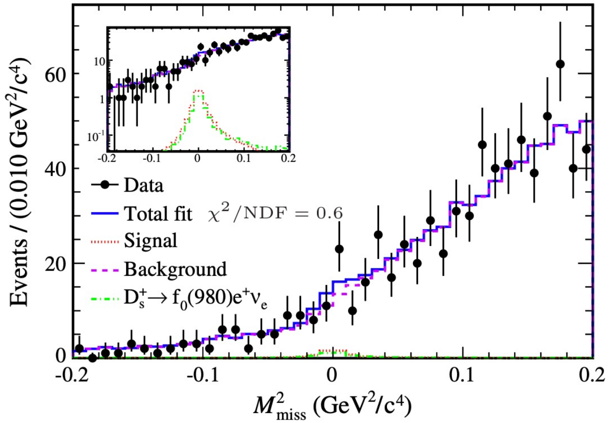


- **First form factor measurement** with simple pole form:

  ➔ $f_+^{f_0}(0)|V_{cs}| = 0.504 \pm 0.017 \pm 0.035$

  ➔ $f_+^{f_0}(0) = 0.518 \pm 0.018 \pm 0.036$ ($|V_{cs}| = 0.97349 \pm 0.00016$ PDG2022)

	This work	CLFD [6]	DR [6]	QCDSR [7]	QCDSR [8]	LCSR [9]	LFQM [11]	CCQM [12]
$f_+^{f_0}(0)$	$0.518 \pm 0.018_{\text{stat}} \pm 0.036_{\text{syst}}$	0.45	0.46	0.50 ± 0.13	0.48 ± 0.23	0.30 ± 0.03	0.24 ± 0.05	0.36 ± 0.02
Difference (σ)	—	1.7	1.4	0.1	0.2	4.3	4.3	2.8
ϕ	$\phi = (19.7 \pm 12.8)^\circ$	$(32 \pm 4.8)^\circ$	$(41.3 \pm 5.5)^\circ$	35°	$(8^{+21}_{-8})^\circ$	—	$(56 \pm 7)^\circ$	31°



- **First search** of $D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-$ ($M_{\pi^+\pi^-} < 0.45$ GeV/c²)
- $\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-) < 3.3\times 10^{-4}$

Study of the $f_0(980)$ and $f_0(500)$ through the decay $D_s^+ \to \pi^+\pi^- e^+\nu_e$

Phys. Rev. Lett. 132, 141901 (2024)

- $7.33\ \text{fb}^{-1}$ data @ 4.128-4.226 GeV ➔ $N_{\text{sig}} = 439 \pm 33$
- $\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^+\pi^-) = (1.72 \pm 0.13 \pm 0.10)\times 10^{-3}$
  - ➔ **$s\bar{s}$ is dominant** based on $|f_0(980)\rangle = \sin\phi |\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})\rangle + \cos\phi\,|s\bar{s}\rangle$

    $\phi = (19.7 \pm 12.8)^\circ$
- **First form factor measurement** with simple pole form:
  - ➔ $f_+^{f_0}(0)|V_{cs}| = 0.504 \pm 0.017 \pm 0.035$
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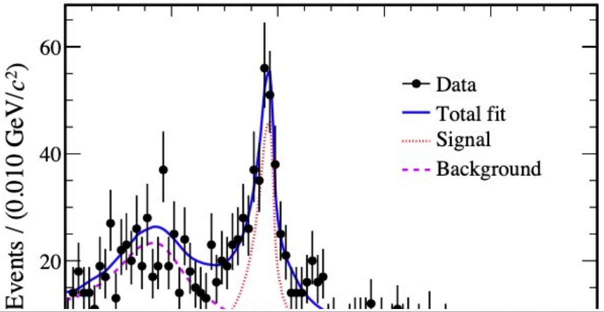
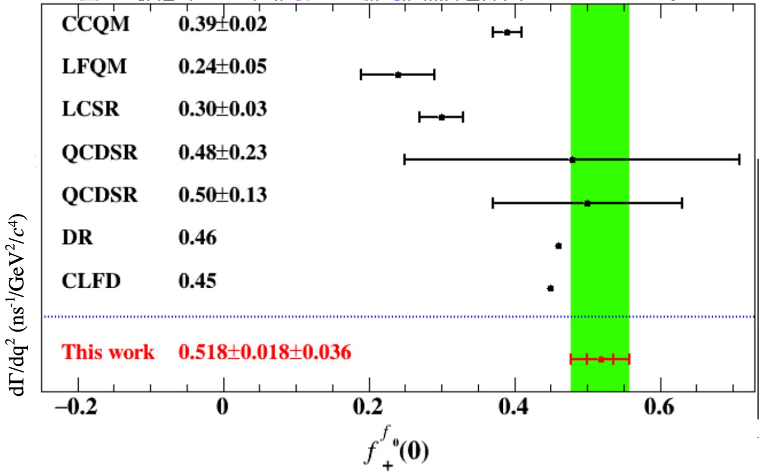
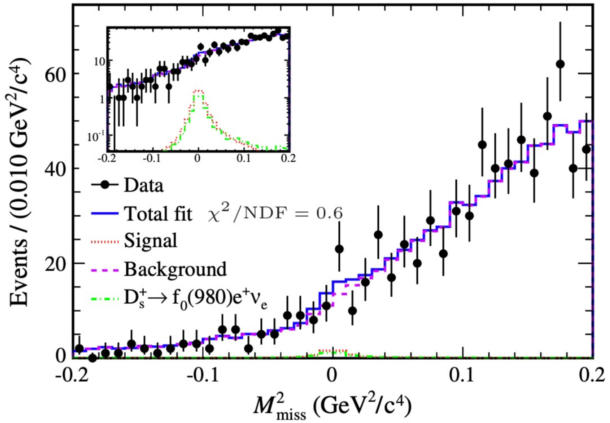
Difference (σ)	—	1.7	1.4	0.1	0.2	4.3	4.3	2.8
ϕ	$\phi = (19.7 \pm 12.8)^\circ$	$(32 \pm 4.8)^\circ$	$(41.3 \pm 5.5)^\circ$	35°	$(8^{+21}_{-8})^\circ$	—	$(56 \pm 7)^\circ$	31°

- **First search** of $D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-$ ($M_{\pi^+\pi^-} < 0.45\ \text{GeV/c}^2$)
- $\mathcal{B}(D_s^+ \to f_0(500)e^+\nu_e, f_0(500) \to \pi^+\pi^-) < 3.3\times 10^{-4}$





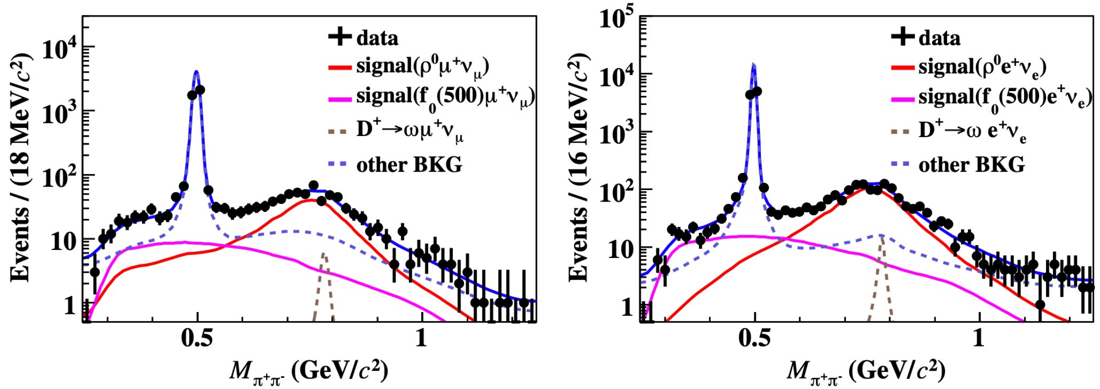


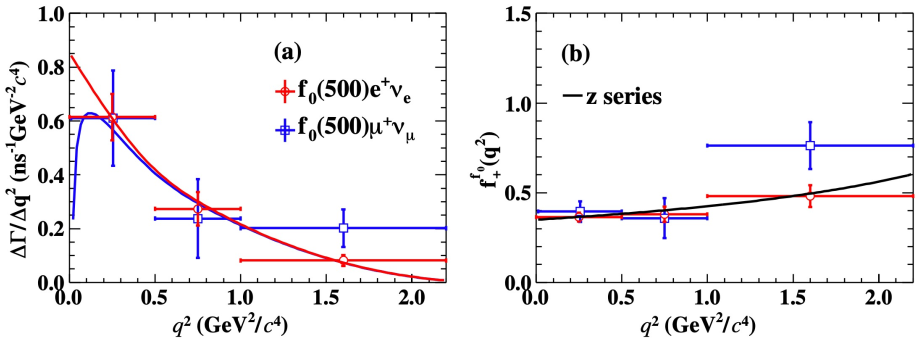
Study of the decay $D^+ \to f_0(500)\ell^+\nu_\ell$

arXiv: 2401.13225 (Submitted to PRL)

- 2.93 fb^{-1} data @ 3.773 GeV
- **First observation** of $D^+ \to f_0(500)(\pi^+\pi^-)\mu^+\nu_\mu$.

Signal mode	N_{obs}	$\mathcal{S}$ (σ)	ϵ_{sig} (%)	$\mathcal{B}_{\mathrm{sig}}(\times 10^{-3})$
$f_0(500)\mu^+\nu_\mu$	209 ± 38	5.9	18.93 ± 0.13	0.72 ± 0.13
$\rho^0\mu^+\nu_\mu$	496 ± 38	> 10	19.86 ± 0.13	1.64 ± 0.13
$f_0(500)e^+\nu_e$	412 ± 43	> 10	44.76 ± 0.25	0.60 ± 0.06
$\rho^0 e^+\nu_e$	1237 ± 47	> 10	44.12 ± 0.25	1.84 ± 0.07





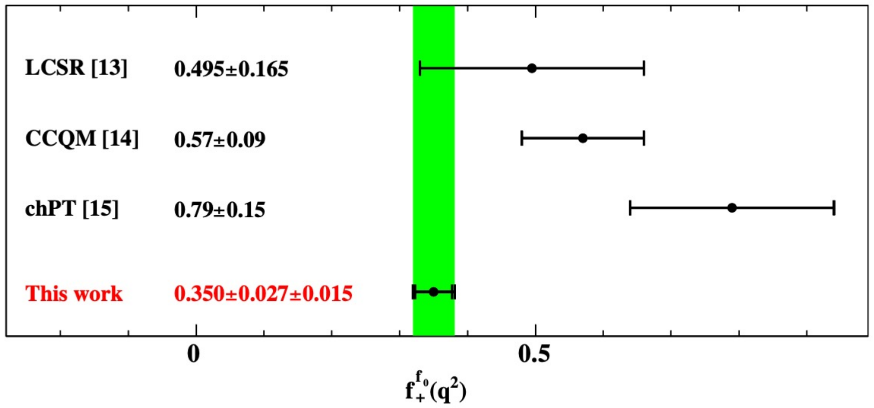
- **First FF measurement** of $D^+ \to f_0(500)(\pi^+\pi^-)\ell^+\nu_\ell$.

Based Z series expansion for FF and Bugg form for $f_0(500)$

➔ $f_+^{f_0}(0)|V_{cd}| = 0.0787 \pm 0.0060 \pm 0.0033$

➔ $f_+^{f_0}(0) = 0.350 \pm 0.027 \pm 0.015$

ps: $|V_{cd}| = 0.22438 \pm 0.00044$ from SM global fit (PDG2022)



Content

湖南大學 HUNAN UNIVERSITY

Light scalar mesons via semi-leptonic charm decays at BESIII

Channel	Publication	Status
$D^0 \to a_0(980)^-(\eta\pi^-)e^+\nu_e$	*PRL 121, 081802(2018)*	Update in process (Draft review)
$D^+ \to a_0(980)^0(\eta\pi^0)e^+\nu_e$	*PRL 121, 081802(2018)*	Update in process (Group review)
$D \to a_0(980)\ (\eta\pi)\mu^+\nu_\mu$	***No***	In process (Group review)
$D \to a_0(980)\ (K\bar{K})e^+\nu_e$	*PRD 109, 072003(2024)*	Published
$D^+ \to f_0(500)(\pi^+\pi^-)e^+\nu_e$	*PRL 122, 062001(2019)*	Update in process (Group review)
$D^+ \to f_0(500)(\pi^+\pi^-)\mu^+\nu_\mu$	*arXiv: 2401.13225*	Submitted to PRL
$D^+ \to f_0(980)(\pi^+\pi^-)e^+\nu_e$	*PRL 122, 062001(2019)*	Update in process (Group review)
$D_s^+ \to a_0(980)^0(\eta\pi^0)e^+\nu_e$	*PRD 103, 092004(2021)*	Published
$D_s^+ \to f_0(980)(\pi^0\pi^0)e^+\nu_e$	*PRD 105, L031101(2022)*	Published
$D_s^+ \to f_0(500)(\pi^0\pi^0)e^+\nu_e$	*PRD 105, L031101(2022)*	Published
$D_s^+ \to f_0(980)(\pi^+\pi^-)e^+\nu_e$	*PRL 132,141901(2024)*	Published
$D_s^+ \to f_0(980)(\pi^+\pi^-)\mu^+\nu_\mu$	***No***	In process (Memo review)
$D_s^+ \to f_0(980)(K^+K^-)e^+\nu_e$	***No***	In process (Draft review)
$D_s^+ \to f_0(980)(K^+K^-)\mu^+\nu_\mu$	*JHEP12(2023)072*	Published

Summary and prospect

Summary:

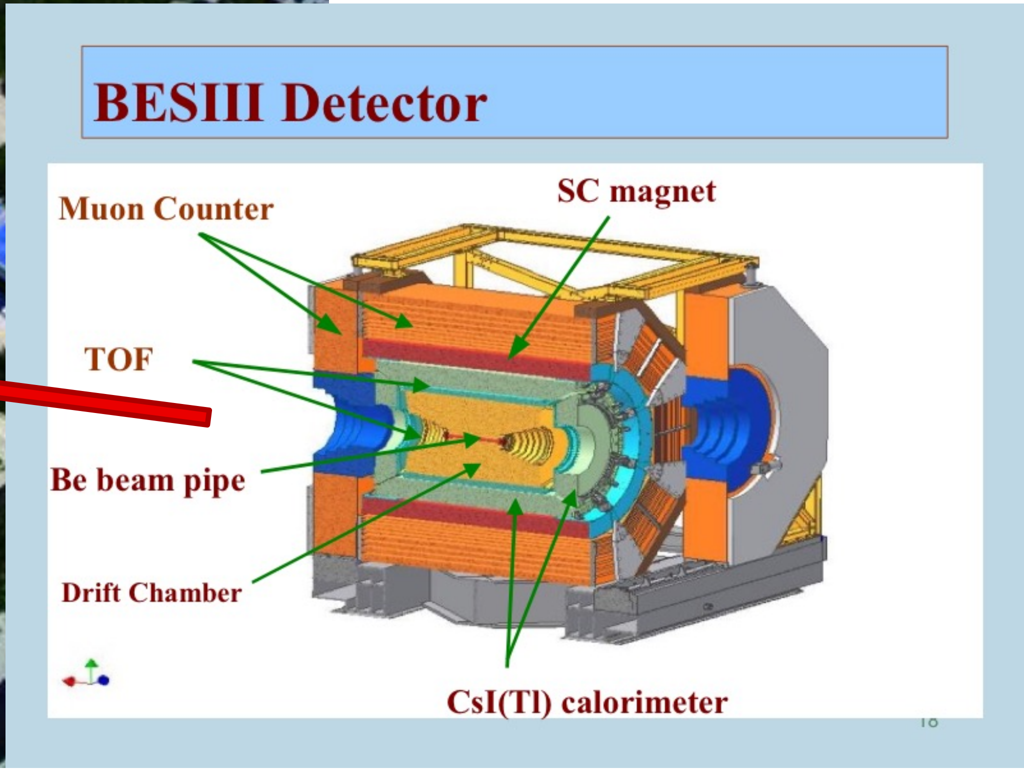
- BESIII has the largest data samples at $D\overline{D}/D_sD_s^*$ threshold.
- Light scalar mesons are studied systematically via semi-leptonic charm decays.
- BFs and FF measurements help to understand the nature of light scalar mesons.

Prospect:

- BESIII has **20 fb**$^{-1}$ @3.773 GeV in total now.
- More scalar mesons could be studied via semi-leptonic charm decays.
  ➔ $\boldsymbol{K^*(700), K_0^*(1430), f_0(1370), f_0(1500), a_0(1450)}$
- More results are on the way!

Thank you!

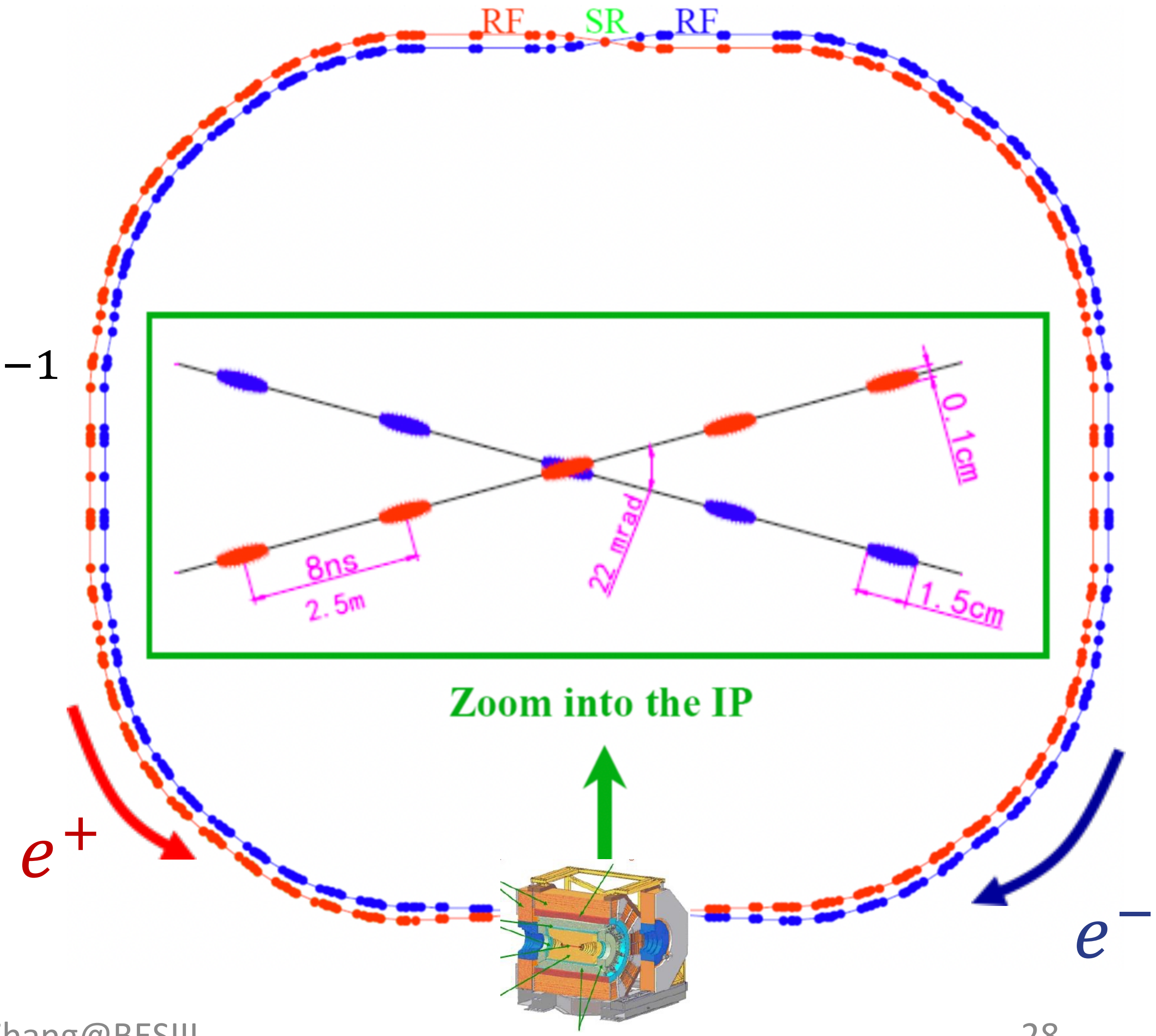
BESIII experiment



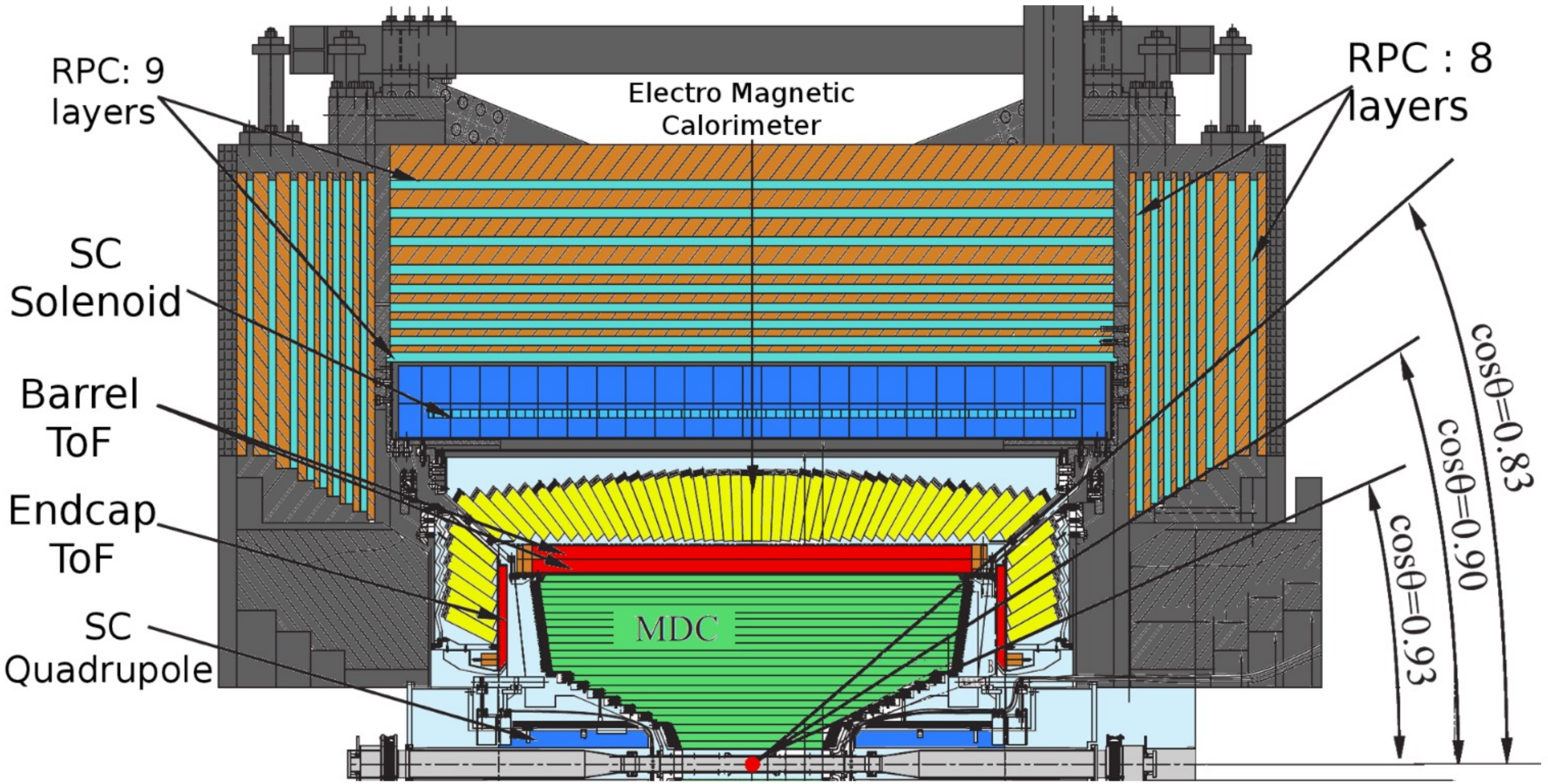
BEPCII collider

- Two ring symmetric e^+e^- collider
- Circumference: 240 m
- Design luminosity: $1\times10^{33} cm^{-2}s^{-1}$

  Achieved time: 5 April, 2016
- E_{cm}: 2 – 5 GeV
- Beam crossing angle: 22 mrad



BESIII detector



MDC

$\frac{\delta p}{p} < 0.5\%$ @1 GeV

$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

TOF

δt 80 ps Barrel

δt 110 ps Endcap

EMC

$\frac{\delta E}{E} < 2.5\%$ @1 GeV

$\delta z = 0.6/\sqrt{E}$

MUC

$\delta(xy) <$2 cm