BESIII上粲介子半轻衰变到轻标量介子的研究进展

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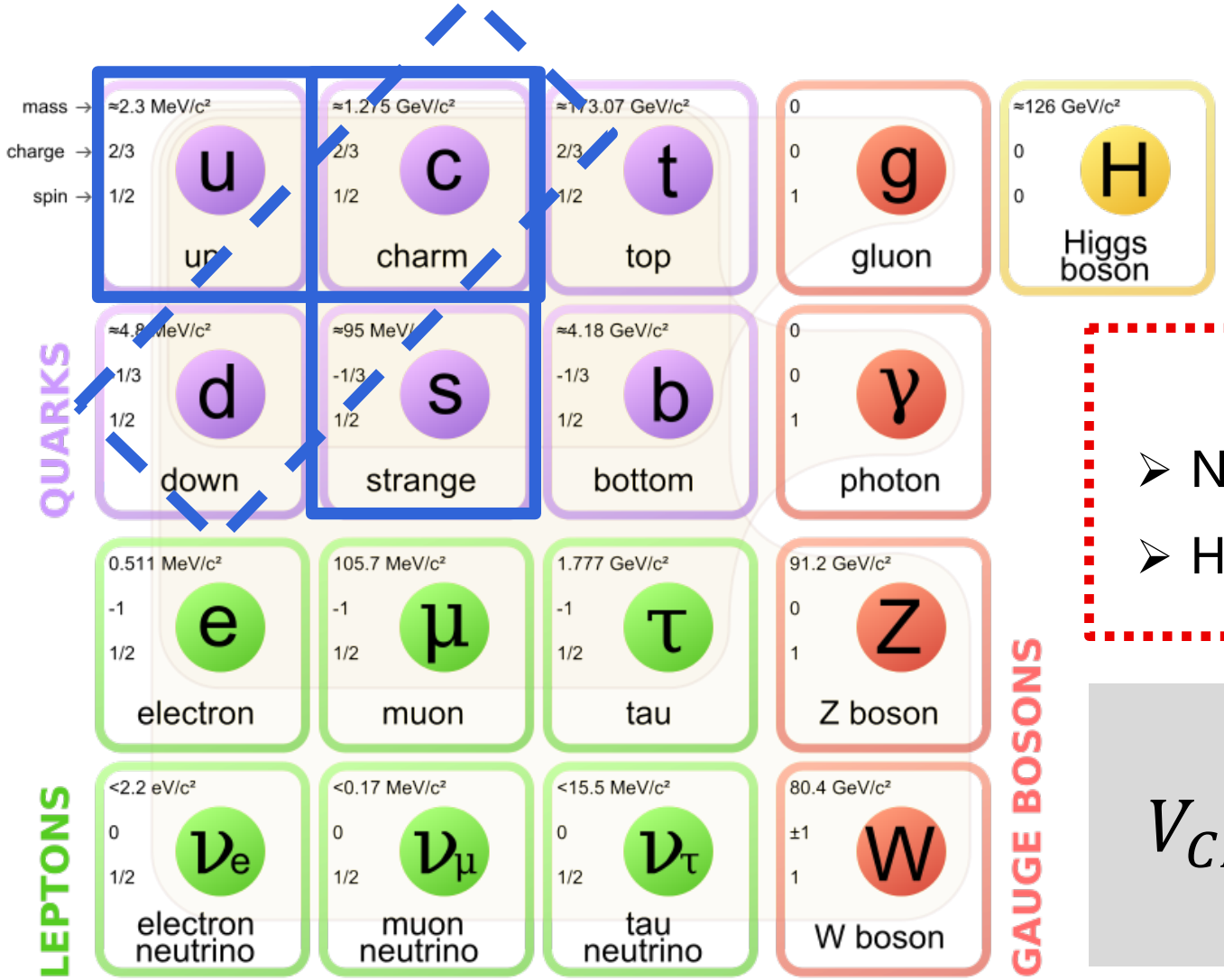
Content

Physics motivation



Charm physics

- Nonperturbative region -> **QCD**
- High precision frontier -> **SM test**

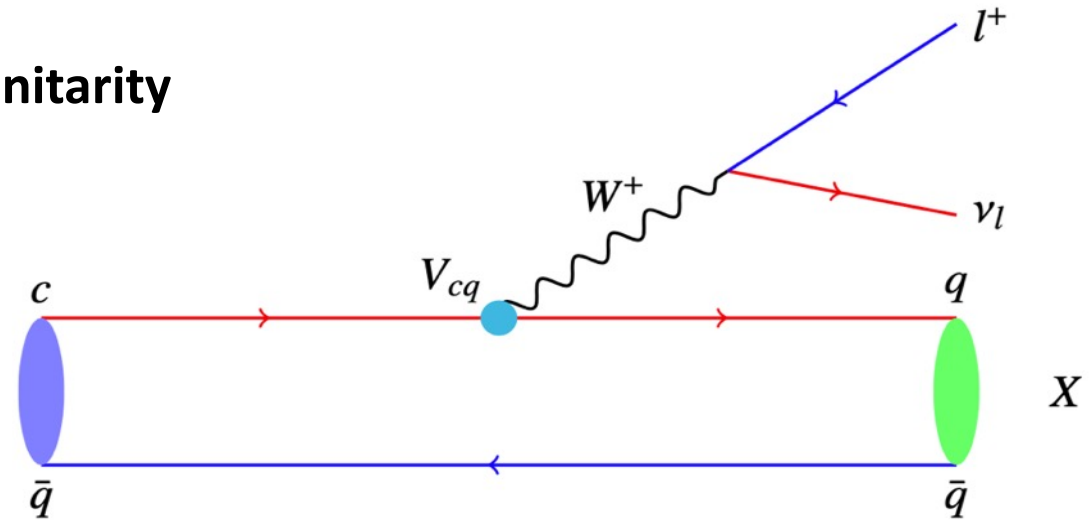
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Physics motivation

- Hadronic Form factor(FF) **-> Test different QCD models**
- CKM matrix elements $V_{cd(s)}$ **-> Test CKM matrix unitarity**
- $\mathcal{B}(D_{(s)} \to X\mu^+\nu_\mu)/\mathcal{B}(D_{(s)} \to Xe^+\nu_e)$

  -> Lepton flavor universality (LFU) test.
- Branching fraction and FF measurement

  -> Good laboratory for **light scalar mesons study**

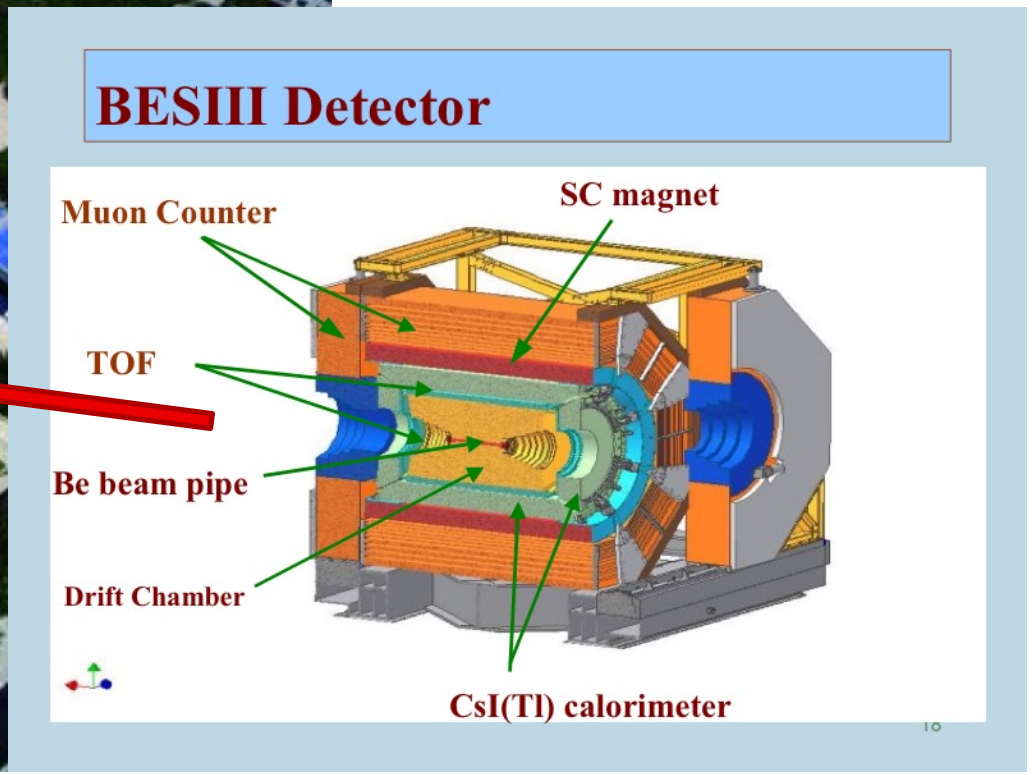


$$A(D \longrightarrow X\ell\upsilon) = \frac{G_F}{\sqrt{2}} V_{cq}^* \upsilon\gamma_\mu(1-\gamma_5)\ell < X|\bar{q}\gamma^\mu(1-\gamma_5)c|D_{(s)} >$$

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

$$\Gamma(D_{(s)} \to V\ell^+\upsilon_\ell) \propto \left|V_{cd(s)}\right|^2 \mathfrak{T}(A_1(q^2), A_2(q^2), V(q^2))dq^2$$

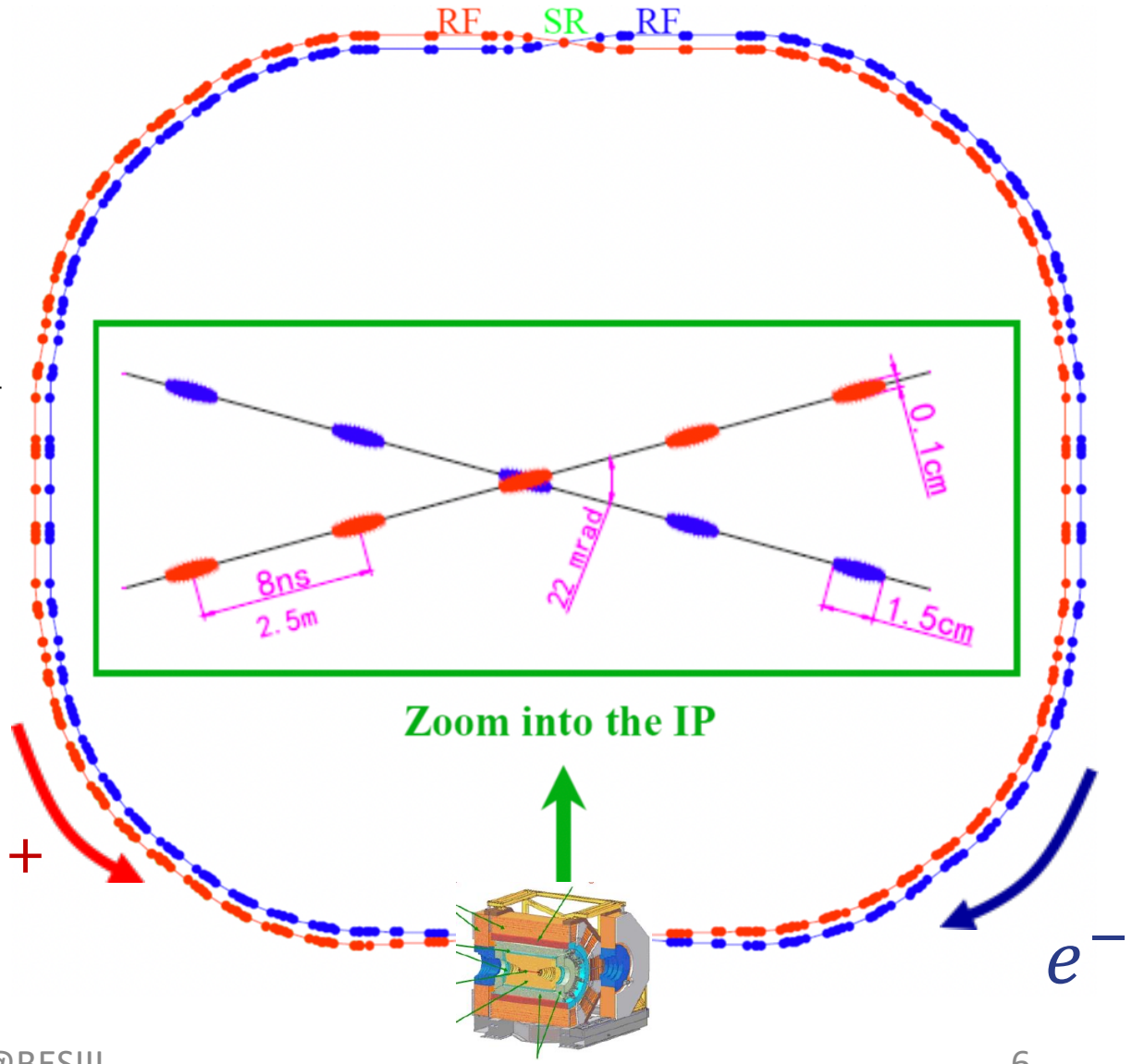
BESIII experiment



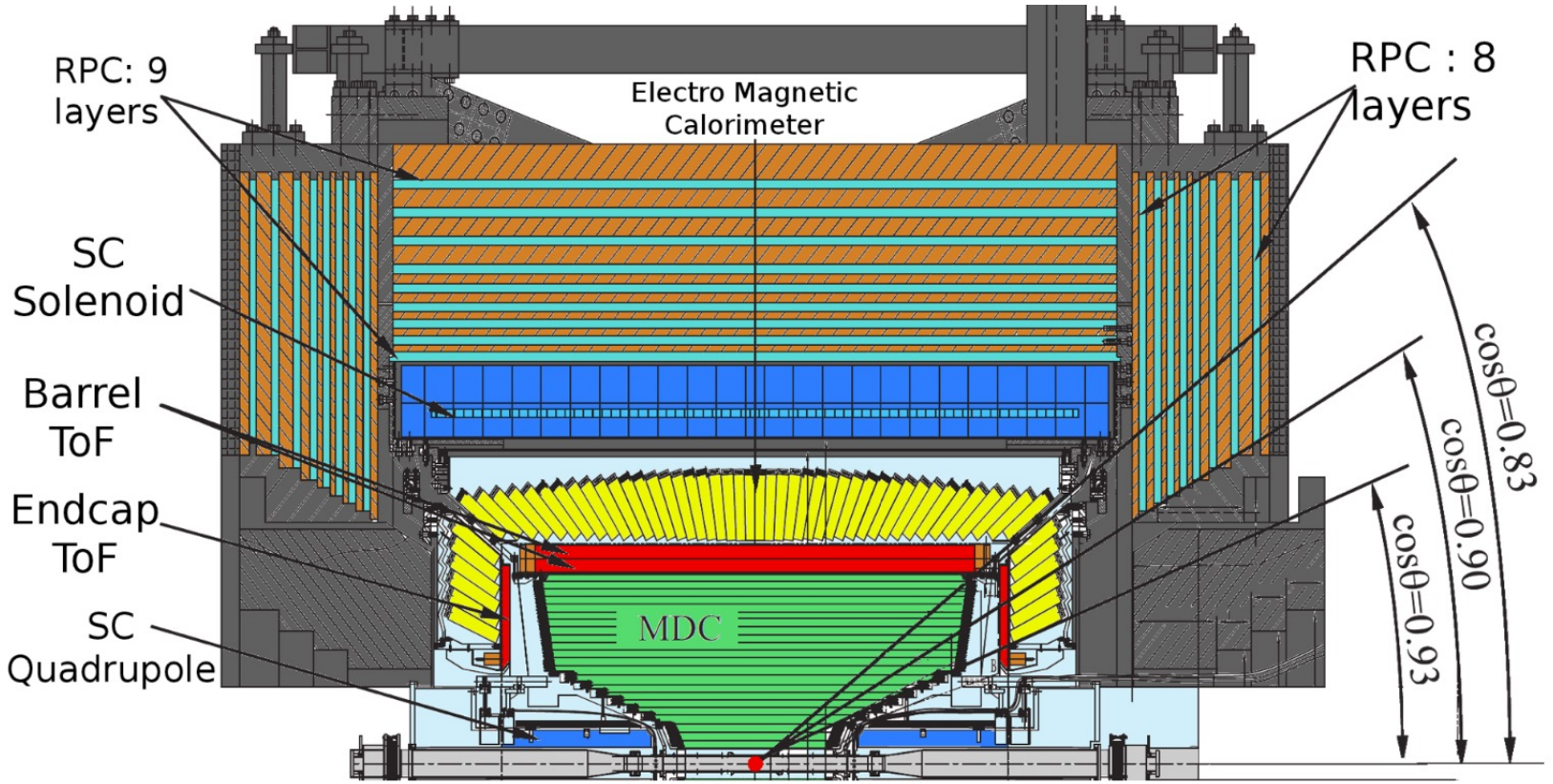
BEPCII collider

- 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



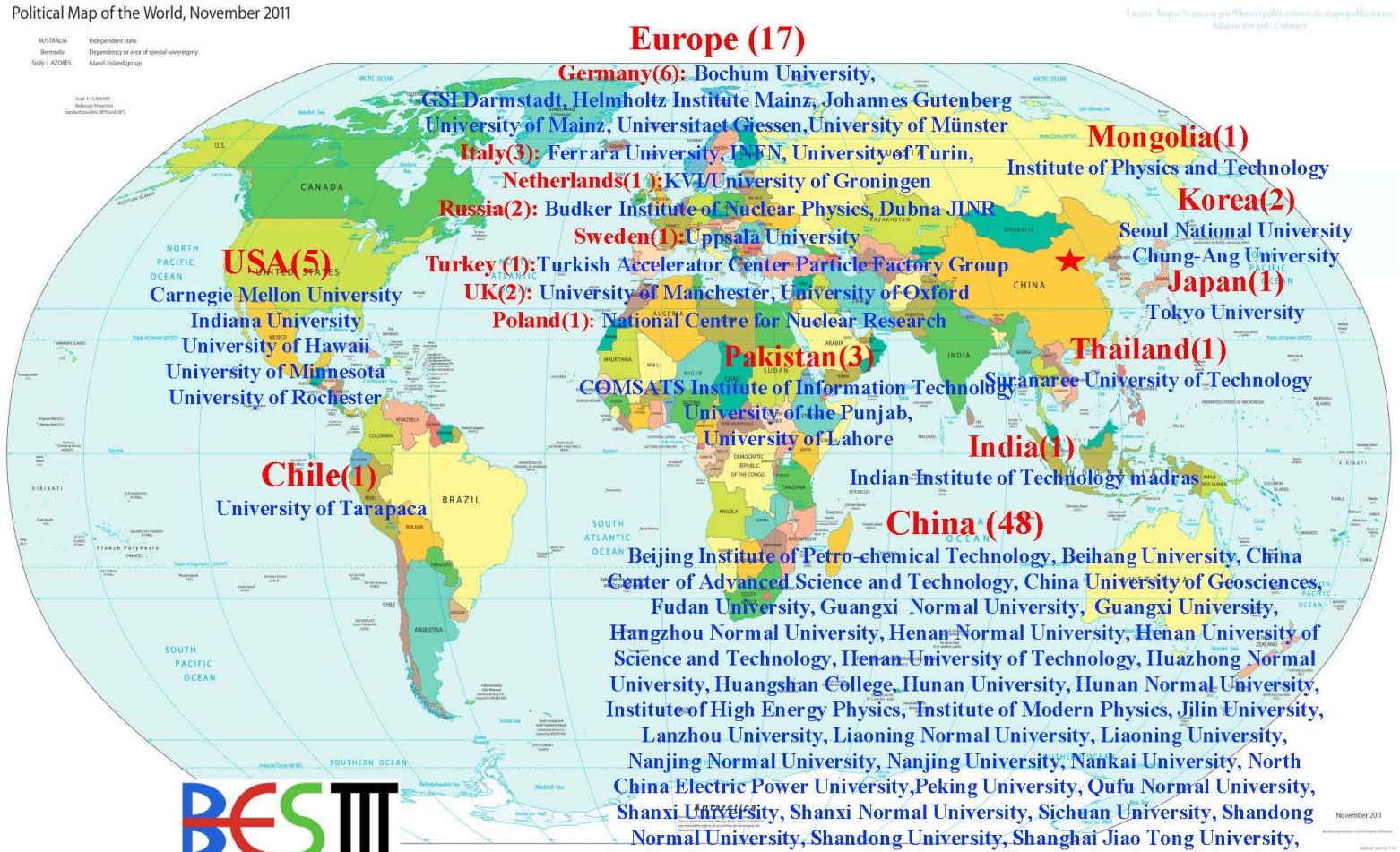
MDC
$\frac{\delta p}{p} < 0.5\%$ @1 GeV
$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

TOF
δt 80 ps Barrel
δt 110 ps Endcap

EMC
$\frac{\delta E}{E} < 2.5\%$ @1 GeV
$\delta z = 0.6/\sqrt{E}$

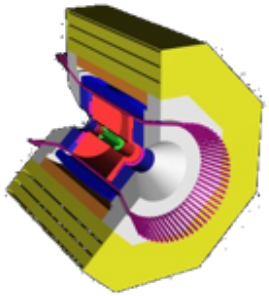
MUC
$\delta(xy)$ <2 cm

BESIII Collaboration



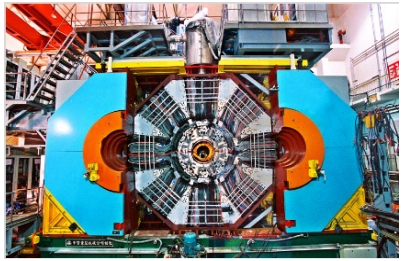
Data sample

CLEO-c



BABAR

BESIII



Belle, Belle-II

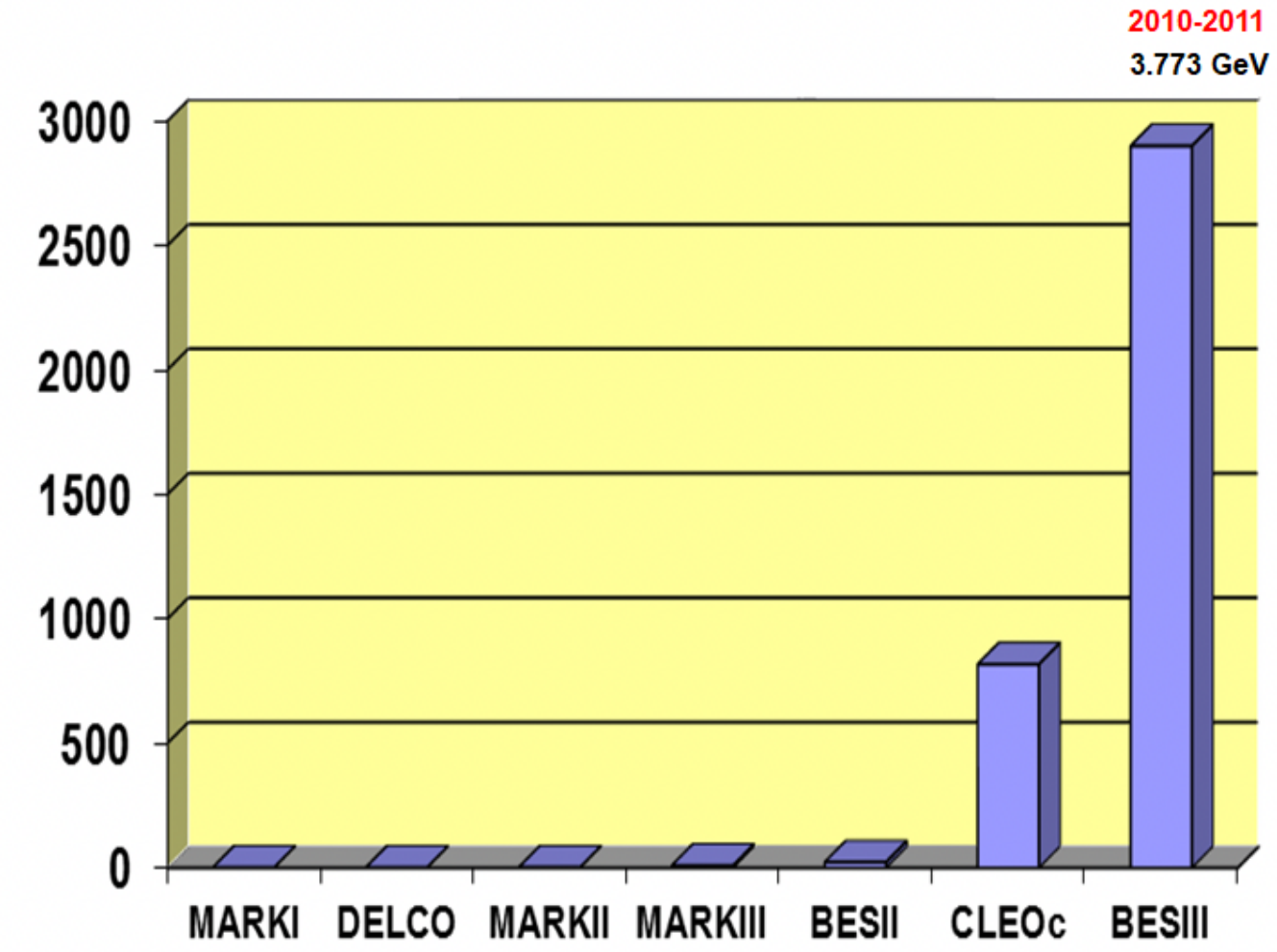
- Symmetric e^+e^- collider
- E_{cm}: 2 – 5 GeV
- Charm collected through pair-production near threshold

- Asymmetric e^+e^- collider
- E_{cm}: 10.8 GeV
- Charm collected through $b\bar{b}$ decays and $c\bar{c}$

Data sample

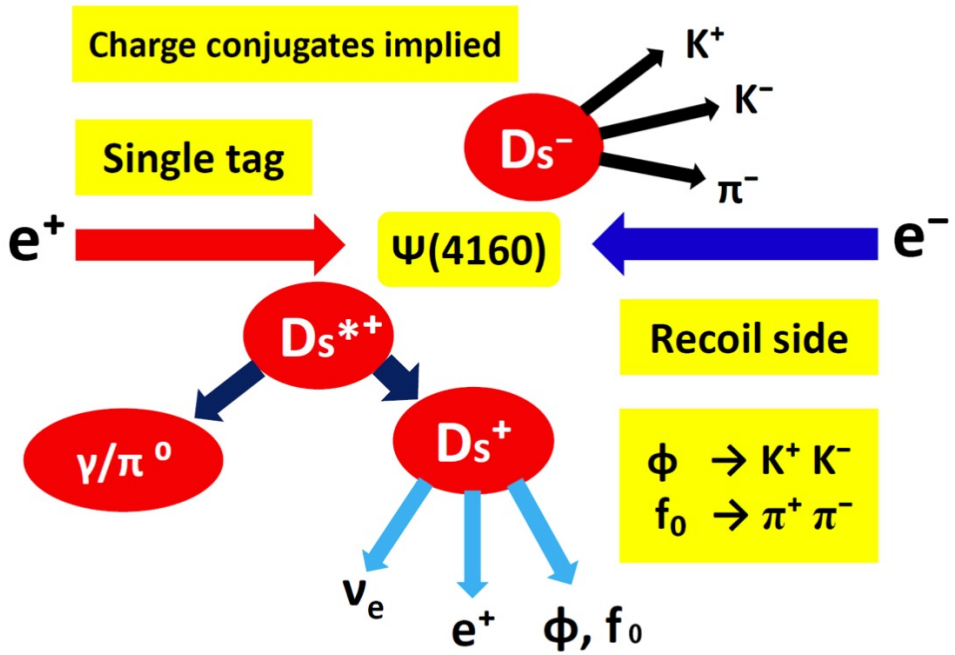
Experiment	Data size	Energy region	Time
BESIII	$D^{+(0)}$: 2.93 fb^{-1} D_s^+: 7.33 fb^{-1}	3.773 GeV 4.123-4.223GeV	2010-2011 2013-2017
CLEO-c	$D^{+(0)}$: 0.82 fb^{-1} D_s^+: 0.6 fb^{-1}	3.770 GeV 4.170 GeV	Till 2008
BABAR	468 fb^{-1}	Near $\Upsilon(4S)$	Till 2008
Belle	976 fb^{-1}	Near $\Upsilon(4S)$	Till 2010

Data sample


D⁰(+) samples at ψ(3770)
2010-2011
3.773 GeV
3000
2500
2000
1500
1000
500
0
MARKI
DELCO
MARKII
MARKIII
BESII
CLEOc
BESIII

Analysis method: Double Tag

Take Ds decay as an example (complicated case)



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

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

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

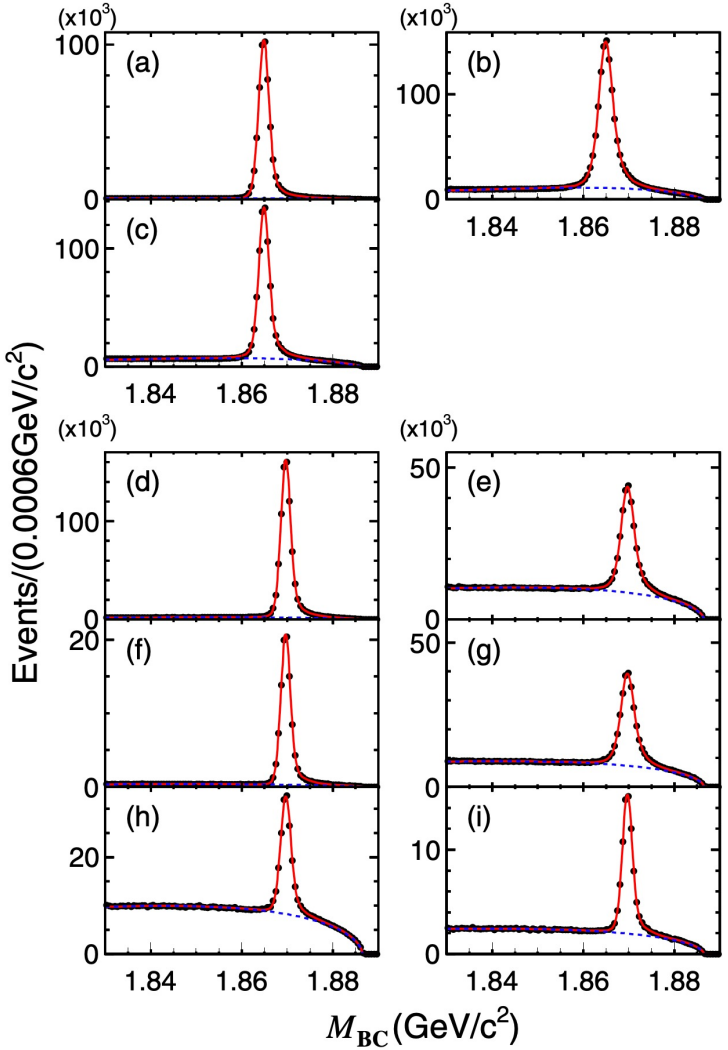
$$\mathcal{B}_{sig} = \frac{N_{sig}}{\mathcal{B}_\gamma \sum_\alpha N_{tag}^\alpha \epsilon_{sig}^\alpha/\epsilon_{tag}^\alpha}$$

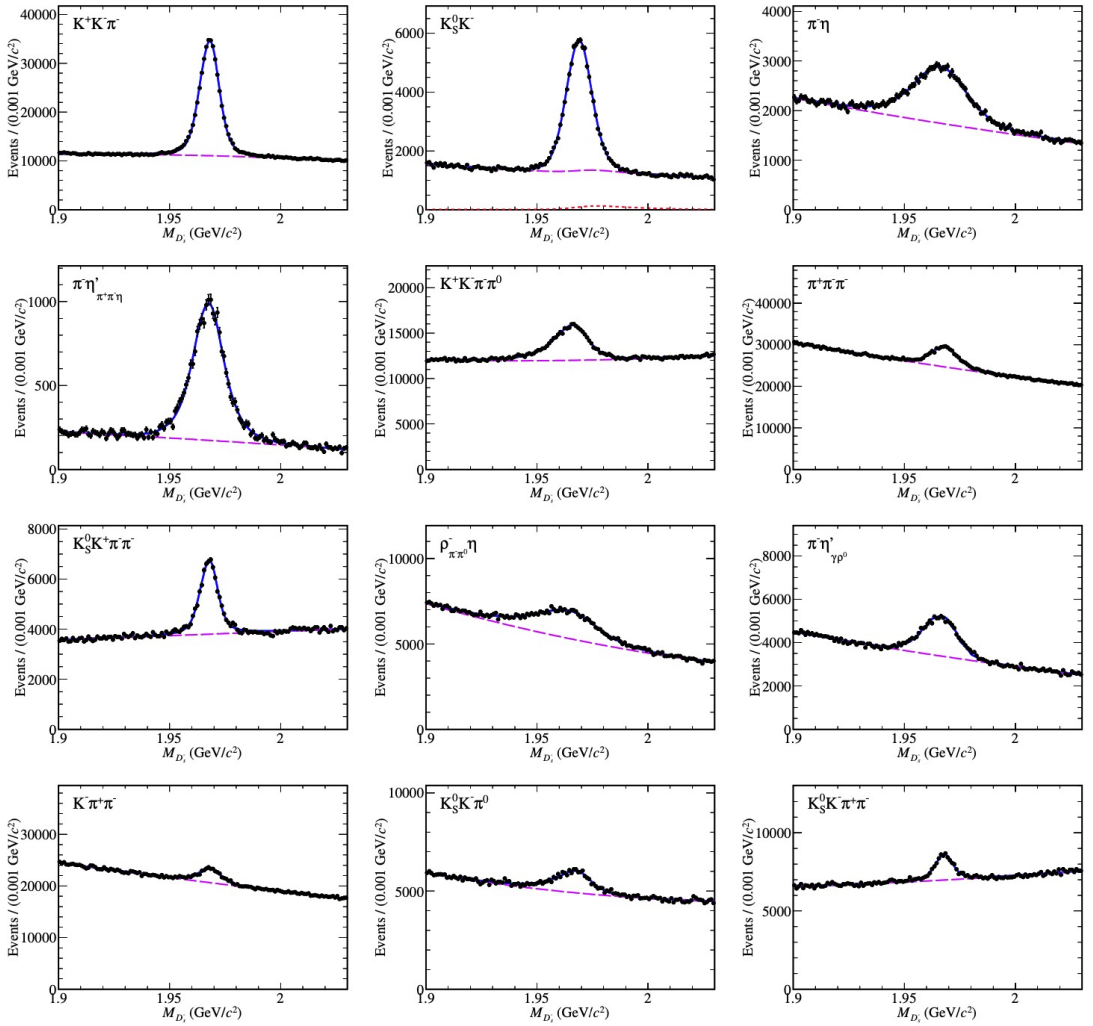
$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$
$$M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}|^2$$

Analysis method: Single Tag sample

D^0: ~2.76 M

D^+: ~1.57 M





D_s: 0.77 M

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

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

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

- Use least χ^2 method to fit the measured partial decay width in different q^2 bin
- Taking the correlations among 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

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

– Series expansion model

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

The differential decay rate of $D_{(s)}$ -> Scalar $\ell\upsilon_\ell$

- Point-like differential decay rate:

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

- Double differential decay rate:

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

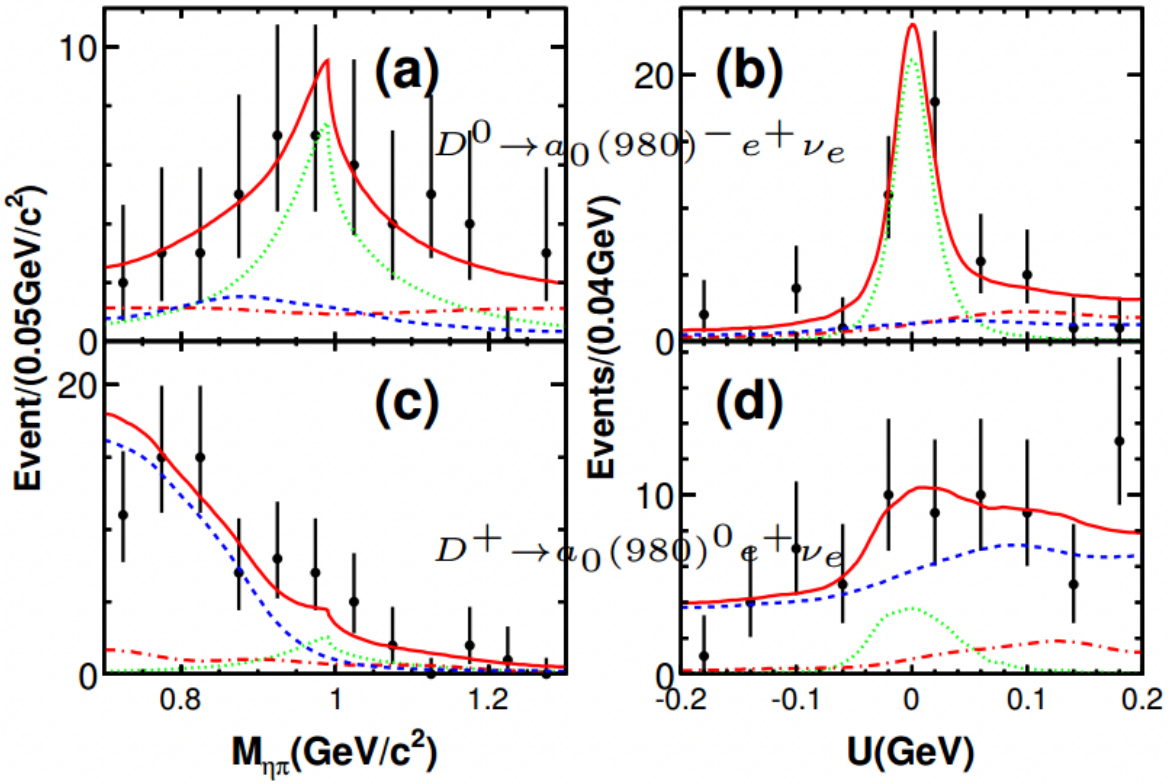
$$\frac{d^2\Gamma(D_{(s)}\to S\ell^+\upsilon_\ell)}{dsdq^2} = \frac{G_F^2|V_{cs}|^2}{192\pi^4 m_{D_{(s)}}^3} \lambda^{\frac{3}{2}}\left(m_{D_{(s)}}^2, s, q^2\right) |f_+(q^2)|^2 P(s)$$

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

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
- $N_{sig}^{D^0} = 25.7^{+6.4}_{-5.7}$
- $N_{sig}^{D^+} = 10.2^{+5.0}_{-4.1}$
- BFs help to understand the nature of the $a_0(980)$



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

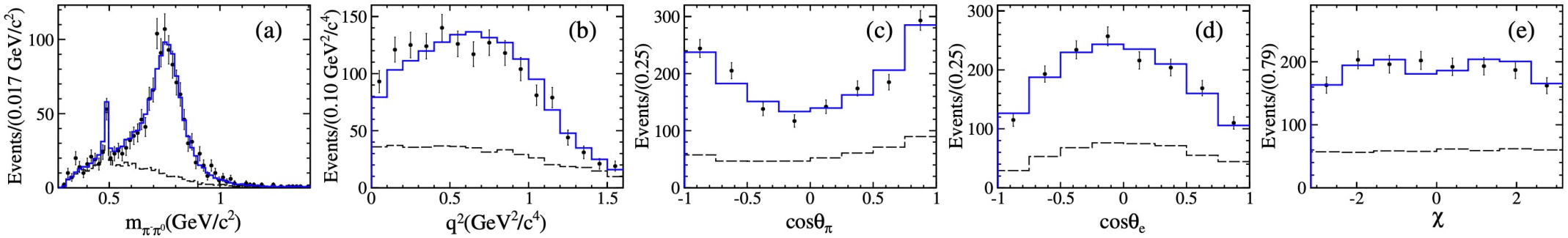
First observation of $D^+ \to f_0(500)e^+\upsilon_e$

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

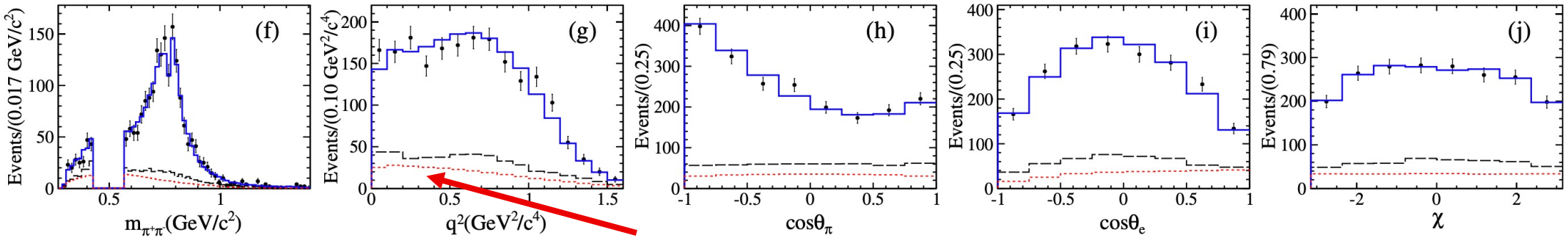
$N_{sig}^{D^0} = 1498$ (Bkg:~33.3%)

$N_{sig}^{D^+} = 2017$ (Bkg:~23.8%)

D^0



D^+



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

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

- $R = \frac{\mathcal{B}(D^+\to f_0(500)e^+\upsilon_e)+\mathcal{B}(D^+\to f_0(980)e^+\upsilon_e)}{\mathcal{B}(D^+\to a_0(980)e^+\upsilon_e)} > 2.7@90\%CL$
- 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

Study of light scalar mesons through $D_s^+ \to \pi^0\pi^0 e^+\nu_e$ 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
- $N_{sig}^{f_0(980)} = 54.8 + 10.1$ (7.8 σ significance)
- First BFs Measurement:

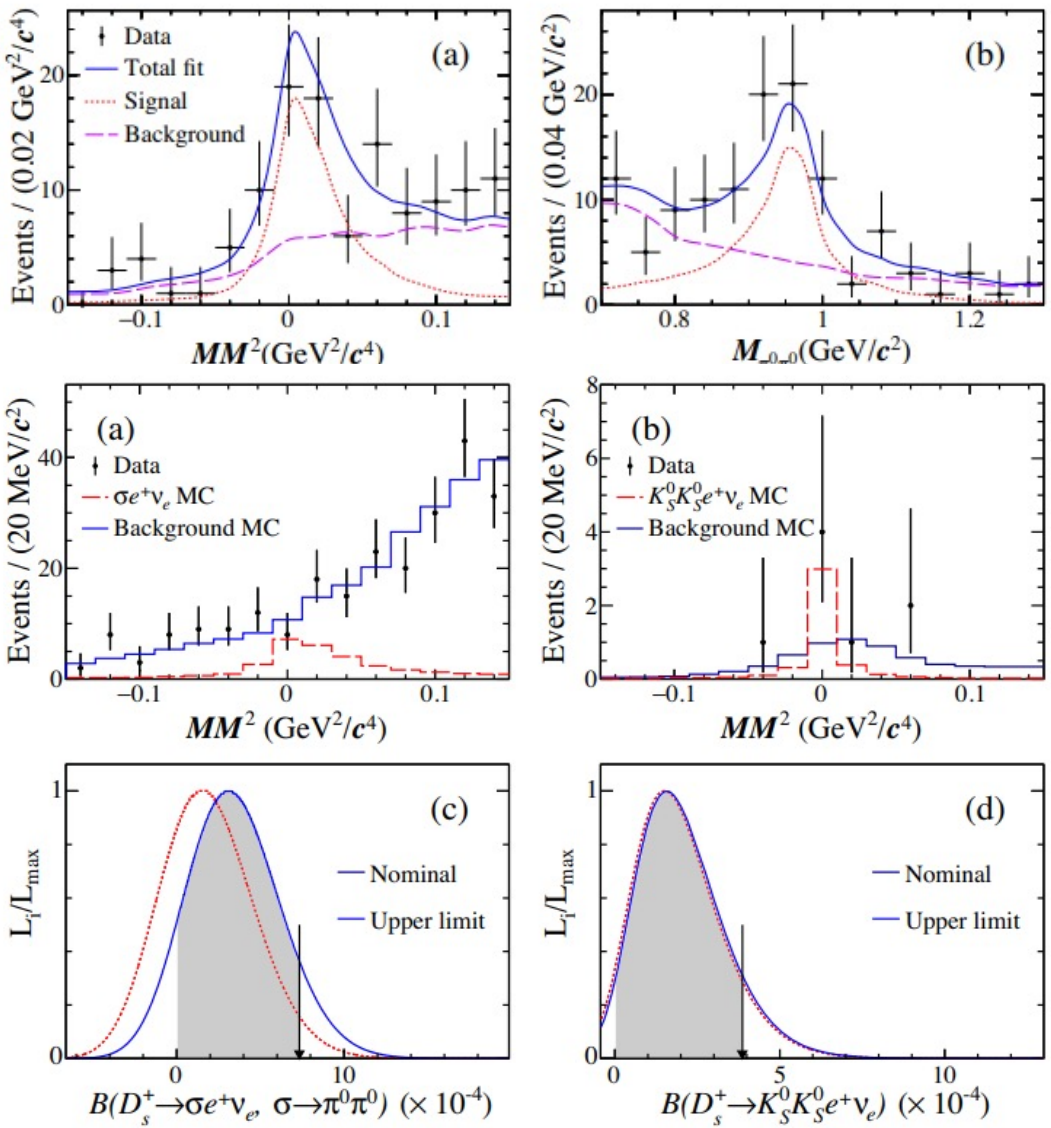
$$\mathcal{B}(D_s^+ \to f_0(980)e^+\nu_e, f_0(980) \to \pi^0\pi^0) = (7.9 \pm 1.4 \pm 0.4)\times 10^{-4}$$

- No significant signal:

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

$$\mathcal{B}(D_s^+ \to K_S^0 K_S^0 e^+\nu_e) < 3.8 \times 10^{-4}$$

- 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 $D_s^+ \to \pi^+\pi^- e^+ \upsilon_e$

Arxiv: 2303.12927 (submitted to PRL)

- 7.33 fb^{-1} data @ 4.128-4.226 GeV
- $N_{sig} = 439 \pm 33$

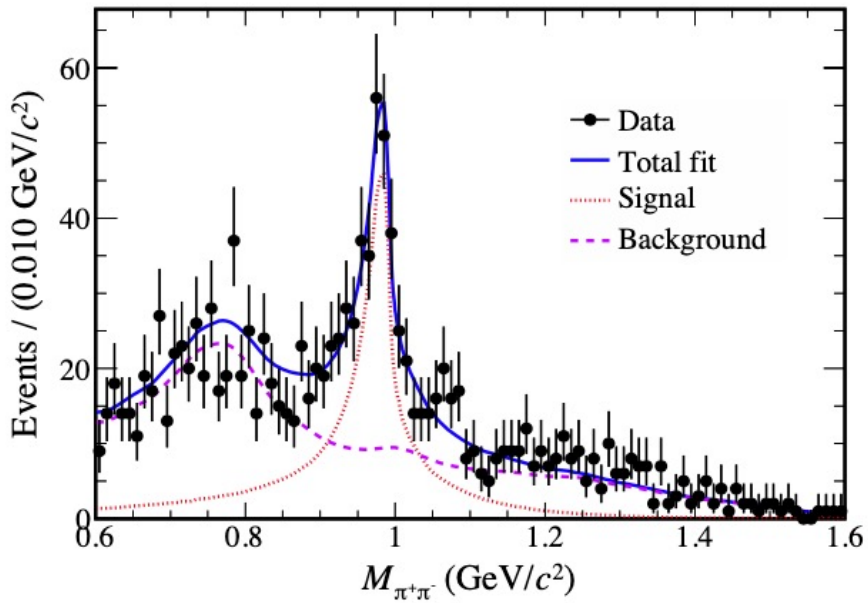
$$\mathcal{B}(D_s^+ \to f_0(980) e^+ \nu_e, f_0(980) \to \pi^+\pi^-) = (1.72 \pm 0.13 \pm 0.10)\times 10^{-3}$$

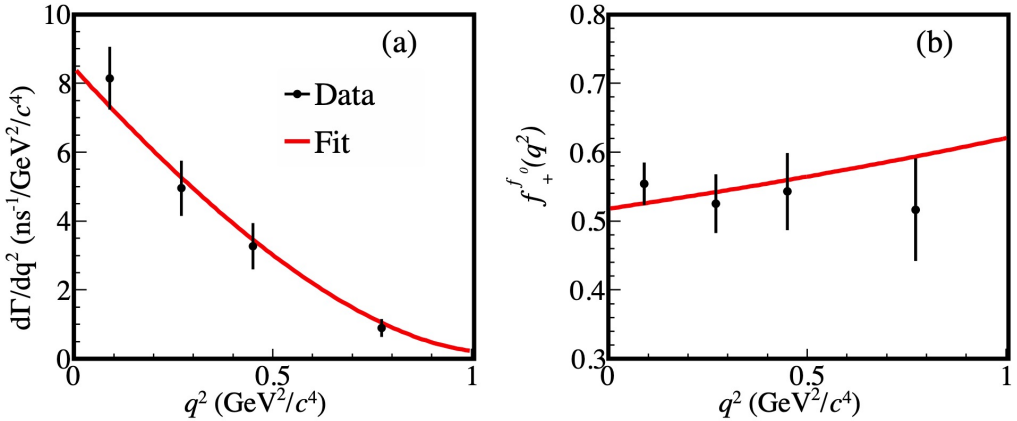
⇢ $s\bar{s}$ is dominant based on $q\bar{q}$ mixture picture

- **First form factor measurement** based on single pole:

$$f_+^{f_0}(0)|V_{cs}| = 0.504 + 0.017 + 0.35$$

ps: Have considered the width effect of the $f_0(980)$





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 D decay.
- BFs and FF measurements help to understand the nature of light scalar mesons.

Prospect:

- BESIII has **8 fb^{-1}** @3.773 GeV now.
- In the coming 2024, BESIII will have **20 fb^{-1}** @3.773 GeV in total.
- More results are on the way!

Thank you!