Study of light scalar mesons via semi-leptonic D decays at BESIII

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强子质量的非微扰起源

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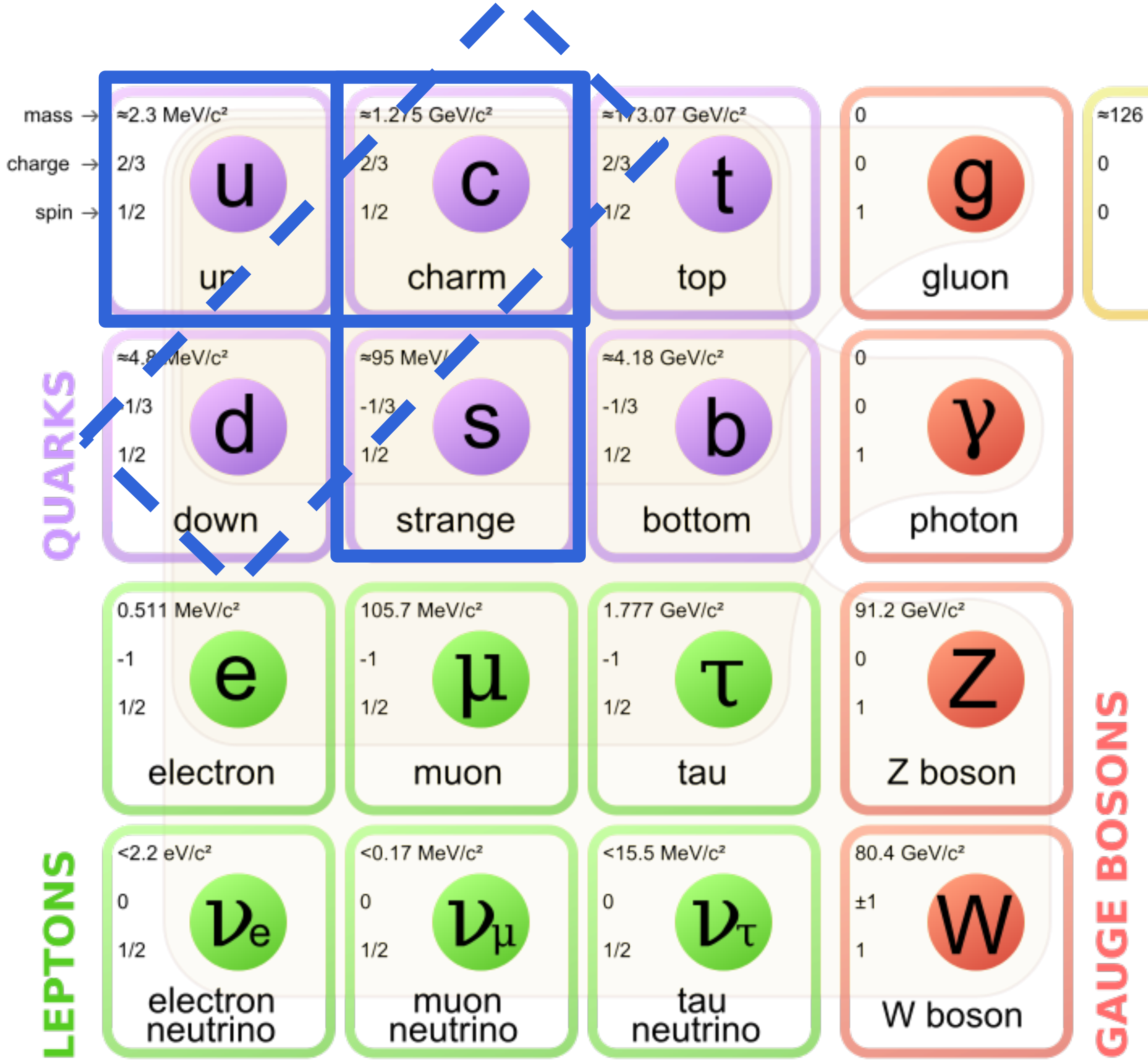
Content

Physics motivation



Charm physics

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

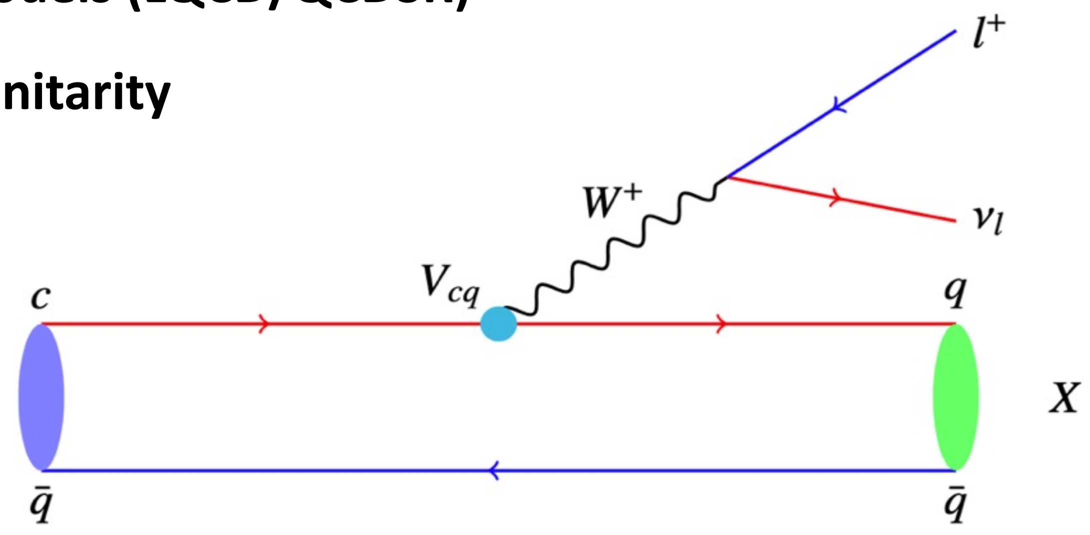
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Physics motivation

- Hadronic Form factor(FF) **-> Test different QCD models (LQCD/QCDSR)**
- 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**



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

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

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

Physics motivation

Light scalar mesons $f_0(500), f_0(980)$ and $a_0(980)$

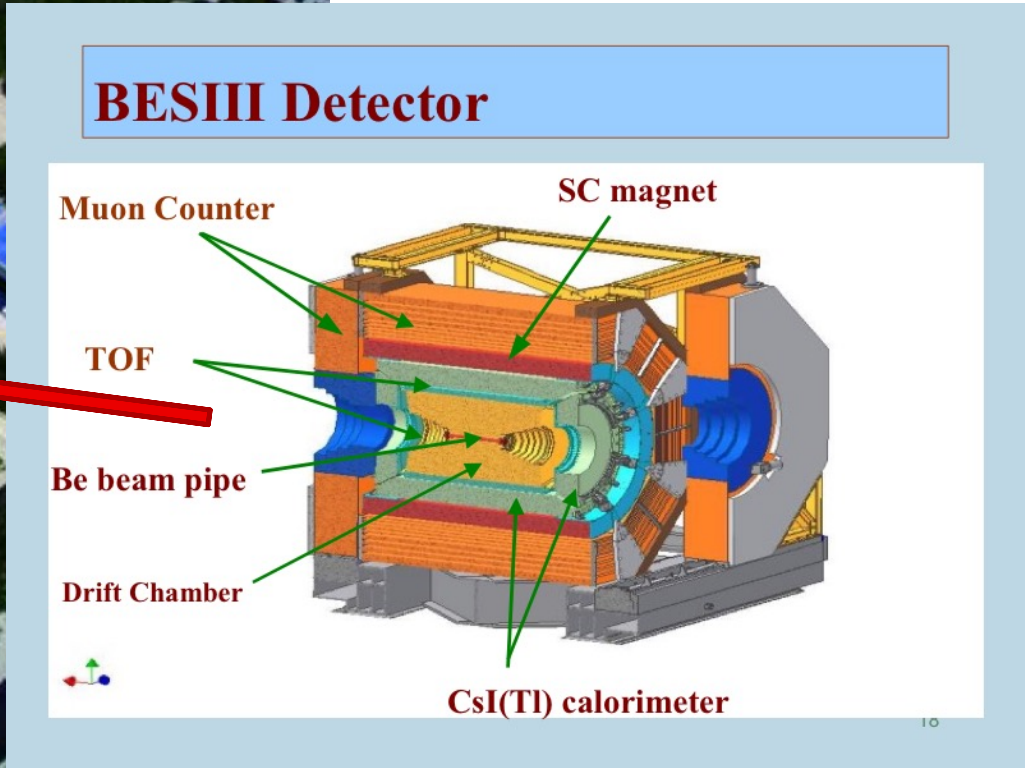
- Play a important role in the dynamics of the spontaneous breaking of QCD chiral symmetry and in **the origin of pseudoscalar meson masses**. (?)
- Help to understand the confinement of quarks. (?)
- Their nontrivial quark structure has remained controversial for many years!
- Interpretations: $q\bar{q}$ mixture; tetraquark; molecule, etc.
- Semi-leptonic D decay is an ideal probe for their nature.

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

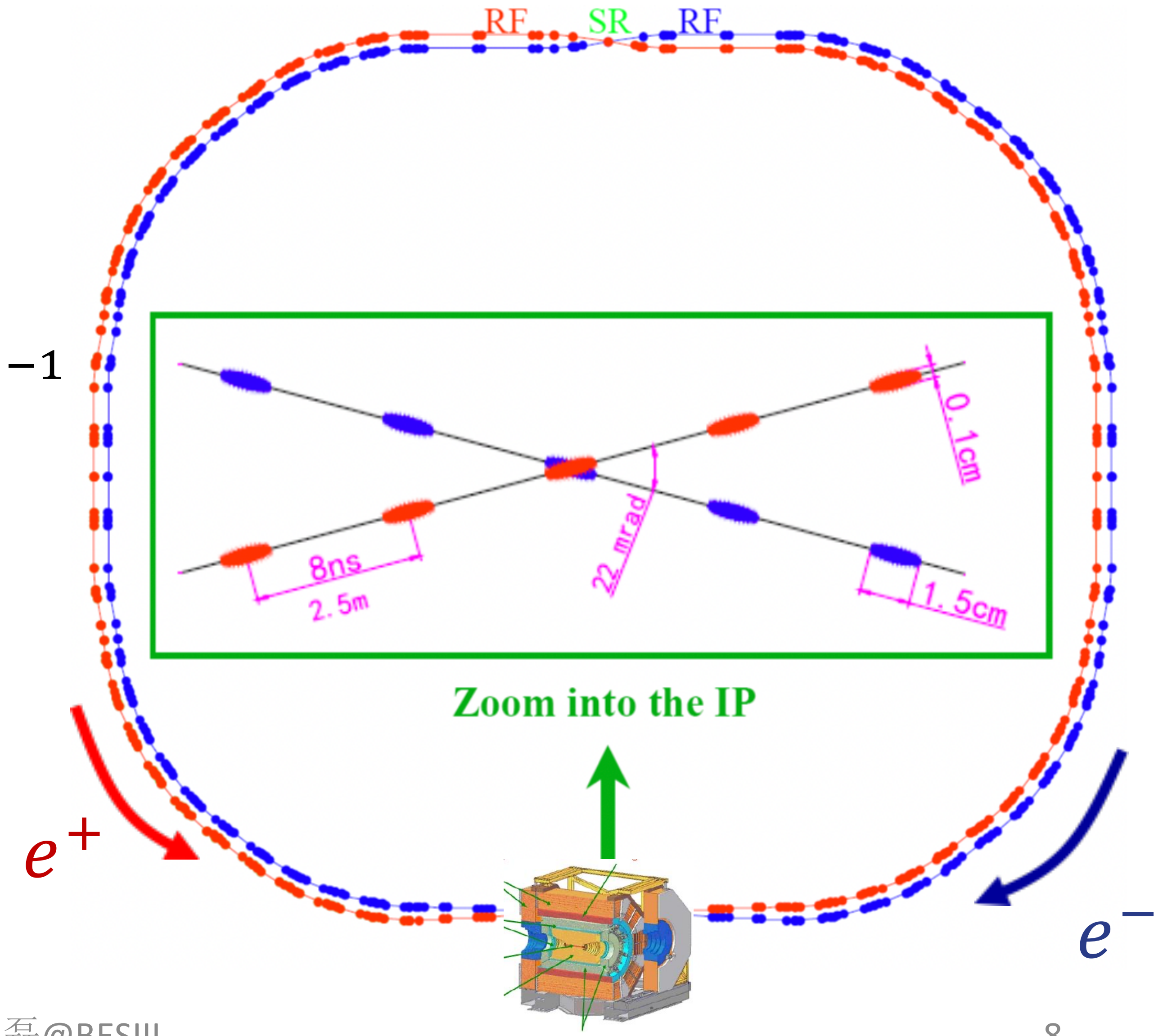
BESIII experiment



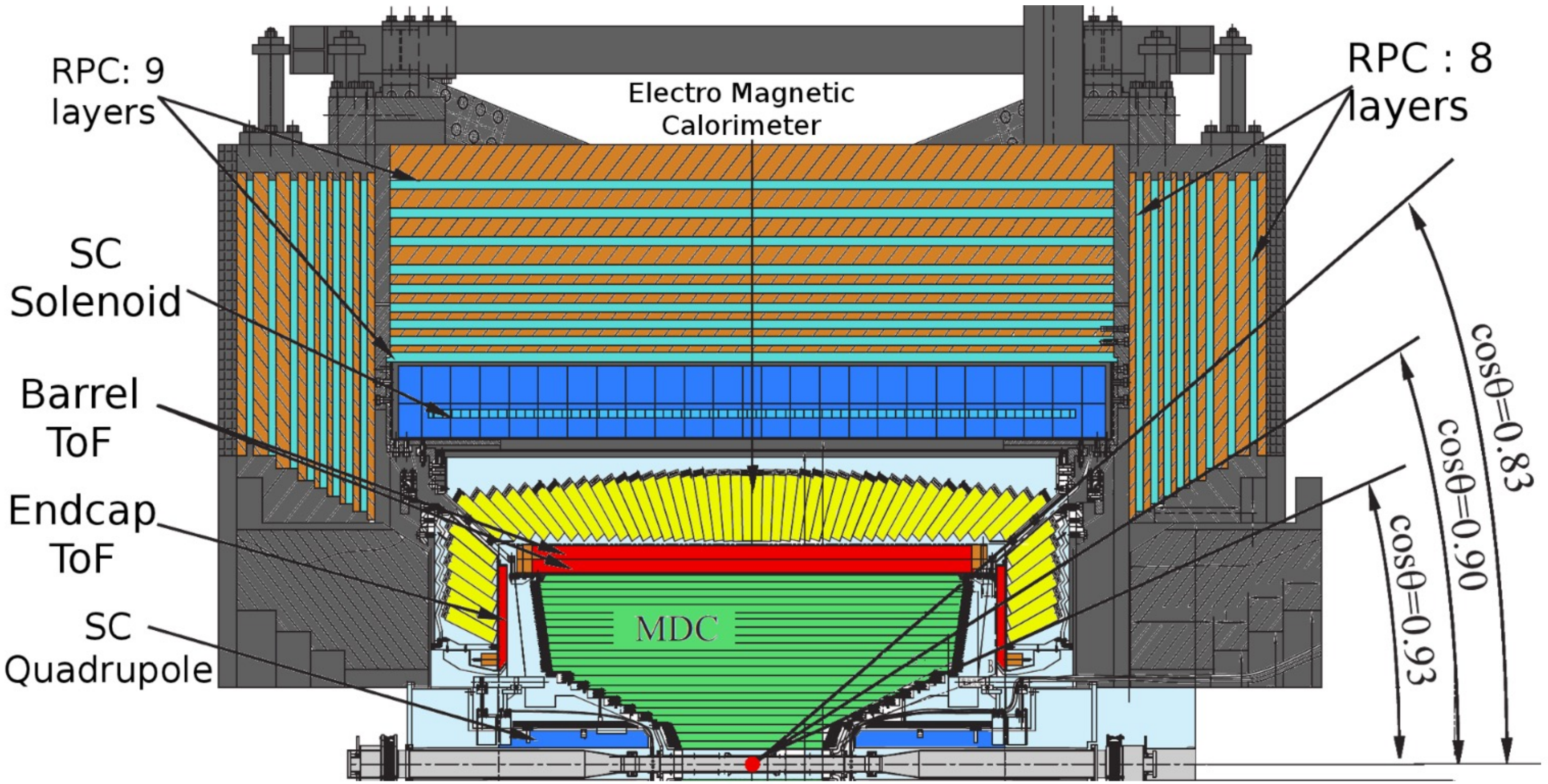
BEPCII collider

- 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



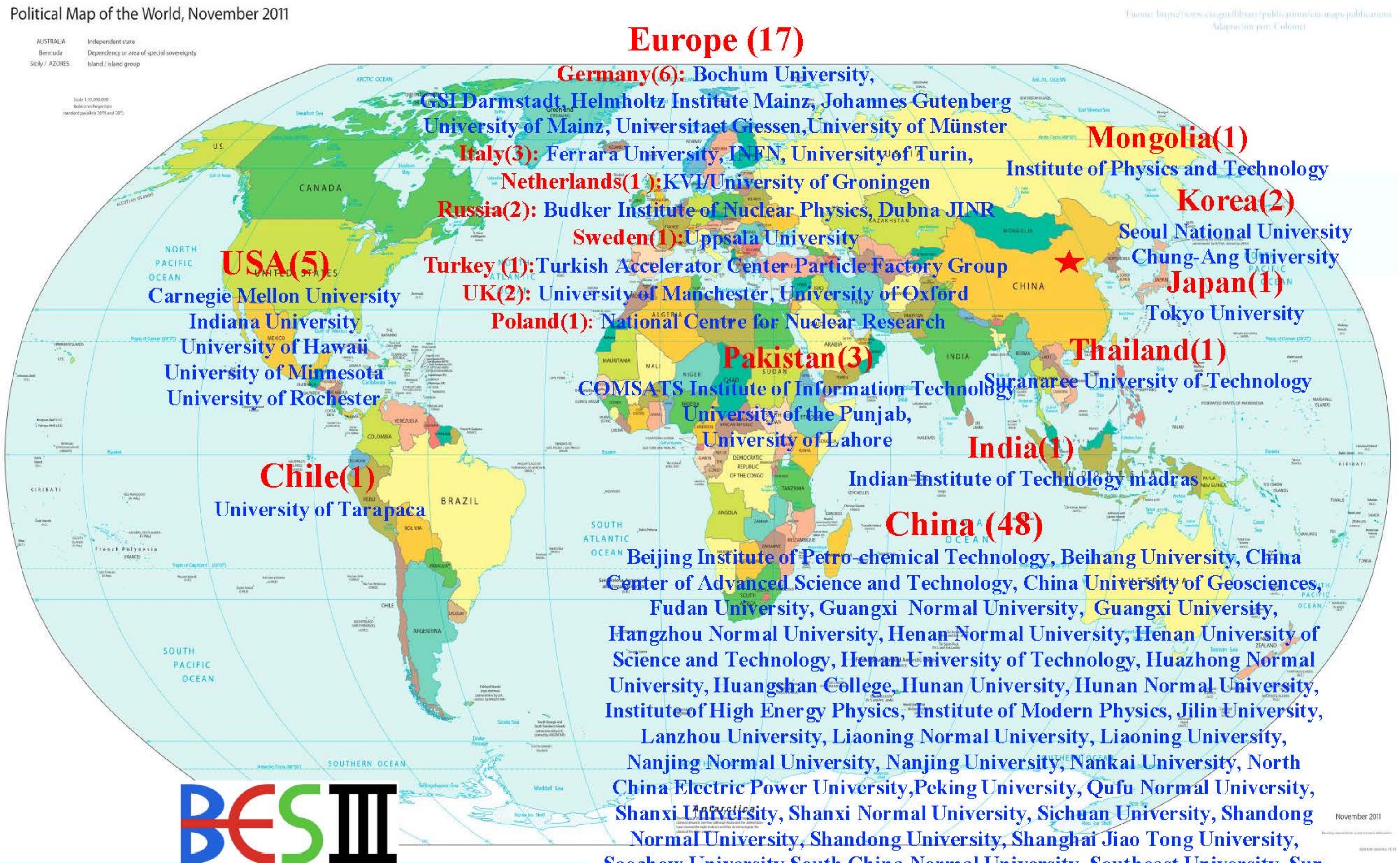
MDC
$\frac{\delta p}{p} < 0.5\%$ @1 GeV
$\frac{\delta(dE/dx)}{dE/dx} < 6\%$

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

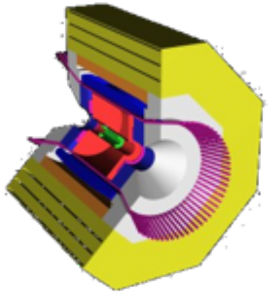
BESIII Collaboration



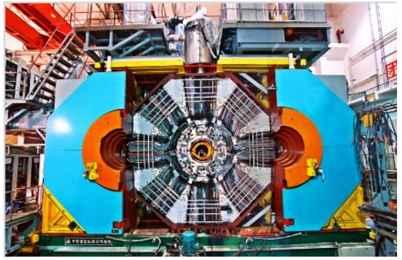
~500 members
From 80 institutions in 17 countries

Data sample

CLEO-c



BESIII



BABAR

Belle, Belle-II

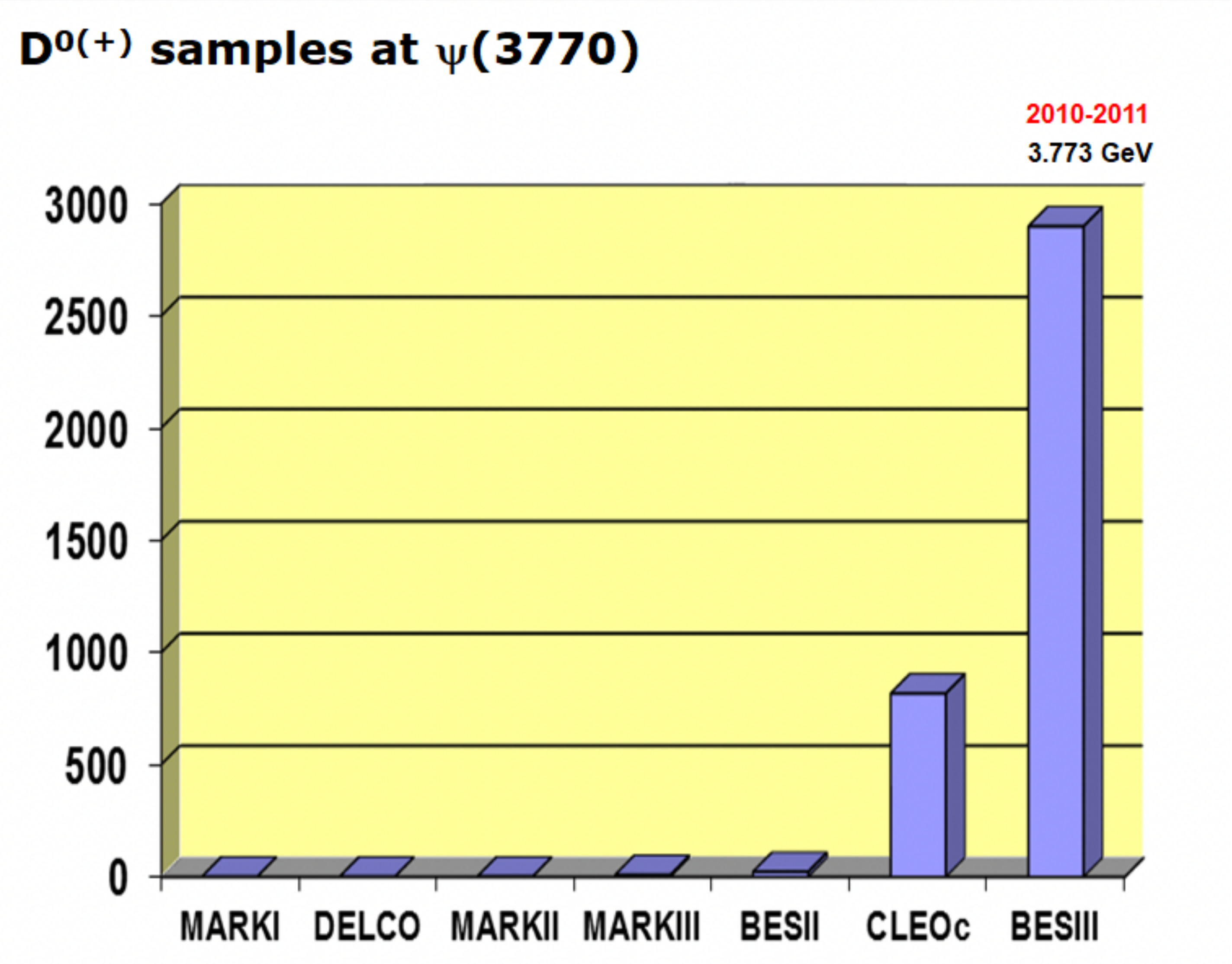
- Symmetric e^+e^- collider
- E_{cm}: 2 – 5 GeV
- Charm collected through pair-production near threshold

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

Data sample

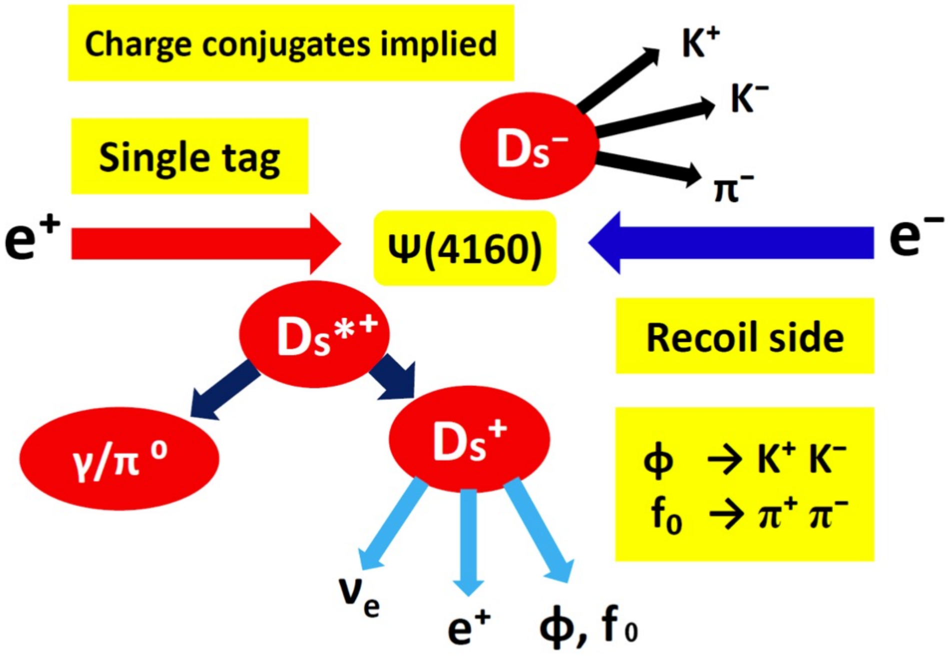
Experiment	Data size	Energy region	Time
BESIII	$D^{+(0)}$: 2.93 fb^{-1} D_s^+: 7.33 fb^{-1}	3.773 GeV 4.123-4.223GeV	2010-2011 2013-2017
CLEO-c	$D^{+(0)}$: 0.82 fb^{-1} D_s^+: 0.6 fb^{-1}	3.770 GeV 4.170 GeV	Till 2008
BABAR	468 fb^{-1}	Near $\Upsilon(4S)$	Till 2008
Belle	976 fb^{-1}	Near $\Upsilon(4S)$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



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

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

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

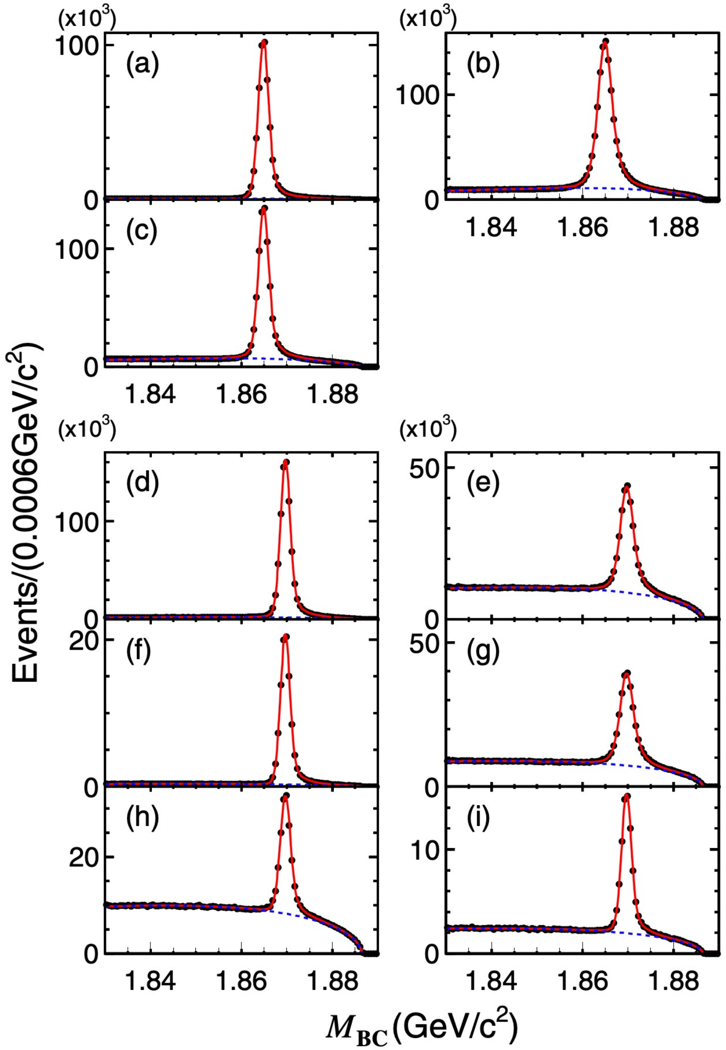
$$\mathcal{B}_{sig} = \frac{N_{sig}}{\mathcal{B}_{\gamma}\sum_{\alpha}N_{tag}^{\alpha}\epsilon_{sig}^{\alpha}/\epsilon_{tag}^{\alpha}}$$

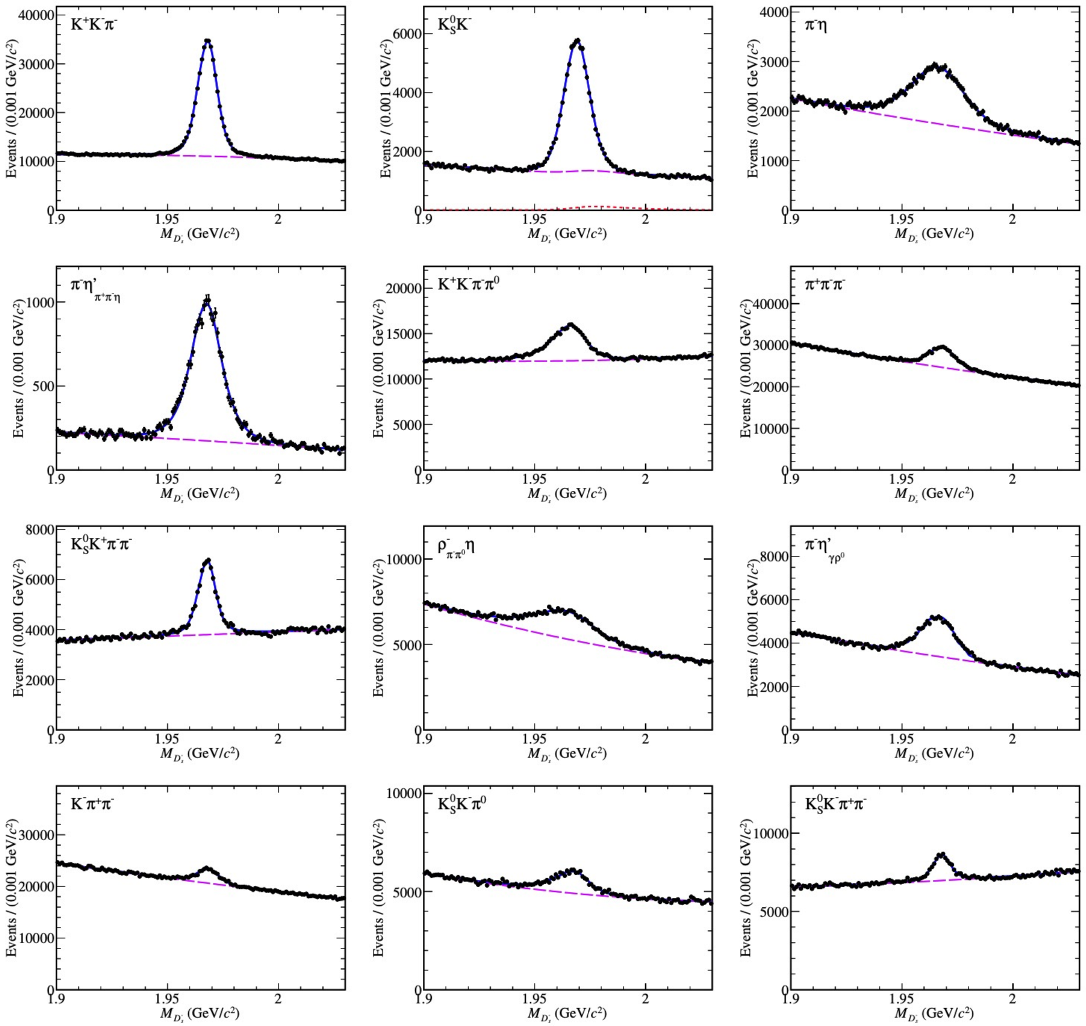
$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$
$$M_{miss}^2 = E_{miss}^2 - |\vec{p}_{miss}|^2$$

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**

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

– **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 $D_{(s)} \to S\,\ell\upsilon_\ell$

- 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))

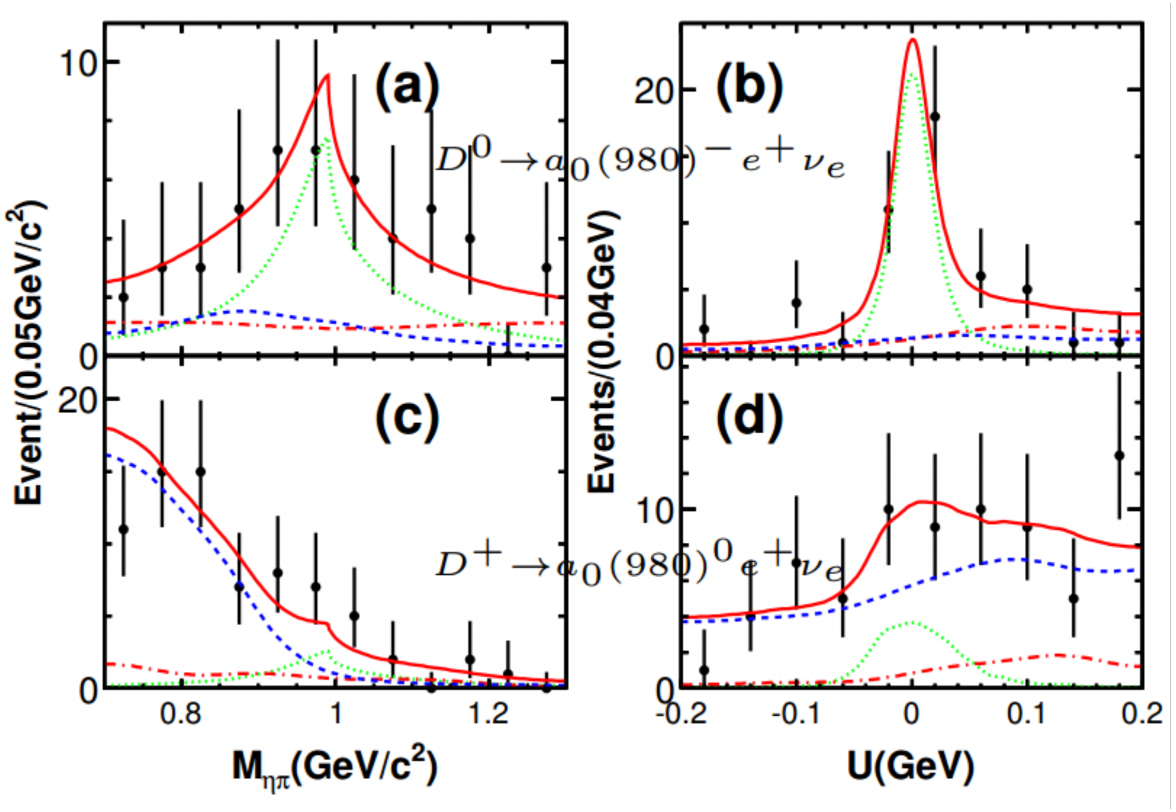
$$\frac{d^2\Gamma(D_{(s)}\to S\ell^+\upsilon_\ell)}{dsdq^2} = \frac{G_F^2|V_{cs}|^2}{192\pi^4 m_{D_{(s)}}^3} \lambda^{\frac{3}{2}}\left(m_{D_{(s)}}^2, s, q^2\right) |f_+(q^2)|^2 P(s)$$

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

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

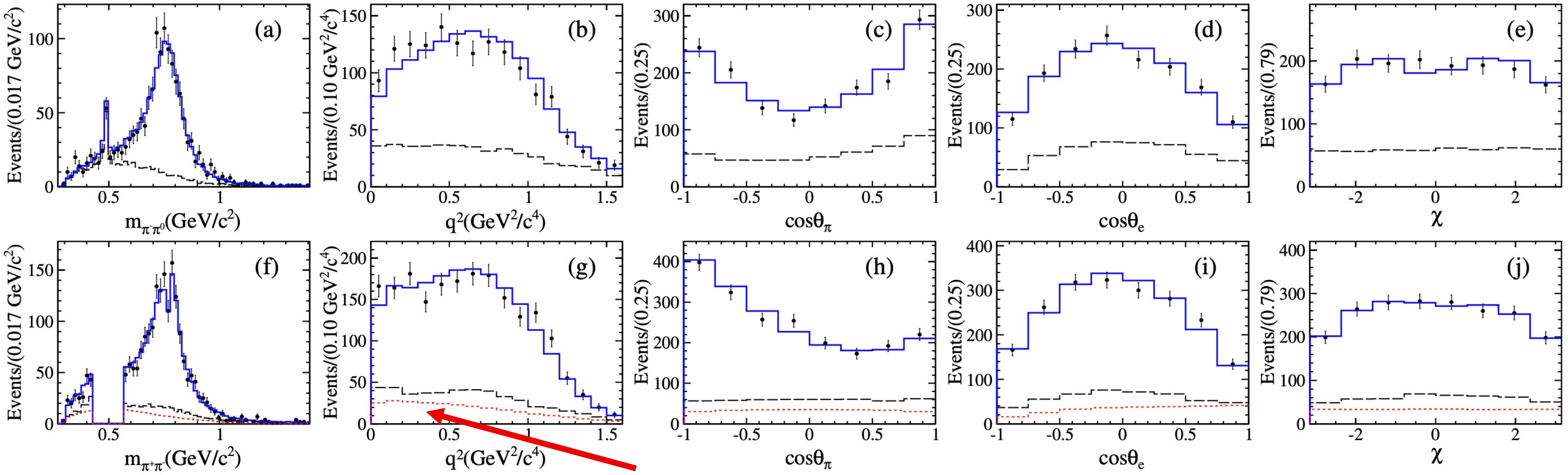
First observation of $D^+ \to f_0(500) e^+ \nu_e$

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

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

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

Study of light scalar mesons through $D_s^+ \to \pi^0\pi^0 e^+\upsilon_e$ and $D_s^+ \to K_S^0 K_S^0\, e^+\upsilon_e$

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

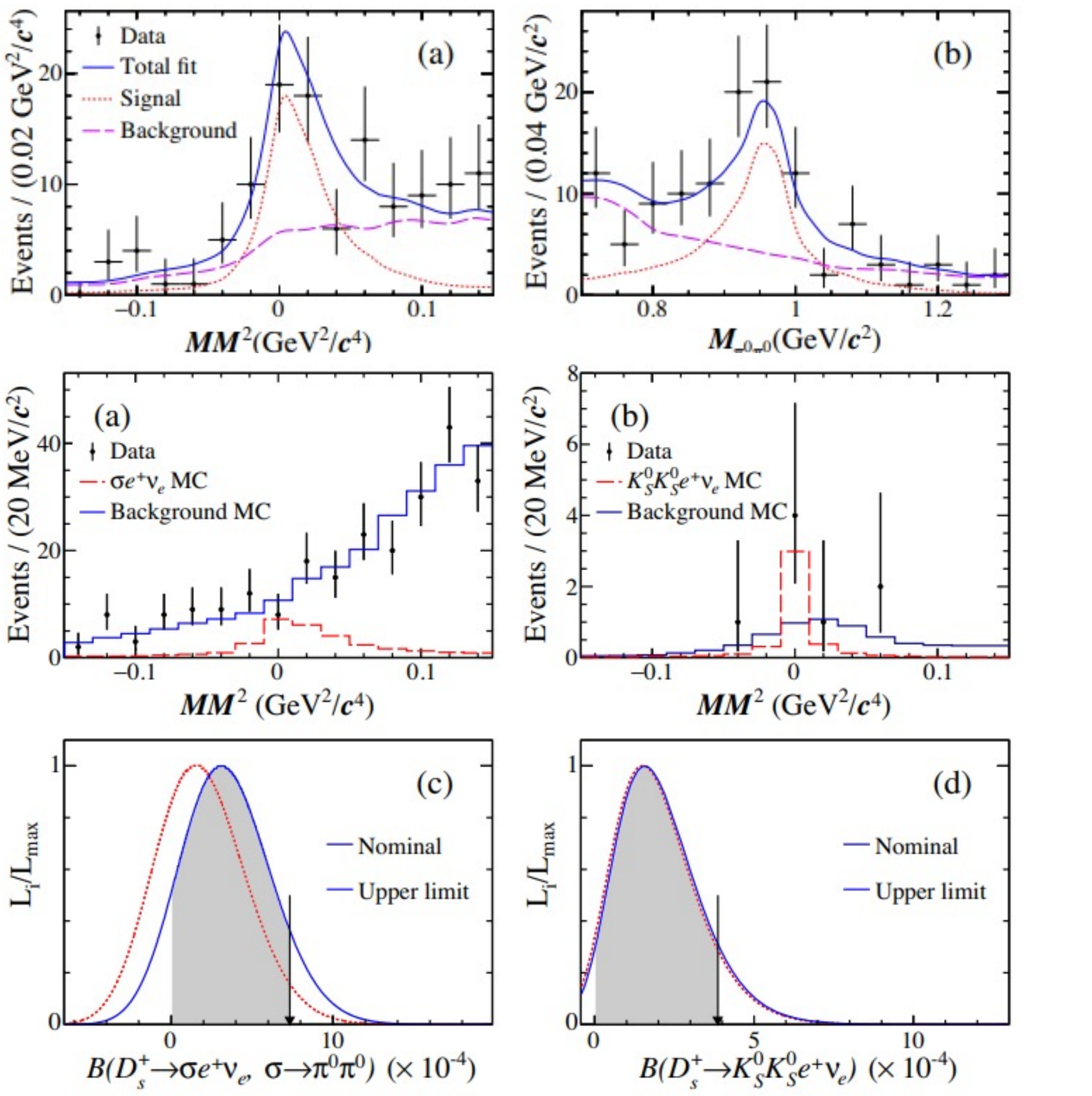
- 6.32 fb^{-1} data @ 4.178-4.226 GeV
- $N_{sig}^{f_0(980)} = 54.8 + 10.1$ (7.8 σ significance)
- First BFs Measurement:

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

- No significant signal:

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

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

Arxiv: 2303.12927 (submitted to PRL)

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

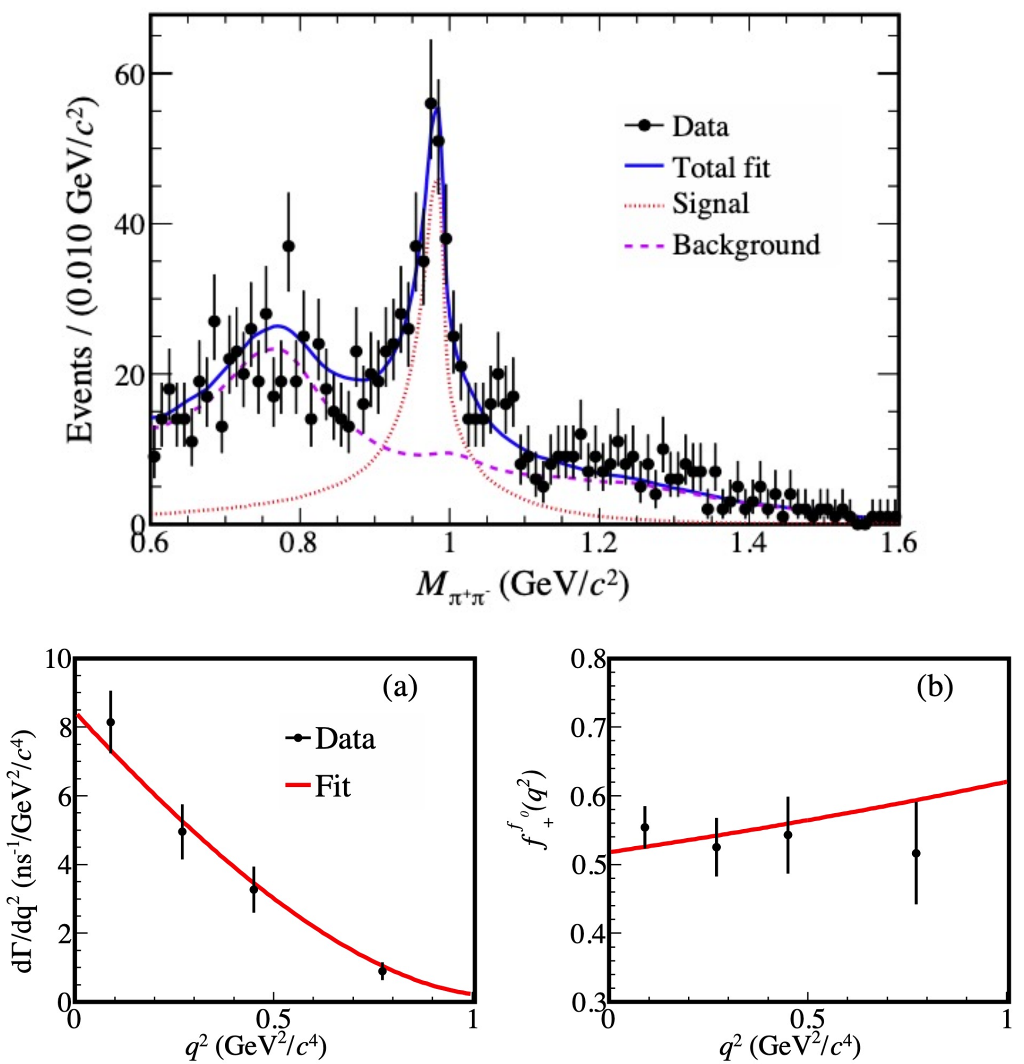
$$\mathcal{B}(D_s^+ \to f_0(980) e^+ \nu_e, f_0(980) \to \pi^+\pi^-)$$
$$= (1.72 \pm 0.13 \pm 0.10) \times 10^{-3}$$

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

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

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

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



Light scalar mesons via semi-leptonic D decays at BESIII

Channel	Publication	Status
$D^0 \to a_0(980)^-(\eta\pi^-)e^+v_e$	PRL 121, 081802(2018)	Update in process
$D^+ \to a_0(980)^0(\eta\pi^0)e^+v_e$	PRL 121, 081802(2018)	Update in process
$D \to a_0(980)\ (\eta\pi^0)\mu^+v_\mu$	--	In process
$D \to a_0(980)\ (K\bar{K})e^+v_e$	--	In process (Draft)
$D^+ \to f_0(500)(\pi^+\pi^-)e^+v_e$	PRL 122, 062001(2019)	Update in process
$D^+ \to f_0(500)(\pi^+\pi^-)\mu^+v_\mu$	--	In process (Draft)
$D^+ \to f_0(980)(\pi^+\pi^-)e^+v_e$	PRL 122, 062001(2019)	Update in process
$D_s^+ \to a_0(980)^0(\eta\pi^0)e^+v_e$	PRD 103, 092004(2021)	--
$D_s^+ \to f_0(980)(\pi^0\pi^0)e^+v_e$	PRD 105, L031101(2022)	--
$D_s^+ \to f_0(500)(\pi^0\pi^0)e^+v_e$	PRD 105, L031101(2022)	--
$D_s^+ \to f_0(980)(\pi^+\pi^-)e^+v_e$	2303.12927	Submitted to PRL
$D_s^+ \to f_0(980)(\pi^+\pi^-)\mu^+v_\mu$	--	In process
$D_s^+ \to f_0(980)(K^+K^-)e^+v_e$	--	In process (Draft)
$D_s^+ \to f_0(980)(K^+K^-)\mu^+v_\mu$	--	In process (Pubcomm)

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!