粲介子半轻衰变课题汇报：$D \to S\,\ell\,\nu$

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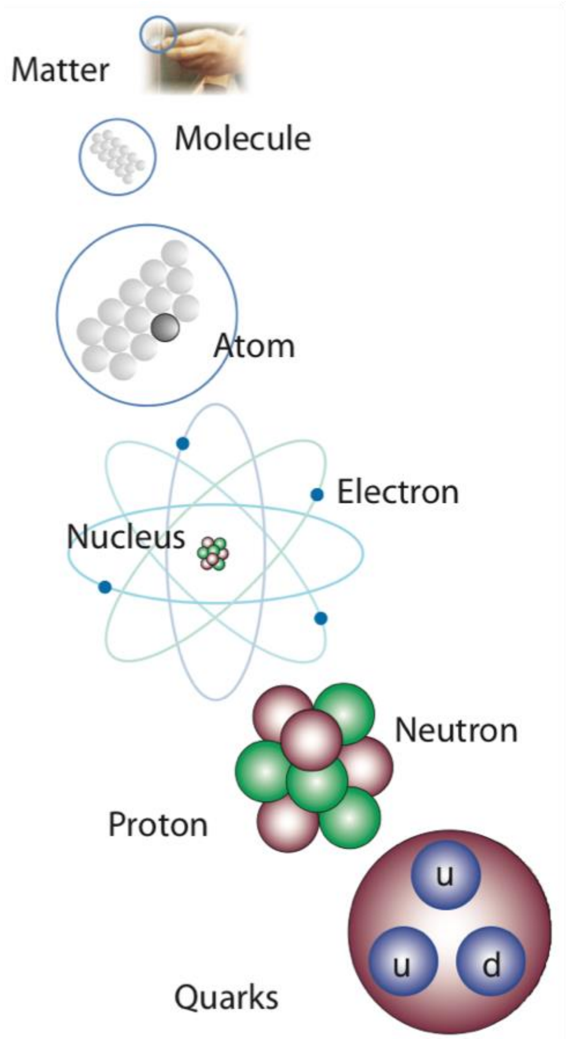
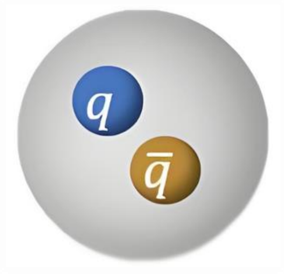
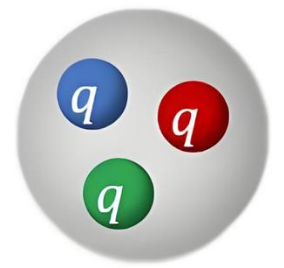
Content

Physics motivation

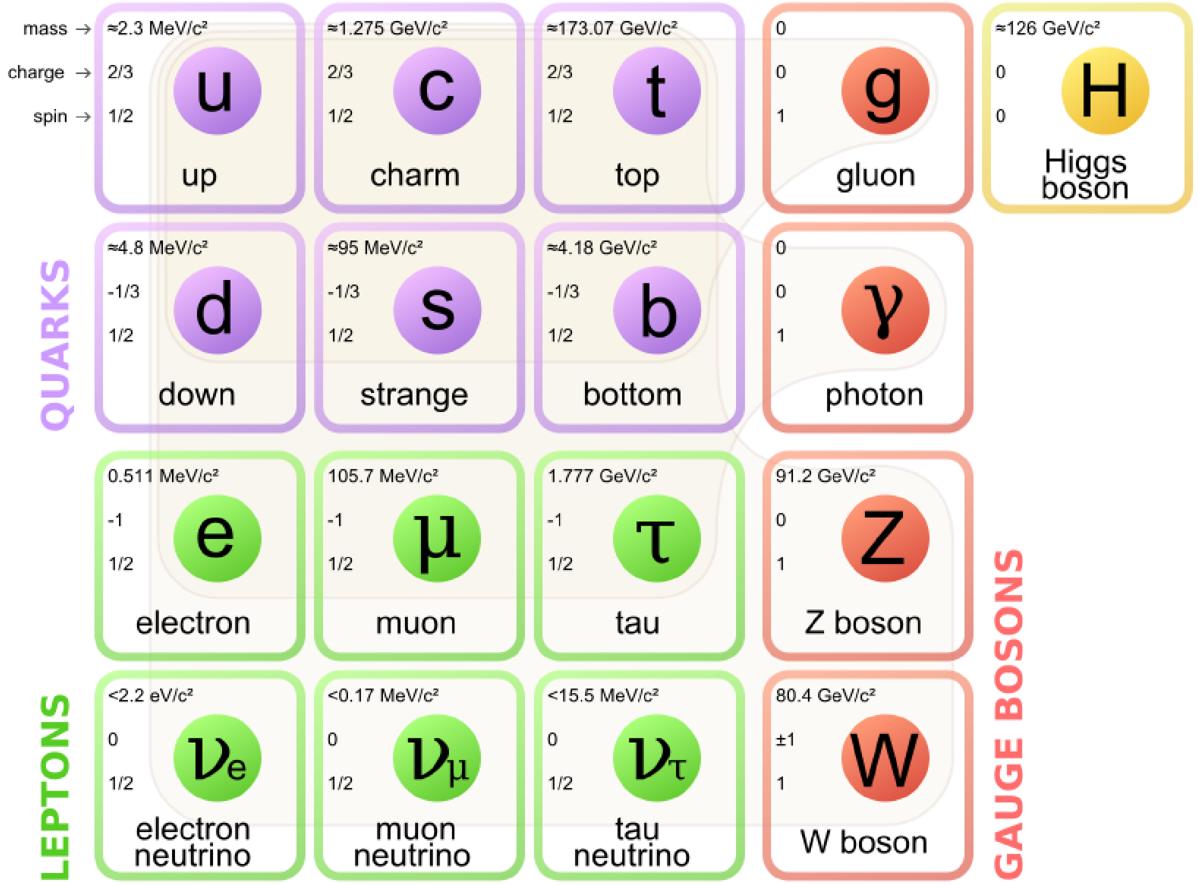




Meson



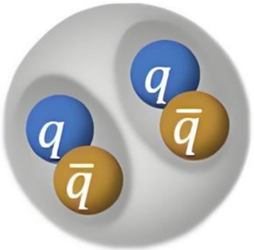
Baryon



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

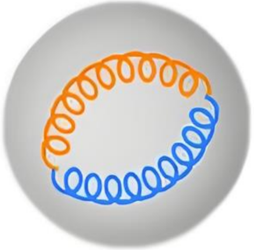
Physics motivation

Tetraquark

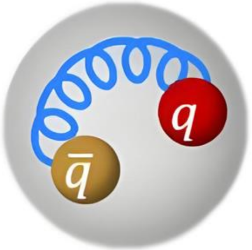


Hadronic molecules

Pentaquark



Glueball



hybrid

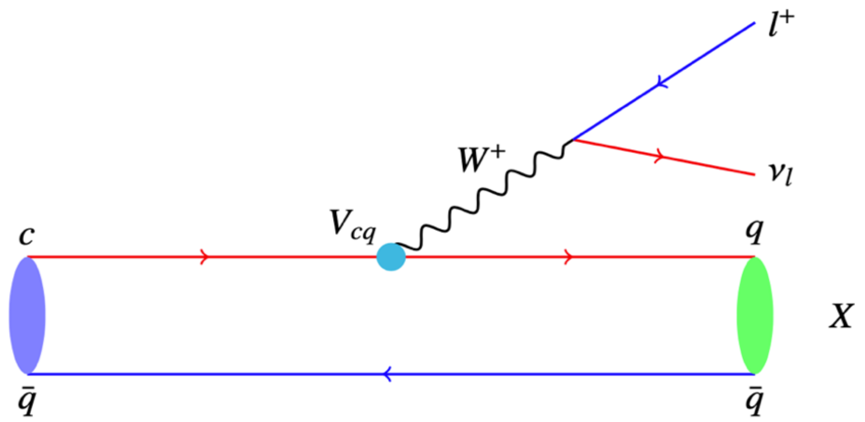
- **How about scalar mesons:**

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

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

Physics motivation

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



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

- **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)**
  - $\mathcal{R}_{\mu/e} = \mathcal{B}(D \to X\mu^+\nu_\mu)/\mathcal{B}(D \to Xe^+\nu_e)$ measurement ➔ **Test lepton flavor universality (LFU)**

Content

Data sample

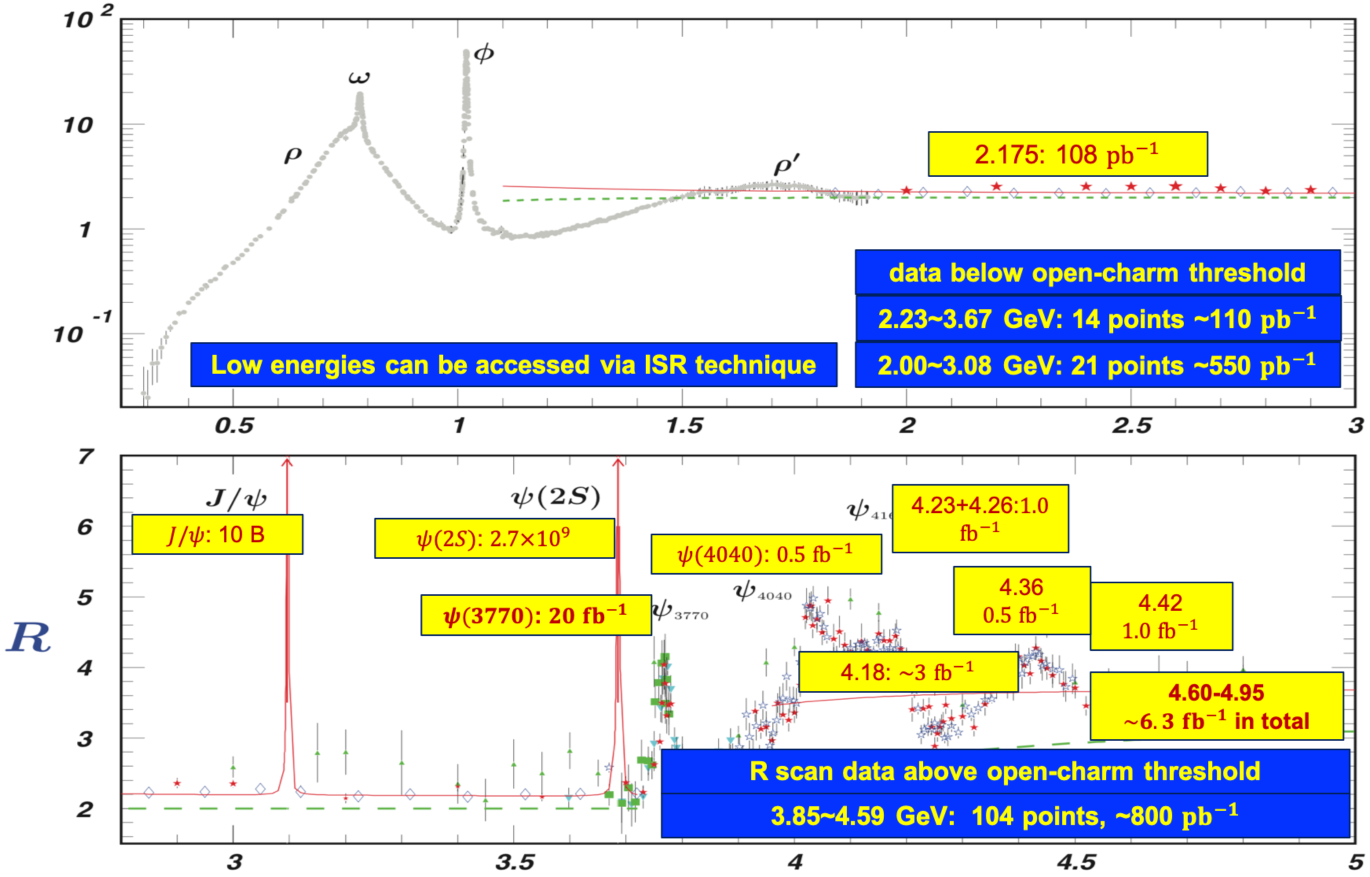
- Symmetric e^+e^- collider @2 – 5GeV
- Pair-production near threshold
- $D\bar{D}$@3.773GeV

  2.93 fb^{-1} 2010-2011

  4.99 fb^{-1} 2021-2022

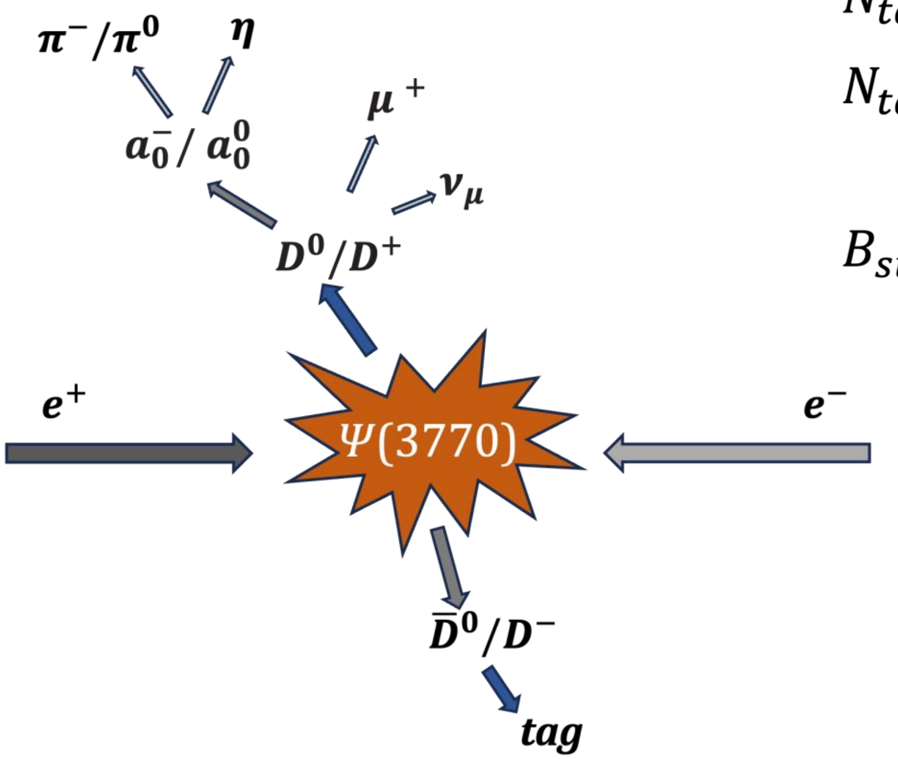
  8.16 fb^{-1} 2021-2022

  4.19 fb^{-1} 2022-2024



~20.3fb^{-1} on the $\psi(3770)$ had been collected!

Analysis method: Double Tag



$N_{tag} = 2N_{D\bar{D}} B_{tag} \epsilon_{tag}$

$N_{tag,sig} = 2N_{D\bar{D}} B_{tag} B_{sig} \epsilon_{tag,sig}$

$$B_{sig} = \frac{N_{tag,sig}^{total}}{\Sigma_\alpha N_{tag}^\alpha \, \epsilon_{tag,sig}^\alpha / \epsilon_{tag}^\alpha}$$

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

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

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

The differential decay rate of $D \to S \ell \nu_\ell$

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

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

- 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 $D \to S \ell \nu_\ell$

- Point-like differential decay rate:

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

- Double differential decay rate:
  (N.N.Achasov *et al*., PRD102,016022(2020); W. Wang, PLB759,501(2016))

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

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

Content

Study of the decay $D^0 \to a_0(980)^-(\eta\pi^-)e^+\nu_e$

Phys. Rev. D 111, L091501 (2025)

- 7.93 fb^{-1} data @ 3.773 GeV ➔ $N_{\mathrm{sig}} = 51.8 \pm 10.0$
- **Updated BF measurement** of $D^0 \to a_0(980)^-\, e^+\nu_e$.

$\mathcal{B}(D^0 \to a_0(980)^- e^+\nu_e, a_0(980)^- \to (\eta\pi^-))$

$= (0.86 \pm 0.17 \pm 0.05) \times 10^{-4}$

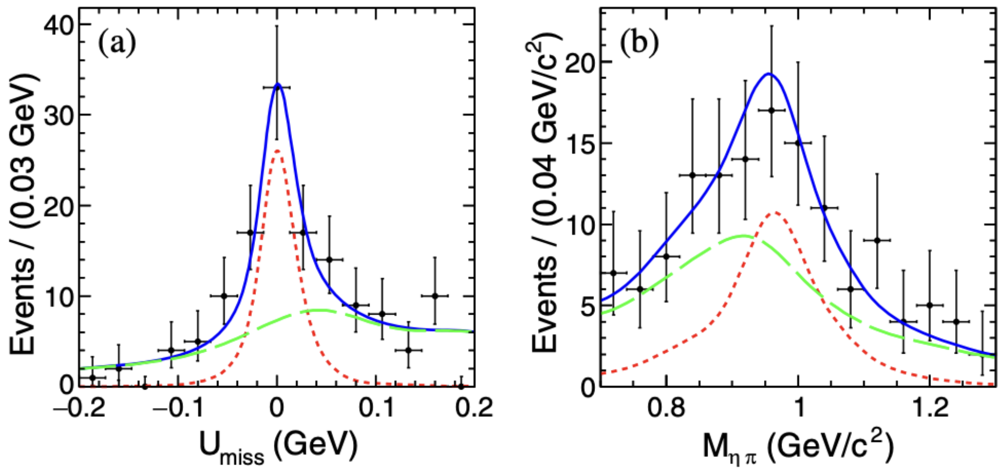
- **First FF measurement:**

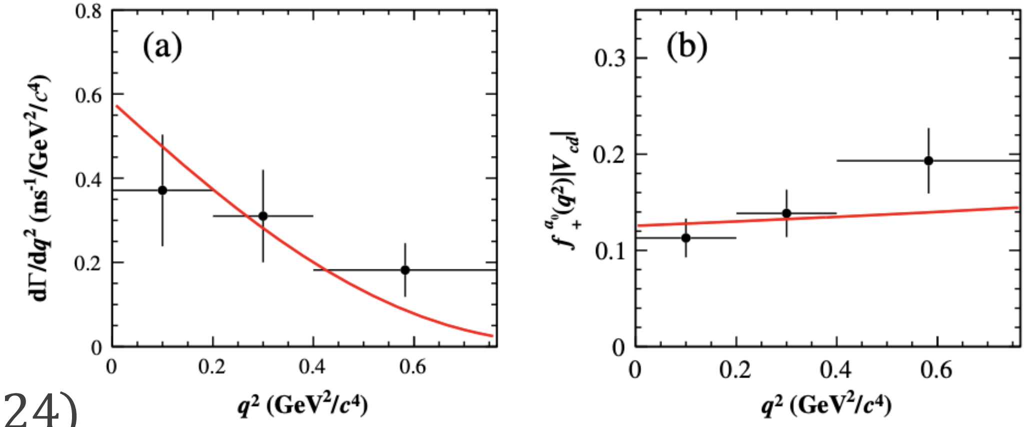
Single-pole form for FF and Bugg form for $a_0(980)^-$

➔ $f_+^{a_0}(0)|V_{cd}| = 0.126 \pm 0.013 \pm 0.003$

➔ $f_+^{a_0}(0) = 0.559 \pm 0.056 \pm 0.013$

ps: $|V_{cd}| = 0.22487 \pm 0.00068$ from SM global fit (PDG2024)





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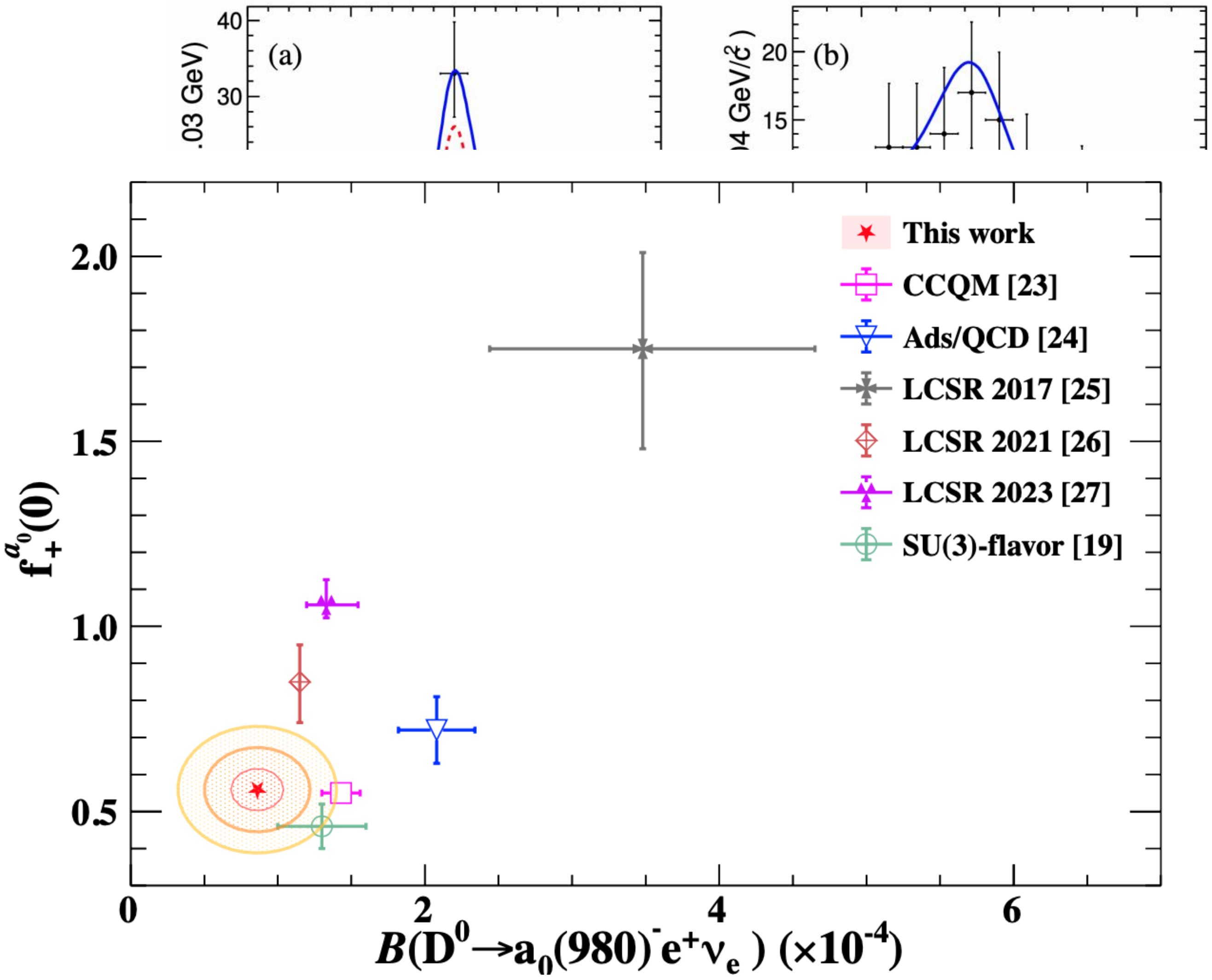
ps: $|V_{cd}| = 0.22487 \pm 0.00068$ from SM glob



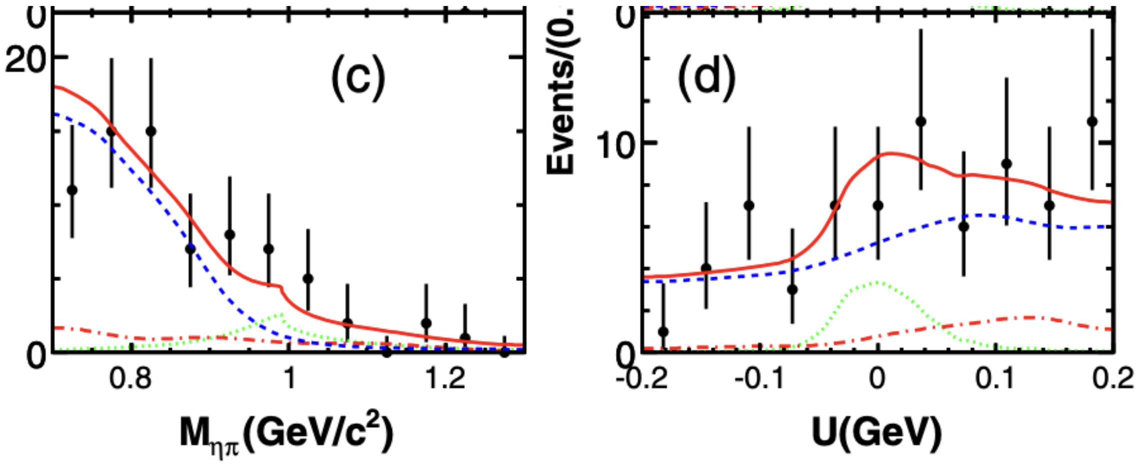
Study of the decay $D^+ \to a_0(980)^0(\eta\pi^0)e^+\nu_e$

Phys. Rev. L 121, 081802(2018)

- 2.93 fb^{-1} data @ 3.773 GeV ➔ $N_{\text{sig}} = 10.2^{+5.0}_{-4.1}$
- Signal significance: 2.9σ
- **First evidence** of $D^+ \to a_0(980)^0\, e^+\nu_e$.

$\mathcal{B}(D^+ \to a_0(980)^0 e^+\nu_e, a_0(980)^0 \to (\eta\pi^0))$

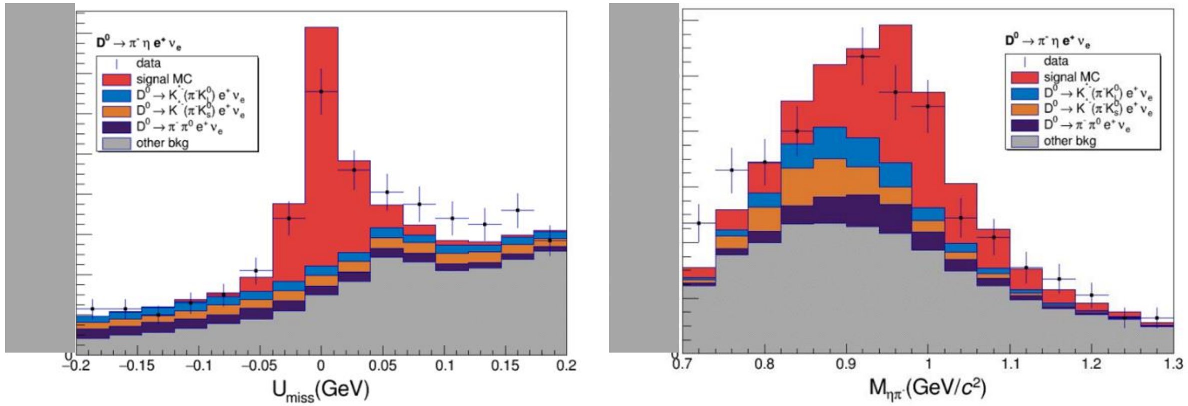
$= (1.66^{+0.81}_{-0.66} \pm 0.11) \times 10^{-4}$



Group report

- 20.3 fb^{-1} data @ 3.773 GeV ➔ $N_{\text{sig}} = \times\times \pm \times\times$
- **Updated BF measurement** of $D^+ \to a_0(980)^0\, e^+\nu_e$.

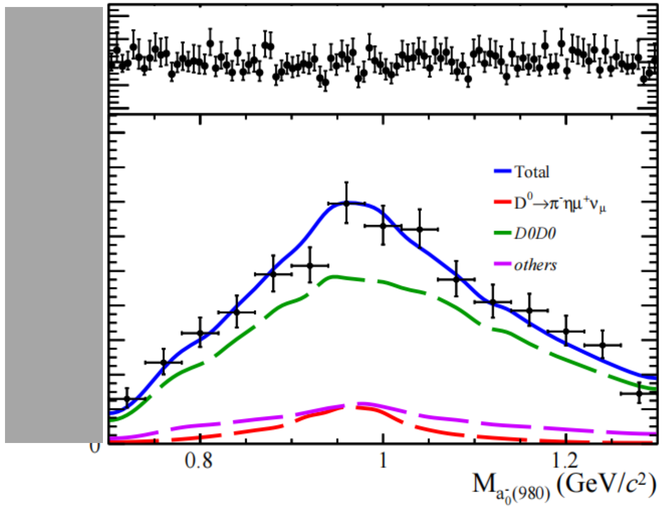
$\mathcal{B}(D^+ \to a_0(980)^0 e^+\nu_e, a_0(980)^0 \to (\eta\pi^0)) = \times\times \pm \times\times$

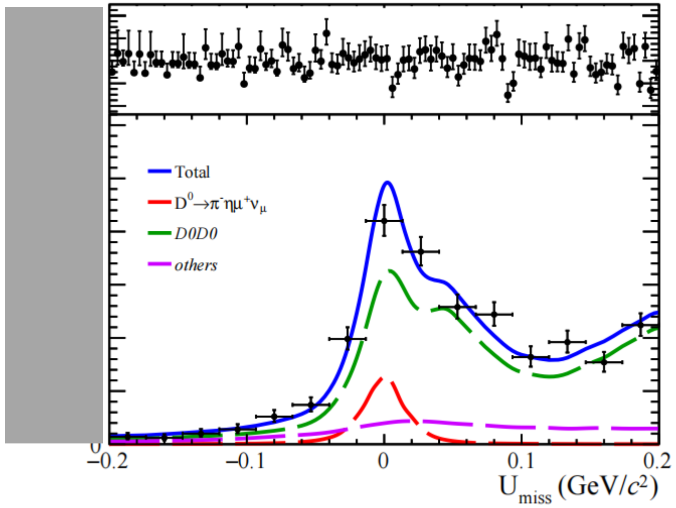


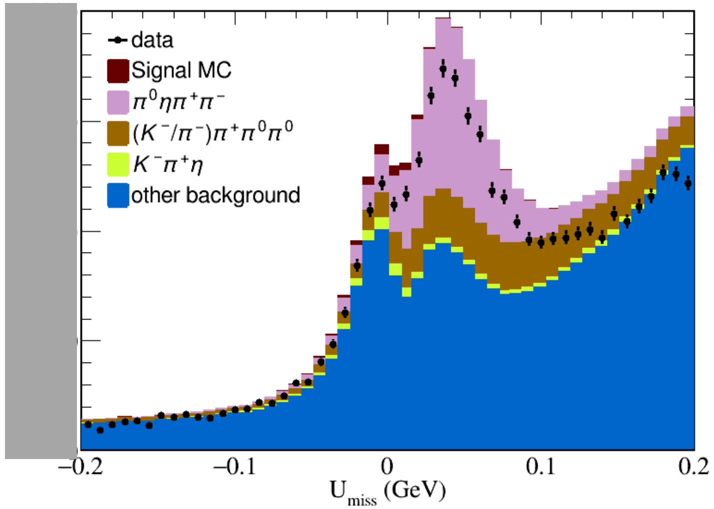
Study of the decay $D^0 \to a_0(980)^-(\eta\pi^-)\mu^+\nu_\mu$

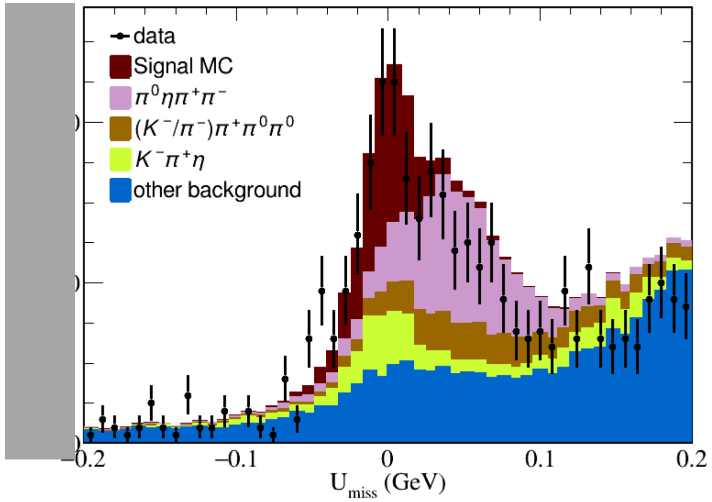
Group report

- $20.3\ \mathrm{fb}^{-1}$ data @ 3.773 GeV
- $N_{\rm sig} = \times\times \pm \times\times$
- $\mathcal{B}\left(D^0 \to a_0(980)^-\mu^+\nu_\mu, a_0(980)^- \to \pi^-\eta\right) = \times\times \pm \times\times$







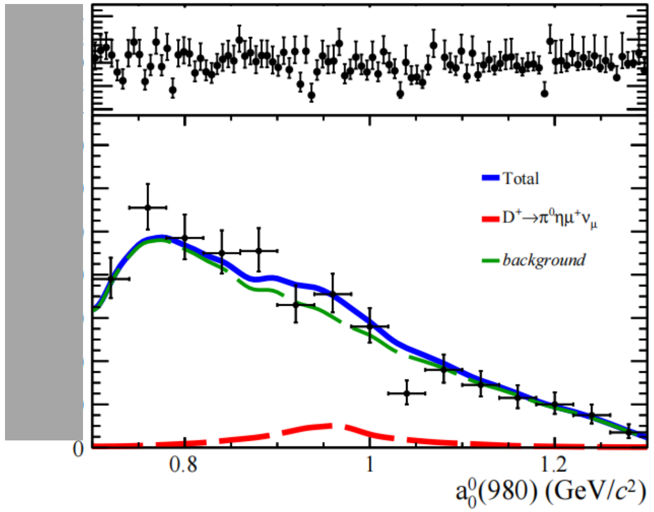


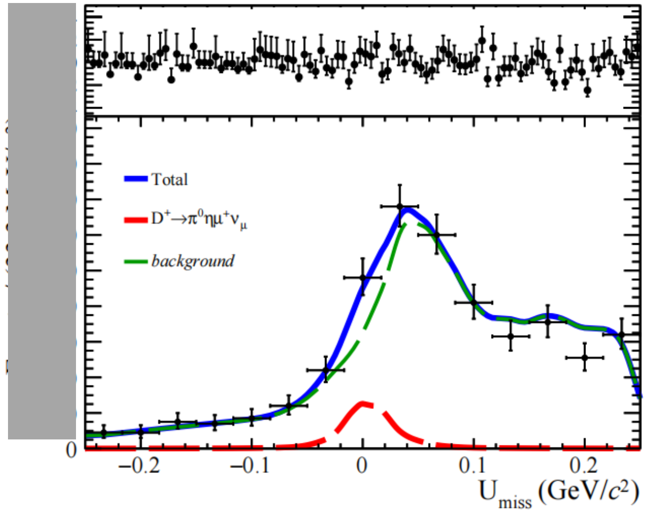
Background of $D^0 \to a_0(980)^-(\pi^-\eta)\mu^+\nu_\mu$

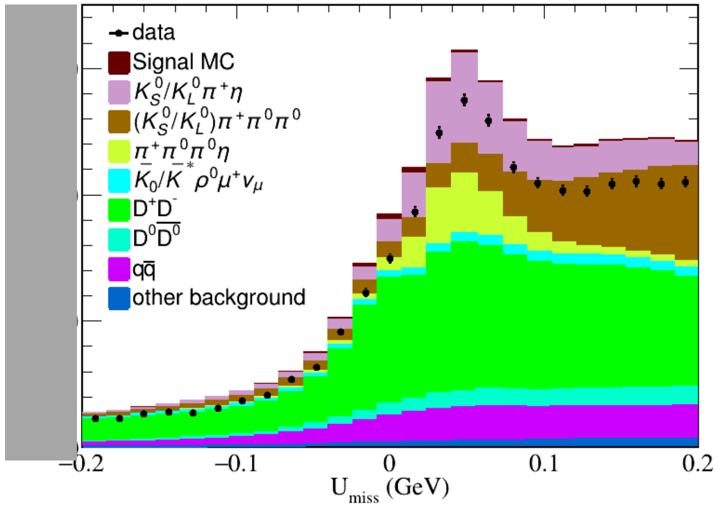
Study of the decay $D^+ \to a_0(980)^0(\eta\pi^0)\mu^+\nu_\mu$

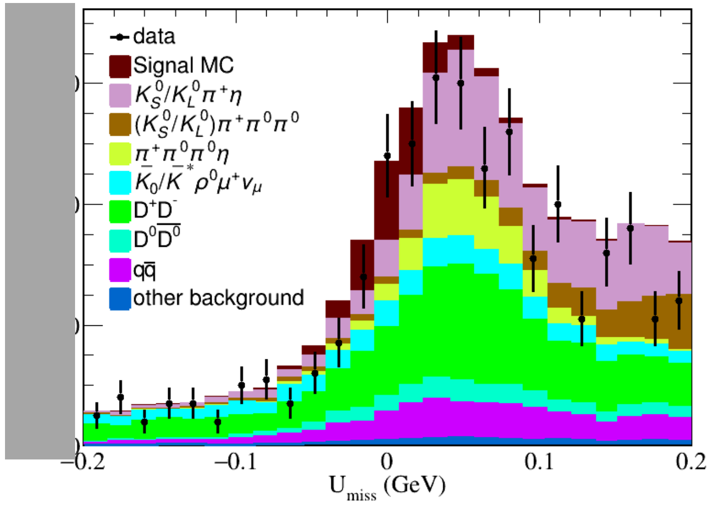
Group report

- $20.3\ \mathrm{fb}^{-1}$ data @ 3.773 GeV ➔ $N_{sig} = \times\times \pm \times\times$
- $\mathcal{B}(D^+ \to a_0(980)^0\mu^+\nu_\mu, a_0(980)^0 \to \pi^0\eta) = \times\times \pm \times\times$
- **Isospin conservation check:** $\frac{\Gamma(D^0\to a_0^-\mu^+\nu_\mu)}{2\Gamma(D^+\to a_0^0\mu^+\nu_\mu)} = \times\times \pm \times\times$







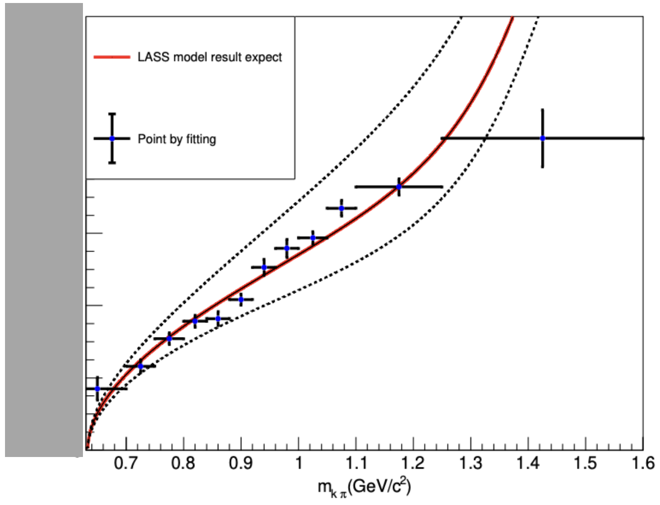


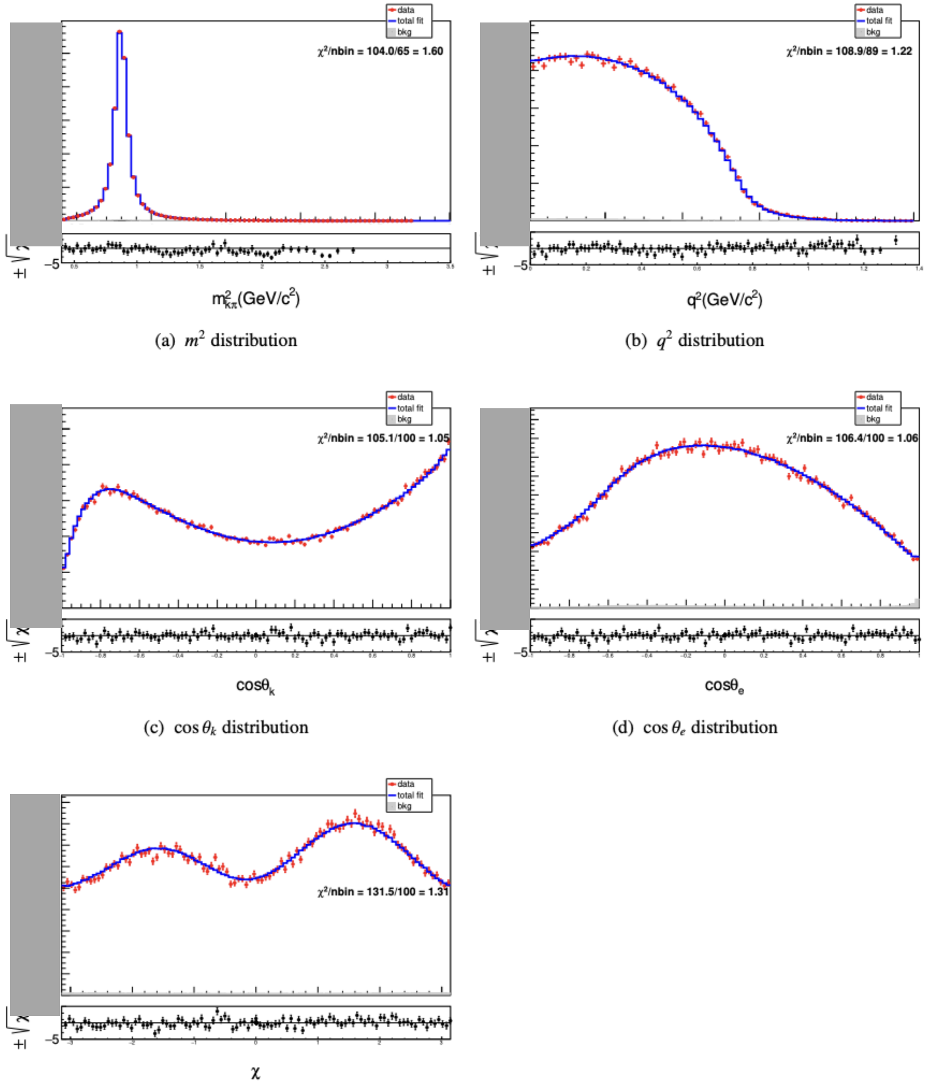
Background of $D^+ \to a_0(980)^0(\pi^0\eta)\mu^+\nu_\mu$

Study of the decay $D^+ \to K^-\pi^+e^+\nu_e$

BAM-962

- 20.3 fb^{-1} data @ 3.773 GeV ➔ $N_{\text{sig}} = \times\times$
- **BF measurement** : $\mathcal{B}(D^+ \to K^+\pi^-e^+\nu_e) = \times\times \pm \times\times \pm \times$
- $f_{S-wave} = \times\times \pm \times\times \pm \times\times$
- *S−wave:* $\mathcal{B}(D^+ \to (K^+\pi^-)_{S-wave}e^+\nu_e) = \times\times \pm \times\times \pm \times\times$





(a) m^2 distribution

(b) q^2 distribution

(c) $\cos\theta_k$ distribution

(d) $\cos\theta_e$ distribution

(e) χ distribution

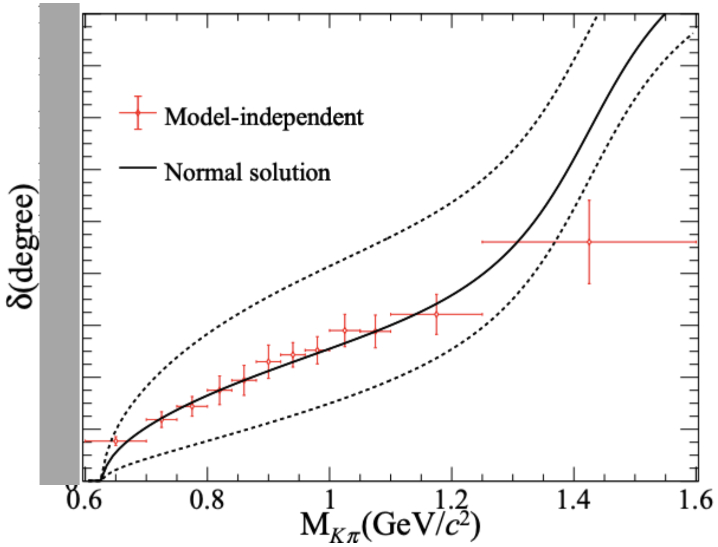
Study of the decay $D^0 \to K^-\pi^0 e^+\nu_e$

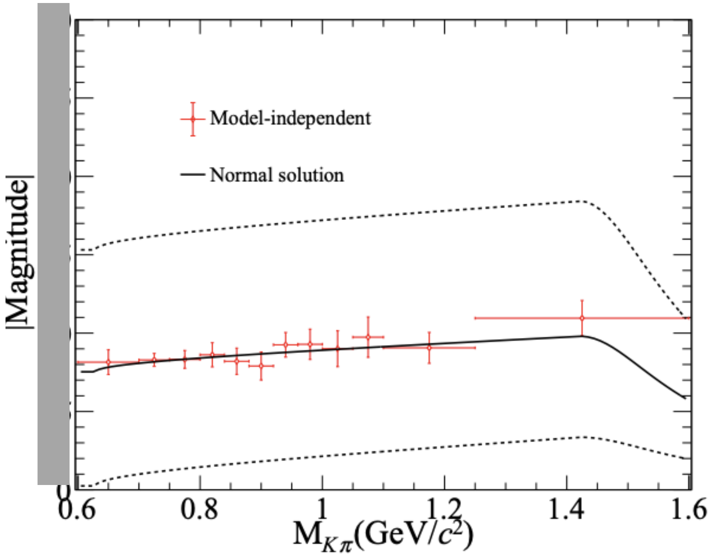
BAM-829

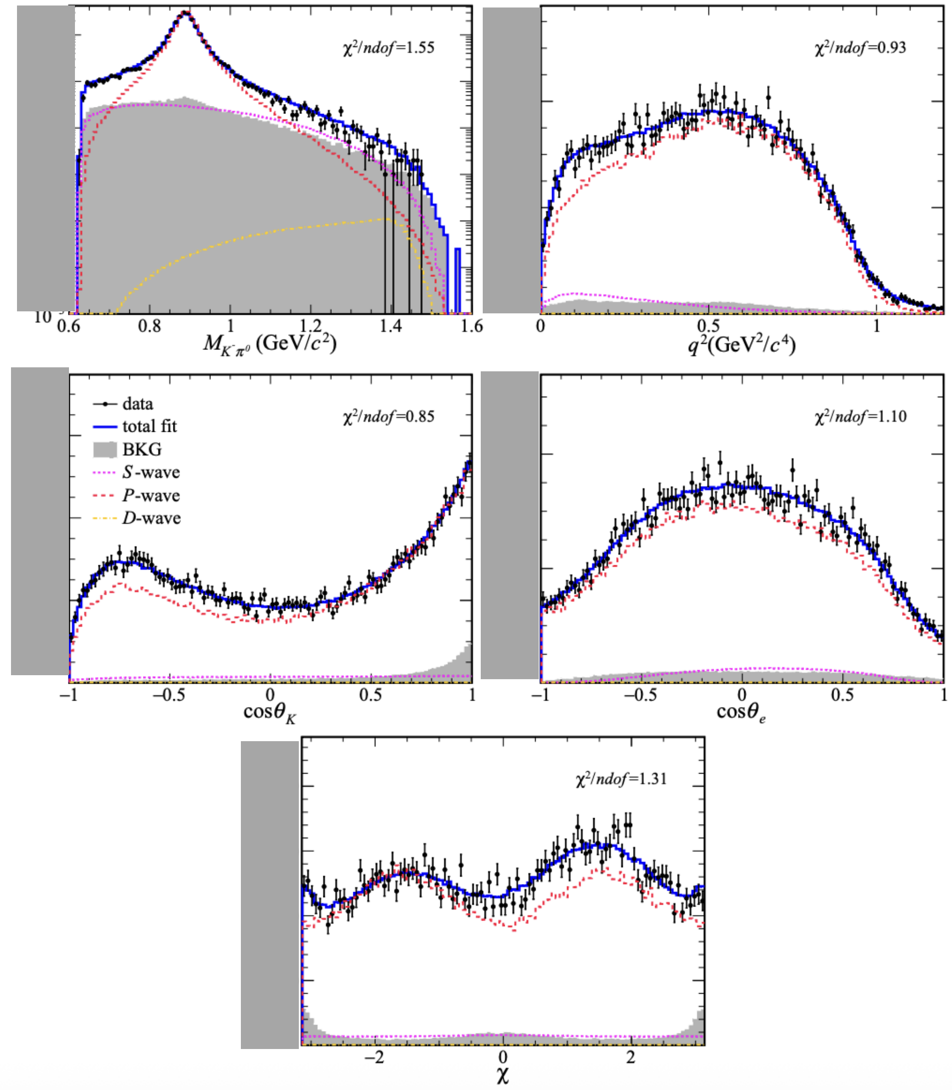
- 20.3 fb^{-1} data @ 3.773 GeV ➔ $N_{\mathrm{sig}} = \times\times \pm \times\times$
- **First BF measurement**： $\mathcal{B}(D^0 \to K^-\pi^0 e^+\nu_e) = \times\times \pm \times\times \pm \times$

$f_{S-wave} = \times\times \pm \times\times \pm \times\times$

S–wave: $\mathcal{B}(D^0 \to (K^-\pi^0)_{S-wave} e^+\nu_e) = \times\times \pm \times\times \pm \times\times$







Content

$D \to S\, \ell^+ \nu_\ell$

Decay Mode	BESIII Publication	BESIII Prospect
$D^0 \to a_0(980)^-(\eta\pi^-)e^+\nu_e$	PRL121, 081802(2018)/2.93fb^{-1} **PRD111, L091501 (2025)/7.93fb^{-1}**	Group report (20.3 fb^{-1})
$D^+ \to a_0(980)^0(\eta\pi^0)e^+\nu_e$	PRL121, 081802(2018)/2.93fb^{-1}	Group report (20.3 fb^{-1})
$D \to a_0(980)\ (\eta\pi)\mu^+\nu_\mu$	None	Group report (20.3 fb^{-1})
$D \to a_0(980)\ (K\bar{K})e^+\nu_e$	**PRD109, 072003(2024)/7.93fb^{-1}**	Group report (20.3 fb^{-1})
$D^+ \to f_0(500)(\pi^+\pi^-)e^+\nu_e$	PRL 122, 062001(2019)/2.93fb^{-1} **PRD110, 092008(2024)/2.93fb^{-1}**	Charm group review (20.3 fb^{-1})
$D^+ \to f_0(500)(\pi^+\pi^-)\mu^+\nu_\mu$	**PRD110, 092008(2024)/2.93fb^{-1}**	Group report (20.3 fb^{-1})
$D^+ \to f_0(980)(\pi^+\pi^-)e^+\nu_e$	PRL122, 062001(2019)/2.93fb^{-1}	Charm group review (20.3 fb^{-1})
$D^+ \to K^-\pi^+e^+\nu_e$	PRD94, 032001 (2016)/2.93fb^{-1}	CWR review (20.3 fb^{-1})
$D^+ \to K^-\pi^+\mu^+\nu_\mu$	None	Group report (20.3 fb^{-1})
$D^+ \to K^0_S\pi^0\ell^+\nu_\ell$	JHEP10(2024)199/(e)7.93fb^{-1} **arXiv:2506.05761/20.3fb^{-1}**	Summitted to PRL
$D^0 \to K^-\pi^0e^+\nu_e$	None	CWR review (20.3 fb^{-1})
$D^0 \to K^-\pi^0\mu^+\nu_\mu$	**PRL134,011803(2025)/7.93fb^{-1}**	Group report (20.3 fb^{-1})
$D^0 \to K^0_S\pi^-\ell^+\nu_\ell$	JHEP03(2025)197/(e)7.93fb^{-1} **arXiv:2504.10867/(μ)7.93fb^{-1}**	CWR review (20.3 fb^{-1})

Summary and prospect

Summary:

- BESIII has the largest data samples at $D\overline{D}$ threshold.
- Scalar mesons are studied systematically via semi-leptonic charm decays.
- BFs/FF measurements help to test different QCD modes and understand their nature!

Prospect:

- BESIII has **20.3 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!

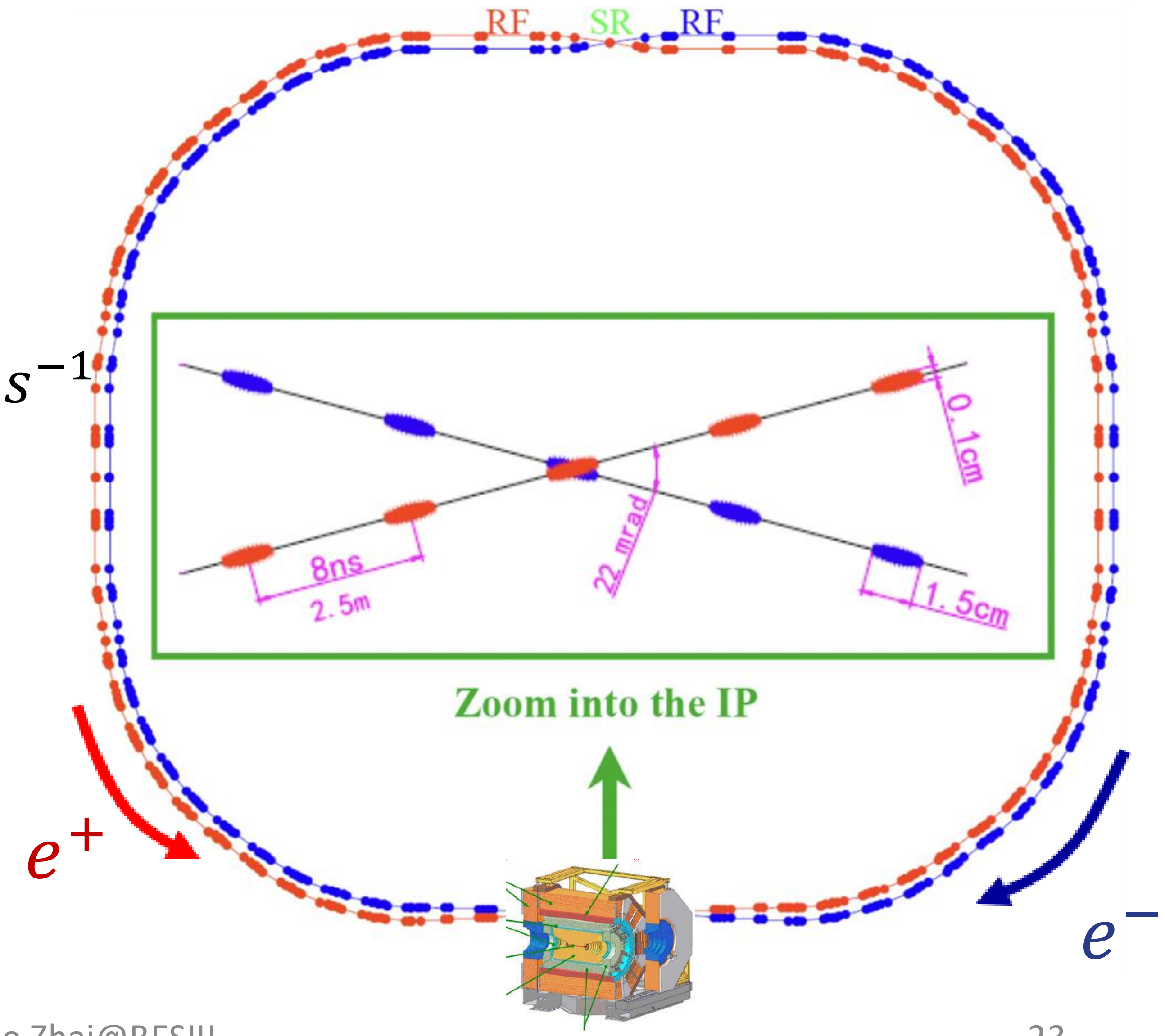
Thank you!

BESIII experiment

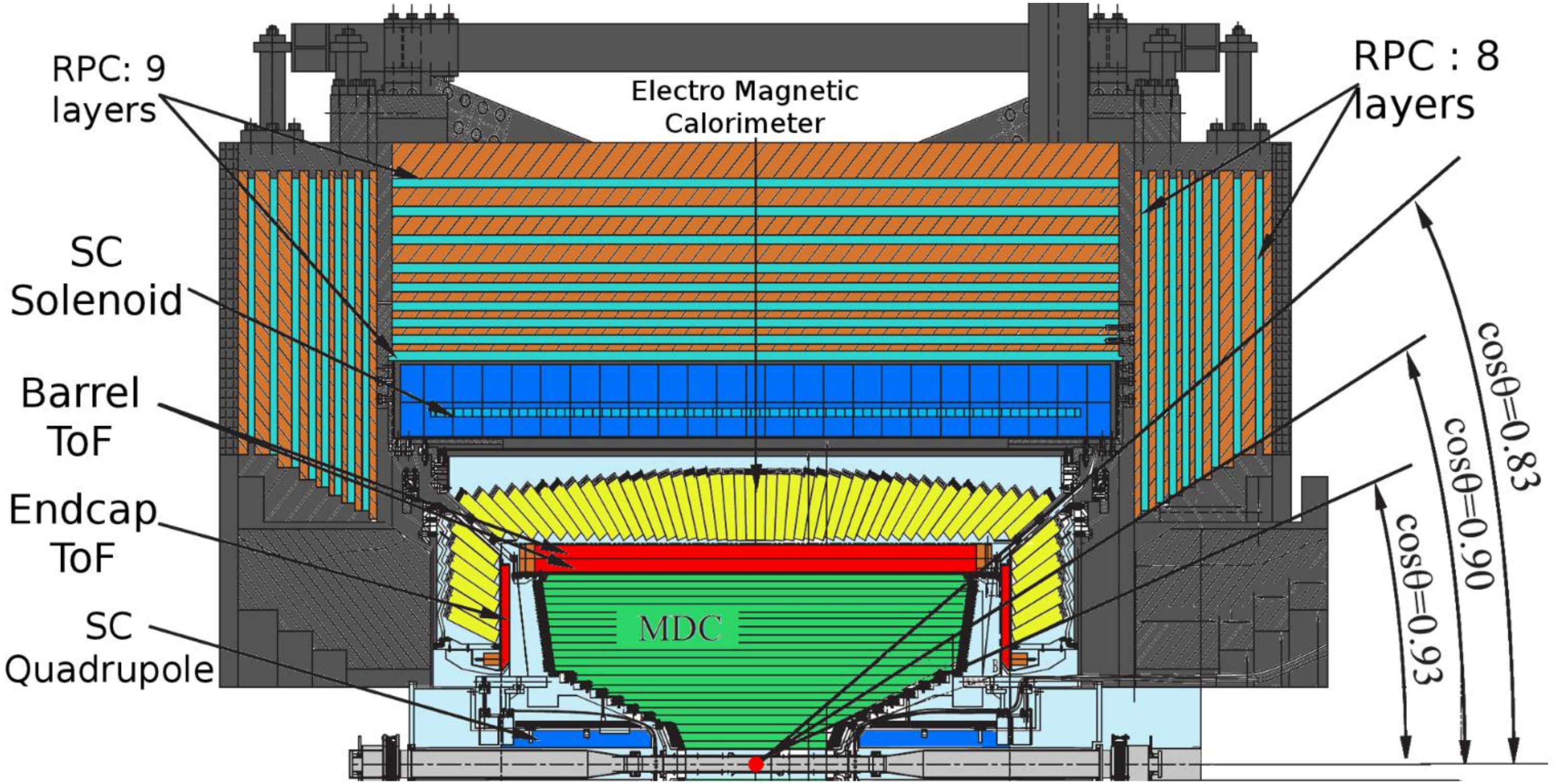
BEPCII collider

- Two ring symmetric e^+e^- collider
- Circumference: 240 m
- Design luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$

  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