

# Overview of recent BESIII results and prospects

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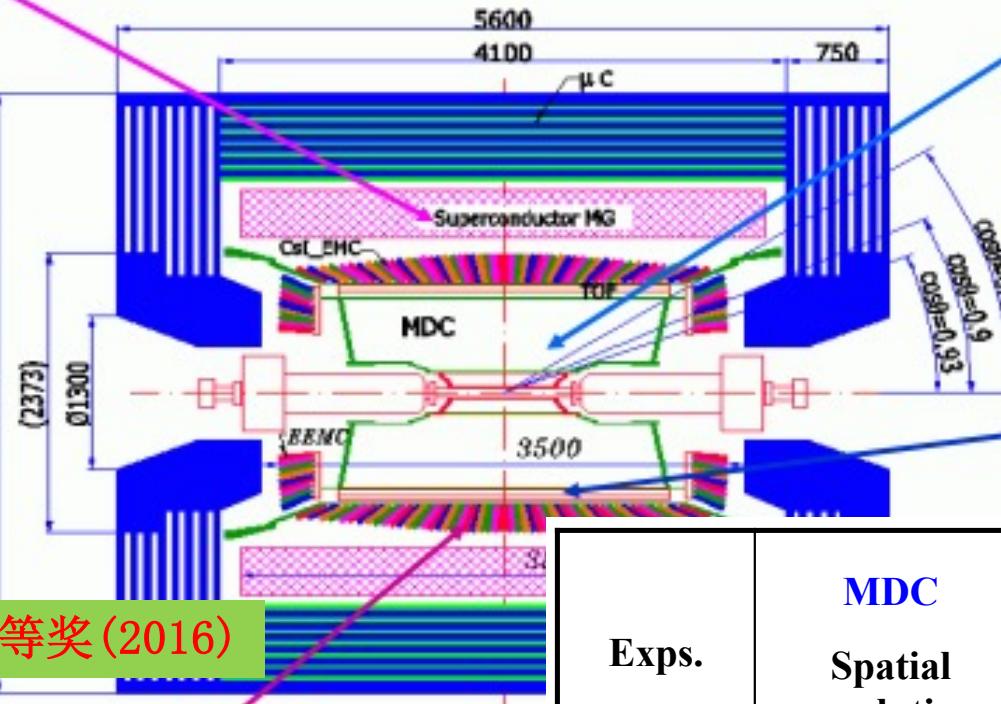
北京大学物理学院

全国第十九届重味物理和CP破坏研讨会

2022年12月9日



Magnet: 1 T Super conducting



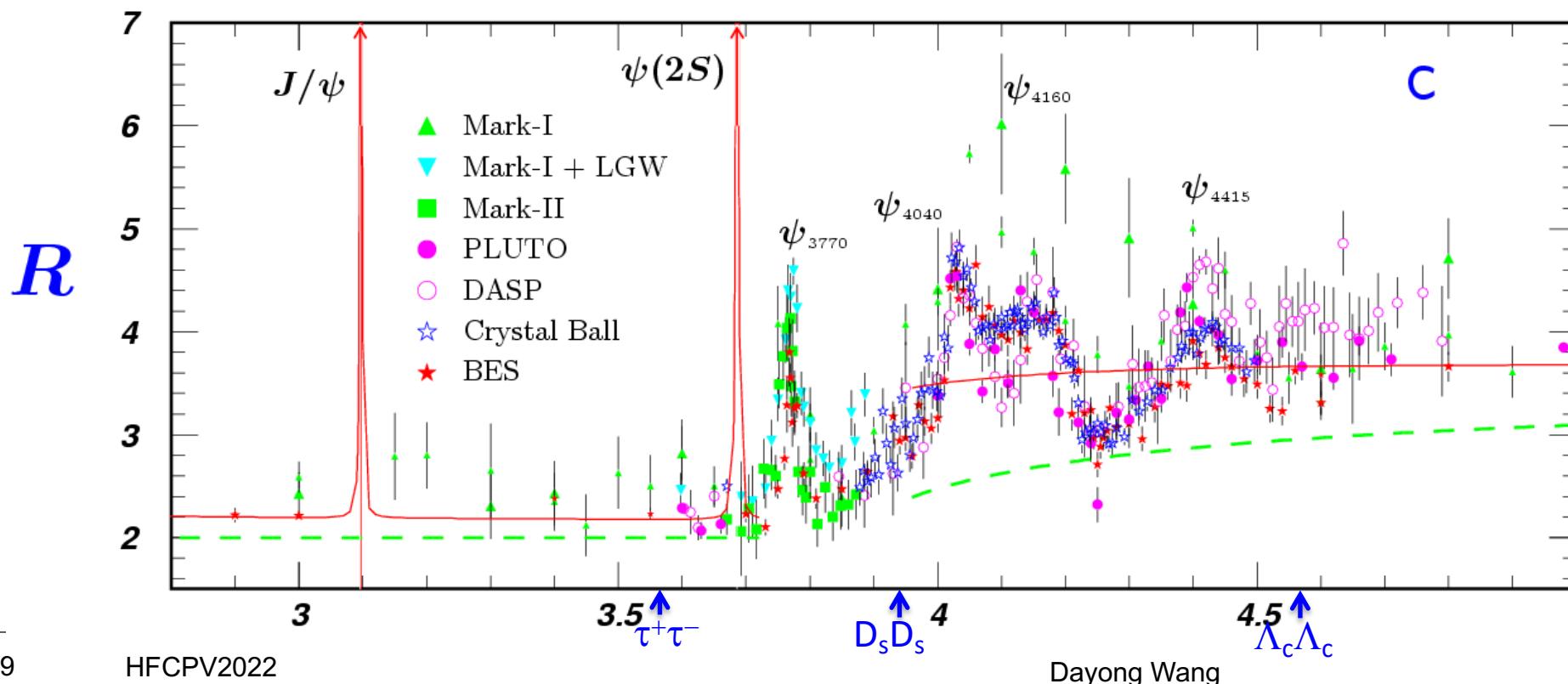
国家科技进步一等奖(2016)

high lumi, large datasets, hermetic detector with good performance and clean environment

- First collision in 2008, physics run started in 2009
- Operation c.m. energy: 2.0-4.95GeV
- BEPCII reached peak lumi of  $1 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$  @ 1.89GeV in April 2016
- 2020: energy upgrade to 2.45 GeV & top-up mode
- Secured the running for another 5-10 years, with small(but critical) energy increase and lumi upgrade

Exps.	MDC Spatial resolution	MDC $dE/dx$ resolution	EMC Energy resolution
CLEO-c	110 $\mu\text{m}$	5%	2.2-2.4 %
BaBar	125 $\mu\text{m}$	7%	2.67 %
Belle	130 $\mu\text{m}$	5.6%	2.2 %
<b>BESIII</b>	<b>115 <math>\mu\text{m}</math></b>	<5% (Bhabha)	<b>2.4%</b>

- Rich of **resonances**, charmonia and charmed mesons.
- **Threshold characteristics** (pairs of  $\tau$ , D,  $D_s$ , charmed baryons...).
- **Transition** between perturbative and non-perturbative **QCD**.
- New **hadrons**: glueballs, hybrids, multi-quark states
- New **Physics**: large datasets, hermetic detector, good performance



2009: 106M  $\psi(2S)$ 225M  $J/\psi$ 2010:  $0.98 \text{ fb}^{-1}$   $\psi(3770)$  (for  $D^{0(+)}$ )2011:  $2.93 \text{ fb}^{-1}$   $\psi(3770)$  (for  $D^{0(+)}$ , total)  
 $0.48 \text{ fb}^{-1}$  @4.01 GeV2012: 0.45B  $\psi(2S)$  (total)  
1.30B  $J/\psi$  (total)2013:  $1.09 \text{ fb}^{-1}$  @4.23 GeV  
 $0.83 \text{ fb}^{-1}$  @4.26 GeV  
 $0.54 \text{ fb}^{-1}$  @4.36 GeV  
 $10 \times 0.05 \text{ fb}^{-1}$  XYZ scan@3.81-4.42 GeV2014:  $1.03 \text{ fb}^{-1}$  @4.42 GeV  
 $0.11 \text{ fb}^{-1}$  @4.47 GeV  
 $0.11 \text{ fb}^{-1}$  @4.53 GeV  
 $0.05 \text{ fb}^{-1}$  @4.575 GeV  
 $0.57 \text{ fb}^{-1}$  @4.60 GeV (for  $\Lambda_c^+$ )  
 $0.80 \text{ fb}^{-1}$  R scan @3.85-4.59 GeV

# Data samples collected by BESIII so far



2015: R-scan 2-3 GeV+2.175 GeV

2016:  $3.20 \text{ fb}^{-1}$  @4.178 GeV (for  $D_s^+$ )2017:  $7 \times 0.50 \text{ fb}^{-1}$  XYZ scan@4.19-4.27 GeV2018: More  $J/\psi$ +tuning new RF cavity2019: 10B  $J/\psi$  (total) $8 \times 0.50 \text{ fb}^{-1}$  XYZ scan@4.13, 4.16, 4.29-4.44 GeV2020:  $3.8 \text{ fb}^{-1}$  @ 4.61-4.7 GeV (XYZ& $\Lambda_c^+$ )2021:  $2.0 \text{ fb}^{-1}$  @ 4.74-4.946 GeV2021: 2.7B  $\psi(2S)$  (total)2022:  $2 \times 0.4 \text{ fb}^{-1}$ @3.65, 3.682 GeV,  
 $8 \text{ fb}^{-1}$   $\psi(3770)$  (for  $D^{0(+)}$ , total)

More than  $37 \text{ fb}^{-1}$  of data taken between 2 and 4.95 GeV

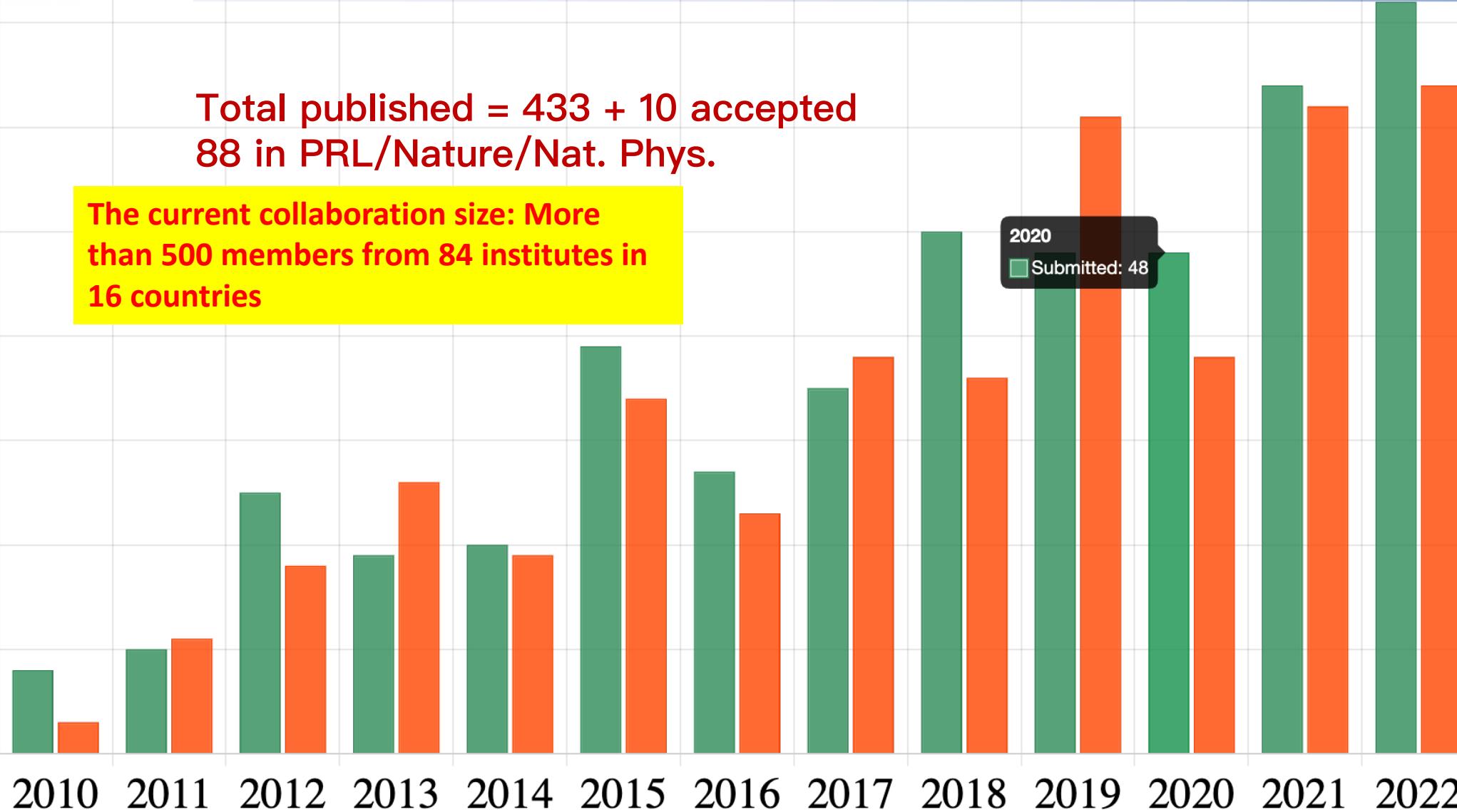
Total published = 433 + 10 accepted

88 in PRL/Nature/Nat. Phys.

The current collaboration size: More than 500 members from 84 institutes in 16 countries

2020

Submitted: 48





## ■ Physics of BESIII experiment

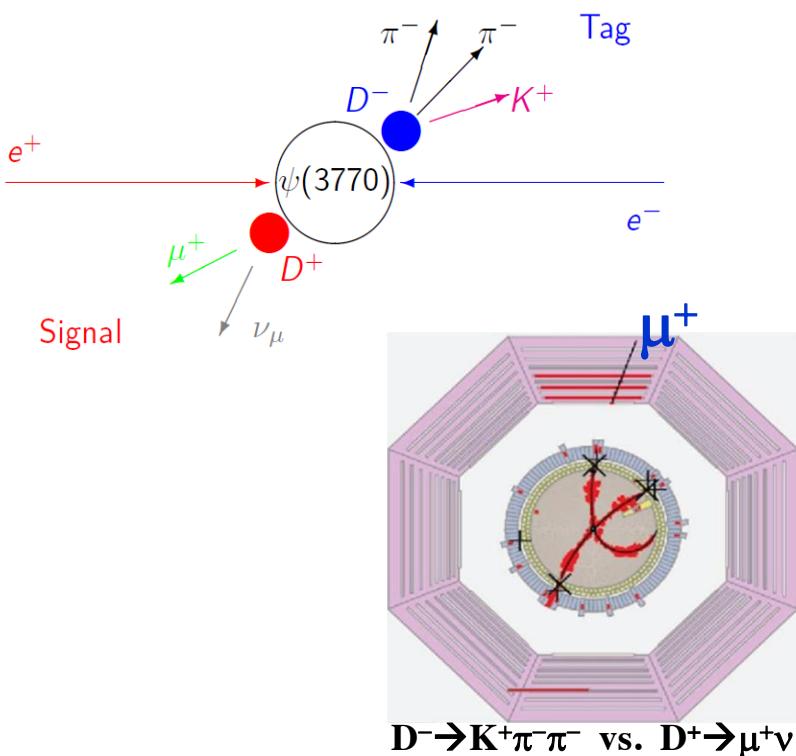
- ◆ NSR, Volume 8, Issue 11, November 2021

BESIII publication webpage:

<http://english.ihep.cas.cn/bes/re/pu/pjp/>

## ■ More details in later talks in this workshop

- ◆ Strong phase measurement of D decays at BESIII, Yu Zhang
- ◆ Recent studies on  $\Lambda_c$  decays at BESIII, Pei-Rong Li
- ◆ Hadronic decays of charmed meson at BESIII, Yu Lu
- ◆ Charm leptonic and rare decays at BESIII, Zhengyun You
- ◆ Recent XYZ and charmonium results at BESIII, Kai Zhu
- ◆ Hyperon CPV at BESIII, Jianyu Zhang



- $e^+e^- \rightarrow D\bar{D}$  ( $\Lambda_c^+\Lambda_c^-$ ), near Thrs.
- Double tag analysis
  - ✓ Tagging  $D^- (\bar{D}^0)$ ,  $\Lambda_c^-$  from hadronic decay modes

$$M_{BC} = \sqrt{E_{beam}^2 - p_{D_{tag}}^2}$$

- ✓ (semi-)leptonic decay event can be well reconstructed in the recoil side of the tagged  $\bar{D}$  ( $\Lambda_c^-$ )

$$M_{missing}^2 = E_{miss}^2 - \mathbf{p}_{miss}^2 \sim 0$$

$$U_{miss} \equiv E_{miss} - |\vec{p}_{miss}| \sim 0$$

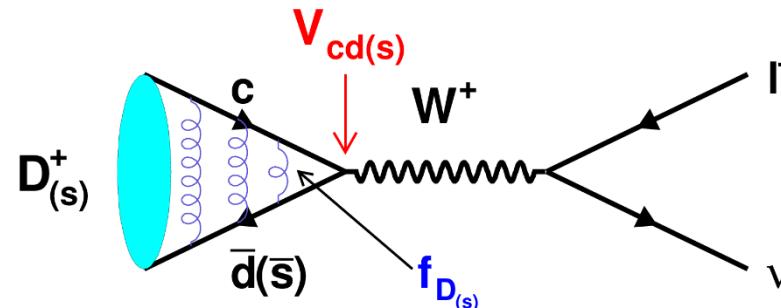
- ❑ Event is very clean
- ❑ High tagging efficiency
- ❑ Most systematic uncertainties can be cancelled
- ❑ Could measure absolute BFs

### Charmed hadrons:

- Produced in pair
- Quantum correlated  $D^0\bar{D}^0$

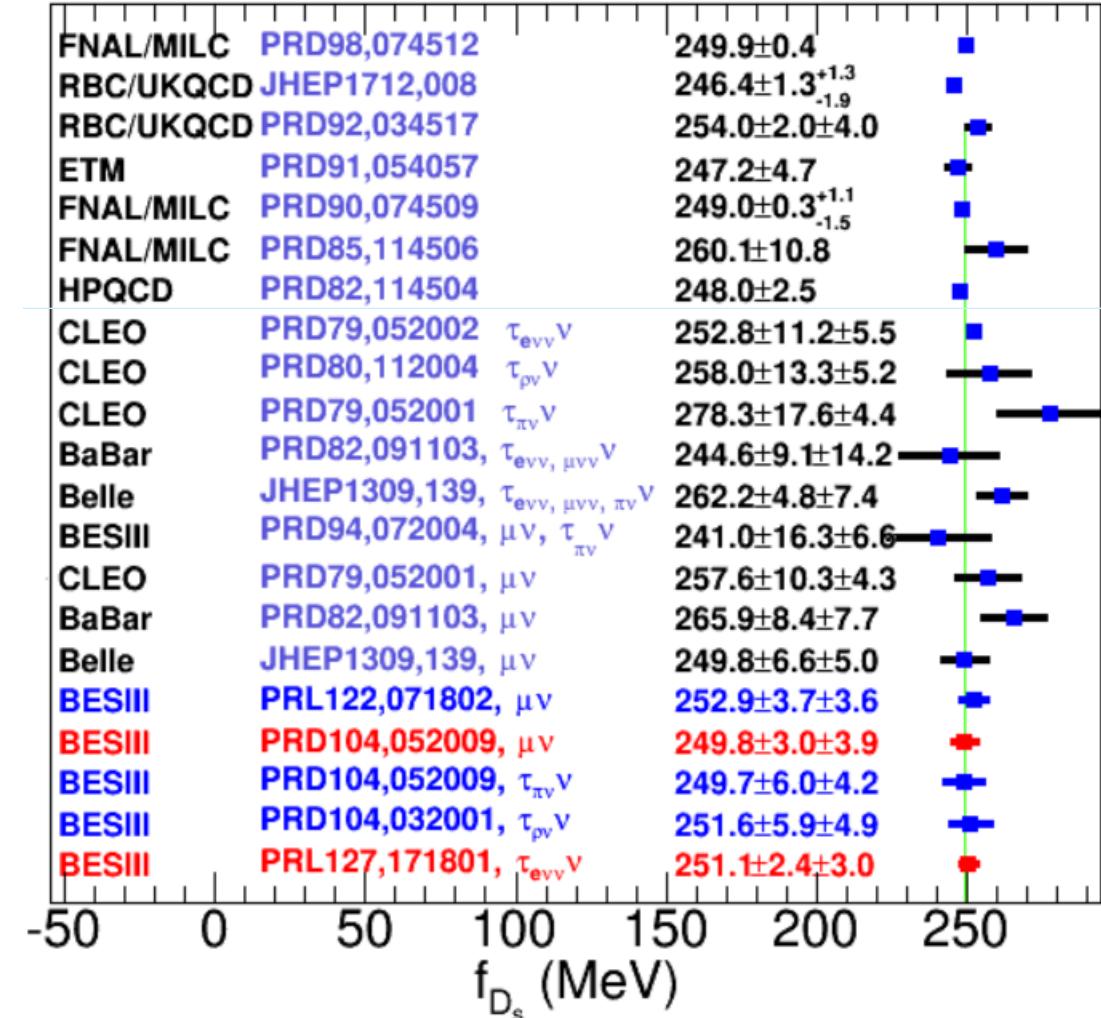
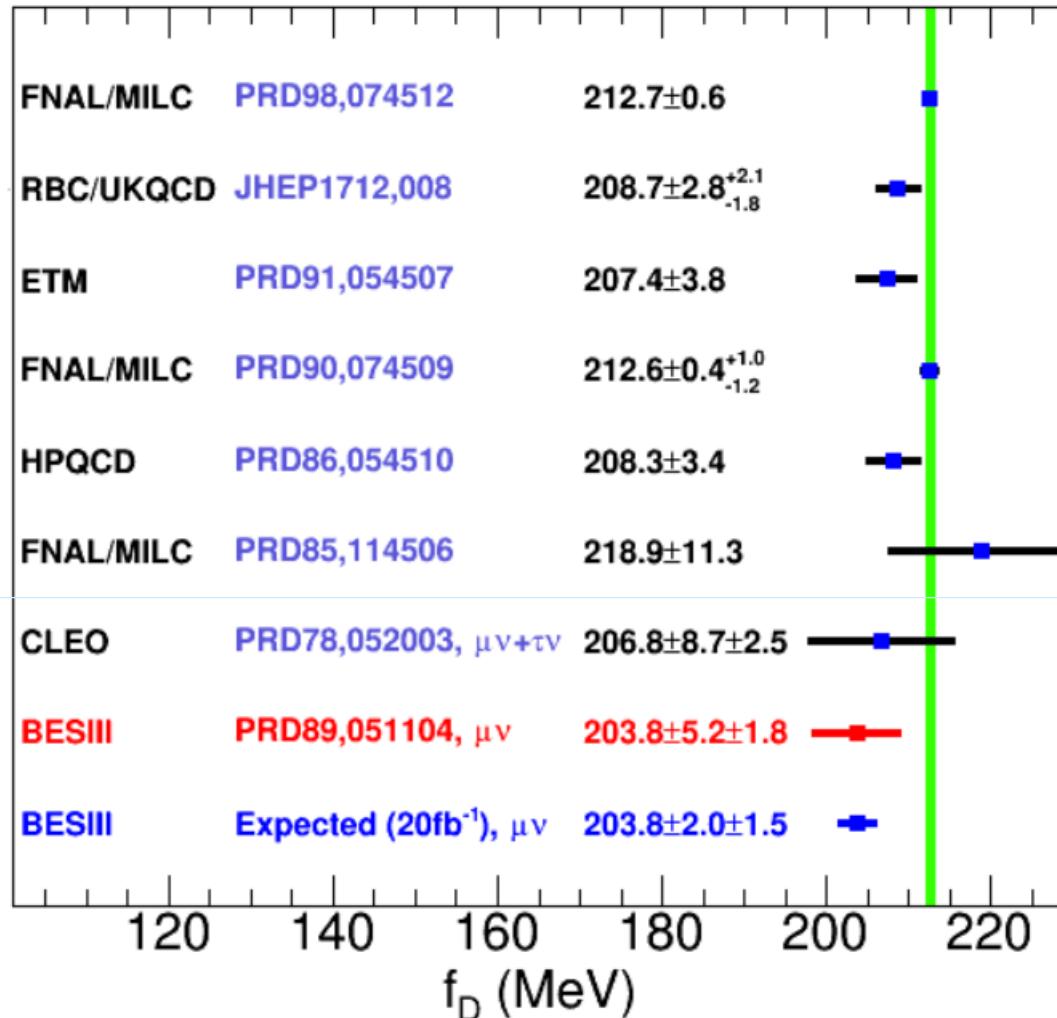
$2.93 \rightarrow 8 \text{ fb}^{-1}$  @ 3.773 GeV  $\rightarrow D^0\bar{D}^0$  and  $D^+D^-$   
 $0.48 \text{ fb}^{-1}$  @ 4.009 GeV  $\rightarrow D_s^+D_s^-$   
 $7.33 \text{ fb}^{-1}$  @ 4.13-4.23 GeV  $\rightarrow D_s^*\bar{D}_s$   
 $4.5 \text{ fb}^{-1}$  @ 4.6-4.7 GeV  $\rightarrow \Lambda_c^+\bar{\Lambda}_c^-$

- Extract decay constant  $f_{D(s)}$  incorporates the strong interaction effects (wave function at the origin)
- To validate Lattice QCD calculation of  $f_{B(s)}$  and provide constraint of CKM- unitarity

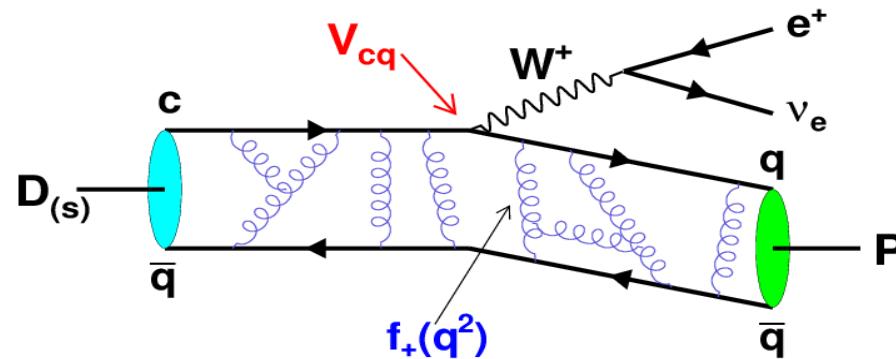


Decay rate (Exp.)  $\Gamma(D_{(s)} \rightarrow \ell \nu) = |V_{cd(s)}|^2 \times f_{D_{(s)}}^2 \times \frac{G_F^2}{8\pi} m_\ell^2 m_{D_{(s)}} (1 - m_\ell^2/m_{D_{(s)}}^2)^2$

Decay constant (LQCD)  
CKM matrix element



- form factor (FF)
  - ◆ Measure  $|V_{cx}| \times \text{FF}$
  - ◆ CKM-unitarity  $\Rightarrow |V_{cx}|$ , extract FF, test LQCD
  - ◆ Input LQCD FF to test CKM-unitarity



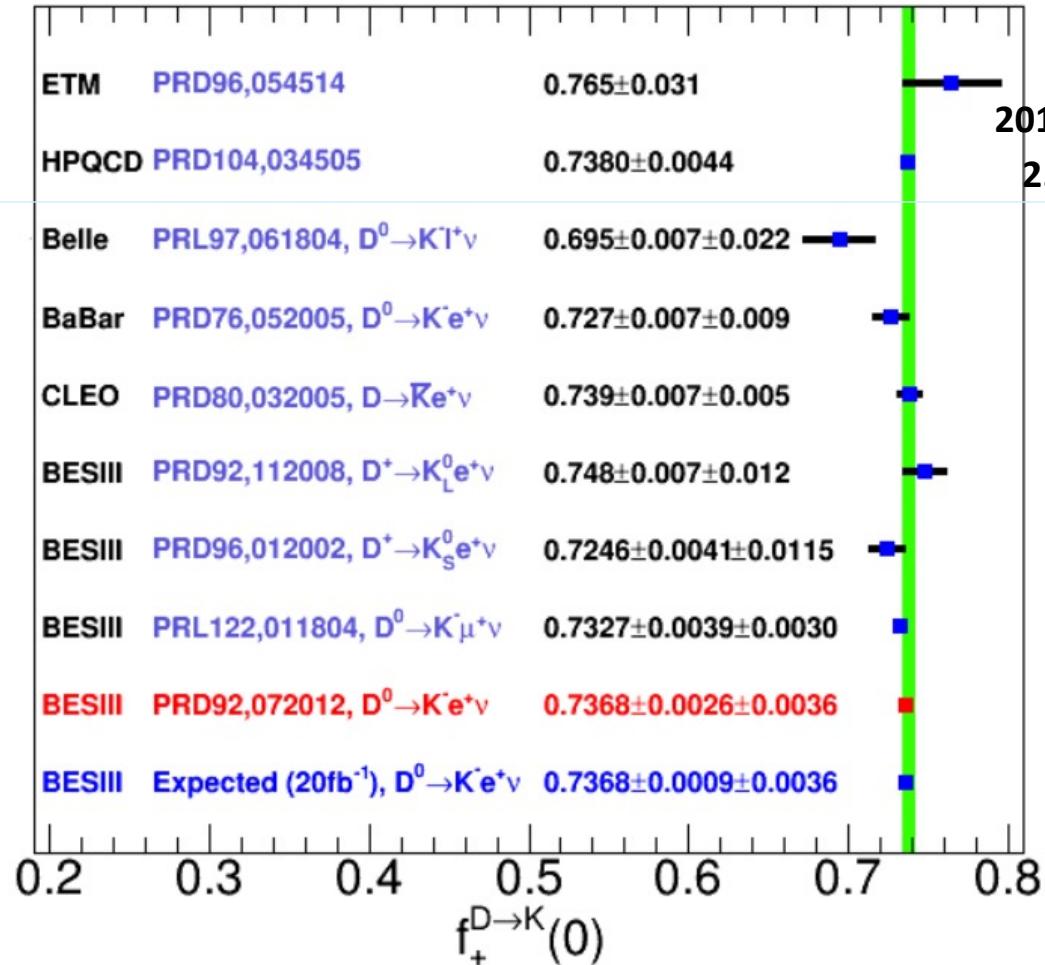
At zero positron mass limit:

Differential rate (Exp.)

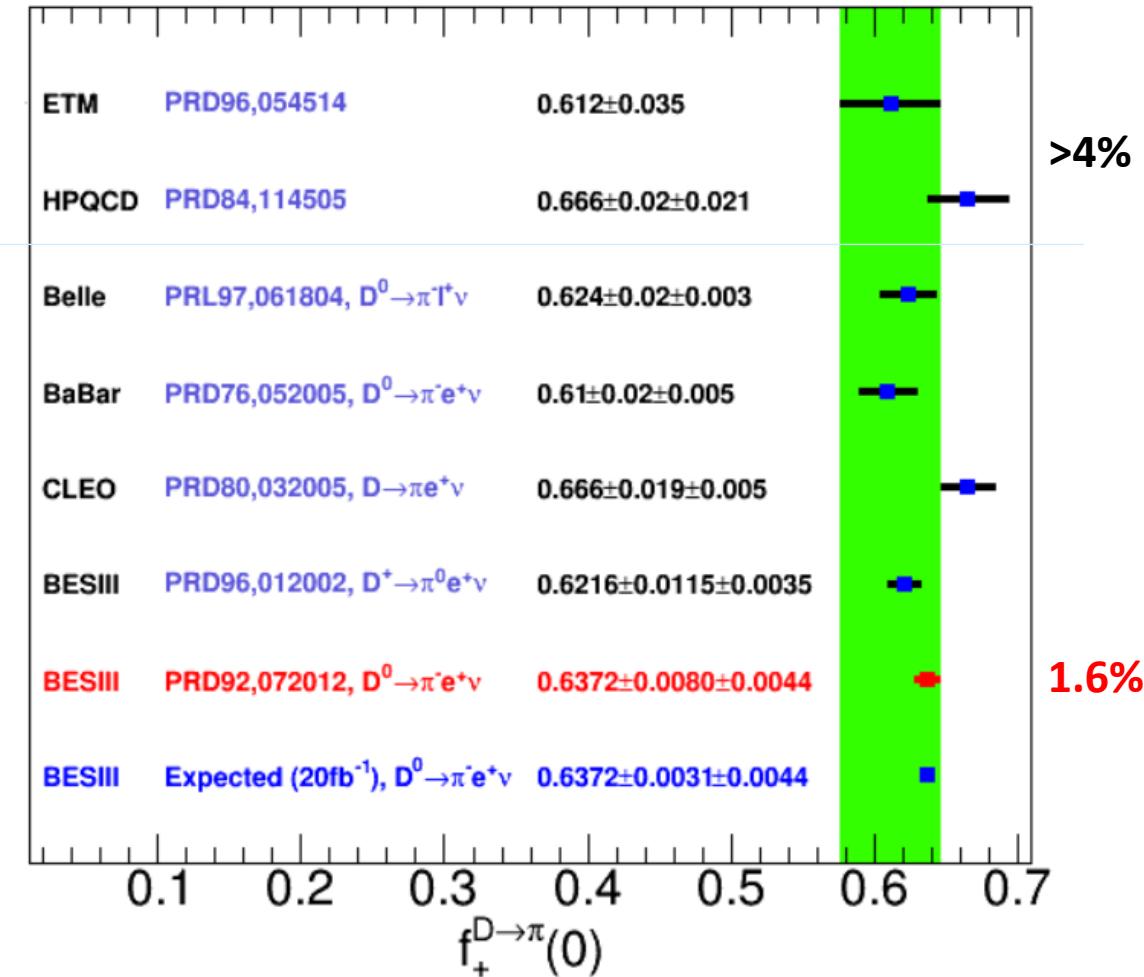
$$\frac{d\Gamma(D_{(s)} \rightarrow K(\pi) l\nu)}{dq^2} = \frac{G_F^2}{24\pi^3} \left| V_{cs(d)} \right|^2 P_{K(\pi)}^3 \left| f_+(q^2) \right|^2$$

CKM matrix element

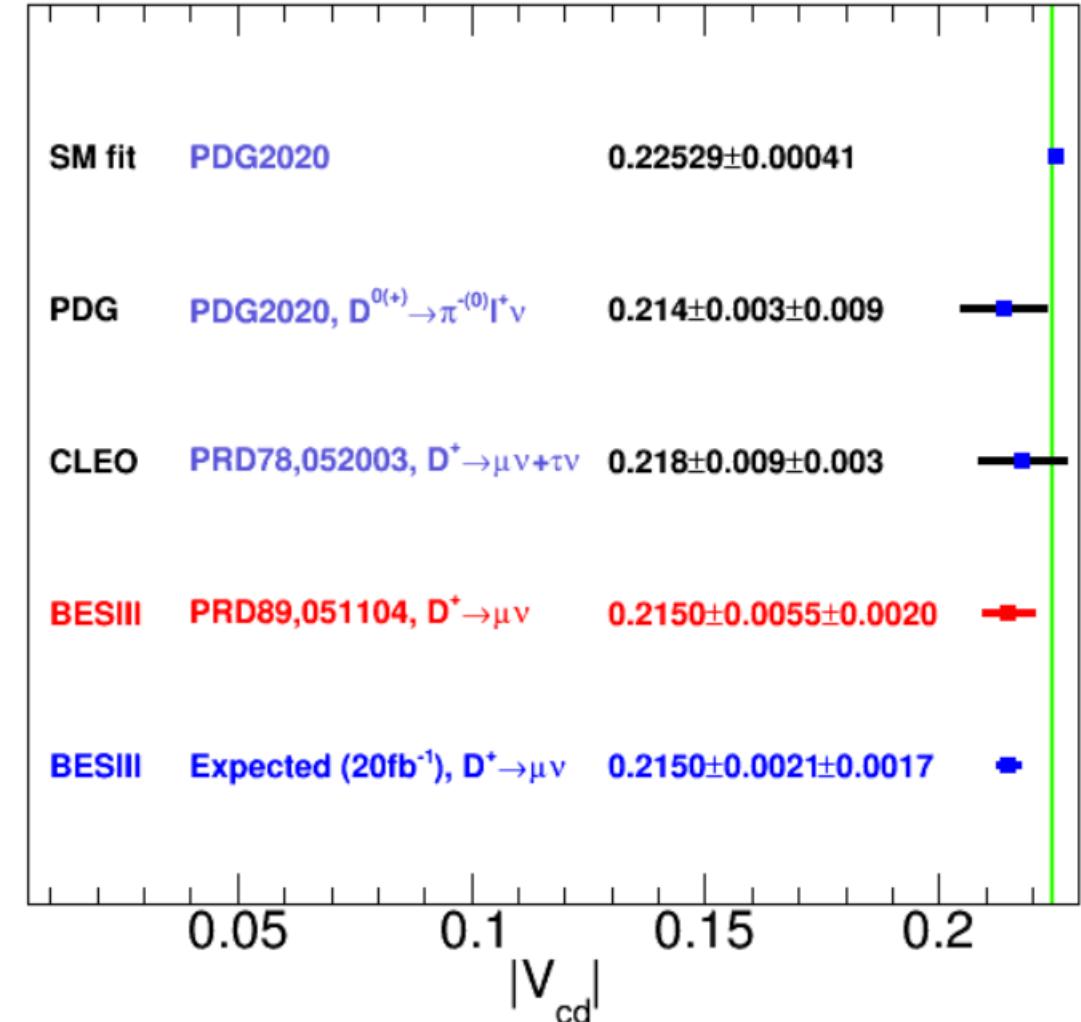
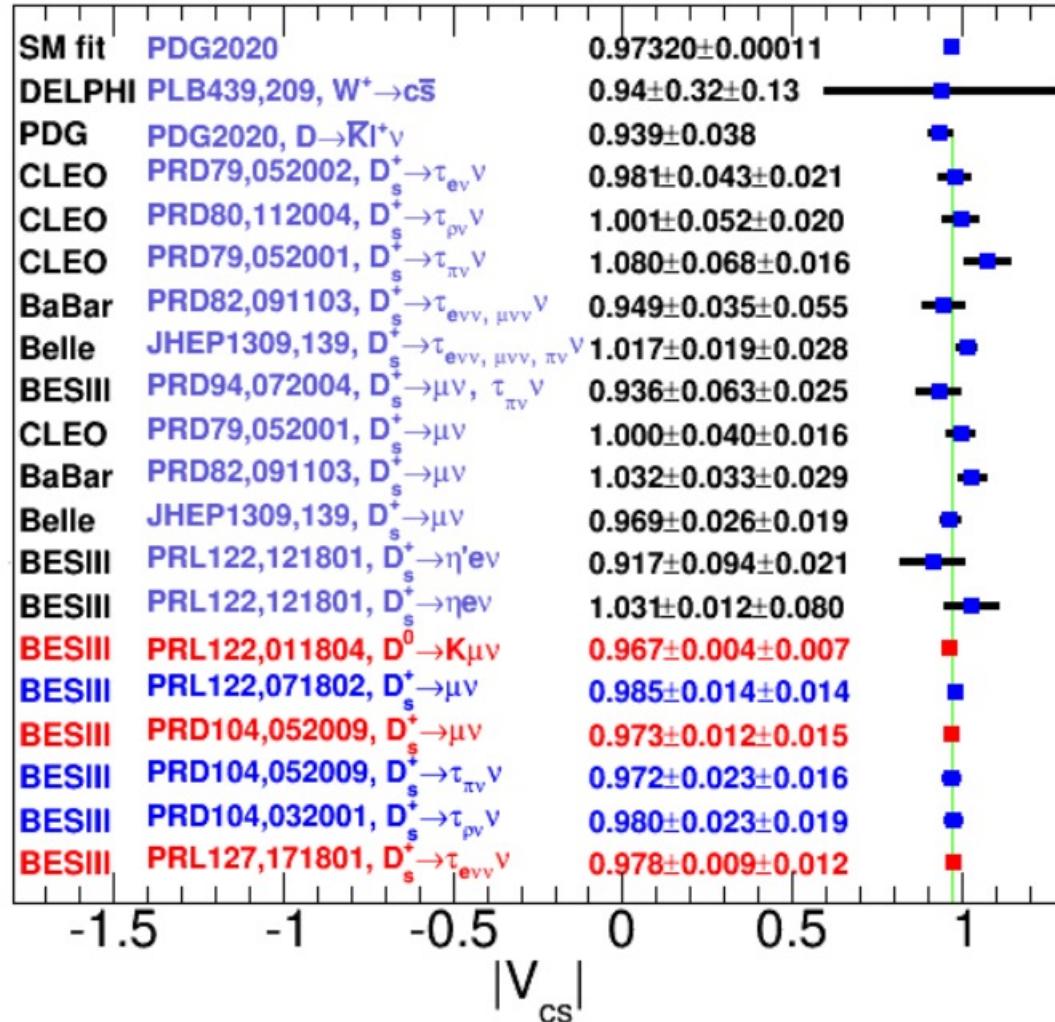
Form factor (LQCD)



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



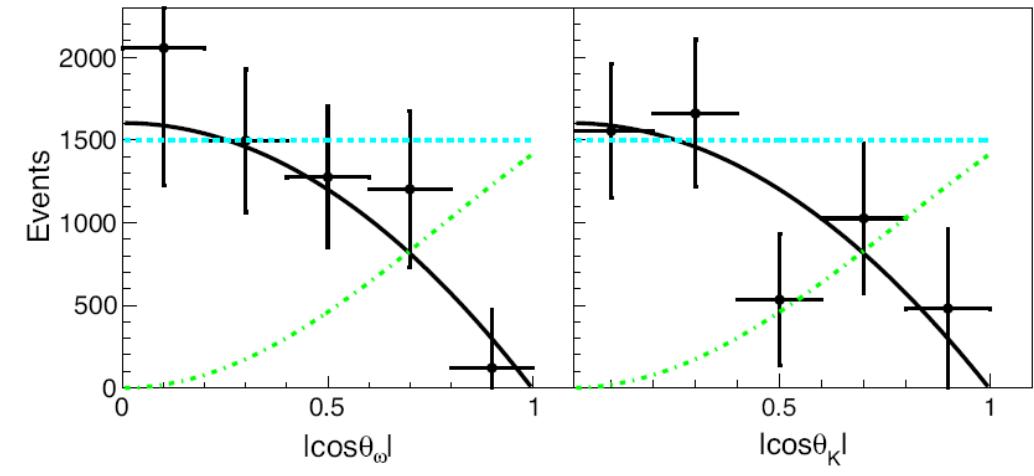
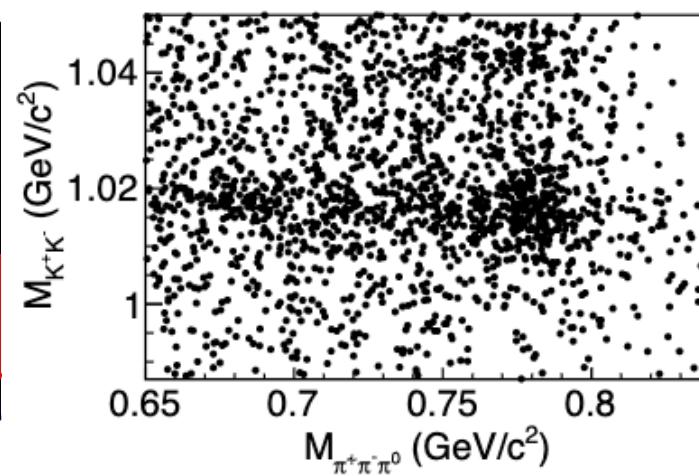
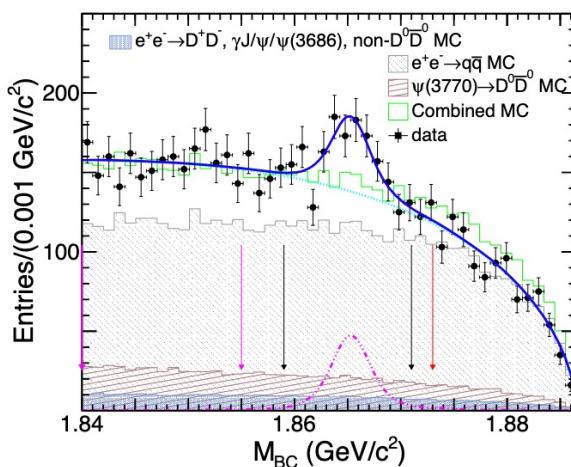
Experimental precision of  $f_+^{D \rightarrow \pi}(0)$  is still dominated by statistical uncertainties



- Strong phase measurement with quantum correlated  $\psi'' \rightarrow D^0\bar{D}^0$  is crucial in the model-independent determinations of  $\gamma$  and charm mixing/direct CPV.
- Probe non-perturbative QCD
  - Help to understand hadron spectroscopy – Study SU(3) flavor symmetry
  - Study short and long distance effects

### Observation of $D^+ \rightarrow \omega\phi$

PRL128, 011803(2022)

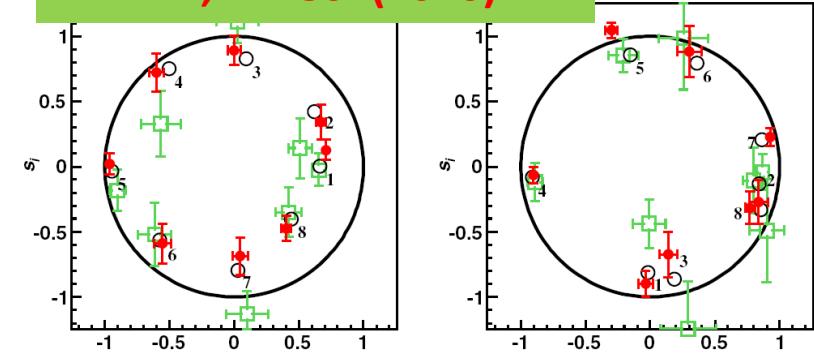


The  $\omega$  and  $\phi$  in the  $D^0$  decay are transversely polarized, which contradicts predictions from the naive factorization and Lorentz invariant-based symmetry models.

# Strong phases in hadronic $D^0 / \bar{D}^0$ decays

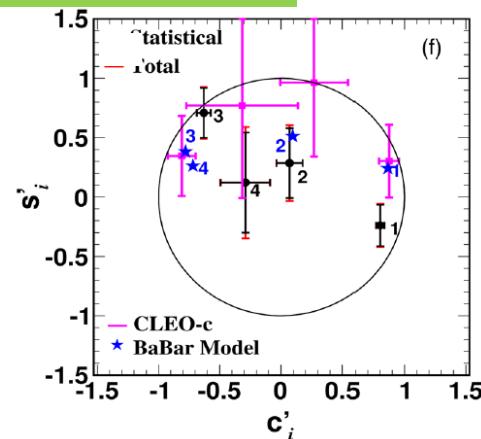
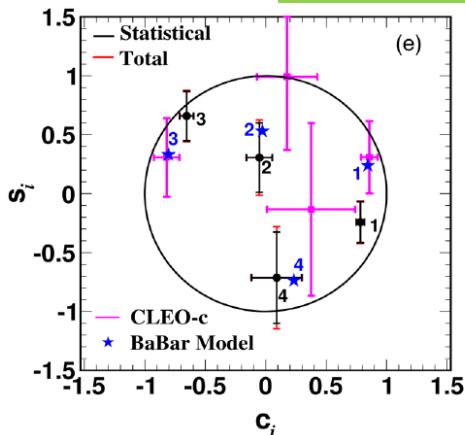
$D \rightarrow K_{S/L}^0 \pi^+ \pi^-$

PRL124, 241802(2020)



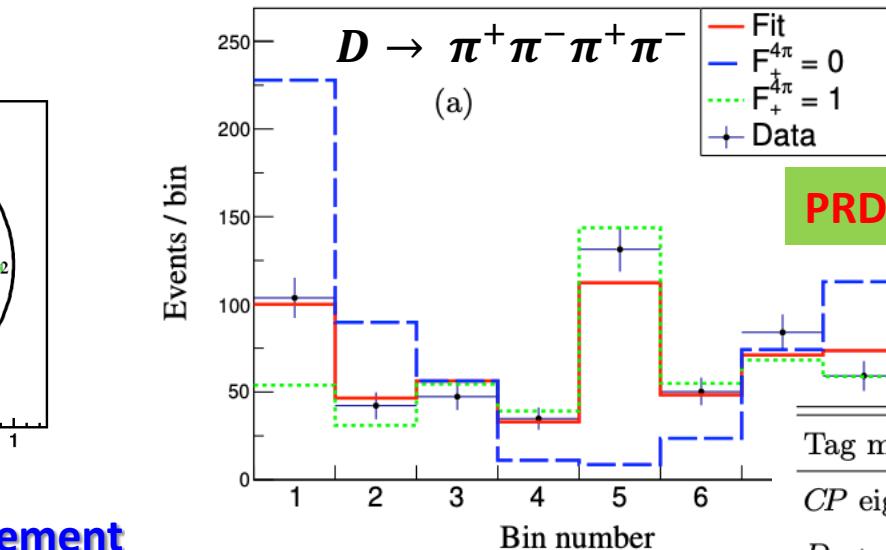
$D \rightarrow K_{S/L}^0 K^+ K^-$

PRD102, 052008(2020)



Constraint on  $\gamma$  measurement

$D \rightarrow K^- \pi^+ \pi^+ \pi^-$  and  $K^- \pi^+ \pi^0$



PRD106, 092004(2022)

Tag modes	$F_+^{4\pi}$
$CP$ eigenstates	$0.721 \pm 0.019 \pm 0.007$
$D \rightarrow \pi^+ \pi^- \pi^0$	$0.753 \pm 0.028 \pm 0.010$
$D \rightarrow K_{S,L}^0 \pi^+ \pi^-$	$0.754 \pm 0.031 \pm 0.009$
Combination	$0.735 \pm 0.015 \pm 0.005$

Analysis	Resonance	
$D_s^+ \rightarrow K^+ K^- \pi^+ \pi^- \pi^+$	$a_1(1260)^+$	JHEP07(2022)051
$D_s^+ \rightarrow K_S^0 K_S^0 \pi^+$	$a_0(1710)^0, f_0(1710)$	PRD105(2022) L051103
$D_s^+ \rightarrow K_S^0 K^+ \pi^0$	$a_0(1817)^+$	<u>PRL129, 182001 (2022)</u>
$D_s^+ \rightarrow K^+ \pi^+ \pi^-$	$f_0(500), f_0(980), f_0(1370)$	JHEP08(2022)196
$D_s^+ \rightarrow \pi^+ \pi^0 \pi^0$	$f_0(980), f_0(1370), f_2(1270)$	JHEP01(2022)052

Charge conjugate channels are included.

- Amplitude analysis,  $N_{\text{tot}} = 1050$  with a signal purity of  $(94.7 \pm 0.7)\%$
- Observed  $a_0(1817)^+(\rightarrow K_S^0 K^+)$ : isovector partner of  $f_0(1710)$ ?

$$M = (1.817 \pm 0.008_{\text{stat.}} \pm 0.020_{\text{syst.}}) \text{GeV}/c^2$$

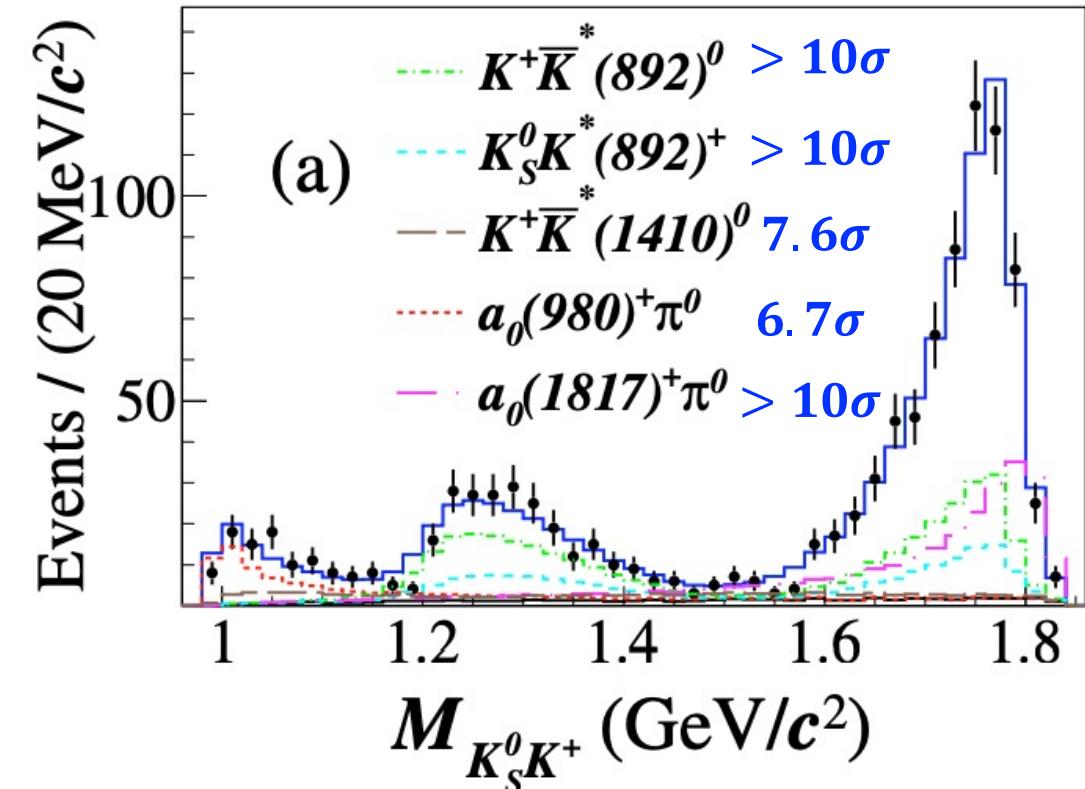
$$\Gamma = (0.097 \pm 0.022_{\text{stat.}} \pm 0.015_{\text{syst.}}) \text{GeV}$$

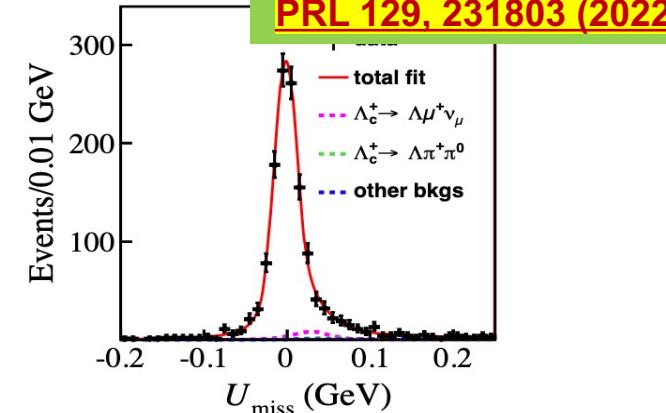
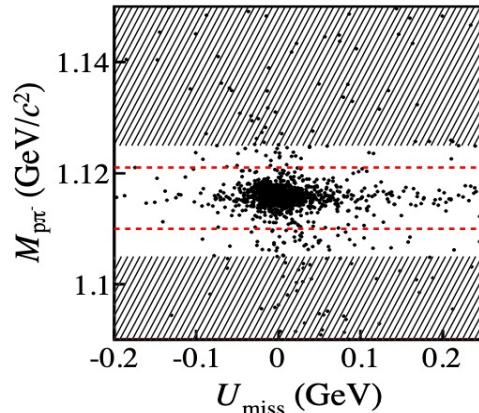
- The measured ratio for  $a_0(980)^+$ :

$$\frac{B[a_0(980)^+ \rightarrow \bar{K}^0 K^+]}{B[a_0(980)^+ \rightarrow \pi^+ \eta]} = (13.7 \pm 3.6_{\text{stat.}} \pm 4.2_{\text{syst.}})\%$$

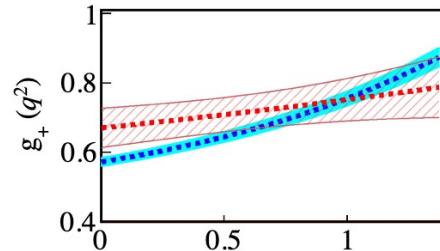
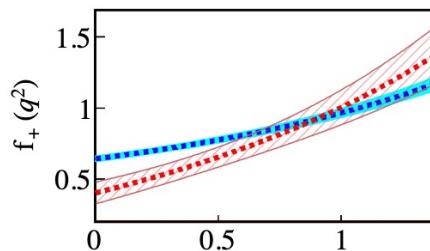
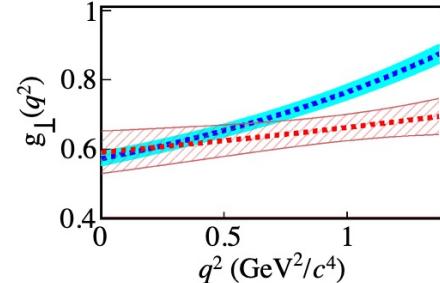
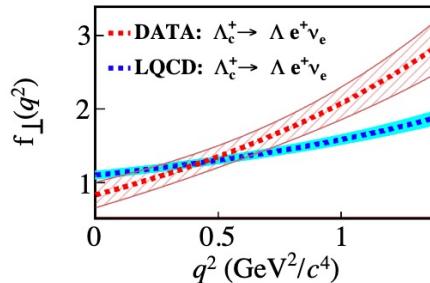
A key experimental input for the calculation of the coupling constants of the  $a_0(980)$ , and helps to determine its quark composition

[PRL129, 182001 \(2022\)](#)

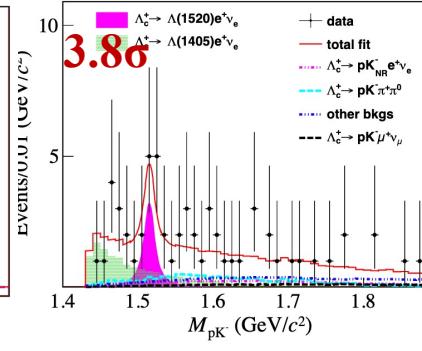
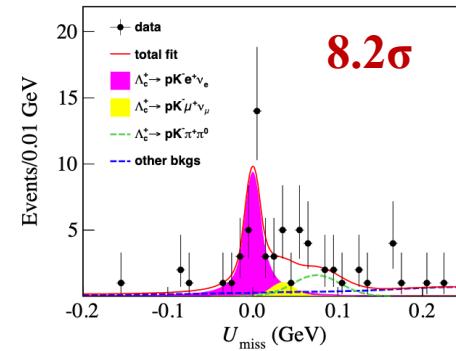


Determination of form factors of  $\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e$ 

$$B(\Lambda_c^+ \rightarrow \Lambda e^+ \nu_e) = (3.56 \pm 0.11 \pm 0.07)\%$$



First direct comparisons on differential decay rates and form factors with LQCD

Observation of  $\Lambda_c^+ \rightarrow p K^- e^+ \nu$ 

$$B(\Lambda_c^+ \rightarrow p K^- e^+ \nu) = (0.88 \pm 0.17 \pm 0.07) \times 10^{-3}$$

$$B(\Lambda_c^+ \rightarrow \Lambda(1405)e^+ \nu) = (1.69 \pm 0.76 \pm 0.16) \times 10^{-3}$$

$$B(\Lambda_c^+ \rightarrow \Lambda(1520)e^+ \nu) = (0.99 \pm 0.51 \pm 0.10) \times 10^{-3}$$

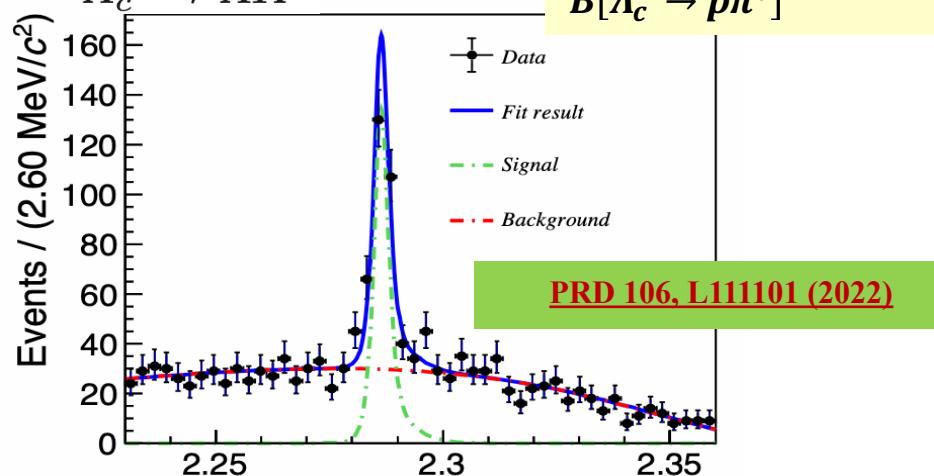
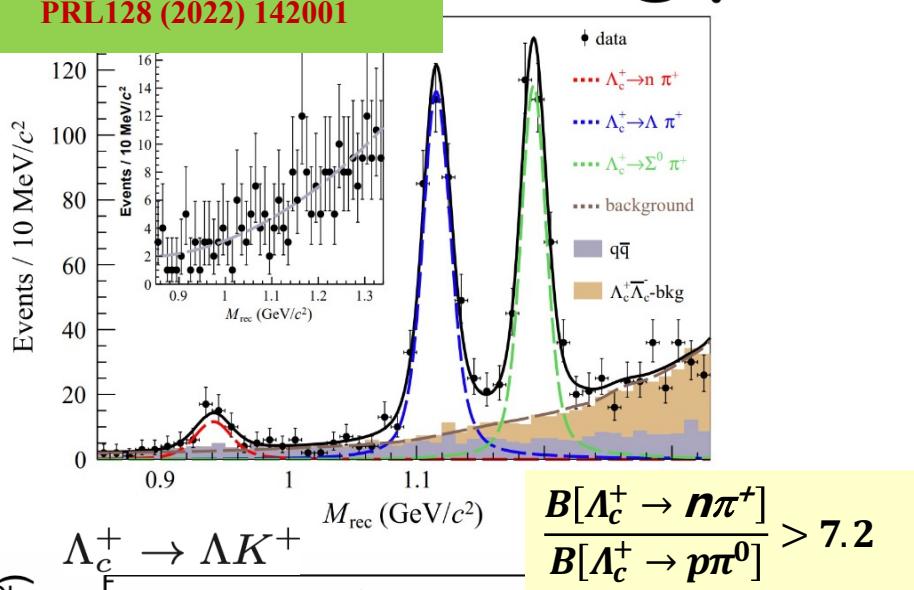
- Second leptonic decay of  $\Lambda_c^+$  is observed!
- Good channel to study  $\Lambda$  excited states, such as  $\Lambda(1405)$ ,  $\Lambda(1520)$

# Recent results on $\Lambda_c^+$ hadronic decays



Observation of  $\Lambda_c^+ \rightarrow n\pi^+$

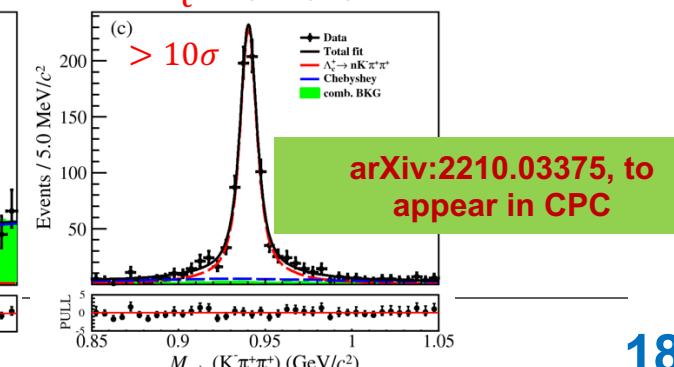
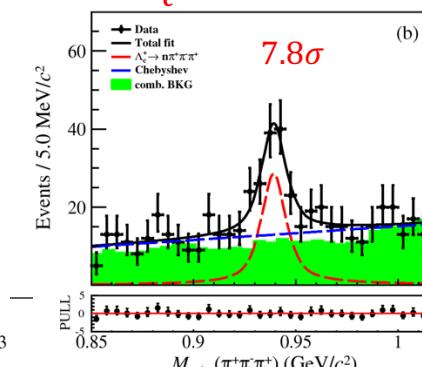
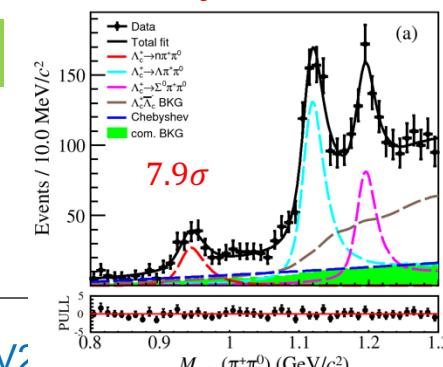
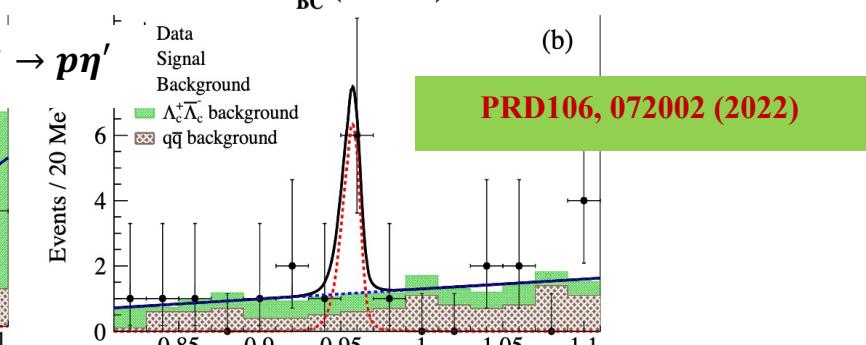
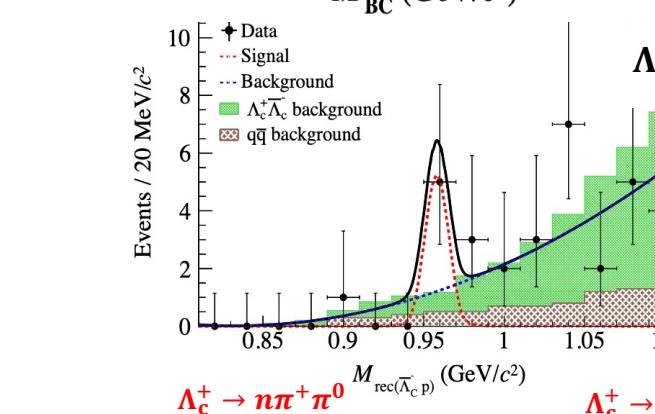
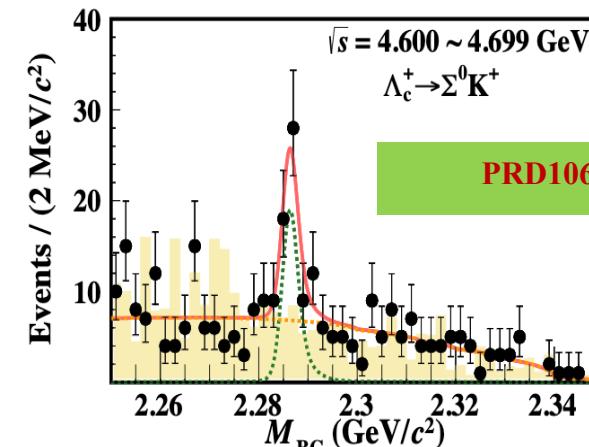
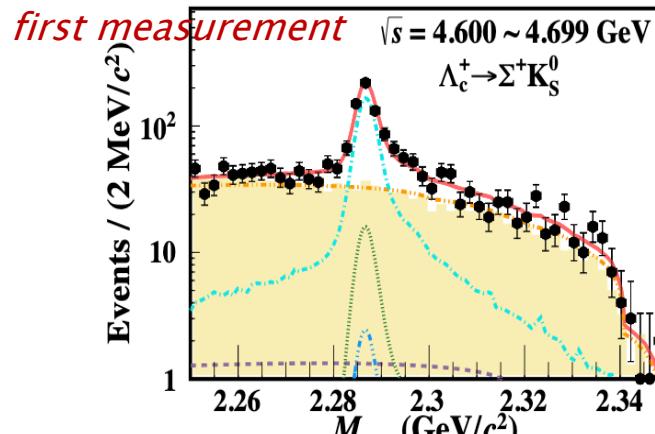
PRL128 (2022) 142001



Many CS modes are explored.

Determination of the BF for  $\Lambda_c^+ \rightarrow \Sigma^+ K_S$  and  $\Sigma^0 K^+$

first measurement  $\sqrt{s} = 4.600 \sim 4.699 \text{ GeV}$

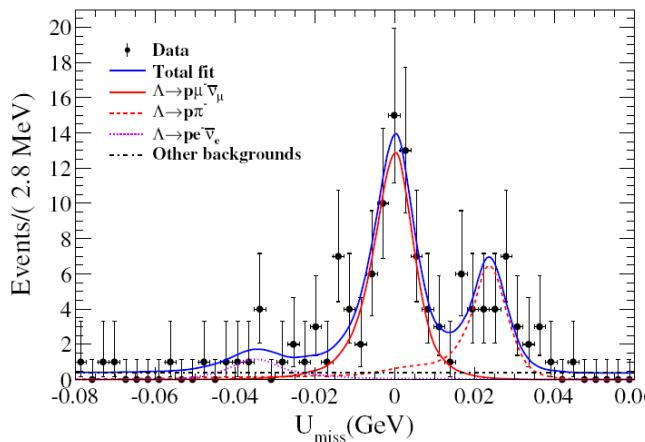


# Decay properties of hyperons

With world largest  $J/\psi$  sample , BESIII is also a hyperon factory!

$\Lambda \rightarrow p\mu^-\bar{\nu}_\mu$  via  $J/\psi \rightarrow \Lambda\bar{\Lambda}$

PRL127(2021)121802



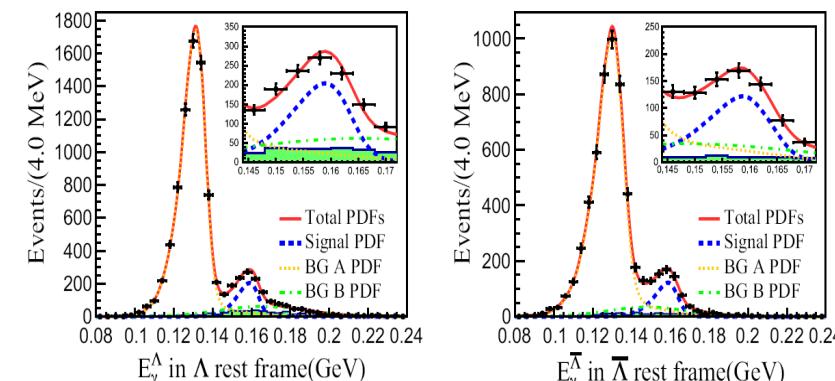
$$B_{\Lambda \rightarrow p \mu^- \bar{\nu}_\mu} = (1.48 \pm 0.21 \pm 0.08) \times 10^{-4}$$

$$A_{CP} = (B_\Lambda - B_{\bar{\Lambda}})/(B_\Lambda + B_{\bar{\Lambda}}) = 0.02 \pm 0.14 \pm 0.02$$

$$B_{\Lambda \rightarrow p \mu^- \bar{\nu}_\mu}/B_{\Lambda \rightarrow p e^- \bar{\nu}_e} = 0.178 \pm 0.028$$

$\Lambda \rightarrow n\gamma$  via  $J/\psi \rightarrow \Lambda\bar{\Lambda}$

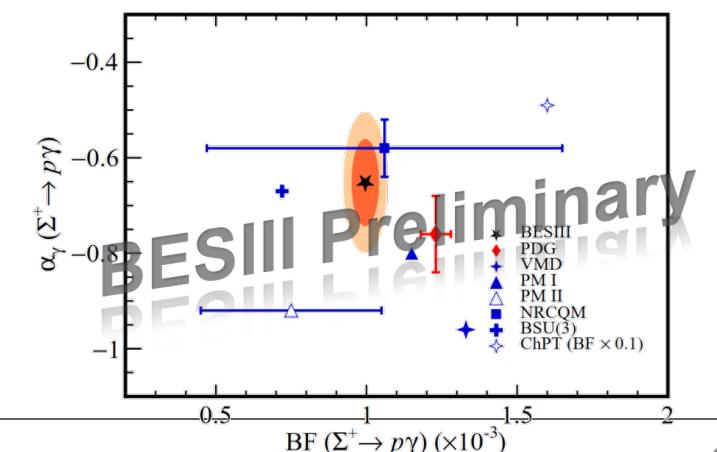
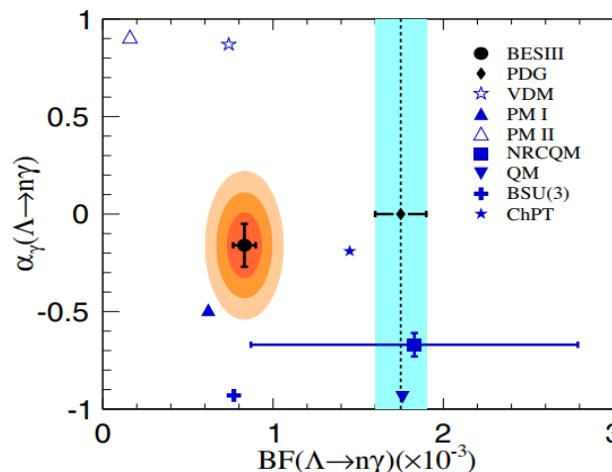
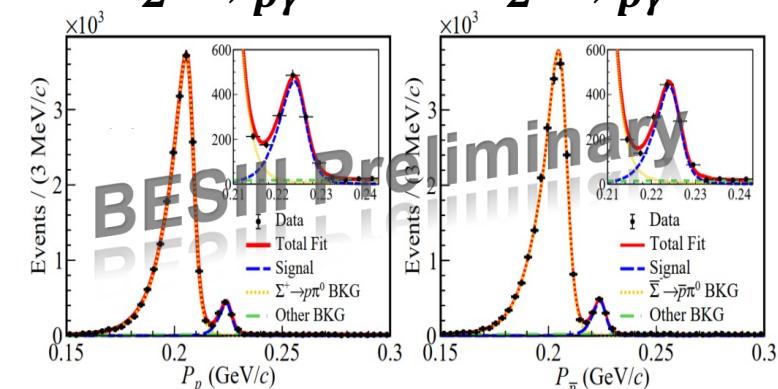
PRL129(2022)122002

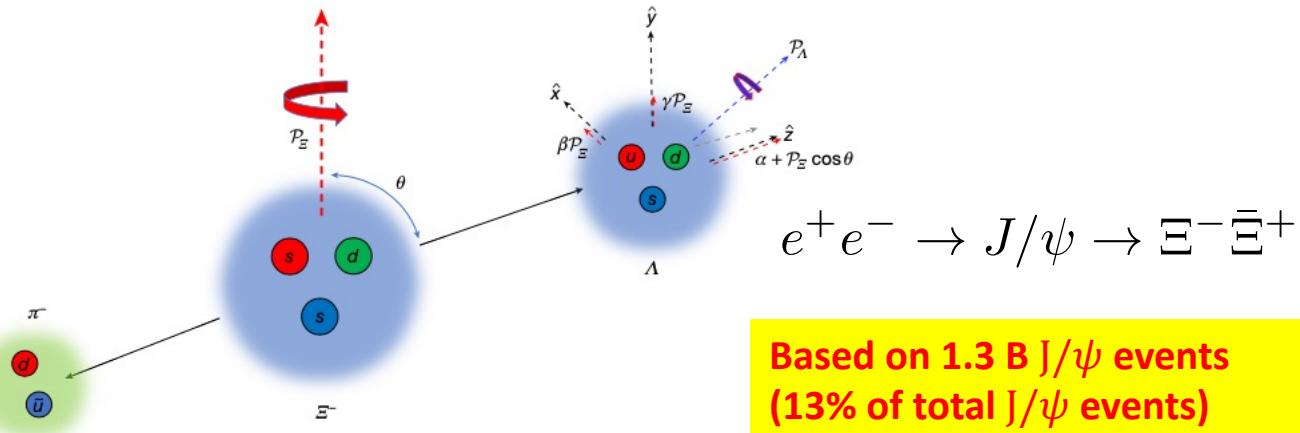


$\Sigma^+ \rightarrow p\gamma$  via  $J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$

$\Sigma^+ \rightarrow p\gamma$

$\bar{\Sigma}^- \rightarrow \bar{p}\gamma$





- ✓ First measurement of polarization
- ✓ First direct determination of all  $\Xi$  decay parameters
- ✓ First extraction of weak phase difference from baryon weak decays
- ✓ Three CP tests

[Nature 606, 64 \(2022\)](#)

Parameter	This work	Previous result
$a_\psi$	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	-
$a_\Xi$	$-0.376 \pm 0.007 \pm 0.003$	$-0.401 \pm 0.010$
$\phi_\Xi$	$0.011 \pm 0.019 \pm 0.009$ rad	$-0.037 \pm 0.014$ rad
$\bar{a}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	-
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	-
$a_\Lambda$	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$
$\bar{a}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$
$\xi_p - \xi_s$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	-
$\delta_p - \delta_s$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad
$A_{CP}^\Xi$	$(6 \pm 13 \pm 6) \times 10^{-3}$	-
$\Delta\phi_{CP}^\Xi$	$(-5 \pm 14 \pm 3) \times 10^{-3}$ rad	-
$A_{CP}^\Lambda$	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad	-

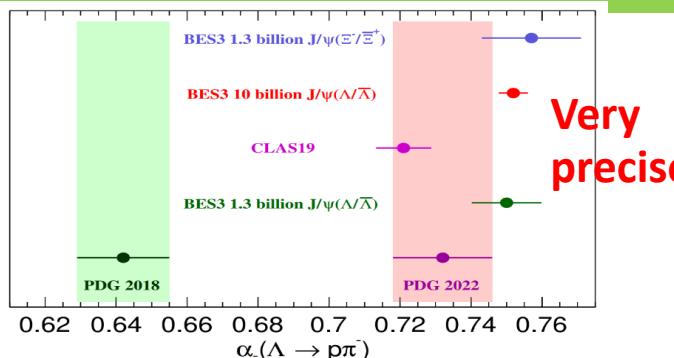
HyperCP(2004):  $\phi_{\Xi, \text{HyperCP}} = -0.042 \pm 0.011 \pm 0.011$

the same precision for  $\phi$  as HyperCP with **three orders of magnitude** smaller data sample!

- Relative phase between electronic and magnetic form factors:  $\Delta\Phi$
- Decay asymmetry parameter:  $\alpha$
- New window to test CP violation of hyperons:  $A_{CP} = (\alpha_+ + \alpha_-) / (\alpha_+ - \alpha_-)$



Nat. Phys. 15, 631(2019) → PRL129, 131801(2022)

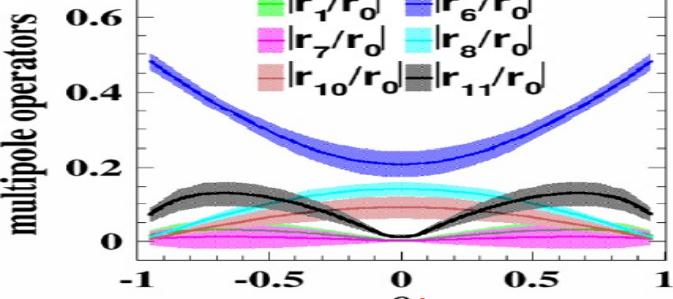


$$\Delta\Phi = (0.7521 \pm 0.0042 \pm 0.0066) \text{ rad}$$

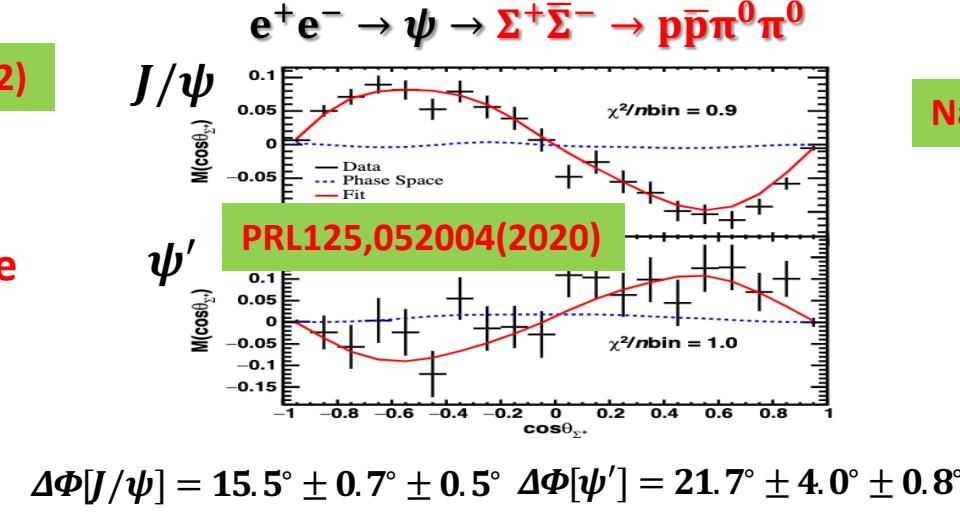
$$A_{CP} = (-0.25 \pm 0.46 \pm 0.12)\%$$



PRL126, 092002(2021)

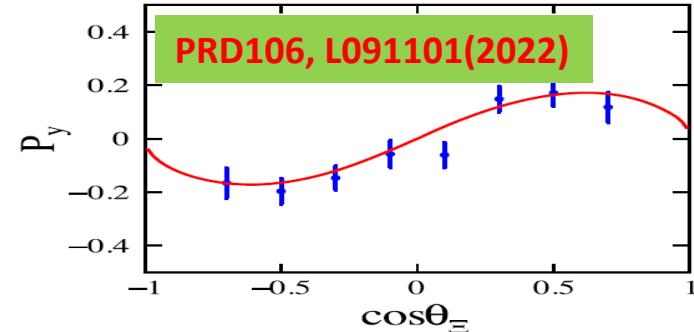
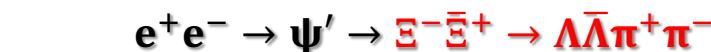


Spin of  $\Omega^-$  is set to be 3/2 for the first time



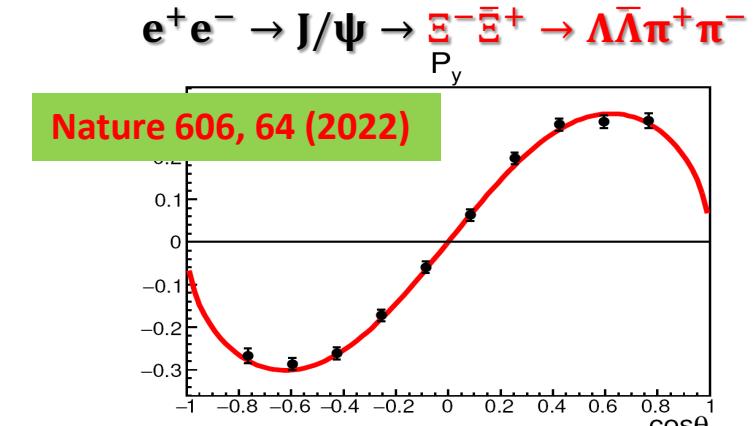
$$\Delta\Phi[J/\psi] = 15.5^\circ \pm 0.7^\circ \pm 0.5^\circ \quad \Delta\Phi[\Psi'] = 21.7^\circ \pm 4.0^\circ \pm 0.8^\circ$$

$$A_{CP} = (-0.4 \pm 3.7 \pm 1.0)\%$$



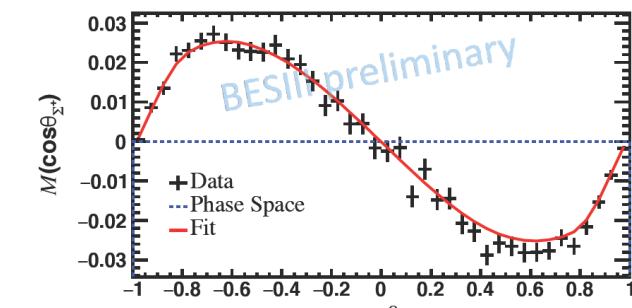
$$\Delta\Phi = (0.667 \pm 0.111 \pm 0.058) \text{ rad}$$

$$A_{CP} = (1.5 \pm 5.1 \pm 1.0)\%$$



$$\Delta\Phi = (1.213 \pm 0.046 \pm 0.016) \text{ rad}$$

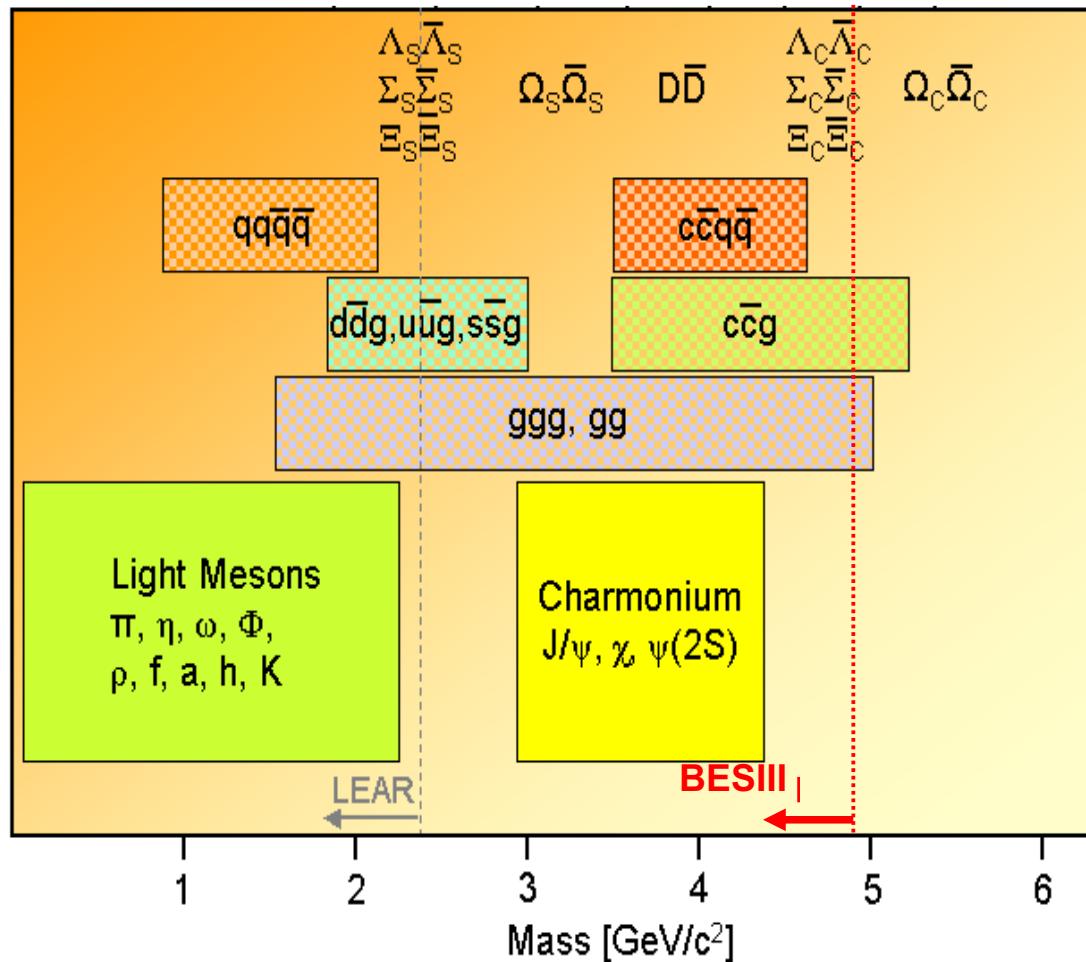
$$A_{CP} = (0.60 \pm 1.34 \pm 0.56)\%$$



$$\Delta\Phi = (-0.277 \pm 0.004 \pm 0.0xx) \text{ rad}$$

$$A_{CP} = (8.0 \pm 5.2 \pm x.x)\%$$

Two-body  
Thresholds  
Molecules  
Gluonic  
Excitation  
 $q\bar{q}$   
Mesons

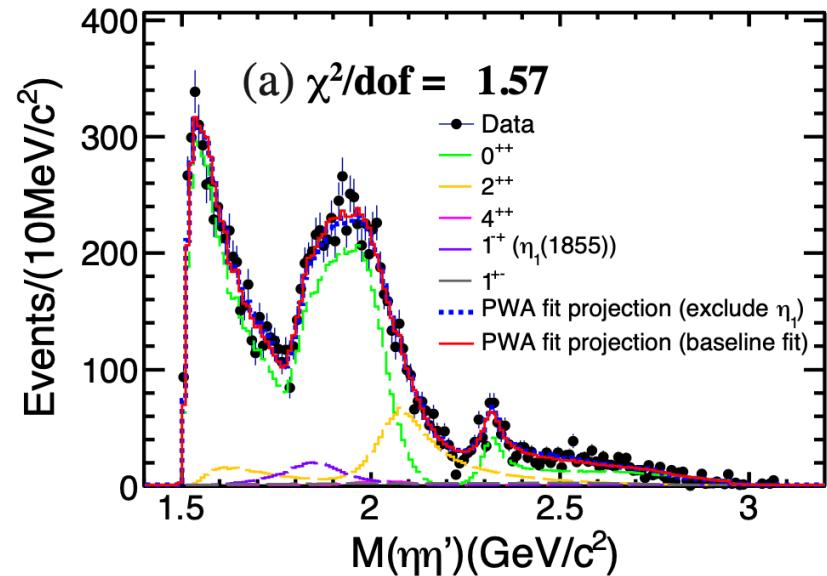


## Hadron physics opportunities:

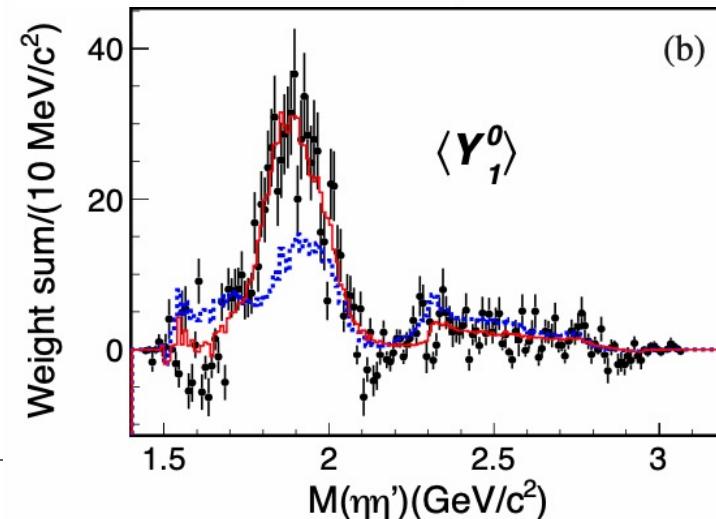
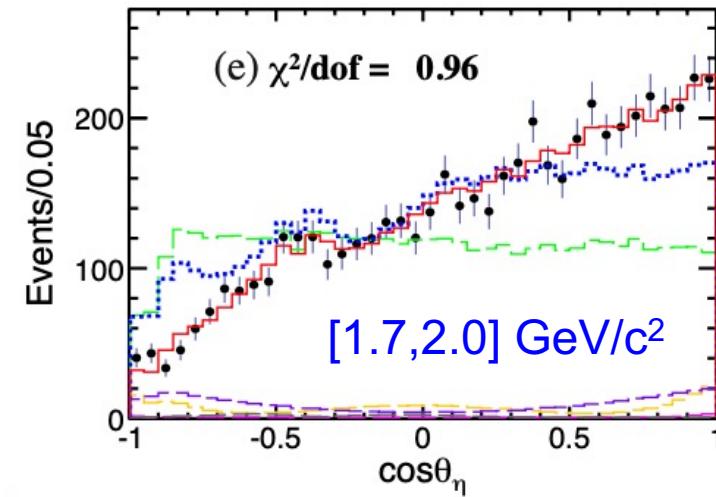
- Precision hadron spectroscopy → understand the established hadron states
- Search for the unexpected hadron states and spectroscopy study → explore nature of exotic hadron states

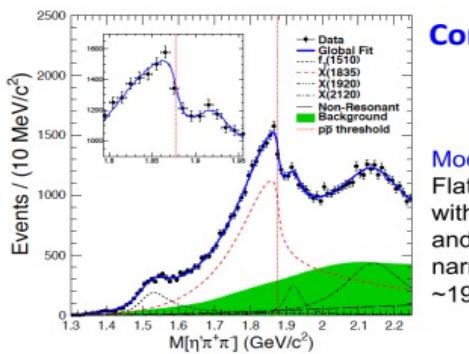
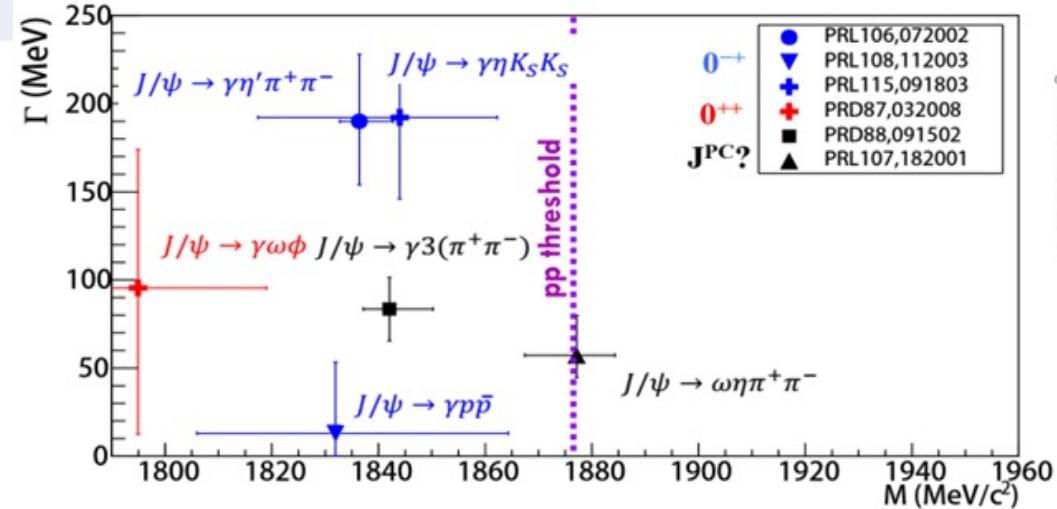
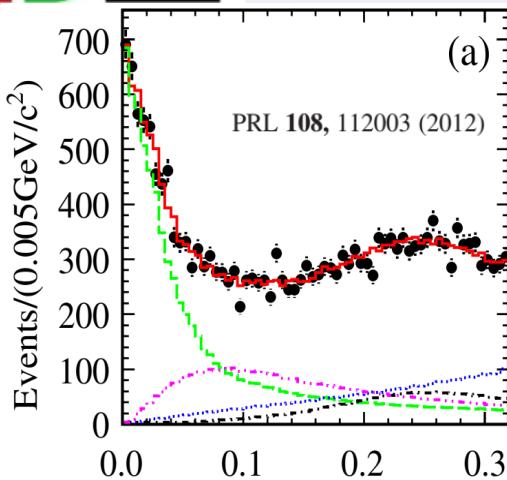
Partial wave analysis of  $J/\psi \rightarrow \gamma\eta\eta'$ 

[Phys. Rev. Lett. 129, 192002 \(2022\)](#)  
[Phys. Rev. D 106, 072012 \(2022\)](#)

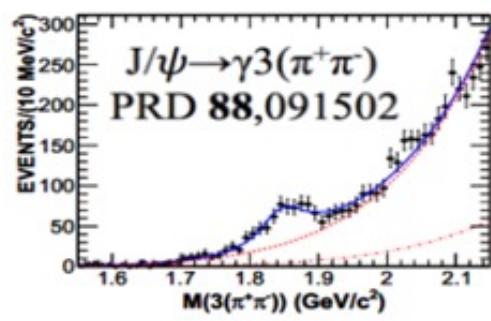
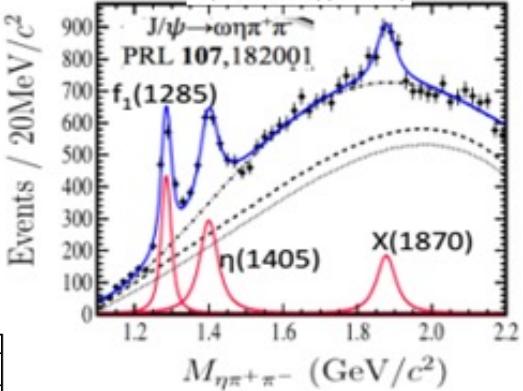
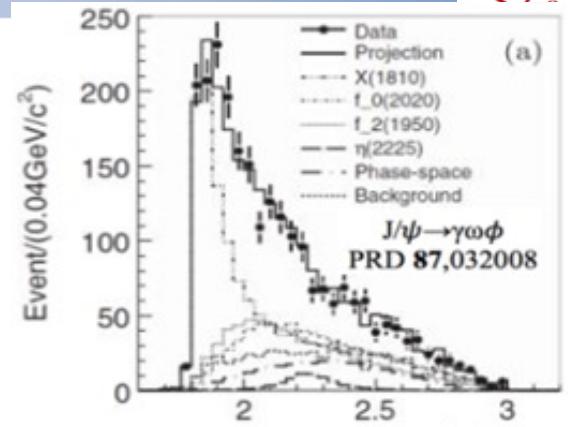
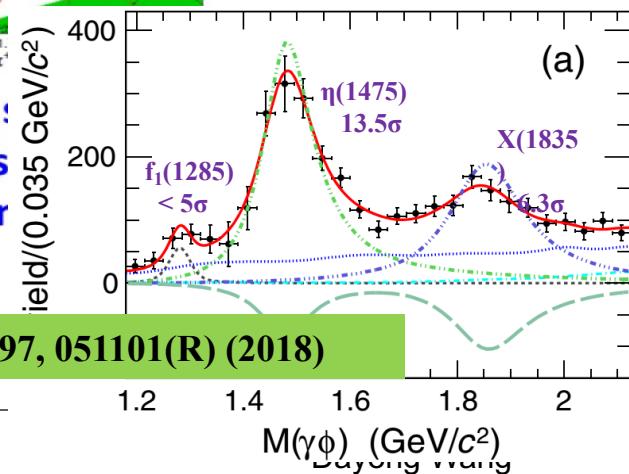


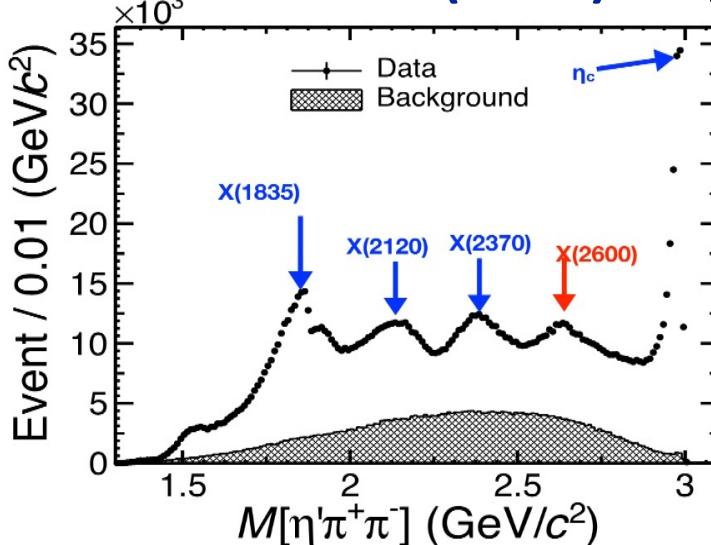
- critical to establish the  $1^{-+}$  hybrid nonet.
- supporting  $f_0(1710)$  overlap with glueball



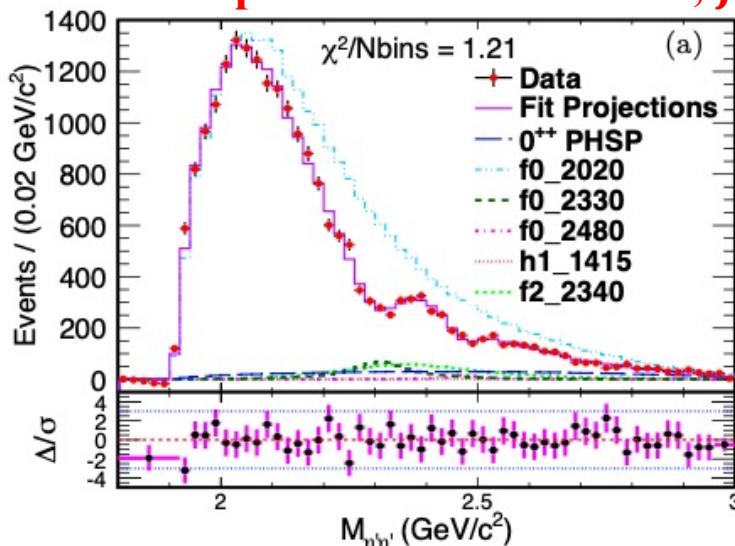


- Suggest the existence of a state, either a broad one with couplings to  $p\bar{p}$ , or a narrow state just below the  $p\bar{p}$  mass
- Support the existence of a  $p\bar{p}$  molecule-like state or bound state
- Any relations?
- What is the role of the  $p\bar{p}$  threshold (and other thresholds)?
- Patterns in the production and decay modes





Observed a possible new  $0^{++}$  state,  $f_0(2480)$



# Newly published PWA results



PRL129(2022)042001

$J^{PC}$ : unknown

$$M = 2618.3 \pm 2.0^{+16.3}_{-1.4} \text{ MeV}/c^2$$

$$\Gamma = 195 \pm 5^{+26}_{-17} \text{ MeV}$$

$\eta$  radial excitation or exotic hadron?

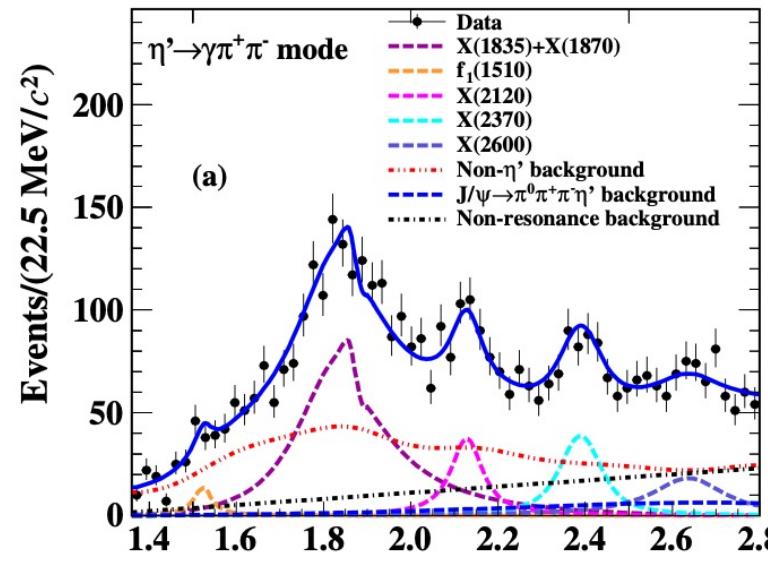
Resonance	$M(\text{MeV}/c^2)$	$\Gamma(\text{MeV})$	B.F.	Sig.( $\sigma$ )
$f_0(2020)$	$1982 \pm 3^{+54}_0$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$	$\gg 25$
$f_0(2330)$	$2312 \pm 2^{+10}_0$	$134 \pm 5^{+30}_9$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$	16.3
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$	5.2
$f_1(1415)$	$1384 \pm 6^{+9}_0$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$	5.3
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$	16.1
$0^{++}$ PHSP	...	...	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$	15.7

$J/\psi \rightarrow \gamma \eta' \eta'$

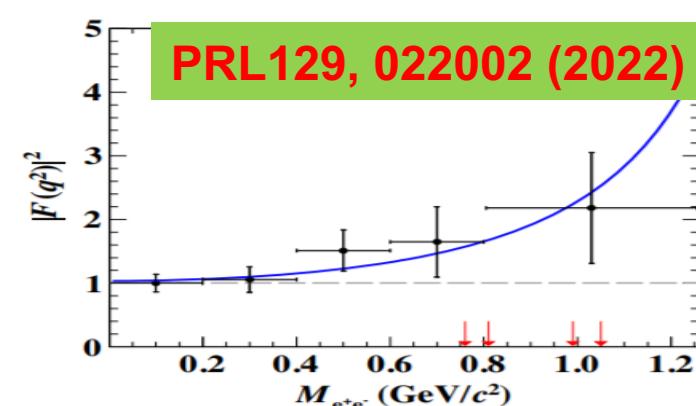
The large production rate of  $f_0(2020)$  in radiative  $J/\psi$  decay suggests that it has a large overlap with scalar glueball. But, its mass is lower than LQCD calculation

# EM Dalitz decay studies

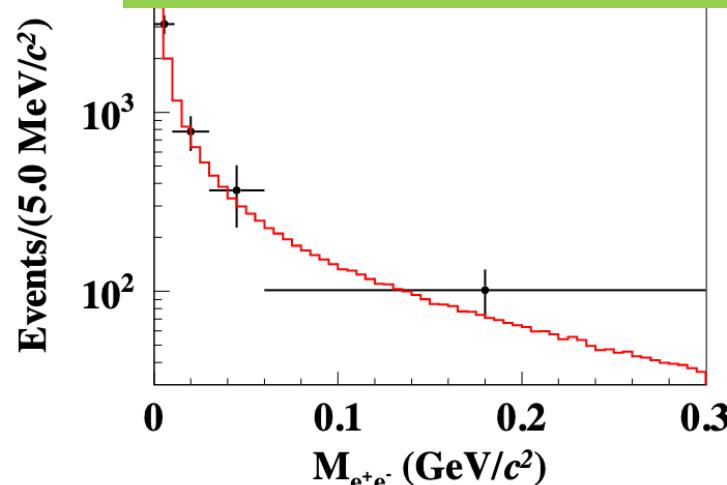
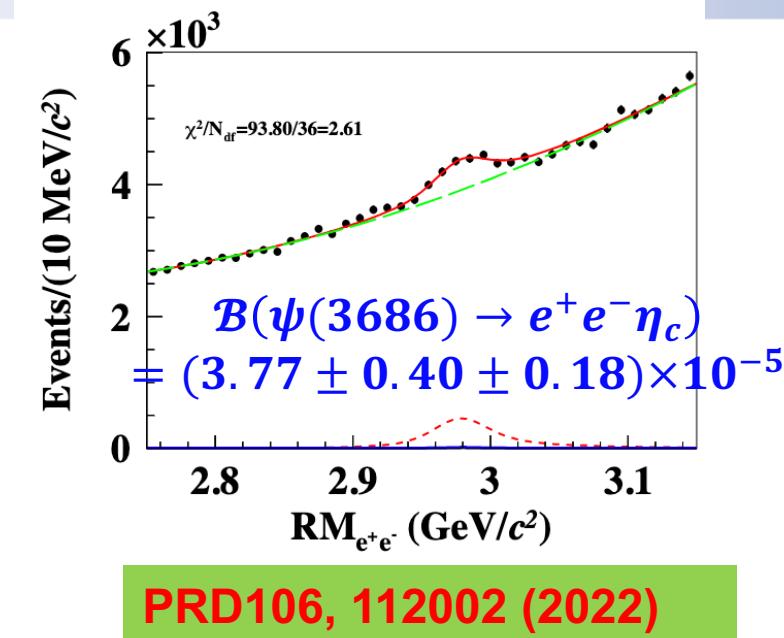
- X(1835) in  $J/\psi \rightarrow e^+e^- \eta'\pi^+\pi^-$



PRL129, 022002 (2022)

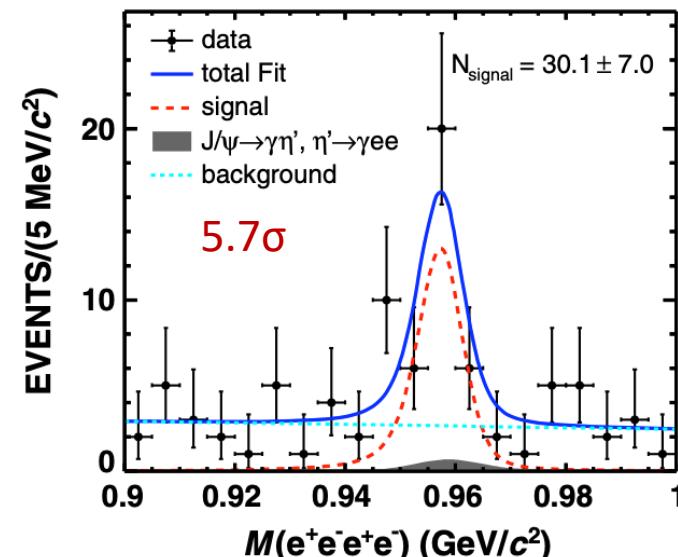


$$\Lambda = [1.75 \pm 0.29(\text{stat}) \pm 0.05(\text{syst})] \text{ GeV}/c^2$$



consistent with the theoretical prediction from the VMD model

- Observation of double Dalitz decay

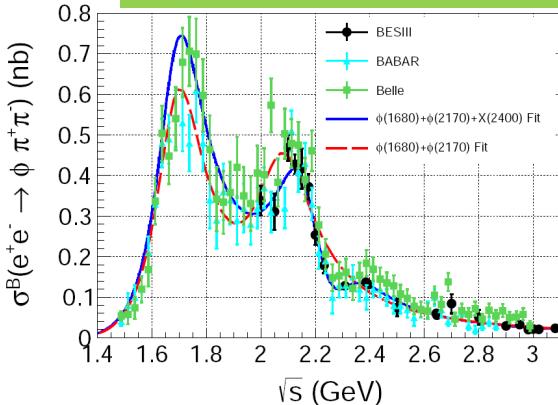


$$B(\eta' \rightarrow e^+e^-e^+e^-) = (4.5 \pm 1.0 \pm 0.5) \times 10^{-6}$$

# New results on Y(2175)/phi(2170)

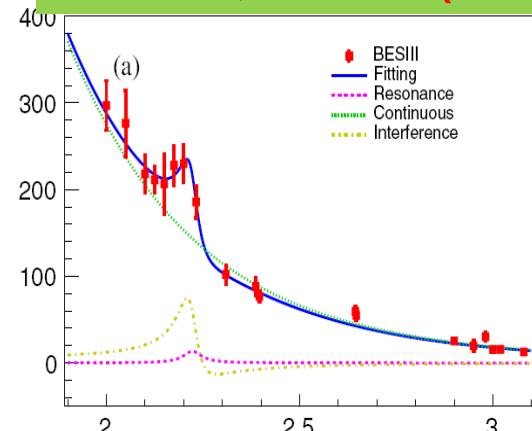
$$e^+e^- \rightarrow \phi\pi^+\pi^-$$

arXiv:2112.23219



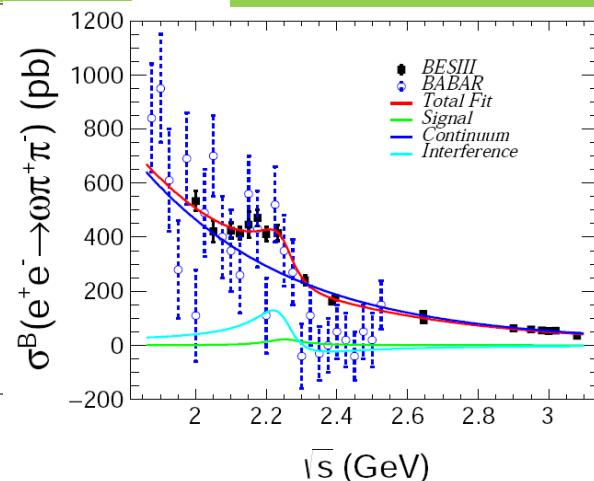
$$e^+e^- \rightarrow \omega\pi^0\pi^0$$

PRD105, 032005 (2022)



$$e^+e^- \rightarrow \omega\pi^+\pi^-$$

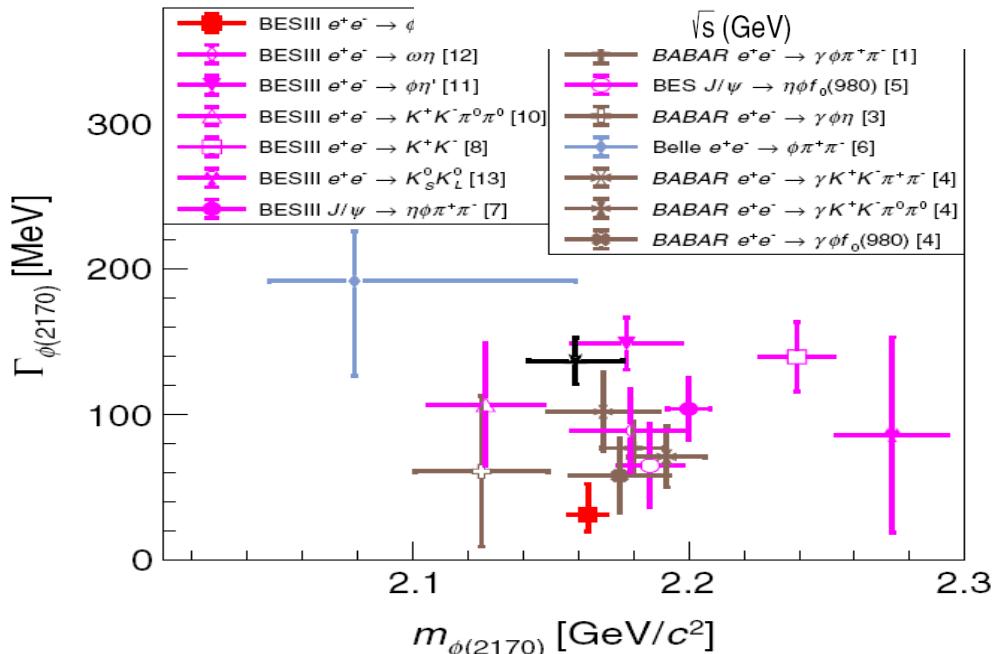
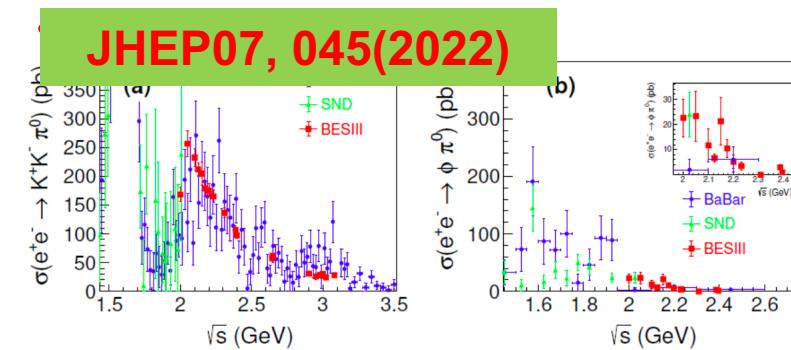
arXiv:2208.0450



$$e^+e^- \rightarrow K^+K^-\pi^0$$

- M=2190±19±37 MeV/c<sup>2</sup>, Γ=191±28±60 MeV from PWA of K\*(892)K and K<sub>2</sub>\*(1430)K;

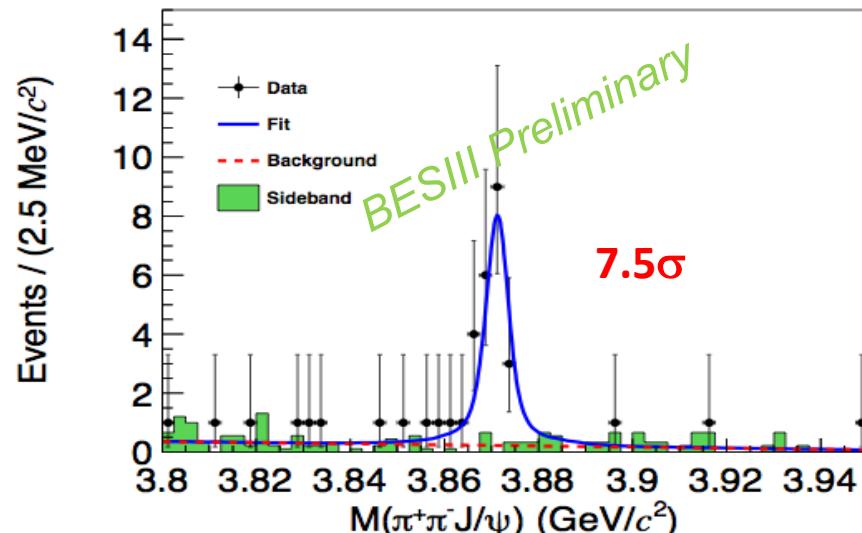
JHEP07, 045(2022)



- Different masses and widths
- Limited decay modes
- Nature is mysterious
- More studies are desirable

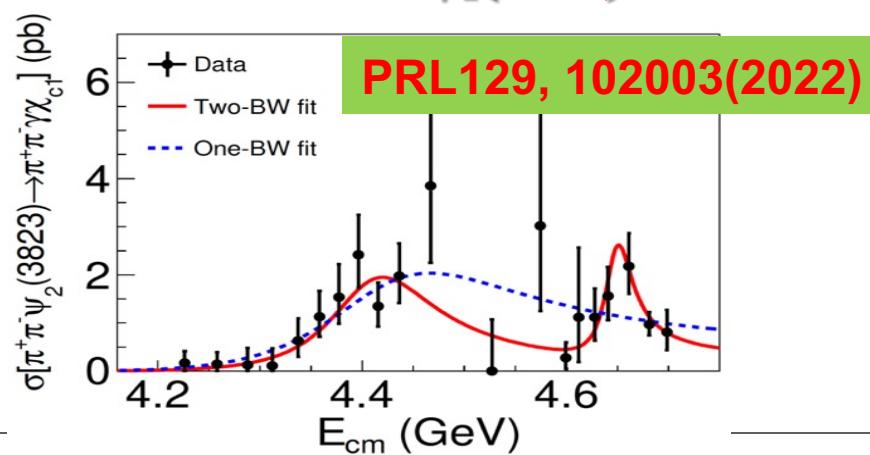
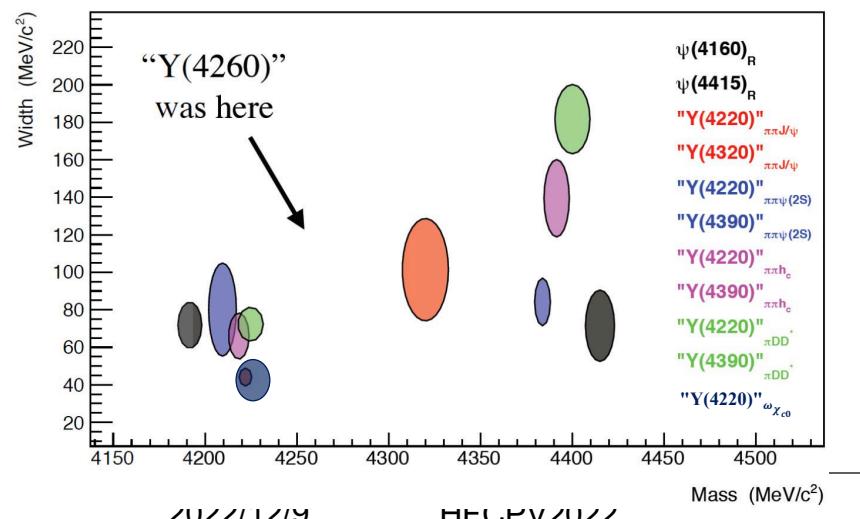
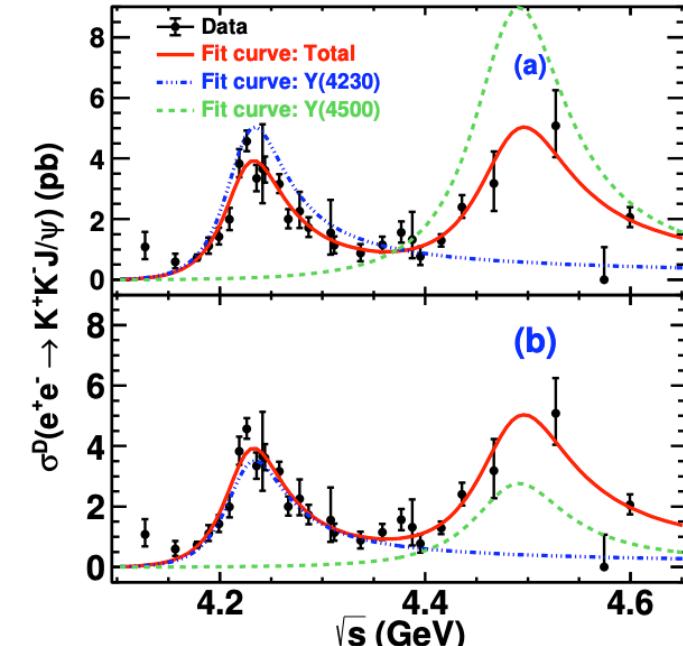
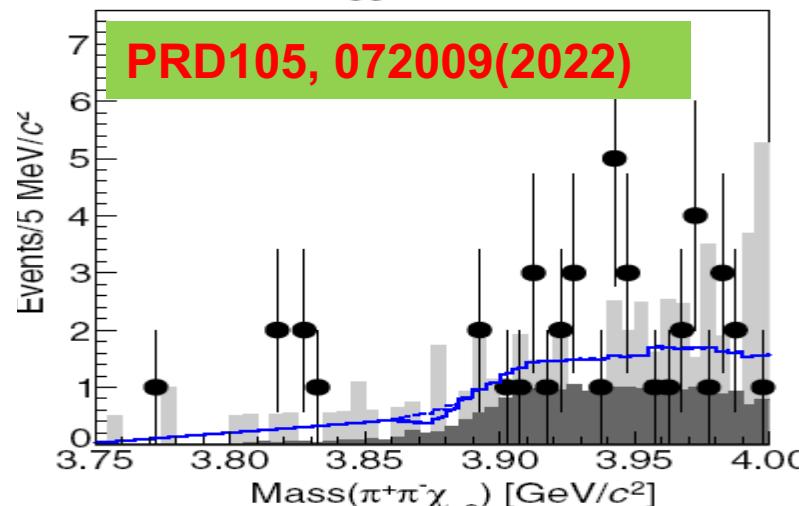
■ **X(3872) Main production channel:  $e^+e^- \rightarrow \gamma X(3872)$**

$$e^+e^- \rightarrow \omega X(3872) \rightarrow \omega\pi^+\pi^-J/\psi$$

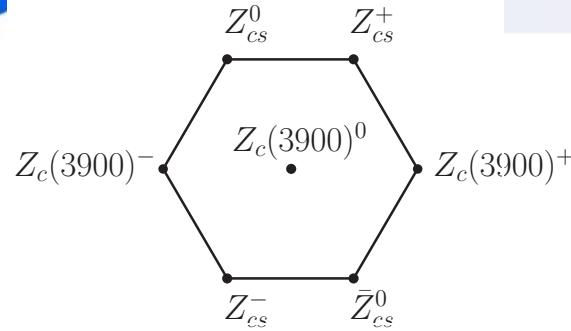


$$X(3872) \rightarrow \pi^0\chi_{c0} \text{ and } \pi\pi\chi_{c0}$$

$$\chi_{c0} \rightarrow \pi^+\pi^-$$

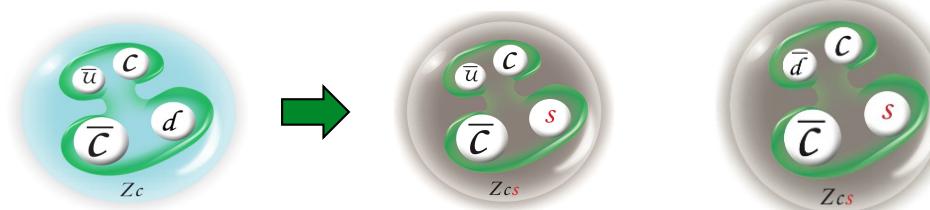


# Observation of $Z_{cs}(3985)$



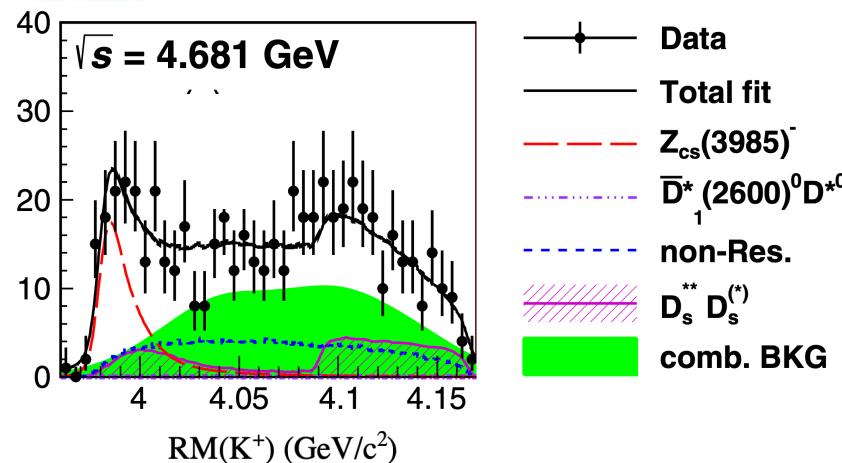
"Tetra"-Octet?

Given tetraquark state assumption, there should exist SU(3) partner  $Z_{cs}$  state with strangeness



$$e^+e^- \rightarrow K^+ (D_s^- D^{*0} + D_s^{*-} D^0)$$

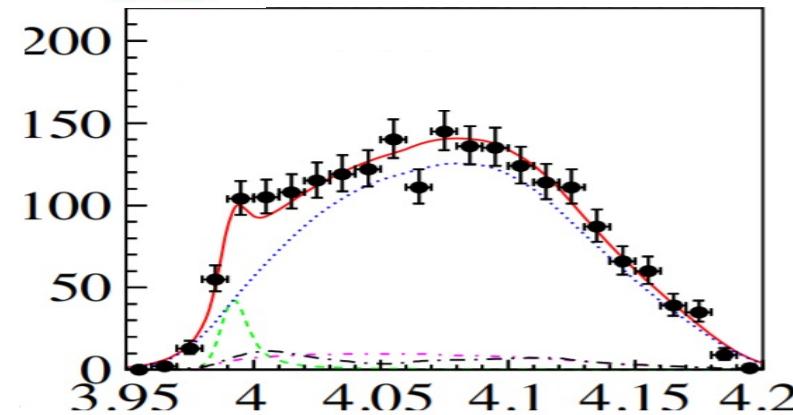
BESIII PRL126(2021)102001



- $M = (3985.2^{+2.1}_{-2.0} \pm 1.7) \text{ MeV}/c^2$
- $\Gamma = (13.8^{+8.1}_{-5.2} \pm 4.9) \text{ MeV}$
- Open charm final state

$$e^+e^- \rightarrow K_s^0 (D_s^+ D^{*-} + D_s^{*+} D^-)$$

BESIII PRL129(2022)112003



- $M = 3992.2 \pm 1.7 \pm 1.6 \text{ MeV}/c^2$
- $\Gamma = (7.7^{+4.1}_{-3.8} \pm 4.3) \text{ MeV}$
- Open charm final state

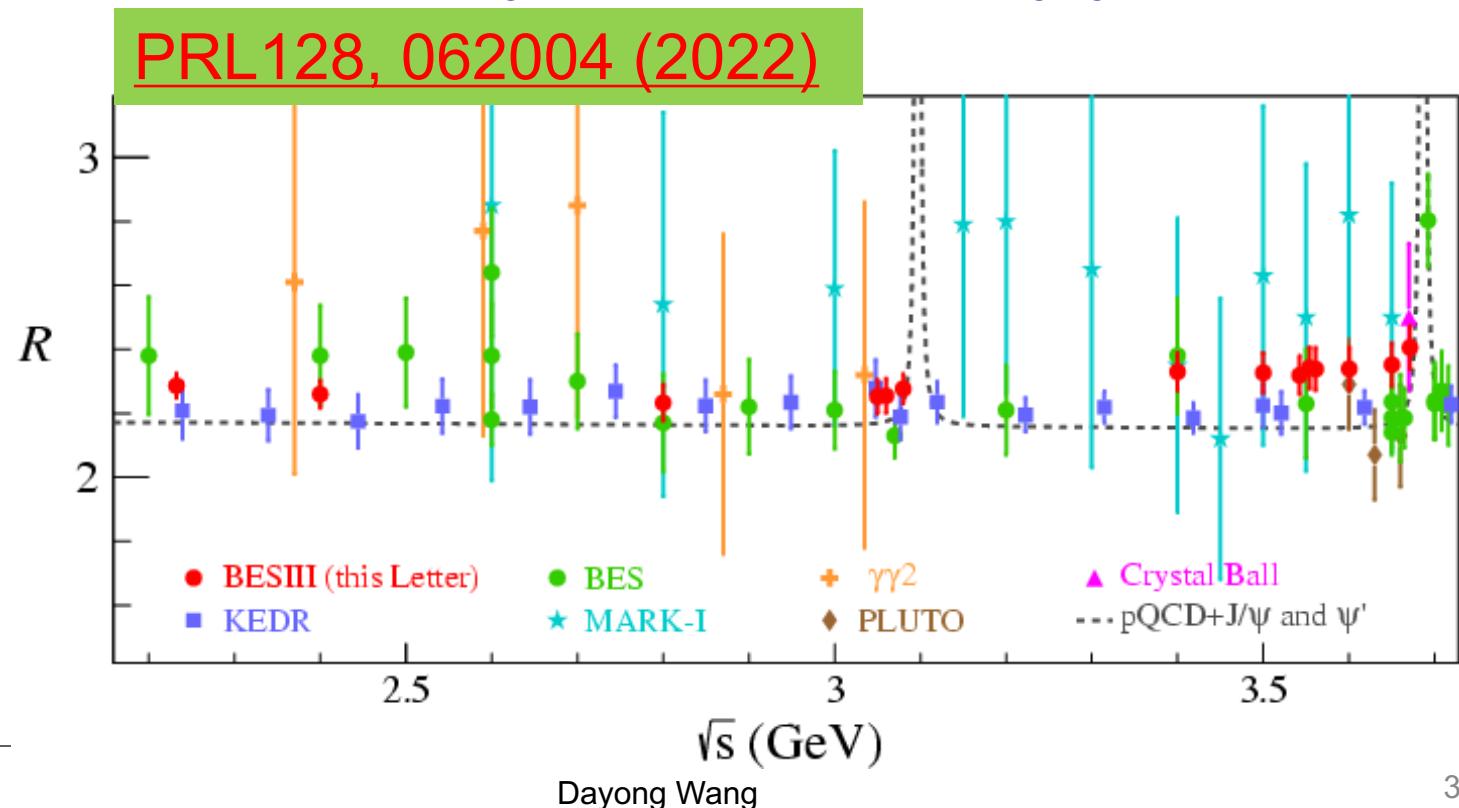
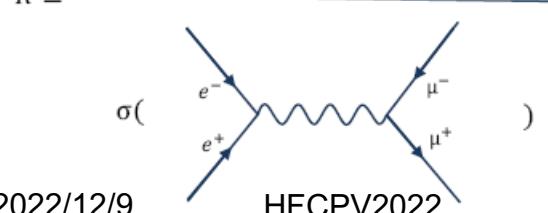
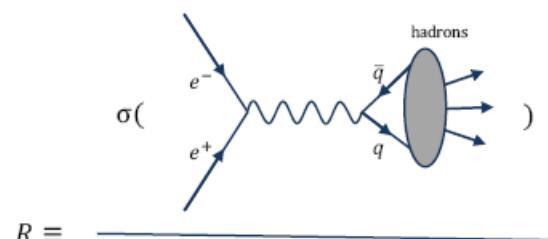
Close in mass but very different widths with LHCb  $Z_{cs}(4000)^+$ !

- LHCb  $B^+ \rightarrow \phi(J/\psi K^+)$
- $M = (4003 \pm 6^{+4}_{-14}) \text{ MeV}/c^2$
  - $\Gamma = (131 \pm 15 \pm 26) \text{ MeV}$
  - $J^P = 1^+$
  - Hidden charm final state

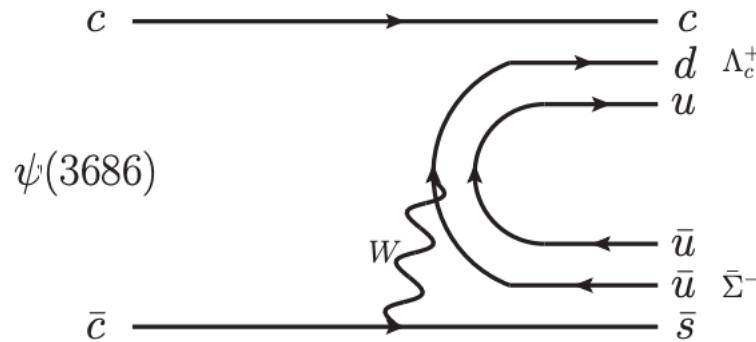
- Measurement of R values in 14 energy points of 2.23-3.67 GeV
- Precision is < 3% and twofold better than previous best measurement
- Crucial input parameters to calculate the running coupling constant
- Help to constrain the muon g-2

Milestone achievement from efforts of many people in many years

$$R \equiv \frac{\sigma^0(e^+e^- \rightarrow \text{hadrons})}{\sigma^0(e^+e^- \rightarrow \mu^+\mu^-)} \equiv \frac{\sigma_{\text{had}}^0}{\sigma_{\mu\mu}^0}$$

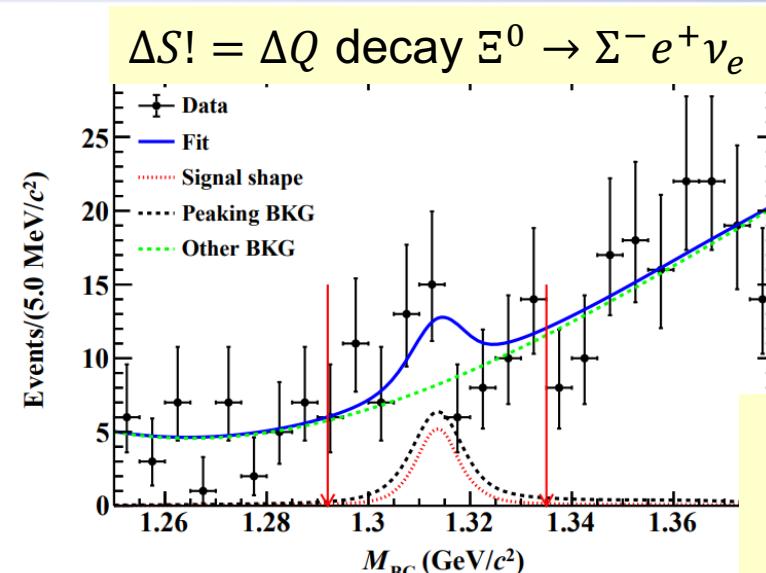
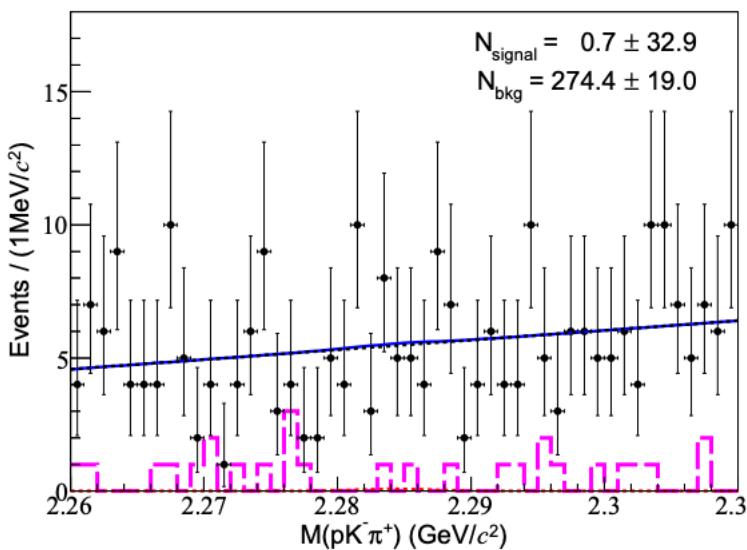


# Search for rare decays



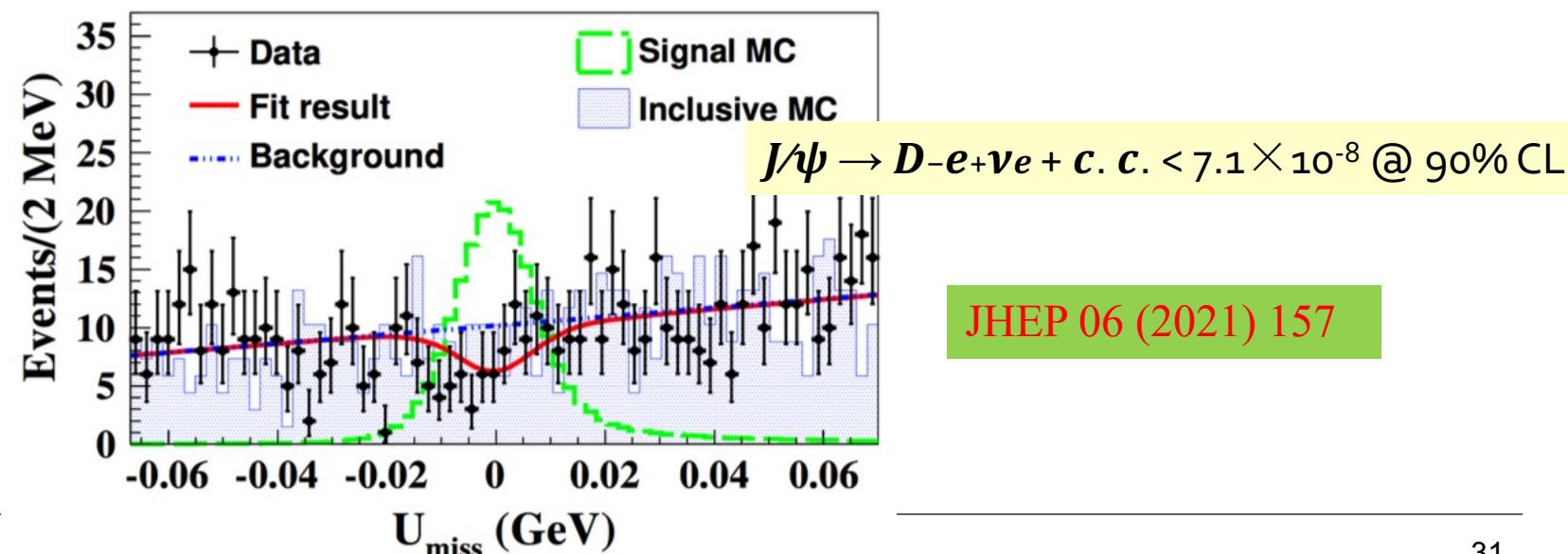
$$B(\psi(3686) \rightarrow \Lambda_c^+ \text{ anti-}\Sigma^-) < 1.4 \times 10^{-5}.$$

Chinese Phys. C 47, 013002 (2022)

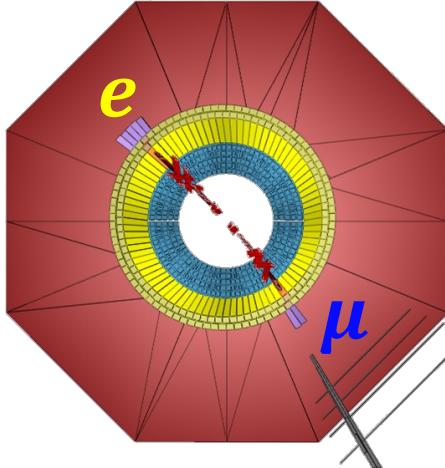


arXiv: 2208.09221  
Submitted to Phys. Rev. D

$\text{BF} < 1.6 \times 10^{-4}$  @ 90% C. L.  
One order of magnitude improvement over PDG

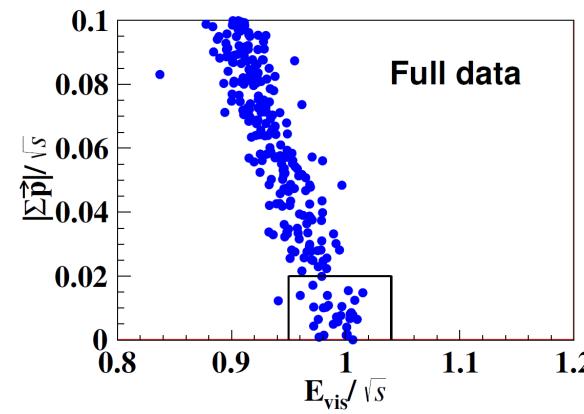
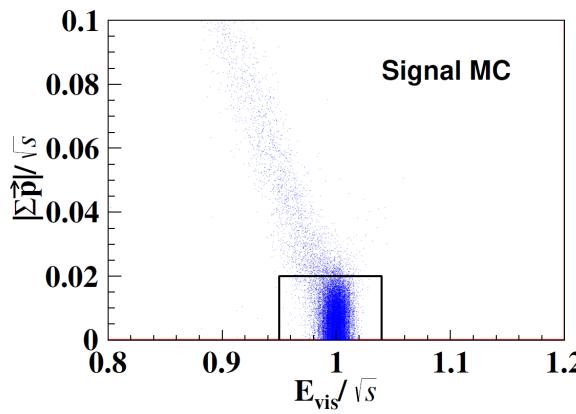


JHEP 06 (2021) 157

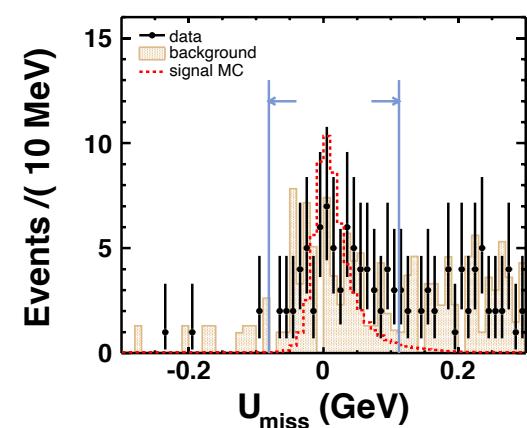
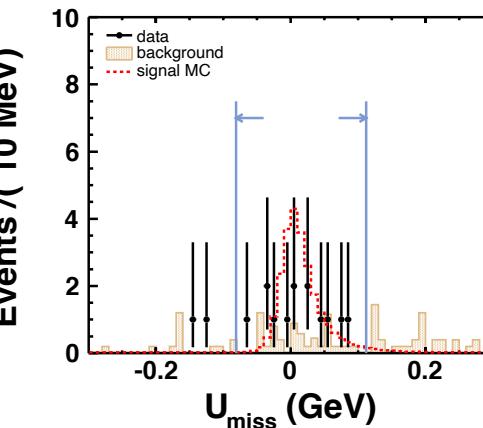


- ✓ Analyzing 9B  $J/\psi$  events
- ✓  $\mathcal{B}(J/\psi \rightarrow e\mu) < 4.5 \times 10^{-9}$  @ 90% C.L.
- ✓ Improve the previous best limit by factor of  $> 30$
- ✓ The most precise CLFV search in heavy quarkonium

**SCIENCE CHINA:  
PMA66, 221011 (2023)**



- Analyzing 10B  $J/\psi$  events, with searching process  $J/\psi \rightarrow e\tau, \tau \rightarrow \pi\pi^0\nu$



Combined result:

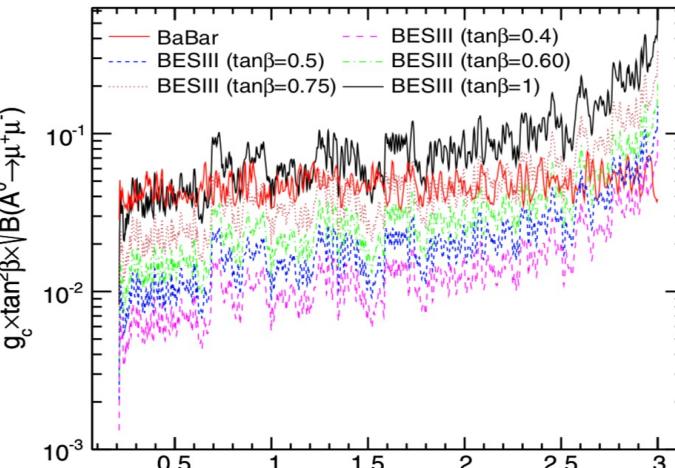
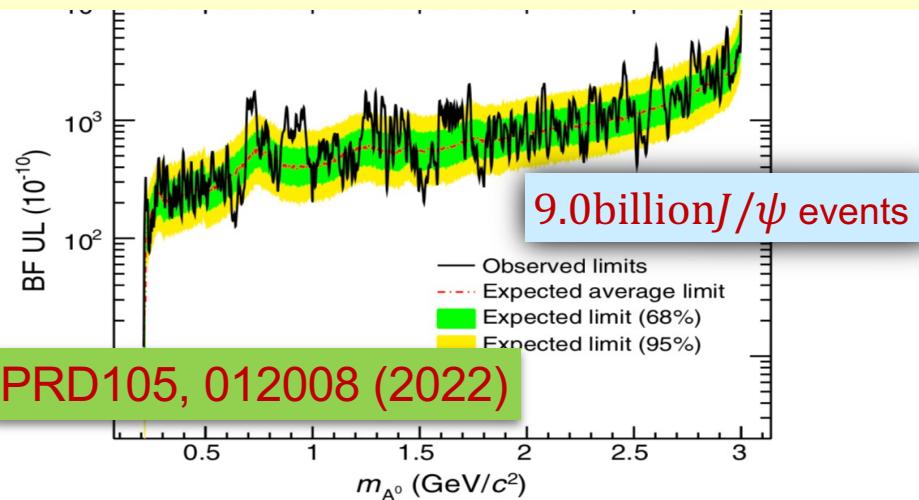
$$\mathcal{B}R(J/\psi \rightarrow e\tau) < 7.5 \times 10^{-8} \text{ @ 90% C.L.}$$

This result improves the previous published limits by **two orders of magnitude** and comparable with the theoretical predictions.

Data	Source	Mode	$ \Delta(B - L) $	UL on BF @ 90% CL
$\sqrt{s} = 3.773 \text{ GeV } 2.93 \text{ fb}^{-1}$ $N_{D^+D^-}^{\text{tot}} = (8,296 \pm 31 \pm 64) \times 10^3$ $N_{D^0\bar{D}^0}^{\text{tot}} = (10,597 \pm 28 \pm 98) \times 10^3$	$D$ mesons	$D^+ \rightarrow \bar{\Lambda} e^+$	0	$6.5 \times 10^{-7}$
		$D^+ \rightarrow \bar{\Sigma}^0 e^+$	0	$1.3 \times 10^{-6}$
		$D^+ \rightarrow \Lambda e^+$	2	$1.1 \times 10^{-6}$
		$D^+ \rightarrow \Sigma^0 e^+$	2	$1.7 \times 10^{-6}$
		$D^0 \rightarrow \bar{p} e^+$ PRD 105 032006 (2022)	2	$1.2(2.2) \times 10^{-6}$
		$D^+ \rightarrow \bar{n} e^+$ Arxiv: 2209.05787, PRD	0/2	$1.4(2.5) \times 10^{-5}$
		$D^0 \rightarrow K^- \pi^+ e^+ e^+$	2	$2.8 \times 10^{-6}$
		$D^+ \rightarrow K_S^0 \pi^- e^+ e^+$	2	$3.3 \times 10^{-6}$
		$D^+ \rightarrow K^- \pi^0 e^+ e^+$	2	$8.5 \times 10^{-6}$
$\sqrt{s} = 3.097 \text{ GeV}$ $N_{J/\psi}^{\text{tot}} = (1,310.6 \pm 7.0) \times 10^6$	$J/\psi$ meson	$J/\psi \rightarrow \Lambda_c^+ e^-$	0	$6.9 \times 10^{-8}$
		$J/\psi \rightarrow p K^- \bar{\Lambda} \rightarrow p K^- \bar{\Lambda}$	2 [BF ratio $P(\Lambda) < 4.4 \times 10^{-6}$ ]	
	$\Sigma^-$ hyperon	$\Sigma^- \rightarrow p e^- e^-$	2	$6.7 \times 10^{-5}$
		$\Sigma^- \rightarrow \Sigma^+ X$	2	$1.4 \times 10^{-4}$
	$\Xi^0$ hyperon	$\Xi^0 \rightarrow K^\pm e^\mp + cc.$	2	In progress

# BSM particle searches

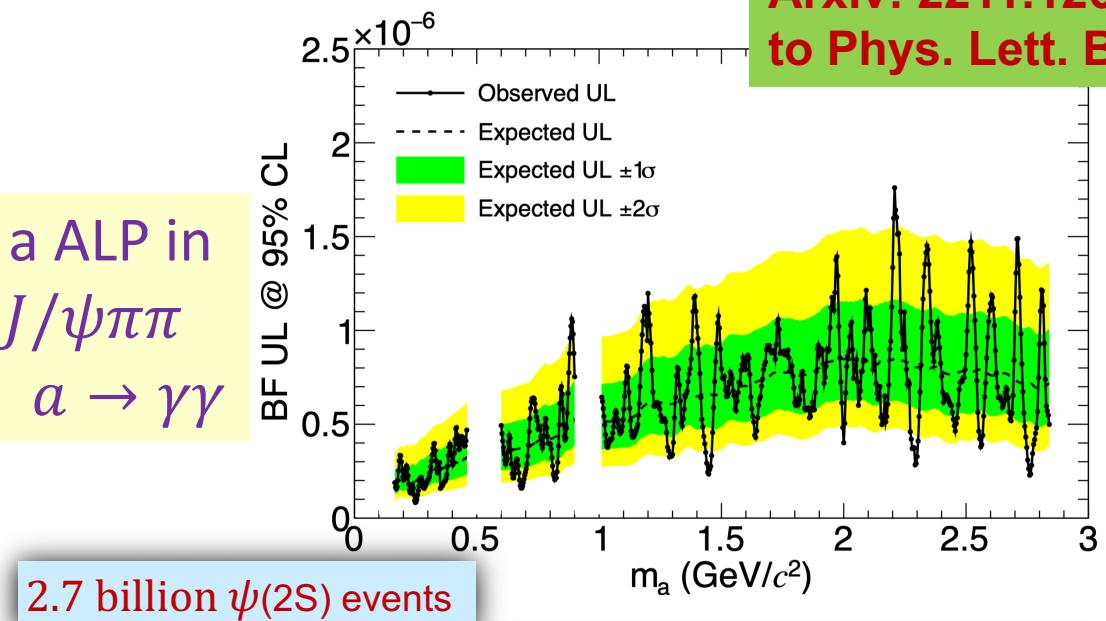
- Search for a CP-odd Higgs boson in  $J/\psi \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$



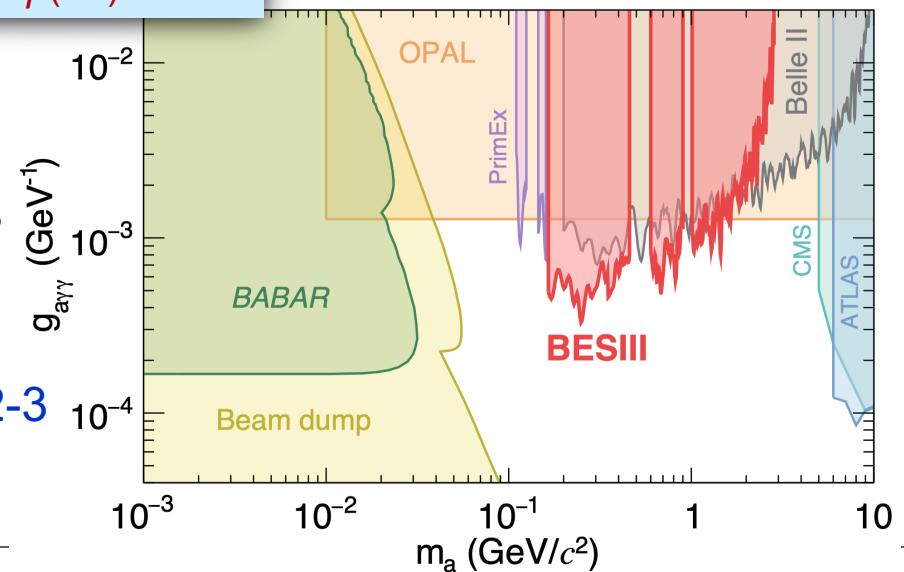
2022/12/9

HFCPV2022

- Search for a ALP in  $\psi(2s) \rightarrow J/\psi \pi\pi$   
 $J/\psi \rightarrow \gamma a, a \rightarrow \gamma\gamma$

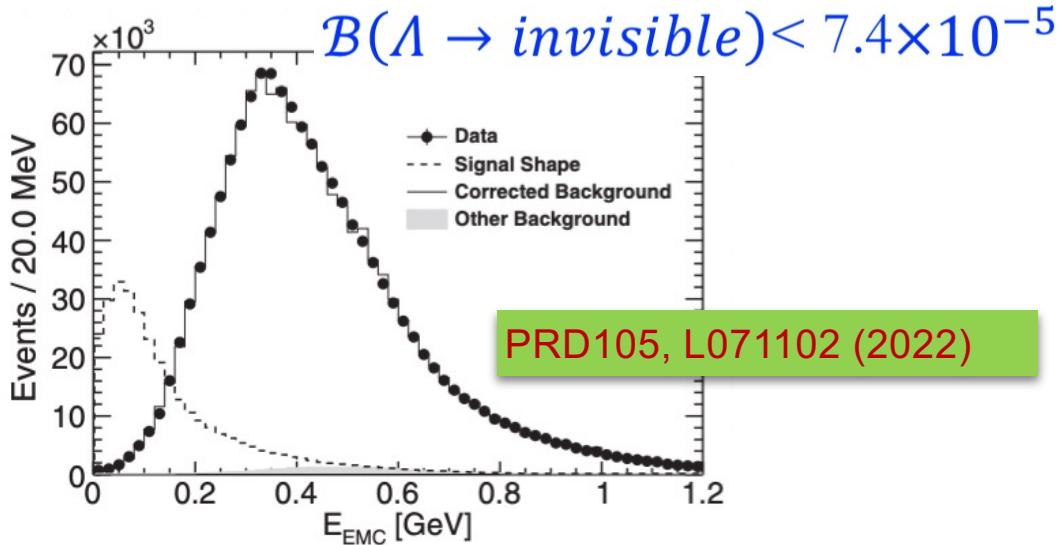


- The most stringent constraints for  $0.165 \leq m_a \leq 1.468 \text{ GeV}/c^2$
- $g_{a\gamma\gamma} > 3 \times 10^{-4} \text{ GeV}^{-1}$  for  $m_a$  around  $0.25 \text{ GeV}/c^2$ , a factor of 2-3 better than Belle II measurement

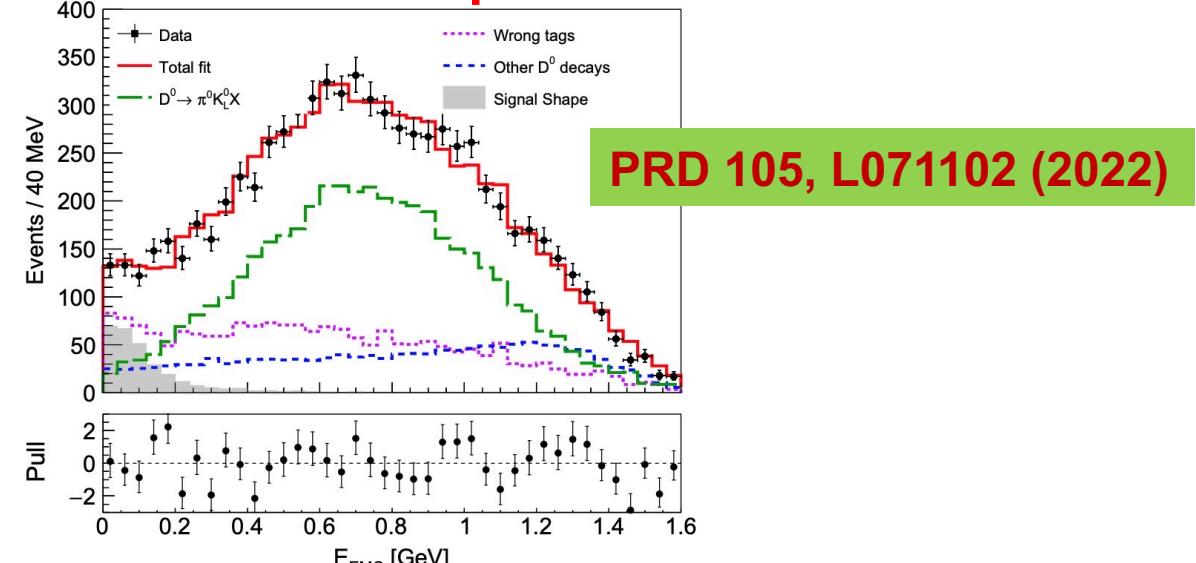


# New search results with invisible signatures

The first search of baryon invisible decay



Search of FCNC process with invisibles



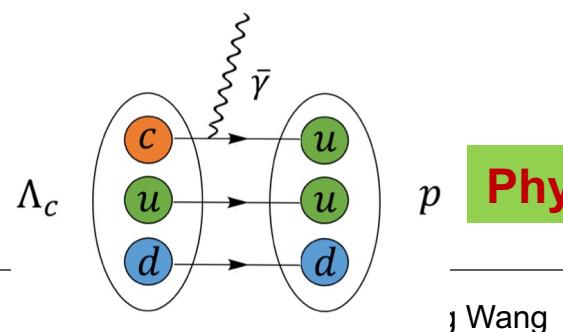
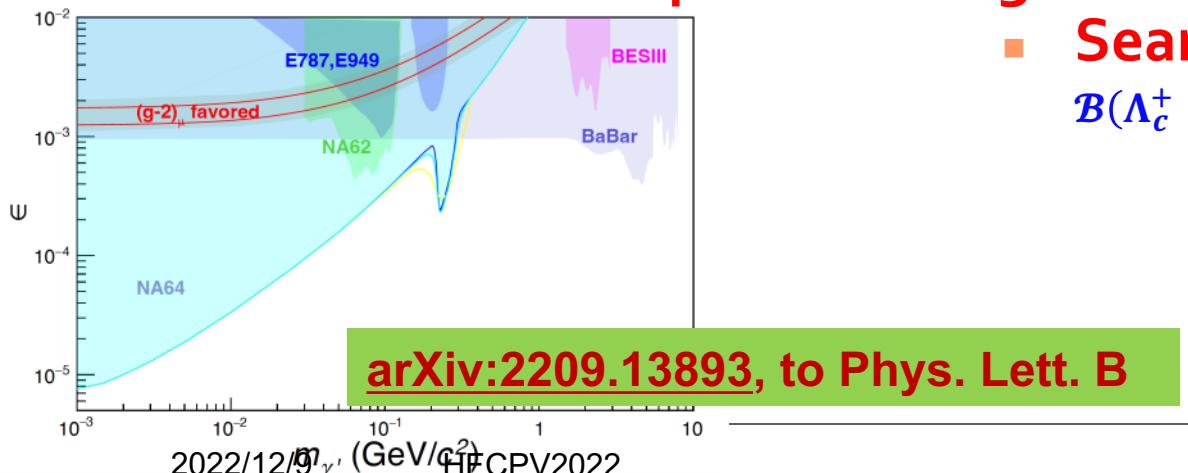
$$\mathcal{B}(D^0 \rightarrow \pi^0 \nu \bar{\nu}) < 2.1 \times 10^{-4} @ 90\% \text{C. L.}$$

The first constraint on charmed hadron to di-neutrino

- Search for massless dark photon in  $\Lambda_c \rightarrow p + \text{invisible}$

$$\mathcal{B}(\Lambda_c^+ \rightarrow p \gamma') < 8.0 \times 10^{-5} @ 90\% \text{C. L.}$$

Search for invisible dark photon using ISR



Phys. Rev. D 106, 072008 (2022)

J Wang

Table 7.1: List of data samples collected by BESIII/BEPCII up to 2019, and the proposed samples for the remainder of the physics program. The most right column shows the number of required data taking days in current ( $T_C$ ) or upgraded ( $T_U$ ) machine. The machine upgrades include top-up implementation and beam current increase.

Energy	Physics motivations	Current data	Expected final data	$T_C / T_U$
1.8 - 2.0 GeV	$R$ values Nucleon cross-sections	N/A	$0.1 \text{ fb}^{-1}$ (fine scan)	60/50 days
2.0 - 3.1 GeV	$R$ values Cross-sections	Fine scan (20 energy points)	Complete scan (additional points)	250/180 days
✓ $J/\psi$ peak	Light hadron & Glueball $J/\psi$ decays	$3.2 \text{ fb}^{-1}$ (10 billion)	$3.2 \text{ fb}^{-1}$ (10 billion)	N/A
✓ $\psi(3686)$ peak	Light hadron & Glueball Charmonium decays	$0.67 \text{ fb}^{-1}$ (0.45 billion)	$4.5 \text{ fb}^{-1}$ (3.0 billion)	150/90 days
✓ $\psi(3770)$ peak	$D^0/D^\pm$ decays	$2.9 \text{ fb}^{-1}$	$20.0 \text{ fb}^{-1}$	610/360 days
3.8 - 4.6 GeV	$R$ values $XYZ$ /Open charm	Fine scan (105 energy points)	No requirement	N/A
4.180 GeV	$D_s$ decay $XYZ$ /Open charm	$3.2 \text{ fb}^{-1}$	$6 \text{ fb}^{-1}$	140/50 days
4.0 - 4.6 GeV	$XYZ$ /Open charm Higher charmonia cross-sections	$16.0 \text{ fb}^{-1}$ at different $\sqrt{s}$	$30 \text{ fb}^{-1}$ at different $\sqrt{s}$	770/310 days
4.6 - 4.9 GeV	Charmed baryon/ $XYZ$ cross-sections	$0.56 \text{ fb}^{-1}$ at 4.6 GeV	$15 \text{ fb}^{-1}$ at different $\sqrt{s}$	1490/600 days
4.74 GeV	$\Sigma_c^+ \Lambda_c^-$ cross-section	N/A	$1.0 \text{ fb}^{-1}$	100/40 days
4.91 GeV	$\Sigma_c \bar{\Sigma}_c$ cross-section	N/A	$1.0 \text{ fb}^{-1}$	120/50 days
4.95 GeV	$\Xi_c$ decays	N/A	$1.0 \text{ fb}^{-1}$	130/50 days

Future Physics Programme of  
BESIII (white book)

Chin. Phys. C 44, 040001 (2020)  
arXiv:1912.05983

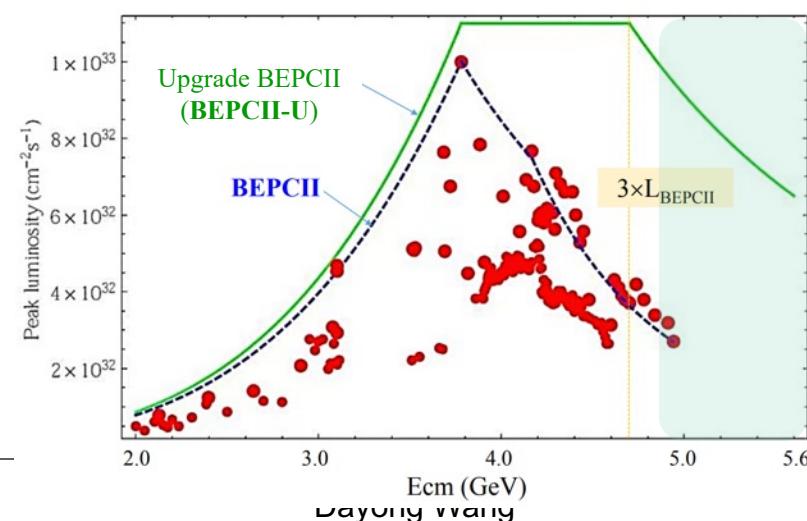
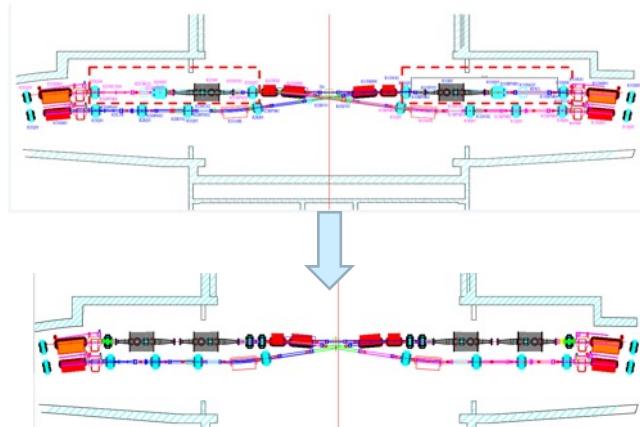
8  $\text{fb}^{-1}$  in hand, another 12  $\text{fb}^{-1}$  to  
be collected in the coming 2 years

~55  $\text{fb}^{-1}$

- ✓ An upgrade of BEPCII (**BEPCII-U**) has been approved in July 2021:  
**the optimized energy is 2.35 GeV with luminosity 3 times higher than current BEPCII and extend the maximum energy to 5.6 GeV**

- Add another cavity per beam to improve the RF power
- Change optics slightly, increase number of bunches
- Challenges: high beam intensities, backgrounds and aging effect in the detector
- Small risk: can continue running with better performance than BEPCII
- Timescale: 2.5 years construction + 0.5 year installation
- Installation: July – December 2024 and the upgraded machine ready

in Jan. 2025



- ✓ Detailed studies of the known  $Z_c(s)$  states and search for more exotic states in the higher energy region within a considerable amount of data sets.
- ✓ Cover all the ground-state charmed baryons: production & decays, CPV search



Few data and potential physics for XYZ  
and charmed baryons

- **BESIII is successfully operating since 2008, with good performance of the machine and the detector**
  - collect large data samples in the energy range 2.0~5.6 GeV
- **BESIII has performed wide range of physics studies**
  - ◆ Light hadron spectroscopy and decays
  - ◆ Charmonia transitions and XYZ
  - ◆ R value and QCD studies
  - ◆ Charmed meson and charmed baryon
  - ◆ Rare decays and new physics search
- **BESIII has great potential with unique datasets and analysis techniques. Operation for another 5-10 years foreseen**
  - BEPCII-U: 3x upgrade on luminosity, with energy to 5.6GeV
  - ...More to come!