Flavor physics at BESIII

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On behalf of the BESIII Collaboration

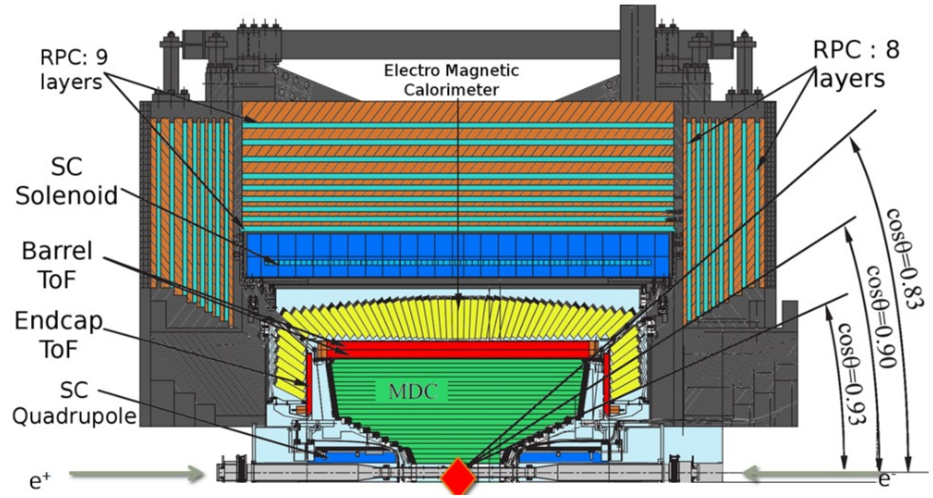
第4届LHCb前沿物理研讨会

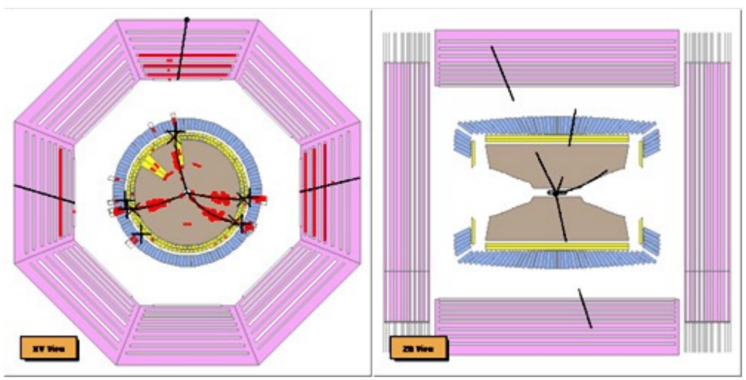
2024.07.28 烟台

Outline

- BEPCII & BESIII
- Recent Highlights on Flavor Physics
- Summary & Prospect

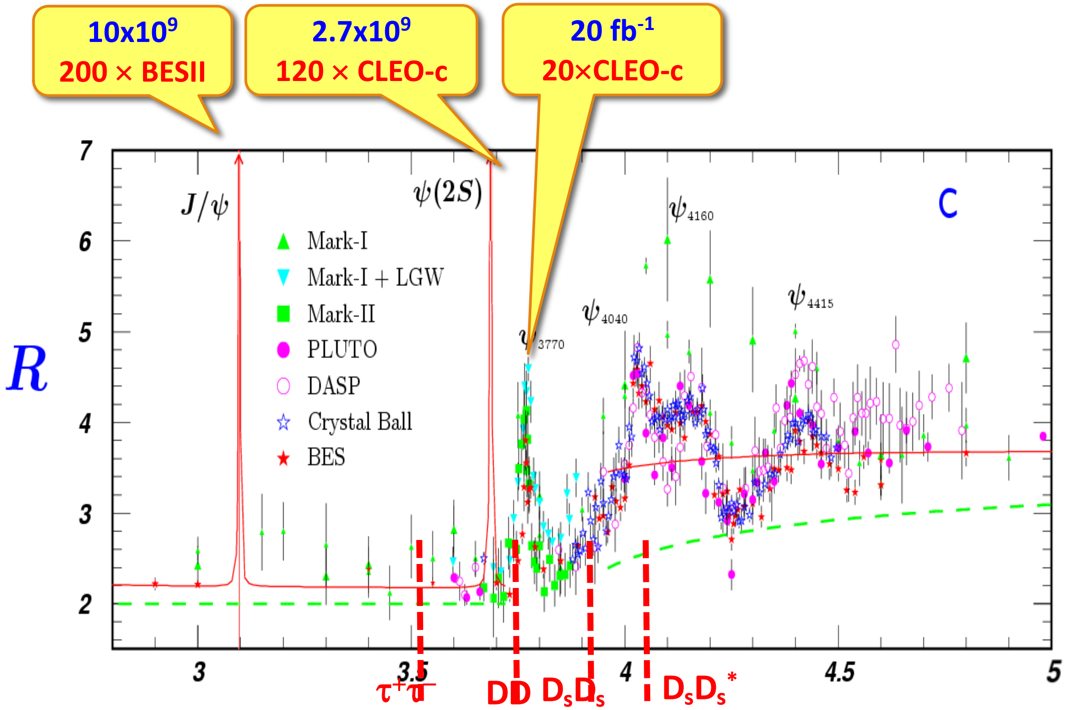
BEPCII & BESIII





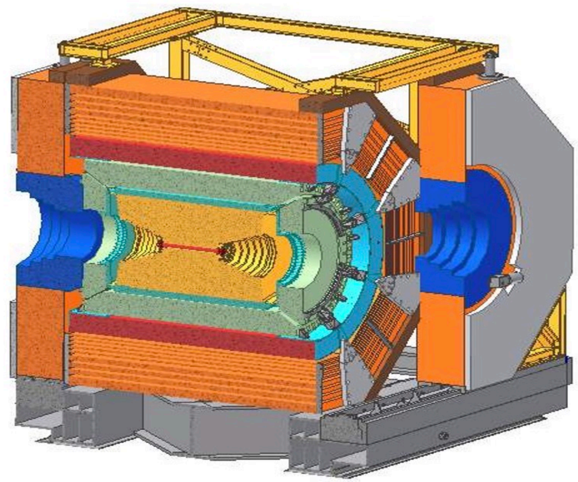
First HEP collider in China (1988)
c.m.s energy： 2 ~ 4.95 GeV
Max luminosity： $1\times10^{33}cm^{-2}s^{-1}$

BESIII: τ-charm factory



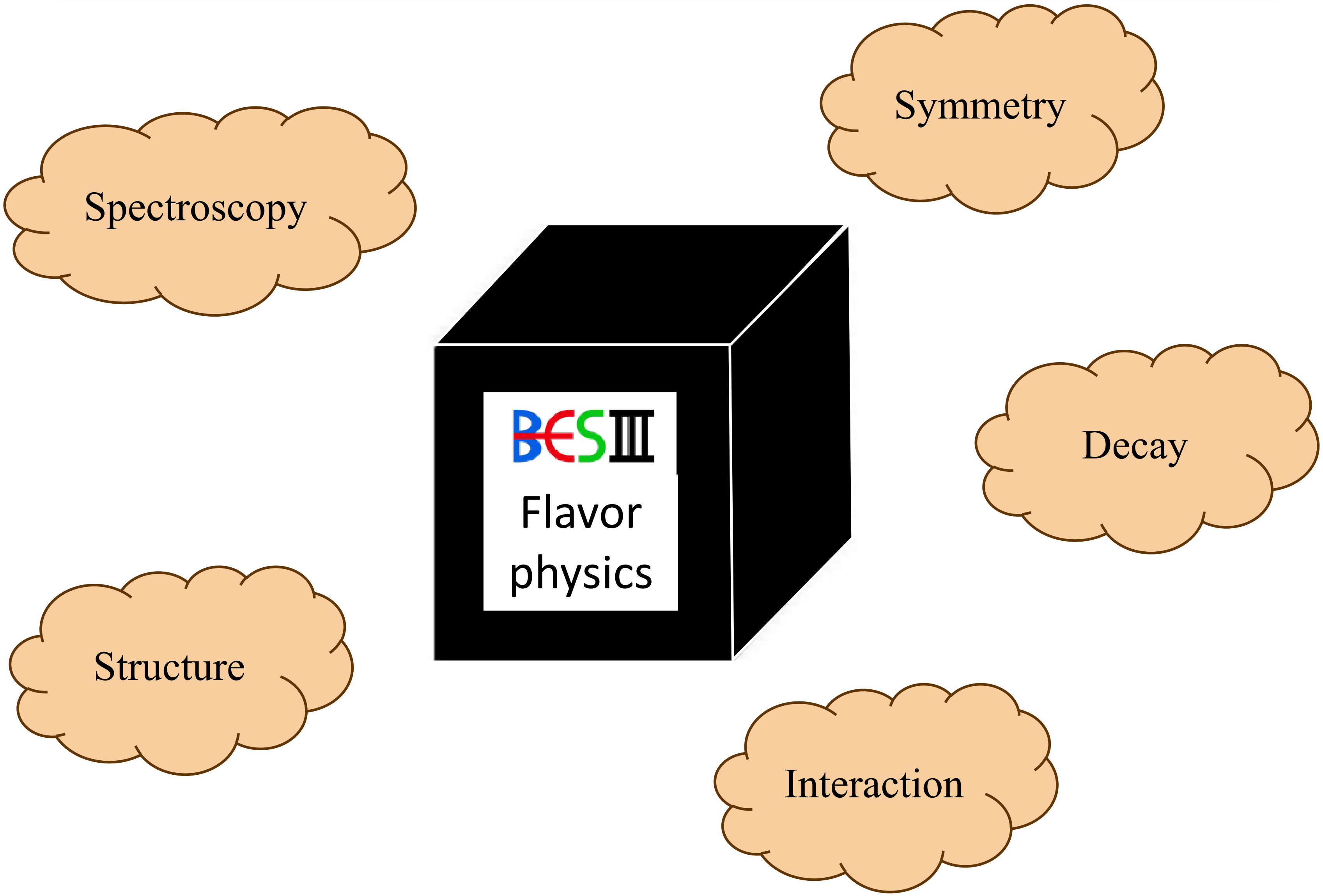
BESIII: ~55 fb^{-1} data in $E_{cm} = 2 \sim 4.95$ GeV

World largest data sample directly collected in the τ-charm region



- **Charmonium physics**
- **Light hadron physics**
- **Charm physics**
- **R-QCD physics**
- **New physics**

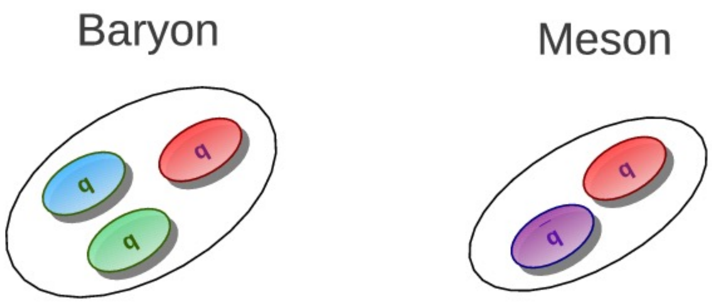
BESIII flavor physics



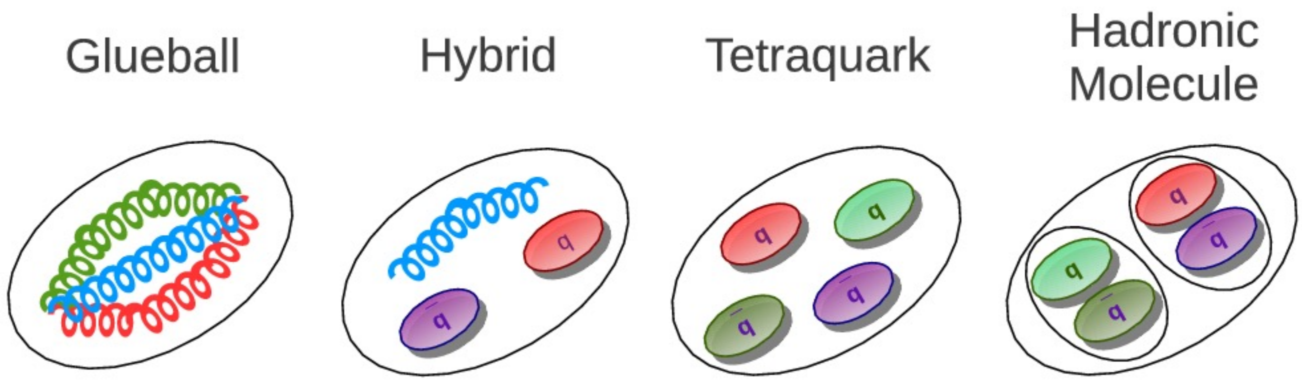
Spectroscopy

Ordinary vs exotic matter

- Conventional hadrons

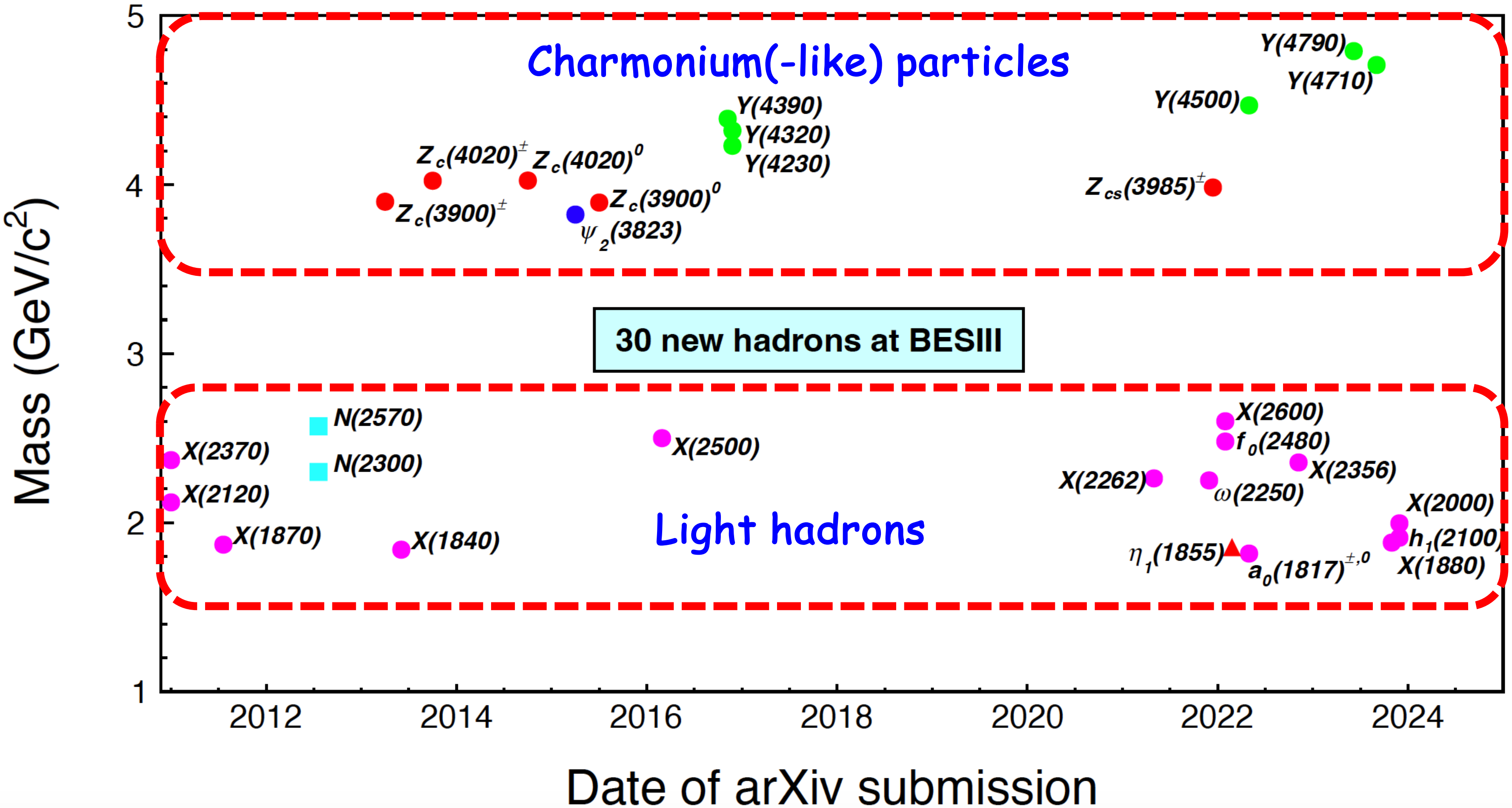


- QCD allows for “exotics”



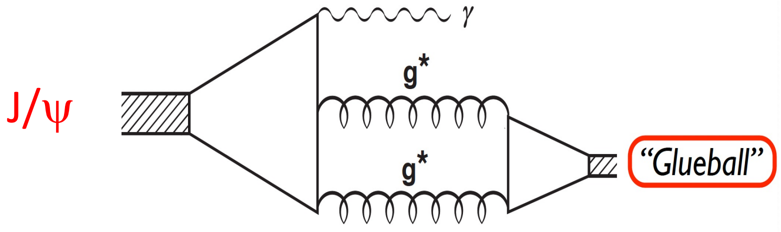
- Searching for those states provides test of QCD

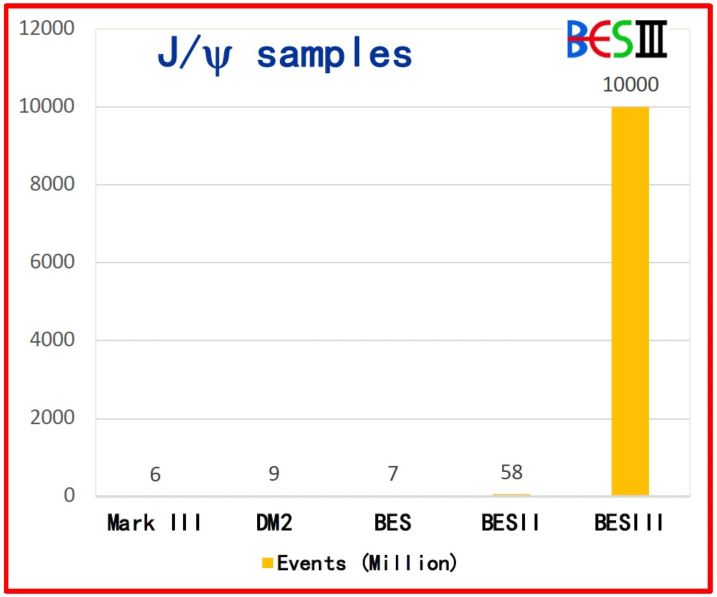
New resonant structures at BESIII



Glueball searches

- **Two big issues**
  - What is the production mechanism to utilize?
  - What is the mixing with quark model mesons?





- Production rate could be calculable in LQCD, but the manifestation of a "glueball" can be tricky!

Chanowitz, Phys.Rev.Lett. 95(2005)172001

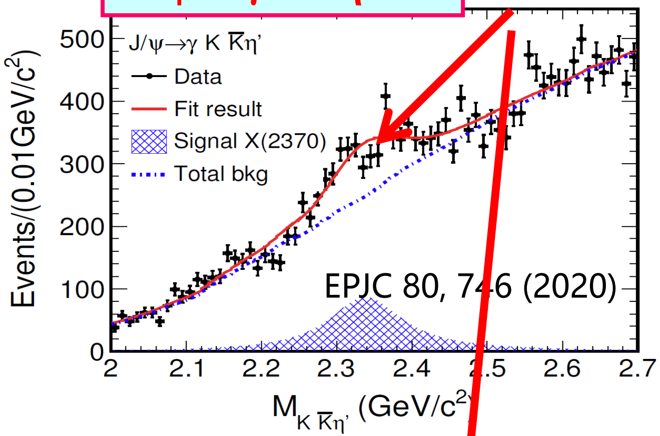
Systematic studies needed

- Outnumbering of conventional QM states
- Abnormal properties ? Eg., small production rate in two photon process

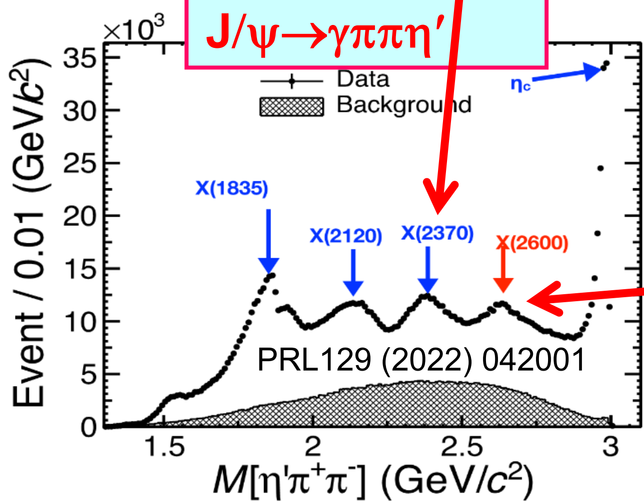
Glueball candidate

J/ψ→γKKη′

X(2370)



J/ψ→γππη′



X(2370) and X(2600): new glueball candidate ?

An updated review of the new hadron states

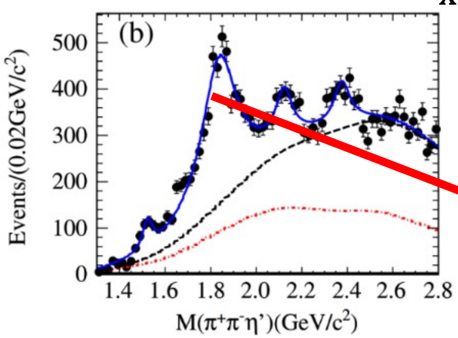
H.X.Chen, W Chen, X Liu, Y.R. Liu, S.L. Zhu Rept.Prog.Phys. 86 (2023) 2, 026201

Motivated by the newly observed resonance $X(2600)$ by BESIII Collaboration, we examine the trigluon glueball interpretation for it in the framework of QCD sum rules. We evaluate the mass spectra of the trigluon glueballs with quantum numbers 0^{-+} and 2^{-+} up to dimension 8 condensate in the operator product expansion. Our numerical results indicate that the mass of the 2^{-+} trigluon glueball is about 2.66 ± 0.06 GeV, which is consistent with the mass of the $X(2600)$ within the uncertainties, while 0^{-+} has a mass of 2.01 ± 0.14 GeV. The possible decay channels of the 2^{-+} state are analyzed, which are crucial in decoding $X(2600)$'s internal structure and are hopefully measurable in BESIII, BEllEII, PANDA, and LHCb experiments.

QCD sum rules

S.Q. Zhang et al, PRD 106 (2022) 7, 074010

$X(p\bar{p})$: Baryonium state?



X(1835) observed in $J/\psi\to\gamma\eta'\pi^+\pi^-$

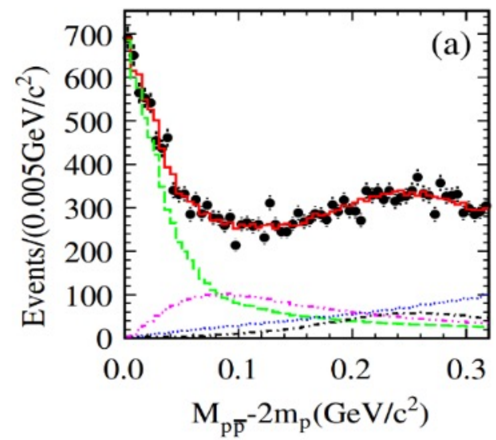
X(1835) $J^{PC}=0^{-+}$
$M = 1844 \pm 9^{+16}_{-25}$ MeV/c^2
$\Gamma = 192^{+20+62}_{-17-43}$ MeV/c^2

PRL 106, 072002 (2011)

X($p\bar{p}$) observed in $J/\psi\to\gamma p\bar{p}$

X($p\bar{p}$) $J^{PC}=0^{-+}$
$M = 1832^{+19}_{-5}{}^{+18}_{-17} \pm 19$ MeV/c^2
$\Gamma = 13 \pm 19$ MeV/c^2 (< 76 MeV/c^2 @ 90% C.L.)

PRL 108, 112003 (2012)

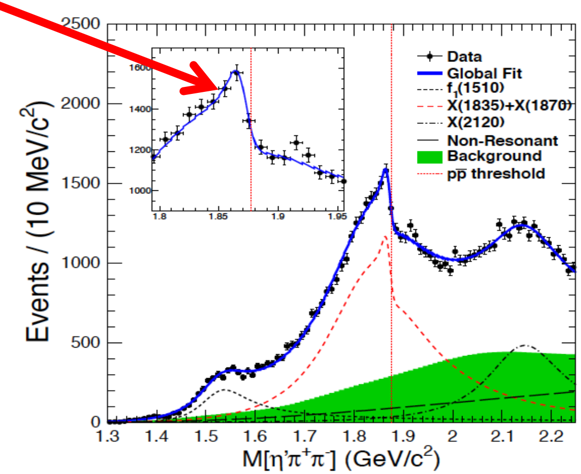


connection between X(1835) and X($p\bar{p}$)

The anomalous line shape :

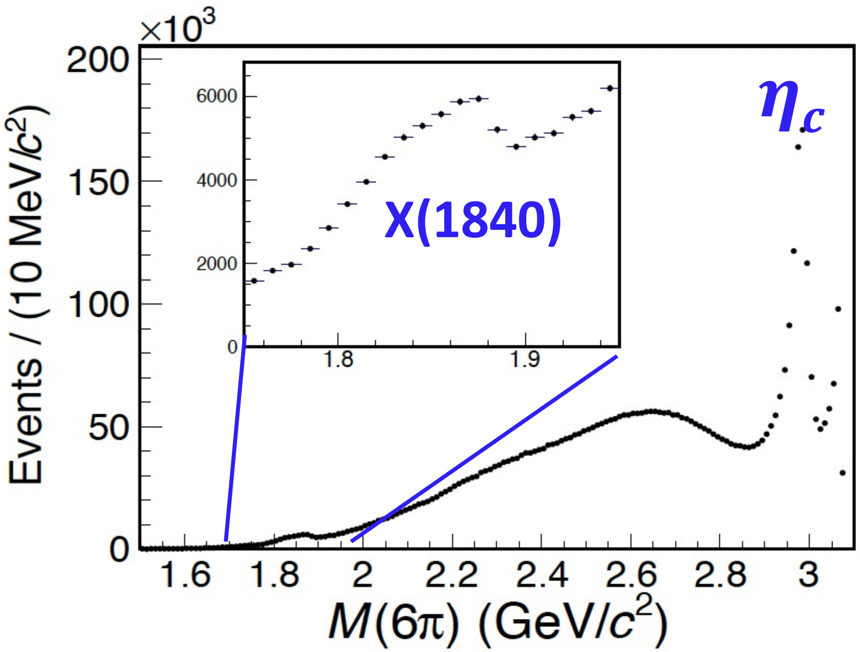
-- Suggest the existence of a state, either a broad state with strong couplings to $p\bar{p}$, or a narrow state just below the $p\bar{p}$ mass threshold

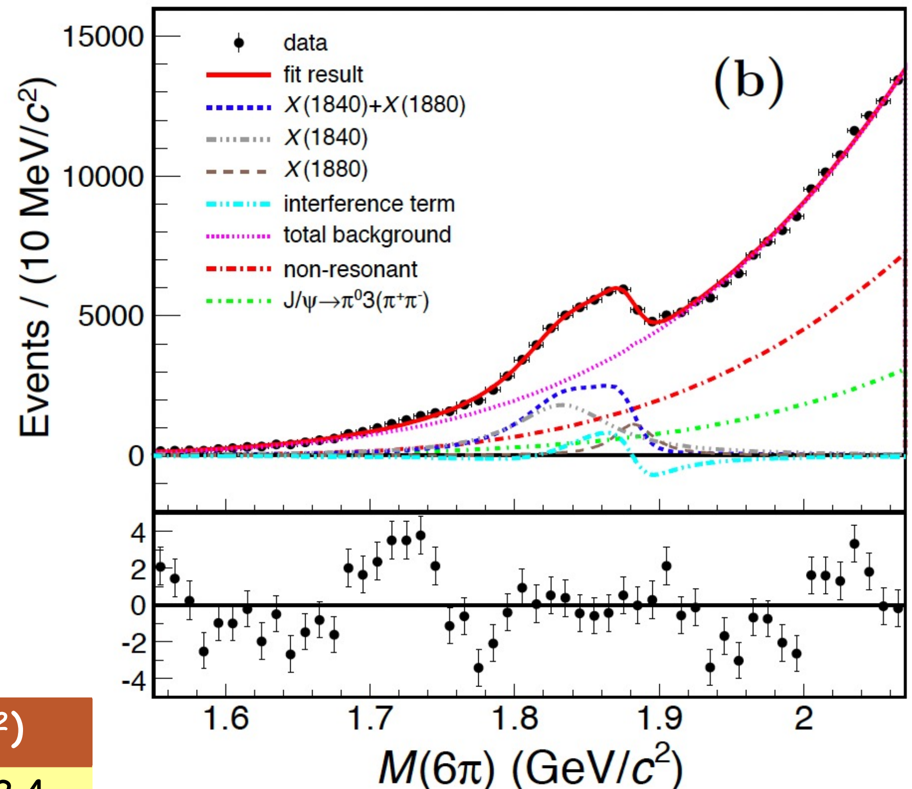
-- the existence of a $p\bar{p}$ molecule-like state or bound state?



PRL 117, 042002 (2016)

A narrow state around $p\bar{p}$ threshold



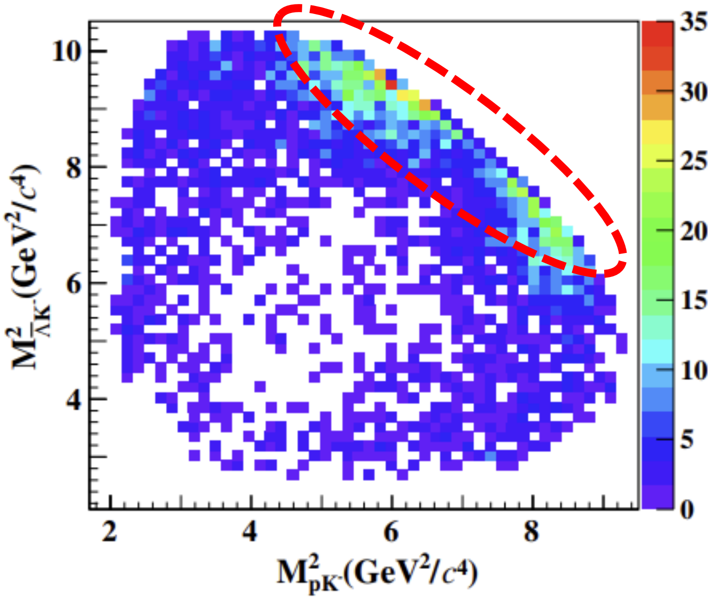


Resonance	M(MeV/c²)	Γ(MeV/c²)
X(1880)	1882.1±1.7±0.7	30.7±5.5±2.4
X(1840)	1832.5±3.1±2.5	80.7±5.2±7.7

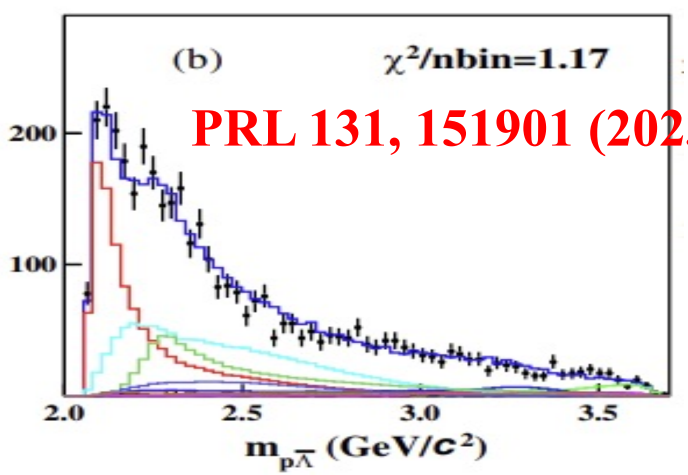
PRL 132, 151904 (2024)

Support the existence of $p\bar{p}$ bound state !

A narrow state around $p\bar{\Lambda}$ threshold



$\sqrt{s}$	$\mathcal{L}_{int}$	M_{pole}	Γ_{pole}
4.008	482.0 ± 4.7	2082^{+13}_{-9}	56^{+15}_{-14}
4.178	3189.0 ± 31.9	2083^{+6}_{-4}	63^{+8}_{-7}
4.226	1100.9 ± 7.0	2086^{+11}_{-8}	71^{+15}_{-13}
4.258	828.4 ± 5.5	2081^{+9}_{-6}	52^{+10}_{-9}
4.416	1090.7 ± 7.2	2085^{+10}_{-7}	59^{+11}_{-9}
4.682	1669.3 ± 9.0	2090^{+9}_{-7}	55^{+8}_{-5}
Average	—	2084^{+4}_{-2}	58^{+4}_{-3}



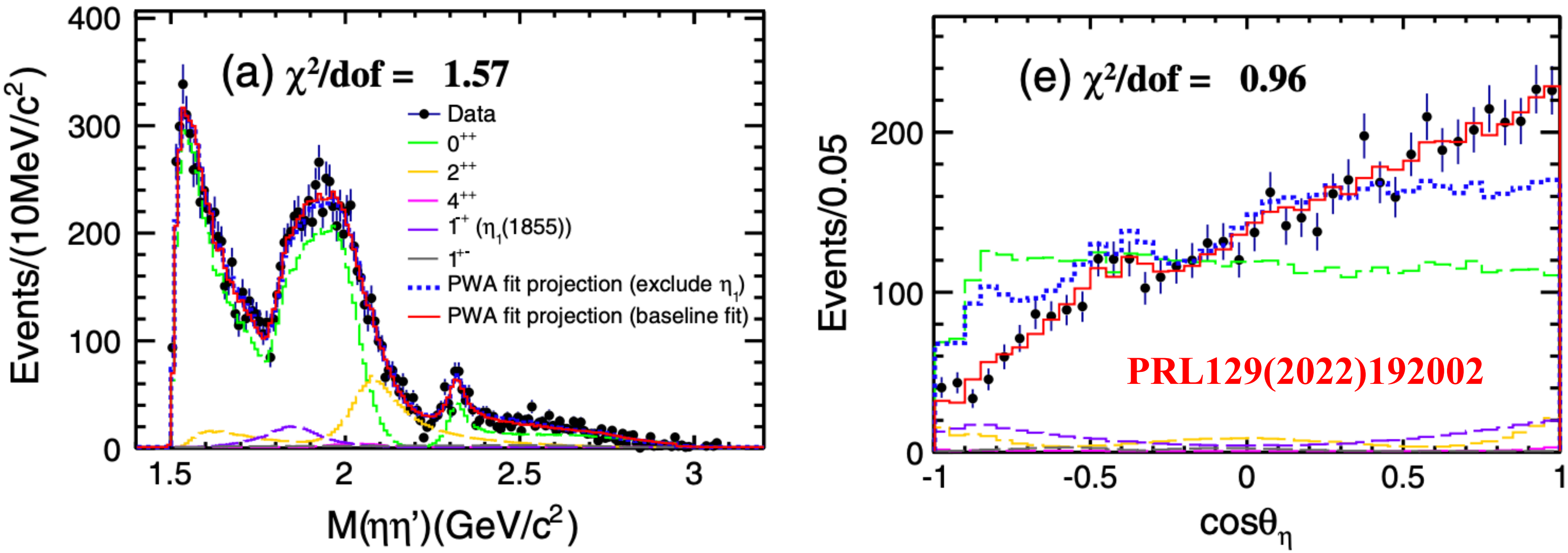
PRL 131, 151901 (2023)

A narrow structure in the $p\bar{\Lambda}$ system, named as $X(2085)$, is observed with greater than 20σ, J^P is determined to be 1^+, pole position is:

$$M_{pole} = (2084^{+4}_{-2} \pm 9)\ \mathrm{MeV/c^2}$$

$$\Gamma_{pole} = (58^{+4}_{-3} \pm 25)\ \mathrm{MeV}$$

Observation of 1^{-+} $\eta_1(1885)$ in $J/\psi\rightarrow\gamma\eta\eta'$



$M = \mathbf{1855 \pm 9^{+6}_{-1}}$ MeV/c²

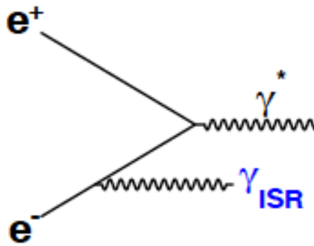
$\Gamma = \mathbf{188 \pm 18^{+3}_{-8}}$ MeV

Isoscalar state with exotic quantum numbers $J^{PC}=1^{-+}$

Critical to establish the 1^{-+} spectroscopy !

More works in progress for establishing the state with I=1

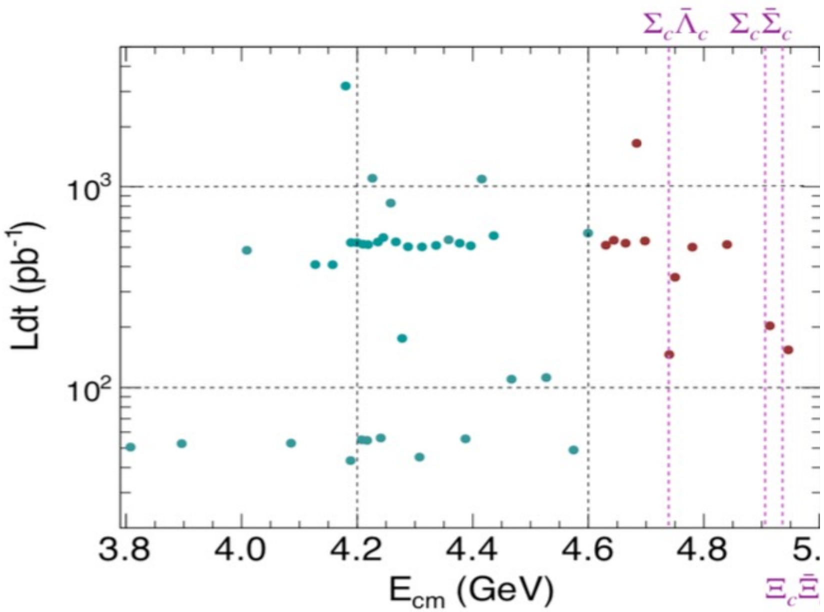
Charmonium(-like) states

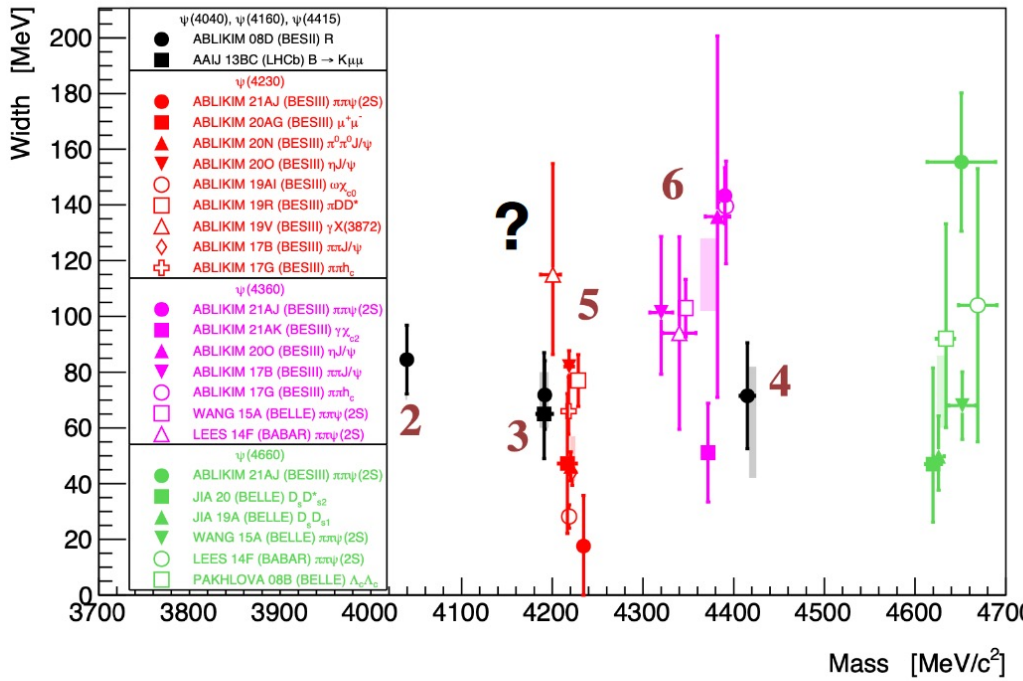


$J^{PC} = 1^{--}$

ψ', ψ'', Y…

XYZ studies with ~25 fb^{-1} data above 3.8 GeV

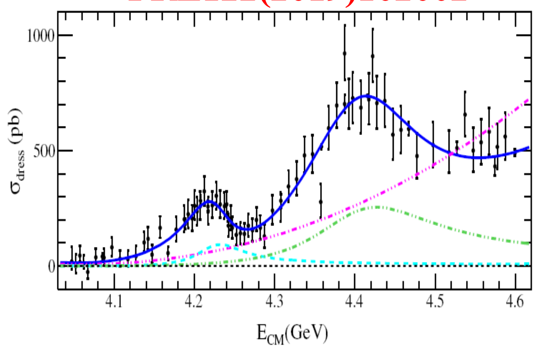




Fine structure of Y(4260)→Y(4220)+Y(4320)?

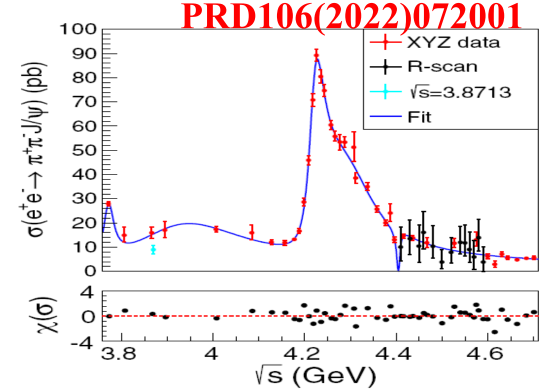
$e^+e^- \to \pi^+ D^0 D^{*-}$+c.c.

PRL122(2019)102002

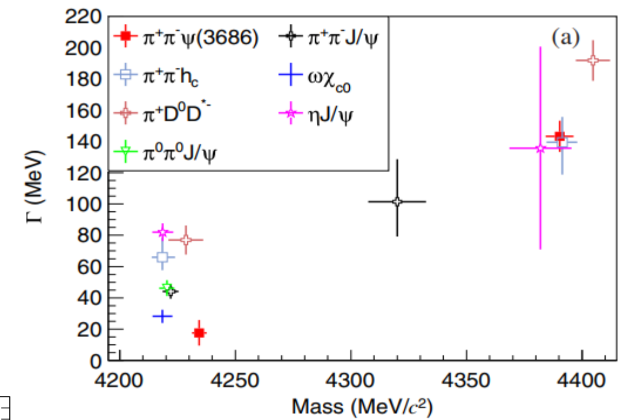


$e^+e^- \to \pi^+\pi^- J/\psi$

PRD106(2022)072001

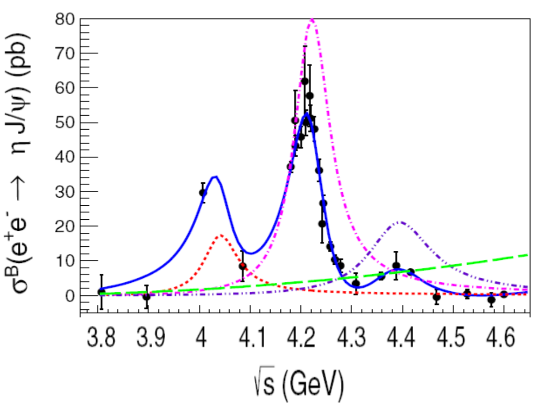


Different masses and widths in various processes



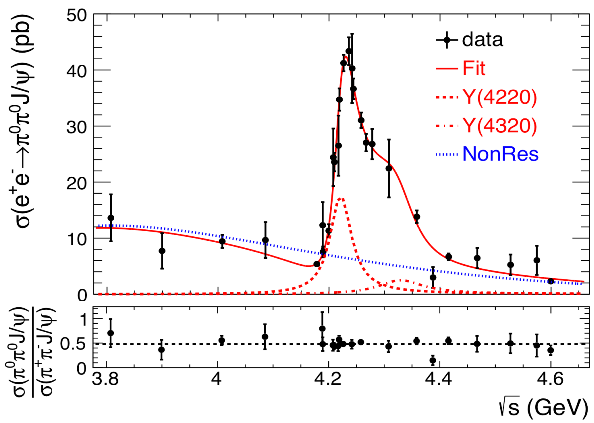
$e^+e^- \to \eta J/\psi$

PRD102(2020)031101(RC)



$e^+e^- \to \pi^0\pi^0 J/\psi$

PRD102(2020)012009

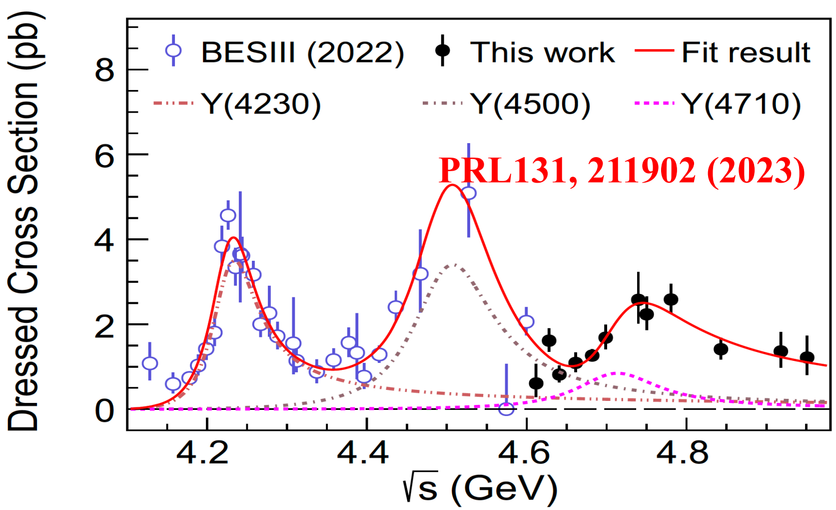


Mass ~ 4220 MeV/c^2

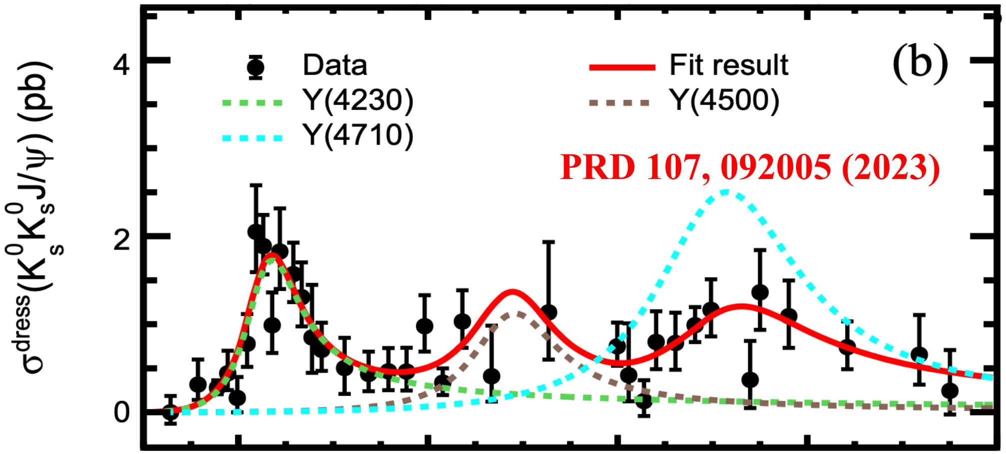
width ~ 50 MeV

Observations of Y(4230), Y(4500) and Y(4710)

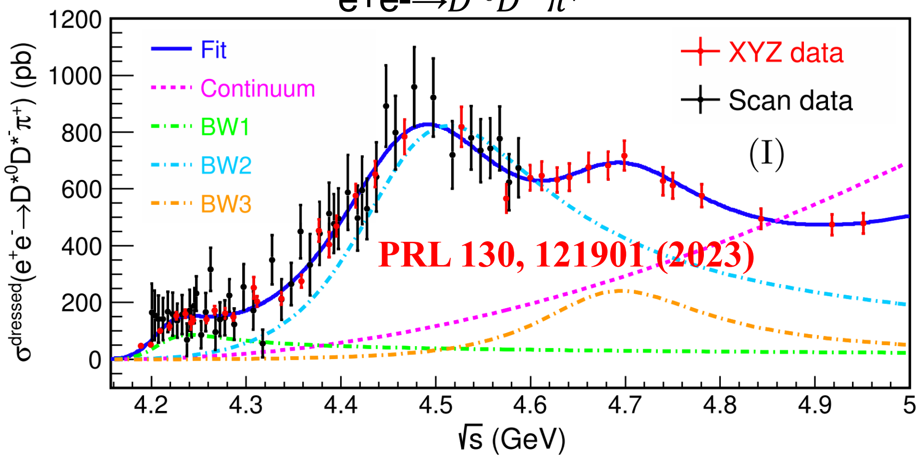
$e^+e^- \to K^+K^-J/\psi$



$e^+e^- \to K_SK_SJ/\psi$



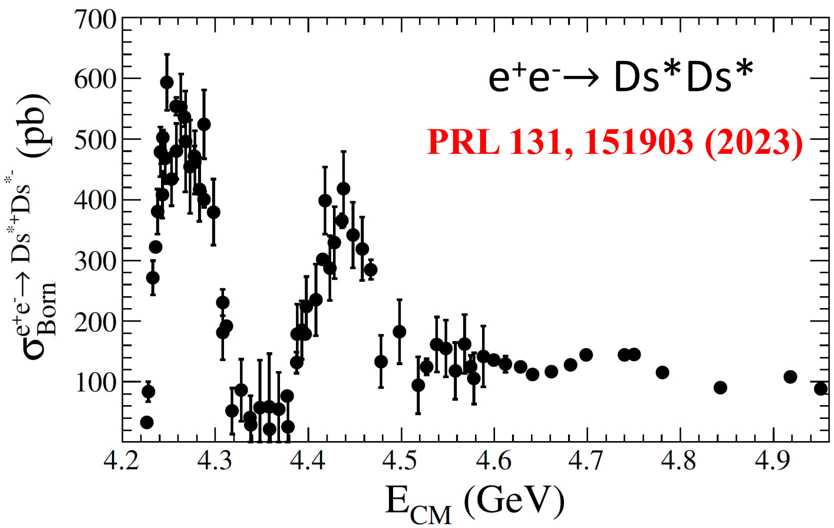
e+e-$\to D^{*0}D^{*-}\pi^+$



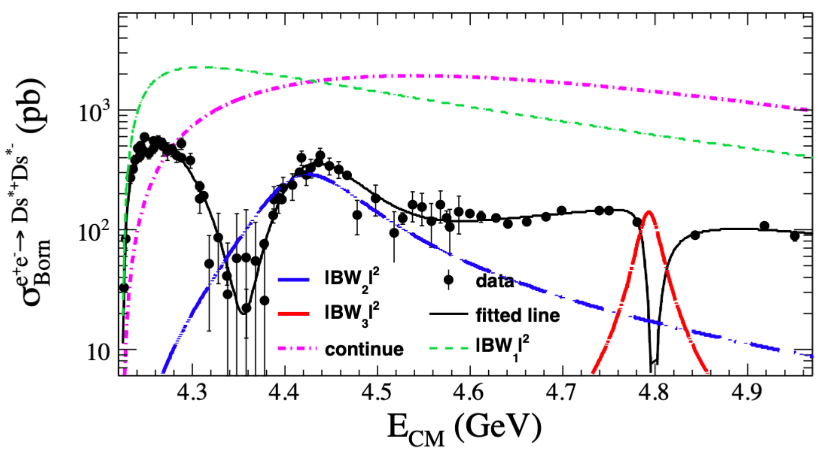
- New decay mode of Y(4230)
- Confirmation of Y(4500)
- Y(4710): one of the heaviest vector charmonium-like state, hybrid, 5S charmonium, 5S-4D/6S-5D mixing?

Mass ~ 4710 MeV/c^2, Width ~ 180 MeV

Observation of a new charmonium-like state Y(4790)

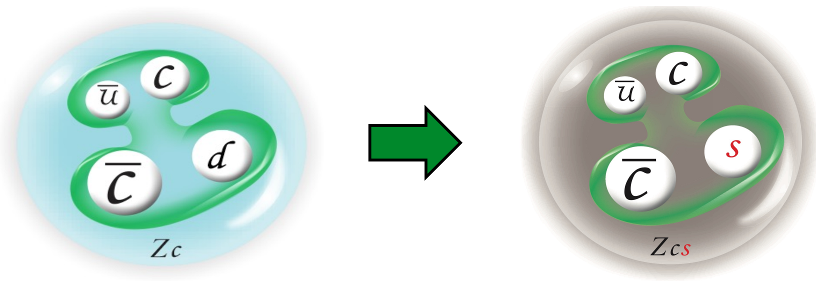


	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.5±9.0	4193.8±7.5	4195.3±7.5
Γ_1 (MeV)	55±17	61.2±9.0	61.8±9.0
M_2 (MeV/c^2)	4414.5±3.2	4412.8±3.2	4411.0±3.2
Γ_2 (MeV)	122.6±7.0	120.3±7.0	120.0±7.0
M_3 (MeV/c^2)	4793.3±7.5	4789.8±9.0	4786±10
Γ_3 (MeV)	27.1±7.0	41±39	60±35



- Y(4160) or Y(4260) [strong coupling to Ds*Ds*?]
- Consistent with Y(4415)
- Y(4790): necessary to improve fit quality (>6s)

Observation of $Z_{cs}(3985)$

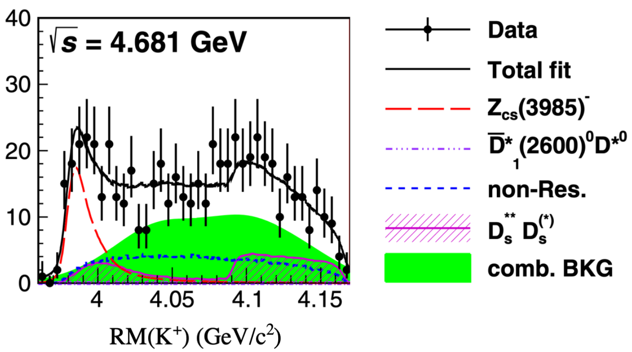


$e^+e^- \rightarrow K^+K^-J/\psi$

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

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

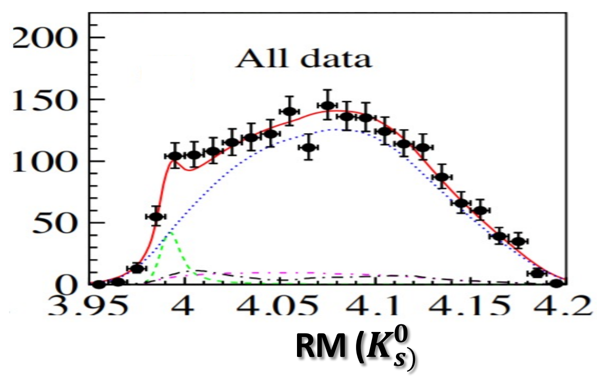
PRL126(2021)102001



- M=$(3985.2^{+2.1}_{-2.0}\pm1.7)$ MeV/c^2
- Γ =$(13.8^{+8.1}_{-5.2}\pm4.9)$ MeV

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

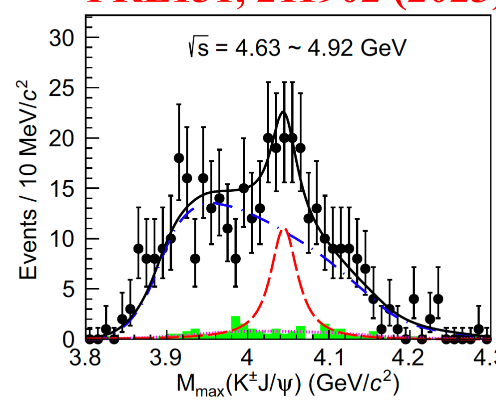
PRL129(2022)112003



- M=$3992.2 \pm 1.7 \pm 1.6)$ MeV/c^2
- Γ =$(7.7^{+4.1}_{-3.8}\pm4.3)$ MeV

$e^+e^- \rightarrow K^+K^-J/\Psi$

PRL131, 211902 (2023)



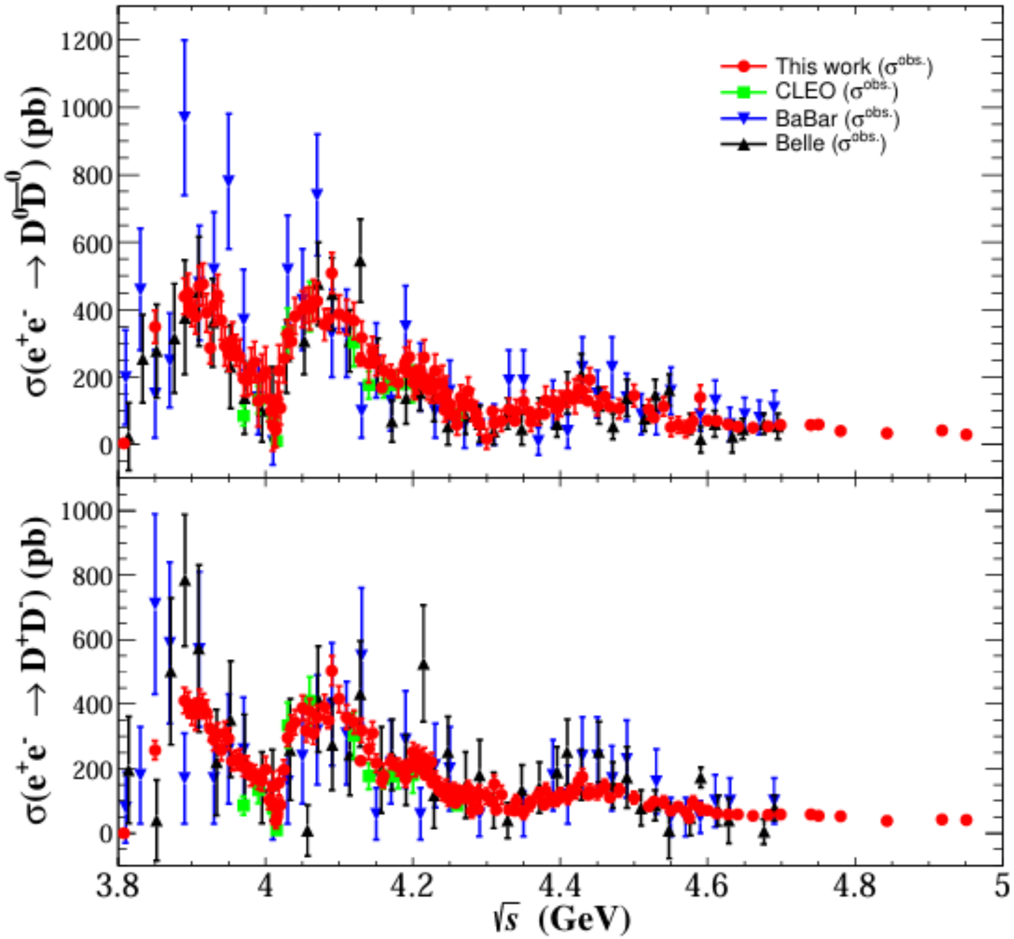
Not significant !

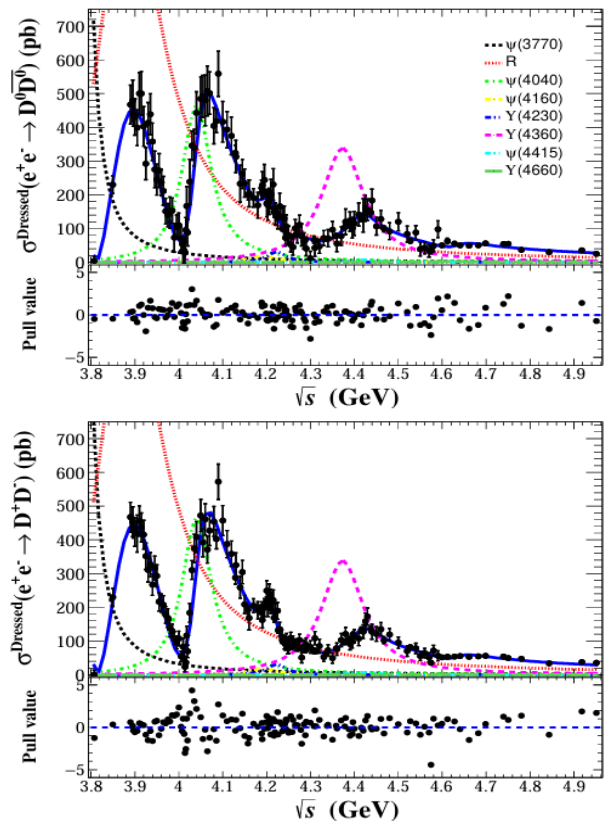
Close mass but very different widths for Zcs(4000) at LHCb ! **LHCb: PRL127, 082001 (2021)**

Observation of a new structure around 3.9 GeV/c^2

Cross section of $e^+e^- \to D^+D^-/D^0\bar{D}^0$:

arXiv:2402.03829





Resonance	R
Mass (MeV/c^2)	3872.5±14.2±3.0
Width (MeV/c^2)	179.7±14.1±7.0
$\Gamma_{ee}\mathcal{B}$ (eV)	202-292
$S(\sigma)$	> 20

Recent studies on the Λ_c^+ measurments at BESIII

- Λ_c^+ leptonic decays
  - ◻ $\Lambda_c^+ \to \Lambda e^+\nu_e, \Lambda\mu^+\nu_\mu$: PRL 129.231803 (2022). PRD 108.L031105 (2023).
  - ◻ $\Lambda_c^+ \to pK^-e^+\nu_e$: PRD 106.112010 (2022).
  - ◻ $\Lambda_c^+ \to Xe^+\nu_e$: PRD 107.052005 (2023).
  - ◻ $\Lambda_c^+ \to \Lambda\pi^+\pi^-e^+\nu_e,\ pK_S^0\pi^-e^+\nu_e$: PLB 843.137993 (2023).

- Λ_c^+ hadronic decays(two body)
  - ◻ $\Lambda_c^+ \to n\pi^+$: PRL 128.142001 (2022).
  - ◻ $\Lambda_c^+ \to p\eta'$: PRD 106.072002 (2022).
  - ◻ $\Lambda_c^+ \to p\eta, p\omega$: JHEP 11.137 (2023).
  - ◻ $\Lambda_c^+ \to p\pi^0, p\eta$: arXiv2311.06883.
  - ◻ $\Lambda_c^+ \to \Lambda K^+$: PRD 106.L111101 (2022).
  - ◻ $\Lambda_c^+ \to \Sigma^0K^+, \Sigma^+K_S^0$: PRD 106.052003 (2022).
  - ◻ $\Lambda_c^+ \to \Xi^0K^+$ ✓ : PRL 132.031801(2024)
- Λ_c^+ hadronic decays(multi-body)
  - ◻ $\Lambda_c^+ \to n\pi^+\pi^0$、$n\pi^+\pi^-\pi^+$、$nK^-\pi^+\pi^+$: CPC 47.023001 (2023).
  - ◻ $\Lambda_c^+ \to nK_S^0\pi^+, nK_S^0K^+$: arXiv2311.17131.
  - ◻ $\bar{\Lambda}_c^- \to \bar{n}X$: PRD 108.L031101 (2023).
  - ◻ $\Lambda_c^+ \to \Lambda\pi^+\pi^0$: JHEP 12.033 (2022).
  - ◻ $\Lambda_c^+ \to \Lambda K^+\pi^0, \Lambda K^+\pi^+\pi^-$: arXiv2311.12903.
  - ◻ $\Lambda_c^+ \to \Sigma^-K^+\pi^+$: arXiv2309.05484.
  - ◻ $\Lambda_c^+ \to \Xi^0K^+\pi^0$: arXiv2311.02347.

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

PRL 132, 031801 (2024)

Theory or experiment	$\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ $(\times 10^{-3})$	$\alpha_{\Xi^0 K^+}$	$\lvert A \rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\lvert B \rvert$ $(\times 10^{-2} G_F\ \mathrm{GeV}^2)$	$\delta_p - \delta_s$ (rad)
Körner (1992), CCQM [7]	2.6	0	-	-	-
Xu (1992), Pole [8]	1.0	0	0	7.94	-
Źencaykowski (1994), Pole [9]	3.6	0	-	-	-
Ivanov (1998), CCQM [10]	3.1	0	-	-	-
Sharma (1999), CA [11]	1.3	0	-	-	-
Geng (2019), SU(3) [12]	5.7 ± 0.9	$0.94^{+0.06}_{-0.11}$	2.7 ± 0.6	16.1 ± 2.6	-
Zou (2020), CA [5]	7.1	0.90	4.48	12.10	-
Zhong (2022), SU(3)[a] [13]	$3.8^{+0.4}_{-0.5}$	$0.91^{+0.03}_{-0.04}$	3.2 ± 0.2	$8.7^{+0.6}_{-0.8}$	-
Zhong (2022), SU(3)[b] [13]	$5.0^{+0.6}_{-0.9}$	0.99 ± 0.01	$3.3^{+0.5}_{-0.7}$	$12.3^{+1.2}_{-1.8}$	-
BESIII (2018) [14]	$5.90 \pm 0.86 \pm 0.39$	-	-	-	-
PDG Fit (2022) [3]	5.5 ± 0.7	-	-	-	-

- $\Lambda_c^+ \to \Xi^0 K^+$ is pure W-exchange process which have significant contributions in charmed baryon decay.
- Nonfactorizable W-exchange diagram cannot be calculated using theoretical approaches.
-
- Long-standing puzzle on how large the S-wave amplitude.
- Experimental measurement of decay asymmetry is crucial and urgent.

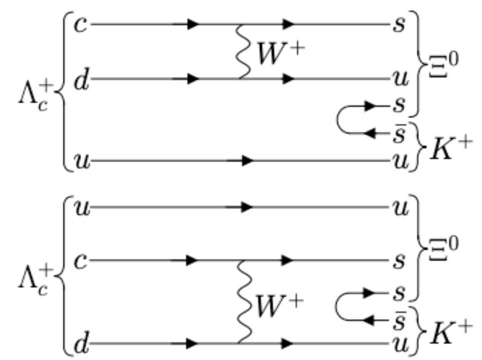


FIG. 1. Feynman diagrams for $\Lambda_c^+ \to \Xi^0 K^+$

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$

$$\alpha_{BP} = \frac{2\mathrm{Re}(s^* p)}{|s|^2 + |p|^2}, \quad \beta_{BP} = \frac{2\mathrm{Im}(s^* p)}{|s|^2 + |p|^2}, \quad \gamma_{BP} = \frac{|s|^2 - |p|^2}{|s|^2 + |p|^2},$$

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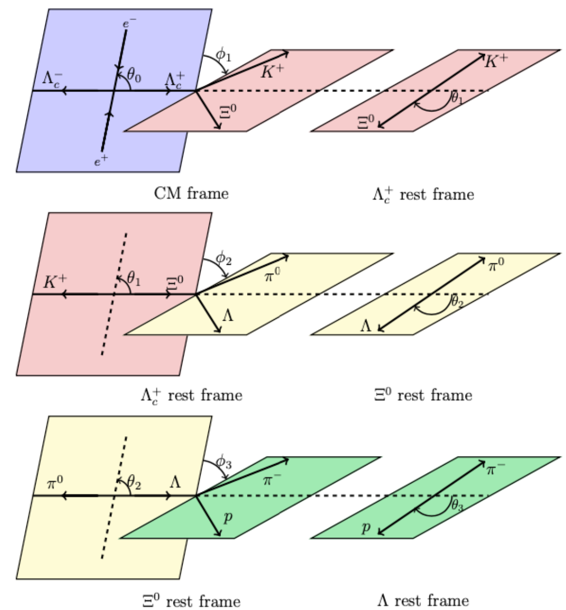
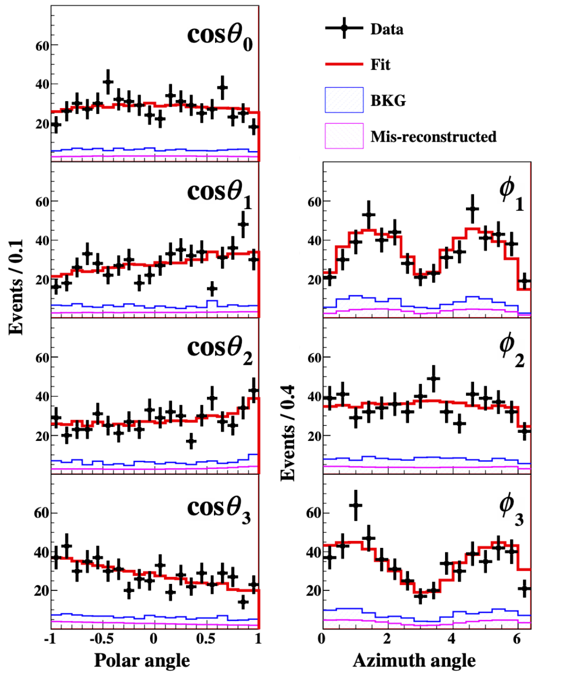
Level	Decay	Helicity angle	Helicity amplitude
0	$e^+e^- \to \Lambda_c^+(\lambda_1)\,\bar{\Lambda}_c^-(\lambda_2)$	(θ_0)	A_{λ_1,λ_2}
1	$\Lambda_c^+ \to \Xi^0(\lambda_3)\,K^+$	(θ_1,ϕ_1)	B_{λ_3}
2	$\Xi^0 \to \Lambda(\lambda_4)\,\pi^0$	(θ_2,ϕ_2)	C_{λ_4}
3	$\Lambda \to p(\lambda_5)\,\pi^-$	(θ_3,ϕ_3)	D_{λ_5}



$$\begin{aligned}
&\frac{d\Gamma}{d\cos\theta_0\ d\cos\theta_1\ d\cos\theta_2\ d\cos\theta_3\ d\phi_1\ d\phi_2\ d\phi_3} \\
&\propto 1 + \alpha_0\cos^2\theta_0 \\
&+ (1 + \alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0 K^+}\alpha_{\Lambda\pi^0}\cos\theta_2 \\
&+ (1 + \alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0 K^+}\alpha_{p\pi^-}\cos\theta_2\cos\theta_3 \\
&+ (1 + \alpha_0\cos^2\theta_0)\ \alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\cos\theta_3 \\
&- (1 + \alpha_0\cos^2\theta_0)\ \alpha_{\Xi^0 K^+}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0} + \phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0 K^+}\sin\theta_1\sin\phi_1 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Lambda\pi^0}\sin\theta_1\sin\phi_1\cos\theta_2 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{\Xi^0 K^+}\alpha_{\Lambda\pi^0}\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_3 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\alpha_{p\pi^-}\sin\theta_1\sin\phi_1\cos\theta_2\cos\theta_3 \\
&- \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\sin\theta_1\sin\phi_1\sin\theta_2\sin\theta_3\cos(\Delta_{\Lambda\pi^0} + \phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{\Lambda\pi^0}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0 K^+} + \phi_2) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{\Lambda\pi^0}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0 K^+} + \phi_2) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin\theta_2\cos(\Delta_{\Xi^0 K^+} + \phi_2)\cos\theta_3 \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \alpha_{p\pi^-}\cos\phi_1\sin\theta_2\sin(\Delta_{\Xi^0 K^+} + \phi_2)\cos\theta_3 \\
&- \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\sin(\Delta_{\Xi^0 K^+} + \phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0} + \phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\ \sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\theta_1\sin\phi_1\cos\theta_2\cos(\Delta_{\Xi^0 K^+} + \phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0} + \phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\cos(\Delta_{\Xi^0 K^+} + \phi_2)\sin\theta_3\sin(\Delta_{\Lambda\pi^0} + \phi_3) \\
&+ \sqrt{1-\alpha_0^2}\ \sin\Delta_0\sin\theta_0\cos\theta_0\sqrt{1-\alpha^2_{\Xi^0 K^+}}\sqrt{1-\alpha^2_{\Lambda\pi^0}}\ \alpha_{p\pi^-}\cos\phi_1\cos\theta_2\sin(\Delta_{\Xi^0 K^+} + \phi_2)\sin\theta_3\cos(\Delta_{\Lambda\pi^0} + \phi_3)
\end{aligned}$$

- The joint angular distribution for $\Lambda_c^+ \to \Xi^0 K^+$ is derived based on helicity amplitude.

Decay asymmetry for pure W-exchange process $\Lambda_c^+ \to \Xi^0 K^+$



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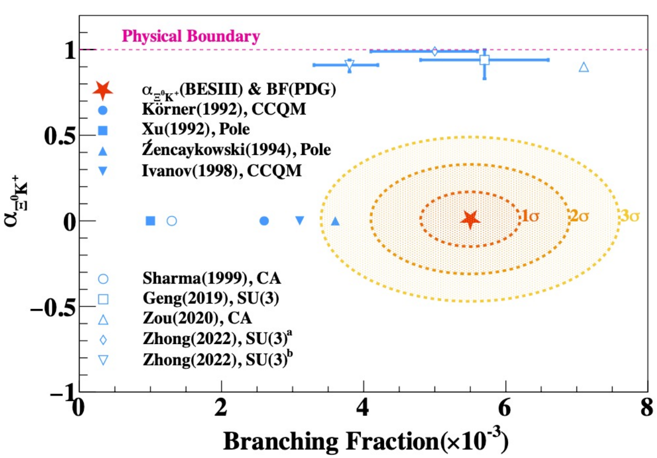
- From the fit, we obtain $\alpha_{\Xi^0 K^+} = 0.01 \pm 0.16_{stat} \pm 0.03_{syst}$ and $\beta_{\Xi^0 K^+} = -0.64 \pm 0.69_{stat} \pm 0.13_{syst}$ and $\gamma_{\Xi^0 K^+} = -0.77 \pm 0.58_{stat} \pm 0.11_{syst}$
- $\alpha_{\Xi^0 K^+}$ is in good agreement with zero=>strong identification for theoretical predictions.

$$\Gamma = \frac{\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)}{\tau_{\Lambda_c^+}} = \frac{|\vec{p}_c|}{8\pi}\left[\frac{(m_{\Lambda_c^+} + m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|A|^2 + \frac{(m_{\Lambda_c^+} - m_{\Xi^0})^2 - m_{K^+}^2}{m_{\Lambda_c^+}^2}|B|^2\right]$$

$$\alpha_{\Xi^0 K^+} = \frac{2\kappa|A||B|\cos(\delta_p - \delta_s)}{|A|^2 + \kappa^2|B|^2},$$

$$\Delta_{\Xi^0 K^+} = \arctan\frac{2\kappa|A||B|\sin(\delta_p - \delta_s)}{|A|^2 - \kappa^2|B|^2},$$



- Especially, $\cos(\delta_p - \delta_s)$ is measured to close to zero.=>not considered in previous literature.
- Fills the long-standing puzzle on how to model $\alpha_{\Xi^0 K^+}$ and $\mathcal{B}(\Lambda_c^+ \to \Xi^0 K^+)$ simultaneously.

Decay asymmetry parameter in $\Lambda_c^+ \to \Xi^0 K^+$

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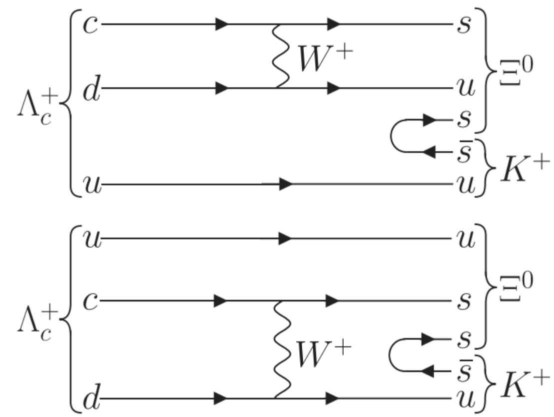
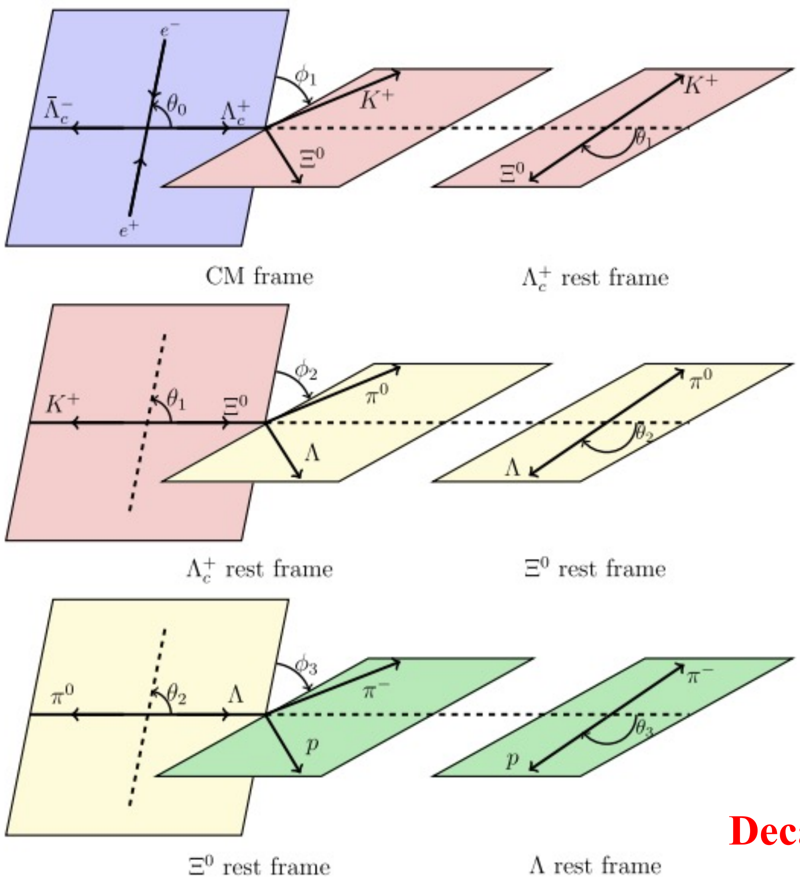
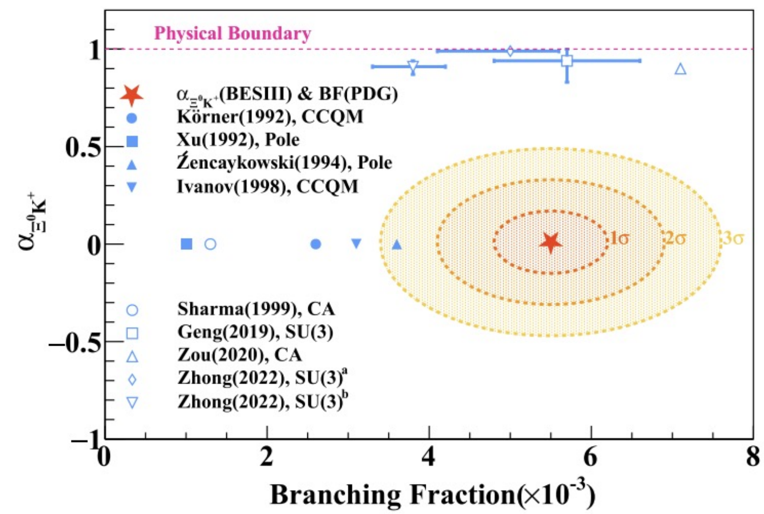
- Helicity frame:

W-boson-exchange decay:







Decay asymmetry parameter: $\alpha = 0.01 \pm 0.16 \pm 0.03$

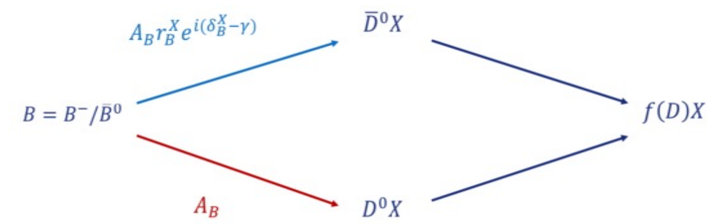
Phase between S and P wave: $\delta_P - \delta_S = -1.55 \pm 0.25 \pm 0.05, or\ 1.59 \pm 0.25 \pm 0.05$

Recent studies on the charmed mesons at BESIII

- $D^{\pm}, D^0, D_s^+$ purely leptonic decays
  - $D_s^{*+} \to e^+\nu_e$: PRL 131, 141802 (2023).
  - $D_s^+ \to \mu^+\nu_\mu$: PRD 108, 112001 (2023).
  - $D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$: JHEP 09 ,124 (2023).
  - $D_s^+ \to \tau^+\nu_\tau, \tau^+ \to \pi^+\bar{\nu}_\tau$: PRD 108, 092014 (2023).
- $D^{\pm}, D^0, D_s^+$ semi-leptonic decays
  - $D_s^+ \to K_1(1270)/b_1(1235)e^+\nu_e$: PRD 108, 112002 (2023).
  - $D_s^+ \to \eta(\eta')e^+\nu_e$: PRD 108, 092003 (2023).
- $D^{\pm}, D^0, D_s^+$ hadronic decays
  - $D^+ \to K_S^0\pi^+\pi^0\pi^0$: JHEP 09 ,077 (2023).
  - $D_s^+ \to \omega\pi^+\eta$: PRD 107, 052010 (2023).
- $D^{\pm}, D^0, D_s^+$ inclusive decays
  - $D^{+/0} \to K_S^0 X$: PRD 107, 112005 (2023).
  - $D^{+/0} \to \pi^+\pi^+\pi^- X$: PRD 107, 032002 (2023).
  - $D_s^+ \to \pi^+\pi^+\pi^- X$: PRD 108, 032001 (2023).
- Strong phase in $D^{\pm}, D^0, D_s^+$ decays
  - $D^0 \to K_S^0\pi^+\pi^-\pi^0$: PRD 108, 032003 (2023). ✓
  - $D^0 \to K^+K^-\pi^+\pi^-$: PRD 107, 032009 (2023).
- Others
  - Determination of spin and parity of D_s^* : PLB 846, 138245 (2023). ✓
  - $D_s^* \to \gamma D_s$: PRD 107, 032011 (2023).

Strong phase in D^0 decays

- Determination of the CP-even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$ [PRD 108, 032003 (2023)]



- The CKM unitarity angle $\gamma = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$.
- The important source of CP violation for the quark sector.
- Search for indirect new physics.
- Test of CKM unitary.
- With F_+^f, the γ angle can be extracted.

$$Y^{\mp} = h^{\mp}\int_{\mathbf{x}\in\mathcal{D}} \mathcal{P}(B^{\mp}(\mathbf{x}))\,\mathrm{d}\mathbf{x} = h^{\mp}\left[1 + r_B^2 + \left(2F_+^f - 1\right)2r_B\cos\left(\delta_B \mp \gamma\right)\right]$$

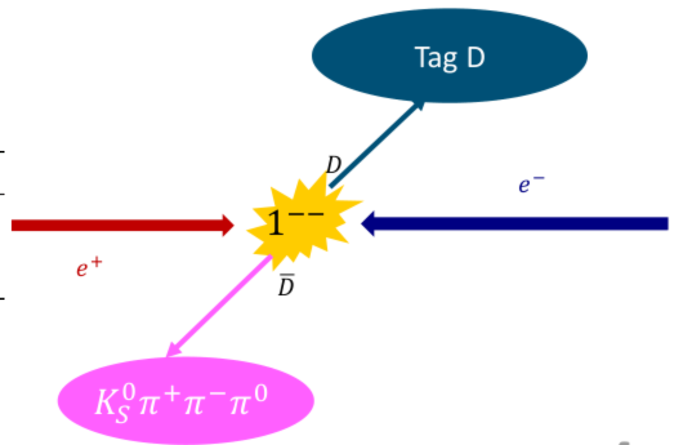
$\Rightarrow$ Important to determine F_+ for $D \to K_S^0\pi^+\pi^-\pi^0$.

- Double tag method:

- With CP tags
- With $\pi^+\pi^-\pi^0$ tag
- With $K_S^0\pi^+\pi^-\pi^0$ tag
- With $K_S^0\pi^+\pi^-$ tag

Mixed CP tag modes

Type	Modes
CP-even	$K^+K^-, \pi^+\pi^-, K_S^0\pi^0\pi^0, K_L^0\omega, K_L^0\pi^0$
CP-odd	$K_S^0\pi^0, K_S^0\eta(\gamma\gamma), K_S^0\eta'(\eta\pi^+\pi^-), K_S^0\eta'(\gamma\pi^+\pi^-)$
Mixed CP	$\pi^+\pi^-\pi^0, \pi^+\pi^-\pi^+\pi^-, K_{S,L}^0\pi^+\pi^-, K_S^0\pi^+\pi^-\pi^0$

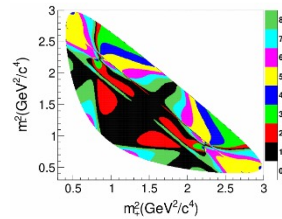


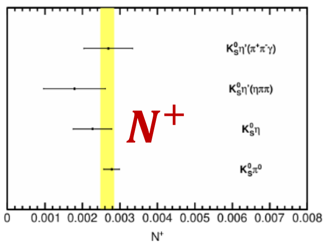
Strong phase in D^0 decays

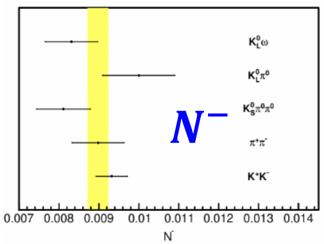
- Determination of the CP-even fraction of $D^0 \to K_S^0\pi^+\pi^-\pi^0$ [PRD 108, 032003 (2023)]

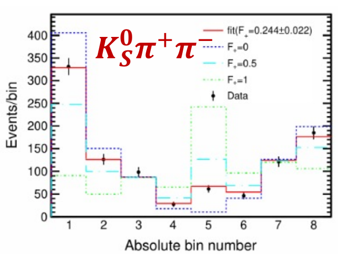
- Determination of F_+:

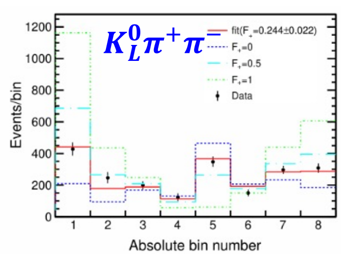
  - With CP tags: $N^{\pm} = \mathcal{B}(S)\varepsilon(S)\left[1-\eta_{\text{CP}}^{\mp}\left(2F_+^S-1\right)\right]$ $\quad F_+ = \dfrac{N^+}{N^+ + N^-}$
  - With $\pi^+\pi^-\pi^0$ tag: $\dfrac{N^{\pi^+\pi^-\pi^0}}{\langle N^+\rangle} = \dfrac{\left[1-\left(2F_+^S-1\right)\left(2F_+^{\pi^+\pi^-\pi^0}-1\right)\right]}{2F_+^S}$ $\quad F_+^S = \dfrac{\langle N^+\rangle F_+^{\pi^+\pi^-\pi^0}}{N^{\pi^+\pi^-\pi^0} - \langle N^+\rangle + 2\langle N^+\rangle F_+^{\pi^+\pi^-\pi^0}}$
  - With $K_S^0\pi^+\pi^-\pi^0$ tag: $N^S = 2B_S\,\varepsilon(S)F_+^S\left(1-F_+^S\right)$ $\quad F_+^S = \dfrac{N^S}{\langle N^-\rangle}$
  - With $K_S^0\pi^+\pi^-$ and $K_L^0\pi^+\pi^-$ tags: Divided into 8 bins of δ_D.











- F_+ Results:

Method	F_+
CP tags	$0.229 \pm 0.013 \pm 0.0018$
$\pi^+\pi^-\pi^0$ tag	$0.227 \pm 0.014 \pm 0.0027$
$\pi^+\pi^-\pi^+\pi^-$ tag	$0.227 \pm 0.016 \pm 0.0034$
$K_S^0\pi^+\pi^-\pi^0$ self-tag	$0.244 \pm 0.019 \pm 0.0022$
$K_{S,L}^0\pi^+\pi^-$	$0.244 \pm 0.021 \pm 0.0062$
combined	$0.234 \pm 0.0096 \pm 0.0018$

Spin and parity of D_s^* meson

- Determination of spin and parity for D_s^* meson. [PLB 846, 138245 (2023)]

- There is no decisive experimental results of spin and parity have been reported for the ground 1S states $D_{(s)}^*$. In PDG, the status of J^P for D^{*0} and D^{*+} are assigned to be 1^- while they need to be confirmed experimentally.

CHARMED, STRANGE MESONS
$(C = S = \pm1)$
$D_s^+ = c\bar{s}$, $D_s^- = \bar{c}s$, similarly for D_s^*'s

$D_s^{*\pm}$ $I(J^P) = 0(?^?)$

J^P is natural, width and decay modes consistent with 1^-

CHARMED MESONS
$(C = \pm1)$
$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\overline{D}^0 = \bar{c}u$, $D^- = \bar{c}d$, similarly for D^*'s

$D^*(2007)^0$ $I(J^P) = 1/2(1^-)$ I, J, P need confirmation.

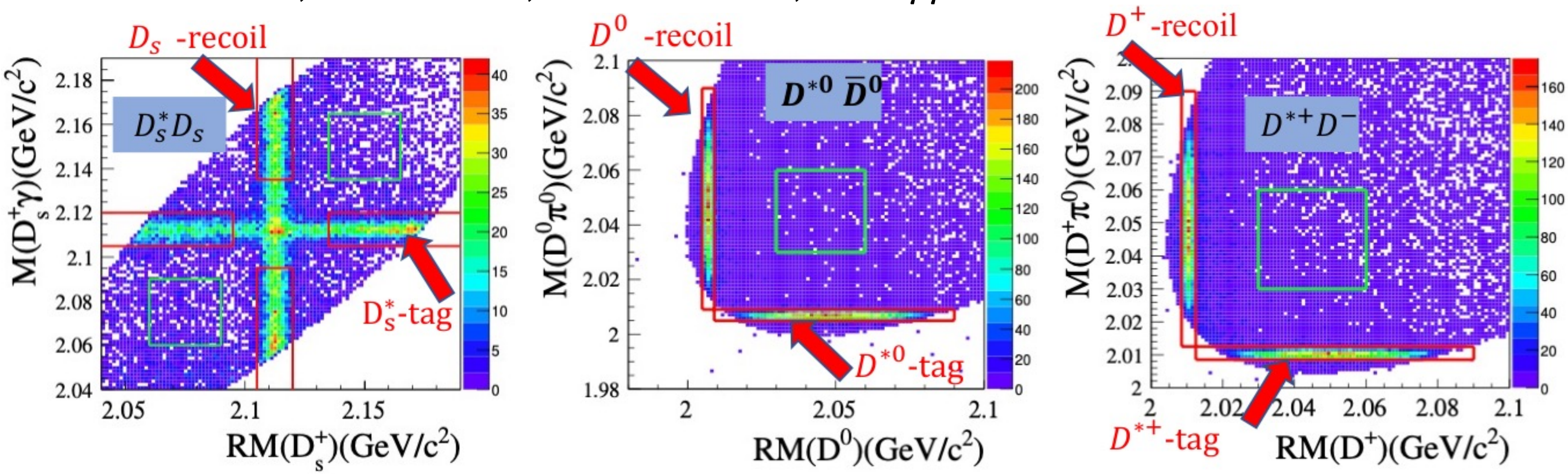
J consistent with 1, value 0 ruled out (NGUYEN 1977).

CHARMED MESONS
$(C = \pm1)$
$D^+ = c\bar{d}$, $D^0 = c\bar{u}$, $\overline{D}^0 = \bar{c}u$, $D^- = \bar{c}d$, similarly for D^*'s

$D^*(2010)^\pm$ $I(J^P) = 1/2(1^-)$ I, J, P need confirmation.

Decay chains:

- $e^+e^- \to D_s^{*+}D_s^-, D_s^{*+} \to \gamma D_s^+, D_s^+ \to K_S^0 K^+$
- $e^+e^- \to D^{*0}\overline{D}^0, D^{*0} \to \pi^0 D^0, D^0 \to K^-\pi^+, \pi^0 \to \gamma\gamma$
- $e^+e^- \to D^{*+}D^-, D^{*+} \to \pi^0 D^+, D^+ \to K^-\pi^+\pi^+, \pi^0 \to \gamma\gamma$



Spin and parity of D_s^* meson

- Determination of spin and parity for D_s^* meson. [PLB 846, 138245 (2023)]

- $J^P = 1^-$ for $D_s^{*\pm}$:

$$\mathcal{W}^{(1-)} \sim (3 + cos2\theta_1) - 4cos2\phi_1 sin\theta_0 sin\theta_1$$

- $J^P = 2^+$ for $D_s^{*\pm}$:

$$\mathcal{W}^{(2+)} \sim (3 + cos2\theta_0)(2 + cos2\theta_1 + cos4\theta_1) - 4(1 + 2cos2\theta_1)cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$

- $J^P = 3^-$ for $D_s^{*\pm}$:

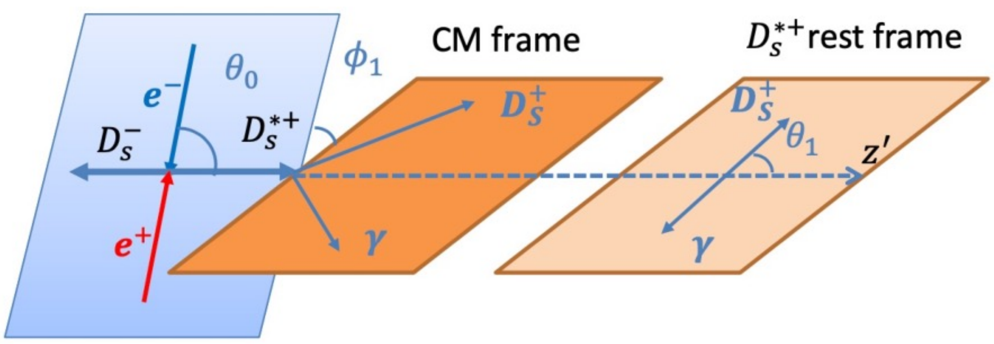
$$\mathcal{W}^{(3-)} \sim (398 + 271cos2\theta_1 + 130cos4\theta_1 + 255cos6\theta_1) - 16(163 + 380cos2\theta_0 + 255cos4\theta_0)(163 + 380cos2\theta_1 + 225cos4\theta_1)cos2\phi_1 \sin^2\theta_0 \sin^2\theta_1$$

- Test three possible J^P numbers for $D_s^{*\pm}$

J^P	$e^+e^- \to D_s^{*\pm}D_s^{\mp}$	$D_s^{*\pm} \to \gamma D_s^{\pm}$	$D_s^{*\pm} \to \pi^0 D_s^{\pm}$
0^-	O (Yes)	O (Yes)	× (No)
0^+	×	×	O
1^+	O	O	×
1^-	O[P]	O[P]	O[P]
1^+	O	O	×
2^-	O	O	×
2^+	O[D]	O[D]	O[D]
3^-	O[E]	O[E]	O[E]
3^+	O	O	×

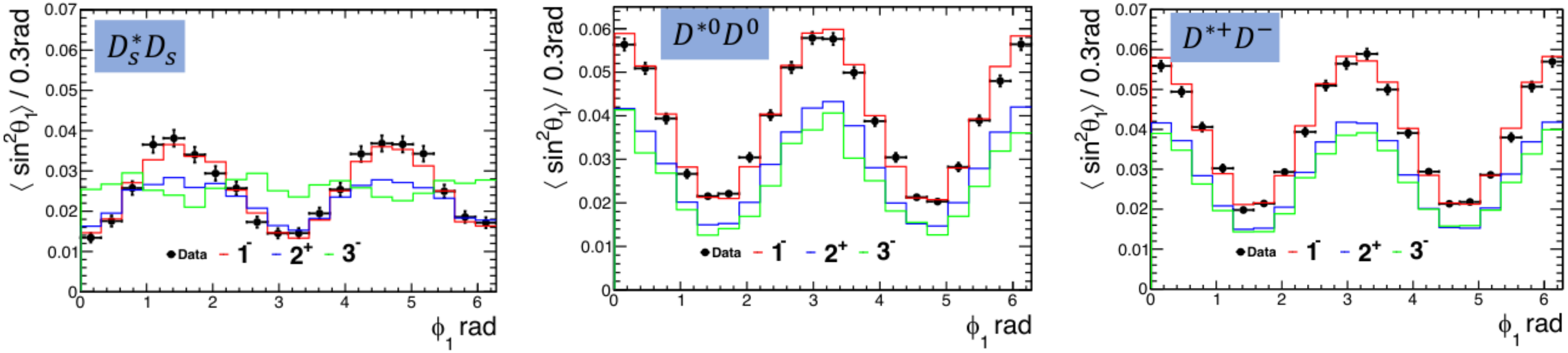
- Exactly same for D^{*0} and D^{*+}

$$\langle \sin^2\theta_1 \rangle \sim \phi_1$$



Spin and parity of D_s^* meson

- Determination of spin and parity for D_s^* meson. [PLB 846, 138245 (2023)]
- Fit result $\langle \sin^2\theta_1 \rangle$ v.s. ϕ_1:



- $\langle \sin^2\theta_1 \rangle$ $v.s.$ ϕ_1 illustrate the different behavior.
- Data obviously favor the 1^- assignment over the 2^+ and 3^-.

- Estimation of statistical significance:

$$S = \sqrt{2(\ln \mathcal{L}_{max}(H_1) - \ln \mathcal{L}_{max}(H_0))}$$

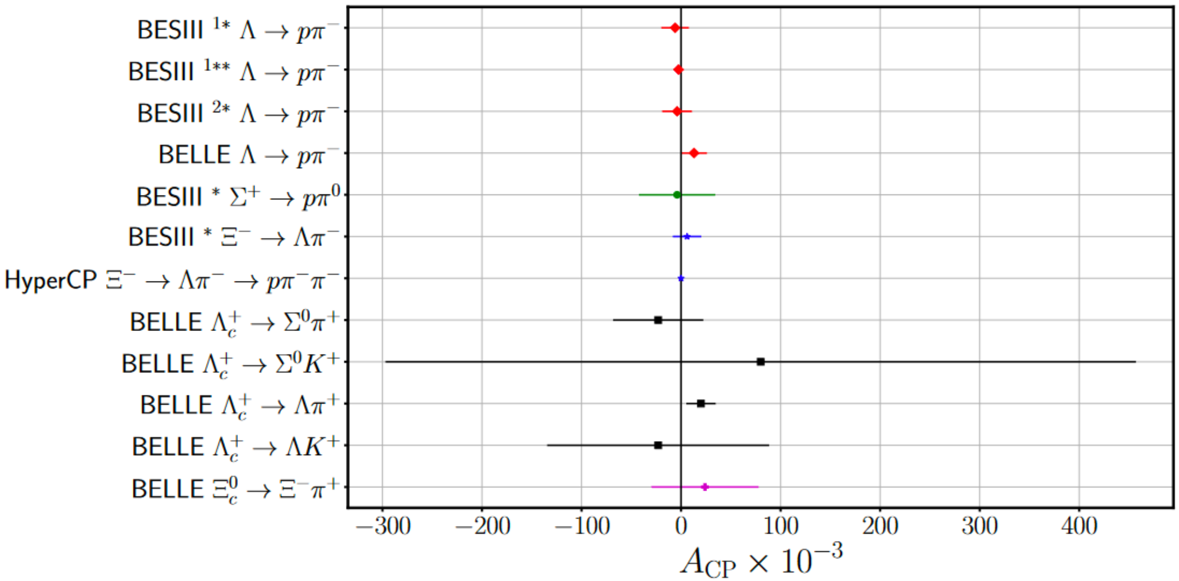
process	$2\|\ln(\mathcal{L}^{J^P=2^+}/\mathcal{L}^{J^P=1^-,2^+})\|$	significance	$2\|\ln(\mathcal{L}^{J^P=3^-}/\mathcal{L}^{J^P=1^-,3^-})\|$	significance
D_s^{*+}	1101.67	$>32\sigma$	2104.36	$>32\sigma$
D^{*0}	29251.08	$>32\sigma$	30989.46	$>32\sigma$
D^{*+}	25672.06	$>32\sigma$	31718.66	$>32\sigma$

The J^P is determined 1^- with large than 32σ significance against 2^+ and 3^- hypotheses.

Symmetry study

CP tests at BESIII & Belle

- SM predicts very small violations of charge conjugation and parity (CP) symmetry.
- Sizeable CP violations prerequisite for Baryogenesis
- Spin-carrying hyperons precision probe of CP symmetry.



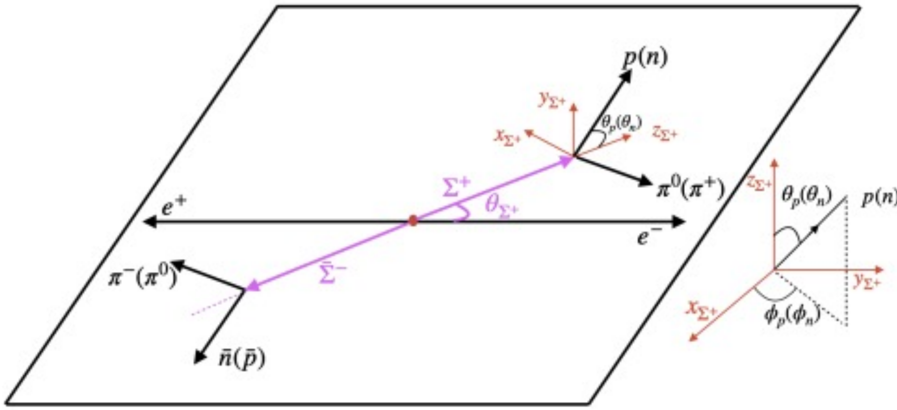
BESIII:
Nature Phys. 15, p 631-634 (2019)
Phys. Rev. Lett. 125, 052004 (2020)
Nature 606, 64-69 (2022)
Phys. Rev. Lett. 129, 131801 (2022)
Phys. Rev. D 108, L031106 (2023)

Belle:
Sci. Bull. 68, 583-592 (2023)

HyperCP:
Phys. Rev. Lett. 93, 262001, 2004.

CP test in $\Sigma^+ \to n\pi^+$

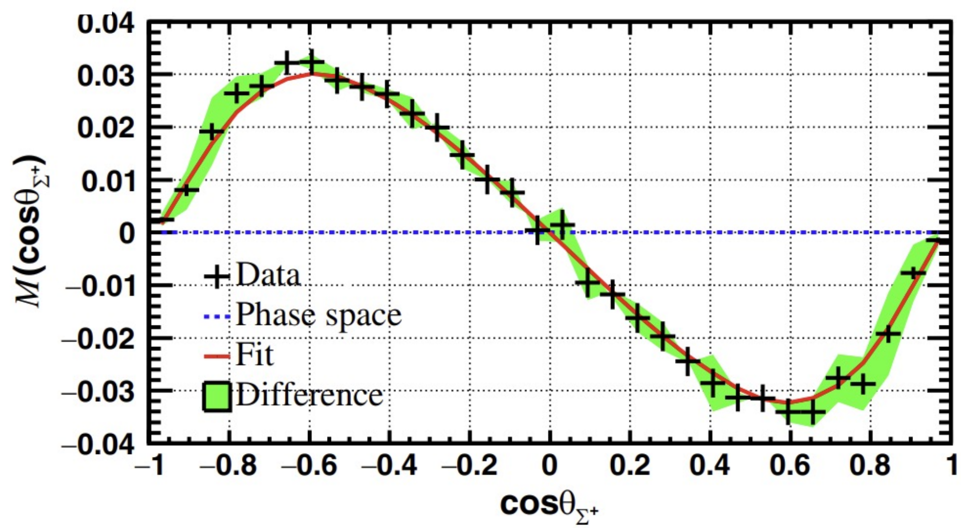
- Helicity frame definition:



Differential cross-section:

$$\mathcal{W}(\xi) = \mathcal{T}_0(\xi) + \alpha_{J/\psi}\mathcal{T}_5(\xi) + \alpha\bar{\alpha}\left(\mathcal{T}_1(\xi) + \sqrt{1-\alpha_{J/\psi}^2}\cos(\Delta\Phi)\mathcal{T}_2(\xi) + \alpha_{J/\psi}\mathcal{T}_6(\xi)\right) + \sqrt{1-\alpha_{J/\psi}^2}\sin(\Delta\Phi)(\alpha\mathcal{T}_3(\xi) + \bar{\alpha}\mathcal{T}_4(\xi)),$$

PRL 131, 191802 (2023)



The weak decay parameters are determined to be:

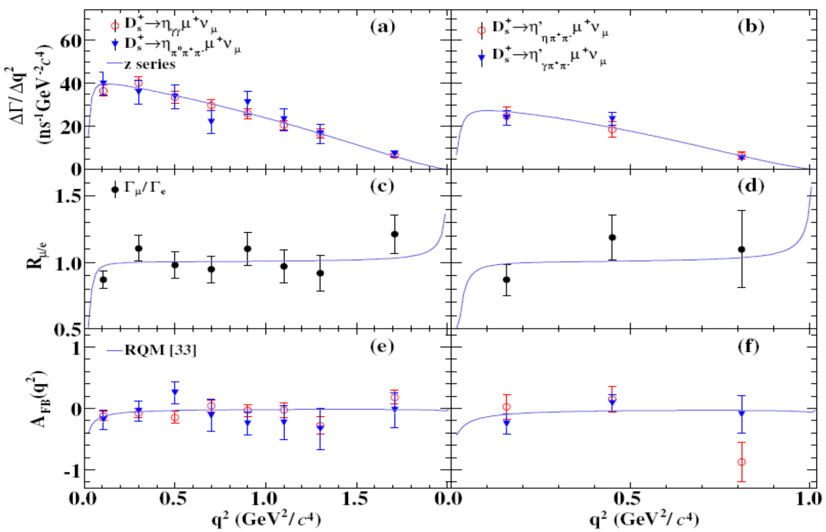
$$\alpha_+ = 0.0481 \pm 0.0031 \pm 0.0019$$

$$\alpha_- = -0.0565 \pm 0.0047 \pm 0.0022$$

$$A_{CP} = -0.080 \pm 0.052 \pm 0.028$$

LFU tests in Charm decays at BESIII

$D_s^+ \to \eta^{(\prime)}\mu^+\nu_\mu$ PRL 132,091802(2024)



$$R_{D_s^+\eta} = \frac{\Gamma[D_s^+ \to \eta\mu^+v]}{\Gamma[D_s^+ \to \eta e^+v]} = 0.984 \pm 0.032$$

$$R_{D_s^+\eta'} = \frac{\Gamma[D_s^+ \to \eta'\mu^+v]}{\Gamma[D_s^+ \to \eta' e^+v]} = 0.989 \pm 0.089$$

$D_s^+ \to \phi\mu^+\nu_\mu$ JHEP12(2023)072

$$R_{D_s^+\phi} = \frac{\Gamma[D_s^+ \to \phi\mu^+v]}{\Gamma[D_s^+ \to \phi e^+v]} = 0.94 \pm 0.08$$

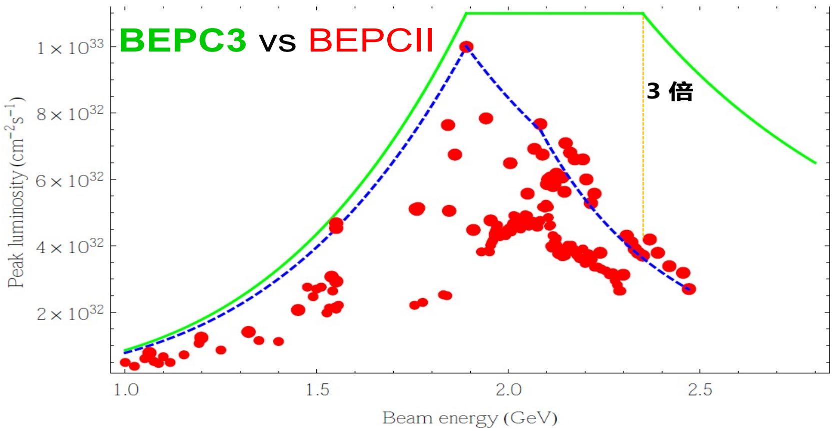
The $D^+ \to \tau^+\nu$ and seven semimuonic D decays are observed for the first time. Five semimuonic charm decays are measured with better precision

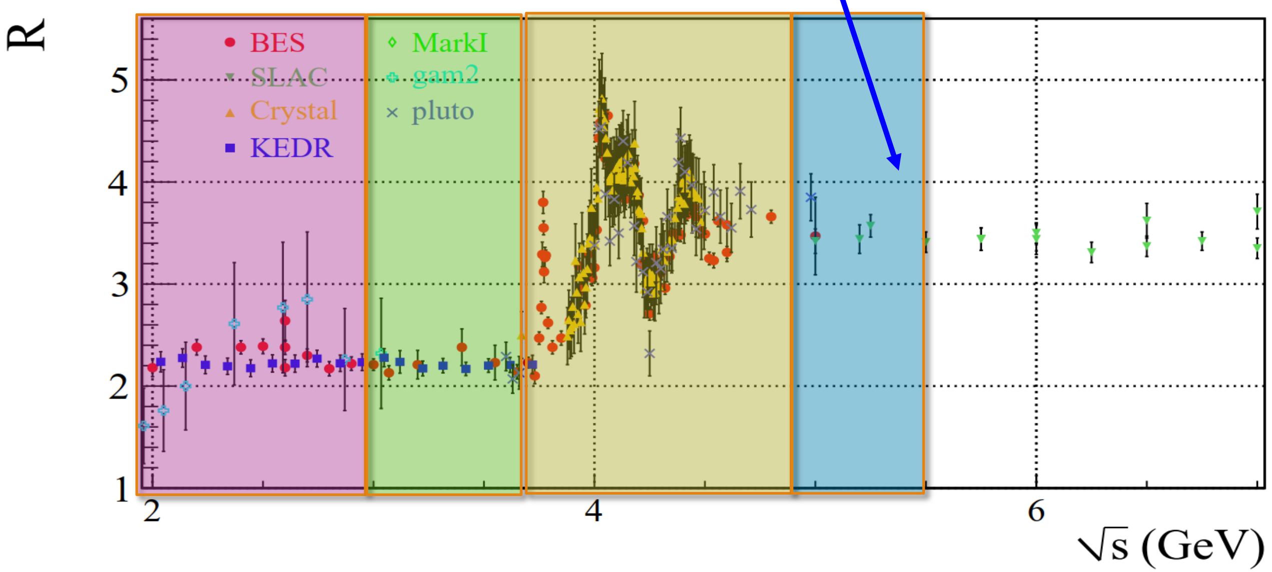
		BF ratios	References
μ/e	$D^0 \to K^-$	$0.978 \pm 0.007 \pm 0.012$	PRL122(2019)011804
	$D^0 \to \pi^-$	$0.922 \pm 0.030 \pm 0.022$	PRL121(2018)171803
	$D^0 \to \rho^-$	0.90 ± 0.11	PRD104(2021)L091003
	$D^+ \to \bar{K}^0$	1.00 ± 0.03	EPJC76(2016)369
	$D^+ \to \pi^0$	$0.964 \pm 0.037 \pm 0.026$	PRL121(2018)171803
	$D^+ \to \omega$	1.05 ± 0.14	PRD101(2020)072005
	$D^+ \to \eta$	0.91 ± 0.13	PRL124(2020)231801
	$D_s^+ \to \eta$	$0.984 \pm 0.028 \pm 0.016$	arXiv:2307.12852 accepted by PRL
	$D_s^+ \to \eta'$	$0.989 \pm 0.082 \pm 0.034$	
	$D_s^+ \to \phi$	0.94 ± 0.08	JHEP12(2023)072
	$\Lambda_c^+ \to \Lambda$	$0.98 \pm 0.05 \pm 0.03$	PRD108(2023)L031105
τ/μ	$D^+ \to \tau^+\nu$	$3.21 \pm 0.64 \pm 0.43$	PRL123(2019)211802
	$D_s^+ \to \tau^+\nu$	10.05 ± 0.35	PRL127(2021)171801

Plan of BEPCII/BESIII upgrade

Chin. Phys. C 44 (2020) 4, 040001

- Optimize E_{cm} at 4.7 GeV with luminosity 3 times higher than the current BEPCII → more effective data taking
- CGEM inner tracker
- Extend the maximum E_{cm} up to 5.6 GeV → more physics opportunity



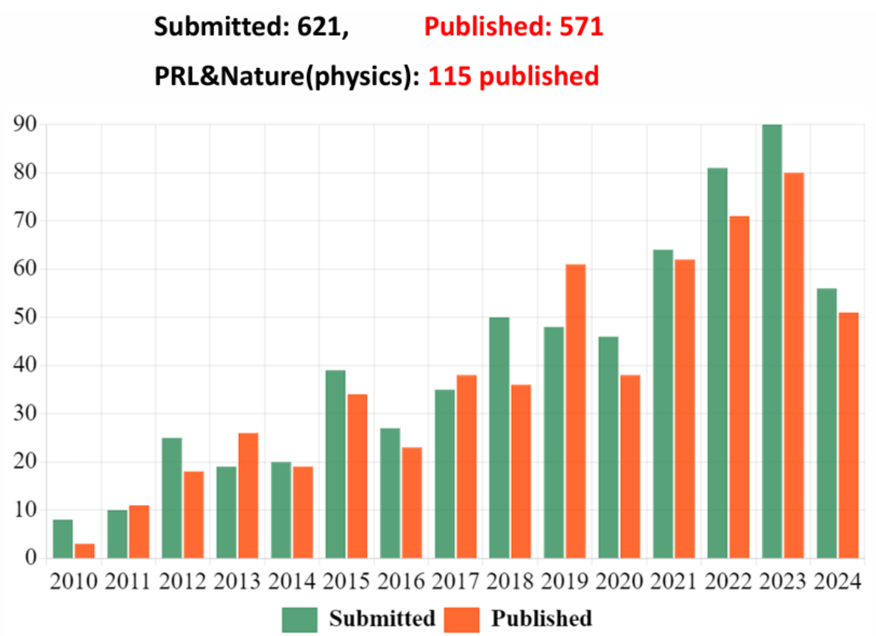


Nearly blank at 5-7GeV

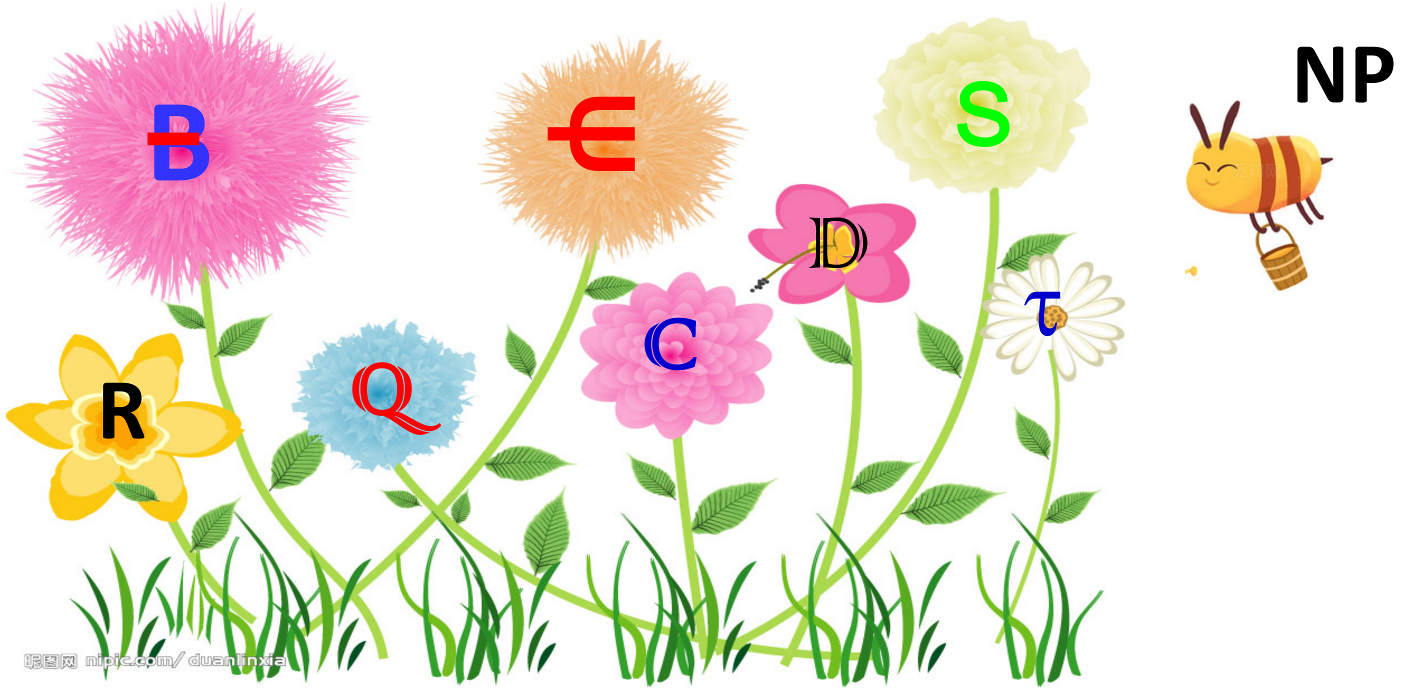
Summary & Prospect

- World largest data samples at BESIII
  - An excellent laboratory to study a wide physics program
- Recent highlights of BESIII results on flavor physics are briefly overviewed
  - A personal selection of latest BESIII results
- Latest large data-sets under study
- BEPCII-U: 3x lum above 4 GeV &max energy to 5.6 GeV) !

July 2024



More important results are expected from BESIII !



Many thanks for your attention !