Charmonium-like States at BESIII

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On behalf of BESIII collaboration

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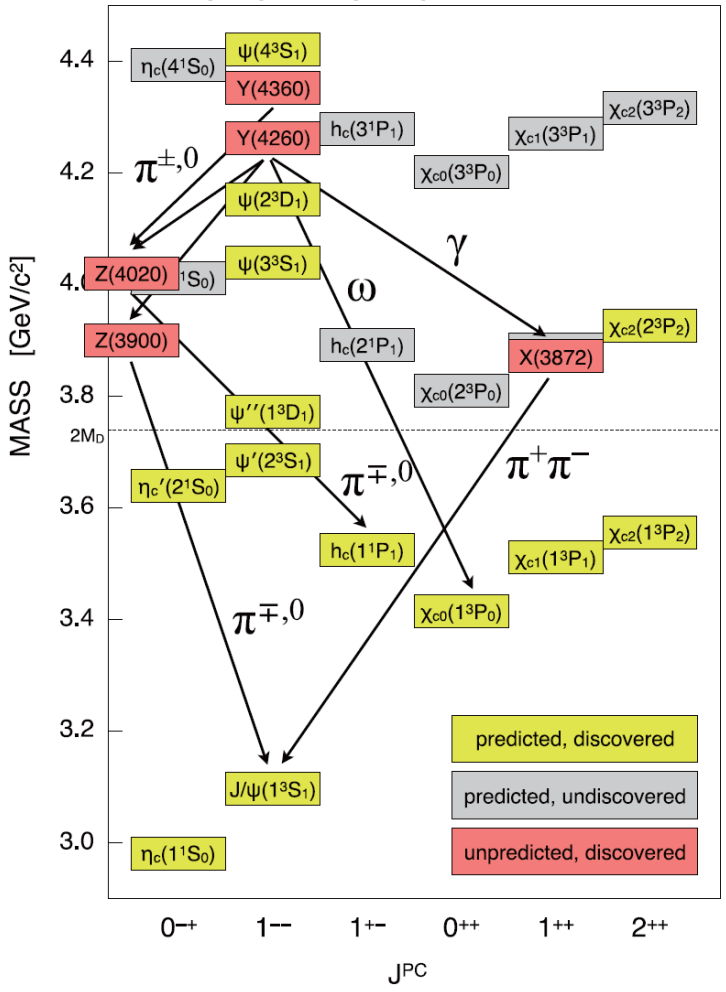
Outline

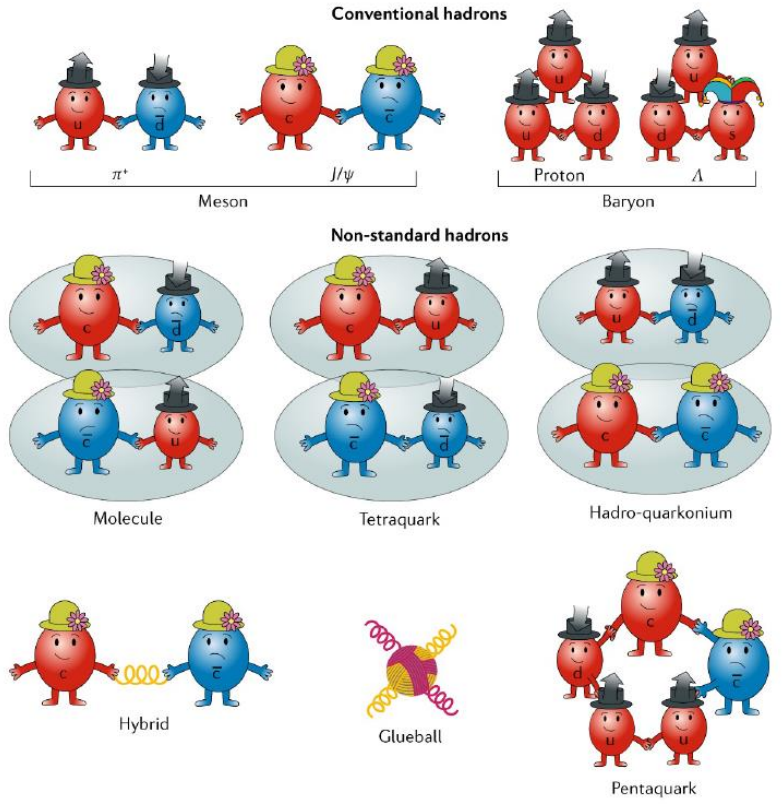
- Introduction of charmonium-like (XYZ) states and BESIII
- Very recent results at BESIII:
  1. Z: PWA of $e^+e^- \to \pi^+\pi^- J/\psi$
  2. Y: cross sections of $e^+e^- \to \pi^+\pi^- h_c$
  3. X: search for 1^{-+} states in $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536)$ + c.c., $e^+e^- \to \gamma\eta^{(\prime)}\eta_c$
- Upgrade of BEPCII and prospects of BESIIII

What are charmonium-like (XYZ) states

charmonia: $c\bar{c}$



Exotic states with hidden charm



CZY & S. L. Olsen, *Nature Reviews Physics* **1**, 480 (2019)

Y: vector states

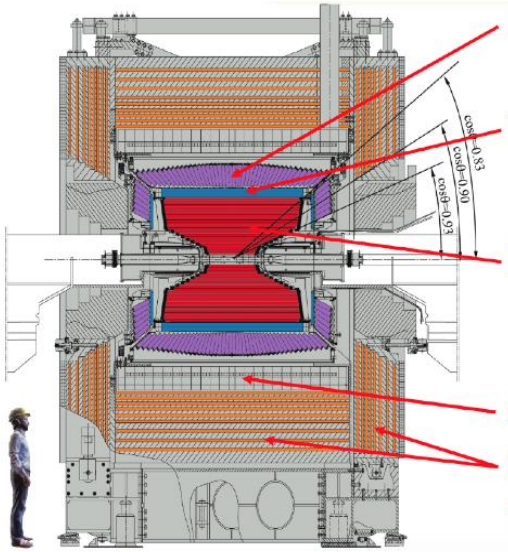
Z: $isospin \neq 0$

X: remained

Primarily studies the properties of charmonium-like states, including but are not limited to

- Searching for new states
- Determining the internal structure
- Measuring masses and widths
- Measuring transitions and decays
- Searching for new decay channels

BESIII at BEPCII



EMC: CsI crystals
ΔE/E = 2.5% @ 1 GeV - Barrel
ΔE/E = 5.0% @ 1 GeV - Endcaps

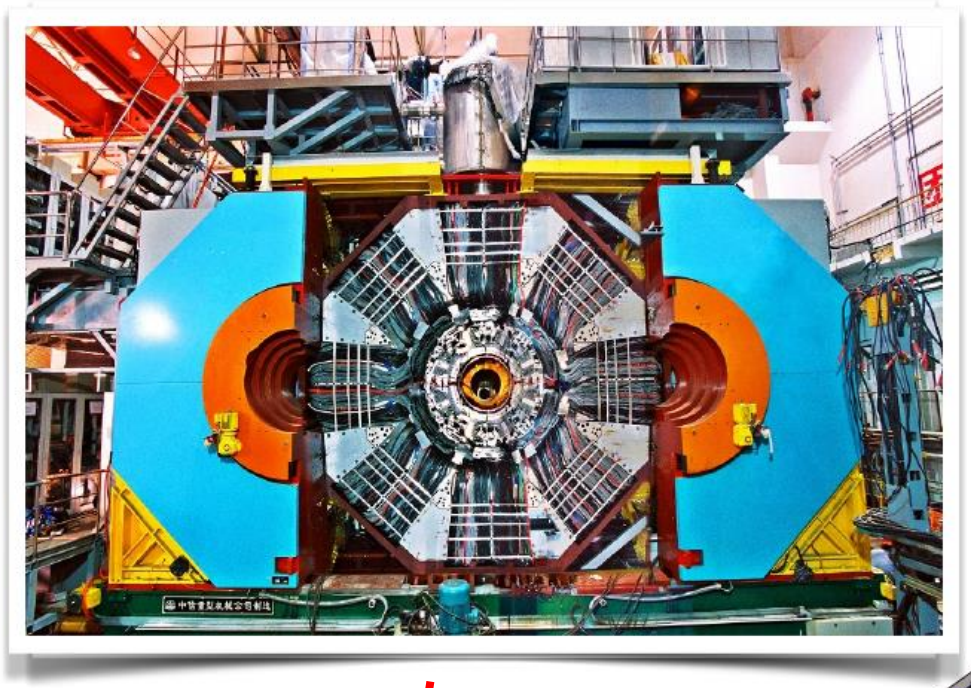
TOF:
σ_T = 80 ps Barrel
σ_T = 110 (60) ps Endcap

MDC: small cell & He gas
σ_{xy}= 130 μm
σ_p/p = 0.5% @1GeV
dE/dx = 6%

Magnet: 1T Super conducting

Muon ID: 9 layer RPC

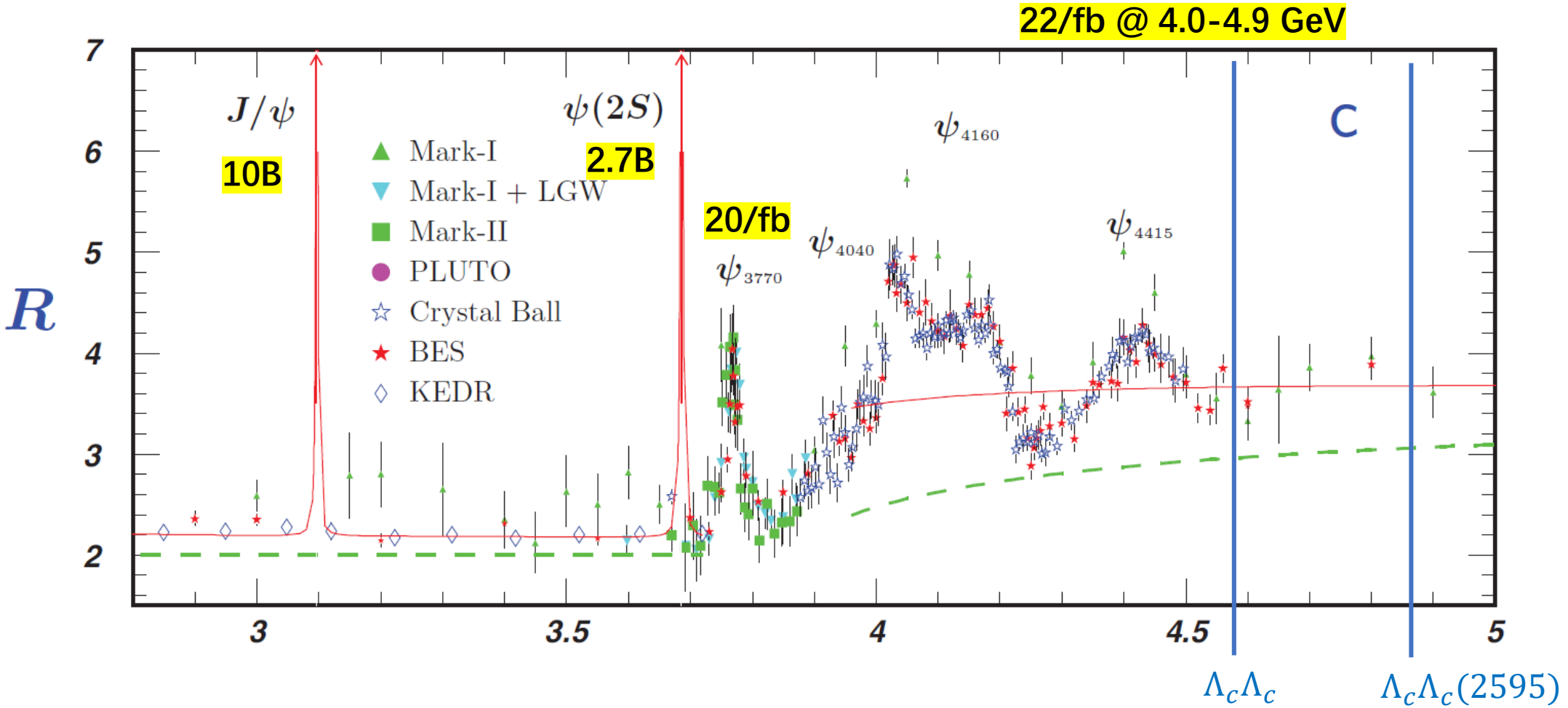
Trigger: Tracks & Showers



- Center of mass energy range: $\sqrt{s}$ = 2 - 4.9 GeV
- Single beam current: 0.91 A
- Crossing angle: 11 mrad
- Design luminosity: $1 \cdot 10^{33}$ cm^{-2} s^{-1}
- Achieved luminosity: $1.01 \cdot 10^{33}$ cm^{-2} s^{-1}

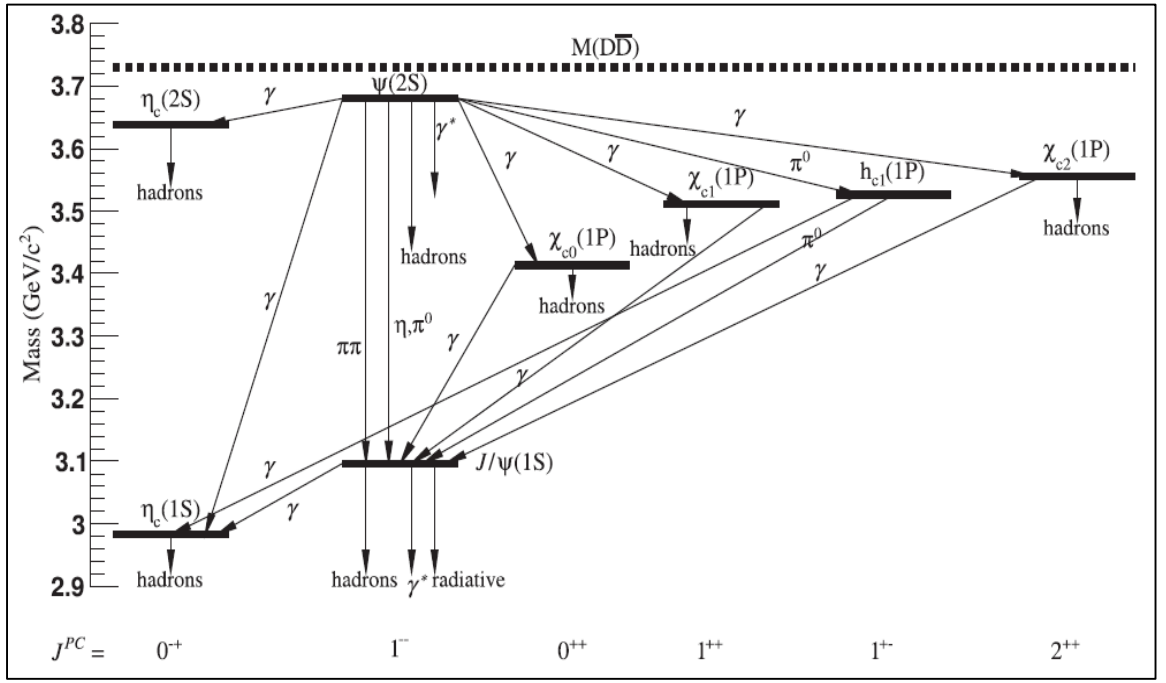
BESIII data samples

Abundant physical topics: D and Λ_c decays, light hadrons, charmonium and XYZ, τ and R-value, new physics, etc.

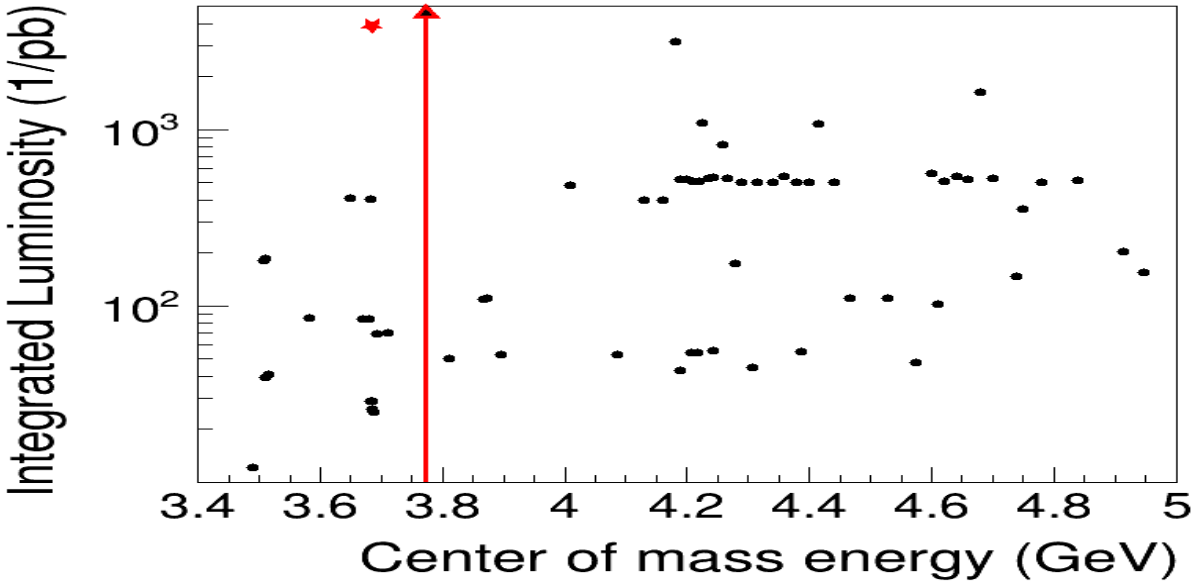


How to study charmonium(-like) sates at BESIII

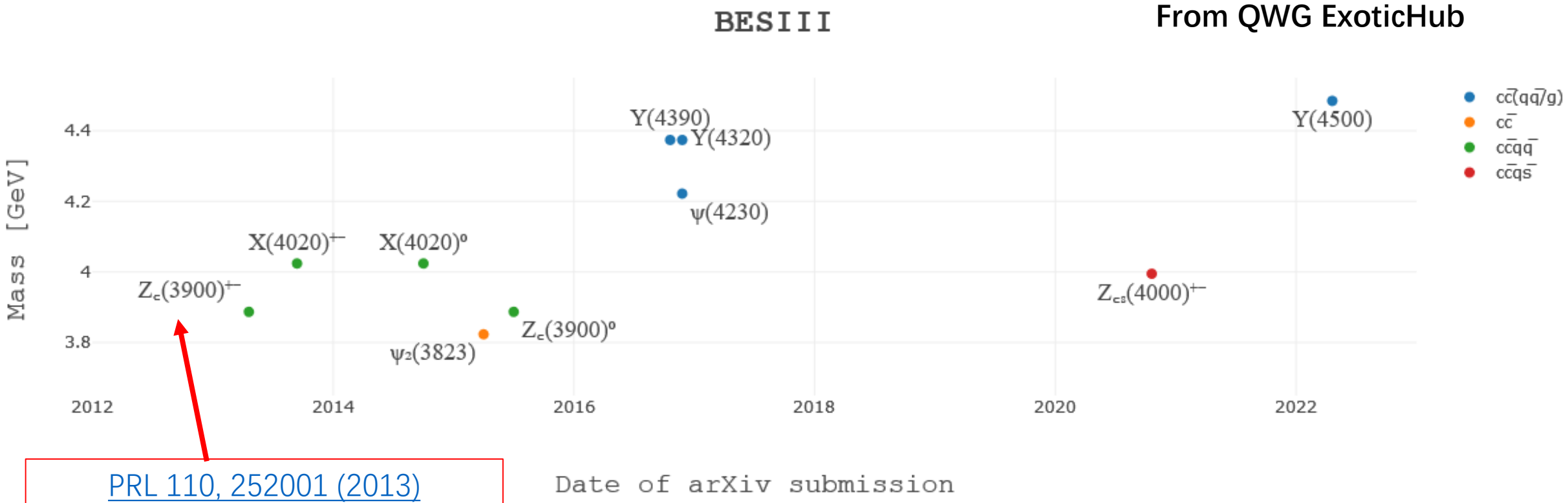
- Below charm threshold
  - 2.7B $\psi(2S)$ sample
  - Transitions from $\psi(2S)$



- Above charm threshold
  - $20\ fb^{-1}$ collision data @ 3.773 GeV
  - $22\ fb^{-1}$ scan data above 4 GeV
  - Line shapes of cross -sections for Y, whose (radiative & hadronic) transitions for X and Z



Previous discovered



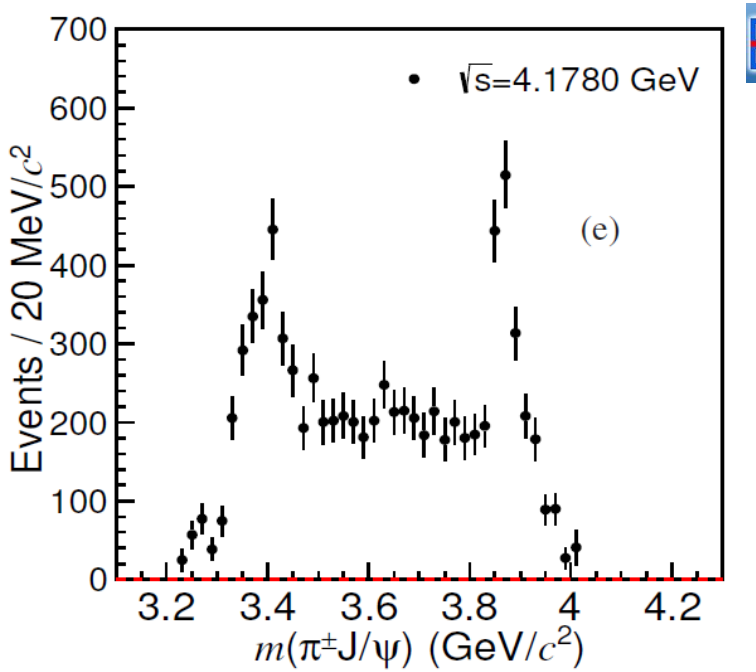
PRL 110, 252001 (2013)
Cited **1209** times till Aug.12 2025
(counted by Inspire)

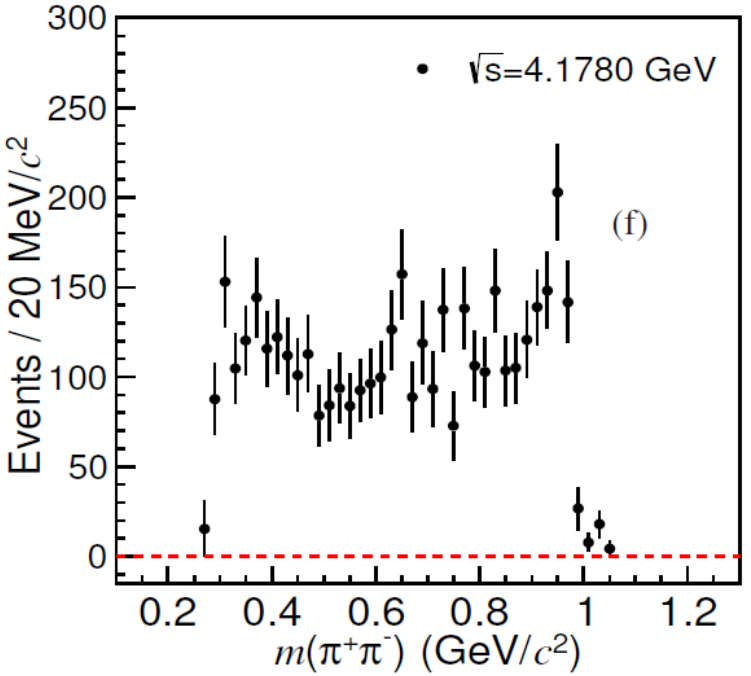
BESIII has published about 120 XYZ relevant papers till Aug. 2025.

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

arXiv:2505.13222

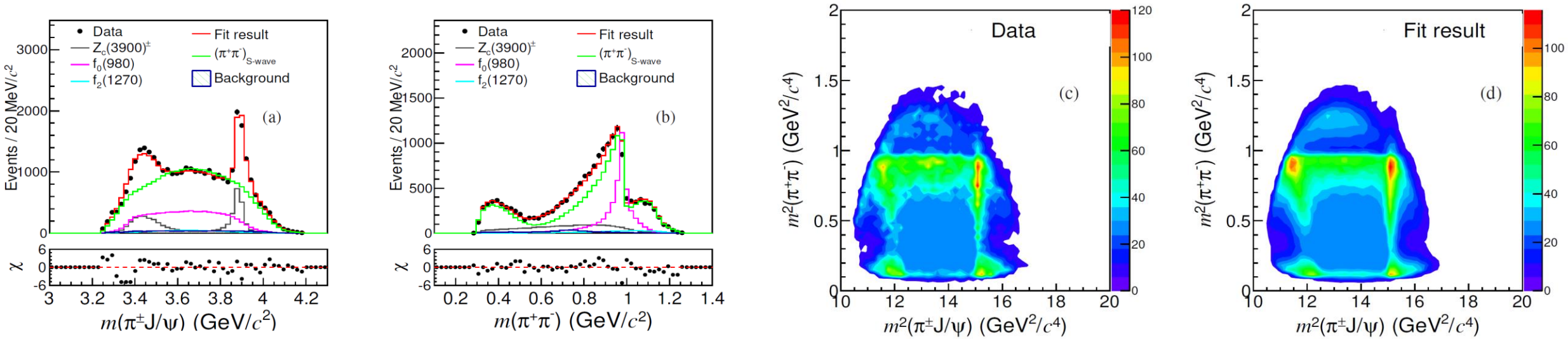
- $Z_c^{\pm}(3900)$ ($T_{c\bar{c}1}(3900)$)
  - Discovered in $J/\psi\pi$ (by BESIII and Belle) and confirmed in $D\bar{D}^*$ and $\eta_c\rho$
  - Its isospin (neutral) partner has been found also
  - With at least **four quark** component
  - May be strongly correlated to $Y(4230)$
- Data sample: $\sqrt{s} = 4.13 - 4.36$ GeV, 12 fb^{-1}, 17 points
- Final states: $\pi^+\pi^- l^+ l^-$,
- Preliminary selection criteria are same to previous published paper, BDT suppress backgrounds, 5C kinematic fit (4C+constraint on J/ψ)





- PWA: helicity-covariant method
- $\pi^+ Z_c^-(3900)$, $f_j J/\psi$ ($f_j = f_0(500), f_0(980), f_0(1370), f_2(1270)$)
  - BW or K-matrix parametrizations

arXiv:2505.13222



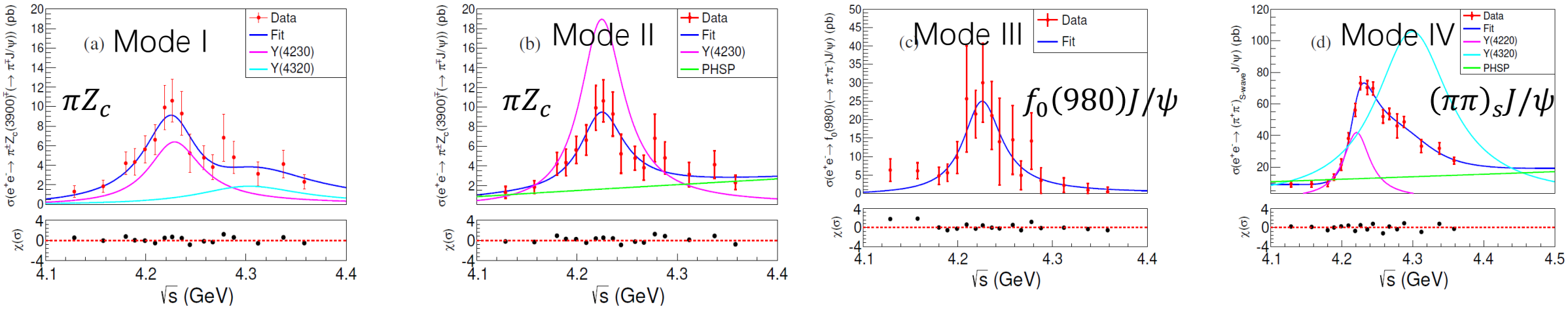
Summed all data samples

mass and width of the $Z_c(3900)^{\pm}$ are determined to be $3884.6 \pm 0.7 \pm 3.3$ MeV/c^2 and $37.2 \pm 1.3 \pm 6.6$ MeV,

- Fit to cross-sections of $e^+e^- \to \pi Z_c, f_0(980)J/\psi, (\pi\pi)_s J/\psi$
- Mode I: 2BW, II: BW+PHSP, III: 1BW, IV: 2BW+PHSP

Mass and width of Y(4230): $4225.8 \pm 4.2 \pm 3.1\ \mathrm{MeV}/c^2$ and $55.3 \pm 9.5 \pm 11.1\ \mathrm{MeV}$

arXiv:2505.13222



Process	$(\Gamma_{ee}\mathcal{B})_1$	R_1	$(\Gamma_{ee}\mathcal{B})_2$	R_2	$(\Gamma_{ee}\mathcal{B})_3$	R_3
$\pi^\pm Z(3900)^\mp$	1.1 ± 0.2	0.4 ± 0.5	0.2 ± 0.1	0.8 ± 1.3	0.2 ± 0.1	3.6 ± 2.4
$f_0(980)J/\psi$	3.4 ± 0.5	1.0 ± 0.4	0.4 ± 0.2	1.5 ± 1.9	0.5 ± 0.3	3.3 ± 2.7
$(\pi^+\pi^-)S_{\mathrm{wave}}J/\psi$	1.3 ± 0.1	0.4 ± 0.3	0.2 ± 0.1	0.8 ± 1.3	2.0 ± 0.2	7.6 ± 1.0

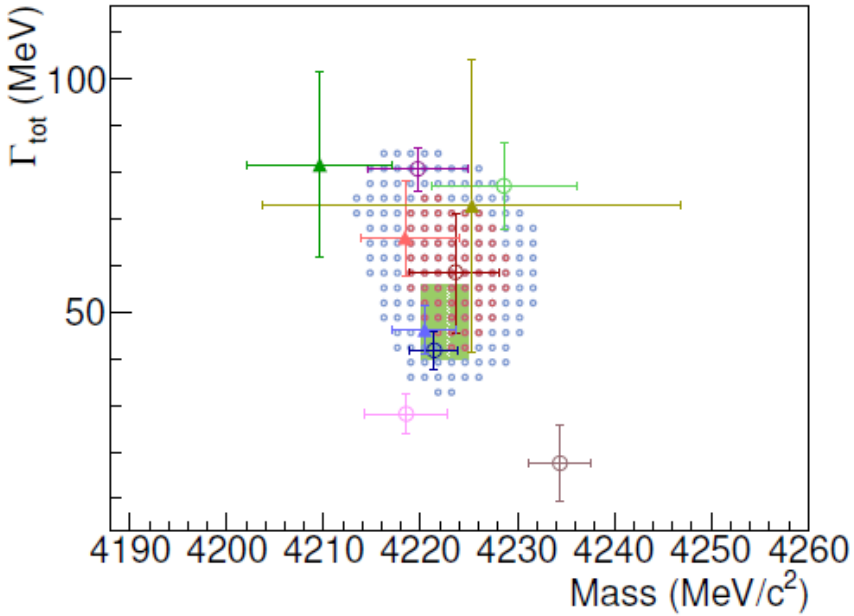
three solutions

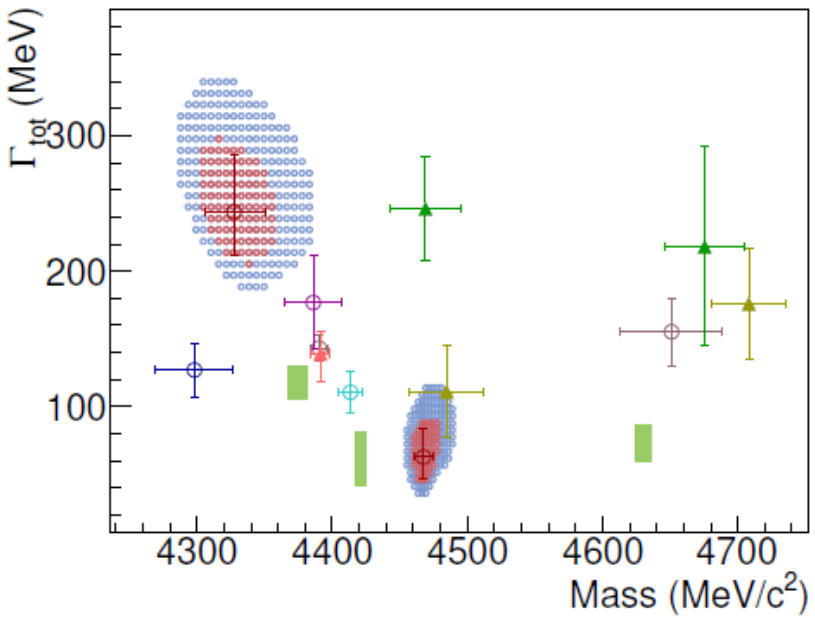
"R_n" are the ratios of $(\Gamma_{ee}\mathcal{B})_{Y(4320)}/(\Gamma_{ee}\mathcal{B})_{Y(4220)}$

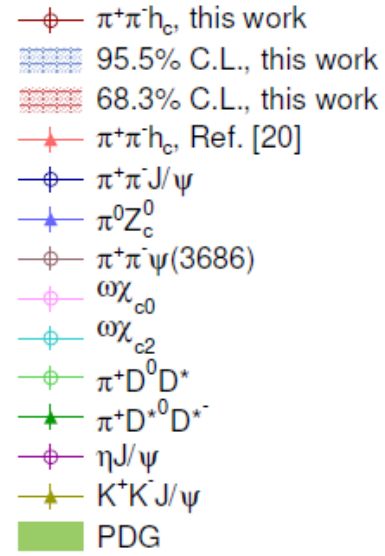
Cross sections of $e^+e^- \to \pi^+\pi^- h_c$

- Vector charmonium-(like) states are overpopulated than the predictions by the potential model

PRL 135, 071901 (2025)



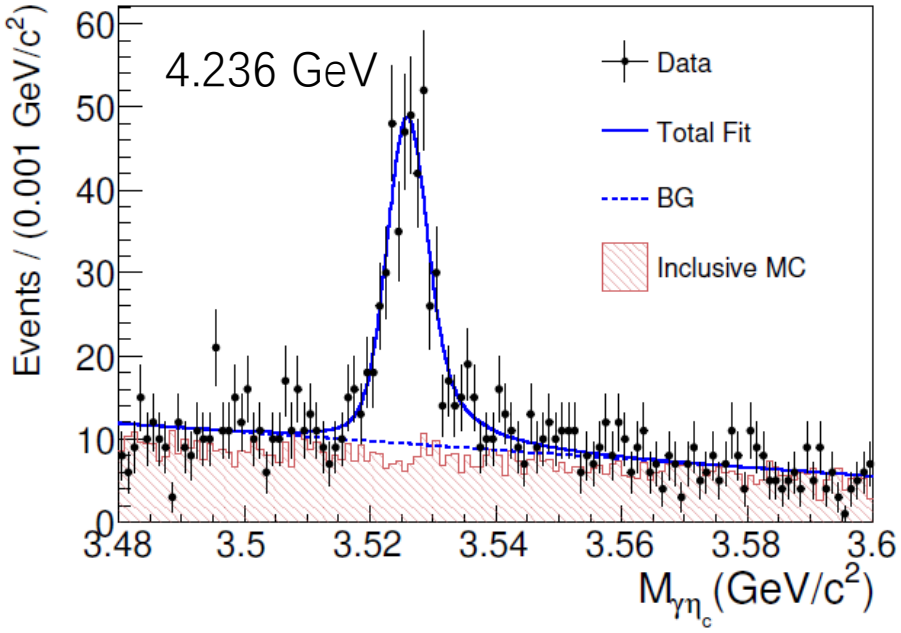




- Data samples: $\sqrt{s} = 4.01 - 4.95$ GeV, $22.2\ fb^{-1}$, 59 points

PRL 135, 071901 (2025)

In this study, the h_c is reconstructed via its electric-dipole transition $h_c \to \gamma\eta_c$ with $\eta_c \to X_i$, where X_i signifies 16 exclusive hadronic final states: $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-p\bar{p}$, $3(\pi^+\pi^-)$, $2(\pi^+\pi^-)K^+K^-$, $K_S^0K^\pm\pi^\mp$, $K_S^0K^\pm\pi^\mp\pi^+\pi^-$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K^+K^-\eta$, $\pi^+\pi^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-\pi^0)$. The K_S^0 is reconstructed using its decay to $\pi^+\pi^-$, while π^0 and η are reconstructed through their $\gamma\gamma$ final state.



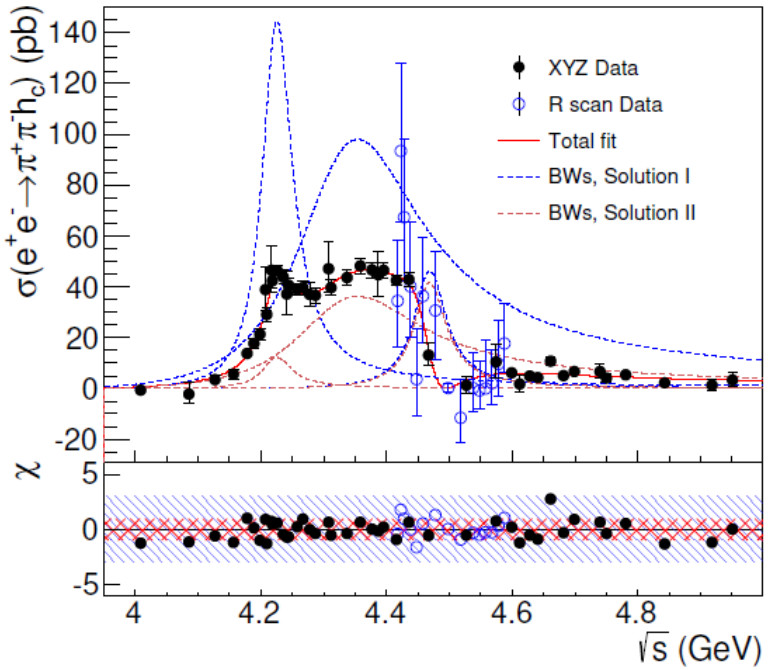
Signal events yield: unbinned maximum likelihood fit
- XYZ-I (large statistics): simultaneous fit
- XYZ-II (medium statistics): summed over fit
- R-scan (least statistics): summed over fit with background shape fixed

PRL 135, 071901 (2025)

$$\frac{N^{\rm obs}}{\mathcal{L}\cdot(1+\delta)\cdot(1/|1-\Pi|^2)\cdot\mathcal{B}(h_c\to\gamma\eta_c)\cdot\Sigma_{i=1}^{16}\epsilon_i\mathcal{B}(\eta_c\to X_i)}$$

$$|BW_1(\sqrt{s})+e^{i\phi_2}BW_2(\sqrt{s})+e^{i\phi_3}BW_3(\sqrt{s})|^2$$

$$\frac{M_k}{\sqrt{s}}\cdot\frac{\sqrt{12\pi(\Gamma_{ee}\mathcal{B}(R_k\to\pi^+\pi^-h_c))_k\Gamma_k}}{s-M_k^2+iM_k\Gamma_k}\cdot\sqrt{\frac{PS(\sqrt{s})}{PS(M_k)}}$$



Two solutions are found

Parameter	R_1	R_2	R_3 $>5\sigma$
M (MeV/c^2)	$4223.6^{+3.6+2.6}_{-3.7-2.9}$	$4327.4^{+20.1+10.7}_{-18.8-9.3}$	$4467.4^{+7.2+3.2}_{-5.4-2.7}$
Γ (MeV)	$58.5^{+10.8+6.7}_{-11.4-6.5}$	$244.1^{+34.0+24.2}_{-27.1-18.3}$	$62.8^{+19.2+9.9}_{-14.4-7.0}$
$\Gamma_{ee}\cdot\mathcal{B}(R\to\pi^+\pi^-h_c)$ (eV)	$10.2^{+1.2+1.4}_{-1.5-1.4}$ $(0.9^{+0.4+0.3}_{-0.4-0.2})$	$29.1^{+5.7+4.4}_{-3.9-3.4}$ $(10.8^{+2.5+1.9}_{-1.8-1.5})$	$3.9^{+3.5+1.7}_{-1.7-0.5}$ $(3.5^{+3.0+1.5}_{-1.6-0.7})$
ϕ (rad)	–	$3.6^{+0.1+0.1}_{-0.1-0.1}$ $(0.7^{+0.3+0.2}_{-0.3-0.2})$	$0.7^{+0.3+0.1}_{-0.3-0.2}$ $(-2.2^{+0.3+0.2}_{-0.3-0.1})$

$\psi(4230)$

$\psi(4360)$?
Mass consistent
Width 100 MeV larger

$\psi(4500)$

Phys. Rev. D 112, 032002 (2025)

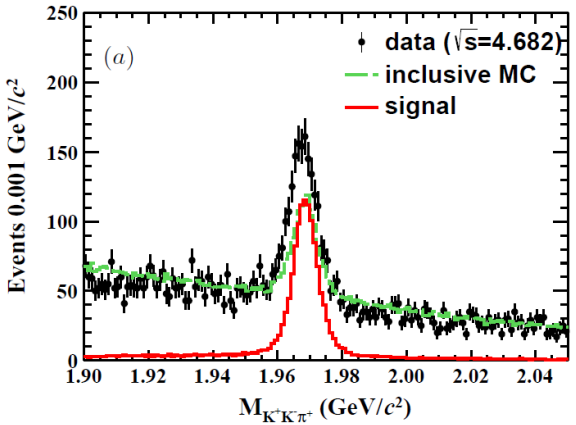
Search for $\mathbf{1^{-+}}$ states in $\boldsymbol{e^+e^- \to \gamma D_s^+ D_{s1}^-(2536)}$ + c.c.

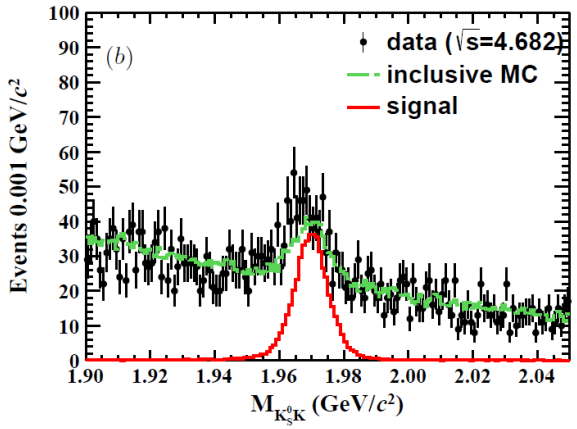
- $X(3872)$, $Y(4230)$ and $Z_c(3900)$ are exotic states.
- Some states are more exotic than the other exotic states.
  - Such as $J^{PC} = 0^{--}$, $even^{+-}$, odd^{-+}, cannot be $q\bar{q}$
  - Light section: $\pi_1(1400)$, $\pi_1(1600)$, $\eta_1(1855)$ with $J^{PC} = 1^{-+}$
- Q. Wang, Phys. Rev. D 89, 114013(2014) predicts 1^{-+} molecule state $\bar{D}D_1(2420)$
- Extend to D meson with strange quark, $D_s^+ D_{s1}^-(2536)$
- Data sample: $\sqrt{s} = 4.61\ -4.95$ GeV, $5.8\ fb^{-1}$

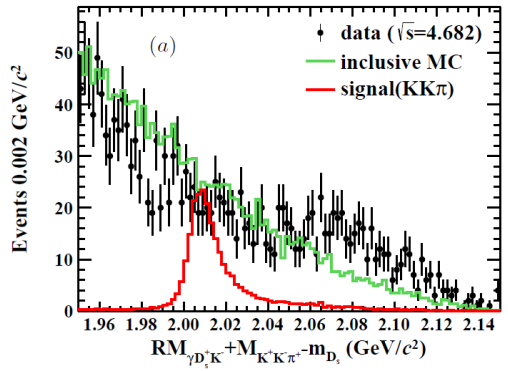
Phys. Rev. D 112, 032002 (2025)

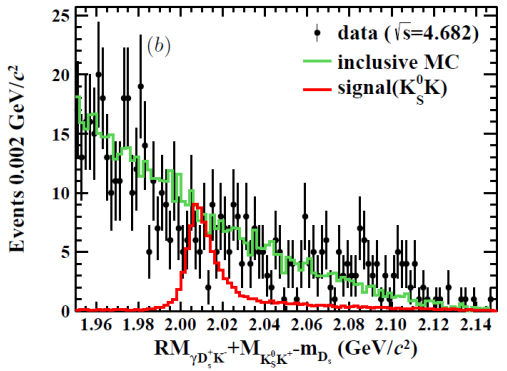
Search for $\mathbf{1^{-+}}$ states in $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536)$ + c.c.

- Partial reconstruction:
  - $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536)$, $D_s^+ \to K^+K^-\pi^+$, $D_{s1}^-(2536) \to K^-\bar{D}^{*0}$
  - $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536)$, $D_s^+ \to K_s(\pi^+\pi^-)K^+$, $D_{s1}^-(2536) \to K^-\bar{D}^{*0}$







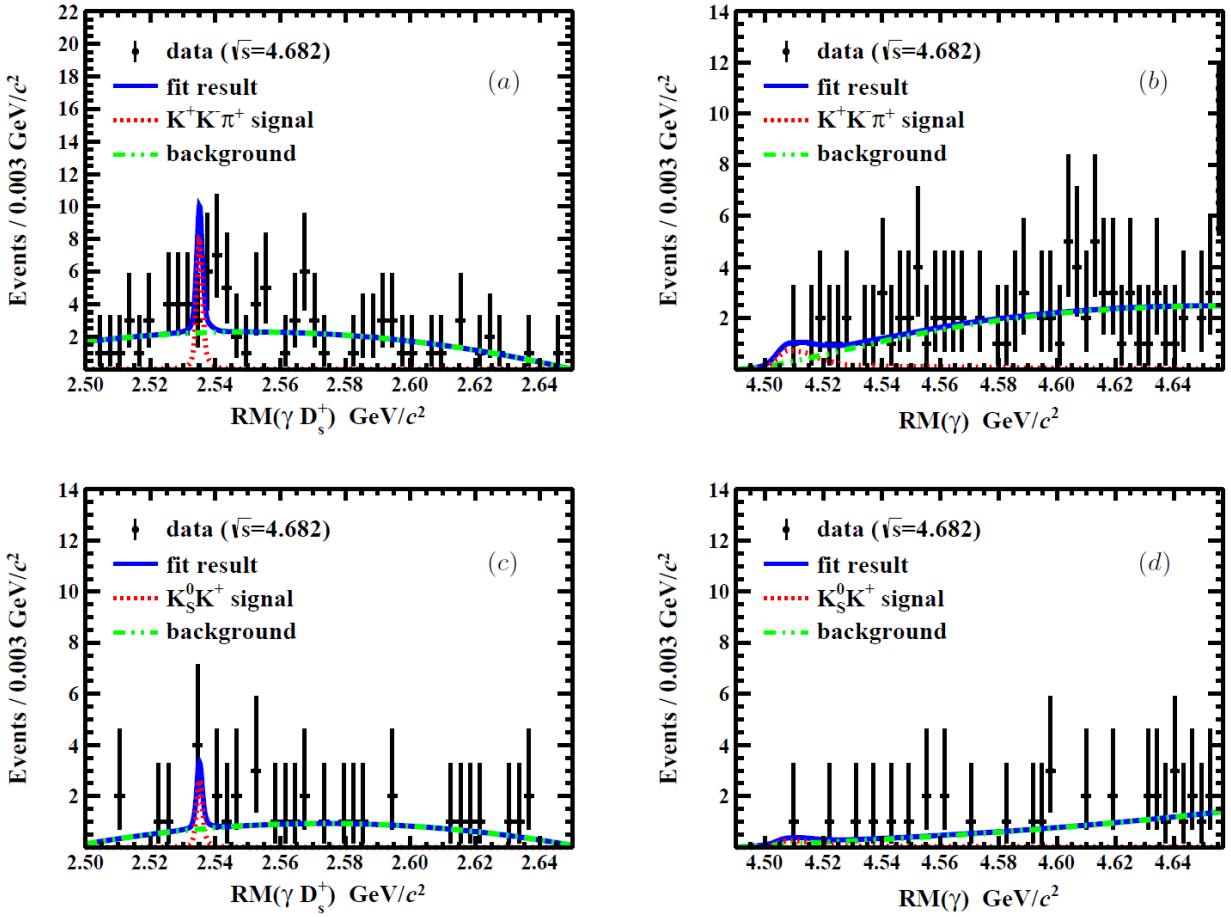


Clear D_s are observed, but no significant $\bar{D}^{*0}$

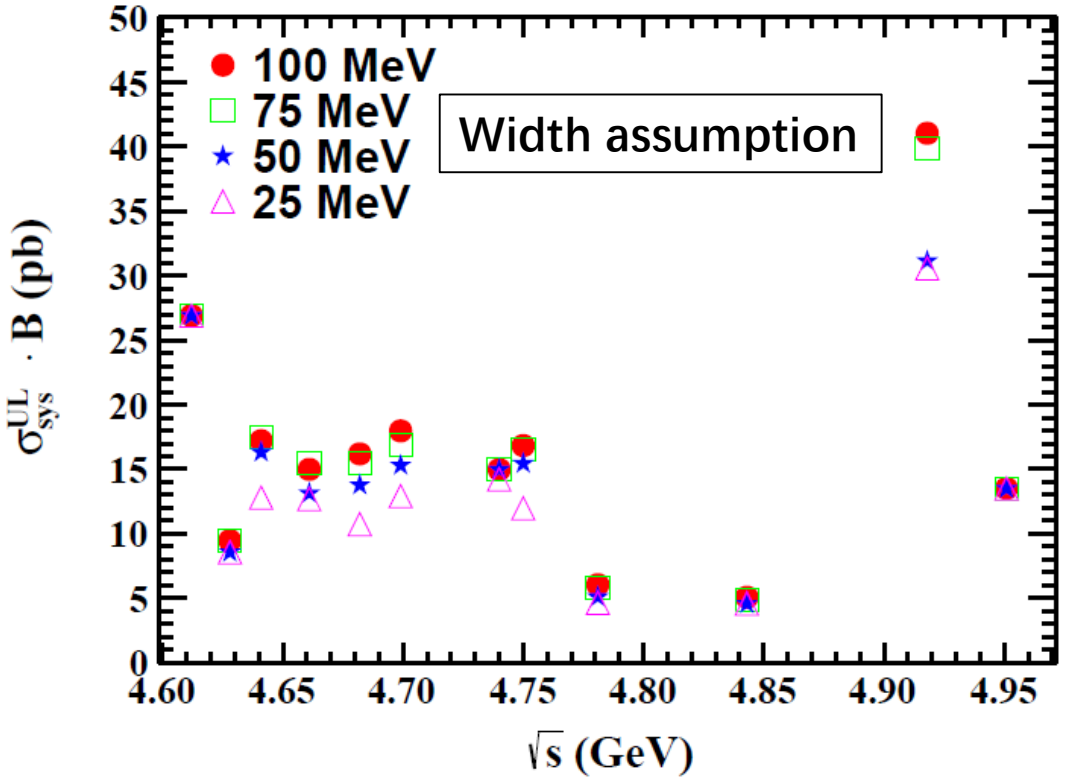
Phys. Rev. D 112, 032002 (2025)

Search for 1^{-+} states in $e^+e^- \to \gamma D_s^+ D_{s1}^-(2536)$ + c.c.

Unbinned two dimensional simultaneous fit



$$\sigma^{UL} \cdot \mathcal{B} = \frac{N^{UL}_{KK\pi}}{\mathcal{L}_{int} \cdot (1+\delta) \cdot \frac{1}{|1-\Pi|^2} \cdot \epsilon_{KK\pi} \cdot \mathcal{B}_1 \cdot \mathcal{B}_2}$$

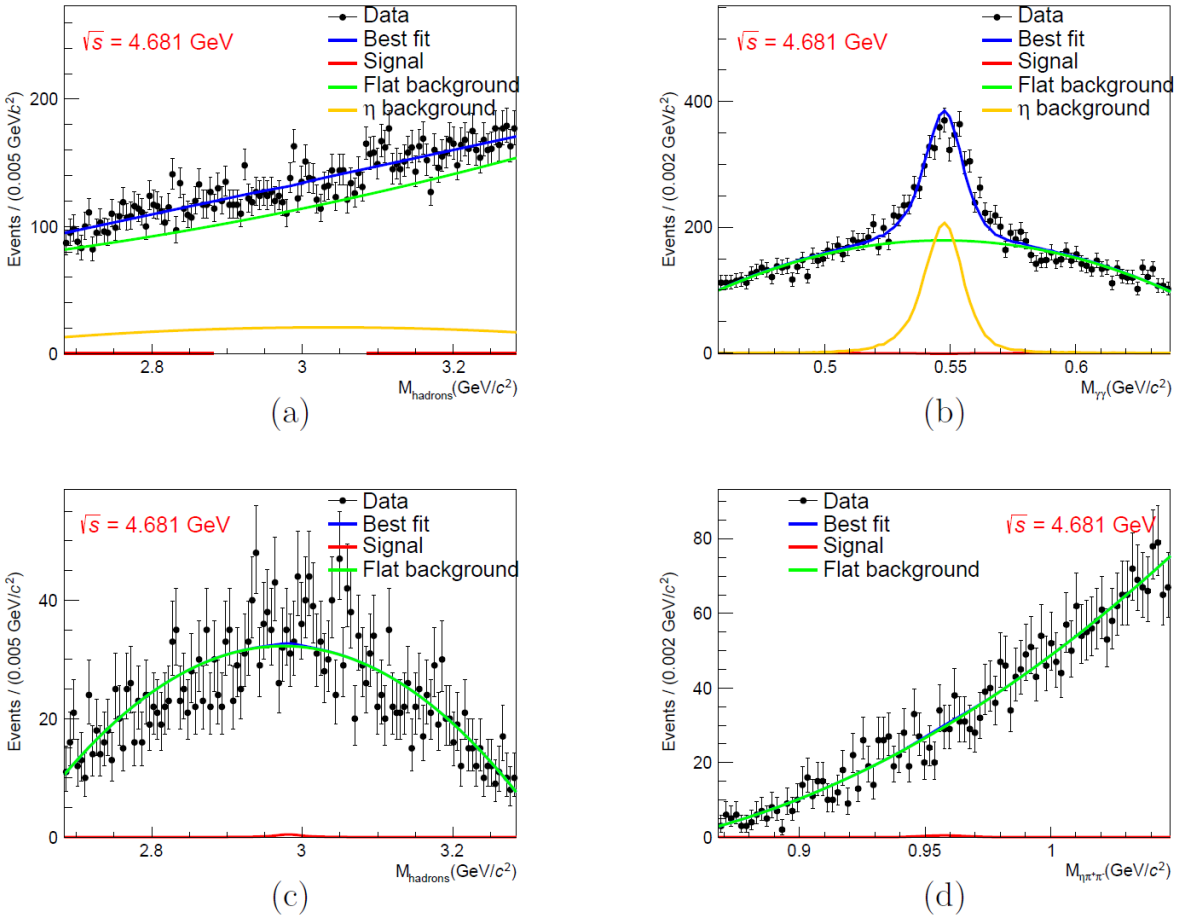


Typically 15 pb around 4.68 GeV

Search for 1^{-+} states in $e^+e^- \to \gamma\eta\eta_c$ and $\gamma\eta'\eta_c$

- Analogy to $\eta_1(1855) \to \eta\eta'$, possible $\eta_{c1} \to \eta^{(\prime)}\eta_c$
- X.-K. Dong, etc. Phys. Rev. D 101, 076003 (2020) and C. Shi, etc. Phys.Rev.D 109, 094513 (2024) predict 1^{-+} charmonium-like hybrid
- Data sample: $\sqrt{s} = 4.26 - 4.68$ GeV, $10.6\ fb^{-1}$
- No obvious signal, unbinned two dimensional maximum likelihood fit

To select candidate events for $e^+e^- \to \gamma\eta^{(\prime)}\eta_c$, the η' is reconstructed through the final states of $\eta\pi^+\pi^-$, the η_c is reconstructed through 16 hadronic final states: $p\bar{p}$, $2(\pi^+\pi^-)$, $2(K^+K^-)$, $K^+K^-\pi^+\pi^-$, $p\bar{p}\pi^+\pi^-$, $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K^+K^-\pi^0$, $p\bar{p}\pi^0$, $K^0_SK^\pm\pi^\mp$, $K^0_SK^\pm\pi^\mp\pi^\pm\pi^\mp$, $\pi^+\pi^-\eta$, $K^+K^-\eta$, $2(\pi^+\pi^-)\eta$, $\pi^+\pi^-\pi^0\pi^0$, and $2(\pi^+\pi^-)\pi^0\pi^0$, in which K^0_S is reconstructed from its $\pi^+\pi^-$ decay, π^0 and η from their $\gamma\gamma$ final state.



Phys. Rev. D 111, 112007 (2025)

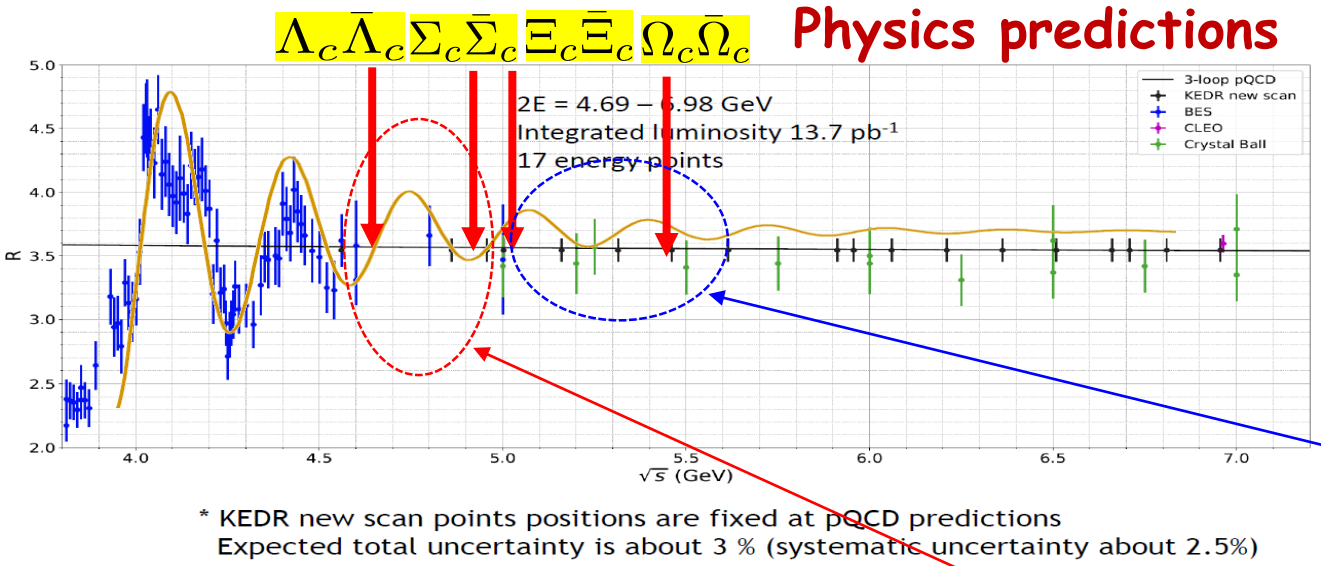
Search for 1^{-+} states in $e^+e^- \to \gamma\eta\eta_c$ and $\gamma\eta'\eta_c$

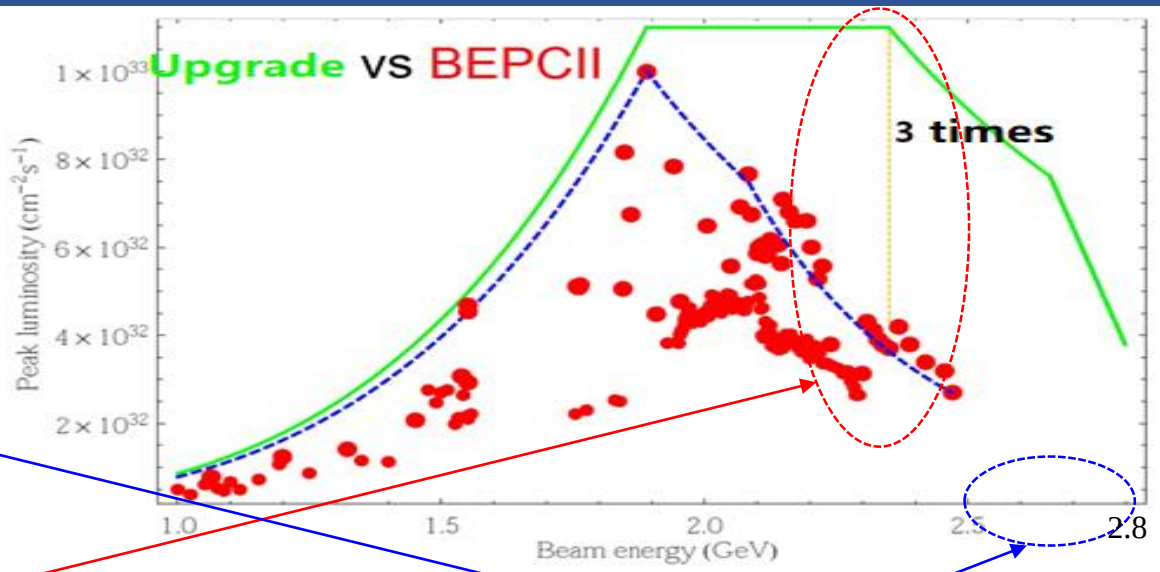
Phys. Rev. D 111, 112007 (2025)

$\sqrt{s}$(GeV)	$\mathcal{L}$(pb^{-1})	$e^+e^- \to \gamma\eta\eta_c$						$e^+e^- \to \gamma\eta'\eta_c$					
		$1+\delta$	$\frac{1}{\lvert 1-\Pi\rvert^2}$	$N_{\rm UL}^{\rm obs}$	$\sum_i(\mathcal{B}_i\epsilon_i)(\%)$	$\sigma_{\rm UL}^{\rm Born}$(pb)	$\mathcal{S}(\sigma)$	$1+\delta$	$\frac{1}{\lvert 1-\Pi\rvert^2}$	$N_{\rm UL}^{\rm obs}$	$\sum_i(\mathcal{B}_i\epsilon_i)(\%)$	$\sigma_{\rm UL}^{\rm Born}$(pb)	$\mathcal{S}(\sigma)$
4.258	828.4	0.86	1.05	76.8	0.38	27.3	0.1	0.85	1.05	65.8	0.17	51.2	2.8
4.267	531.1	0.86	1.05	62.3	0.37	35.3	0.1	0.85	1.05	45.6	0.17	56.4	1.5
4.278	175.7	0.86	1.05	28.2	0.36	49.1	2.2	0.85	1.05	28.3	0.16	110.1	1.9
4.288	502.4	0.86	1.05	30.6	0.37	18.5	0.6	0.86	1.05	33.4	0.17	44.5	2.5
4.308	45.1	0.85	1.05	36.2	0.37	240.8	2.5	0.84	1.05	12.6	0.18	178.9	1.7
4.312	501.2	0.85	1.05	48.5	0.36	29.6	1.9	0.87	1.05	43.7	0.17	56.5	2.8
4.337	505.0	0.85	1.05	61.3	0.37	26.8	0.9	0.87	1.05	44.2	0.17	55.2	2.8
4.358	543.9	0.85	1.05	38.8	0.38	21.1	0.6	0.84	1.05	65.0	0.18	75.5	2.4
4.377	522.7	0.84	1.05	48.4	0.37	28.2	1.5	0.86	1.05	40.2	0.18	48.5	1.0
4.387	55.6	0.84	1.05	13.7	0.38	73.6	2.5	0.84	1.05	14.6	0.18	165.2	1.3
4.396	507.8	0.84	1.05	35.1	0.37	21.1	2.5	0.86	1.05	34.1	0.18	42.7	0.6
4.416	1043.9	0.83	1.05	45.2	0.37	13.2	0.1	0.84	1.05	70.9	0.18	41.9	2.3
4.436	569.9	0.83	1.05	91.3	0.38	49.3	1.1	0.85	1.05	32.4	0.18	35.3	1.1
4.467	111.1	0.82	1.05	27.5	0.38	77.1	0.8	0.82	1.05	13.7	0.18	79.3	0.9
4.527	112.1	0.81	1.05	60.0	0.38	38.9	2.0	0.81	1.05	16.2	0.19	90.0	1.0
4.574	48.9	0.79	1.05	24.1	0.38	179.7	1.5	0.79	1.05	12.6	0.20	158.7	0.4
4.600	586.9	0.78	1.05	60.6	0.38	32.7	2.4	0.78	1.05	17.4	0.20	18.4	0.9
4.611	103.65	0.77	1.05	24.0	0.38	78.5	0.7	0.77	1.05	12.9	0.20	78.3	0.1
4.628	521.53	0.77	1.05	77.6	0.38	48.8	1.3	0.77	1.05	27.4	0.20	33.7	1.2
4.641	551.65	0.76	1.05	28.7	0.38	17.3	2.2	0.76	1.05	25.1	0.20	28.8	0.2
4.661	529.43	0.75	1.05	55.9	0.38	35.4	1.2	0.75	1.05	29.0	0.20	34.4	1.5
4.681	1667.39	0.75	1.05	71.8	0.38	14.5	1.4	0.78	1.05	46.1	0.20	16.5	0.4

No significance reach 3σ. Upper limits are provided.

Overview of BEPCII upgrade project





BEPCII upgrade aims at: **Increase luminosity by a factor of 3** & **Increase beam energy to 2.8GeV**

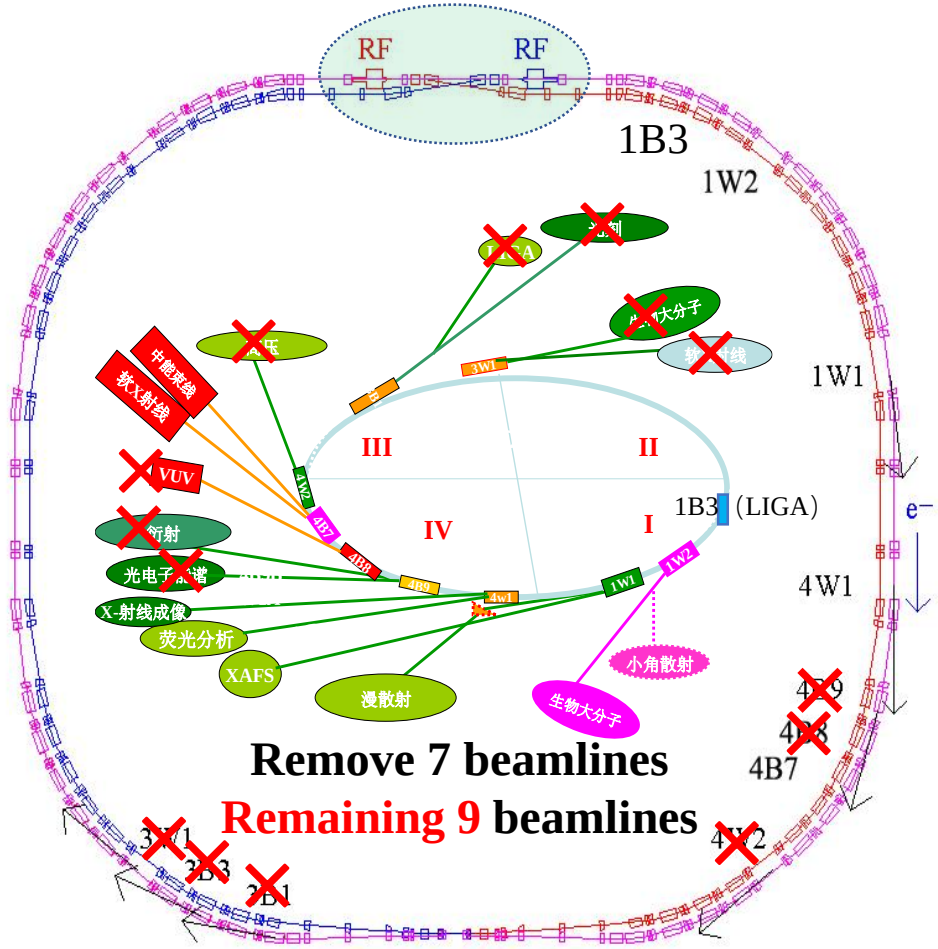
Timeline of BEPCII operation and its upgrade

- **2020** White Paper of BESIII
- **Jun. 2021** Feasibility Study Report
- ***Apr. 2022*** *Design Finished*
- **Jul. 2024** Shutdown for Installation
- BEPCII keep running
- Internal Review of Accelerator — **May. 2020**
- Project Approved — **Jul. 2021**
- Fabrication Finished — **Jun. 2024**
- Commissioning — **Jan. 2025**

Overview of BEPCII upgrade

Key Technologies: Double beam power & Optics upgrade & Higher gradient of magnets

	BEPCII @ 2.35GeV	BEPCII-U @ 2.35GeV	BEPCII-U @ 2.8GeV
L $[10^{32}cm^{-2}s^{-1}]$	**3.5**	**11**	**3.7**
β_y^* [cm]	**1.5**	**1.35**	**3.0**
Beam current [mA]	400	900	450
SR Power [kW]	**110**	**250**	**250**
$\xi_{y,lum}$	0.029	0.033	0.043
Emittance [nmrad]	**147**	**152**	**200**
Couping [%]	**0.53**	**0.35**	**0.5**
Bucket Height	0.0069	0.011	0.009
$\sigma_{z,0}$ [cm]	1.54	1.07	1.4
σ_z [cm]	**1.69**	**1.22**	**1.6**
RF Voltage [MV]	**1.6**	**3.3**	**3.3**



Remove 7 beamlines

Remaining 9 beamlines

No dedicated SR operation, only parasitic SR experiments, 10 months/year BESIII time.

Status of BEPCII-U commissioning

BEPCII-U Operation plan

- Jul. 2024 – Dec. 2024 Summer shutdown for installation
- Jan. 2025 – Jul. 2025 Commissioning & Data taking @1.843GeV $\psi(3686)$
- Aug. 2025 Summer shutdown  We are here
- Sep. 2025 – Jul. 2026 Data taking @1.843GeV & 2.35GeV (project test)
- Aug. 2026 – Sep. 2026 Summer shutdown & LINAC final upgrade
- Oct. 2026 – Sep. 2028 Data taking within beam energy 2.1-2.5GeV
- Sep. 2028 – Jul. 2030 Data taking within beam energy 2.5-2.8GeV

C.H. Yu @ BESIII 2025 summer Col. meeting

Status of BEPCII-U commissioning

BEPCII-U Operation plan

- **Jul. 2024 – Dec. 2024** — **Summer shutdown for installation**
- **Jan. 2025 – Jul. 2025** — **Commissioning & Data taking @1.843GeV $\psi(3686)$**
- **Aug. 2025** — **Summer shutdown** ← We are here
- **Sep. 2025 – Jul. 2026** — **Data taking @1.843GeV & 2.35GeV (project test)**
- **Aug. 20**
- **Oct. 202**
- **Sep. 202**

■ **2025/26** (round 19) — allocation not final

BEPCII-U: demonstrate operation at high energy, show gain in luminosity

Run at 4680 MeV — start collecting $\Lambda_c^+\overline{\Lambda}_c^-$ sample (requested total of 9 fb^{-1})

Scans around $X(3872)$ and χ_{c2} (about one month each)

C.H. Yu @ BESIII 2025 summer Col. meeting

Summary

- The BESIII experiment has made crucial contributions to the study of exotic charmonium-like states, leveraging its unique data samples and excellent detector performance.
- Looking ahead, further exciting results are anticipated with increased statistics. These future studies are expected to enable the discovery of novel states, including those containing a strange quark component, and the application of refined techniques such as partial wave analysis and improved parameterization methods like the K-matrix approach. Additionally, research will focus on elucidating the correlations between charmonium-like states and their underlying nature. Collectively, these advances promise to deepen our understanding of non-perturbative strong interactions.

Thanks for your attention!

backup

BESIII has studied XYZ states via e^+e^- annihilation samples exclusively

- $\gamma\eta_c$, $\gamma\pi^0\eta_c$
- $\pi^+\pi^-\eta_c$
- $\pi^+\pi^-\pi^0\eta_c$, $\pi^+\pi^-\eta\eta_c$
- $\gamma\pi^+\pi^-J/\psi$, $\gamma\phi J/\psi$, $\gamma\omega J/\psi$, $\gamma\gamma J/\psi$
- $\pi^0 J/\psi$, **$\eta J/\psi$**, **$\eta' J/\psi$**
- **$\pi^+\pi^- J/\psi$**, **$\pi^0\pi^0 J/\psi$**, $\pi^0\eta J/\psi$, **$K^+K^- J/\psi$**, **$K^0_S K^0_S J/\psi$**,
- **$J/\psi X$**

- $\gamma\chi_{cJ}$, $\gamma\pi^+\pi^-\chi_{c1}$, $\gamma\pi^0\chi_{c1}$, $\pi^0\pi^0\chi_{c1,2}$
- **$\omega\chi_{cJ}$**, $\phi\chi_{cJ}$
- $\pi^+\pi^-\chi_{cJ}$
- ηh_c
- **$\pi^+\pi^- h_c$**, **$\pi^0\pi^0 h_c$**, $K^0_S K^0_S h_c$
- $\gamma\gamma\psi(2S)$,
- **$\eta\psi(2S)$**, $\eta'\psi(2S)$
- **$\pi+\pi-\psi(2S)$**, **$\pi^0\pi^0\psi(2S)$**, **$K^+K^-\psi(2S)$**, **$K^0_S K^0_S\psi(3686)$**
- **$\psi(2S)X$**

- $\pi^+\pi^-\psi(3770)$, $K^+K^-\psi(3770)$
- $\gamma X(3872)$, $\gamma\pi^0X(3872)$, $\omega X(3872)$, $\phi X(3872)$
- X(3872) lineshape
- $\gamma\gamma\psi_2(3823)$
- $\pi^+\pi^-\psi_2(3823)$, $\pi^0\pi^0\psi_2(3823)$

- Other channels, such as updated $\pi^0\pi^0\psi', \pi^0\pi^0h_c$ are on going