Universität Münster

Charmonium-like States at BESIII

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BESIII

DFG

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Graduiertenkolleg 2149
Research Training Group

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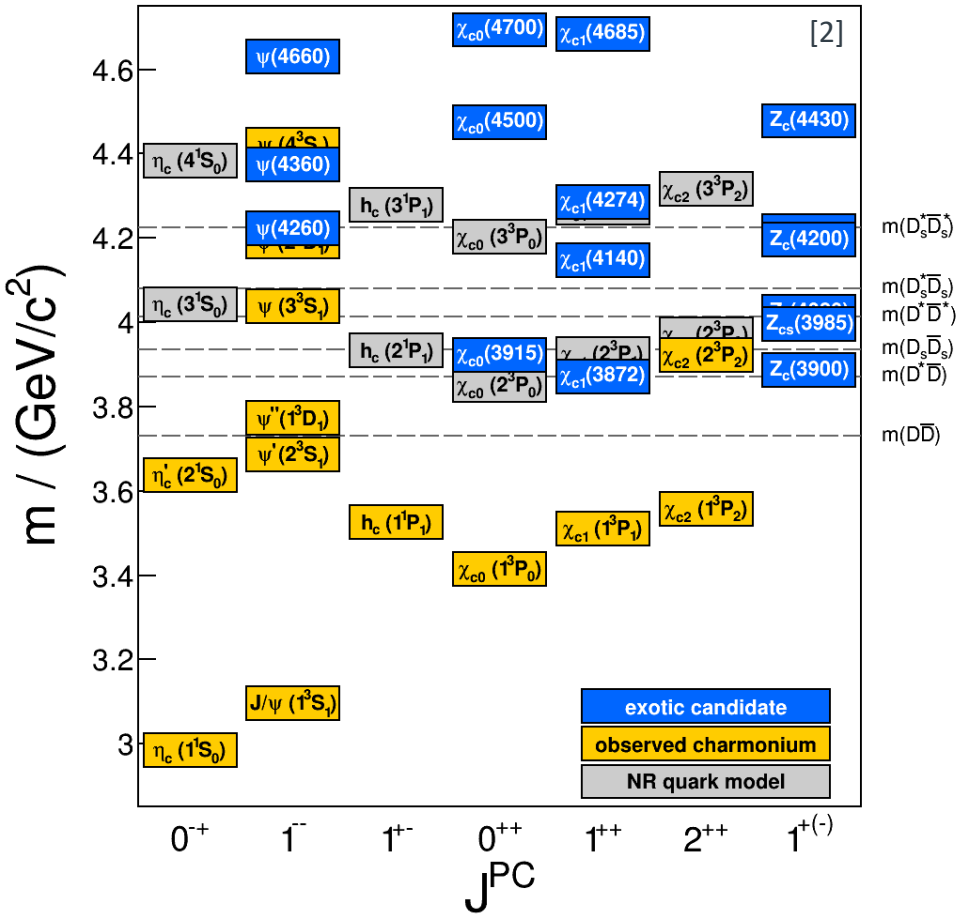
The Charmonium-like Spectrum

Charmonium states below the $D\bar{D}$ threshold and $J^{PC} = 1^{--}$ states are **well understood**

Still **missing states** which are predicted by a non-relativistic quark model[1]

Additional states with **unexpected properties**:

- Supernumerary 1^{--} states
- χ_{cJ} states with unusual decay behavior and/or width
- States with isospin and/or strangeness



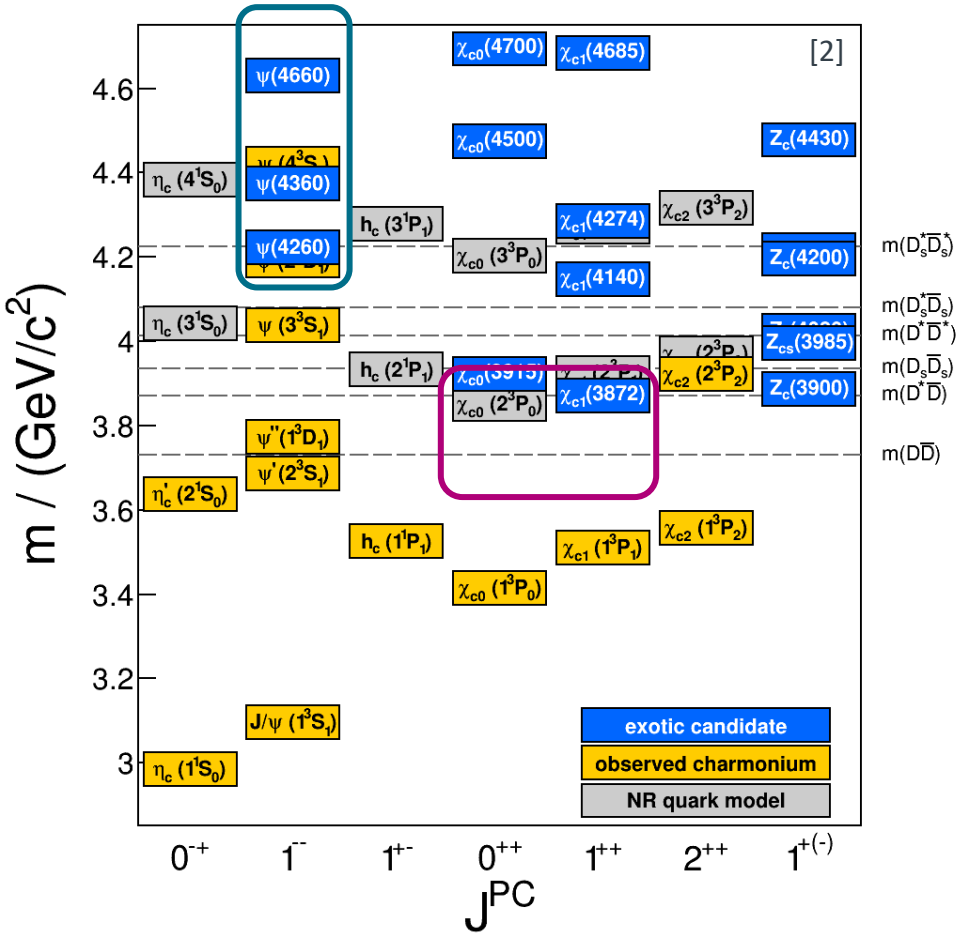
[1] PRD 72, 054026 (2005)
[2] Masses from PTEP 2022, 083C01

Outline

This talk will focus on recent BESIII analyses:

1. Search for Charmonium-like states with $J^{PC} = 1^{--}$ in
   - $e^+e^- \to D^{*0}D^{*-}\pi^+$ [PRL 130, 121901 (2023)]
   - $e^+e^- \to D_s^{*+}D_s^{*-}$ [PRL 131, 151903 (2023)]
2. Search for a scalar partner of the $\chi_{c1}(3872)$ in
   - $\psi(3770) \to \gamma\eta\eta'$
   - $\psi(3770) \to \gamma\pi^+\pi^- J/\psi$

[PRD 108, 052012 (2023)]



[2] Masses from PTEP 2022, 083C01

The BESIII Experiment

Beijing Spectrometer III at the Beijing Electron Positron Collider II at the Institute of High Energy Physics

τ-charm factory: $2.0\ \mathrm{GeV} \leq \sqrt{s} \leq 5.0\ \mathrm{GeV}$

Max. luminosity: $10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $\sqrt{s} = 3.77\ \mathrm{GeV}$

93% of 4π solid angle coverage

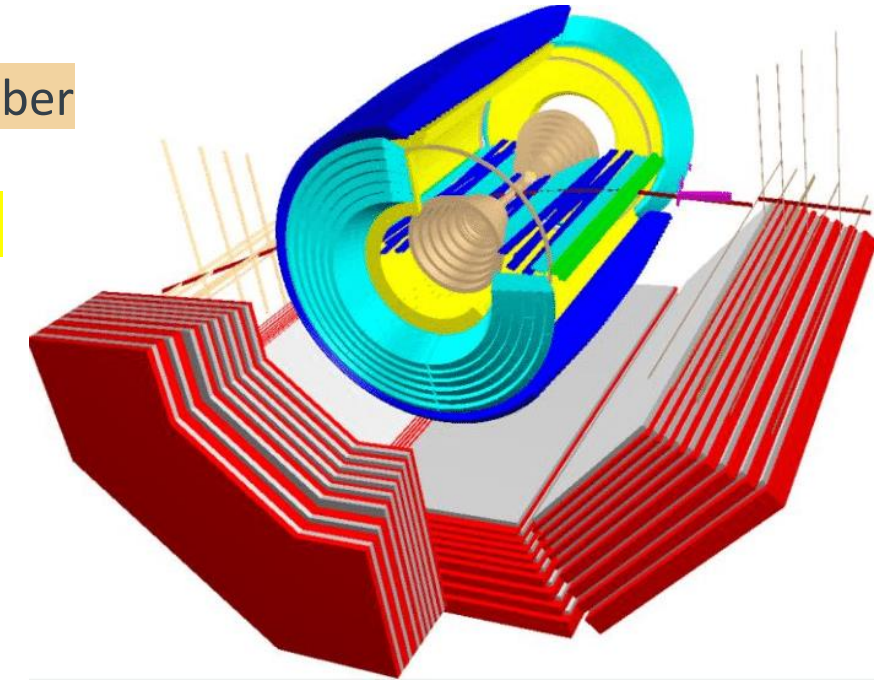
Multilayer Drift Chamber

Time-of-Flight System

EM Calorimeter

1T Solenoid Magnet

Muon Detector



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

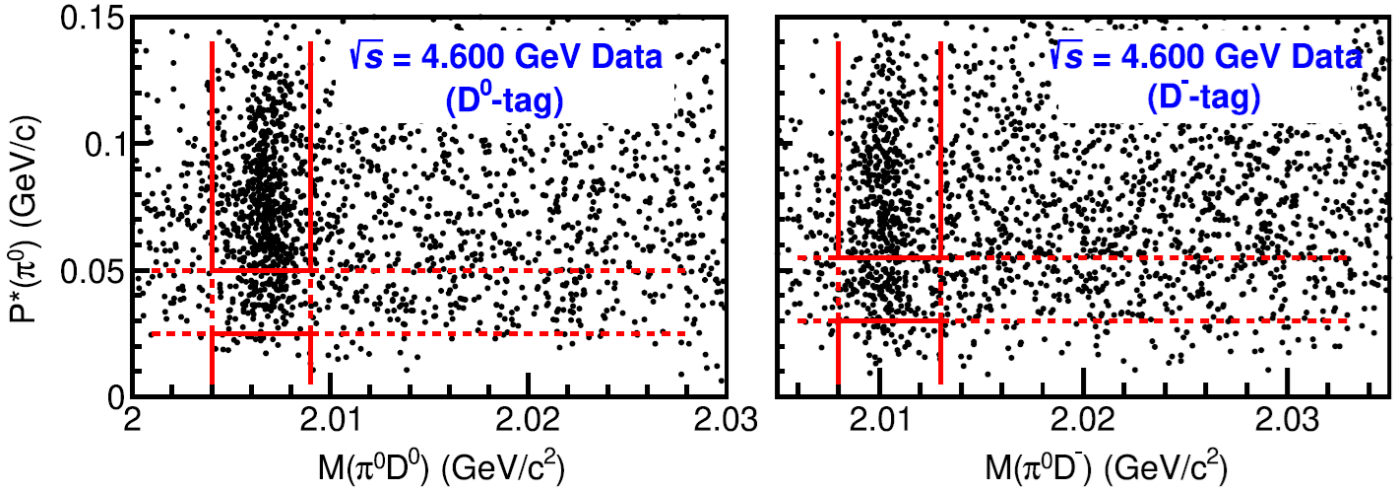
[PRL 130, 121901 (2023)]

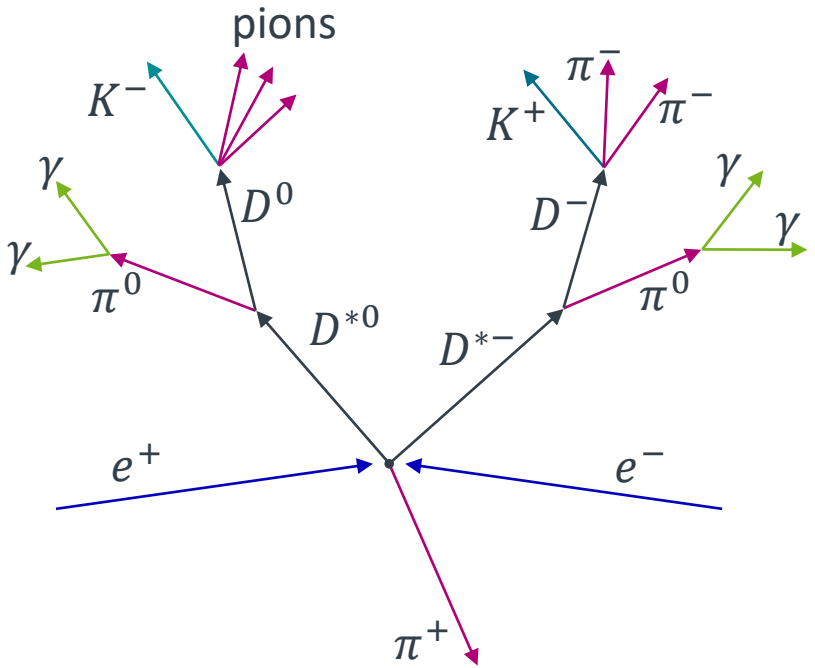
- Analysis of **86 data samples** with $4.19\ \text{GeV} \leq \sqrt{s} \leq 4.95\ \text{GeV}$ with $\mathcal{L}_{\text{int}} = 17.9\ \text{fb}^{-1}$
- Reconstruct **either D^{*0} or D^{*-}** and bachelor π^+
- Cut on the D^0/D^- and D^{*0}/D^{*-} candidate's invariant mass
- Kinematic constraints to assign π^0 to the D^{*0} or D^{*-}

$D^{*0} \to D^0\pi^0, D^{*-} \to D^-\pi^0$

$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$

$D^- \to K^+\pi^-\pi^-, \pi^0 \to \gamma\gamma$





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

[PRL 130, 121901 (2023)]

Simultaneous fit to the $D^{*0}\pi^+$ and $D^{*-}\pi^+$ recoil mass to get σ_{dressed}:

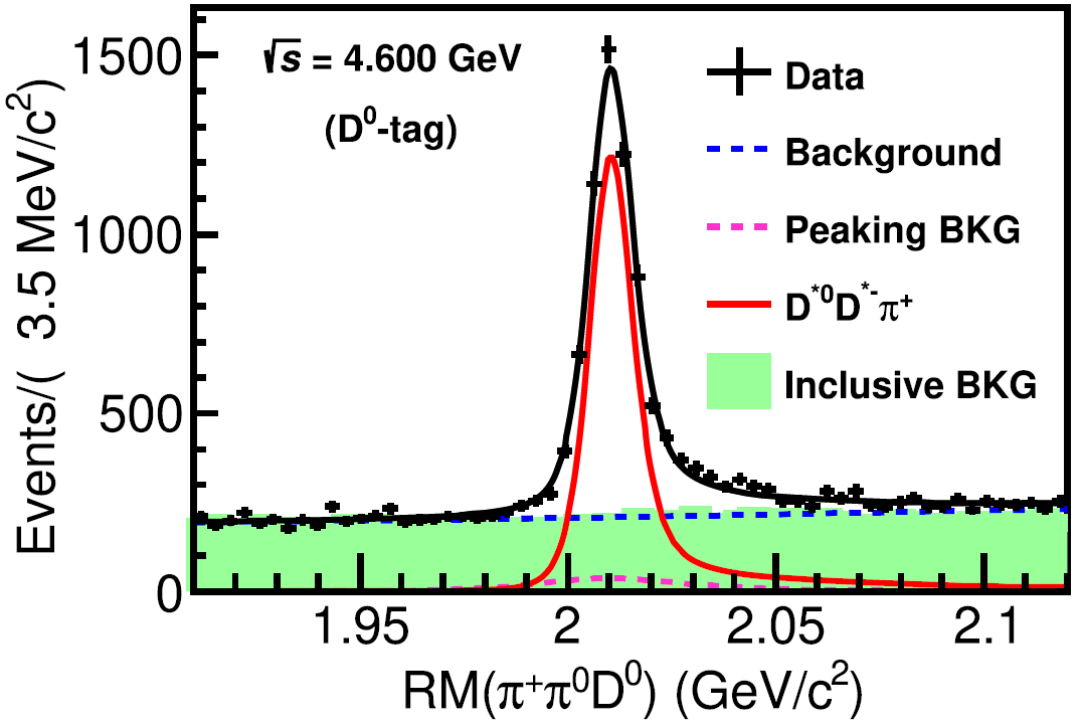
Smooth background described by second-order polynomial

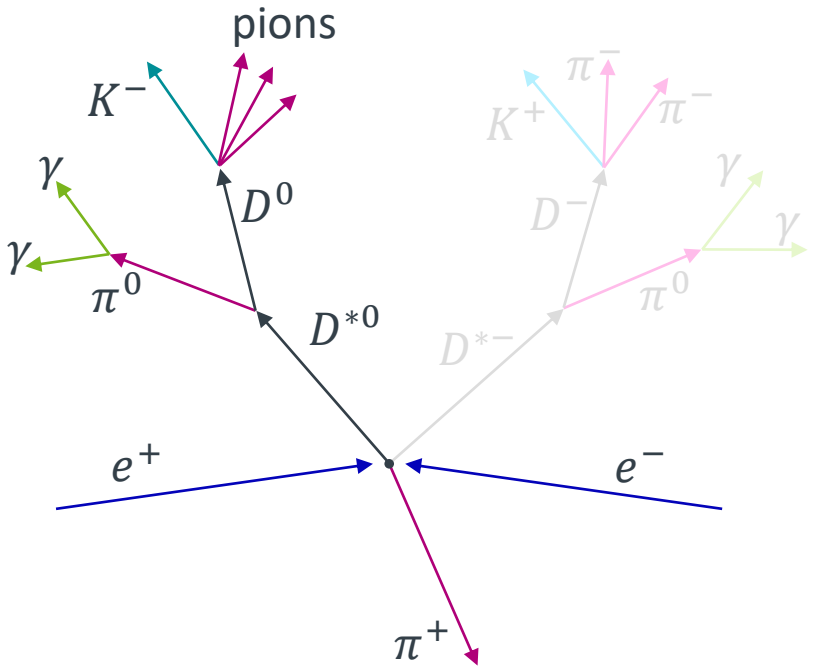
Signal and combinatorial peaking background line shape from MC

$D^{*0} \to D^0\pi^0$, $D^{*-} \to D^-\pi^0$

$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$

$D^- \to K^+\pi^-\pi^-$, $\pi^0 \to \gamma\gamma$





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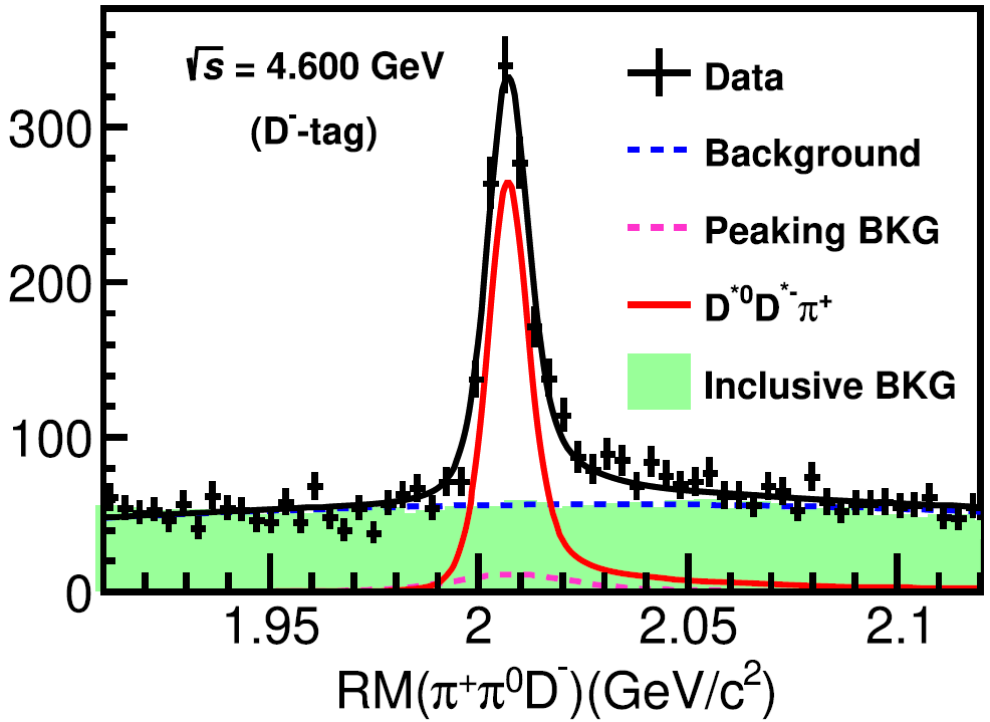
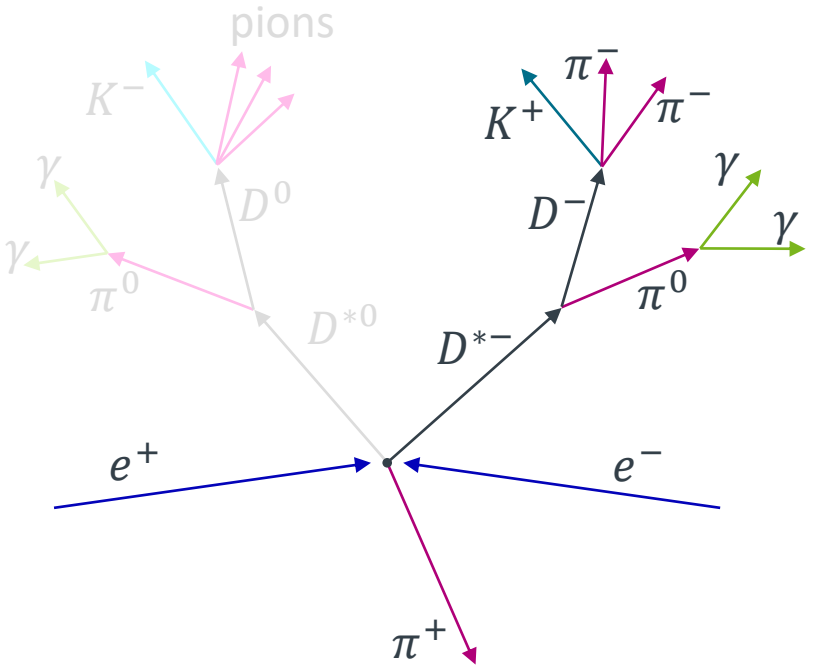




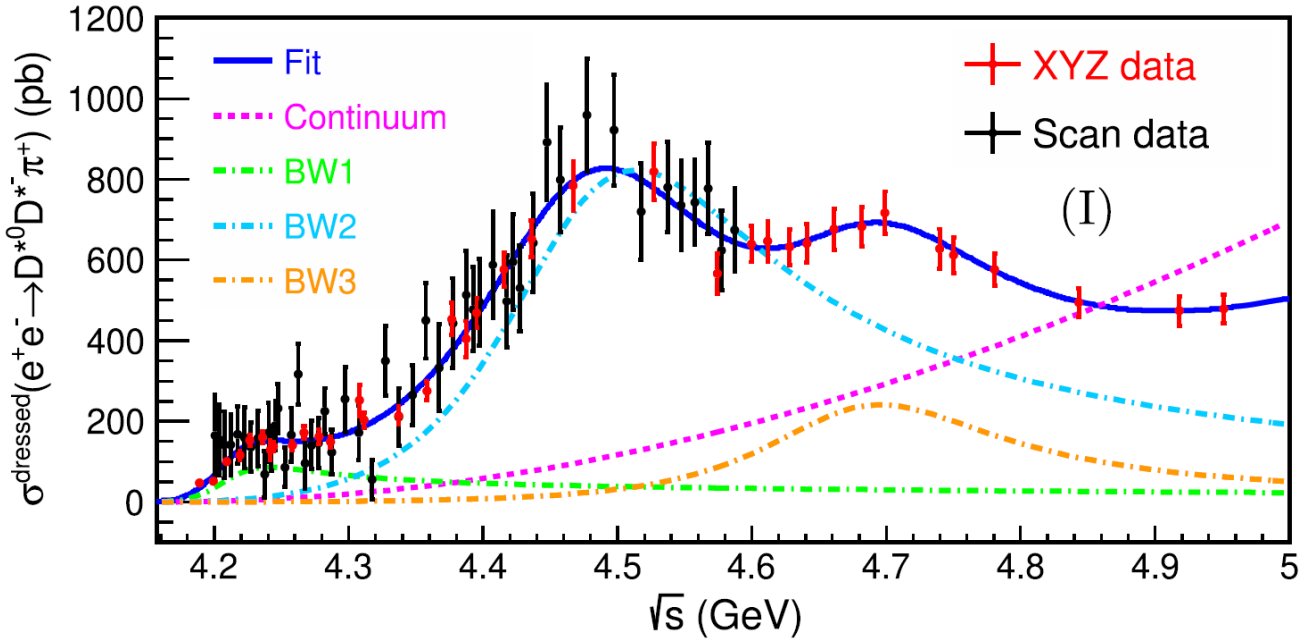
Analysis of $e^+e^- \to D^{*0}D^{*-}\pi^+$

[PRL 130, 121901 (2023)]

- **Dressed cross section** calculated via:

$$\sigma_{\text{dressed}} = \frac{N_D^{\text{obs}}}{\mathcal{L}_{\text{int}}\varepsilon_D\mathcal{B}_D(1+\delta_{\text{ISR}})}$$

- Cross section fitted with **coherent sum** of three Breit-Wigner amplitudes and PHSP term
- All resonance parameters (m_i, Γ_i and $\Gamma_i^{ee}\mathcal{B}_i$) and the relative phases (ϕ_i) **determined by the fit**
- Significance of third BW compared to two BW solution: $\mathbf{10.8\sigma}$
- **Eight solutions** with the same reduced χ^2, m_i and Γ_i, but different $\Gamma_i^{ee}B_i$ and ϕ_i



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

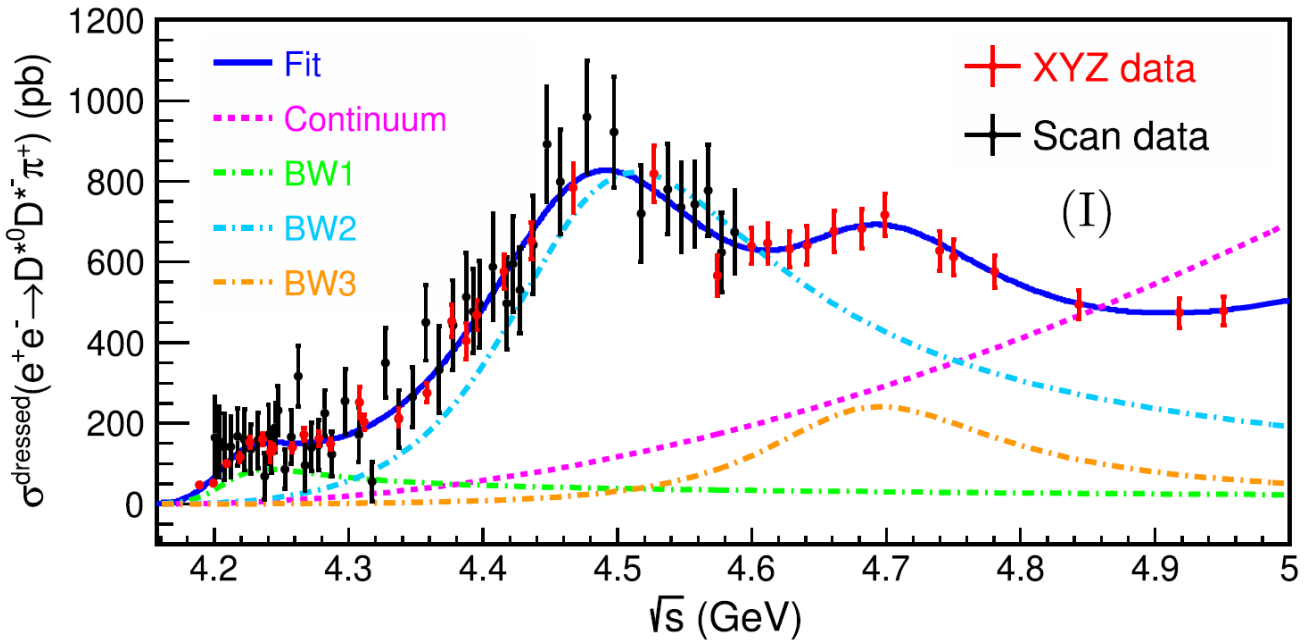
[PRL 130, 121901 (2023)]

Resulting resonance properties:

BW1: Compatible with the $\psi(4230)$[3]
Result on electronic width **disfavors hybrid interpretation**[4]

BW2: Compatible with the $\psi(4500)$ observed in $e^+e^- \to K^+K^-J/\psi$[5]
$\mathcal{B}(\psi \to D^*\bar{D}^*\pi)/\mathcal{B}(\psi \to K\bar{K}J/\psi) > 10^2$ is **inconsistent with tetraquark hypothesis**[6,7]

BW3: Compatible with the $\psi(4660)$ seen in $e^+e^- \to \pi^+\pi^-\psi(2S)$[8]
First observation in open charm decay



[3] AHEP 2018, 5428734
[4] CPC 40, 081002 (2016)
[5] CPC 46, 111002 (2022)
[6] PRD 73, 094510 (2006)
[7] PRD 107, 016001 (2023)
[8] PRD 104, 052012 (2021)

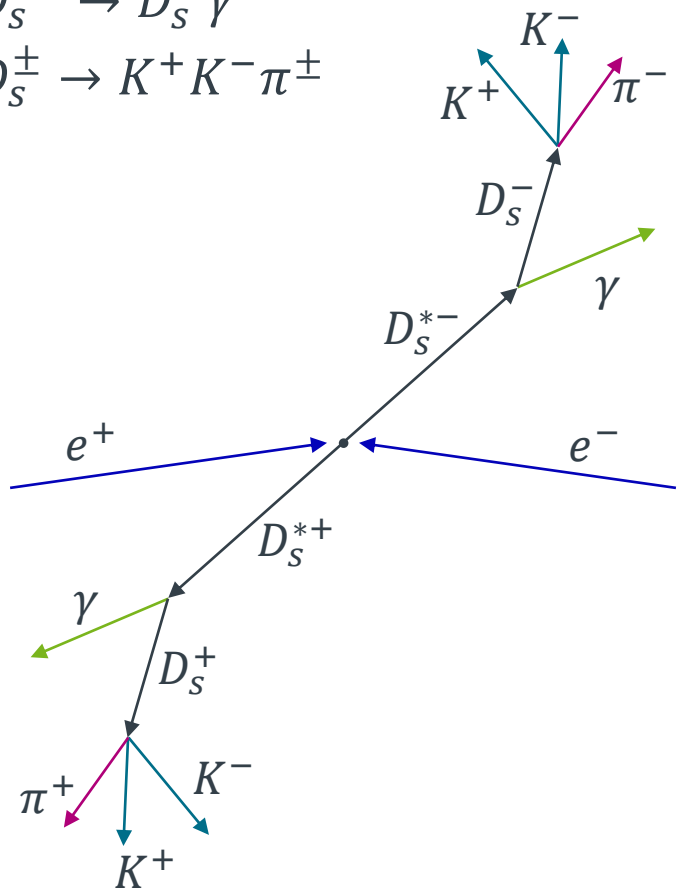
Analysis of $e^+e^- \to D_s^{*+}D_s^{*-}$

[PRL 131, 151903 (2023)]

- Analysis of **76 data samples** with $4.23\ \text{GeV} \leq \sqrt{s} \leq 4.95\ \text{GeV}$ with $\mathcal{L}_{\text{int}} = 15.7\ \text{fb}^{-1}$
- Reconstruct **either D_s^{*+} or D_s^{*-}**
- Cut on the $D_s^{\pm}$ invariant mass and on the $D_s^{*\mp}$ missing mass
- **Peaking background** from $e^+e^- \to \gamma_{\text{ISR}} D_s^{\pm} D_s^{*\mp}$ estimated from $e^+e^- \to D_s^{\pm} D_s^{*\mp}$ cross section

$D_s^{*\pm} \to D_s^{\pm}\gamma$

$D_s^{\pm} \to K^+K^-\pi^{\pm}$



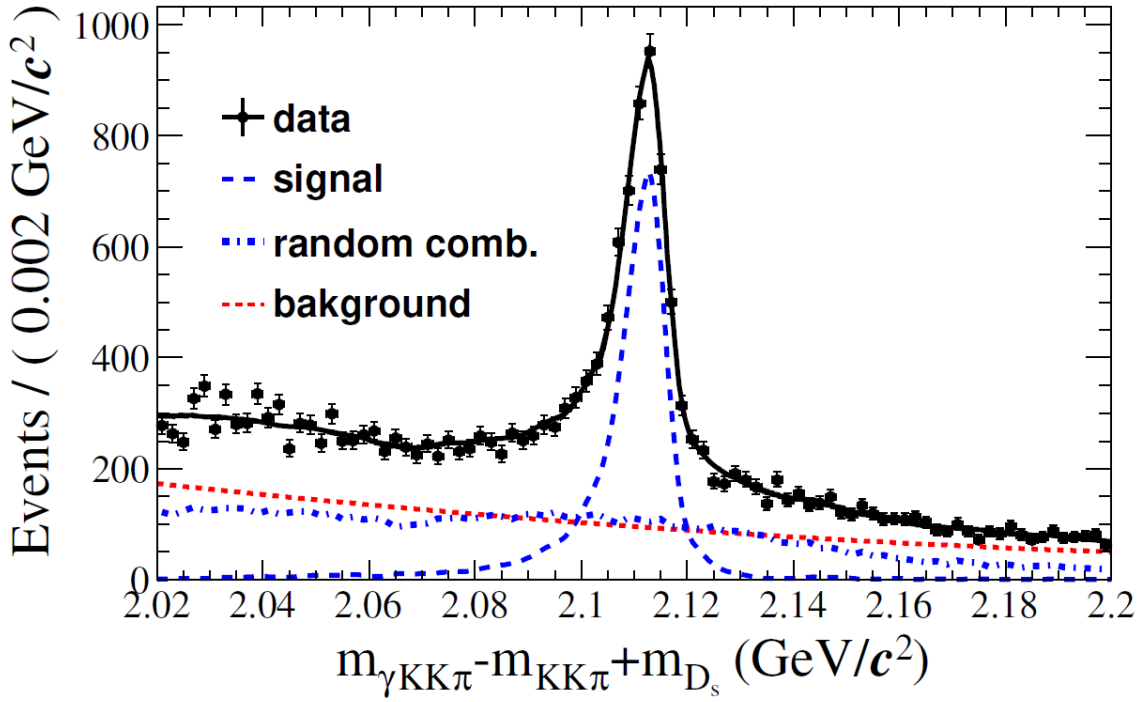
Analysis of $e^+e^- \to D_s^{*+}D_s^{*-}$

[PRL 131, 151903 (2023)]

Fit to the $\gamma KK\pi$ spectrum **containing all combinations**

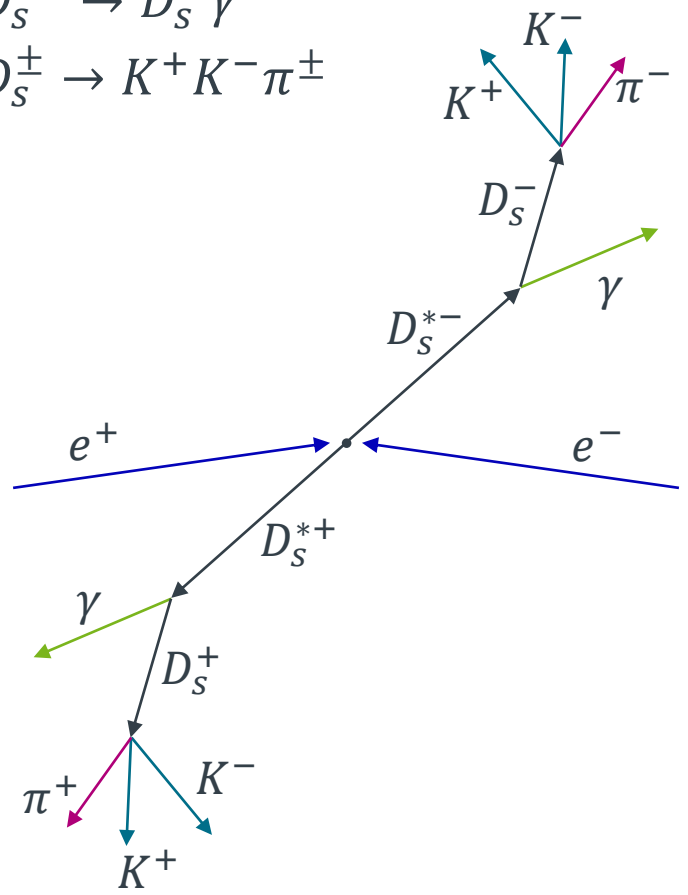
Smooth background described by second-order polynomial

Signal and combinatorial background line shape from MC



$D_s^{*\pm} \to D_s^{\pm}\gamma$

$D_s^{\pm} \to K^+K^-\pi^{\pm}$



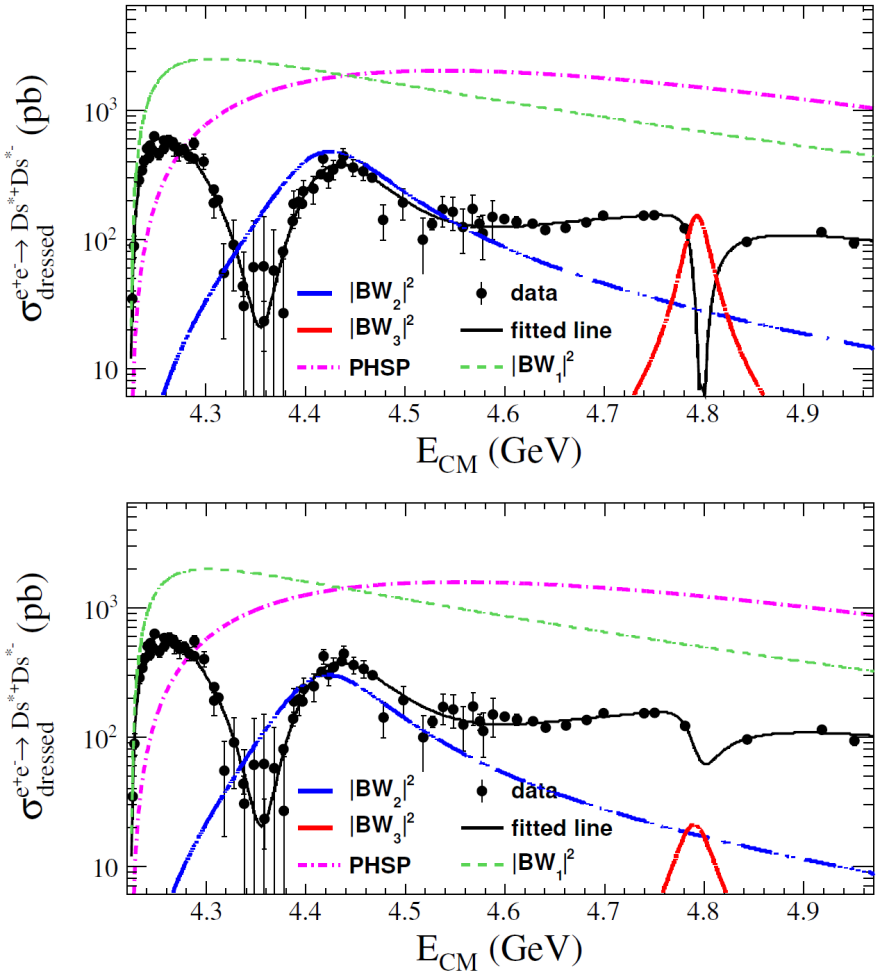
Analysis of $e^+e^- \to D_s^{*+}D_s^{*-}$

[PRL 131, 151903 (2023)]

- **Dressed cross section** calculated via:

$$\sigma_{\text{dressed}} = \frac{N_{D_s^*}^{\text{fit}} - N_{D_s^{\pm}D_s^{*\mp}}}{2\mathcal{L}_{\text{int}}\varepsilon\mathcal{B}(1+\delta_{\text{ISR}})}$$

- Cross section fitted with **coherent sum** of three Breit-Wigner amplitudes and a two-body PHSP term (all in P-wave)
- All resonance parameters (m_i, Γ_i and $\Gamma_i^{ee}B_i$) and the relative phases (ϕ_i) are **determined by the fit**
- Significance of third BW compared to two BW solution: $\mathbf{5.9\sigma}$
- Three solutions with similar reduced χ^2, m_i and Γ_i, but different $\Gamma_i^{ee}B_i$ and ϕ_i



Analysis of $e^+e^- \to D_s^{*+}D_s^{*-}$

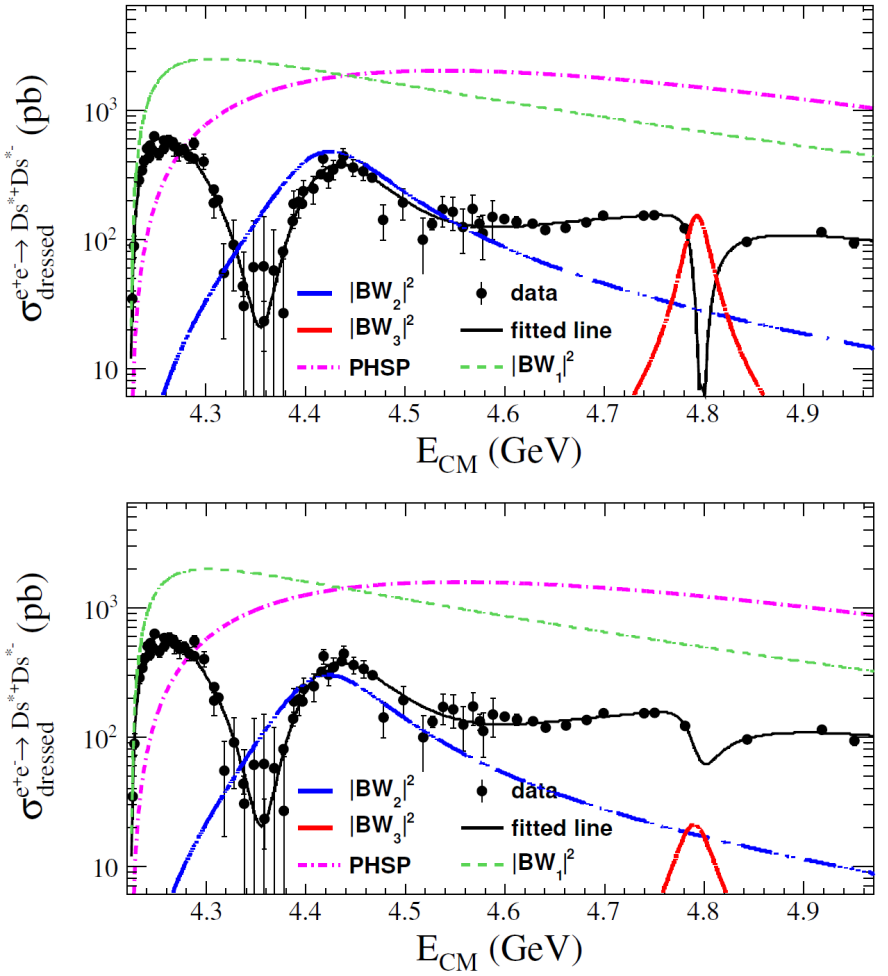
[PRL 131, 151903 (2023)]

Resulting resonance properties:

BW1: **Compatible with $\psi(4160)$** observed in $e^+e^- \to$ hadrons[9] and $B^- \to K^-\mu^+\mu^-$[10], **candidate for $\psi(2D)$**
Compatible with $\psi(4230)$[11] considering sys. uncertainties

BW2: Mass compatible with $\psi(4415)$[11], but width differs by 3σ
Candidate for the $\psi(4S)$, first observation of this decay

BW3: Compatible with evidence for $\psi(4710)$ seen in $e^+e^- \to K_S^0 K_S^0 J/\psi$[12] and $e^+e^- \to \Lambda_c^+\Lambda_c^-$[13]
Candidate for the $\psi(5S)$



[9] PLB 660, 315319 (2008)
[10] PRL 111, 112003 (2013)
[11] PTEP 2022, 083C01
[12] PRD 107, 092005 (2023)
[13] EPL 85, 61002 (2009)

Search for a scalar partner of the $\chi_{c1}(3872)$

[PRD 108, 052012 (2023)]

Analysis of the $\psi(3770)$ **data set** corresponding to $\mathcal{L}_{\mathrm{int}} = 2.93\ \mathrm{fb}^{-1}$

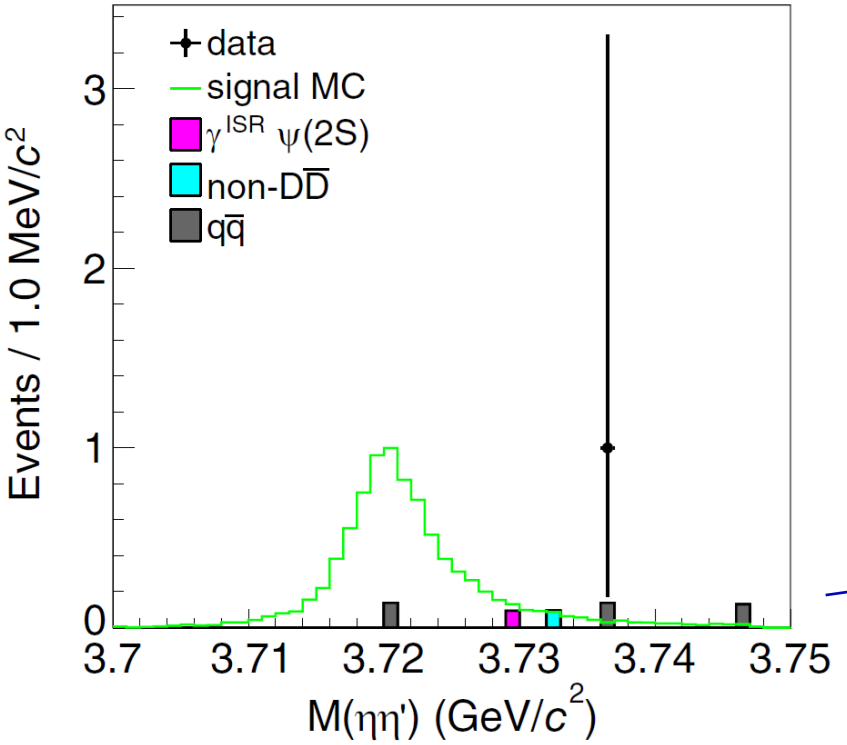
Cuts on the intermediate resonances, here: η and η'

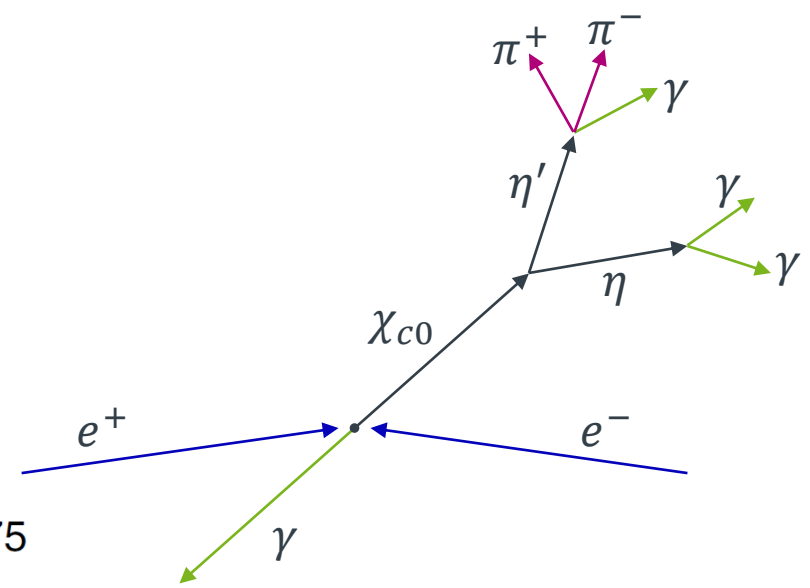
$\psi(3770) \to \gamma\chi_{c0}(3700)$
$\chi_{c0}(3700) \to \eta\eta'$
$\eta' \to \gamma\pi^+\pi^-, \eta \to \gamma\gamma$

Bayesian method to determine upper limit on $\mathcal{B}(\psi \to \gamma\chi_{c0}) \cdot \mathcal{B}(\chi_{c0} \to \eta\eta')$ including systematic uncertainties

Best limit for $m_{\chi_{c0}} = 3710\ \mathrm{MeV/c^2}$ of $\mathcal{B}^{\mathrm{up}} = \mathbf{8.9 \cdot 10^{-6}}$ **at 90% C.L.**

Upper limit gets worse with increasing mass of the χ_{c0}





Search for a scalar partner of the $\chi_{c1}(3872)$

[PRD 108, 052012 (2023)]

Analysis of the $\psi(3770)$ **data set** corresponding to $\mathcal{L}_{\text{int}} = 2.93\ \text{fb}^{-1}$

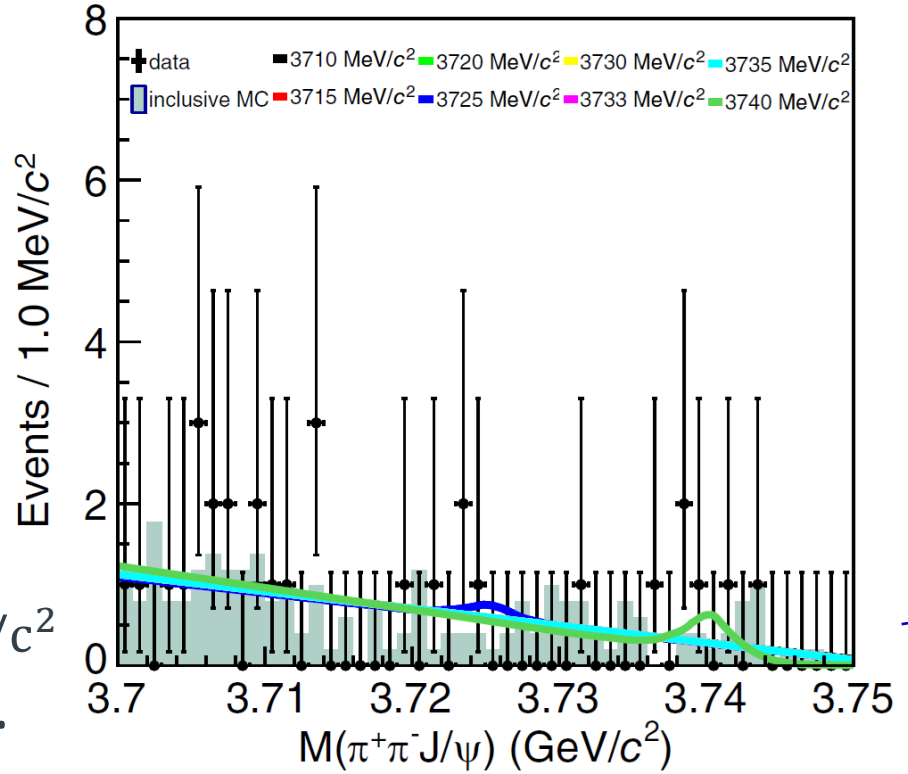
Cuts on the intermediate J/ψ resonance

Combined fit to both J/ψ decays

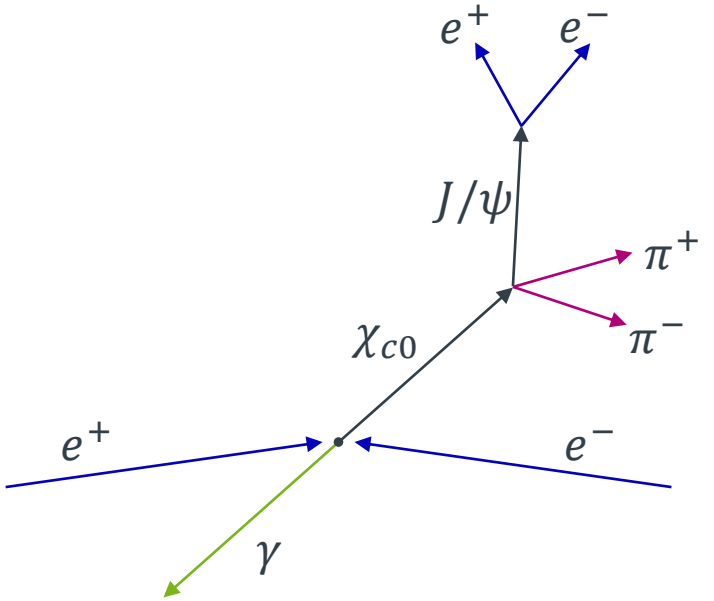
Signal described by MC shape with **different masses** of the χ_{c0}

Resulting likelihood profiles give the upper limit

Best limit for $m_{\chi_{c0}} = 3730\ \text{MeV/c}^2$ of $\mathcal{B}^{\text{up}} = 8.6 \cdot 10^{-6}$ **at 90% C.L.**



$\psi(3770) \to \gamma\chi_{c0}(3700)$
$\chi_{c0}(3700) \to \pi^+\pi^- J/\psi$
$J/\psi \to e^+e^-$



Search for a scalar partner of the $\chi_{c1}(3872)$

[PRD 108, 052012 (2023)]

Theory predictions for $\chi_{c1}(3872)$ as **hadronic molecule**:

- **Scalar partner** with slightly lower mass[14,15]
- Candidate is the predicted $\boldsymbol{D\bar{D}}$ **molecule** with a mass of $\sim 3720\ \mathrm{MeV}/c^2$[14,15]

$$\psi(3770) \to \gamma\chi_{c0}(3700)$$
$$\chi_{c0}(3700) \to \eta\eta', \pi^+\pi^- J/\psi$$
$$\eta' \to \gamma\pi^+\pi^-, \eta \to \gamma\gamma$$
$$J/\psi \to e^+e^-, \mu^+\mu^-$$

Experimental **hints for a $\boldsymbol{D\bar{D}}$ state** with mass of $\sim 3700\ \mathrm{MeV}/c^2$ seen in:

- $e^+e^- \to J/\psi D\bar{D}$[16,17] and $\gamma\gamma \to D\bar{D}$[18]

First search for $\chi_{c0} \to \eta\eta'$ and $\chi_{c0} \to \pi^+\pi^- J/\psi$ presented here

- Theoretical prediction for $\mathcal{B}(\psi \to \gamma\chi_{c0}) \cdot \mathcal{B}(\chi_{c0} \to \eta\eta')$ of $1 \cdot 10^{-5}$[19] **excluded for masses smaller than $\boldsymbol{3730\ \mathrm{MeV}/c^2}$**
- Upper limit on $\mathcal{B}(\psi \to \gamma\chi_{c0}(3700)) \cdot \mathcal{B}(\chi_{c0}(3700) \to \pi^+\pi^- J/\psi)$ gives **constraint on the isospin violation seen in $\boldsymbol{\chi_{c1}(3872) \to \pi^+\pi^- J/\psi}$**[20]

[14] PRD 87, 076006 (2013)
[15] PRD 86, 056004 (2012)
[16] PRL 100, 202001 (2008)
[17] EPJA 36, 189 (2008)
[18] PRL 96, 082003 (2006)
[19] EPJA 49, 52 (2013)
[20] PLB 590, 209 (2004)

Conclusion and Outlook

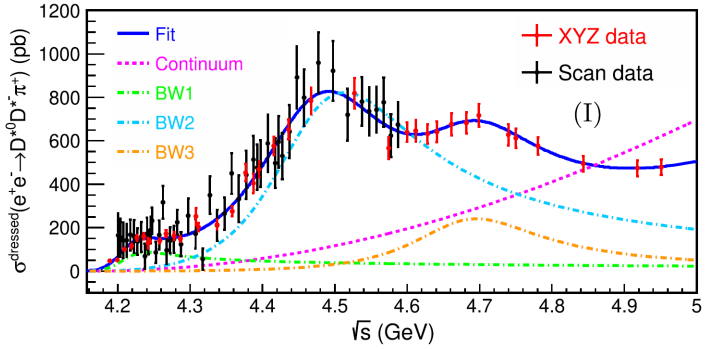
BESIII is **still actively taking data** in the charmonium region (at the moment increasing the $\psi(3770)$ dataset)

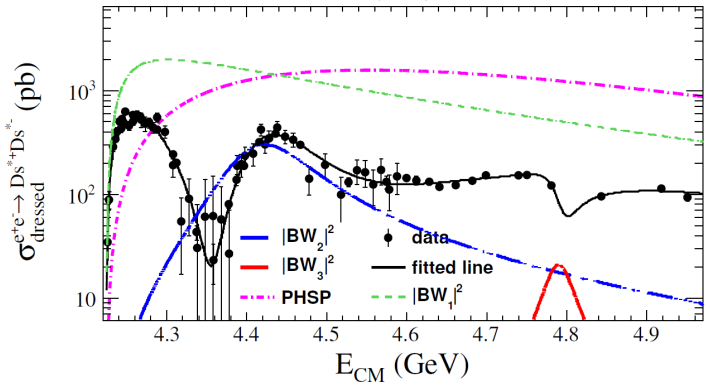
New and exciting results in the **search for $J^{PC} = 1^{--}$ resonances**

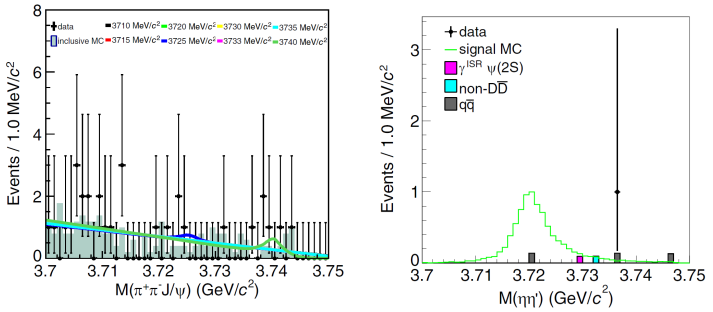
Large datasets at known resonances allow to **search for charmonium(-like) states with all quantum numbers**

In the future **sophisticated theoretical models** needed to describe line shape of e.g. the 1^{--} resonances, like it is done in the bottomonium region[21]

Upgrade of BEPCII in 2024 will allow BESIII to **measure up to center-of-mass energies of 5.6 GeV**







[21] PRD 106, 094013 (2022)

Thank you for your attention!

Backup slides

Data sets

World's largest data sets at 1^{--} resonances:

$$J/\psi, \psi(2S), \psi(3770)$$

Energy scan in the "XYZ" region:

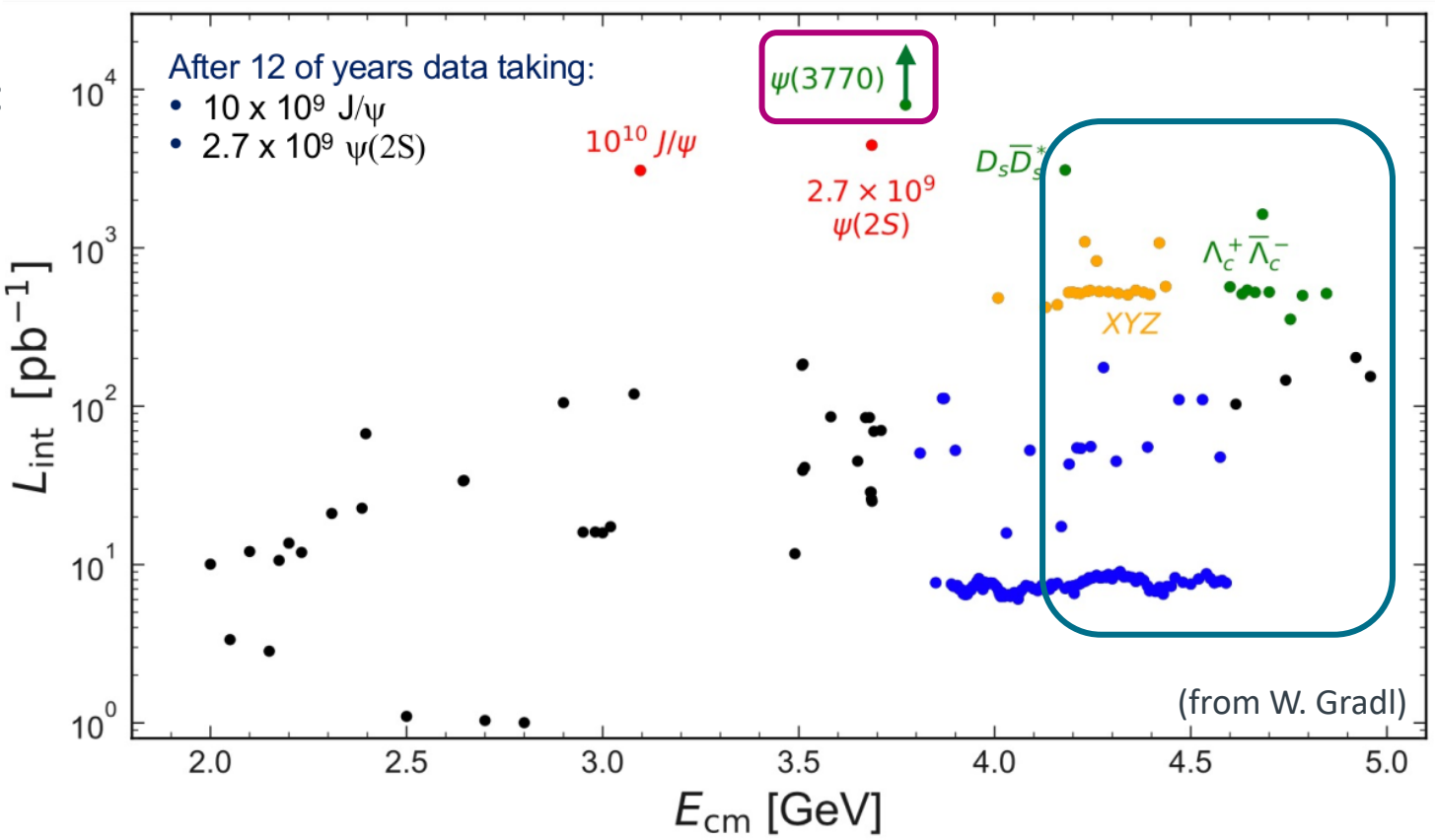
$$4.0\ \text{GeV} \leq \sqrt{s} \leq 5.0\ \text{GeV}$$

Scans around resonances:

$$\chi_{c1}, \psi(2S), \psi(3770)$$

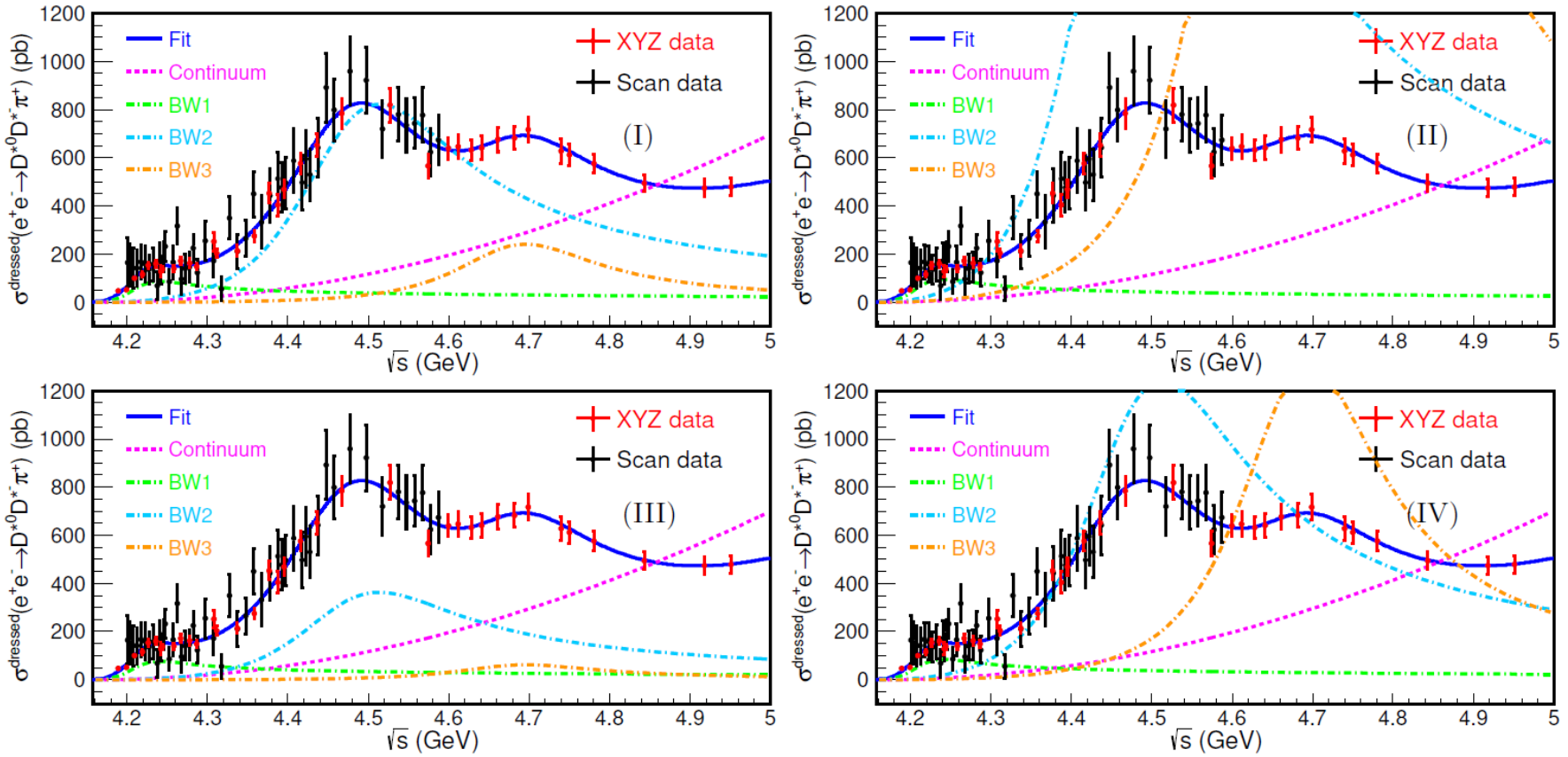
Additional data sets at lower energies:

$$2.0\ \text{GeV} \leq \sqrt{s} \leq 3.0\ \text{GeV}$$



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

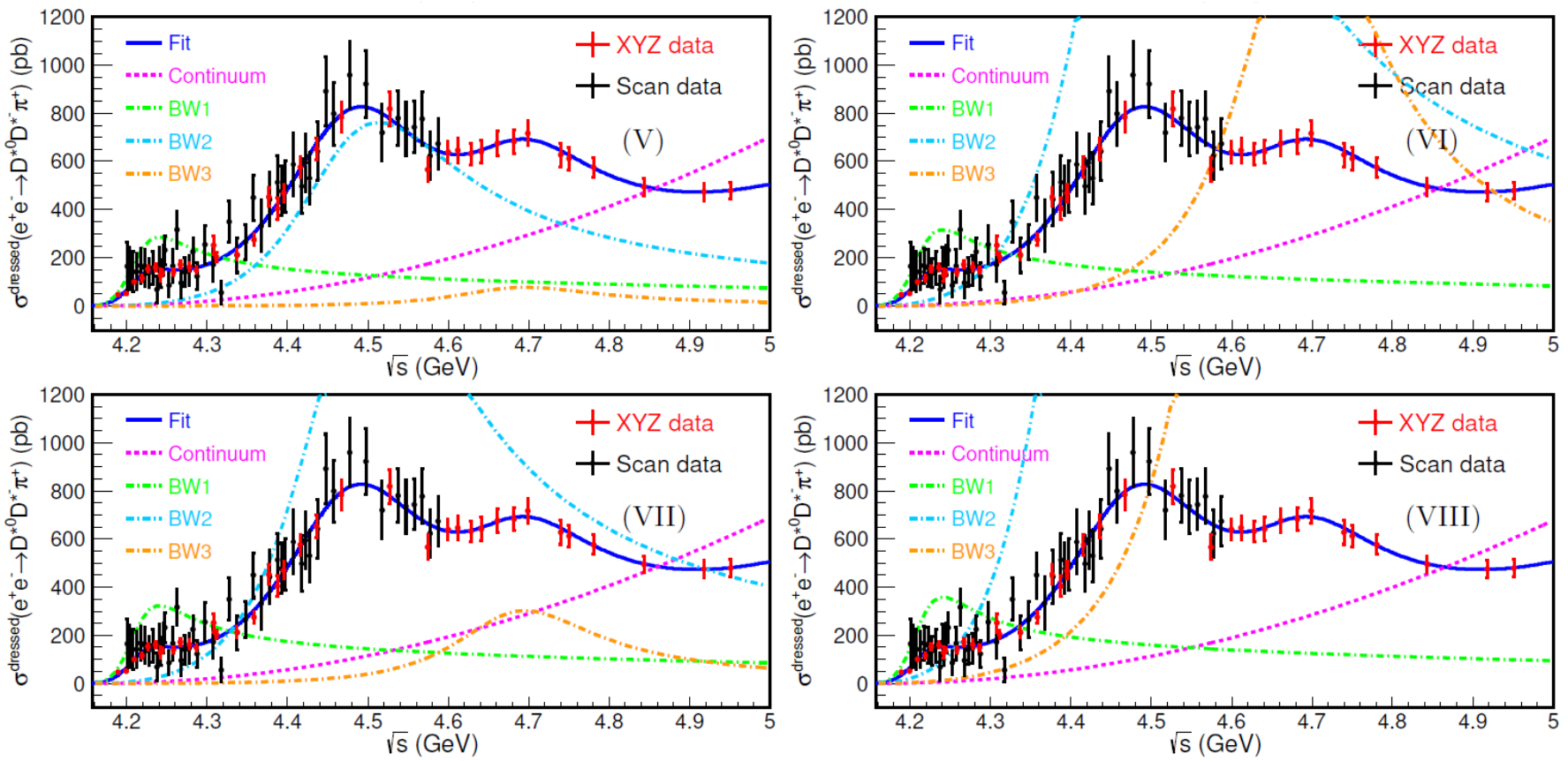
[PRL 130, 121901 (2023)]



Solutions I-IV of the fit to the $e^+e^- \to D^{*0}D^{*-}\pi^+$ cross section

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

[PRL 130, 121901 (2023)]



Solutions V-VIII of the fit to the $e^+e^- \to D^{*0}D^{*-}\pi^+$ cross section

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

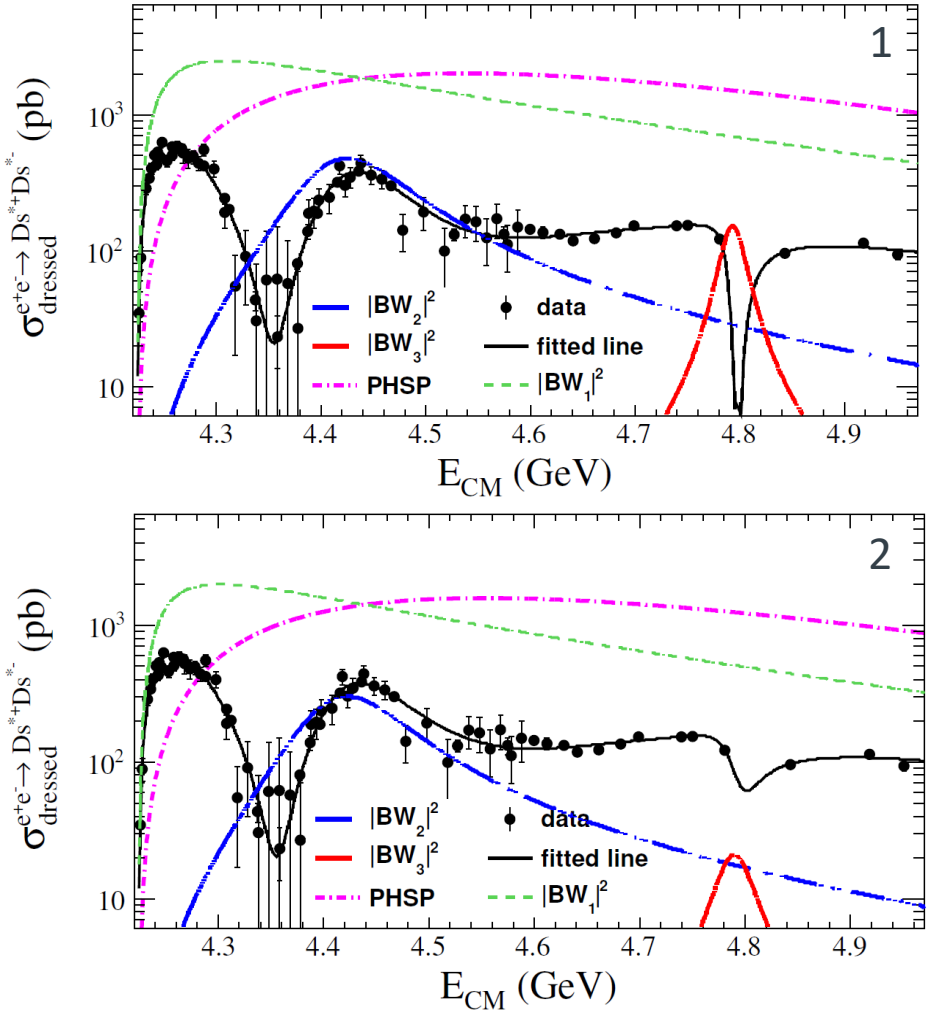
[PRL 130, 121901 (2023)]

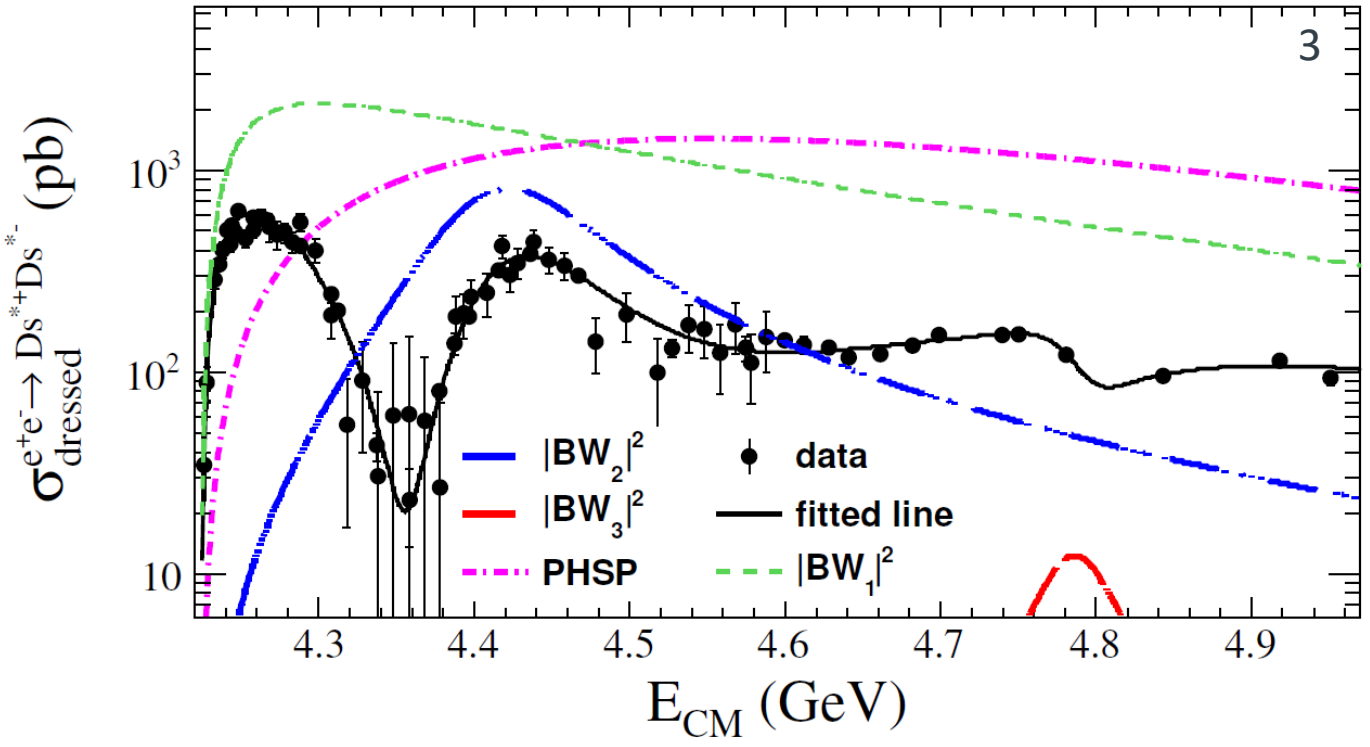
	I	II	III	IV	V	VI	VII	VIII
$C_1(10^{-3})$				4.2 ± 1.5				
m_1 (MeV/c^2)				4209.6 ± 4.7				
Γ_1^{tot} (MeV)				81.6 ± 17.8				
$\Gamma_1^{ee}\mathcal{B}_1$ (eV)	5.4 ± 1.1	6.0 ± 1.3	4.8 ± 0.9	5.3 ± 1.1	17.9 ± 7.2	19.8 ± 6.6	20.2 ± 7.4	22.4 ± 9.0
ϕ_1 (rad)	3.1 ± 0.5	3.8 ± 0.4	1.9 ± 0.7	2.6 ± 0.6	4.2 ± 0.3	4.8 ± 0.2	5.4 ± 0.3	6.0 ± 0.3
m_2 (MeV/c^2)				4469.1 ± 26.2				
Γ_2^{tot} (MeV)				246.3 ± 36.7				
$\Gamma_2^{ee}\mathcal{B}_2$ (eV)	243.3 ± 83.5	832.5 ± 716.5	107.4 ± 50.6	367.4 ± 370.8	225.5 ± 94.9	770.8 ± 383.8	510.1 ± 202.3	1744.3 ± 926.9
ϕ_2 (rad)	4.4 ± 0.3	-0.9 ± 0.3	2.6 ± 0.6	3.7 ± 0.8	1.9 ± 0.8	3.0 ± 0.4	3.7 ± 0.3	-1.5 ± 0.3
m_3 (MeV/c^2)				4675.3 ± 29.5				
Γ_3^{tot} (MeV)				218.3 ± 72.9				
$\Gamma_3^{ee}\mathcal{B}_3$ (eV)	75.8 ± 148.8	1601.9 ± 1152.6	19.4 ± 27.1	411.6 ± 230.5	24.4 ± 34.5	515.6 ± 244.6	95.1 ± 173.1	2005.3 ± 1166.1
ϕ_3 (rad)	4.9 ± 1.4	-2.9 ± 0.4	2.1 ± 0.4	0.6 ± 1.1	1.7 ± 0.5	6.5 ± 0.5	4.5 ± 1.3	-3.3 ± 0.3

Fitted parameters of the fit to the $e^+e^- \to D^{*0}D^{*-}\pi^+$ cross section

Analysis of $e^+e^- \to D_s^{*+}D_s^{*-}$

[acc. by PRL, arXiv:2305.10789]





Solutions 1-3 of the fit to the $e^+e^- \to D_s^{*+}D_s^{*-}$ cross section

Analysis of $e^+e^- \to D_s^{*+}D_s^{*-}$

[acc. by PRL, arXiv:2305.10789]

	Result 1	Result 2	Result 3
M_1 (MeV/c^2)	4186.8±8.7	4194.1±6.8	4195.6±6.5
Γ_1 (MeV)	55±15	61.1±8.5	61.7±7.7
M_2 (MeV/c^2)	4414.6±3.4	4411.9±3.2	4411.1±3.2
Γ_2 (MeV)	122.5±7.5	120.2±7.4	119.9±7.3
M_3 (MeV/c^2)	4793.3±6.7	4789.7±8.7	4786.0±9.4
Γ_3 (MeV)	27.1±6.5	42±75	60±34

	Result 1	Result 2	Result 3
a_1 (MeV)	4.3±2.1	2.74±0.94	2.85±0.87
$(\Gamma_{e^+e^-}B(D_s^*D_s^*))_2$ (eV)	74.6 ± 7.3	46.0 ± 6.1	123 ± 14
ϕ_2 (rad)	-1.29±0.12	-0.981±0.068	-2.244±0.070
$(\Gamma_{e^+e^-}B(D_s^*D_s^*))_3$ (eV)	6 ± 22	1.3 ± 2.8	1.13 ± 0.48
ϕ_3 (rad)	1.15±0.58	0.96±0.89	-1.07±0.45
n	9.73±0.18	9.270±0.044	9.301±0.045
a_0 ($\times 10^4$ GeV^{n-1})	7.1 ± 2.3	3.16 ± 0.54	3.2 ± 1.8
ϕ_0 (rad)	2.959±0.043	3.087±0.022	2.675±0.029

Fitted parameters of the fit to the $e^+e^- \to D_s^{*+}D_s^{*-}$ cross section

Search for a scalar partner of the $\chi_{c1}(3872)$

[PRD 108, 052012 (2023)]

Analysis of the $\psi(3770)$ **data set** corresponding to $\mathcal{L}_{\text{int}} = 2.93\ \text{fb}^{-1}$

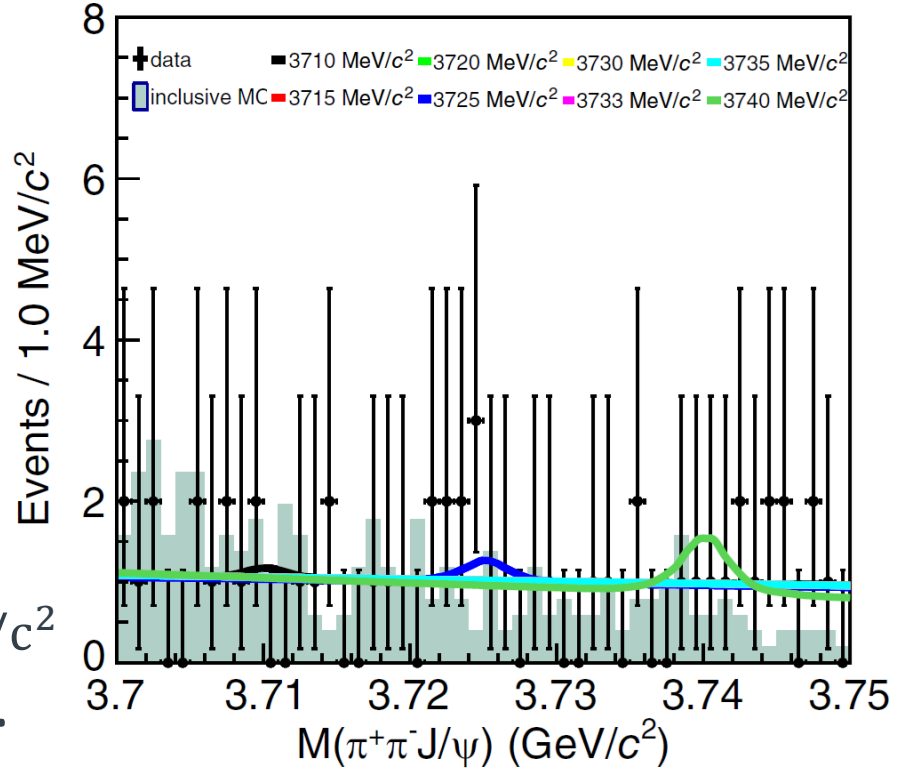
Cuts on the intermediate J/ψ resonance

Combined fit to both J/ψ decays

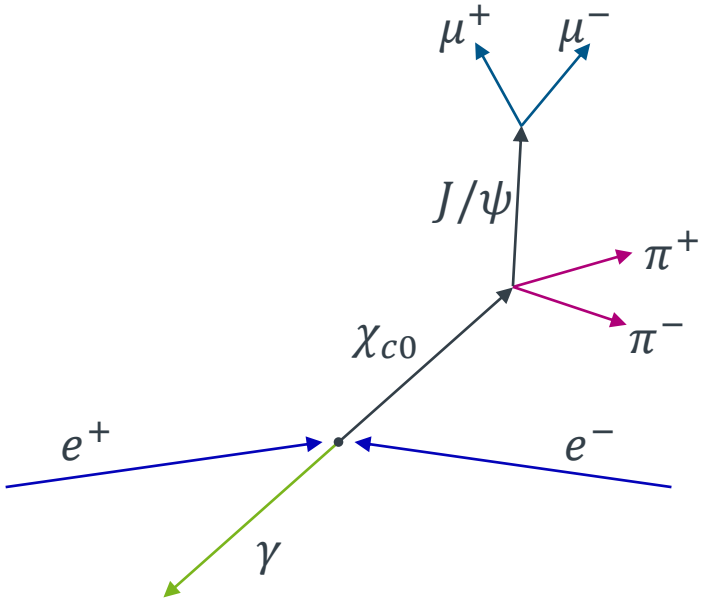
Signal described by MC shape with **different masses** of the χ_{c0}

Resulting likelihood profiles give the upper limit

Best limit for $m_{\chi_{c0}} = 3730\ \text{MeV/c}^2$ of $\mathcal{B}^{\text{up}} = \mathbf{8.6 \cdot 10^{-6}}$ **at 90% C.L.**



$\psi(3770) \to \gamma\chi_{c0}(3700)$
$\chi_{c0}(3700) \to \pi^+\pi^- J/\psi$
$J/\psi \to \mu^+\mu^-$



Search for a scalar partner of the $\chi_{c1}(3872)$

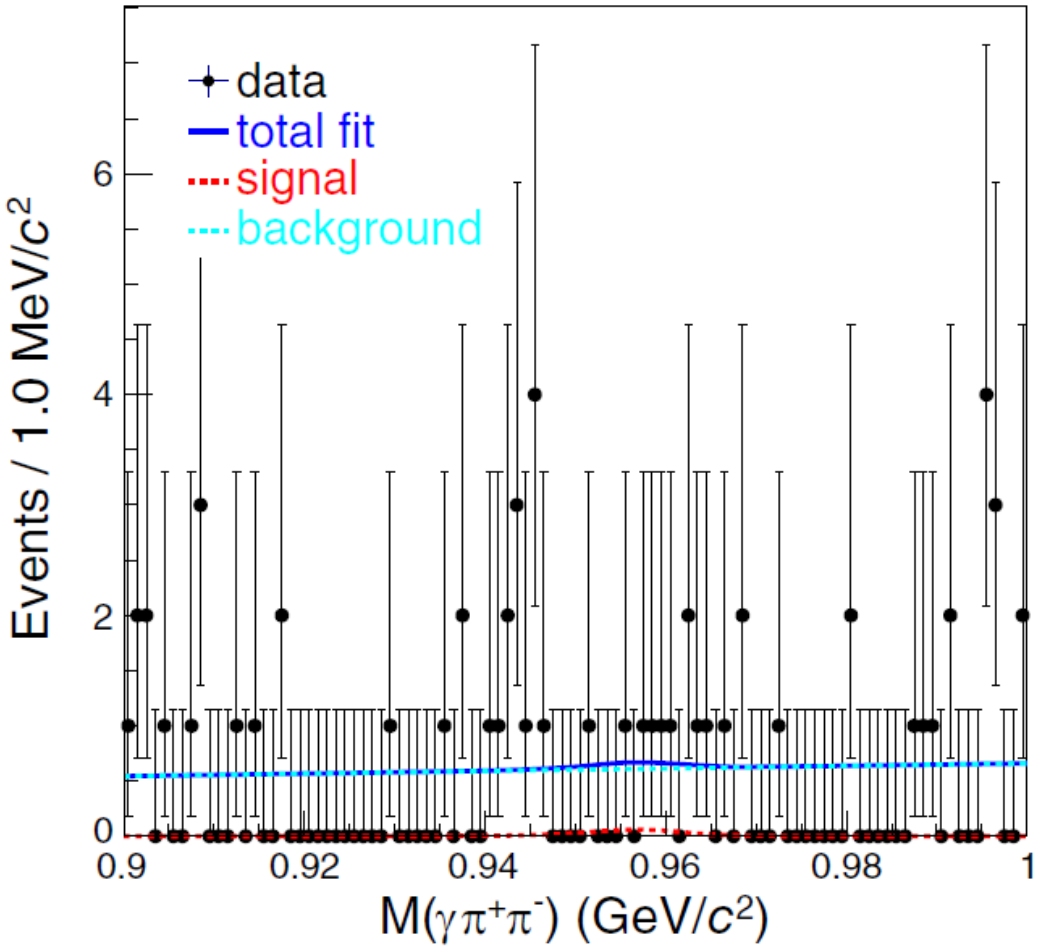
[PRD 108, 052012 (2023)]

$M(X(3700))$ (MeV/c^2)		3710	3715	3720	3725	3730	3733	3735	3740
$\psi(3770) \to \gamma\eta\eta'$	ε_0 (%)	10.56	10.50	10.14	9.77	9.31	8.99	8.70	8.15
	$\mathcal{B}^{\rm up}(\times 10^{-6})$	8.9	9.0	9.3	9.7	10	18	18	19
$\psi(3770) \to \gamma\pi^+\pi^- J/\psi$	ε_0^{ee} (%)	15.68	15.59	15.88	15.50	15.38	15.32	14.83	13.76
	$\varepsilon_0^{\mu\mu}$ (%)	24.10	23.97	24.02	23.93	23.67	23.54	23.16	21.80
	$\mathcal{B}^{\rm up}(\times 10^{-5})$	2.2	1.2	1.8	3.0	0.86	1.0	1.3	3.4

Upper limits on the product branching ratios $\mathcal{B}\big(\psi(3770) \to \gamma\chi_{c0}(3700)\big) \cdot \mathcal{B}(\chi_{c0}(3700) \to \eta\eta')$ and $\mathcal{B}\big(\psi(3770) \to \gamma\chi_{c0}(3700)\big) \cdot \mathcal{B}(\chi_{c0}(3700) \to \pi^+\pi^- J/\psi)$ in dependence of the mass of the χ_{c0}

Search for a scalar partner of the $\chi_{c1}(3872)$

[PRD 108, 052012 (2023)]



Upper limit for $\mathcal{B}(\psi(3770) \to \gamma\eta\eta')$:

$\mathcal{B}^{\mathrm{up}} = 4.8 \cdot 10^{-5}$ at 90% C.L.