Charmonium Decays at BESIII

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Outline

- BESIII Experiment
- Charmonia at BESIII
- The Singlet $\eta_c(2S)$ Charmonium
- Investigating the $\psi(3770)$ Resonance
- ID of the $\psi_2(3823)$ State
- 2^3P_1 or not-2^3P_1, the $\chi_{c1}(3872)$ Nature
- Summary

DISCLAIMER

This presentation is not an encyclopaedic review of all the charmonium decays at BESIII

BESIII Experiment

BESIII (BEijing Spectrometer III) is an experiment located at the BEPCII (Beijing Electron Positron Collider II) at IHEP (Institute of High Energy Physics)

e^+e^- collider ⇝ Direct production of vector states ($J^{PC} = 1^{--}$)
High statistics @ψ(nS) ⇝ Probe with high precision the (non-)vector states
Unique opportunities above **3.8 GeV**

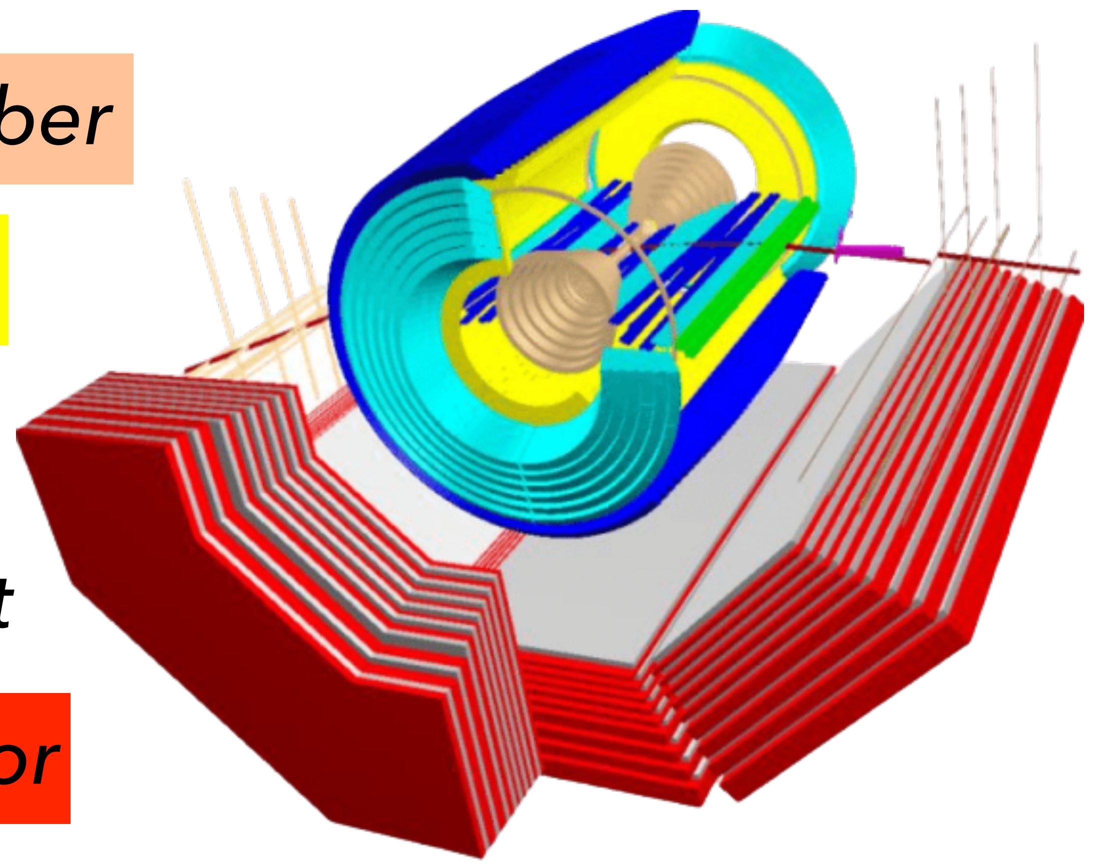
Multi-layer Drift Chamber

Time of Flight Detector

EM Calorimeter

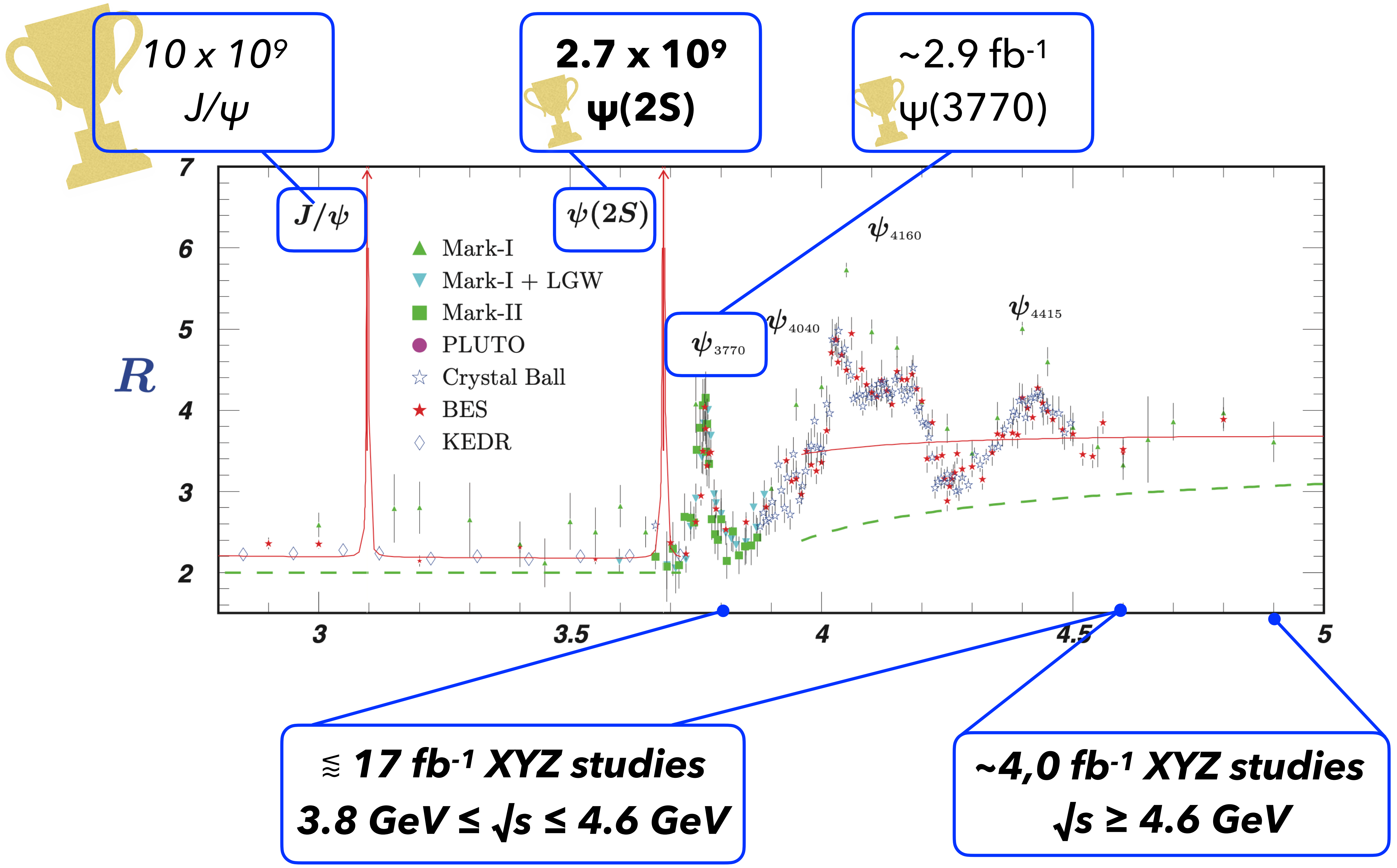
1T Solenoidal Magnet

Muon Detector



τ-charm factory 2.0 GeV ≤ $\sqrt{s}$ ≤ 4.9 GeV

with an instantaneous luminosity of 10^{33} $cm^{-2}s^{-1}$ @ $\sqrt{s}$ = 3.77 GeV



Charmonia at BESIII

[I] A. Guo, "The Vector Charmoniumlike Spectrum at BESIII (Non-Open Charm Decays)"
[II] K. Han, "Status of Z_{cs} States at BESII"
[III] X. Hou, "New Results on the X(3872) from BESIII"
[IV] K. Zhu, "The Vector Charmoniumlike Spectrum at BESIII (Open Charm Decays)"
[V] V. Prasad, "Search for rare phenomena at BESIII"

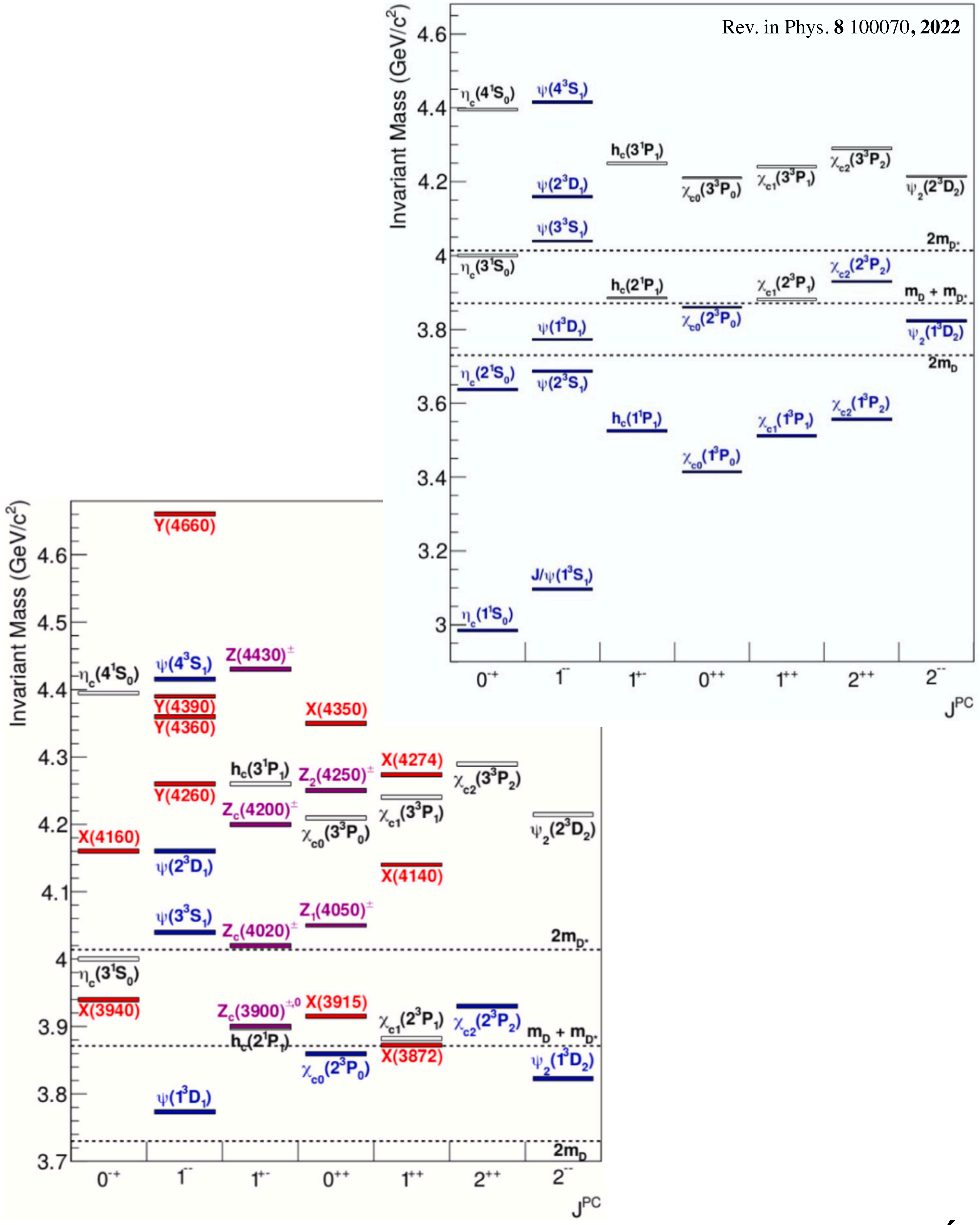
Charmonium resonances are located in the transition region of perturbative and non-perturbative QCD

Non-vector and above-threshold states are partly unknown

Vector states can be used either to reach non-1-- ones or as a way to test pQCD predictions (e.g., 12% rule, $\mathcal{A}$(EM - strong), …)

Gateway to the XYZ exotic states[I, II, III, IV]

Another way to probe the SM (via weak decays)[V]



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Charmonia at BESIII

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Gateway to the XYZ exotic states[I, II, III, IV]

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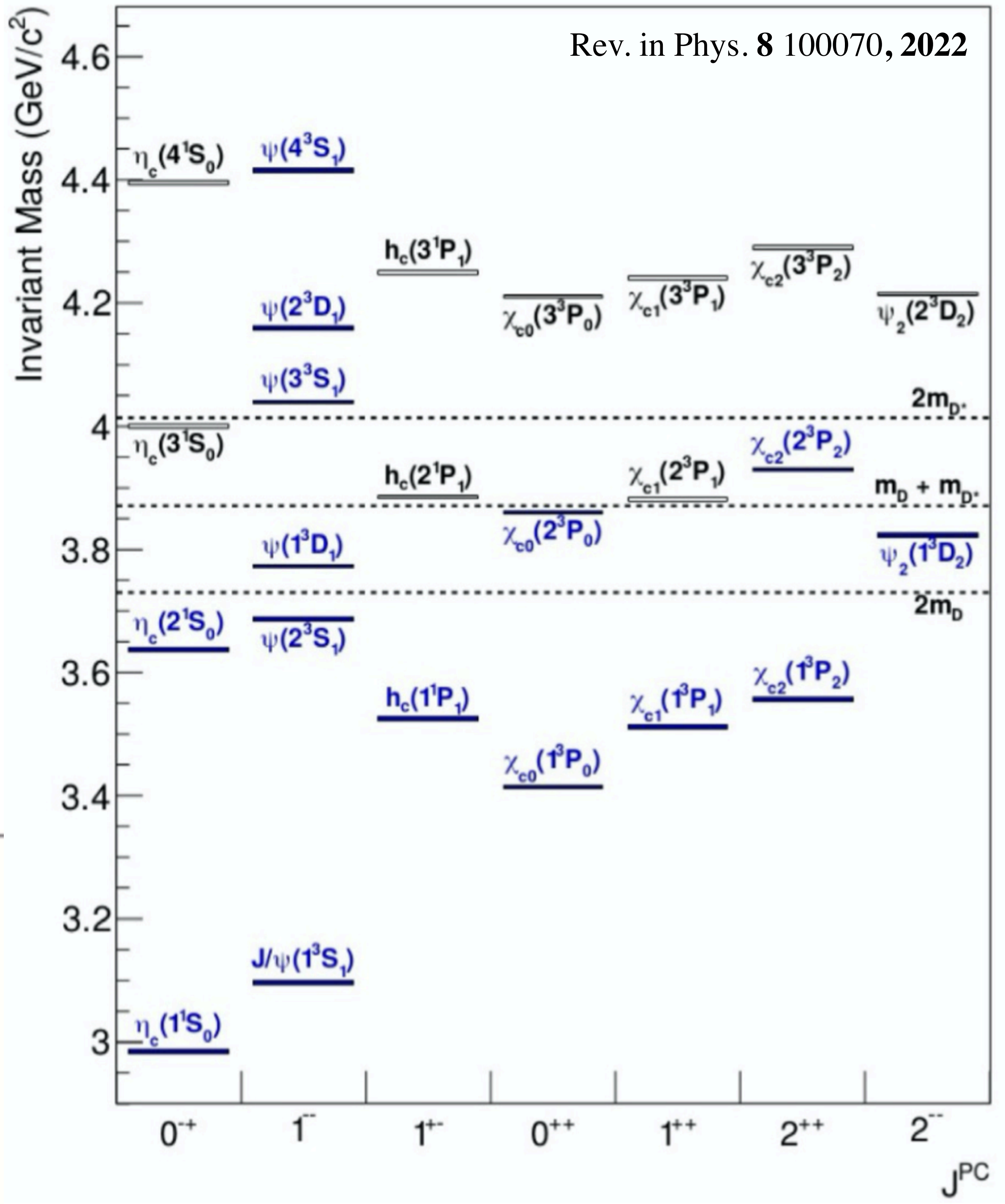
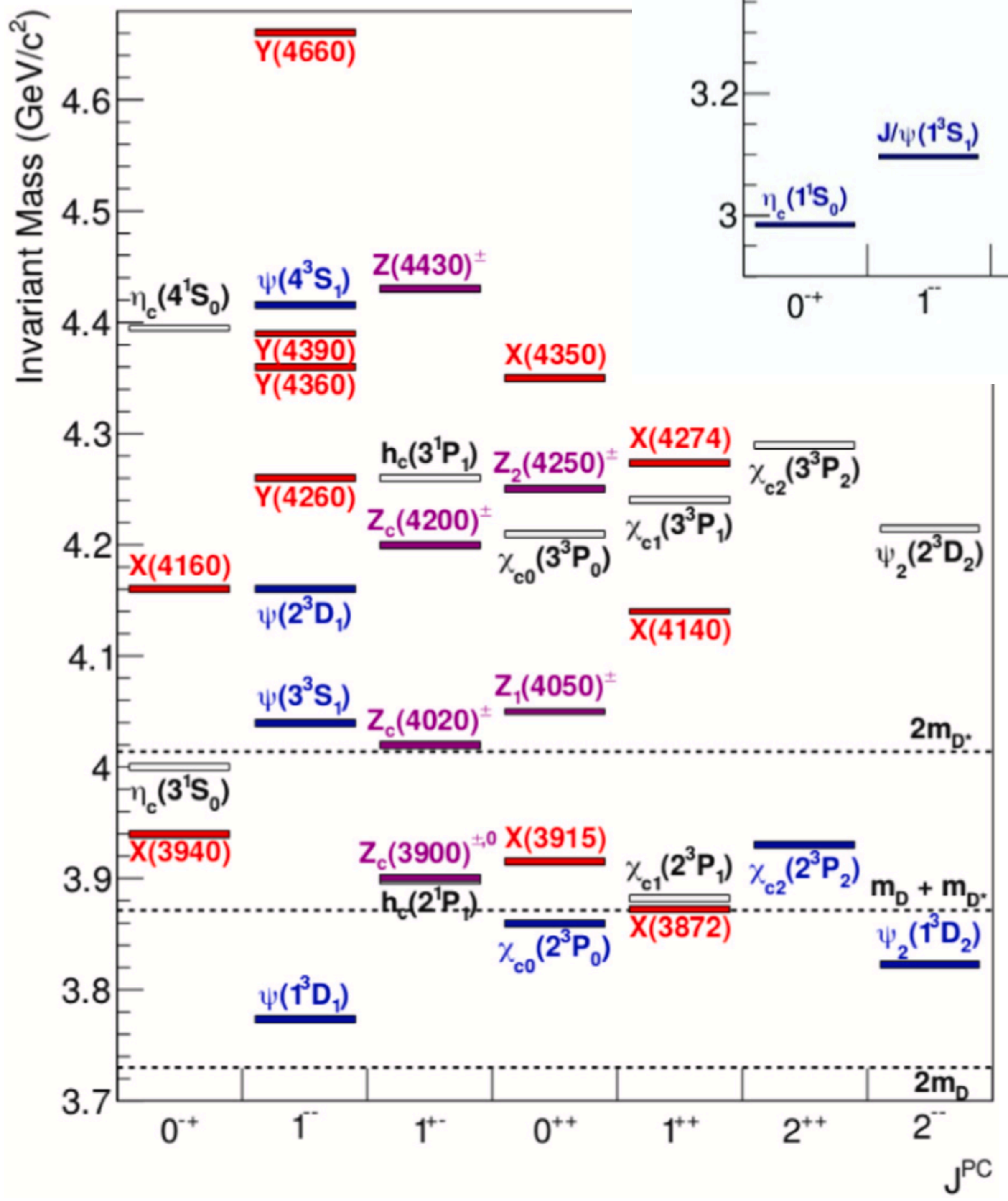
BESIII can perform such studies, but we will focus on what BESIII can provide to expand the knowledge on the charmonium spectrum itself:

1. **Search for $\eta_c(2S) \to \pi^+\pi^-\eta_c$ and $\eta_c(2S) \to \pi_+\pi_-K_{0S}K_\pm\pi_\mp$ decays**
2. Observation of $\psi(3686) \to \Omega^- K^+$ anti-Ξ^0 + c.c.
3. ***Observation of of $e^+e^- \to \pi^0\pi^0\psi_2(3823)$***
4. Observation of $\chi_{cJ} \to 3(K^+K^-)$
5. **Observation […] and discovery of the charmless decay $\psi(3770) \to K_S^0 K_L^0$**
6. **Search for the decay $\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$**
7. **Updated measurements of the M1 transition $\psi(3686) \to \gamma\eta_c(2S)$ with $\eta_c(2S) \to K\bar{K}\pi$**
8. Observation of the $\psi(3686)$ decays into Σ^+anti-$\Sigma^-\omega$ and Σ^+anti-$\Sigma^-\phi$
9. Observation of the decay $\chi_{cJ} \to \Omega^-$ anti-Ω^+
10. Helicity amplitude analysis of $\chi_{cJ} \to \phi\phi$
11. **Observation of $\psi(3770) \to \eta J/\psi$**
12. **Evidence for $\eta_c(2S) \to \pi^+\pi^-\eta$ decay**





The Singlet $\eta_c(2S)$ Charmonium

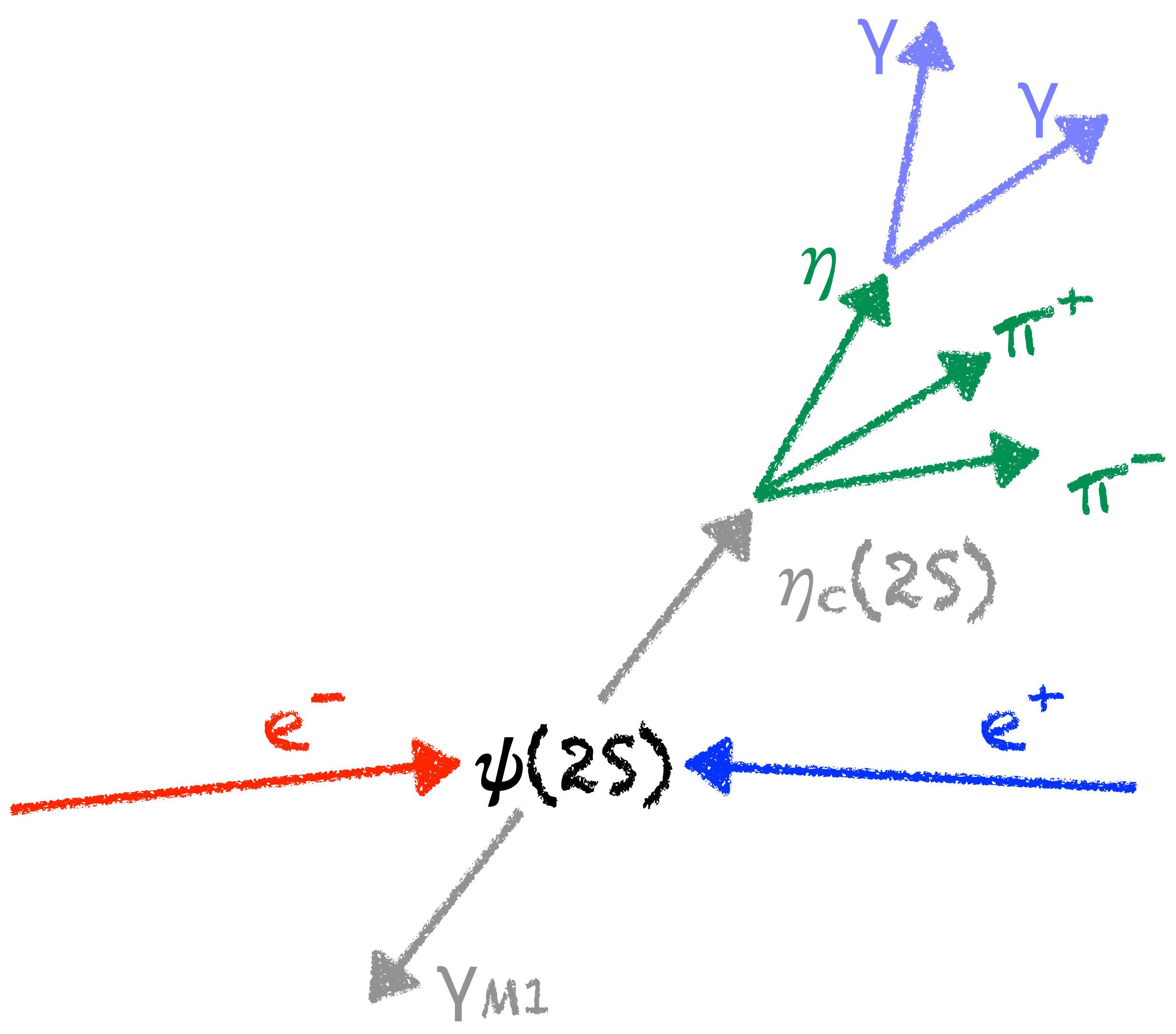
$\eta_c(2S) \to \pi^+\pi^-\eta$ Decay

Phys. Rev. D **107**, 052007 (2023)

Using the 448 million $\psi(2S)$ data set

Search for the $\boldsymbol{\eta_c(2S) \to \pi^+\pi^-\eta}$ **decay** through the M1 $\psi(2S) \to \gamma\eta_c(2S)$ transition **and determination of $\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta)$**

Fit to the $M(\pi^+\pi^-\gamma\gamma)$ at [3.35, 3.70] GeV/c^2 to properly estimate the $\chi_{c1,2} \to \pi^+\pi^-\eta$ contributions (found to be compatible to PDG values)



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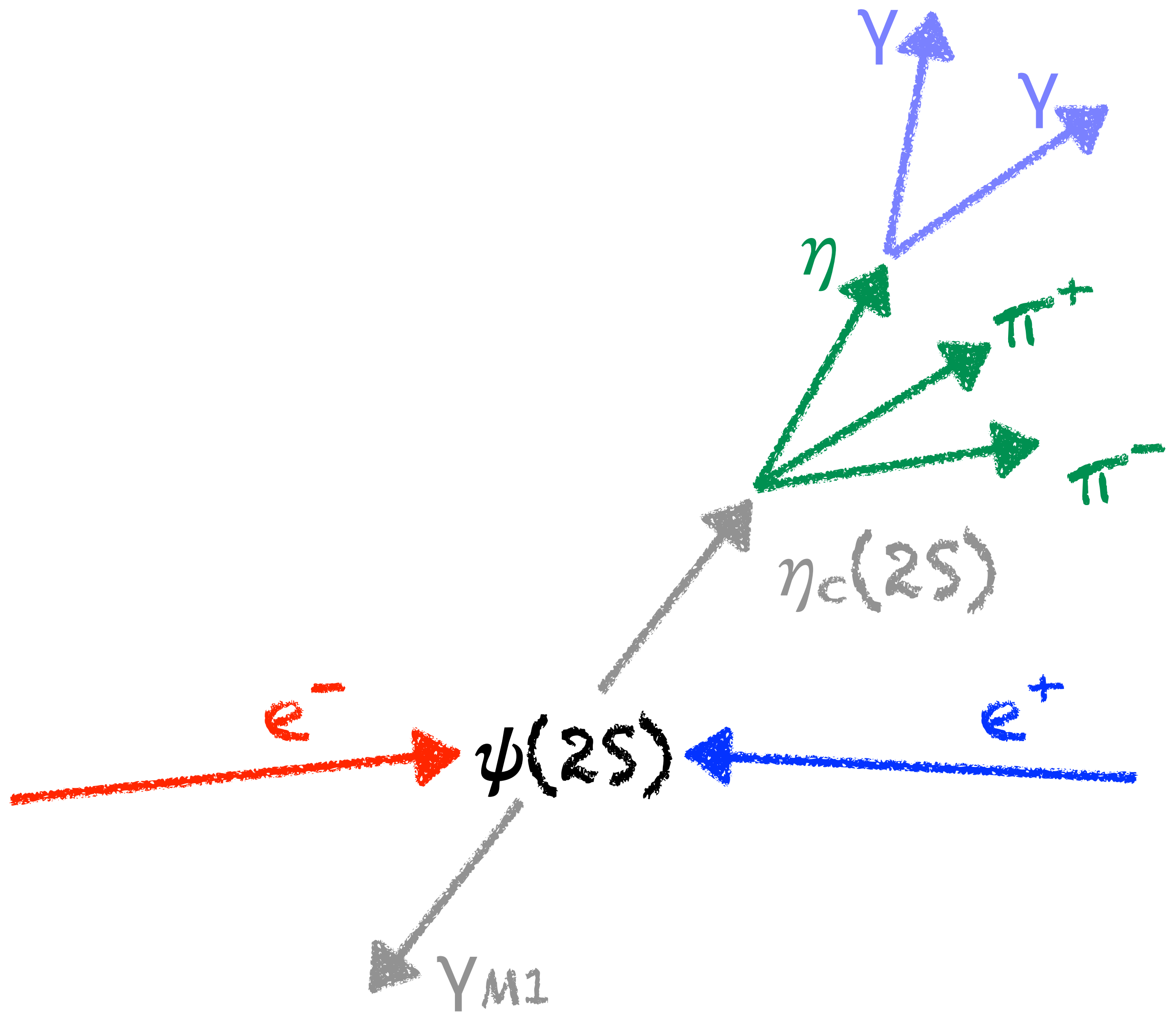

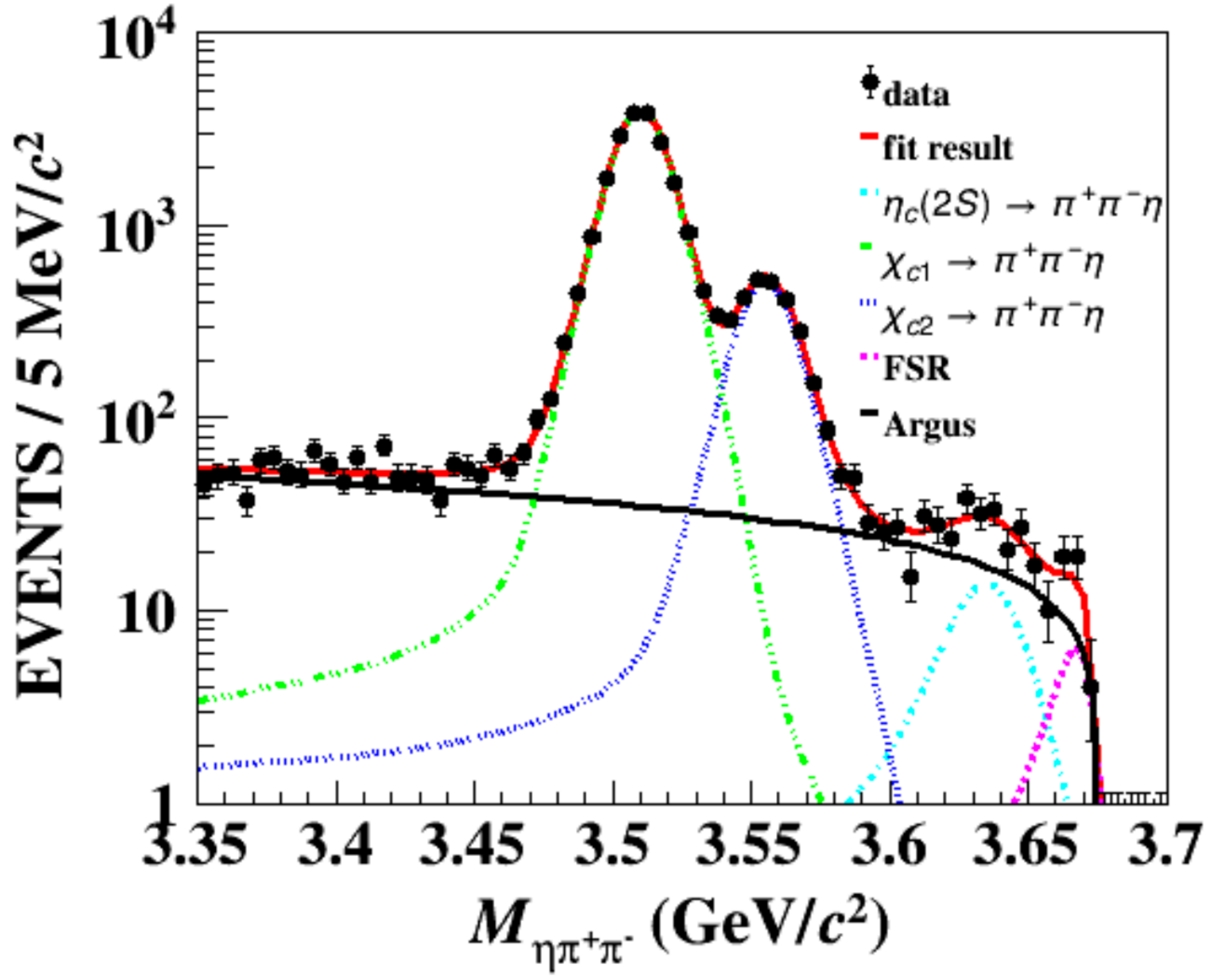

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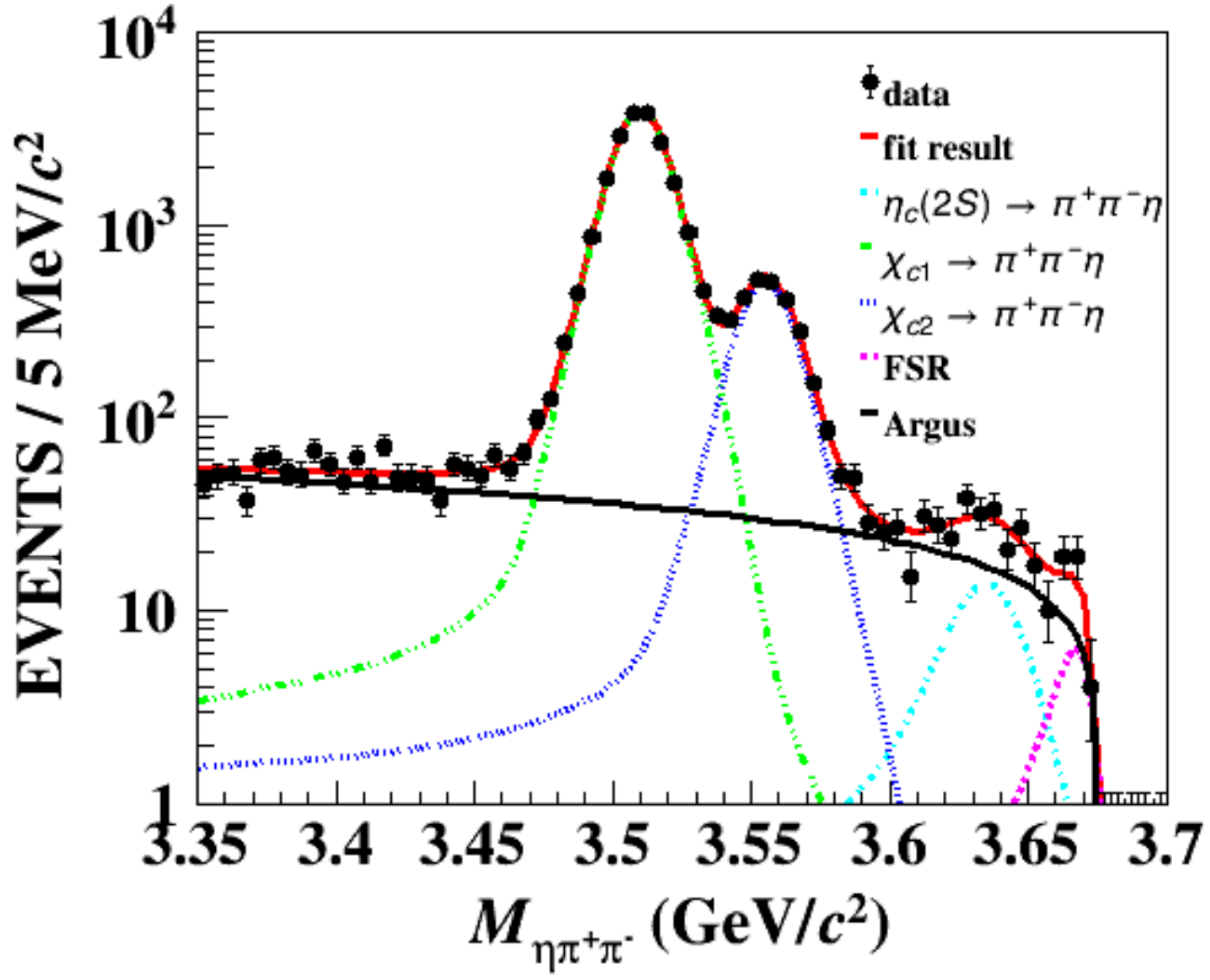
N_{sig}	$N_{\psi(3686)}(\times 10^6)$	ϵ	$BR_1(\times 10^{-4})$	$BR_2(\times 10^{-2})$
106 ± 29	448.1 ± 2.9	0.202	7 ± 5	39.41 ± 0.20

First evidence
@3.5σ

$$\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta) = \frac{N_{\rm sig}}{N_{\psi(3686)}\ \epsilon\ BR_1(\psi(3686) \to \gamma\eta_c(2S))\ BR_2(\eta \to \gamma\gamma)}$$

$$= (42.4 \pm 11.6 \pm 3.8 \pm 30.8) \times 10^{-4}$$

Stat. Syst. δ(BR_1)



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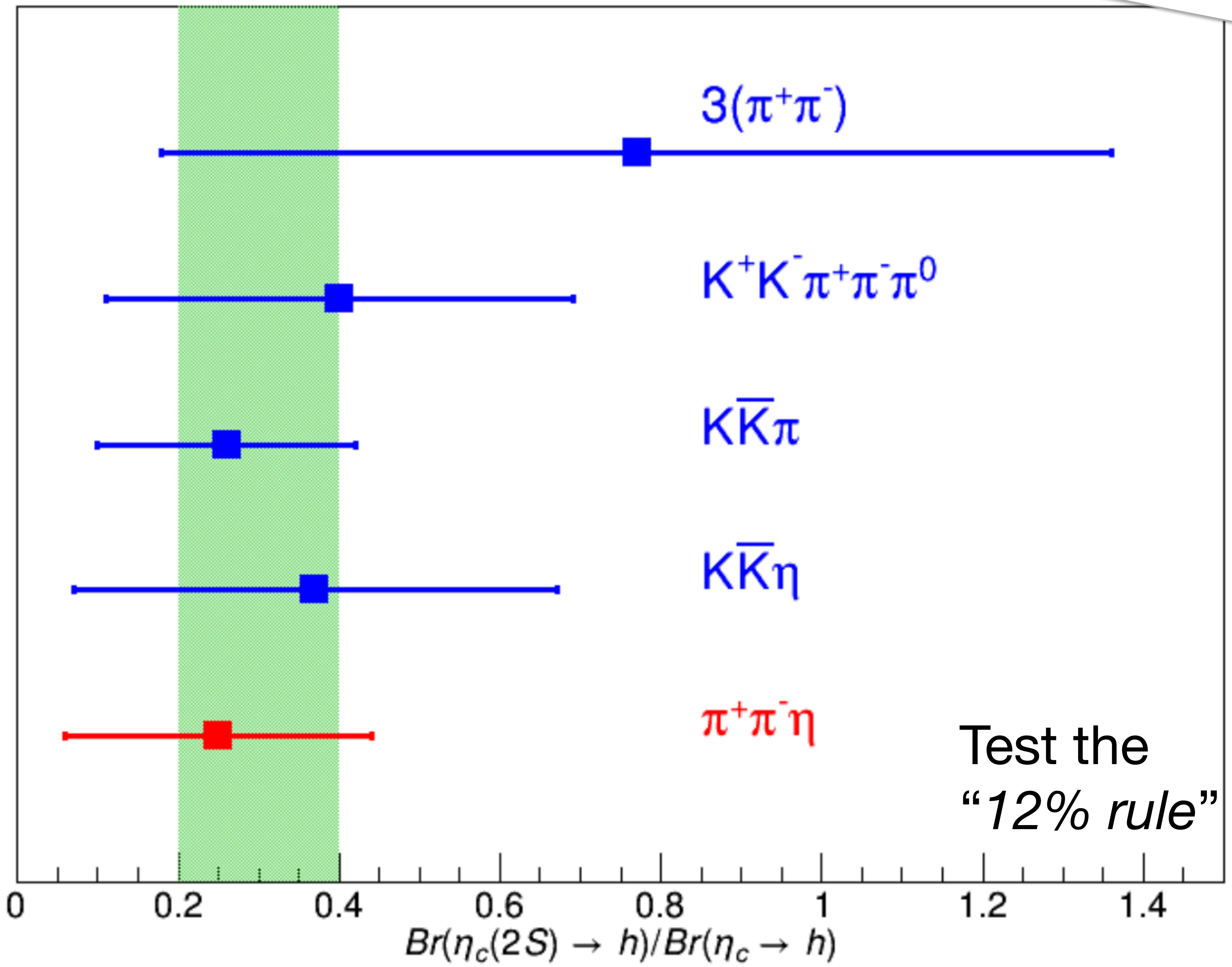


Test the "*12% rule*"

Predictions for 0^{-+} glueball-charmonium mixing

Ref. [1] ⇝ ~12.8%
Ref. [2] ⇝ ~1.00

[1] Phys. Rev. D **44**, 1597 (1991)
[2] Commun. Theor. Phys. **25**, 471 (1996)

The Singlet $\eta_c(2S)$ Charmonium

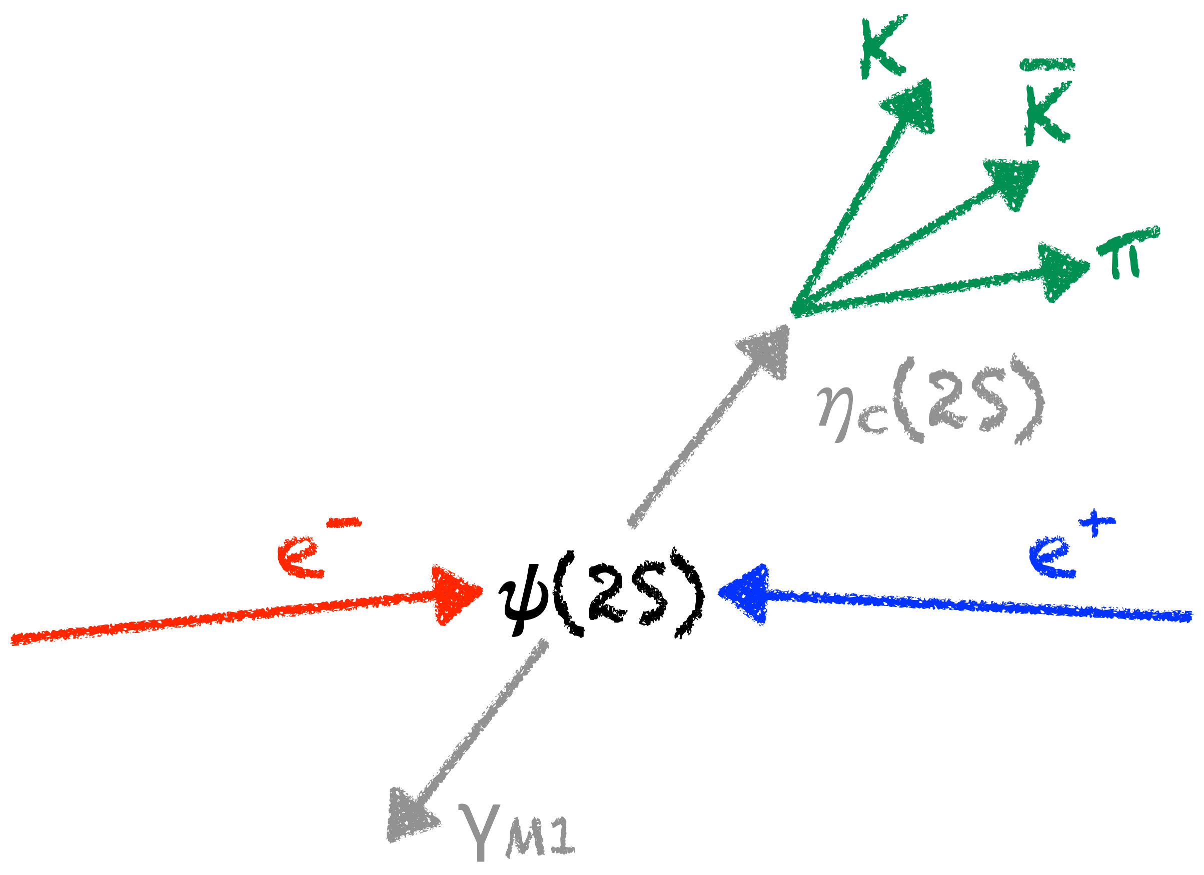
$\eta_c(2S) \to K\bar{K}\pi$ Decay

arXiv:2309.14689
Accepted by PRD

Using the 3 billion $\psi(2S)$ data set

Search for the $\boldsymbol{\eta_c(2S) \to K\bar{K}\pi}$ **decay** and **estimation of the M1 $\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S))$**

Simultaneous fit to the **$M(K^+K^-\pi^0)$** and **$M(K_S^0K^\pm\pi^\mp)$** spectra



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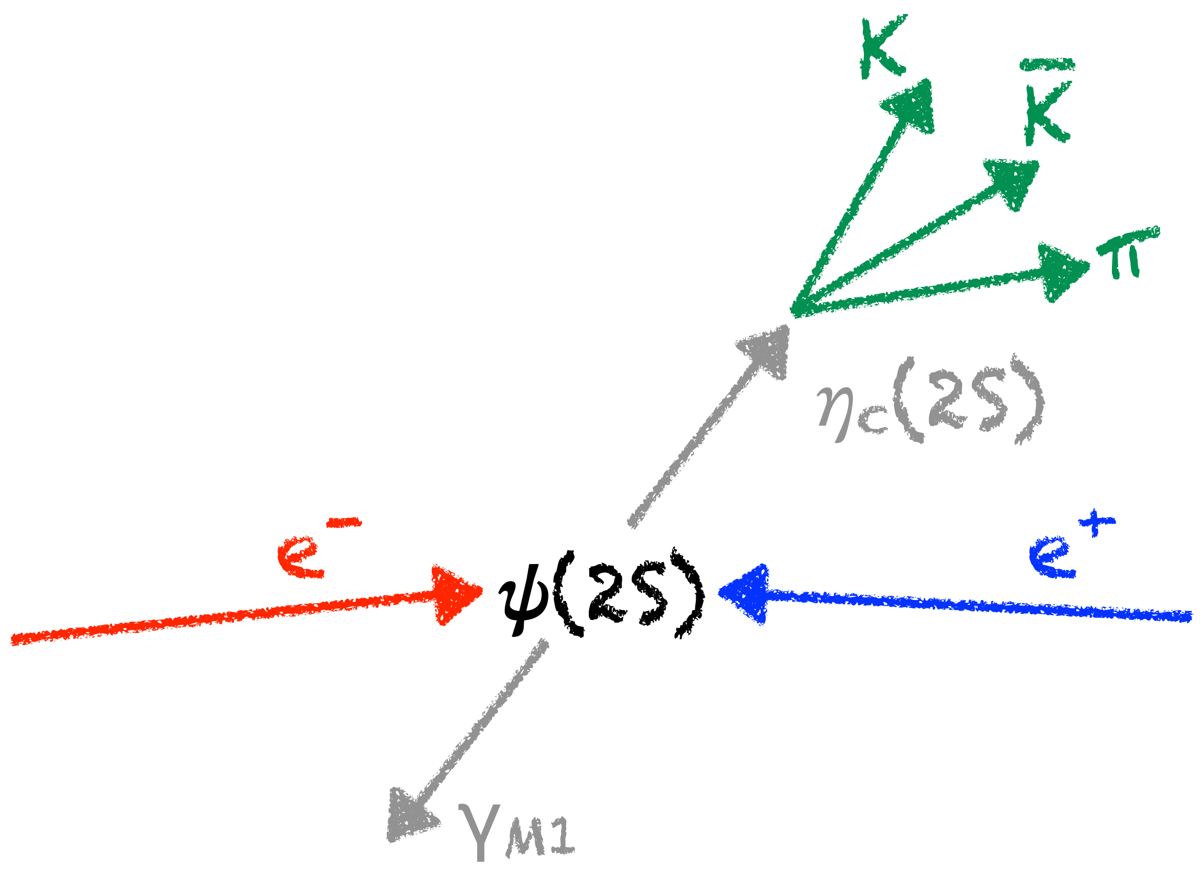

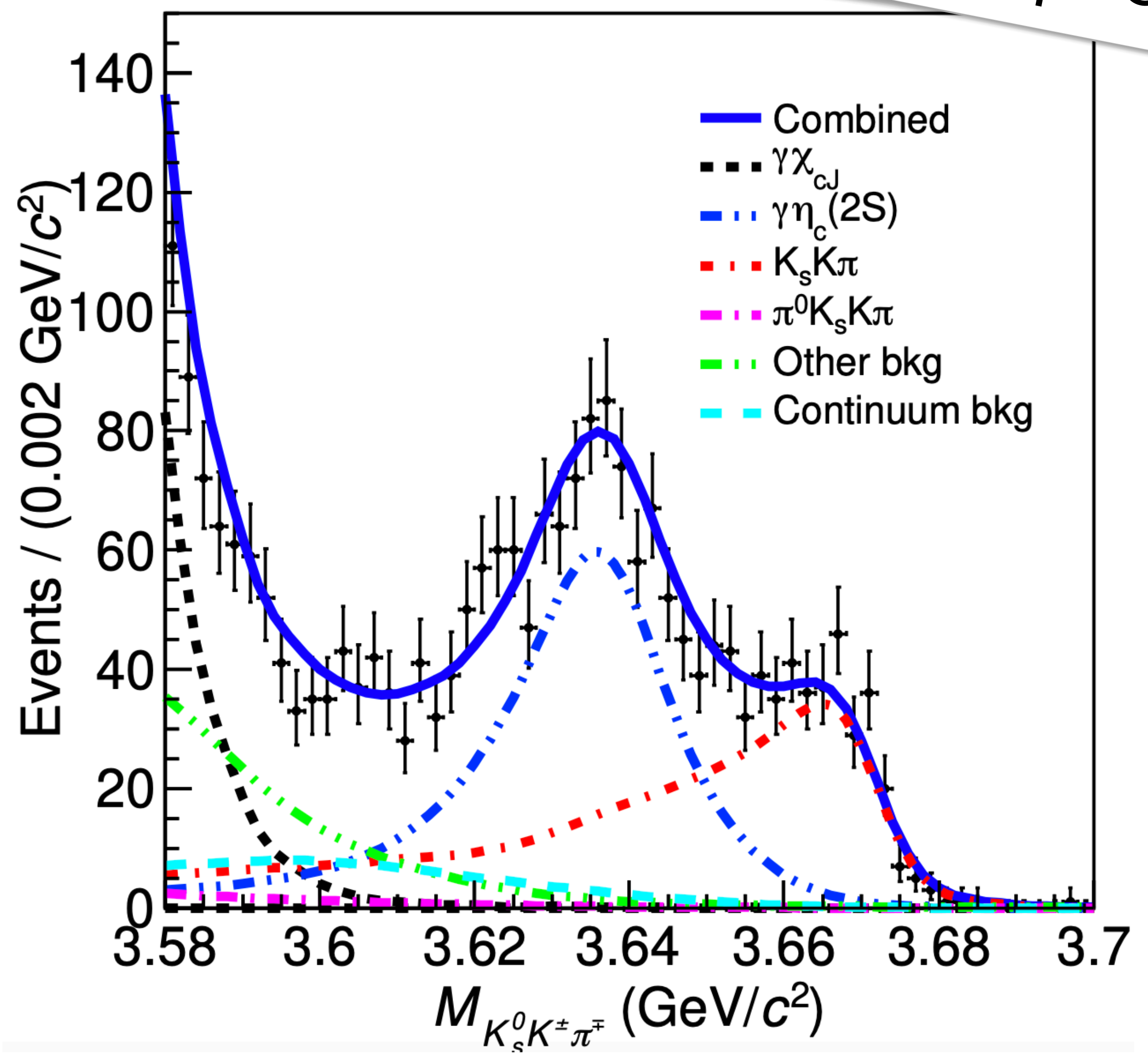

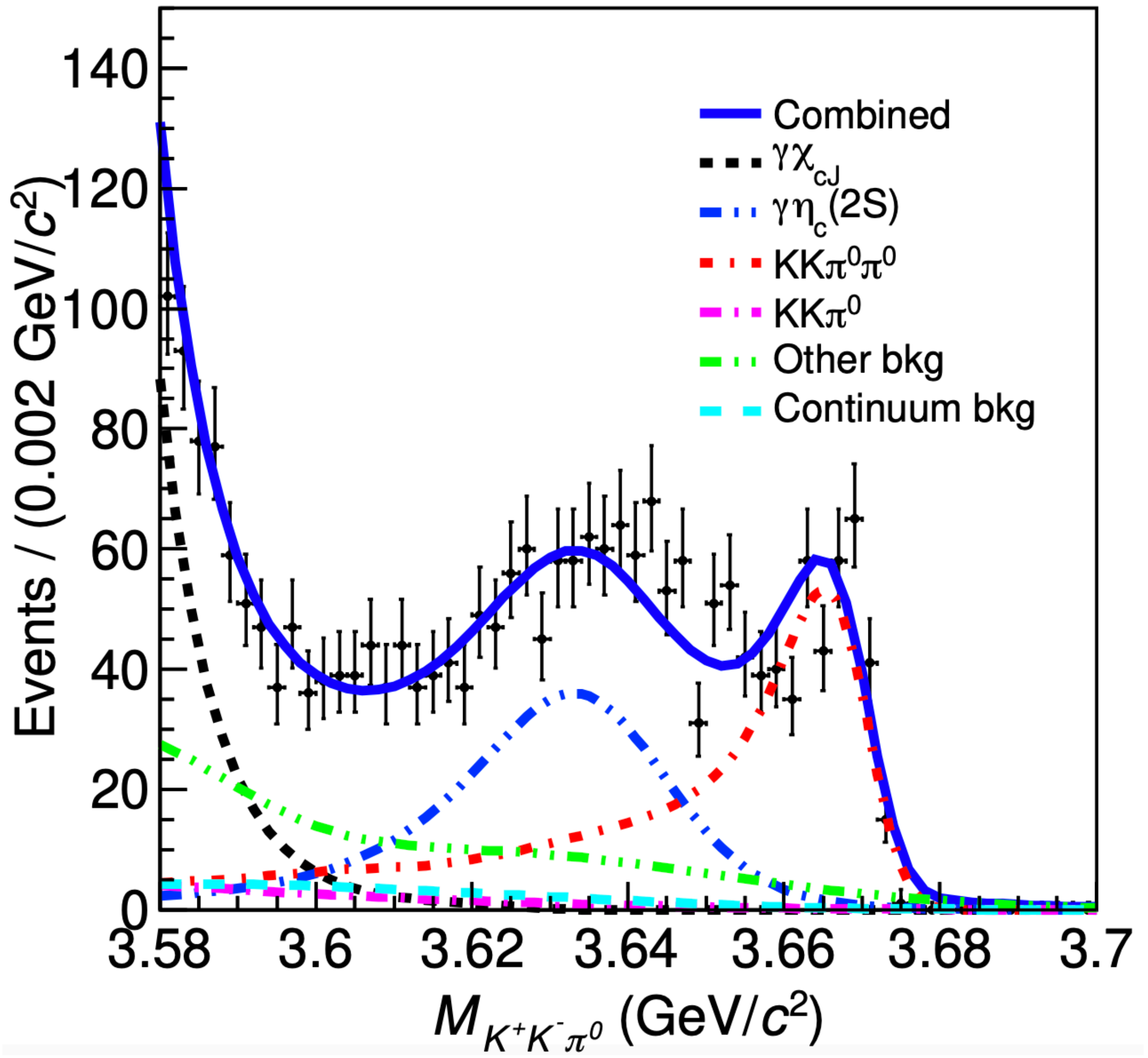

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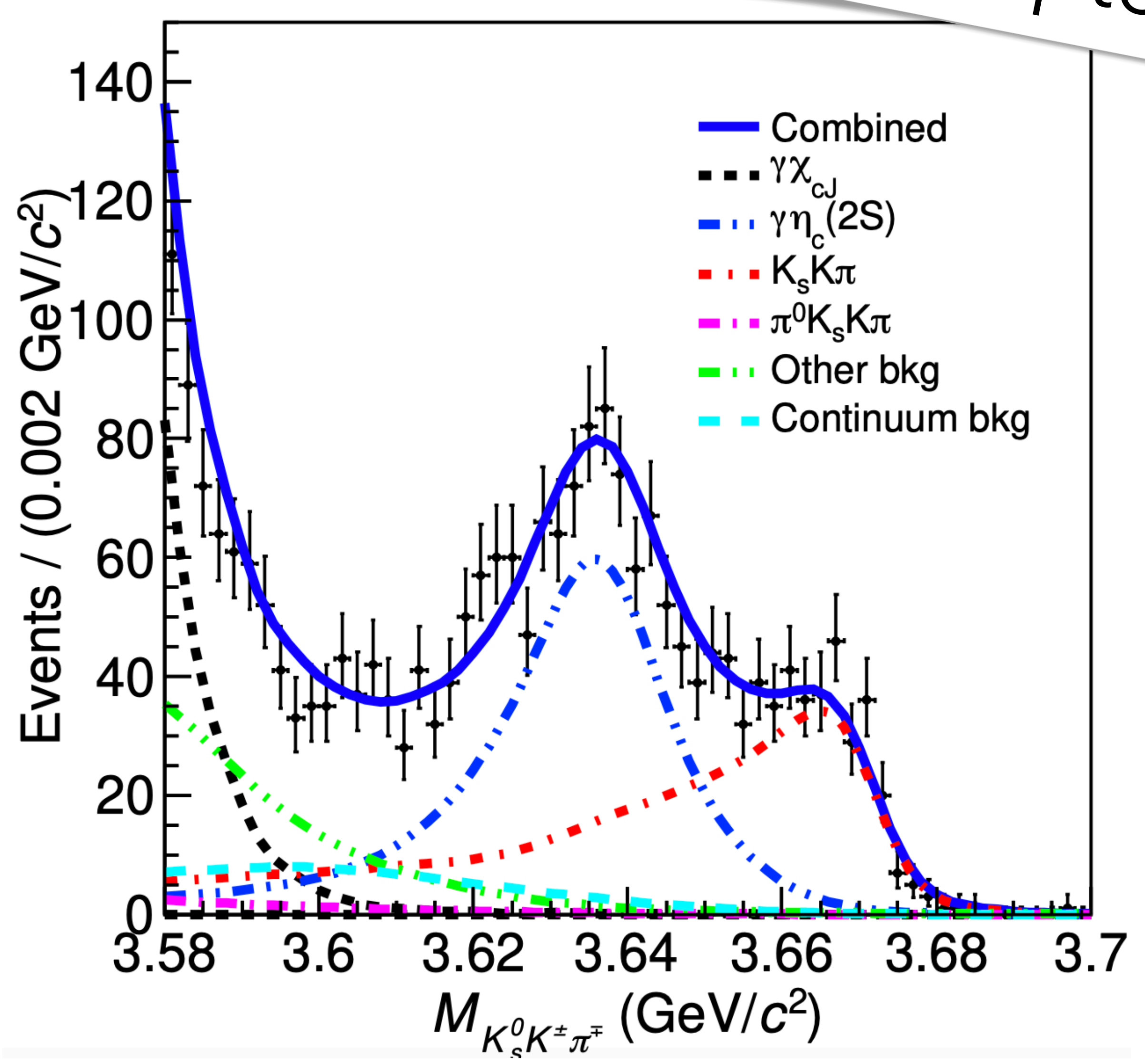
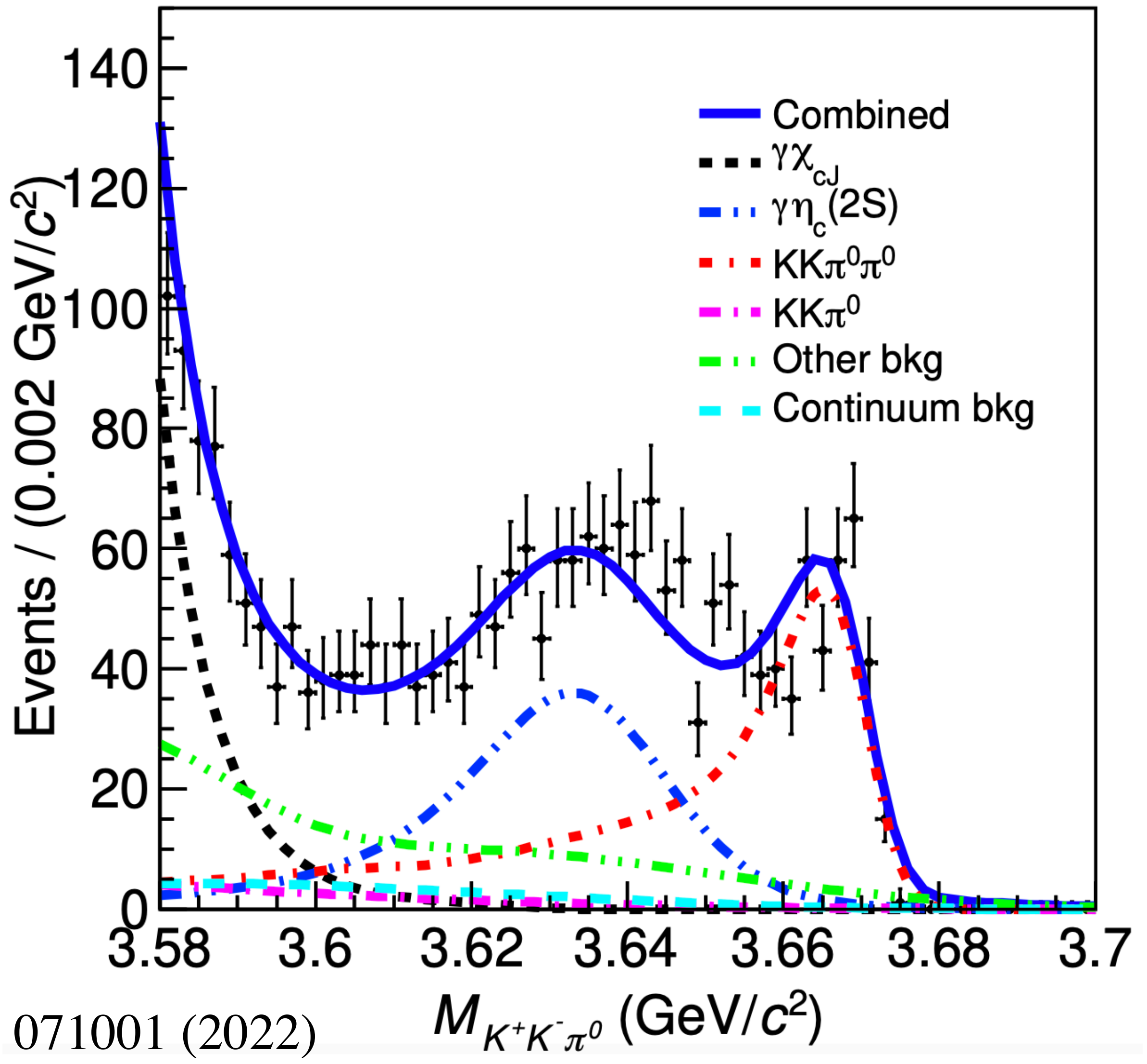
Hence, we obtain…

From $\mathcal{B}(\eta_c(2S) \to K\bar{K}\pi) = (1.86^{+0.68}_{-0.49})\%$ [3]

	Mass (MeV/c^2)	Width (MeV)	$\mathcal{B}(\psi(3686) \to \gamma\eta_c(2S))$ ($\times 10^{-4}$)	$\Gamma(\psi(3686) \to \gamma\eta_c(2S))$ (keV)
This work	$3637.8 \pm 0.8 \pm 0.2$	$10.5 \pm 1.7 \pm 3.5$	$5.2 \pm 0.3 \pm 0.5 ^{+1.9}_{-1.4}$	$0.15 ^{+0.06}_{-0.04}$
World average	3637.6 ± 1.2	$11.3 ^{+3.2}_{-2.9}$	7 ± 5	0.21 ± 0.15





[3] Chin. Phys. C 46 071001 (2022)

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$\eta_c(2S) \to K\bar{K}\pi$ Decay

arXiv:2309.14689
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Comparison with theoretical expectations…

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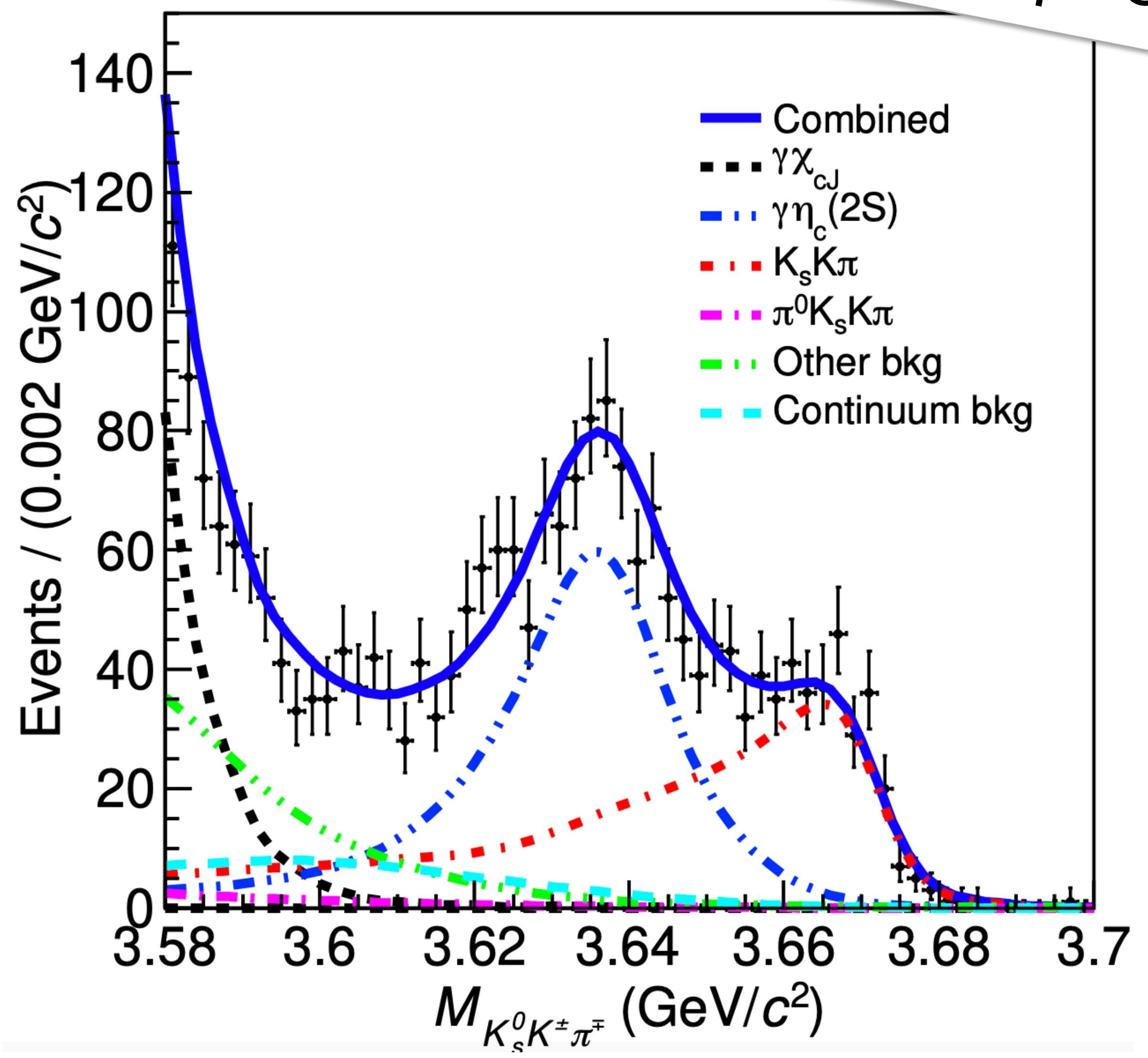
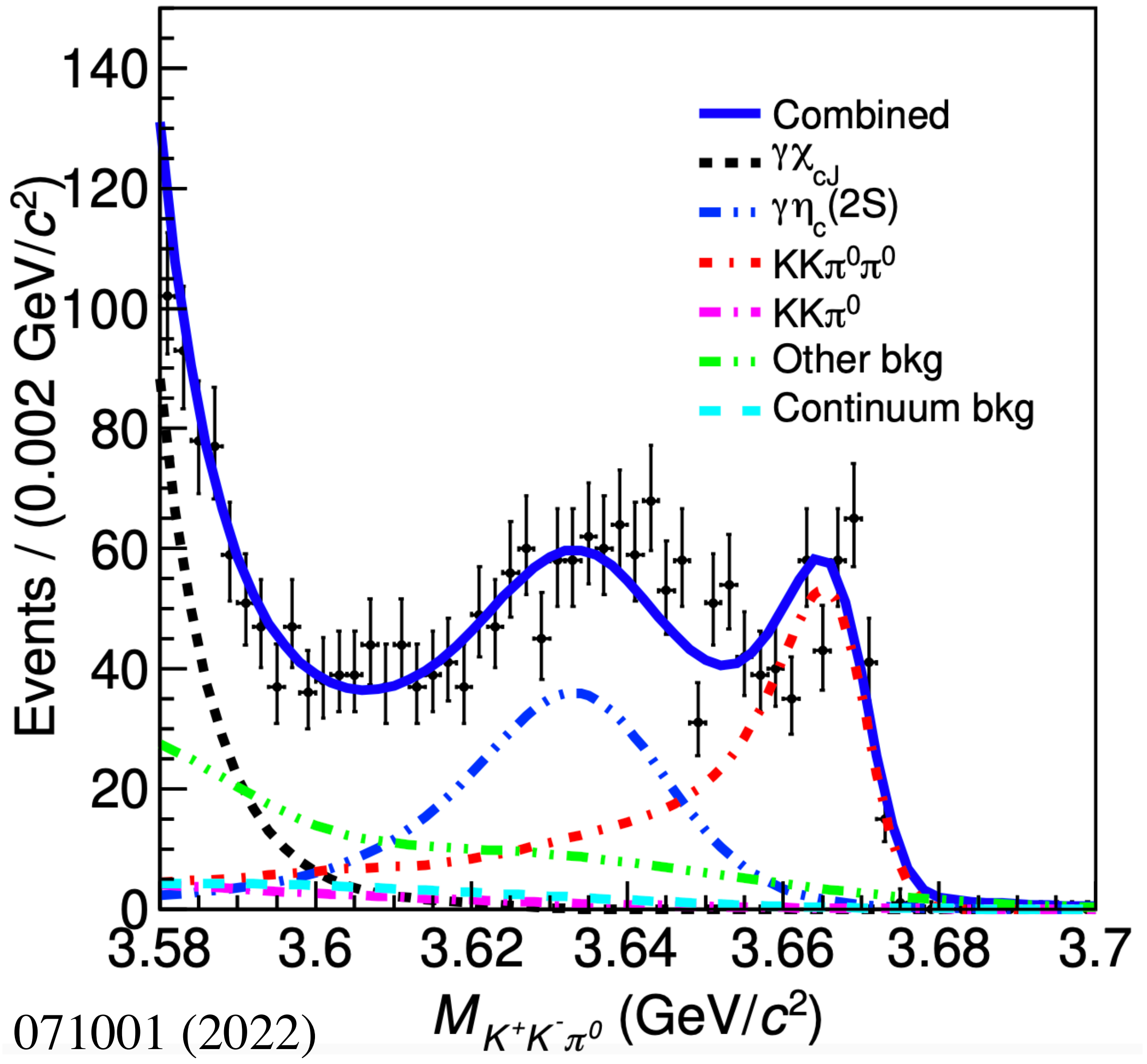
NR model [4]	3630	7.14 ± 0.19	0.21
GI model [4]	3623	5.80 ± 0.16	0.17
Meson loop correction [5]	N/A	2.72 ± 1.00	0.08 ± 0.03
Light-front quark model [6]	3637	3.9	0.11
Effective field theory [7]	N/A	$0.6 - 36.0$	N/A





[3] Chin. Phys. C 46 071001 (2022)
[4] Phys. Rev. D 72, 054026 (2005)
[5] Phys. Lett. B 670, 55-60 (2008)
[6] Eur. Phys. J. A 48, 66 (2012)
[7] arXiv:0909.2812 [hep-ex]

The Singlet $\eta_c(2S)$ Charmonium

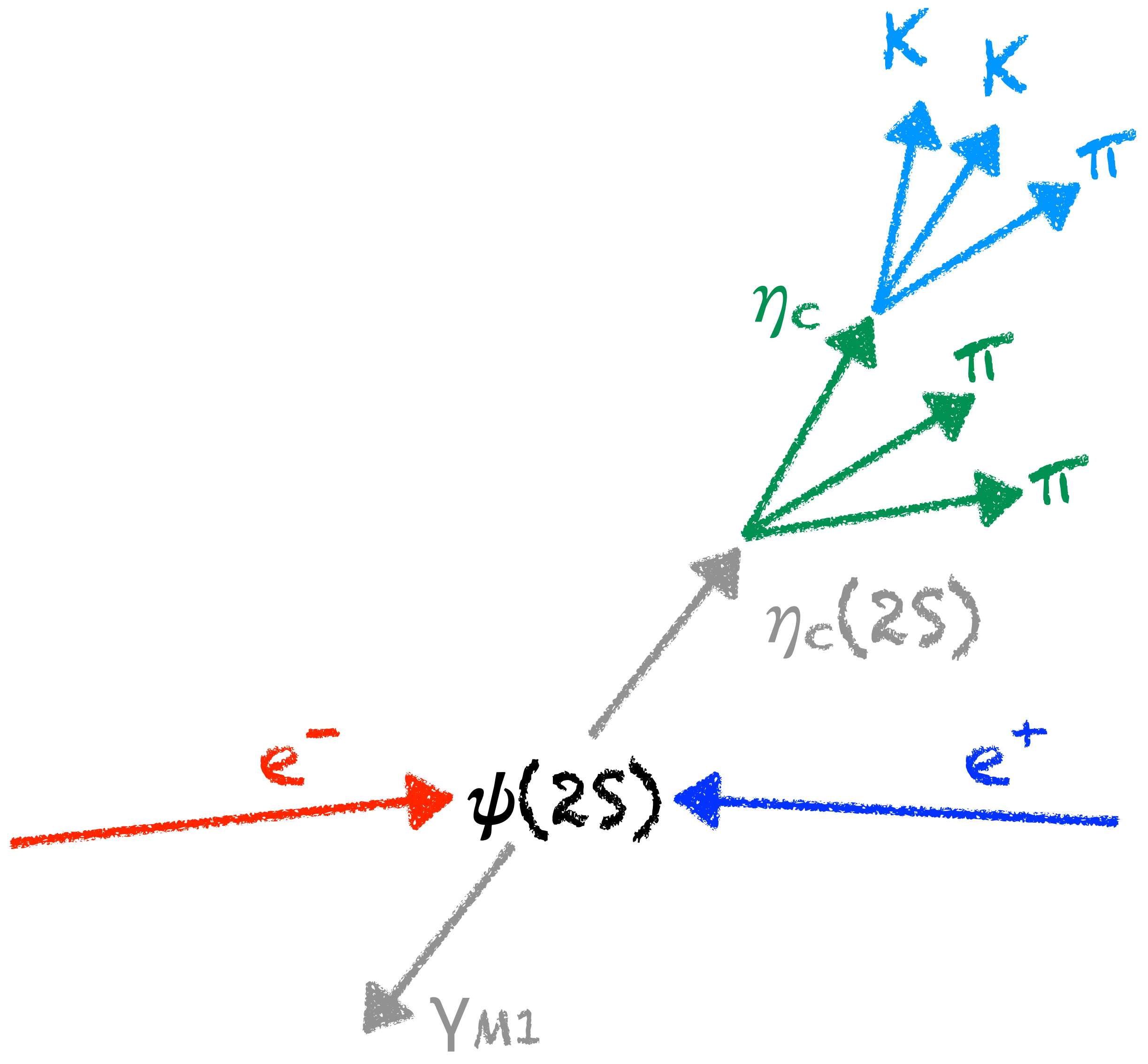
$\eta_c(2S) \to \pi^+\pi^-(\eta_c/K_S{}^0K^\pm\pi^\mp)$ Decay

arXiv:2401.05457
Submitted to PRD

Using the 3 billion $\psi(2S)$ data set

Search for the two-pion ***$\eta_c(2S)$* $\to \pi^+\pi^-\eta_c \to \pi^+\pi^-$*$(K\bar{K}\pi)$*** *and* ***$\eta_c(2S)$* $\to \pi^+\pi^-K_S{}^0K^\pm\pi^\mp$ transitions**

Fit to $M(\pi^+\pi^-K_S{}^0K^\pm\pi^\mp)$ to search **for** the ***$\eta_c(2S)$* $\to \pi^+\pi^-K_S{}^0K^\pm\pi^\mp$ decay**



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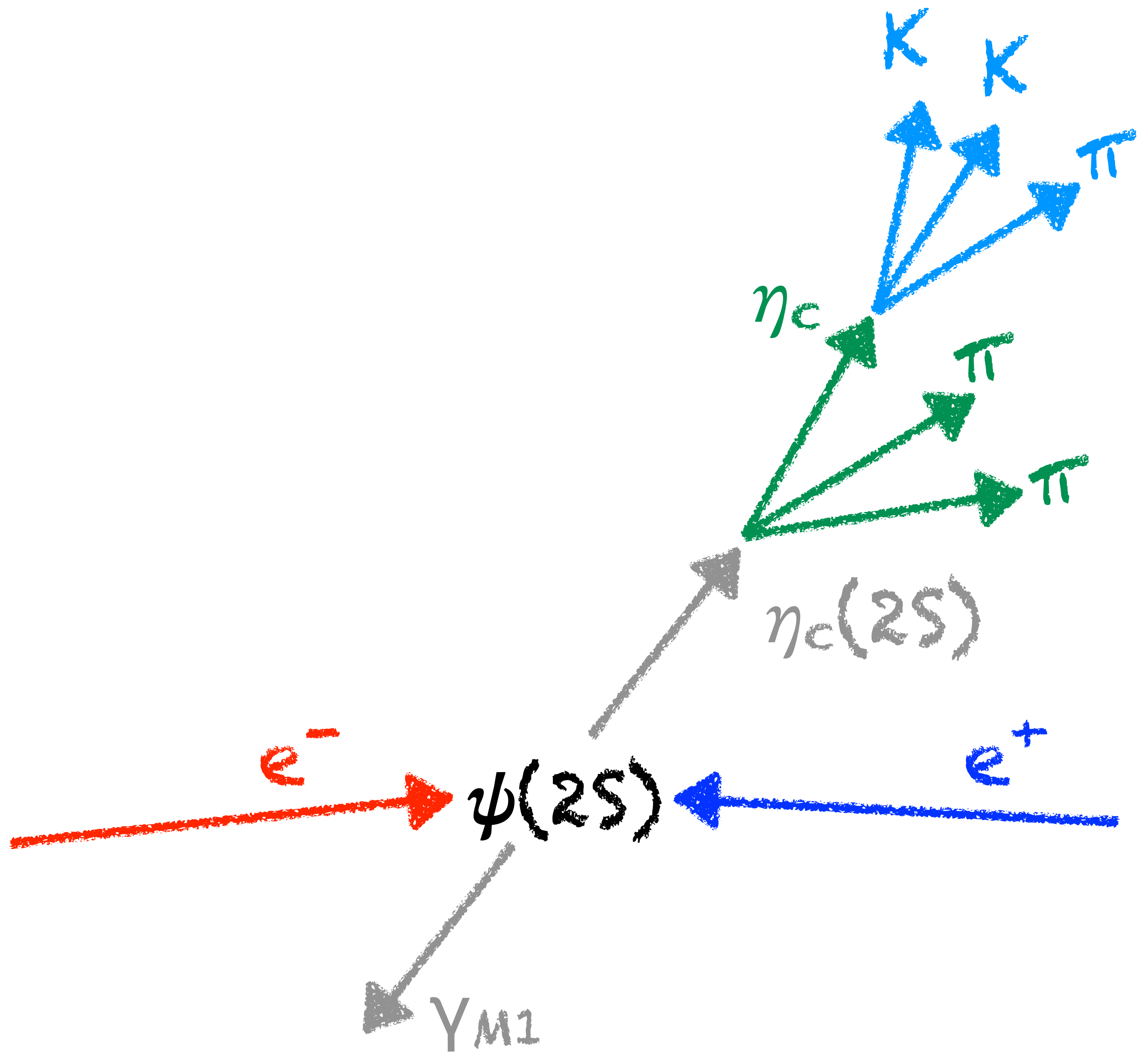

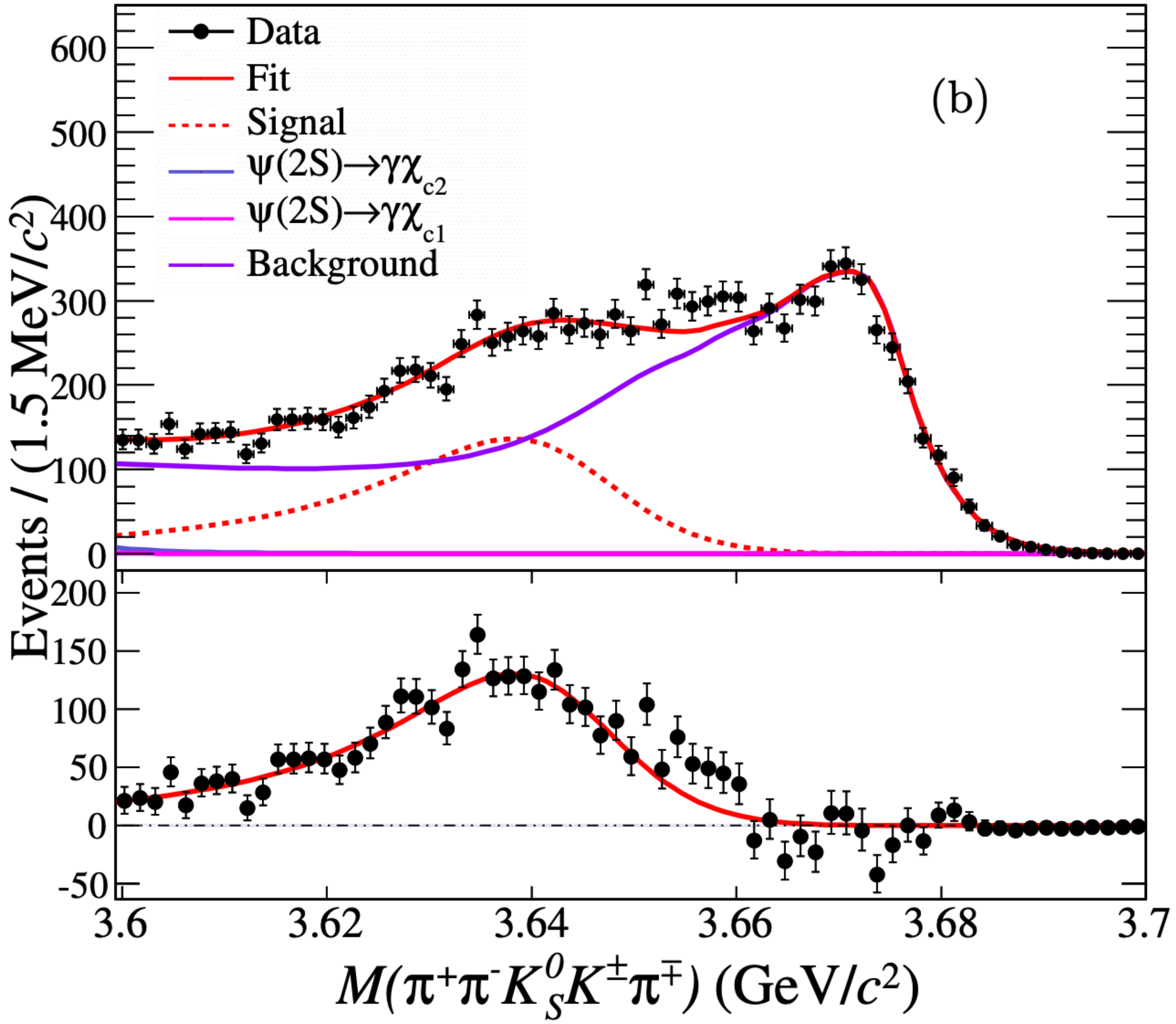

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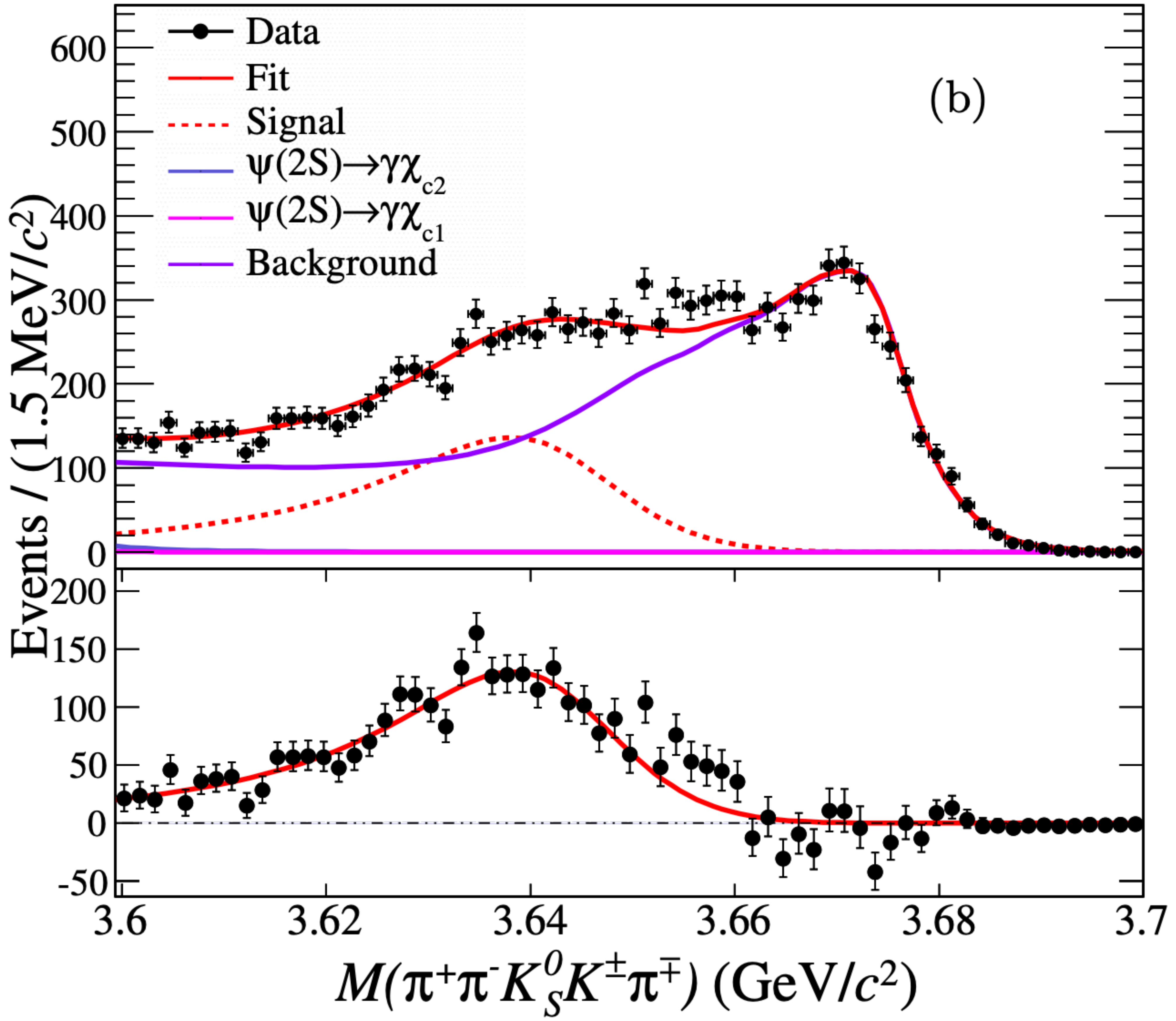
Fit to $\boldsymbol{M(\pi^+\pi^- K_S^0 K^\pm \pi^\mp)}$ to search **for the** $\boldsymbol{\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp}$ **decay**

$\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta_c) < 2.21 \times 10^{-5}$ @90% C.L.



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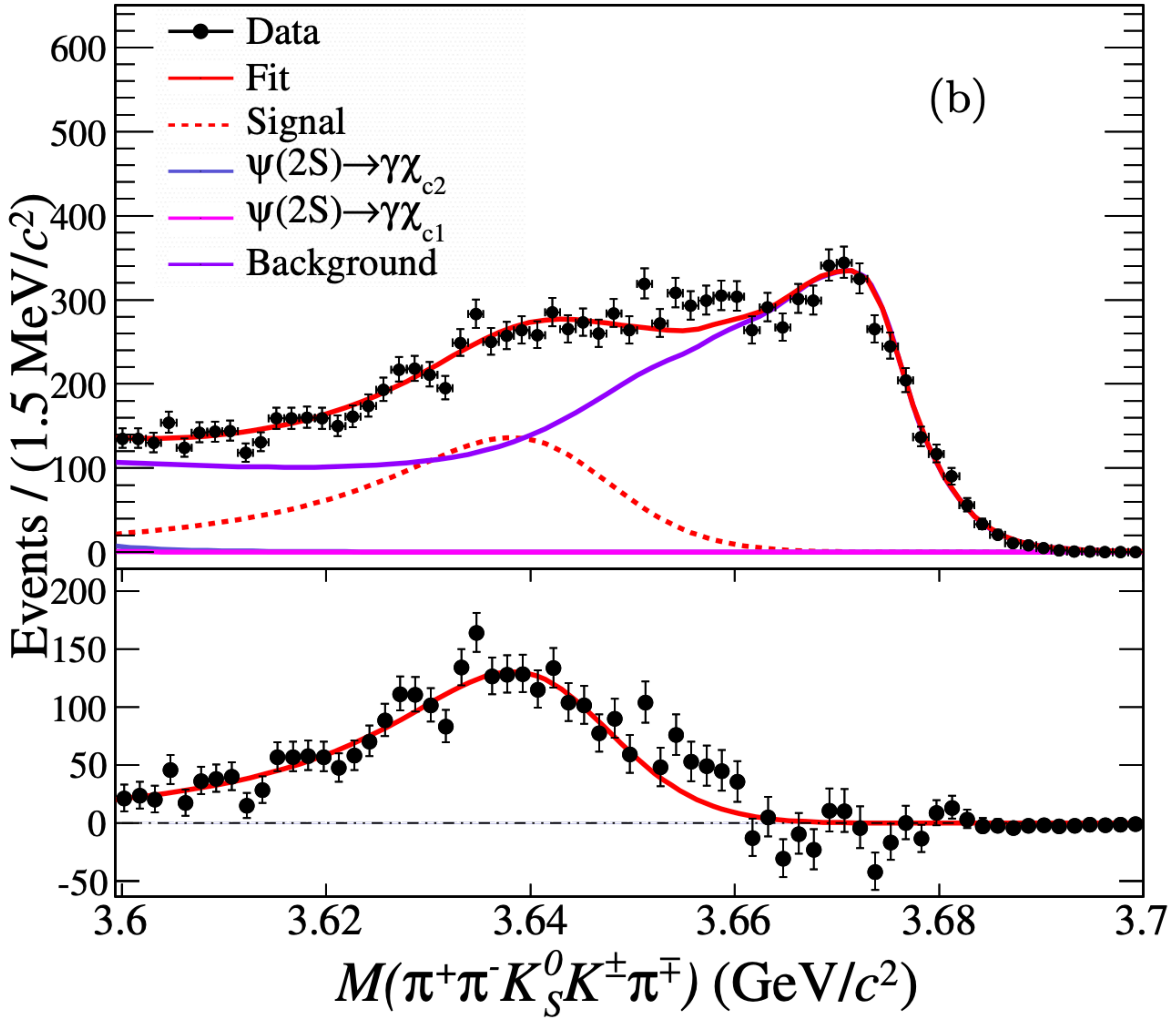
Refs. [8, 9] estimate $\boldsymbol{\mathcal{B}(\psi(2S) \to \gamma\eta_c(2S)) \times \mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta_c) \sim 2.6 \times 10^{-5}}$
(additional suppression from stronger chromo-magnetic interaction)



[8] Mod. Phys. Lett. A 17, 1533 (2002)
[9] Phys. Rev. D 74, 054022 (2006)

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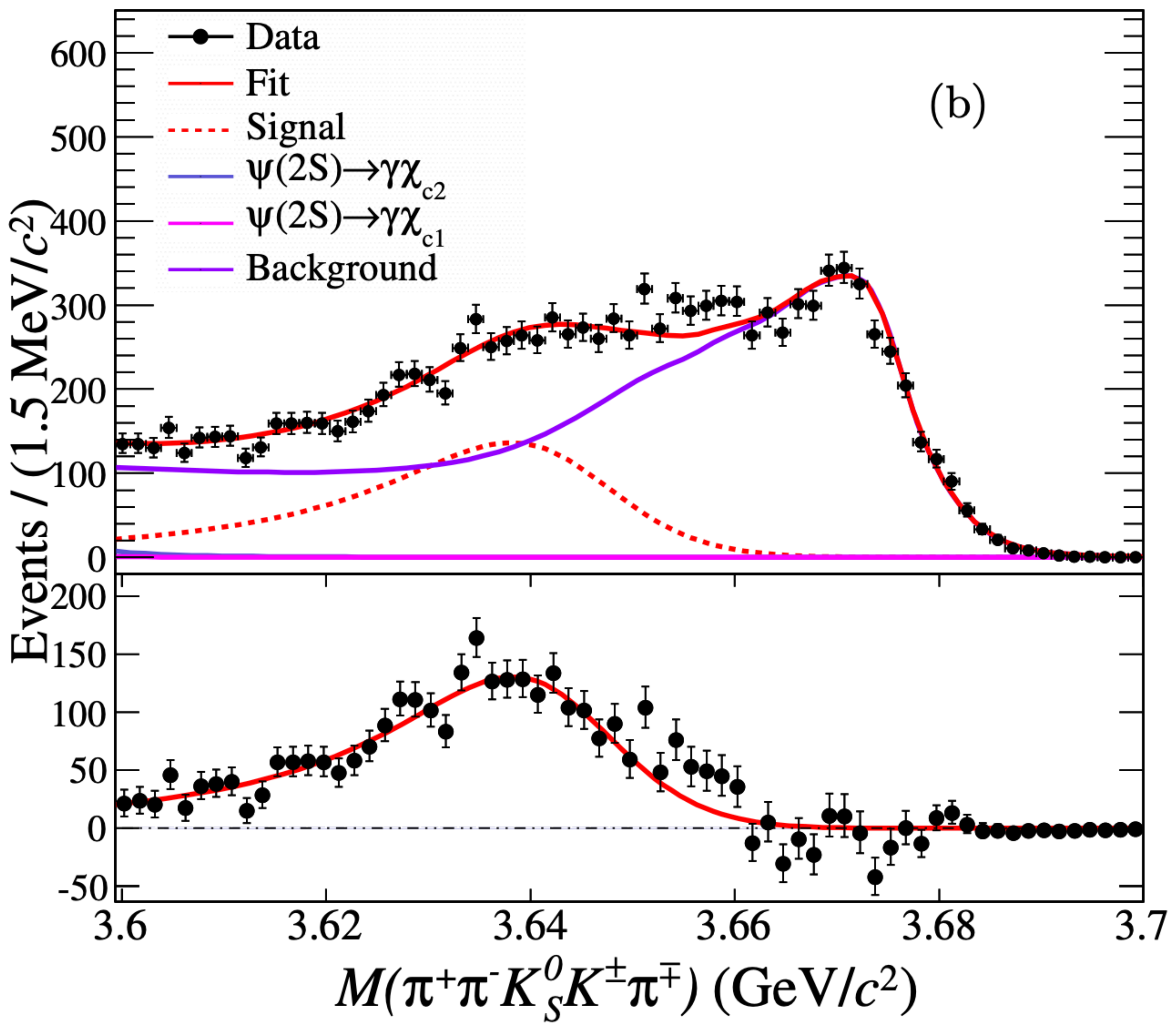
(additional suppression from stronger chromo-magnetic interaction)

For the first time

$\mathcal{B}(\eta_c(2S) \to \pi^+\pi^- K_S^0 K^\pm \pi^\mp) = (1.33 \pm 0.11 \pm 0.4 \pm 0.95)$ %

NB The sum of $\mathcal{B}(\eta_c(2S))$ is ~ 3%



[8] Mod. Phys. Lett. A 17, 1533 (2002)
[9] Phys. Rev. D 74, 054022 (2006)

Investigating the $\psi(3770)$ Resonance

$\psi(3770) \to \eta J/\psi$

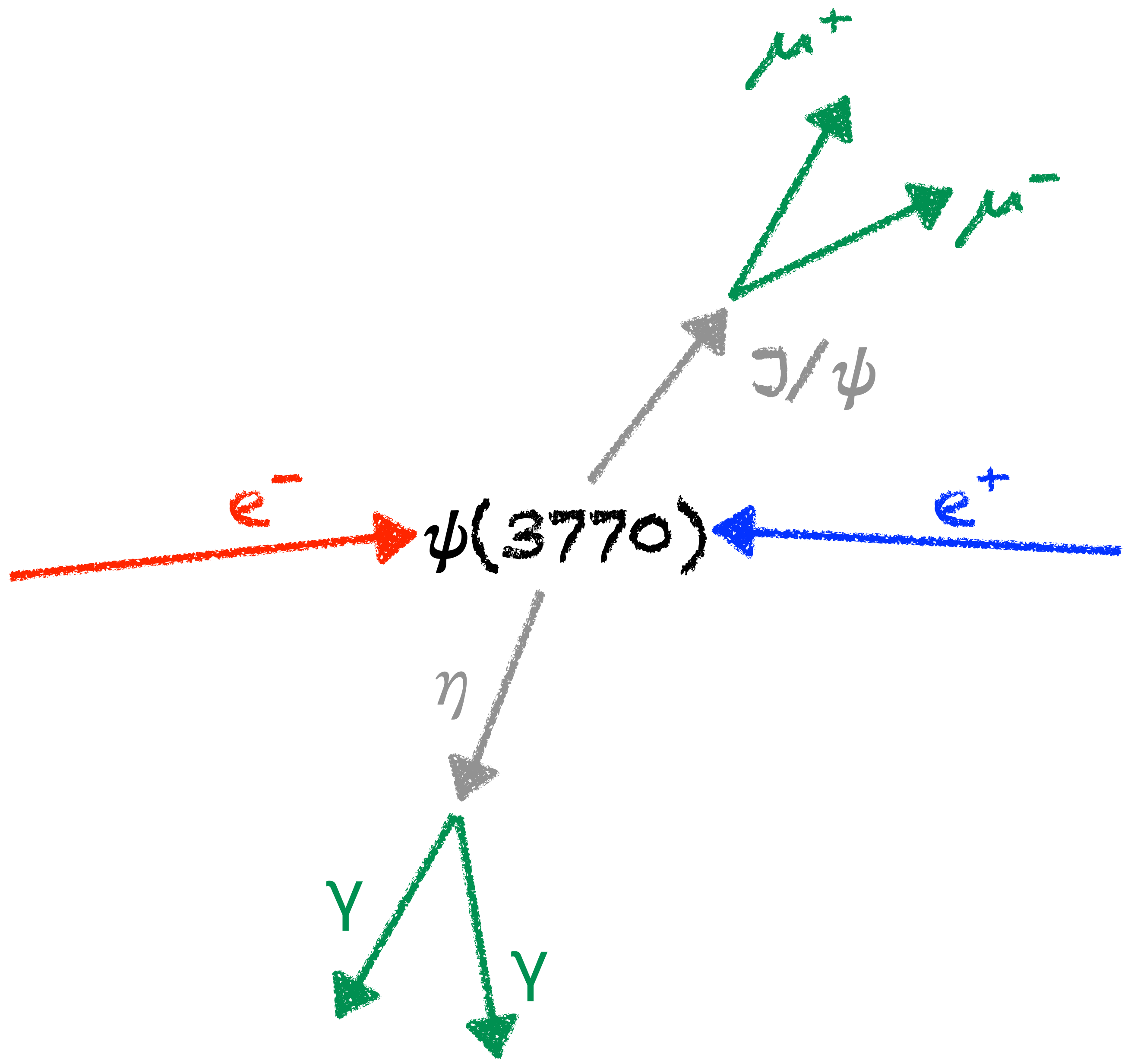
Phys. Rev. D **107**, L091101 (2023)

Using the 2.9 fb^{-1} $\psi(3770)$ data set

Search for the $\psi(3770) \to \eta J/\psi$ decay, and **study of the $\sigma(e^+e^- \to \eta J/\psi)$ line-shape @$\sqrt{s}$ = [3.773, 4.600] GeV**

From Ref. [10], data points @$\sqrt{s}$ = [3.8, 4.6] GeV are taken

Two hypotheses are considered, the $\psi(3770)$ contribution is added either coherently or incoherently



Investigating the $\psi(3770)$ Resonance

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Phys. Rev. D **107**, L091101 (2023)

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Search for the ψ(3770) → ηJ/ψ decay, and **study of the σ(e^+e^- → ηJ/ψ) line-shape @√s = [3.773, 4.600] GeV**

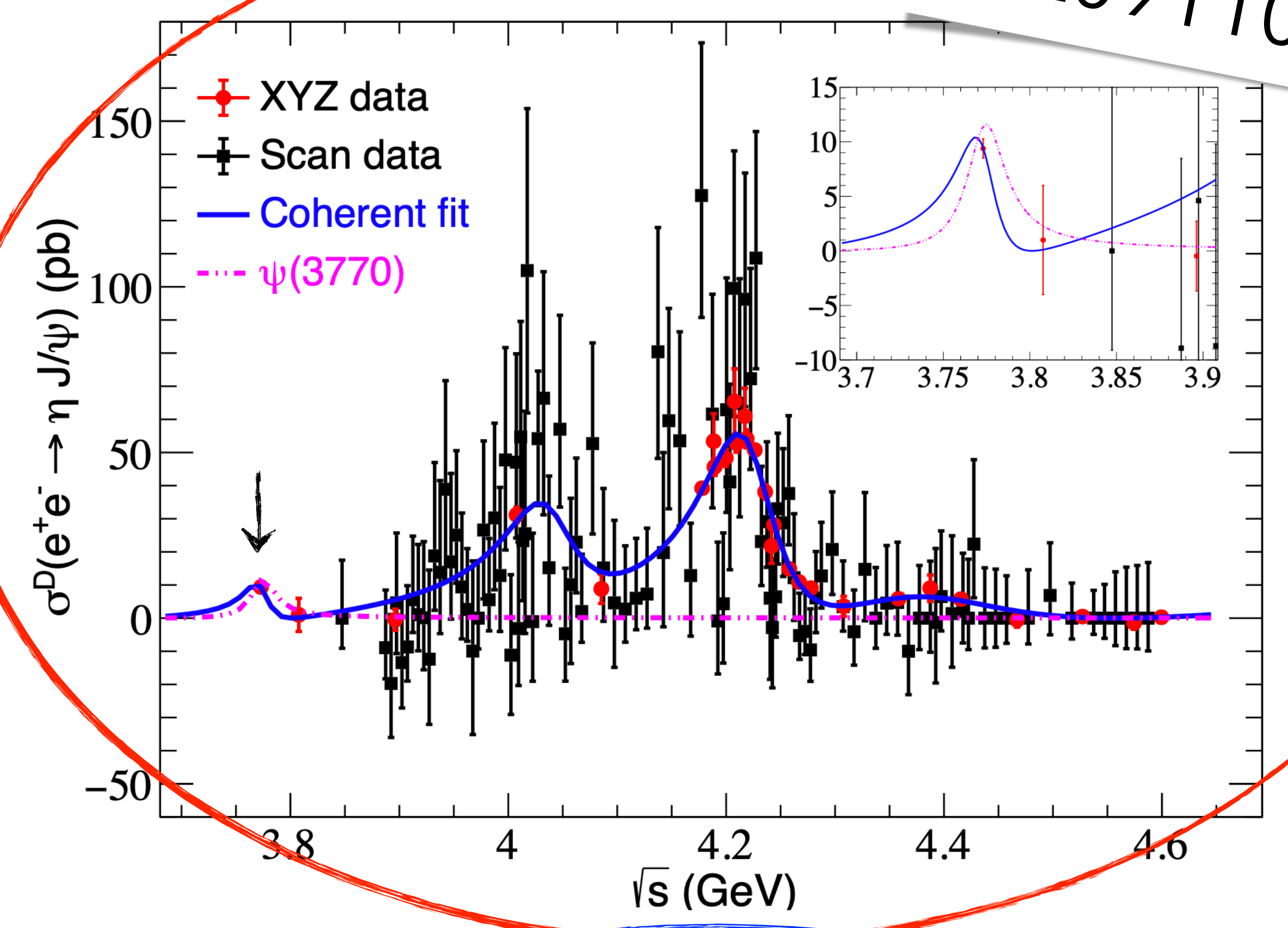
From Ref. [10], data points @√s = [3.8, 4.6] GeV are taken

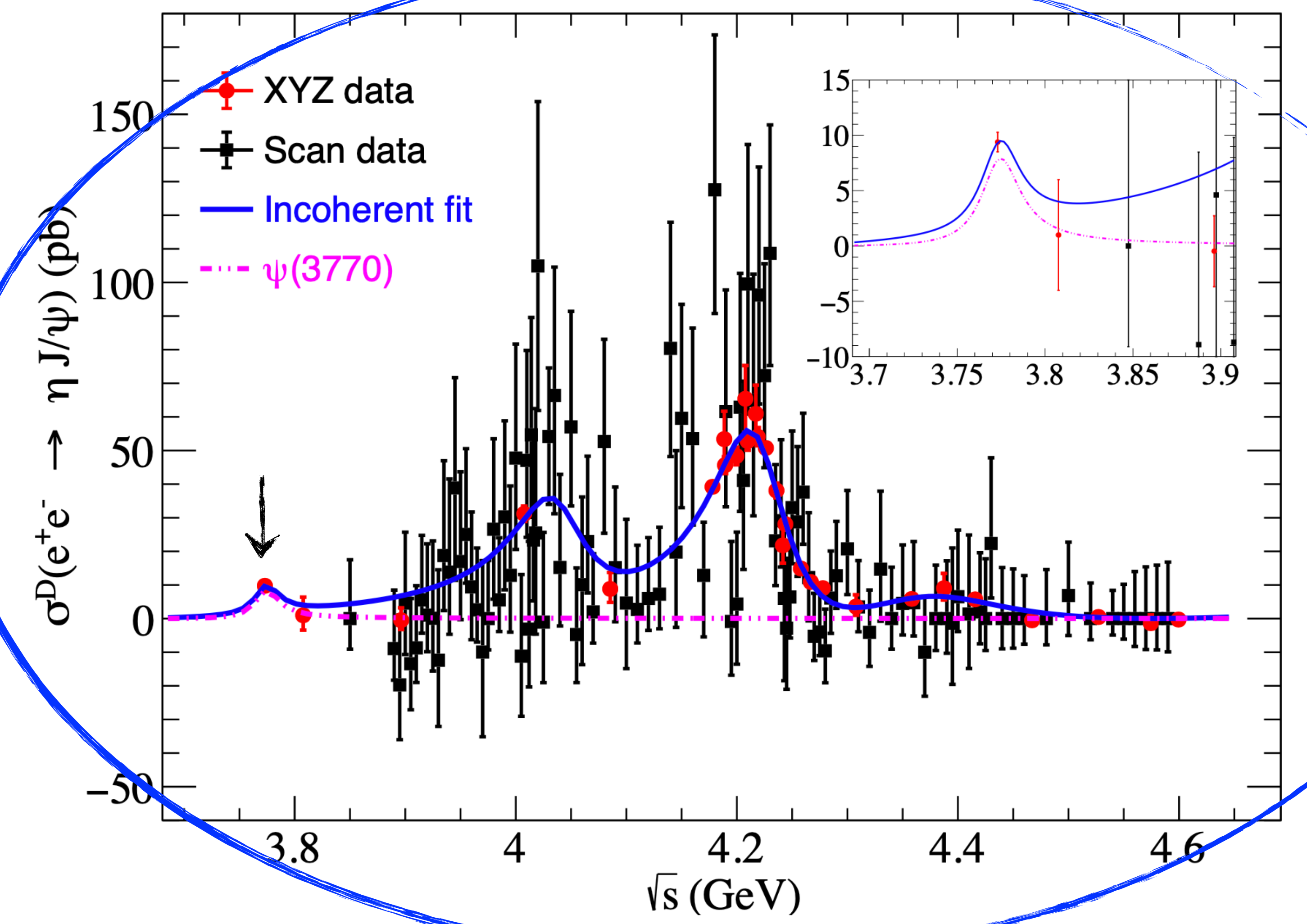
Two hypotheses are considered, the ψ(3770) contribution is added either coherently or incoherently

Fit scenario		$\mathcal{B}(\psi(3770) \to \eta J/\psi)$ $(\times 10^{-4})$	ϕ_1(rad)
Coherent fit	Solution1	$11.6 \pm 6.1 \pm 1.0$	4.0±0.5
	Solution2	$12.0 \pm 6.3 \pm 1.1$	4.3±0.5
	Solution3	$11.6 \pm 6.1 \pm 1.0$	3.8±0.5
	Solution4	$11.9 \pm 6.3 \pm 1.1$	4.1±0.5
Incoherent fit		$7.9 \pm 1.0 \pm 0.7$	-

Compatible with CLEO result[11] (w/o interference) of 8.7 ± 3.3 ± 2.2 x 10^{-4}

In **agreement with Ref. [12]** hypothesis of **tetra-quark admixture** in the **ψ(3770)**
$\mathcal{B}$(ψ(3770) → η J/ψ) ~ 15 x 10^{-4}





[10] Phys. Rev. D **102**, 031101 (R) (2020)
[11] Phys. Rev. Lett. **96**, 082004 (2006)
[12] Phys. Rev. D **71**, 114003 (2005)

Investigating the $\psi(3770)$ Resonance

$\psi(3770) \to K_S^0 K_L^0$

arXiv:2312.10962v1
Accepted by PRL

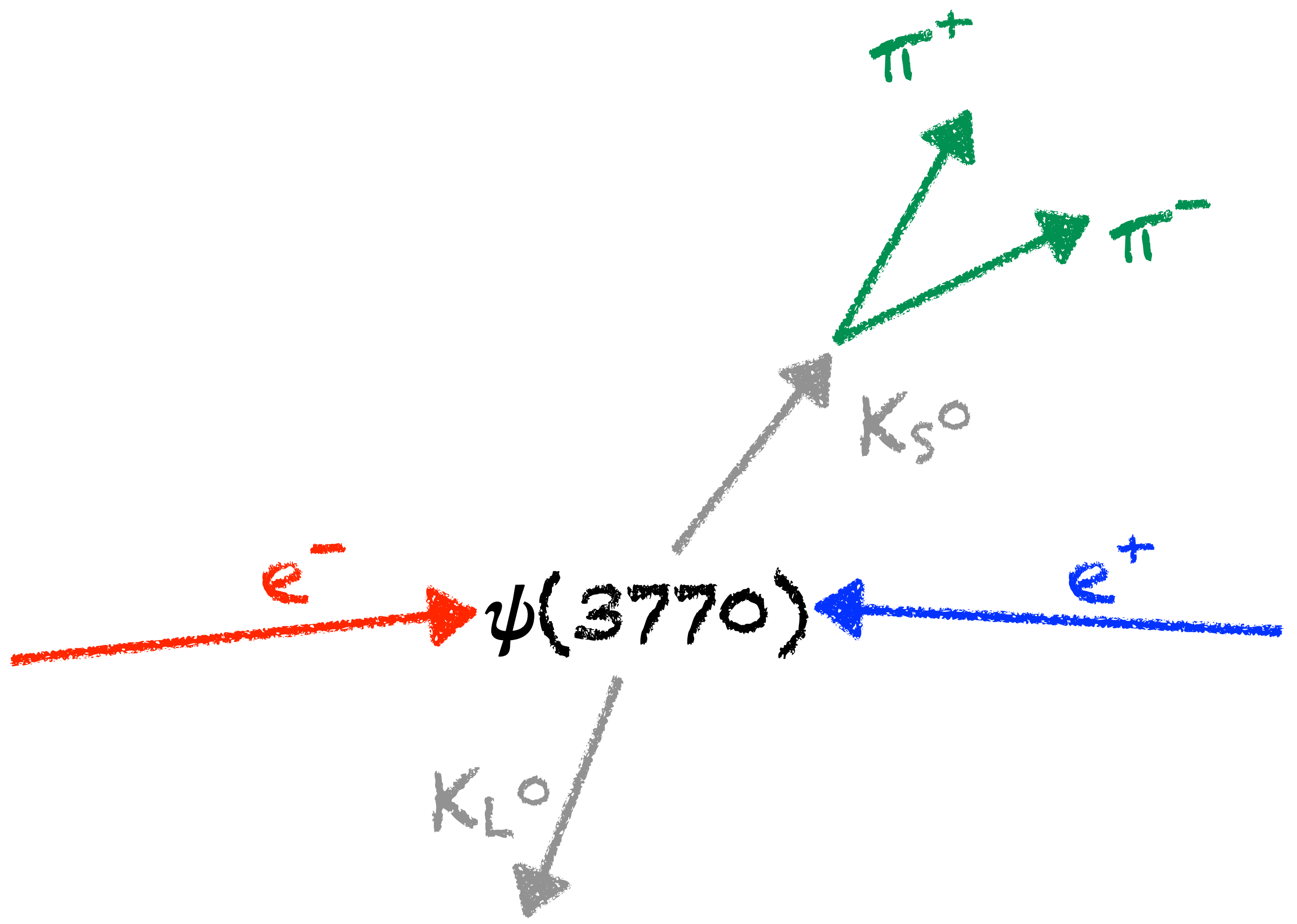
Using the 26.5 fb^{-1} @$\sqrt{s}$ = [3.51, 4.95] GeV

Search for the **$\psi(3770) \to K_S^0 K_L^0$** decay, and **study of the $\sigma(e^+e^- \to K_S^0 K_L^0)$ line-shape**

Fit to E_K/E_{Beam} to extrapolate the $\sigma(e^+e^- \to K_S^0 K_L^0)$ line-shape

The **$K_S^0 K_L^0$** channel is important to **understand** the "**12% rule**" violation, as $\mathcal{R}(K_S^0 K_L^0)$ is found to deviate by more than 3σ [13, 14]

Refs. [15, 16] propose the ψ(3686) and ψ(3770) to be **mixtures** of pure $\psi(2^3S_1)$ and $\psi(1^3D_1)$ states, estimating $\mathcal{B}$**($\psi(3770) \to K_S^0 K_L^0$) ~ [0.02, 5.3]×10^{-5}**



[13] Phys. Rev. D 96, 112001 (2017)
[14] Phys. Rev. Lett. **92**, 052001 (2004)
[15] Phys. Rev. D 64, 094002 (2001)
[16] Phys. Rev. D 70, 077505 (2004)

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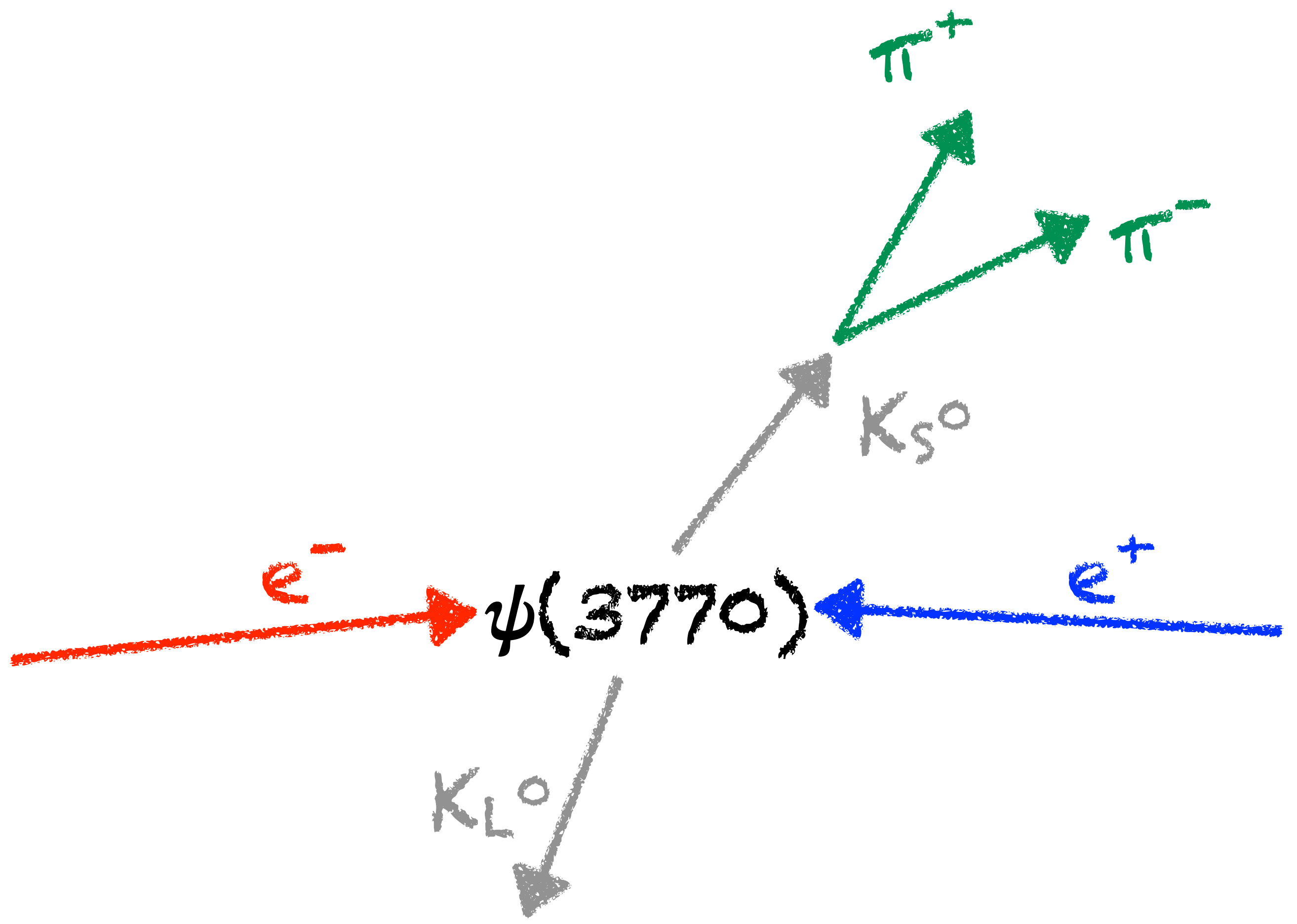

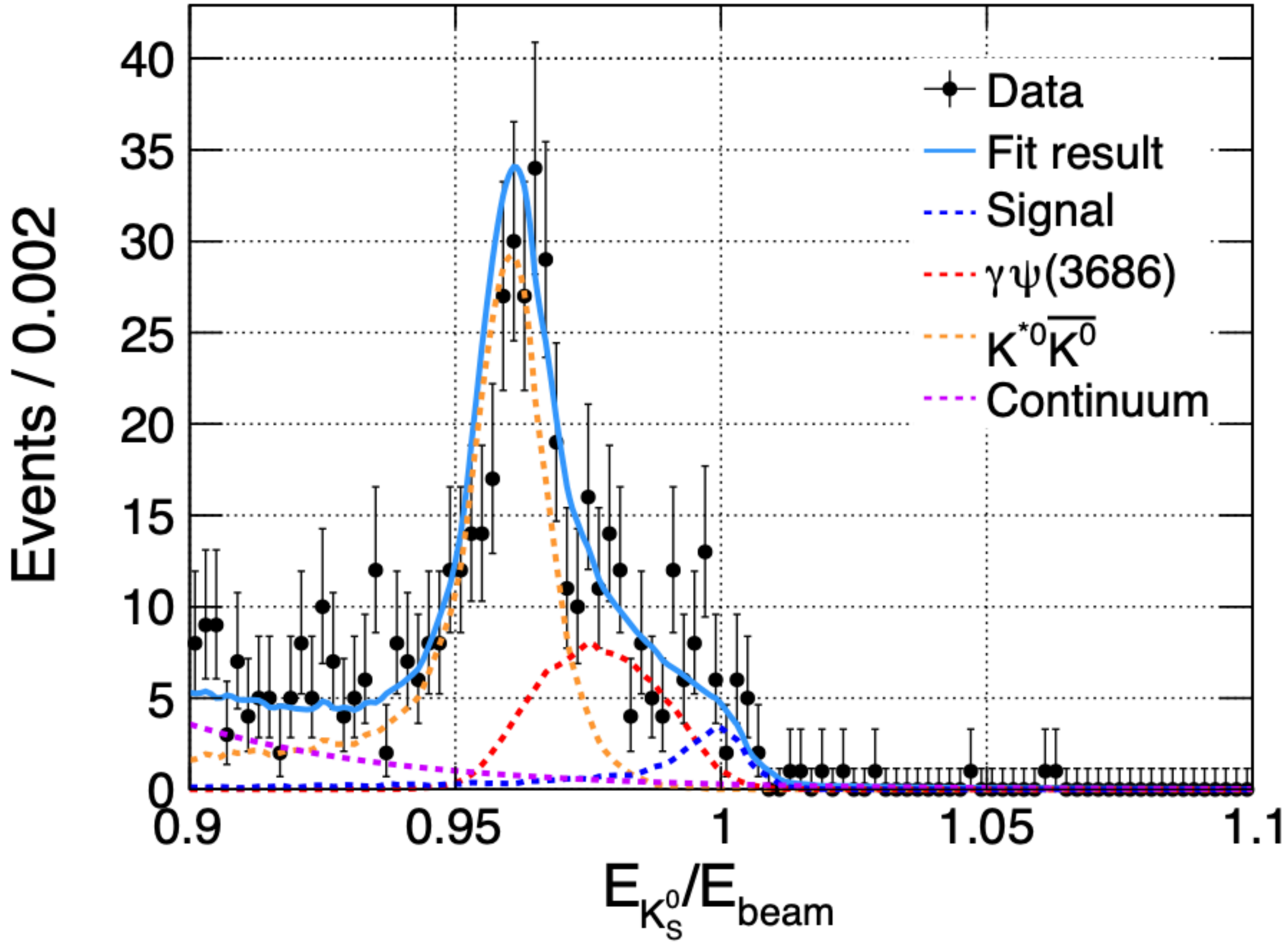

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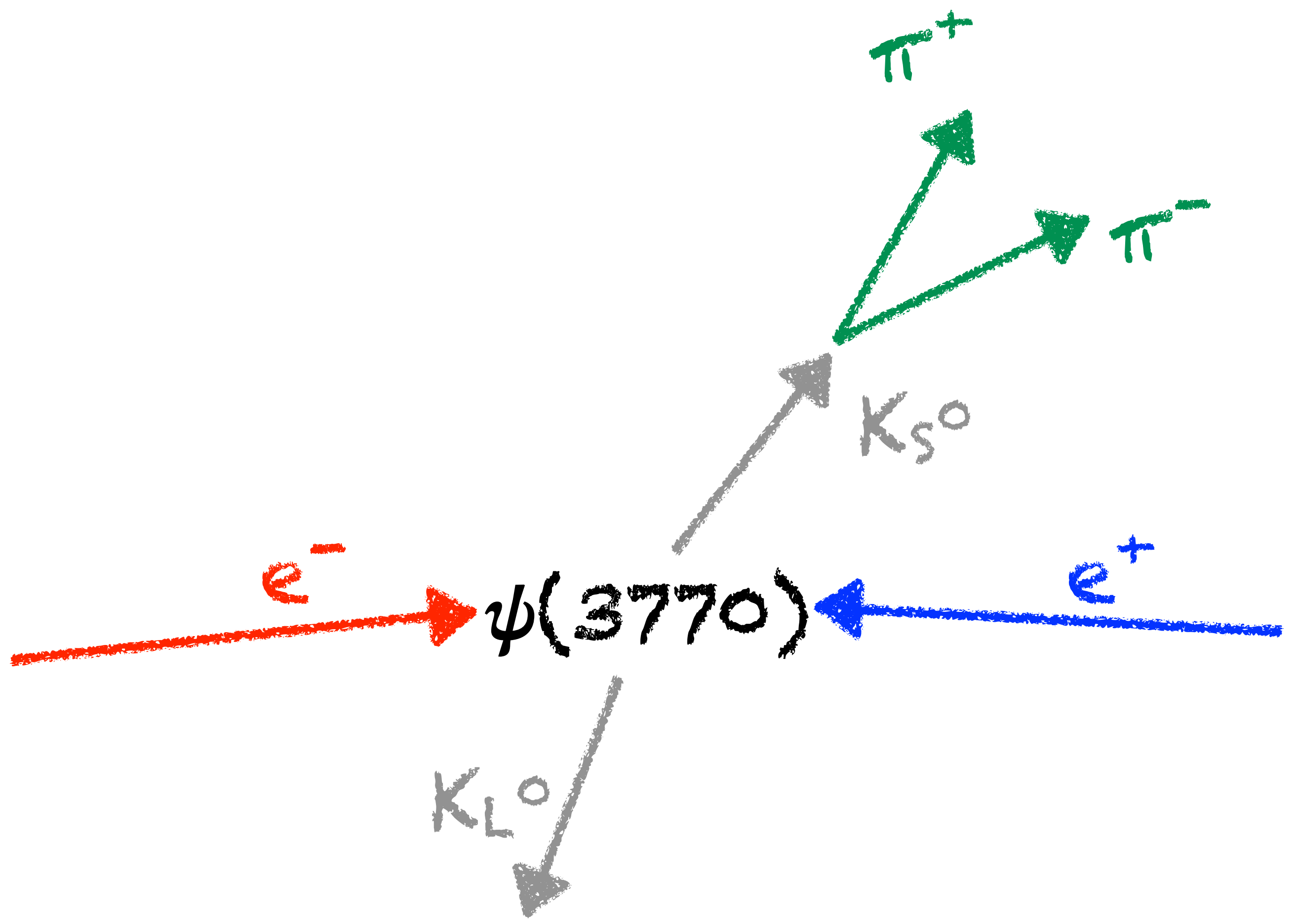
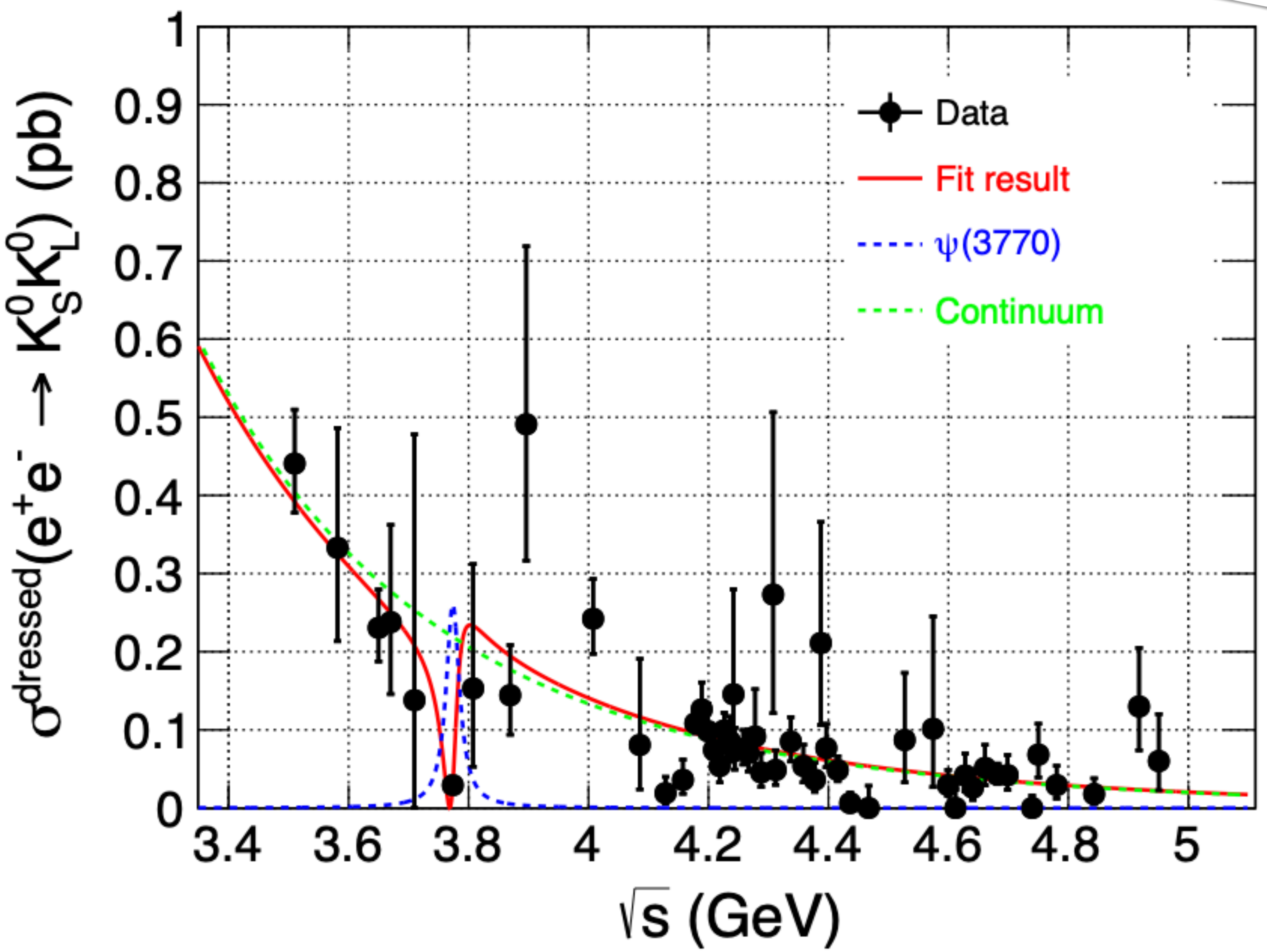




Investigating the *ψ(3770)* Resonance

$\psi(3770) \to K_S^0 K_L^0$

arXiv:2312.10962v1
Accepted by PRL

Using the 26.5 fb^{-1} @$\sqrt{s}$ = [3.51, 4.95] GeV

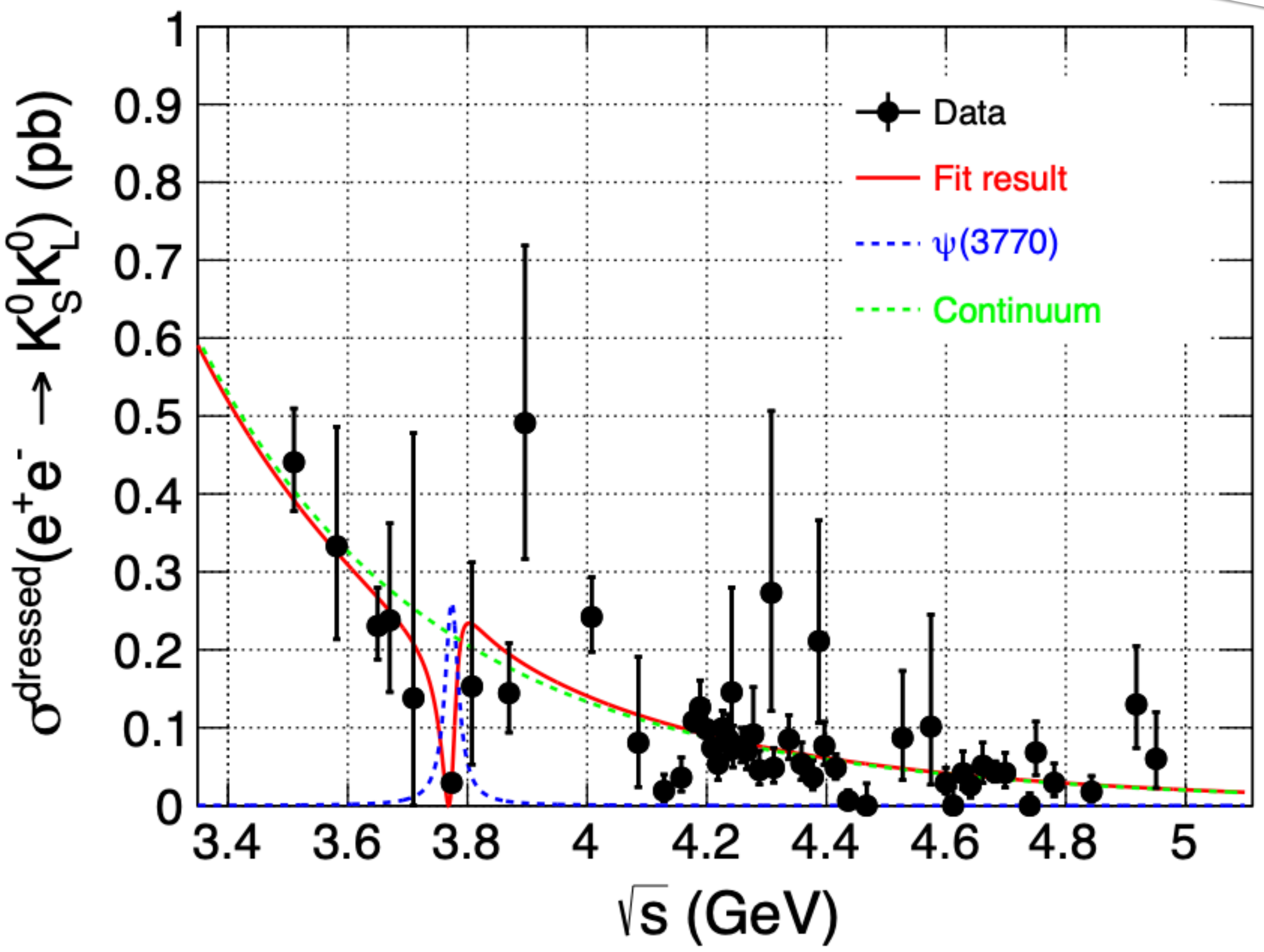
Search for the **$\psi(3770) \to K_S^0 K_L^0$** decay, and **study of the $\sigma(e^+e^- \to$ $K_S^0 K_L^0$) line-shape**

Fit to E_K/E_{Beam} to extrapolate the **$\sigma(e^+e^- \to$ $K_S^0 K_L^0$) line-shape**

Adding the ψ(3770) and the continuum contributions coherently,

$\mathcal{B}(\psi(3770) \to K_S^0 K_L^0) = (2.63^{+1.40}_{-1.59}) \times 10^{-5}$

in agreement with the prediction [16]



[16] Phys. Rev. D 70, 077505 (2004)

ID of the $\psi_2(3823)$ State

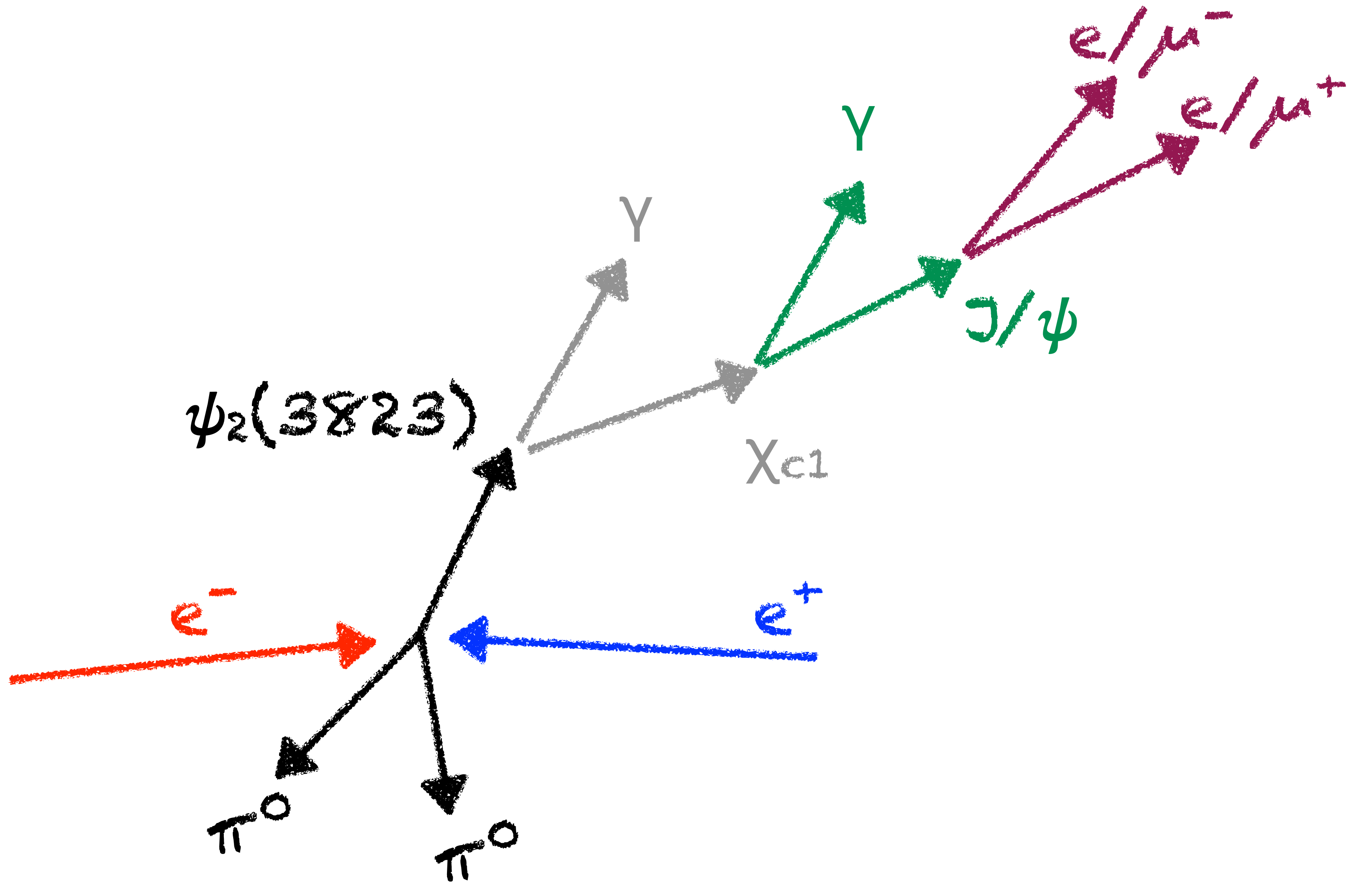
$\psi_2(3823) \to \gamma\chi_{c1} \to \gamma\gamma J/\psi$

JHEP **02**, (2023) 171

Using 20 energy points @$\sqrt{s}$ = **[4.230, 4.700] GeV** for a $\mathcal{L}_{int}$ = 11.3 fb^{-1}

Study of the **$\sigma(e^+e^- \to \pi^0\pi^0\psi_2(3823))$**, (employing a partial) reconstruction technique: $\pi^0\pi^0$, $(\gamma)\gamma$ & J/ψ ($\to \ell^+\ell^-$)

Fit to $M(\gamma\gamma J/\psi)$ to estimate $\psi_2(3823)$ mass and $N^{\pi\pi\psi}_{obs}$



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JHEP **02**, (2023) 171

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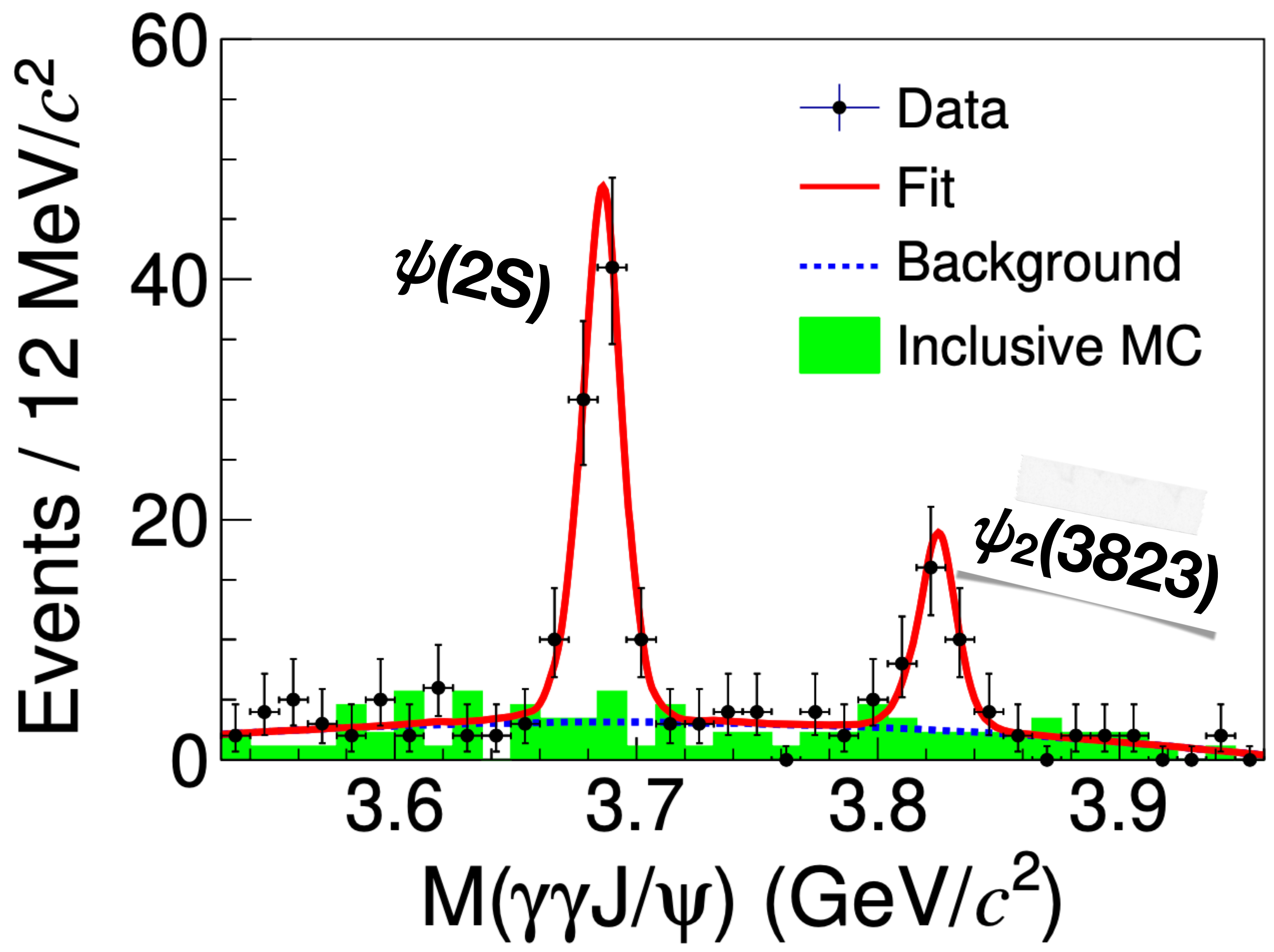

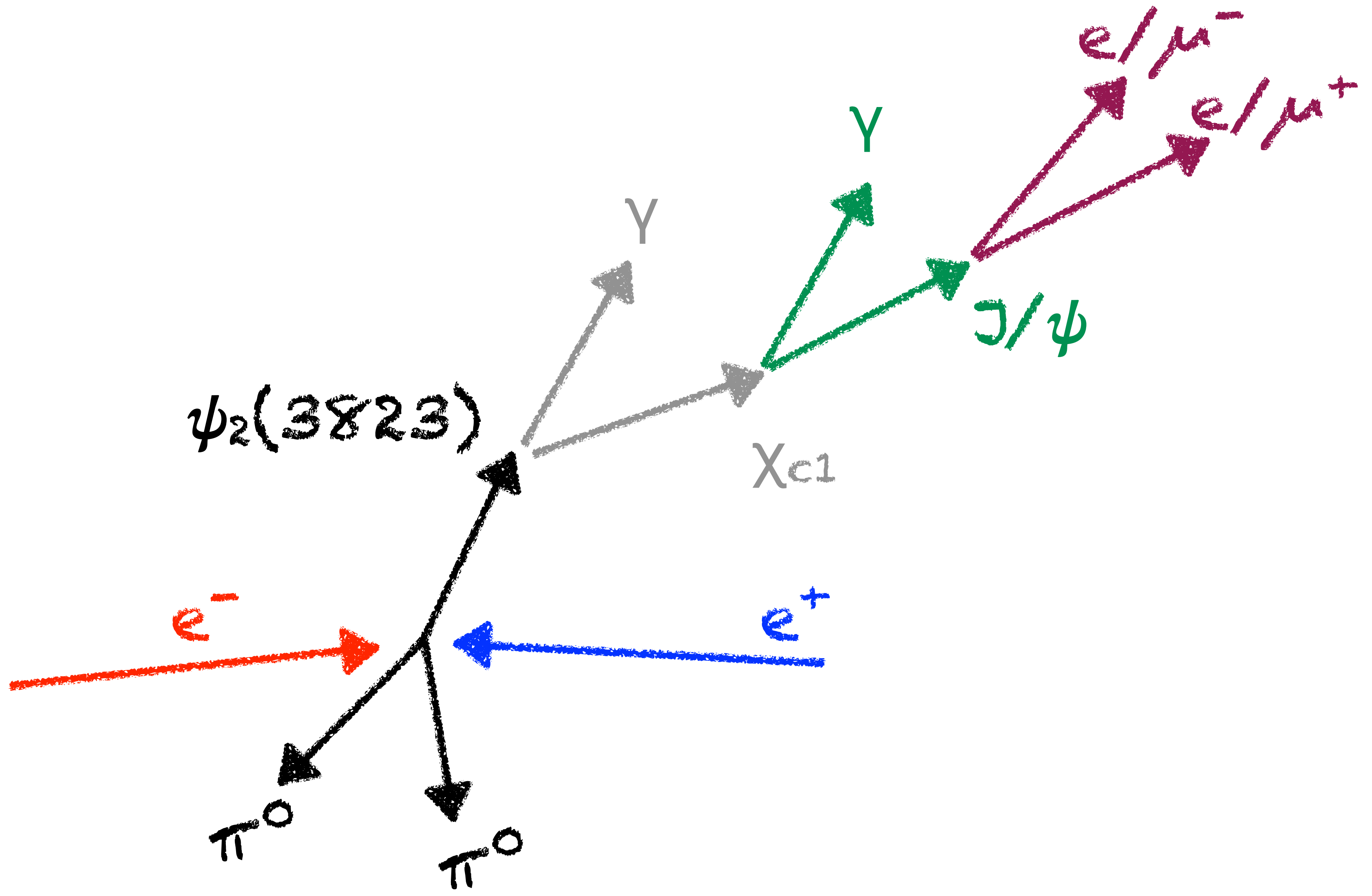

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JHEP **02**, (2023) 171

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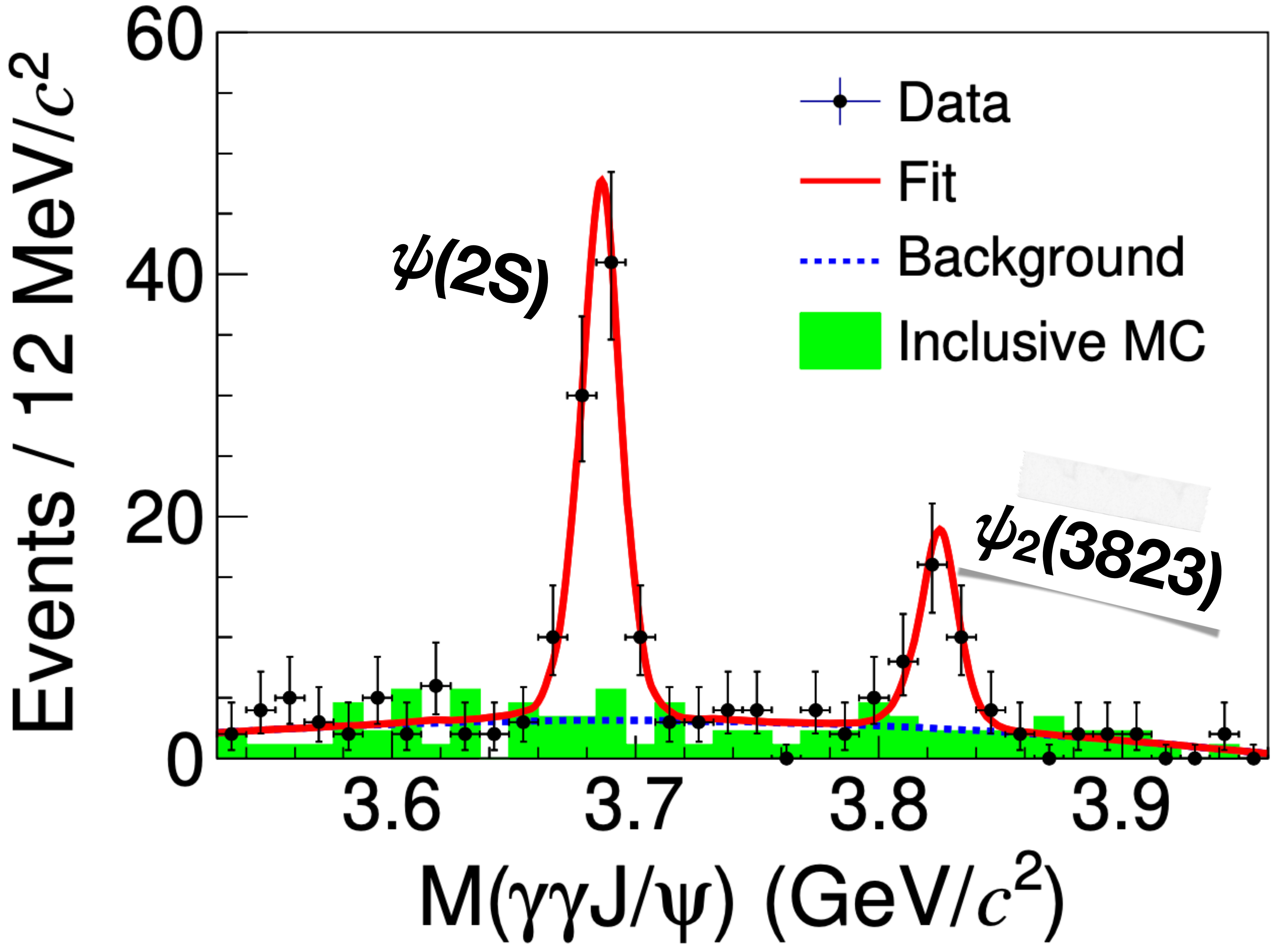
Fit to $M(\gamma\gamma J/\psi)$ to estimate $\psi_2(3823)$ mass and $N^{\pi\pi\psi}_{obs}$

3824.3 ± 2.4 ± 0.9 MeV/c^2

$\Gamma_{\psi_2(3823)}$ < 18.8 MeV



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JHEP **02**, (2023) 171

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Fit to M(γγJ/ψ) to estimate ψ_2(3823) mass and $N^{\pi\pi\psi}_{obs}$

3824.3 ± 2.4 ± 0.9 MeV/c²
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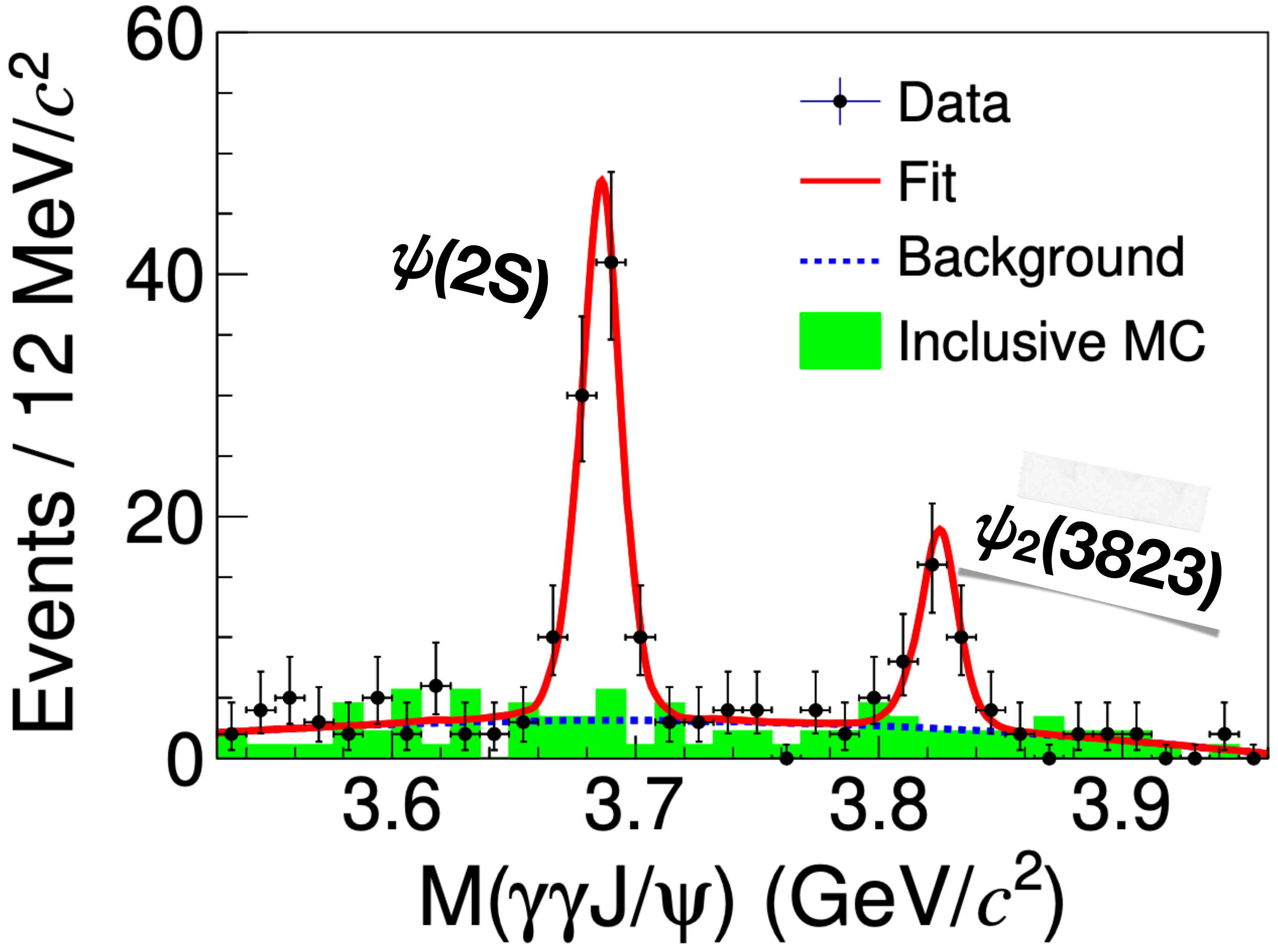

Due to the limited statistics, a cross-section scan cannot be performed with enough significance…

$$\mathcal{R} = \frac{\sigma^{Avg\,Born}_{\pi^0\pi^0\psi_2}}{\sigma^{Avg\,Born}_{\pi^+\pi^-\psi_2}} = \frac{N_{\pi^0\pi^0\psi_2}(\sum_i \mathcal{L}_i(1+\delta)_i\epsilon_i)_{\pi^+\pi^-\psi_2}}{N_{\pi^+\pi^-\psi_2}(\sum_i \mathcal{L}_i(1+\delta)_i\epsilon_i)_{\pi^0\pi^0\psi_2}} \cdot \frac{1}{\mathcal{B}^2(\pi^0 \to \gamma\gamma)}$$

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JHEP **02**, (2023) 171

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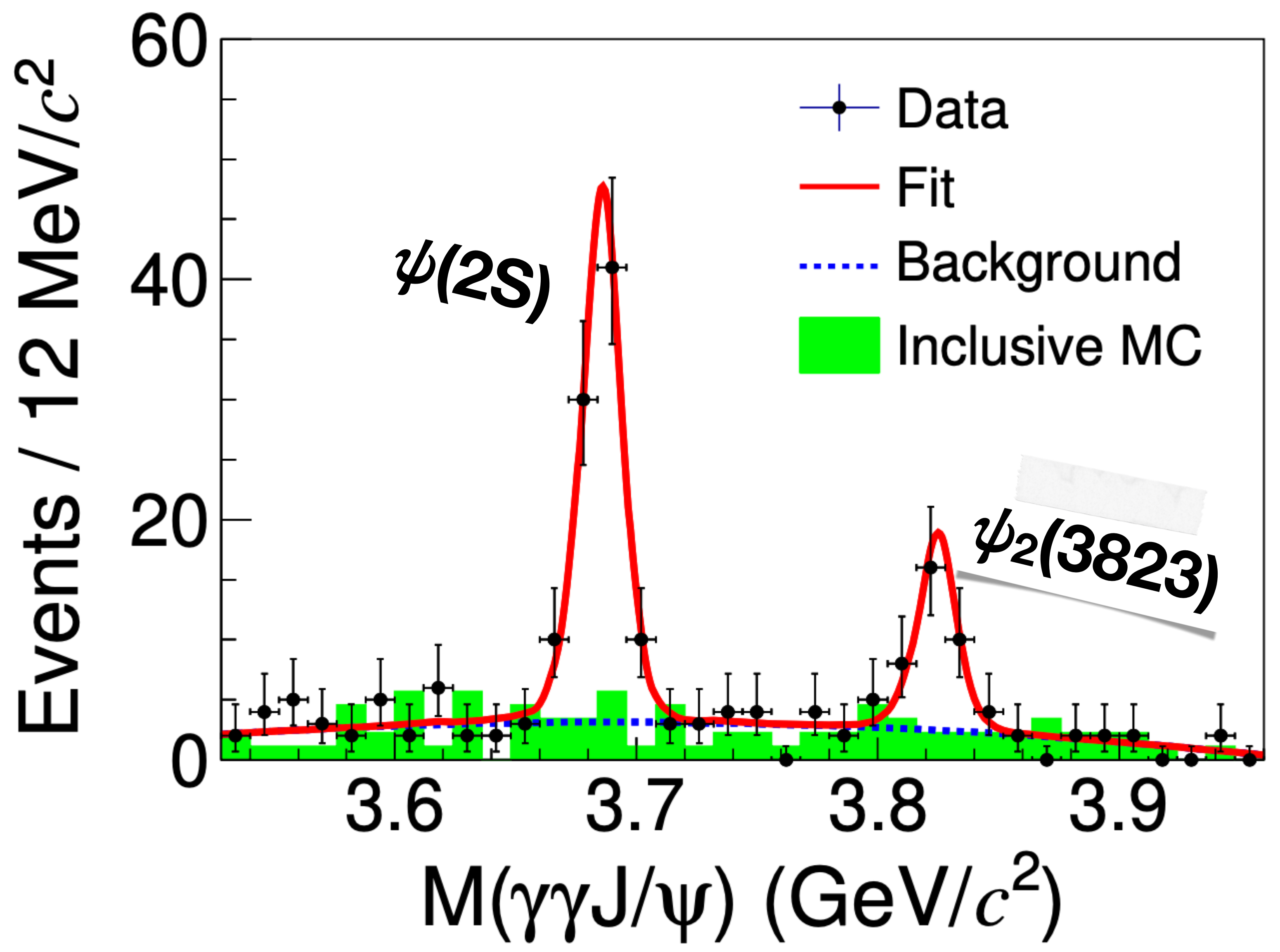

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Consistent with isospin symmetry

ID of the $\psi_2(3823)$ State

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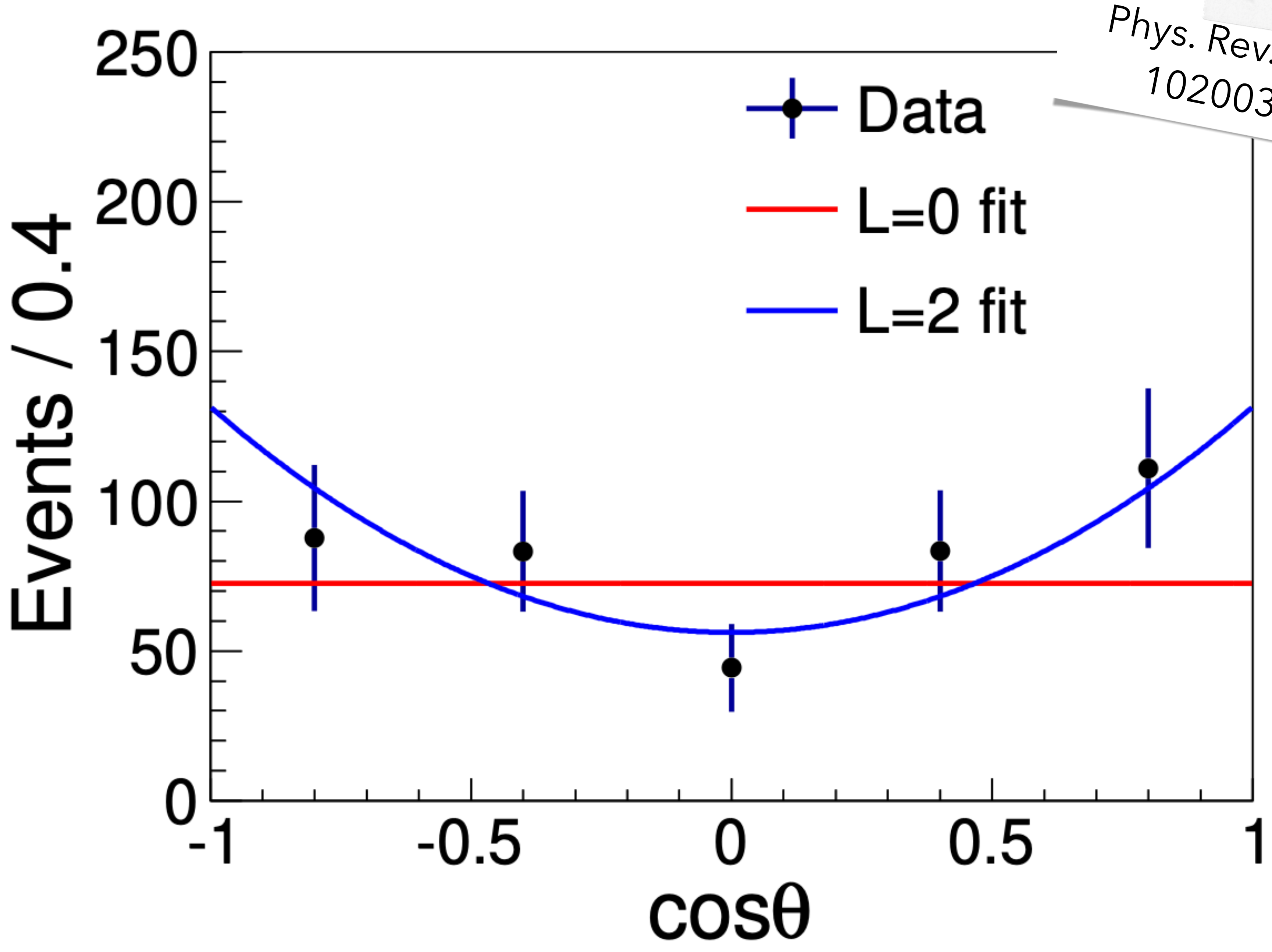
The $\pi^+\pi^-$ system in $e^+e^- \to \pi^+\pi^-\psi_2(3823)$ process is expected to be dominated by S-wave

If this was true and $\psi_2(3823)$ was a $\psi_2(1^3D_2)$ state, the relative orbital angular momentum should be 2



Phys. Rev. Lett. **129**, 102003 (2023)

JHEP **02**, (2023) 171

Since $\rho^0 \to \pi^0\pi^0$ is forbidden, the observation of $e^+e^- \to \pi^0\pi^0\psi_2(3823)$ corroborates the S-wave ($f_0(500) \to \pi^0\pi^0$) expectation

This, together with mass estimations and width upper limits **supports** the **$J^{PC} = 2^{--}$ assignment** and the **hypothesis** that the **$\psi_2(3823)$ is** a **$\psi_2(1^3D_2)$ state**

2^3P_1 or not-2^3P_1, the $\chi_{c1}(3872)$ Nature

$\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$

arXiv:2312.13593
Submitted to PRD

Using 15 energy points @**$\sqrt{s}$ = [4.16, 4.34] GeV**

Search for the di-pion $e^+e^- \to$ **$\gamma\chi_{c1}(3872) \to \gamma\pi^+\pi^-\chi_{c1}$** process,

with **$\chi_{c1} \to \gamma J/\psi \to \gamma\ell\ell$**

Simultaneous fit to **$M_{recoil}(\gamma_{rad})$** for the $\gamma\pi\pi\ell\ell$ and $\gamma\pi\ell\ell$ events

In the assumption that the $\chi_{c1}(3872)$ is a pure $\chi_{c1}(2^3P_1)$ state [19]

$$\frac{\Gamma(2^3P_1 \to \pi^0\chi_{c1})}{\Gamma(2^3P_1 \to \pi^+\pi^-\chi_{c1})} \sim 0.04$$

[19] Phys. Rev. D 77, 014013 (2008)

2^3P_1 or not-2^3P_1, the $\chi_{c1}(3872)$ Nature

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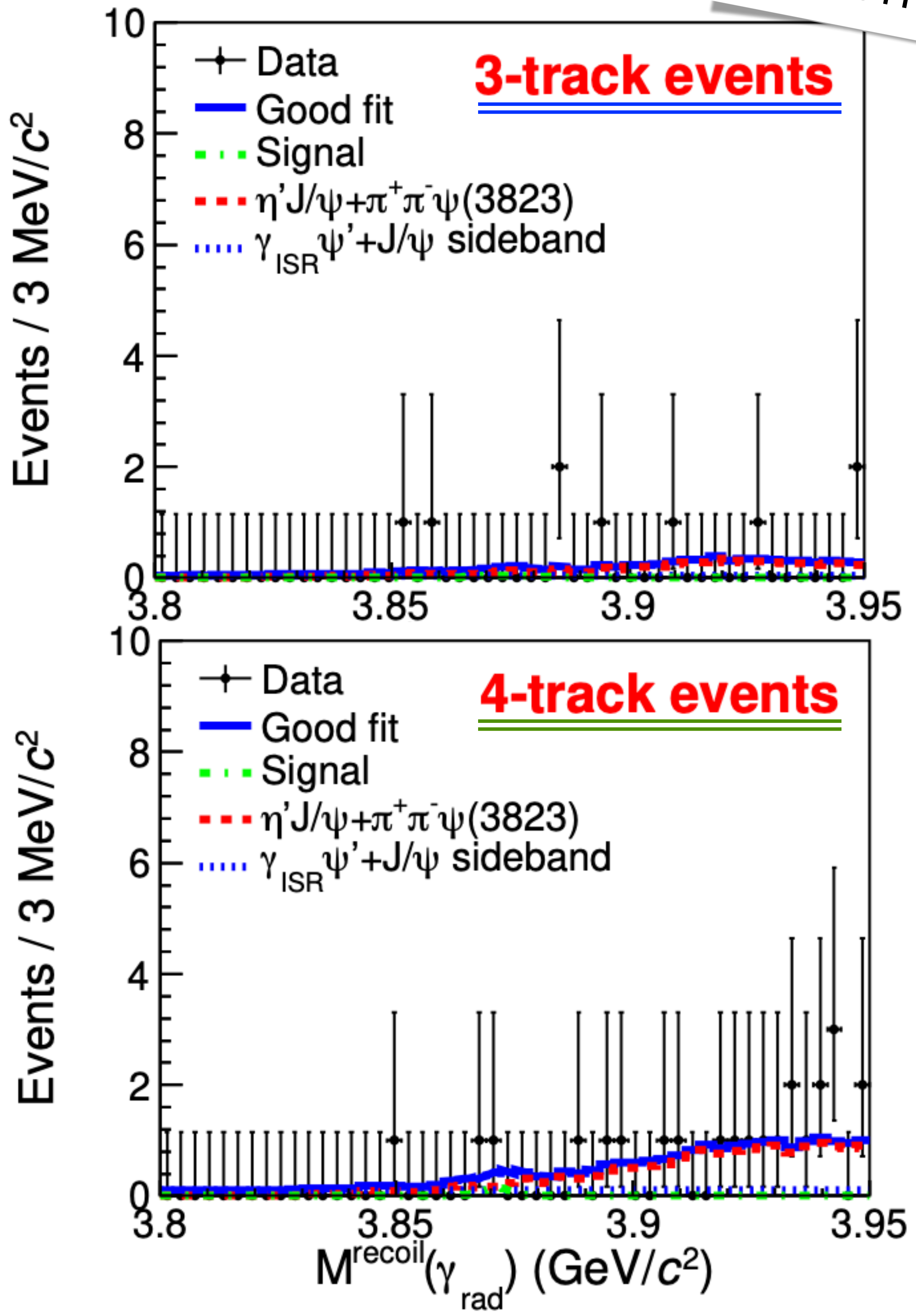

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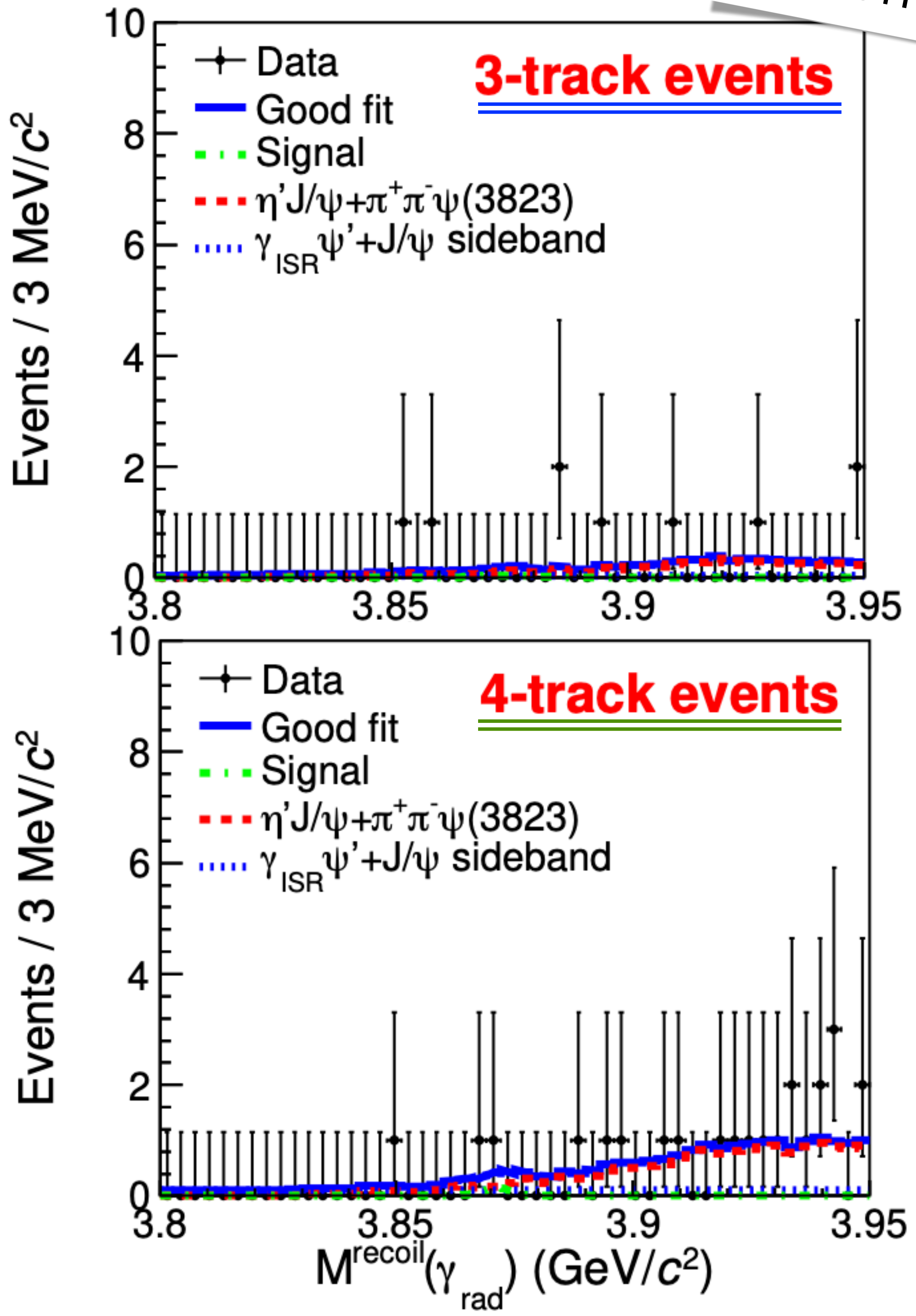

No $\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$ events are found…

$$\mathcal{R} := \frac{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1})}{\mathcal{B}(\chi_{c1}(3872) \to \pi^+\pi^- J/\psi)} < 0.18$$

2^3P_1 or not-2^3P_1, the $\chi_{c1}(3872)$ Nature

$\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1}$

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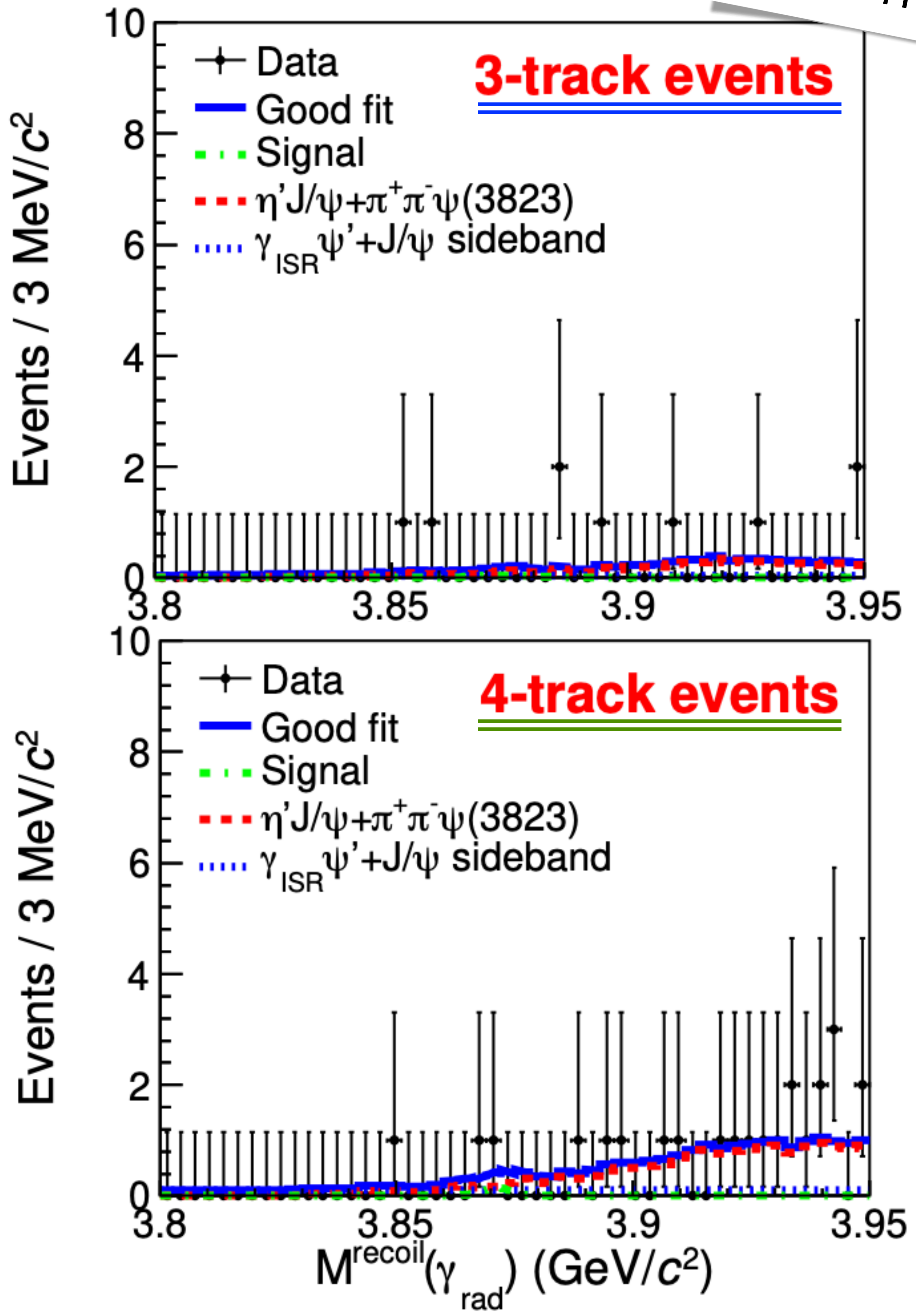

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which allows to estimate…

$$\frac{\Gamma(\chi_{c1}(3872) \to \pi^0\chi_{c1})}{\Gamma(\chi_{c1}(3872) \to \pi^+\pi^-\chi_{c1})} > 0.5$$

favouring the a non-conventional component for the $\chi_{c1}(3872)$ state [20]

[20] Phys. Rev. D 78, 094019 (2008)

Summary

BESIII started taking data in '08, and since then it has been **exploring and shedding light** on the **charmonium decays**

The **largest datasets** of **$c\bar{c}$ vector** states collected by BESIII provide the power not to only search for rare vector decays but also to **probe theoretical predictions** with **non-vector decays**

Datasets above the **$D\bar{D}$ threshold** shed new light on charmonium decays and allow us to **discern** among **theoretical expectations** and to **understand** the **nature of charmonia**

Thanks to its **tuneable centre-of-mass energy** in the charmonium range and **leptonic beams**, **BESIII** will be **competitive** even with relatively small datasets

Finally, **new data sets** are currently being taken and analysed

~$2.7x10^9$ @$\psi(2S)$

~$20fb^{-1}$@$\psi(3770)$

Thank you for the attention!

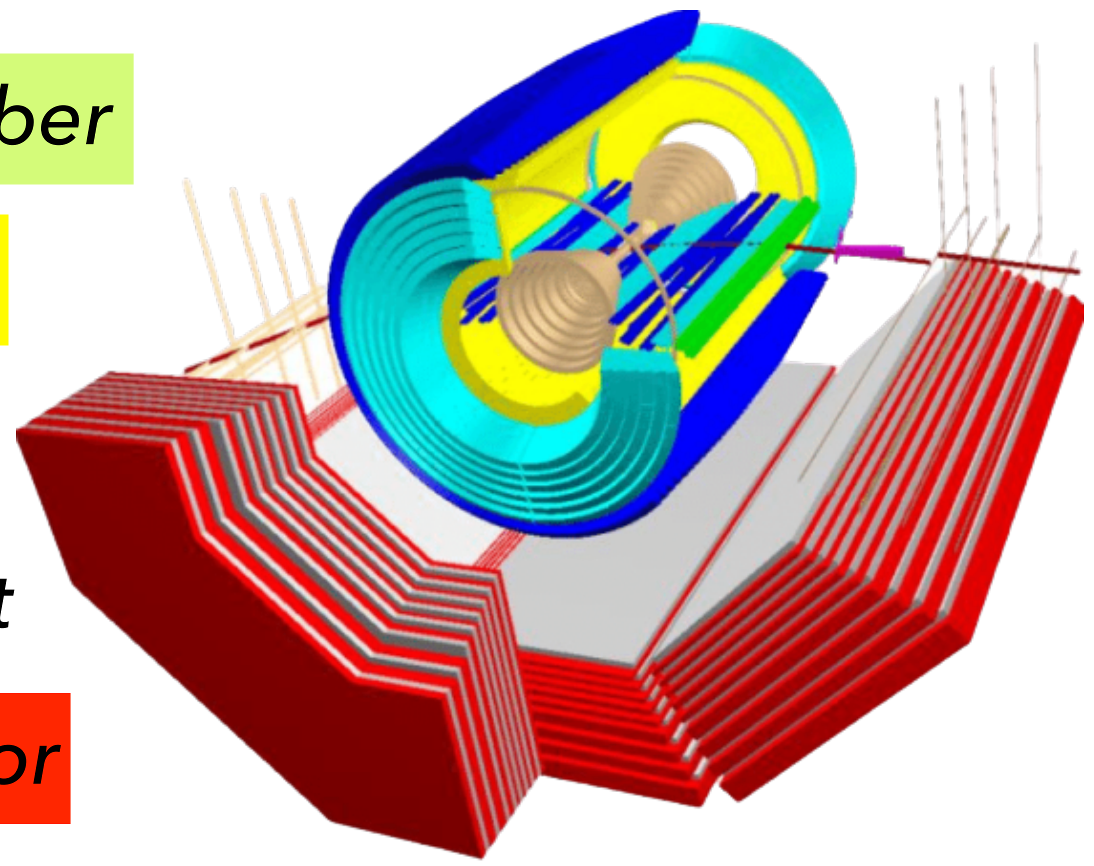
Backup Slides

BESIII Collaboration

~500 members
From 82 institutions in 17 countries

BESIII Experiment

BESIII (BEijing Spectrometer III) is an experiment located at the BEPCII (Beijing Electron Positron Collider II) at IHEP (Institute of High Energy Physics)



τ-charm factory 2.0 GeV ≤ $\sqrt{s}$ ≤ 4.9 GeV with a 10^{33} $cm^{-2}s^{-1}$ designed luminosity @ $\sqrt{s}$ = 3.77 GeV

MDC		
Single wire $\sigma_{r\phi}$ (1 GeV)	130	μm
σ_z (1 GeV)	~2	mm
σ_p/p (1 GeV)	0.5	%
$\sigma_{dE/dx}$ (1 GeV)	6	%
EMC		
σ_E/E (1 GeV)	2.5	%
Position resolution (1 GeV)	0.6	cm
TOF		
σ_T		
Barrel (1 GeV/c muons)	100	ps
End cap (0.8 GeV/c pions)	65	ps
Muon Identifier		
No. of layers (barrel/end cap)	9/8	
Cut-off momentum	0.4	GeV/c
Solenoid field	1.0	T
$\Delta\Omega/4\pi$	93	%

BESIII Experiment

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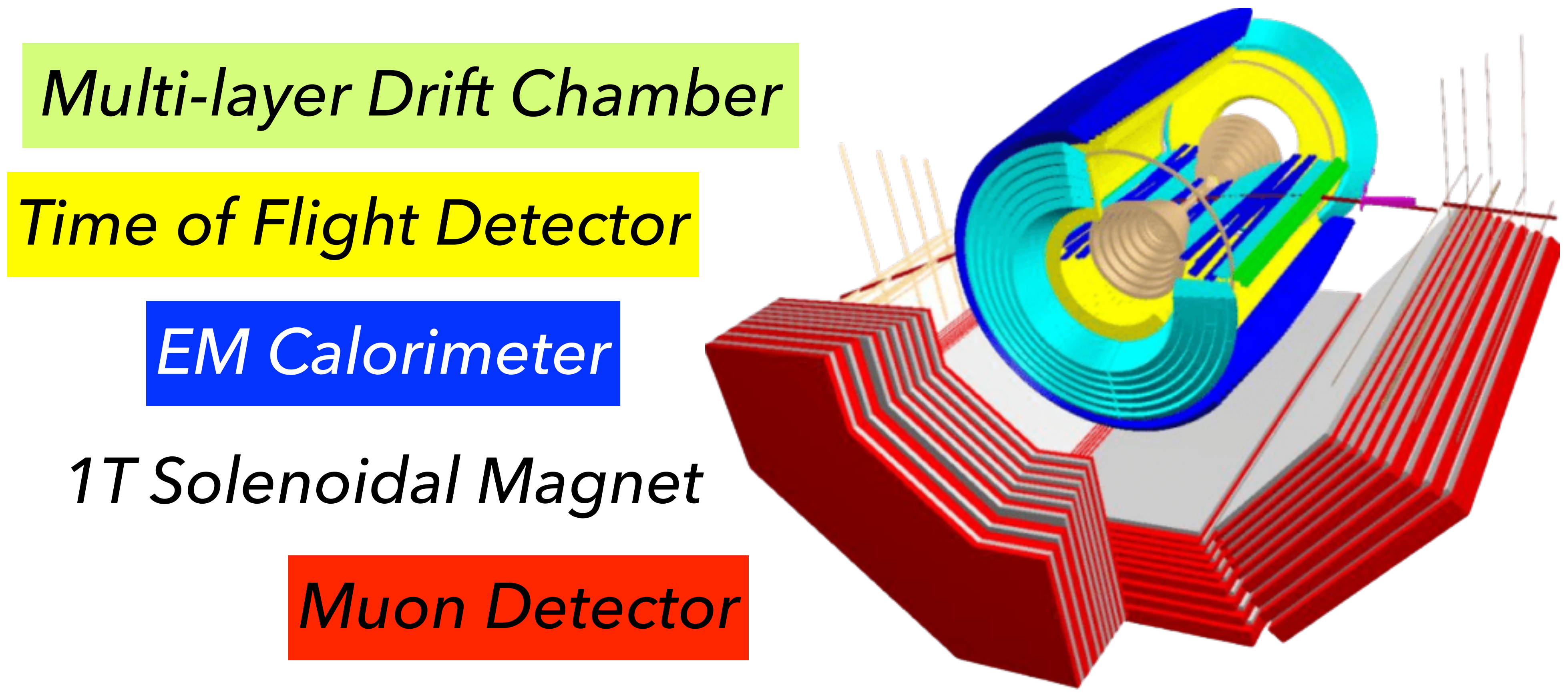


τ-charm factory 2.0 GeV ≤ $\sqrt{s}$ ≤ 4.9 GeV

with a 10^{33} $cm^{-2}s^{-1}$ designed luminosity

@ $\sqrt{s}$ = 3.77 GeV

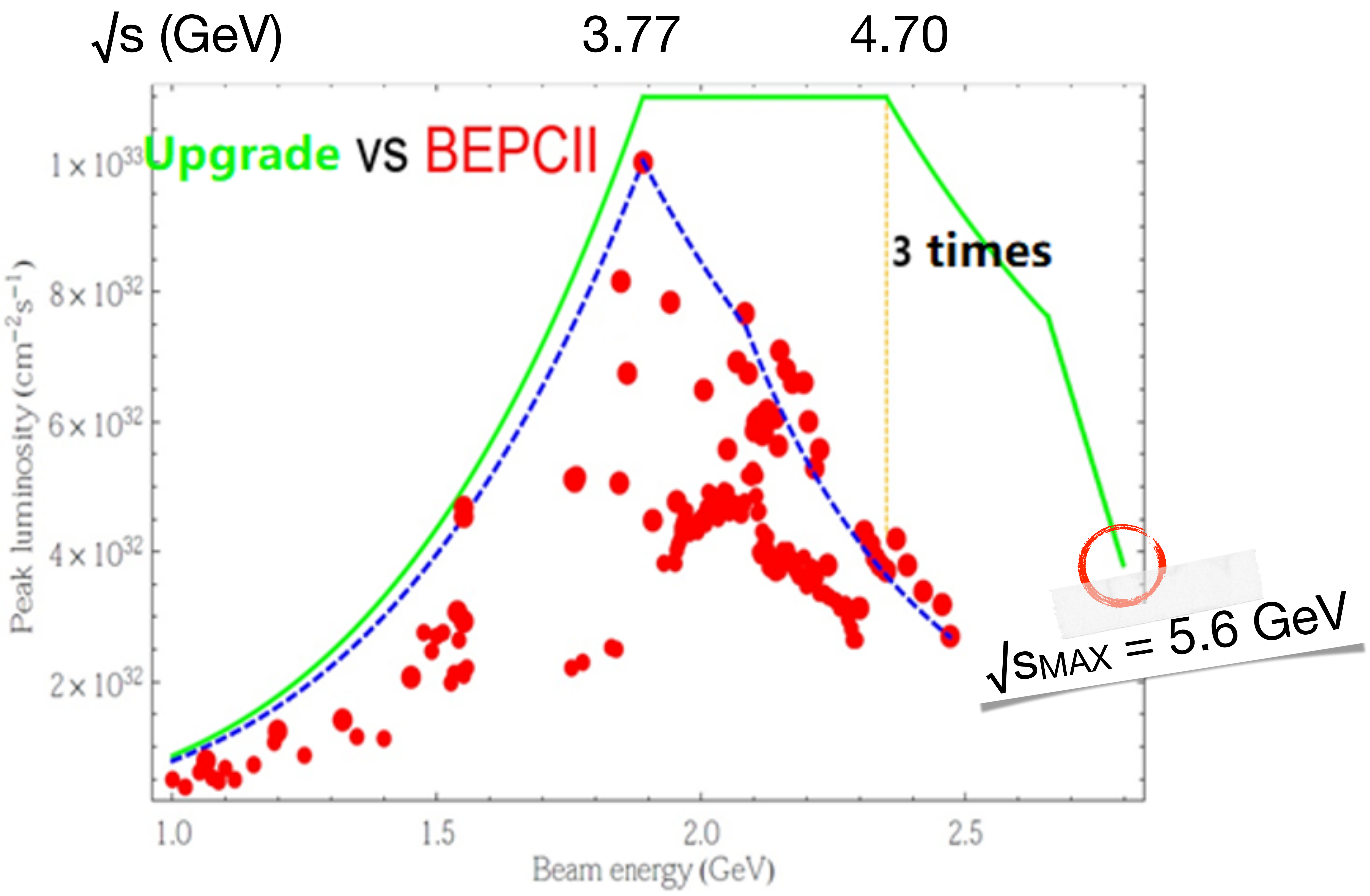
Data sets

2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10 × 50 pb^{-1} scan 3.81 — 4.42 GeV
2014: 1029 pb^{-1} at 4.42 GeV
110 pb^{-1} at 4.47 GeV
110 pb^{-1} at 4.53 GeV
48 pb^{-1} at 4.575 GeV
567 pb^{-1} at 4.6 GeV
0.8 fb^{-1} R-scan 3.85 — 4.59 GeV
2015: R-scan 2 — 3 GeV + 2.175 GeV
2016: ~3fb^{-1} at 4.18 GeV (for D_s)
2017: 7 × 500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8 × 500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020: 3.8 fb^{-1} scan 4.61 - 4.7 GeV
2021: 2 fb^{-1} scan 4.74 - 4.946 GeV
3.0B (total) $\psi(2S)$

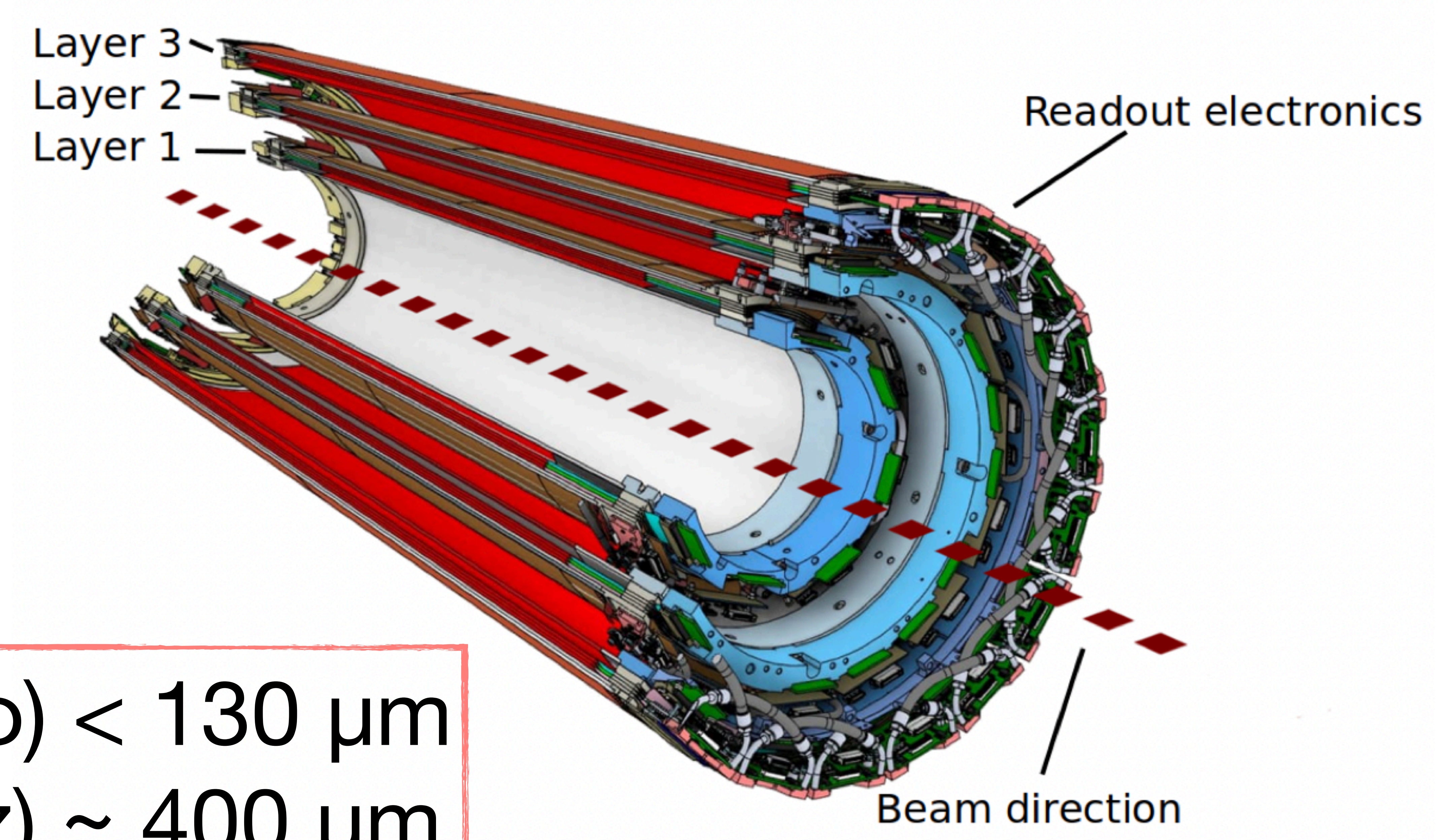
Upgrading the BESIII Experiment

Born Cross-sections

Energy & Luminosity



CGEM-IT



$\delta(\phi) < 130\ \mu m$
$\delta(z) \sim 400\ \mu m$