Latest results on charmonium decays at BESIII

Marco Scodeggio
on behalf of the BESIII Collaboration

BESIII

Dipartimento
di Fisica
e Scienze della Terra

Lake Louise Winter Institute
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INFN
Istituto Nazionale di Fisica Nucleare

FE

Outline:

- BESIII Experiment
- Preamble… Why Charmonia?
- Observation of $\psi(3770) \to \eta J/\psi$
- Evidence for $\eta_c(2S) \to \pi^+\pi^-\eta$ decay
- Study of the $h_c(1\,^1P_1)$ meson via $\psi(2S) \to \pi^0 h_c$ decays at BESIII
- Summary

DISCLAIMER 1

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

DISCLAIMER 2

The presented topics are the latest I personally selected among many possibilities

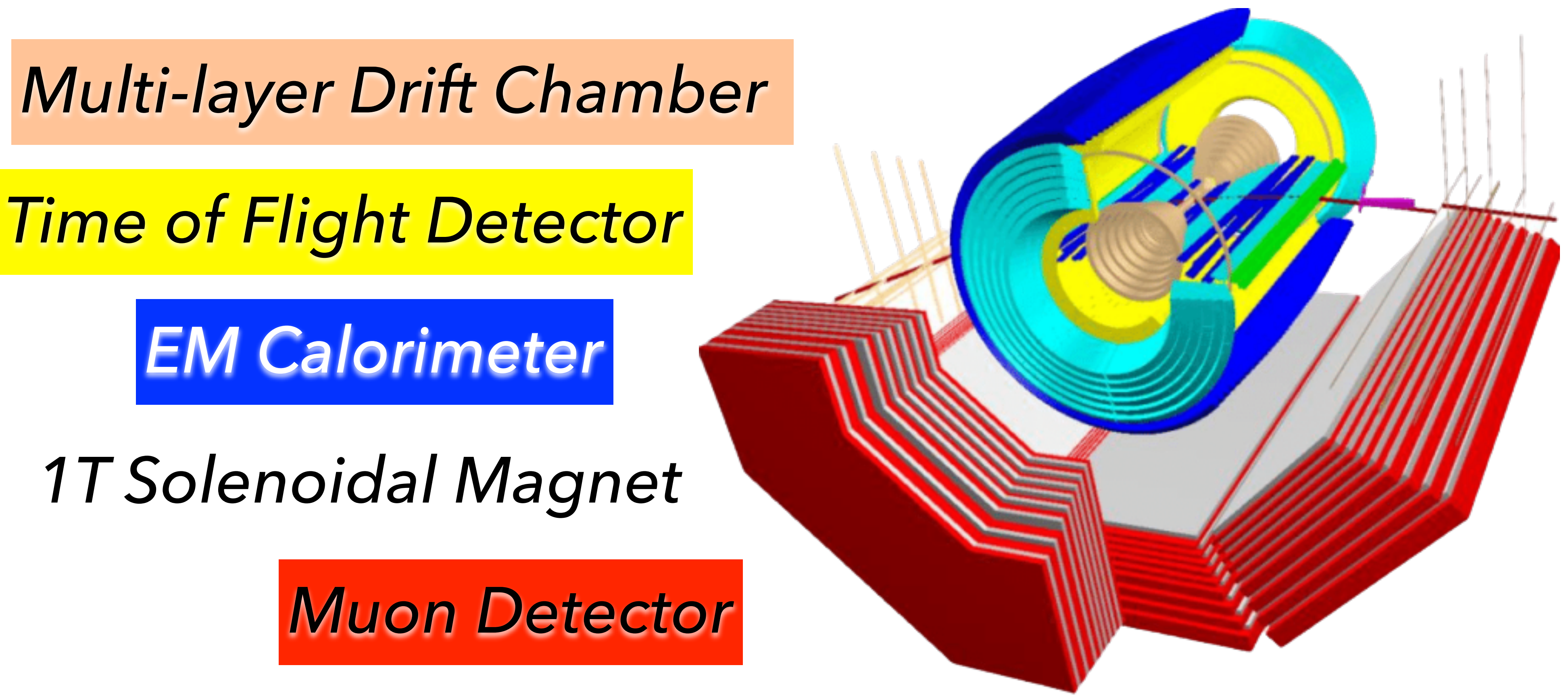
BESIII Experiment

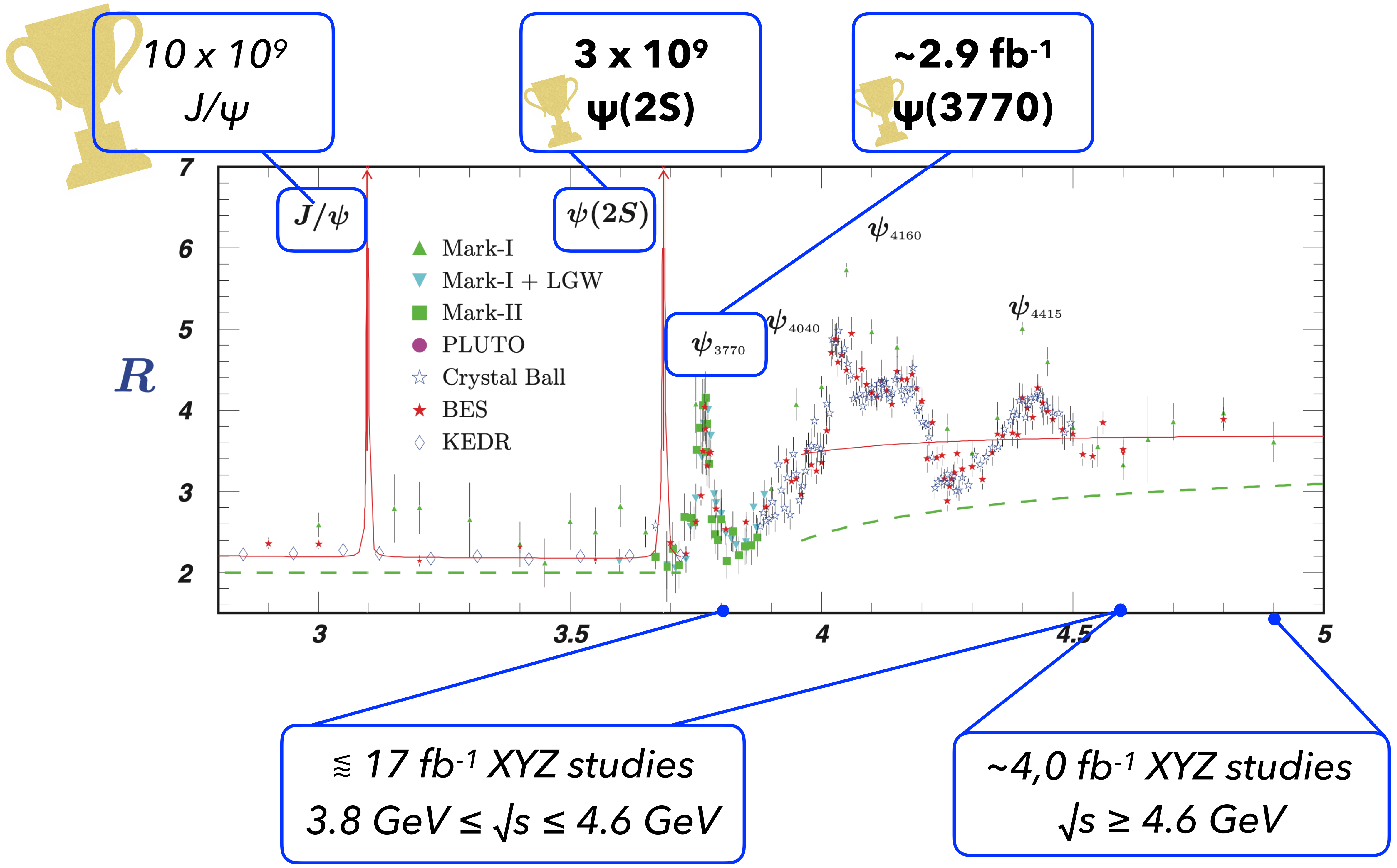
BESIII (BEijing Spectrometer III) is an experiment located at the BEPCII (Beijing Electron Positron Collider II) at IHEP (Institute of High Energy Physics)

Being **BEPCII** an **e^+e^- collider**, BESIII can profit from **direct production** of **vector states** ($J^{PC} = 1^{--}$)

The **statistics of the ψ(nS)** decays allows to probe and study with **high precision** also the non-vector states

BESIII has also **unique opportunities** with datasets **above 3.8 GeV**





τ-charm factory 2.0 GeV ≤ $\sqrt{s}$ ≤ 4.9 GeV with a 1.05×10^{33} $cm^{-2}s^{-1}$ peak luminosity @ $\sqrt{s}$ = 3.77 GeV

Preamble

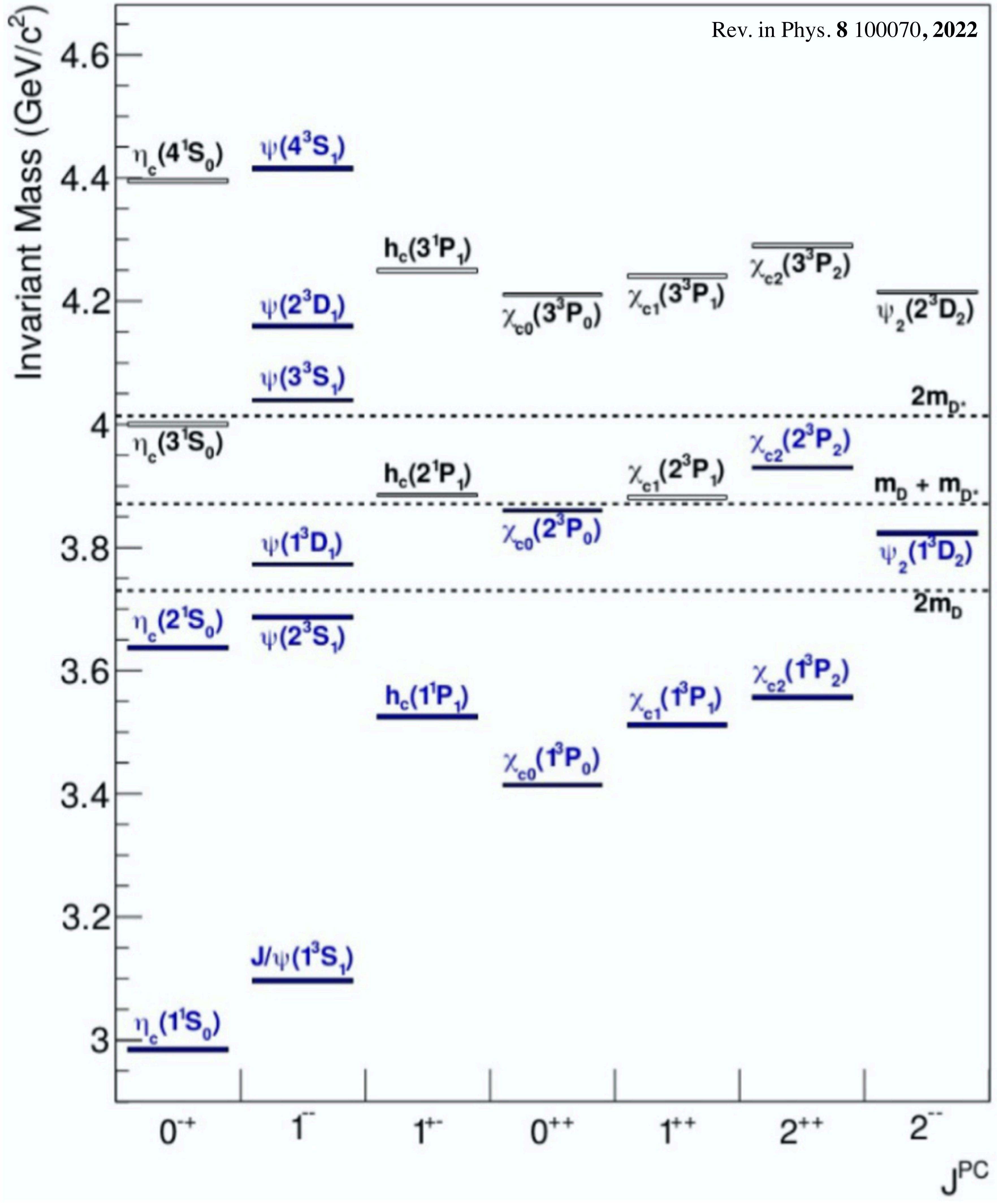
Charmonium resonances are located in the transition region of perturbative and non-perturbative QCD

Non-vector states still mostly 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

Another way to probe the SM (via weak decays)



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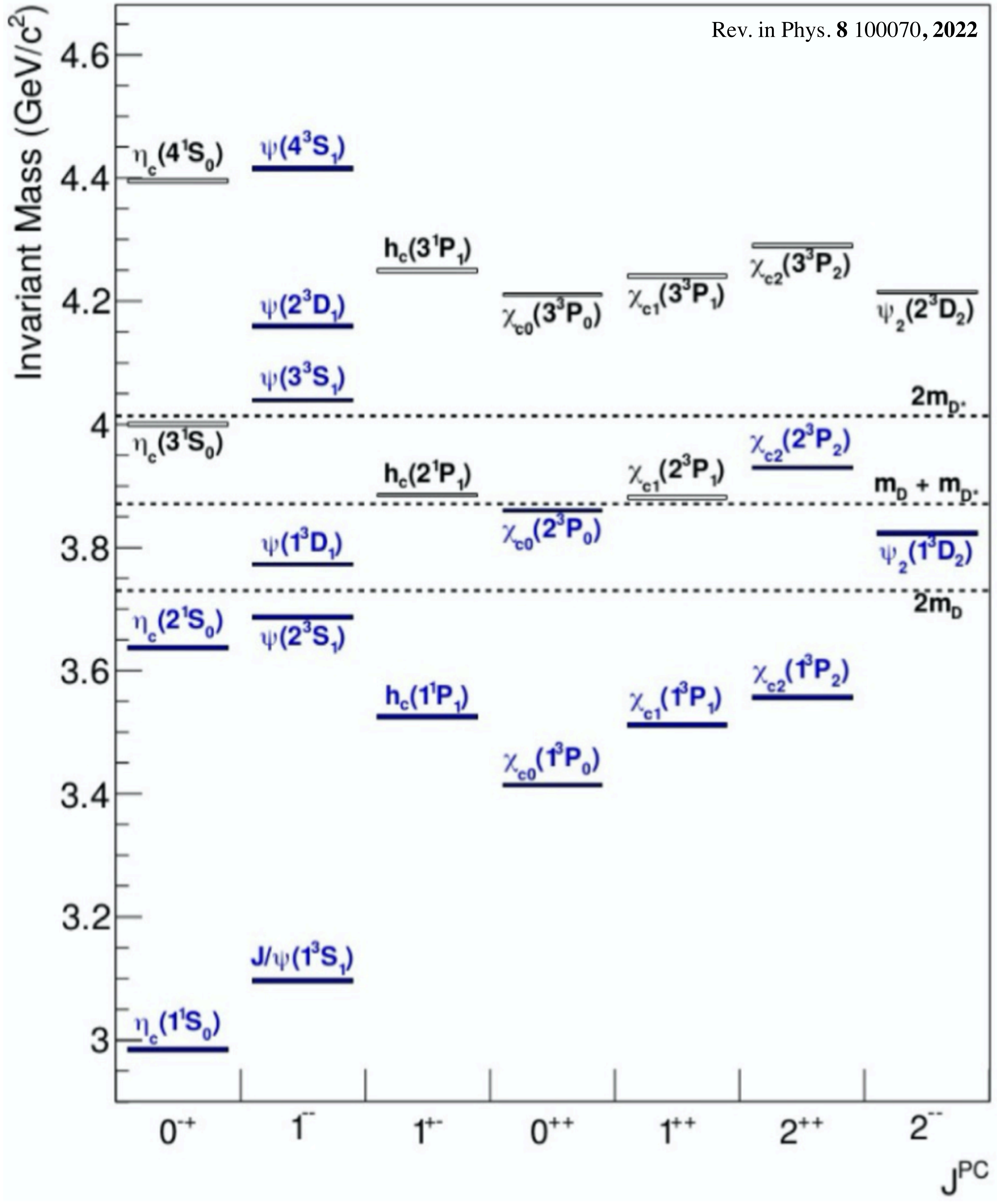

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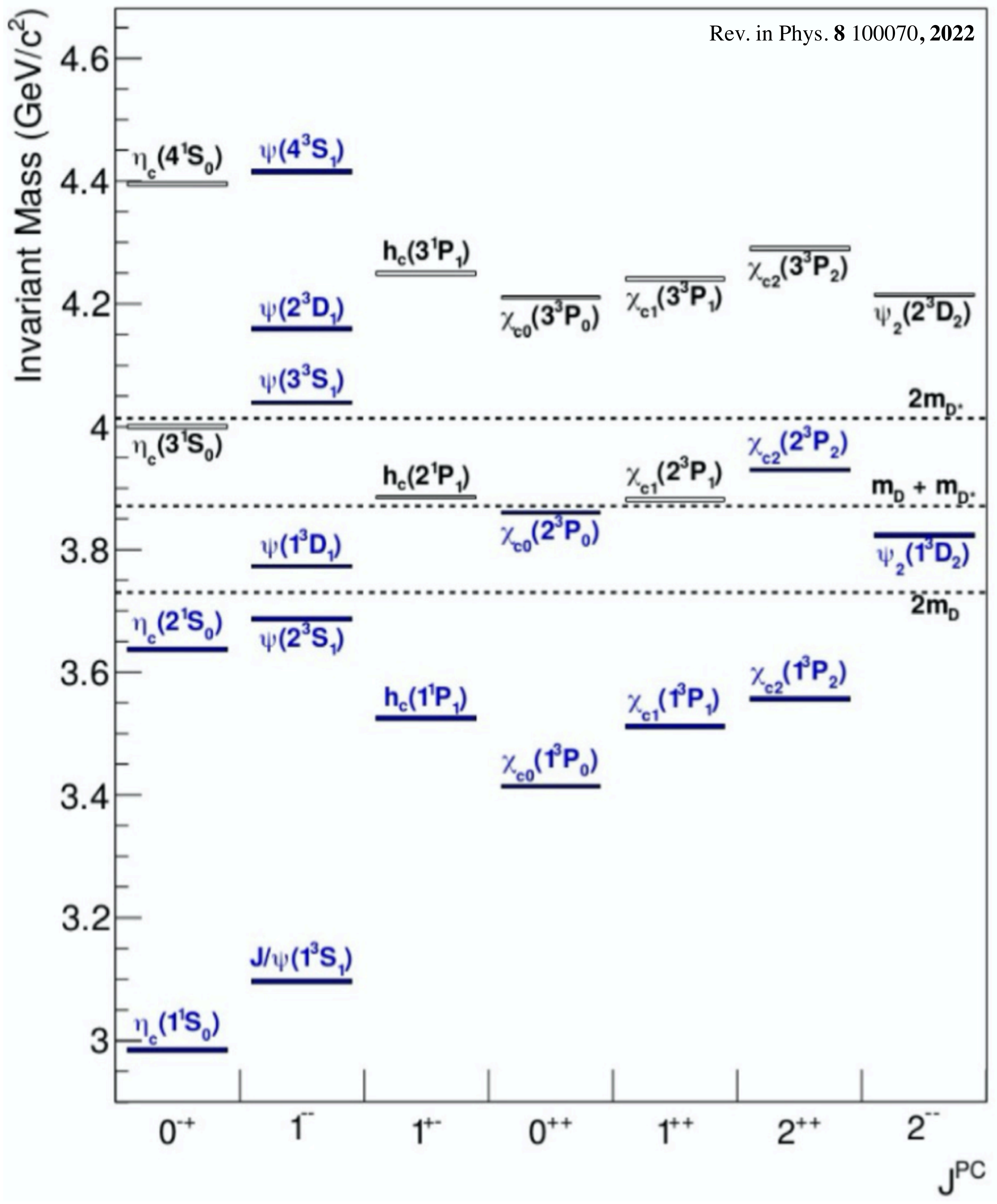

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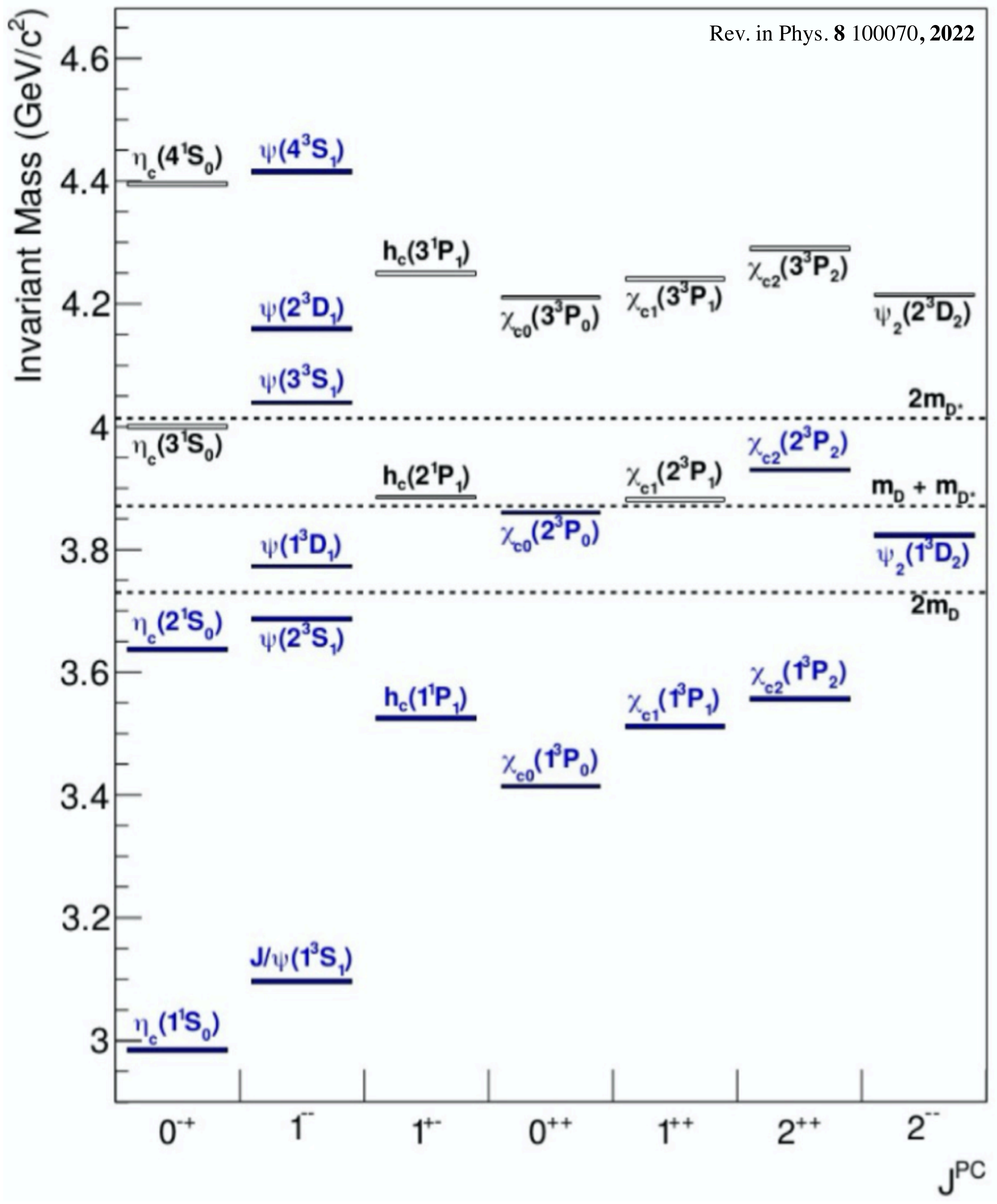

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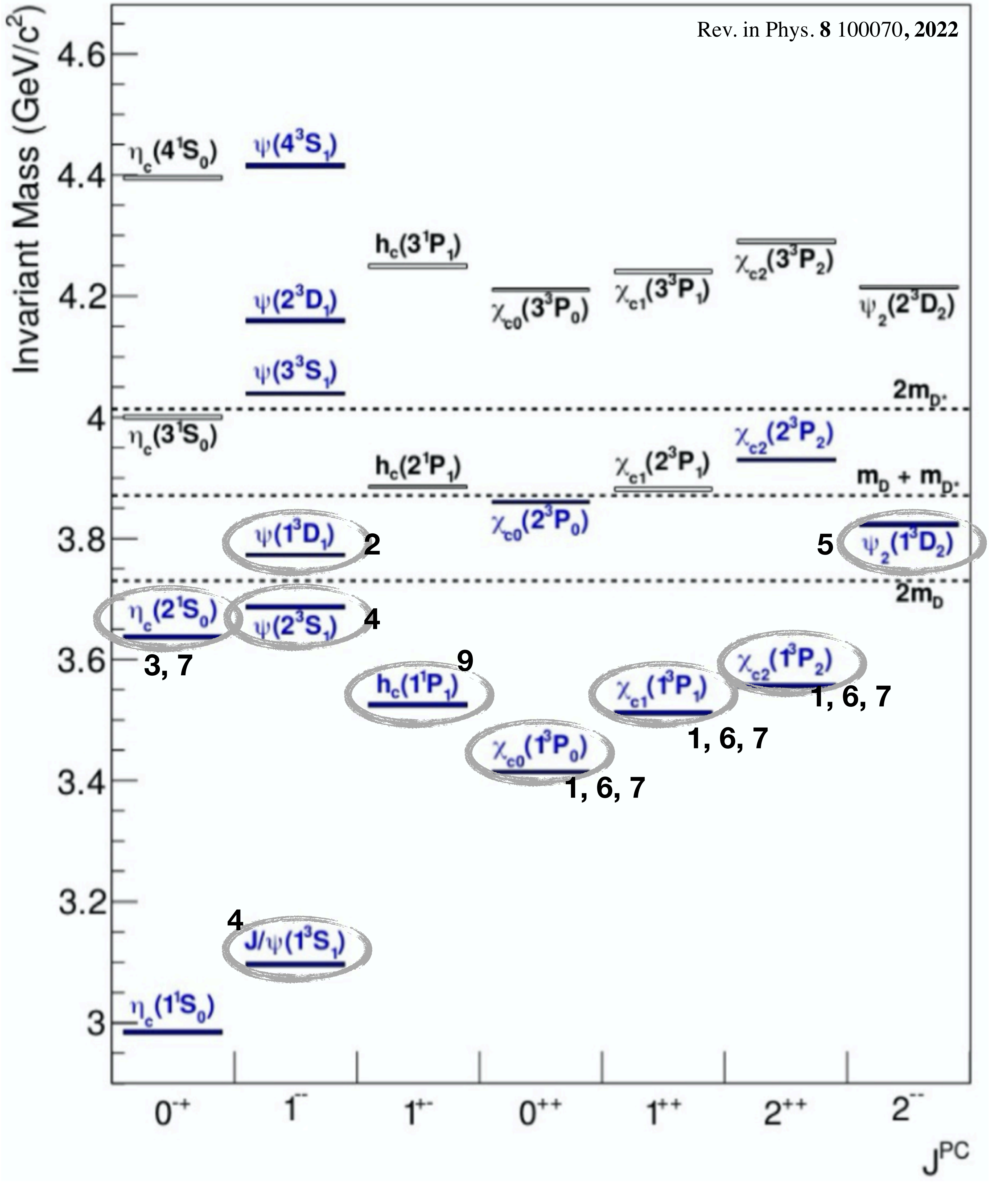


BESIII has the capability to perform such studies and many charmonium analyses could be discussed:

1. *Helicity amplitude analysis of $\chi_{cJ} \to \phi\,\phi$*
2. ***Observation of $\psi(3770) \to \eta J/\psi$***
3. ***Evidence for $\eta_c(2S) \to \pi^+\pi^-\eta$ decay***
4. *Observation of the J/ψ and $\psi(3686)$ decays into $\eta\ \Sigma^+$ anti-Σ^-*
5. *Observation of of $e^+e^- \to \pi^0\pi^0\psi_2(3823)$*
6. *Observation of $\chi_{cJ} \to \Lambda$ anti-$\Lambda\ \eta$*
7. *Observation of $\eta_c(2S) \to 3(\pi^+\pi^-)$ and measurements of $\chi_{cJ} \to 3(\pi^+\pi^-)$ in $\psi(3686)$ radiative transitions*
8. ***Study of the $h_c(1P)$ meson via $\psi(2S) \to \pi^0 h_c$ decays at BESIII***
9. […]

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

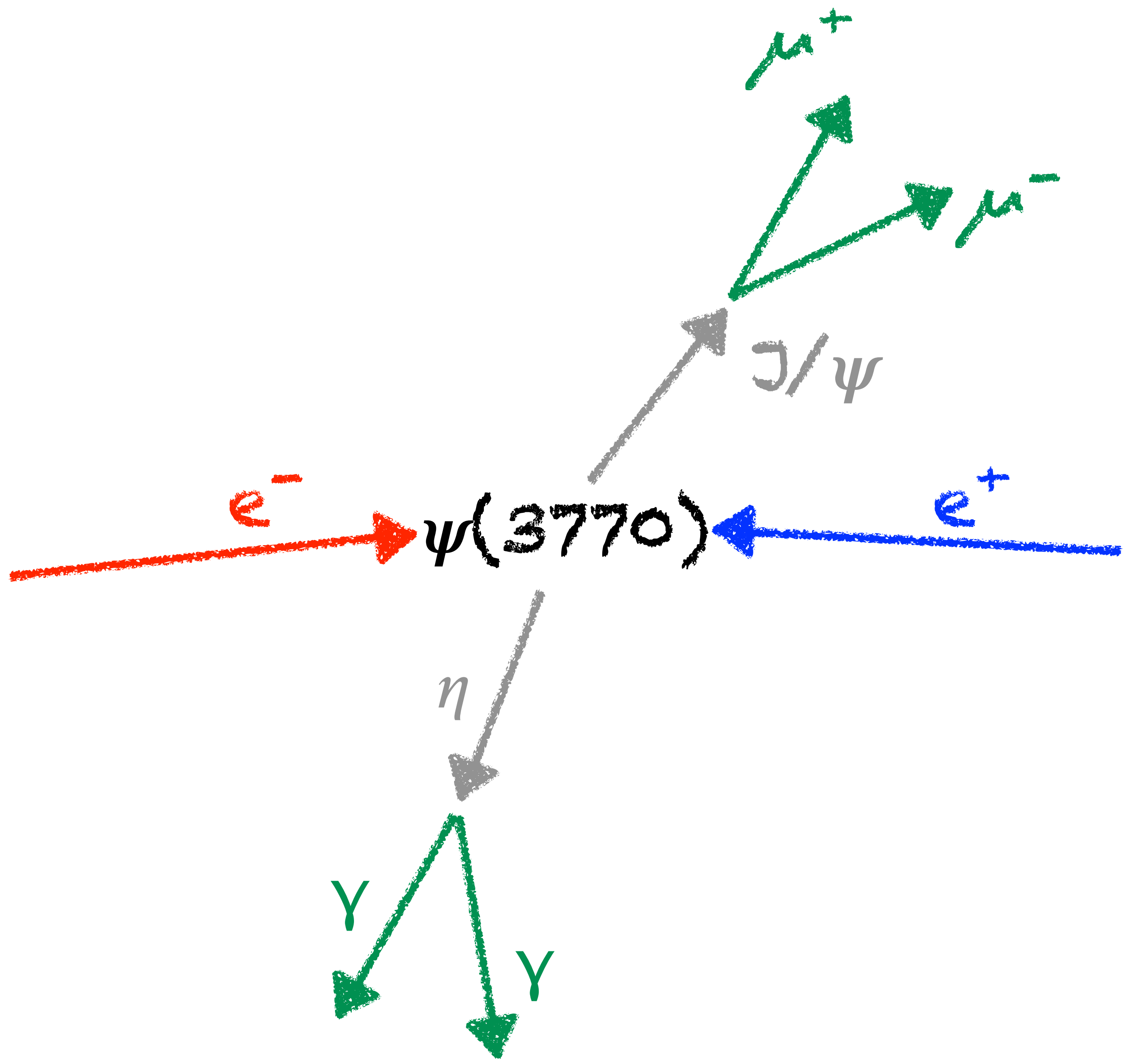
arXiv:2212.12165
Submitted to PRL

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

Heap observed in $M'(\gamma\gamma)$ ($\equiv M(\gamma\gamma) + M(\mu\mu) - m_{J/\psi}$) correlated to the J/ψ resonance in the $M(\mu\mu)$ spectrum

To extract the signal yield, a fit to $M'(\gamma\gamma)$ is performed in the $M(\mu\mu)$ signal region



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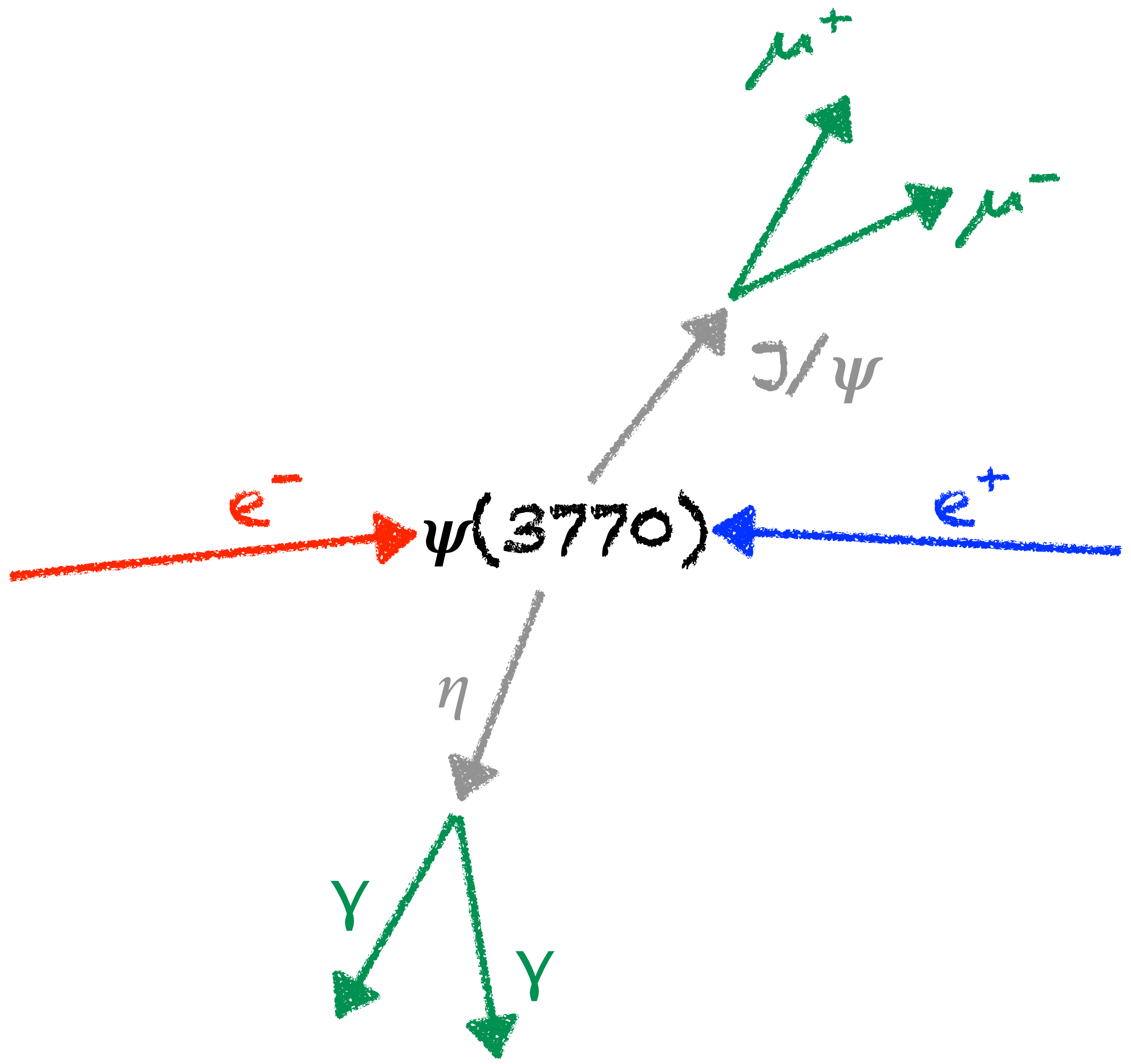

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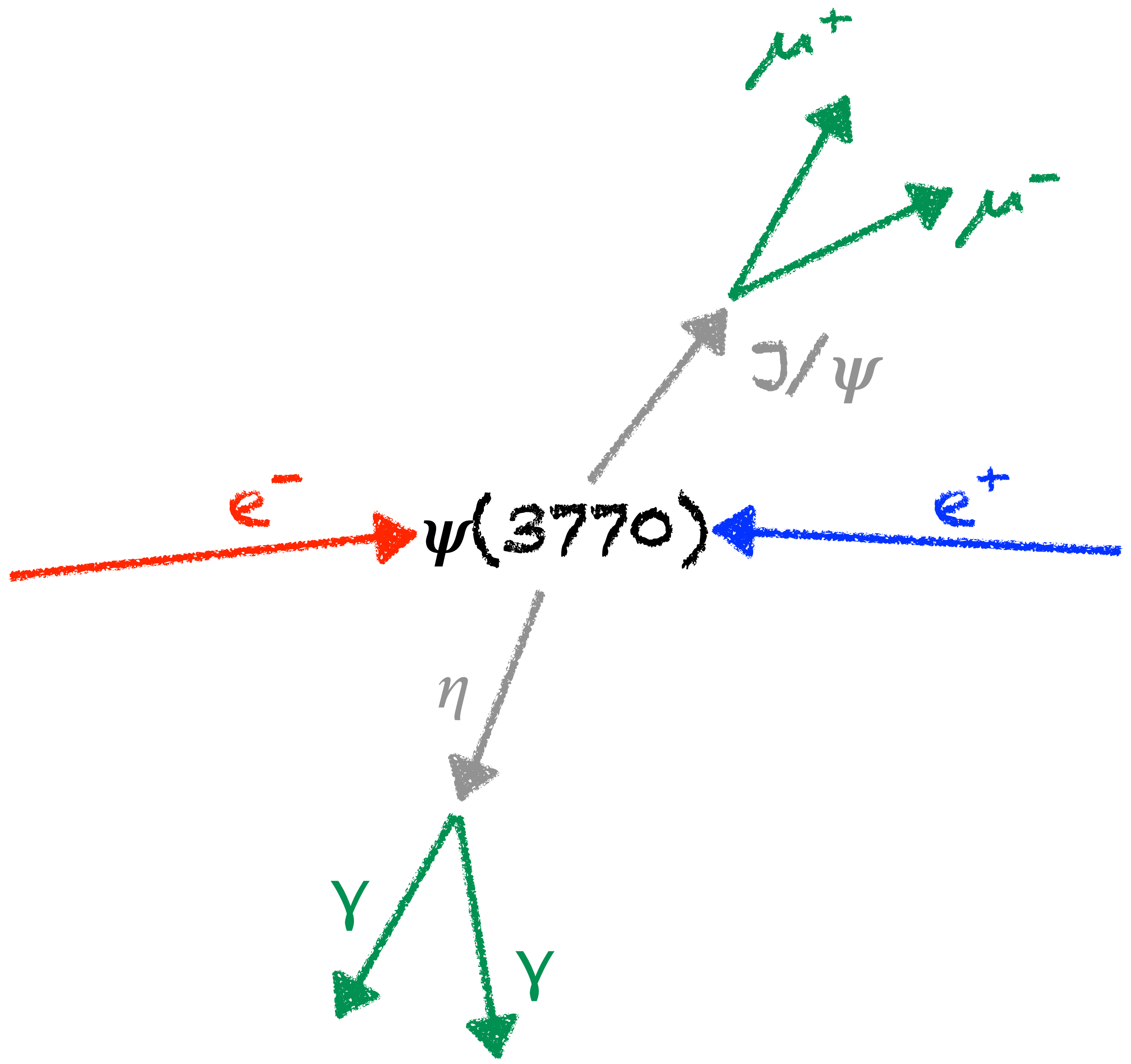

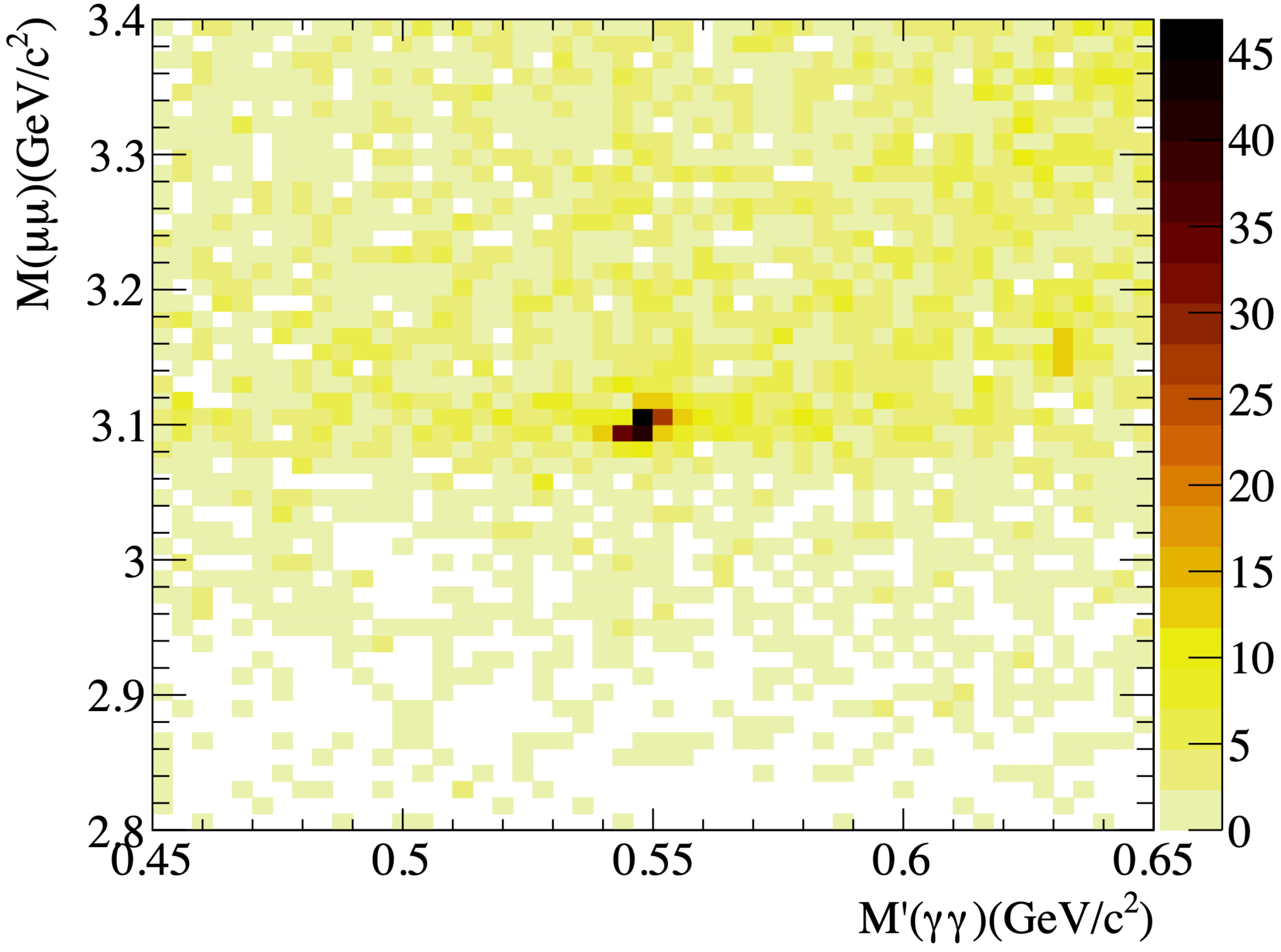

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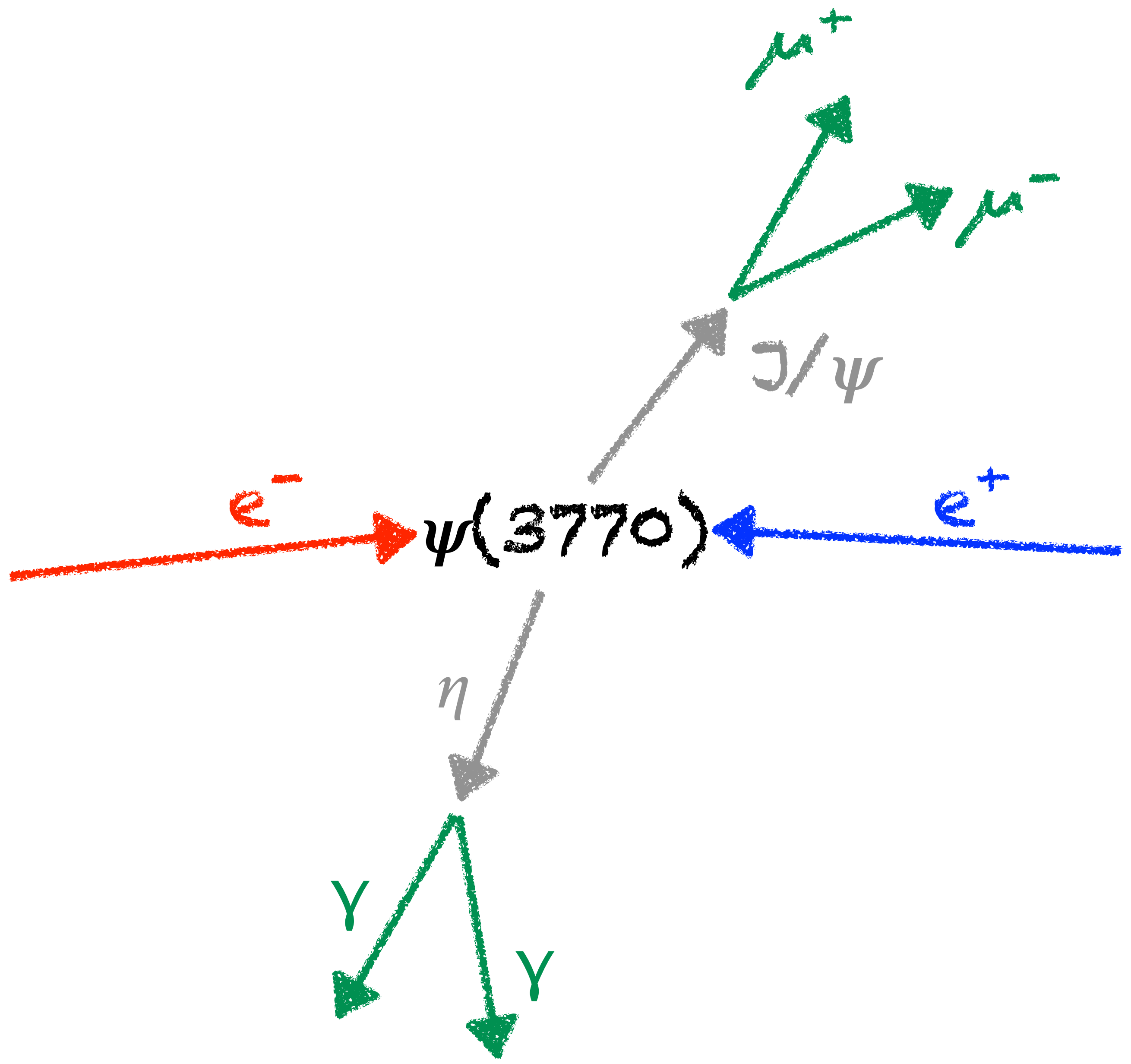

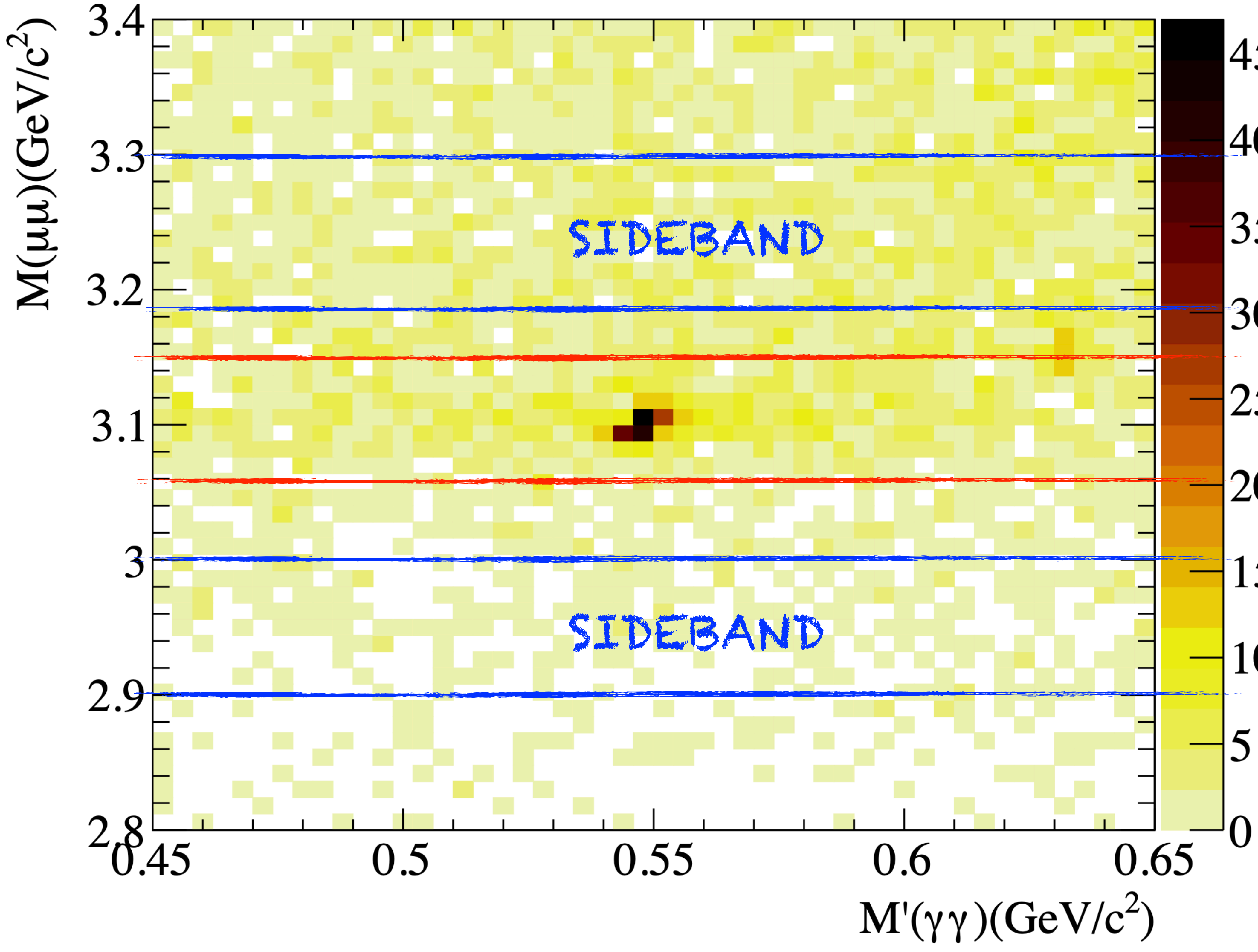

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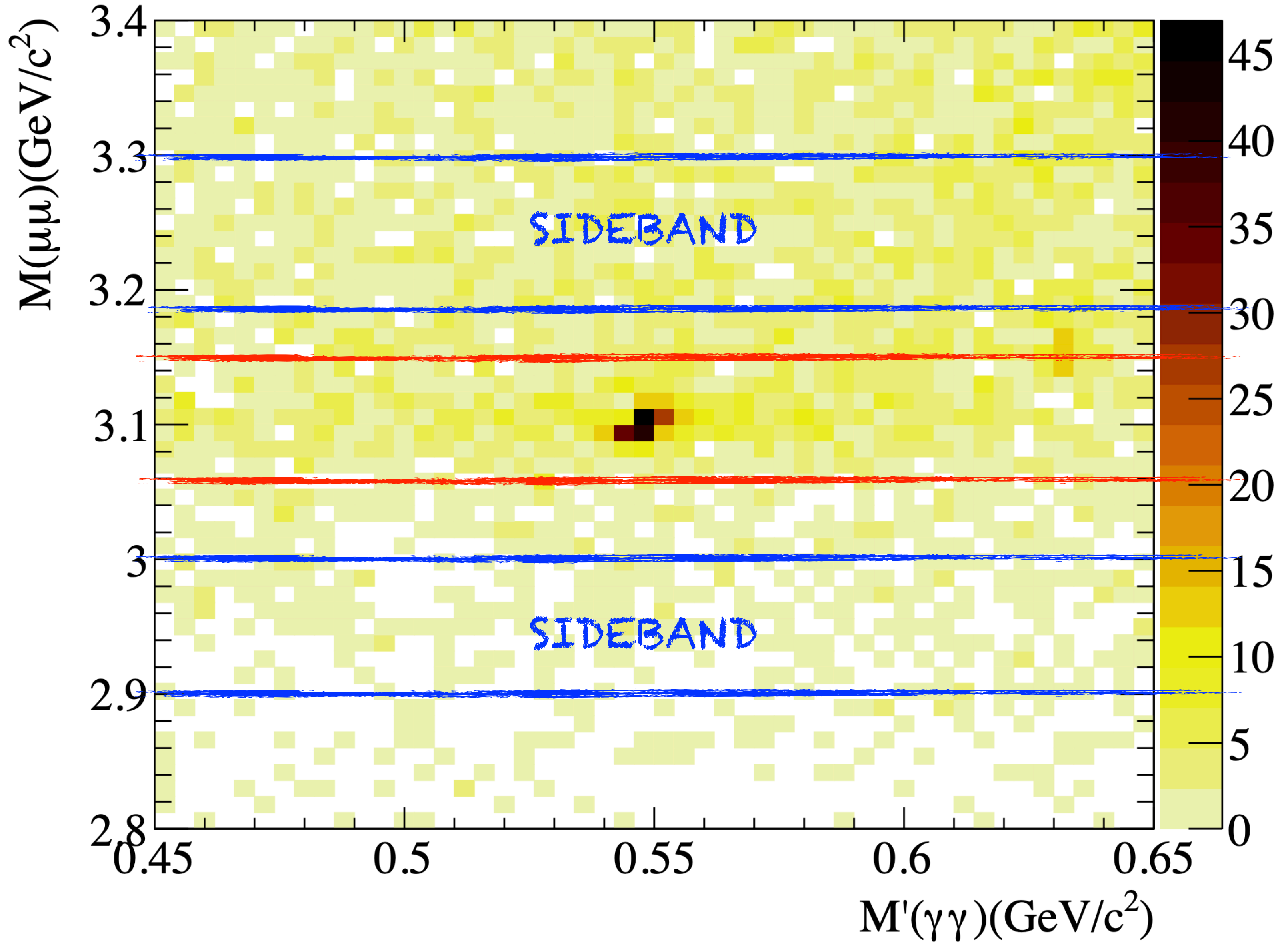

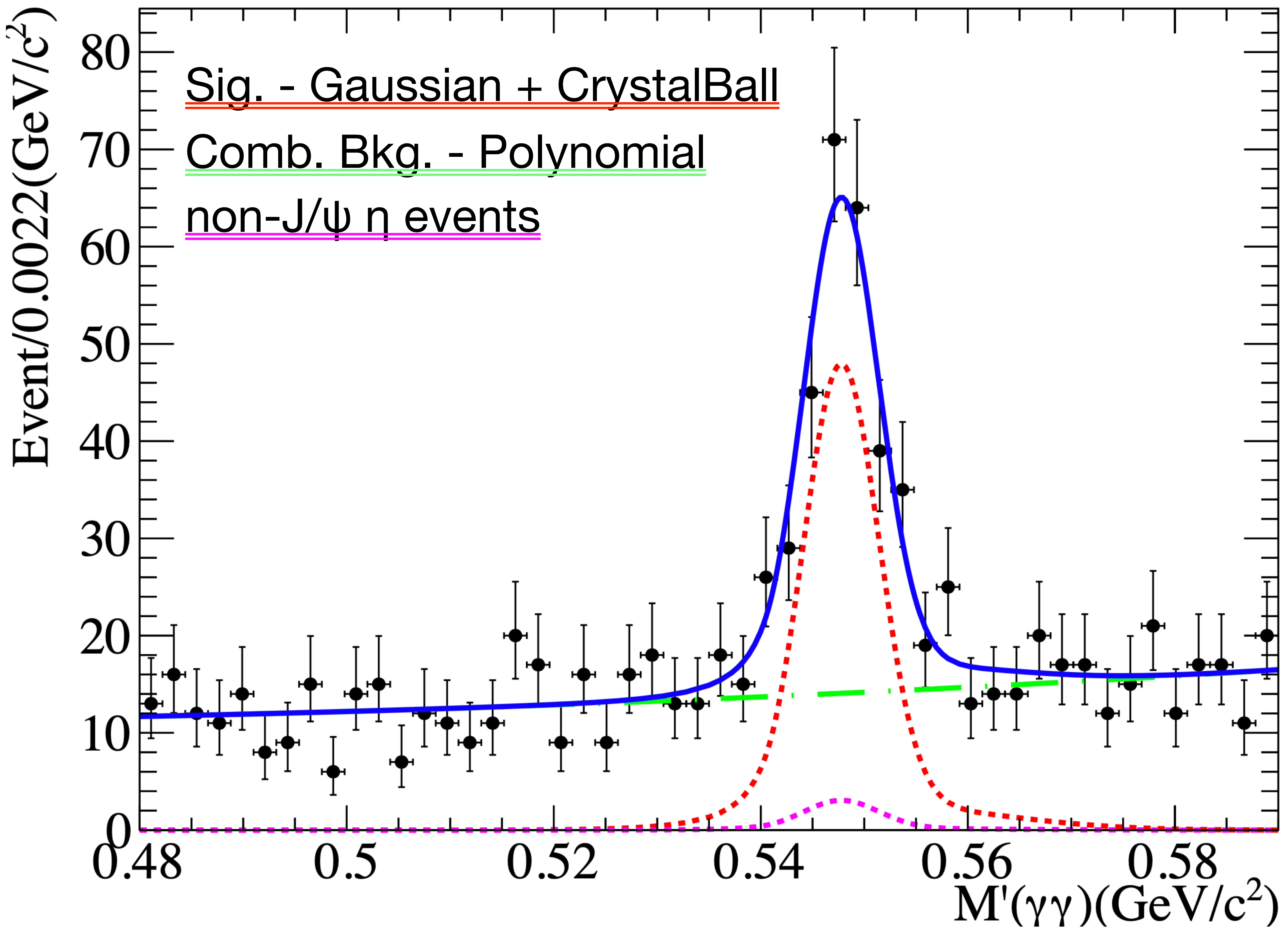

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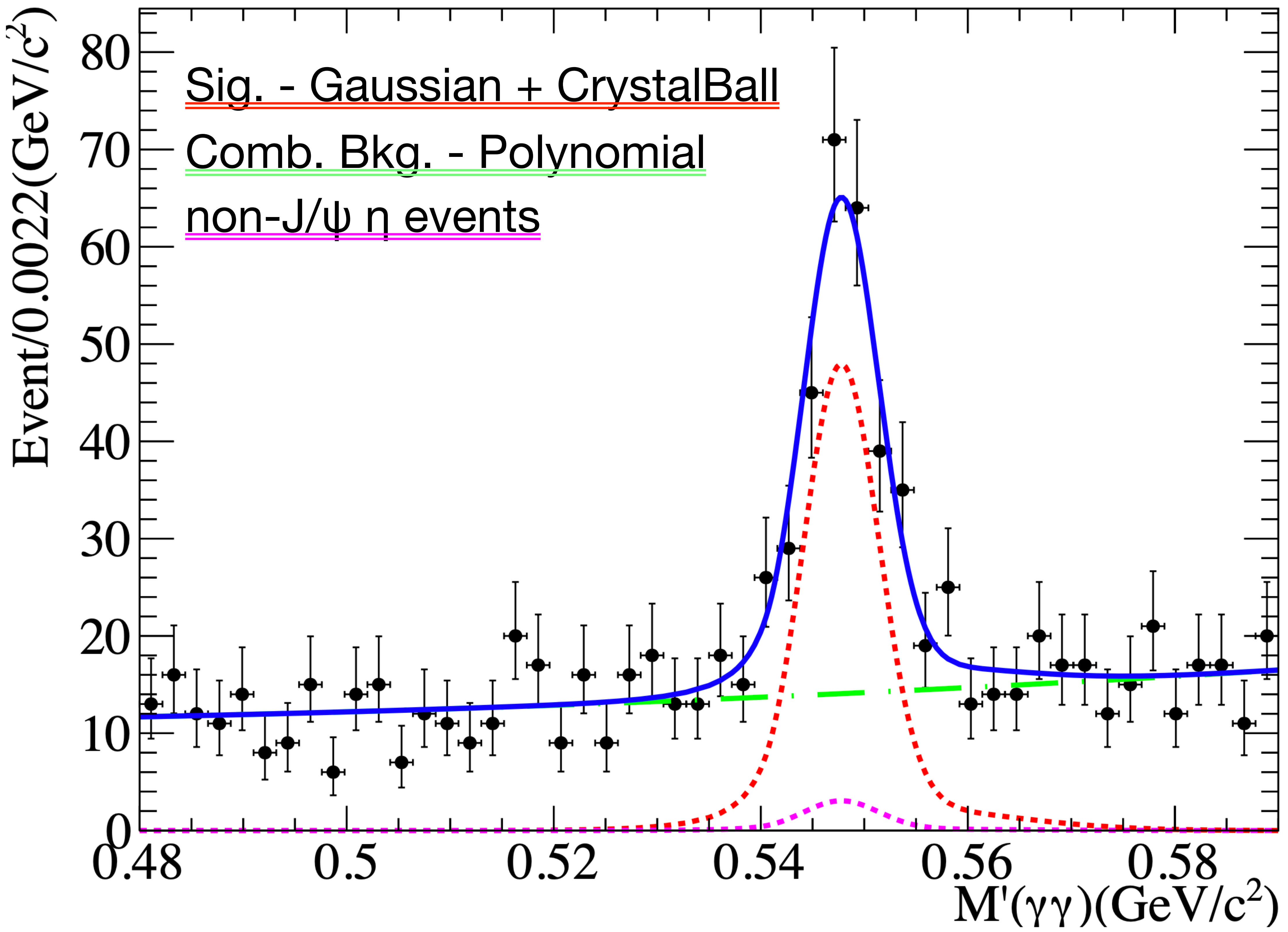
$$\sigma^B = \frac{N^{\text{obs}}}{\mathcal{L}\,\epsilon\,(1+\delta)_{\text{ISR}}\,\frac{1}{|1-\Pi^2|_{\text{VP}}}}$$

N^{obs}	$\sigma^B(\text{pb})$
222 ± 22	8.89 ± 0.88

First time observation @7.4σ



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

From Ref. [1], 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

[1] Phys. Rev. D **102**, 031101 (R)

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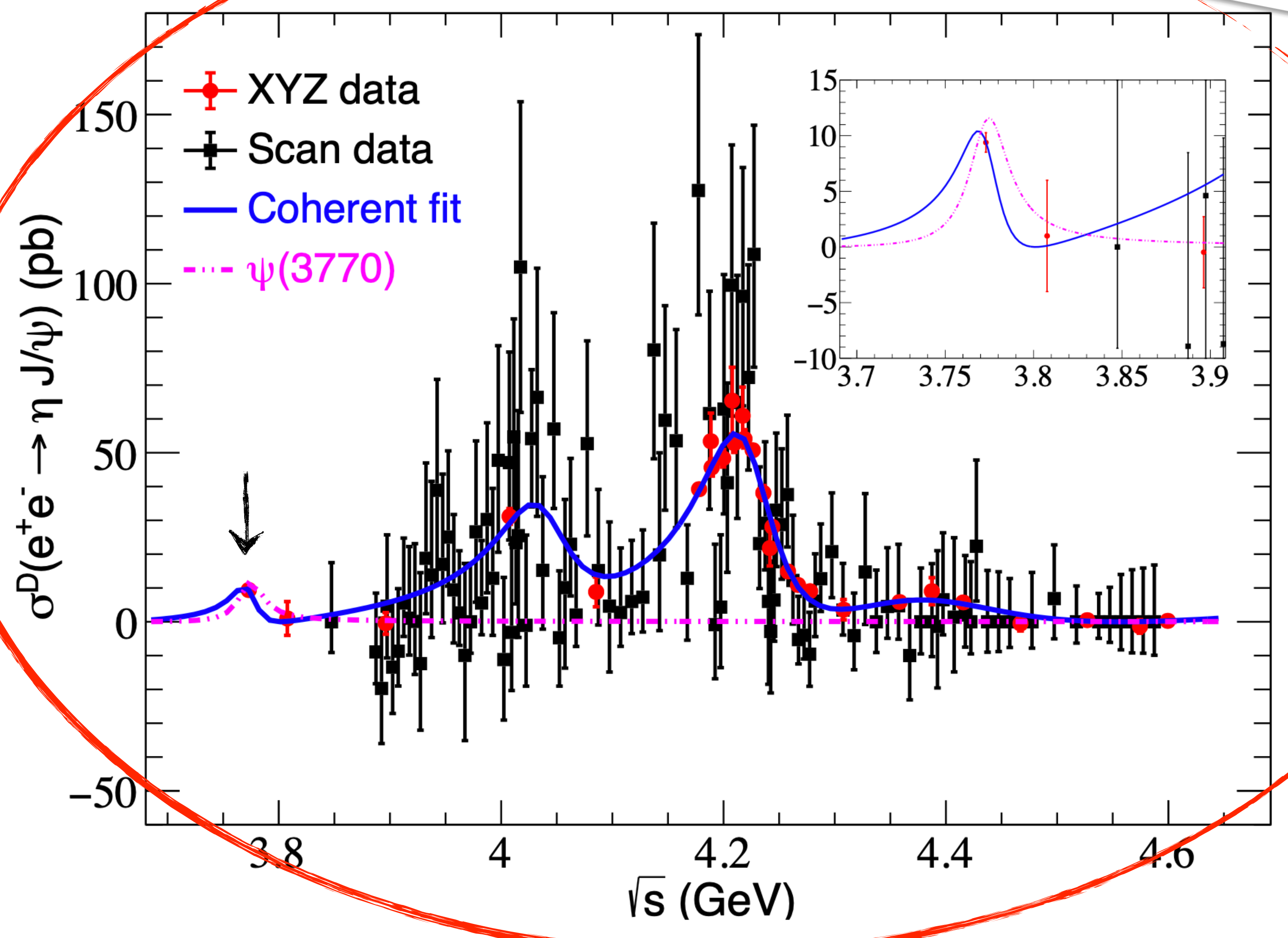

$$\sigma_{\text{co.}} = |C \cdot \sqrt{\Phi(s)} + e^{i\phi_1}\text{BW}_{\psi(3770)} + e^{i\phi_2}\text{BW}_{\psi(4040)} + e^{i\phi_3}\text{BW}_{Y(4230)} + e^{i\phi_4}\text{BW}_{Y(4390)}|^2$$

$$BW = \frac{\sqrt{12\pi\mathcal{B}\Gamma_{ee}\Gamma}}{s - M^2 + iM\Gamma}\sqrt{\frac{\Phi(s)}{\Phi(M^2)}}$$

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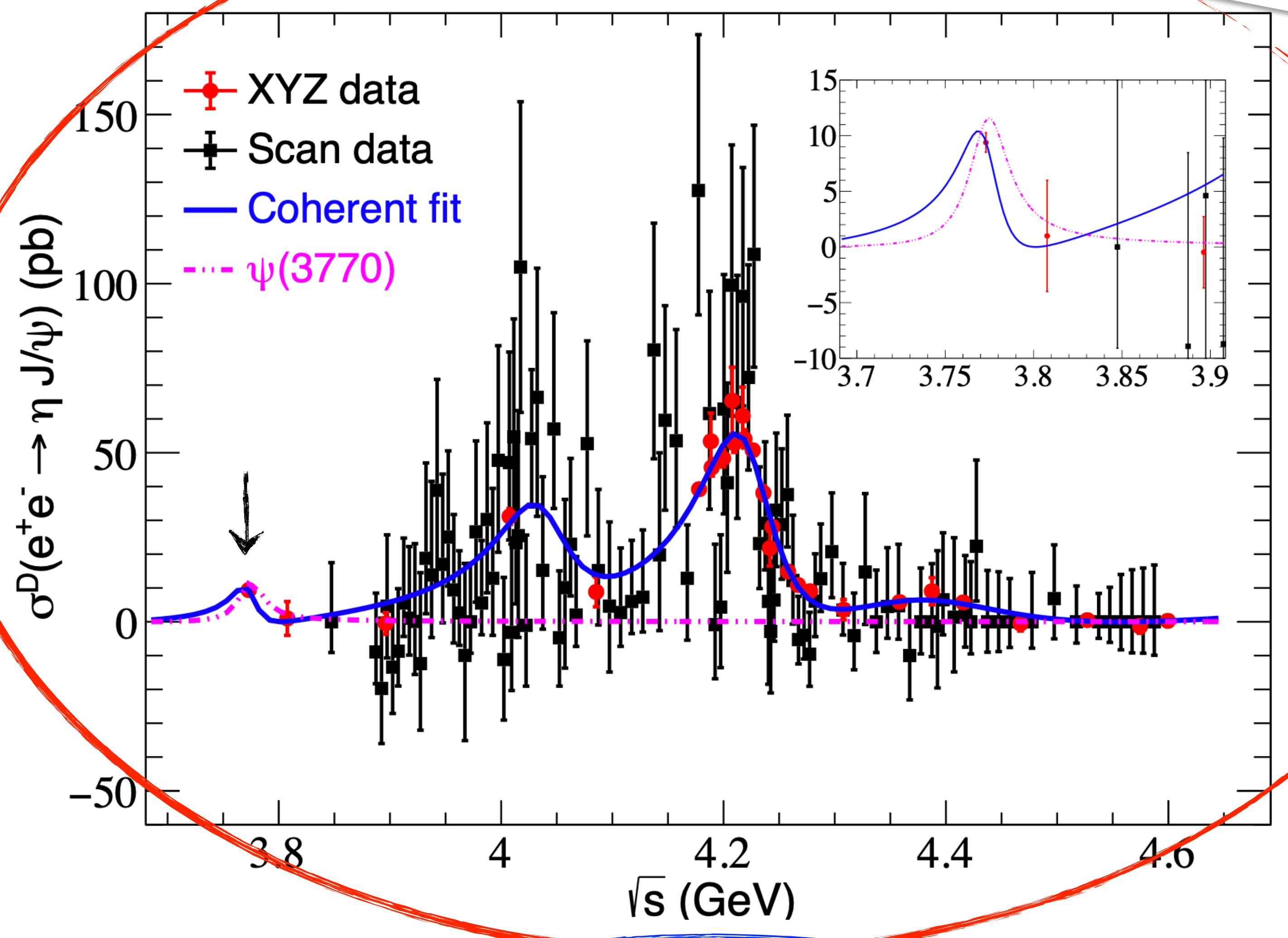

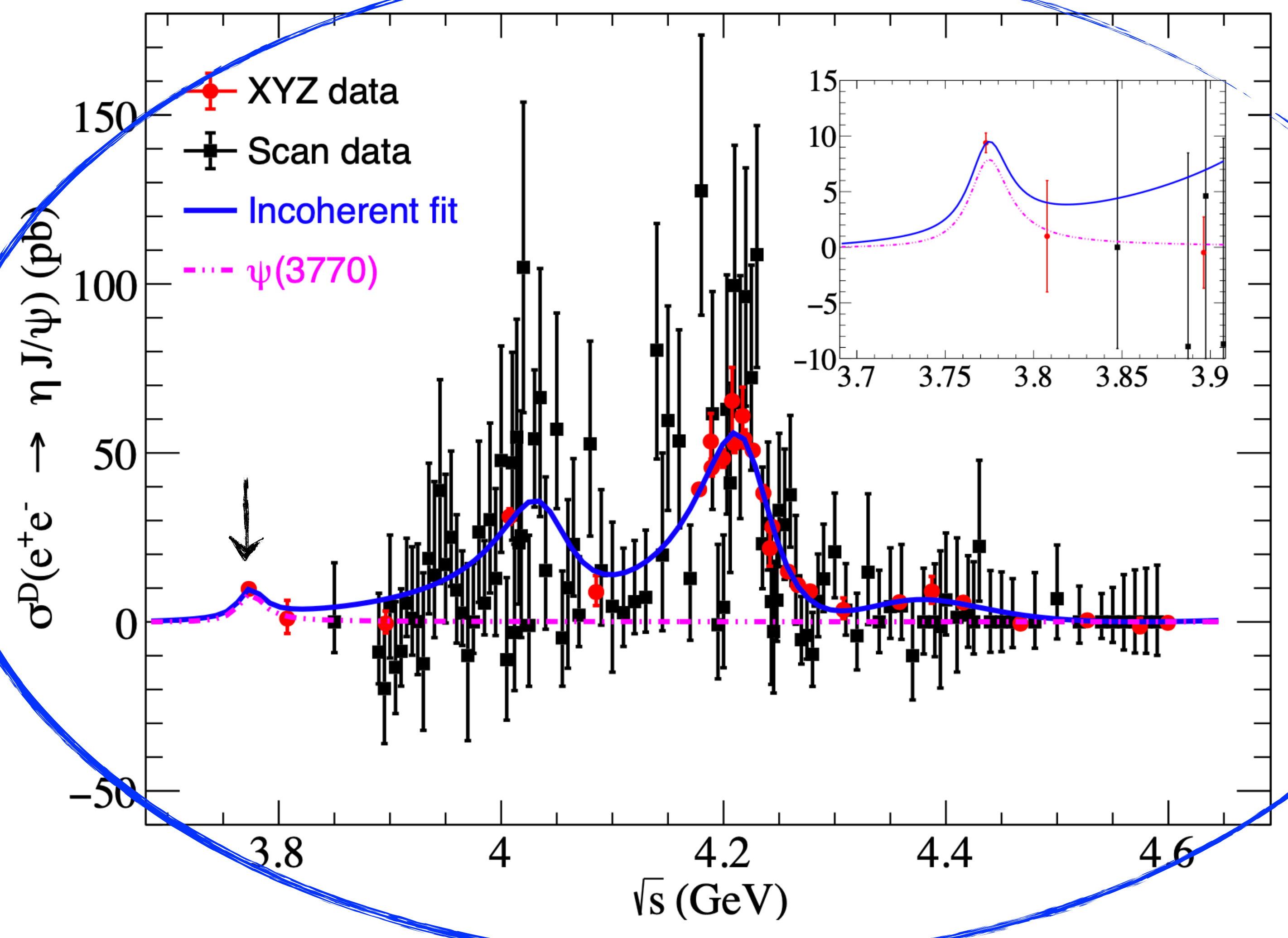

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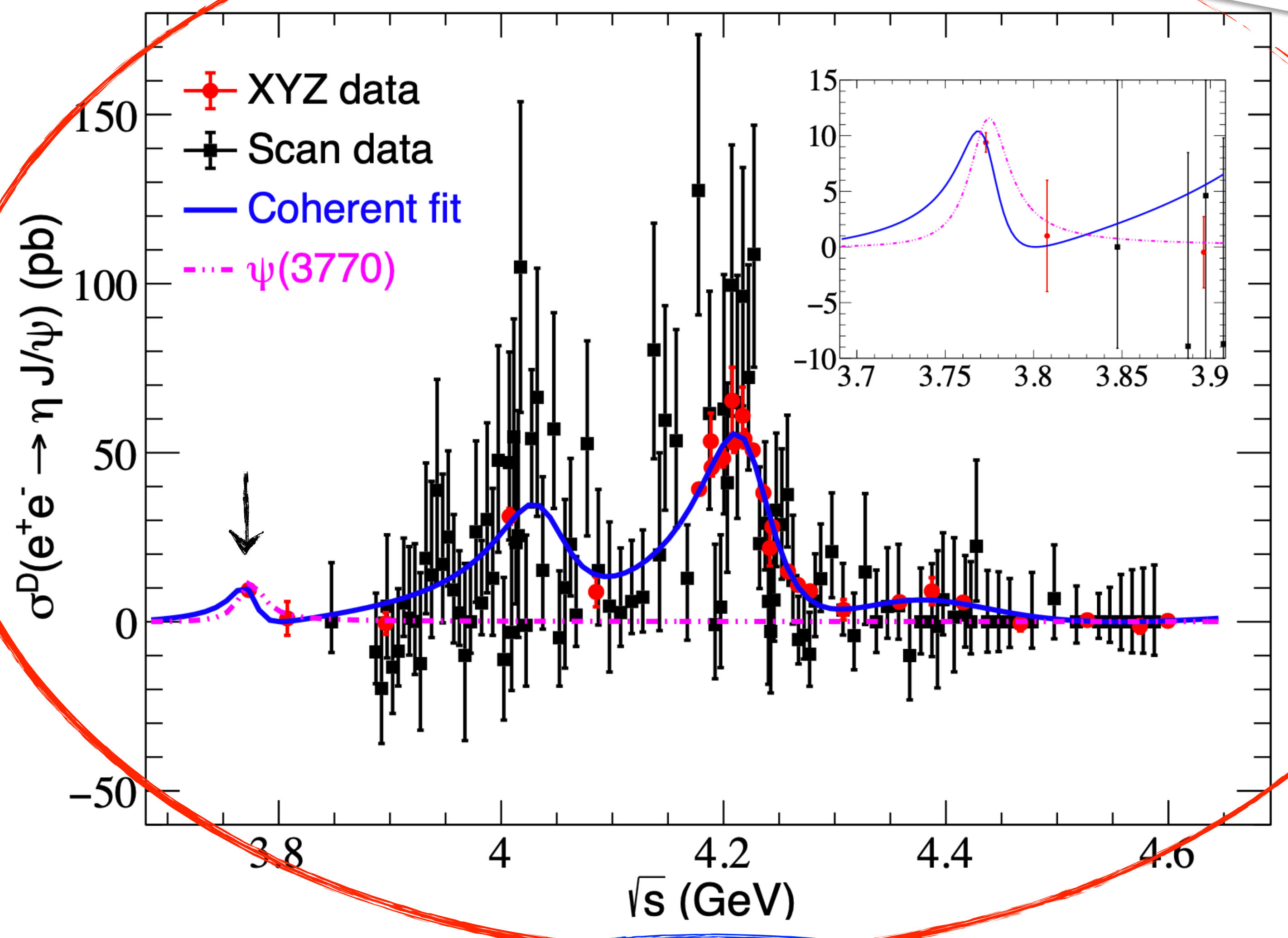
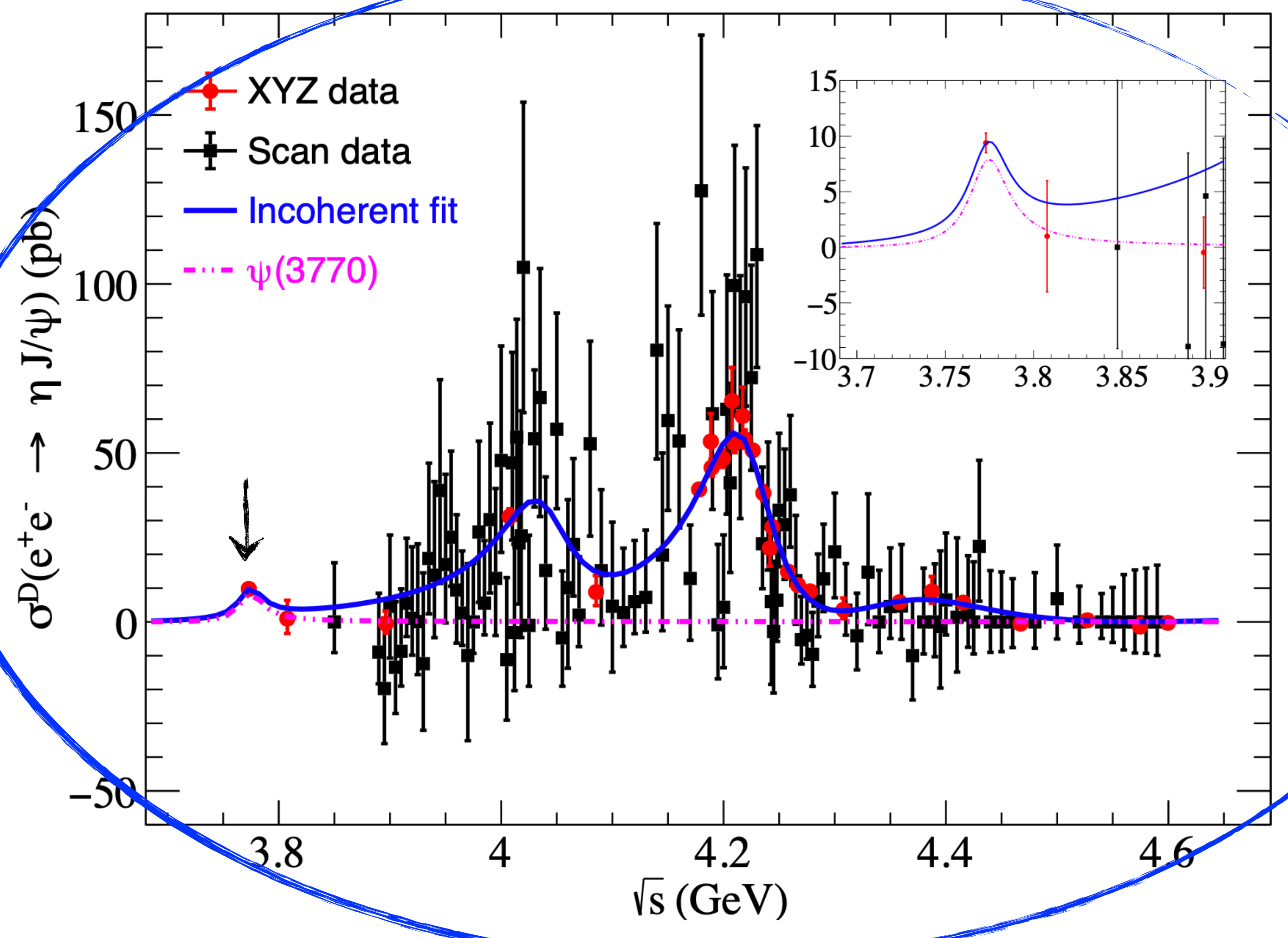
Fit scenario		$\mathcal{B}(\psi(3770) \to \eta J/\psi)$ $(\times 10^{-4})$	ϕ_1(rad)
Coherent fit	Solution1	$11.6 \pm 6.1 \pm 1.0$	4.0±0.5
	Solution2	$12.0 \pm 6.3 \pm 1.1$	4.3±0.5
	Solution3	$11.6 \pm 6.1 \pm 1.0$	3.8±0.5
	Solution4	$11.9 \pm 6.3 \pm 1.1$	4.1±0.5
Incoherent fit		$7.9 \pm 1.0 \pm 0.7$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





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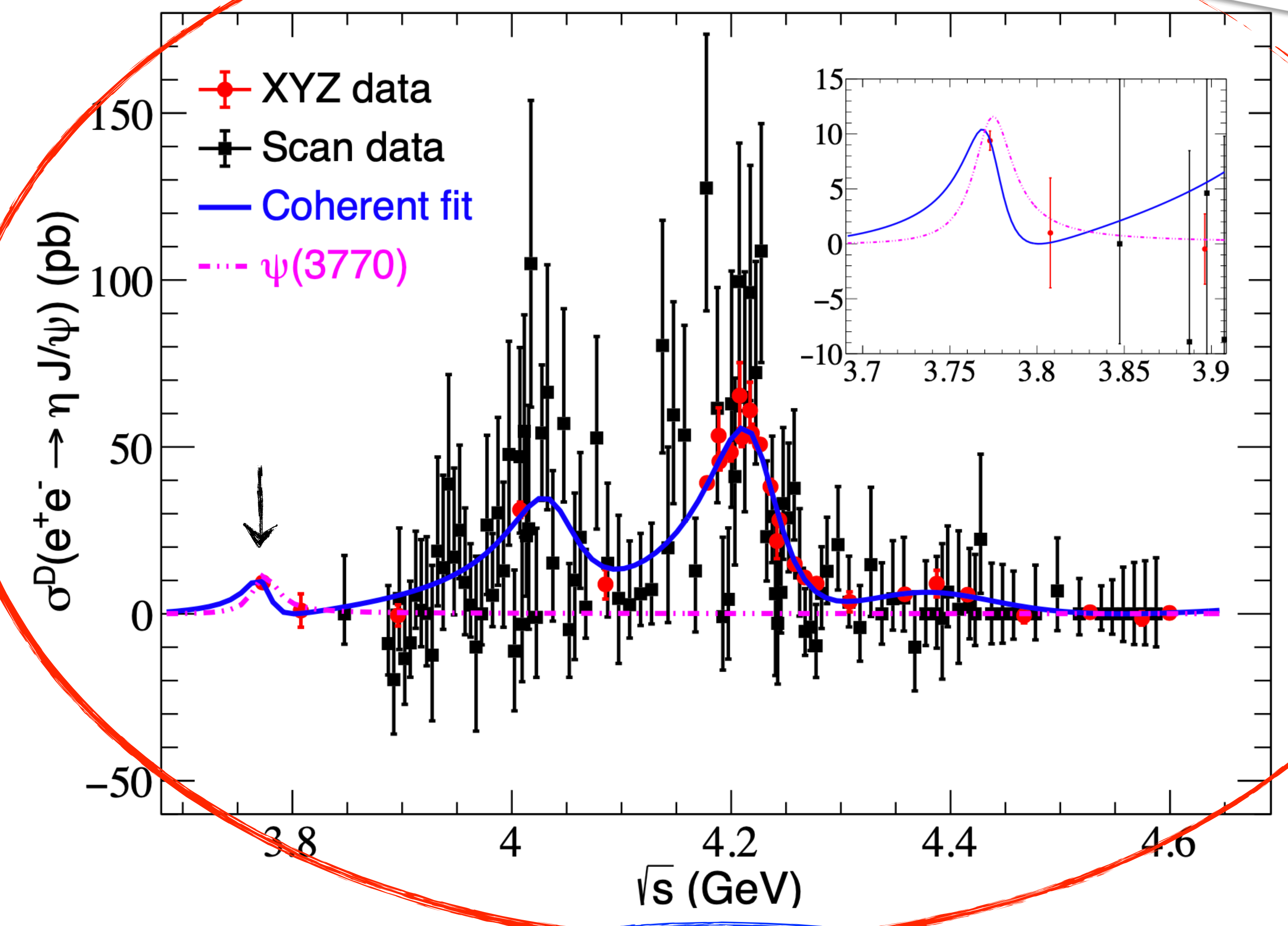
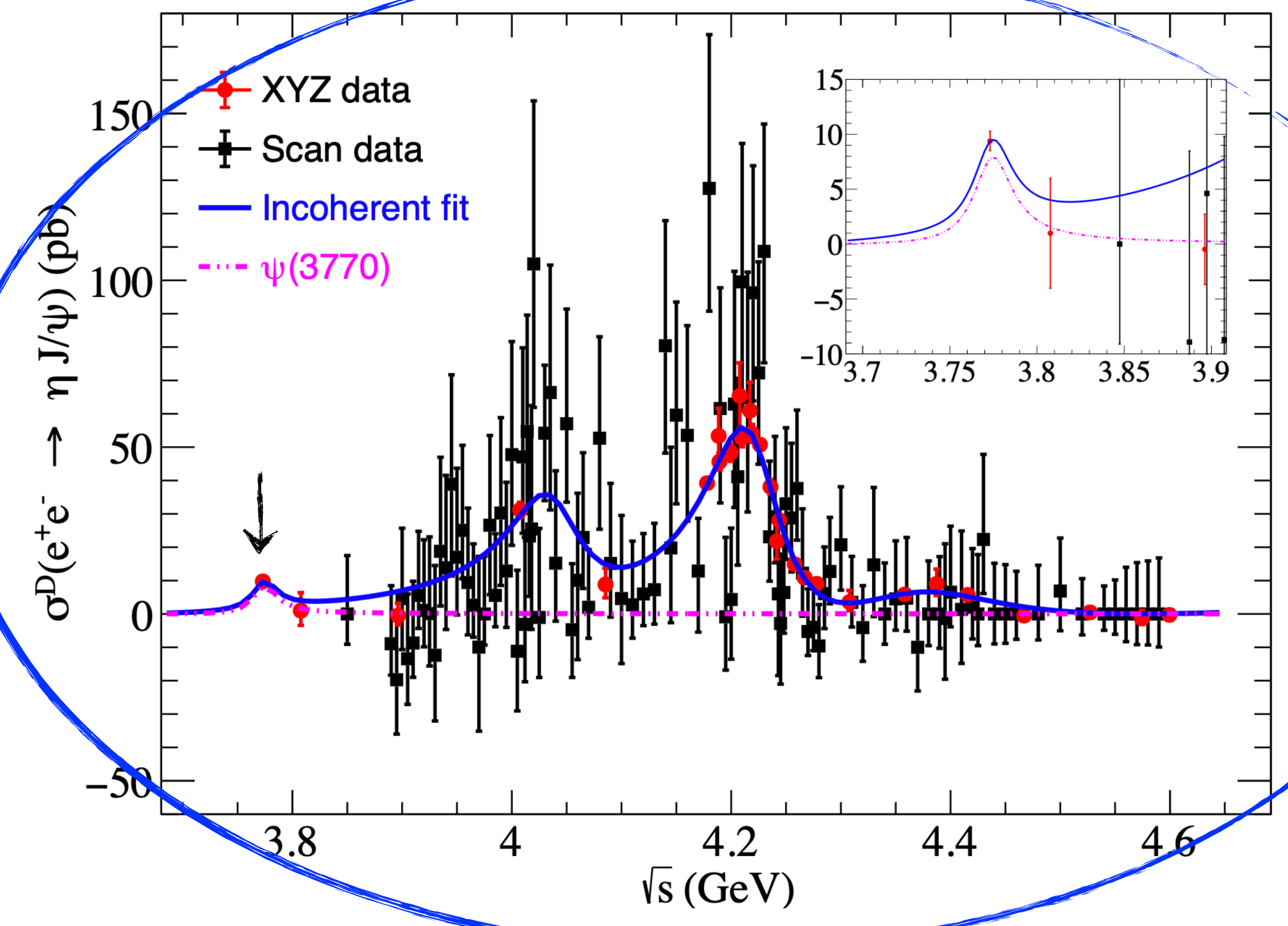




Compatible with CLEO result[2] (w/o interference) of $8.7 \pm 3.3 \pm 2.2 \times 10^{-4}$

In **agreement with Ref. [3]** hypothesis of **tetra-quark admixture** in the **ψ(3770)**
$\mathcal{B}(\psi(3770) \to \eta J/\psi) \sim 15 \times 10^{-4}$

[1] Phys. Rev. D **102**, 031101 (R)
[2] Phys. Rev. Lett. **96**, 082004
[3] Phys. Rev. D **71**, 114003

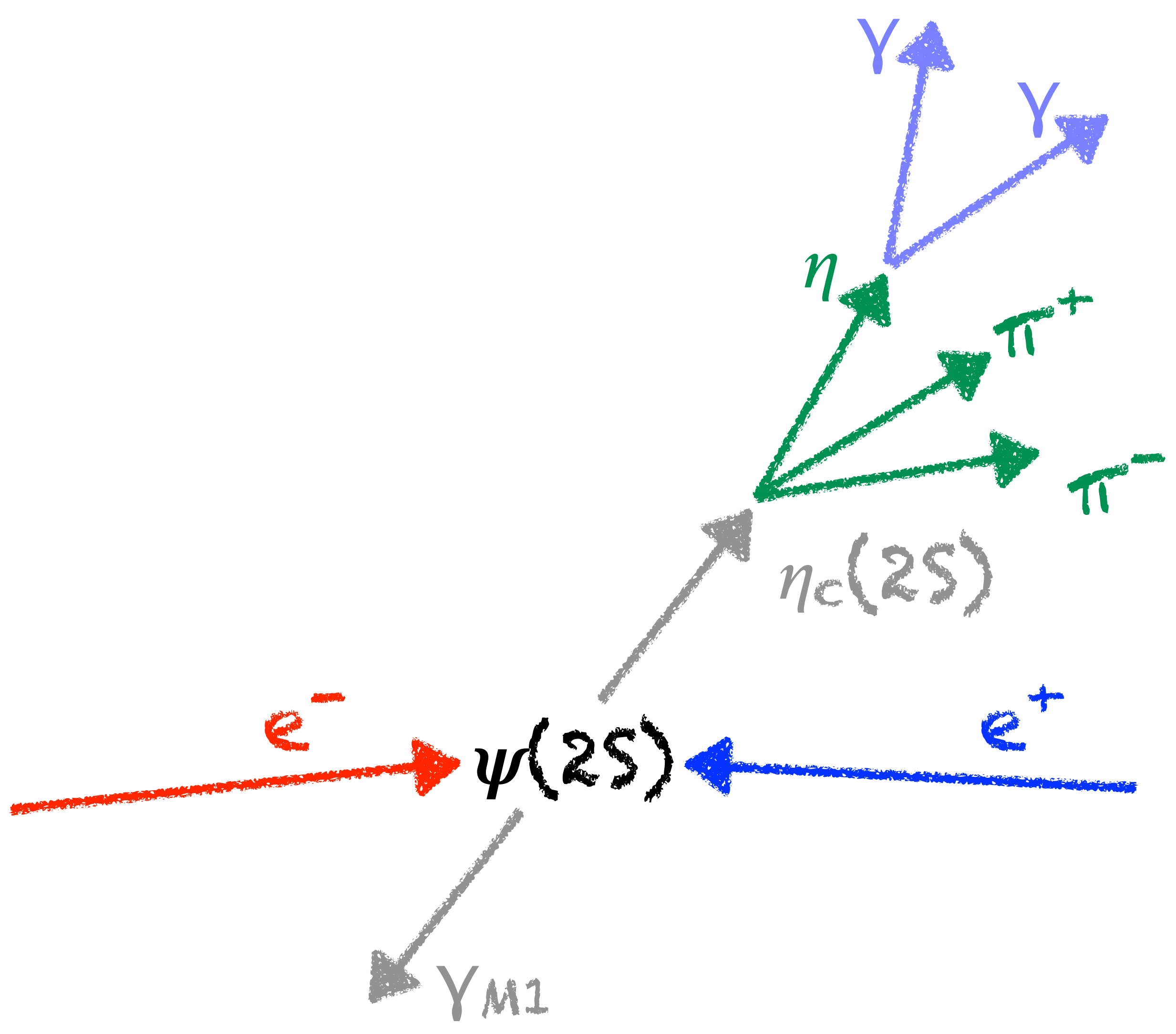
Evidence for $\eta_c(2S) \to \pi^+\pi^- \eta$ decay

arXiv:2211.11935
Submitted to PRD

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** $\boldsymbol{\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta)}$

Due to the small energy of the γ_{M1}, having the background under control is fundamental



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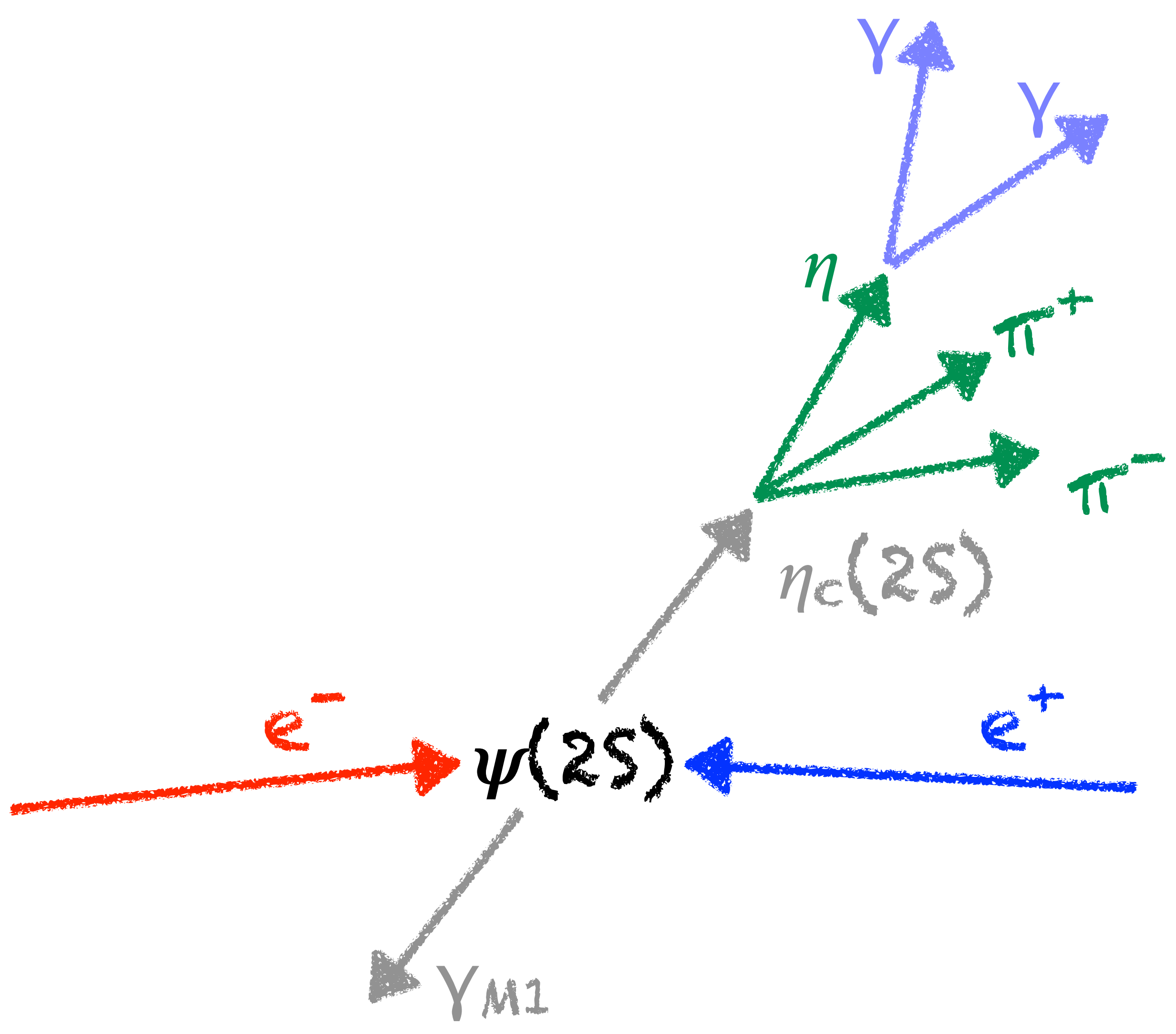

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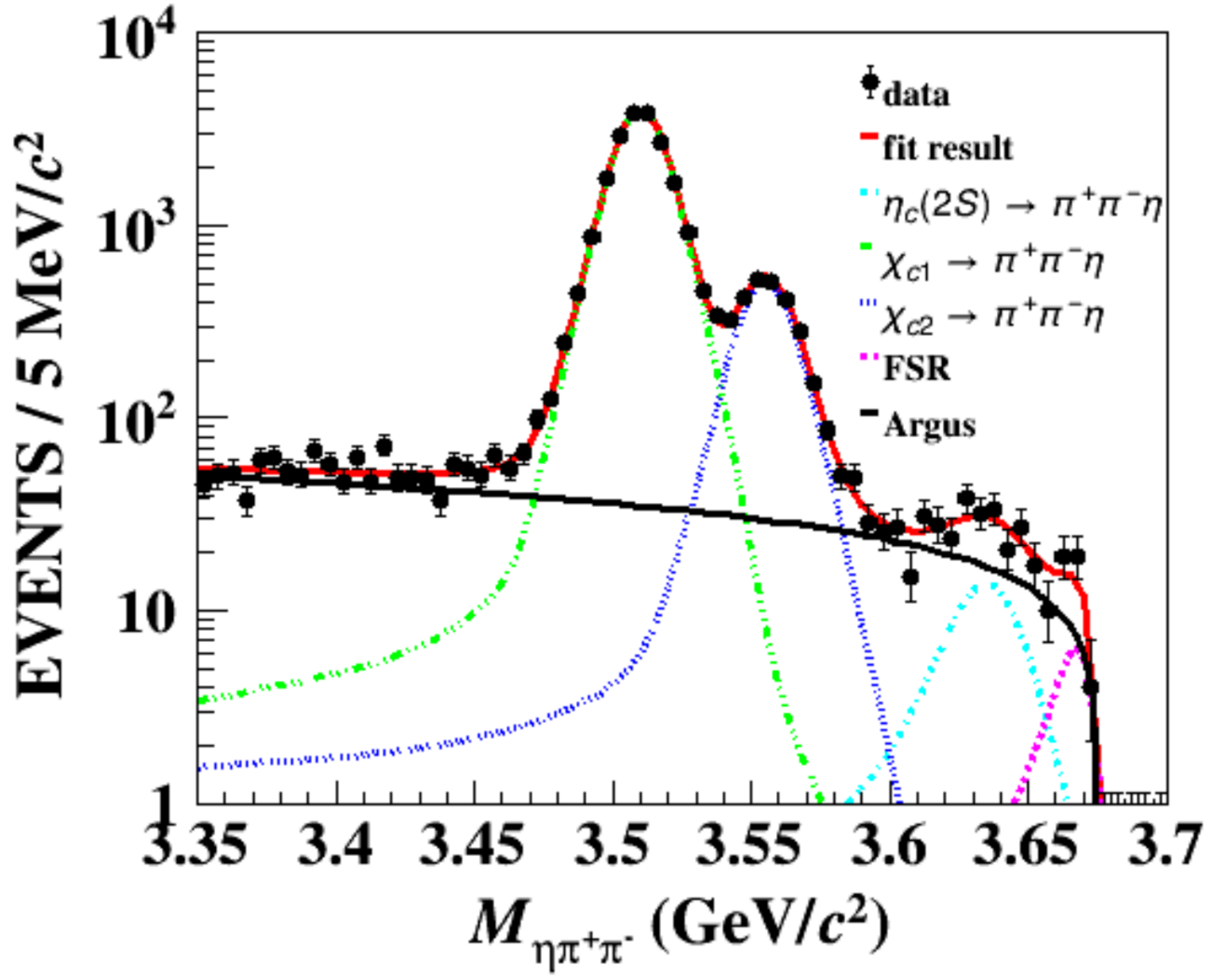
Due to the small energy of the γ_{M1}, having the background under control is fundamental

I. $\psi(2S) \rightarrow \pi^+\pi^-\eta$

II. $J/\psi \rightarrow \mu^+\mu^-\gamma_{FSR}$

III. $\psi(2S) \rightarrow \pi^+\pi^-\eta\gamma_{FSR}$

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



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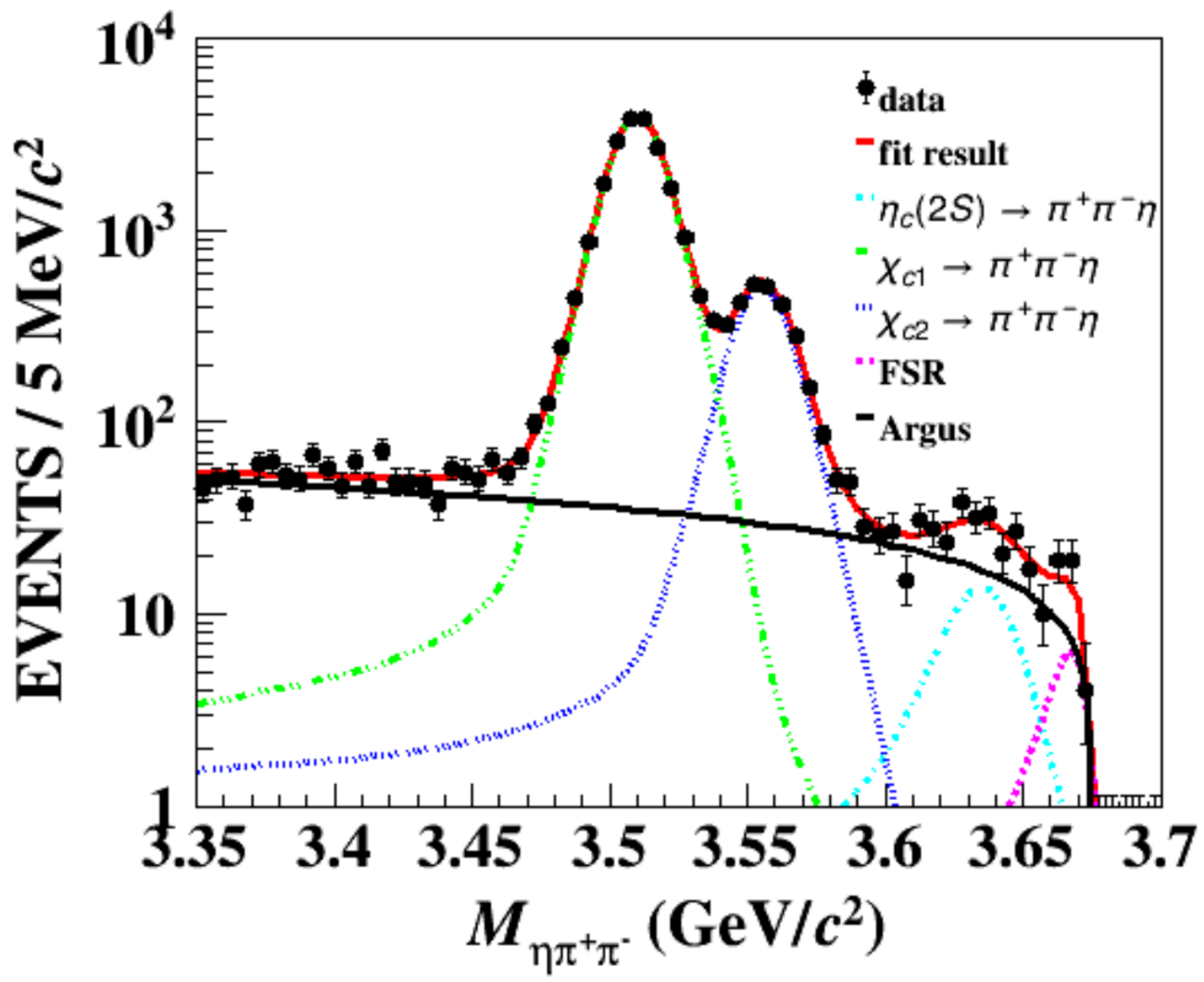
Fit to the M($\pi^+\pi^-\gamma\gamma$) at [3.35, 3.70] GeV/c^2 to properly estimate the $\chi_{c1,2} \to \pi^+\pi^-\eta$ contributions (found to be compatible to PDG values)

N_{sig}
106 ± 29

First evidence
@3.5σ



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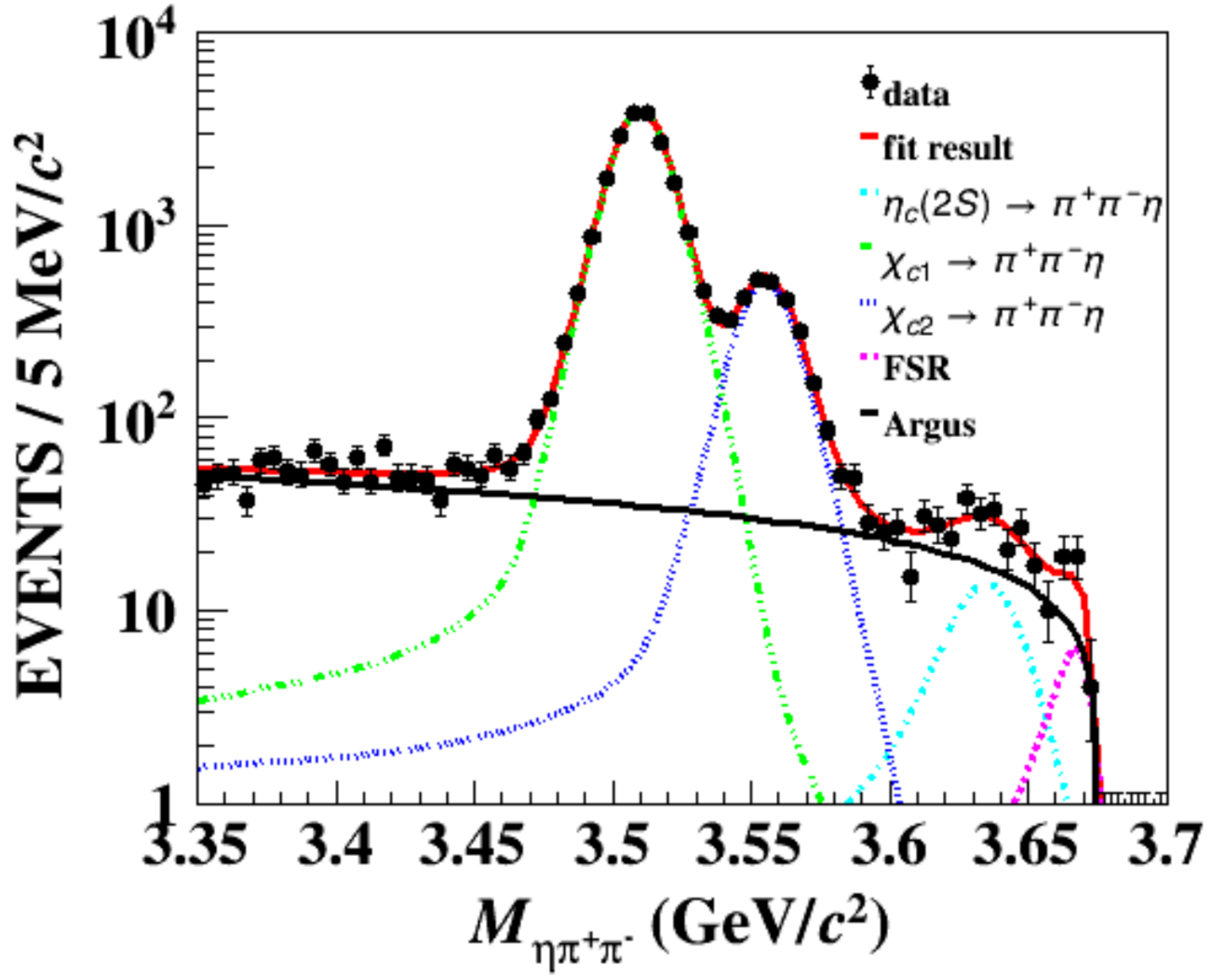
$$\mathcal{B}(\eta_c(2S) \to \pi^+\pi^-\eta) = \frac{N_{\rm sig}}{N_{\psi(3686)}\ \epsilon\ BR_1(\psi(3686) \to \gamma\eta_c(2S))\ BR_2(\eta \to \gamma\gamma)}$$



Evidence for $\eta_c(2S) \to \pi^+\pi^- \eta$ decay

arXiv:2211.11935
Submitted to PRD

Using the 448 million ψ(2S) data set

Search for the **$\eta_c(2S) \to \pi^+\pi^-\eta$ 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)

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

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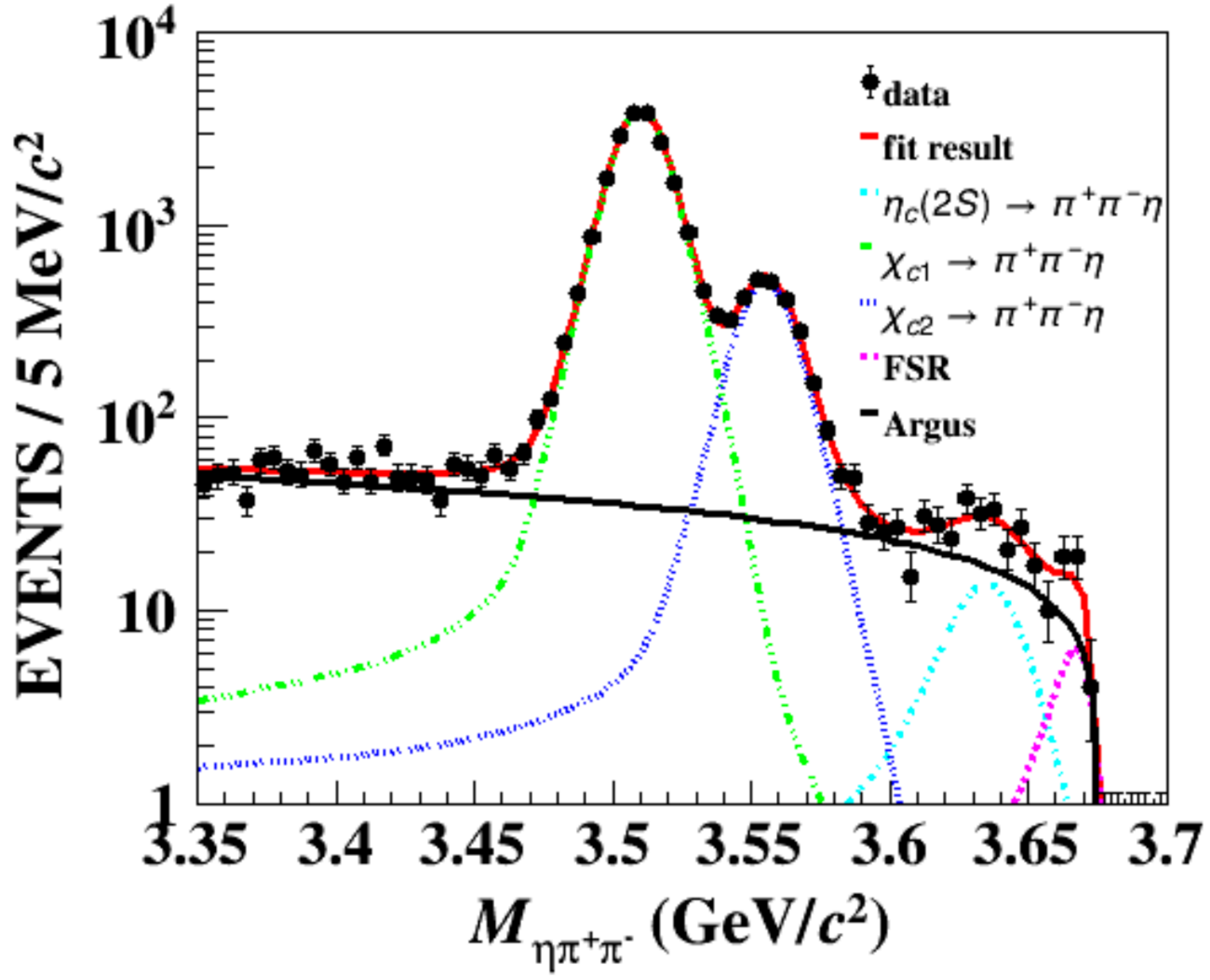
$$= (42.4 \pm 11.6 \pm 3.8 \pm 30.8) \times 10^{-4}$$

Stat. Syst. $\delta(BR_1)$



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Stat. Syst. $\delta(BR_1)$

Proceed to test the "*12% rule*" (ratio of the 2S/1S to light hadron branching fractions is ~ 12%)

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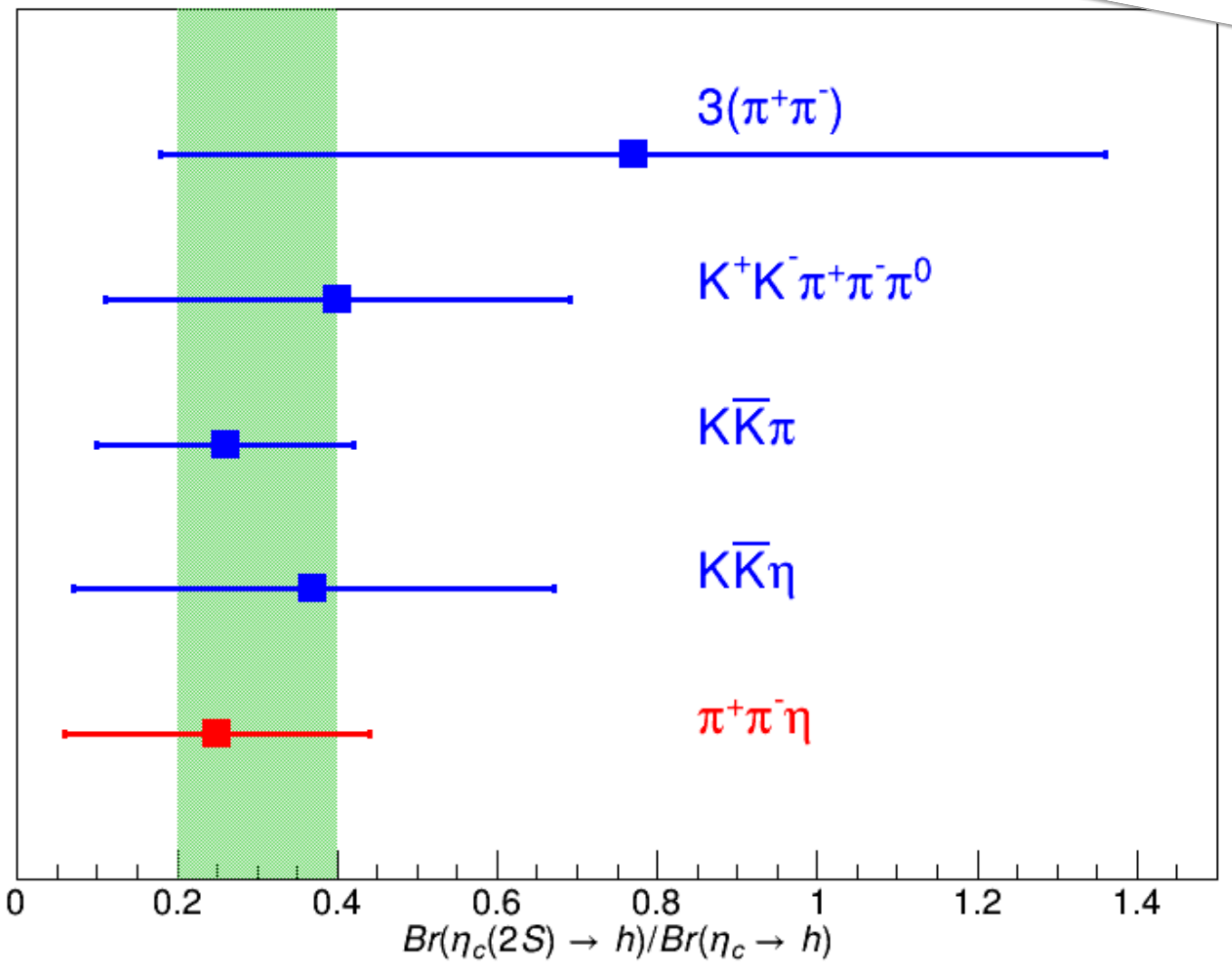


In the case of 0^{-+} glueball-charmonium mixing, Ref. [4] and Ref. [5] predict ~12.8% and ~1.00, respectively

Proceed to test the "*12% rule*" (ratio of the 2S/1S to light hadron branching fractions is ~ 12%)

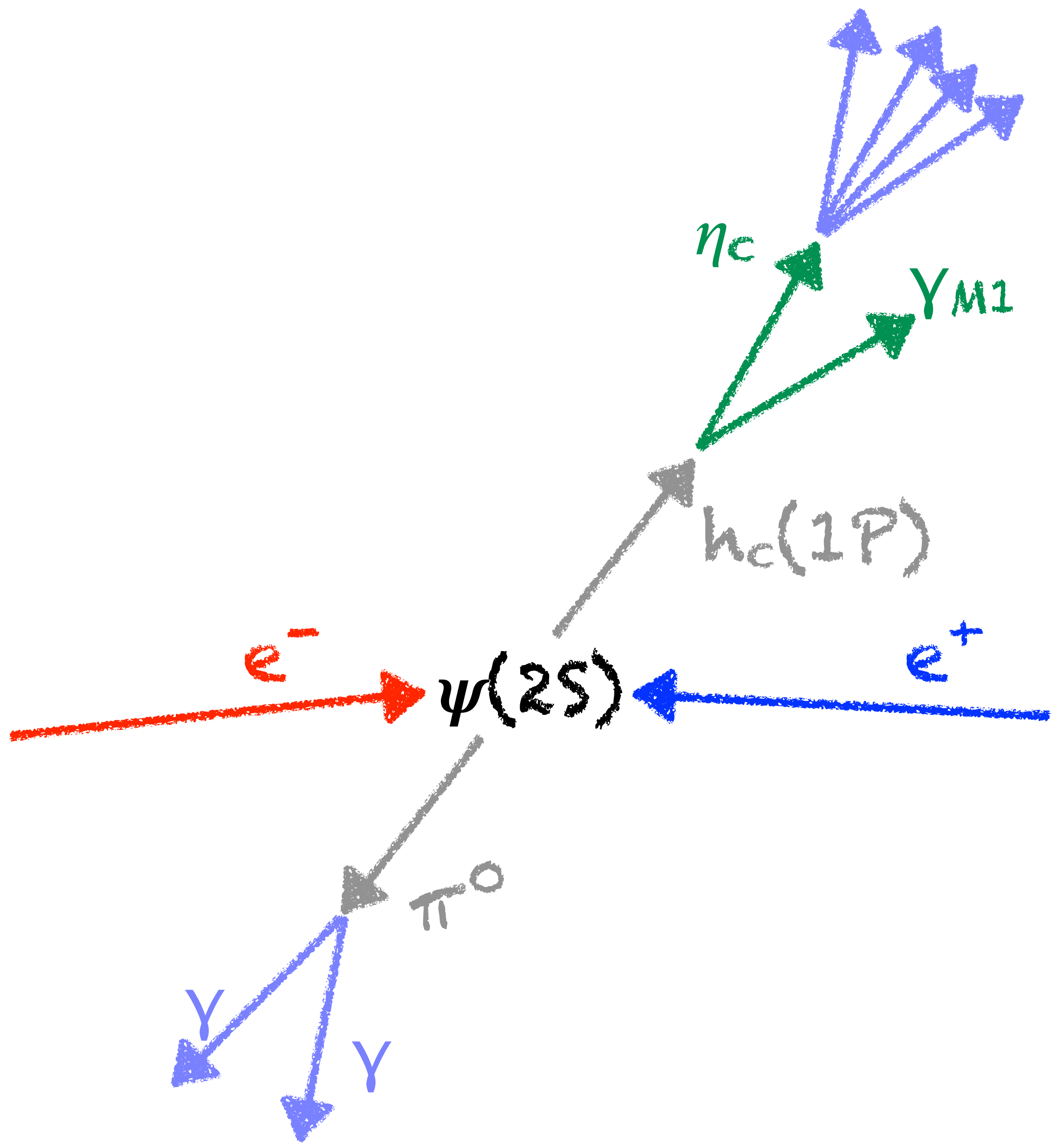
[4] Phys. Rev. D **44**, 1597 (1991)
[5] Commun. Theor. Phys. **25**, 471 (1996)

Study of the $h_c(1\,^1P_1)$ meson via $\psi(2S) \to \pi^0 h_c$ decays at BESIII

PRD **106**, 072007 (2022)

Using 448 million ψ(2S) events

Search for the **E1** $\boldsymbol{h_c \to \gamma\eta_c}$ **transition** through the $\psi(2S) \to \pi^0 h_c$ decay to **determine** $\mathbf{h_c}$**(1P) features and** the **relative** $\mathcal{B}$



[10] Ann. Rev. Nucl. Part. Sci. **37**, 325 (1987)

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PRD **106**, 072007 (2022)

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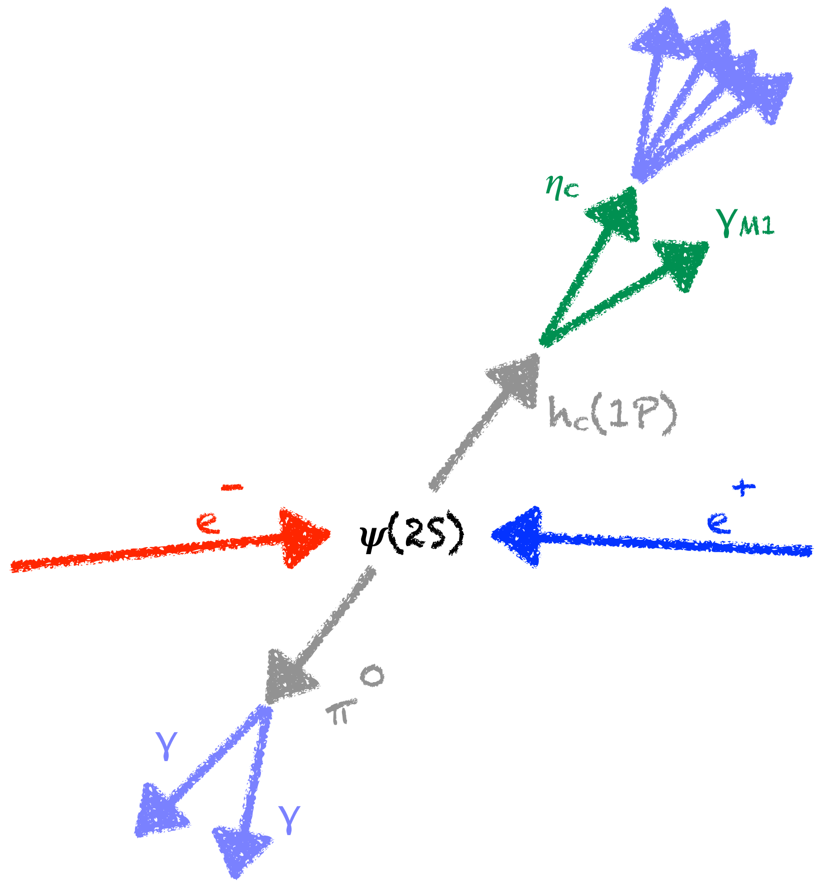
Search for the **E1 $h_c \to \gamma\eta_c$ transition** through the $\psi(2S) \to \pi^0 h_c$ decay to **determine $h_c(1P)$ features and** the **relative $\mathcal{B}$**

The h_c mass is reconstructed via the π^0 recoil mass (RM(π^0))

$$RM(\pi^0) = \sqrt{(E_{\psi(2S)} - E_{\pi^0})^2 - (\bar{p}_{\psi(2S)} - \bar{p}_{\pi^0})^2}$$



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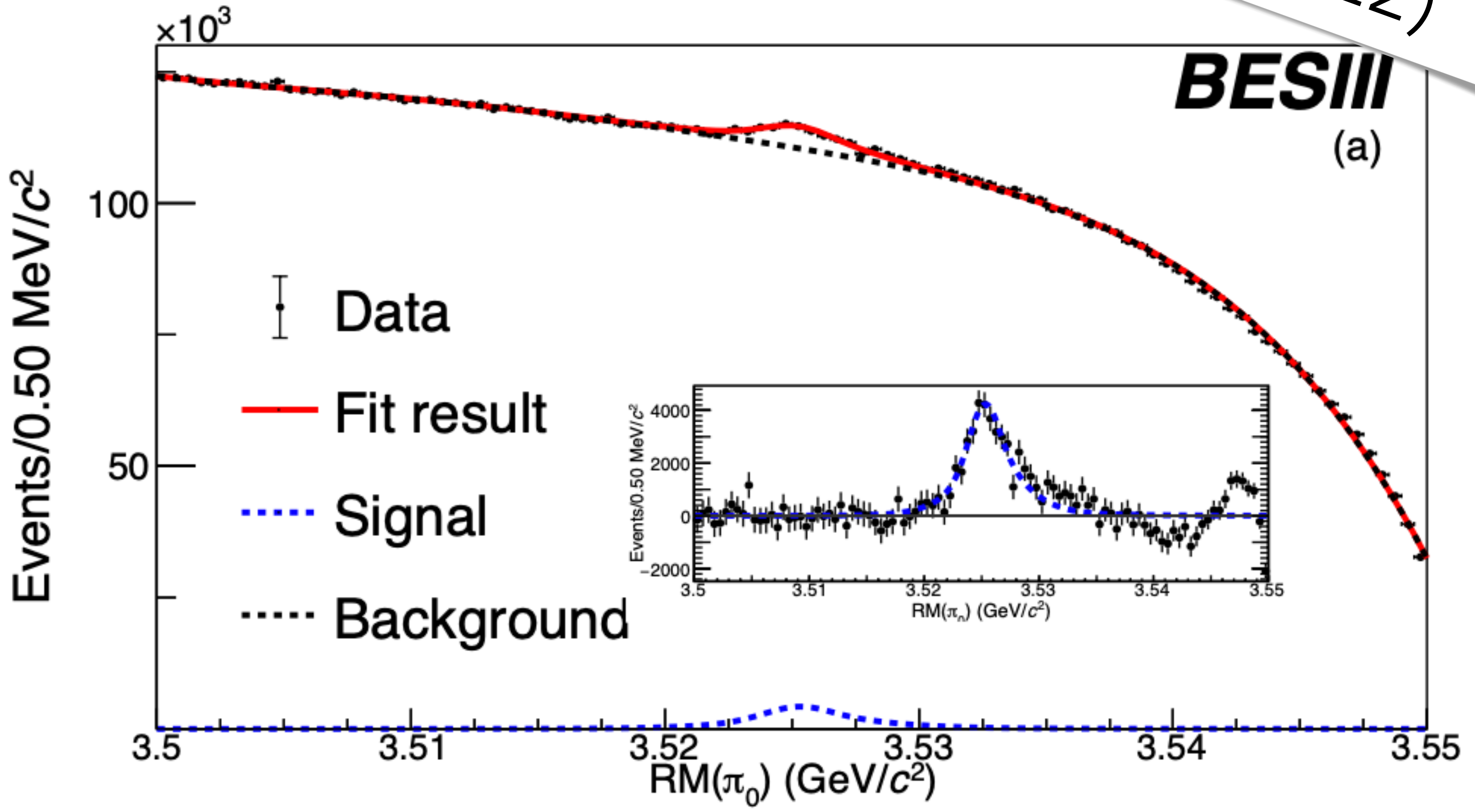
either allowing the h_c to decay inclusively



[10] Ann. Rev. Nucl. Part. Sci. **37**, 325 (1987)

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PRD **106**, 072007 (2022)

Using 448 million ψ(2S) events

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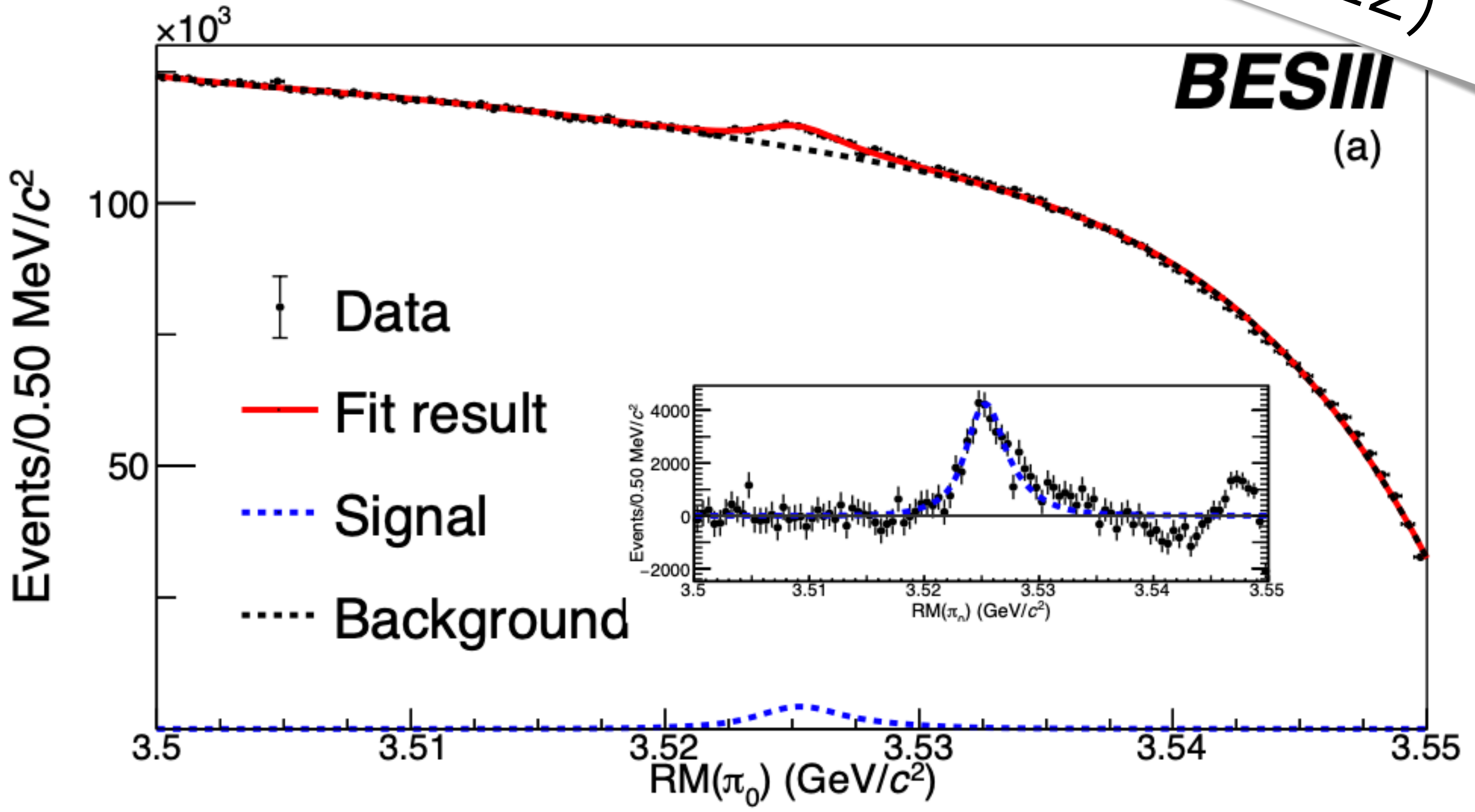
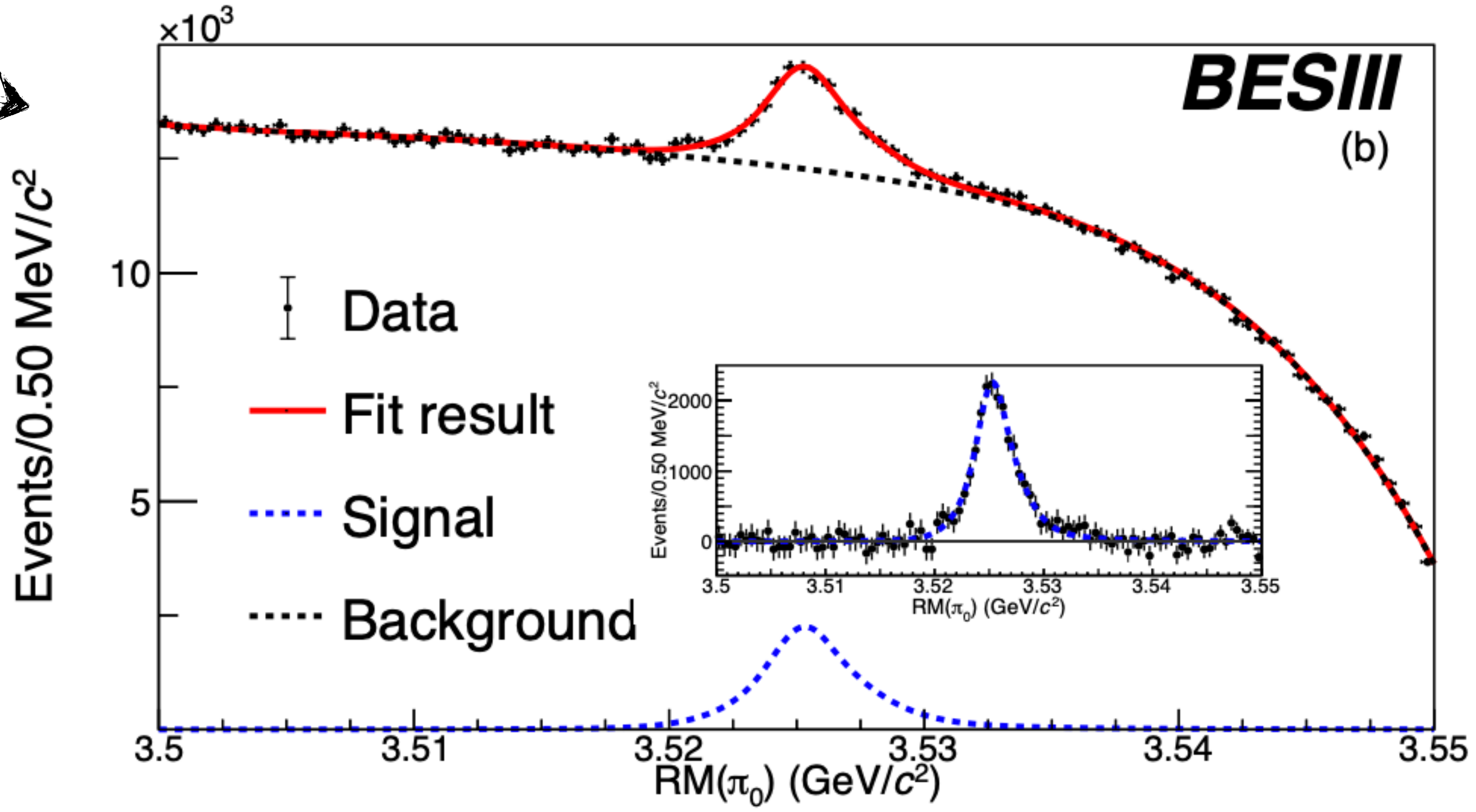
either allowing the h_c to decay inclusively

or tagging the γ_{E1} of the $h_c \to \gamma\eta_c$ transition





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PRD **106**, 072007 (2022)

Variable	Value	PDG value
$M(h_c)$ (MeV/c^2)	$3525.32 \pm 0.06 \pm 0.15$	3525.38 ± 0.11
$\Gamma(h_c)$ (MeV)	$0.78^{+0.27}_{-0.24} \pm 0.12$	$0.70 \pm 0.28 \pm 0.22$ (BESIII [6])
$N_{\rm Tag}(h_c)$	23118^{+1500}_{-1398}	...

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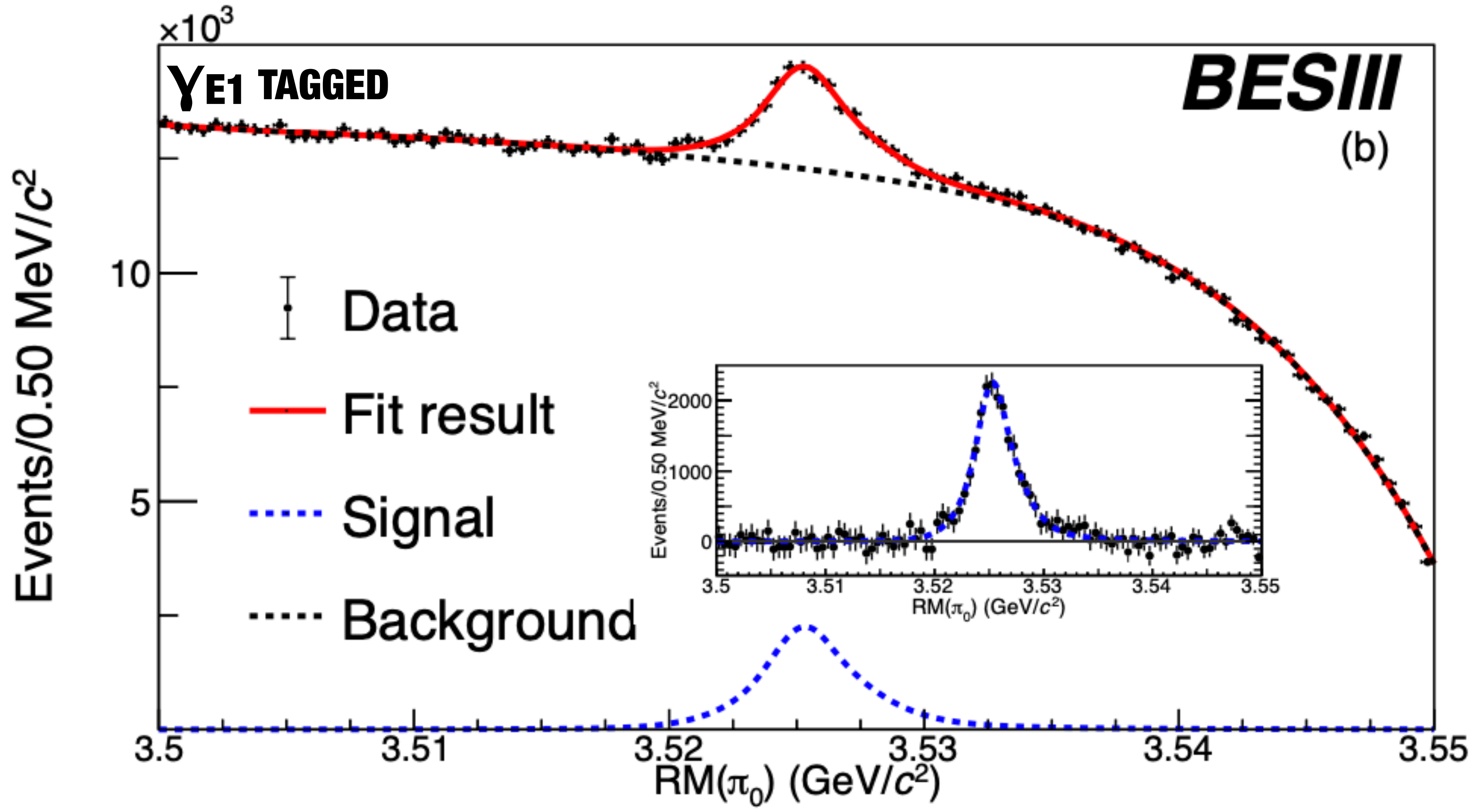
$$RM(\pi^0) = \sqrt{(E_{\psi(2S)} - E_{\pi^0})^2 - (\bar{p}_{\psi(2S)} - \bar{p}_{\pi^0})^2}$$

Being the S/B more favourable, the **tagged data set** is used to estimate the ***h_c* mass** and **width**, which is the **2nd estimate ever** of this parameter



[6] Phys. Rev. Lett. **104**, 132002

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PRD **106**, 072007 (2022)

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$N_{\text{Tag}}(h_c)$	23118^{+1500}_{-1398}	...
$\mathcal{B}_{\text{Inc}} \times \mathcal{B}_{\text{Tag}}$ (10^{-4})	$4.22^{+0.27}_{-0.26} \pm 0.19$	4.58 ± 0.64 (BESIII [7]) 4.16 ± 0.48 (CLEO [8])

Using 448 million ψ(2S) events

Search for the **E1 $h_c \to \gamma\eta_c$ transition** through the $\psi(2S) \to \pi^0 h_c$ decay to **determine h_c(1P) features and** the **relative $\mathcal{B}$**

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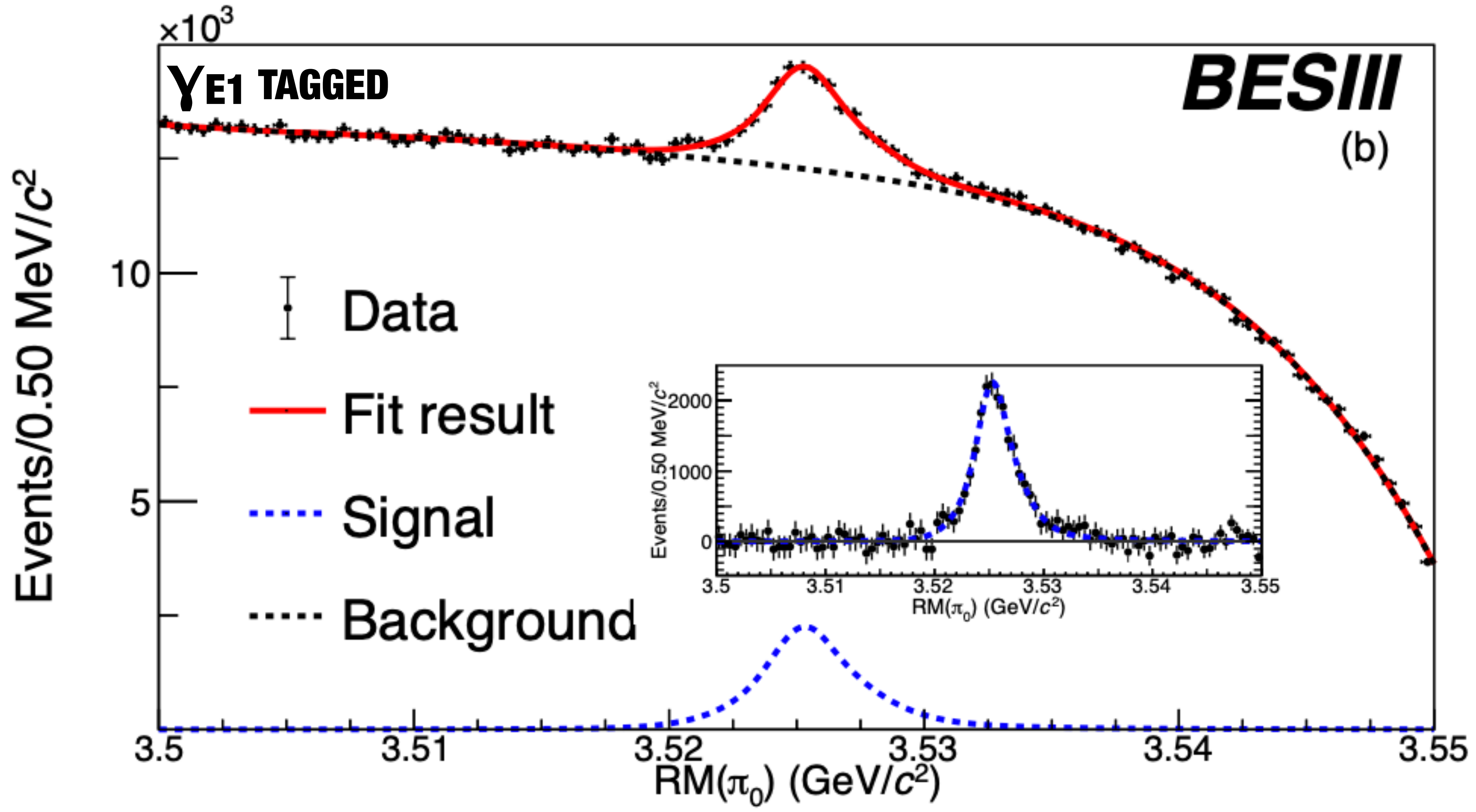
$$\mathcal{B}_{\text{Inc}}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_{\text{Tag}}(h_c \to \gamma\eta_c) = \frac{N_{\text{Tag}}}{\epsilon_{\text{Tag}} \times N(\psi(2S)) \times \mathcal{B}(\pi^0 \to \gamma\gamma)}$$



[6] Phys. Rev. Lett. **104**, 132002
[7] Phys. Rev. D **86**, 092009
[8] Phys. Rev. Lett. **101**, 182003

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PRD **106**, 072007 (2022)

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Search for the **E1 $h_c \to \gamma\eta_c$ transition through the $\psi(2S) \to \pi^0 h_c$** decay to determine h_c(1P) features and the **relative $\mathcal{B}$**

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$$\mathcal{B}_{\rm Inc}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_{\rm Tag}(h_c \to \gamma\eta_c) = \frac{N_{\rm Tag}}{\epsilon_{\rm Tag} \times N(\psi(2S)) \times \mathcal{B}(\pi^0 \to \gamma\gamma)}$$

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$$\mathcal{B}_{\rm Tag}(h_c \to \gamma\eta_c) = \frac{\mathcal{B}_{\rm Inc}(\psi(2S) \to \pi^0 h_c) \times \mathcal{B}_{\rm Tag}(h_c \to \gamma\eta_c)}{\mathcal{B}_{\rm Inc}(\psi(2S) \to \pi^0 h_c)} = \frac{N_{\rm Tag} \times \epsilon_{\rm Inc}}{N_{\rm Inc} \times \epsilon_{\rm Tag}}$$

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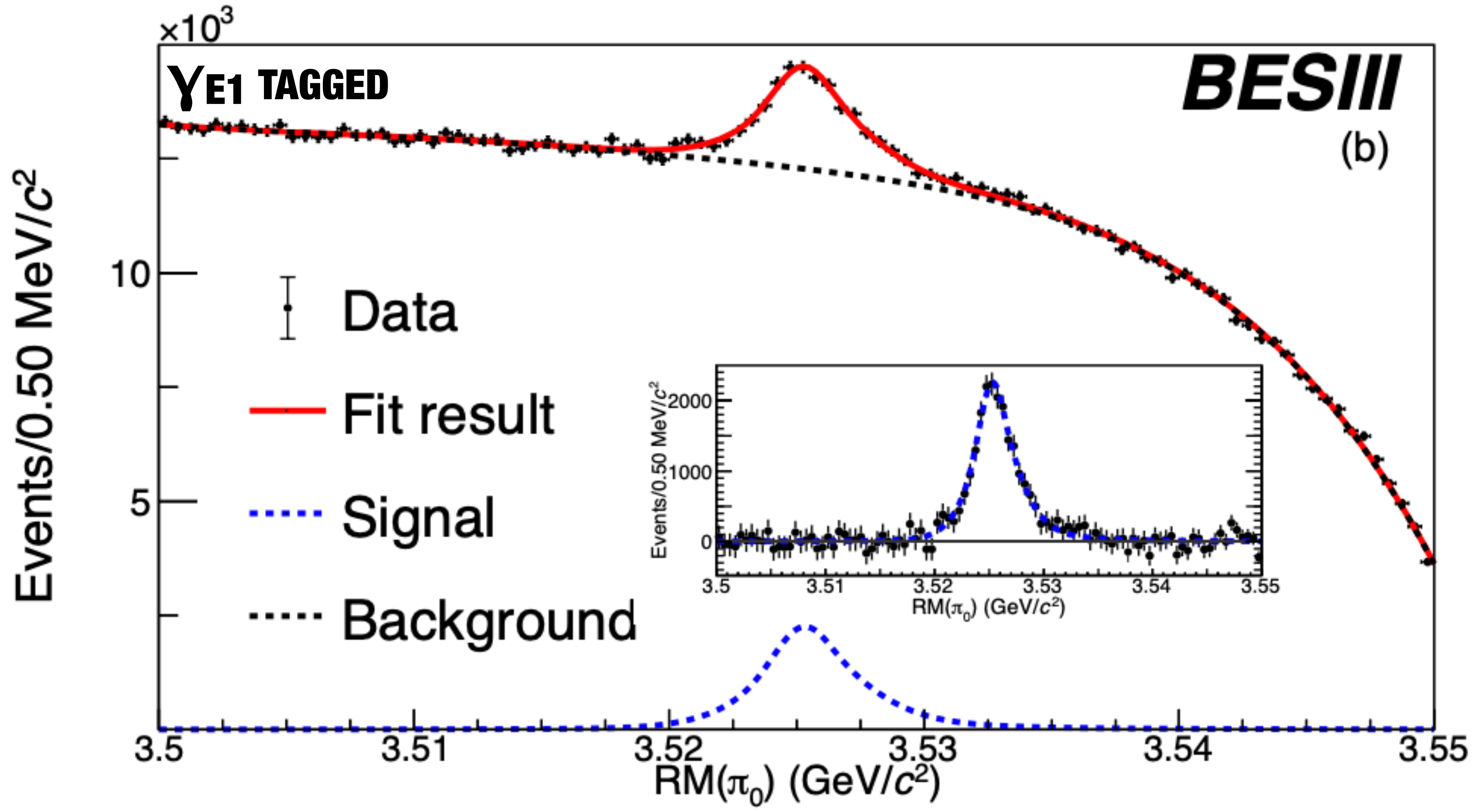
$N_{\rm Inc}(h_c)$	46187 ± 2123	...
$\mathcal{B}_{\rm Inc}$ (10^{-4})	$7.32 \pm 0.34 \pm 0.41$	$8.40 \pm 1.30 \pm 1.00$ (BESIII [7]) $9.00 \pm 1.5 \pm 1.3$ (CLEO [9])
$\mathcal{B}_{\rm Tag}$ (%)	$57.66^{+3.62}_{-3.50} \pm 0.58$	$53 \pm 7 \pm 8$ (BESIII [7]) $48 \pm 6 \pm 7$ (CLEO [8])

Most precise single estimates



[6] Phys. Rev. Lett. **104**, 132002
[7] Phys. Rev. D **86**, 092009
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[9] Phys. Rev. D **84**, 032008

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PRD **106**, 072007 (2022)

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Search for the **E1** $h_c \to \gamma\eta_c$ transition through the $\psi(2S) \to \pi^0 h_c$ decay to determine **h_c(1P) features** and the relative $\mathcal{B}$

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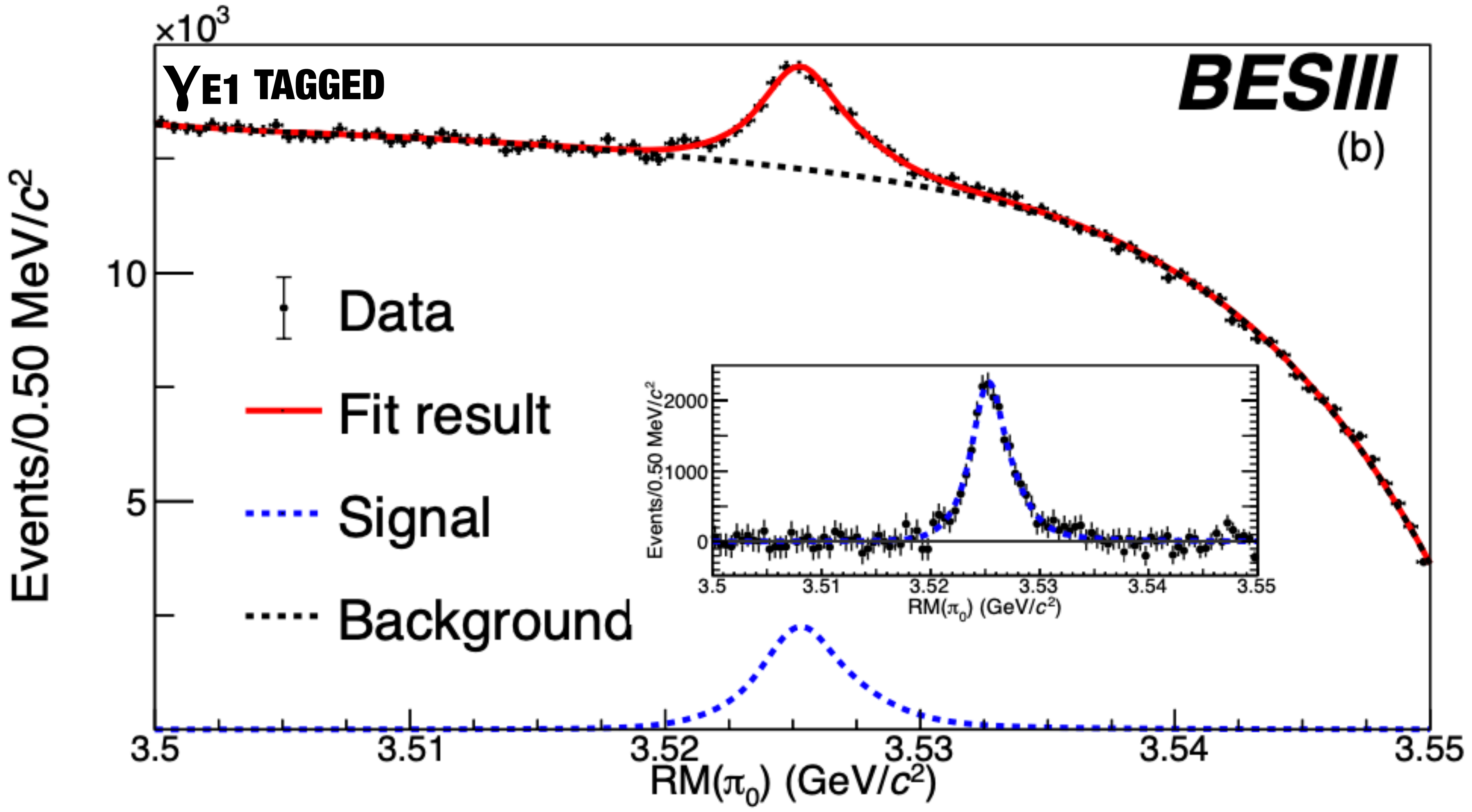
$\mathcal{B}_{\text{Tag}}$ (%)	$57.66^{+3.62}_{-3.50} \pm 0.58$	$53 \pm 7 \pm 8$ (BESIII [7]) $48 \pm 6 \pm 7$ (CLEO [8])

With respect to the **center-of-gravity mass** (M(c.o.g.)) of the three **$\chi_{cJ}(1^3P_J)$** states

$$M(\text{c.o.g.}) = \frac{M(\chi_{c0}) + 3M(\chi_{c1}) + 5M(\chi_{c2})}{9}$$

no mass splitting ($\Delta_{hyp} = 0.03 \pm 0.06 \pm 0.15$ MeV/c^2) is observed **as** predicted by potential model **calculations**[10,11]



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[8] Phys. Rev. Lett. **101**, 182003
[9] Phys. Rev. D **84**, 032008
[10] Ann. Rev. Nucl. Part. Sci. **37**, 325 (1987)
[11] Phys. Rev. D **96**, 056015

Summary

The **largest datasets** of **$c\bar{c}$ vector** states collected by BESIII provide the power to **investigate** not only **rare vector decays**, but also to **study** the **h_c(1P)**, χ_{cJ}(1P) and **η_c(2S)** states and their decays

Also **datasets above** the **$D\bar{D}$ threshold** can shed new light on charmonium decays and hint at possible **connections** between **XYZ states and** conventional **charmonia**

3 analyses are **discussed** in this talk:

Observation of $\psi(3770) \rightarrow \eta J/\psi$

arXiv:2212.12165 Submitted to PRL

Evidence for $\eta(2S) \rightarrow \pi^+\pi^-\eta$ decay

arXiv:2211.11935 Submitted to PRD

Study of the $h_c(1^1P_1)$ meson via $\psi(2S) \rightarrow \pi^0 h_c$ decays at BESIII

Phys. Rev. D **103**, L091102

More interesting **results** are expected **with** the **full** ψ(2S) and ψ(3770) **data samples**

Thank you for the attention!

Back-up Slides

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

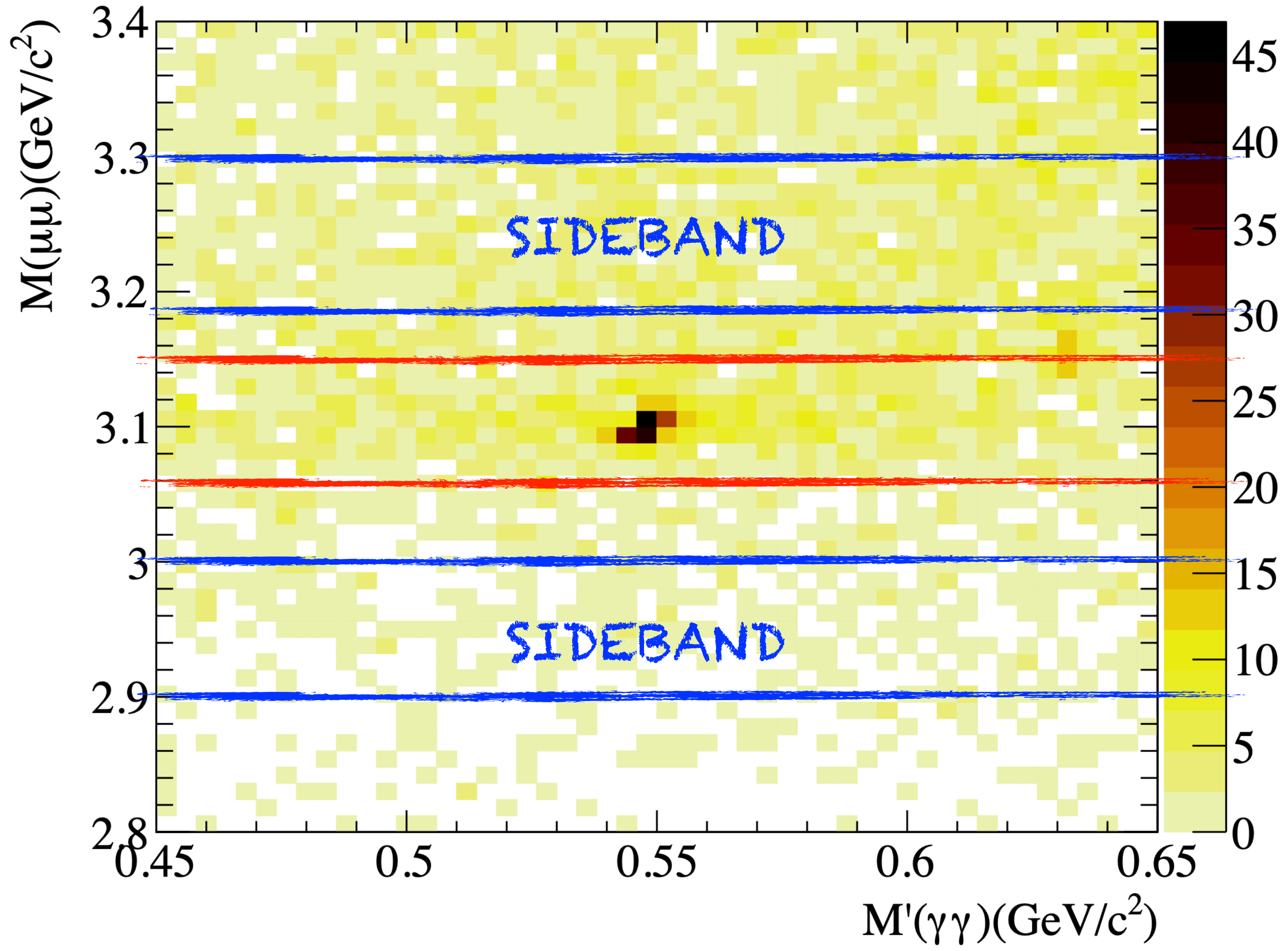
arXiv:2212.12165
Submitted to PRL

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

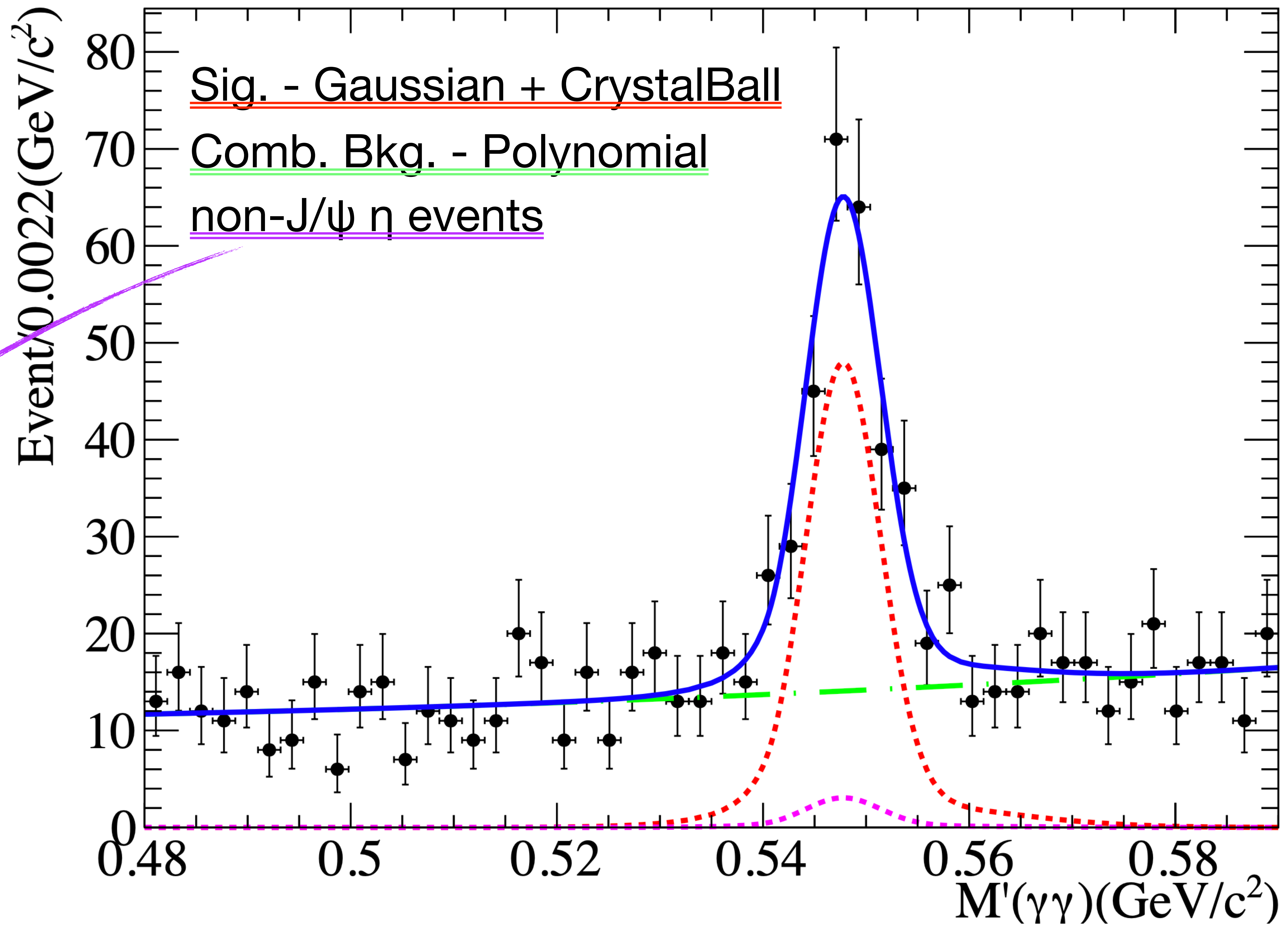
Search for the $\psi(3770) \to \eta J/\psi$ decay, and study of the $\sigma(e^+e^- \to \eta J/\psi)$ line-shape @$\sqrt{s}$ = [3.773, 4.600] GeV

Heap observed in $M'(\gamma\gamma)$ ($\equiv M(\gamma\gamma) + M(\mu\mu) - m_{J/\psi}$) correlated to the J/ψ resonance in the $M(\mu\mu)$ spectrum

To extract the signal yield , a fit to $M'(\gamma\gamma)$ is performed in the $M(\mu\mu)$ signal region



Estimated from a fit to the $M'(\gamma\gamma)$ in the $M(\mu\mu)$ sidebands and normalised by the ratio of non-J/ψ events in the $M(\mu\mu)$ signal region and sideband regions



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Due to the small energy of the γ_{M1}, having the background under control is fundamental

I. $\psi(2S) \to \pi^+\pi^-\eta$ with a misidentified photon is reduced via a kinematic fit

II. $J/\psi \to \mu^+\mu^-\gamma_{FSR}$ is removed by rejecting $M(\pi^+\pi^-\gamma_{M1}) > 3$ GeV/c^2 events

III. $\psi(2S) \to \pi^+\pi^-\eta\gamma_{FSR}$ cannot be reduced, hence a MC shape is used, the contribution is fixed to the ratio of events with and without an γ_{FSR} (MC-data corrected using a $\psi(2S) \to \gamma\chi_{c0} \to \gamma[\gamma_{FSR}2(\pi^+\pi^-)]$ control sample)