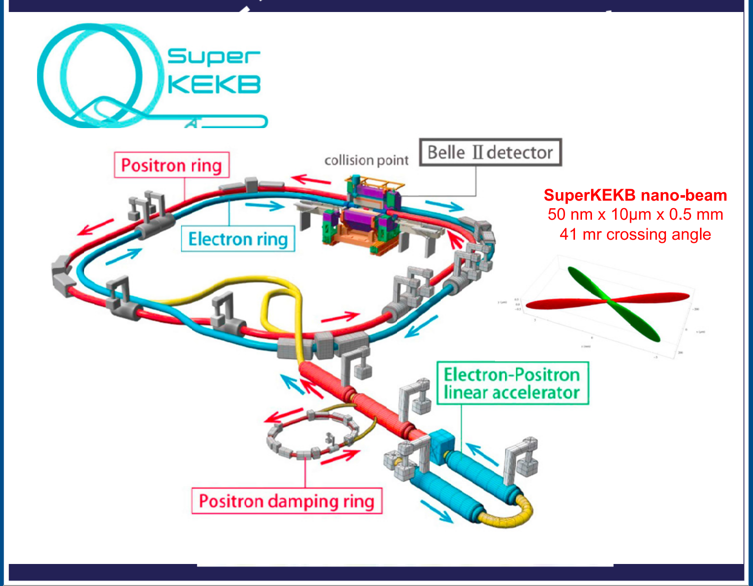
# Exotic Hadrons at Belle & Belle II and the Importance of the Force





Vladimir Savinov (University of Pittsburgh), on behalf of the Belle and Belle II Collaborations

This talk is about our encounters

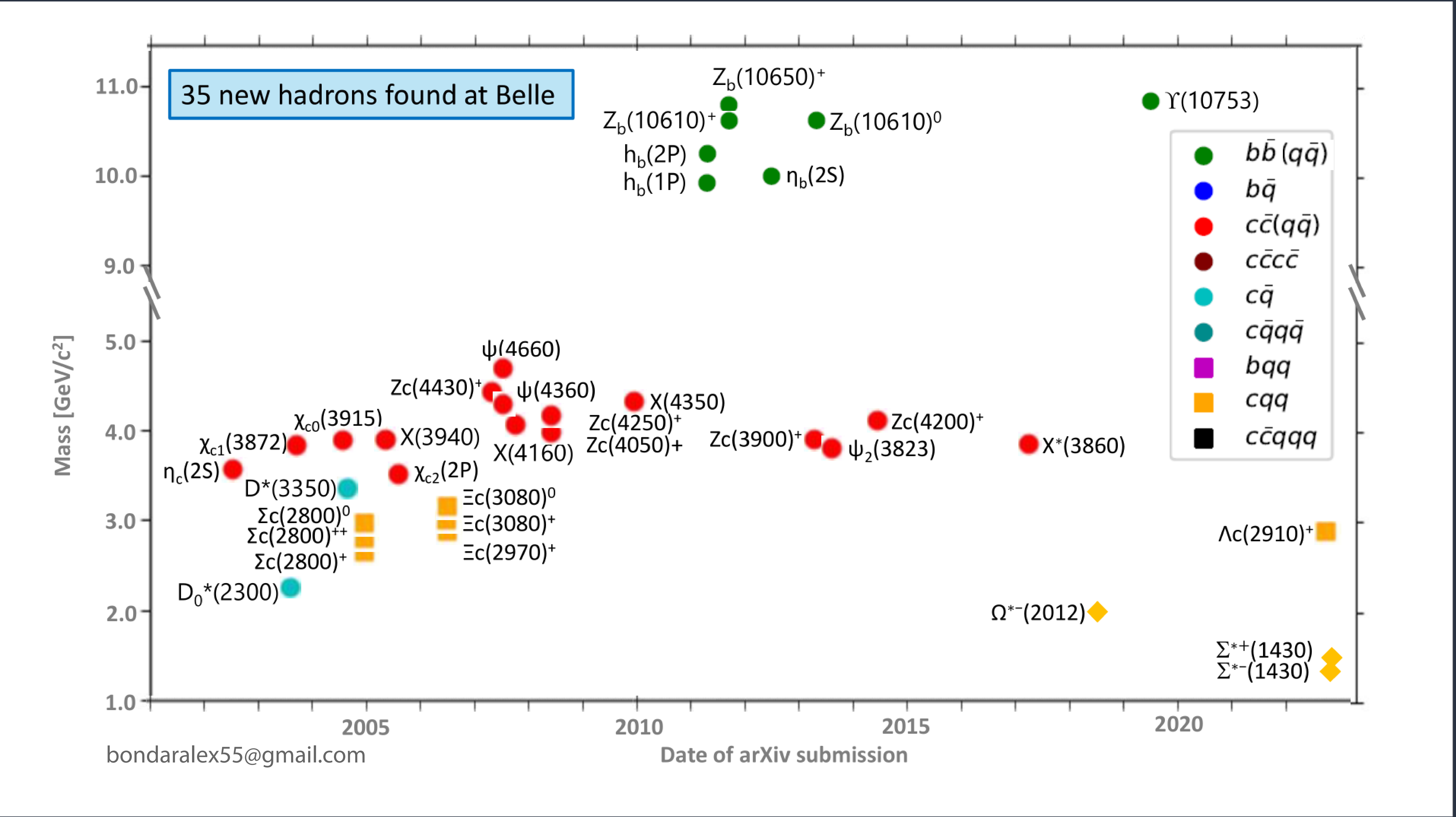
with the (Strong) Force

which binds us all

# “We” are the Belle and Belle II Collaborations (many more people than shown here)

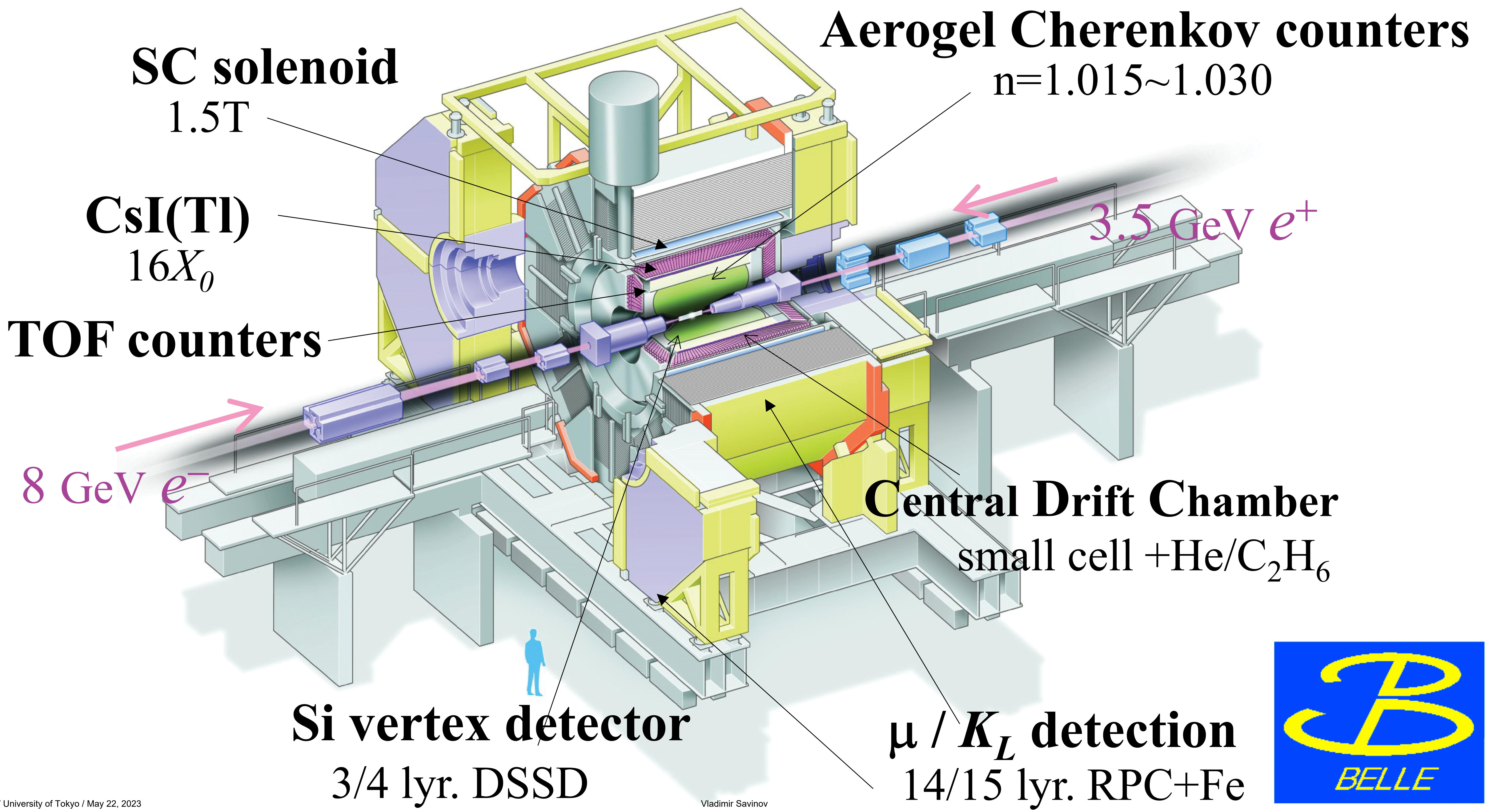
https://www.facebook.com/belle2collab

# Some of our most important encounters with the Force



# Our Excellent Tools (with great thanks to many, many exceptional individuals)

## Belle Detector



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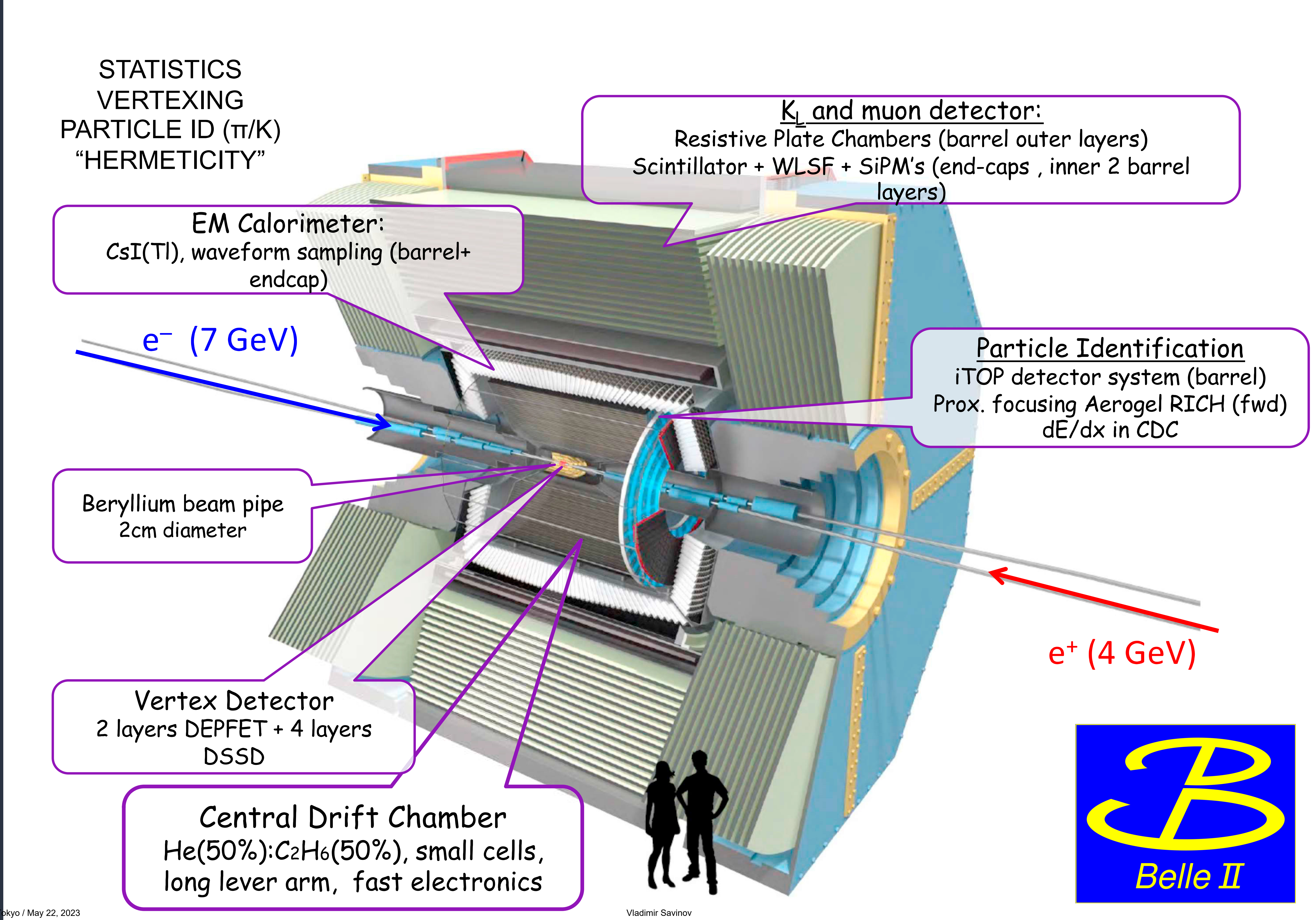
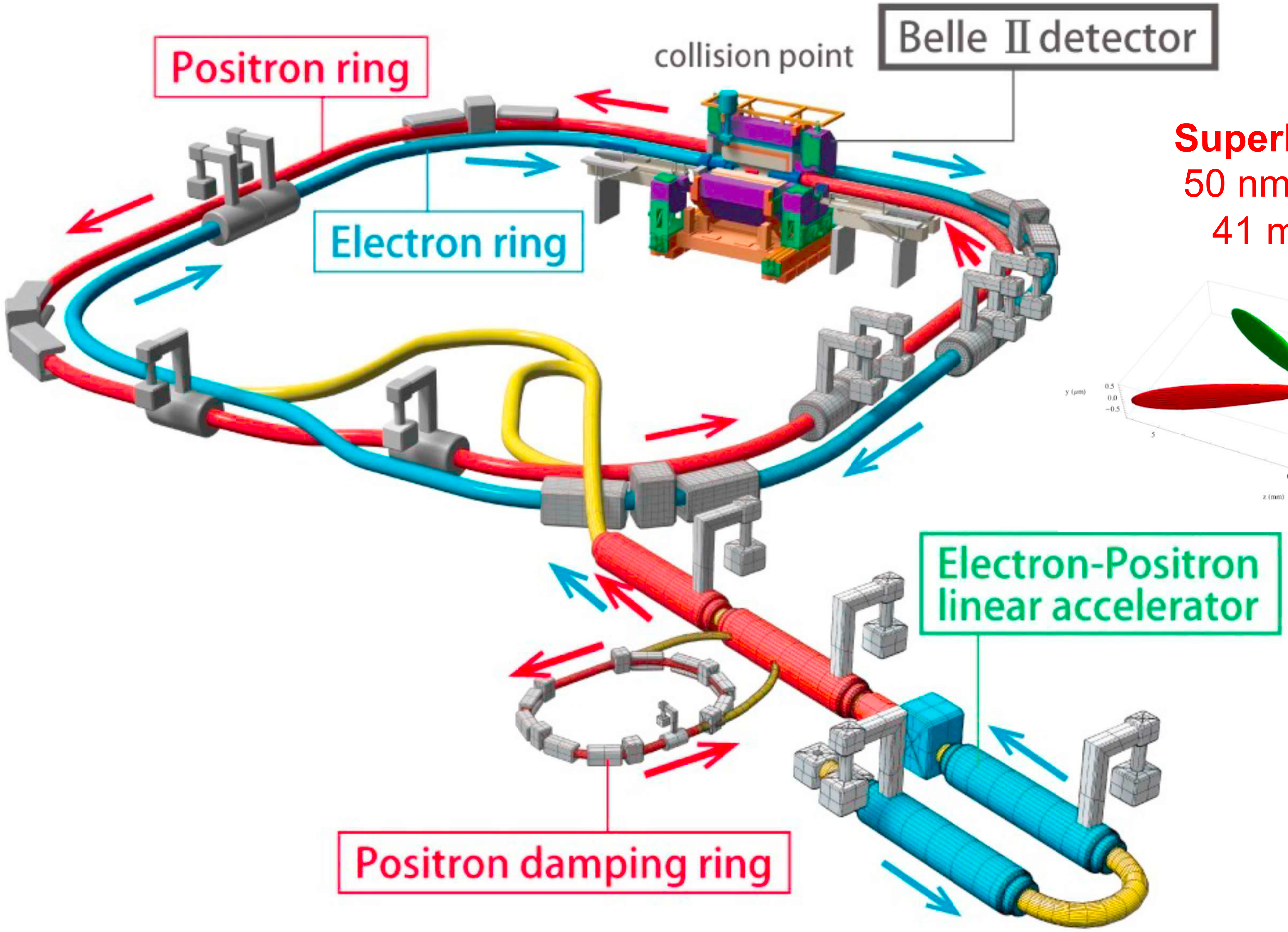
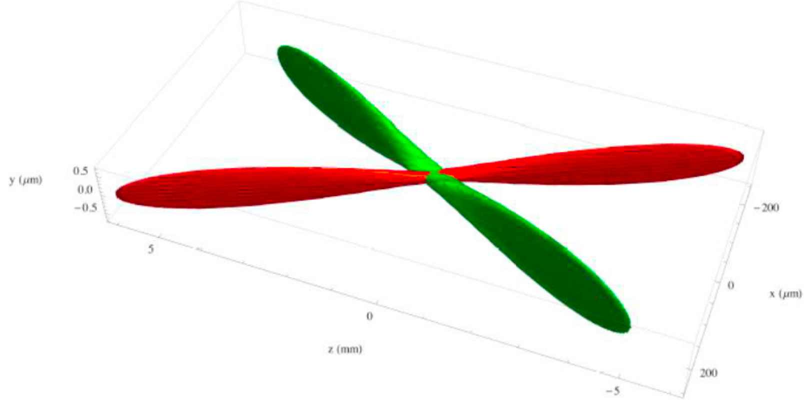


# Our Excellent Tools (with great thanks to many, many exceptional individuals)

and KEKB which came before this




**SuperKEKB nano-beam**
50 nm x 10μm x 0.5 mm
41 mr crossing angle



This talk is about (primarily, already published)

experimental results

References to proper theoretical analyses

could be found in recent excellent reviews

(there are many such, I made an unbiased choice here)

# The $XYZ$ states: experimental and theoretical status and perspectives

Nora Brambilla, Simon Eidelman, Christoph Hanhart, Alexey Nefediev, Cheng-Ping Shen, Christopher E. Thomas, Antonio Vairo, Chang-Zheng Yuan

The quark model was formulated in 1964 to classify mesons as bound states made of a quark-antiquark pair, and baryons as bound states made of three quarks. For a long time all known mesons and baryons could be classified within this scheme. Quantum Chromodynamics (QCD), however, in principle also allows the existence of more complex structures, generically called exotic hadrons or simply exotics. These include four-quark hadrons (tetraquarks and hadronic molecules), five-quark hadrons (pentaquarks) and states with active gluonic degrees of freedom (hybrids), and even states of pure glue (glueballs). Exotic hadrons have been systematically searched for in numerous experiments for many years. Remarkably, in the past fifteen years, many new hadrons that do not exhibit the expected properties of ordinary (not exotic) hadrons have been discovered in the quarkonium spectrum. These hadrons are collectively known as $XYZ$ states. Some of them, like the charged states, are undoubtedly exotic. Parallel to the experimental progress, the last decades have also witnessed an enormous theoretical effort to reach a theoretical understanding of the $XYZ$ states. Theoretical approaches include not only phenomenological extensions of the quark model to exotics, but also modern non-relativistic effective field theories and lattice QCD calculations. The present work aims at reviewing the rapid progress in the field of exotic $XYZ$ hadrons over the past few years both in experiments and theory. It concludes with a summary on future prospects and challenges.

| | |
|---|---|
| Comments: | 178 pages, 106 figures; updated/accepted version to appear in Physics Reports |
| Subjects: | **High Energy Physics - Experiment (hep-ex)**; High Energy Physics - Lattice (hep-lat); High Energy Physics - Phenomenology (hep-ph) |
| Report number: | TUM-EFT 125/19 |
| Cite as: | arXiv:1907.07583 **[hep-ex]** |
| | (or arXiv:1907.07583v2 **[hep-ex]** for this version) |
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journal homepage: www.elsevier.com/locate/revip


# XYZ states: An experimental point-of-view

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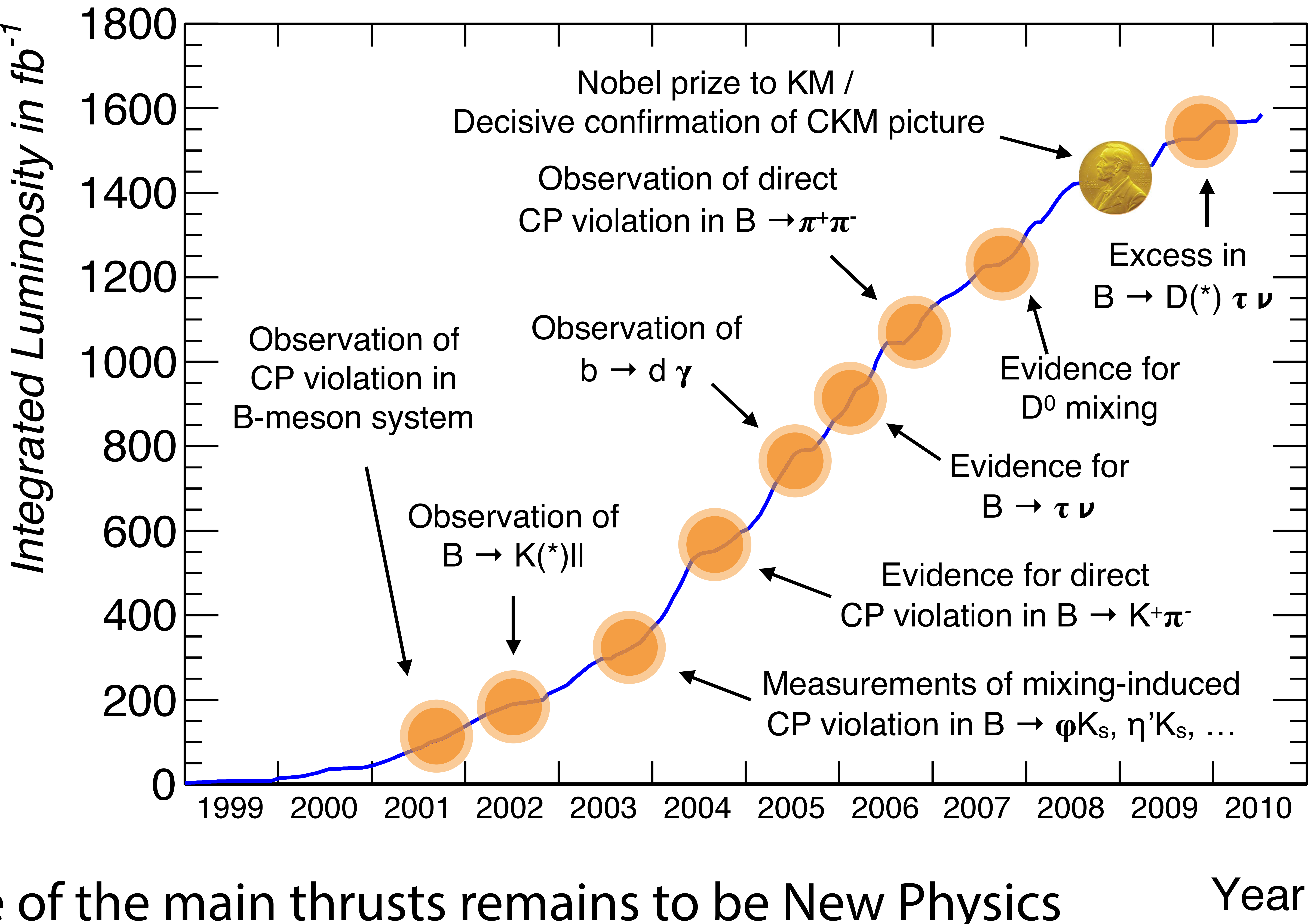
ABSTRACT

Since 2003, a new family of states without a clear theoretical interpretation has been measured in the heavy quarkonium spectrum, the so-called $XYZ$ states. While the nature of these states is so far unclear, the experimental search is one of the most active fields in the intensity frontier. In this review, the most important and representative results obtained in this field in recent years are going to be illustrated, providing insights into the nature of these exotic states. The focus will be on the experimental side, describing how it is possible to investigate their exotic nature with respect to the conventional quarkonium states.




One of the main thrusts remains to be New Physics

# In Memoriam: Mikhail "Misha" Voloshin, 1953-2020

With great almost unbearable sadness I have to inform you of a sudden death of Mikhail (Misha) Voloshin, one of great theorists of the golden age of HEP. He was born in 1953 in the Soviet Union. He appeared in the ITEP Theory Department very early in his career. His first student work (suggested to him by Okun and Kobzarev) was the false vacuum decay. He brilliantly solved this problem within a week, thus creating a beautiful theory of this phenomenon (independently and before Coleman). I vividly remember this fateful week and the excitement that followed.

Misha's career started right around the time of the discovery of the J/psi in November 1974 (The November Revolution). He became one of QCD's leading practicioners. He was a standard bearer in this area till his last days. He was a resource for both experimentalists and theorists throughout the world. He combined extremely high standards and principles with passion to physics as an experiment-based science. He hated questionable arguments and unsubstantiated assumptions.

In fact Misha was a universalist who thoroughly knew not only HEP, but all basic aspects of physics, he felt physics laws with his heart.

I and all my colleagues at FTPI will miss him. This is an understatement. Misha died on March 20, 2020 from heart failure. In fact, he was fighting lymphoma for some time.

-Misha Shifman

UNIVERSITY OF MINNESOTA
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College of Science and Engineering

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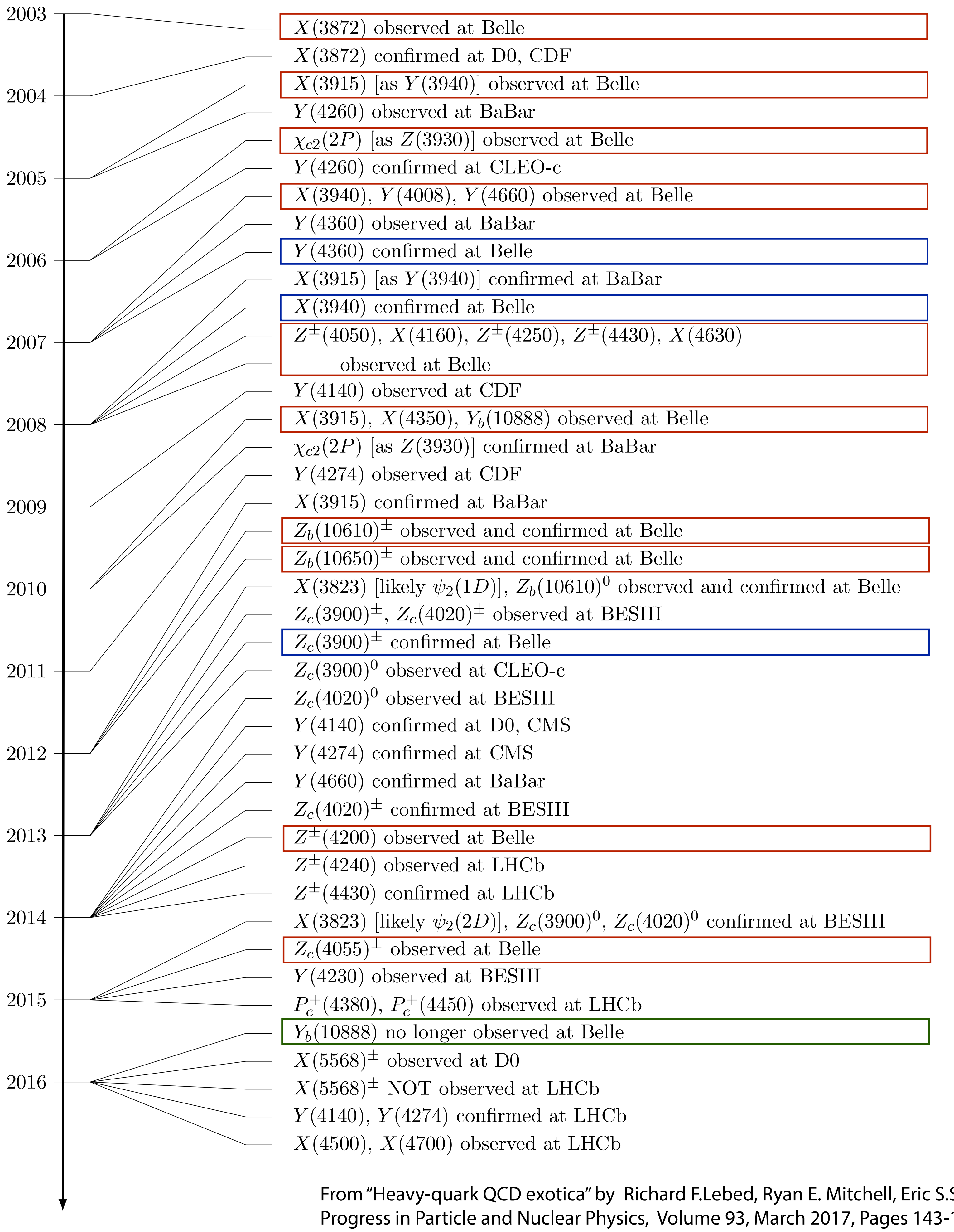
Misha Voloshin (at B2TiP @Pittsburgh, rephrased): here is our New (Old) Physics

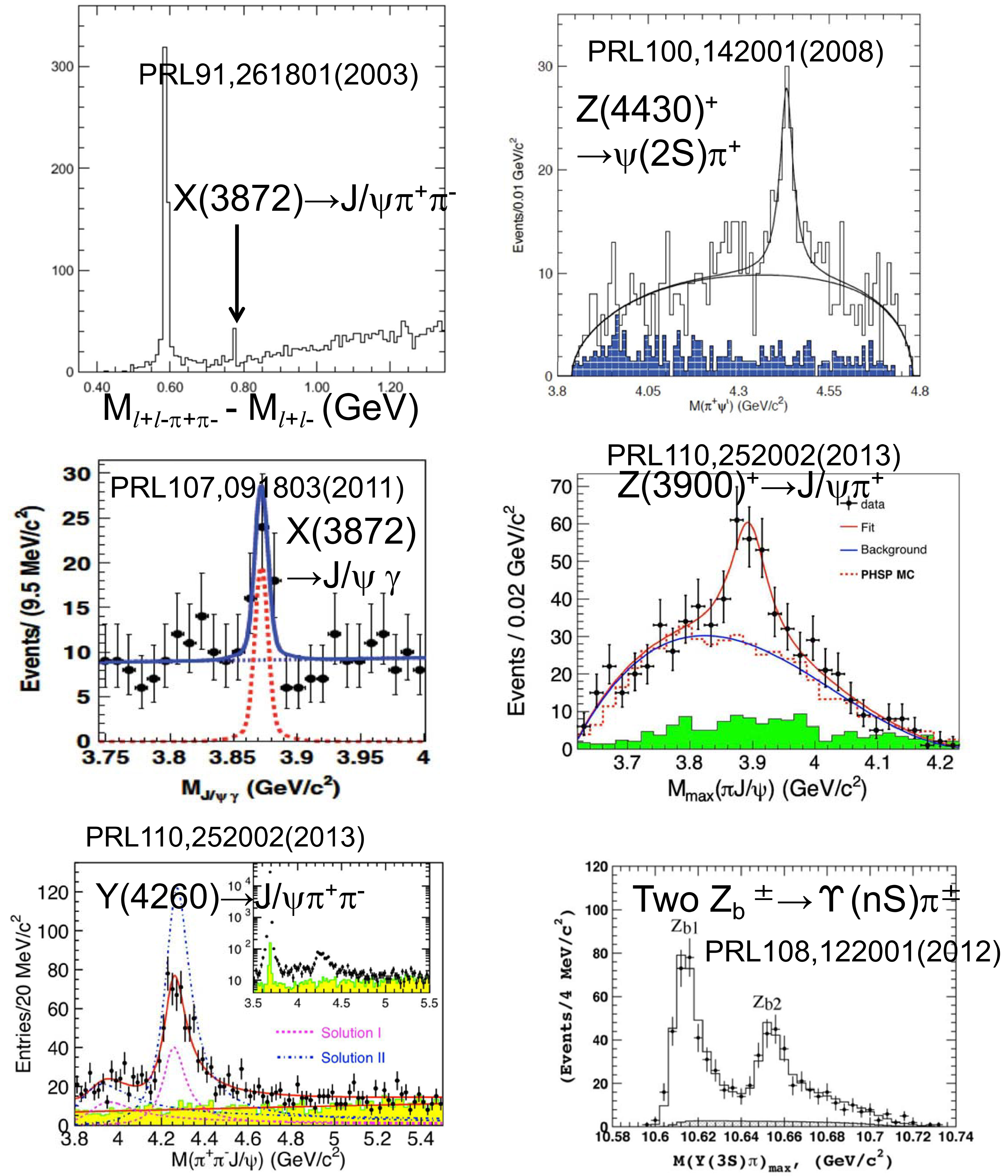
# Renaissance of QCD and Hadron Spectroscopy

Active data analyysis and discoveries continue!




From "Heavy-quark QCD exotica" by Richard F.Lebed, Ryan E. Mitchell, Eric S.Swanson
Progress in Particle and Nuclear Physics, Volume 93, March 2017, Pages 143-194

# XYZ Discoveries at Belle



# Still Crazy (about non-perturbative QCD) After All These Years

Currently, none of the models provide a unified description of observations!

Some states (e.g. famous X(3872)) are best described by a "mixture of models"

Belle/Belle II role and one of the most important goals is more data (analysis).

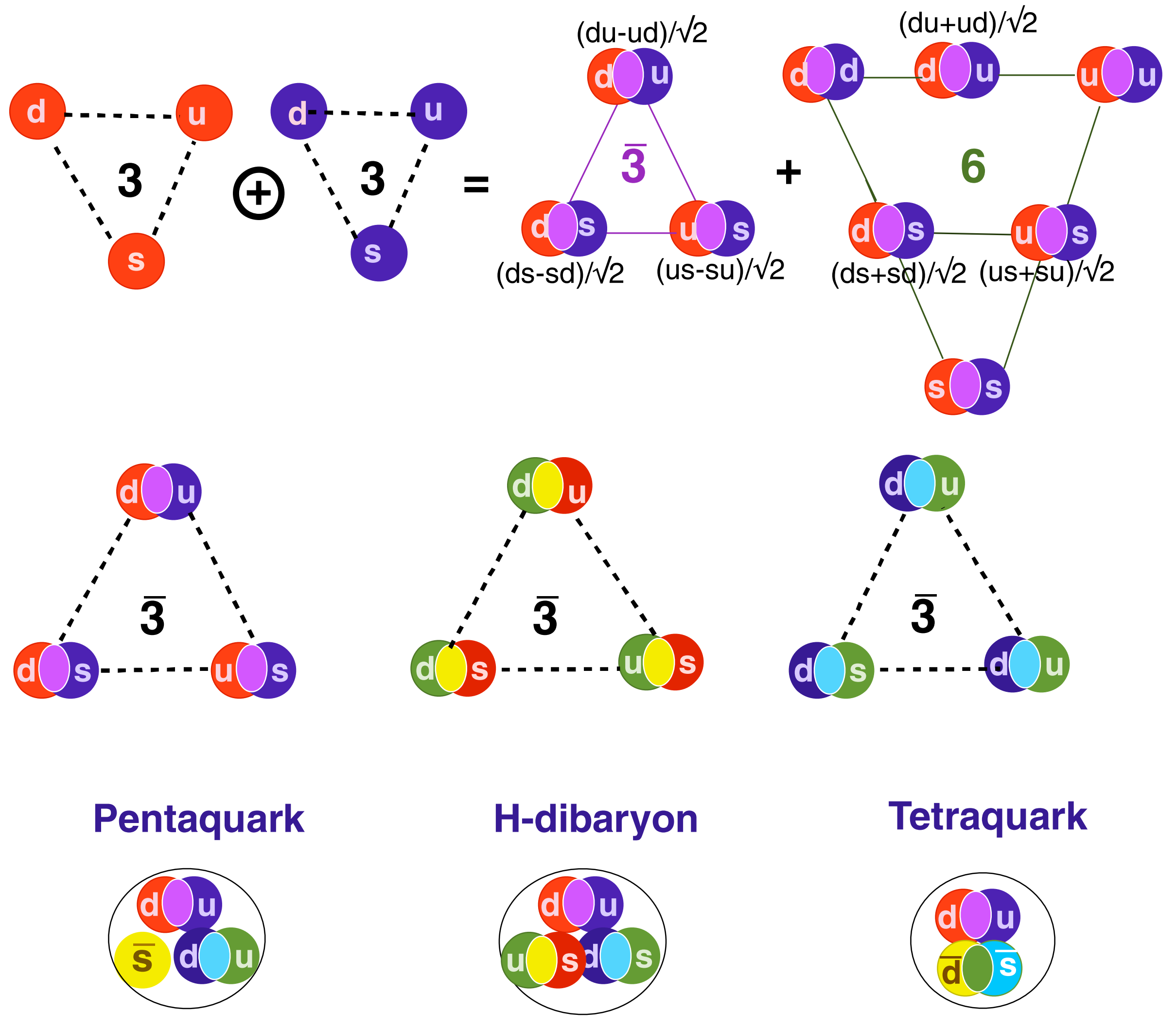
A better understanding of non-perturbative QCD remains to be important, topical and necessary after all these years.

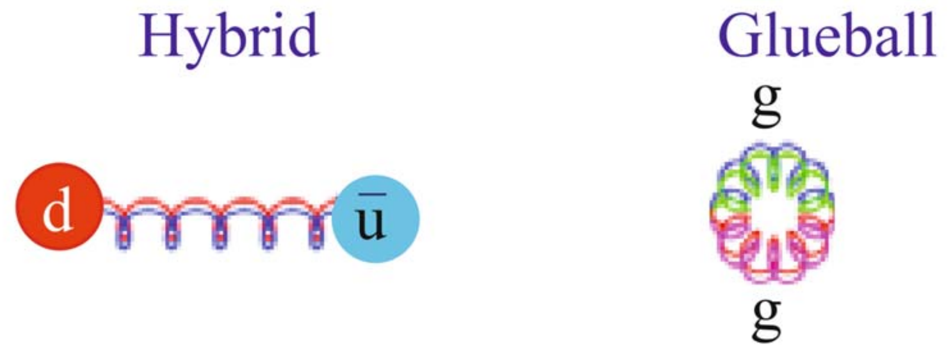
Our analyses, however, are often driven by creative ideas in phenomenology.

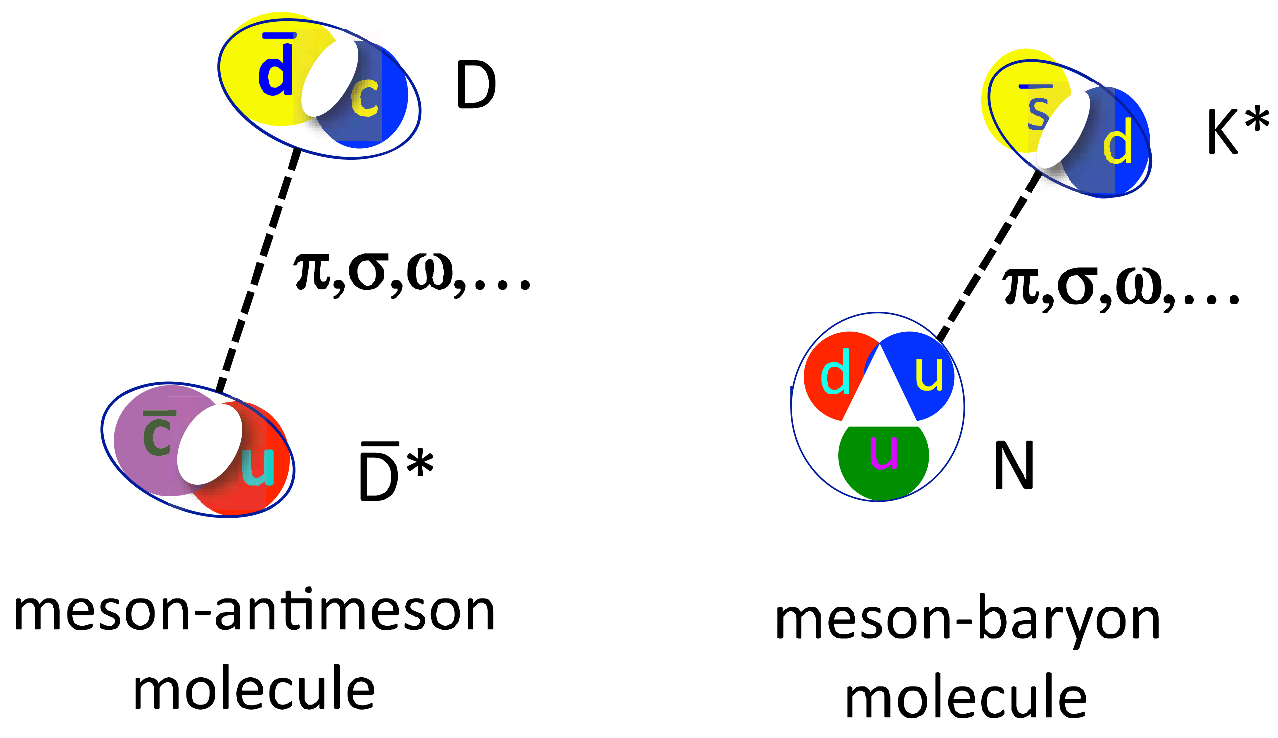
# MODELS FOR NONSTANDARD HADRONS

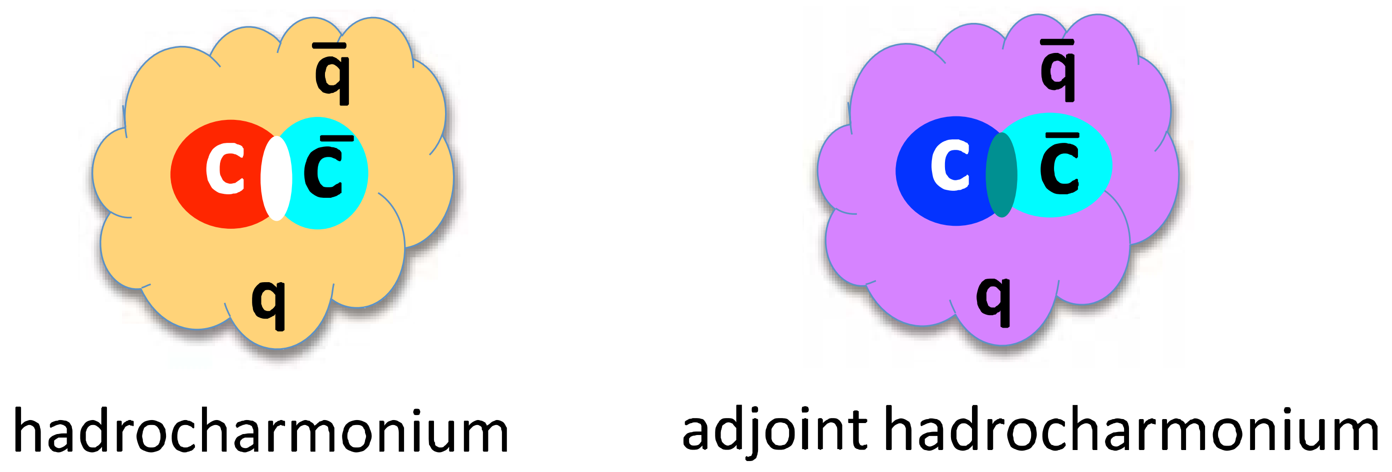
(from Olsen, Skwarnicki, and Zieminska, REVIEW OF MODERN PHYSICS, VOLUME 90, JANUARY–MARCH 2018)

## QCD diquarks



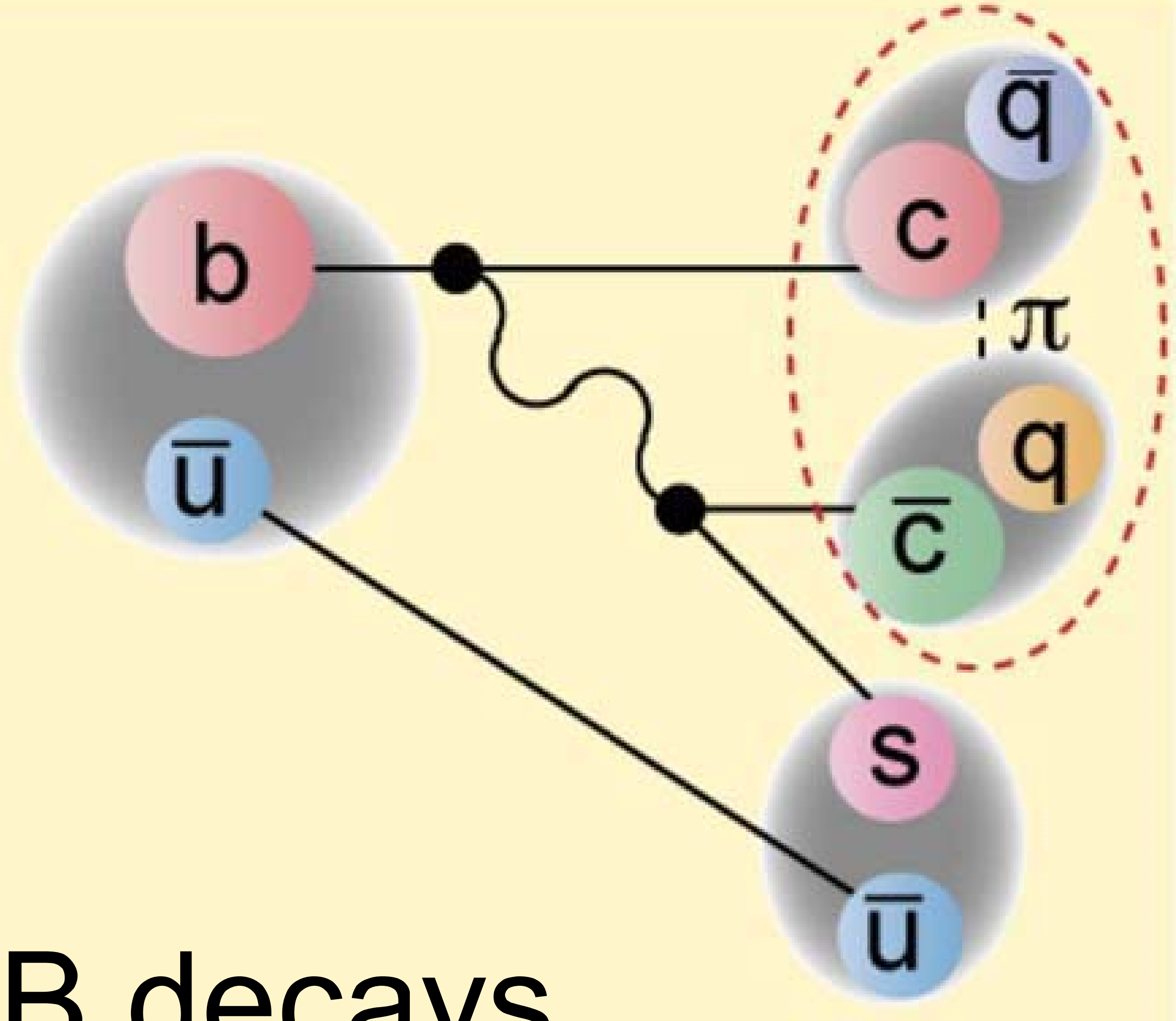



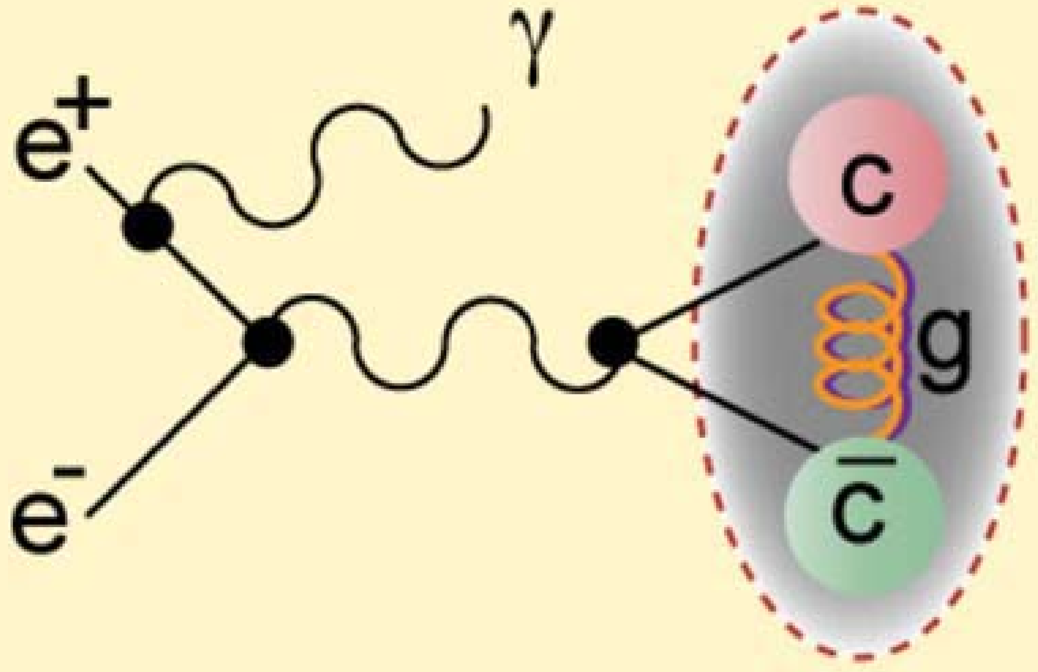




+Kinematically induced resonance-like mass peaks (such as, e.g. threshold cusps)

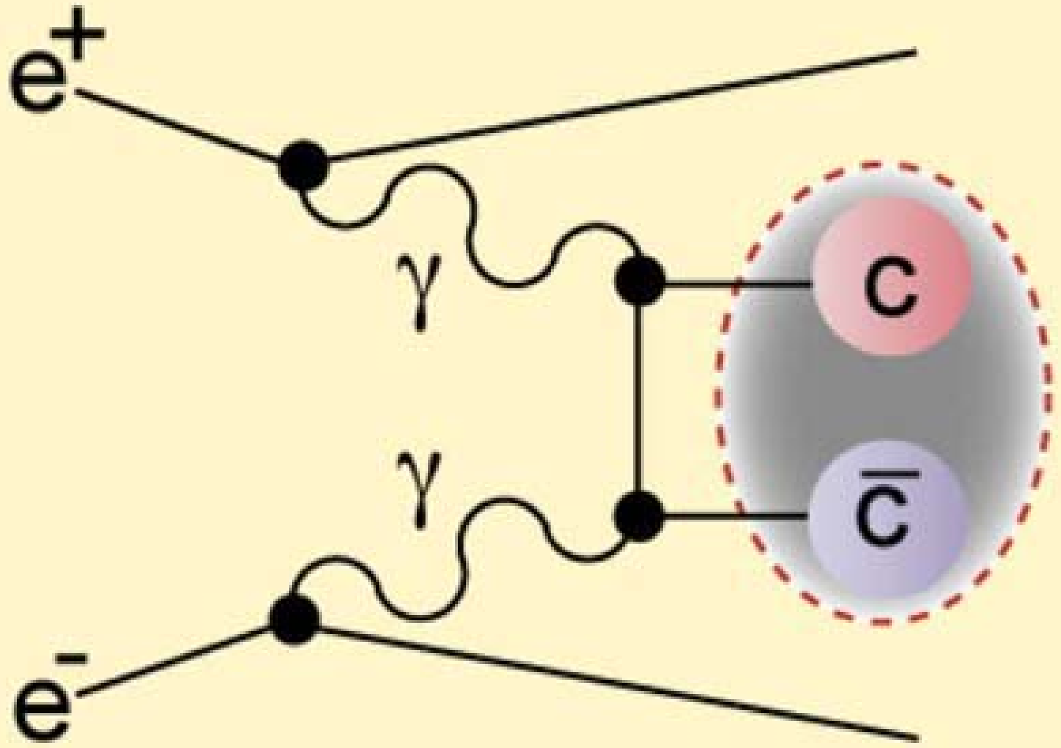
Lattice QCD should (in principle) be able to predict all colorless states and effects but huge amount of resources would be needed



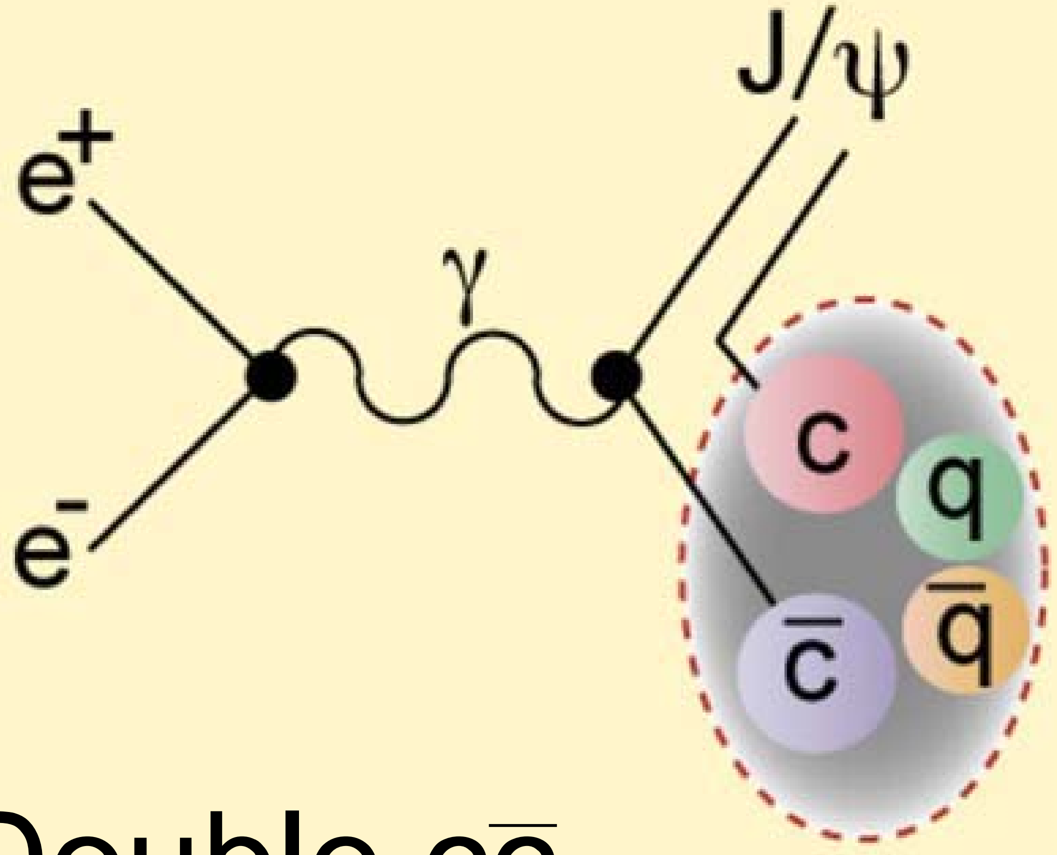

B decays



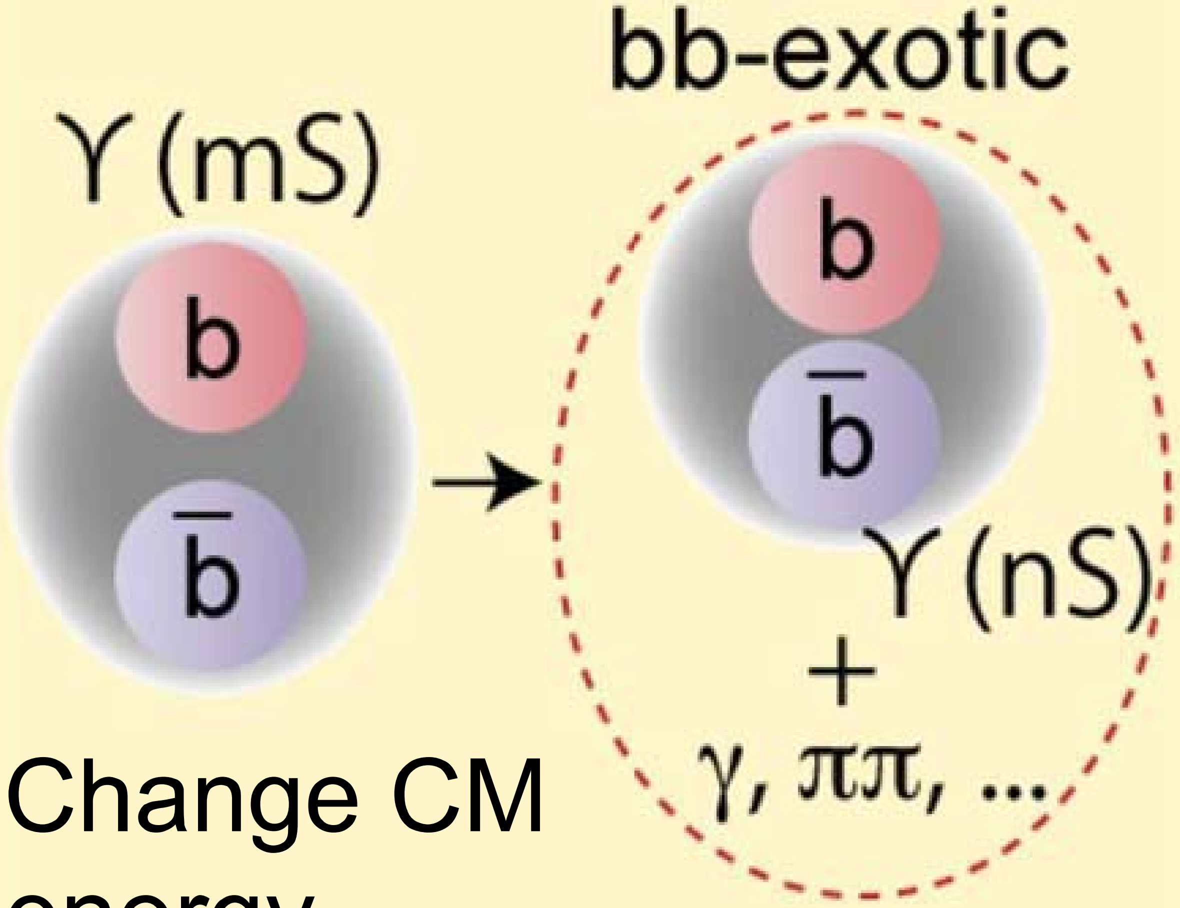

Initial state radiation




$\gamma\gamma$ collisions




Double $c\bar{c}$




Change CM energy

# Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays

S.-K. Choi *et al.* (Belle Collaboration)

Phys. Rev. Lett. **91**, 262001 – Published 23 December 2003



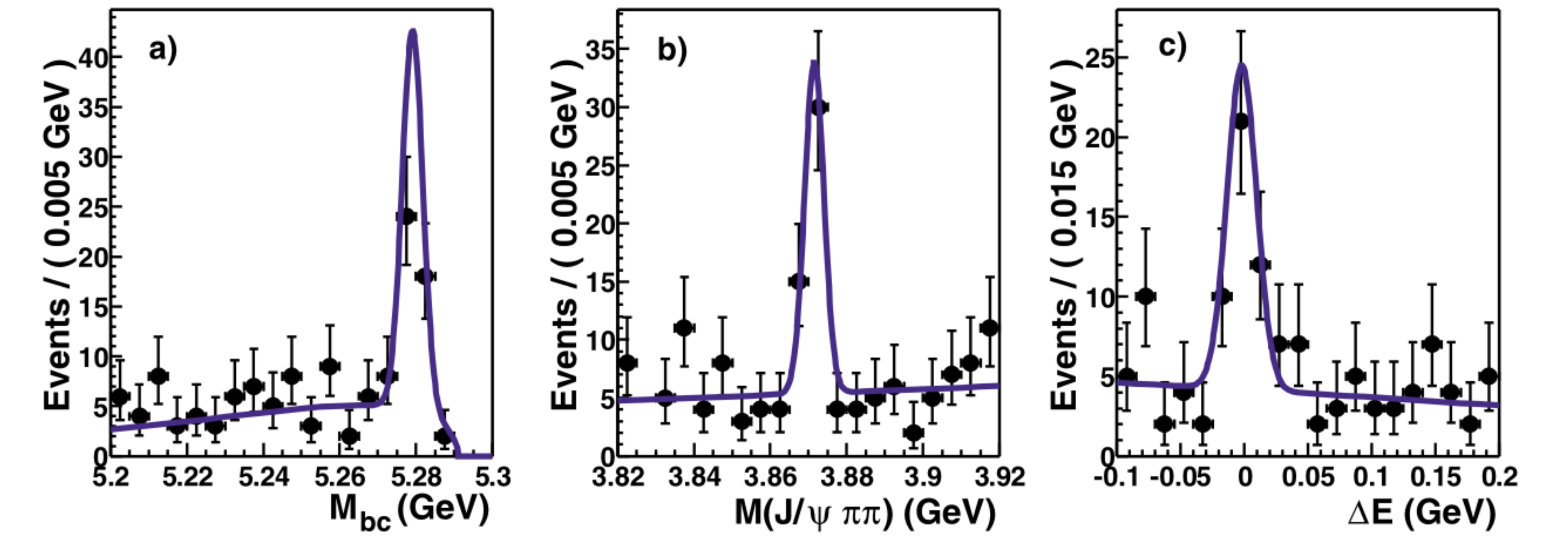



FIG. 2 (color online). Signal-band projections of (a) $M_{bc}$, (b) $M_{\pi^+\pi^-J/\psi}$, and (c) $\Delta E$ for the $X(3872) \to \pi^+\pi^-J/\psi$ signal region with the results of the unbinned fit superimposed.

## ABSTRACT

We report the observation of a narrow charmoniumlike state produced in the exclusive decay process $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$. This state, which decays into $\pi^{+}\pi^{-}J/\psi$, has a mass of $3872.0 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$ MeV, a value that is very near the $M_{D^0} + M_{D^{*0}}$ mass threshold. The results are based on an analysis of 152M $B$-$\overline{B}$ events collected at the $\Upsilon(4S)$ resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of $10\sigma$.

**Observation of a Narrow Charmoniumlike State in Exclusive $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$ Decays**

S.-K. Choi,[5] S. L. Olsen,[6] K. Abe,[7] T. Abe,[7] I. Adachi,[7] Byoung Sup Ahn,[14] H. Aihara,[43] K. Akai,[7] M. Akatsu,[20] M. Akemoto,[7] Y. Asano,[48] T. Aso,[47] V. Aulchenko,[1] T. Aushev,[11] A. M. Bakich,[38] Y. Ban,[31] S. Banerjee,[39] A. Bondar,[1] A. Bozek,[25] M. Bračko,[18,12] J. Brodzicka,[25] T. E. Browder,[6] P. Chang,[24] Y. Chao,[24] K.-F. Chen,[24] B. G. Cheon,[37] R. Chistov,[11] Y. Choi,[37] Y. K. Choi,[37] M. Danilov,[11] L. Y. Dong,[9] A. Drutskoy,[11] S. Eidelman,[1] V. Eiges,[11] J. Flanagan,[7] C. Fukunaga,[45] K. Furukawa,[7] N. Gabyshev,[7] T. Gershon,[7] B. Golob,[17,12] H. Guler,[6] R. Guo,[22] C. Hagner,[50] F. Handa,[42] T. Hara,[29] N. C. Hastings,[7] H. Hayashii,[21] M. Hazumi,[7] L. Hinz,[16] Y. Hoshi,[41] W.-S. Hou,[24] Y. B. Hsiung,[24,*] H.-C. Huang,[24] T. Iijima,[20] K. Inami,[20] A. Ishikawa,[20] R. Itoh,[7] M. Iwasaki,[43] Y. Iwasaki,[7] J. H. Kang,[52] S. U. Kataoka,[21] N. Katayama,[7] H. Kawai,[2] T. Kawasaki,[27] H. Kichimi,[7] E. Kikutani,[7] H. J. Kim,[52] Hyunwoo Kim,[14] J. H. Kim,[37] S. K. Kim,[36] K. Kinoshita,[3] H. Koiso,[7] P. Koppenburg,[7] S. Korpar,[18,12] P. Križan,[17,12] P. Krokovny,[1] S. Kumar,[30] A. Kuzmin,[1] J. S. Lange,[4,33] G. Leder,[10] S. H. Lee,[36] T. Lesiak,[25] S.-W. Lin,[24] D. Liventsev,[11] J. MacNaughton,[10] G. Majumder,[39] F. Mandl,[10] D. Marlow,[32] T. Matsumoto,[45] S. Michizono,[7] T. Mimashi,[7] W. Mitaroff,[10] K. Miyabayashi,[21] H. Miyake,[29] D. Mohapatra,[50] G. R. Moloney,[19] T. Nagamine,[42] Y. Nagasaka,[8] T. Nakadaira,[43] T. T. Nakamura,[7] M. Nakao,[7] Z. Natkaniec,[25] S. Nishida,[7] O. Nitoh,[46] T. Nozaki,[7] S. Ogawa,[40] Y. Ogawa,[7] K. Ohmi,[7] Y. Ohnishi,[7] T. Ohshima,[20] N. Ohuchi,[7] K. Oide,[7] T. Okabe,[20] S. Okuno,[13] W. Ostrowicz,[25] H. Ozaki,[7] H. Palka,[25] H. Park,[15] N. Parslow,[38] L. E. Piilonen,[50] H. Sagawa,[7] S. Saitoh,[7] Y. Sakai,[7] T. R. Sarangi,[49] M. Satapathy,[49] A. Satpathy,[7,3] O. Schneider,[16] A. J. Schwartz,[3] S. Semenov,[11] K. Senyo,[20] R. Seuster,[6] M. E. Sevior,[19] H. Shibuya,[40] T. Shidara,[7] B. Shwartz,[1] V. Sidorov,[1] N. Soni,[30] S. Stanič,[48,†] M. Starič,[12] A. Sugiyama,[34] T. Sumiyoshi,[45] S. Suzuki,[51] F. Takasaki,[7] K. Tamai,[7] N. Tamura,[27] M. Tanaka,[7] M. Tawada,[7] G. N. Taylor,[19] Y. Teramoto,[28] T. Tomura,[43] K. Trabelsi,[6] T. Tsukamoto,[7] S. Uehara,[7] K. Ueno,[24] Y. Unno,[2] S. Uno,[7] G. Varner,[6] K. E. Varvell,[38] C. C. Wang,[24] C. H. Wang,[23] J. G. Wang,[50] Y. Watanabe,[44] E. Won,[14] B. D. Yabsley,[50] Y. Yamada,[7] A. Yamaguchi,[42] Y. Yamashita,[26] H. Yanai,[27] Heyoung Yang,[36] J. Ying,[31] M. Yoshida,[7] C. C. Zhang,[9] Z. P. Zhang,[35] and D. Žontar[17,12]

(Belle Collaboration)

# PDG Naming Scheme and Historical / Discovery Nomenclature

| | $PC$ | $-+$ | $+-$ | $--$ | $++$ |
|---|---|---|---|---|---|
| Isospin | heavy quark content | | | | |
| $I=0$ | with $c\bar{c}$ | $\eta_c$ | $h_c$ | $\psi$ | $\chi_c$ |
| $I=0$ | with $b\bar{b}$ | $\eta_b$ | $h_b$ | $\Upsilon$ | $\chi_b$ |
| $I=1$ | with $c\bar{c}$ | $(\Pi_c)$ | $Z_c$ | $(R_c)$ | $(W_c)$ |
| $I=1$ | with $b\bar{b}$ | $(\Pi_b)$ | $Z_b$ | $(R_b)$ | $(W_b)$ |

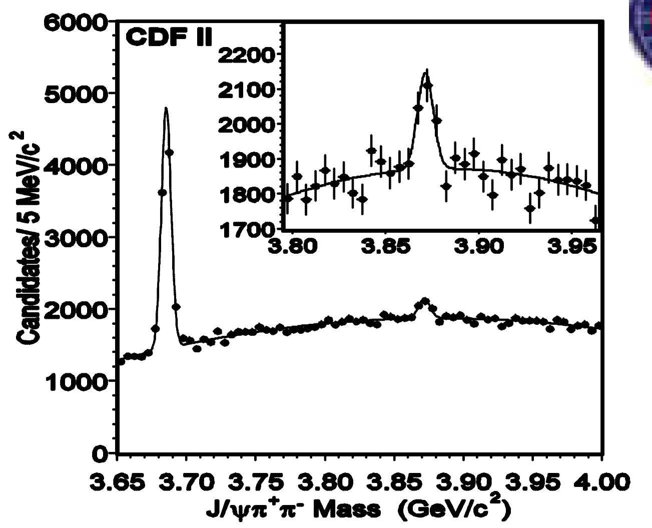
e.g., $Y(4660)$ is now also known as $\psi(4660)$

$X(3872)$ is now $\chi_{c1}(3872)$ and ...

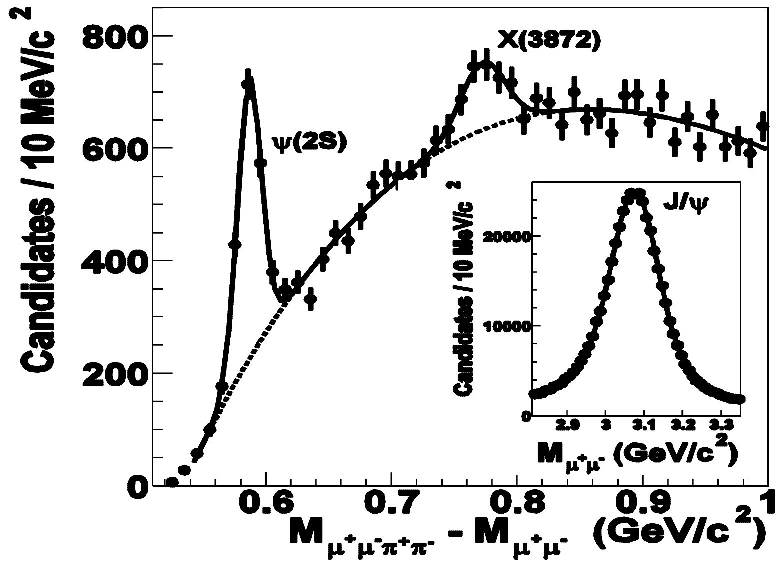
in the PDG naming scheme $X$(mass) would be a state with not-yet-measured quantum numbers

# $\chi_{c1}(3872)$ ($J^{PC} = 1^{++}$ / LHCb), formerly known as $X(3872)$: the most enigmatic state

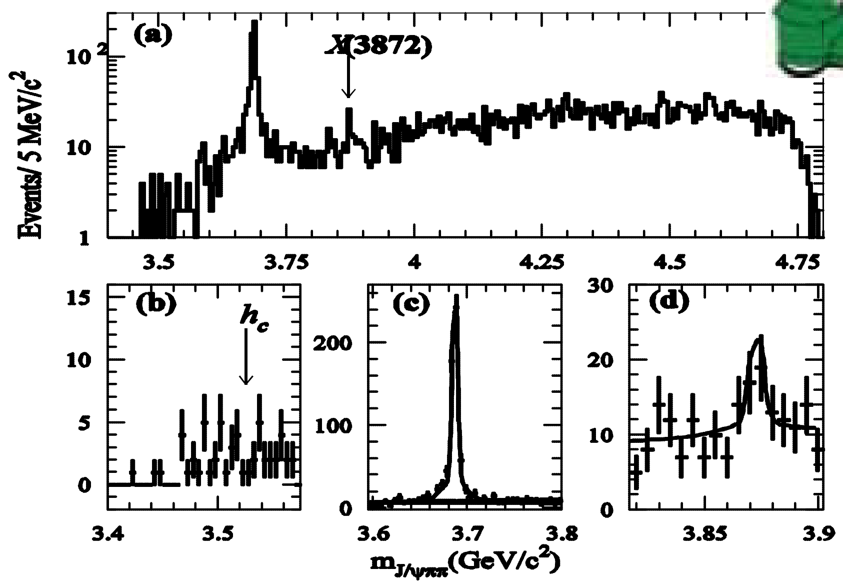
PRL.93.072001 (2004)

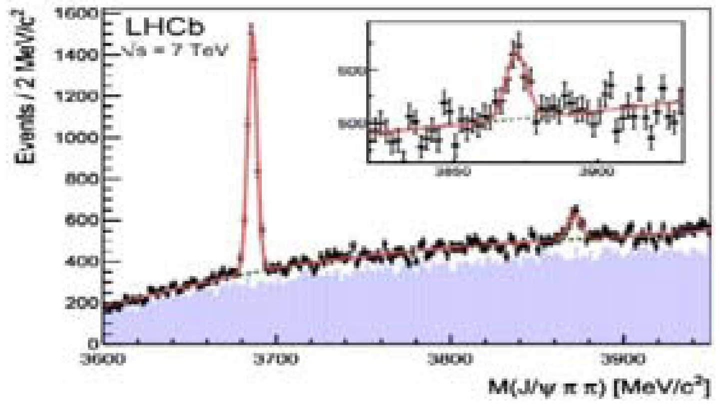



PRL.93.162002 (2004)

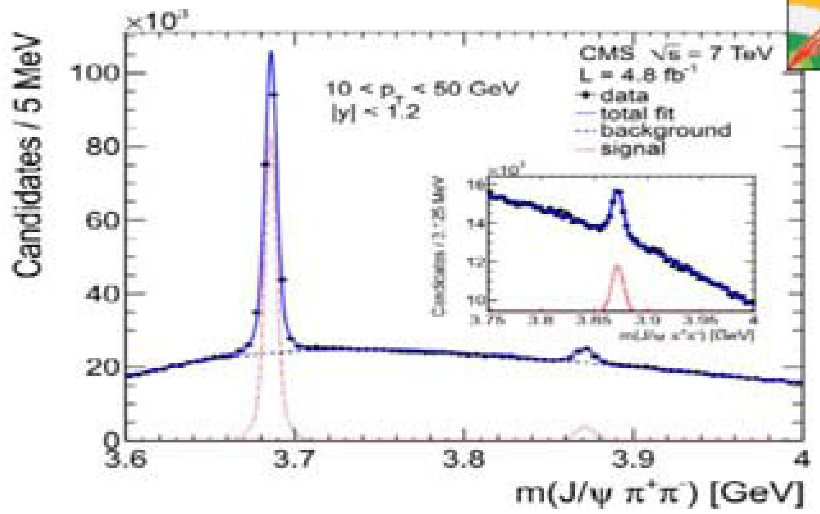



PRD.71.071103 (2005)

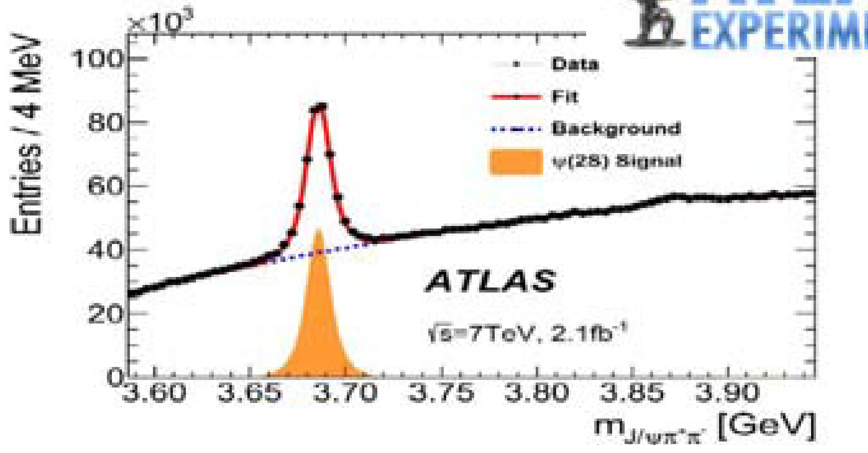



EPJC.72.1972 (2012)



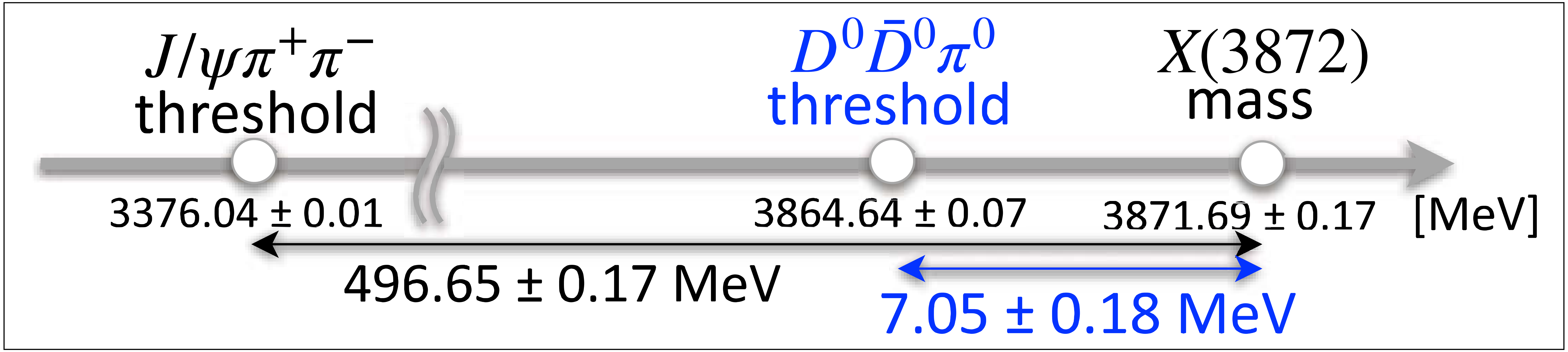

JHEP.04.154 (2013)




JHEP.79.2014 (2014)

- No quark model prediction in this mass region
- Mass is consistent with DD* with O(0.1) MeV precision suggesting DD* molecular state
- Differential cross section for "prompt production" (not from a B meson decay) is measured by LHC, though this should be suppressed for molecular state!
- Suggests X(3872) is superposition of molecular and $c\bar{c}$ state
- Precise measurements of production and decay processes are essential to understand the exotic nature

## $\chi_{c1}(3872)$ ($J^{PC} = 1^{++}$ / LHCb), formerly known as $X(3872)$: the most enigmatic state



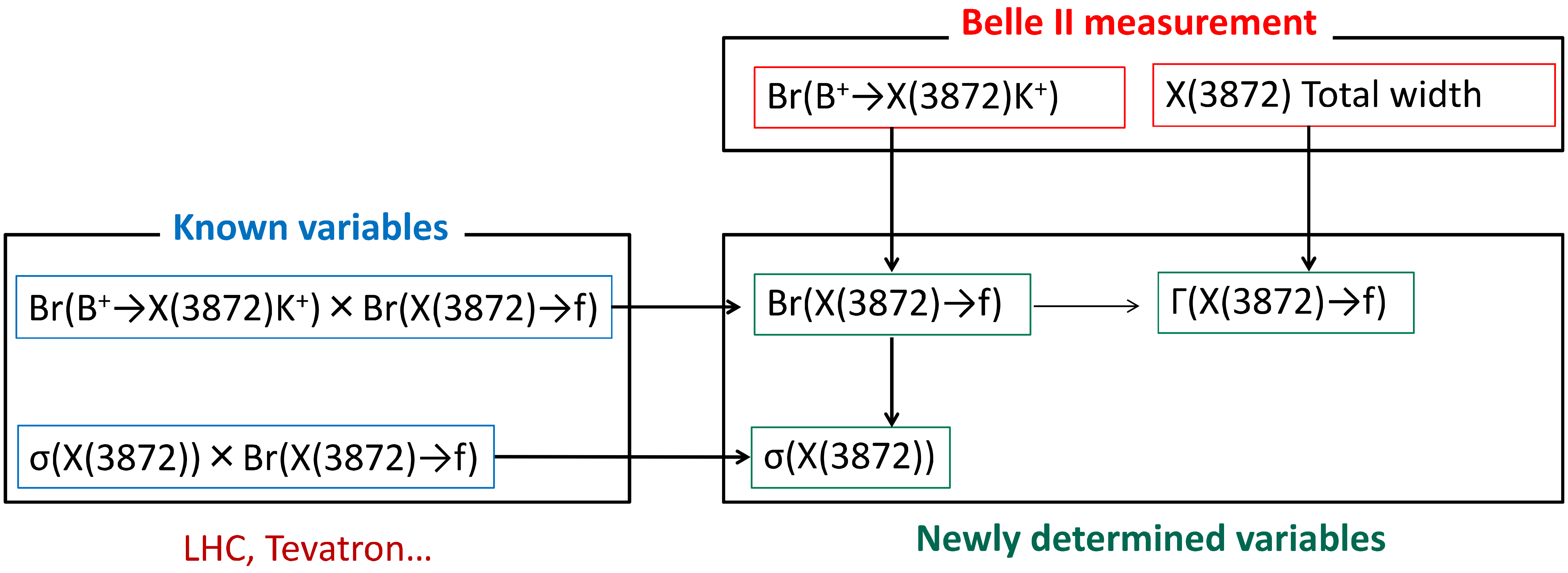

- Previous study (Phys. Rev. D 84, 052004 (2011))
  - Used $X(3872) \to J/\psi\pi^+\pi^-$ mode
  - Used a Breit-Wigner (convolved with resolution) fit to mass spectrum

| | | |
|---|---|---|
| $\Gamma_{tot}$ < 1.2 MeV (90% C.L.) | < | Mass resolution 1.86 ± 0.01 MeV/c[2] |

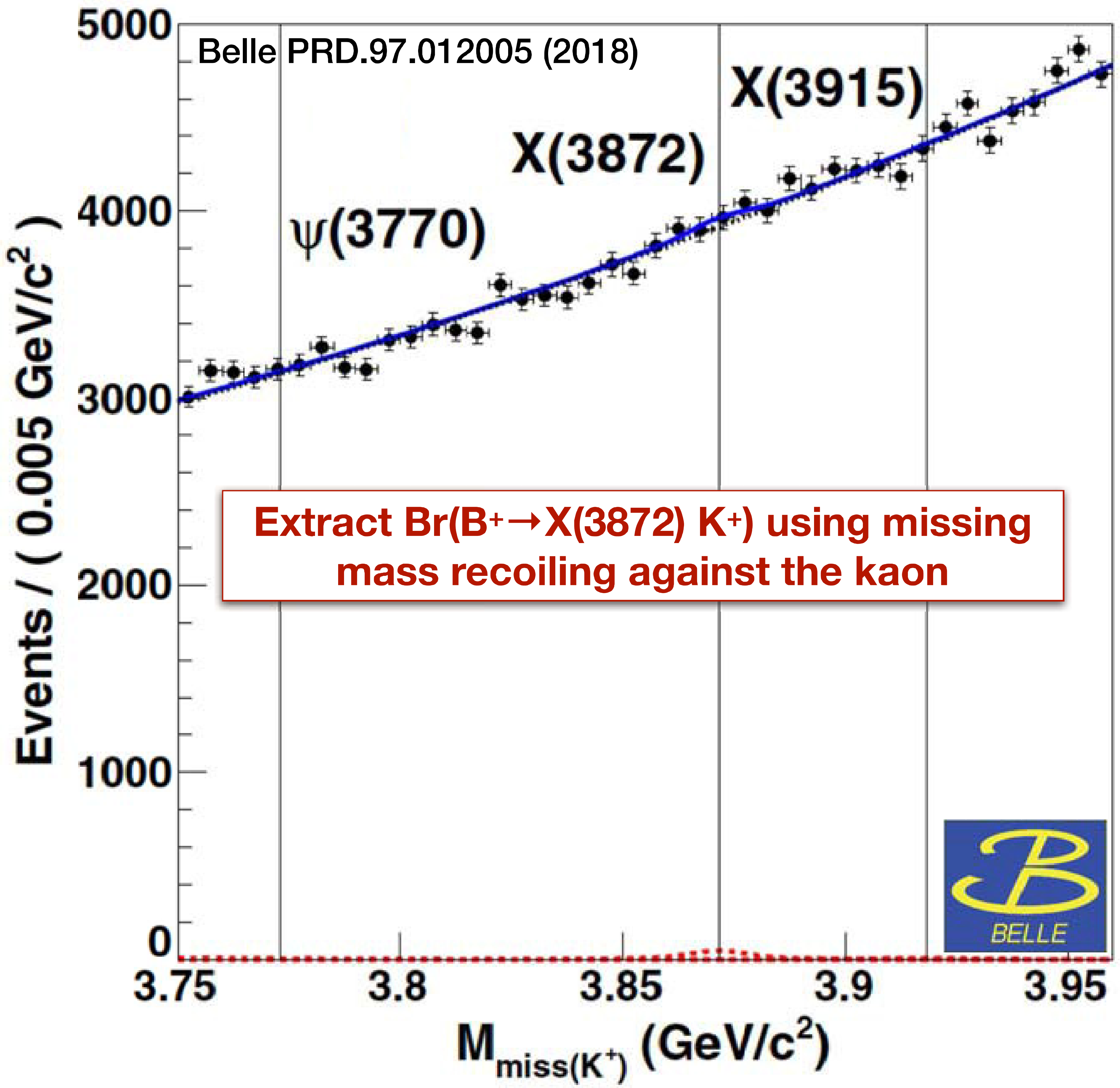
**Improvement of mass resolution is essential**

# The Nature of X(3872): Prospects with Belle II

- Many decay modes have been observed: $J/\psi\ \rho$, $J/\psi\ \omega$, $J/\psi\ \gamma$, $\psi(2S)\ \gamma$, $DD^*$, $DD\pi^0$. etc.
- Branching fractions and decay widths not known
  - Essential dynamic information!
- Belle II can contribute to a deeper understanding of this state!



# Toward X(3872) Total and Partial Widths Measurements with Belle II



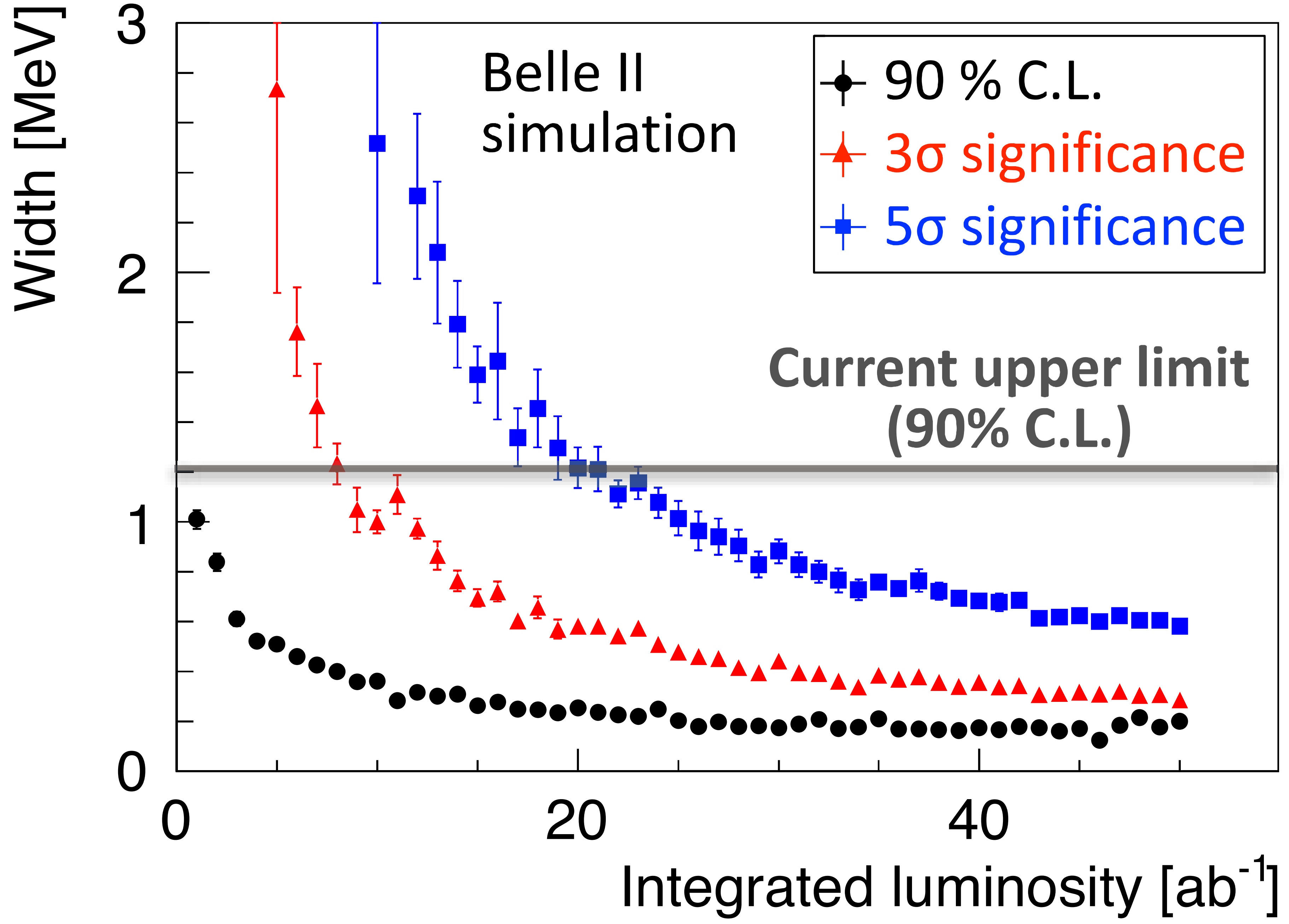

**Extract Br($B^+ \to X(3872)\ K^+$) using missing mass recoiling against the kaon**

**Mass resolution for $D\bar{D}\pi^0$ is ~680 keV: ~3 times better than $J/\psi\pi^+\pi^-$**
**Previously unmeasured due to low statistics**

With the full data sample of Belle II (50 $ab^{-1}$), total width with values up to

**[90% C.L.] ~ 180 keV**
**[3σ significance] ~ 280 keV**
**[5σ significant] ~ 570 keV**

can be measured.




Master thesis of H. Hirata (KMI / Nagoya University) arXiv > hep-ex > arXiv:2302.02127 Accepted for publication in Phys. Rev. D

## High Energy Physics - Experiment

[Submitted on 4 Feb 2023]

# Study of the lineshape of $X(3872)$ using $B$ decays to $D^0\overline{D}^{*0}K$

We present a study of the $X(3872)$ lineshape in the decay $B \to X(3872)K \to D^0\overline{D}^{*0}K$ using a data sample of $772 \times 10^6$ $B\overline{B}$ pairs collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The peak near the threshold in the $D^0\overline{D}^{*0}$ invariant mass spectrum is fitted using a relativistic Breit-Wigner lineshape. We determine the mass and width parameters to be $m = 3873.71^{+0.56}_{-0.50}(\mathrm{stat}) \pm 0.13(\mathrm{syst})\ \mathrm{MeV}/c^2$ and $\Gamma_0 = 5.2^{+2.2}_{-1.5}(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{MeV}$, respectively. The branching fraction is found to be $\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to D^0\overline{D}^{*0}) = (0.97^{+0.21}_{-0.18}(\mathrm{stat}) \pm 0.10(\mathrm{syst})) \times 10^{-4}$. The signal from $B^0$ decays is observed for the first time with $5.2\sigma$ significance, and the ratio of branching fractions between charged and neutral $B$ decays is measured to be $\mathcal{B}(B^0 \to X(3872)K^0)/\mathcal{B}(B^+ \to X(3872)K^+) = 1.34^{+0.47}_{-0.40}(\mathrm{stat})^{+0.10}_{-0.12}(\mathrm{syst})$. The peak is also studied using a Flatté lineshape. We determine the lower limit on the $D\overline{D}^*$ coupling constant $g$ to be $0.075$ at 95% credibility in the parameter region where the ratio of $g$ to the mass difference from the $D^0\overline{D}^{*0}$ threshold is equal to $-15.11\ \mathrm{GeV}^{-1}$, as measured by LHCb.

Is $X(3872)$ a loosely bound state, an admixture of a molecular state and a pure charmonium resonance, a tetraquark, or a cusp at the $D^0\bar{D}^{*0}$ threshold? Measurement of the lineshape in various decay modes can help to discriminate among different scenarios for the structure of this state. In this study two models for the lineshape in the decay to $D^0\bar{D}^{*0}$ are examined: a Breit-Wigner, and a Flatté-inspired parametrization.

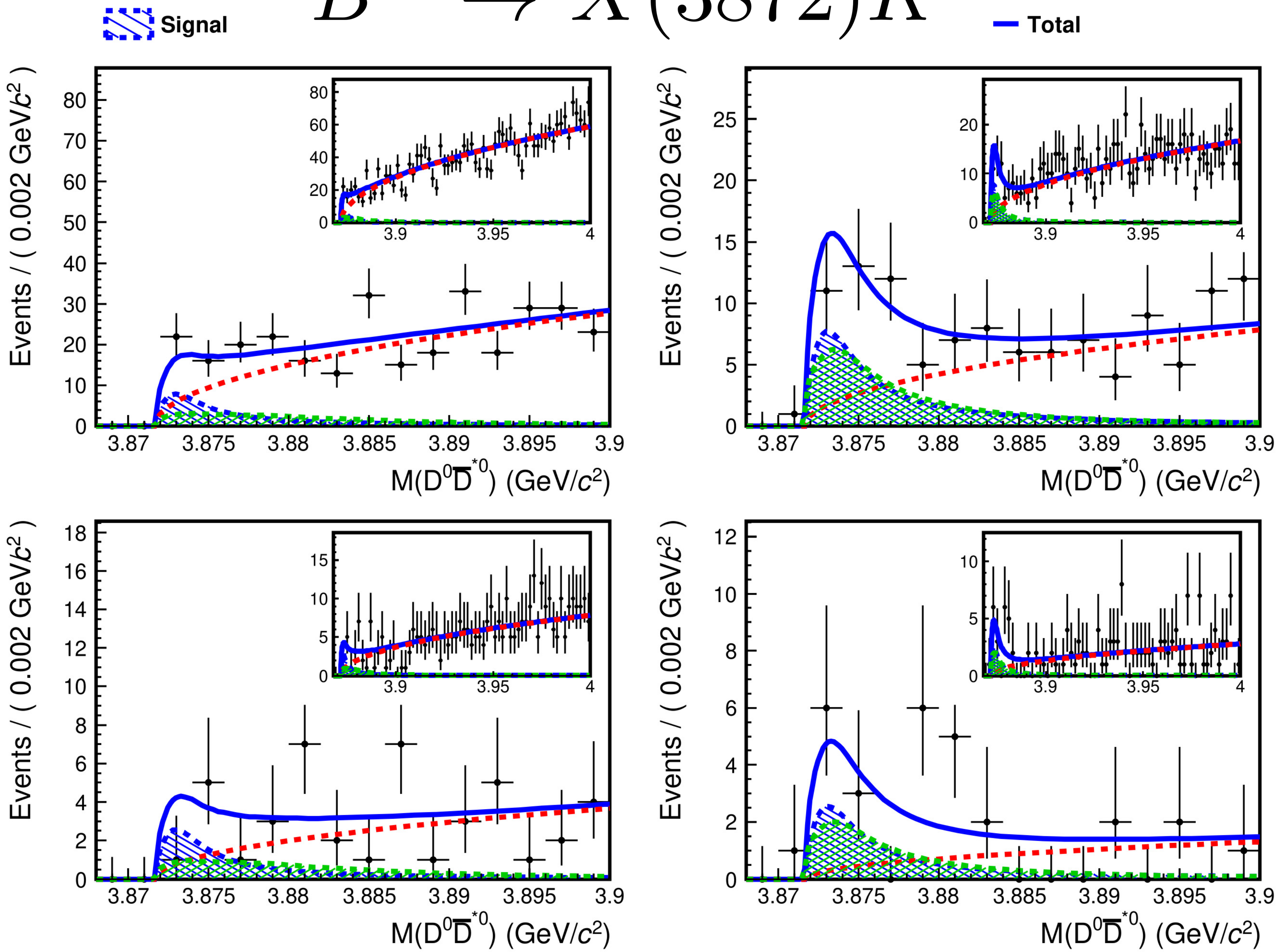
In the future, a high statistics simultaneous fit of the $B \to X(3872)/(\to J/\psi\pi^+\pi^-)K$ and $B \to X(3872)/(\to D^0\bar{D}^{*0})K$ decay modes would be greatly beneficial for determining the lineshape and the ratio of branching fractions further constraining the models.

**Studies of the lineshape allow the theorists to assess the extent of the compact hidden charm structure**

# Study of the lineshape of $X(3872)$ using $B$ decays to $D^0\overline{D}^{*0}K$

$B^+ \to X(3872)K^+$

$\overline{D}^{*0} \to \overline{D}^0\gamma$




$\overline{D}^{*0} \to \overline{D}^0\pi^0$

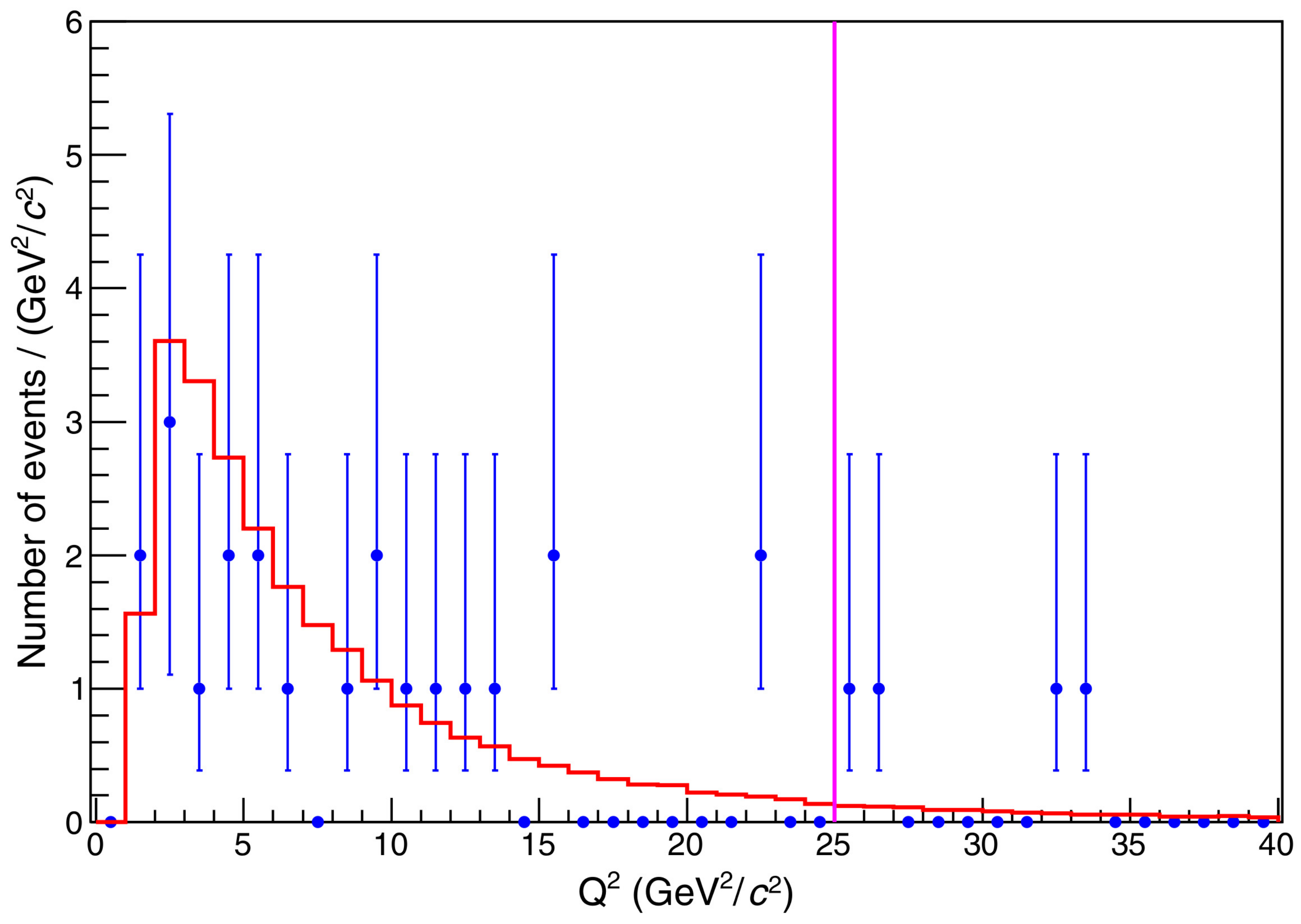
$B^0 \to X(3872)K^0$

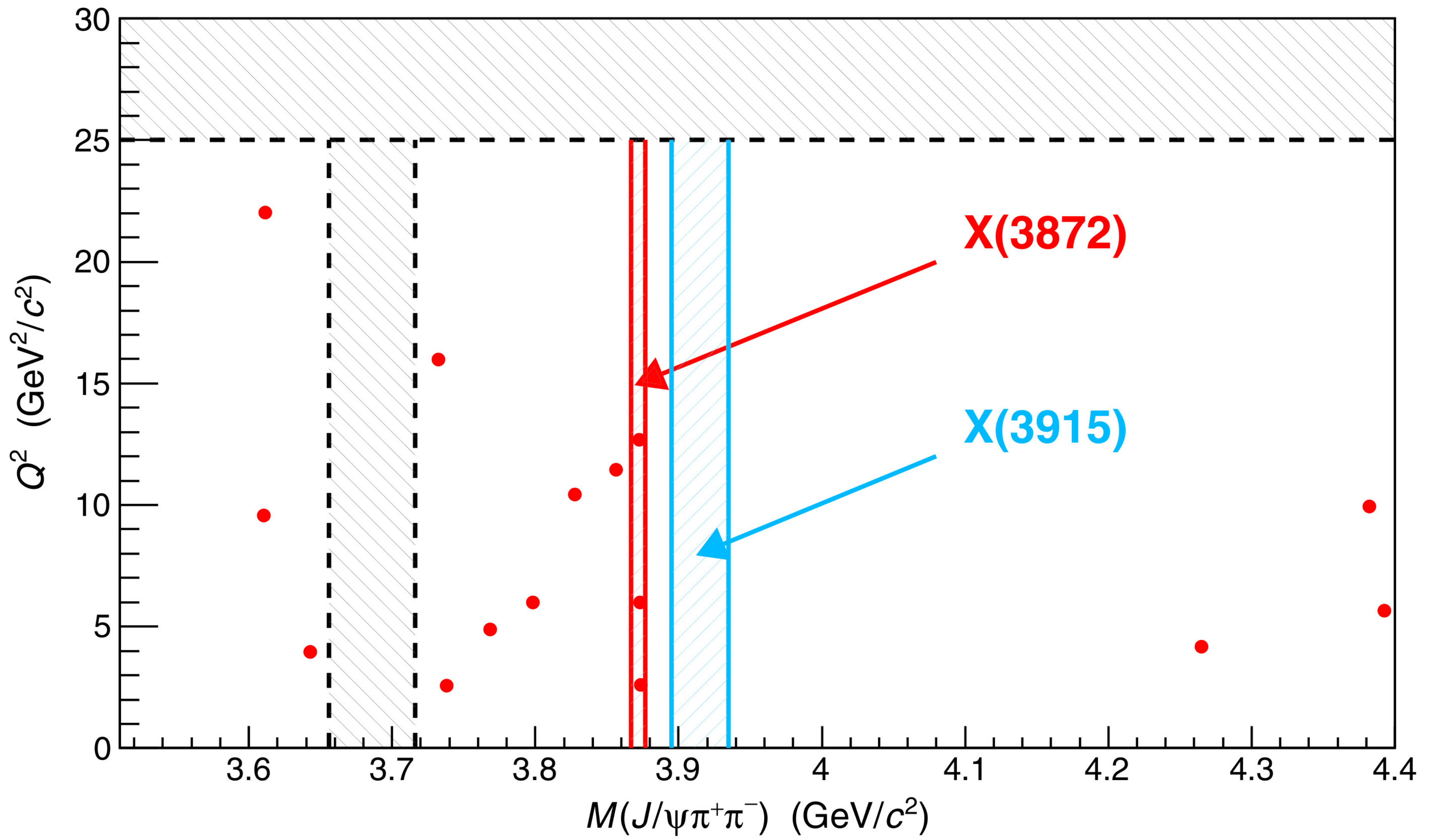
The $M(D^0\overline{D}^{*0})$ distributions with the fit result with the relativistic Breit-Wigner lineshape

PHYSICAL REVIEW LETTERS **126,** 122001 (2021)

# Evidence for $X(3872) \rightarrow J/\psi\pi^+\pi^-$ Produced in Single-Tag Two-Photon Interactions

We report the first evidence for $X(3872)$ production in two-photon interactions by tagging either the electron or the positron in the final state, exploring the highly virtual photon region. The search is performed in $e^+e^- \rightarrow e^+e^- J/\psi\pi^+\pi^-$, using 825 $\mathrm{fb}^{-1}$ of data collected by the Belle detector operated at the KEKB $e^+e^-$ collider. We observe three $X(3872)$ candidates, where the expected background is $0.11 \pm 0.10$ events, with a significance of $3.2\sigma$. We obtain an estimated value for $\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)$ assuming the $Q^2$ dependence predicted by a $c\bar{c}$ meson model, where $-Q^2$ is the invariant mass squared of the virtual photon. No $X(3915) \rightarrow J/\psi\pi^+\pi^-$ candidates are found.

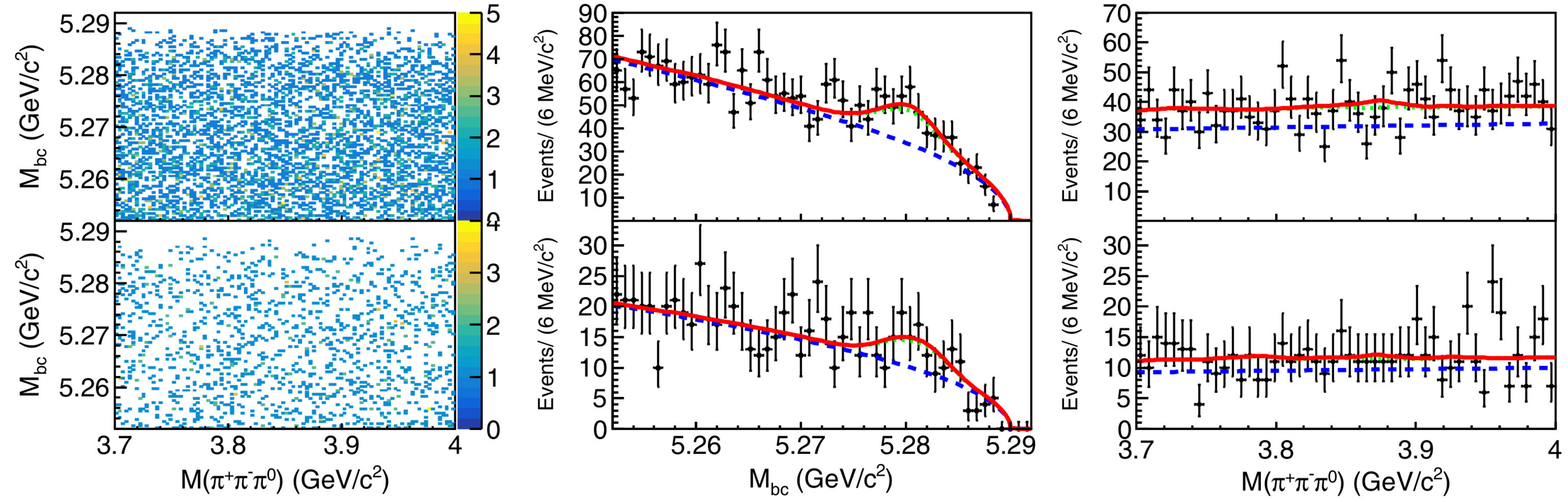


PHYSICAL REVIEW D **107,** 052004 (2023)

# Search for $X(3872) \to \pi^+\pi^-\pi^0$ at Belle

We present a search for the decay $X(3872) \to \pi^+\pi^-\pi^0$ in the $(772 \pm 11) \times 10^6$ $\Upsilon(4S) \to B\bar{B}$ data sample collected at the Belle detector, where the $X(3872)$ is produced in $B^\pm \to K^\pm X(3872)$ and $B^0 \to K_S^0 X(3872)$ decays. We do not observe a signal, and set 90% credible upper limits for two different models of the decay processes: if the decay products are distributed uniformly in phase space, $\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0) < 1.3\%$, and if $M(\pi^+\pi^-)$ is concentrated near the mass of the $D^0\bar{D}^0$ pair in the process $X(3872) \to D^0\bar{D}^{*0} + \text{c.c.} \to D^0\bar{D}^0\pi^0 \to \pi^+\pi^-\pi^0$, $\mathcal{B}(X(3872) \to \pi^+\pi^-\pi^0) < 1.2 \times 10^{-3}$.

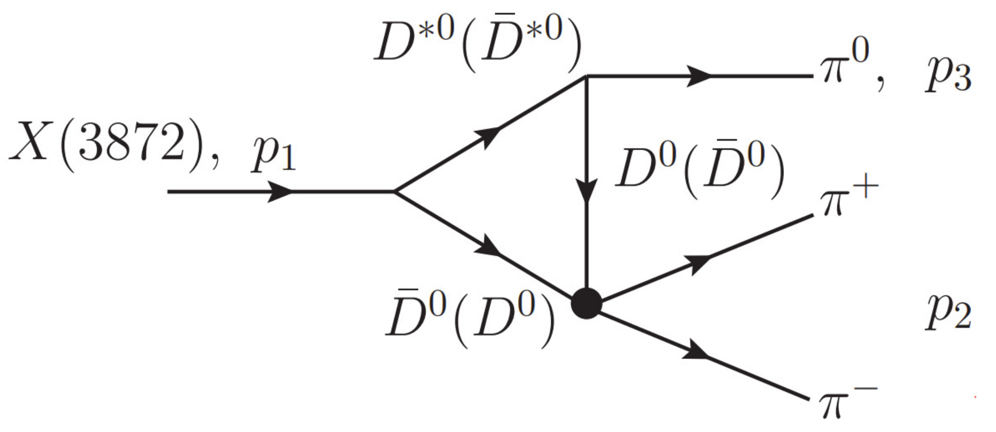



This measurement may be used to provide constraints on the triangle logarithmic singularity of $X(3872) \to D^0\bar{D}^{*0} \to D^0\bar{D}^{*0}\pi^0$

PHYSICAL REVIEW D **99,** 116023 (2019)

## Decay $X(3872) \to \pi^0\pi^+\pi^-$ and $S$-wave $D^0\bar{D}^0 \to \pi^+\pi^-$ scattering length

N. N. Achasov and G. N. Shestakov



arXiv > hep-ex > arXiv:2301.09421

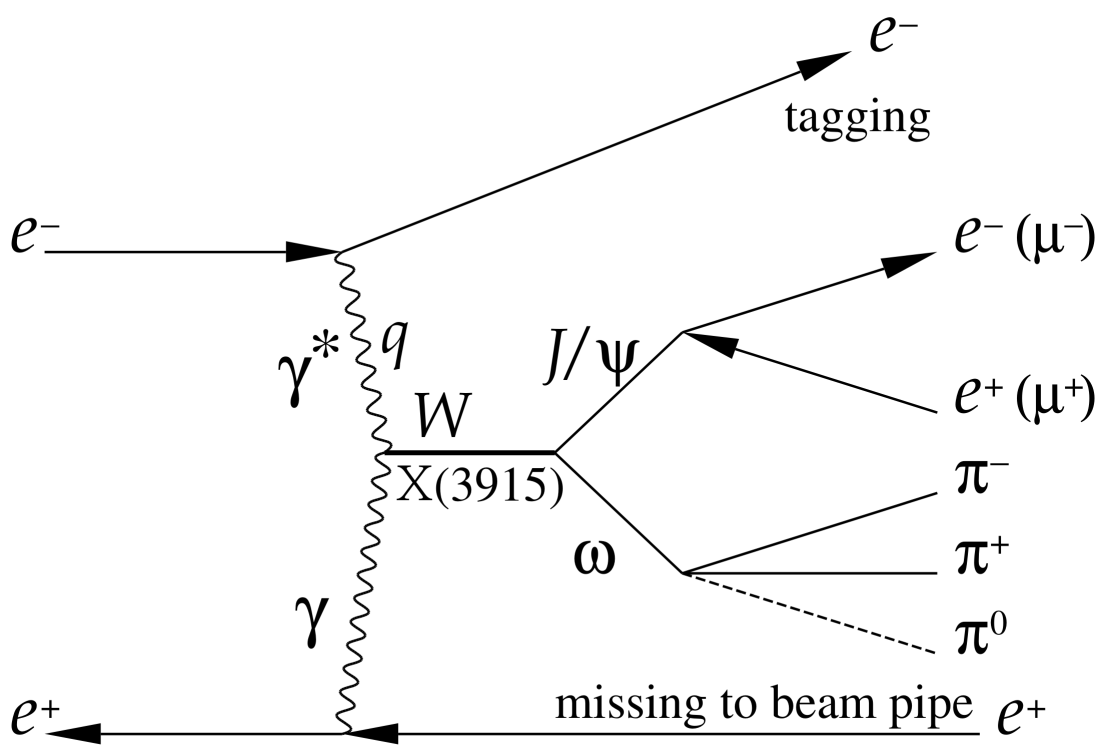
**High Energy Physics - Experiment**

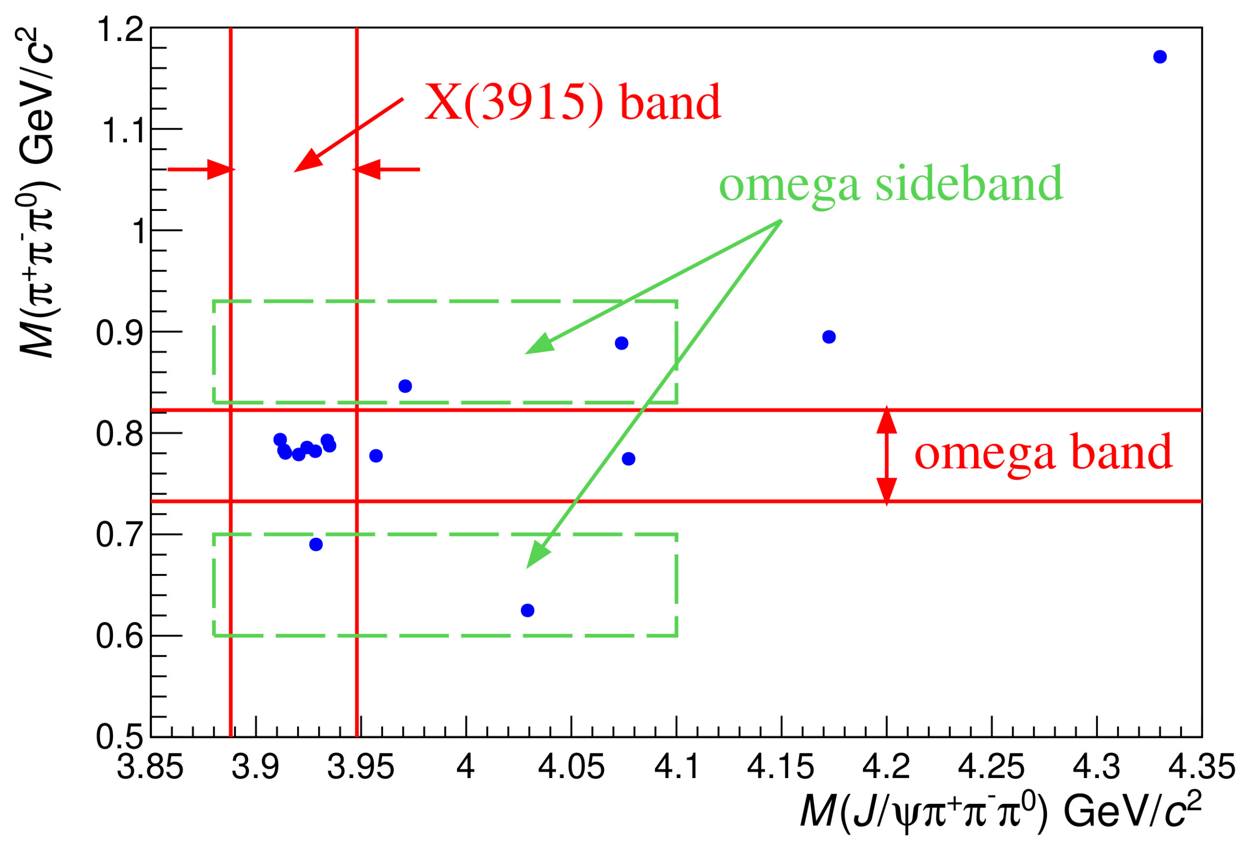
[Submitted on 17 Jan 2023]

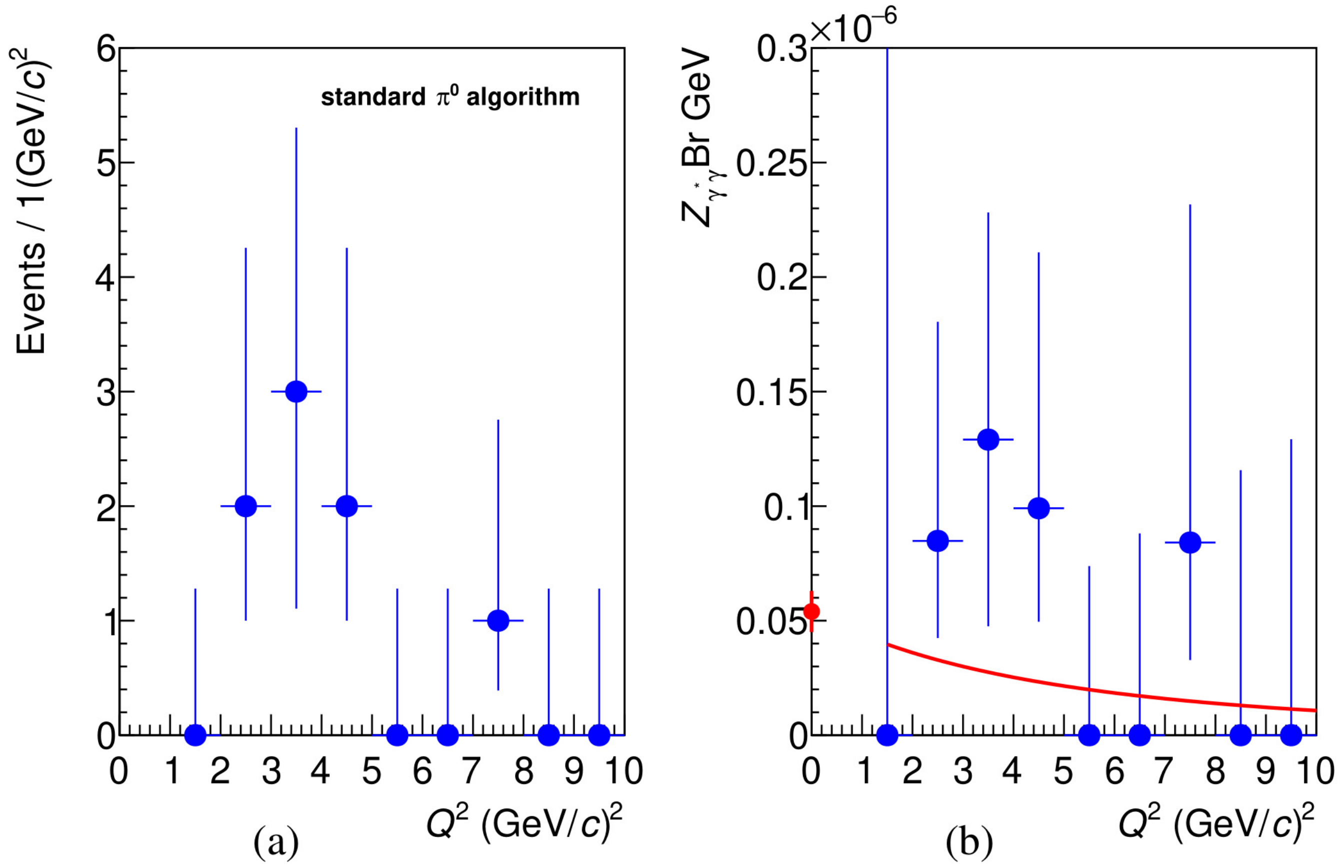
$(\chi_{c0}(3915))$

# First measurement of the Q^2 distribution of X(3915) single-tag two-photon production


We report the first measurement of the $Q^2$ distribution of $X(3915)$ produced by single-tag two-photon interactions. The decay mode used is $X(3915) \to J/\psi\omega$. The covered $Q^2$ region is from 1.5 $(\mathrm{GeV}/c)^2$ to 10.0 $(\mathrm{GeV}/c)^2$. The observed number of events is $7.9 \pm 3.1(\mathrm{stat.}) \pm 1.5(\mathrm{syst.})$, in comparison to the expectation of $4.1 \pm 0.7$ derived from the standard value at $Q^2 = 0$ measured in the no-tag two-photon process and extrapolated to the higher $Q^2$ region using a $c\bar{c}$ model. The measured $Q^2$ distribution does not show a significant shift to lower $Q^2$ in contrast to the expectation from some types of non-$c\bar{c}$ models. It agrees with $X(3915)$ being a charmonium state, though it does not exclude a non-$c\bar{c}$ state with compact size or large compact components.

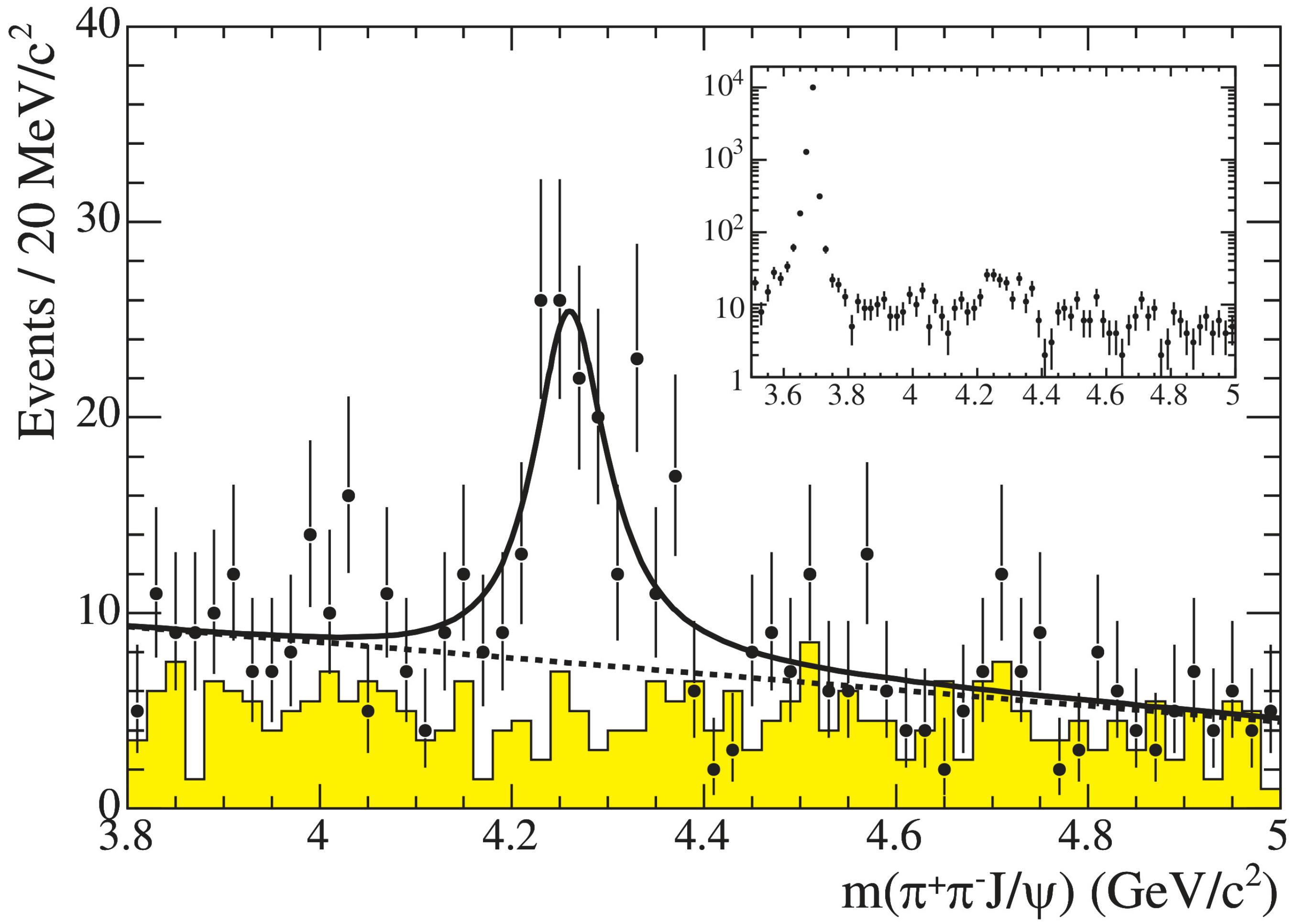



# $\psi(4230)$ (a.k.a. $Y(4230)$; earlier name $\psi(4260)$, discovered as $Y(4260)$) and $Y$ Matters

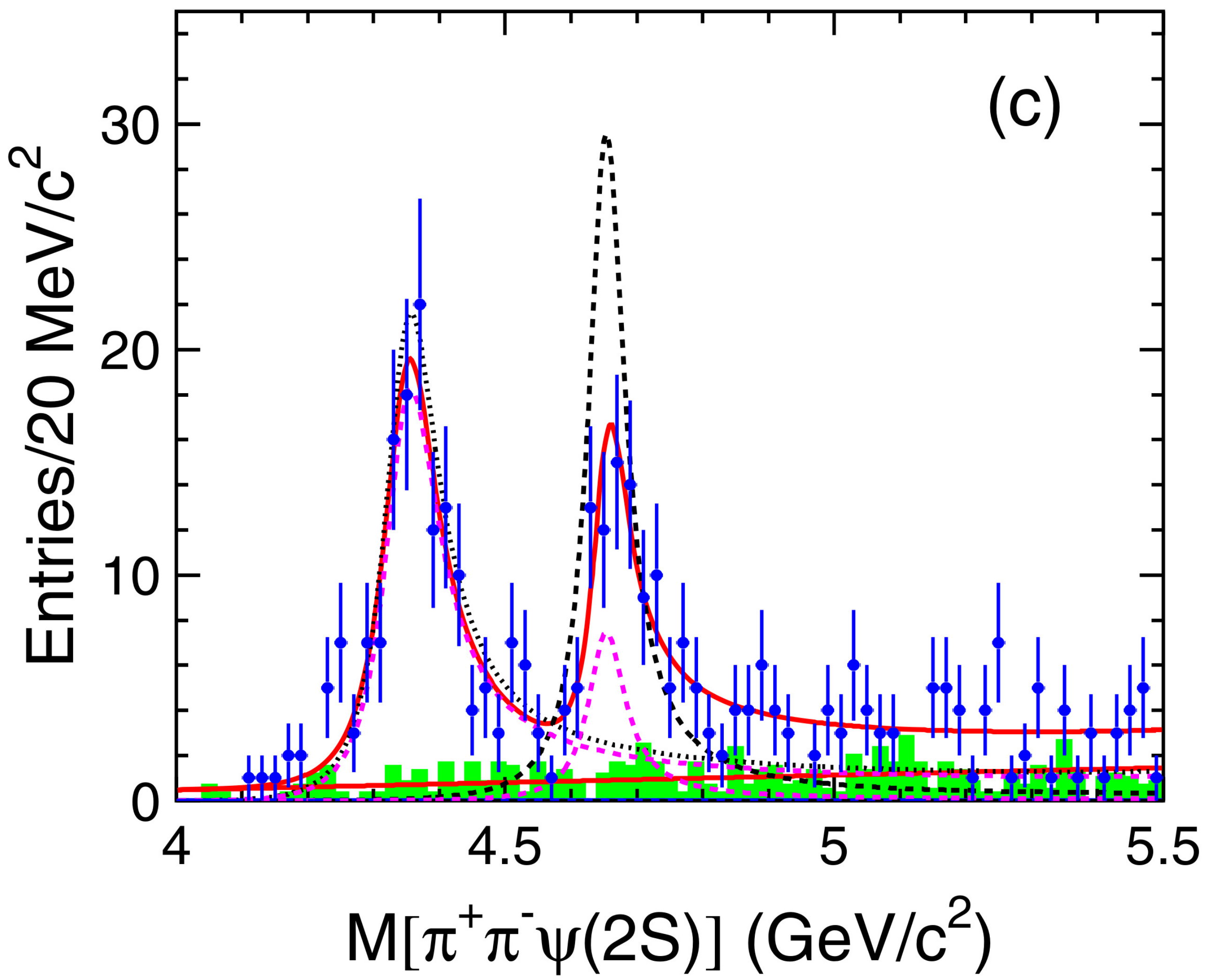
PRL **95,** 142001 (2005) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2005

**Observation of a Broad Structure in the $\pi^+\pi^- J/\psi$ Mass Spectrum around 4.26 GeV/$c^2$**



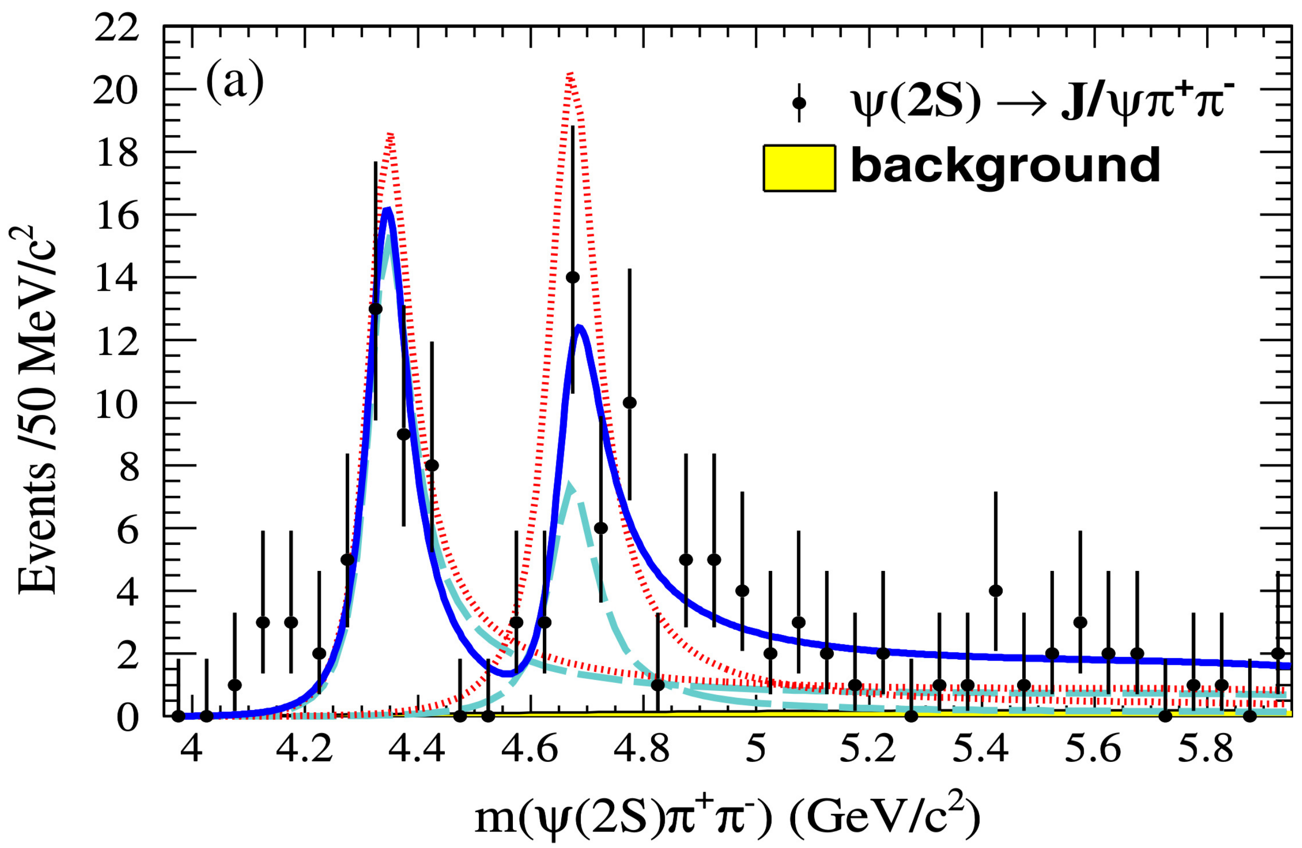

PHYSICAL REVIEW D **91,** 112007 (2015)

**Measurement of $e^+e^- \to \pi^+\pi^-\psi(2S)$ via initial state radiation at Belle**




PHYSICAL REVIEW D **89,** 111103(R) (2014)

**Study of the reaction $e^+e^- \to \psi(2S)\pi^+\pi^-$ via initial-state radiation at *BABAR***



# $\psi(4230)$ (a.k.a. $Y(4230)$; earlier name $\psi(4260)$, discovered as $Y(4260)$) and $Y$ Matters

*G. Mezzadri and S. Spataro* — *Reviews in Physics 8 (2022) 100070*

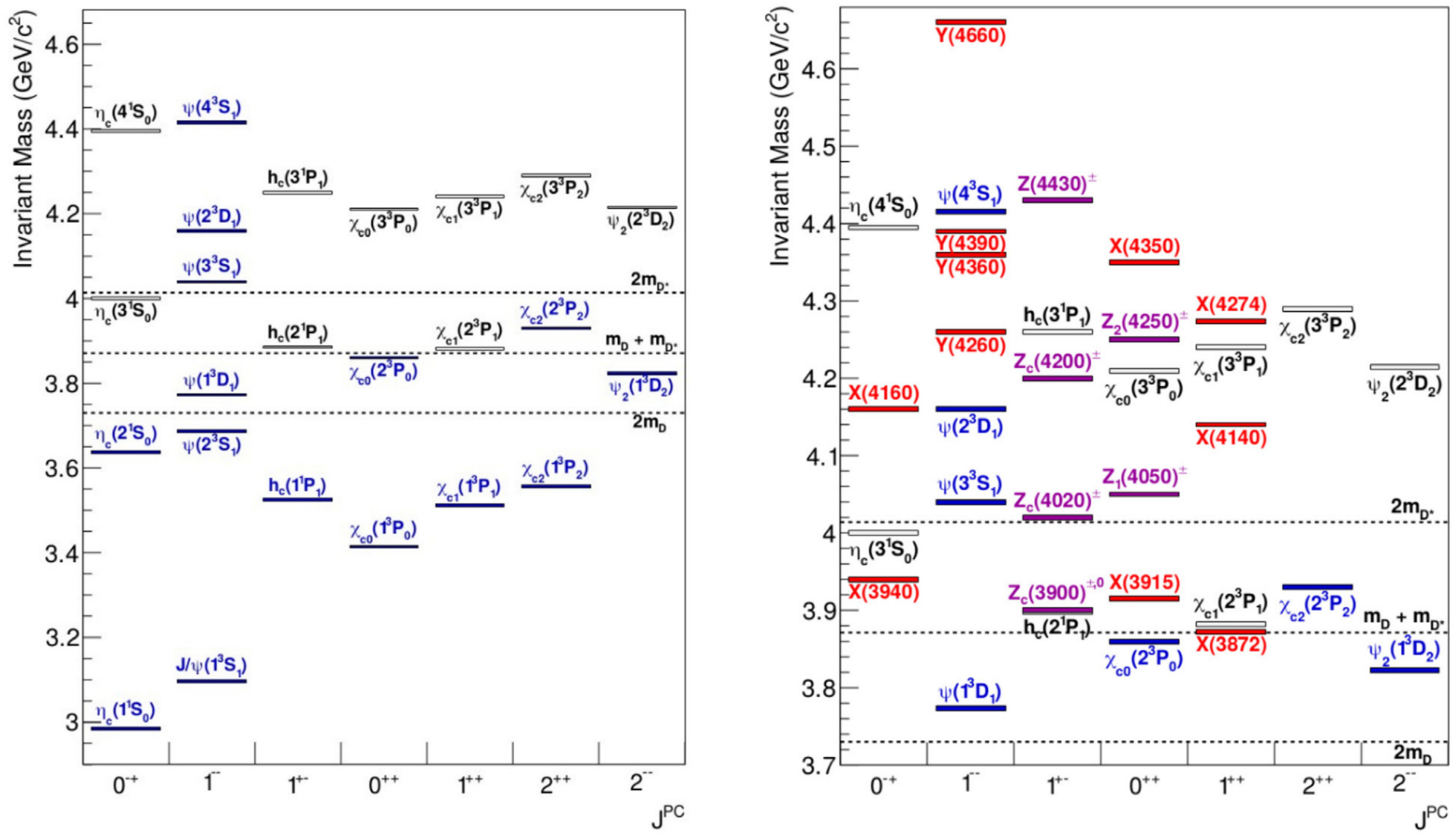
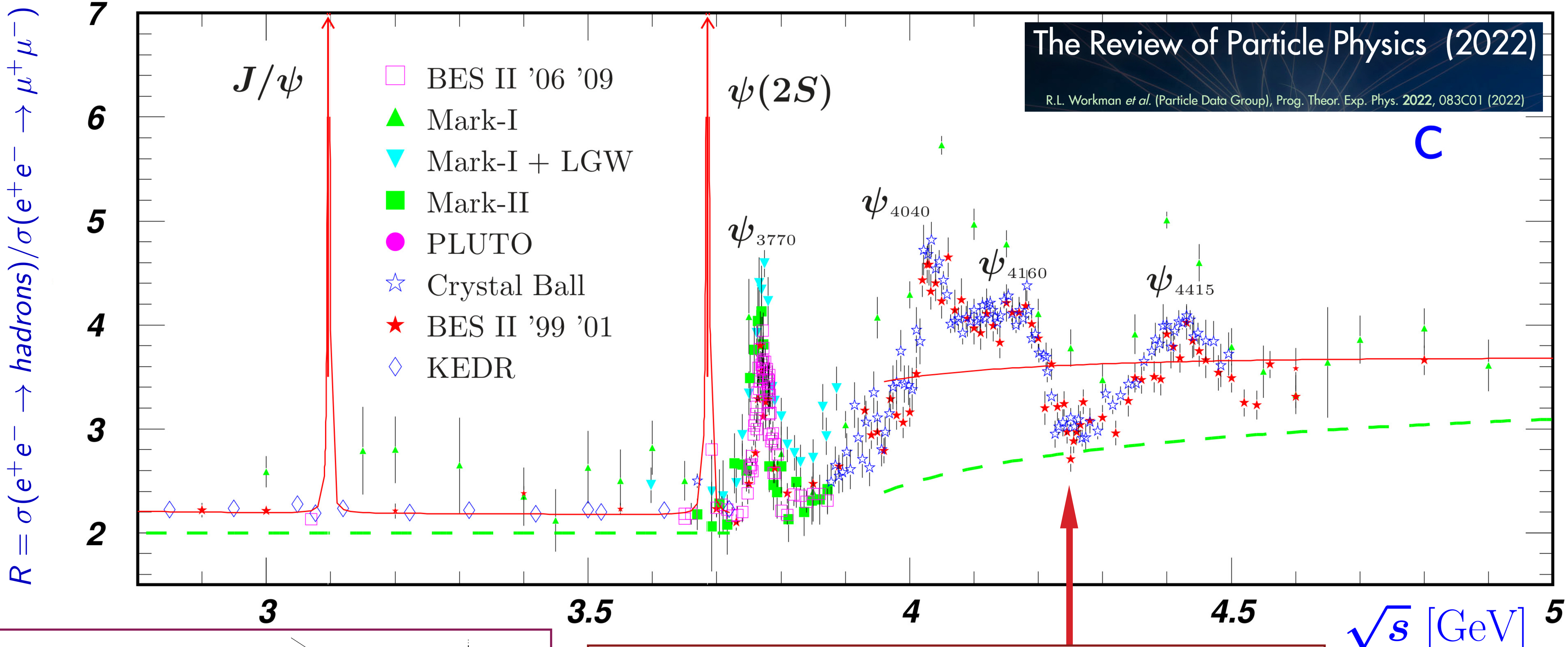
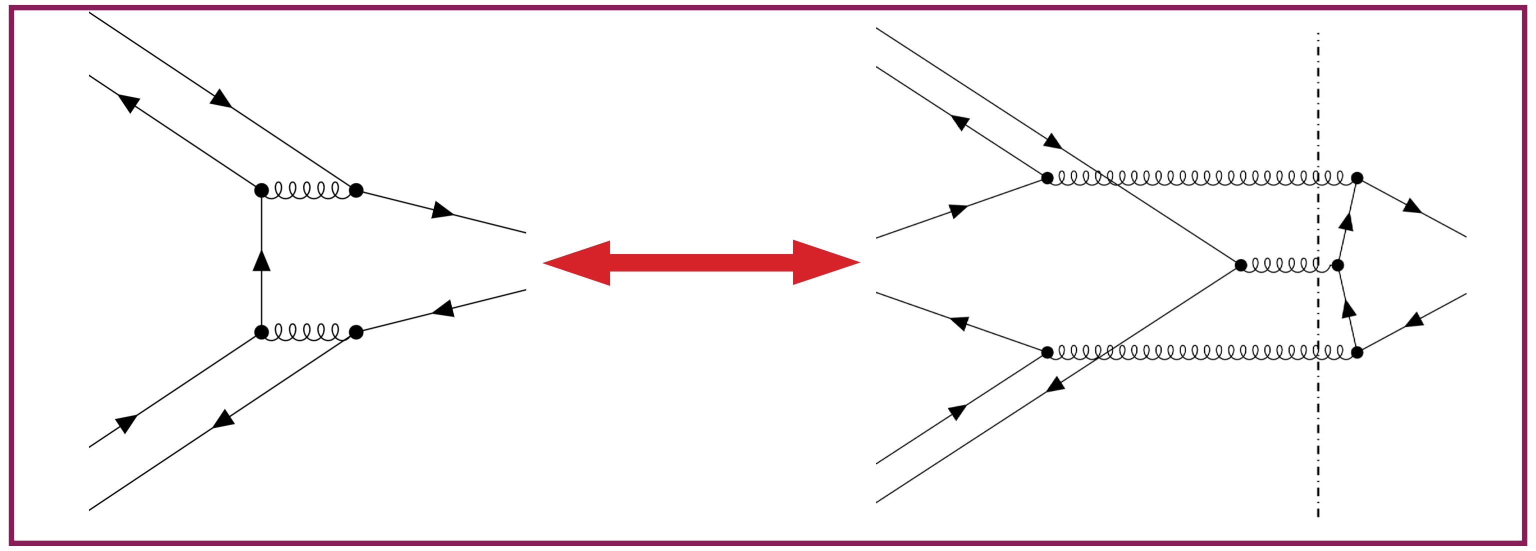



**Fig. 2.** States of the charmonium spectrum: (left) full charmonium spectrum before 2003; (right) charmonium spectrum above the open-charm threshold nowadays. The blue boxes show the predicted and discovered charmonium states; the gray boxes represent the predicted conventional charmonium states but not yet discovered; the red boxes represent the neutral non-conventional $XYZ$ mesons, while the magenta boxes show the charged non-conventional states.

# $\psi(4230)$ (a.k.a. $Y(4230)$; earlier name $\psi(4260)$, discovered as $Y(4260)$) and $Y$ Matters




A dip in the $Y(4260)$ region, a violation of the OZI rule? A destructive interference?



Belle / Belle II investigated the situation in the bottom sector also

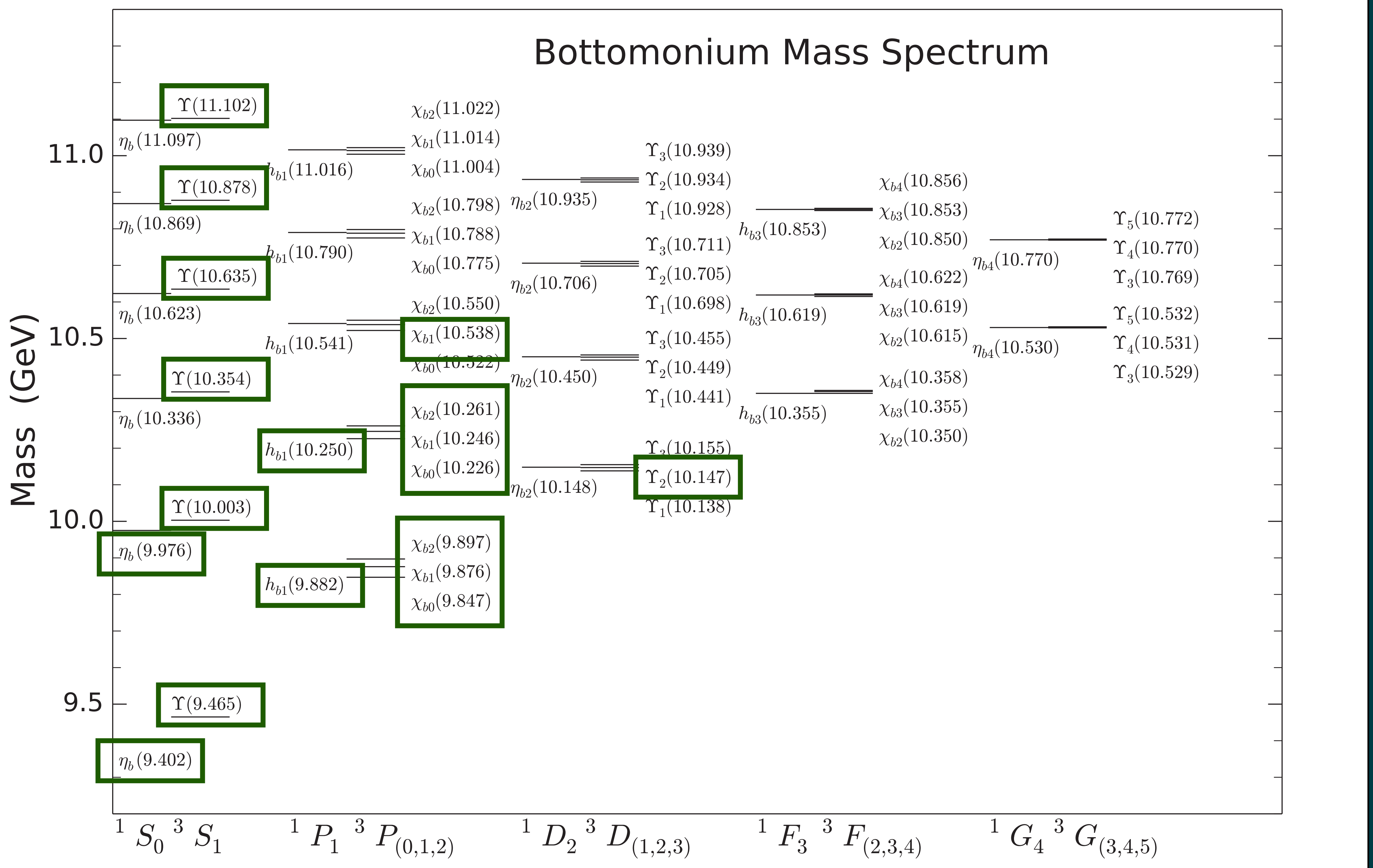
Exotics: Heavy Pentaquarks and Tetraquarks
Ahmed Ali, Jens Soren Lange, and Sheldon Stone
Progress in Particle and Nuclear Physics
Volume 97, November 2017, Pages 123-198

$$V_0^{c\bar{c}}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

$$V_{\alpha_s}^{c\bar{c}}(r) = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

$$\vec{T} \equiv (\vec{S}_c \cdot \hat{r})(\vec{S}_{\bar{c}} \cdot \hat{r}) - \frac{1}{3}\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

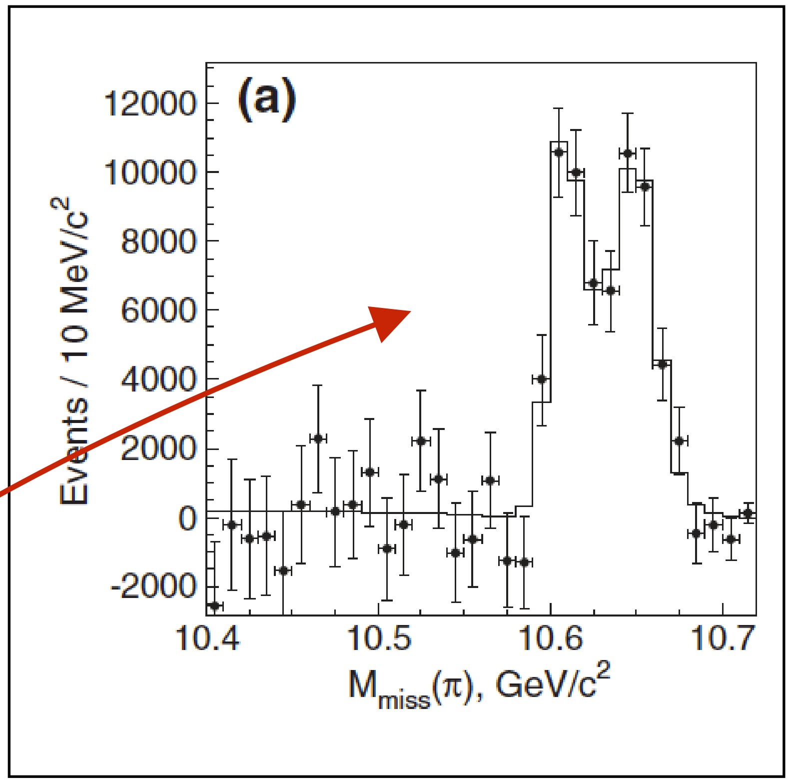
T. Barnes, S. Godfrey, E. S. Swanson, Higher charmonia, Phys. Rev. D72 (2005) 054026. arXiv:hep-ph/0505002, doi:10.1103/PhysRevD.72.054026.




S. Godfrey and K. Moats, Bottomonium mesons and strategies for their observation, Phys. Rev. D 92, 054034 (2015)
S. Godfrey and N. Isgur, Mesons in a relativized quark model with chromodynamics, Phys. Rev. D 32, 189 (1985).

# Belle has done an excellent job filling in the gaps and more. Belle II now continues this work

Belle discovered some of the expected quarkonium states and discovered the exotic states in the bottom sector

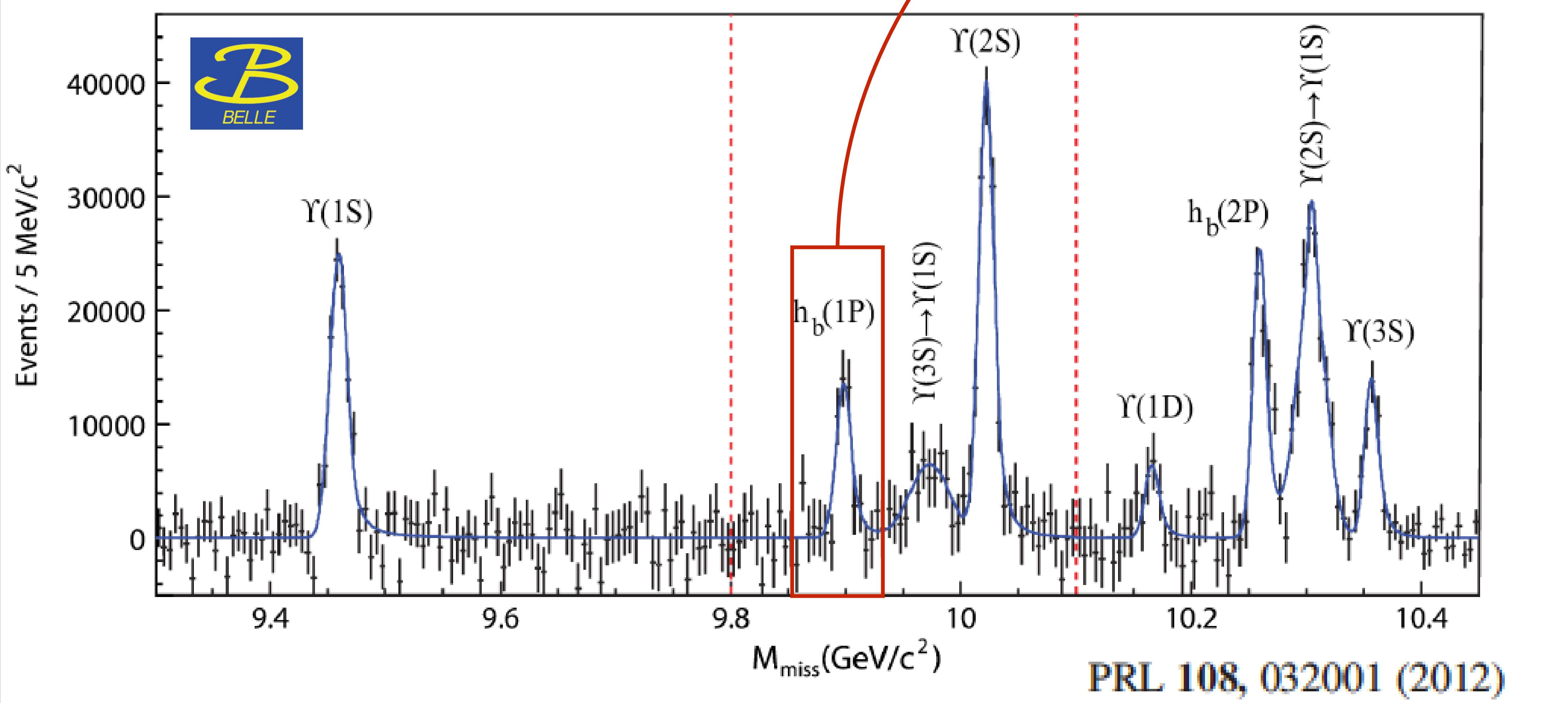



$h_b(1P)\pi^+\pi^-$

$Z_b(10\,610)$ and $Z_b(10\,650)$

**PRL 108, 122001 (2012)**

**First Observation of the *P*-Wave Spin-Singlet Bottomonium States $h_b(1P)$ and $h_b(2P)$**




PRL 108, 032001 (2012)

**Bottomonium-like states: Physics case for energy scan above the $B\bar{B}$ threshold at Belle-II**

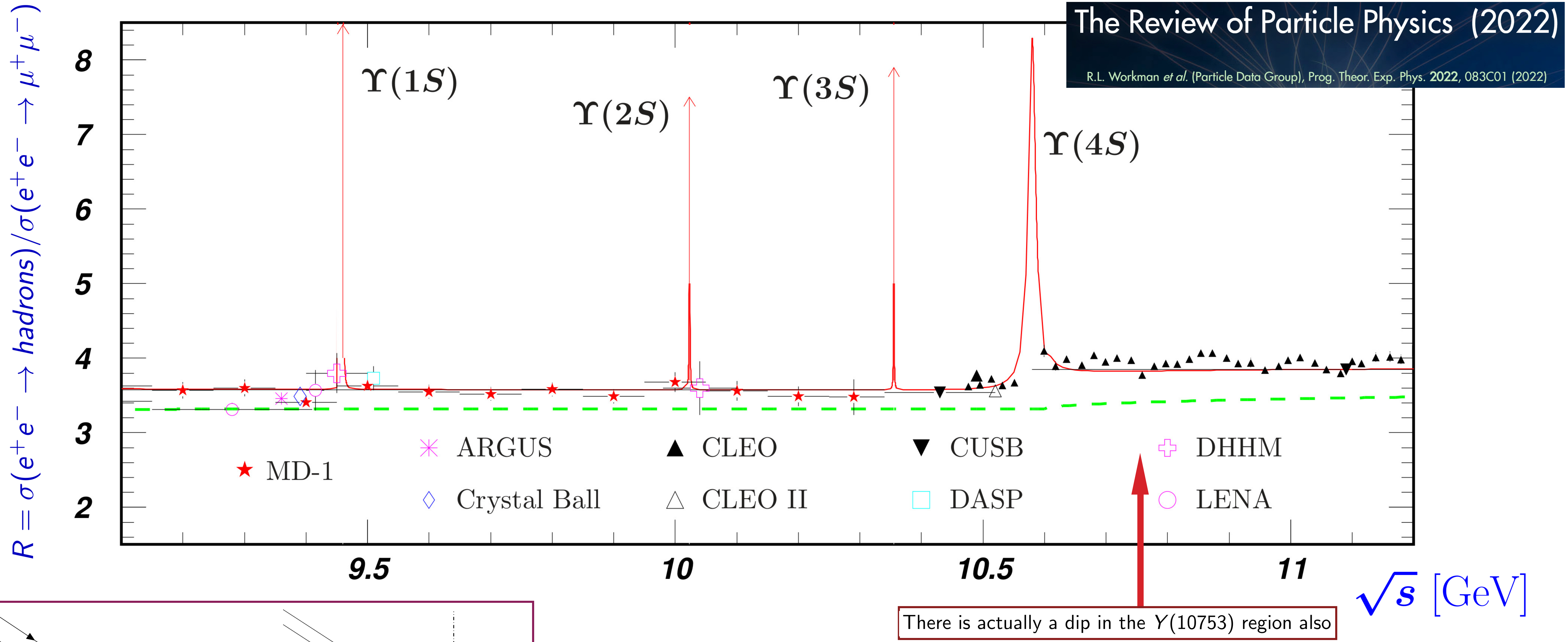
*A. E. Bondar, R. V. Mizuk & M. B. Voloshin*

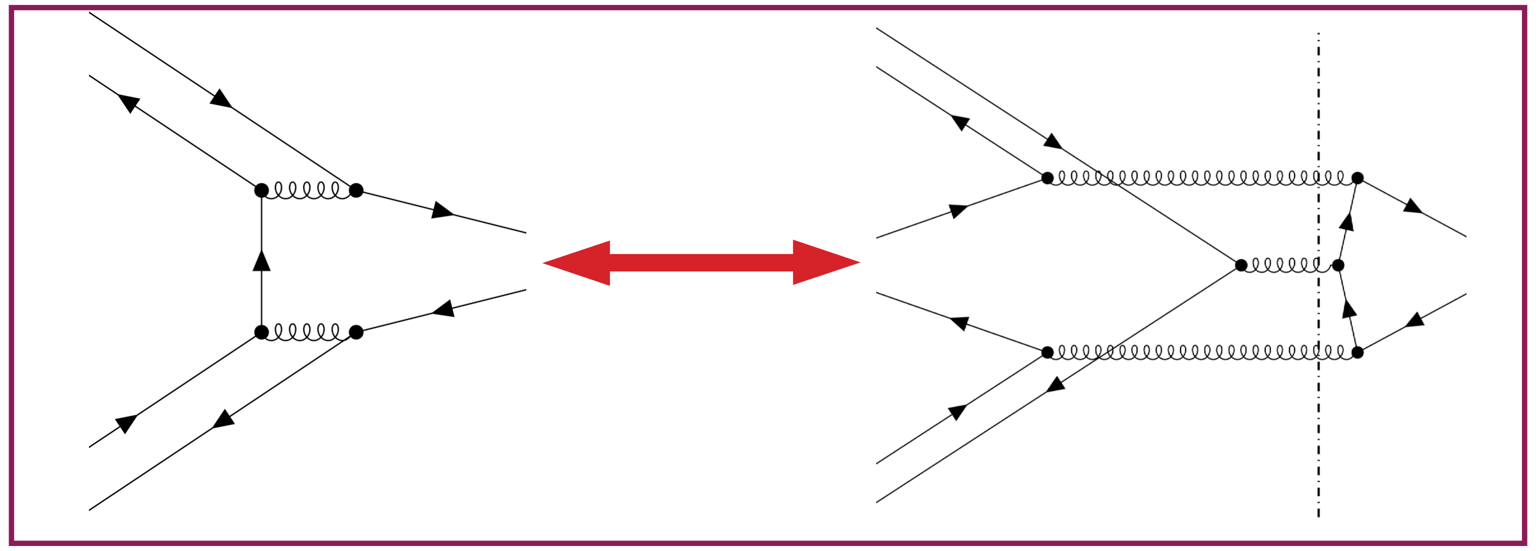
Modern Physics Letters A
Vol. 32, No. 4 (2017) 1750025 (18 pages)
© World Scientific Publishing Company
DOI: 10.1142/S0217732317500250

Table 5. Expected molecular states with the structure $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$.

| $I^G(J^P)$ | Name | Composition | Co-produced particles (Threshold, GeV/$c^2$) | Decay channels |
|---|---|---|---|---|
| $1^+(1^+)$ | $Z_b$ | $B\bar{B}^*$ | $\pi$ [10.75] | $\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$ |
| $1^+(1^+)$ | $Z_b'$ | $B^*\bar{B}^*$ | $\pi$ [10.79] | $\Upsilon(nS)\pi$, $h_b(nP)\pi$, $\eta_b(nS)\rho$ |
| $1^-(0^+)$ | $W_{b0}$ | $B\bar{B}$ | $\rho$ [11.34], $\gamma$ [10.56] | $\Upsilon(nS)\rho$, $\eta_b(nS)\pi$ |
| $1^-(0^+)$ | $W_{b0}'$ | $B^*\bar{B}^*$ | $\rho$ [11.43], $\gamma$ [10.65] | $\Upsilon(nS)\rho$, $\eta_b(nS)\pi$ |
| $1^-(1^+)$ | $W_{b1}$ | $B\bar{B}^*$ | $\rho$ [11.38], $\gamma$ [10.61] | $\Upsilon(nS)\rho$ |
| $1^-(2^+)$ | $W_{b2}$ | $B^*\bar{B}^*$ | $\rho$ [11.43], $\gamma$ [10.65] | $\Upsilon(nS)\rho$ |
| $0^-(1^+)$ | $X_{b1}$ | $B\bar{B}^*$ | $\eta$ [11.15] | $\Upsilon(nS)\eta$, $\eta_b(nS)\omega$ |
| $0^-(1^+)$ | $X_{b1}'$ | $B^*\bar{B}^*$ | $\eta$ [11.20] | $\Upsilon(nS)\eta$, $\eta_b(nS)\omega$ |
| $0^+(0^+)$ | $X_{b0}$ | $B\bar{B}$ | $\omega$ [11.34], $\gamma$ [10.56] | $\Upsilon(nS)\omega$, $\eta_b(nS)\eta$ |
| $0^+(0^+)$ | $X_{b0}'$ | $B^*\bar{B}^*$ | $\omega$ [11.43], $\gamma$ [10.65] | $\Upsilon(nS)\omega$, $\eta_b(nS)\eta$ |
| $0^+(1^+)$ | $X_b$ | $B\bar{B}^*$ | $\omega$ [11.39], $\gamma$ [10.61] | $\Upsilon(nS)\omega$ |
| $0^+(2^+)$ | $X_{b2}$ | $B^*\bar{B}^*$ | $\omega$ [11.43], $\gamma$ [10.65] | $\Upsilon(nS)\omega$ |

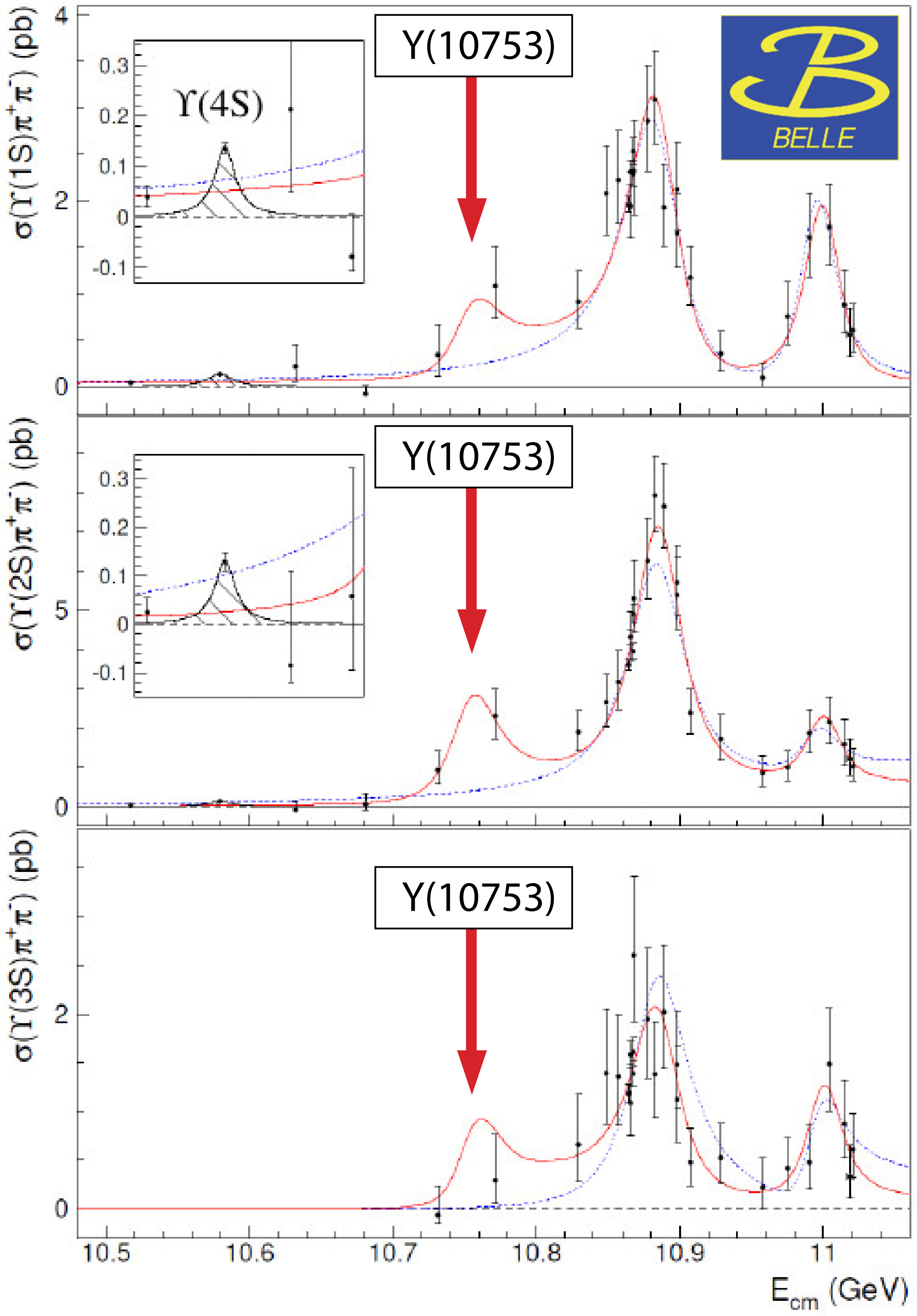
# $\Upsilon(10753)$ (a.k.a. $Y(10753)$) and More $Y$ Matters



New important measurements in the bottom sector from Belle II

# Observation of a New Structure in Energy Scan Between 10.52 and 11.02 GeV (Belle)




## Investigation inspired/motivated by the the Y(4260) analyses

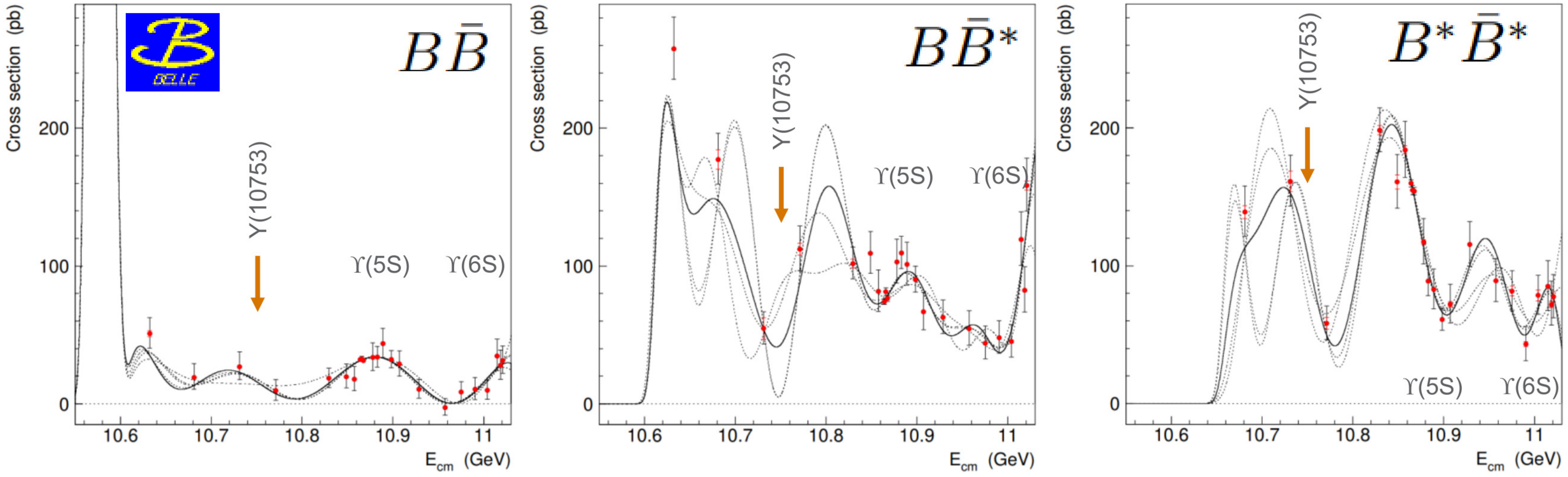
$$e^+e^- \to \Upsilon(nS)\pi^+\pi^- \ (n = 1, 2, 3)$$

**JHEP 10 (2019) 220**

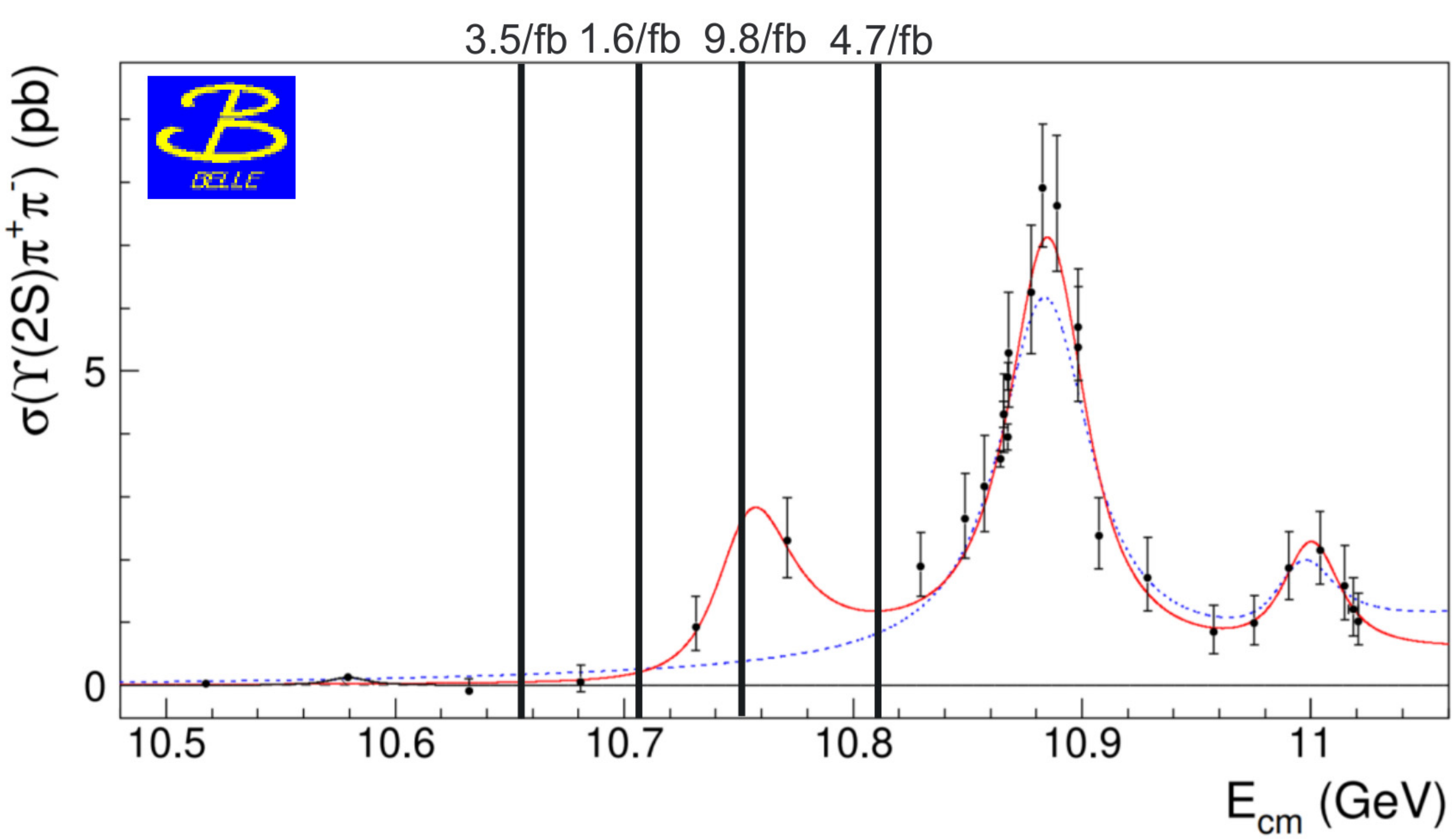
The new structure could have a resonant origin and correspond to a signal for the not yet observed $\Upsilon(3D)$ state provided $S-D$ mixing is enhanced [8], or an exotic state, e.g. a compact tetraquark [9] or hadrobottomonium [10]. It could also be a non-resonant effect due to some complicated rescattering. Information on the cross section energy dependence for more channels, with both hidden and open $b$ flavor, is needed to clarify the nature of the new structure.

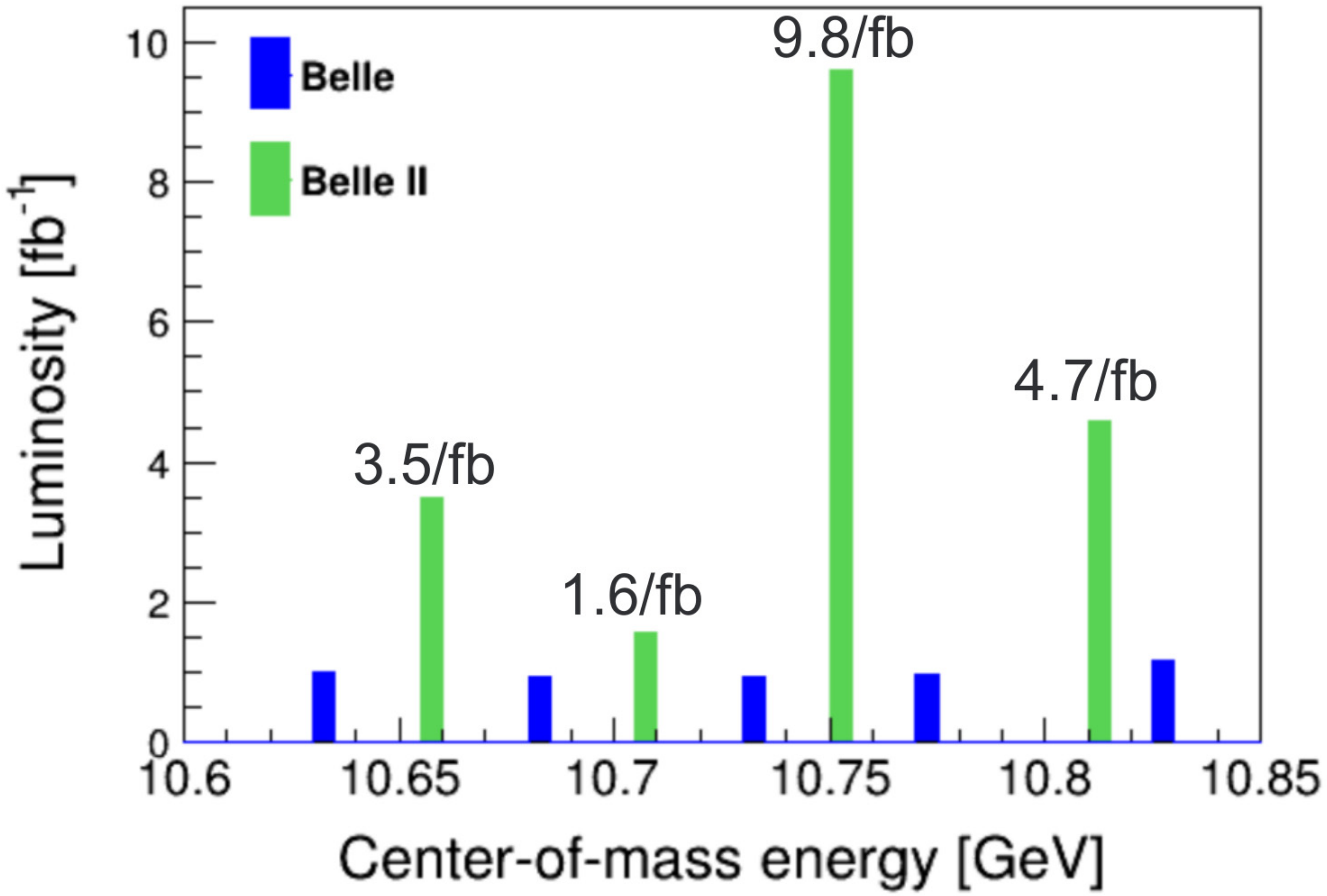
The original analysis was followed by the cross section measurements using seven points in the energy scan below $\Upsilon(5S)$ with $\sim 1\text{fb}^{-1}$ of data.

**JHEP 06 (2021) 137**



# Belle II Energy Scan / Nov. 2021 / Additional High Statistics Data Points




PHYSICAL REVIEW LETTERS **130,** 091902 (2023)

**Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and Search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV**

The first results from Nov. 2021 Belle II energy scan!

$\sqrt{s}$ = 10.701, 10.745, and 10.805 GeV, corresponding to 1.6, 9.8, and 4.7 $fb^{-1}$ of integrated luminosity

# Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and Search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

We study the processes $e^+e^- \to \omega\chi_{bJ}(1P)$ ($J = 0$, 1, or 2) using samples at center-of-mass energies $\sqrt{s} = 10.701$, 10.745, and 10.805 GeV, corresponding to 1.6, 9.8, and 4.7 fb$^{-1}$ of integrated luminosity, respectively. These data were collected with the Belle II detector during special operations of the SuperKEKB collider above the $\Upsilon(4S)$ resonance. We report the first observation of $\omega\chi_{bJ}(1P)$ signals at $\sqrt{s} = 10.745$ GeV. By combining Belle II data with Belle results at $\sqrt{s} = 10.867$ GeV, we find energy dependencies of the Born cross sections for $e^+e^- \to \omega\chi_{b1,b2}(1P)$ to be consistent with the shape of the $\Upsilon(10753)$ state. These data indicate that the internal structures of the $\Upsilon(10753)$ and $\Upsilon(10860)$ states may differ. Including data at $\sqrt{s} = 10.653$ GeV, we also search for the bottomonium equivalent of the $X(3872)$ state decaying into $\omega\Upsilon(1S)$. No significant signal is observed for masses between 10.45 and 10.65 GeV/$c^2$.

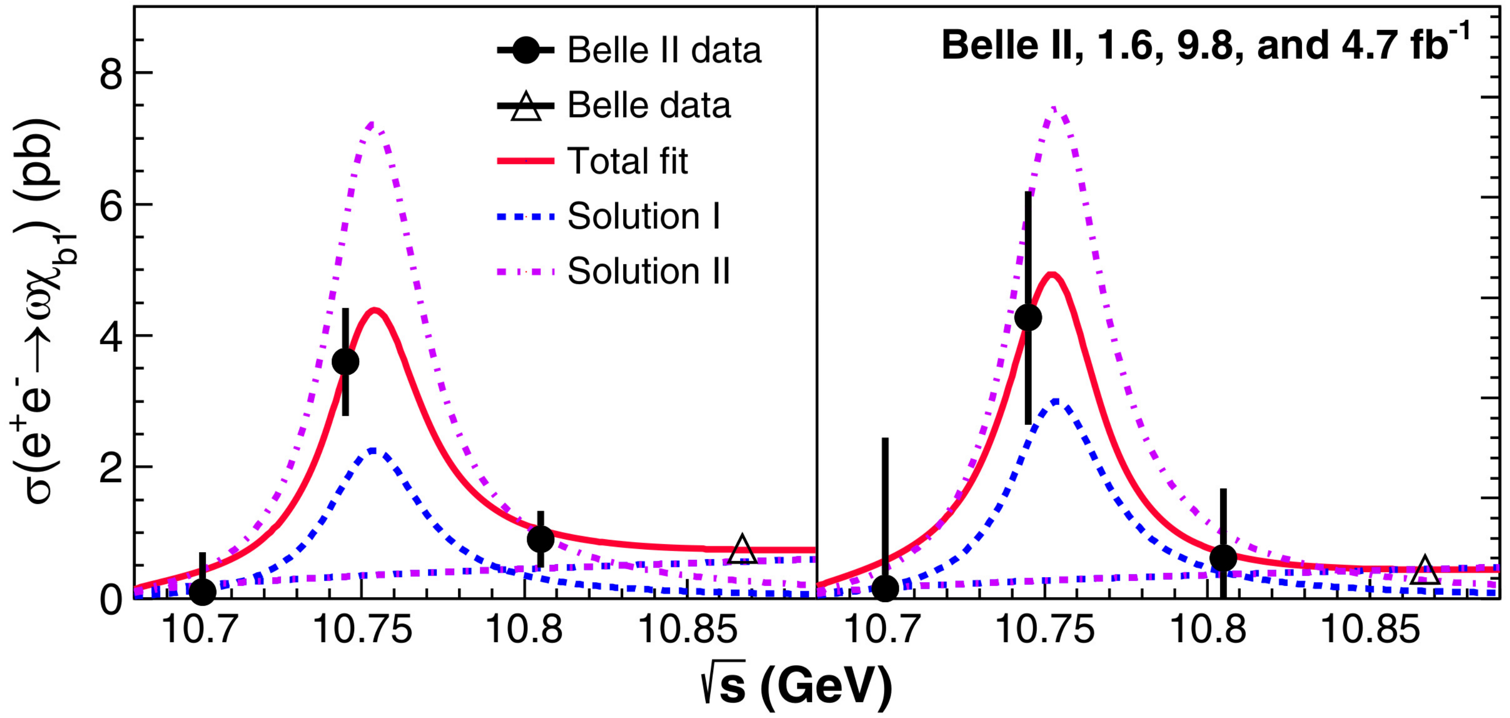



FIG. 2. Energy dependence of the Born cross sections for (left) $e^+e^- \to \omega\chi_{b1}$ and (right) $e^+e^- \to \omega\chi_{b2}$. Circles show the measurements reported here, triangles are the results of the Belle experiment [41]. Error bars represent combined statistical and systematic uncertainties. Curves show the fit results and various components of the fit function.

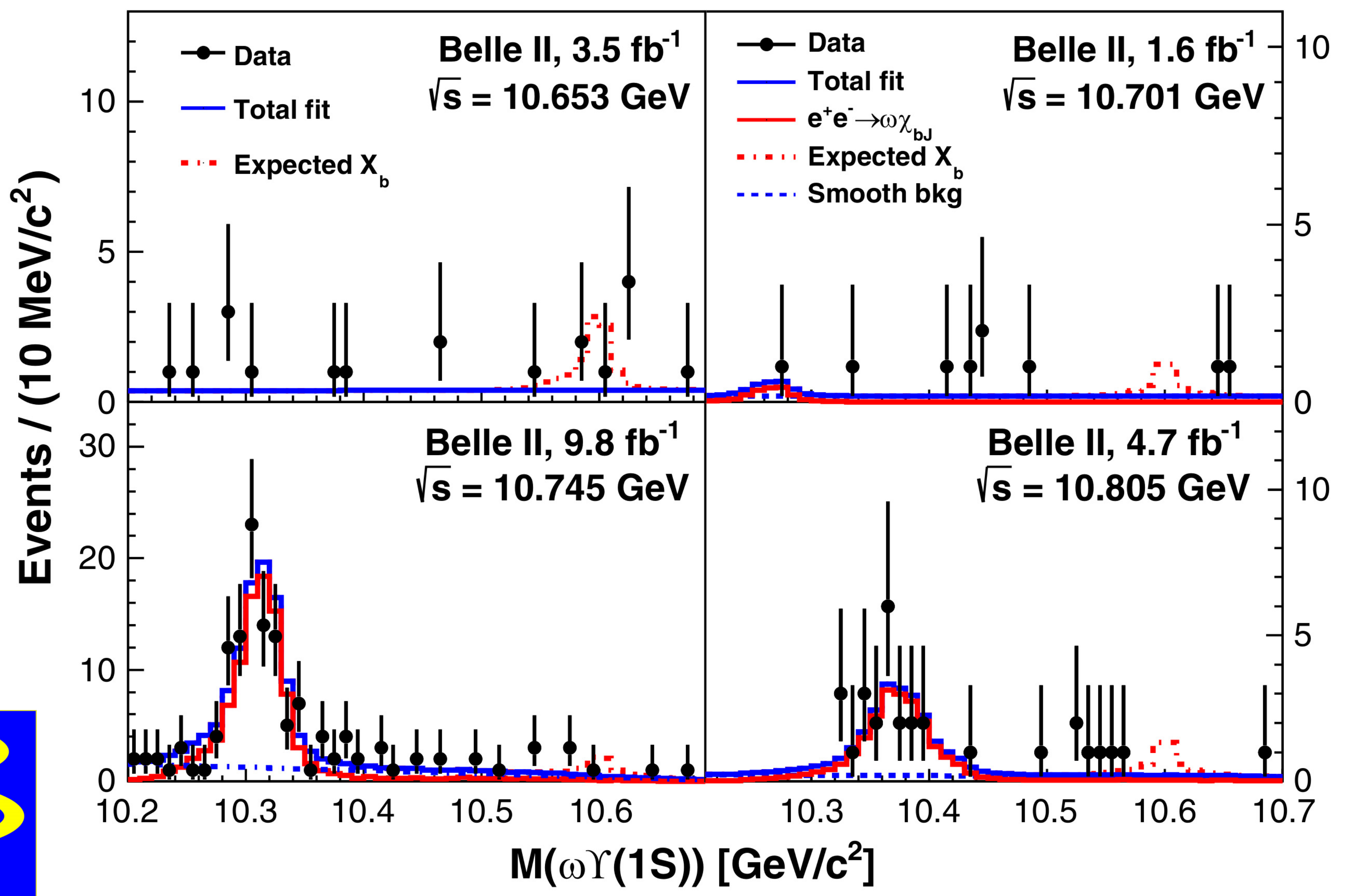



FIG. 3. Distributions of $\omega\Upsilon(1S)$ mass from data at $\sqrt{s} =$ 10.653, 10.701, 10.745, and 10.805 GeV. The red dash-dotted histograms are from simulated events $e^+e^- \to \gamma X_b[\to\omega\Upsilon(1S)]$ with the $X_b$ mass fixed at 10.6 GeV/$c^2$ and yields fixed at the upper limit values.

Belle II

PHYSICAL REVIEW LETTERS **130,** 091902 (2023)

# Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and Search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

This analysis shows that the $e^+e^- \to \omega\chi_{bJ}$ process observed near $\Upsilon(10\,860)$ by Belle could be due to the tail of the $\Upsilon(10\,753)$. The large difference between the small value of the $\omega\chi_{bJ}$ to $\pi^+\pi^-\Upsilon(nS)$ production rate at the $\Upsilon(10\,860)$ and the value at the $\Upsilon(10\,753)$ may indicate different internal structures for these two states, which otherwise have the same quantum numbers and are only 110 MeV/$c^2$ apart.

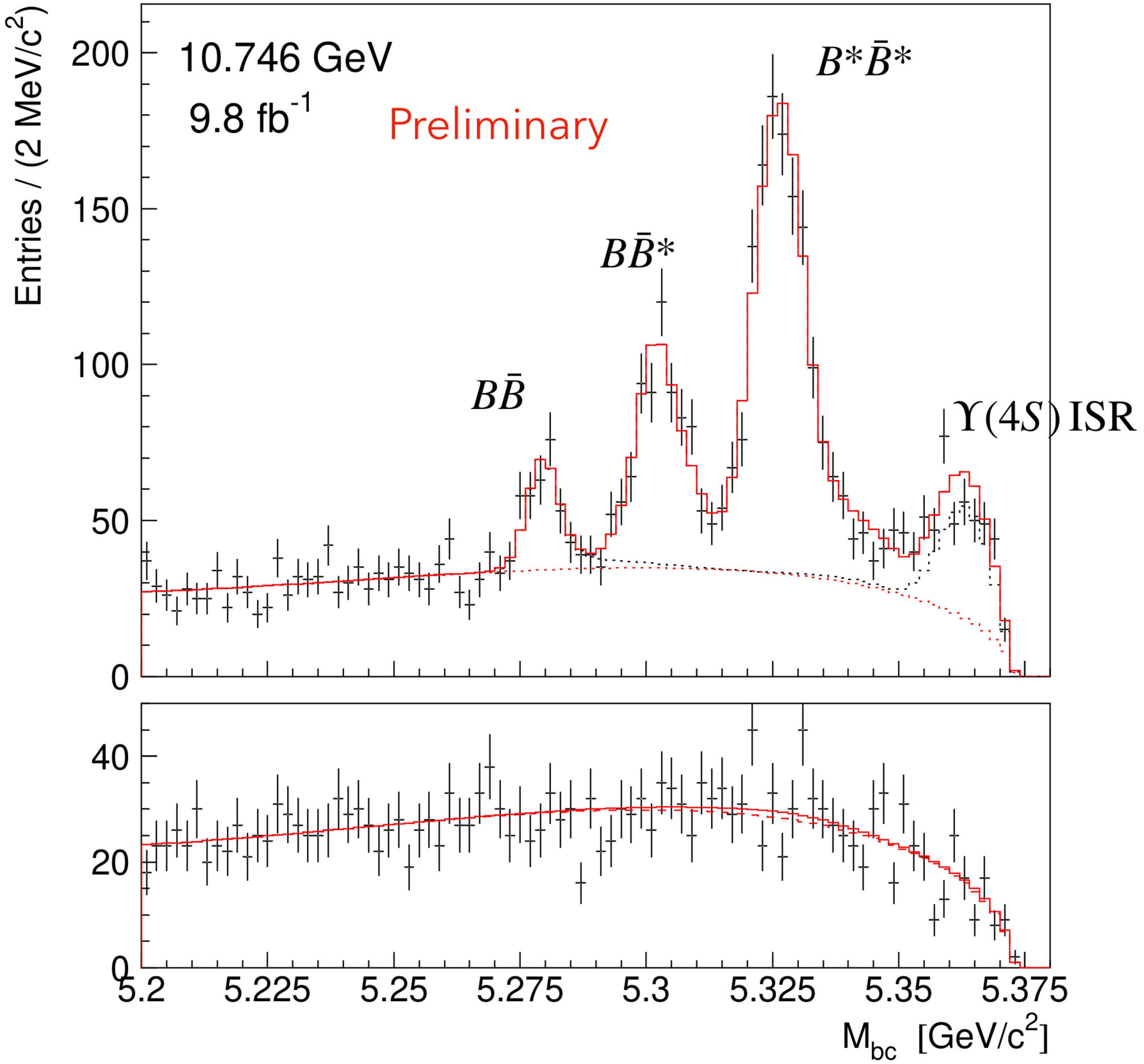
The observed ratio $\sigma_B(e^+e^- \to \omega\chi_{b1})/\sigma_B(e^+e^- \to \omega\chi_{b2}) = 1.3 \pm 0.6$ at $\sqrt{s} = 10.745$ GeV, where the statistical uncertainties and all the uncommon systematic uncertainties are included, contradicts the expectation for a pure $D$-wave bottomonium state of 15 [60,61]. There is also a $1.8\sigma$ difference with the prediction for a $S$-$D$-mixed state of 0.2 [8].

# Measurement of the energy dependence of the $e^+e^- \to B\bar{B}, B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections at Belle II

As shown at Moriond'23

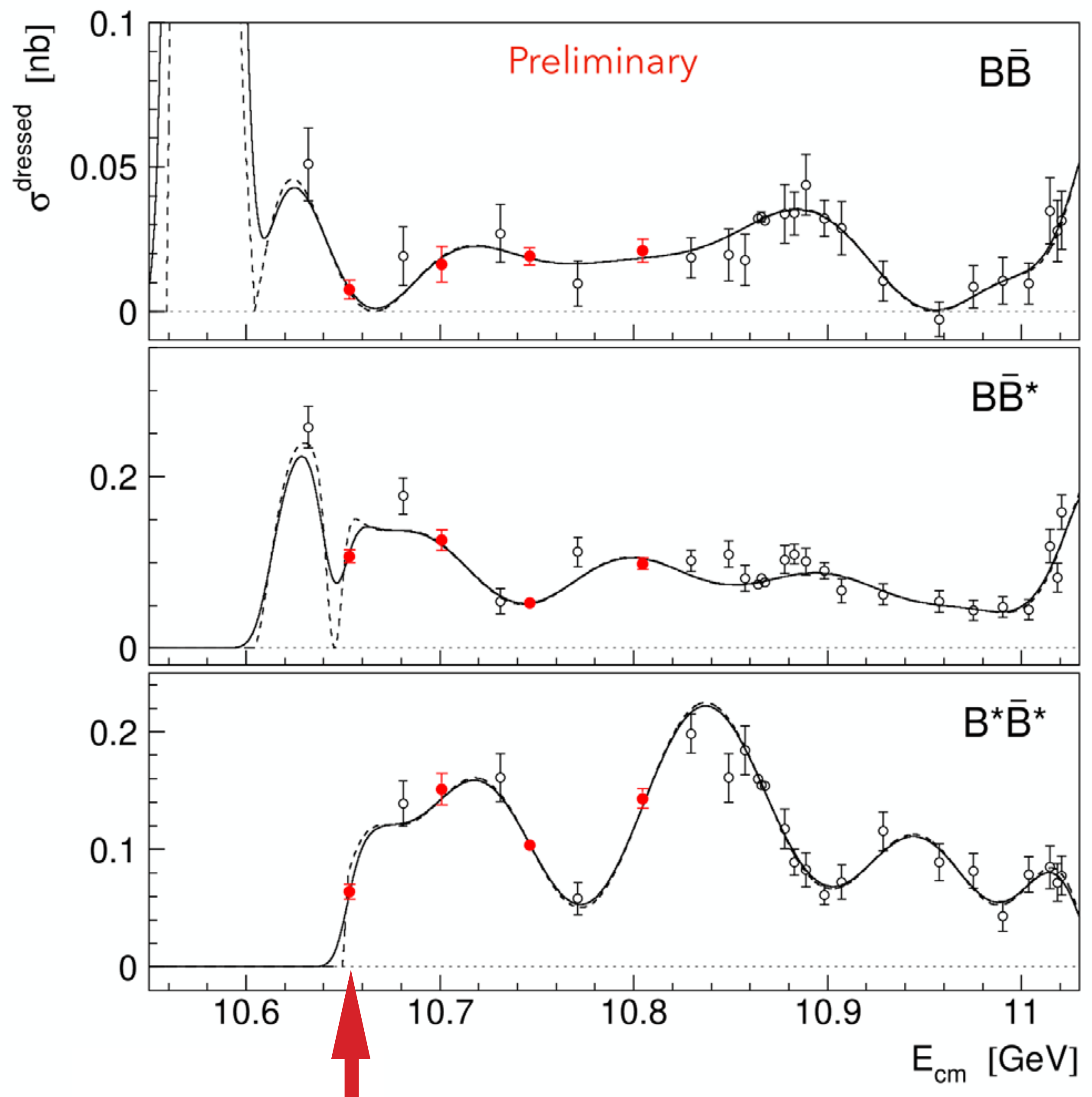
- More points in energy scan further our understanding of this energy region
- Full Event Interpretation (FEI) method:
  - fully reconstruct one $B$ in hadronic decays
  - Use beam energy-constrained $B$ mass, $M_{\rm bc}$, to identify different signals:

$$M_{\rm bc} = \sqrt{(E_{\rm cm}/2)^2 - p_B^2}$$



# Measurement of the energy dependence of the $e^+e^- \to B\bar{B}, B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections at Belle II

exclusive cross-section



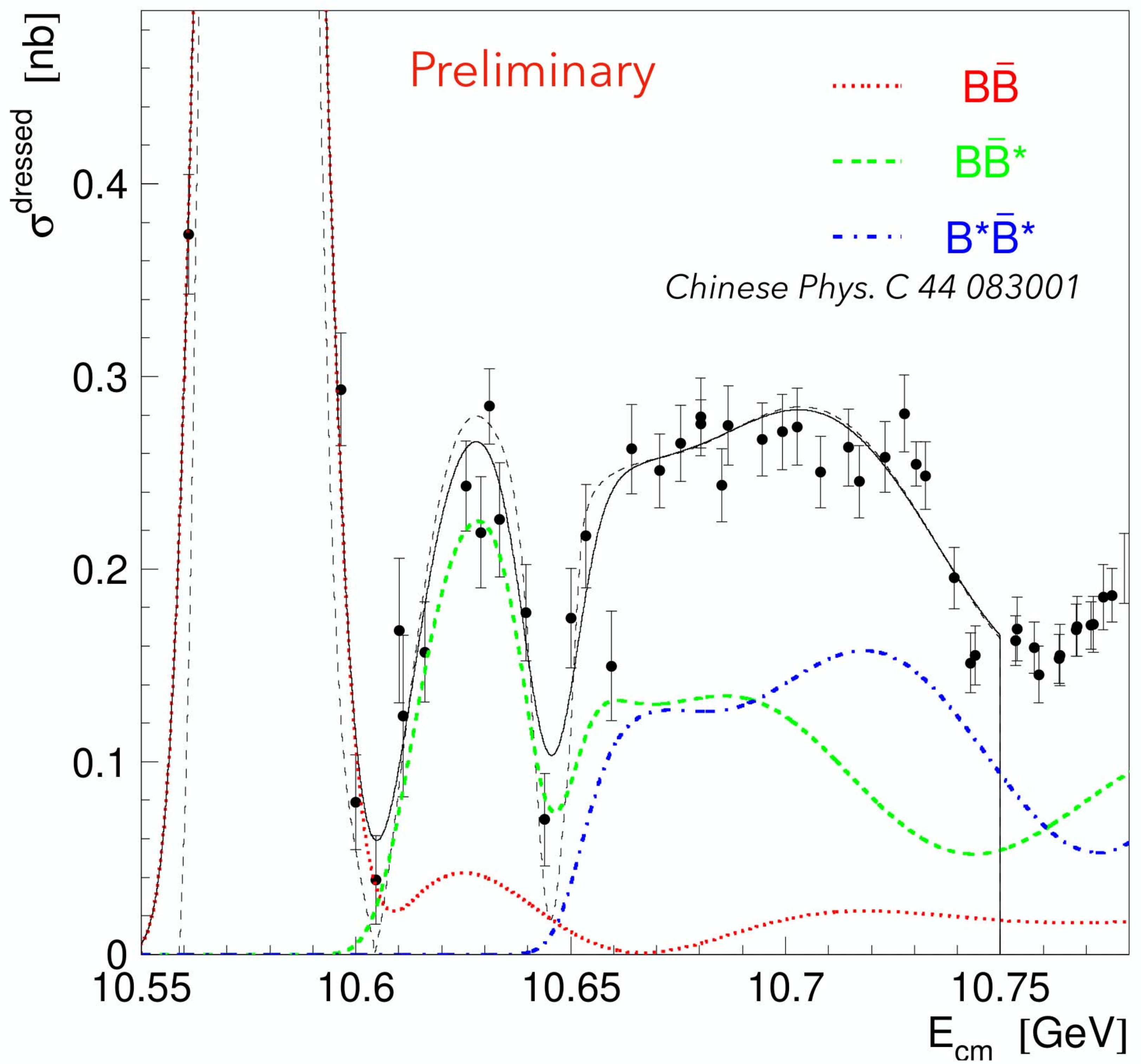

Belle

+

Belle II

Note the surprisingly rapid growth of the $B^*\bar{B}^*$ cross section just 3 MeV above the $B^*\bar{B}^*$ threshold (beam energy spread 5 MeV).
This could be explained by a resonance or a bound state in this region.
A similar phenomenon of a narrow resonance realizes near the $D^*\bar{D}^*$ threshold.

total cross-section




Resuts of a simultaneous fit to exclusive and total cross sections

ABSTRACT: We report the first measurement of the inclusive $e^+e^- \to b\bar{b} \to D_s^\pm X$ and $e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X$ cross sections in the energy range from 10.63 to 11.02 GeV. Based on these results, we determine $\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X)$ and $\sigma(e^+e^- \to B\bar{B} X)$ in the same energy range. We measure the fraction of $B_s^0$ events at $\Upsilon(10860)$ to be $f_s = (22.0^{+2.0}_{-2.1})\%$. We determine also the ratio of the $B_s^0$ inclusive branching fractions $\mathcal{B}(B_s^0 \to D^0/\bar{D}^0 X)/\mathcal{B}(B_s^0 \to D_s^\pm X) = 0.416 \pm 0.017 \pm 0.090$. The results are obtained using the data collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider.

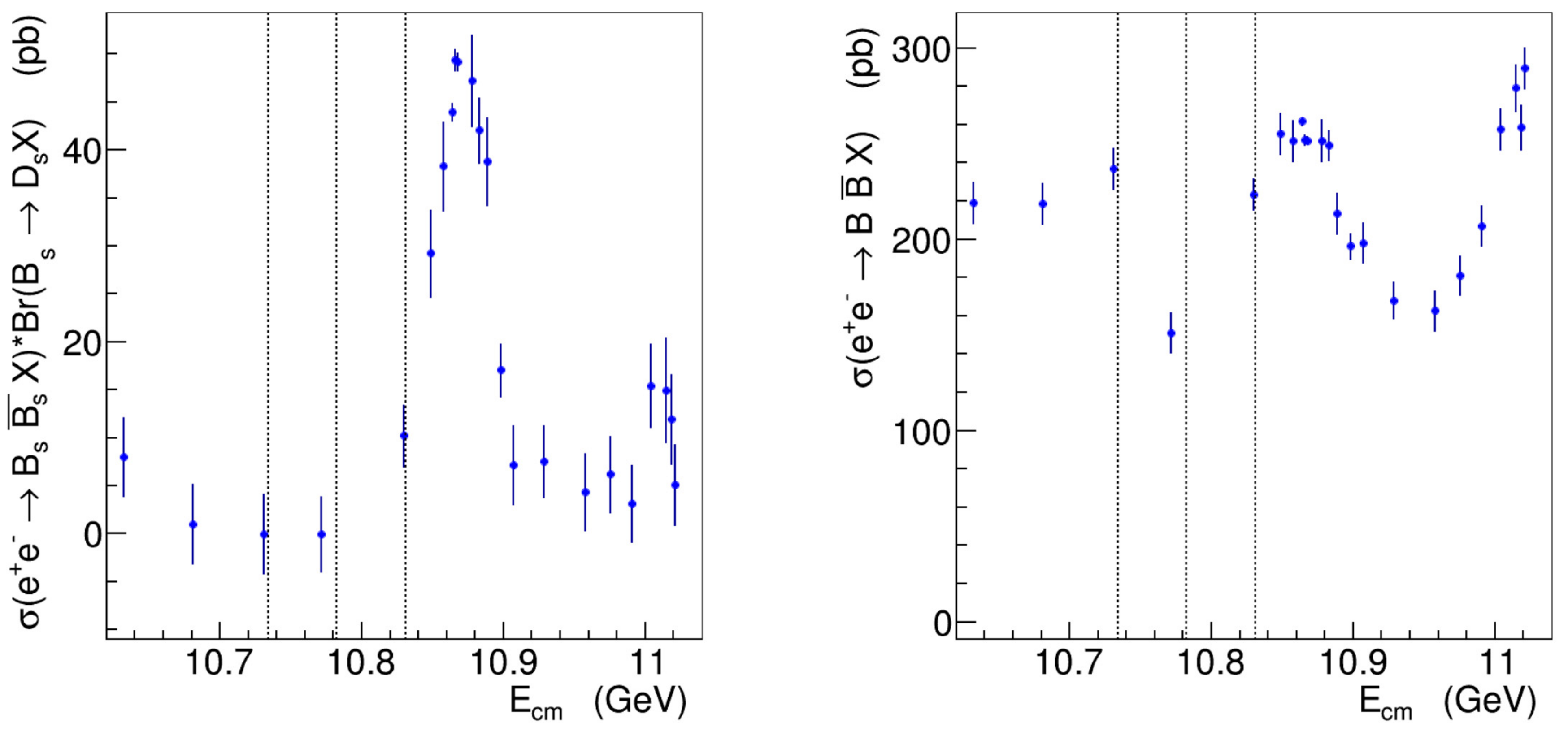



**Figure 11**. The energy dependence of the product $\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X) \cdot \mathcal{B}(B_s^0 \to D_s^\pm X)$ (left) and the $\sigma(e^+e^- \to B\bar{B} X)$ (right). Shown are statistical uncertainties calculated using Eq. (6.1) based on the statistical uncertainties of $U = \sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)$ and $W = \sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X)$. The dashed lines indicate the $B_s^0\bar{B}_s^0$, $B_s^0\bar{B}_s^*$ and $B_s^*\bar{B}_s^*$ thresholds.

Hadronic states in the bottomonium spectrum lying above the open-bottom threshold demonstrate properties at odds with the standard quark model scheme. In particular, the structures $Z(10610)$ and $Z(10650)$, observed by Belle in 2012 [1], are charged and contain at least four quarks. The mass splittings for the high-lying vector bottomonia do not follow the quark model expectations either. The rates of their transitions to lower bottomonia with the emission of light hadrons are much higher compared to the expectations for ordinary bottomonium, in violation of the Okubo-Zweig-Iizuka rule [2, 3], and their $\eta$ transitions are not suppressed relative to the dipion transitions, which violates Heavy Quark Spin Symmetry [4, 5]. For a review, see, e.g. Ref. [6]. Studies of various cross sections above the open-bottom threshold can help us to understand the properties of the resonances lying in this energy region.

$$
\begin{aligned}
\mathcal{B}(B \to D_s^\pm X) &= (11.28 \pm 0.03 \pm 0.43)\%,\\
\mathcal{B}(B \to D^0/\bar{D}^0 X) &= (66.63 \pm 0.04 \pm 1.77)\%,\\
\mathcal{B}(\Upsilon(5S) \to D_s^\pm X) &= (44.7 \pm 0.3 \pm 2.7)\%,\\
\mathcal{B}(\Upsilon(5S) \to D^0/\bar{D}^0 X) &= (111.7 \pm 0.5 \pm 6.0)\%.
\end{aligned}
$$

We have measured the inclusive cross sections $\sigma(e^+e^- \to b\bar{b} \to D_s^\pm X)$, $\sigma(e^+e^- \to b\bar{b} \to D^0/\bar{D}^0 X)$, $\sigma(e^+e^- \to B\bar{B} X)$ and the product $\sigma(e^+e^- \to B_s^0\bar{B}_s^0 X) \cdot \mathcal{B}(B_s^0 \to D_s^\pm X)$ in the energy range from 10.63 to 11.02 GeV. Results are presented in Table 6. The energy dependence of the $e^+e^- \to B_s^0\bar{B}_s^0 X$ cross section shows a clear peak near the $\Upsilon(5S)$ energy and a hint of a peak near the $\Upsilon(6S)$. The obtained results can be used in a combined analysis of the data in various final states within coupled-channel approaches to investigate the nature and properties of the bottomonium and bottomonium-like states lying above the $B\bar{B}$ threshold.

# First search for the $\eta_{c2}(1D)$ in $B$ decays at Belle

JHEP05(2020)034

ABSTRACT: The first dedicated search for the $\eta_{c2}(1D)$ is carried out using the decays $B^+ \to \eta_{c2}(1D)K^+$, $B^0 \to \eta_{c2}(1D)K^0_S$, $B^0 \to \eta_{c2}(1D)\pi^- K^+$, and $B^+ \to \eta_{c2}(1D)\pi^+ K^0_S$ with $\eta_{c2}(1D) \to h_c\gamma$. No significant signal is found. For the $\eta_{c2}(1D)$ mass range between 3795 and 3845 MeV/$c^2$, the branching-fraction upper limits are determined to be $\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 3.7 \times 10^{-5}$, $\mathcal{B}(B^0 \to \eta_{c2}(1D)K^0_S) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 3.5 \times 10^{-5}$, $\mathcal{B}(B^0 \to \eta_{c2}(1D)\pi^- K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 1.0 \times 10^{-4}$, and $\mathcal{B}(B^+ \to \eta_{c2}(1D)\pi^+ K^0_S) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) < 1.1 \times 10^{-4}$ at 90% C.L. The analysis is based on the 711 fb$^{-1}$ data sample collected on the $\Upsilon(4S)$ resonance by the Belle detector, which operated at the KEKB asymmetric-energy $e^+e^-$ collider.

| Channel | Mass, MeV/$c^2$ | Yield | Local significance |
|---|---|---|---|
| $B^+ \to \eta_{c2}(1D)K^+$ | $3809.6 \pm 4.3$ | $3.3 \pm 3.0$ | $1.3\sigma$ |
| $B^0 \to \eta_{c2}(1D)K^0_S$ | $3814.4 \pm 2.7$ | $2.7 \pm 2.3$ | $1.5\sigma$ |
| $B^+ \to \eta_{c2}(1D)K^+$ and $B^0 \to \eta_{c2}(1D)K^0_S$ | $3821.8 \pm 4.4$ | $1.6 \pm 3.2$ | $0.7\sigma$ |
| $B^0 \to \eta_{c2}(1D)\pi^- K^+$ | $3797.0 \pm 1.6$ | $9.4 \pm 5.1$ | $2.1\sigma$ |
| $B^+ \to \eta_{c2}(1D)\pi^+ K^0_S$ | $3842.3 \pm 3.4$ | $2.6 \pm 3.1$ | $1.0\sigma$ |

The $1^1D_2$ charmonium state, the $\eta_{c2}(1D)$, has not been observed experimentally yet. Various potential models [2, 6–8] predict that the masses of the $\eta_{c2}(1D)$ and $\psi_2(1D)$ are very close to each other (see also the summary table in ref. [9]). While the predicted $\eta_{c2}(1D)$ mass can vary by up to 70 MeV/$c^2$ between models, the typical value of the mass difference between the $\eta_{c2}(1D)$ and $\psi_2(1D)$ in a given model is about 2 MeV/$c^2$. Lattice calculations [10, 11] also find that the $\eta_{c2}(1D)$ and $\psi_2(1D)$ masses are close to each other. The mass difference calculated from the results of ref. [11] is $m_{\eta_{c2}(1D)} - m_{\psi_2(1D)} = 9 \pm 10$ MeV/$c^2$ assuming uncorrelated uncertainties, where the uncertainty is statistical only.

In addition, the hyperfine splitting of the 1D charmonium states is expected to be small; one can use the known masses of the $1^3D_J$ states to estimate the expected $\eta_{c2}(1D)$ mass: $m_{\eta_{c2}(1D)} \approx (3m_{\psi(3770)} + 5m_{\psi_2(1D)} + 7m_{X(3842)})/15 \approx 3822$ MeV/$c^2$. Thus, the $\eta_{c2}(1D)$ mass is expected to be around 3820 MeV/$c^2$, which is below the $D^*\bar{D}$ threshold. The decay $\eta_{c2}(1D) \to D\bar{D}$ is forbidden by parity conservation. The $\eta_{c2}(1D)$ remains the only unobserved conventional charmonium state that does not have open-charm decays.

The measured upper limit for $\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma)$ is consistent with the existing theoretical prediction of $(1.72 \pm 0.42) \times 10^{-5}$ [15]. A data sample of about 10 ab$^{-1}$ is required to reach the expected value of branching-fraction product $\mathcal{B}(B^+ \to \eta_{c2}(1D)K^+) \times \mathcal{B}(\eta_{c2}(1D) \to h_c\gamma) \sim 1.0 \times 10^{-5}$. Thus, the Belle II experiment should be able to observe the $\eta_{c2}(1D)$ or exclude the predicted branching fraction in the future [36].

# Observation of a vector charmoniumlike state in $e^+e^- \to D_s^+ D_{s1}(2536)^- + \text{c.c.}$

Using a data sample of 921.9 $\text{fb}^{-1}$ collected with the Belle detector, we study the process of $e^+e^- \to D_s^+ D_{s1}(2536)^- + \text{c.c.}$ via initial-state radiation. We report the first observation of a vector charmoniumlike state decaying to $D_s^+ D_{s1}(2536)^- + \text{c.c.}$ with a significance of $5.9\sigma$, including systematic uncertainties. The measured mass and width are $(4625.9^{+6.2}_{-6.0}(\text{stat}) \pm 0.4(\text{syst}))\ \text{MeV}/c^2$ and $(49.8^{+13.9}_{-11.5}(\text{stat}) \pm 4.0(\text{syst}))\ \text{MeV}$, respectively. The product of the $e^+e^- \to D_s^+ D_{s1}(2536)^- + \text{c.c.}$ cross section and the branching fraction of $D_{s1}(2536)^- \to \bar{D}^{*0} K^-$ is measured from the $D_s \bar{D}_{s1}(2536)$ threshold to 5.59 GeV.

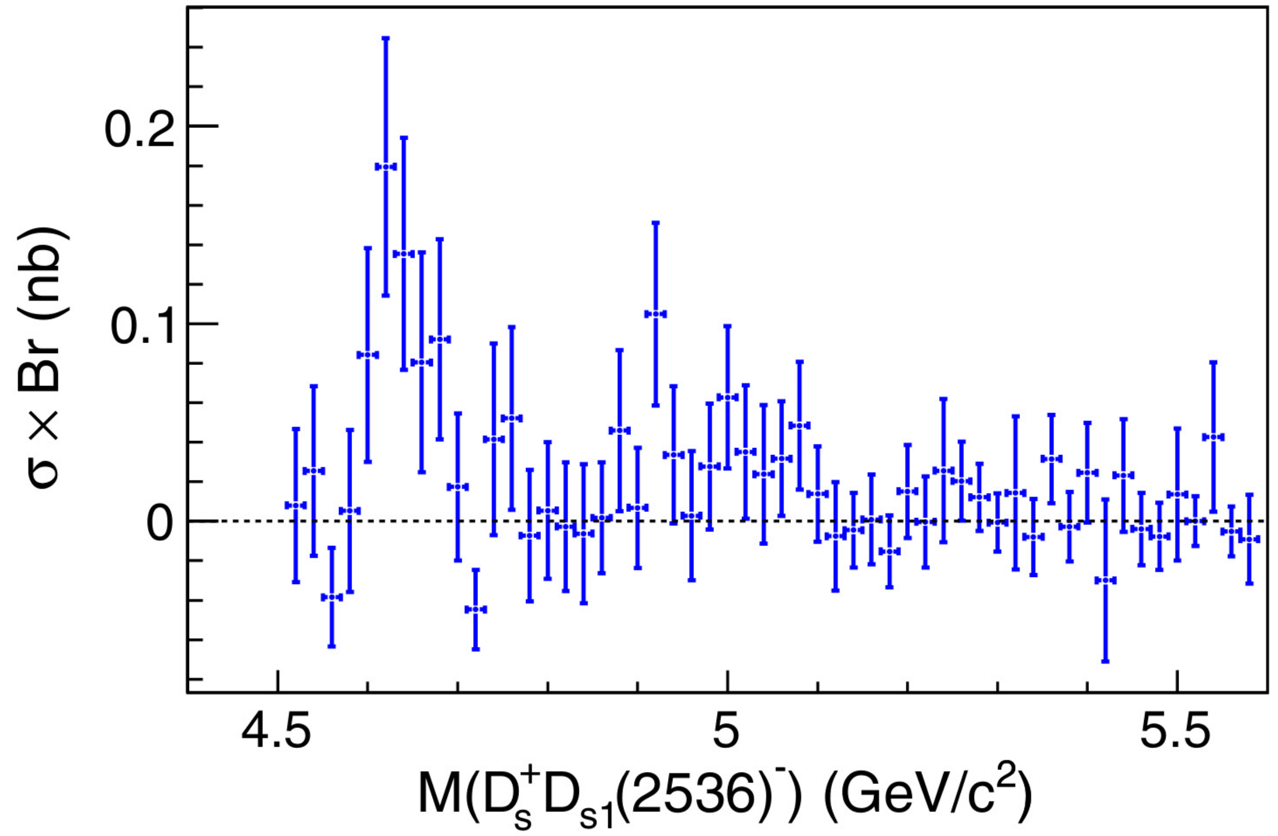



FIG. 3. The product of the $e^+e^- \to D_s^+ D_{s1}(2536)^-$ cross section and branching fraction $\mathcal{B}(D_{s1}(2536)^- \to \bar{D}^{*0} K^-)$ as a function of $M(D_s^+ D_{s1}(2536)^-)$; here the statistical and systematic uncertainties are summed in quadrature. Here, the correlated systematic uncertainties from the detection efficiency, branching fraction, and luminosity are not included.

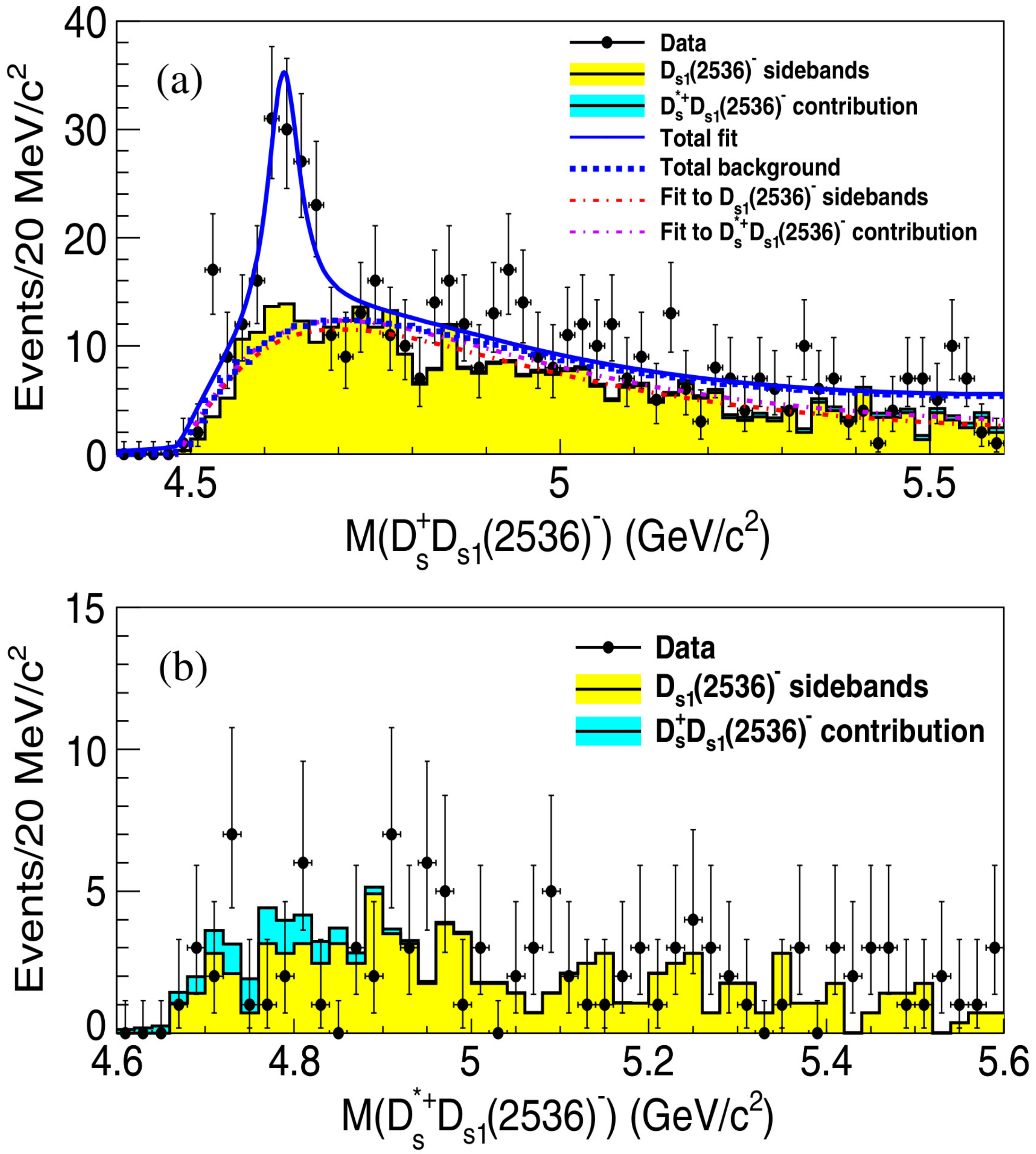



FIG. 2. (a) The $D_s^+ D_{s1}(2536)^-$ invariant mass spectrum for $e^+e^- \to D_s^+ D_{s1}(2536)^-$. (b) The $D_s^{*+} D_{s1}(2536)^-$ invariant mass spectrum for $e^+e^- \to D_s^{*+} D_{s1}(2536)^-$. All the components including those from the fit to the $D_s^+ D_{s1}(2536)^-$ invariant mass spectrum are indicated in the labels and described in the text. Note that the cyan shaded histograms in the top/bottom show the $D_s^+ D_{s1}(2536)^- / D_s^{*+} D_{s1}(2536)^-$ invariant mass spectrum from $D_s^{*+} D_{s1}(2536)^- / D_s^+ D_{s1}(2536)^-$ background contribution after applying the requirements to reconstruct $e^+e^- \to D_s^+ D_{s1}(2536)^- / e^+e^- \to D_s^{*+} D_{s1}(2536)^-$.

PHYSICAL REVIEW D **101,** 091101(R) (2020)

# Evidence for a vector charmoniumlike state in $e^+e^- \to D_s^+ D_{s2}^*(2573)^- + \mathrm{c.c.}$

We report the measurement of $e^+e^- \to D_s^+ D_{s2}^*(2573)^- + \mathrm{c.c.}$ via initial-state radiation using a data sample of an integrated luminosity of 921.9 fb$^{-1}$ collected with the Belle detector at the $\Upsilon(4S)$ and nearby. We find evidence for an enhancement with a $3.4\sigma$ significance in the invariant mass of $D_s^+ D_{s2}^*(2573)^- + \mathrm{c.c.}$ The measured mass and width are $(4619.8^{+8.9}_{-8.0}(\mathrm{stat.}) \pm 2.3(\mathrm{syst.}))$ MeV/$c^2$ and $(47.0^{+31.3}_{-14.8}(\mathrm{stat.}) \pm 4.6(\mathrm{syst.}))$ MeV, respectively. The mass, width, and quantum numbers of this enhancement are consistent with the charmoniumlike state at 4626 MeV/$c^2$ recently reported by Belle in $e^+e^- \to D_s^+ D_{s1}(2536)^- + \mathrm{c.c.}$ The product of the $e^+e^- \to D_s^+ D_{s2}^*(2573)^- + \mathrm{c.c.}$ cross section and the branching fraction of $D_{s2}^*(2573)^- \to \bar{D}^0 K^-$ is measured from $D_s^+ D_{s2}^*(2573)^-$ threshold to 5.6 GeV.

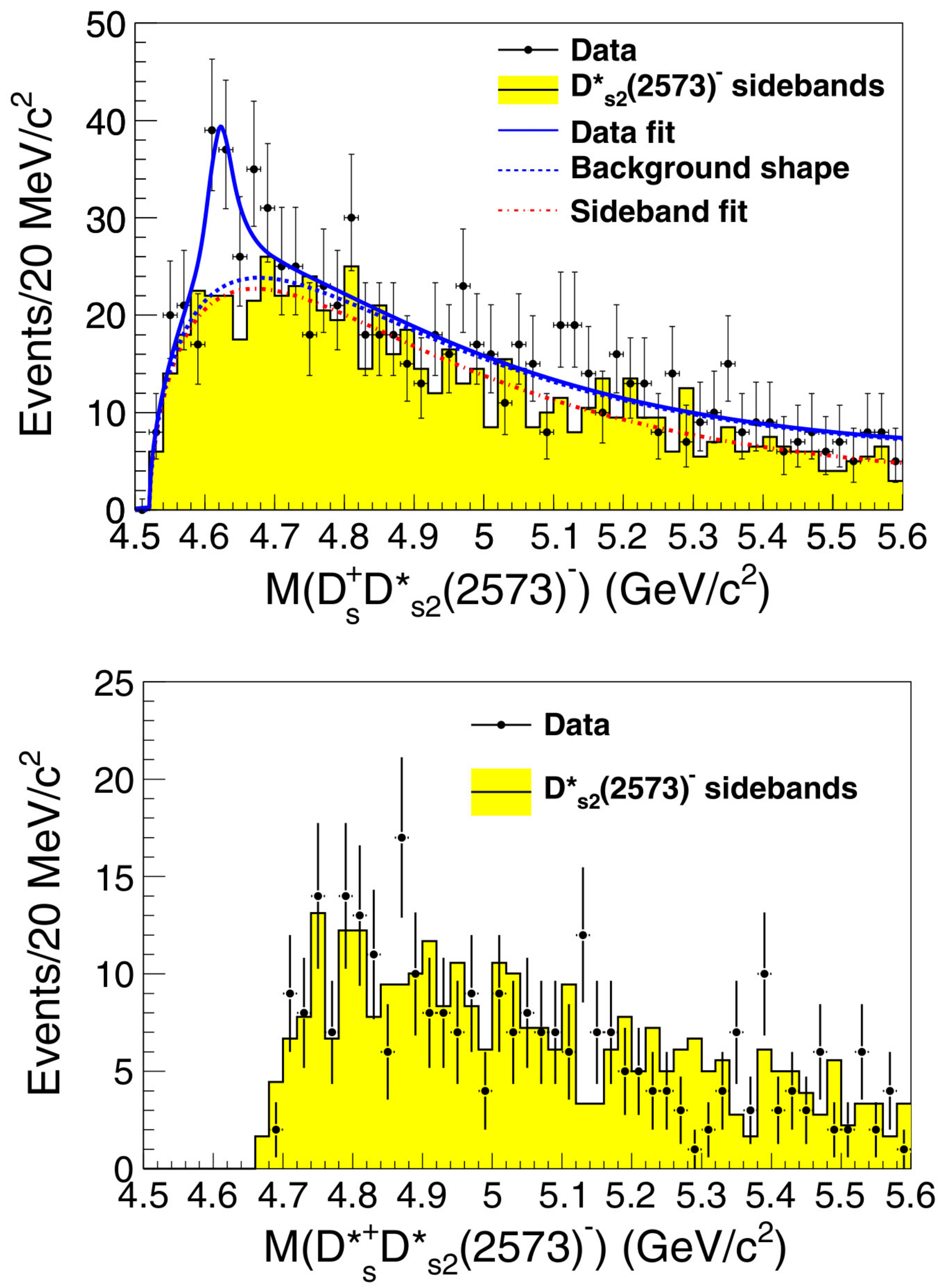



FIG. 3. The $D_s^+ D_{s2}^*(2573)^-$ (top) and $D_s^{*+} D_{s2}^*(2573)^-$ (bottom) invariant mass spectra for $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ and $e^+e^- \to D_s^{*+} D_{s2}^*(2573)^-$. All the components including those from the fit to the $D_s^+ D_{s2}^*(2573)^-$ invariant mass spectrum are indicated in the labels and described in the text.

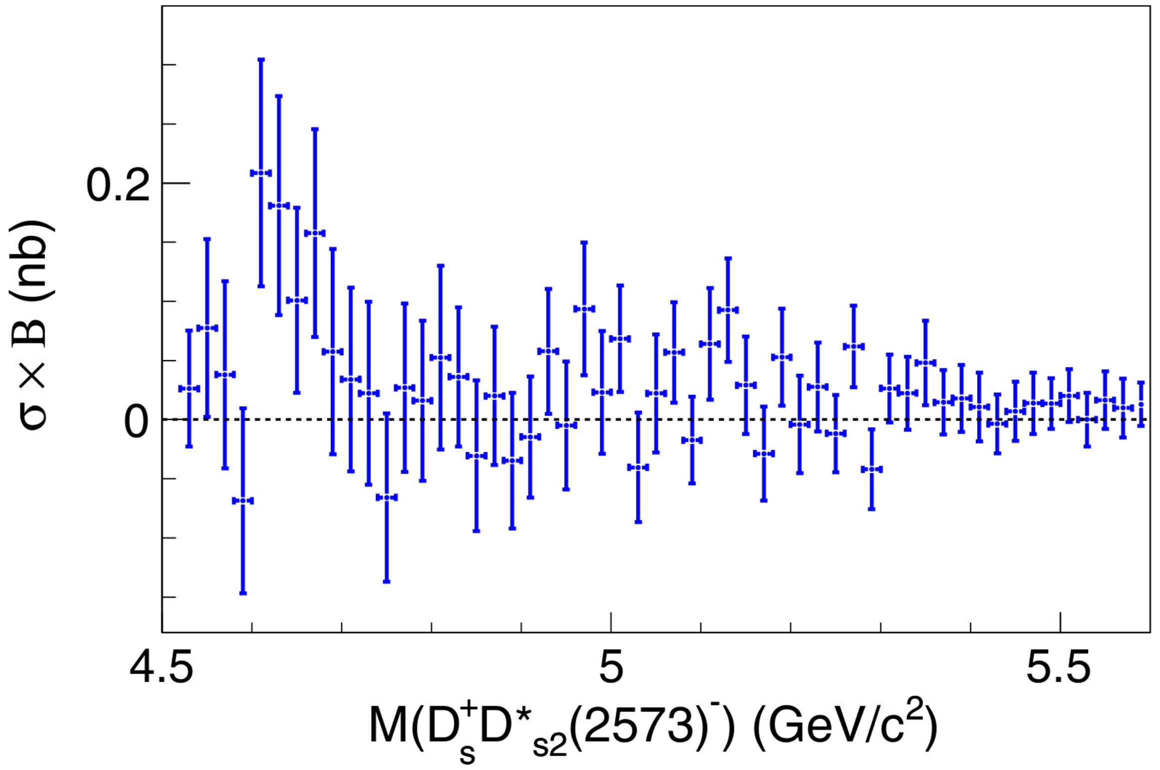
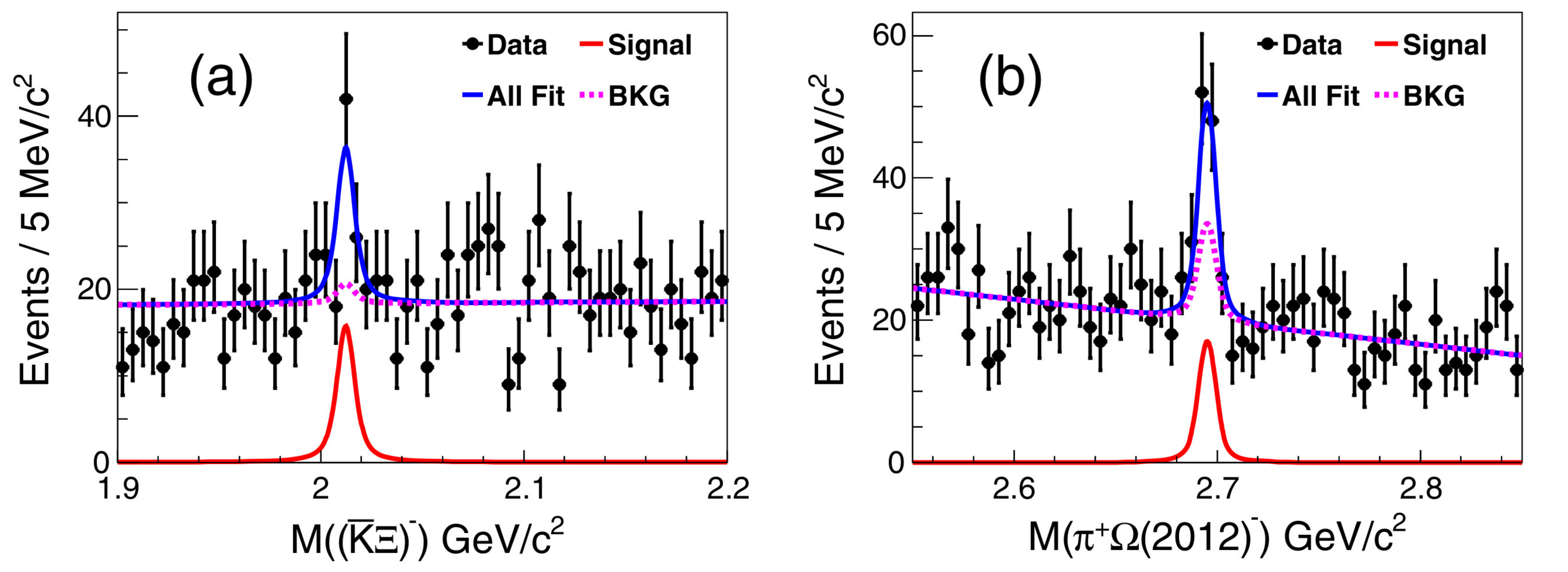



FIG. 4. The product of the $e^+e^- \to D_s^+ D_{s2}^*(2573)^-$ cross section and branching fraction $\mathcal{B}(D_{s2}^*(2573)^- \to \bar{D}^0 K^-)$ as a function of $M(D_s^+ D_{s2}^*(2573)^-)$ with statistical uncertainties only.

PHYSICAL REVIEW D **104,** 052005 (2021)

# Evidence for the decay $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$

Using a data sample of 980 $\mathrm{fb}^{-1}$ collected with the Belle detector operating at the KEKB asymmetric-energy $e^+e^-$ collider, we present evidence for the $\Omega(2012)^-$ in the resonant substructure of $\Omega_c^0 \to \pi^+(\bar{K}\Xi)^-$ ($(\bar{K}\Xi)^- = K^-\Xi^0 + \bar{K}^0\Xi^-$) decays. The significance of the $\Omega(2012)^-$ signal is $4.2\sigma$ after considering the systematic uncertainties. The ratio of the branching fraction of $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^-$ relative to that of $\Omega_c^0 \to \pi^+\Omega^-$ is calculated to be $0.220 \pm 0.059(\mathrm{stat.}) \pm 0.035(\mathrm{syst.})$. The individual ratios of the branching fractions of the two isospin modes are also determined and found to be $\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^-) \times \mathcal{B}(\Omega(2012)^- \to K^-\Xi^0)/\mathcal{B}(\Omega_c^0 \to \pi^+K^-\Xi^0) = (9.6 \pm 3.2(\mathrm{stat.}) \pm 1.8(\mathrm{syst.}))\%$ and $\mathcal{B}(\Omega_c^0 \to \pi^+\Omega(2012)^-) \times \mathcal{B}(\Omega(2012)^- \to \bar{K}^0\Xi^-)/\mathcal{B}(\Omega_c^0 \to \pi^+\bar{K}^0\Xi^-) = (5.5 \pm 2.8(\mathrm{stat.}) \pm 0.7(\mathrm{syst.}))\%$.

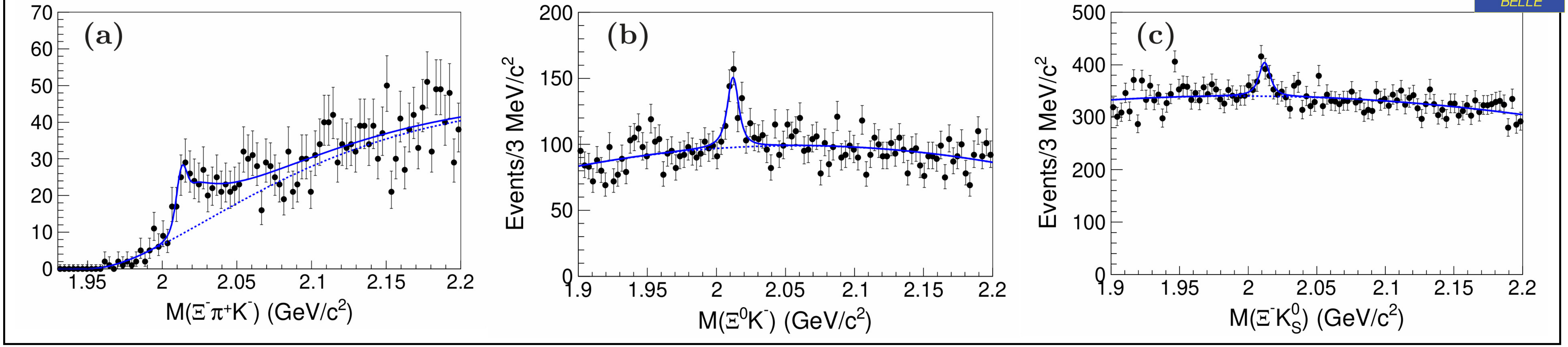



A window onto $\Omega(2012)^-$: is it a $1P$ orbital excitation / a hadronic molecule / a pentaquark?

# Observation of $\Omega(2012)^- \to \Xi(1530)\bar{K}$ and measurement of the effective couplings of $\Omega(2012)^-$ to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$

arXiv > hep-ex > arXiv:2207.03090

Using $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ data collected by the Belle detector, we discover a new resonant three-body decay $\Omega(2012)^- \to \Xi(1530)^0 K^- \to \Xi^-\pi^+K^-$ with a significance of $5.2\sigma$. The mass of the $\Omega(2012)^-$ is $(2012.5 \pm 0.7 \pm 0.5)$ MeV and its effective couplings to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$ are $(41.1 \pm 35.8 \pm 6.0) \times 10^{-2}$ and $(1.7 \pm 0.3 \pm 0.3) \times 10^{-2}$, where the first uncertainties are statistical and the second are systematic. The ratio of the branching fraction for the resonant three-body decay to that for the two-body decay to $\Xi\bar{K}$ is $0.97 \pm 0.24 \pm 0.07$, consistent with the molecular model of $\Omega(2012)^-$, which predicts comparable rates for $\Omega(2012)^-$ decay to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$.



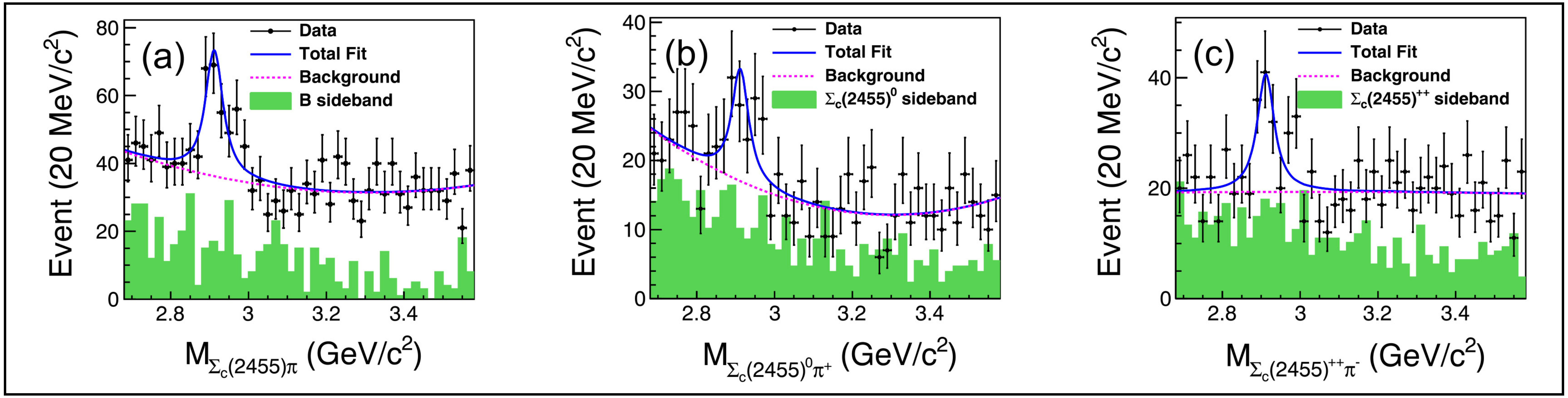

The results for the ratio of the branching fractions are consistent with the proposed molecular interpetation:

M. P. Valderrama, Phys. Rev. D **98**, 054009 (2018).
R. Pavao and E. Oset, Eur. Phys. J. C **78**, 857 (2018).
Y. Huang, M. Z. Liu, J. X. Lu, J. J. Xie, and L. S. Geng, Phys. Rev. D **98**, 076012 (2018).
T. Gutsche and V. E. Lyubovitskij, J. Phys. G **48**, 025001 (2021).

PHYSICAL REVIEW LETTERS **130**, 031901 (2023)

# Evidence of a New Excited Charmed Baryon Decaying to $\Sigma_c(2455)^{0,++}\pi^{\pm}$

We present the study of $\bar{B}^0 \to \Sigma_c(2455)^{0,++}\pi^{\pm}\bar{p}$ decays based on $772 \times 10^6$ $B\bar{B}$ events collected with the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. The $\Sigma_c(2455)^{0,++}$ candidates are reconstructed via their decay to $\Lambda_c^+\pi^{\mp}$ and $\Lambda_c^+$ decays to $pK^-\pi^+$, $pK_S^0$, and $\Lambda\pi^+$ final states. The corresponding branching fractions are measured to be $\mathcal{B}(\bar{B}^0 \to \Sigma_c(2455)^0\pi^+\bar{p}) = (1.09 \pm 0.06 \pm 0.07) \times 10^{-4}$ and $\mathcal{B}(\bar{B}^0 \to \Sigma_c(2455)^{++}\pi^-\bar{p}) = (1.84 \pm 0.11 \pm 0.12) \times 10^{-4}$, which are consistent with the world average values with improved precision. A new structure is found in the $M_{\Sigma_c(2455)^{0,++}\pi^{\pm}}$ spectrum with a significance of $4.2\sigma$ including systematic uncertainty. The structure is possibly an excited $\Lambda_c^+$ and is tentatively named $\Lambda_c(2910)^+$. Its mass and width are measured to be $(2913.8 \pm 5.6 \pm 3.8)$ MeV/$c^2$ and $(51.8 \pm 20.0 \pm 18.8)$ MeV, respectively. The products of branching fractions for the $\Lambda_c(2910)^+$ are measured to be $\mathcal{B}(\bar{B}^0 \to \Lambda_c(2910)^+\bar{p}) \times \mathcal{B}(\Lambda_c(2910)^+ \to \Sigma_c(2455)^0\pi^+) = (9.5 \pm 3.6 \pm 1.6) \times 10^{-6}$ and $\mathcal{B}(\bar{B}^0 \to \Lambda_c(2910)^+\bar{p}) \times \mathcal{B}(\Lambda_c(2910)^+ \to \Sigma_c(2455)^{++}\pi^-) = (1.24 \pm 0.35 \pm 0.10) \times 10^{-5}$. Here, the first and second uncertainties are statistical and systematic, respectively.

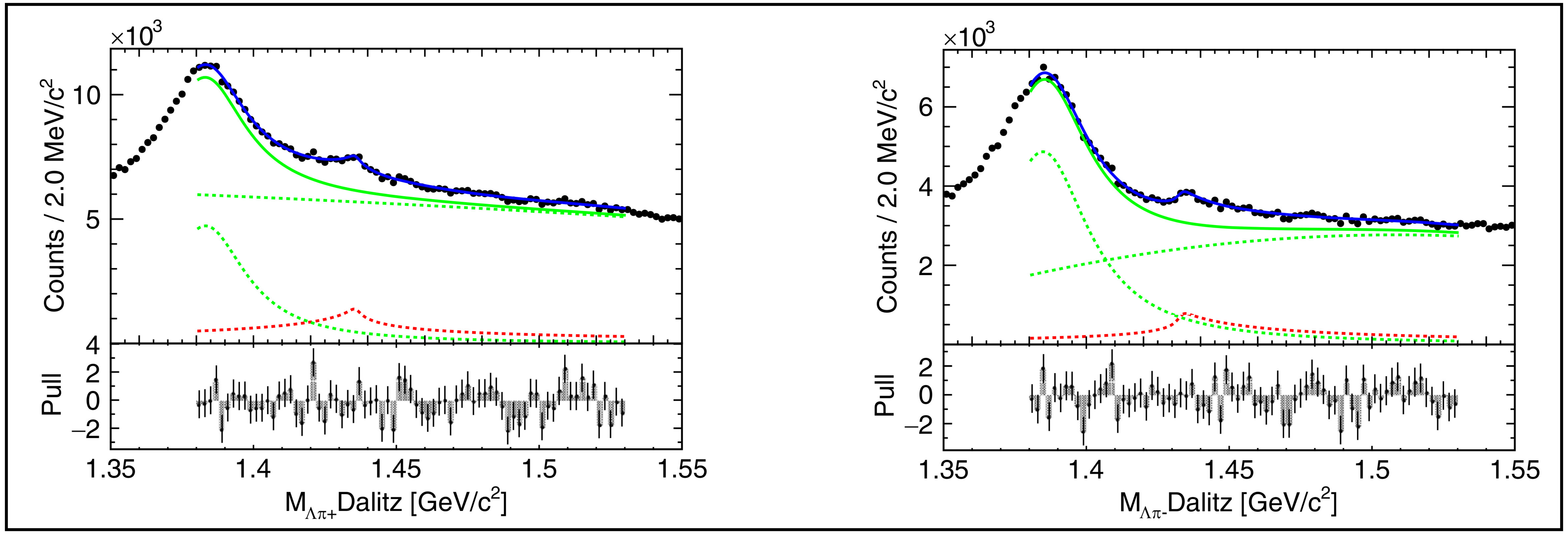



The numerous degrees of freedom in the internal structure of charmed baryons is an excellent QCD laboratory

PHYSICAL REVIEW LETTERS **130,** 151903 (2023)

# First Observation of $\Lambda\pi^+$ and $\Lambda\pi^-$ Signals near the $\bar{K}N(I=1)$ Mass Threshold in $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ Decay

Using the data sample of 980 $\mathrm{fb}^{-1}$ collected with the Belle detector operating at the KEKB asymmetric-energy $e^+e^-$ collider, we present the results of an investigation of the $\Lambda\pi^+$ and $\Lambda\pi^-$ invariant mass distributions looking for substructure in the decay $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$. We find a significant signal in each mass distribution. When interpreted as resonances, we find for the $\Lambda\pi^+$ ($\Lambda\pi^-$) combination a mass of $1434.3 \pm 0.6(\mathrm{stat}) \pm 0.9(\mathrm{syst})\ \mathrm{MeV}/c^2$ [$1438.5 \pm 0.9(\mathrm{stat}) \pm 2.5(\mathrm{syst})\ \mathrm{MeV}/c^2$], an intrinsic width of $11.5 \pm 2.8(\mathrm{stat}) \pm 5.3(\mathrm{syst})\ \mathrm{MeV}/c^2$ [$33.0 \pm 7.5(\mathrm{stat}) \pm 23.6(\mathrm{syst})\ \mathrm{MeV}/c^2$] with a significance of $7.5\sigma$ ($6.2\sigma$). As these two signals are very close to the $\bar{K}N$ threshold, we also investigate the possibility of a $\bar{K}N$ cusp, and find that we cannot discriminate between these two interpretations due to the limited size of the data sample.

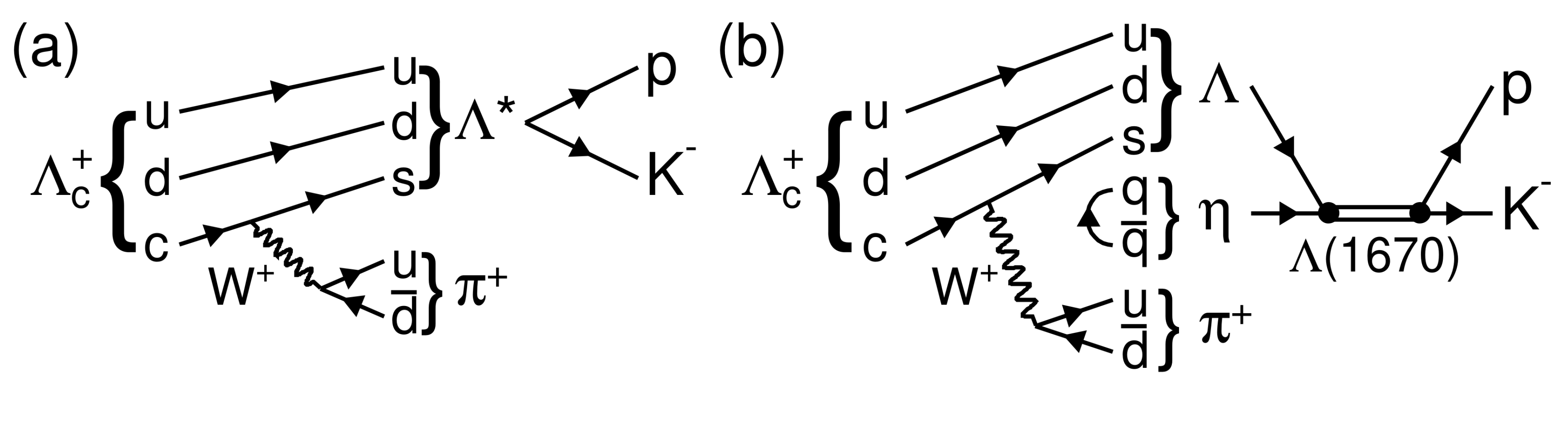



An effort in the direction of figuring out if a threshold enhancement is a cusp, a resonance or something else

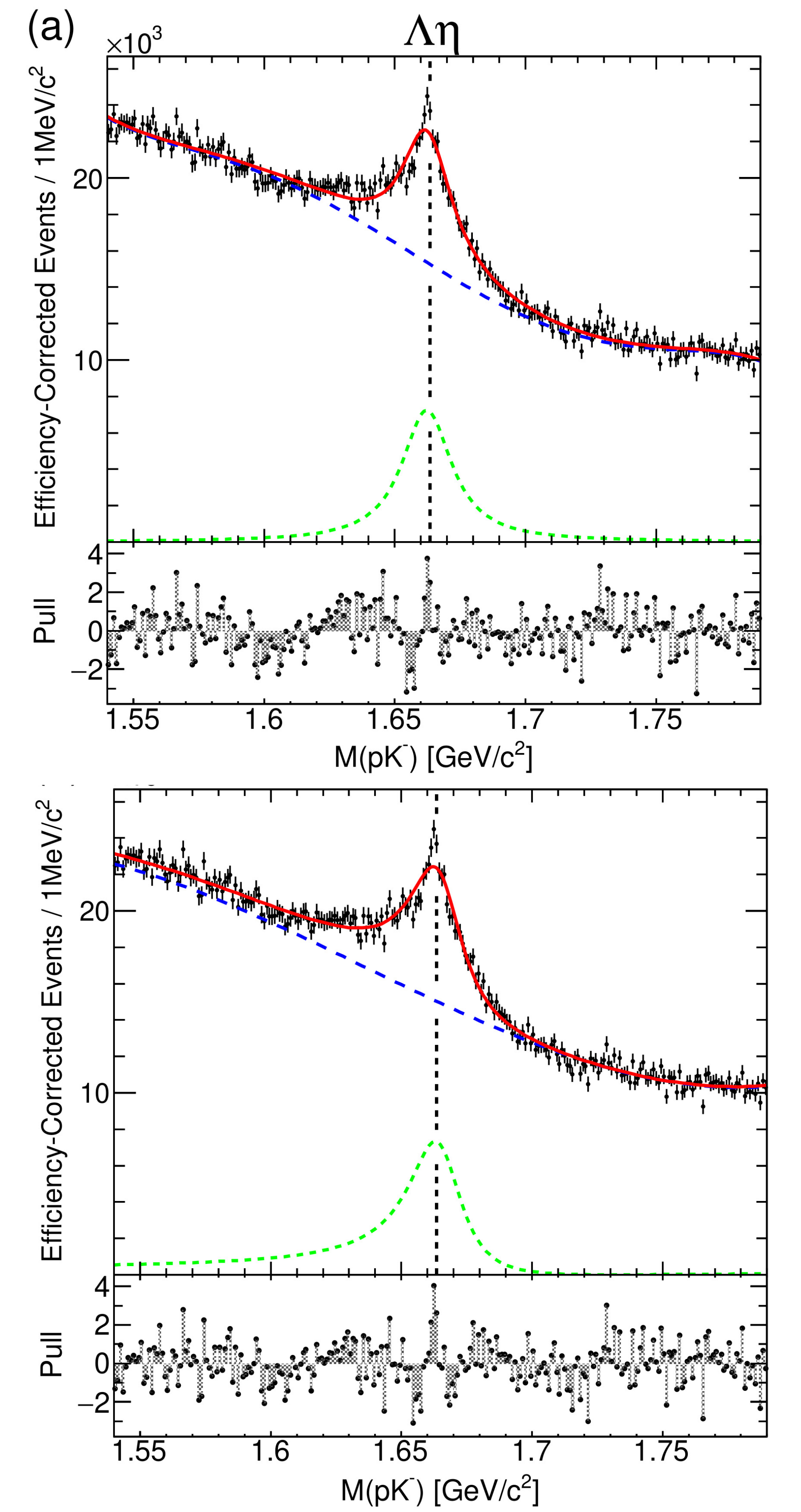
# Observation of a Threshold Cusp at the $\Lambda\eta$ Threshold in the $pK^-$ Mass Spectrum with $\Lambda_c^+ \to pK^-\pi^+$ Decays

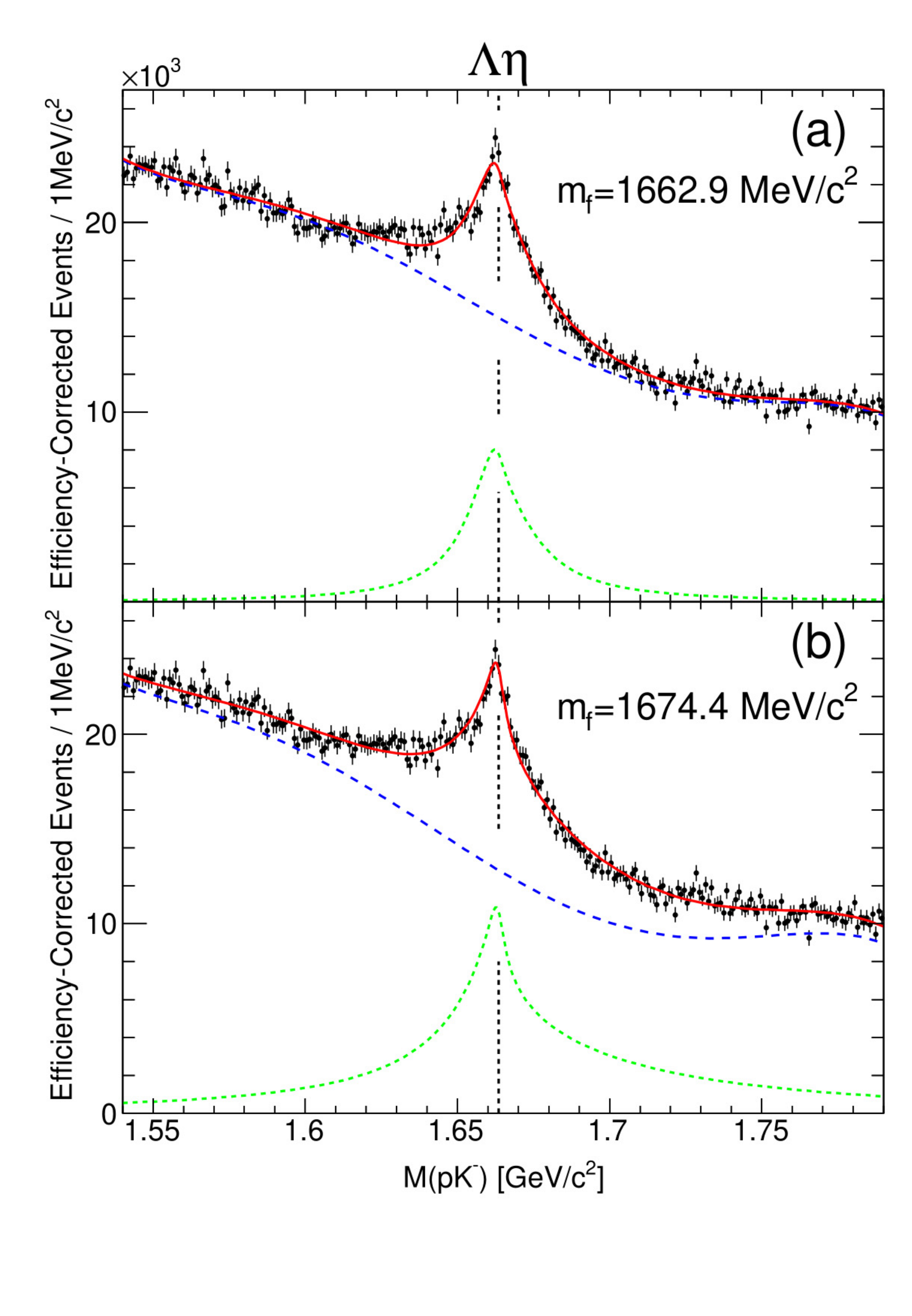
arXiv > hep-ex > arXiv:2209.00050

We observe a narrow peaking structure in the $pK^-$ invariant-mass spectrum near the $\Lambda\eta$ threshold. The peak is clearly seen in 1.5 million events of $\Lambda_c^+ \to pK^-\pi^+$ decay using the 980 fb$^{-1}$ data sample collected by the Belle detector at the KEKB asymmetric-energy $e^+e^-$ collider. We try two approaches to explain this structure: as a new resonance and as a cusp at the $\Lambda\eta$ threshold. The best fit is obtained with a coherent sum of a Flatté function and a constant background amplitude with the $\chi^2/\text{n.d.f} = 257/243$ ($p = 0.25$), while the fits to Breit-Wigner functions are unfavored by more than $7\sigma$. The best fit explains the structure as a cusp at the $\Lambda\eta$ threshold and the obtained parameters are consistent with the known properties of $\Lambda(1670)$. The observation gives the first identification of a threshold cusp in hadrons from the spectrum shape.




Feynman diagrams for (a) a new $\Lambda^*$ resonance and (b) a visible $\Lambda\eta$ threshold cusp enhanced by the $\Lambda(1670)$ pole in $\Lambda_c^+ \to pK^-\pi^+$ decay.

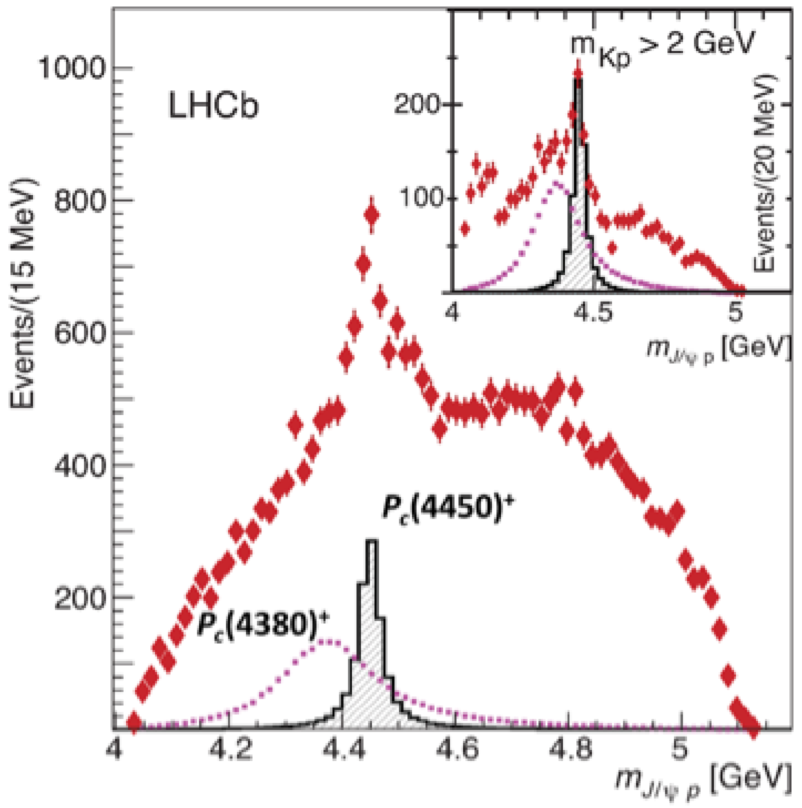



**High statistics around the mass thresholds of two hadrons are of great importance for studies of exotic states**

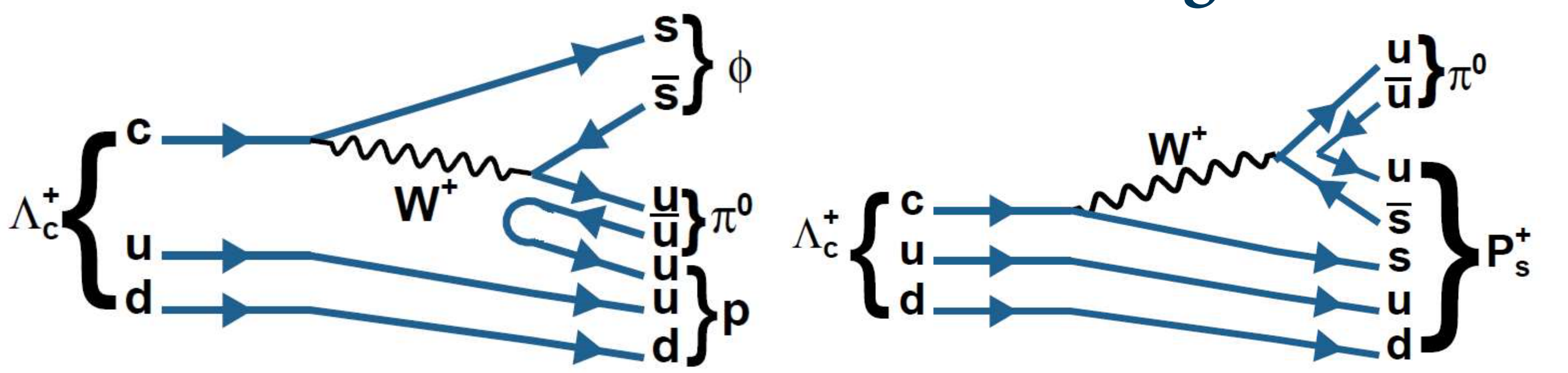
## Search for the $P_s^+$ pentaquark (motivated by LHCb discoveries) (Phys. Rev. **D96**, 051102 (2017))

R. Aaij *et al.* (LHCb Collaboration), Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays, Phys. Rev. Lett. **115**, 072001 (2015).

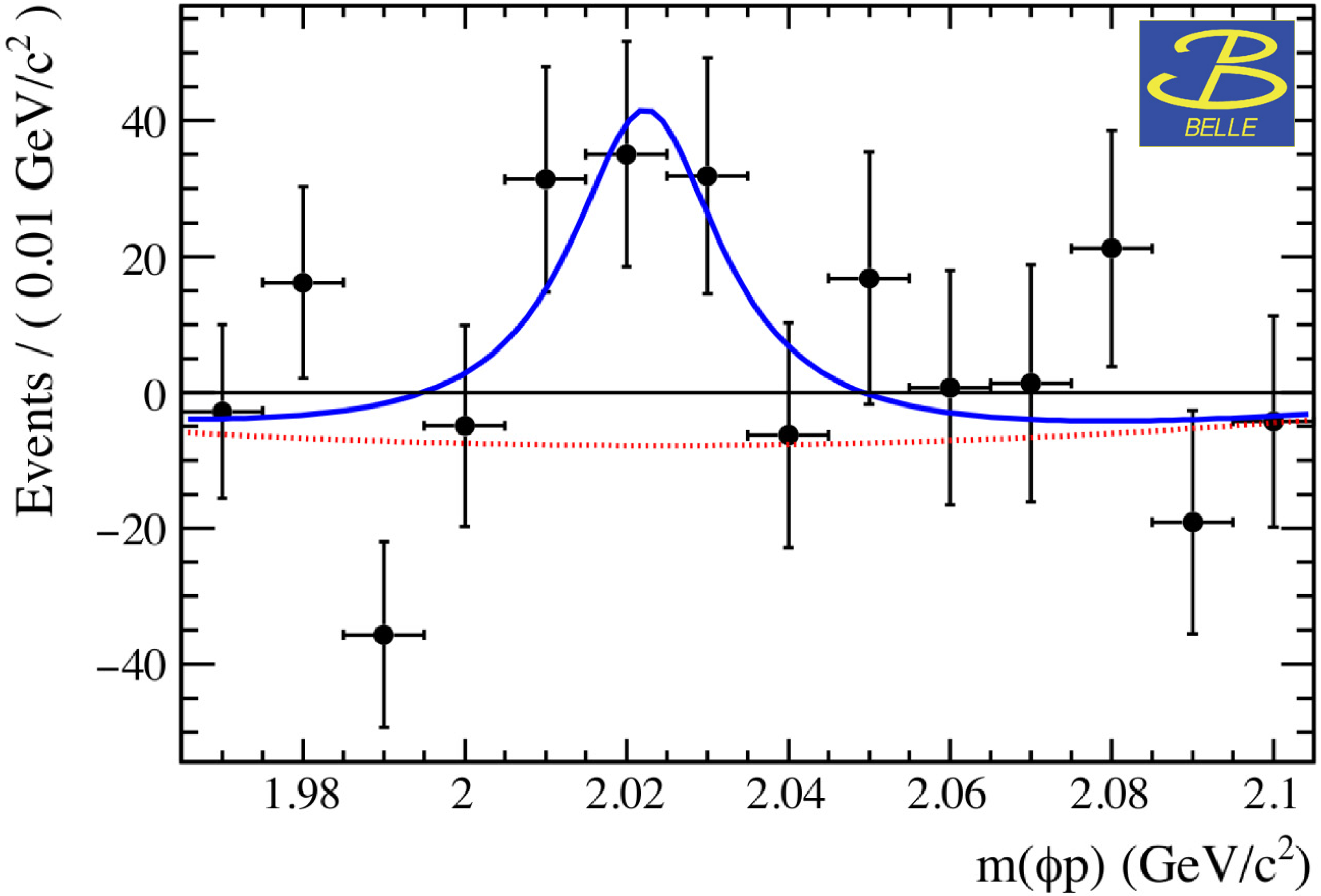



Hidden charm

Hidden strangeness




From 2D fit with three components in each bin of shown invariant mass




$$\mathcal{B}(\Lambda_c^+ \to P_s^+ \pi^0) \times \mathcal{B}(P_s^+ \to \phi p) < 8.3 \times 10^{-5}$$

PHYSICAL REVIEW D **105,** 032002 (2022)

# Search for tetraquark states $X_{cc\bar{s}\bar{s}}$ in $D_s^+ D_s^+$ $(D_s^{*+} D_s^{*+})$ final states at Belle

A search for double-heavy tetraquark state candidates $X_{cc\bar{s}\bar{s}}$ decaying to $D_s^+ D_s^+$ and $D_s^{*+} D_s^{*+}$ is presented for the first time using the data samples of $102 \times 10^6$ $\Upsilon(1S)$ and $158 \times 10^6$ $\Upsilon(2S)$ events, and the data samples at $\sqrt{s} = 10.52$, 10.58, and 10.867 GeV corresponding to integrated luminosities of 89.5, 711.0, and 121.4 fb$^{-1}$, respectively, accumulated with the Belle detector at the KEKB asymmetric energy electron-positron collider. The invariant-mass spectra of the $D_s^+ D_s^+$ and $D_s^{*+} D_s^{*+}$ are studied to search for possible resonances. No significant signals are observed, and the 90% confidence level upper limits on the product branching fractions $[\mathcal{B}(\Upsilon(1S,2S) \to X_{cc\bar{s}\bar{s}} + \text{anything}) \times \mathcal{B}(X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+ (D_s^{*+} D_s^{*+}))]$ in $\Upsilon(1S,2S)$ inclusive decays and the product values of Born cross section and branching fraction $[\sigma(e^+e^- \to X_{cc\bar{s}\bar{s}} + \text{anything}) \times \mathcal{B}(X_{cc\bar{s}\bar{s}} \to D_s^+ D_s^+ (D_s^{*+} D_s^{*+}))]$ in $e^+e^-$ collisions at $\sqrt{s} = 10.52$, 10.58, and 10.867 GeV under different assumptions of $X_{cc\bar{s}\bar{s}}$ masses and widths are obtained.

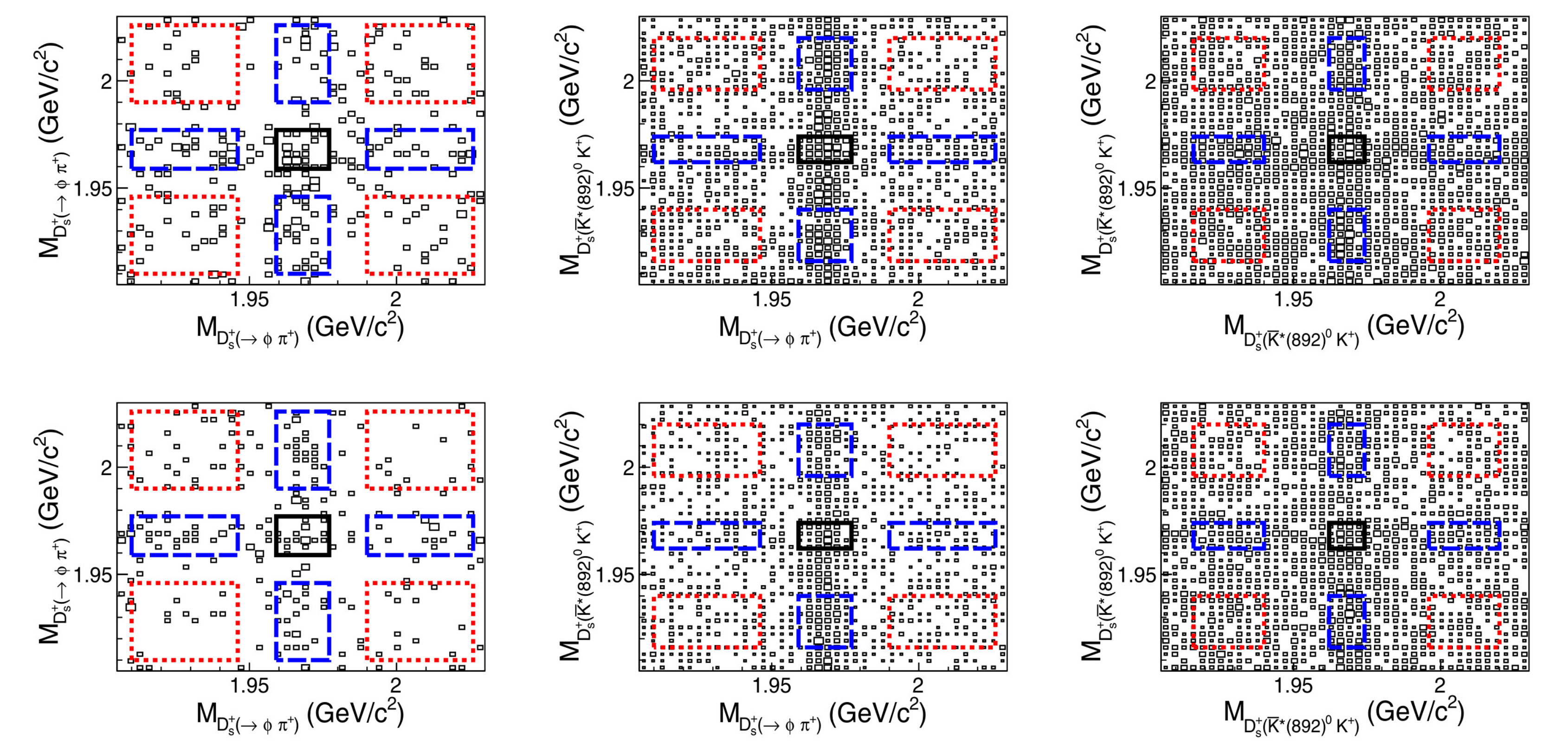


TABLE VI. Summary of 90% CL upper limits with the systematic uncertainties included on the cross sections of $e^+e^- \to X_{cc\bar{s}\bar{s}} (\to D_s^{*+} D_s^{*+}) + \text{anything}$ at $\sqrt{s} = 10.52/10.58/10.867$ GeV.

| | $\sigma(e^+e^- \to X_{cc\bar{s}\bar{s}} + \text{anything}) \times \mathcal{B}(X_{cc\bar{s}\bar{s}} \to D_s^{*+} D_s^{*+})$ $(\times 10^2 fb)$ | | | | | | |
|---|---|---|---|---|---|---|---|
| $M_{X_{cc\bar{s}\bar{s}}}$ | $\Gamma_{X_{cc\bar{s}\bar{s}}}$ (MeV) | | | | | | |
| (MeV/$c^2$) | 2.58 | 3.58 | 4.58 | 5.58 | 6.58 | 7.58 | 8.58 |
| 4801 | 14.5/8.5/16.2 | 14.1/8.5/20.7 | 13.4/10.8/20.4 | 14.1/10.7/23.7 | 10.3/10.9/23.8 | 11.5/11.7/23.2 | 11.1/12.7/24.1 |
| 4806 | 14.5/6.1/21.2 | 14.2/6.2/18.3 | 13.5/8.3/17.3 | 14.1/7.7/18.2 | 14.0/10.4/18.3 | 15.5/12.6/17.8 | 11.1/13.6/23.7 |
| 4811 | 14.5/3.8/21.0 | 14.2/6.3/20.2 | 13.5/7.8/19.9 | 14.1/7.8/20.9 | 26.2/10.4/23.2 | 23.7/12.7/22.6 | 23.0/13.9/23.4 |
| 4816 | 14.1/4.7/16.3 | 13.8/6.8/20.8 | 24.6/6.6/26.3 | 25.8/9.1/27.6 | 25.6/9.5/27.8 | 28.3/12.4/23.3 | 27.5/13.0/24.2 |
| 4821 | 25.8/6.7/16.9 | 25.2/7.5/16.2 | 24.1/7.5/21.2 | 25.1/9.0/22.3 | 24.9/9.2/19.3 | 27.6/9.5/30.2 | 26.8/11.0/31.4 |
| 4826 | 26.4/8.6/16.4 | 25.8/9.3/15.8 | 24.6/9.1/15.6 | 25.7/9.1/18.6 | 25.5/10.2/18.7 | 28.3/11.2/23.4 | 27.5/11.4/24.3 |
| 4831 | 27.1/7.0/21.1 | 26.5/8.6/20.3 | 25.2/11.0/20.1 | 26.4/11.2/21.0 | 34.7/11.5/23.4 | 38.5/12.0/22.8 | 37.4/12.5/23.6 |
| 4836 | 13.8/6.6/16.2 | 13.5/7.5/15.6 | 32.0/9.7/23.3 | 33.4/9.4/23.7 | 33.1/9.6/23.8 | 36.6/12.2/23.2 | 35.6/13.8/24.1 |
| 4841 | 24.7/6.9/21.9 | 24.2/6.7/18.1 | 23.1/7.2/17.9 | 24.1/8.9/18.8 | 23.9/9.9/24.3 | 34.9/12.0/29.6 | 34.0/13.4/30.8 |

Motivated by the LHCb observation of an open-double-charm state $T_{cc}^+$ in the $D^0 D^0 \pi^+$ mass spectrum near threshold

# Many other recent publications by Belle in the area of hadronic physics are not discussed in this talk

PHYSICAL REVIEW D **102,** 112001 (2020)

**Search for a doubly charged *DDK* bound state in $\Upsilon(1S, 2S)$ inclusive decays and via direct production in $e^+e^-$ collisions at $\sqrt{s} = 10.520$, 10.580, and 10.867 GeV**

PHYSICAL REVIEW D **103,** L111101 (2021)

**First determination of the spin and parity of the charmed-strange baryon $\Xi_c(2970)^+$**

PHYSICAL REVIEW D **104,** 012012 (2021)

**Search for the $\eta_{c2}(1D)$ in $e^+e^- \to \gamma\eta_{c2}(1D)$ at $\sqrt{s}$ near 10.6 GeV at Belle**

PHYSICAL REVIEW D **107,** 012006 (2023)

**Study of $e^+e^- \to \eta\phi$ via initial state radiation at Belle**

PHYSICAL REVIEW D **107,** 032008 (2023)

**Measurement of the mass and width of the $\Lambda_c(2625)^+$ charmed baryon and the branching ratios of $\Lambda_c(2625)^+ \to \Sigma_c^0\pi^+$ and $\Lambda_c(2625)^+ \to \Sigma_c^{++}\pi^-$**

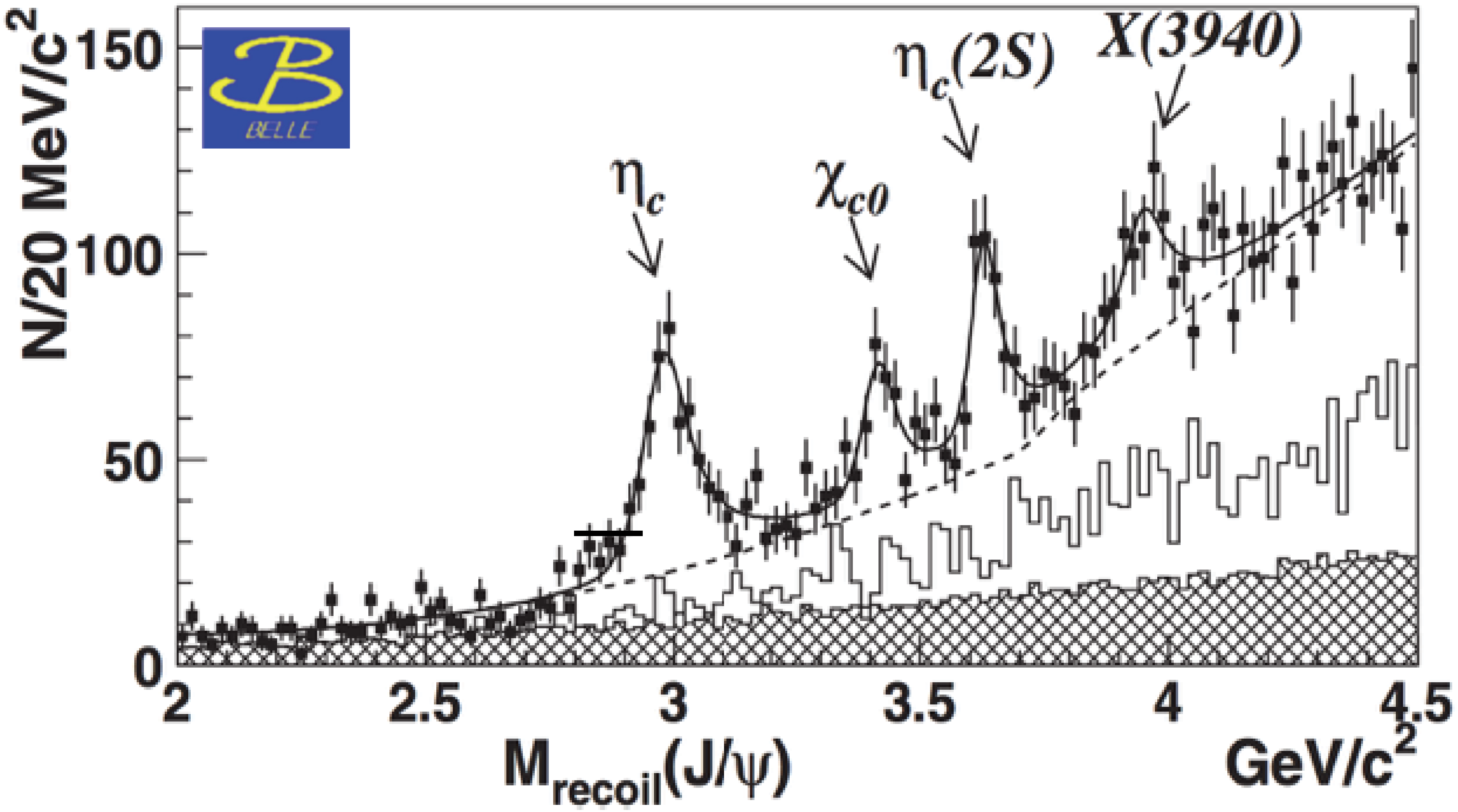
BELLE

# Double Charmonium Production at Belle (II) - new results coming soon

- Observed in combinations of J=1 and J=0

  $e^+e^- \rightarrow c\bar{c}\ (0+/-)\ c\bar{c}\ (1-/+)$

*Belle, PRL 98, 082001 (2005)*




➡ **Belle II**

- angular distributions, production
- probe for new states

Also, from Belle II Physics Book (arXiv:1808.10567 [hep-ex]):

The discovery of a number of double-charmonium production processes in $e^+e^-$ annihilation at $B$-factories was initiated by the observation of $e^+e^- \to J/\psi X$, where $X$ is $\eta_c$, $\chi_{c0}$, $\eta_c(2S)$ by Belle [1445]. This production mechanism provides a powerful tool for an understanding of the interplay between perturbative QCD (pQCD) (and its expansions beyond the leading order) and non-perturbative effects, in particular with application of the light-cone approximation and the nonrelativistic QCD (NRQCD) factorisation approaches. The first calculations using NRQCD within the leading order pQCD for the $e^+e^- \to J/\psi\,\eta_c$ cross-section gave a value, which was an order of magnitude smaller than the measured cross section [1446]. The importance of relativistic corrections was realised in Ref. [1447, 1448]; the authors, using the light-cone approximation to take into account the relative momentum of heavy quarks in the charmonium states, managed to calculate the cross section which is close to the experimental value. Some authors have been able to reproduce the experimental result using next-to-leading (NLO) corrections [1449, 1450]. The present variety of different alternative approaches that explain the experimental result points to the need to check the suggested models with new data.

# The So What Slide

## The *XYZ* states: experimental and theoretical status and perspectives

Nora Brambilla[l,m], Simon Eidelman[b,k,h], Christoph Hanhart[f,*], Alexey Nefediev[h,i,j], Cheng-Ping Shen[e,a,*], Christopher E. Thomas[d], Antonio Vairo[l], Chang-Zheng Yuan[g,c]

experiments for many years. Remarkably, in the past fifteen years, many new hadrons that do not exhibit the expected properties of ordinary (not exotic) hadrons have been discovered in the quarkonium spectrum. These hadrons are collectively known as *XYZ* states. Some of them, like the charged states, are undoubtedly exotic. Parallel to the experimental progress, the last decades have also witnessed an enormous theoretical effort to reach a theoretical understanding of the *XYZ* states. Theoretical approaches include not only phenomenological extensions of the quark model to exotics, but also modern non-relativistic effective field theories and lattice QCD calculations. The present work aims at reviewing the rapid progress in the field of exotic *XYZ* hadrons over the past few years both in experiments

All these efforts are of paramount importance also so the theorists could develop/improve new/old approaches to low-energy QCD, which is exceptionally important also for the interpretation of data in searches for New Physics (e.g., flavor anomalies, muon anomalous magnetic moment and such)

# What We Have Achieved, Where We Stand, and Where We Are Going

- Ingredients
  - Talented Belle physicists
  - Exceptional KEK accelerator physicists
  - Outstanding technicians, engineers and support personnel
  - Common goals and perseverance
- Outcomes
  - $X(3872)$ 2003 Revolution
  - Renewed interest to low-energy hadronic physics
  - Wide-range experimental program around the world
  - Significant theoretical developments
- The Future
  - Belle II is continuing on the path of excellence paved by Belle
  - Look forward to more interesting results

# Luminosity Outlook