# Measurements of $\eta_c$ and $h_c$ decays into light hadrons at BESIII

On behalf of the BESIII Collaboration

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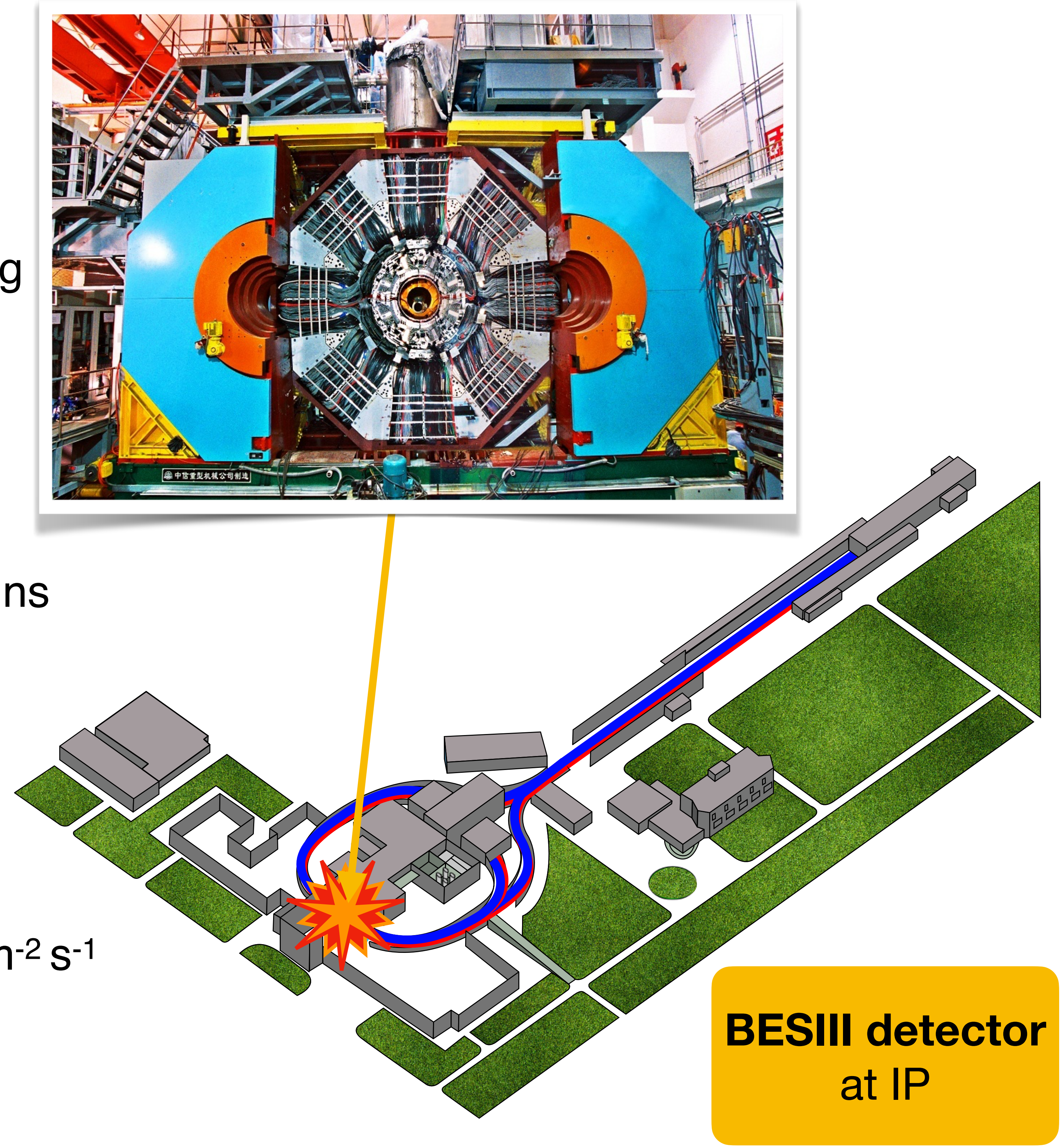
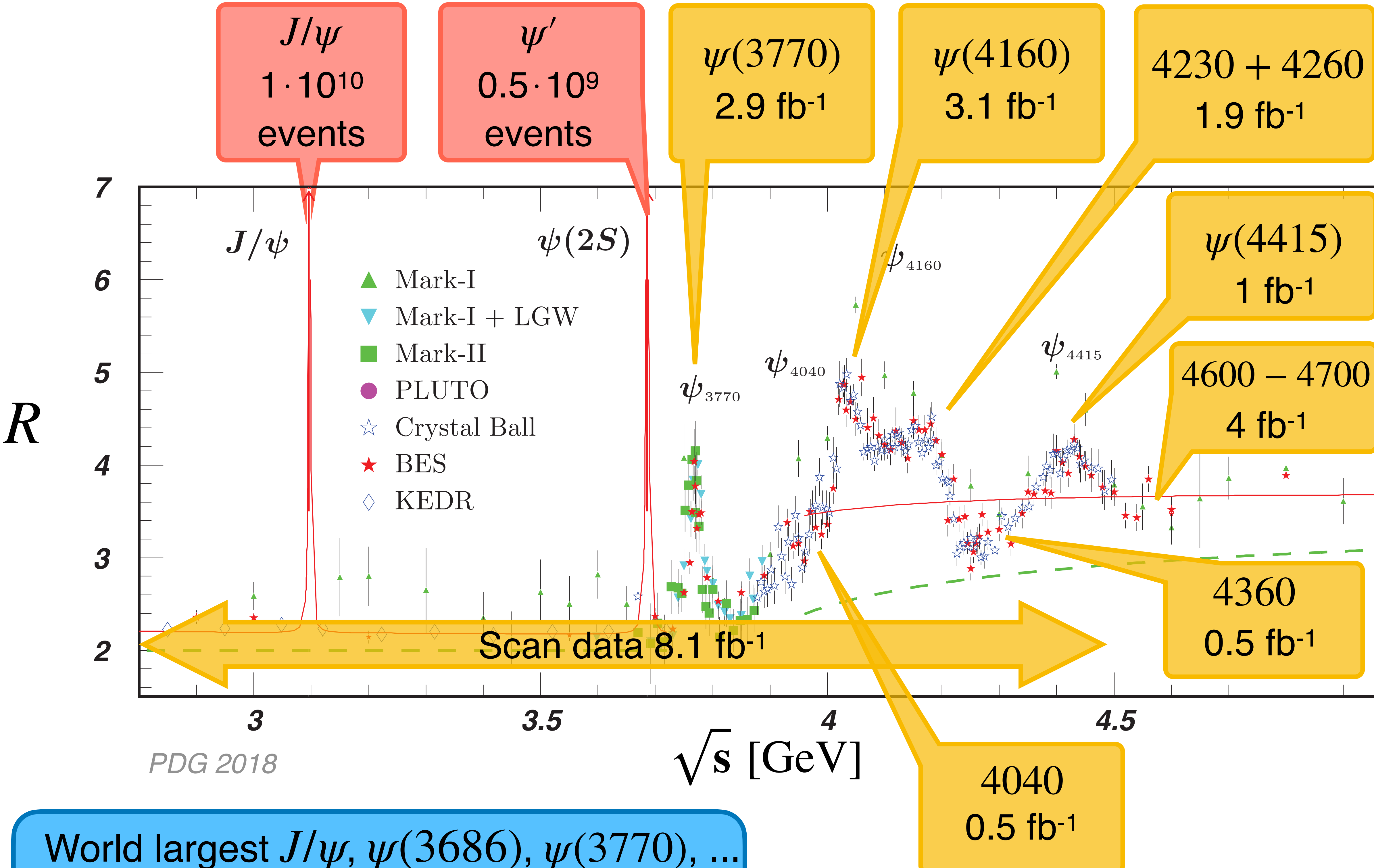
# BESIII at BEPCII

- Symmetric $e^+e^-$ collider in Beijing
- Update of BEPC accelerator
  - 2004: construction started
  - 2008: first collisions
  - 2009-today: BESIII physics runs
- Energy range: $\sqrt{s}$ = 2 - 4.9 GeV
- Crossing angle: 11 mrad
- Design luminosity: $1 \cdot 10^{33} cm^{-2} s^{-1}$
- Achieved luminosity: $1.01 \cdot 10^{33} cm^{-2} s^{-1}$



# Data Samples collected at BESIII

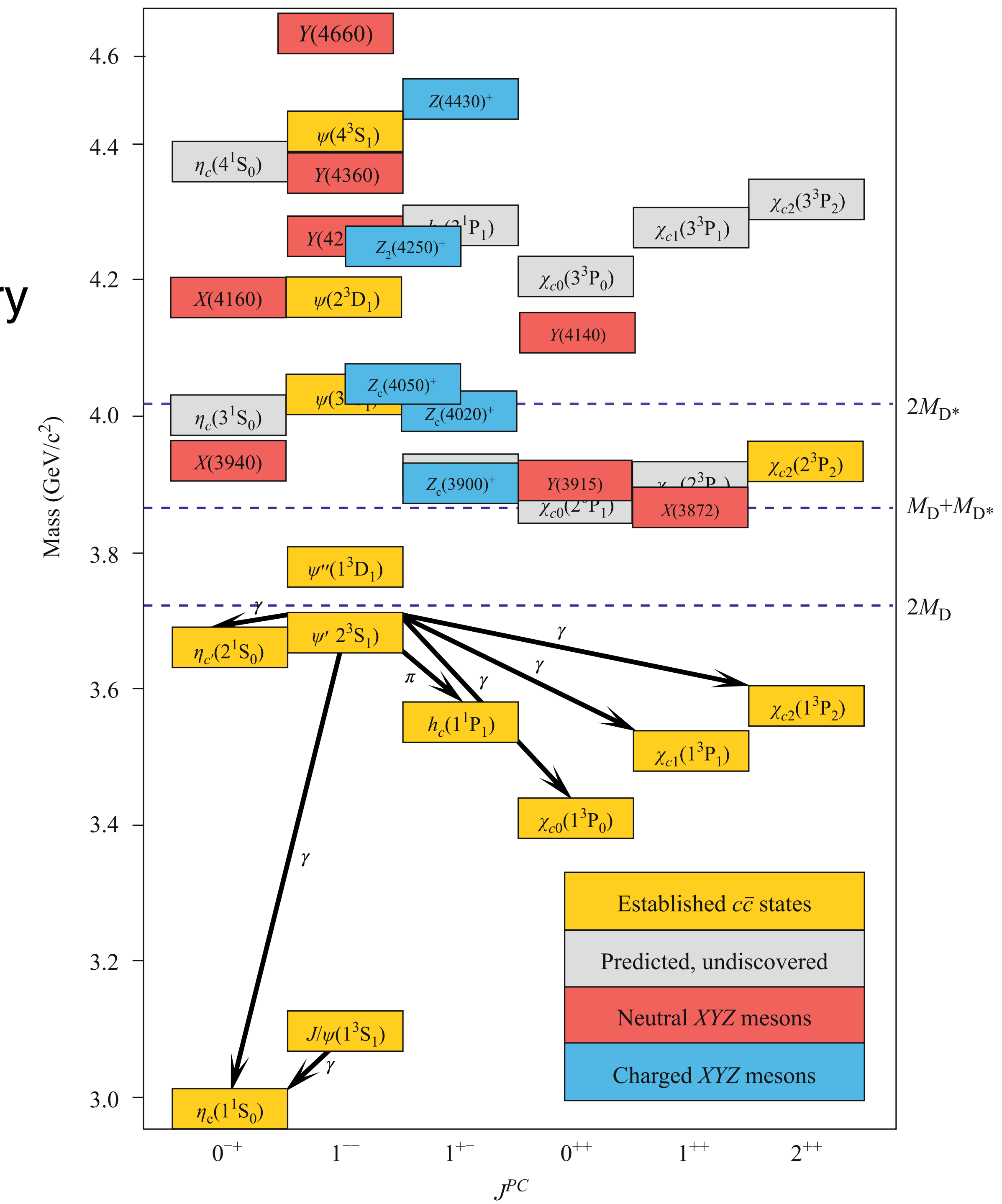



World largest $J/\psi$, $\psi(3686)$, $\psi(3770)$, ... data samples on resonance

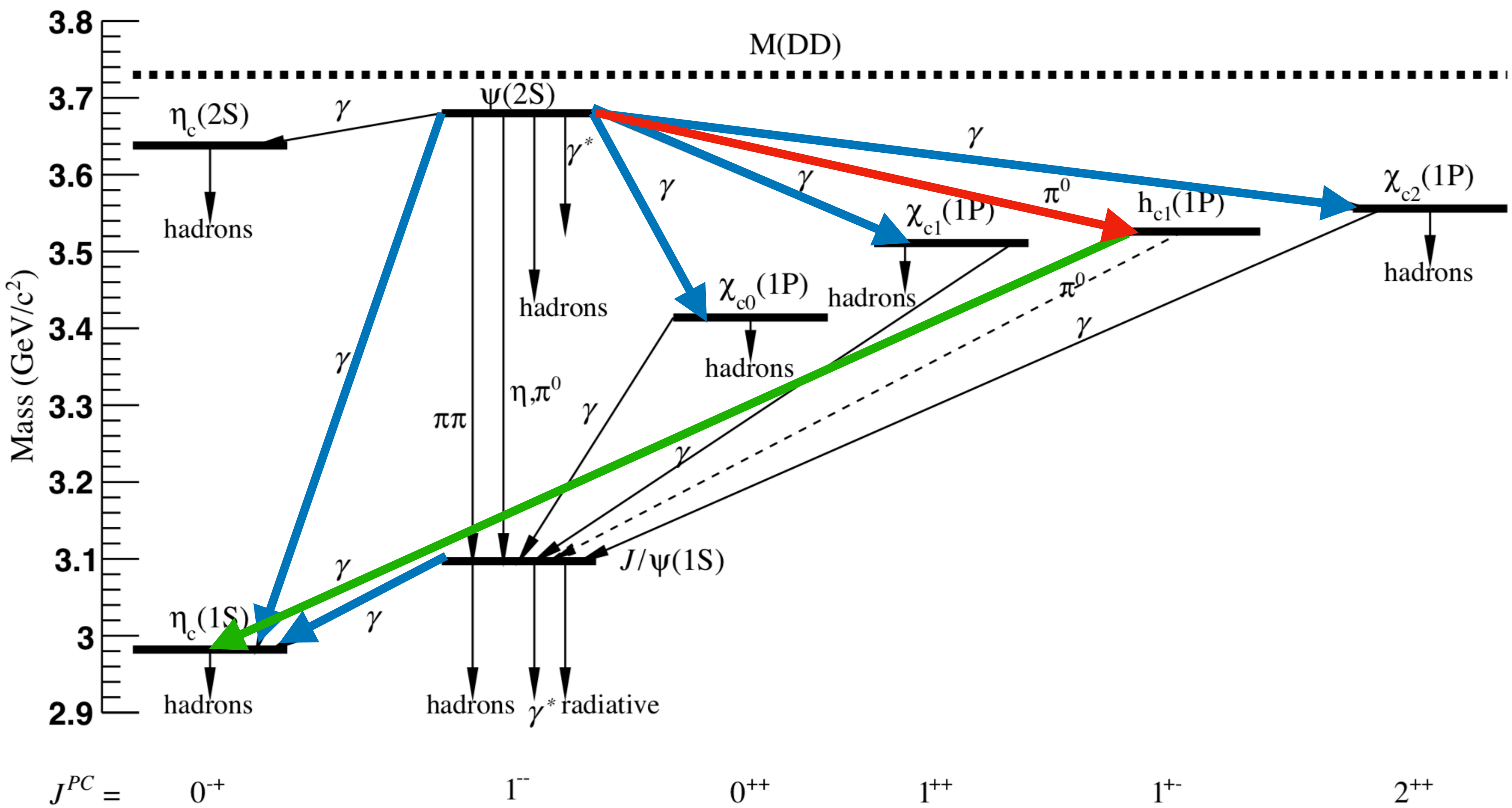
# What we can learn from Charmonium Decays

- Charmonium region opens a window to study the transition region between low and high energy and therefore the transition region between non-perturbative and perturbative QCD
- Masses are well measured and agree well with theory
- Decays are more difficult, since below $D\bar{D}$ threshold strong/OZI charmonium decays dominate
- Due to the high mass of the c quark non relativistic models are quite successful
- Necessary adjustments: NR models + relativistic corrections + pQCD
- Lattice predictions are quite successful at predicting masses
- Studying hadronic transitions of the spin-singlet P-wave state $h_c$ offers a opportunity to study spin-spin interactions

➡ We experimentalists try our best to provide precise data to help theory



# Experimental Challenges




- In $e^+e^-$ annihilation only particles carrying quantum numbers of the photon ($1^{--}$) can be produced directly
- Knowledge of decay behaviour still sparse for non vector states
- $\chi_{cJ}$, $\eta_c$ and $h_c$ states can only be accessed via (rare) transitions ➡ limits statistics right from the beginning
- Often large background contamination, e.g. $h_c \to \gamma\eta_c$, can cause peaking background

# Experimental Challenges

- E.g. BESIII sensitivity to new $h_c$ decay modes:
  - ~ 448.1 M $\psi(3686)$ events on tape, $\mathrm{BF}(\psi(3686) \to \pi^0 h_c) = 8.6 \cdot 10^{-4}$, efficiency ~ some % (other subsequent BF…) ➡ $\sim 10^{-3}$
- BESIII is currently taking more data at $\psi(3686)$ ~ 2.5 Billion ➡ $\sim 10^{-4}$
- Another challenge often arises from low energetic photons
- Hadronic transitions offer access to the soft-gluon regime (non perturbative)
- Predictions vary, e.g. $h_c \to \pi\pi J/\psi : 0.05\% - 2\ \%$ PRD 37, 1210, PRD 52, 1710
- Best measurement: $\mathrm{BF}(\mathrm{h_c} \to \pi\pi\, J/\psi) < 3.6 \cdot 10^{-3}$ very low and at the limit of statistics PRD 99, 052008
- $h_c \to \gamma\eta_c$ is the prominent decay channel in every calculation, but predictions of the decay to light hadrons range from 14% – 48%, depending on the theoretical model

PLB 65, 157 (1976), PRD 46, R1914 (1992), Phys. Rep. 41, 1 (1978), PRD 37, 1210 (1988)

➥ Only a few measurements of new $h_c$ and $\eta_c$ decays exist

- Experimental measurements of new decay modes are therefore needed to test and improve those models

# First observations of $h_c \to \text{hadrons}$

Phys. Rev. D **99**, 072008 (2019)

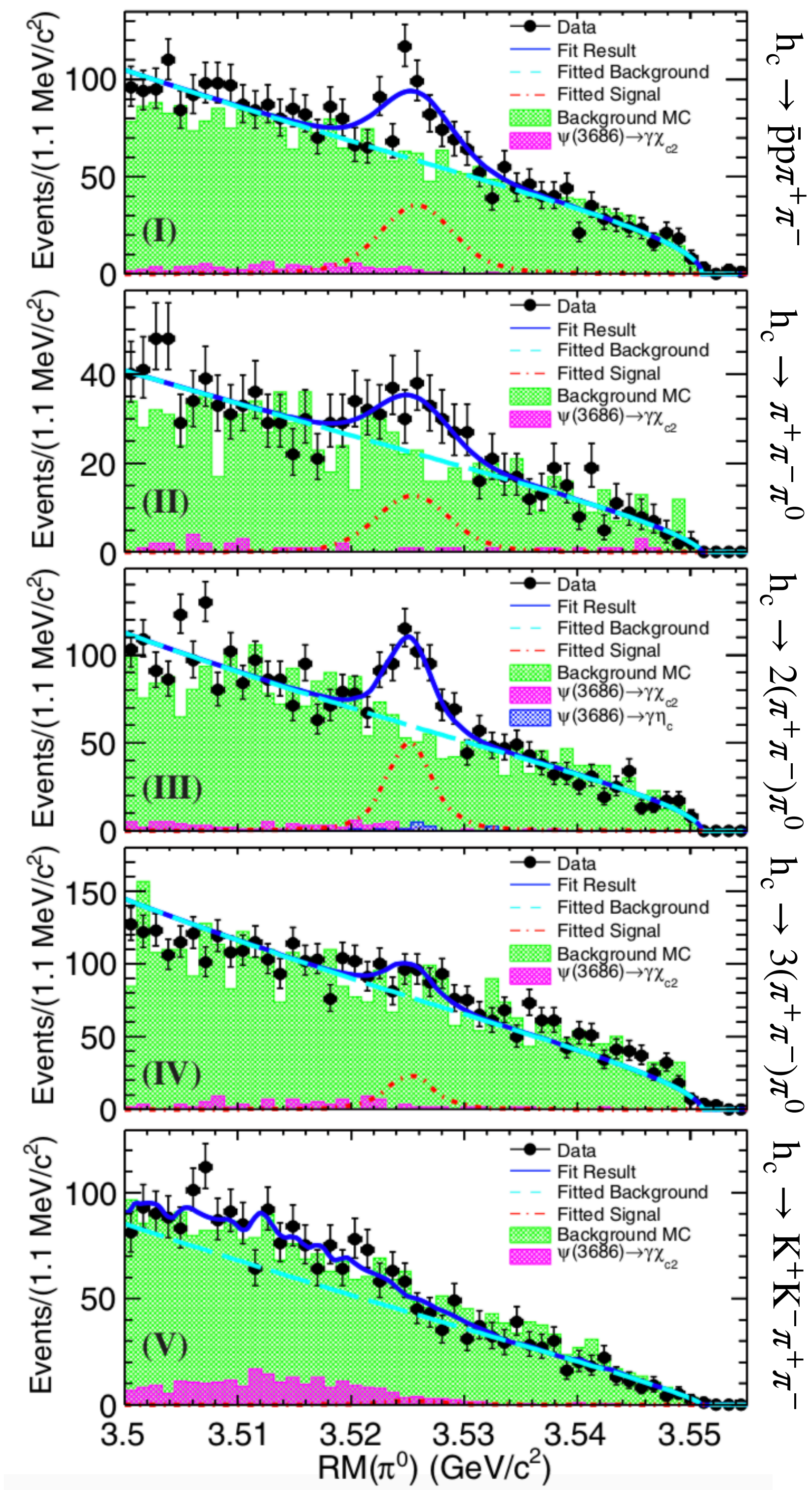
# First observations of $h_c \to$ hadrons

- Knowledge on decay behaviour of $h_c$ still sparse since discovery in 2005 PRL 95, 102003
- Only few decay modes have been observed ( $BF(h_c \to \gamma\eta_c) = 51\ \%$, others $3\ \%$)

*observed for the first time*

| Mode | | $\mathcal{B}_{h_c}(10^{-3})$ | S.S. | $\mathcal{B}_{h_c}^{PDG}(10^{-3})$ |
|---|---|---|---|---|
| I | $h_c \to p\bar{p}\pi^+\pi^-$ | $2.89 \pm 0.32 \pm 0.55$ | $7.4\sigma$ | $\cdots$ |
| II | $h_c \to \pi^+\pi^-\pi^0$ | $1.60 \pm 0.40 \pm 0.32$ | $4.6\sigma$ | $<2.2$ |
| III | $h_c \to 2(\pi^+\pi^-)\pi^0$ | $7.44 \pm 0.94 \pm 1.52$ | $9.1\sigma$ | $22^{+8}_{-7}$ |
| IV | $h_c \to 3(\pi^+\pi^-)\pi^0$ | $4.65 \pm 2.17 \pm 1.08$ | $2.1\sigma$ | $<29$ |
| | | $<8.7$ | $\cdots$ | |
| V | $h_c \to K^+K^-\pi^+\pi^-$ | $<0.6$ | $\cdots$ | $\cdots$ |

- Still no conclusion whether hadronic decays, radiative decays or transition play the dominant role of remaining decay modes




PRD **99**, 072008 (2019)

## Search for new hadronic decays of $h_c$ and observation of $h_c \to K^+K^-\pi^+\pi^-\pi^0$

Phys. Rev. D **102**, 112007 (2020)

# Search for new hadronic decays of $h_c$ and observation of $h_c \to K^+K^-\pi^+\pi^-\pi^0$

- Systematic study of ten hadronic final states of $h_c$ via $\psi(3686) \to \pi^0 h_c$ **for the first time**
- In addition to multi-pion final states, multi particle final states, involving kaons were studied to find ‚missing' decays
- In case of absent signals upper limits were determined

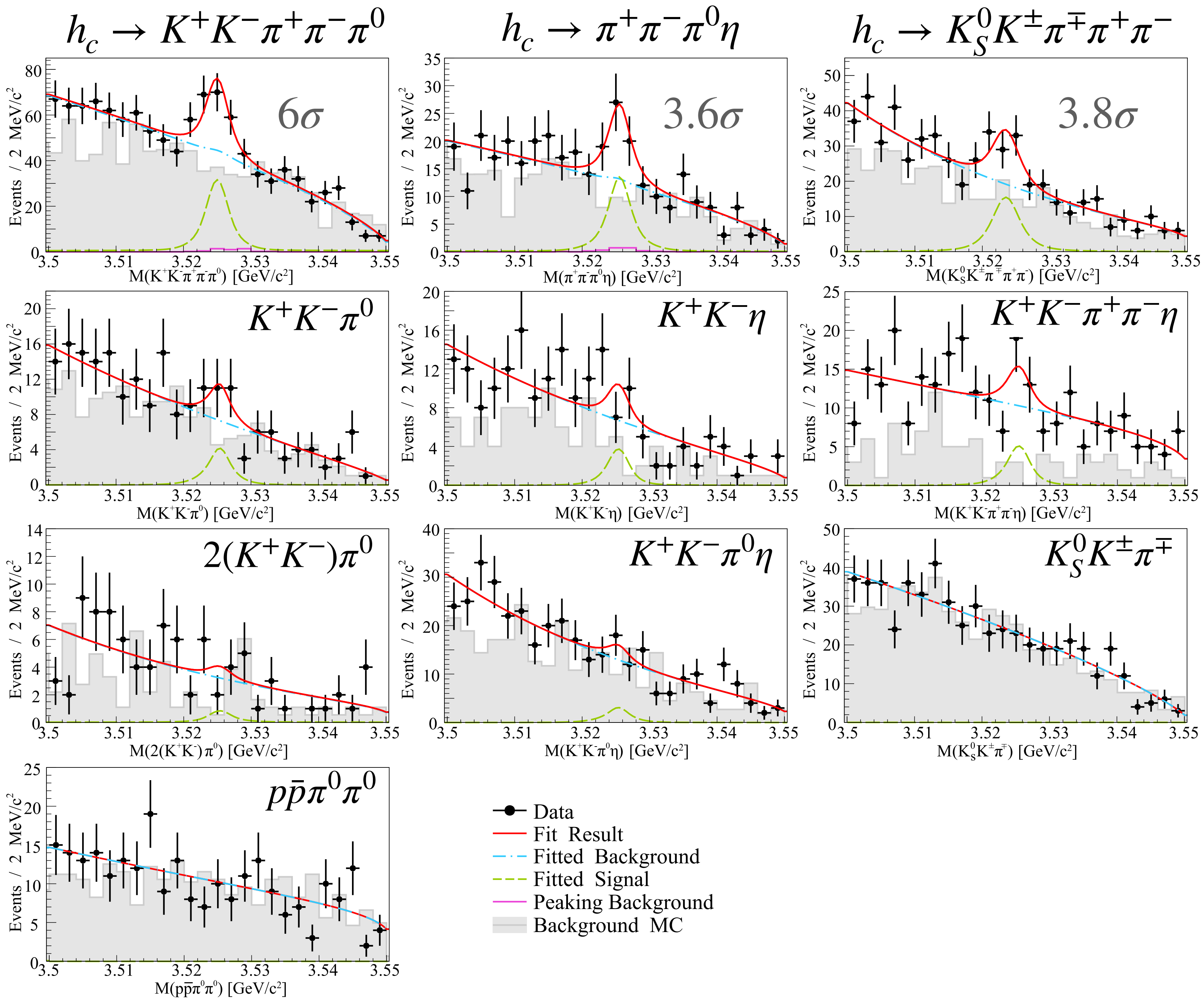
*observed for the first time*

| Mode | $X$ | $N_{h_c}$ | $\varepsilon(\%)$ | $\mathcal{B}(\psi(3686) \to \pi^0 h_c) \times \mathcal{B}(h_c \to X)$ | $\mathcal{B}(h_c \to X)$ |
|---|---|---|---|---|---|
| (i) | $K^+K^-\pi^+\pi^-\pi^0$ | $80 \pm 15$ | 6.5 | $(2.8 \pm 0.5 \pm 0.3) \times 10^{-6}$ | $(3.3 \pm 0.6 \pm 0.6) \times 10^{-3}$ |
| (ii) | $\pi^+\pi^-\pi^0\eta$ | $35 \pm 9$ | 3.3 | $(6.2 \pm 1.6 \pm 0.7) \times 10^{-6}$ | $(7.2 \pm 1.8 \pm 1.3) \times 10^{-3}$ |
| | | $<50.0$ | | $<1.5 \times 10^{-5}$ | $<1.8 \times 10^{-2}$ |
| (iii) | $K_S^0 K^\pm \pi^\mp \pi^+\pi^-$ | $41 \pm 13$ | 5.5 | $(2.4 \pm 0.7 \pm 0.3) \times 10^{-6}$ | $(2.8 \pm 0.9 \pm 0.5) \times 10^{-3}$ |
| | | $<65.3$ | | $<3.9 \times 10^{-6}$ | $<4.7 \times 10^{-3}$ |
| (iv) | $K^+K^-\pi^0$ | $<20.1$ | 9.8 | $<4.8 \times 10^{-7}$ | $<5.8 \times 10^{-4}$ |
| (v) | $K^+K^-\eta$ | $<18.5$ | 14.3 | $<7.5 \times 10^{-7}$ | $<9.1 \times 10^{-4}$ |
| (vi) | $K^+K^-\pi^+\pi^-\eta$ | $<24.1$ | 6.9 | $<2.0 \times 10^{-6}$ | $<2.5 \times 10^{-3}$ |
| (vii) | $2(K^+K^-)\pi^0$ | $<11.7$ | 6.7 | $<2.1 \times 10^{-7}$ | $<2.5 \times 10^{-4}$ |
| (viii) | $K^+K^-\pi^0\eta$ | $<20.2$ | 6.3 | $<1.8 \times 10^{-6}$ | $<2.2 \times 10^{-3}$ |
| (ix) | $K_S^0 K^\pm \pi^\mp$ | $<17.4$ | 14.4 | $<4.8 \times 10^{-7}$ | $<5.7 \times 10^{-4}$ |
| (x) | $p\bar{p}\pi^0\pi^0$ | $<11.8$ | 8.7 | $<4.4 \times 10^{-7}$ | $<5.2 \times 10^{-4}$ |

- No explanation for missing $h_c$ decays was found even though most scenarios were covered!

PRD **102**, 112007 (2020)

# Search for new hadronic decays of $h_c$ and observation of $h_c \to K^+K^-\pi^+\pi^-\pi^0$




*Significance*

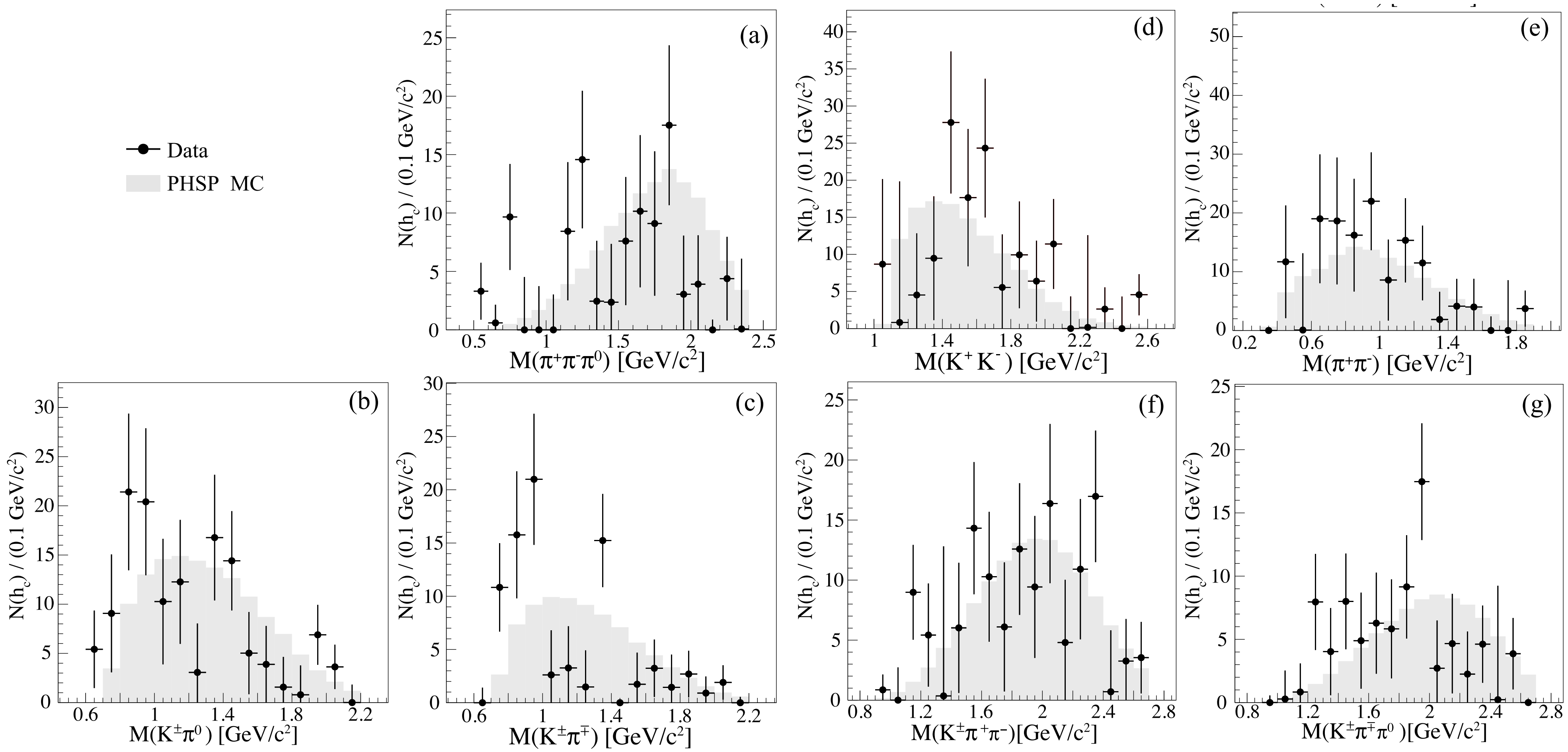
$< 3\sigma$

$< 3\sigma$

PRD **102**, 112007 (2020)

# Search for new hadronic decays of $h_c$ and observation of $h_c \to K^+K^-\pi^+\pi^-\pi^0$

- Search for subprocesses in the decay $h_c \to K^+K^-\pi^+\pi^-\pi^0$
- Signal yield determined by fits in bins of the respective subsystem
- Enhancements in the invariant $K\pi$ and $KK\pi$ masses hints to likely subprocess involving excited kaons as $h_c \to \left(K^*(892)/K^*_{0,2}(1430)\right)\left(K_2(1820)/K^*_2(1980)\right)$
- This would also explain the evidence for $h_c \to K^0_S K^\pm\pi^\mp\pi^+\pi^-$




PRD **102**, 112007 (2020)

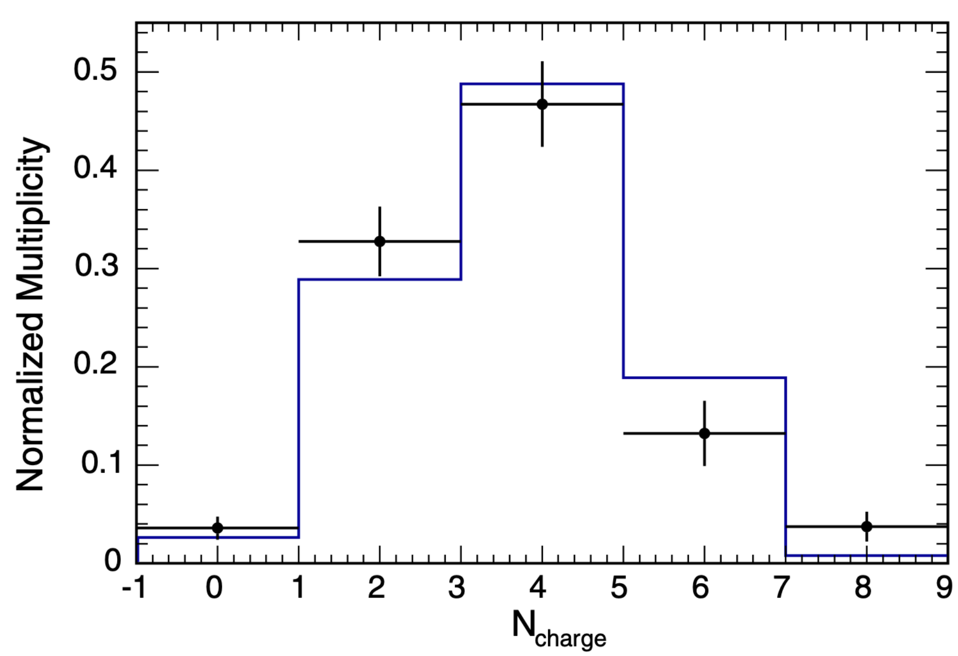
## Measurements of the branching fractions of $\eta_c \to K^+K^-\pi^0,\ K_S^0K^\pm\pi^\mp,\ 2\left(\pi^+\pi^-\pi^0\right)$, and $p\bar{p}$

Phys. Rev. D **100**, 012003 (2019)

# Measurements of the branching fractions of $\eta_c \to K^+K^-\pi^0$, $K_S^0K^\pm\pi^\mp$, $2\left(\pi^+\pi^-\pi^0\right)$, and $p\bar{p}$

- Studied via $e^+e^- \to \pi^+\pi^- h_c$ , $h_c \to \gamma\eta_c$ at $\sqrt{s} = 4.23, 4.26, 4.36, 4.42\,\mathrm{GeV}$
- Less background expected than in $J/\psi \to \gamma\eta_c$
- Results more precise than previous reports
- Additional inclusive measurement of charged track multiplicity in $\eta_c$ decays

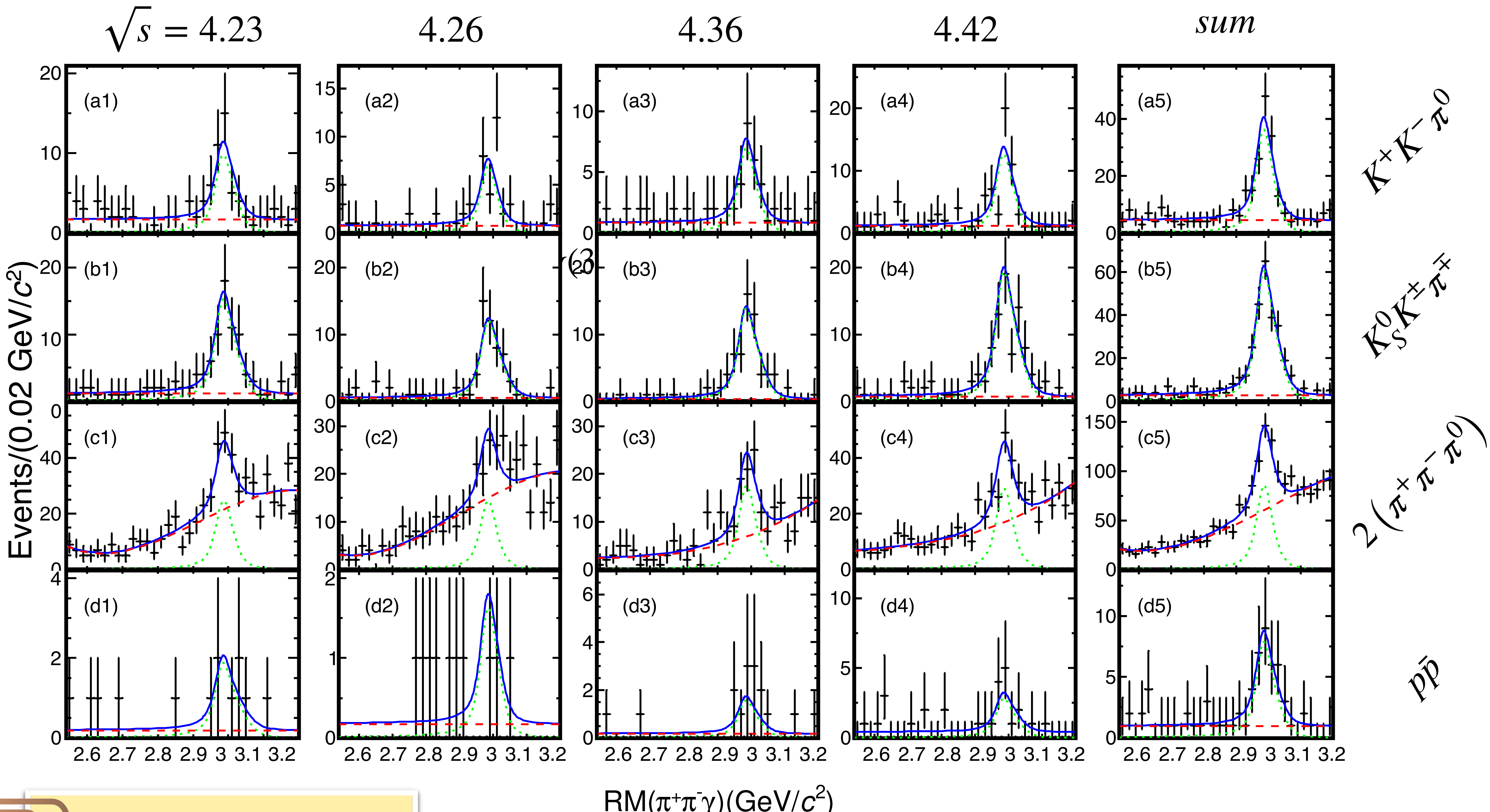
| Final states | BF (%) |
|---|---|
| $K^+K^-\pi^0$ | $1.15 \pm 0.12 \pm 0.10$ |
| $K_S^0K^\pm\pi^\mp$ | $2.60 \pm 0.21 \pm 0.20$ |
| $2(\pi^+\pi^-\pi^0)$ | $15.3 \pm 1.8 \pm 1.8$ |
| $p\bar{p}$ | $0.120 \pm 0.026 \pm 0.015$ |




| $N_{\mathrm{charge}}$ | Normalized values |
|---|---|
| 0 | $0.036 \pm 0.011 \pm 0.007$ |
| 2 | $0.328 \pm 0.035 \pm 0.043$ |
| 4 | $0.467 \pm 0.044 \pm 0.064$ |
| 6 | $0.132 \pm 0.033 \pm 0.022$ |
| ≥8 | $0.037 \pm 0.015 \pm 0.009$ |

PRD **100**, 012003 (2019)

# Measurements of the branching fractions of $\eta_c \to K^+K^-\pi^0, K_S^0K^\pm\pi^\mp, 2\left(\pi^+\pi^-\pi^0\right)$, and $p\bar{p}$




PRD **100**, 012003 (2019)

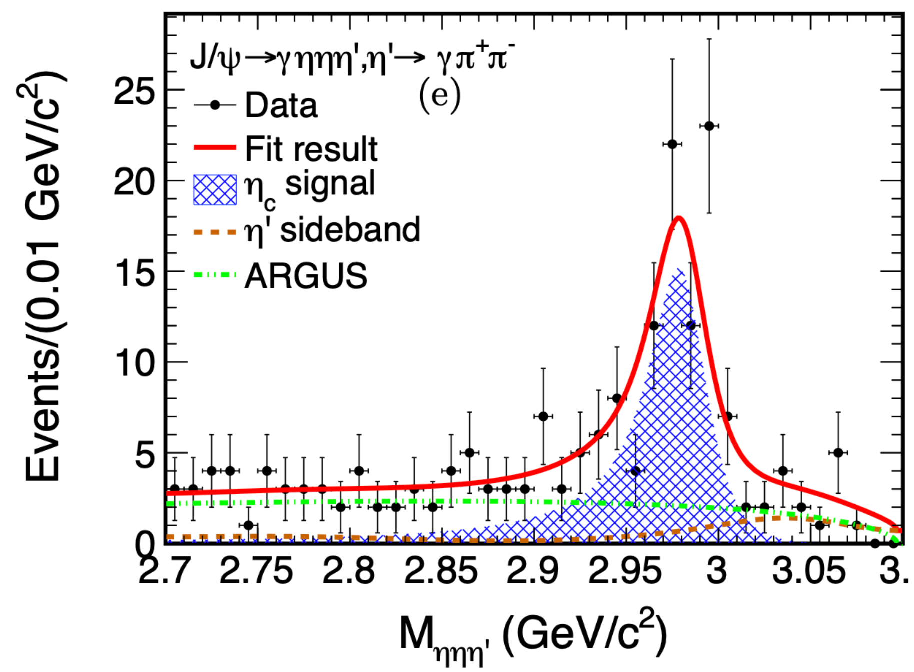
## Search for the X(2370) and observation of $\eta_c \to \eta\eta\eta'$ in $J/\psi \to \gamma\eta\eta\eta'$

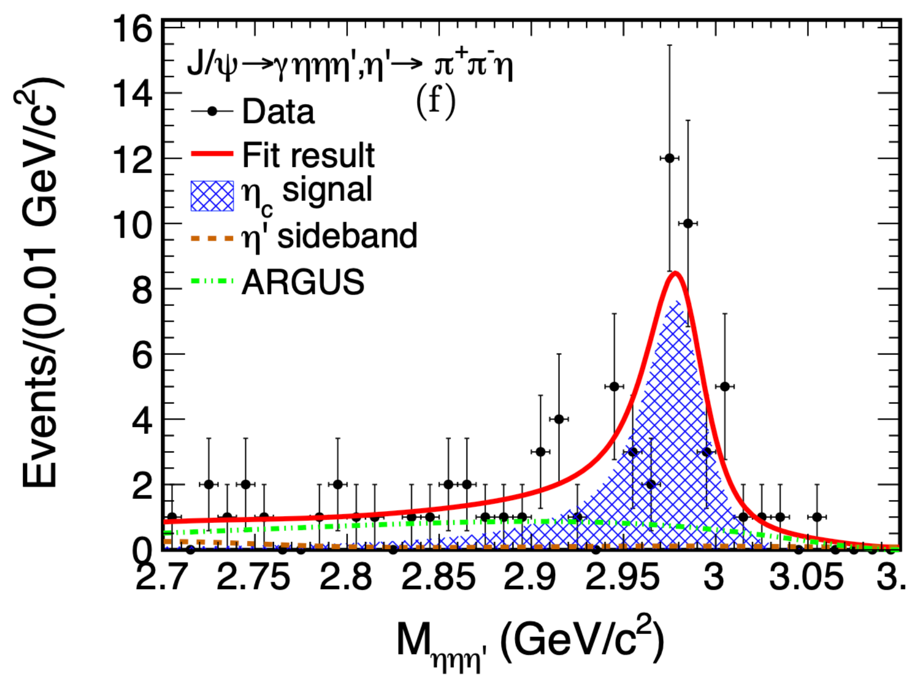
Phys. Rev. D **103**, 012009 (2021)

# Search for the X(2370) and observation of $\eta_c \to \eta\eta\eta'$ in $J/\psi \to \gamma\eta\eta\eta'$

- Main goal of the analysis was to study gluon rich decays and search for signatures of the $0^{-+}$ glueball candidate $X(2370)$
- Previous indications by BESIII: $J/\psi \to \gamma\pi^+\pi^-\eta', \gamma KK\eta'$ PRL 106.072002, EPJ C 80 746
- $\eta'$ reconstructed in $\gamma\pi^+\pi^-$ and $\pi^+\pi^-\eta$ decay modes
- No signal of $X(2370)$ found but signal of $\eta_c$ instead
- $BF(J/\psi \to \gamma\eta_c) \cdot BF(\eta_c \to \eta\eta\eta') = (4.86 \pm 0.62 \pm 0.45) \cdot 10^{-5}$
- Consistent with theoretical prediction $< 1 \cdot 10^{-4}$

EPJ A 54, 139 (2018)




PRD **103**, 012009 (2021)

# Summary and Perspectives

- Although the charmonium spectrum below the open charm threshold seems to be well established, knowledge of decay behaviour still sparse
- Theoretical models need experimental input to improve accuracy
- Experimentalists need guidance to search for specific reactions
- The largest data samples of $\psi(3686)$ and $J/\psi$ have been collected at BESIII

- BESIII currently accumulates more data at $\psi(3686)$
  ➡ 5 times more data soon!
- Many off-resonance samples available
- This offers unique possibilities to study rare processes and to improve statistical accuracy
- Energy range extended to almost $\sqrt{s} = 5\,\mathrm{GeV}$ recently!

- Further results from BESIII expected soon!