Charmonium Studies at BESIII

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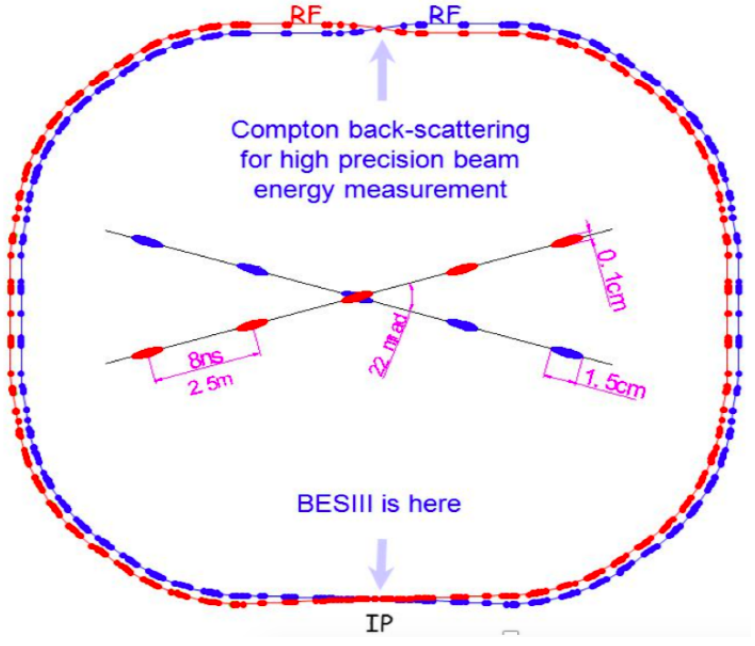
(on behalf of the BESIII collaboration)

International Workshop on e^+e^- collisions from Phi to Psi

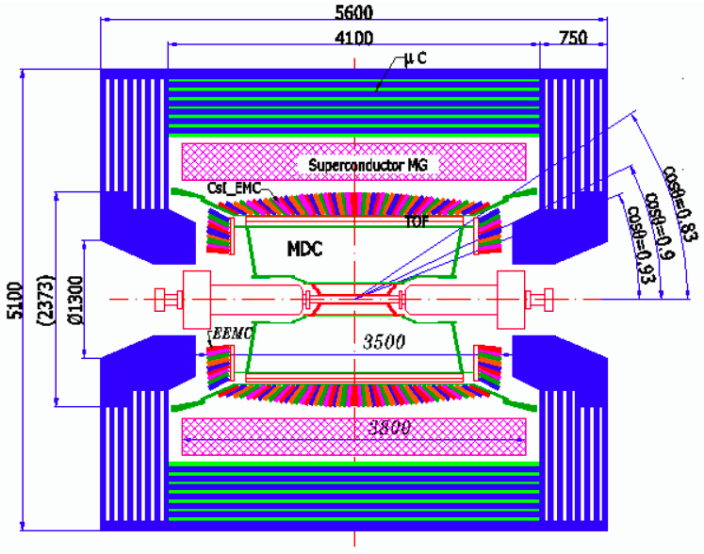
25 Feb. 2019 - 01 Mar. 2019 Budker INP, Novosibirsk

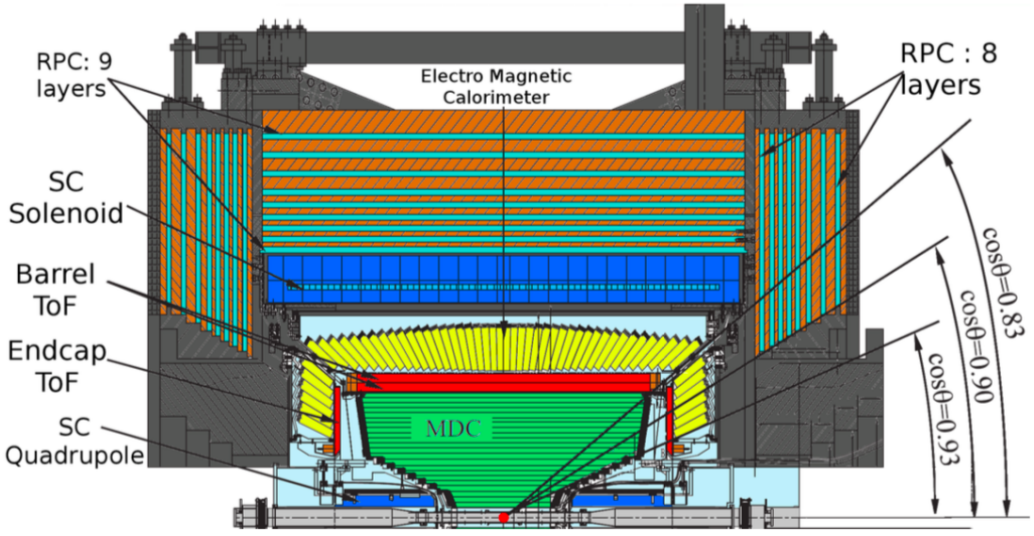
BEPCII Storage Rings

- A τ-charm factory (update of BEPC, first collisions July 2008)
- Beam energy: 1 - 2.3 GeV
- Optimum energy: 1.89 GeV
- Sigle beam current: 0.91 A
- Crossing angle: 11 mrad
- Design luminosity: 1×10^{33} cm^{-2}s^{-1}
- Reached luminosity: 1×10^{33} cm^{-2}s^{-1}



BESIII Detector





MDC:
Main Drift Chamber
$\sigma(p)/p \sim 0.5\%$
$\sigma_{dE/dx} \sim 5.0\%$

TOF:
Time of Flight
$\sigma(t) \sim 80$ ps (barrel)
$\sigma(t) \sim 70$ ps (endcap)

EMC:
Electromagnetic Calorimeter
$\sigma(E)/E \sim 2.5\%$
$\sigma_{z\phi}(E) \sim 0.5 - 0.7$ cm

MUC:
Muon Detector
$\sigma(xy) < 2$ cm

- J/ψ (~10 billion), ψ' (~0.45 billion) ...
- Low background

Recent Charmonium Studies at BESIII

- "12% rule" - $\frac{B(\psi' \to ggg)}{B(J/\psi \to ggg)} = \frac{\Gamma(\psi' \to e^+e^-)\cdot\Gamma(J/\psi)}{\Gamma(J/\psi \to e^+e^-)\cdot\Gamma(\psi')} = (12.2 \pm 2.4)\%$
- Quark model SU(3) flavor symmetry proposed $\eta - \eta'$ mixing angle - QCD inspired calculation and quark-line rule predicted a similar range
- OZI suppressed decays - Most of the hadronic χ_{cJ} decay modes are suppressed by OZI rule.
- Theory model different predictions test - Predictions related to the branching fractions, width *etc*. may be different based on different theoretical models.
- Investigation of internal structure and the interactions of the mesons with the electromagnetic field.
- Dark photon, Baryon number violation, Flavor changing neutral current ...

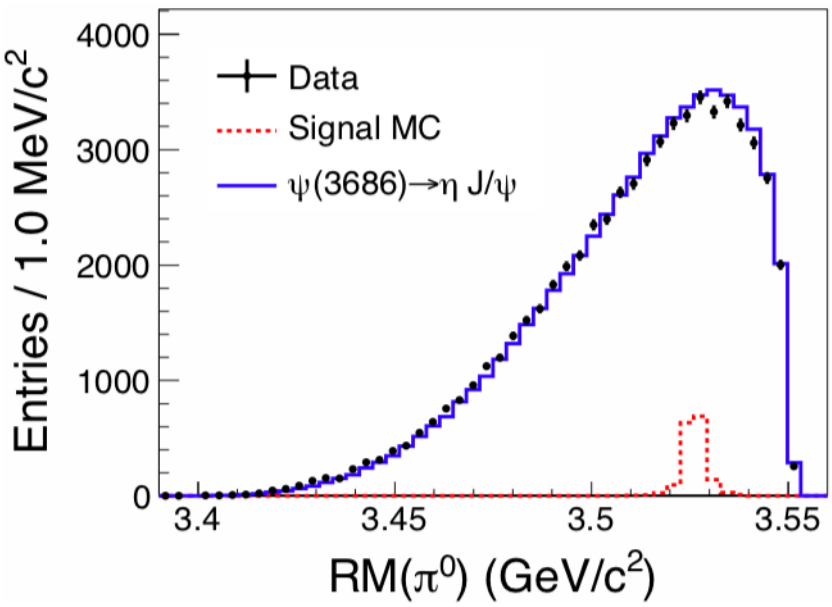
Some Recent Charmonium Analyses

- Search for $h_c \to \pi^+\pi^- J/\psi$ via $\psi' \to \pi^0\pi^+\pi^- J/\psi$
- Observation of OZI suppressed decays $\chi_{cJ} \to \omega\phi$
- Observation of electromagnetic Dalitz decays $\chi_{cJ} \to \mu^+\mu^- J/\psi$
- Observation of $\chi_{cJ} \to 4K_S^0$
- Observation of $h_c \to$ hadrons
- Observation of $\psi' \to p\bar{p}\eta'$
- Observation of $\psi' \to \eta' e^+ e^-$
- Observation of $\psi' \to n\bar{n}$
- Improved measurement of $\psi' \to p\bar{p}$
- Improved measurement of $J/\psi \to p\bar{p}\eta'$
- Improved measurement of $J/\psi \to \eta' e^+ e^-$

Search for $h_c \to \pi^+\pi^- J/\psi$ via $\psi' \to \pi^0\pi^+\pi^- J/\psi$

PRD 97, 052008 (2018)

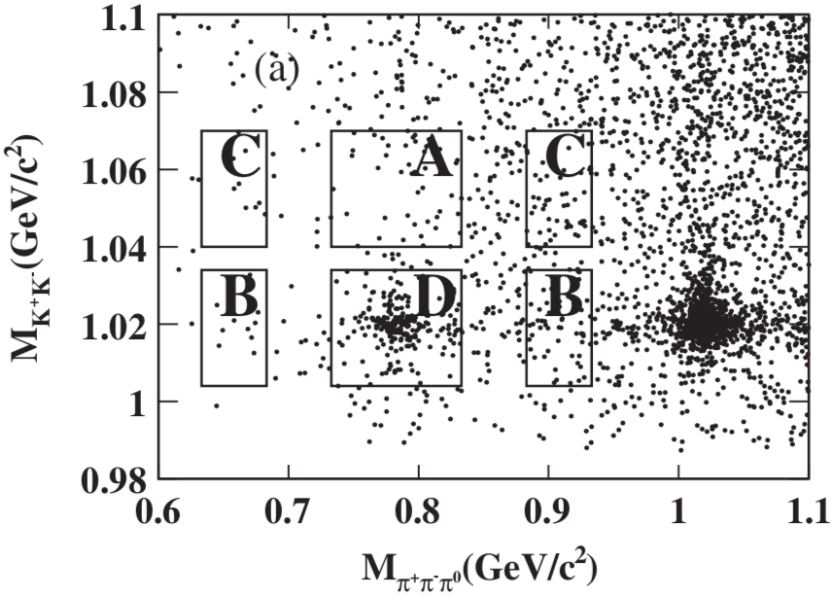
- In the framework of QCD Multipole Expansion, the branching fraction of $h_c \to \pi^+\pi^- J/\psi$ (including charged and neutral modes) is predicted to be 2%, while it is predicted to be 0.05% when neglecting the nonlocality in time
- $B(h_c \to \pi^+\pi^- J/\psi) < 3.6 \times 10^{-3}$ (90% C.L.)

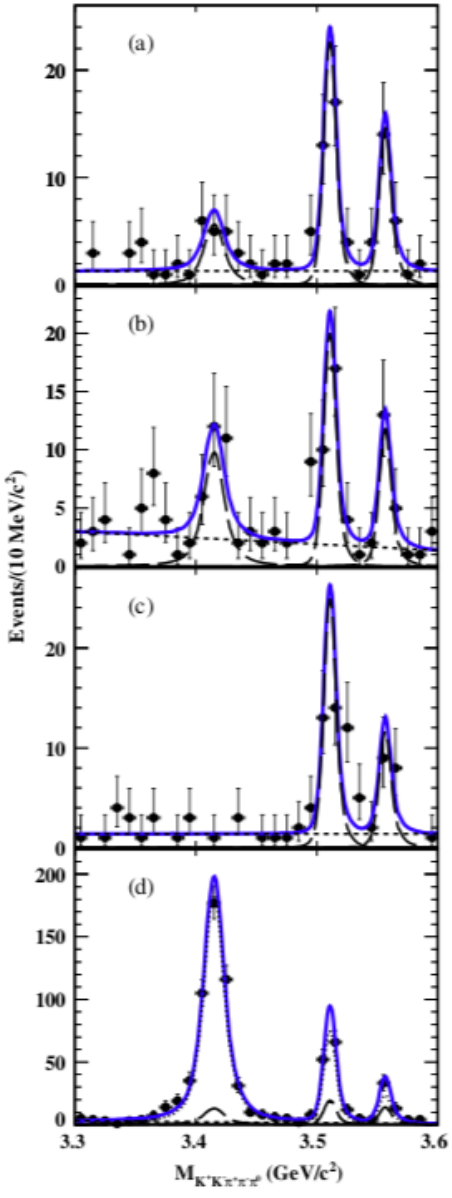


Observation of OZI suppressed decays $\chi_{cJ} \to \omega\phi$

PRD 99, 012015 (2019)

- Hadronic χ_{cJ} decays are import probes of the strong force dynamics.
- Hadronic $\chi_{cJ} \to VV$ decays are ideal objects to exploit the glueball-$q\bar{q}$ mixing and the quark-gluon coupling of the strong interactions at the relatively low energies.



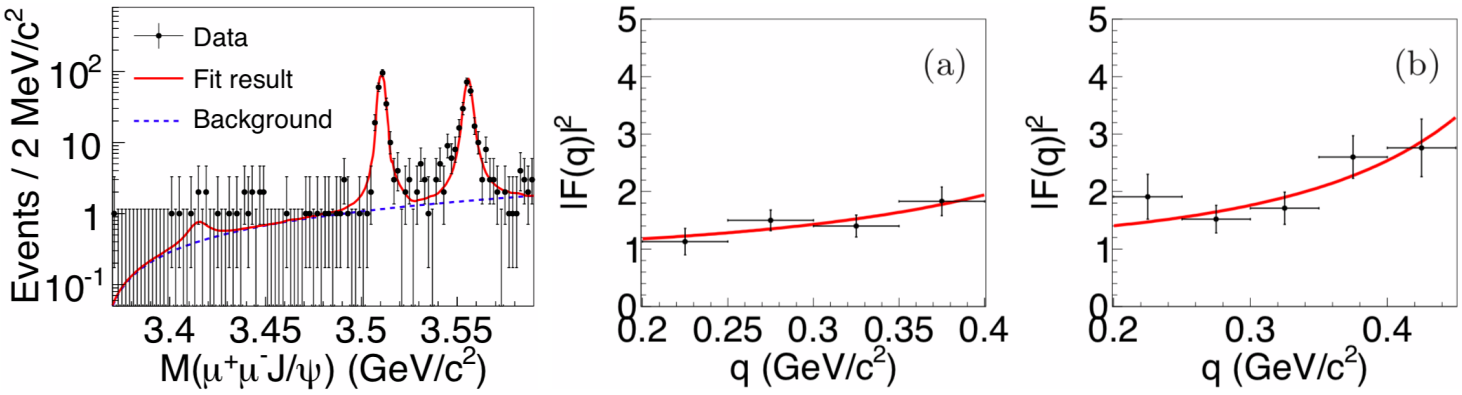


- $B(\chi_{c0} \to \omega\phi) = (13.84 \pm 0.70 \pm 1.08) \times 10^{-5}$
- $B(\chi_{c1} \to \omega\phi) = (2.80 \pm 0.32 \pm 0.30) \times 10^{-5}$
- $B(\chi_{c2} \to \omega\phi) = (1.00 \pm 0.25 \pm 0.14) \times 10^{-5}$ (4.8σ)

Study of electromagnetic Dalitz decays $\chi_{cJ} \to \mu^+\mu^- J/\psi$

arXiv:1901.06627

- Provide information on the internal structure and the interactions of the mesons with the electromagnetic field
- q-dependent transition form factor serves as a sensitive probe to the inner struture of the mesons involved



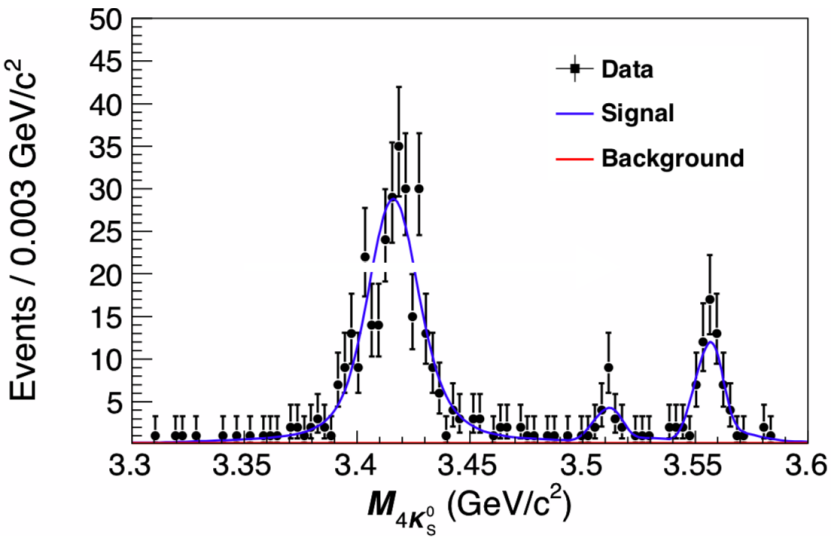
- $|F(q)|^2 = 1/(1 - q^2/\Lambda^2)$ distribution deviates from one, which indicates the TFF should be considered in the branching fraction calculation

Decay mode	Yields	Efficiency (%)	Branching fraction	$\frac{\mathcal{B}(\chi_{cJ}\to\mu^+\mu^- J/\psi)}{\mathcal{B}(\chi_{cJ}\to e^+e^- J/\psi)}$
$\chi_{c0} \to \mu^+\mu^- J/\psi$	< 9.5	9.40	$< 2.0 \times 10^{-5}$	< 0.14
$\chi_{c1} \to \mu^+\mu^- J/\psi$	221.9 ± 15.3	16.94	$(2.51 \pm 0.18 \pm 0.20) \times 10^{-4}$	$(6.73 \pm 0.51 \pm 0.50) \times 10^{-2}$
$\chi_{c2} \to \mu^+\mu^- J/\psi$	218.9 ± 16.1	18.42	$(2.33 \pm 0.18 \pm 0.29) \times 10^{-4}$	$(9.40 \pm 0.79 \pm 1.15) \times 10^{-2}$

Observation of $\chi_{cJ} \to 4K_S^0$

arXiv:1901.08207

- Theoretical predictions of χ_{cJ} decays to baryon anti-baryon pairs based on the color octet mechanism were inconsistent with experimental measurements
- More χ_{cJ} studies are mandatory to further understand χ_{cJ} decay dynamics.



- $B(\chi_{c0} \to 4K_S^0) = (5.76 \pm 0.34 \pm 0.38) \times 10^{-4}$
- $B(\chi_{c1} \to 4K_S^0) = (0.35 \pm 0.09 \pm 0.03) \times 10^{-4}$
- $B(\chi_{c2} \to 4K_S^0) = (1.14 \pm 0.15 \pm 0.08) \times 10^{-4}$

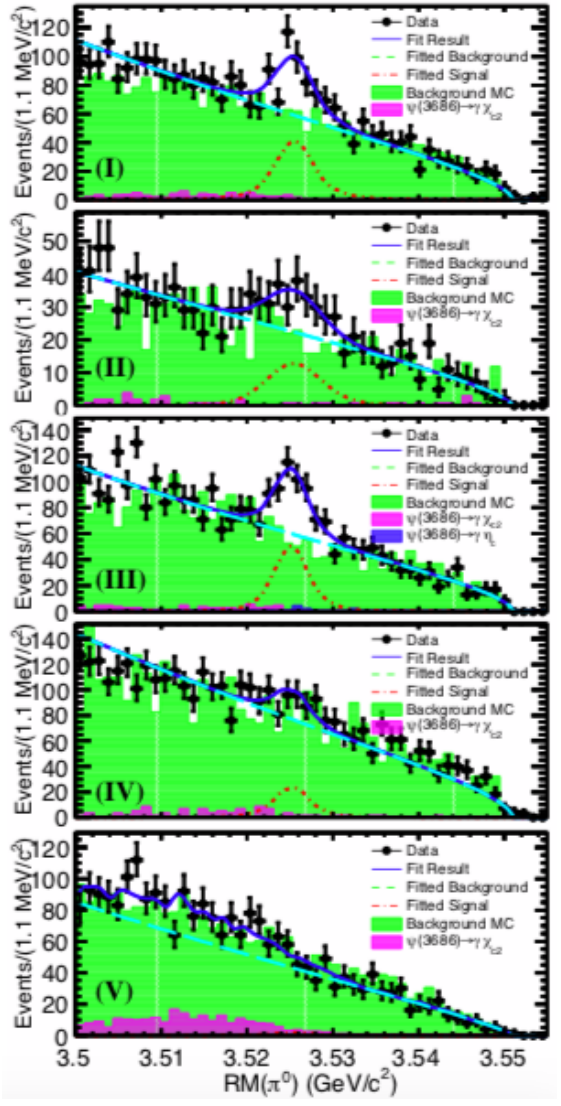
First observations of $h_c \to$ hadrons

arXiv:1810.12023

- Perturbative QCD and non-relativistic QCD predicted ratios of the hadronic widths of h_c to η_c ($\Gamma^{had}_{h_c}/\Gamma^{had}_{\eta_c}$) are very different, as well as h_c to J/ψ ($\Gamma^{had}_{h_c}/\Gamma^{had}_{J/\psi}$).

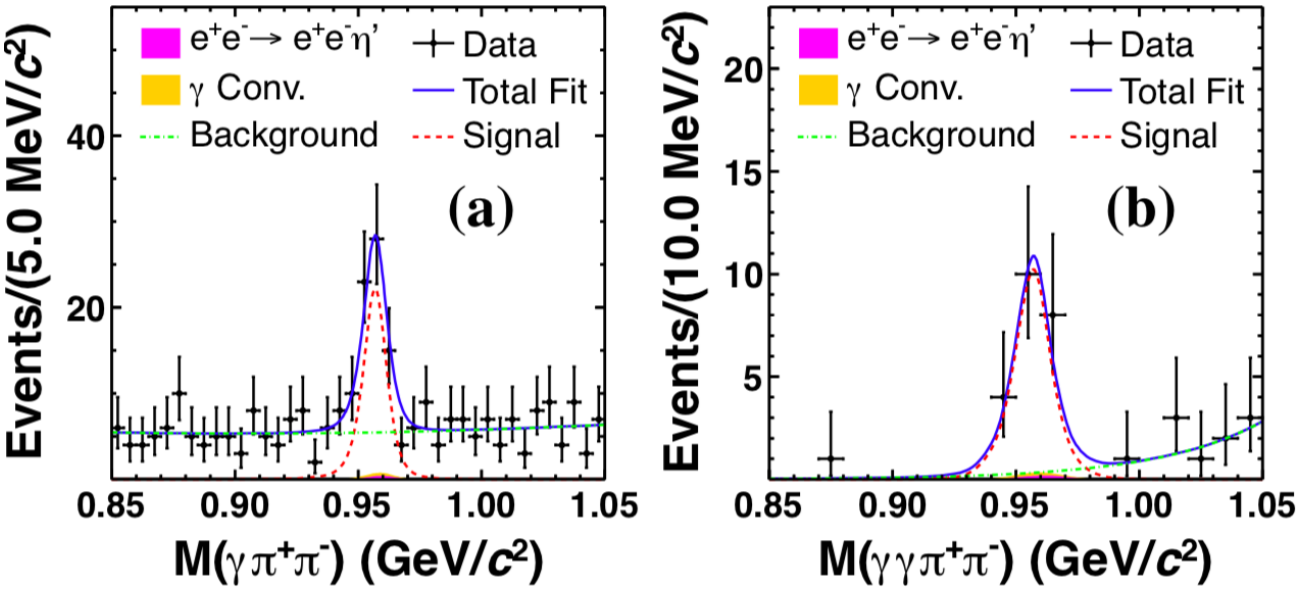
Mode	$B_{h_c}(10^{-3})$	S.S.	$B^{\rm PDG}_{h_c}(10^{-3})$
$h_c \to p\bar{p}\pi^+\pi^-$	$2.89 \pm 0.32 \pm 0.55$	7.4σ	–
$h_c \to \pi^+\pi^-\pi^0$	$1.60 \pm 0.40 \pm 0.32$	4.6σ	< 2.2
$h_c \to 2(\pi^+\pi^-)\pi^0$	$7.44 \pm 0.94 \pm 1.52$	9.1σ	22^{+8}_{-7}
$h_c \to 3(\pi^+\pi^-)\pi^0$	$4.65 \pm 2.17 \pm 1.08$ < 8.7	2.1σ –	< 29
$h_c \to K^+K^-\pi^+\pi^-$	< 0.6	–	–

	Model/Mode	Ratio
$\Gamma^{\rm had}_{h_c}/\Gamma^{\rm had}_{\eta_c}$	pQCD	0.010 ± 0.001
	NRQCD	0.083 ± 0.018
	$p\bar{p}\pi^+\pi^-$	0.012 ± 0.008
	$K^+K^-\pi^+\pi^-$	< 0.083
$\Gamma^{\rm had}_{h_c}/\Gamma^{\rm had}_{J/\psi}$	pQCD	0.68 ± 0.07
	NRQCD	8.03 ± 1.31
	$p\bar{p}\pi^+\pi^-$	3.63 ± 2.25
	$\pi^+\pi^-\pi^0$	0.57 ± 0.38
	$2(\pi^+\pi^-)\pi^0$	1.43 ± 0.90
	$3(\pi^+\pi^-)\pi^0$	< 2.26
	$K^+K^-\pi^+\pi^-$	< 0.68



Observation of $\psi' \to \eta' e^+ e^-$

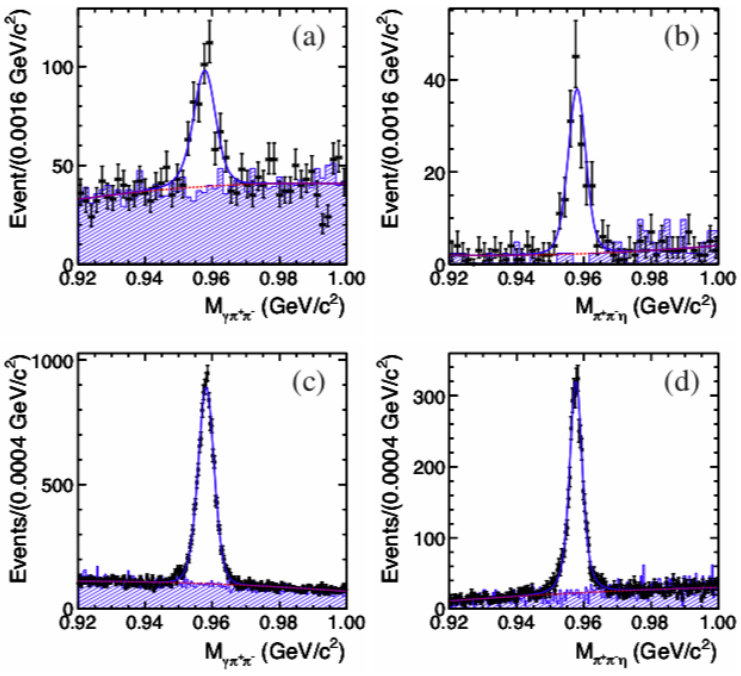
PLB 783, 452 (2018)



- The electronmagnetic (EM) Dalitz decays is of great interest of our understanding of both the intrinsic structure of hadrons and the fundamental mechanisms of the interactions between photons and hadrons.
- By studying $\psi' \to \eta' e^+ e^-$, it is important to understand the interaction of charmonium vector states width photon, and helpful for further studies on the $\psi \to VP$ process.
- We observe the charmonium EM Dalitz decay $\psi' \to \eta' e^+ e^-$ for the first time. The branching fraction is measured to be $(1.64 \pm 0.22 \pm 0.09) \times 10^{-6}$.

Observation of $\psi' \to p\bar{p}\eta'$ and improved measurement of $J/\psi \to p\bar{p}\eta'$

PRD 99, 032006 (2019)

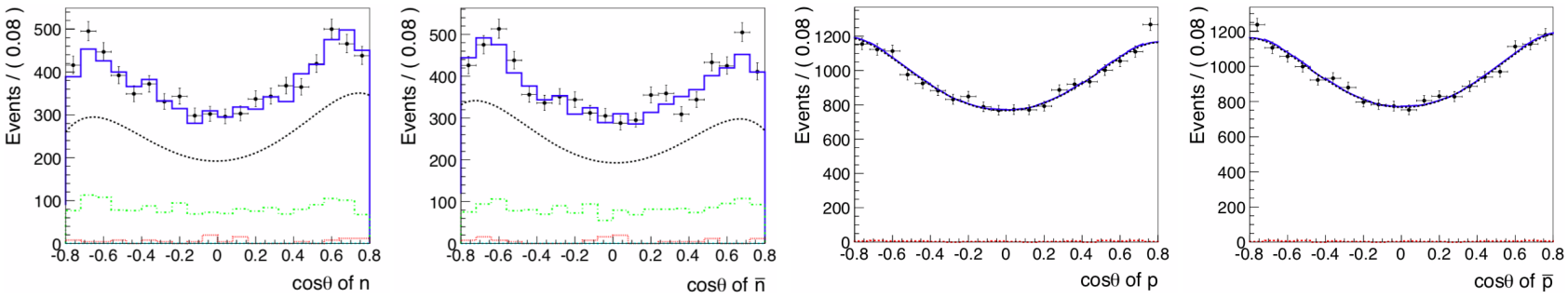


- $B(\psi' \to p\bar{p}\eta') = (1.10 \pm 0.10 \pm 0.08) \times 10^{-5}$
  $B(J/\psi \to p\bar{p}\eta') = (1.26 \pm 0.02 \pm 0.07) \times 10^{-4}$
- Quark model SU(3) flavour symmetry proposed $\eta - \eta'$ mixing angle is calculated as
  $-24^\circ \pm 9^\circ$ with $\psi' \to p\bar{p}\eta'$, $p\bar{p}\eta$
  $-24^\circ \pm 11^\circ$ with $J/\psi \to p\bar{p}\eta'$, $p\bar{p}\eta$,
  which is expected to be $-(10^\circ \pm 17^\circ)$ based on QCD inspired calculation or $-(13^\circ \pm 16^\circ) \pm 6^\circ$ based on the quark-line rule (QLR)..
- "12% rule" is tested to be $\frac{B(\psi' \to p\bar{p}\eta')}{B(J/\psi \to p\bar{p}\eta')} = (8.7 \pm 1.0)\%$, which is not taken phase space into account. If considering the phase space and possible intermidiate struture, the "12% rule" will be violated significantly.

Observation of $\psi' \to n\bar{n}$ and improved measurement of $\psi' \to p\bar{p}$

PRD 98, 032006 (2018)

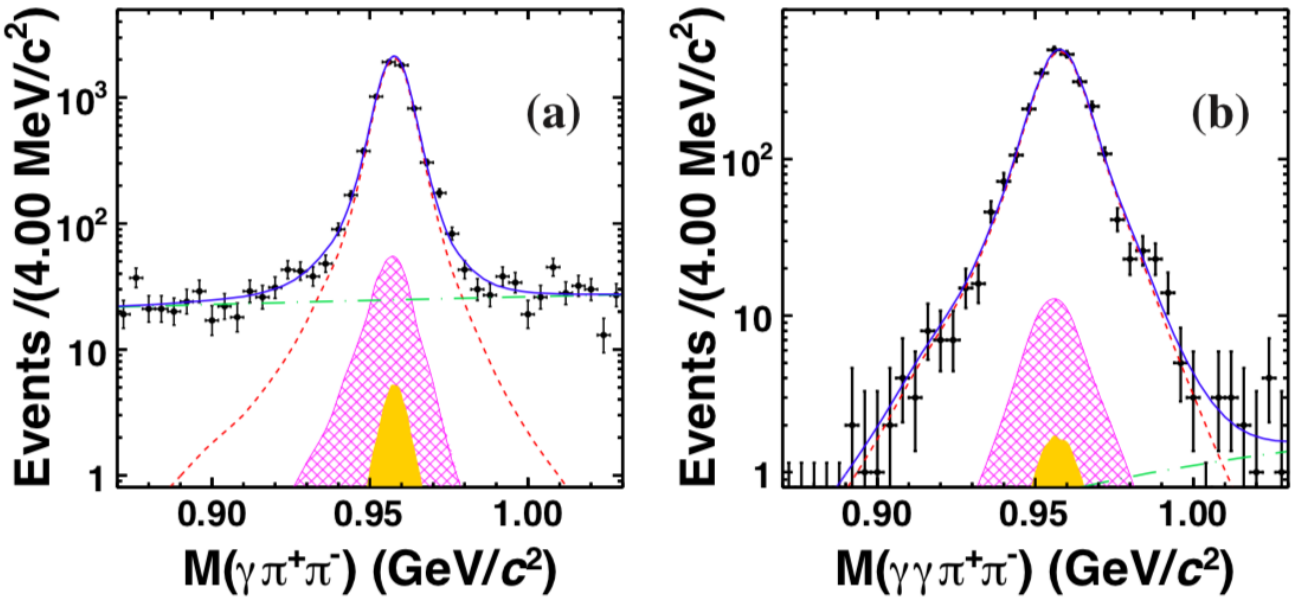
- Allows the determination of the relative phase angle between the amplitudes of the strong and electromagnetic interactions.



- $B(\psi' \to n\bar{n}) = (3.06 \pm 0.06 \pm 0.14) \times 10^{-4}$ and $\alpha_{n\bar{n}} = 0.68 \pm 0.12 \pm 0.11$
- $B(\psi' \to p\bar{p}) = (3.05 \pm 0.02 \pm 0.12) \times 10^{-4}$ and $\alpha_{p\bar{p}} = 1.03 \pm 0.06 \pm 0.03$
- Perturbative QCD "12% rule" is checked with results:
  $\frac{B(\psi' \to p\bar{p})}{B(J/\psi \to p\bar{p})} = (14.8 \pm 1.2)\%$ $\frac{B(\psi' \to n\bar{n})}{B(J/\psi \to n\bar{n})} = (14.4 \pm 0.6)\%$
- Via $J/\psi \to n\bar{n}, p\bar{p}$ with close BFs and α, it's expected if the strong interaction is dominant in $J/\psi \to N\bar{N}$ decay and the relative phase of between the strong and electromagnetic amplitudes is close to 90°
- In contrast, in ψ' decays, the BFs are close, but αs are not, which may imply a more complex mechanism in $J/\psi \to N\bar{N}$. More studies are deserved.

Measurement of $B(J/\psi \to \eta' e^+ e^-)$

PRD 99, 012013 (2019)



- Provides important information on the interaction at the $V - P$ transition vertex
- $B(J/\psi \to \eta' e^+ e^-) = (6.59 \pm 0.07 \pm 0.17) \times 10^{-5}$
- Compatible with the previous BESIII measurement and the precision is greatly improved from 6% to 3%

Summary

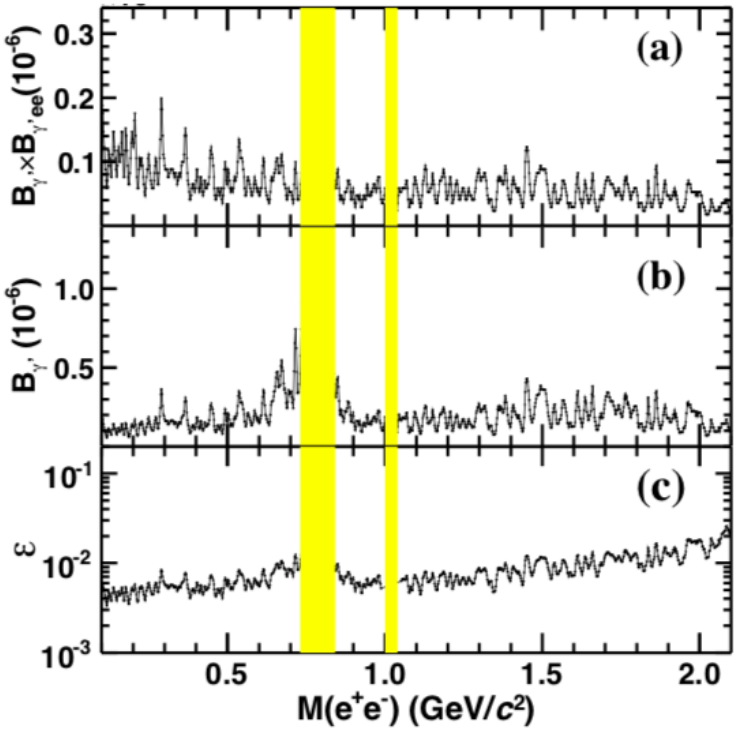
- The largest data samples of J/ψ and ψ' have been collected at BESIII.
- Many interesting charmonium decays have been measured, a few of them are included in this talk.
- In the future, more exciting results are expected, such as missing charmonium states searching, XYZ studies and so on.

Thanks for your attention

Backup

Measurement of $B(J/\psi \to \eta' e^+ e^-)$ and search for a dark photon

PRD 99, 012013 (2019)

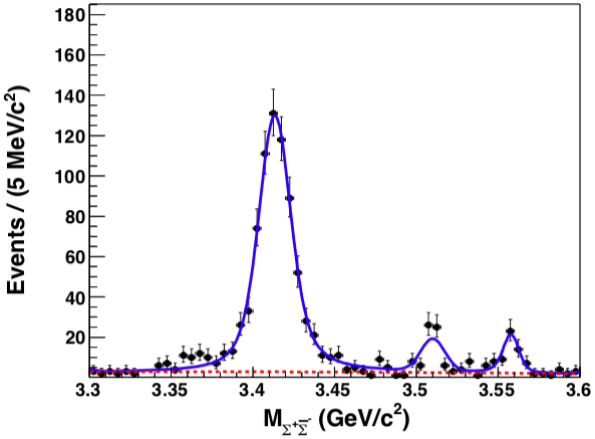


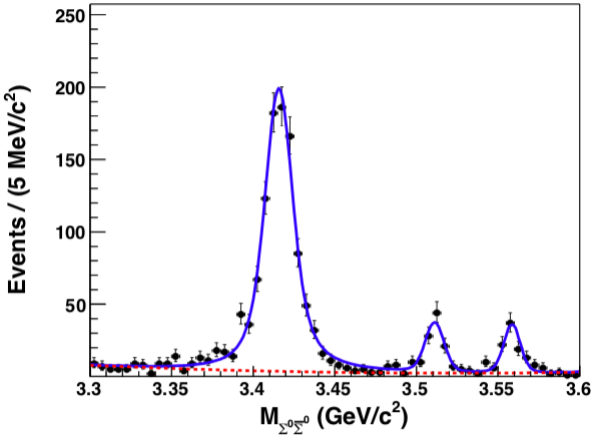
- Many models beyond SM have proposed the existence of a dark sector
- No significant signal of γ' is oberved
- Upper limit at 90% C.L.: $5.7 \times 10^{-8} < B(J/\psi \to \eta'\gamma') < 7.4 \times 10^{-7}$
- Exclusion limit on the mixing strength ϵ between the SM photon and dark photon varies in a range from 3.4×10^{-3} to 2.6×10^{-2} depending on $m_{\gamma'}$. This is among the first searches for the dark photon in the charmonium decays.

Improved measurements of $\chi_{cJ} \to \Sigma^+\bar{\Sigma}^-$ and $\Sigma^0\bar{\Sigma}^0$ decays

PRD 97, 052011 (2018)

- Contributions of the color octet mechanism to decays of P-wave heavy quarkonia have been proposed, and many theoretical predictions for exclusive χ_{cJ} decays to baryon anti-baryon pairs have been made. However, there are large differences between predictions and the experimental measurements.





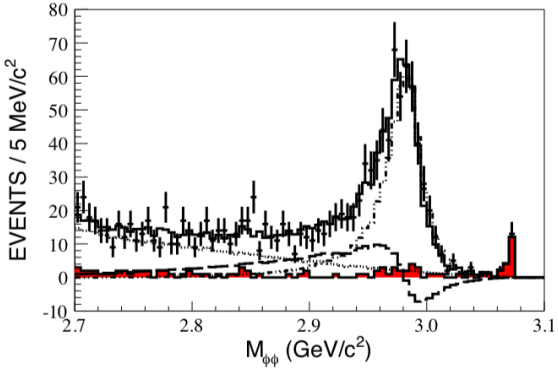
Channel	This work
$\chi_{c0} \to \Sigma^+\bar{\Sigma}^-$	$50.4 \pm 2.5 \pm 2.7$
$\chi_{c1} \to \Sigma^+\bar{\Sigma}^-$	$3.7 \pm 0.6 \pm 0.2$
$\chi_{c2} \to \Sigma^+\bar{\Sigma}^-$	$3.5 \pm 0.7 \pm 0.3$
$\chi_{c0} \to \Sigma^0\bar{\Sigma}^0$	$47.7 \pm 1.8 \pm 3.5$
$\chi_{c1} \to \Sigma^0\bar{\Sigma}^0$	$4.3 \pm 0.5 \pm 0.3$
$\chi_{c2} \to \Sigma^0\bar{\Sigma}^0$	$3.9 \pm 0.5 \pm 0.3$

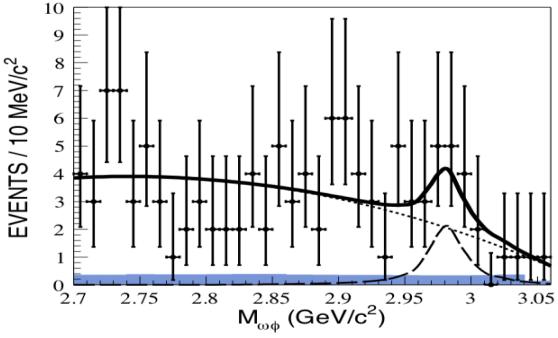
- Currect results of $\chi_{c1,2} \to \Sigma^+\bar{\Sigma}^-$ and $\Sigma^0\bar{\Sigma}^0$ are in good agreement with theoretical predictions based on the color octet contribution model.
- The results of $\chi_{c0} \to \Sigma^+\bar{\Sigma}^-$ and $\Sigma^0\bar{\Sigma}^0$ are still inconsistent with the prediction based on the charm meson loop mechanism.
- The ratio beteen charged and neutral decay modes is consistent with the expectation from isospin symmetry.

Improved measurements of branching fractions for $\eta_c \to \phi\phi$ and $\omega\phi$

PRD 95, 092004 (2017)

- Decays of η_c into vector meson pairs have stood as a bewildering puzzle in charmonium physics for a long time.
- Highly suppressed at leading order in QCD, due to the helicity selection rule (HSR), predicted $B(\eta_c \to \phi\phi) \sim 2 \times 10^{-7}$
- Improved calculations with next-to-leading order and relativistic corrections in QCD yield branching fractions varying from 10^{-5} to 10^{-4}





Experiment	$Br(J/\psi \to \gamma\eta_c)Br(\eta_c \to \phi\phi)(\times 10^{-5})$	$Br(\eta_c \to \phi\phi)$ $(\times 10^{-3})$
BESIII	$4.3 \pm 0.5^{+0.5}_{-1.2}$	$2.5 \pm 0.3^{+0.3}_{-0.7} \pm 0.6$
BESII [5]	3.3 ± 0.8	1.9 ± 0.6
DM2 [30]	3.9 ± 1.1	2.3 ± 0.8
Theoretical	Prediction	$Br(\eta_c \to \phi\phi)$ $(\times 10^{-3})$
	pQCD[10]	$(0.7 \sim 0.8)$
	$^3P_0$ quark model [13]	$(1.9 \sim 2.0)$
	Charm meson loop [14]	2.0

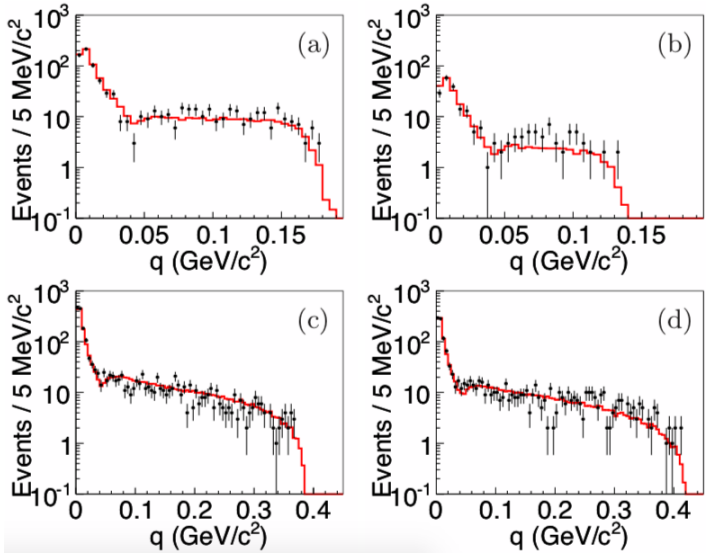
- Nonperturbative mechanisms play an important role in charmonium decay.
- Doubly OZI suppressed decay $B(\eta_c \to \omega\phi) < 2.5 \times 10^{-4}$
- The importance of QCD higher twist contributions or the presence of a non-pQCD mechanism.

Observation of $\psi' \to e^+e^-\chi_{cJ}$ and $\chi_{cJ} \to e^+e^- J/\psi$

PRL 118, 221802 (2017)

Mode	Yields	Efficiency(%)	Branching fraction	$\frac{\mathcal{B}(\psi(3686)\to e^+e^-\chi_{cJ})}{\mathcal{B}(\psi(3686)\to\gamma\chi_{cJ})}$	$\frac{\mathcal{B}(\chi_{cJ}\to e^+e^- J/\psi)}{\mathcal{B}(\chi_{cJ}\to\gamma J/\psi)}$
$\psi(3686) \to e^+e^-\chi_{c0}$	48 ± 10	6.06	$(11.7 \pm 2.5 \pm 1.0) \times 10^{-4}$	$(9.4 \pm 1.9 \pm 0.6) \times 10^{-3}$	–
$\psi(3686) \to e^+e^-\chi_{c1}$	873 ± 30	5.61	$(8.6 \pm 0.3 \pm 0.6) \times 10^{-4}$	$(8.3 \pm 0.3 \pm 0.4) \times 10^{-3}$	–
$\psi(3686) \to e^+e^-\chi_{c2}$	227 ± 16	3.19	$(6.9 \pm 0.5 \pm 0.6) \times 10^{-4}$	$(6.6 \pm 0.5 \pm 0.4) \times 10^{-3}$	–
$\chi_{c0} \to e^+e^- J/\psi$	56 ± 11	6.95	$(1.51 \pm 0.30 \pm 0.13) \times 10^{-4}$	–	$(9.5 \pm 1.9 \pm 0.7) \times 10^{-3}$
$\chi_{c1} \to e^+e^- J/\psi$	1969 ± 46	10.35	$(3.73 \pm 0.09 \pm 0.25) \times 10^{-3}$	–	$(10.1 \pm 0.3 \pm 0.5) \times 10^{-3}$
$\chi_{c2} \to e^+e^- J/\psi$	1354 ± 39	11.23	$(2.48 \pm 0.08 \pm 0.16) \times 10^{-3}$	–	$(11.3 \pm 0.4 \pm 0.5) \times 10^{-3}$

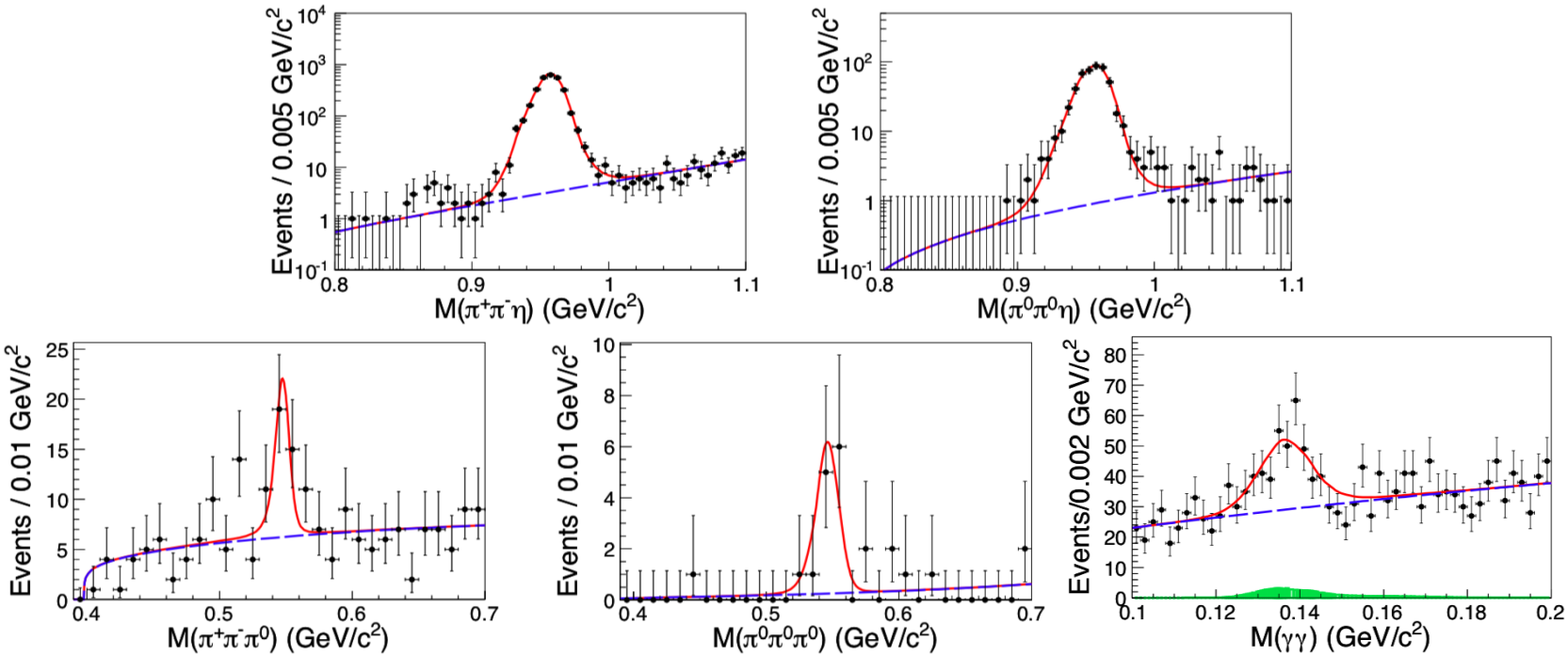
- The measured q^2 distribution are consistent with those of the signal MC simulation based on the assumption of a point-like meson.
- This first observation of the q^2-dependent charmonium EM Dalitz transitions can help understand the discrepancy between the experimental measurements and the theoretical predictions of the $\psi' \to \gamma\chi_{cJ}$ branching fractions.



Measurement of branching fractions for $\psi' \to \gamma\eta',\ \gamma\eta$ and $\gamma\pi^0$

PRD 96, 052003 (2017)

- Important tests for the different theoretical predictions, such as $\eta_c - \eta'$ mixing, final state radiation by light quarks, and the vector-meson dominance model in association with $\eta_c - \eta'$ mixing.
- The ratio $R_{J/\psi} = \frac{B(J/\psi \to \gamma\eta)}{B(J/\psi \to \gamma\eta')}$ has been predicted based on the first order perturbative QCD calculation, and $R_{\psi'} = \frac{B(\psi' \to \gamma\eta)}{B(\psi' \to \gamma\eta')}$ is expected to be approximately equal to $R_{J/\psi}$.
- The decay ratioes of J/ψ and $\psi' \to \gamma\pi^0$ are expected to be smaller than $\gamma\eta$ or $\gamma\eta'$ as a consequence of suppressed gluon coupling to isovector current.



Measurement of branching fractions for $\psi' \to \gamma\eta'$, $\gamma\eta$ and $\gamma\pi^0$

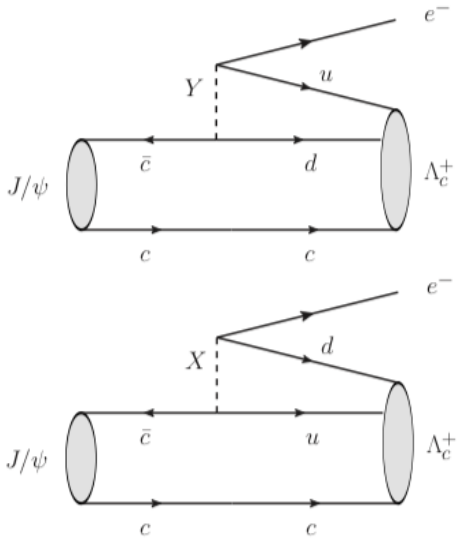
PRD 96, 052003 (2017)

Decay mode	Significance	$N_{\rm sig}^{\rm cor}$	$\mathcal{B}(\psi(3686) \to \gamma\eta'/\eta/\pi^0)$	Previous results from BESIII [11]
$\psi(3686) \to \gamma\eta'$	$> 10\sigma$	56053.5 ± 980.8	$(125.1 \pm 2.2 \pm 6.2) \times 10^{-6}$	$(126 \pm 3 \pm 8) \times 10^{-6}$
$\psi(3686) \to \gamma\eta$	7.3σ	382.5 ± 78.9	$(0.85 \pm 0.18 \pm 0.04) \times 10^{-6}$	$(1.38 \pm 0.48 \pm 0.09) \times 10^{-6}$
$\psi(3686) \to \gamma\pi^0$	6.7σ	423.4 ± 71.4	$(0.95 \pm 0.16 \pm 0.05) \times 10^{-6}$	$(1.58 \pm 0.40 \pm 0.13) \times 10^{-6}$

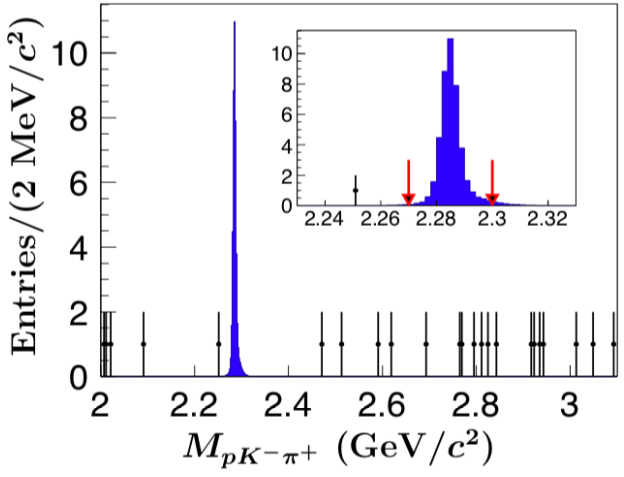
- $R_{\psi'}$ is about 30 times smaller than $R_{J/\psi}$. The larger difference could be explained by the approach proposed in Ref. PLB 697, 52 (2011).
- $B(\psi' \to \gamma\pi^0)$ predicted in Ref. PLB 697, 52 (2011) turns out to be one order smaller than this measurement.

Search for Baryon and Lepton Number Violation in $J/\psi \to \Lambda_c^+ e^- + c.c.$

arXiv:1803.04789



- Various grand unified theories and many standard model extensions predict baryon number violation. But nucleon decay has not yet been observed.
- The CLEO Collaboration searched for very rare processes which violate BN conservation in decays of heavy-flavor mesons. In particular, they suggested to look for the process $D_0 \to \bar{p} + e^+$, which is an inverse process of $p \to \pi^0 e^+$ at the quark level.



- $B(J/\psi \to \Lambda_c^+ e^-) < 6.9 \times 10^{-8}$
- More than two orders of magnitude more strict than that of CLEO's measurement in the analogous process. The result is one of the best constraints from meson decays and is consistent with the conclusion drawn from the proton decay experiment.

Search for the rare decay of $\psi' \to \Lambda_c^+ \bar{p} e^+ e^- + c.c.$ at BESIII

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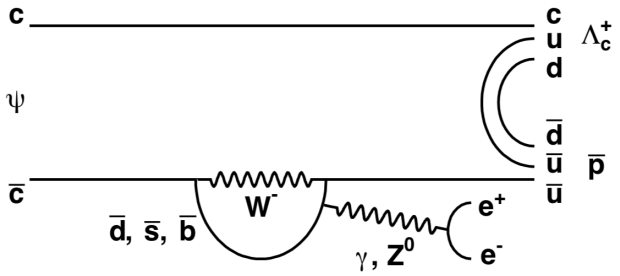
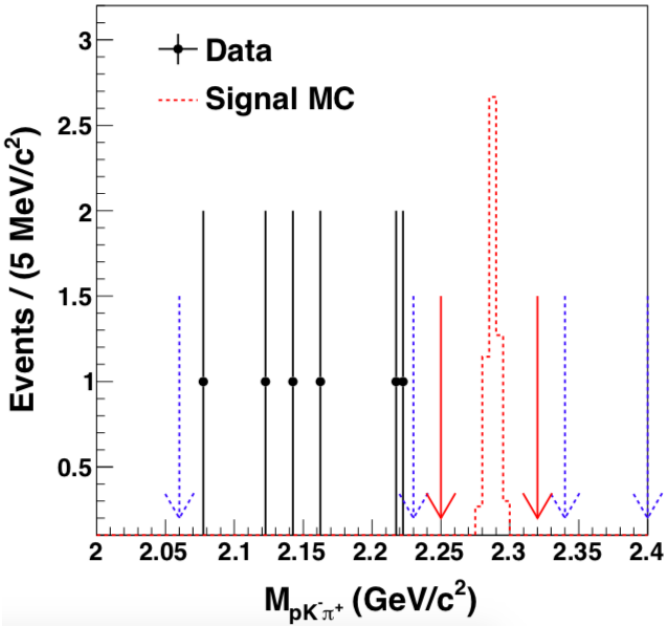
- Flavor changing neutal current transition of heaven quarkonium are of great interest since they can provide indications for physics beyond the SM.
- Four-quark operator description predict these BFs in the range from 10^{-5} to 10^{-6}, which is within the sensitivity of the BESIII experiments.





- No signal event is observed and the upper limit on the BF at the 90% C.L. is determiend to be 1.6×10^{-6}. The result is within the expectation of the SM, and no evidence for new physics is found.