中国地质大学
China University of Geosciences

The study of exotic states $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ in pp collisions

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7th workshop on the XYZ particles

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Outline

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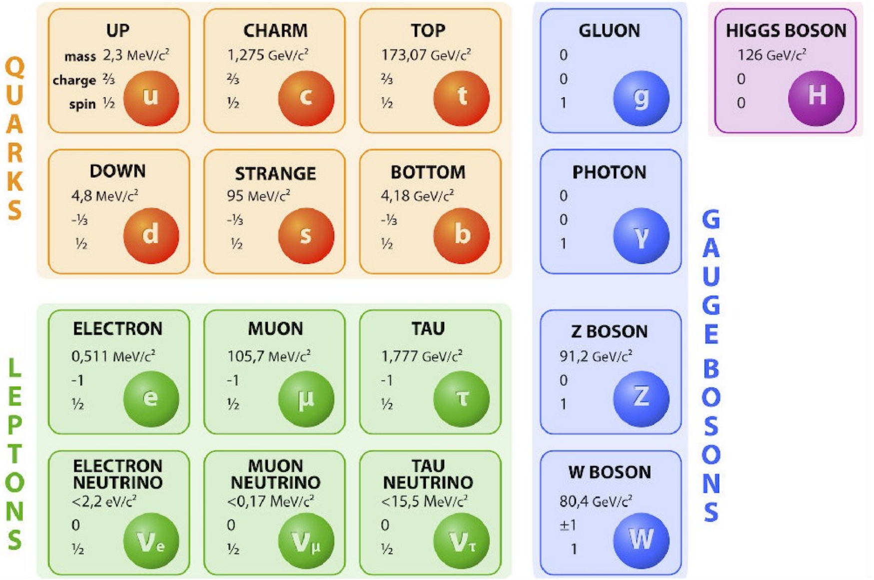
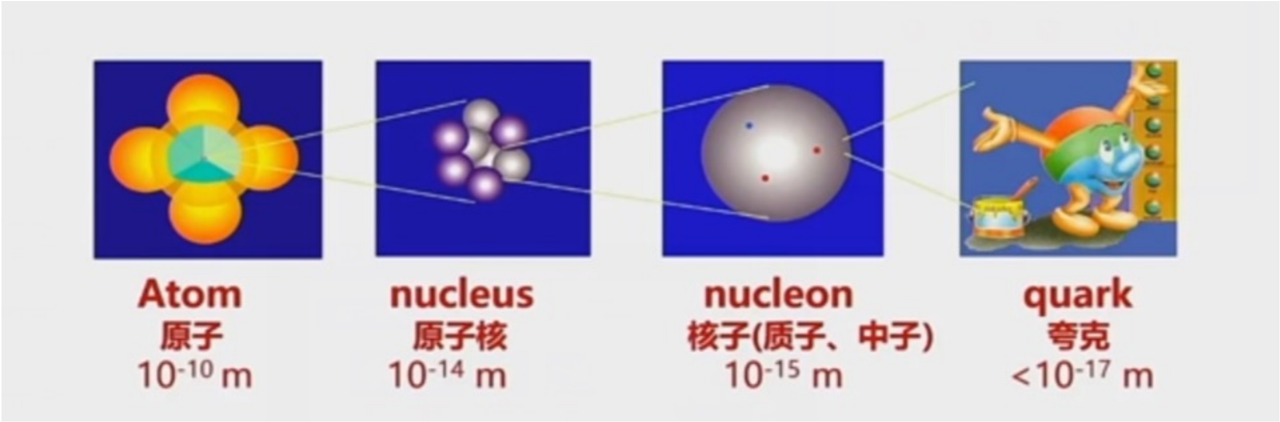
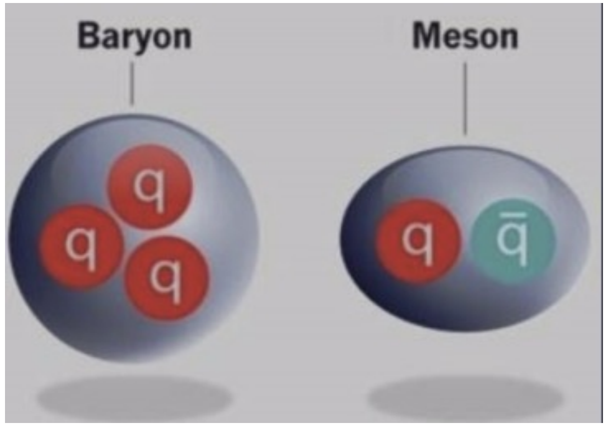
Introduction

Particle physicists believe that quarks are the building block for the matter in our viable universe. Due to the color confinement of strong interaction, quarks are bounded into the color neutral hadrons with different configurations.



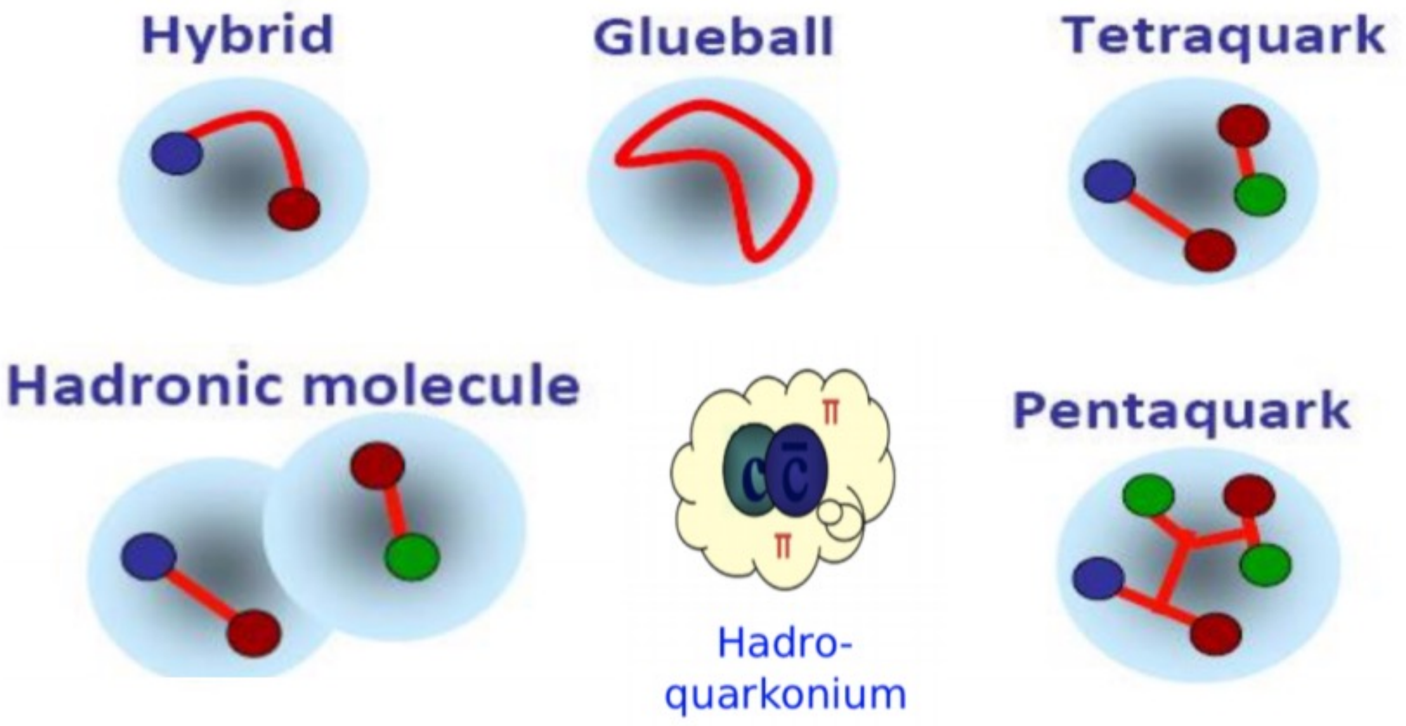




Introduction

However, other unconventional configurations with more quarks or gluons are also allowed to exist in the quark model framework.

exotic state



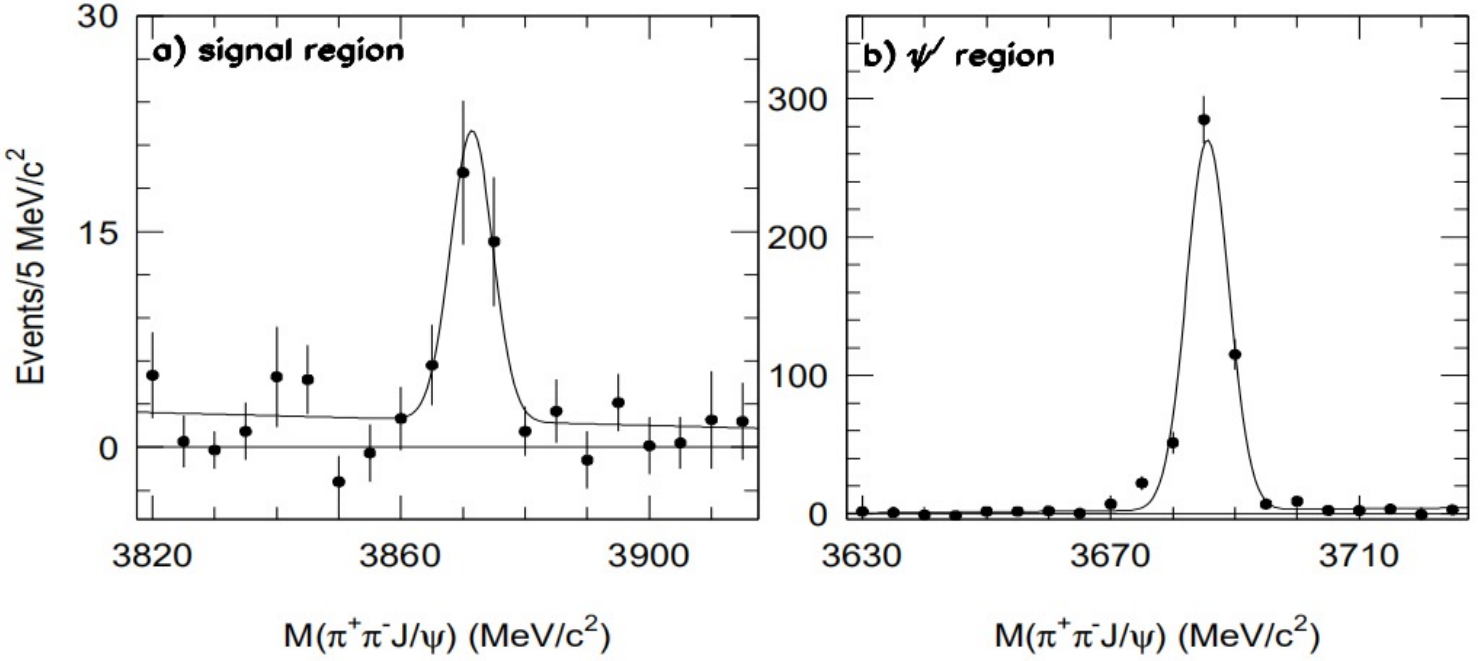
Observantstion of Multiquark State

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

The first candidate for exotic state —— $X(3872)$

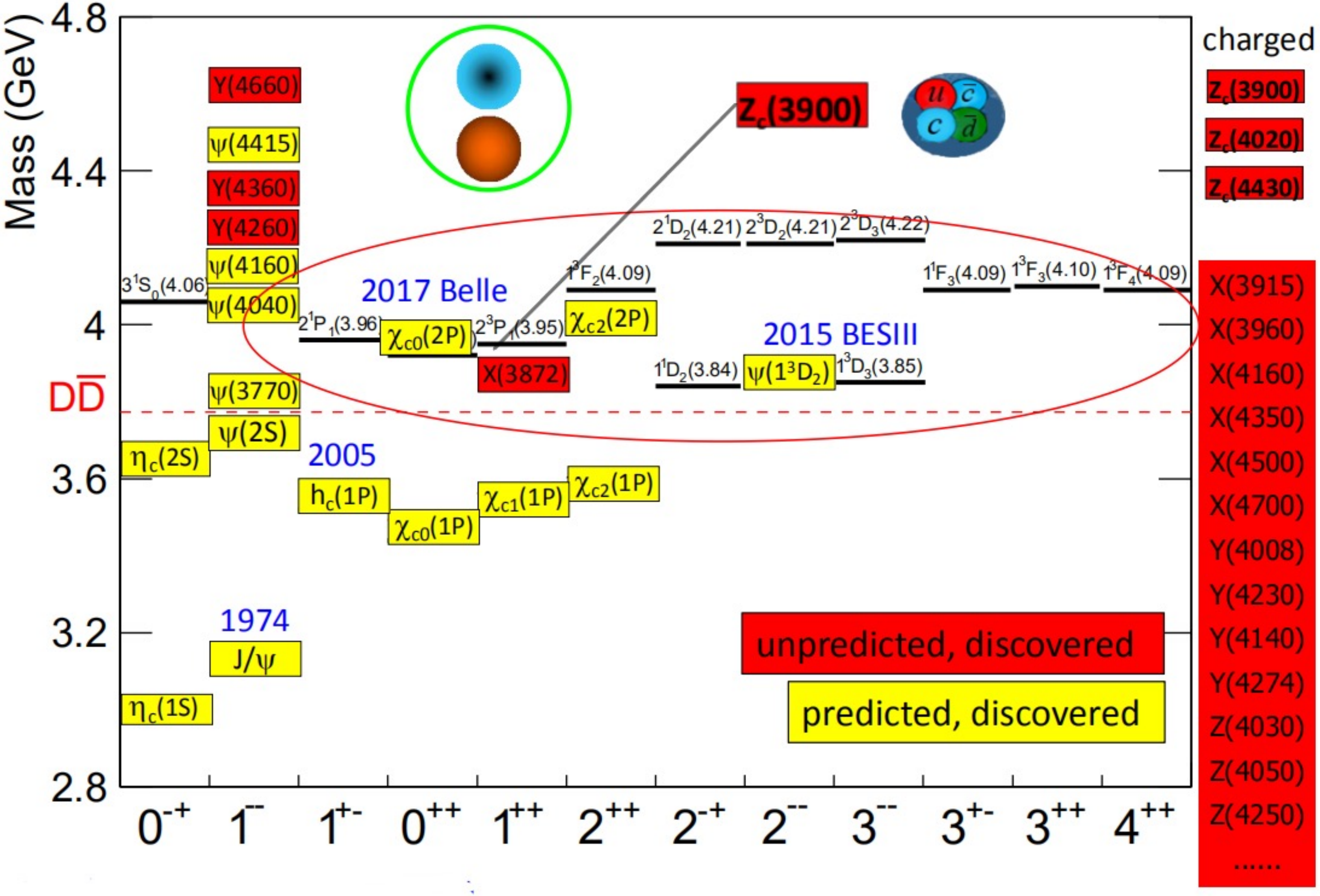
$M = 3872.0 \pm 0.6 \pm 0.5 \ \ \mathrm{MeV/c^2}$

$\Gamma < 2.3 \ \ \mathrm{MeV}$



Phys.Rev.Lett. 91 (2003) 262001

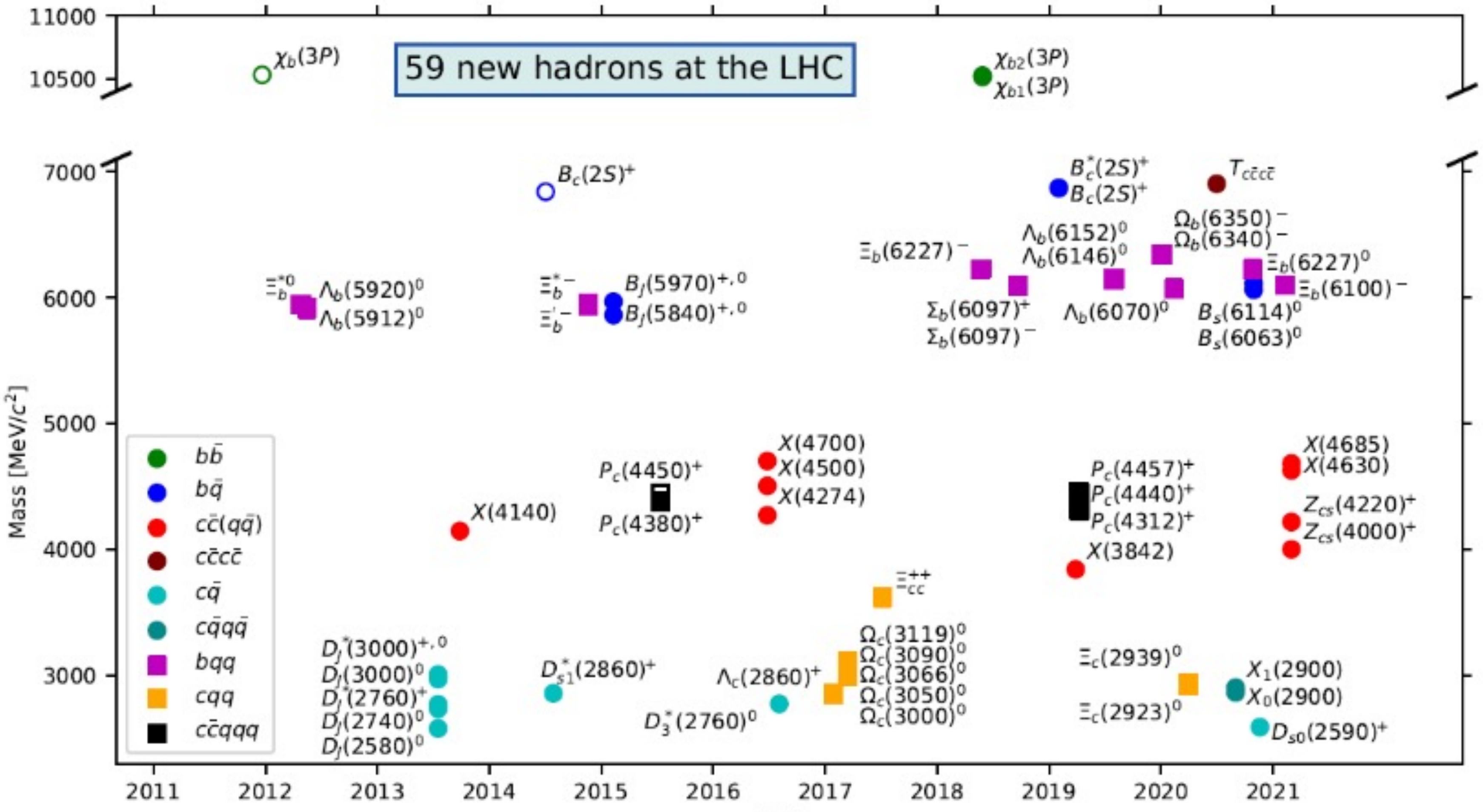
Observantstion of Multiquark State



Observantstion of Multiquark State

Over the past 10 years ,59 new hadrons and counting at the LHC

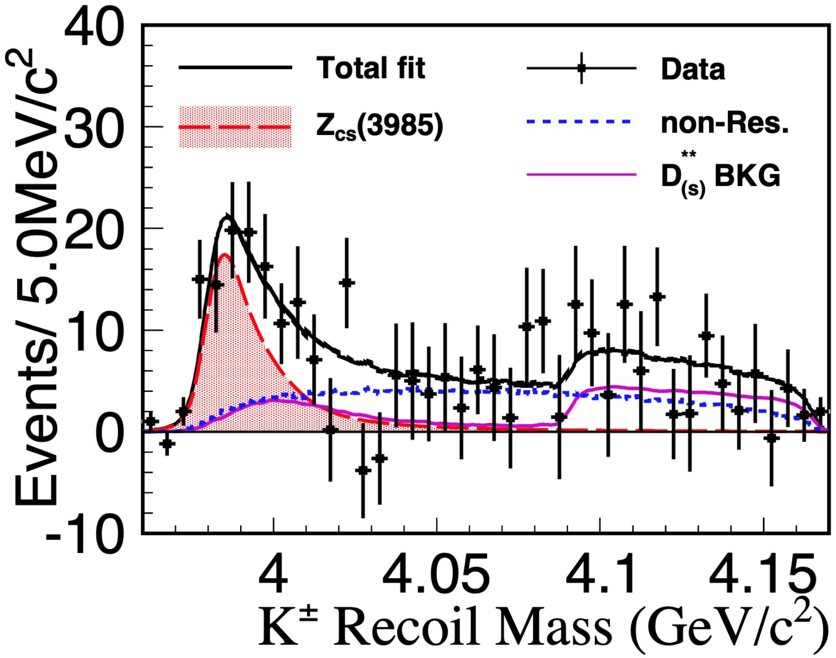
particle mass

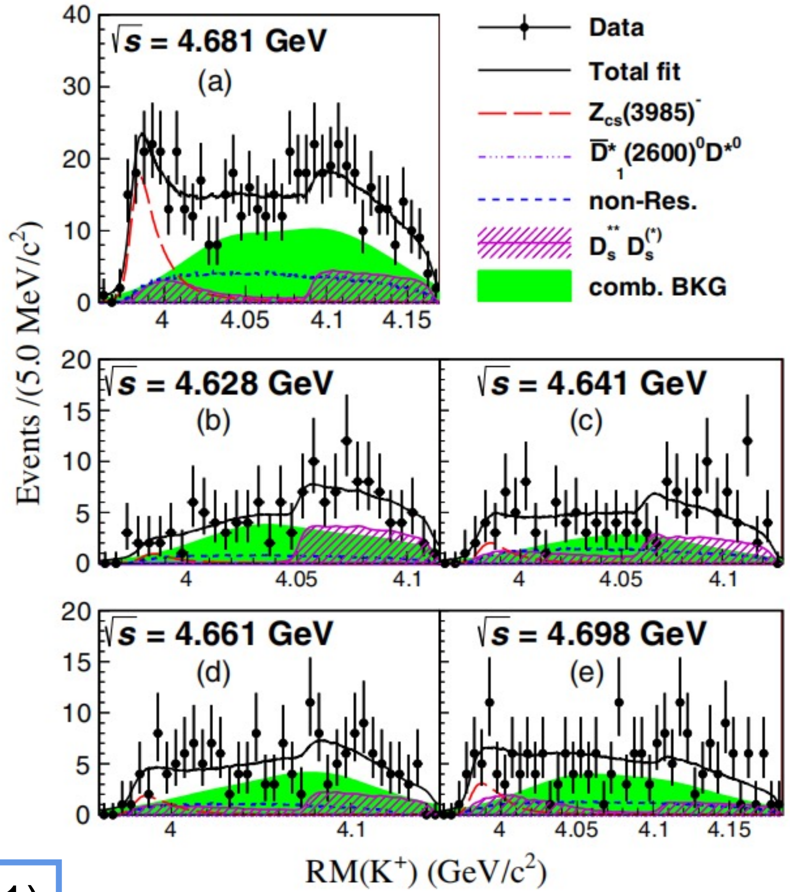


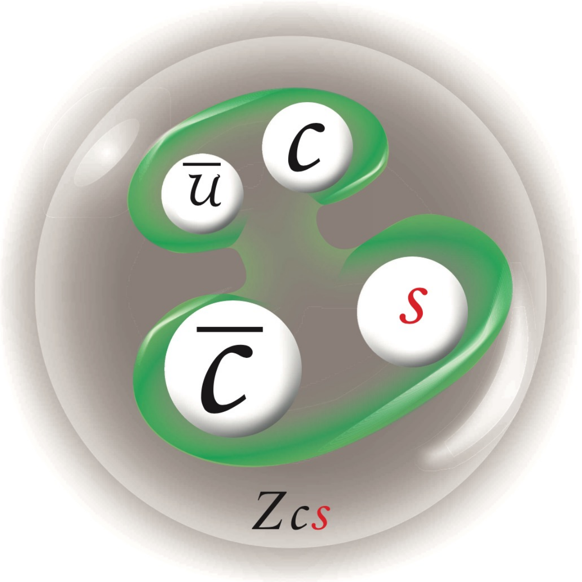
years of discovery

Observantstion of Multiquark State

Observation of a Near-Threshold Structure in the K^+ Recoil-Mass Spectra in $e^+e^- \rightarrow K^+(D_s^- D^{*0} + D_s^{*-} D^0)$







$$M = 3872.0 \pm 0.6 \pm 0.5 \;\; \mathrm{MeV/c^2}$$

$$\Gamma < 2.3 \;\; \mathrm{MeV}$$

Phys.Rev.Lett. 126, 102001 (2021)

Observantstion of Multiquark State

Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$

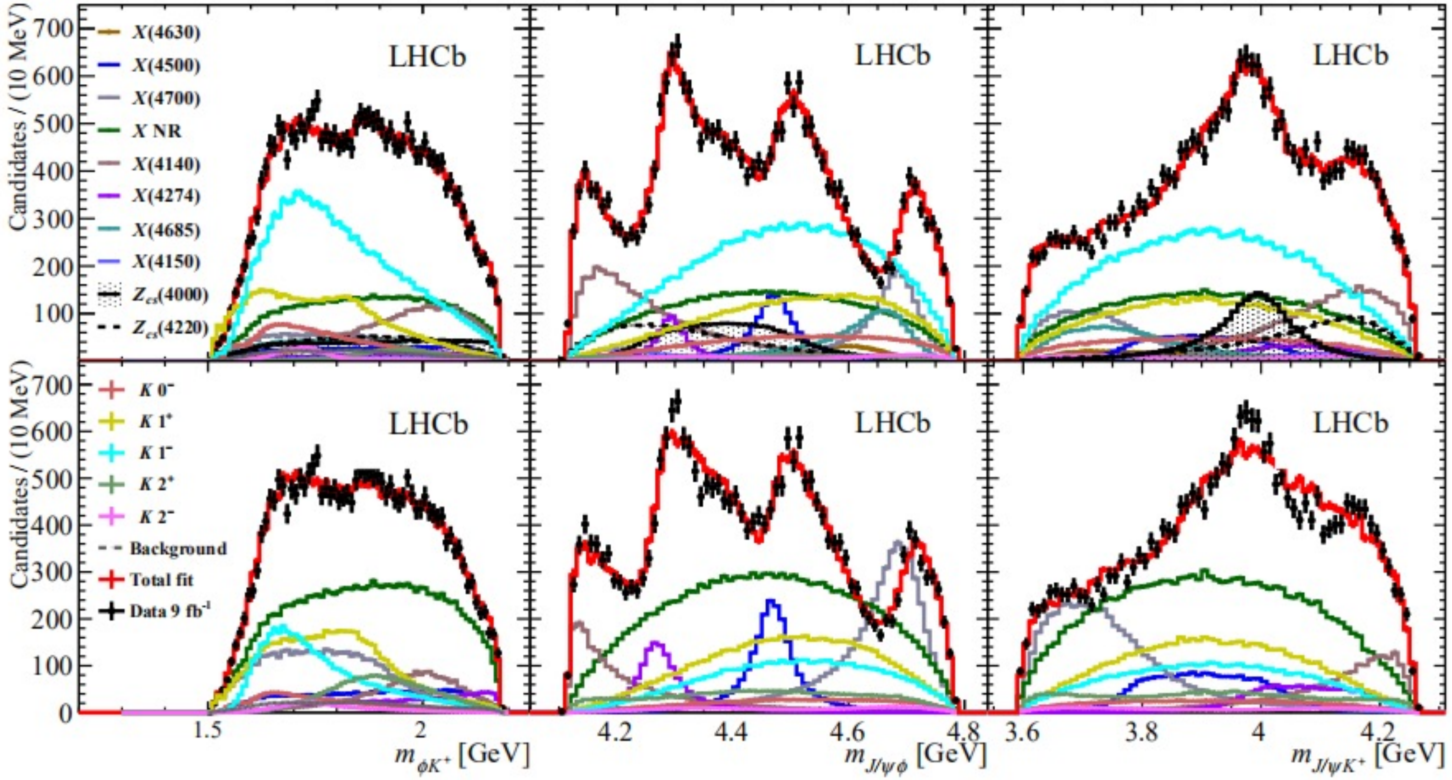


Figure 3: Distributions of ϕK^+ (left), $J/\psi\phi$ (middle) and $J/\psi K^+$ (right) invariant masses for the $B^+ \to J/\psi\phi K^+$ candidates (black data points) compared with the fit results (red solid lines) of the default model (top row) and the Run 1 model (bottom row).

Observantstion of Multiquark State

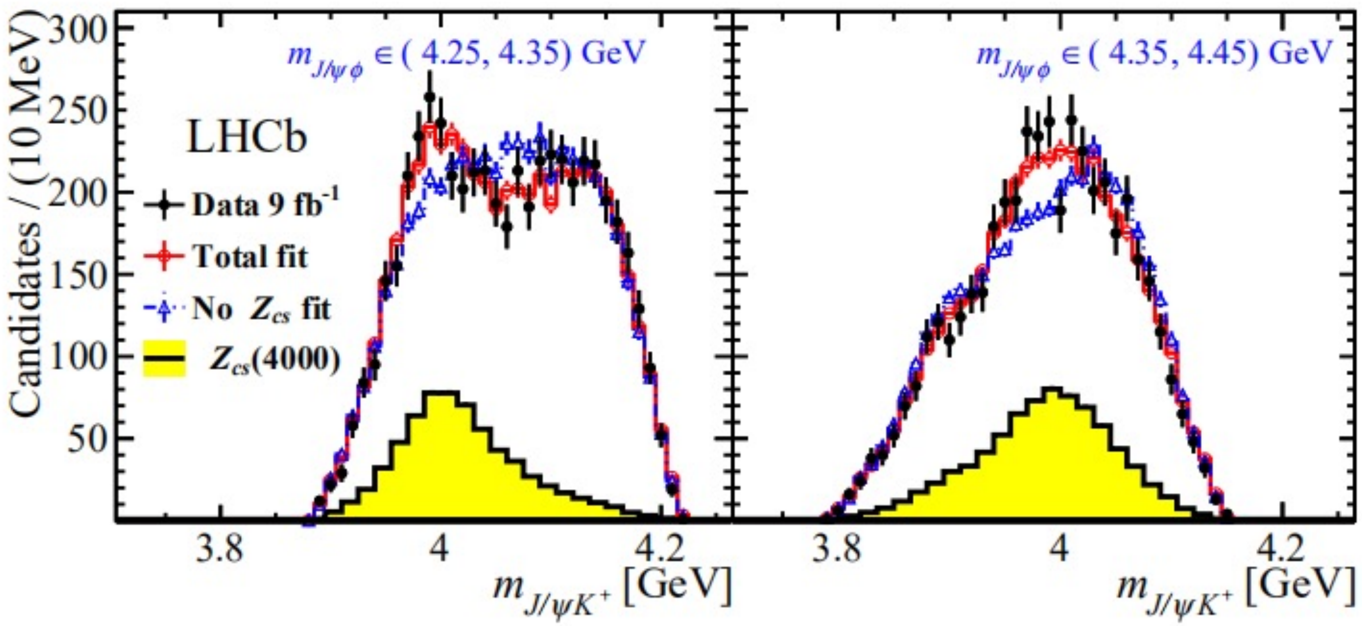


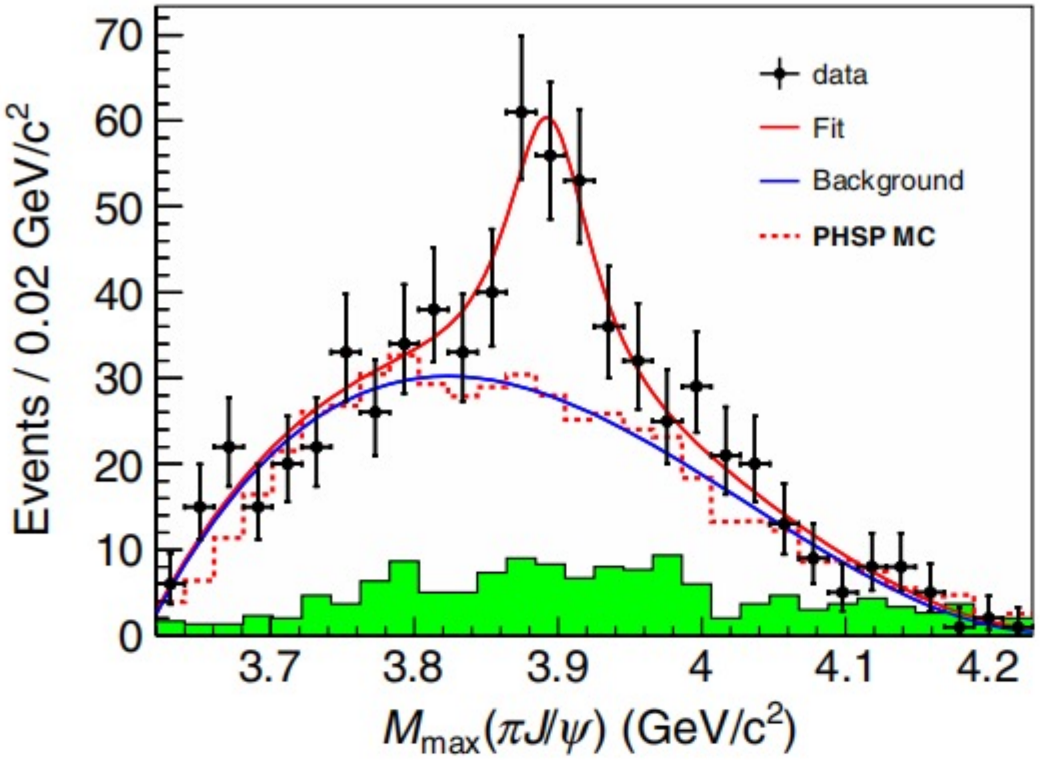
Figure 4: Fit projections onto $m_{J/\psi K^+}$ in two slices of $m_{J/\psi\phi}$ for the default model with and without the 1^+ Z_{cs}^+ states. The narrow Z_{cs}^+ state at 4 GeV is evident.

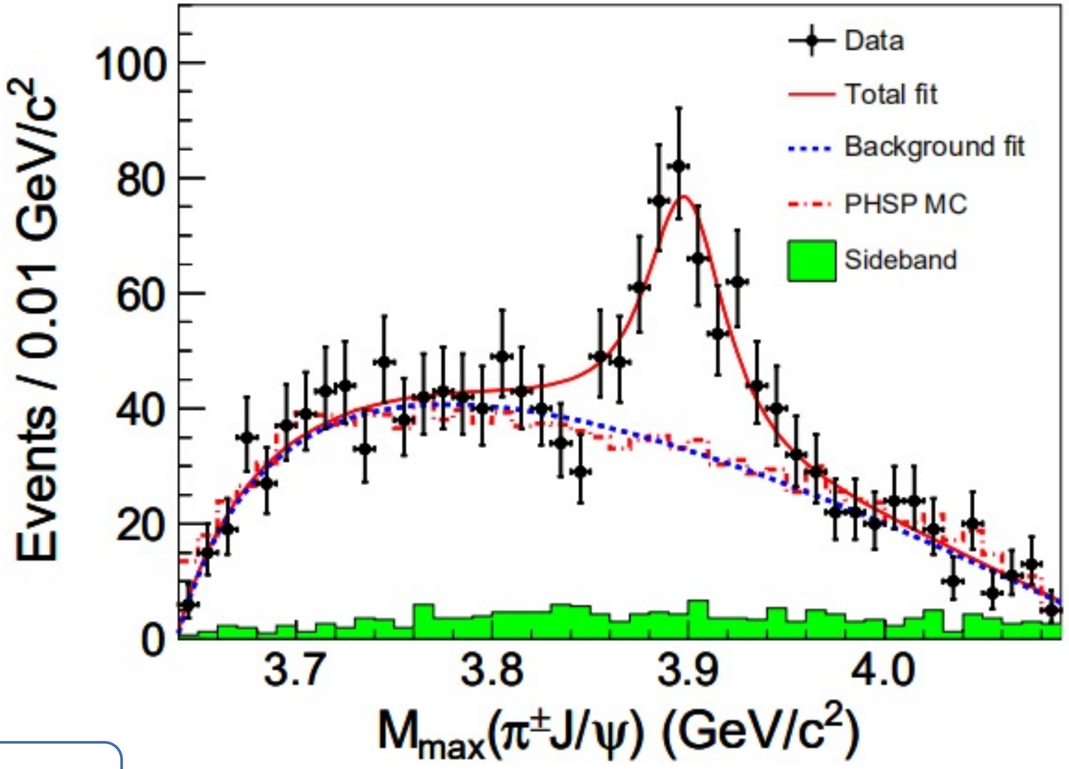
$$M = 4003 \pm 6^{+4}_{-14} \ \text{MeV/c}^2$$

$$\Gamma = 131 \pm 15 \pm 26 \ \text{MeV}$$

$$J^P = 1^+$$

Observantstion of Multiquark State





BESIII PRL 110, 252002 (2013)

$e^+ e^-$ collision

Belle PRL 110, 252002 (2013)

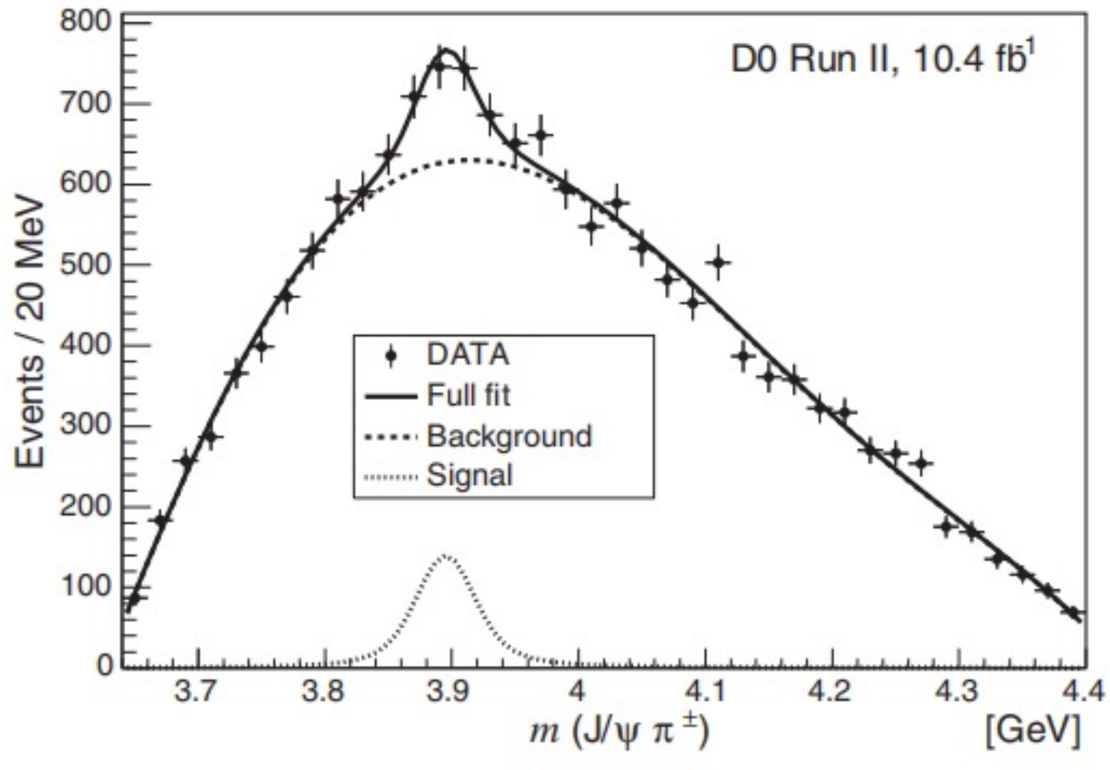
$$M = 3899.0 \pm 3.6 \pm 4.9\, MeV/c^2$$

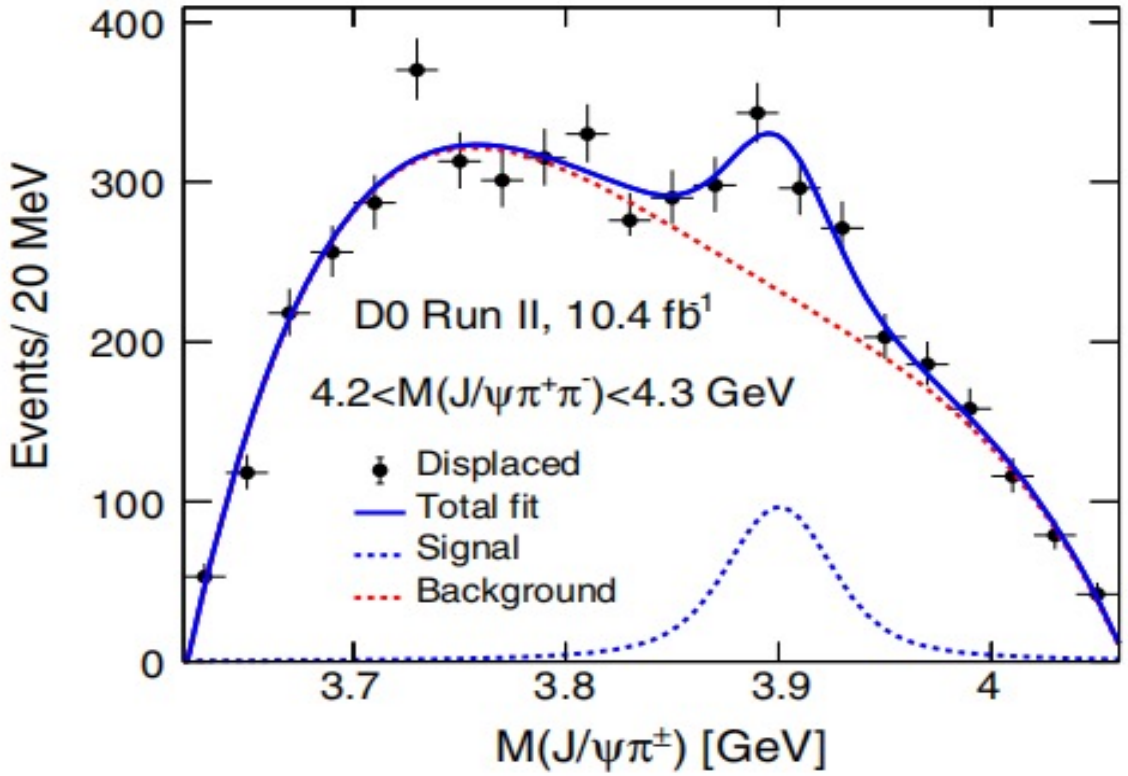
$$\Gamma = 46 \pm 10 \pm 20 MeV$$

$$M = 3894.5 \pm 6.6 \pm 4.5\, MeV/c^2$$

$$\Gamma = 63 \pm 24 \pm 26 MeV$$

Observantstion of Multiquark State





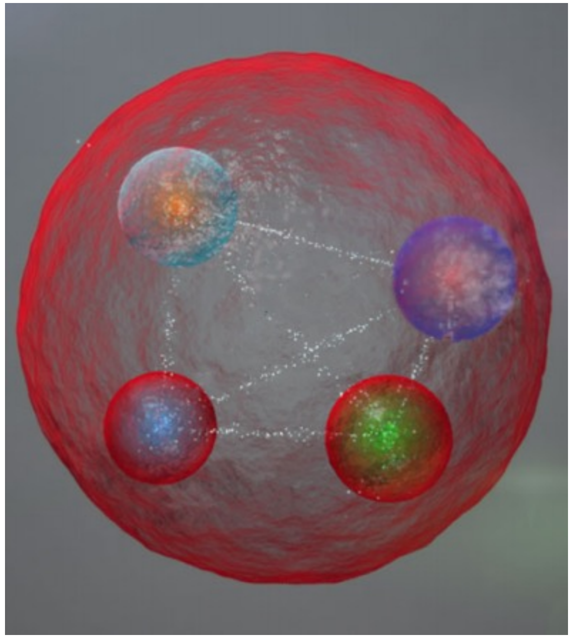
D0 PRD 98, 052010 (2018)

pp collision

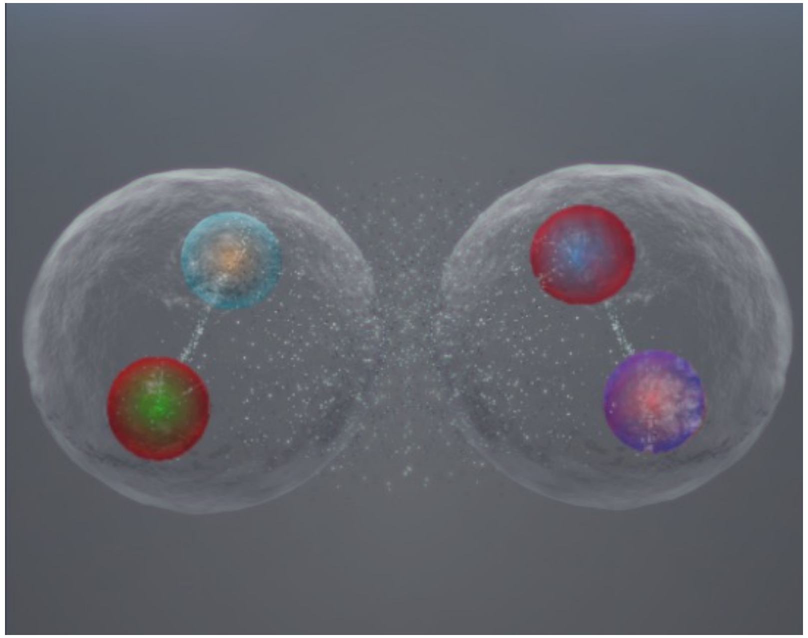
D0 PRD 100, 012005 (2019)

Observantstion of Multiquark State

It is speculated that $Z_c^{\pm}(3900)$consists of at least four quarks: $c\bar{c}u\bar{d}$ or $c\bar{c}\bar{u}d$.



Tetraquark



Hadronic molecule

Analysis Method

The **discovery** for **Exotic State in the high energy experiment** have been widely fascinating the sights of particle and nuclear physicists.

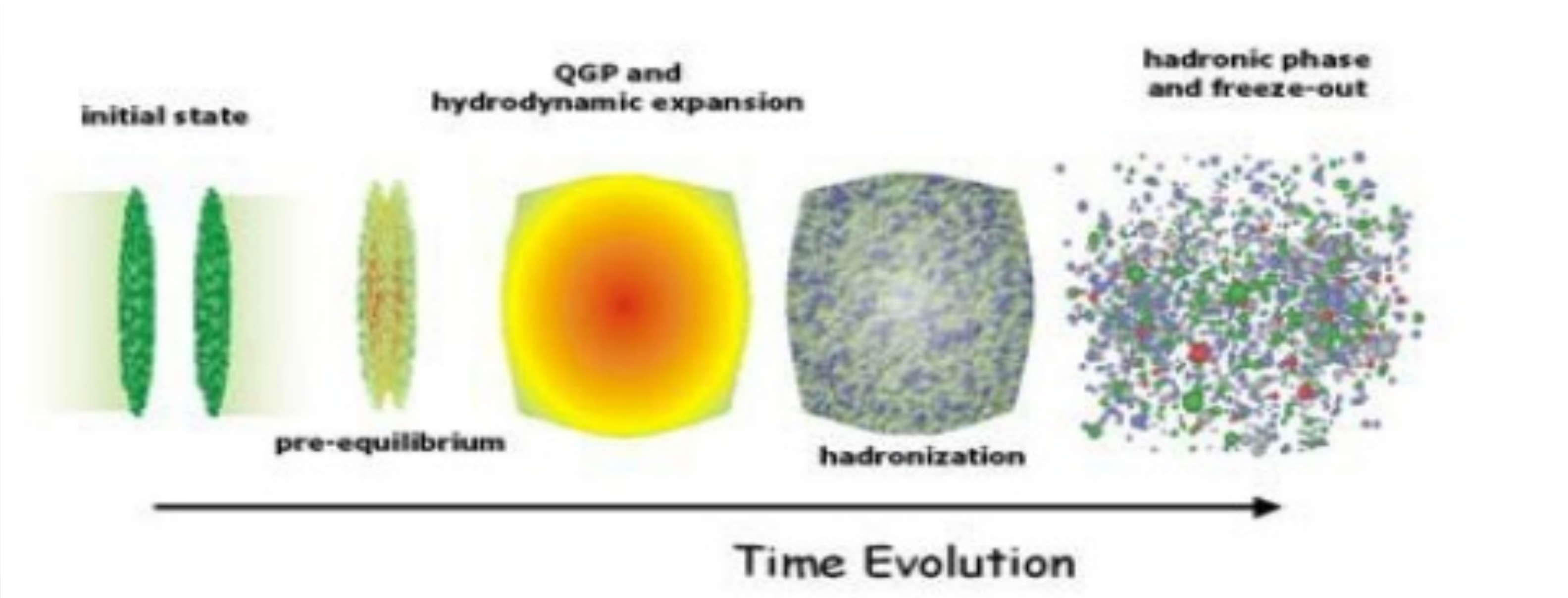
So we try to proposed a dynamically constrained phase space coalescence model + PACIAE model and used to investigate the production of **Multiquark Exotic State** in high energy collisions .

PRC 102, 054319 (2020) ; EPJC (2021) 81:198 ; arXiv:2105.06261

Analysis Method

PACIAE model

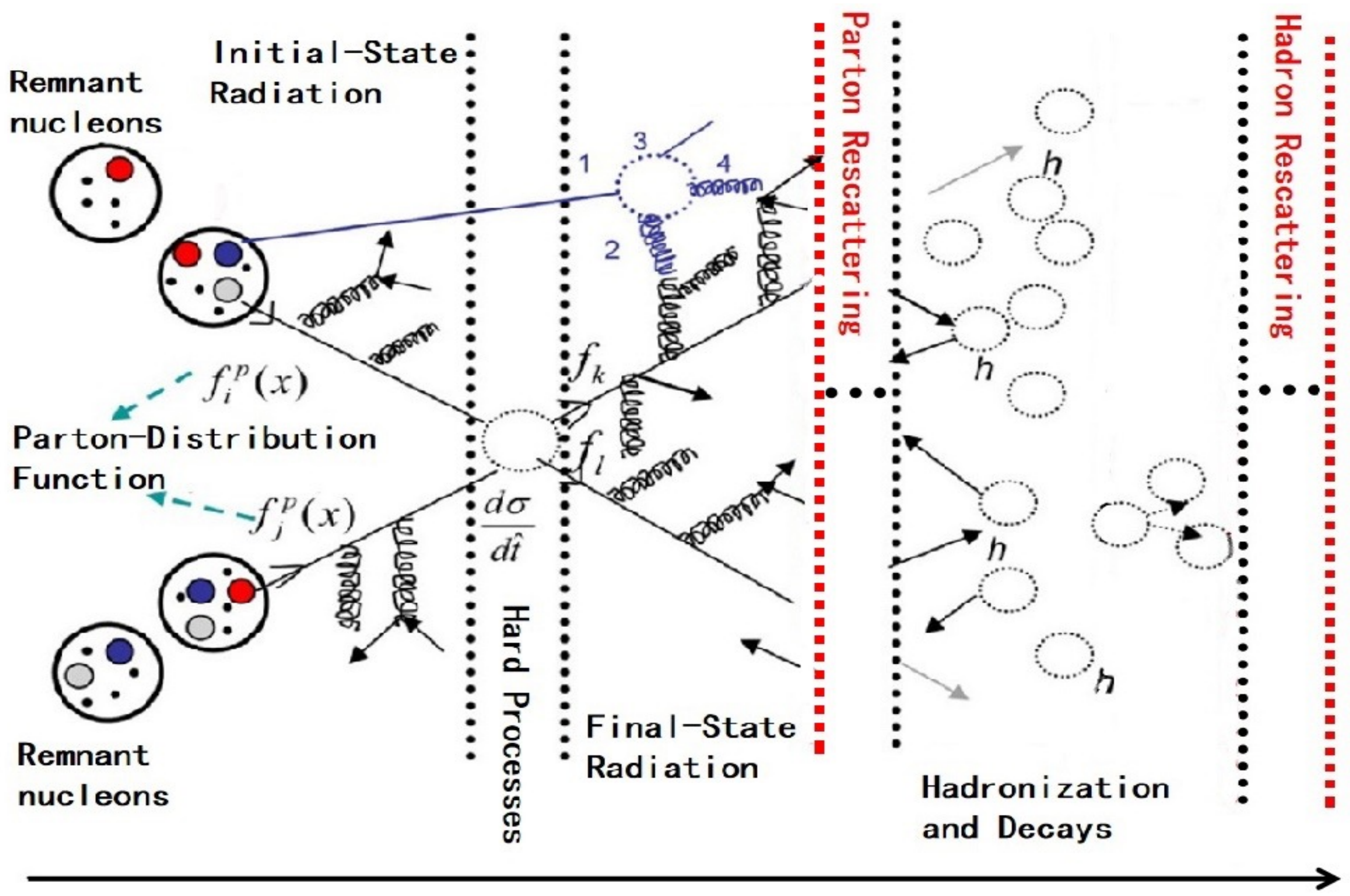
It is the parton and hadron cascade Model based on PYTHIA.

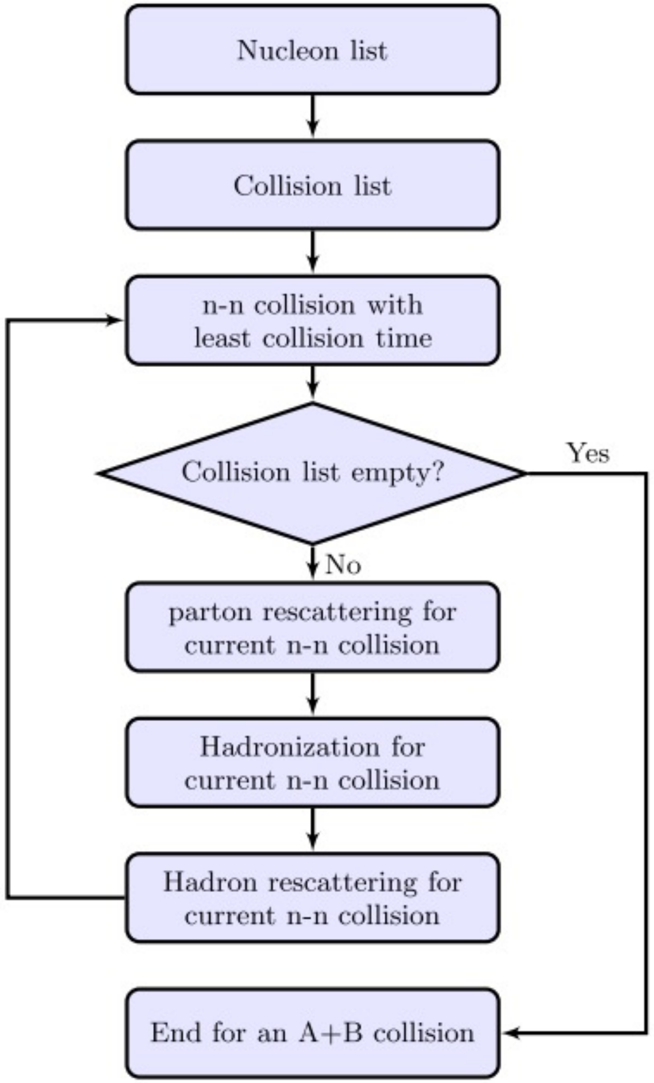


1. The parton initial state is obtained.
2. The parton rescattering is proceeded until partonic freez-out.
3. Then the hadronization is followed.
4. At last the hadronic rescattering is proceeded until hadronic freez-out.

Ben-Hao Sa ,etal. Comput. Phys. Commun., 183, 333 (2012).

PACIAE Model





Analysis Method —— DCPC Model

Dynamically constrained phase space coalescence model (DCPC)

In the theoretical studies, the yield of nuclei or bound states is usually calculated in two steps:

(1)The nucleons or hadrons are calculated by the transport model.

(2)The nuclei or bound states are calculated by the phase space coalescence model with Wigner function or by the statistical model .

We proposed a **dynamically constrained phase space coalescence model** to calculate the yield of Multiquark exotic states after the transport model simulations.

Phys. Rev. C 85 024907 (2012) ; ***PRC 86, 054910(2012).***

Analysis Method —— DCPC Model

Dynamically constrained phase space coalescence model

As the uncertainty principle $\Delta\vec{q}\Delta\vec{p} \sim h^3$

one can only say particle lies somewhere within a six dimension quantum ``box" or “state" of volume of $\Delta q \Delta p$

However, we can estimate the yield of a single particle by

$$Y_1 = \int_{E_a \le H \le E_b} \frac{d\vec{q}\,d\vec{p}}{h^3}.$$

Similarly for the yield of N particles cluster

$$Y_N = \int \cdots \int_{E_a \le H \le E_b} \frac{d\vec{q}_1 d\vec{p}_1 \cdots d\vec{q}_N d\vec{p}_N}{h^{3N}}.$$

Phys. Rev. C 85 024907 (2012)；*PRC 86, 054910(2012).*

Analysis Method —— DCPC Model

The yield of $J/\psi\pi^{\pm}$, for instance, is assumed to be

$$Y_{Z_c^{\pm}(3900)\to J/\psi\pi^{\pm}} = \int \cdots \int \delta_{12} \frac{d\vec{q}_{\pi^{\pm}} d\vec{p}_{\pi^{\pm}} d\vec{q}_{J/\psi} d\vec{p}_{J/\psi}}{h^6}$$

$$\delta_{12} = \begin{cases} 1 \quad if\ 1 \equiv \pi^{\pm}, 2 \equiv J/\psi; \\ \quad m_0 - \Delta m \leq m_{inv} \leq m_0 + \Delta m; \\ \quad \mid \vec{q}_{12} \mid \leq R_0; \\ 0 \quad \text{otherwise.} \end{cases}$$

$$m_{inv} = [(E_{\pi^{\pm}} + E_{J/\psi})^2 - (p_{\pi^{\pm}} + p_{J/\psi})^2]^{1/2}.$$

The Results on Exotic State $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$

Determine the appropriate parameter to simulate the pp collision by PACIAE model:

TABLE I. The yield of $\pi^{\pm}$ and J/ψ in pp collisions at $\sqrt{s} = 7$ TeV simulated by the PACIAE model, and compared with experimental data, with the $|y| < 0.5$, $0.1 < p_T < 3$ GeV/c for $\pi^{\pm}$ and $2.0 < y < 4.5$, $0 < p_T < 14$ GeV/c for J/ψ, respectively. Here, J/ψ is from b decay.

Particle	LHC	PACIAE
J/ψ	$(1.60 \pm 0.01 \pm 0.023) \times 10^{-5}$	$(1.60 \pm 0.03) \times 10^{-5}$
π^+	2.26 ± 0.10	2.26 ± 0.01
π^-	2.23 ± 0.10	2.25 ± 0.03

(ALICE), Eur. Phys. J. C 75, 226 (2015).

EPJC (2021) 81:198； arxiv：2010.10062

The Results on Exotic State $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$

TABLE II. The yields (10^{-6}) of exotic resonant states $Z_c^+(3900)$ and $Z_c^-(3900)$ varies with parameter Δm changing from 8 MeV to 40 MeV in pp collision at $\sqrt{s} = 1.96, 7$ and 13 TeV. $Z_c^{\pm}(3900)$ states decaying to $J/\psi\pi^{\pm}$ are computed with PACIAE + DCPC model with the radius parameter R_0 fixed to 1.74 fm, based on the $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ bound state in the decay chain of b hadrons.

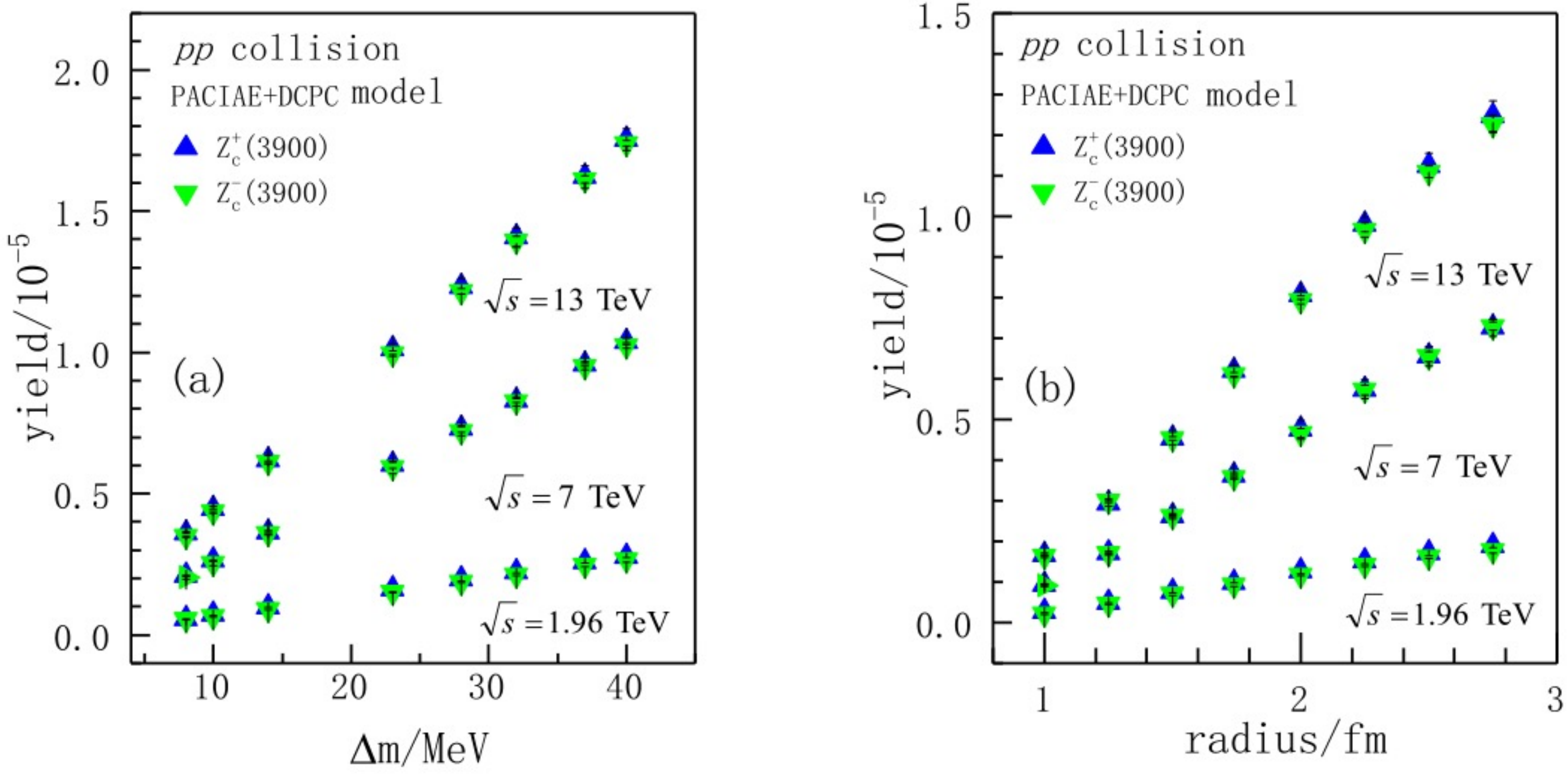
Δm	1.96 TeV		7 TeV		13 TeV	
(MeV)	$Z_c^+(3900)$	$Z_c^-(3900)$	$Z_c^+(3900)$	$Z_c^-(3900)$	$Z_c^+(3900)$	$Z_c^-(3900)$
8	0.57 ± 0.03	0.55 ± 0.03	2.10 ± 0.01	2.02 ± 0.05	3.59 ± 0.09	3.51 ± 0.08
10	0.72 ± 0.02	0.66 ± 0.03	2.63 ± 0.03	2.54 ± 0.07	4.46 ± 0.11	4.38 ± 0.09
14.1	0.99 ± 0.07	0.93 ± 0.05	3.63 ± 0.05	3.58 ± 0.05	6.19 ± 0.14	6.11 ± 0.05
23	1.61 ± 0.10	1.51 ± 0.02	6.02 ± 0.10	5.92 ± 0.20	10.13 ± 0.19	9.95 ± 0.10
28	1.97 ± 0.11	1.87 ± 0.04	7.29 ± 0.10	7.21 ± 0.16	12.32 ± 0.27	12.16 ± 0.10
32	2.24 ± 0.09	2.14 ± 0.05	8.30 ± 0.07	8.26 ± 0.15	14.06 ± 0.32	13.94 ± 0.18
37	2.56 ± 0.13	2.48 ± 0.06	9.58 ± 0.08	9.50 ± 0.11	16.21 ± 0.40	16.13 ± 0.13
40	2.78 ± 0.11	2.66 ± 0.08	10.38 ± 0.12	10.25 ± 0.10	17.52 ± 0.39	17.40 ± 0.09

The Results on Exotic State $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$

TABLE III. The yields (10^{-6}) of exotic resonant states $Z_c^+(3900)$ and $Z_c^-(3900)$ varies with parameter radius changing from 1 fm to 2.75 fm in pp collision at $\sqrt{s} = 1.96, 7$ and 13 TeV $Z_c^{\pm}(3900)$ states decaying to $J/\psi\pi^{\pm}$ are computed with PACIAE + DCPC model with the value of parameter Δm fixed to14.1 MeV, based on the $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ bound state in the decay chain of b hadrons.

R_0	1.96 TeV		7 TeV		13 TeV	
(fm)	$Z_c^+(3900)$	$Z_c^-(3900)$	$Z_c^+(3900)$	$Z_c^-(3900)$	$Z_c^+(3900)$	$Z_c^-(3900)$
1.00	0.27 ± 0.04	0.23 ± 0.02	0.94 ± 0.02	0.92 ± 0.03	1.66 ± 0.05	1.65 ± 0.02
1.25	0.48 ± 0.01	0.47 ± 0.02	1.70 ± 0.02	1.71 ± 0.04	2.93 ± 0.06	2.99 ± 0.04
1.50	0.75 ± 0.02	0.70 ± 0.03	2.63 ± 0.02	2.62 ± 0.06	4.54 ± 0.16	4.54 ± 0.05
1.74	0.99 ± 0.07	0.93 ± 0.05	3.63 ± 0.05	3.58 ± 0.05	6.19 ± 0.14	6.11 ± 0.05
2.00	1.26 ± 0.02	1.18 ± 0.02	4.75 ± 0.23	4.67 ± 0.11	8.06 ± 0.10	7.94 ± 0.10
2.25	1.50 ± 0.03	1.42 ± 0.03	5.74 ± 0.24	5.73 ± 0.12	9.80 ± 0.17	9.67 ± 0.17
2.50	1.71 ± 0.01	1.61 ± 0.03	6.56 ± 0.24	6.55 ± 0.12	11.25 ± 0.30	11.10 ± 0.15
2.75	1.88 ± 0.01	1.79 ± 0.06	7.26 ± 0.20	7.29 ± 0.10	12.47 ± 0.38	12.27 ± 0.21

The Results on Exotic State $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$



increase linearly

FIG. 1. The distribution of the yield of exotic resonant states $Z_c^{\pm}(3900)$ in pp collisions at $\sqrt{s} = 1.96, 7, 13$ TeV, respectively. (a) as a function of mass uncertainty Δm, (b) as a function of radius parameter R_0. The data are calculated using PACIAE+DCPC model based on the $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ bound state in the decay chain of b hadrons.

The Results on Exotic State $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$

So far, $Z_c^{\pm}(3900)$ has three possible decay modes $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$, $D\bar{D}^*$, and $\eta_c(1s)\rho(770)^{\pm}$

according to PDG from BESIII experiment.

$\Gamma(D\bar{D}^*)/\Gamma(J/\psi\pi^{\pm}) = 6.2 \pm 1.1 \pm 2.7$

$\Gamma(\eta_c(1s)\rho(770)^{\pm})/\Gamma(J/\psi\pi^{\pm})$=2.3±0.8,

Using the PACIAE model, the results we get are

$\Gamma(D\bar{D}^*)/\Gamma(J/\psi\pi^{\pm}) = 6.36 \pm 0.02$

$\Gamma(\eta_c(1S)\rho(770)^{\pm})/\Gamma(J/\psi\pi^{\pm}) = 1.78 \pm 0.02$, which are consistent with BESIII results.

Therefore, the yield of $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ decay mode is 10.9% of total yield of $Z_c^{\pm}(3900)$.
So the total yield of $Z_c^{\pm}(3900)$ is approximately the yield of $J/\psi\pi^{\pm}$ decay times a factor of 9.1.

The Results on Exotic State $Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$

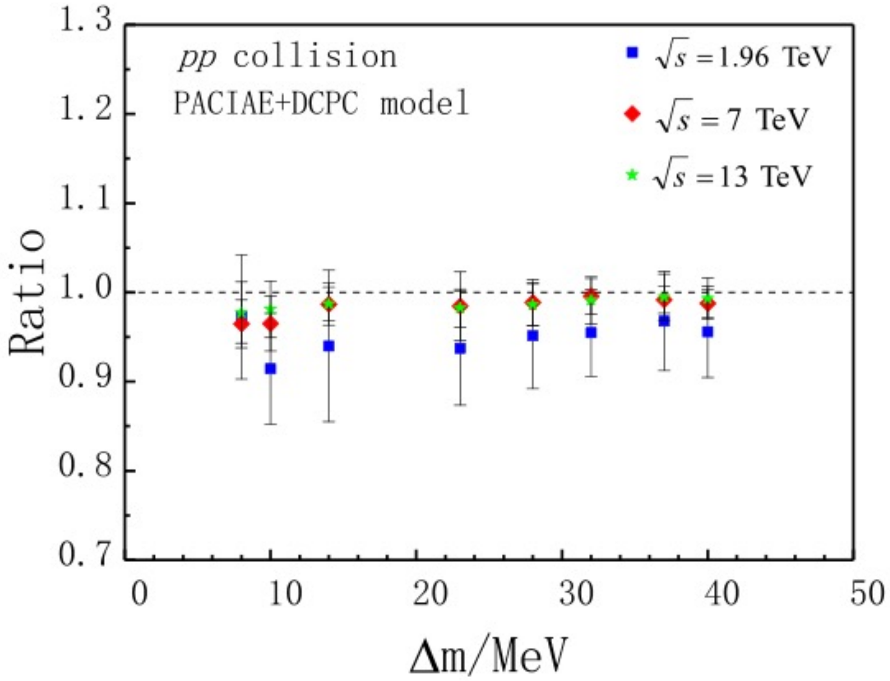
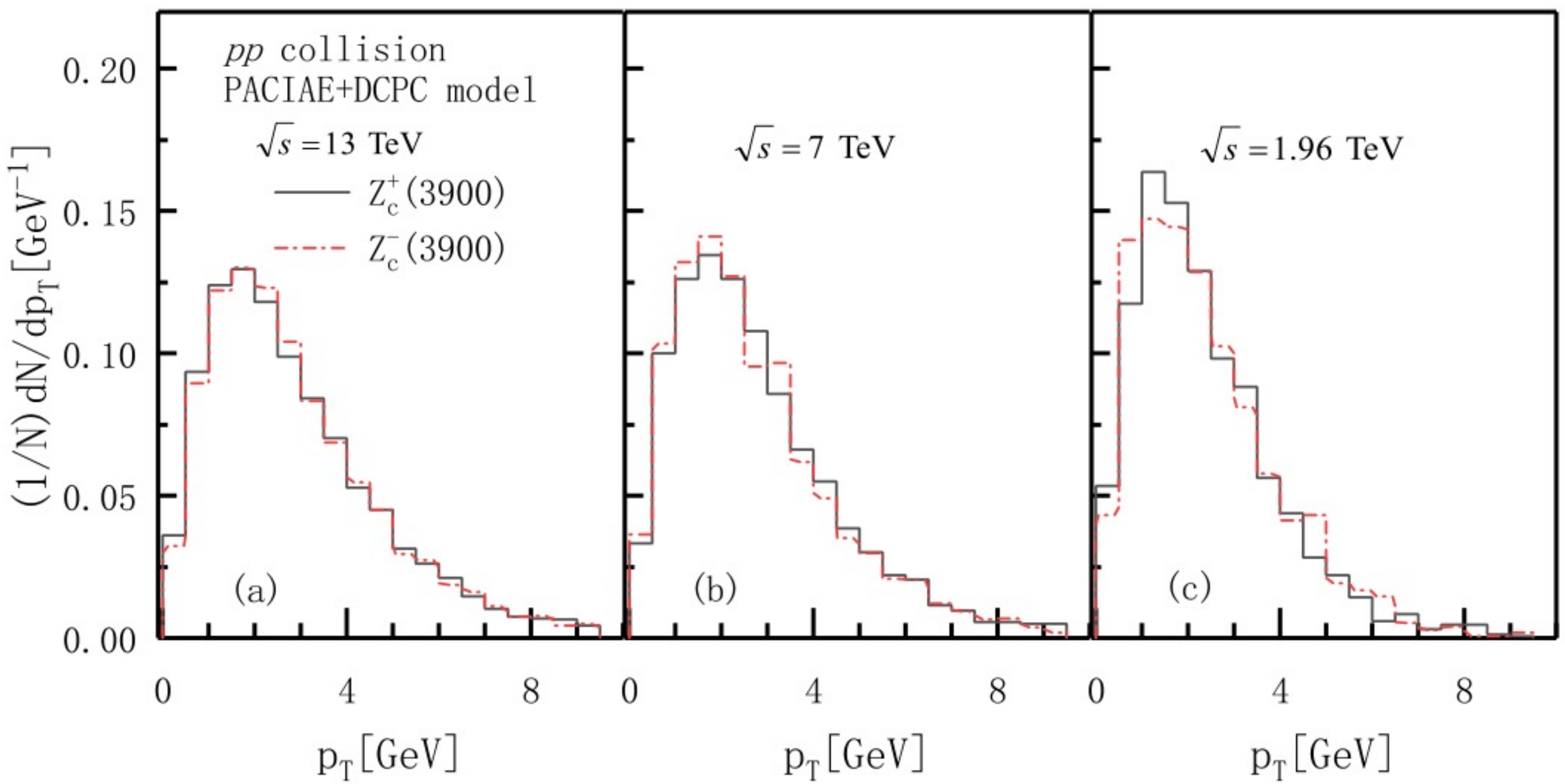


FIG. 2. The ratio distribution of $Z_c^-(3900)$ to $Z_c^+(3900)$ in pp collisions at $\sqrt{s} = 1.96, 7$ and 13 TeV with the value of radius parameter $R_0 = 1.74$ fm, as a function of mass uncertainty Δm.

The ratio is less than 1

The Results on Exotic State $Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$



The value of peak become smaller ; the width of the pt distribution become wider

FIG. 3. The transverse momentum distributions of exotic state $Z_c^+(3900)$ (the solid line) and $Z_c^-(3900)$ (dashed line) calculated by PACIAE+DCPC model simulations with $\Delta m = 14.1$ MeV and $R_0 = 1.74$ fm, based on the $Z_c^{\pm}(3900) \rightarrow J/\psi\pi^{\pm}$ bound state from the decay chain of b hadrons in pp collision at $\sqrt{s} = 1.96, 7$ and 13 TeV, respectively.

The Results on Exotic State $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$

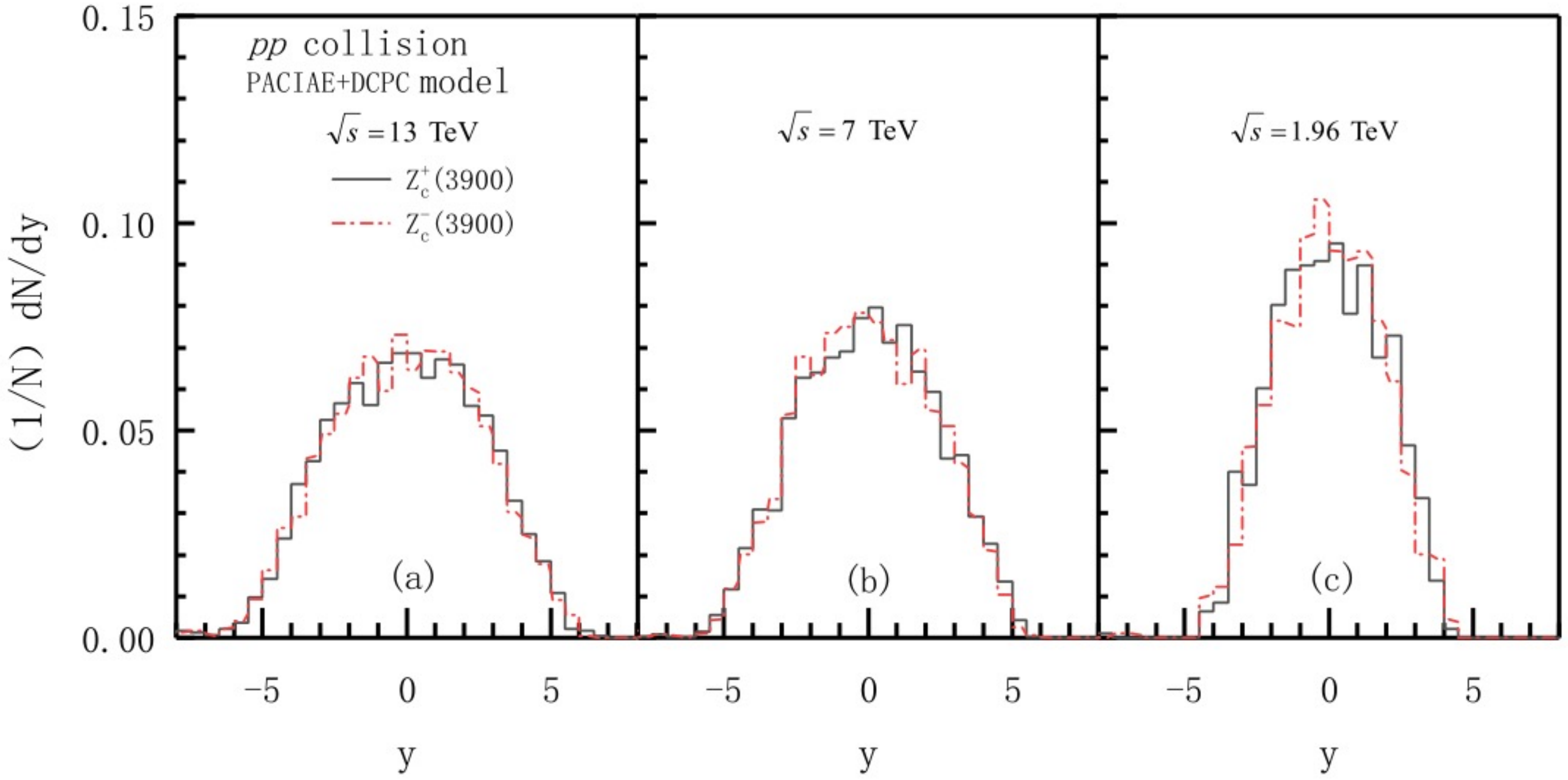


FIG. 4. The rapidity distributions of exotic state $Z_c^+(3900)$ (the solid line) and $Z_c^-(3900)$ (dashed line) calculated by PACIAE+DCPC model simulations with $\Delta m = 14.1$ MeV and $R_0 = 1.74$ fm, based on the $Z_c^{\pm}(3900) \to J/\psi\pi^{\pm}$ bound state from the decay chain of b hadrons in pp collision at $\sqrt{s} = 1.96, 7$ and 13 TeV, respectively.

The value of peak become smaller ; the width of the y distribution become wider

Summary

- Using PACIAE + the dynamically constrained phase space coalescence model to calculate the **multiquark exotic state** $Z_c^{\pm}(3900)$ in high enengy pp collisions, it seams successful.
- Predict the **multiquark exotic state** $Z_c^{\pm}(3900)$ yield, transverse momentum and the rapidity distribution in *pp* collisions at $\sqrt{s}$ = 1.96, 7 and 13 TeV .
- Study energy dependence of **multiquark exotic state** $Z_c^{\pm}(3900)$ produced in pp collisions.
- It turned out that the proposed dynamically constrained phase space coalescence model would be an effective method investigating the production of **multiquark exotic state** in high energy collisions.

Thanks for your attention!