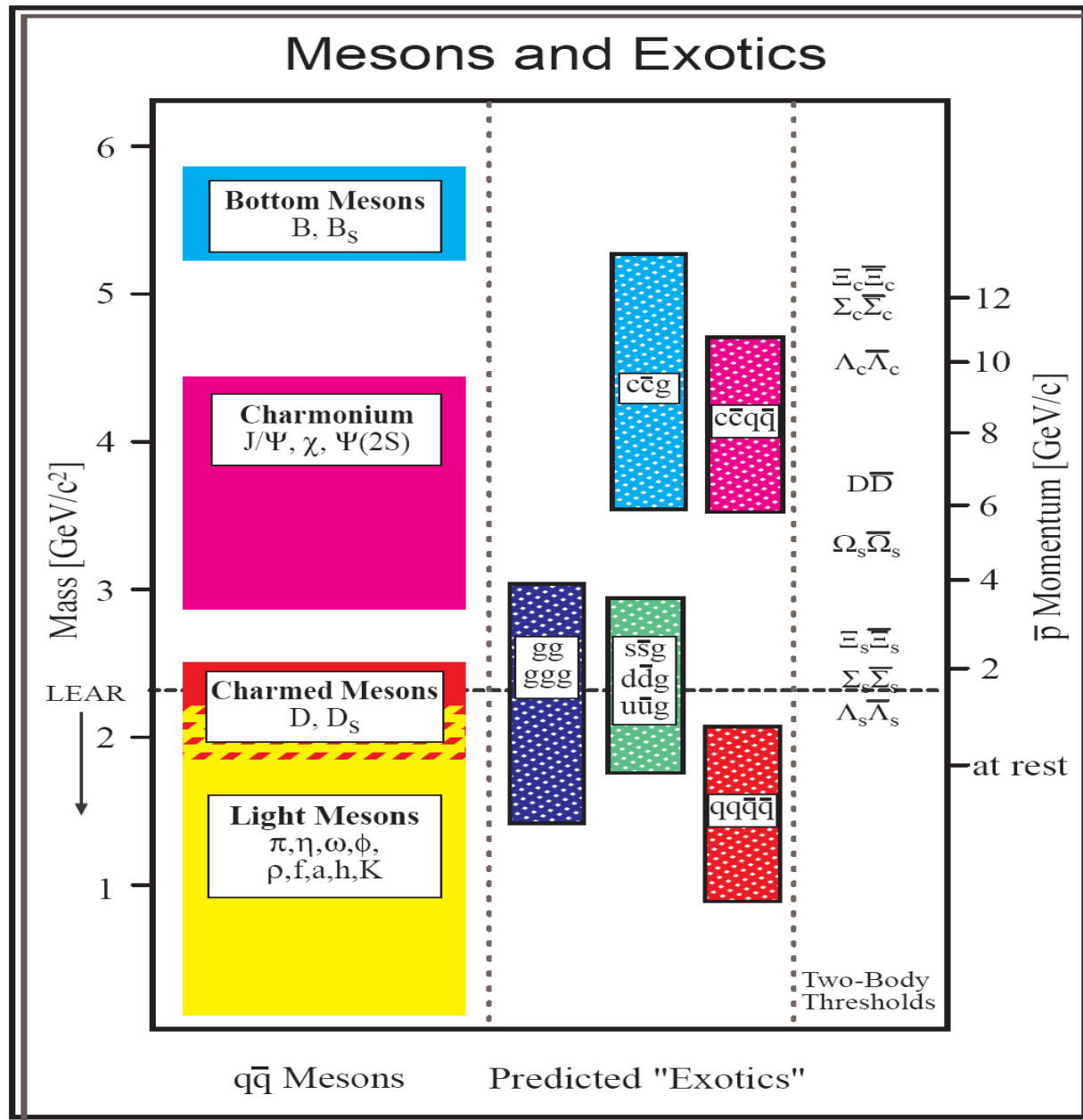


PERSPECTIVE STUDY OF CHARMONIUM AND EXOTICS  
ABOVE  $D\bar{D}$  THRESHOLD

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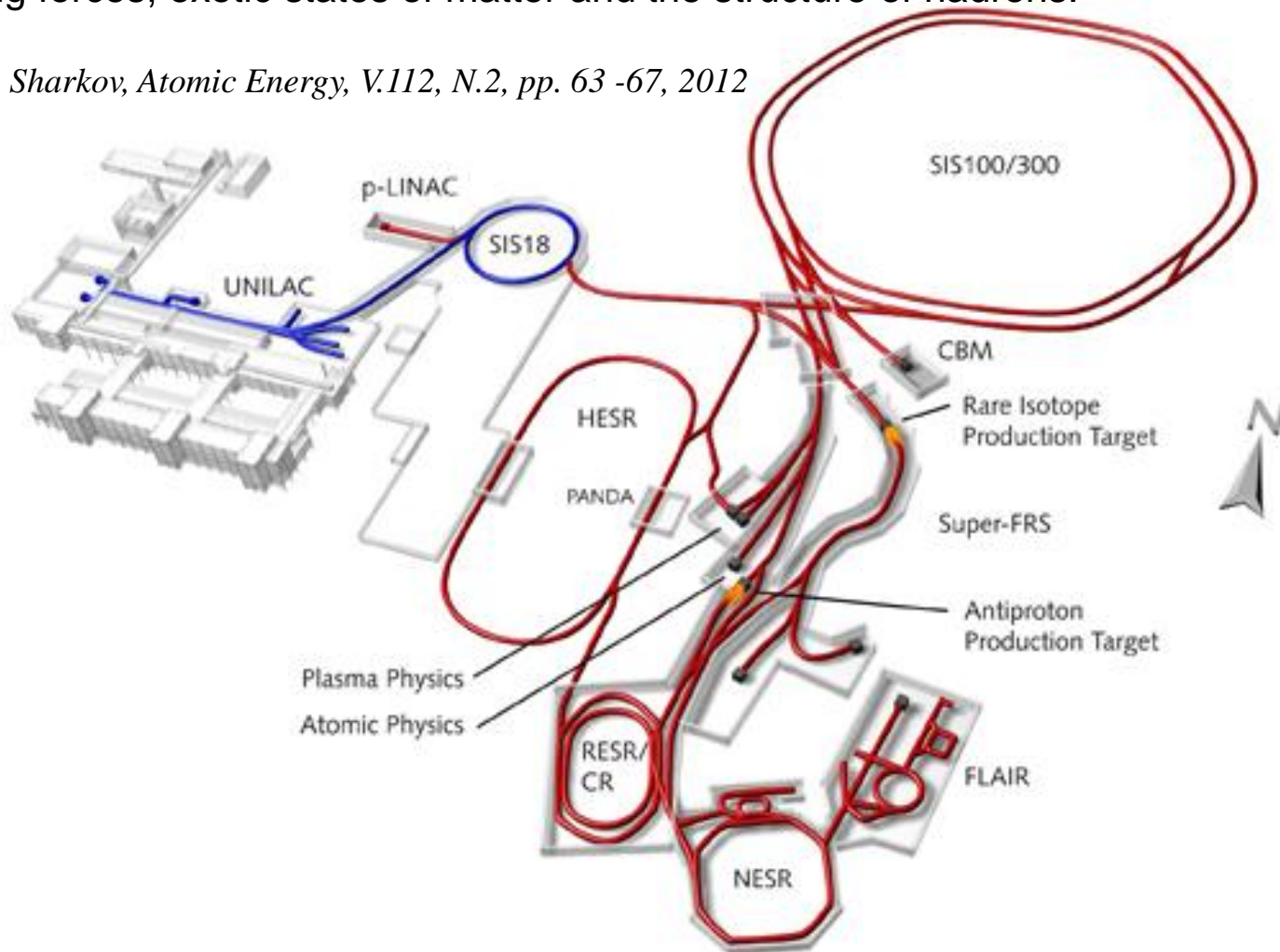
# WHY WE CONCENTRATE ON PHYSICS WITH ANTIPROTONS:



Expected masses of  $q\bar{q}$ -mesons, glueballs, hybrids and two-body production thresholds.

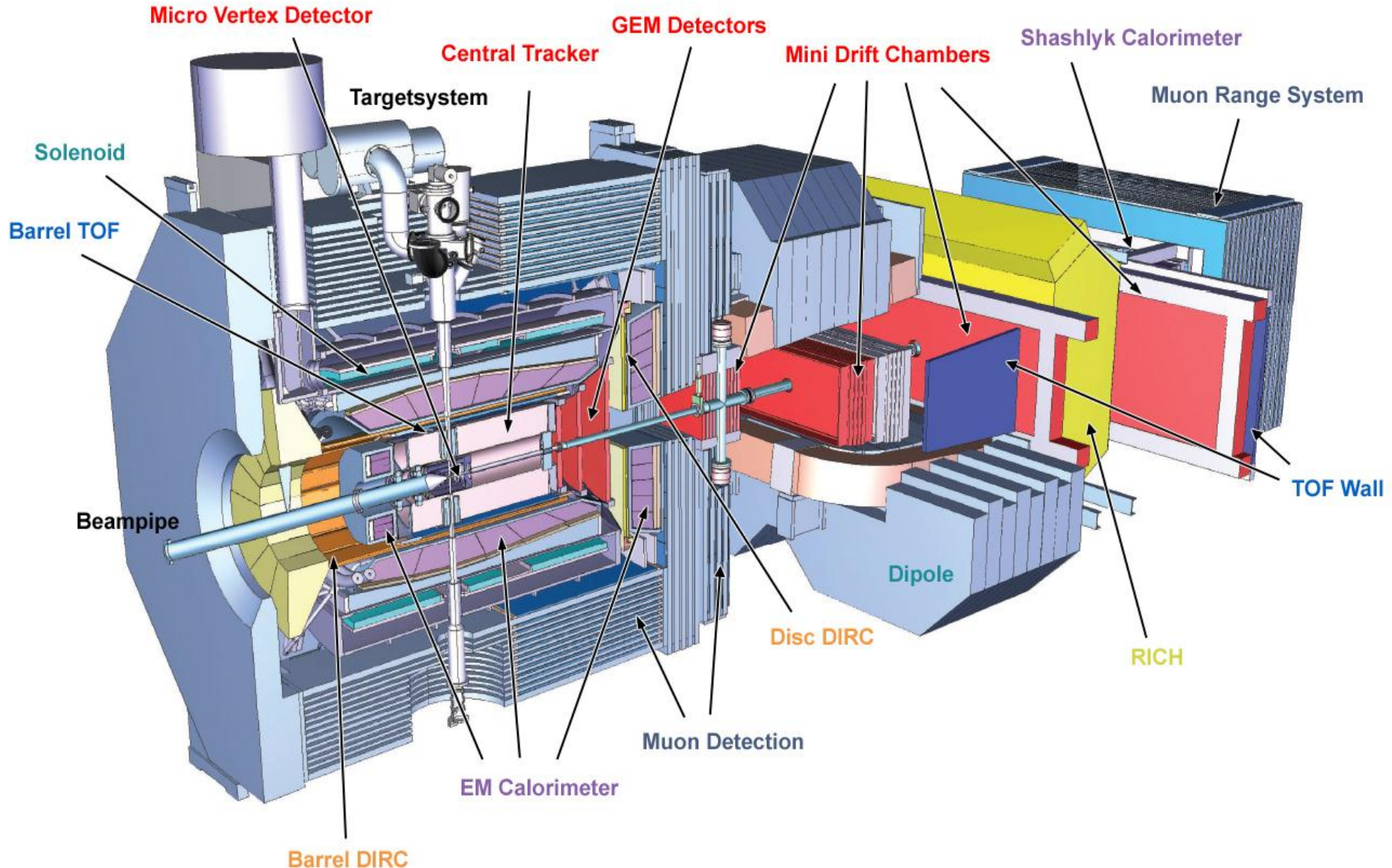
Antiprotons accumulated in the High Energy Storage Ring HESR will collide with the fixed internal hydrogen or nuclear target. High beam luminosity of an order of  $2 \times 10^{32} \text{sm}^{-2} \text{c}^{-1}$  and momentum resolution  $\sigma(p)/p$  of an order of  $10^{-5}$  are expected. The scientists from different countries intend to do fundamental research on various topics around the weak, electromagnetic and strong forces, exotic states of matter and the structure of hadrons.

*B.Yu. Sharkov, Atomic Energy, V.112, N.2, pp. 63 -67, 2012*



*Proposed layout of HESR at FAIR*

# The Versatile PANDA Detector - Full View



In order to yield the necessary information from the antiproton-proton collisions a **versatile detector** will be build being able to provide precise trajectory reconstruction, energy and momentum measurements and **very efficient identification of charged particles in full coverage of the solid angle and wide energy range.**



# Outline

- Conventional & exotic hadrons
- Review of recent experimental data
- Analysis & results
- Summary & perspectives



# PREAMBLE

- ➔ STUDY OF FLAVOUR PARTICLES (CHARMONIUM, CHARMED HYBRIDS & TETRAQUARKS WITH HIDDEN CHARM)
- ➔ ANALYSIS OF SPECTRUM IN MASS REGION ABOVE  $D\bar{D}$ -THRESHOLD. A REVIEW OF THE NEW XYZ-CHARMONIUMLIKE MESONS AND ATTEMPTS OF THEIR POSSIBLE INTERPRETATION
- ➔ DISCUSSION OF THE RESULTS OF CALCULATION FOR THE HIGHER LYING CHARMONIUM & EXOTICS AND THEIR COMPARISON WITH THE RECENTLY REVEALED EXPERIMENTAL DATA ABOVE  $D\bar{D}$ -THRESHOLD
- ➔ APPLICATION OF THE INTEGRAL FORMALISM FOR DECAY OF HADRON RESONANCES TO CALCULATE THE WIDTHS OF FLAVOUR PARTICLES

## Why is charmonium-like (with a hidden charm) state chosen!?

### Charmonium-like state possesses some well favored characteristics:

- is the simplest two-particle system consisting of quark & antiquark;
- is a compact bound system with small widths varying from several tens of keV to several tens of MeV compared to the light unflavored mesons and baryons
- charm quark  $c$  has a large mass ( $1.27 \pm 0.07$  GeV) compared to the masses of  $u$ ,  $d$  &  $s$  ( $\sim 0.1$  GeV) quarks, that makes it plausible to attempt a description of the dynamical properties of charmonium-like system in terms of non-relativistic potential models and phenomenological models;
- quark motion velocities in charmonium-like systems are non-relativistic (the coupling constant,  $\alpha_s \approx 0.3$  is not too large, and relativistic effects are manageable ( $v^2/c^2 \approx 0.2$ ));
- the size of charmonium-like systems is of the order of less than 1 Fm ( $R_{c\bar{c}} \sim \alpha_s \cdot m_q$ ) so that one of the main doctrines of QCD – asymptotic freedom is emerging;

### Therefore:

- ◆ charmonium-like studies are promising for understanding the dynamics of quark interaction at small distances;
- ◆ charmonium-like spectroscopy is a good testing ground for the theories of strong interactions:
  - QCD in both perturbative and nonperturbative regimes
  - QCD inspired potential models and phenomenological models

The quark potential models have successfully described the charmonium spectrum, which generally assumes short-range coulomb interaction and long-range linear confining interaction plus spin dependent part coming from one gluon exchange. The zero-order potential is:

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

where  $\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$  defines a gaussian-smeared hyperfine interaction.

Solution of equation with  $H_0 = p^2/2m_c + V_0^{(c\bar{c})}(r)$  gives zero order charmonium wavefunctions.

*\*T. Barnes, S. Godfrey, E. Swanson, Phys. Rev. D 72, 054026 (2005), hep-ph/0505002 & Ding G.J. et al., arXiv: 0708.3712 [hep-ph], 2008*

The splitting between the multiplets is determined by taking the matrix element of the  $V_{\text{spin-dep}}$  taken from one-gluon exchange Breit-Fermi-Hamiltonian between zero-order wave functions:


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

where  $\alpha_s$  - coupling constant,  $b$  - string tension,  $\sigma$  - hyperfine interaction smear parameter.

Izmestev A. has shown *\*Nucl. Phys., V.52, N.6 (1990) & \*Nucl. Phys., V.53, N.5 (1991)* that in the case of curved coordinate space with radius  $a$  (confinement radius) and dimension  $N$  at the dominant time component of the gluonic potential the quark-antiquark potential defines via Gauss equations. If space of physical system is compact (sphere  $S^3$ ), the harmonic potential assures confinement:

$$\Delta V_N(\vec{r}) = \text{const } G_N^{-1/2}(r) \delta(\vec{r}), \quad V_N(r) = V_0 \int D(r) R^{1-N}(r) dr / r, \quad V_0 = \text{const} > 0.$$

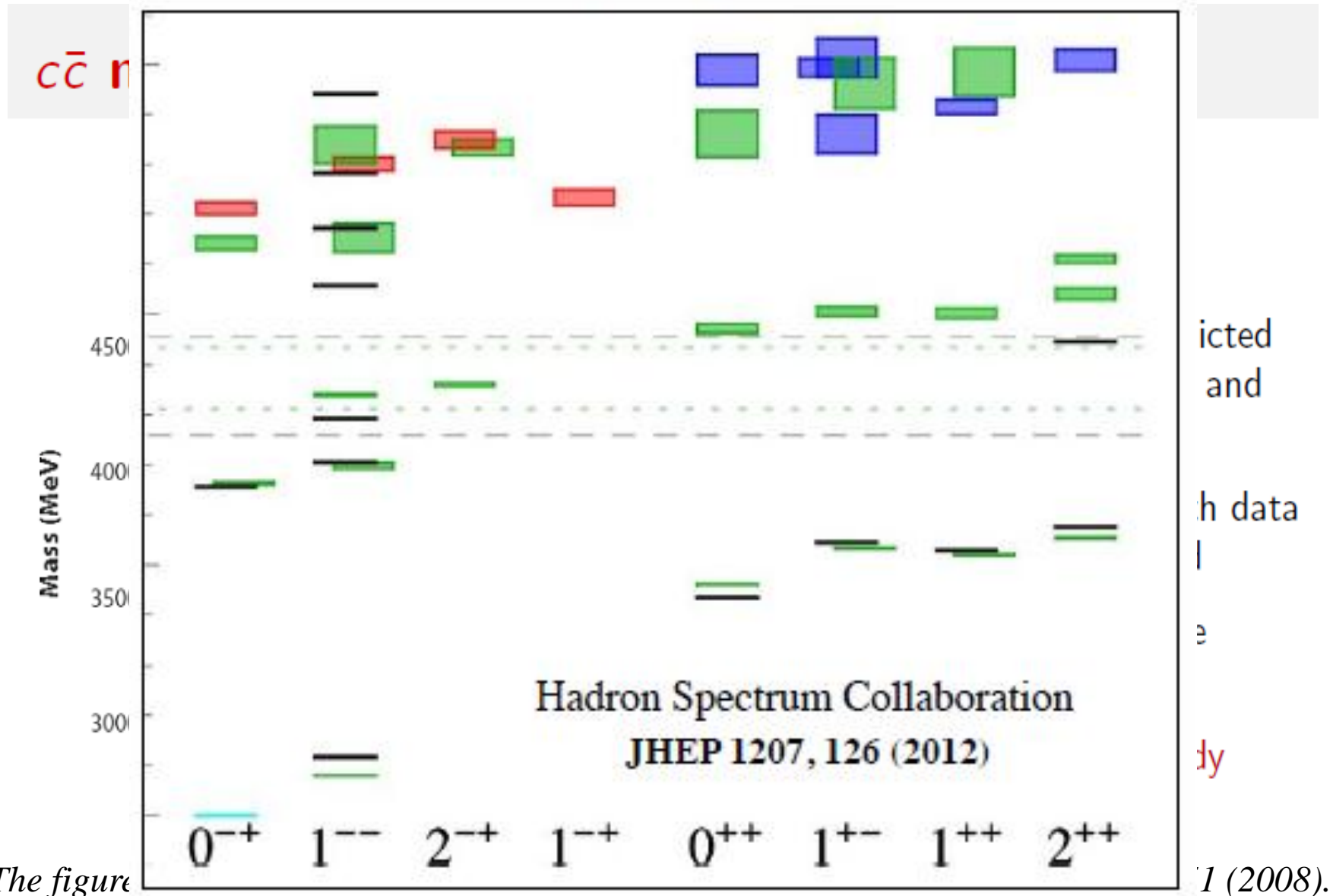
$$R(r) = \sin(r/a), \quad D(r) = r/a, \quad V_3(r) = -V_0 \text{ctg}(r/a) + B, \quad V_0 > 0, \quad B > 0.$$

When cotangent argument in  $V_3(r)$  is small:  $r^2/a^2 \ll \pi^2$ ,  $\left\{ \begin{array}{l} V(r)|_{r \rightarrow 0} \sim 1/r \\ V(r)|_{r \rightarrow \infty} \sim kr \end{array} \right.$   
we get:  $\text{ctg}(r/a) \approx a/r - r/3a$ , 

where  $R(r)$ ,  $D(r)$  and  $G_N(r)$  are scaling factor, gauging and determinant of metric tensor  $G_{\mu\nu}(r)$ .



# A more fundamental approach, Lattice QCD:



The figure

1 (2008).

**The  $c\bar{c}$  system has been investigated in great detail first in  $e^+e^-$ -reactions, and afterwards on a restricted scale ( $E_p \leq 9$  GeV), but with high precision in  $\bar{p}p$ -annihilation (the experiments R704 at CERN and E760/E835 at Fermilab).**

### **The number of unsolved questions related to charmonium has remained:**

- singlet  $^1D_2$  and triplet  $^3D_J$  charmonium states are not determined yet;
- nothing is known about partial width of  $^1D_2$  and  $^3D_J$  charmonium states.
- higher lying singlet  $^1S_0$ ,  $^1P_1$  and triplet  $^3S_1$ ,  $^3P_J$  – charmonium states are poorly investigated;
- only few partial widths of  $^3P_J$ -states are known (some of the measured decay widths don't fit theoretical schemes and additional experimental check or reconsideration of the corresponding theoretical models is needed, more data on different decay modes are desirable to clarify the situation);

#### **AS RESULT:**

- little is known on charmonium states above the  $D\bar{D}$  – threshold ( $S, P, D, \dots$ );
- many recently discovered states above  $D\bar{D}$  - threshold (XYZ-states) expect their verification and explanation (their interpretation now is far from being obvious).

### **IN GENERAL ONE CAN IDENTIFY THREE MAIN CLASSES OF CHARMONIUM DECAYS:**

- decays into particle-antiparticle or  $D\bar{D}$ -pair:  $\bar{p}p \rightarrow (\Psi, \eta_c, \chi_{cJ}, \dots) \rightarrow \Sigma^0 \bar{\Sigma}^0, \Lambda \bar{\Lambda}, \Sigma^0 \bar{\Sigma}^0 \pi, \Lambda \bar{\Lambda} \pi$  ;
- decays into light hadrons:  $\bar{p}p \rightarrow (\Psi, \eta_c, \dots) \rightarrow \rho \pi$ ;  $\bar{p}p \rightarrow \Psi \rightarrow \pi^+ \pi^-$ ,  $\bar{p}p \rightarrow \Psi \rightarrow \omega \pi^0, \eta \pi^0, \dots$  ;
- decays with  $J/\Psi$ ,  $\Psi'$  and  $h_c$  in the final state:  $\bar{p}p \rightarrow J/\Psi + X \Rightarrow \bar{p}p \rightarrow J/\Psi \pi^+ \pi^-$ ,  $\bar{p}p \rightarrow J/\Psi \pi^0 \pi^0$ ;  
 $\bar{p}p \rightarrow \Psi' + X \Rightarrow \bar{p}p \rightarrow \Psi' \pi^+ \pi^-$ ,  $\bar{p}p \rightarrow \Psi' \pi^0 \pi^0$ ;  $\bar{p}p \rightarrow h_c + X \Rightarrow \bar{p}p \rightarrow h_c \pi^+ \pi^-$ ,  $\bar{p}p \rightarrow h_c \pi^0 \pi^0$ .

Besides mesons and baryons, other “exotic” combinations of quarks and gluons could exist (i.e. are not forbidden by QCD). This includes for example

New states may be exotics **somehow expected** by QCD, but **never observed** so far:

## Hybrids:

- Excited gluonic degree of freedom.
- Lowest mass states  $\sim 4.2 \text{ GeV}/c^2$ .

## Hadrocharmonium:

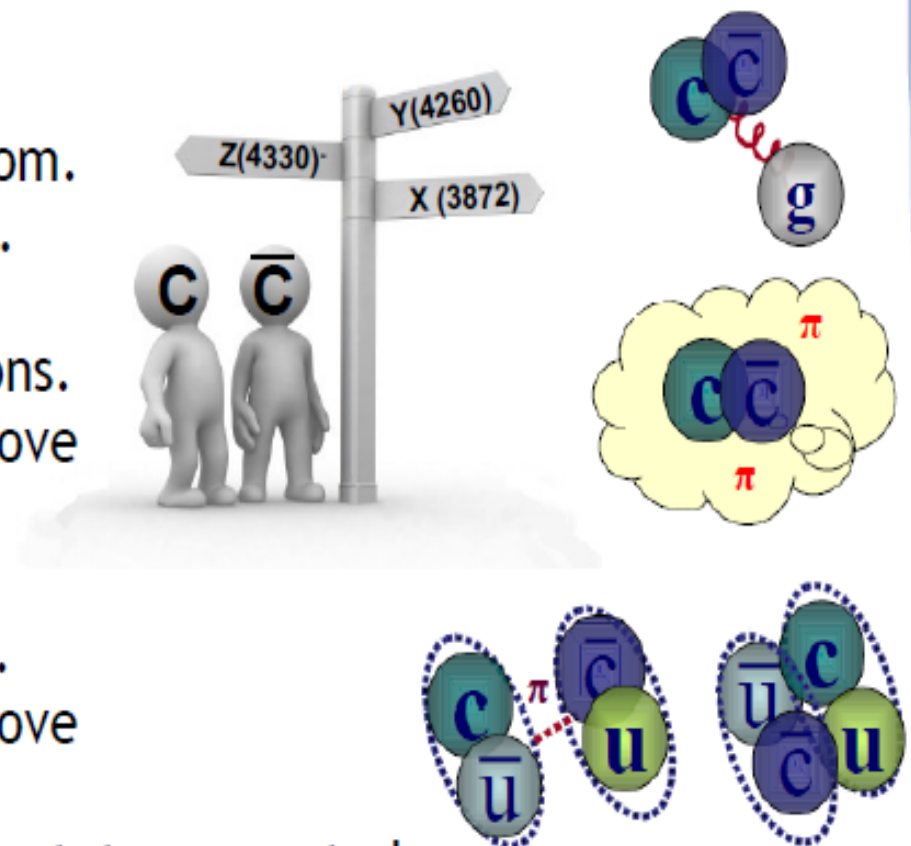
- $c\bar{c}$  state “coated” by light hadrons.
- Compatible with small width above threshold and non-zero charge.

## Multiquark states:

- Tetraquarks &  $D^{(*)}\bar{D}^{(*)}$  molecules.
- Compatible with small width above threshold and non-zero charge.
- Few molecular, lot of tetraquark states expected.

## Threshold effects (npQCD at work):

- Virtual states/cusps at threshold openings.
- Charmonium with mass shifted by nearby  $D^{(*)}\bar{D}^{(*)}$  thresholds.



## Charmonium Spectroscopy

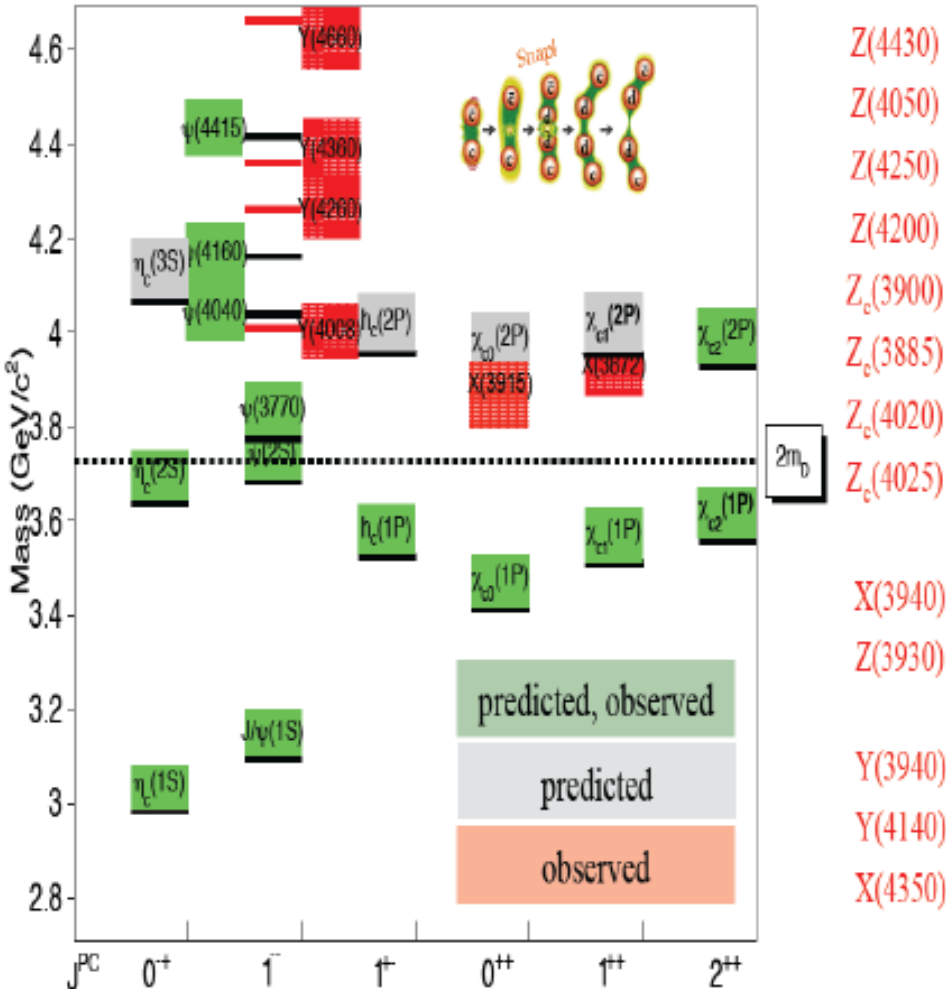
played important role in establishing QCD as theory of strong interactions

- All States below charm threshold have been observed
  - Charm anti-charm potential model described spectrum very well
- Many missing states above charm threshold.
- New states above charm threshold appear
  - Charmonium in final states
  - Not an obvious charmonium state

**Not all of them are charmonia!**

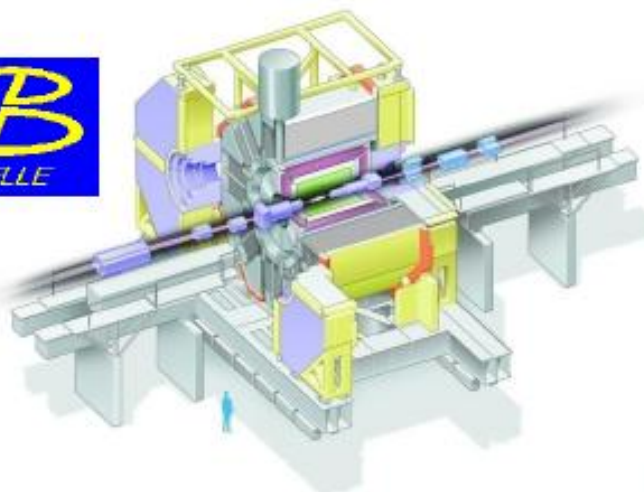
## What are they?

- Charmonium?
- Hybrid?
- Tetraquark?
- Molecule?
- Non-resonance?





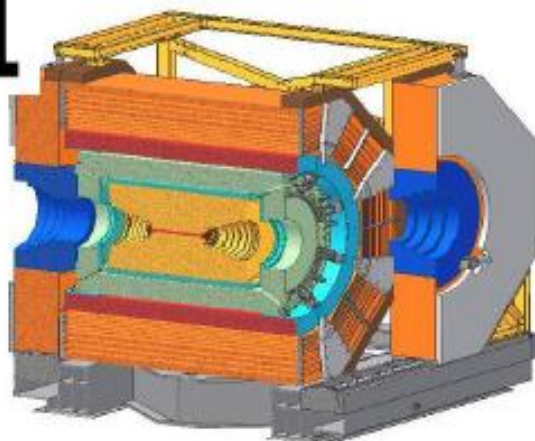
# Results from These Experiments



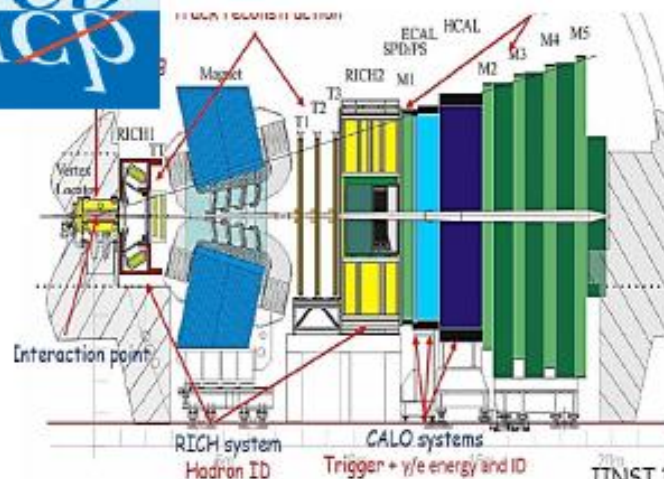
**BABAR**



**BES III**



**LHCb**

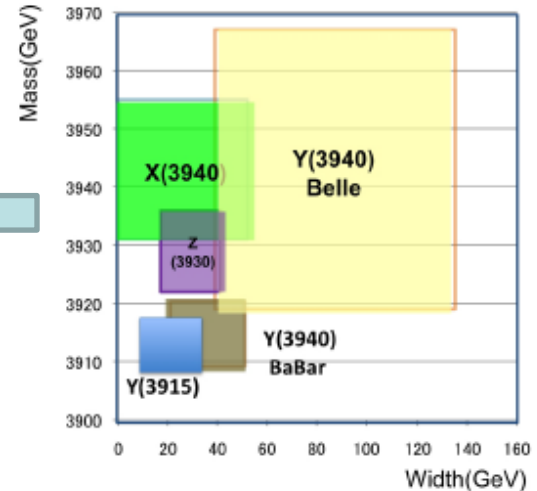


+ CLEO<sub>c</sub>, CDF, CMS/ATLAS ...



# very schematically, clusters of new states

- $X(3872)$ , the first surprise
- the 3940 family
- the  $Y$  family ( $1^{--}$  states):
  - $Y(4260) \rightarrow J/\psi \pi \pi, K^+ K^-$
  - $Y(4350) \rightarrow \psi(2S) \pi^+ \pi^-$
  - $Y(4630) \rightarrow \Lambda_c \bar{\Lambda}_c$
  - $Y(4660) \rightarrow \psi(2S) \pi^+ \pi^-$



## charged states

- $Z(4430) \rightarrow \psi(2S) \pi^\pm$
- $Z_1(4050), Z_2(4250) \rightarrow \chi_{c1}(2S) \pi^\pm$

## $C = +$ states

- $X(4160) \rightarrow D^* \bar{D}^*$
- $Y(4140) \rightarrow J/\psi \phi$
- $X(4350)$

## BES III

$$Z_c(3900)^\pm \rightarrow J/\psi \pi^\pm$$

$$Z_c(3885)^\pm \rightarrow D \bar{D}^*$$

$$Z_c(4025)^\pm \rightarrow D^* \bar{D}^*$$

$$Z_c(4020)^\pm \rightarrow h_c \pi^\pm$$

## BELLE

$$Z_c(4200)^\pm \rightarrow J/\psi \pi^\pm$$

WHAT ARE THESE STATES?  
CHARMONIUM OR EXOTICS?

Two different kinds of experiments are foreseen at FAIR :

- production experiment –  $\bar{p}p \rightarrow X + M$ , where  $M = \pi, \eta, \omega, \dots$  (conventional states plus states with exotic quantum numbers)
- formation experiment (annihilation process) –  $\bar{p}p \rightarrow X \rightarrow M_1 M_2$  (conventional states plus states with non-exotic quantum numbers)

The low laying charmonium hybrid states:

Gluon		
$(q\bar{q})_8$	$1^-$ (TM)	$1^+$ (TE)
$^1S_0, 0^{-+}$	$1^{++}$	$1^{--}$
$^3S_1, 1^{--}$	$0^{+-} \leftarrow$ exotic	$0^{-+}$
	$1^{+-}$	$1^{-+} \leftarrow$ exotic
	$2^{+-} \leftarrow$ exotic	$2^{-+}$

Charmonium hybrids predominantly decay via electromagnetic and hadronic transitions and into the open charm final states:

- $\bar{c}c g \rightarrow (\Psi, \chi_{cJ}) + \text{light mesons } (\eta, \eta', \omega, \phi)$  - these modes supply small widths and significant branch fractions;
- $\bar{c}c g \rightarrow D\bar{D}_J^*$ . In this case  $S$ -wave ( $L = 0$ ) +  $P$ -wave ( $L = 1$ ) final states should dominate over decays to  $D\bar{D}$  (are forbidden  $\rightarrow CP$  violation) and partial width to should be very small.

The most interesting and promising decay channels of charmed hybrids have been, in particular, analyzed:

- $\bar{p}p \rightarrow \tilde{\eta}_{c0,1,2} (0^{-+}, 1^{-+}, 2^{-+}) \eta \rightarrow \chi_{c0,1,2} (\eta, \pi\pi, \dots);$
- $\bar{p}p \rightarrow \tilde{h}_{c0,1,2} (0^{+-}, 1^{+-}, 2^{+-}) \eta \rightarrow \chi_{c0,1,2} (\eta, \pi\pi, \dots);$
- $\bar{p}p \rightarrow \tilde{\Psi} (0^{--}, 1^{--}, 2^{--}) \rightarrow J/\Psi (\eta, \omega, \pi\pi, \dots);$
- $\bar{p}p \rightarrow \tilde{\eta}_{c0,1,2}, \tilde{h}_{c0,1,2}, \tilde{\chi}_{c1} (0^{-+}, 1^{-+}, 2^{-+}, 0^{+-}, 1^{+-}, 2^{+-}, 1^{++}) \eta \rightarrow D\bar{D}_J^* \eta.$

$J^{PC} = 0^{-} \rightarrow \text{exotic!}$

According to the constituent quark model tetraquark states are classified in terms of the diquark and antidiquark spin  $S_{cq}$ ,  $S_{\bar{c}\bar{q}}$ , total spin of diquark-antidiquark system  $S$ , total angular momentum  $J$ , spatial parity  $P$  and charge conjugation  $C$ . The following states with definite quantum numbers  $J^{PC}$  are expected to exist:

! - two states with  $J = 0$  and positive  $P$ -parity  $J^{PC} = 0^{++}$  i.e.,  $|0_{cq}, 0_{\bar{c}\bar{q}}; S = 0, J = 0\rangle$  and  $|1_{cq}, 1_{\bar{c}\bar{q}}; S = 0, J = 0\rangle$ ;

! - three states with  $J = 0$  and negative  $P$ -parity i.e.,  $|A\rangle = |1_{cq}, 0_{\bar{c}\bar{q}}; S = 1, J = 0\rangle$ ;  $|B\rangle = |0_{cq}, 1_{\bar{c}\bar{q}}; S = 1, J = 0\rangle$ ;  $|C\rangle = |1_{cq}, 1_{\bar{c}\bar{q}}; S = 1, J = 0\rangle$ . State  $|C\rangle$  is even under charge conjugation. Taking symmetric and antisymmetric combinations of states  $|A\rangle$  and  $|B\rangle$  we obtain a  $C$ -odd and  $C$ -even state respectively; therefore we have one state with  $J^{PC} = 0^{-}$  i.e.,  $|0^{-}\rangle = \frac{1}{\sqrt{2}}(|A\rangle + |B\rangle)$  and two states

with  $J^{PC} = 0^{+}$  i.e.,  $|0^{+}\rangle_1 = \frac{1}{\sqrt{2}}(|A\rangle - |B\rangle)$ ;  $|0^{+}\rangle_2 = |C\rangle$ .

! - three states with  $J = 1$  and positive  $P$ -parity i.e.,  $|D\rangle = |1_{cq}, 0_{\bar{c}\bar{q}}; S = 1, J = 1\rangle$ ;  $|E\rangle = |0_{cq}, 1_{\bar{c}\bar{q}}; S = 1, J = 1\rangle$ ;  $|F\rangle = |1_{cq}, 1_{\bar{c}\bar{q}}; S = 1, J = 1\rangle$ . State  $|F\rangle$  is odd under charge conjugation. Operating  $|D\rangle$  and  $|E\rangle$  in the same way as for states  $|A\rangle$  and  $|B\rangle$  we obtain one state with  $J^{PC} = 1^{++}$  state i.e.,  $|1^{++}\rangle = \frac{1}{\sqrt{2}}(|D\rangle + |E\rangle)$  and two states with  $J^{PC} = 1^{+}$  i.e.,  $|1^{+}\rangle_1 = \frac{1}{\sqrt{2}}(|D\rangle - |E\rangle)$ ;  $|1^{+}\rangle_2 = |F\rangle$ .

! - one state with  $J = 2$  and positive  $P$ -parity  $J^{PC} = 2^{++}$  i.e.,  $|1_{cq}, 1_{\bar{c}\bar{q}}; S = 1, J = 2\rangle$ .

! •  $\bar{p}p \rightarrow X \rightarrow J/\Psi \rho \rightarrow J/\Psi \pi\pi$ ,  $\bar{p}p \rightarrow X \rightarrow J/\Psi \omega \rightarrow J/\Psi \pi\pi\pi$ ,  $\bar{p}p \rightarrow X \rightarrow \chi_{cJ} \pi$  (decays into  $J/\Psi$ ,  $\Psi'$ ,  $\chi_{cJ}$  and light mesons);

•  $\bar{p}p \rightarrow X \rightarrow D\bar{D}^* \rightarrow D\bar{D} \gamma$ ,  $\bar{p}p \rightarrow X \rightarrow D\bar{D}^* \rightarrow D\bar{D} \eta$  (decays into  $D\bar{D}^*$ -pair).

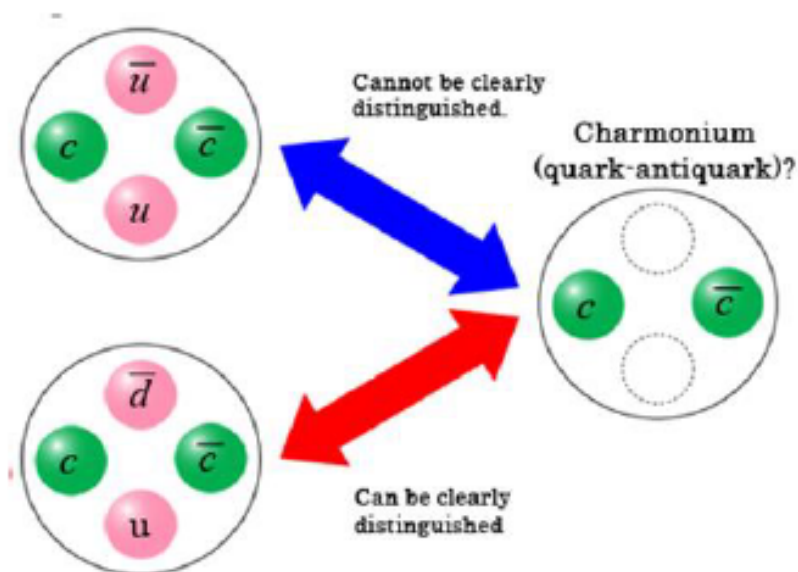
# $Z_c$ States

## The most promising way to searching for the exotic hadrons

- Decay into a charmonium or  $D^{(*)}\bar{D}^{(*)}$  pair
  - thus contains hidden- $c\bar{c}$  pair
- Have electric charge,
  - thus has two more light quarks

**At least 4 quarks, not a conventional meson**

- Observed in final states :
  - $\pi^\pm J/\psi$ ,  $\pi^\pm \psi(2S)$ ,  $\pi^\pm h_c$ ,  $\pi^\pm \chi_{cJ}$ ,  $(D^{(*)}\bar{D}^{(*)})^\pm, \dots$
- Experimental search:
  - BESIII/CLEO-c :  $e^+e^- \rightarrow \pi^\pm + \text{Exotics}$ , ....
  - Belle/BaBar :  $e^+e^- \rightarrow (\gamma_{\text{ISR}})\pi^\pm + \text{Exotics}$ , ....
  - Belle/BaBar/LHCb:  $B \rightarrow K^\pm + \text{Exotics}$ , ...





# The first charged state: Z(4430)!



$$B^\pm \rightarrow Z^\pm K_s \quad \text{or} \quad B^0 \rightarrow Z^0 K^\pm$$

$$Z^\pm \rightarrow \psi(2S) \pi^\pm$$

Total significance: 7.3s

$$M = (4433 \pm 4) \text{ MeV}$$

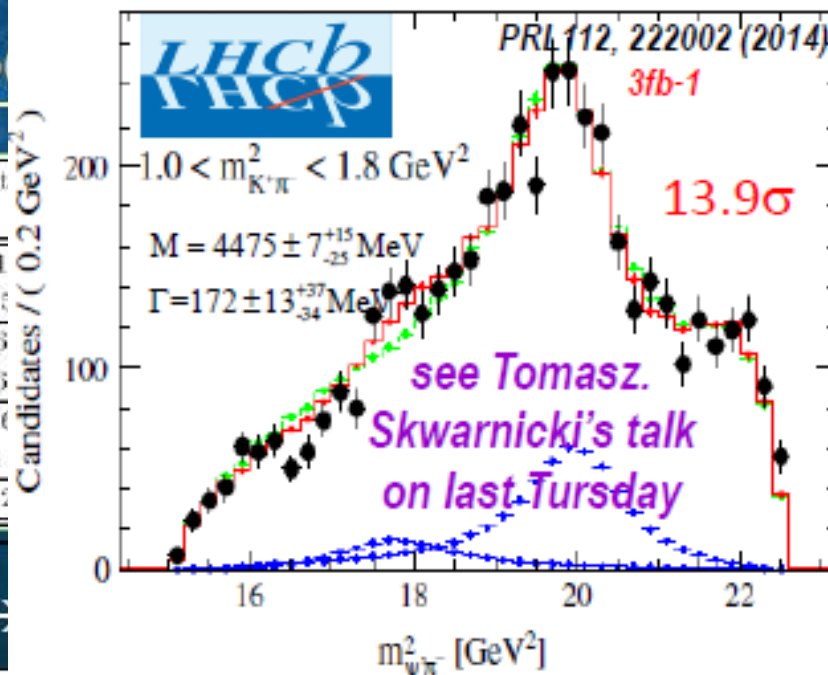
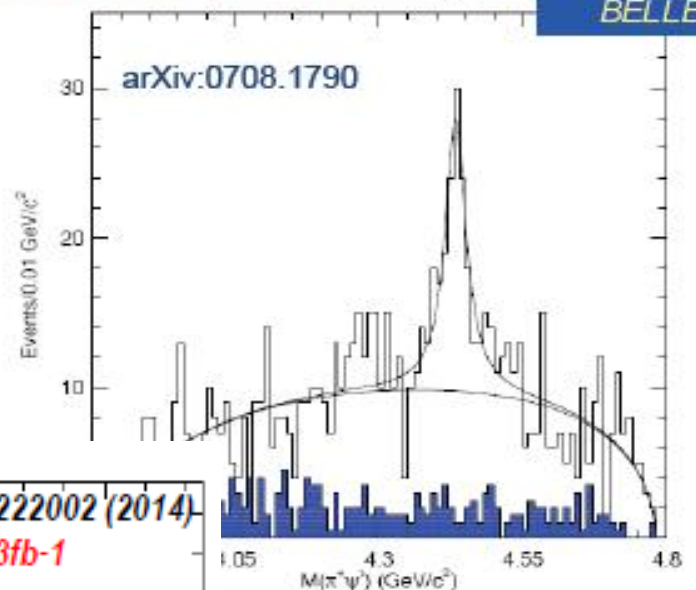
$$\Gamma = (44^{+17}_{-13}) \text{ MeV}$$

Too narrow to  
be a reflection

$$BF(B \rightarrow KZ) \times BF(Z \rightarrow \psi \pi)$$

Subset	Signal event
$\psi' \rightarrow \pi^+ \pi^- J/\psi$	$52.9 \pm 15.1$
$\psi' \rightarrow \ell^+ \ell^-$	$104.8 \pm 34.5$
$J/\psi(\psi') \rightarrow e^+ e^-$	$45.4 \pm 16.6$
$J/\psi(\psi') \rightarrow \mu^+ \mu^-$	$79.4 \pm 24.6$
$K^\pm \pi^\mp \psi'$	$106.5 \pm 26.0$
$K_S \pi^\mp \psi'$	$21.0 \pm 8.3$
vary $K^*$ veto	$238.1 \pm 64.5$

Prior search with  
 $B \rightarrow X^+ K$  with  $X^+ \rightarrow$



Separate in  
samples

Mass consistent  
between  $B^\pm$  and  $B^0$  within  
errors [in  $B^\pm$  decays  $M =$   
 $4433 \pm 9$  MeV :  $BF_\pm/BF_0 = 1.0$

R.Faccini,  
LeptonPhoton  
Conference 2007

Confirmed by LHCb => arXiv:1404.1903v1 [hep-ex] 7 Apr 2014





# Belle observed Two $Z^\pm \rightarrow \chi_{c1} \pi^\pm$

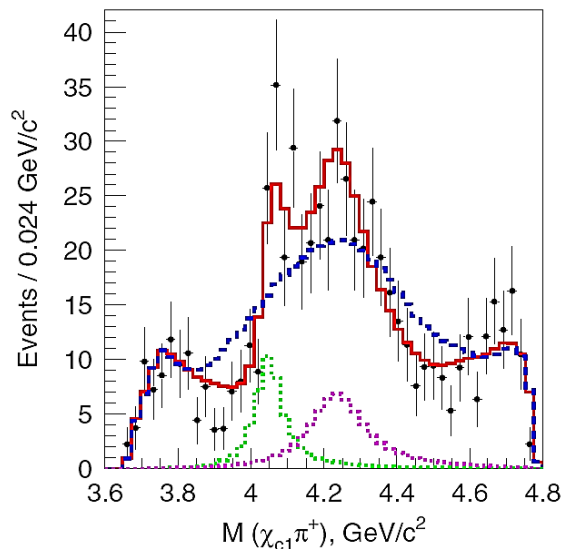
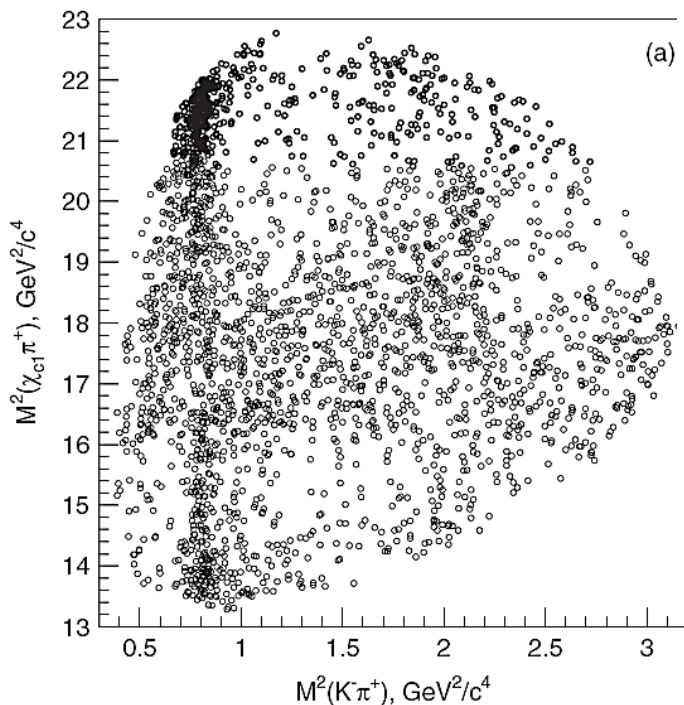
- Dalitz-plot analysis of  $\underline{B}^0 \rightarrow \chi_{c1} \pi^+ K^-$   $\chi_{c1} \rightarrow J/\psi \gamma$  with 657M  $\underline{B}\underline{B}$
- Dalitz plot models: known  $K^* \rightarrow K\pi$  only

$K^*$ 's + one  $Z \rightarrow \chi_{c1} \pi^\pm$

$K^*$ 's + two  $Z^\pm$  states  $\Rightarrow$  favored by data

PRD 78, 072004 (2008)

Significance:  $5.7\sigma$



$M(\chi_{c1} \pi^+)$

for  $1 < M^2(K^- \pi^+) < 1.75 \text{ GeV}^2$

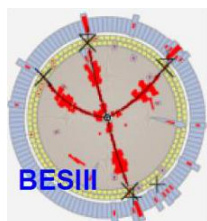
- fit for model with  $K^*$ 's
- fit for double Z model
- $Z_1$  contribution
- $Z_2$  contribution

$$M_{Z_1} = 4051 \pm 14^{+20}_{-41} \text{ MeV}$$

$$\Gamma_{Z_1} = 82^{+21+47}_{-17-22} \text{ MeV}$$

$$M_{Z_2} = 4248^{+44+180}_{-29-35} \text{ MeV}$$

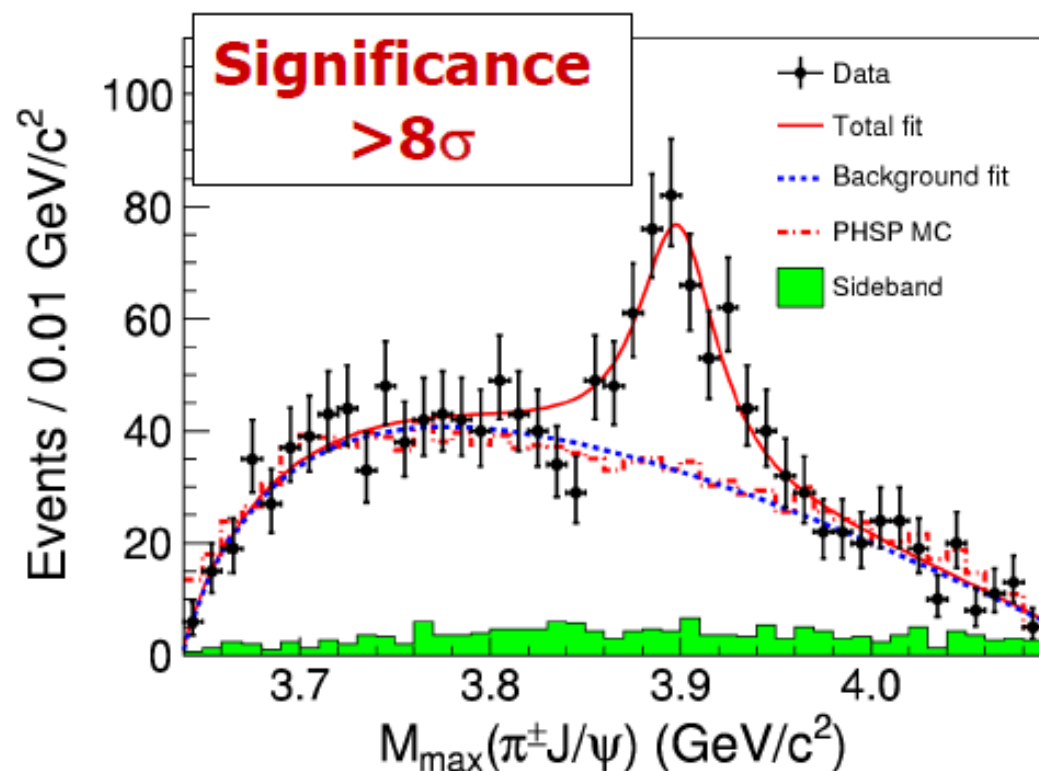
$$\Gamma_{Z_2} = 177^{+54+316}_{-39-61} \text{ MeV}$$



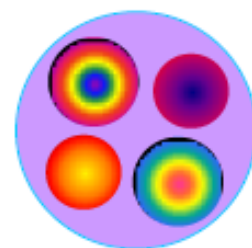
# Observation of $Z_c(3900)$ in $e^+e^- \rightarrow \pi^+\pi^-J/\psi$

BESIII: arXiv:1303.5949

BESIII: PRL110, 252001 (2013)



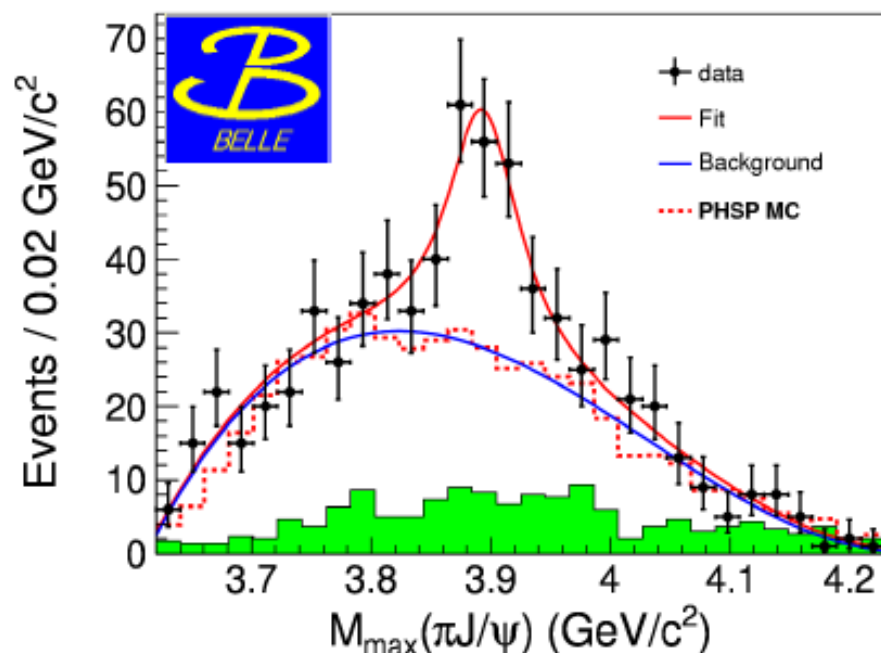
- Couples to  $cc$
- Has electric charge
- At least 4-quarks
- What is its nature?



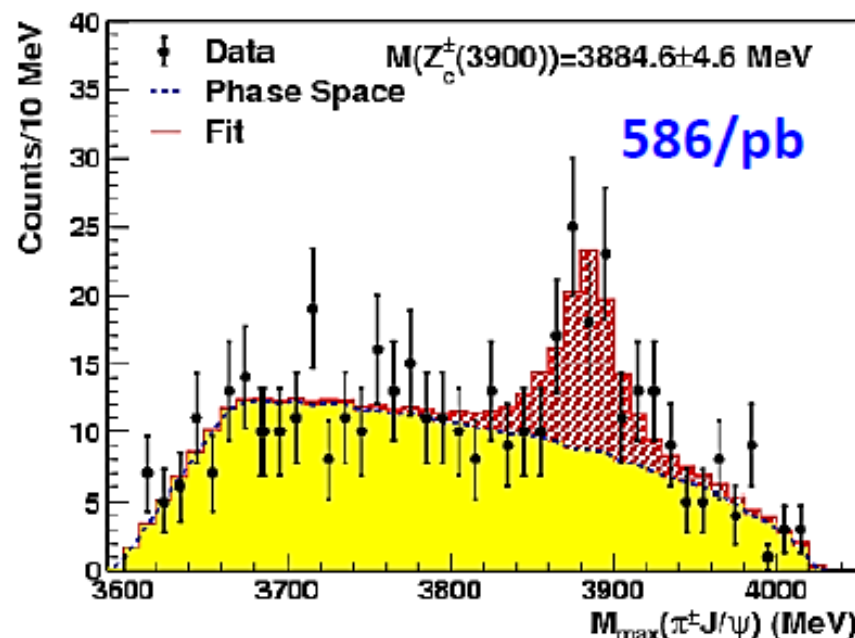
- S-wave Breit-Wigner with efficiency correction
- Mass =  $(3899.0 \pm 3.6 \pm 4.9)$  MeV
- Width =  $(46 \pm 10 \pm 20)$  MeV
- Fraction =  $(21.5 \pm 3.3 \pm 7.5)\%$

**BELLE :  $e^+e^- \rightarrow \pi^+\pi^-J/\psi$  from ISR**  
**Belle: PRL 110, 252002(2013)**

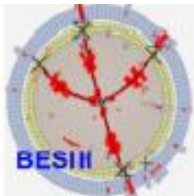
**CLEOc data at 4.17 GeV**  
**arXiv: 1304.3036**



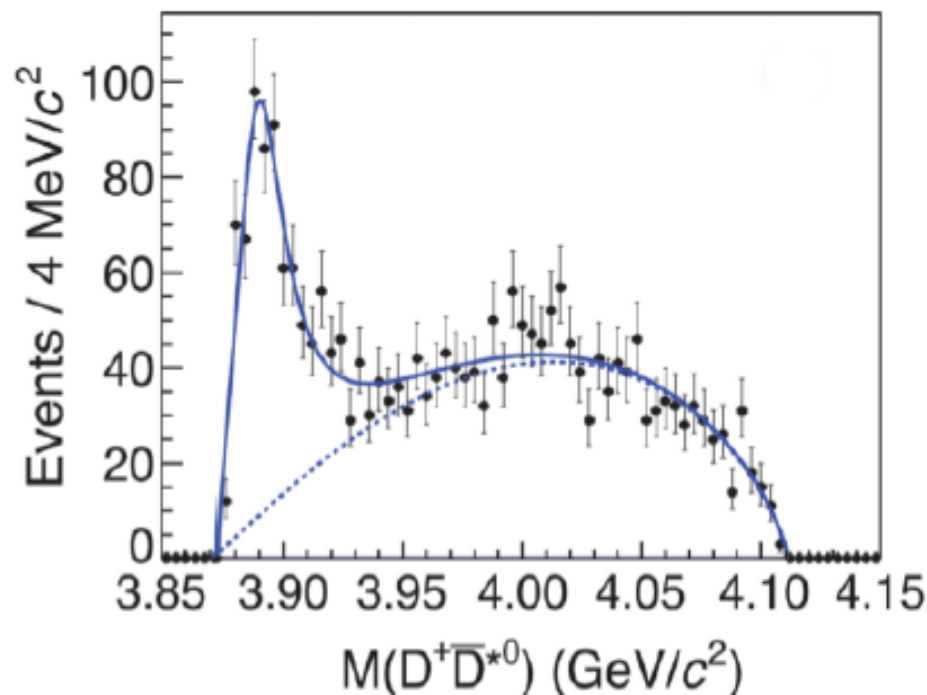
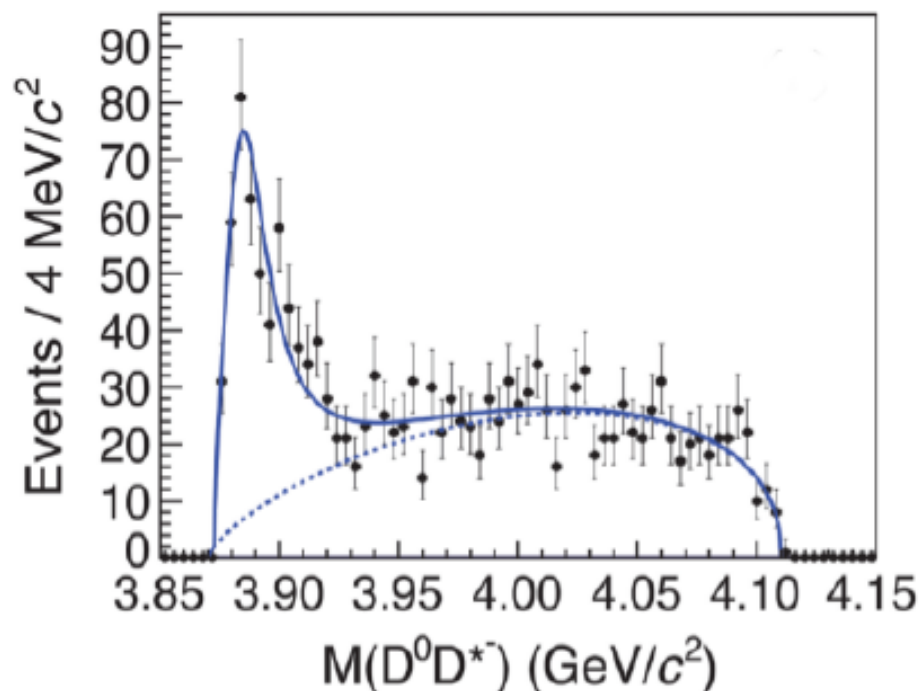
- $M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$
- $\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$
- $159 \pm 49 \text{ events}$
- $>5.2\sigma$



- $M = 3885 \pm 5 \pm 1 \text{ MeV}$
- $\Gamma = 34 \pm 12 \pm 4 \text{ MeV}$
- $81 \pm 20 \text{ events}$
- $6.1\sigma$



$$e^+e^- \rightarrow \pi Z_c(3885) \rightarrow \pi D \bar{D}^* + \text{c.c.}$$



$$M = (3883.9 \pm 1.5 \pm 4.2) \text{ MeV}/c^2$$

$$\Gamma = (24.8 \pm 3.3 \pm 11.0) \text{ MeV}/c^2$$

$$> 18\sigma$$

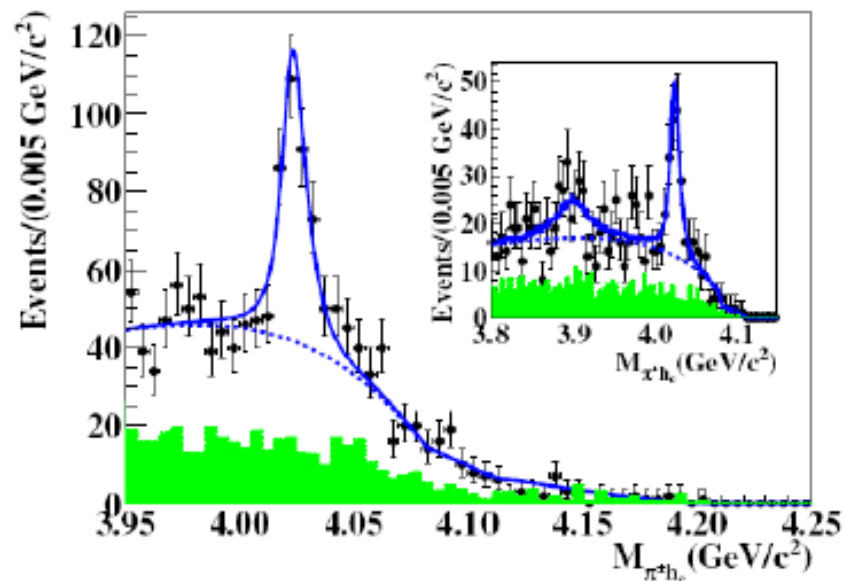
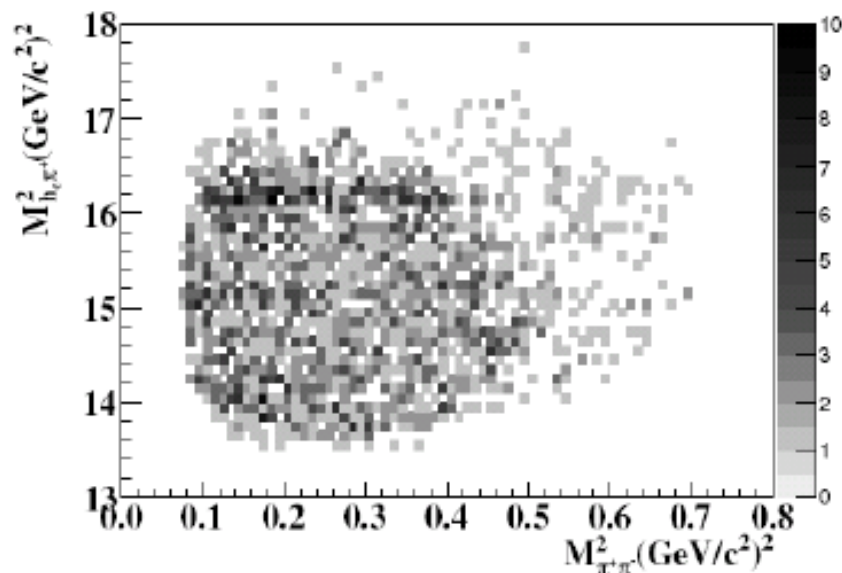
$\pi Z_c(3885)$  ang. dist. favours  $J^P = 1^+$   
disfavours  $1^-$  e  $0^-$

$$\sigma(e^+e^- \rightarrow \pi^- Z_c(3885)^+ \times Z_c(3885)^+ \rightarrow (D \bar{D}^*)^+ + \text{c.c.}) = (83.5 \pm 6.6 \pm 22.0) \text{ pb}$$

$$R = \frac{\Gamma(Z_c(3885) \rightarrow D^* \bar{D}^*)}{\Gamma(Z_c(3900) \rightarrow \pi J/\psi)} = (6.2 \pm 1.1 \pm 2.7)$$

# $Z_c^\pm(4020)$ in $e^+e^- \rightarrow \pi^+\pi^-h_c(1P)$

- Using data taken at 4.23 GeV, 4.26 GeV 4.36 GeV (total  $2.4 \text{ fb}^{-1}$ )
- See structure in  $h_c\pi^\pm$  spectrum, close to  $D^*\bar{D}^*$  threshold :



$$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}/c^2$$

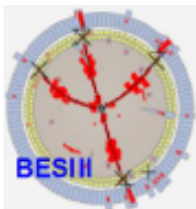
$$\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}$$

[arXiv:1309.1896](https://arxiv.org/abs/1309.1896)

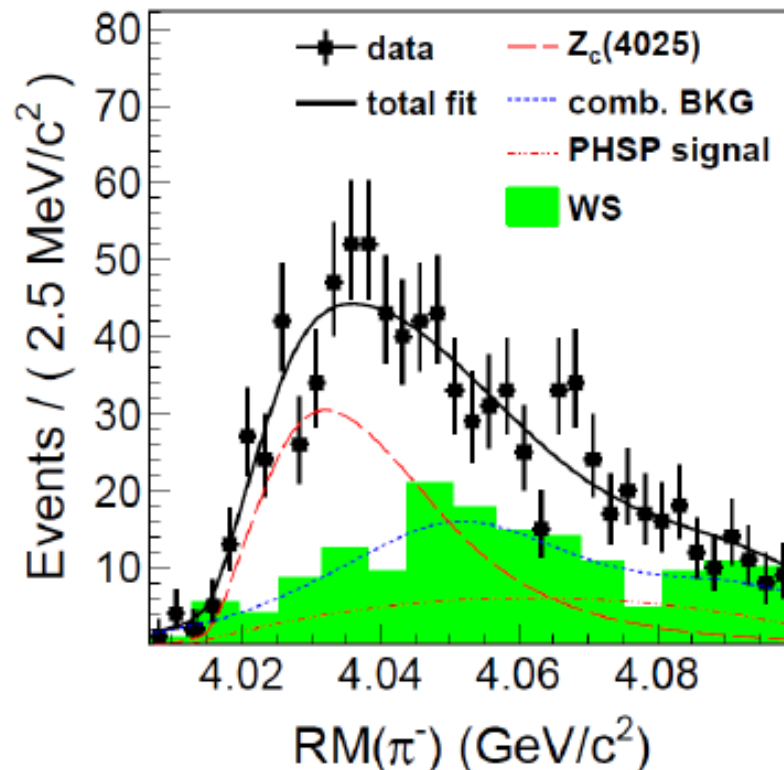
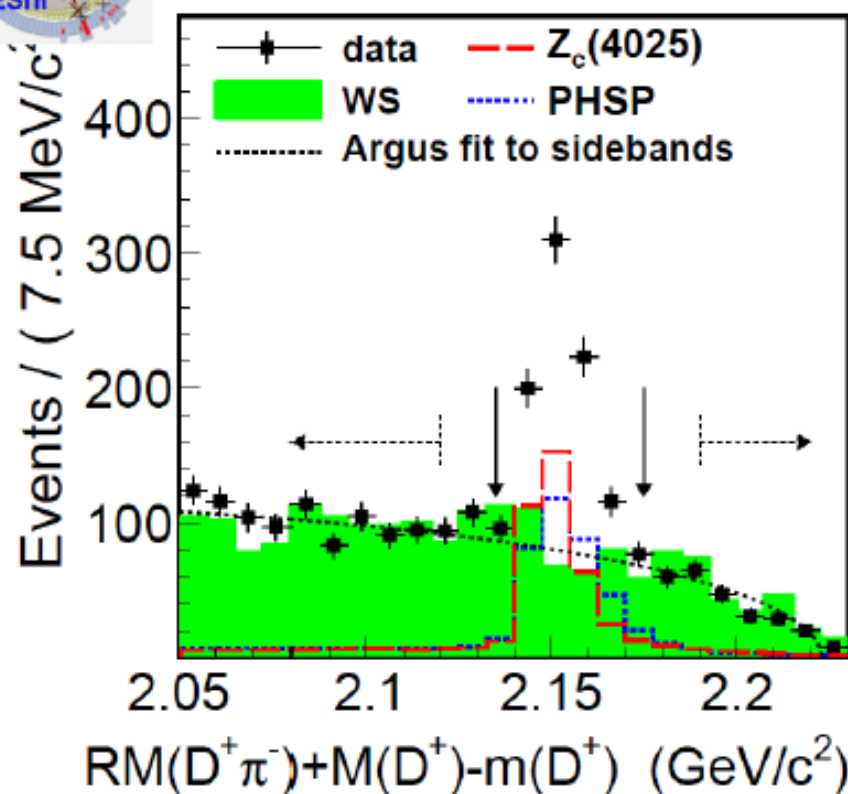
submitted to PRL

No significant signal  $Z_c(3900) \rightarrow h_c\pi^+$  seen : **less than  $2.1 \sigma$**





$$e^+e^- \rightarrow \pi Z_c(4025) \rightarrow \pi^- (D^* \bar{D}^*)^+ + \text{c.c.}$$



Fit to  $\pi^\pm$  recoil mass yields  $401 \pm 47$   $Z_c(4025)$  events. **>10 $\sigma$**

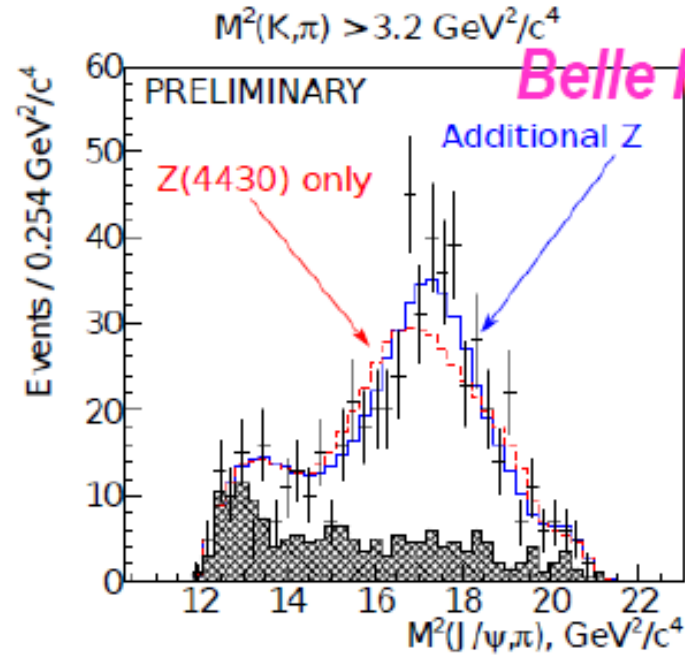
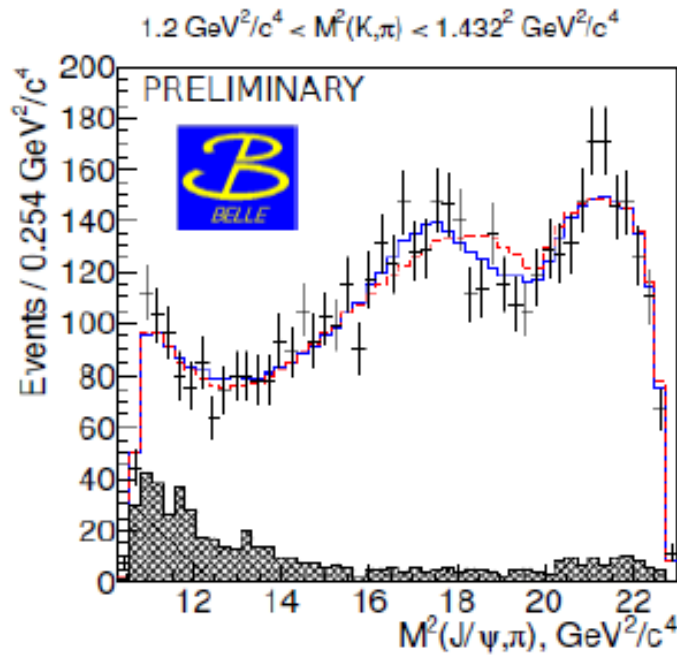
$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$  MeV;  $\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$  MeV

$$R = \frac{\sigma(e^+e^- \rightarrow \pi^\pm Z_c^\mp(4025) \rightarrow \pi^\pm (D^* \bar{D}^*)^\mp)}{\sigma(e^+e^- \rightarrow \pi^\pm (D^* \bar{D}^*)^\mp)} = (65 \pm 9 \pm 6) \%$$

$$\sigma(e^+e^- \rightarrow \pi^\pm (D^* \bar{D}^*)^\mp) = (137 \pm 9 \pm 15) \text{ pb}$$

[arXiv:1308.2760](https://arxiv.org/abs/1308.2760) submitted to PRL

# $B^0 \rightarrow J/\psi k \pi$ @ Belle



*Belle Preliminary*

- 4D amplitude analysis
- New  $Z_c(4200)$  is found ( $J^P = 1^+$ ) with  $7.2\sigma$ :  

$$M = 4196_{-29-6}^{+31+17} \text{ MeV}/c^2, \Gamma = 370_{-70-85}^{+70+70} \text{ MeV}.$$
- Exclusion levels ( $J^P=0^-, 1^-, 2^-, 2^+$ ) :  $6.7\sigma, 7.7\sigma, 5.2\sigma, 7.6\sigma$
- $Z_c(4430)$  is also found ( $4\sigma$ ),  $\frac{B(Z_c(4430)^+ \rightarrow \psi(2S)\pi^+)}{B(Z_c(4430)^+ \rightarrow J/\psi\pi^+)} \sim 10$

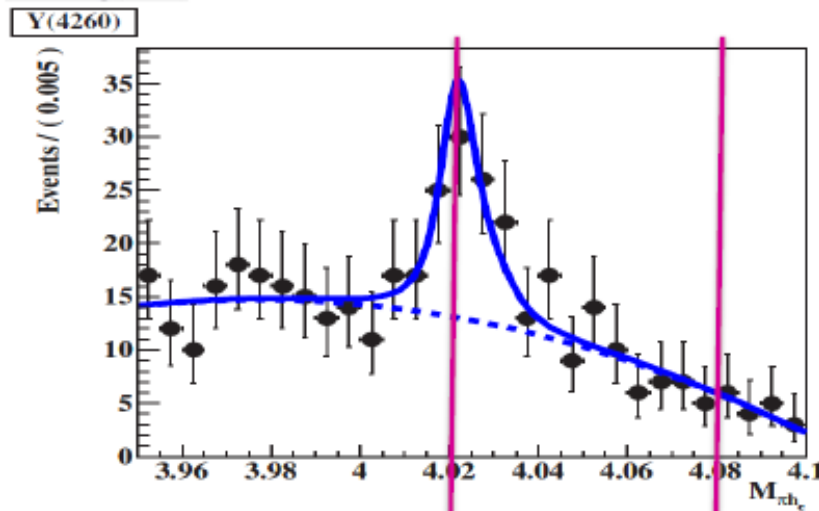
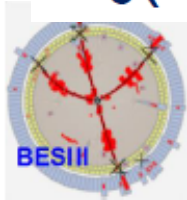
A new charged charmonium-like particle,  $Z_c(4200)$  ?

A new  $Z_c(4430)$  decay mode?

**Need confirmation!**

$Z_c(3885) = Z_c(3900) \Rightarrow$  the same question?

$Z_c(4020) = Z_c(4025)?$



- $M(4020) = 4021.8 \pm 1.0 \pm 2.5 \text{ MeV}$
- $M(4025) = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV}$
- $\Gamma(4020) = 5.7 \pm 3.4 \pm 1.1 \text{ MeV}$
- $\Gamma(4025) = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}$

Close to  $\bar{D}^* D^*$  threshold = 4017 MeV

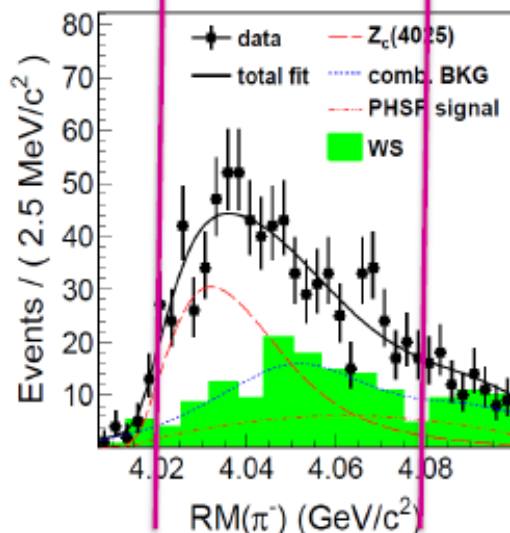
Mass consistent with each other but width  $\sim 2\sigma$  difference

Interference with other amplitudes may change the results

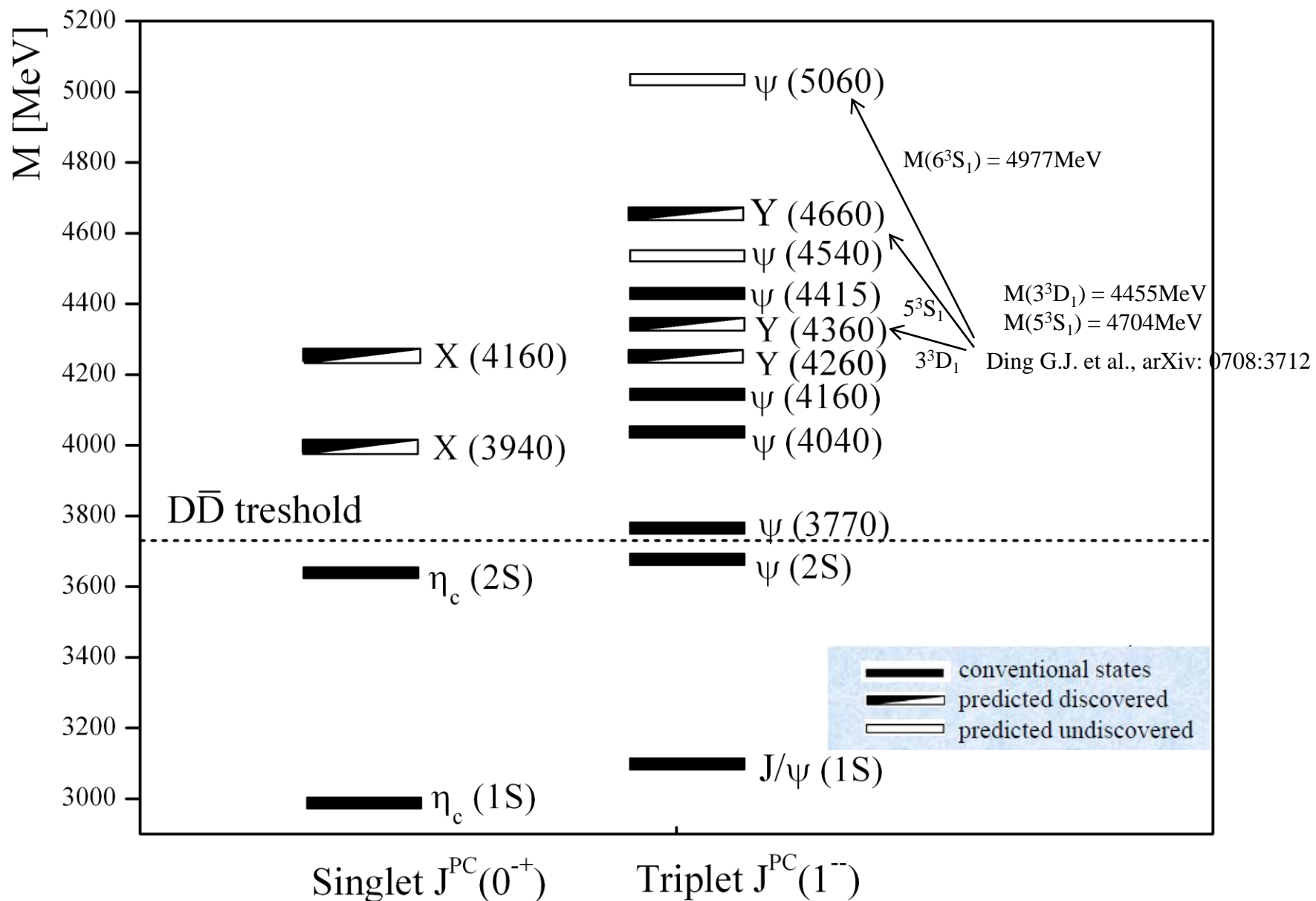
Coupling to  $\bar{D}^* D^*$  is much larger than to  $\pi h_c$  if they are the same state

Will fit with Flatté formula

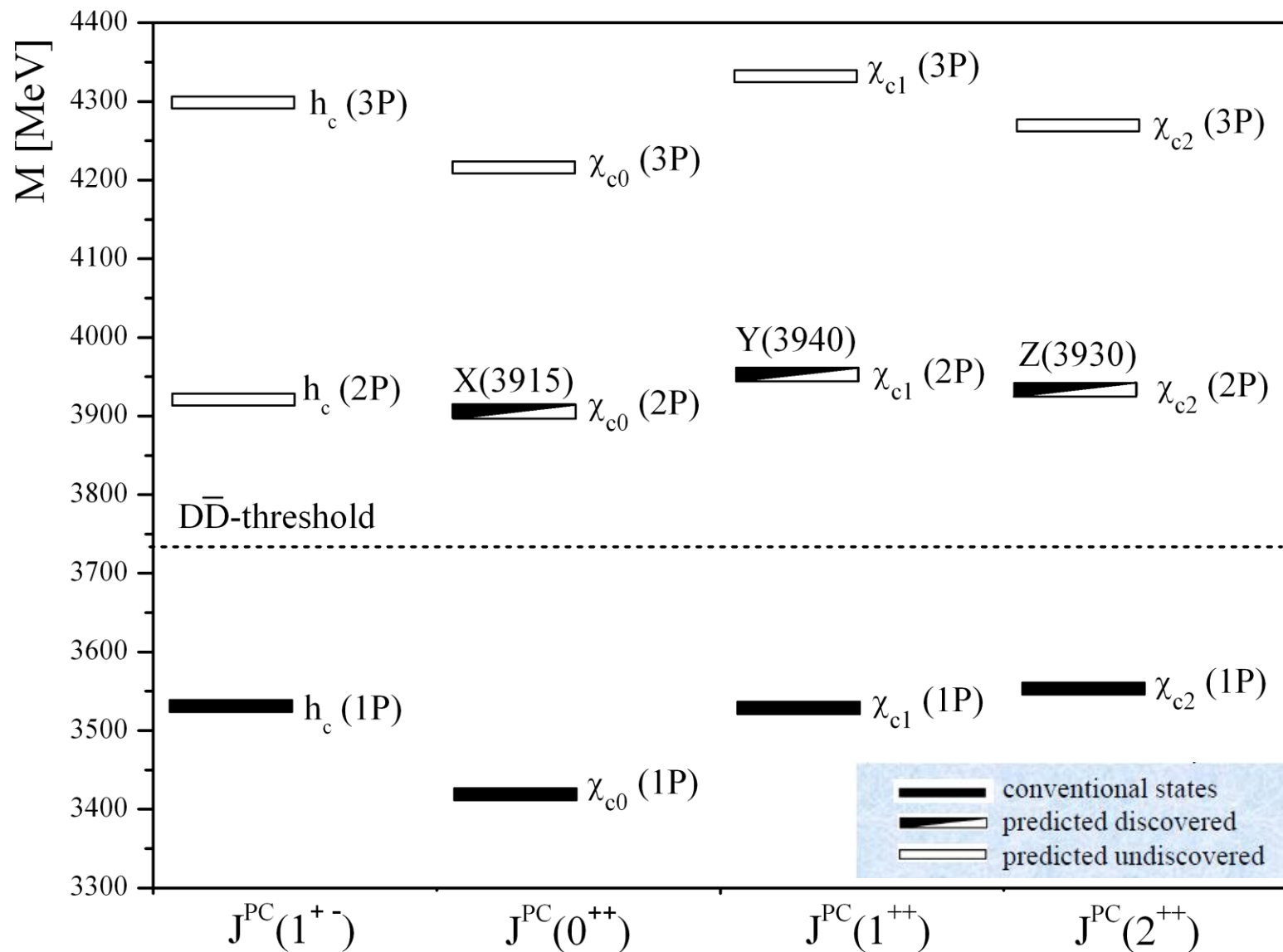
BESIII preliminary  
The  $Z_c$ ' is found!



# THE SPECTRUM OF SINGLET ( $^1S_0$ ) AND TRIPLET ( $^3S_1$ ) STATES OF CHARMONIUM



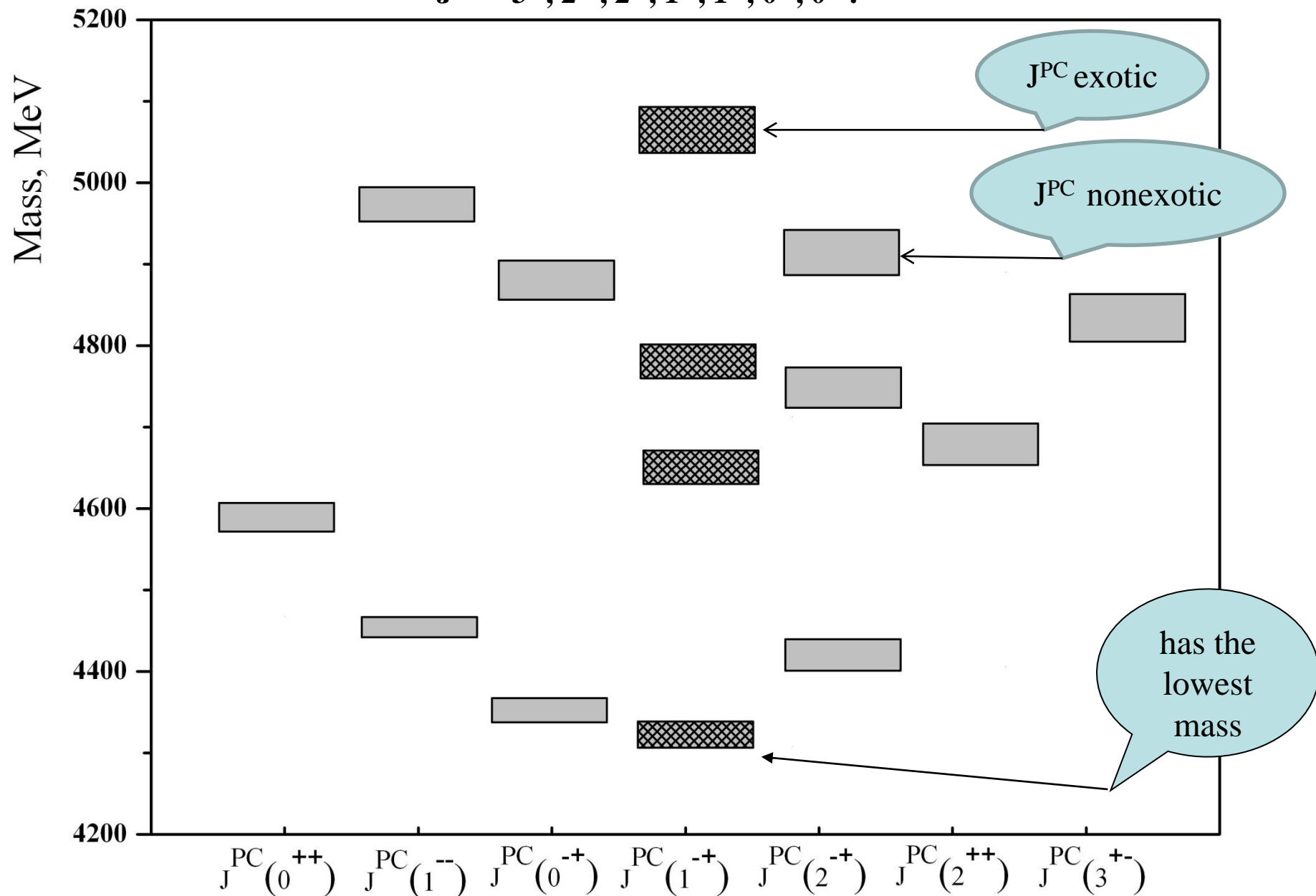
# THE SPECTRUM OF SINGLET ( $^1P_J$ ) AND TRIPLET ( $^3P_J$ ) STATES OF CHARMONIUM





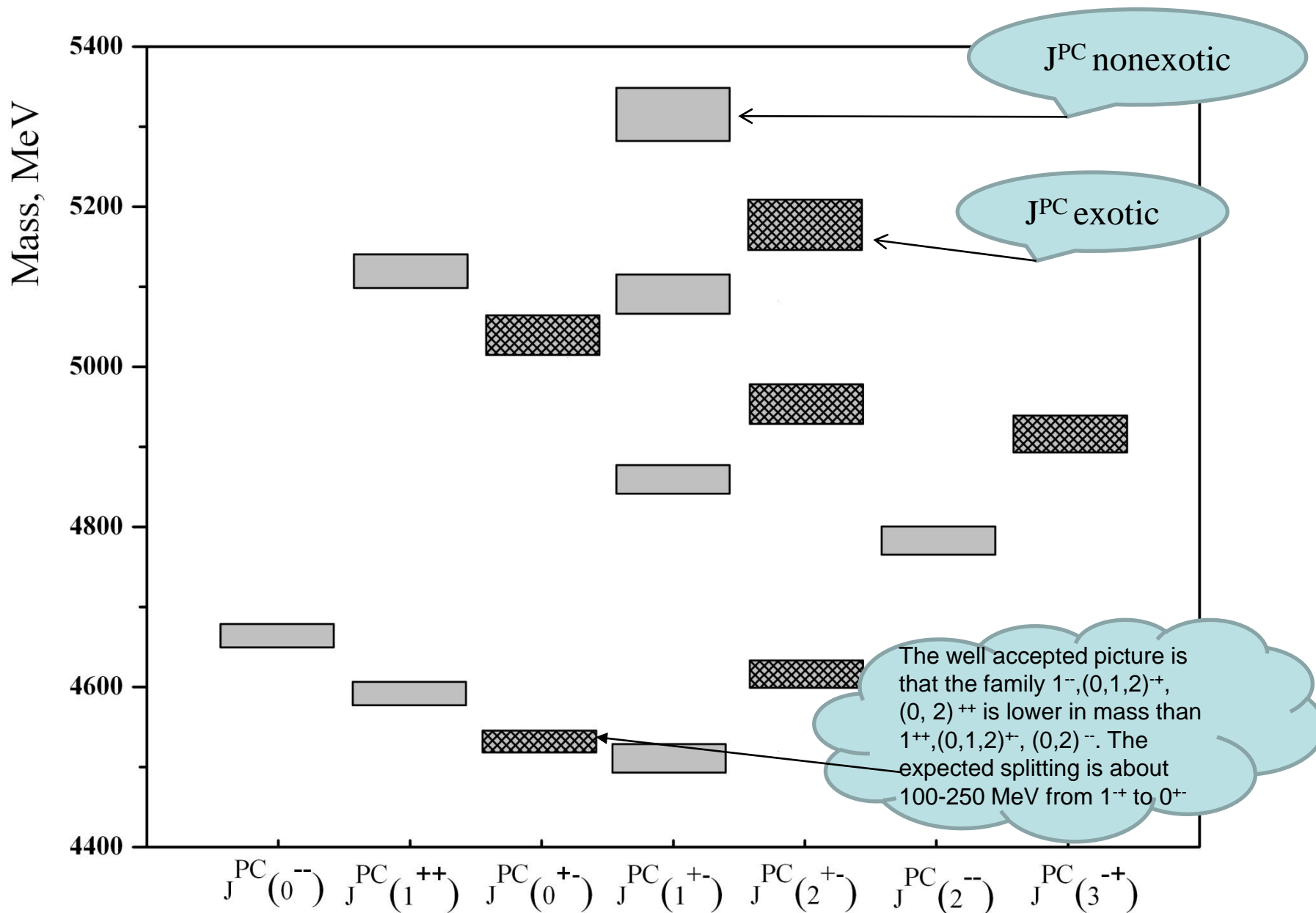
# SPECTRUM OF CHARMED HYBRIDS WITH QUANTUM NUMBERS

$$J^{PC} = 3^{+-}, 2^{++}, 2^{-+}, 1^{+-}, 1^{-+}, 0^{+-}, 0^{++}.$$

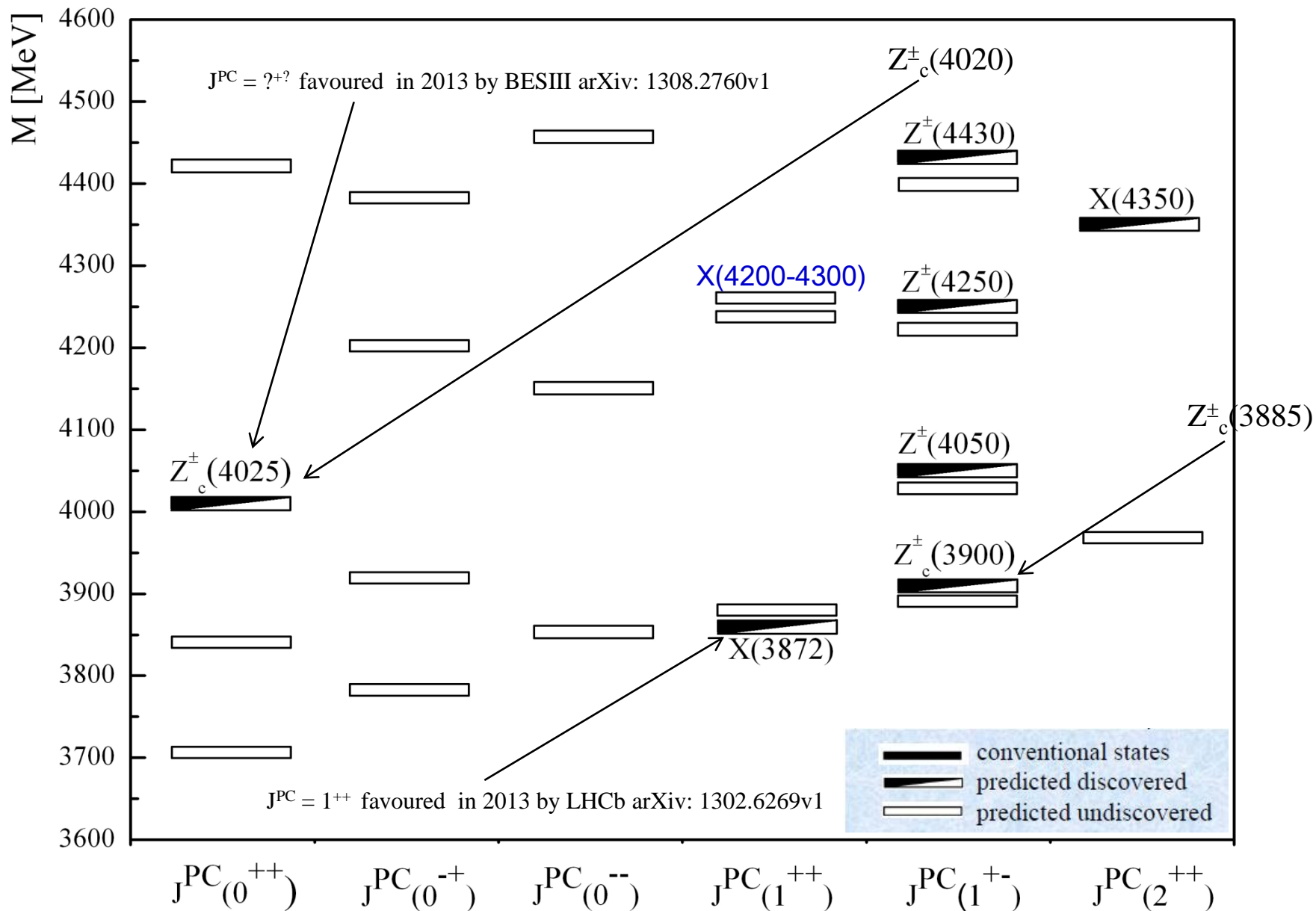


# SPECTRUM OF CHARMED HYBRIDS WITH QUANTUM NUMBERS

$$J^{PC} = 3^{-+}, 2^{-}, 2^{+-}, 1^{+-}, 1^{++}, 0^{+-}, 0^{-+}.$$



# THE SPECTRUM OF TETRAQUARKS WITH THE HIDDEN CHARM



# What to look for

- Does the  $Z(4433)$  exist??
- Better to find charged  $X$  !
- Neutral partners of  $Z(4433) \sim X(1^{+-}, 2S)$  should be close by few MeV and decaying to  $\psi(2S) \pi/\eta$  or  $\eta_c(2S) \rho/\omega$
- What about  $X(1^{+-}, 1S)$ ? Look for any charged state at  $\approx 3880$  MeV (decaying to  $\psi\pi$  or  $\eta_c\rho$ )
- Similarly one expects  $X(1^{++}, 2S)$  states. Look at  $M \sim 4200-4300$ :  $X(1^{++}, 2S) \rightarrow D^{(*)} D^{(*)}$
- Baryon-anti-baryon thresholds at hand (4572 MeV for  $2M_{\Lambda_c}$  and 4379 MeV for  $M_{\Lambda_c} + M_{\Sigma_c}$ ).  $X(2^{++}, 2S)$  might be over  $bb$ -threshold.

## CALCULATION OF WIDTHS

The integral formalism (or in other words integral approach) is based on the possibility of appearance of the discrete quasi stationary states with finite width and positive values of energy in the barrier-type potential. This barrier is formed by the superposition of two type of potentials: short-range attractive potential  $V_1(r)$  and long-distance repulsive potential  $V_2(r)$ .

Thus, the width of a quasi stationary state in the integral approach is defined by the following expression (integral formula):

$$\Gamma = 2\pi \left| \int_0^{\infty} \phi_L(r) V(r) F_L(r) r^2 dr \right|^2$$

$$(r < R): \int_0^R |\phi_L(r)|^2 dr = 1$$

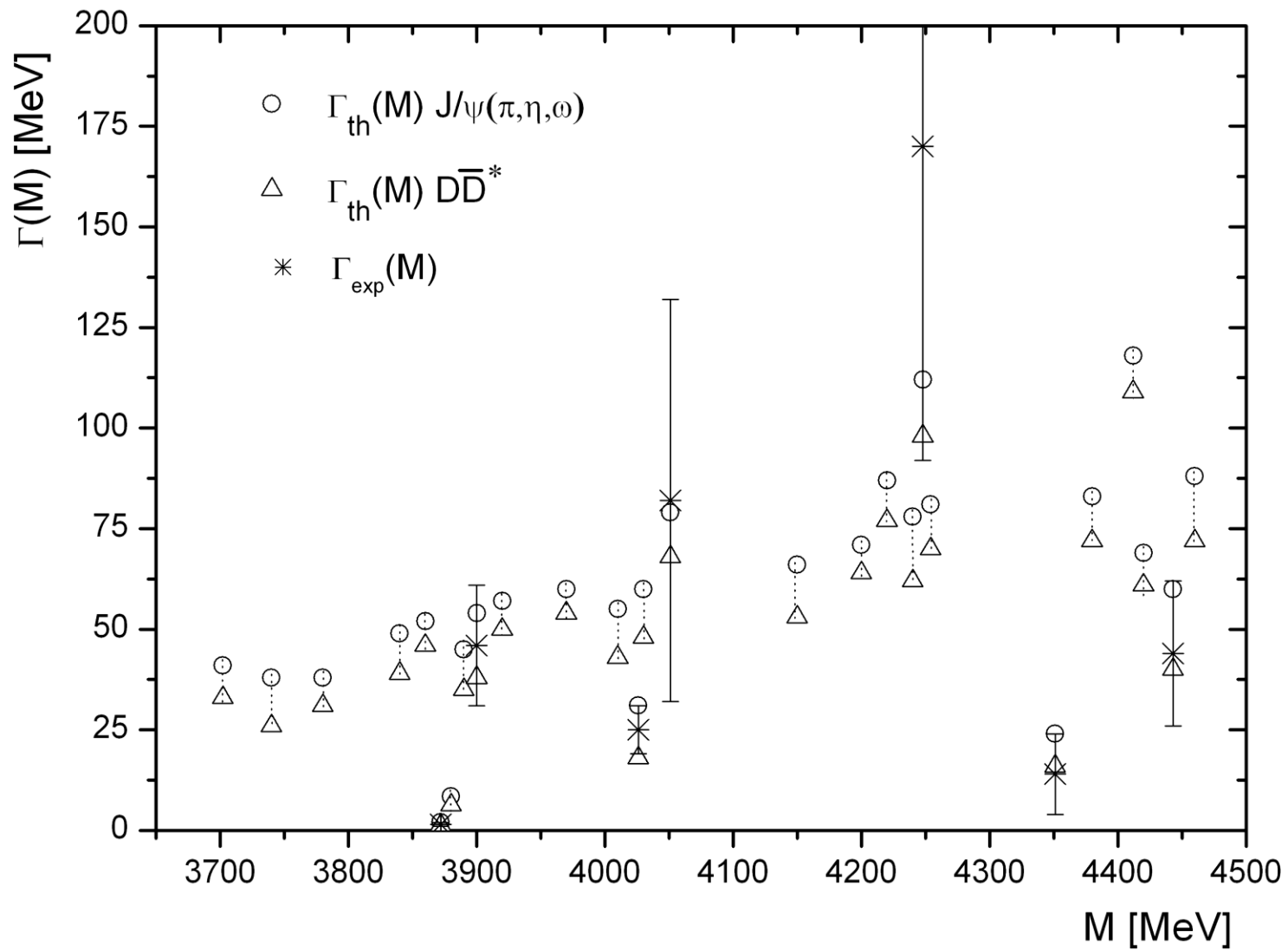
where

where  $F_L(r)$  – is the regular decision in the  $V_2(r)$  potential, normalized on the energy delta-function;  $\phi_L(r)$  – normalized wave function of the resonance state. This wave function transforms into irregular decision in the  $V_2(r)$  potential far away from the internal turning point.

*The integral can be estimated with the well known approximately methods: for example, the saddle-point technique or the other numerical method.*



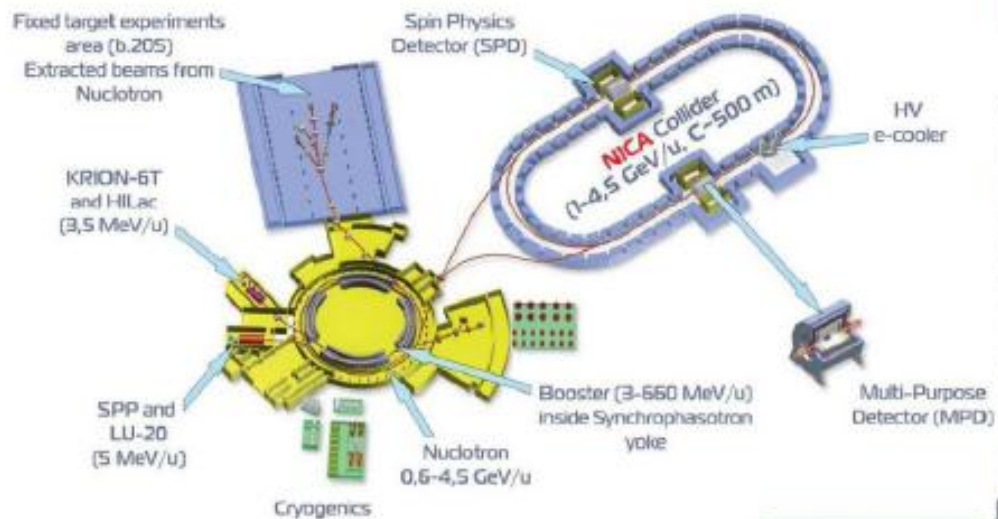
# THE WIDTHS OF TETRAQUARKS WITH THE HIDDEN CHARM



# Multi-Purpose Detector (MPD) at NICA

Новый ускорительный комплекс на встречных пучках NICA (Nuclotron-based Ion Collider fAcility) на базе существующего ускорителя Нуклотрон, позволит исследовать столкновения тяжелых ионов в широком диапазоне атомных масс от Au+Au столкновений при энергии  $\sqrt{s_{NN}} = 4\text{--}11\text{ GeV}$  до протон-протонных столкновений при энергии  $\sqrt{s_{pp}} = 20\text{ GeV}$ .

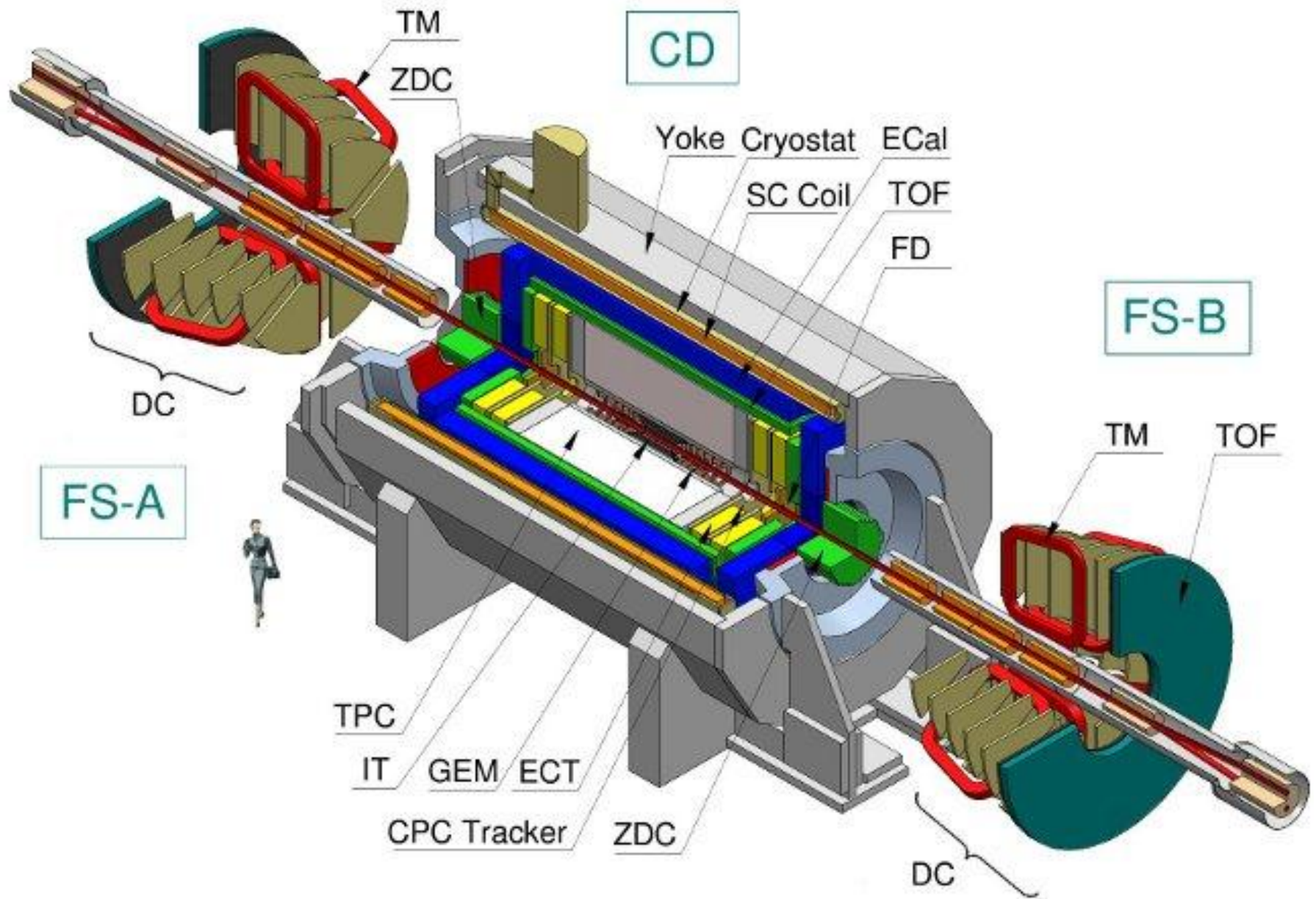
## Superconducting accelerator complex NICA (Nuclotron based Ion Collider fAcility)



Luminosity:  $10^{27}\text{ cm}^{-2}\text{s}^{-1}(\text{Au})$ ,  $10^{32}(\text{p}\uparrow)$



# MULTI-PURPOSE DETECTOR GENERAL VIEW



**WHY WE CONCENTRATE ON PHYSICS WITH PROTON-PROTON COLLISIONS:  
WITH THE CONSTRUCTION OF NICA-MPD A NEW ERA IN PHYSICS WOULD START:**

- search for the bound states with gluonic degrees of freedom: glueballs and hybrids of the type  $gg$ ,  $ggg$ ,  $\bar{Q}Qg$ ,  $Q^3g$  in mass range from 1.3 to 5.0 GeV. Especially pay attention at the states  $\bar{s}s g$ ,  $\bar{c}c g$  in mass range from 1.8 – 5.0 GeV.
- charmonium spectroscopy  $\bar{c}c$  in mass range up to 5.2 GeV  $pA \rightarrow \bar{p}p$   $pA$
- spectroscopy of baryons with strangeness and charm  $\Omega_c^0$ ,  $\Xi_c$ ,  $\Xi'_c$ ,  $\Xi_{cc}^+$ ,  $\Omega_{cc}^+$ ,  $\Sigma_b^*$ ,  $\Omega_b^-$ ,  $\Xi_b^0$ ,  $\Xi_b^-$ .
- charmed and bottom physics:  $pp \rightarrow \Lambda_c X$ ;  $pp \rightarrow \Lambda_c pX$ ;  $pp \rightarrow \Lambda_c pD$ ;  $pp \rightarrow \Lambda_b pB$ .
- study of the hidden flavor component in nucleons and in light unflavored mesons such as  $\eta$ ,  $\eta'$ ,  $h$ ,  $h'$ ,  $\omega$ ,  $\phi$ ,  $f$ ,  $f'$ .
- search for exotic heavy quark resonances near the charm and bottom thresholds, intrinsic strangeness, charm, and bottom phenomena, hidden-color degrees of freedom.
- $D$ -meson spectroscopy and  $D$ -meson interactions:  $D$ -meson in pairs and  $D$ -meson decays to study the physics of electroweak processes to check the predictions of the Standard Model and the processes beyond it.
- $CP$ -violation in strange and charmed sector ( $D$ -meson,  $\Lambda$ -hyperon decays).



# Summary

- A combined approach has been proposed to study charmonium and exotic states with a hidden charm.
- The most promising decay channels of charmonium (decays into light hadrons, particle-antiparticle, decays with  $J/\Psi$ ,  $\Psi'$  and  $h_c$  in the final state), charmed hybrids (decays into charmonium & light mesons, decays into  $D\bar{D}_J^*$  pair) & tetraquarks (decays into charmonium & light mesons, decays into  $D\bar{D}^*$  pair) have been analyzed.
- Many different charmonium & exotic states with a hidden charm are expected to exist in the framework of the combined approach.
- The recently discovered XYZ-particles have been analyzed. Eleven of these states can be interpreted as charmonium (two singlet  $^1S_0$ , two singlet  $^1D_2$ , three triplet  $^3S_1$ , three triplet  $^3P_J$  and one triplet  $^3D_J$ ) and nine as tetraquarks (two neutral and seven charged). **IMPORTANT!!!** It has been shown that charge/neutral tetraquarks must have neutral/charge partners with mass values which differ by few MeV.
- Using the integral approach for the hadron resonance decay, the widths of the expected states of charmonium & exotics were calculated; they turn out to be relatively narrow; most of them are of order of several tens of MeV.
- The branching ratios of charmonium & exotics were calculated. Their values are of the order of  $\beta \approx 10^{-1} - 10^{-2}$  dependent of their decay channel.
- The need for further research charmonium & exotics and their main characteristics in **PANDA (GSI, Darmstadt) & NICA (JINR, Dubna)** experiments has been demonstrated.



# PERSECTIVES AND FUTURE PLANS

- *D*-meson spectroscopy:

- CP*-violation
- Flavour mixing
- Rare decays

- Baryon spectroscopy:

- Strange baryons
- Charmed baryons



- Physics simulation (is in progress nowadays)

# ACKNOWLEDGEMENT

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THANK YOU!