PERSPECTIVE STUDY OF EXOTICS AND BARYONS WITH CHARM AND STRANGENESS

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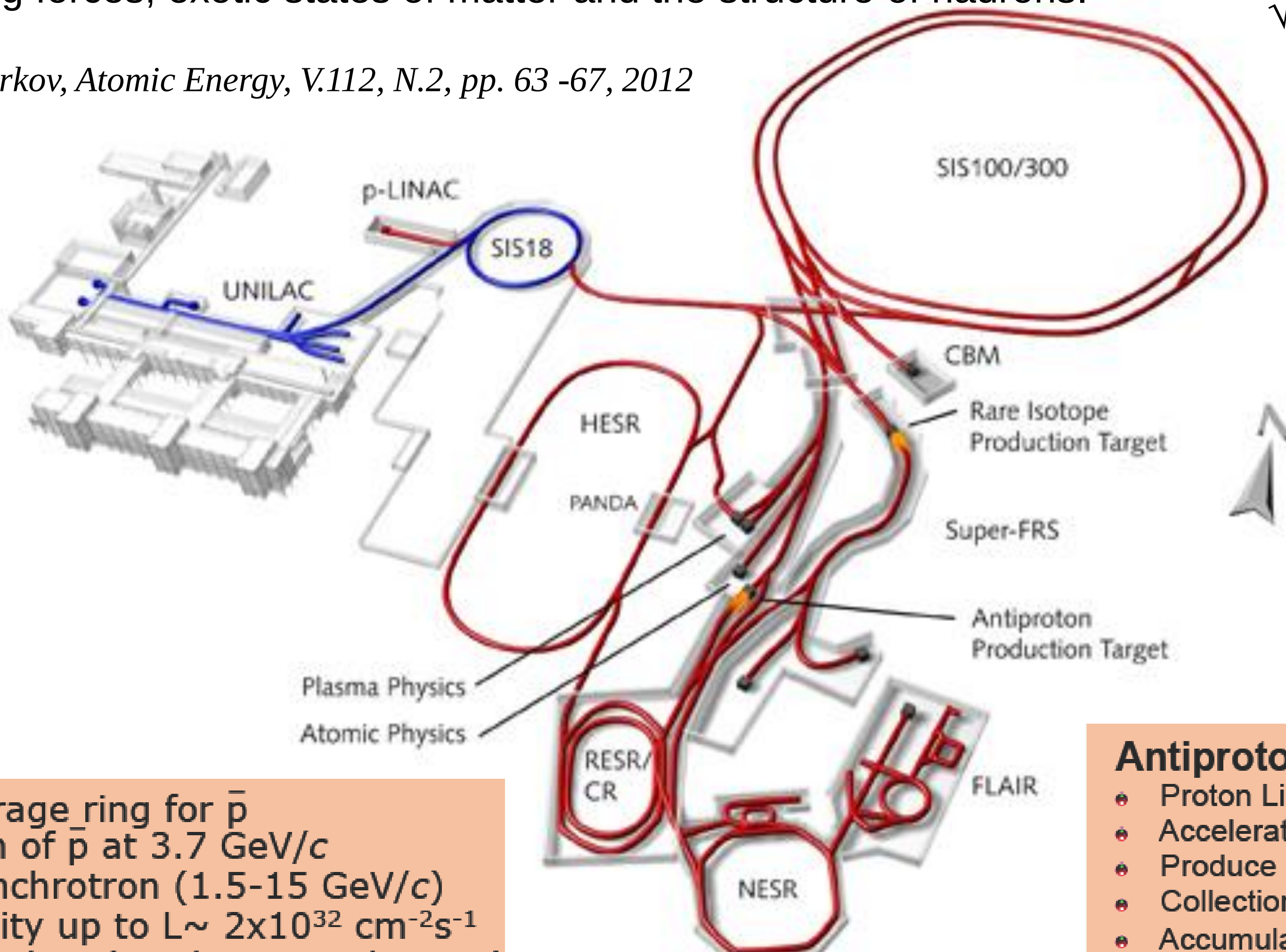
Antiprotons accumulated in the High Energy Storage Ring HESR will collide with the fixed internal hydrogen or nuclear target. High beam luminosity of an order of $2x10^{32} sm^{-2}c^{-1}$ and momentum resolution $\sigma(p)/p$ of an order of 10^{-5} are expected. The scientists from different countries intend to do fundamental research on various topics around the weak, electromagnetic and strong forces, exotic states of matter and the structure of hadrons.

$\sqrt{s} \approx 5.5$ GeV

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



HESR: Storage ring for $\bar{p}$
- Injection of $\bar{p}$ at 3.7 GeV/*c*
- Slow synchrotron (1.5-15 GeV/*c*)
- Luminosity up to L~ $2x10^{32}$ $cm^{-2}s^{-1}$
- Beam cooling (stochastic & electron)

Antiproton production
- Proton Linac 70 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on Cu target
- Collection in CR, fast cooling
- Accumulation in RESR
- Storage and usage in HESR

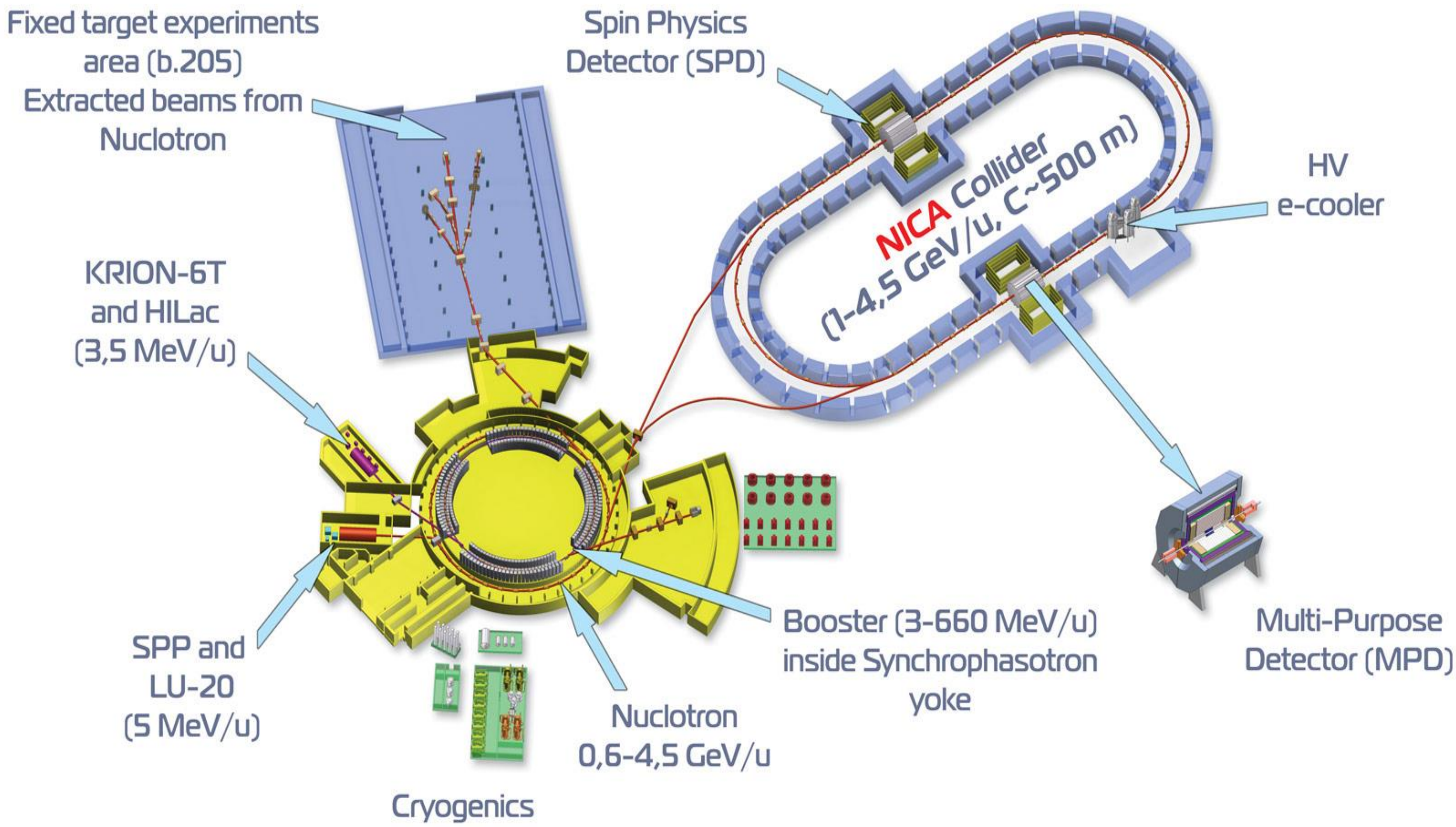
Proposed layout of HESR at FAIR

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

Superconducting accelerator complex NICA

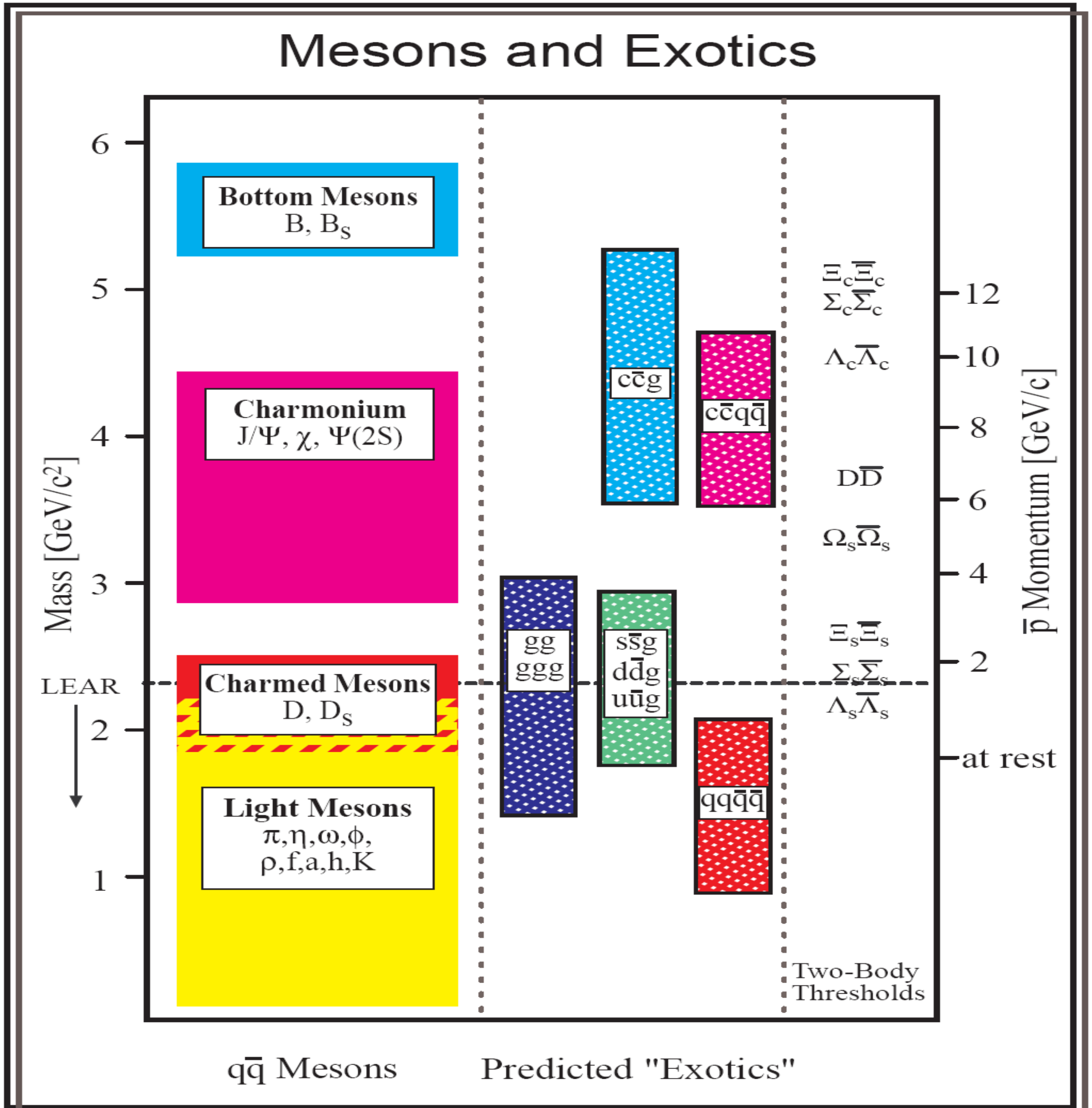
(Nuclotron based Ion Collider fAcility)

$\sqrt{s} \approx 12$ GeV



Proposed layout of NICA complex

WHY WE CONCENTRATE ON PHYSICS WITH ANTIPROTONS AND PROTONS



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

Outline

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

<u>Why is charmonium-like (with a hidden charm) state chosen!?</u>
<u>Charmonium-like state possesses some well favored characteristics:</u>

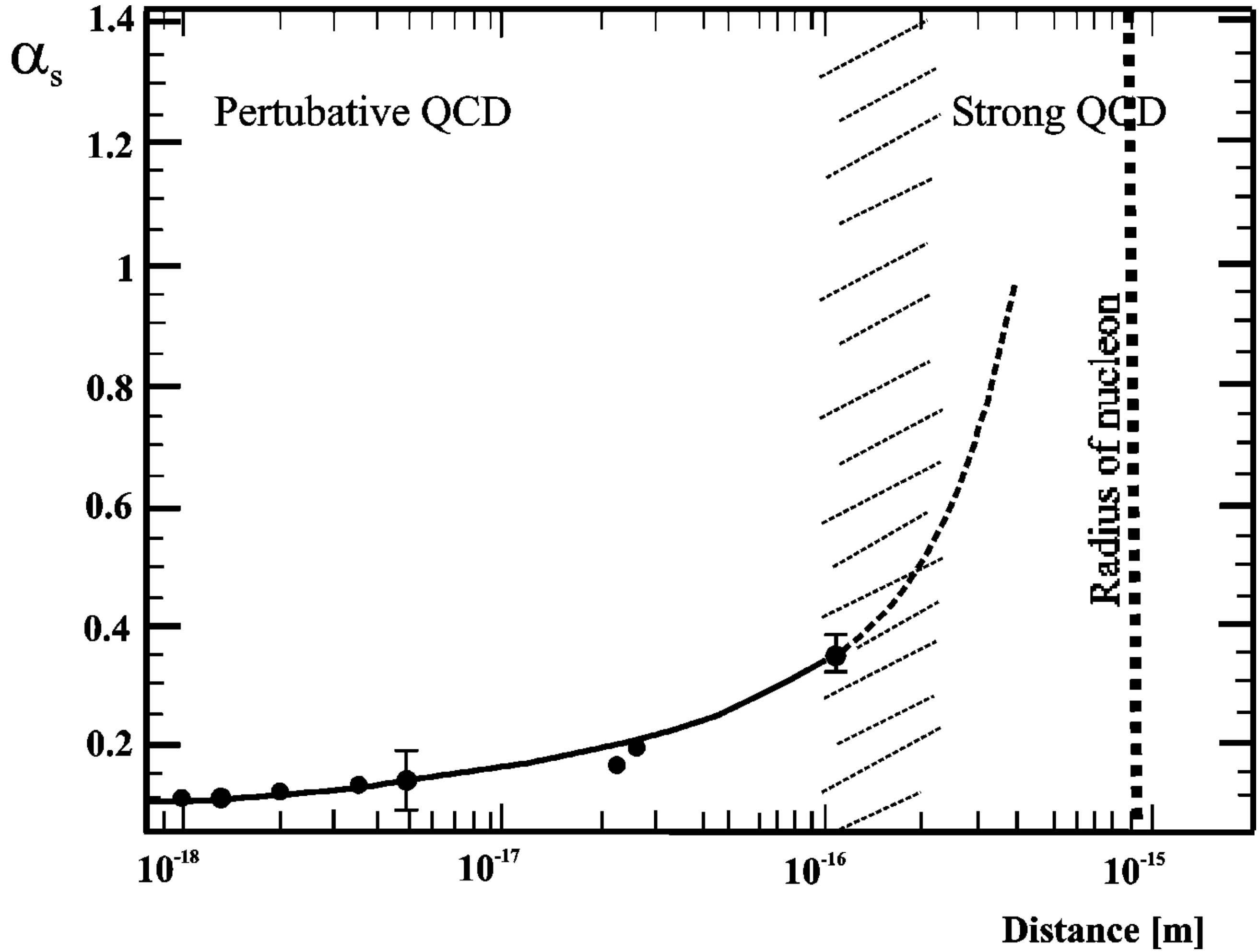
- is the simplest two-particle system consisting of quark & antiquark;
- is a compact bound system with small widths varying from several tens of keV to several tens of MeV compared to the light unflavored mesons and baryons
- charm quark *c* has a large mass (1.27 $\pm$ 0.07 GeV) compared to the masses of *u, d* & *s* (~ 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;

<u>Therefore</u>:

♦ 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



Coupling strength between two quarks as a function of their distance. For small distances ($\leq 10^{-16}$ m) the strengths α_s is ≈ 0.1, allowing a theoretical description by perturbative QCD. For distances comparable to the size of the nucleon, the strength becomes so large (strong QCD) that quarks can not be further separated: they remain confined within the nucleon and another theoretical approaches must be developed and applicable.
For charmonium (charmonium-like) states $\alpha_s \approx 0.3$ and $<v^2/c^2> \approx 0.2$.

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:

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

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. Swangon, 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 $V_{spin\text{-}dep}$ taken from one-gluon exchange Breit-Fermi-Hamiltonian between zero-order wave functions:

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

where α_s - coupling constant, *b* - string tension, σ - 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: ** Advances in Applied Clifford Algebras, V.8, N.2, p.235 - 270 (1998) .*

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

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

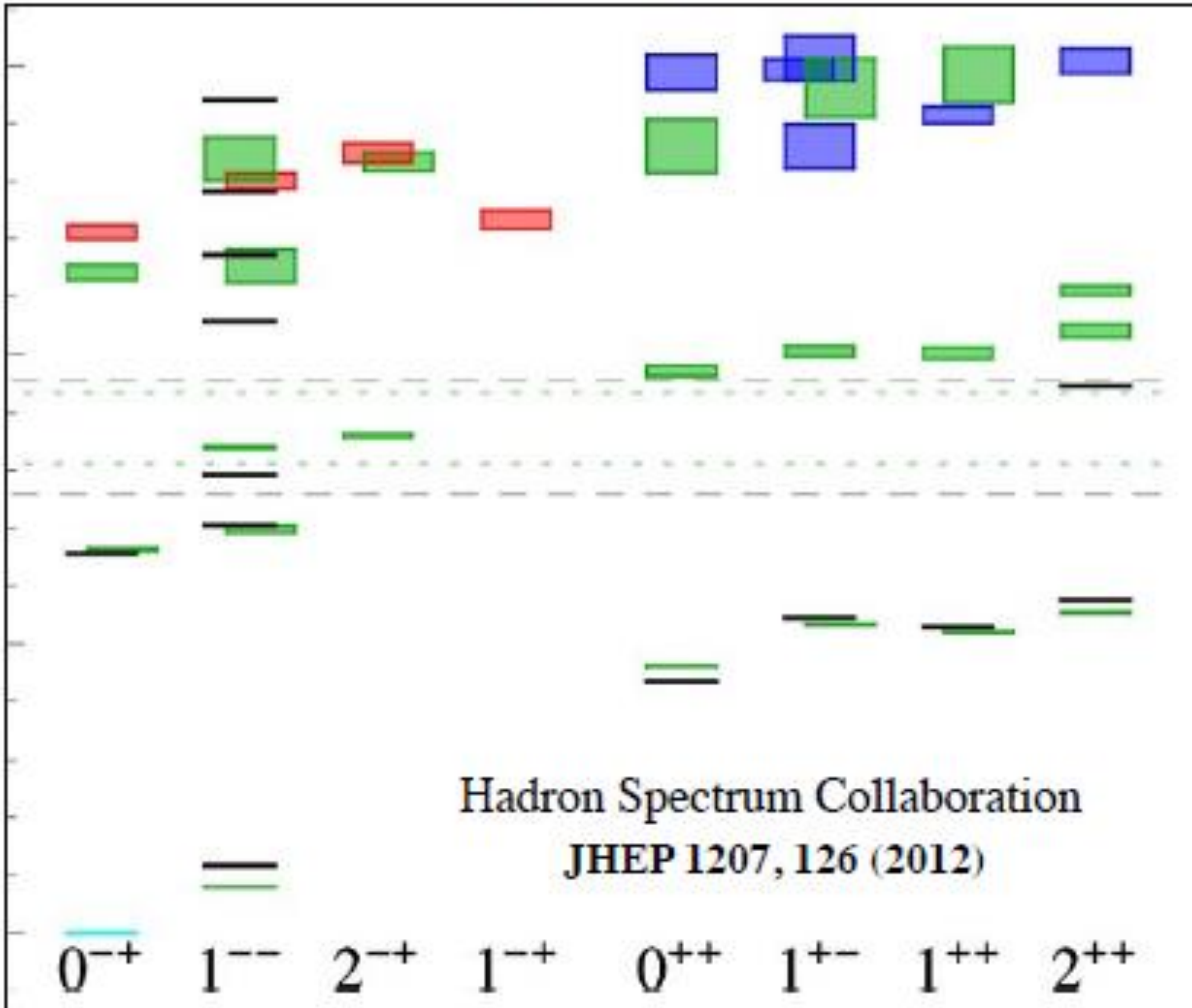
When cotangent argument in $V_3(r)$ is small: $r^2/a^2 << \pi^2$,

we get: $ctg(r/a) \approx a/r - r/3a$, $\Longrightarrow$ $\begin{cases} V(r)|_{r\to 0} \sim 1/r \\ V(r)|_{r\to\infty} \sim kr \end{cases}$

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

<u>The number of unsolved questions related to charmonium has remained:</u>

- **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 laying 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)**;**

<u>**AS RESULT :**</u>

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

<u>IN GENERAL ONE CAN IDENTIFY THREE MAIN CLASSES OF CHARMONIUM DECAYS:</u>

- decays into particle-antiparticle or $D\bar{D}$-pair: $\bar{p}p \to (\Psi, \eta_c, \chi_{cJ}, ..) \to \Sigma^0\bar{\Sigma}^0$, $\Lambda\bar{\Lambda}$, $\Sigma^0\bar{\Sigma}^0\pi$, $\Lambda\bar{\Lambda}\pi$;
- decays into light hadrons: $\bar{p}p \to (\Psi, \eta_c, ..) \to \rho\pi$; $\bar{p}p \to \Psi \to \pi^+\pi^-$, $\bar{p}p \to \Psi \to \omega\pi^0, \eta\pi^0, \ldots$;

! - decays with J/Ψ, Ψ' and h_c in the final state: $\bar{p}p \to J/\Psi + X \Rightarrow \bar{p}p \to J/\Psi\,\pi^+\pi^-$, $\bar{p}p \to J/\Psi\,\pi^0\pi^0$; $\bar{p}p \to \Psi' + X \Rightarrow \bar{p}p \to \Psi'\,\pi^+\pi^-$, $\bar{p}p \to \Psi'\,\pi^0\pi^0$; $\bar{p}p \to h_c + X \Rightarrow \bar{p}p \to h_c\,\pi^+\pi^-$, $\bar{p}p \to h_c\,\pi^0\pi^0$.

CHARMONIUM-LIKE SPECTROSCOPY

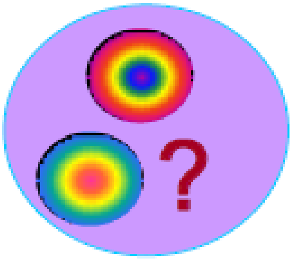
played important role in establishing QCD as theory of strong interactions

- 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?



Nomenclature:

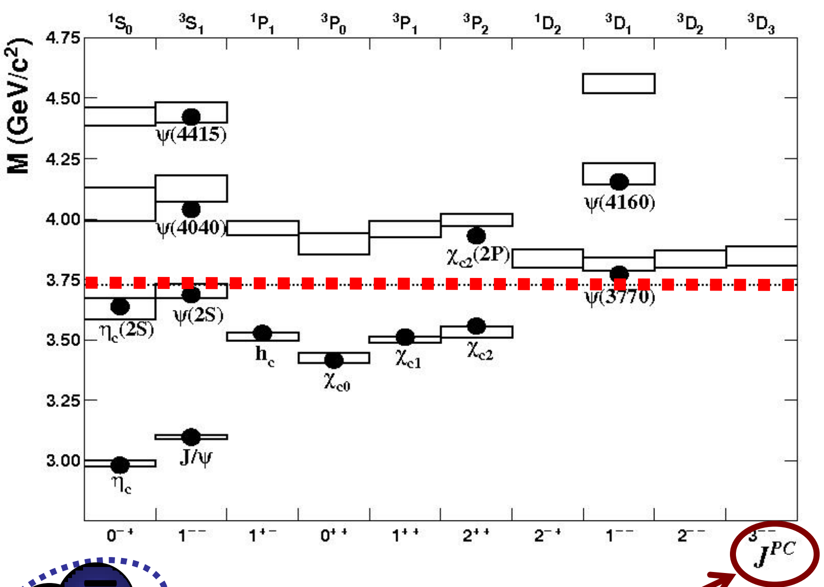
(not valid for all states)

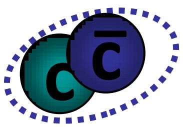
X: charmonium-like with J^{PC} different from 1^{--}
observed in B decays, pp, $p\bar{p}$

Y: charmonium-like with $J^{PC} = 1^{--}$
observed in e^+e^- annihilation, ISR

Z: charmonium-like, charged
must contain $c\bar{c}$ and light $q\bar{q}$ pair

Conventional charmonium





$$\left.\begin{aligned} J &= S + L \\ P &= (-1)^{L+1} \\ C &= (-1)^{L+S} \end{aligned}\right\}$$

$$n^{(2S+1)}L_J$$

n radial quantum number

S total spin of QQbar

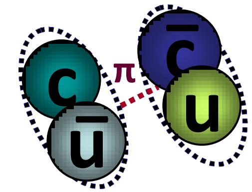
L relative orbital ang. mom.

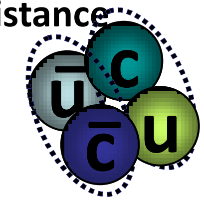
Exotic charmonium-like states

- **Multiquark states**
  - ***Molecular state***

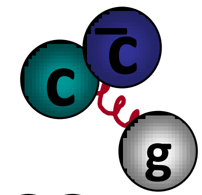
    two loosely bound charm mesons
    - **quark/color exchange at short distances**
    - **pion exchange at large distance**
  - ***Tetraquark***

    tightly bound four-quark state

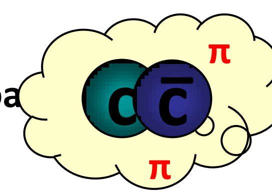




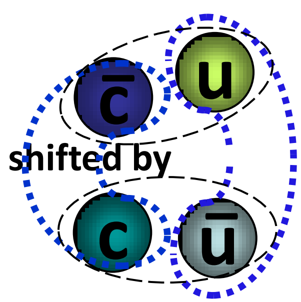
- **Charmonium hybrids**
  - **States with excited gluonic degrees of freedom**



- **Hadro-charmonium**
  - **Specific charmonium state “coa light-hadron matter**



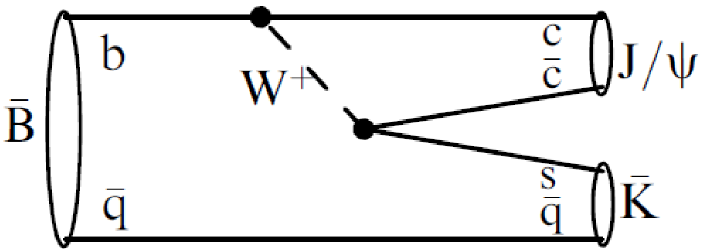
- **Threshold effects**
  - **Virtual states at thresholds**
  - **Charmonium states with masses shifted by nearby $D_{(s)}^{(*)}D_{(s)}^{(*)}$ thresholds**



- Rescattering
  - **Two D-mesons, produced closely**

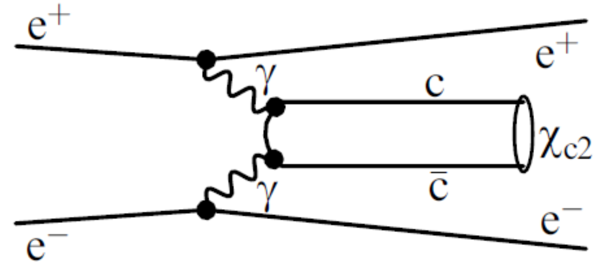
CHARMONIUM – LIKE PRODUCTION MECHANISMS

B-decays



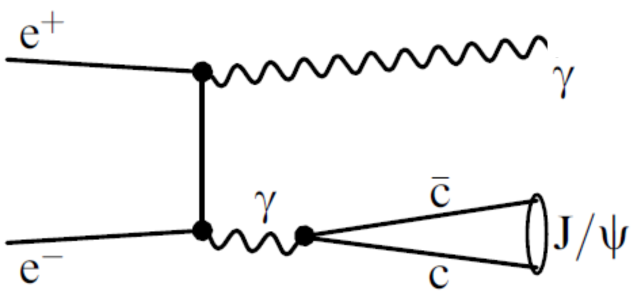
Any quantum numbers are possible, can be measure in angular analysis (Dalitz plot)

γγ fusion



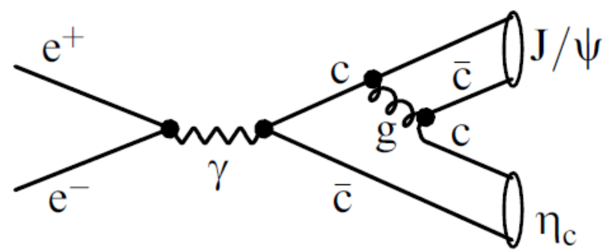
$J^{PC} = 0^{\pm +}, 2^{\pm +}$

annihilation with initial state radiation



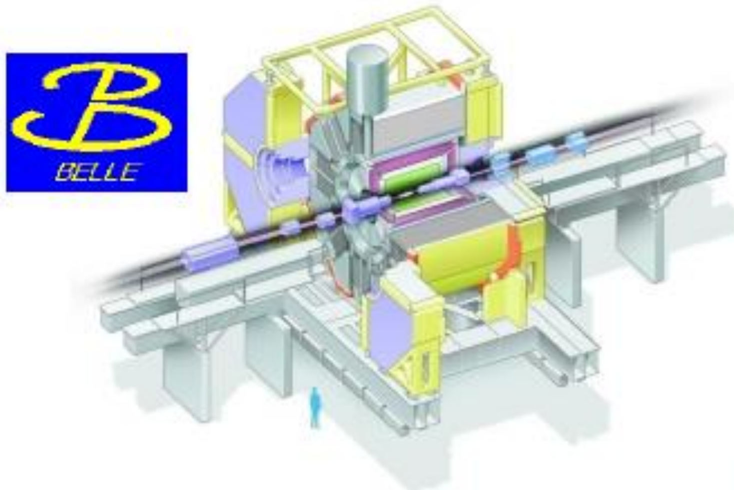
$J^{PC} = 1^{--}$

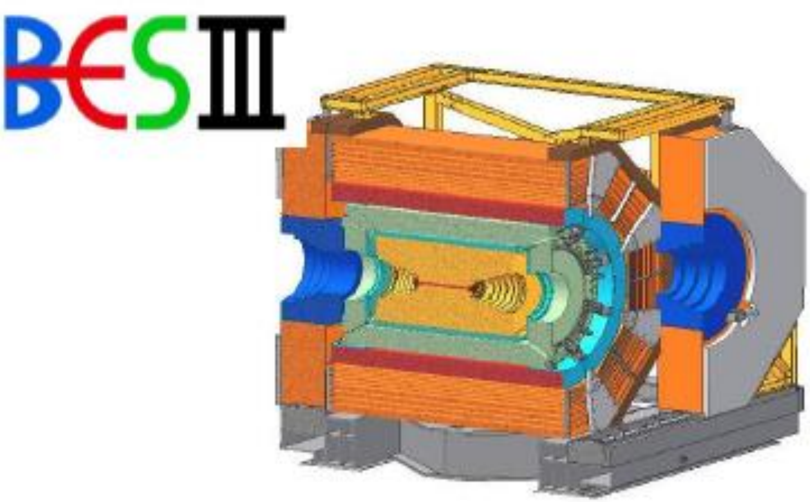
double charmonium production

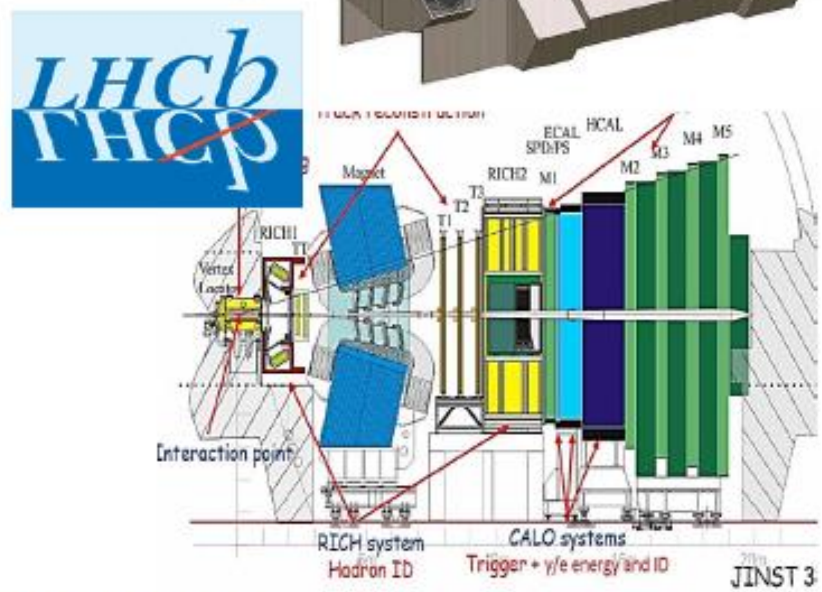


in association with J/ψ only $J^{PC} = 0^{\pm +}$ seen

Results from These Experiments







+ CLEOc, CDF, CMS/ATLAS …

Two different kinds of experiments are foreseen at FAIR :

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

- $c\bar{c}g \to$ (Ψ, χ_{cJ}) + light mesons (η, η', ω, φ) - these modes supply small widths and significant branch fractions;
- $c\bar{c}g \to D\bar{D}_J^*$. In this case *S-wave (L = 0)* + *P-wave (L = 1)* final states should dominate over decays to $D\bar{D}$ (are forbidden → *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:

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

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

According the constituent quark model tetraquark states are classified in terms of the diquark and diantiquark spin S_{cq}, $S_{\overline{cq}'}$, total spin of diquark-diantiquark system S, total angular momentum J, spacial 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.*, $|\, 0_{cq}, 0_{\overline{cq}'}\,; S = 0, J = 0 \,\rangle$ and $|\, 1_{cq}, 1_{\overline{cq}'}\,; S = 0, J = 0 \,\rangle$;

! - three states with $J = 0$ and negative P-parity *i.e.*, $|A\rangle = |\, 1_{cq}, 0_{\overline{cq}'}; S = 1, J = 0 \,\rangle$; $|B\rangle = |\, 0_{cq}, 1_{\overline{cq}'}; S = 1, J = 0 \,\rangle$; $|C\rangle = |\, 1_{cq}, 1_{\overline{cq}'}; S = 1, J = 0 \,\rangle$. 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.*, $|\, 0^{--} \,\rangle = \frac{1}{\sqrt{2}}\left(|A\rangle + |B\rangle\right)$ and two states with $J^{PC} = 0^{-+}$ *i.e.*, $|\, 0^{-+} \,\rangle_1 = \frac{1}{\sqrt{2}}\left(|A\rangle - |B\rangle\right)$; $|\, 0^{-+} \,\rangle_2 = |\, C \,\rangle$.

! - three states with $J = 1$ and positive P-parity *i.e.*, $|D\rangle = |\, 1_{cq}, 0_{\overline{cq}'}; S = 1, J = 1 \,\rangle$; $|E\rangle = |\, 0_{cq}, 1_{\overline{cq}'}; S = 1, J = 1 \,\rangle$; $|F\rangle = |\, 1_{cq}, 1_{\overline{cq}'}; S = 1, J = 1 \,\rangle$. 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.*, $|\, 1^{++} \,\rangle = \frac{1}{\sqrt{2}}\left(|D\rangle + |E\rangle\right)$ and two states with $J^{PC} = 1^{+-}$ *i.e.*, $|\, 1^{+-} \,\rangle_1 = \frac{1}{\sqrt{2}}\left(|D\rangle - |E\rangle\right)$; $|\, 1^{+-} \,\rangle_2 = |F\rangle$.

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

!

- $\bar{p}p \to X \to J/\Psi\,\rho \to J/\Psi\,\pi\pi$; $\bar{p}p \to X \to J/\Psi\,\omega \to J/\Psi\,\pi\pi\pi$, $\bar{p}p \to X \to \chi_{cJ}\,\pi$ (decays into J/Ψ, Ψ', χ_{cJ} and light mesons);
- $\bar{p}p \to X \to D\bar{D}^* \to D\bar{D}\,\gamma$; $\bar{p}p \to X \to D\bar{D}^* \to D\bar{D}\,\eta$ (decays into $D\bar{D}^*$-pair).

Z_c States

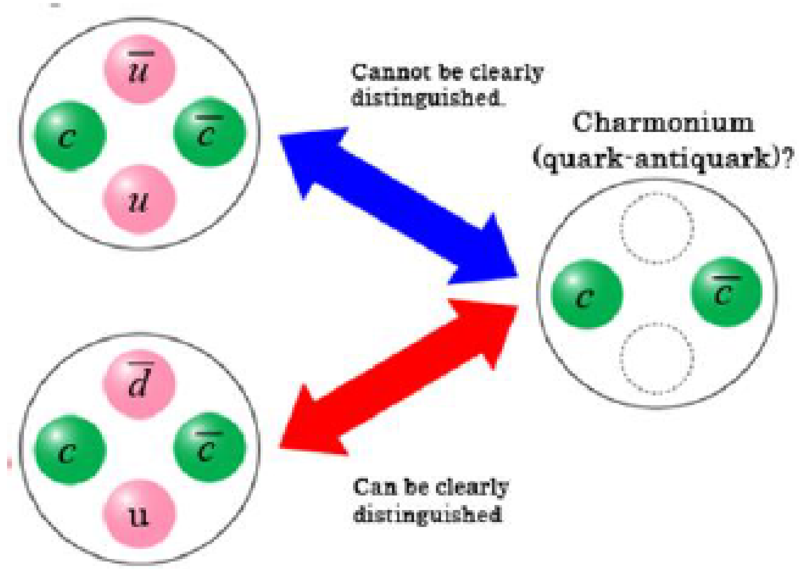
$cuc\bar{c}\bar{d}$ $\qquad$ $cd\bar{c}\bar{s}$ $\qquad$ $cu\bar{c}\bar{s}$

The most promising way to searching for the exotic hadrons

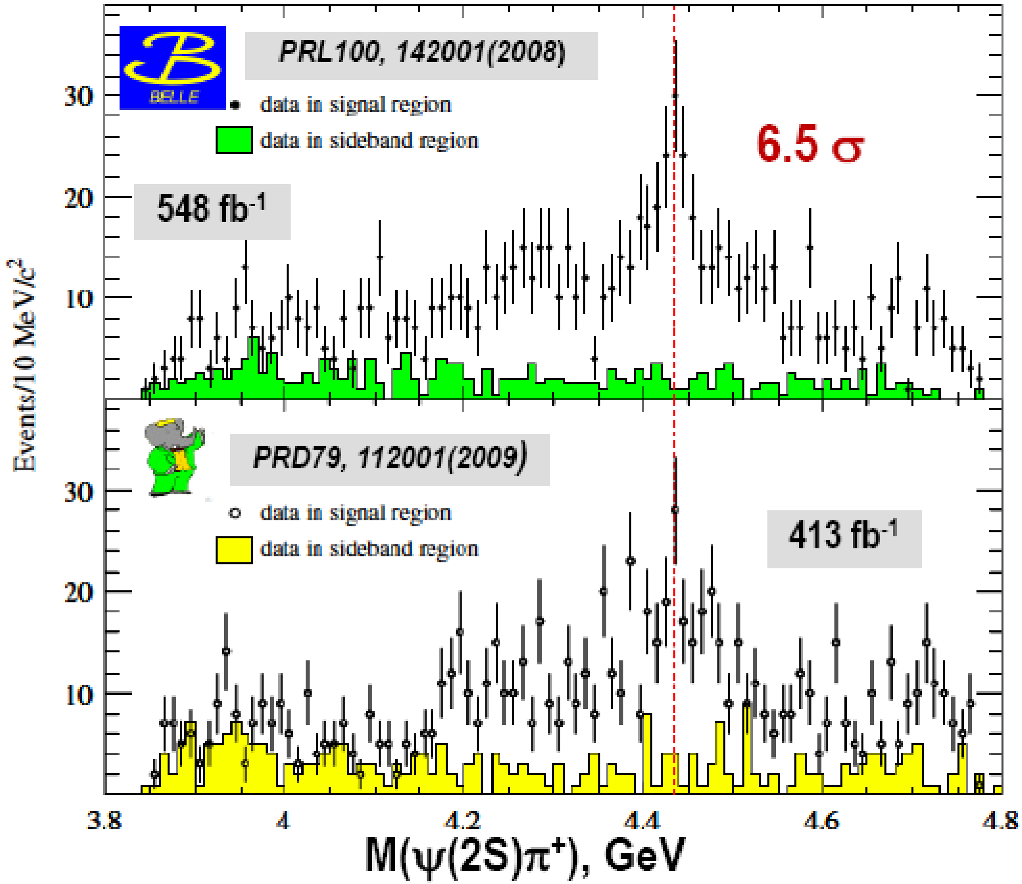
- Decay into a charmonium or $D^{(*)}\bar{D}^{(*)}$ pair
  - thus contains hidden-$c\bar{c}$ pair
- Have electric charge,
  - thus has two more light quarks

At least 4 quarks, not a conventional meson

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



$Z(4430)^+$



The first measurement

Fit to $M(\psi(2S)\pi^+)$

$K^*(890)$ and $K^*(1430)$ veto

$M = (4433 \pm 4 \pm 2)$ MeV/c^2

$\Gamma = (45^{+18}_{-13}{}^{+30}_{-13})$ MeV

PRD 80, 031104 (2009)

Confirmation

Dalitz analysis

$M = (4443^{+15}_{-12}{}^{+17}_{-13})$ MeV/c^2

$\Gamma = (109^{+86}_{-43}{}^{+57}_{-52})$ MeV

PRD 88,074026(2013)

Full amplitude analysis to obtain spin-parity $J^P = 1^+$

$M = (4485 \pm 22 {}^{+28}_{-11})$ MeV/c^2

$\Gamma = (200^{+41}_{-46}{}^{+26}_{-35})$ MeV

$Br(B \to KZ^+) \times Br(Z^+ \to \psi(2S)\pi^+) =$

The first measurement $(4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$

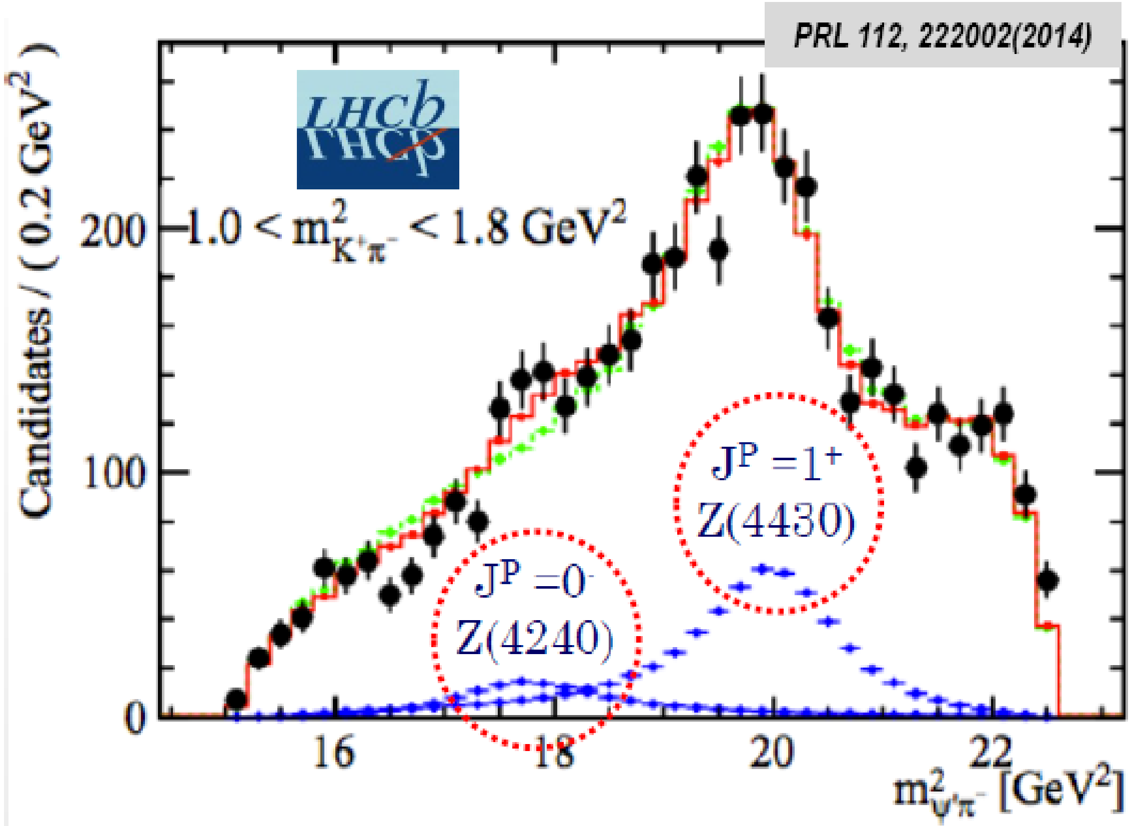
Dalitz analysis $(3.2^{+1.8}_{-0.9}{}^{+5.3}_{-1.6}) \times 10^{-5}$

$< 3.1 \times 10^{-5}$ at 95% CL

BaBar does not confirm Belle, but also does not rule it out!

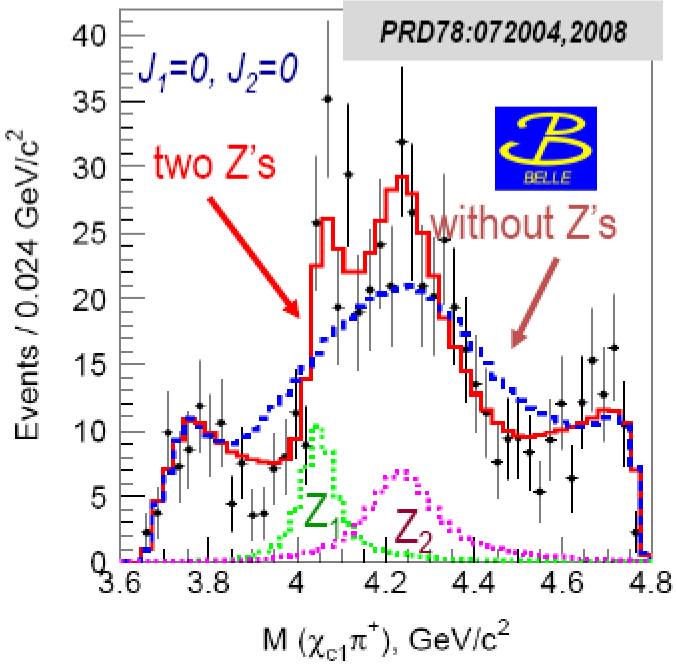
Task for Belle II and LHCb

$Z(4430)^+$ at LHCb



$$M_{Z_0} = 4239 \pm 18^{+45}_{-10}\mathrm{MeV}$$
$$\Gamma_{Z_0} = 220 \pm 47^{+108}_{-74}\mathrm{MeV}$$
$$f_{Z_0} = (1.6 \pm 0.5^{+1.9}_{-0.4})\%$$

- Significance is >14 σ
- Phase motion consistent with resonance (Breit-Wigner)
- Parameters (including quantum numbers) are consistent with the Belle results
- Another peak at 4200 MeV with significance ~5 σ



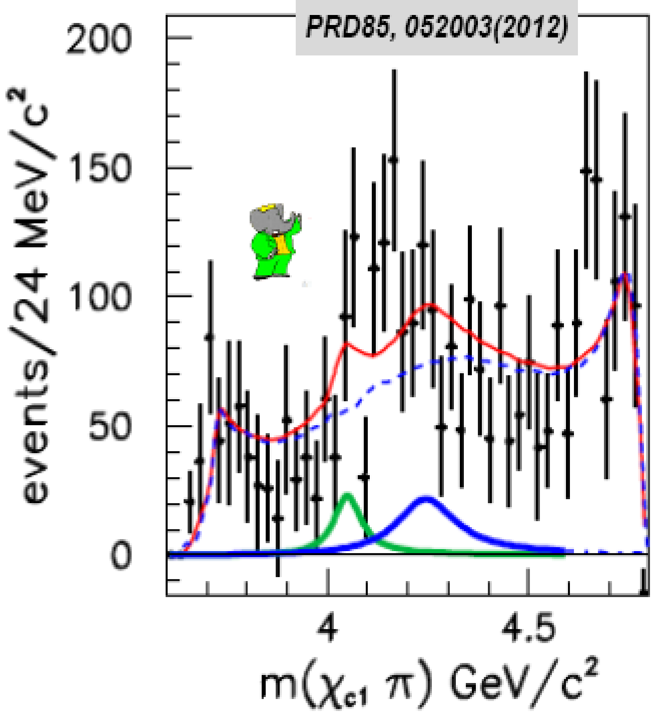
$Z^+_{1,2} \to \chi_{c1}\pi^+$

$B^0 \to \chi_{c1}\pi^+K^-$; $\chi_{c1} \to J/\psi\gamma$

Daliz analysis: fit of $B^0 \to \chi_{c1}K^-\pi^+$ data with a sum of RBW's

- Known $K\pi$ resonances
- K^*'s + one $(\chi_{c1}\pi)$ resonance
- K^*'s + two $(\chi_{c1}\pi)$ resonances
- Favors two Z mesons

$M_1 = (4051 \pm 14^{+20}_{-41})$ MeV/c^2
$\Gamma_1 = (82^{+21}_{-17}{}^{+47}_{-22})$ MeV
$M_2 = (4248^{+44}_{-29}{}^{+180}_{-35})$ MeV/c^2
$\Gamma_1 = (177^{+54}_{-39}{}^{+316}_{-61})$ MeV



$\mathcal{B}(\overline{B}^0 \to K^- Z_1^+) \times \mathcal{B}(Z_1^+ \to \pi^+\chi_{c1}) =$
$(3.1^{+1.5+3.7}_{-0.9-1.7}) \times 10^{-5}$ $< 1.8 \times 10^{-5}$ at 90% CL

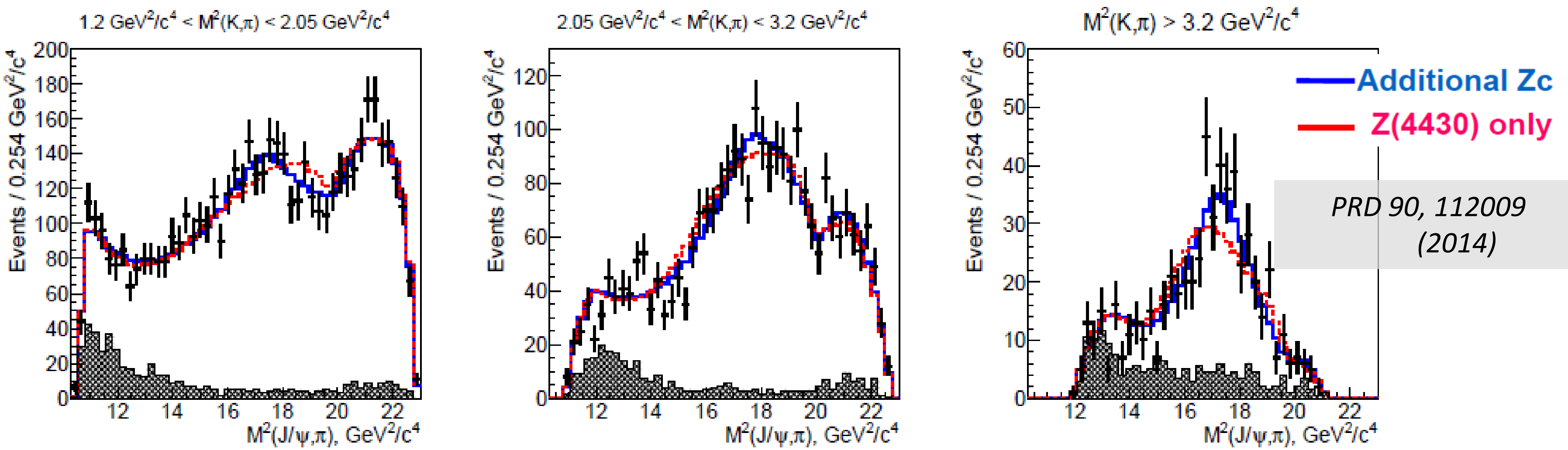
$\mathcal{B}(\overline{B}^0 \to K^- Z_2^+) \times \mathcal{B}(Z_2^+ \to \pi^+\chi_{c1}) =$
$(4.0^{+2.3+19.7}_{-0.9-\ 0.5}) \times 10^{-5}$ $< 4.0 \times 10^{-5}$ at 90% CL

BaBar does not confirm Belle, but also does not rule it out!
Task for Belle II (difficult for LHCb)

Z(4200) at Belle

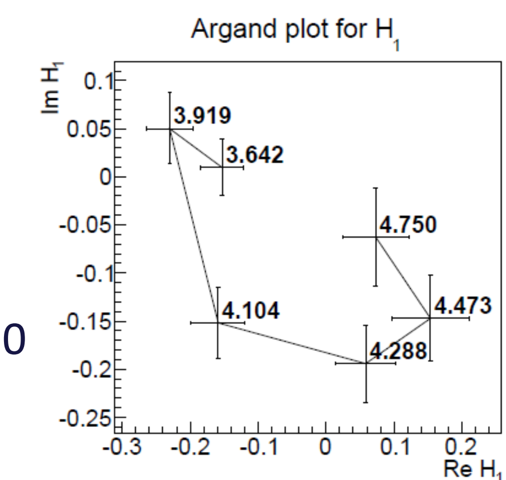
4D-fit: Dalitz+angular variables

$B \to K^- \pi^+ J/\psi(\to \ell^+ \ell^- \psi)$

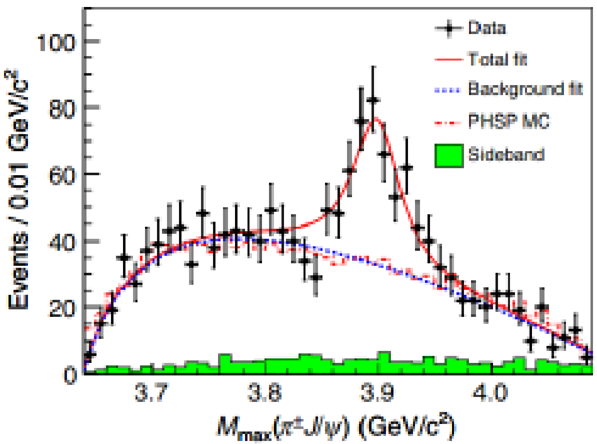


Model: sum of all K(*(*)) + Z

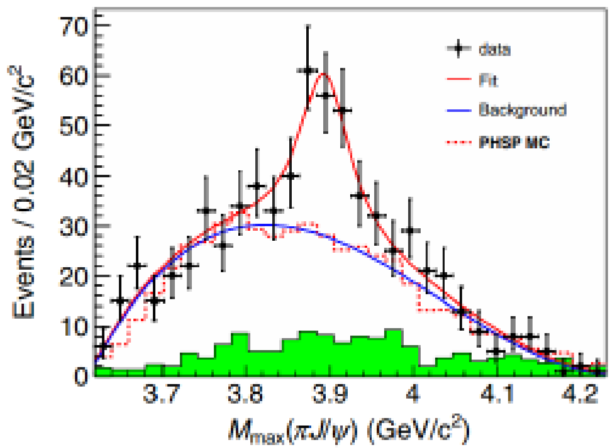
- New Z_c^+ is found ($J^P=1^+$), 6.2 σ with systematics
- $M = 4196\,^{+31\,+17}_{-29\,-13}$ MeV; $\Gamma = 370\,^{+70\,+70}_{-70\,-132}$ MeV
- **Exclusion levels (other** $J^P=0^-, 1^-, 2^-, 2^+$): 6.1σ, 7.4σ, 4.4σ, 7.0σ.
- $Z_c^+(4430)$ is significant (though via negative interference): 4.0 σ evidence for new decay modes → $J/\psi\ \pi$
- **No signal of** $Z_c^+(3900)$



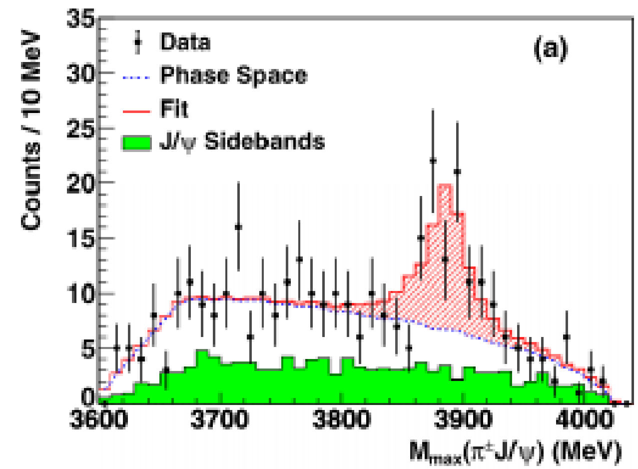
Observation Zc(3900)$^{\pm}$ in $e^+e^- \to \pi^+\pi^- J/\psi$



BESIII data at 4.26 GeV
(PRL 110, 252001)



Belle with ISR data
(PRL 110, 252002)

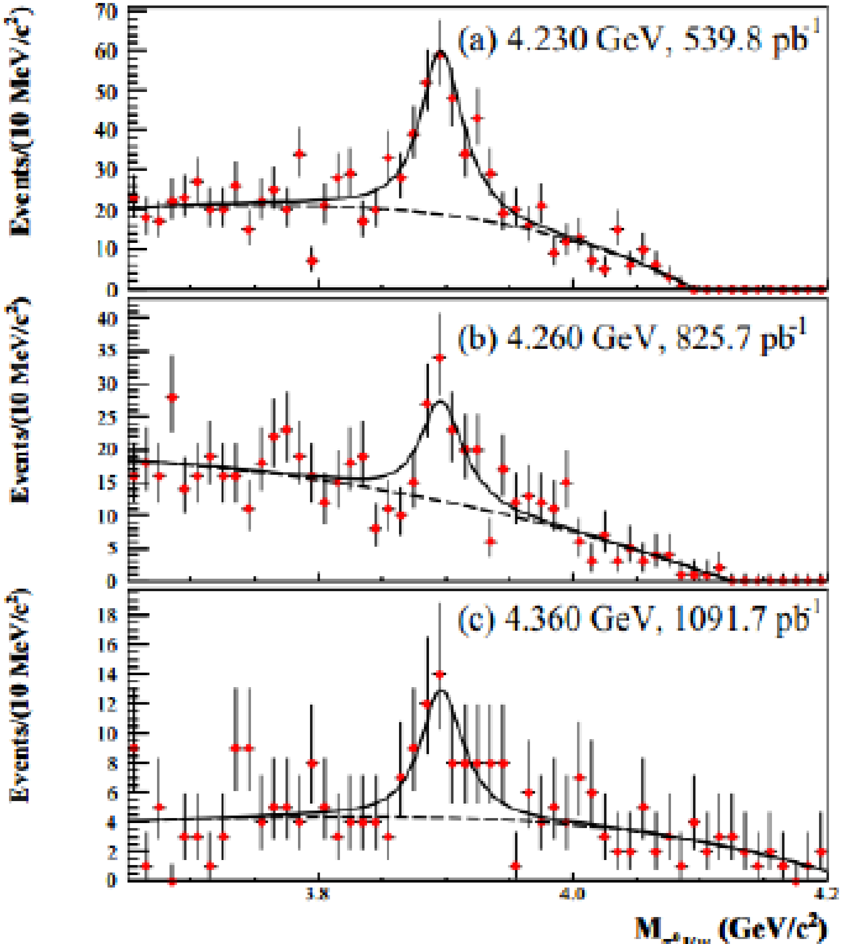


CLEOc data at 4.17 GeV
(PLB 727, 366)

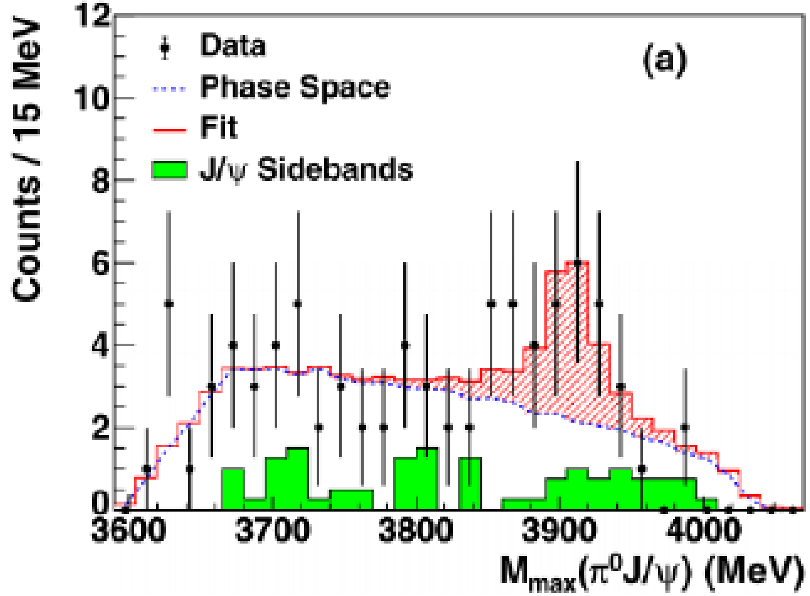
Experiment	Mass (MeV)	Width (MeV)	Significance
BESIII	3899.0±3.6±4.9	46±10±20	> 8.0 σ
Belle	3894.5±6.6±4.5	63±24±26	5.2 σ
CLEO-c	3886±4±2	37±4±8	> 5.0 σ

Observation Zc(3900)^0 in $e^+e^- \to \pi^0\pi^0 J/\psi$

BESIII Preliminary



- **Simultaneous fit:**
  - Significance = 10.4σ
  - $M = 3894.8 \pm 2.3 \pm 2.7$ MeV
  - $\Gamma = 29.6 \pm 8.2 \pm 8.2$ MeV
- **Isospin triplet is established!**

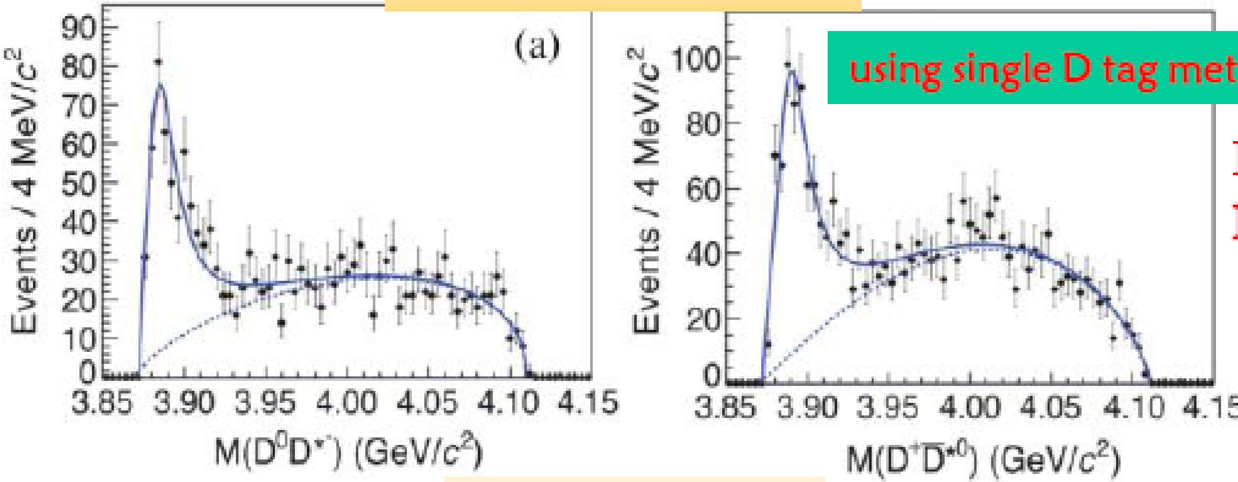


CLEOc data at 4.17 GeV (PLB 727, 366)

Observation of $Z_c(3885)^{\pm}$ in $e^+e^- \rightarrow \pi^{\pm}(D\bar{D}^*)^{\mp}$

PRL112, 022001(2014)

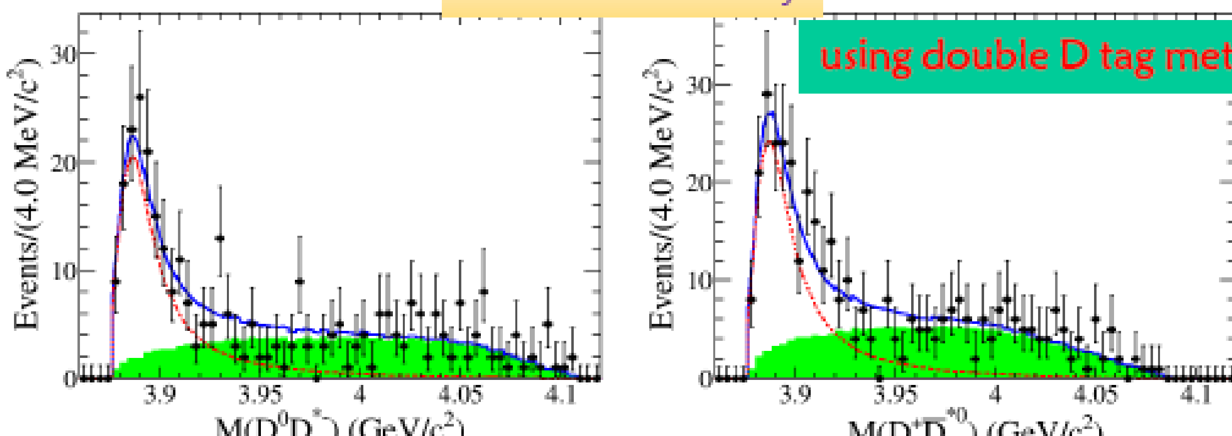
using single D tag method



M=3883.9 ± 1.5 ± 4.2 MeV
Γ=24.8 ± 3.3 ± 11.0 MeV

BESIII Preliminary

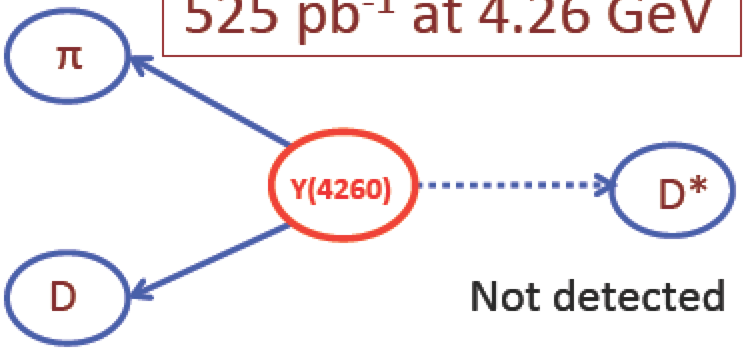
using double D tag method



M=3884.3 ± 1.2 ± 1.5 MeV
Γ=23.8 ± 2.1 ± 2.6 MeV

$e^+e^- \rightarrow \pi^+(DD^*)^-$

525 pb^{-1} at 4.26 GeV



$\pi^{\pm}(DD^*)^{\mp}$ includes 4 decay modes:

1) $\pi^+D^0D^{*-}$+c.c., $D^{*-} \rightarrow \pi^0 D^-$

2) $\pi^+D^-D^{*0}$+c.c., $D^{*0} \rightarrow \gamma/\pi^0 D^0$

We only reconstruct the bachelor pion and a single D.

Type I: If we tag a π^+ and D^0, we select the events:

$\pi^+D^0D^{*-}$ and $\pi^+D^-D^{*0}$ ($D^{*0} \rightarrow \gamma/\pi^0 D^0$)

Type II: If we tag a π^+ and D^-, we select the events:

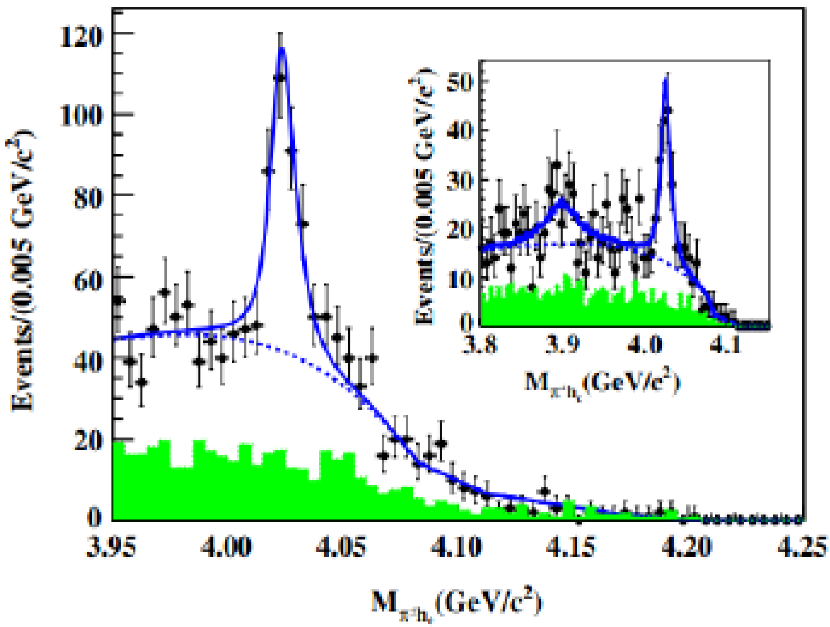
$\pi^+D^0D^{*-}$ ($D^{*-} \rightarrow \pi^0 D^-$) and $\pi^+D^-D^{*0}$ ($D^{*0} \rightarrow \gamma/\pi^0 D^0$)

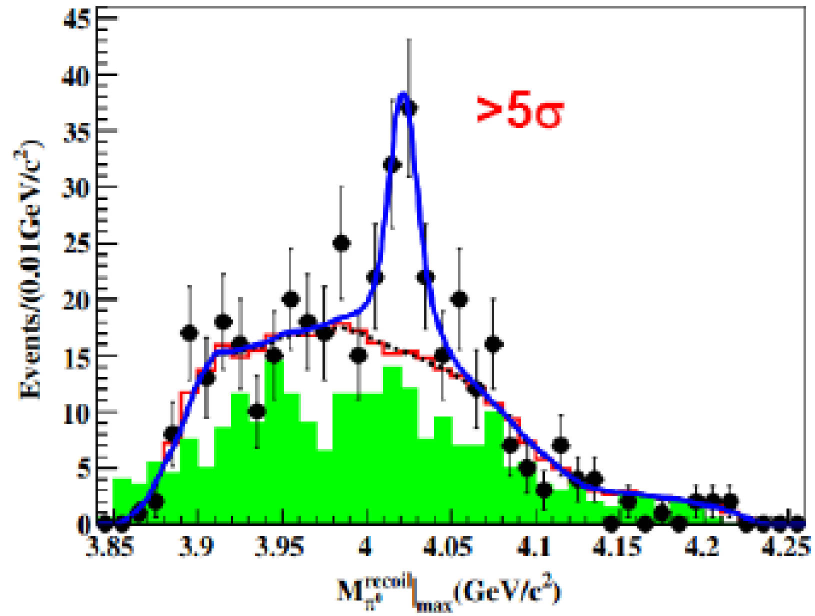
- Sometimes there are cross feeding events, but it's OK.

Observation Zc(4020)$^{\pm/0}$ in $e^+e^- \to \pi^+\pi^- h_c / \pi^0\pi^0 h_c$

PRL111, 242001(2013)

PRL113, 212002(2014)





M=4022.9±0.8 ±2.7 MeV

Γ=7.9±2.7 ±2.6 MeV

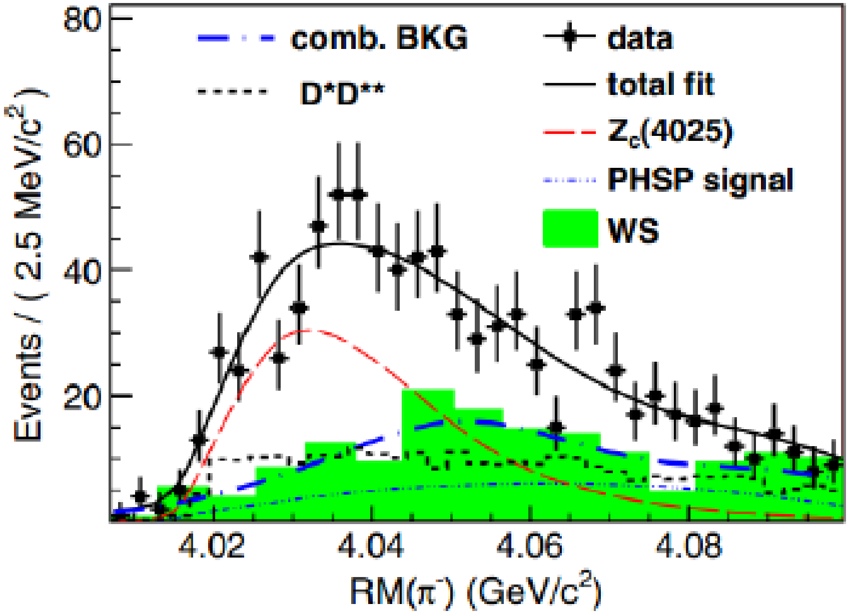
M=4023.9±2.2 ±3.8 MeV

Width is fixed to be same as its charged partner.

Another isospin triplet is established!

Observation of $Z_c(4025)^{\pm/0}$ in $e^+e^- \to \pi^{\pm/0}(D^*\bar{D}^*)^{\mp/0}$

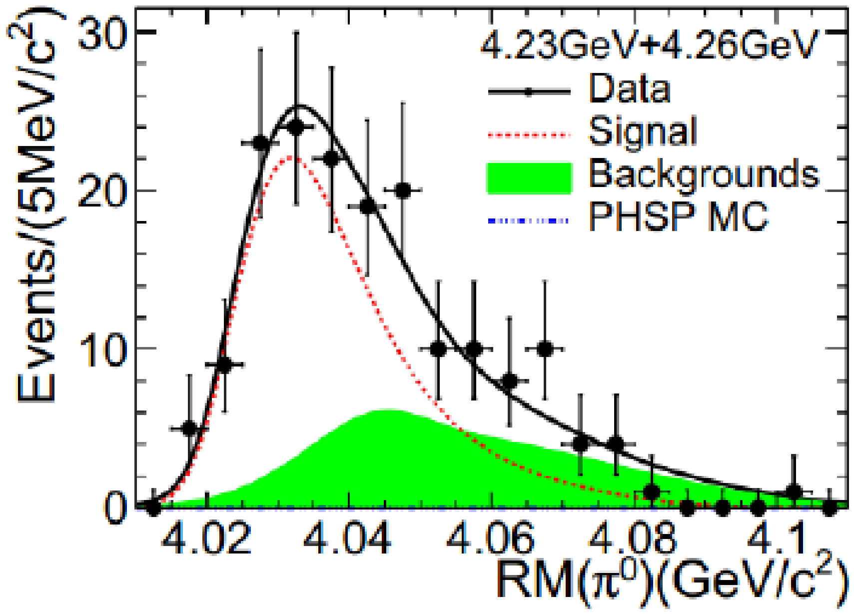
PRL112, 132001(2014)



M=4026.3±2.6±3.7 MeV

Γ=24.8±5.6±7.7 MeV

BESIII Preliminary



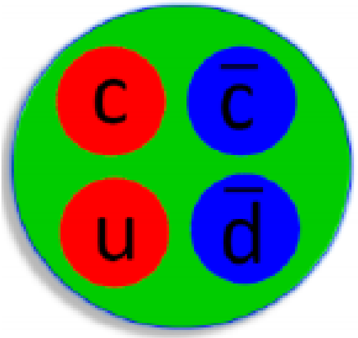
M=4025.5±4.7±3.1 MeV

Γ=23.0±6.0±1.0 MeV

Another isospin triplet is established!

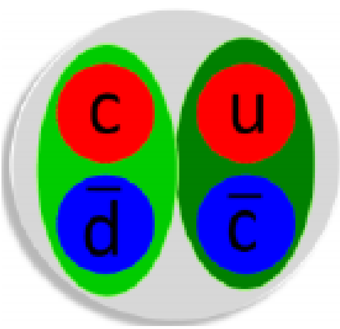
New class of states: Zc

- At least four quarks, not conventional meson.



✓ **Tetraquark state?**

Phys. Rev. D87,125018(2013); Phys. Rev. D88, 074506(2013);
Phys. Rev. D89,054019(2014); Phys. Rev. D90,054009(2014); ...



✓ **$D^{(*)}\bar{D}^{(*)}$ molecule state?**

Phys. Rev. Lett. 111, 132003 (2013); Phys. Rev. D 89, 094026 (2014)
Phys. Rev. D 89, 074029 (2014); Phys. Rev. D 88, 074506 (2013); ...

✓ **Final States Interaction?**

✓ ...

Z_c states at BESIII

channel	mass [MeV]	width [MeV]
$J/\Psi\pi^\pm$	$3899.0 \pm 3.6 \pm 4.9$	$46 \pm 10 \pm 20$
$J/\Psi\pi^0$	3894.8 ± 2.3	29.6 ± 8.2 (prel.)
$(D\bar{D}^*)$	$3883.9 \pm 1.5 \pm 4.2$	$24.8 \pm 3.3 \pm 11.0$
$h_c\pi^\pm$	$4022.9 \pm 0.8 \pm 2.7$	$7.9 \pm 2.7 \pm 2.6$
$h_c\pi^0$	$4023.6 \pm 2.2 \pm 3.9$	fixed
$(D^*\bar{D}^*)$	$4026.3 \pm 2.6 \pm 3.7$	$24.0 \pm 5.6 \pm 7.7$

$Z_c(3900)$ (I

Are thes
states th
same?!

$Z_c(3885)$?

$D\bar{D}^*$ thresh 387

$Z_c(4020)$ (I=

Are thes
states th
same?

$Z_c(4025)$?

$D^*\bar{D}^*$ thresh 4017 MeV

states must contain at least four quarks – what is their nature?

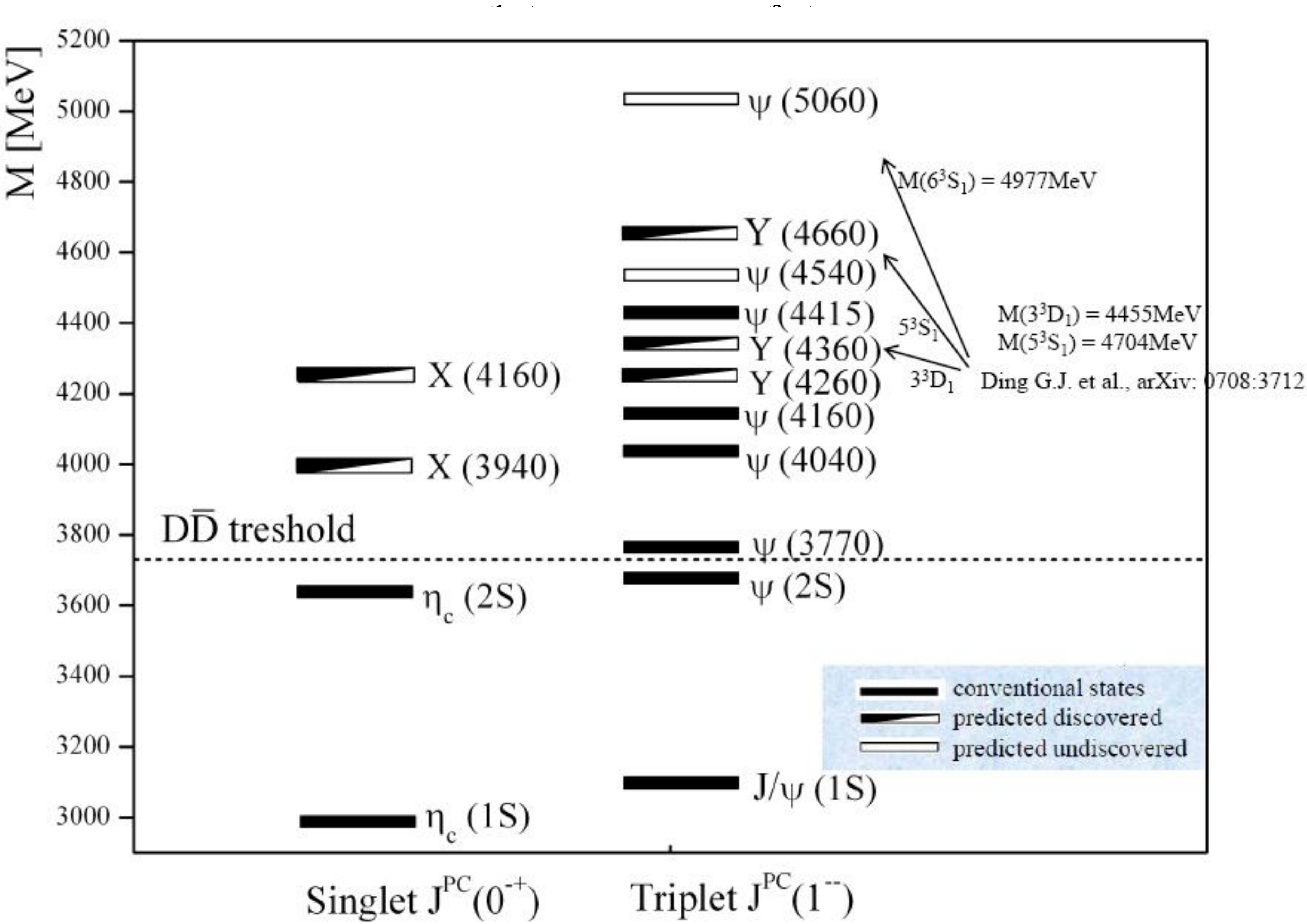
tetraquarks (Maiani, Ali et al.)

hadronic molecules (Meissner, Guo et al.)

hadro-charmonia (Voloshin)

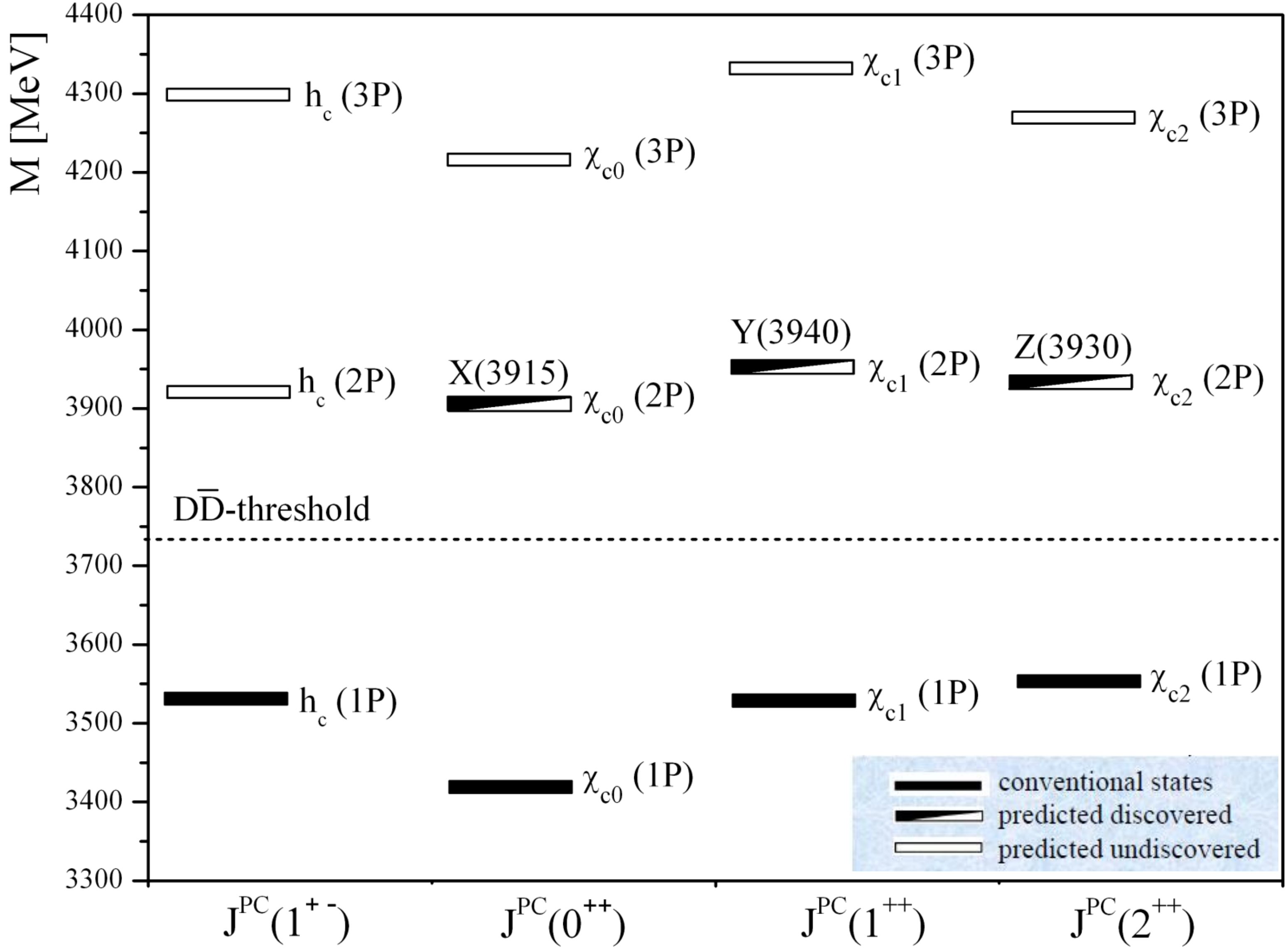
meson loop (Zhao et al.)

ISPE model (Liu et al.)

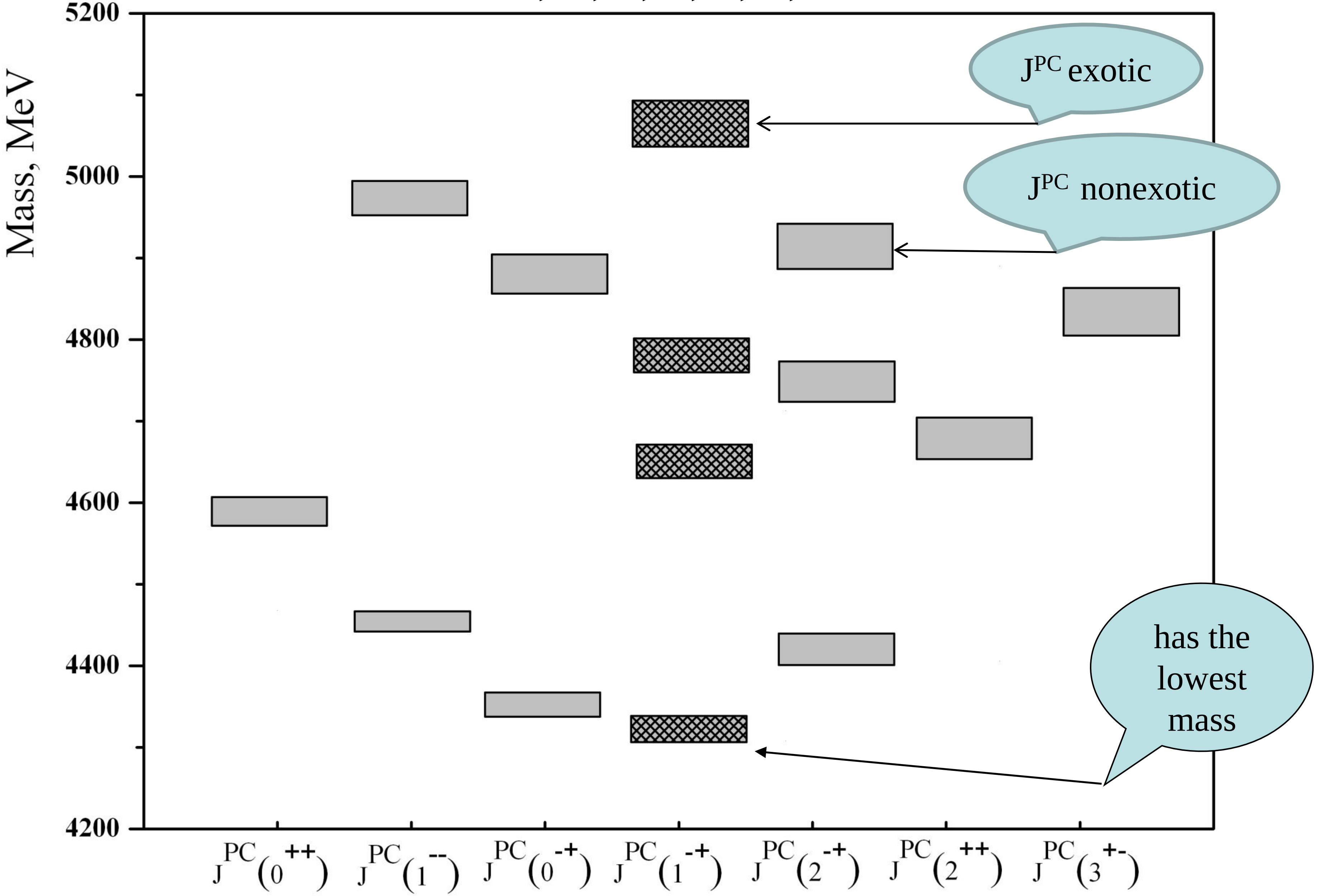


*** However, not easily: potential models need to be elaborated to describe new masses**

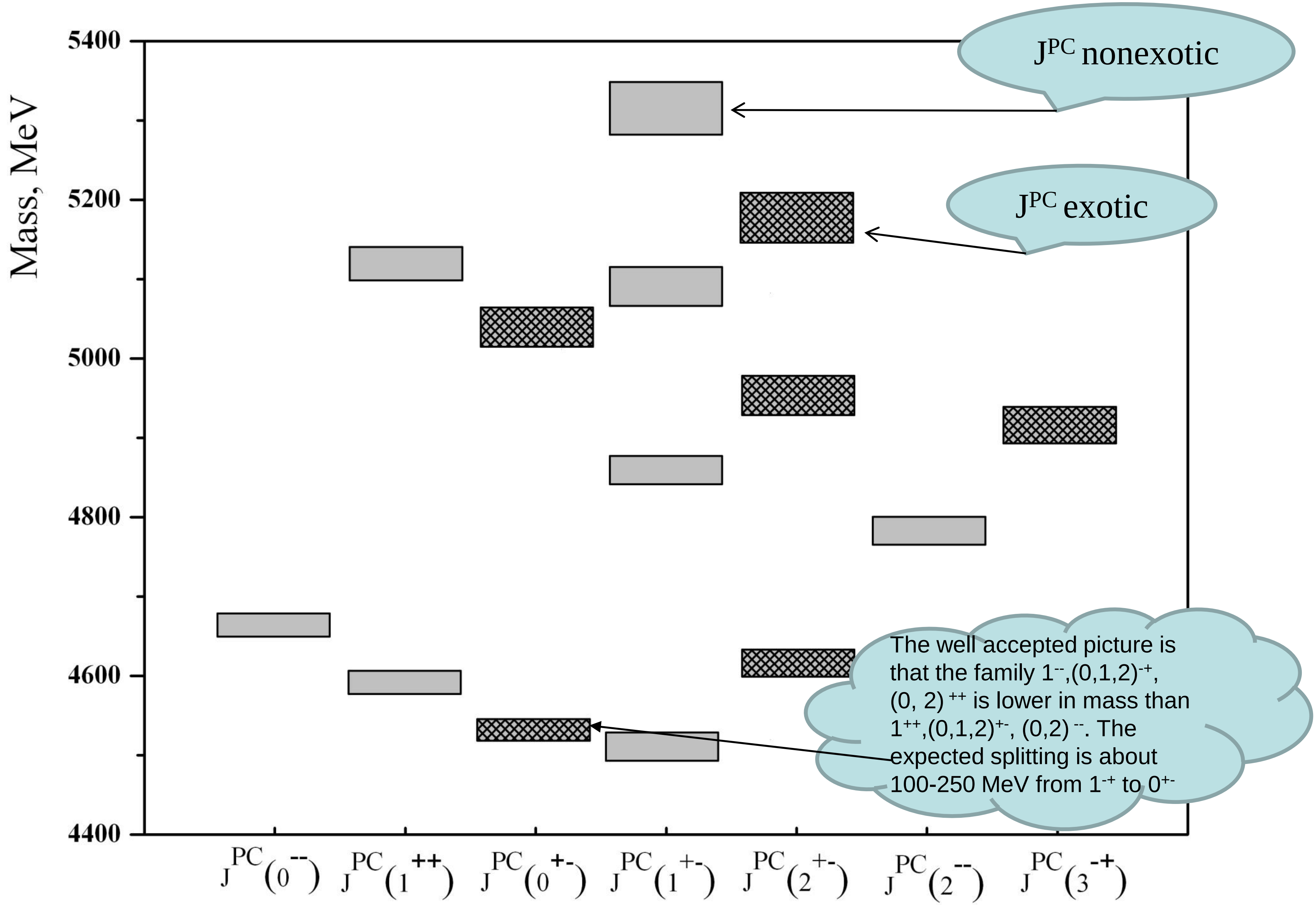
THE SPECTRUM OF SINGLET ($^1P_1$) AND TRIPLET (^3P_J) STATES OF CHARMONIUM



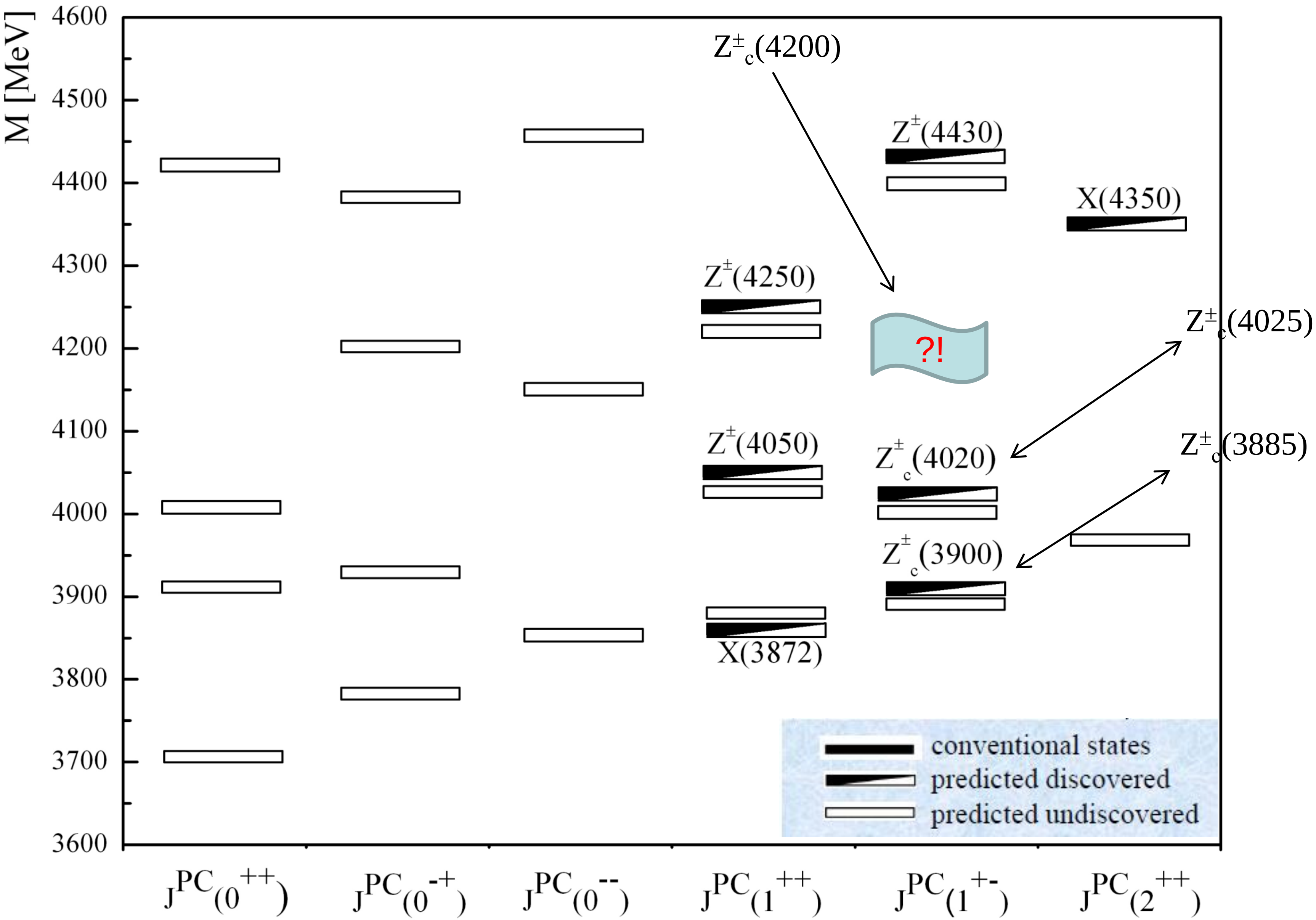
SPECTRUM OF CHARMED HYBRIDS WITH QUANTUM NUMBERS $J^{PC} = 3^{+-}, 2^{++}, 2^{-+}, 1^{-+}, 1^{--}, 0^{-+}, 0^{++}$.



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)~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 ≈ 3880 MeV (decaying to $\psi\pi$ or $\eta_c\rho$)
- Similarly one expects X(1^{++},2S) states. Look at M~4200-4300: X(1^{++},2S)->$D^{(*)}D^{(*)}$
- 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.

(L.Maiani, A.D.Polosa, V.Riquer, 0708.3997

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):

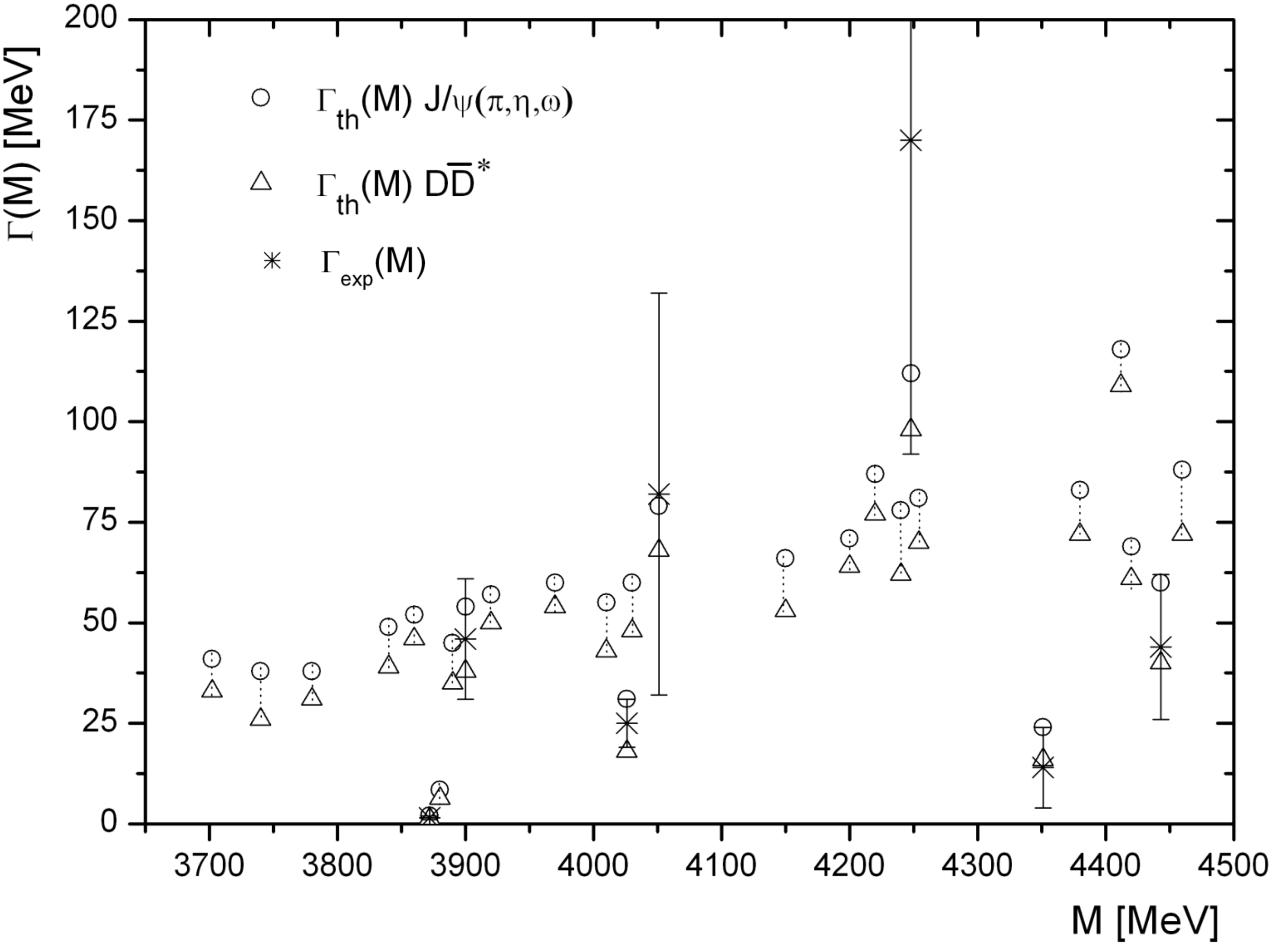
$$\Gamma = 2\pi \left| \int_0^\infty \phi_L(r) V(r) F_L(r) r^2 dr \right|^2$$

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

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.



Γ(M) [MeV]
M [MeV]
Γth(M) J/ψ(π,η,ω)
Γth(M) DD̄*
Γexp(M)
0
25
50
75
100
125
150
175
200
3700
3800
3900
4000
4100
4200
4300
4400
4500

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, $\overline{Q}Qg$, Q^3g in mass range from 1.3 to 5.0 GeV. Especially pay attention at the states $\overline{s}sg$, $\overline{c}cg$ in mass range from 1.8 – 5.0 GeV.

- charmonium spectroscopy $\overline{c}c$, *i.e.* $pp \to \overline{c}c\, pp$ (threshold $\sqrt{s} \approx 5$ GeV)

- hidden charm production cross section is of an order of $\sigma \approx 10\ \mu b$

- spectroscopy of heavy baryons with strangeness, charm and beauty:

$$\Omega^0{}_c, \Xi_c, \Xi'_c, \Xi^+{}_{cc}, \Omega^+{}_{cc}, \Sigma^*{}_b, \Omega^-{}_b, \Xi^0{}_b, \Xi^-{}_b.$$

$pp \to \Lambda_c X$; $pp \to \Lambda_c pX$; $pp \to \Lambda_c pD_s$ $\quad$ $pp \to \Lambda_b X$, $pp \to \Lambda_b pX$; $pp \to \Lambda_b pB_s$

- study of the hidden flavor component in nucleons and in light unflavored mesons such as $\eta, \eta', h, h', \omega, \varphi, f, f'$.

- search for exotic heavy quark resonances near the charm and bottom thresholds.

- *D*-meson spectroscopy and *D*-meson interactions: *D*-meson in pairs and rare *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 - Flavour mixing -Rare decays

PROSPECTS FOR FAIR

- Large cross sections for $\bar{p}p \to \bar{Y}Y^*$
  - $\bar{p}p \to \bar{\Xi}\Xi \approx \mu b$
  - $\bar{p}p \to \bar{\Omega}\Omega \approx 0.002 - 0.06\mu b$
- No extra mesons in the final state needed for strangeness (or charm) conservation
- Symmetry in hyperon and antihyperon observables
- PANDA detector versatile (coverage, resolution, PID...)

Summary

- Obviously, quarkonium physics is in deep crises now: many observed states remain puzzling and can not be explained for many years.
- And this is very good! We live in a very interesting time. It is stimulating and motivating for new searches and new ideas in theory.
- A combined approach has been proposed to study charmonium-like states.
- The most promising decay channels of charmonium-like states have been analyzed. Different charmonium & exotic states with a hidden charm are expected to exist in the framework of the combined approach.
- 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.
- Theorists should work at least as hard as experimentalists to catch up with avalanche of puzzles. Some new theoretical models are sharply needed.
- NICA & PANDA can provide important complimentary information and new discoveries. The need for further charmonium-like research together with charmed and strange baryons research in both experiments has been demonstrated.

THANK YOU!