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

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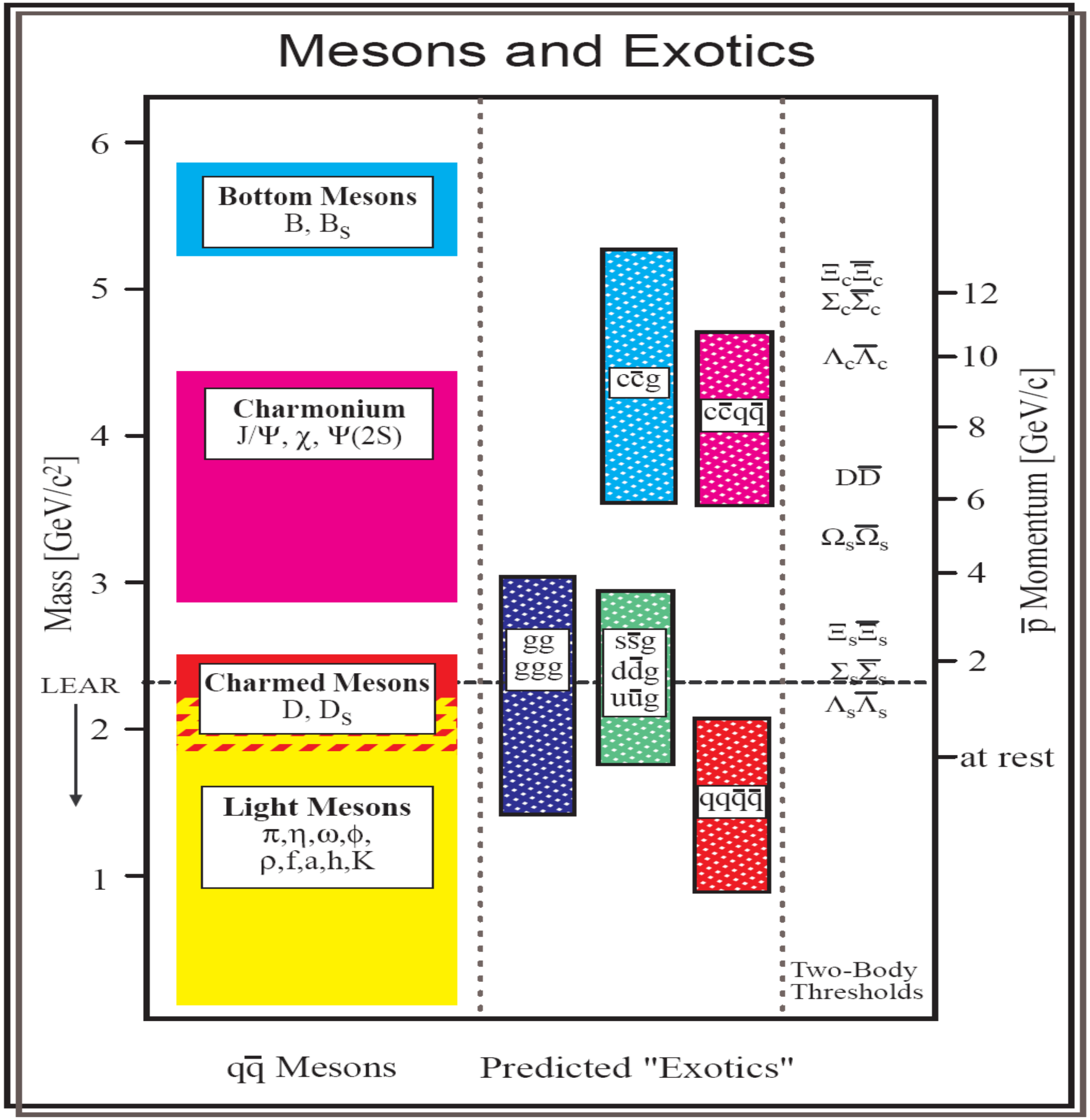
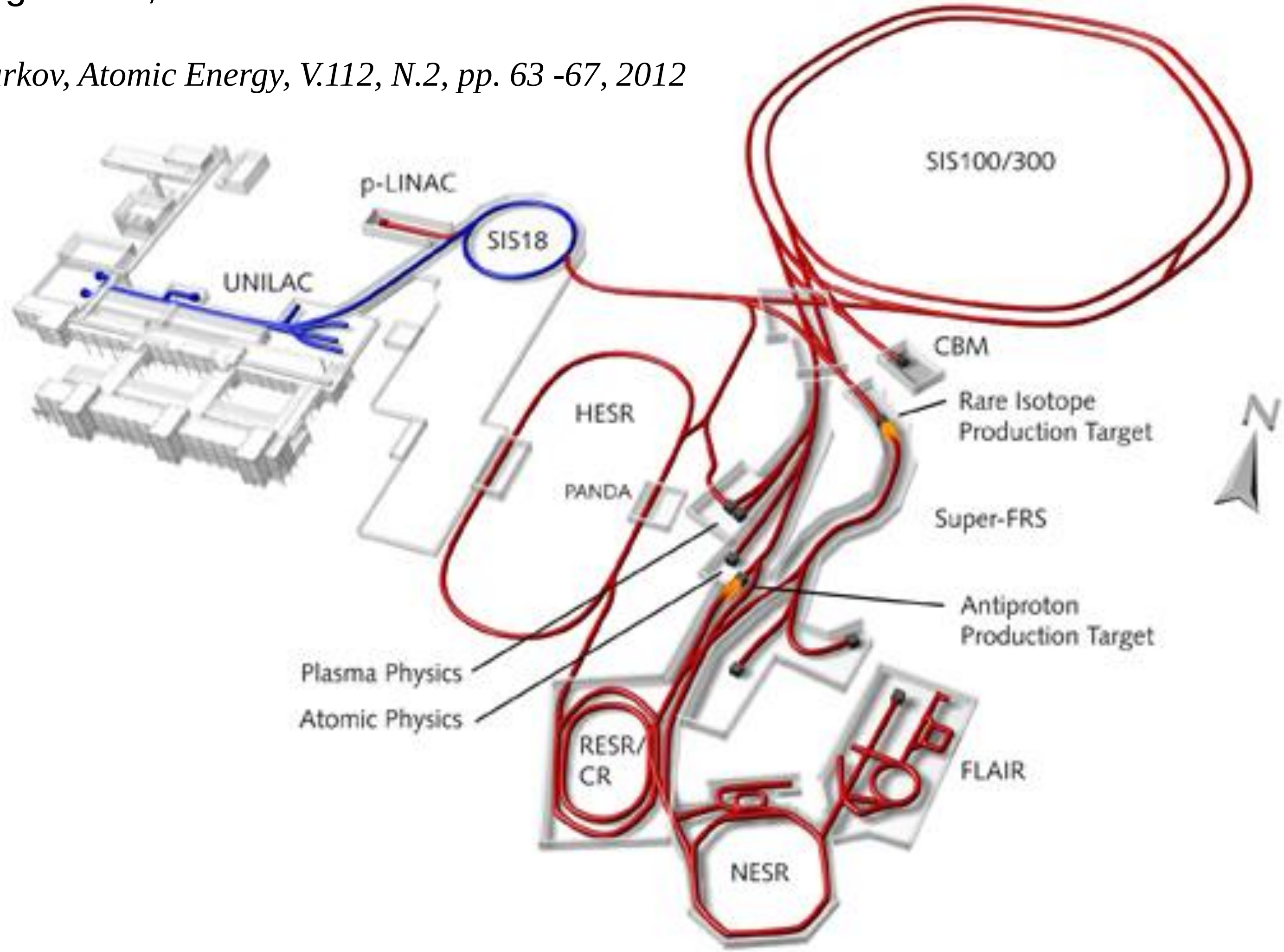
WHY WE CONCENTRATE ON PHYSICS WITH ANTIPROTONS:



Expected masses of $\bar{q}\bar{q}$-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 $2x10^{32}sm^{-2}c^{-1}$ and momentum resolution σ(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

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 CULCULATION 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 ± 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;

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. 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:

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

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) .*

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

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

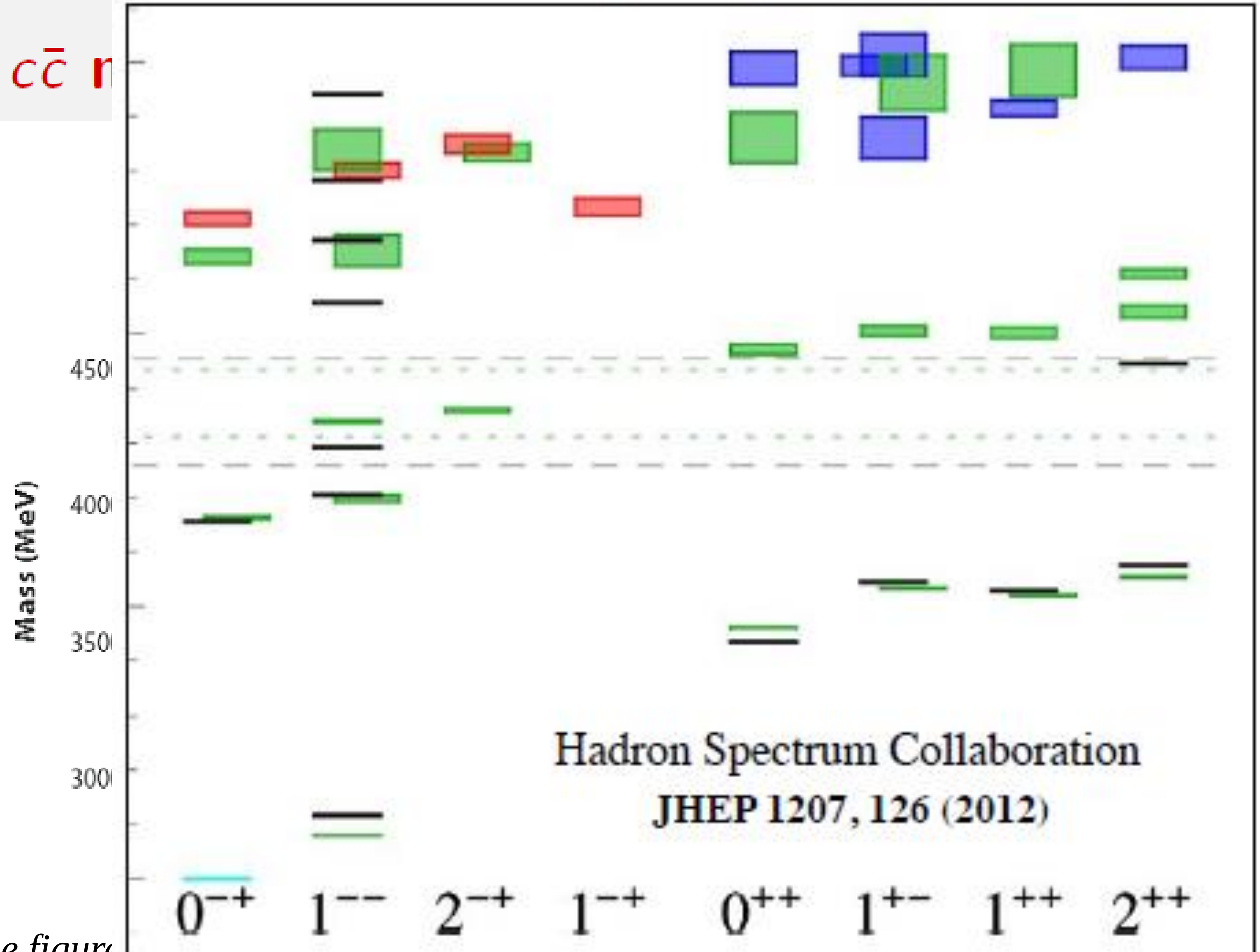
When cotangent argument in $V_3(r)$ is small: $r^2/a^2 \ll \pi^2$,

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

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:



$c\bar{c}$ m

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1 (2008).

The $c\bar{c}$ system has been investigated in great detail first in e^+e^--reactions, and afterwards on a restricted scale ($E_{\bar{p}} \leq 9$ 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 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)**;**

AS RESULT:

- **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).**

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

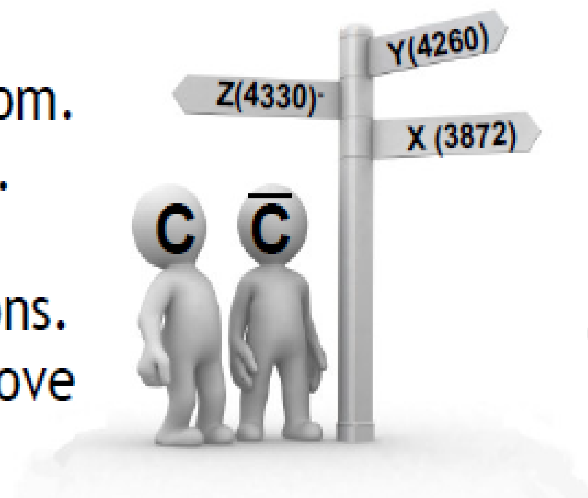
- decays into particle-antiparticle or $D\bar{D}$-pair: $\bar{p}p \rightarrow (\Psi, \eta_c, \chi_{cJ}, ..) \rightarrow \Sigma^0\bar{\Sigma}^0, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0\pi, \Lambda\bar{\Lambda}\pi$;
- decays into light hadrons: $\bar{p}p \rightarrow (\Psi, \eta_c, ..) \rightarrow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

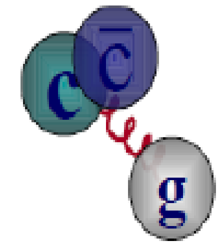
QCD and exotic hadrons

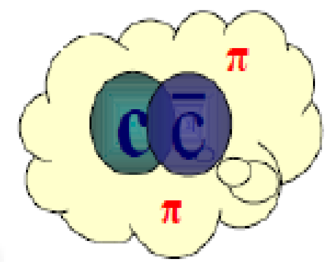
Besides mesons and baryons, other "exotic" combinations of quarks and gluons could exist (i.e. are not forbidden by QCD). This include for example

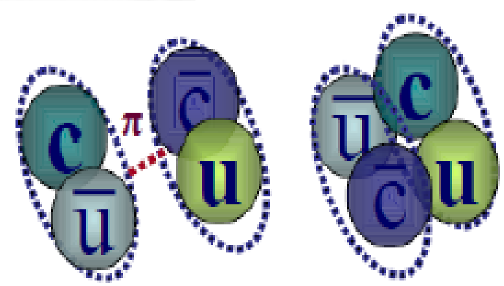
New states may be exotics somehow expected by QCD, but never observed so far:

- Hybrids:
  - Excited gluonic degree of freedom.
  - Lowest mass states ~4.2 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

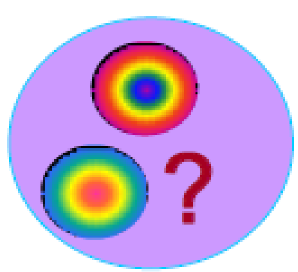
played important role in establishing QCD as theory of strong interactions

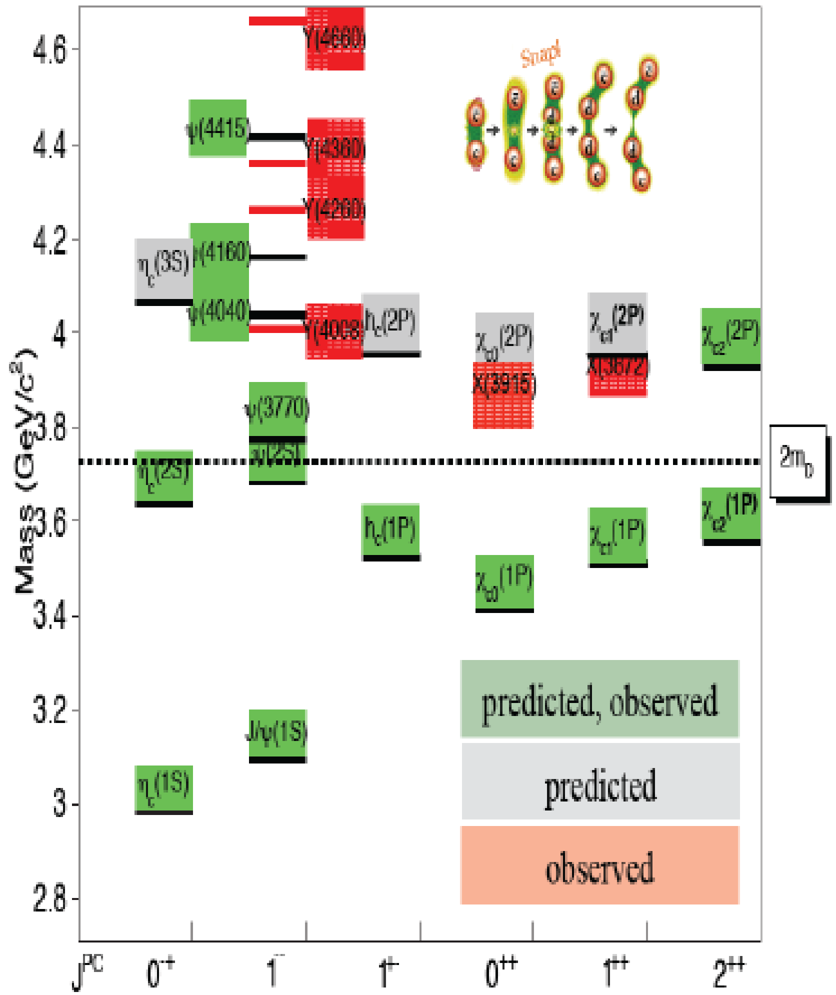
- All States below charm threshold have been observed
  - Charm anti-charm potential model described spectrum very well
- Many missing states above charm threshold.
- New states above charm threshold appear
  - Charmonium in final states
  - Not an obvious charmonium state

Not all of them are charmonia!

What are they?

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

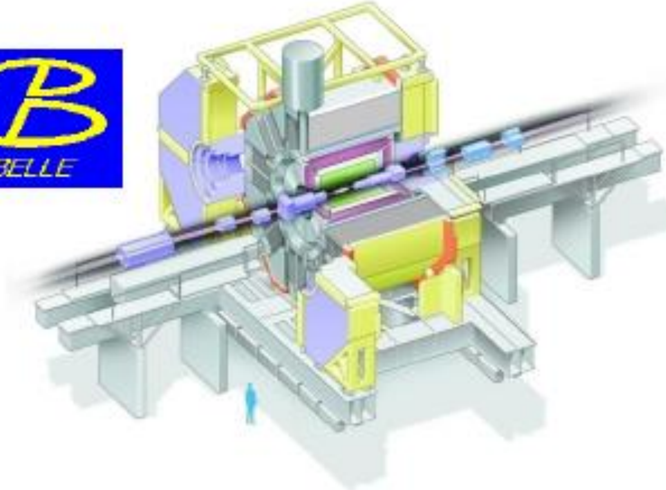




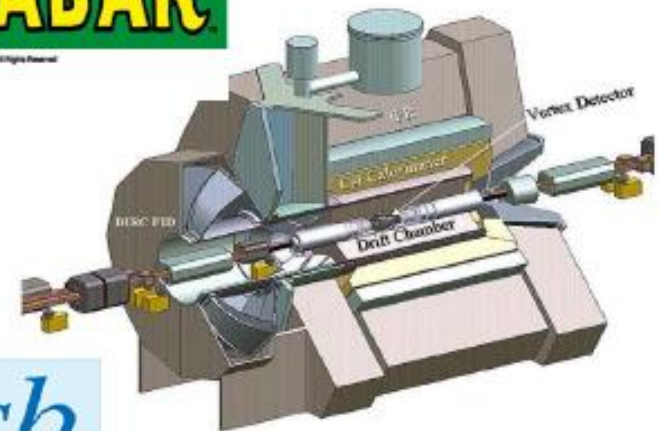
Z(4430)
Z(4050)
Z(4250)
Z(4200)
Z_c(3900)
Z_c(3885)
Z_c(4020)
Z_c(4025)
X(3940)
Z(3930)
Y(3940)
Y(4140)
X(4350)

Results from These Experiments

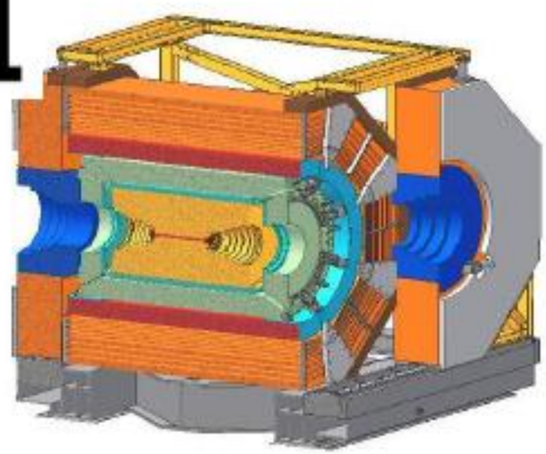
BELLE



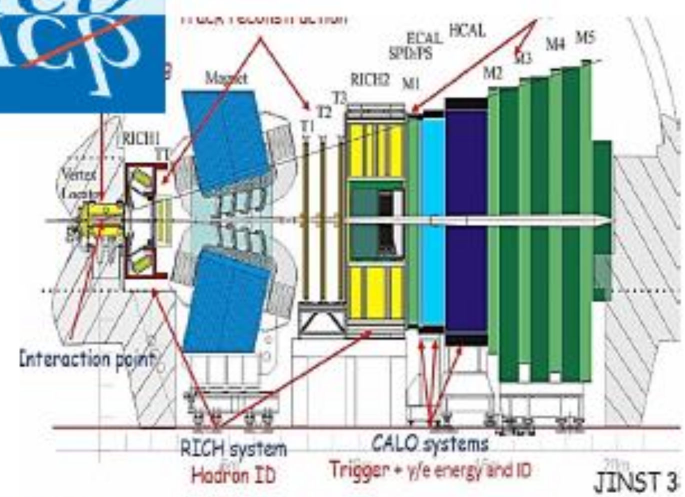
BABAR



BESIII



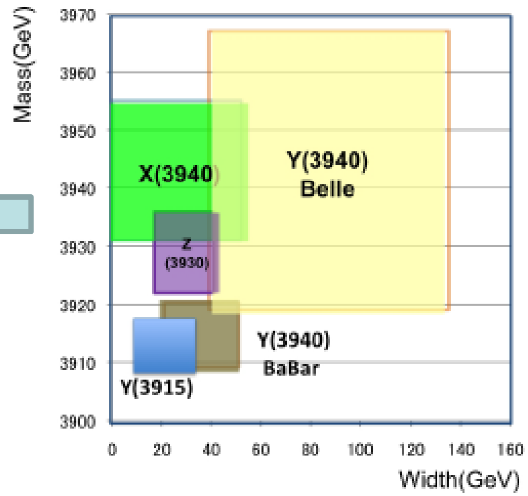
LHCb



+ CLEOc, CDF, CMS/ATLAS …

very schematically, clusters of new states

- $X(3872)$, the first surprise
- the 3940 family



- the Y family (1^{--} states):
  - $Y(4260) \to J/\psi\pi\pi,\ K^+K^-$
  - $Y(4350) \to \psi(2S)\pi^+\pi^-$
  - $Y(4630) \to \Lambda_c\bar{\Lambda}_c$
  - $Y(4660) \to \psi(2S)\pi^+\pi^-$
- charged states
  - $Z(4430) \to \psi(2S)\pi^\pm$
  - $Z_1(4050),\ Z_2(4250) \to \chi_{c1}(2S)\pi^\pm$
- $C = +$ states
- $X(4160) \to D^*\bar{D}^*$
- $Y(4140) \to J/\psi\phi$
- $X(4350)$

BES III

$Z_c(3900)^\pm \to J/\Psi\pi^\pm$

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

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

$Z_c(4020)^\pm \to h_c\,\pi^\pm$

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$Z_c(4200)^\pm \to J/\Psi\pi^\pm$

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 $M = \pi, \eta, \omega, \ldots$ (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:

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

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

$J^{PC} = 0^{--} \rightarrow$ 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.*, $|\, 1_{cq}, 1_{\overline{cq}'};\, S = 1, J = 2\, \rangle$.

!

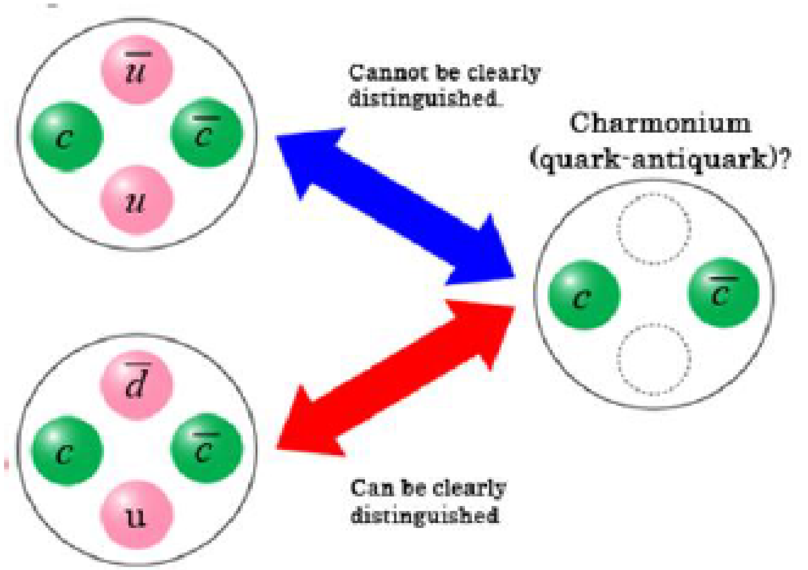
- $\bar{p}p \to X \to J/\Psi\,\rho \to J/\Psi\,\pi\pi$; $\bar{p}p \to X \to J/\Psi\,\omega \to J/\Psi\,\pi\pi\pi$, $\bar{p}p \to X \to \chi_{cJ}\pi$ (decays into J/Ψ, Ψ', χ_{cJ} and light mesons);
- $\bar{p}p \to X \to D\bar{D}^* \to D\bar{D}\,\gamma$; $\bar{p}p \to X \to D\bar{D}^* \to D\bar{D}\,\eta$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

Z_c States

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, ...

The first charged state: Z(4430)!

BELLE

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

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

Total significance: 7.3s

M = (4433±4) MeV

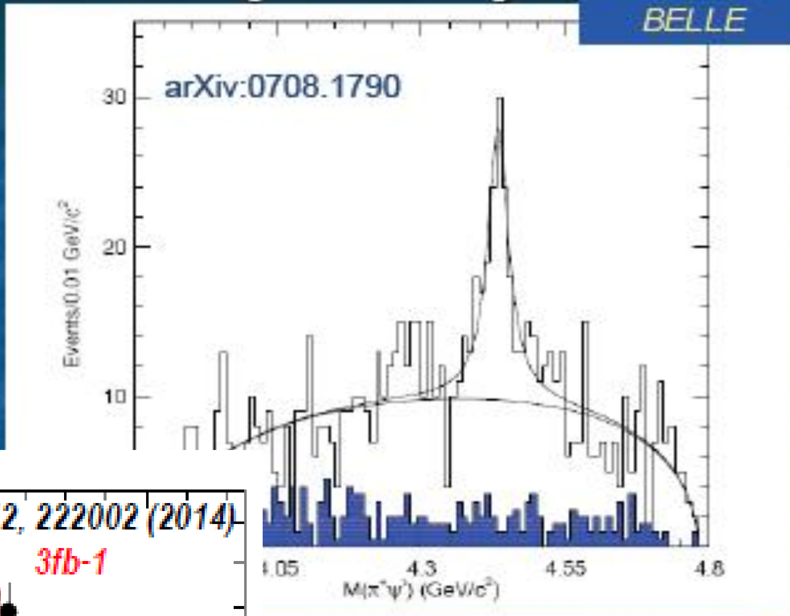
$\Gamma = (44^{+17}_{-13})$ MeV

Too narrow to be a reflection

BF(B→KZ)xBF(Z→ψ...

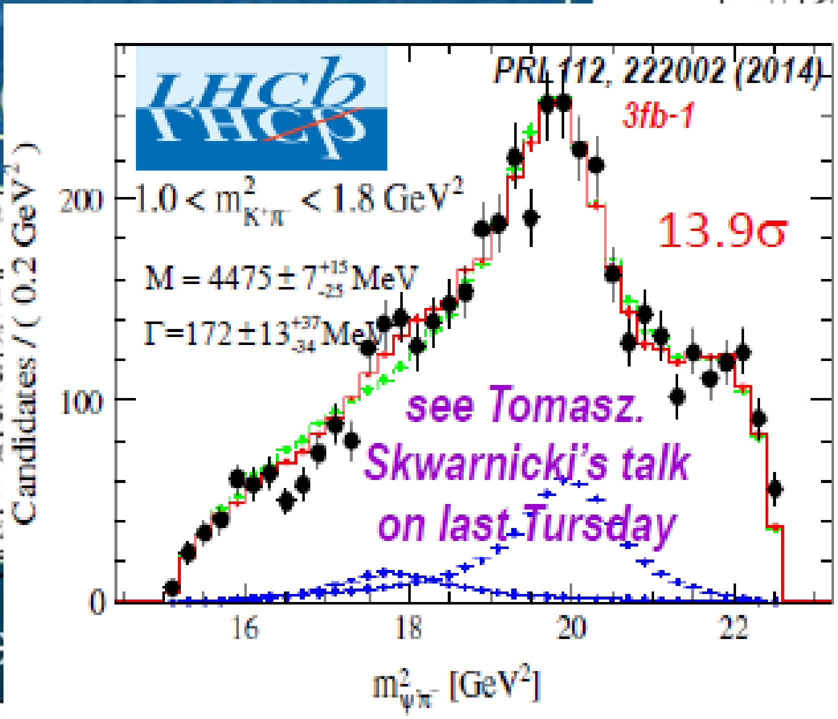
Subset	Signal event...
$\psi' \to \pi^+\pi^- J/\psi$	52.9 ± 15.1
$\psi' \to \ell^+\ell^-$	104.8 ± 34....
$J/\psi(\psi') \to e^+e^-$	45.4 ± 16.6
$J/\psi(\psi') \to \mu^+\mu^-$	79.4 ± 24.6
$K^{\pm}\pi^{\mp}\psi'$	106.5 ± 26....
$K_S\pi^{\mp}\psi'$	21.0 ± 8.3
vary K^* veto	238.1 ± 64....

Prior search with B→X⁺K with X+→...



...k: separate in ...mples

...d mass consistent ...een B± and B0 within ...errors [in B± decays M= ...±9) MeV ; BF.../BF...=1.0 ...]



R.Faccini, LeptonPhoton Conference 2007

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

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

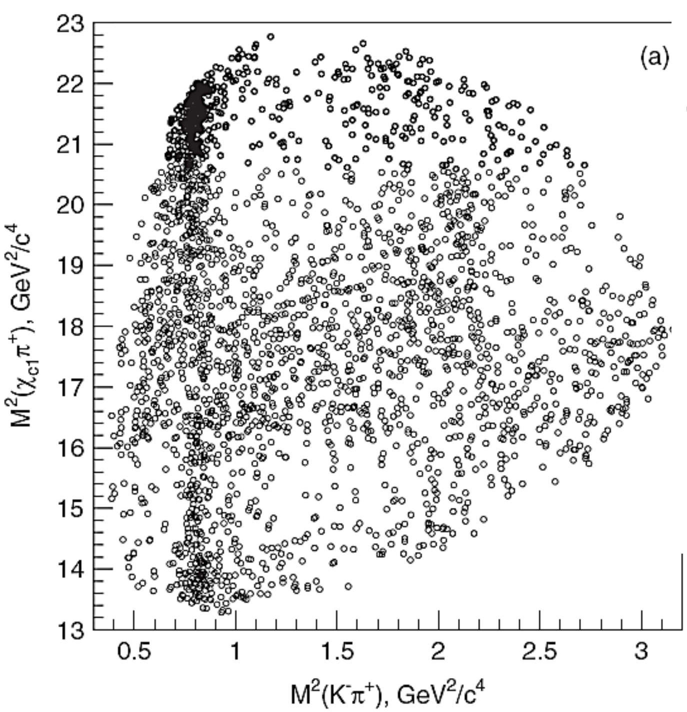
- Dalitz-plot analysis of $\underline{B}^0 \to \chi_{c1}\pi^+K^-$ $\chi_{c1} \to J/\psi\gamma$ with 657M B$\underline{B}$
- Dalitz plot models: known $K^* \to K\pi$ only

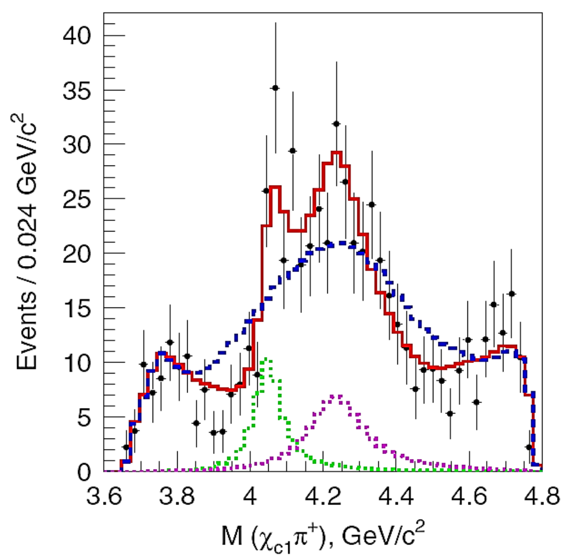
K*'s + one $Z \to \chi_{c1}\pi^\pm$

PRD 78, 072004 (2008)

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

Significance: 5.7σ





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

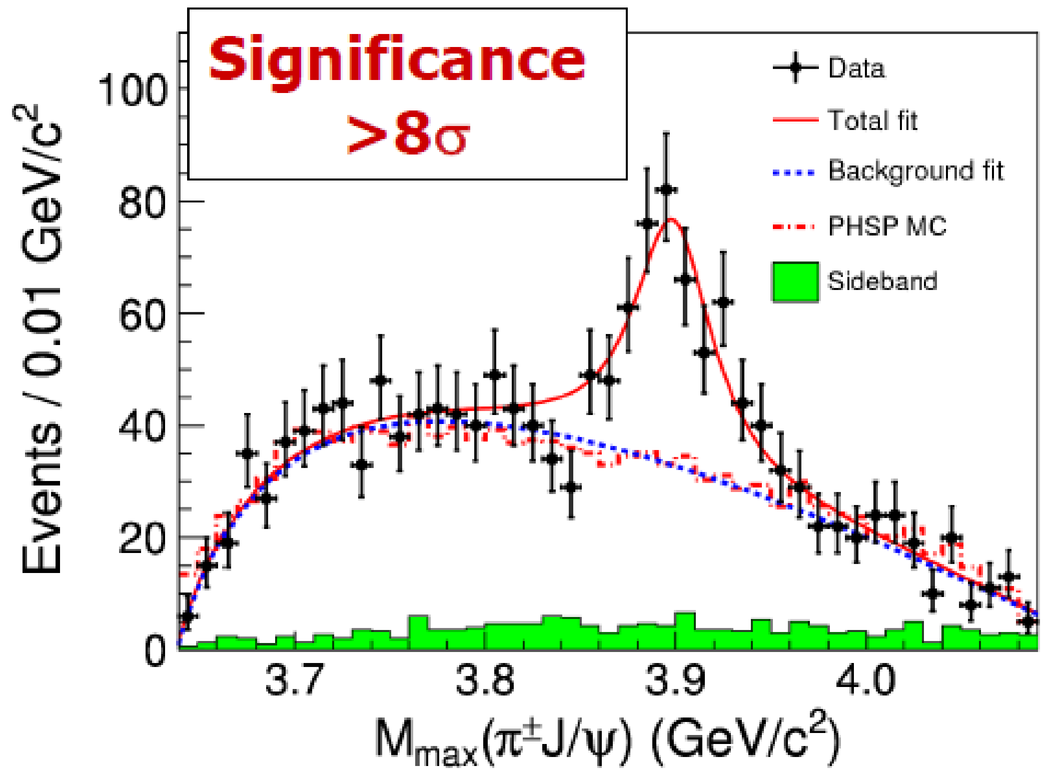
M($\chi_{c1}\pi^+$)
for $1 < M^2(K^-\pi^+) < 1.75$GeV^2

$$M_{Z_1} = 4051 \pm 14\,^{+20}_{-41}\text{ MeV}$$
$$\Gamma_{Z_1} = 82\,^{+21}_{-17}\,^{+47}_{-22}\text{ MeV}$$
$$M_{Z_2} = 4248\,^{+44}_{-29}\,^{+180}_{-35}\text{ MeV}$$
$$\Gamma_{Z_2} = 177\,^{+54}_{-39}\,^{+316}_{-61}\text{ MeV}$$

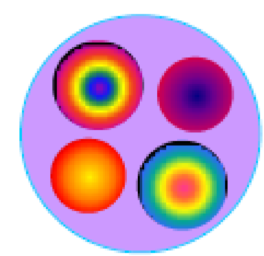
Observation of Zc(3900) in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$

BESIII: arXiv:1303.5949

BESIII: PRL110, 252001 (2013)



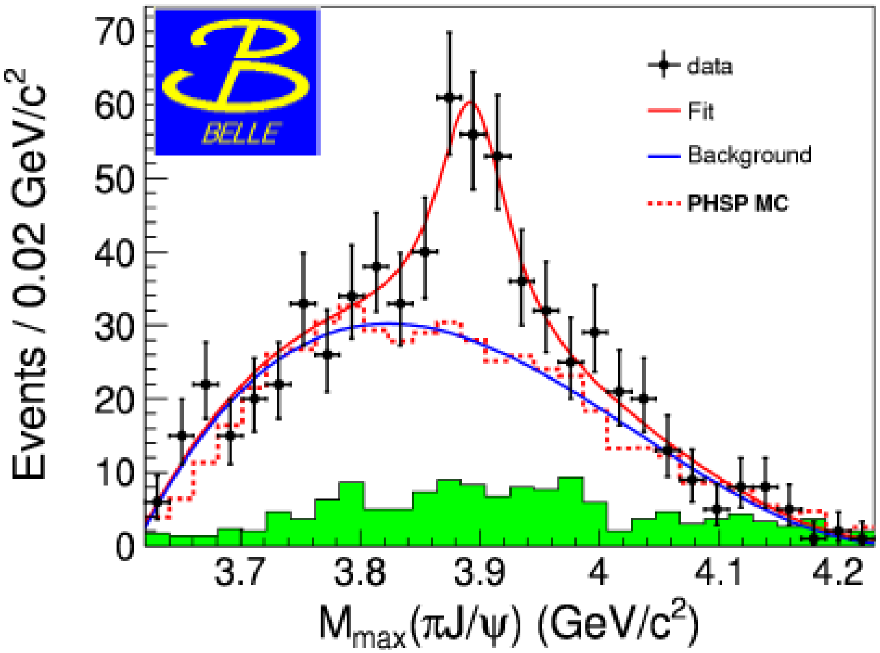
- Couples to cc
- Has electric charge
- At least 4-quarks
- What is its nature?

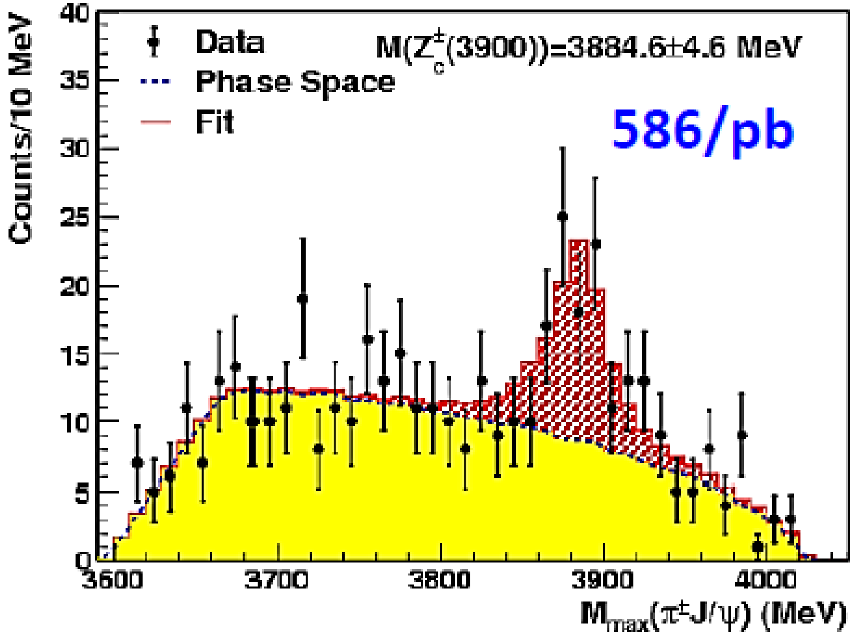


- ➢ S-wave Breit-Wigner with efficiency correction
- ➢ Mass = (3899.0±3.6±4.9) MeV
- ➢ Width = (46±10±20) MeV
- ➢ Fraction = (21.5±3.3±7.5)%

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

CLEOc data at 4.17 GeV
arXiv: 1304.3036

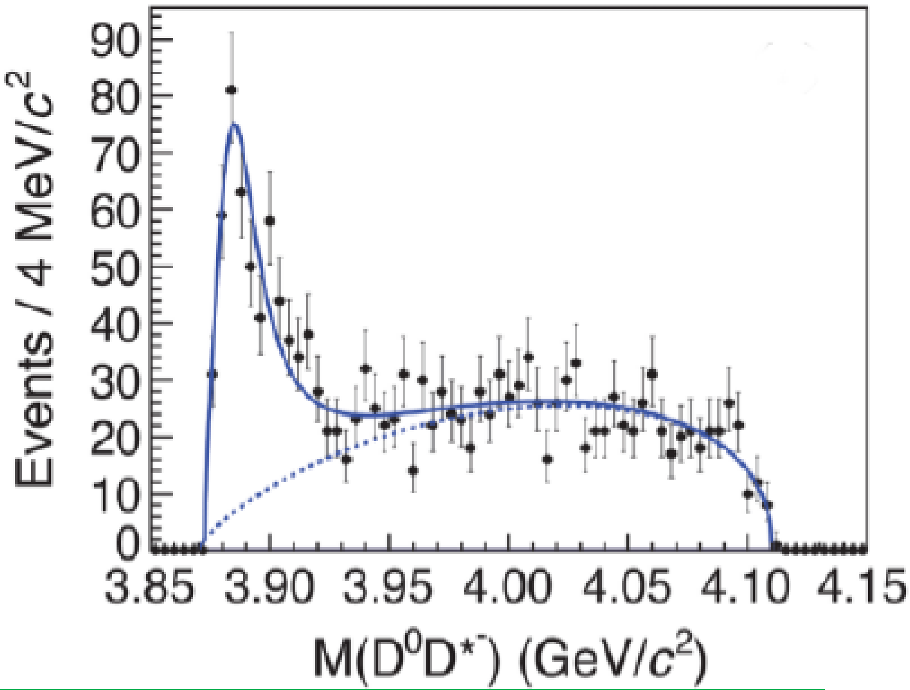


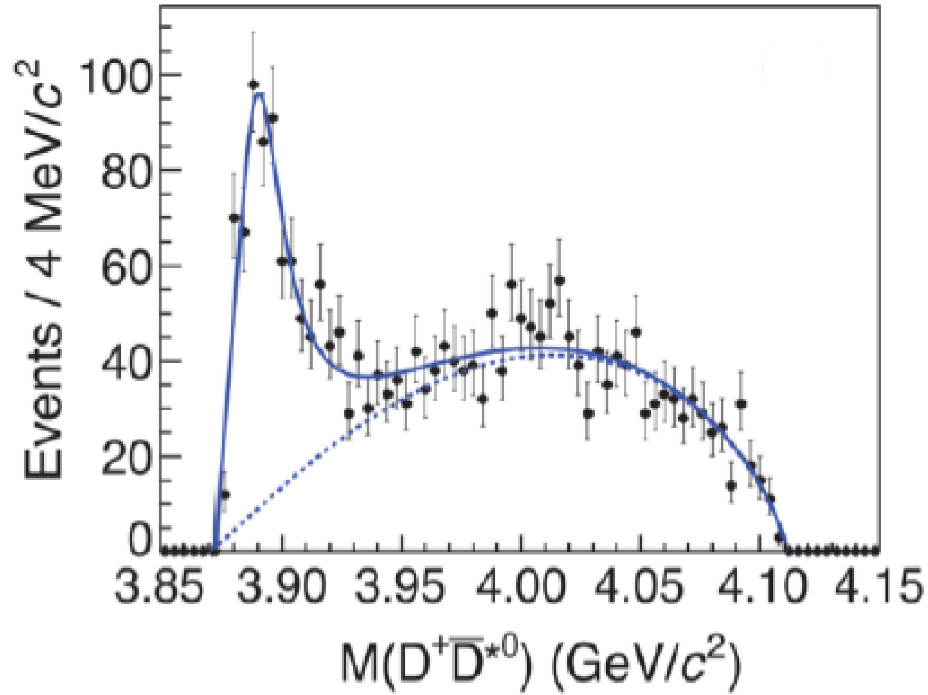


- $M = 3894.5 \pm 6.6 \pm 4.5$ MeV
- $\Gamma = 63 \pm 24 \pm 26$ MeV
- 159 ± 49 events
- $>5.2\sigma$

- $M = 3885 \pm 5 \pm 1$ MeV
- $\Gamma = 34 \pm 12 \pm 4$ MeV
- 81 ± 20 events
- 6.1σ

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





M = (3883.9±1.5±4.2) MeV/c²
Γ = (24.8±3.3±11.0) MeV/c²
>18σ

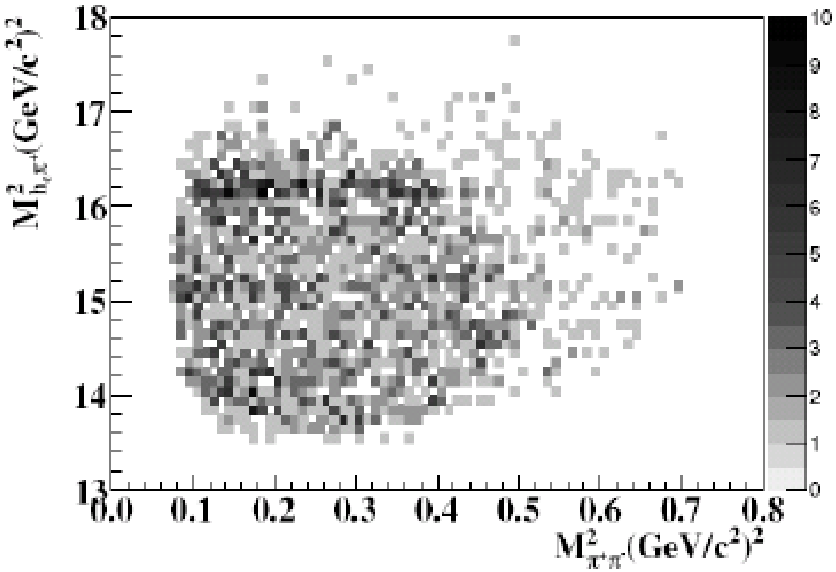
$\pi Z_c(3885)$ ang. dist. favours $J^P = 1^+$
disfavours 1^- e 0^-

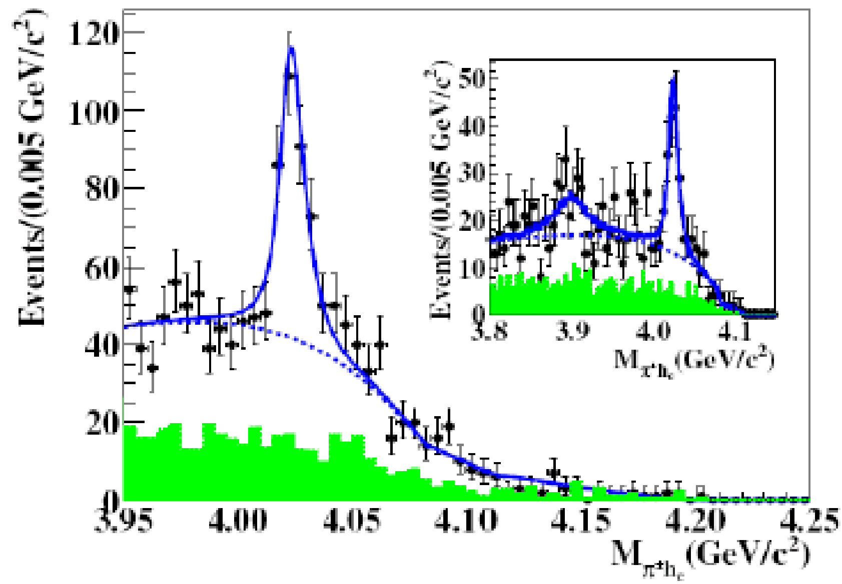
$$\sigma(e^+e^- \to \pi^- Z_c(3885)^+ \times Z_c(3885)^+ \to (D\bar{D}^*)^+ + c.c.) = (83.5 \pm 6.6 \pm 22.0)\ \text{pb}$$

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

$Z^{\pm}_{c}(4020)$ in $e^+e^- \rightarrow \rightarrow \pi^+\pi^- h_c(1P)$

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





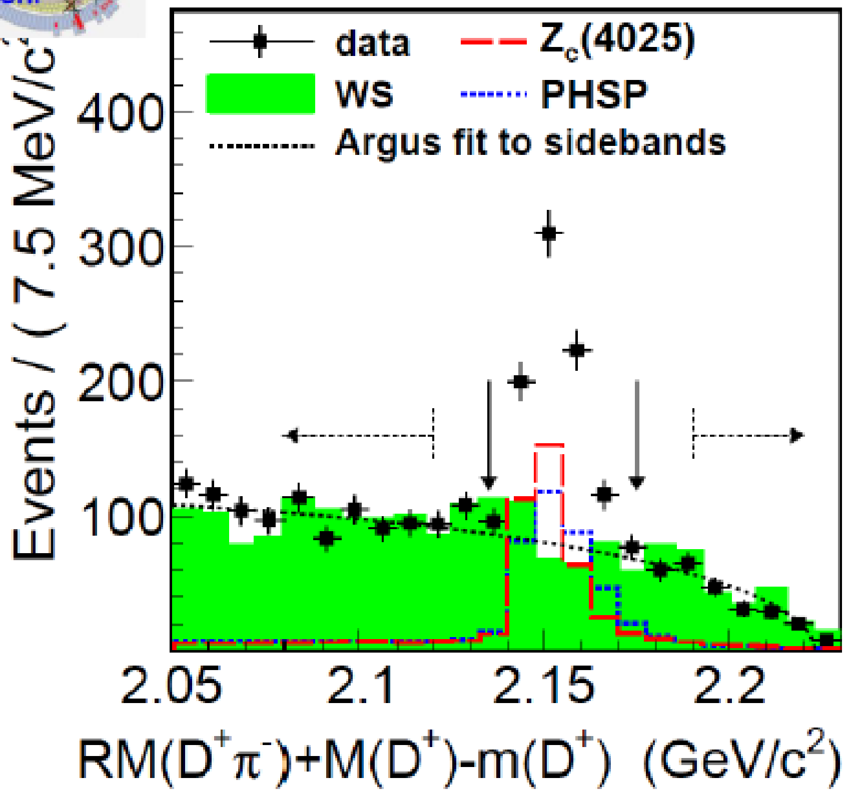
$$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7\, MeV/c^2$$
$$\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6\, MeV$$

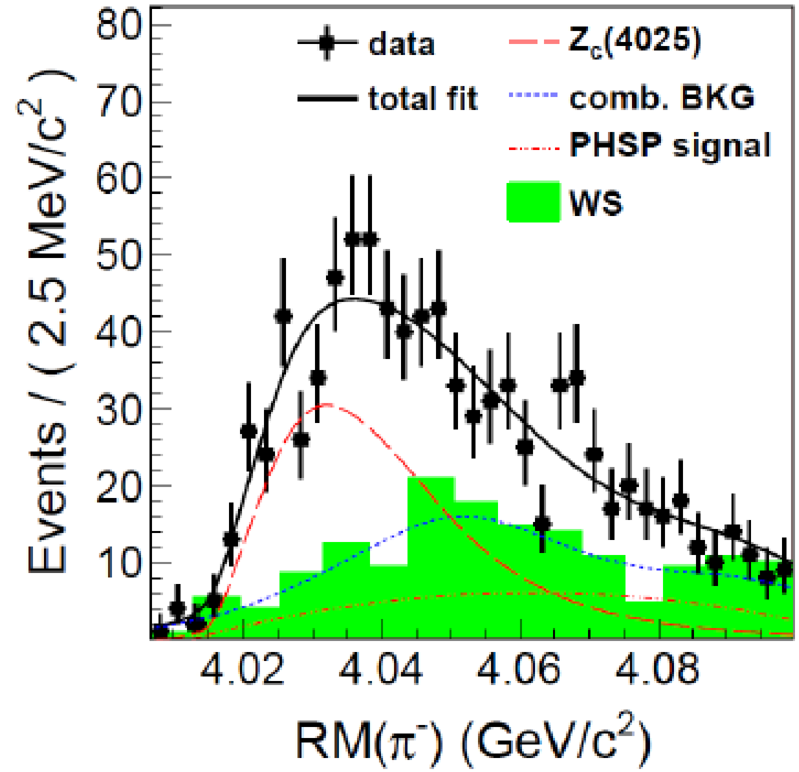
arXiv:1309.1896

submitted to PRL

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

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





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

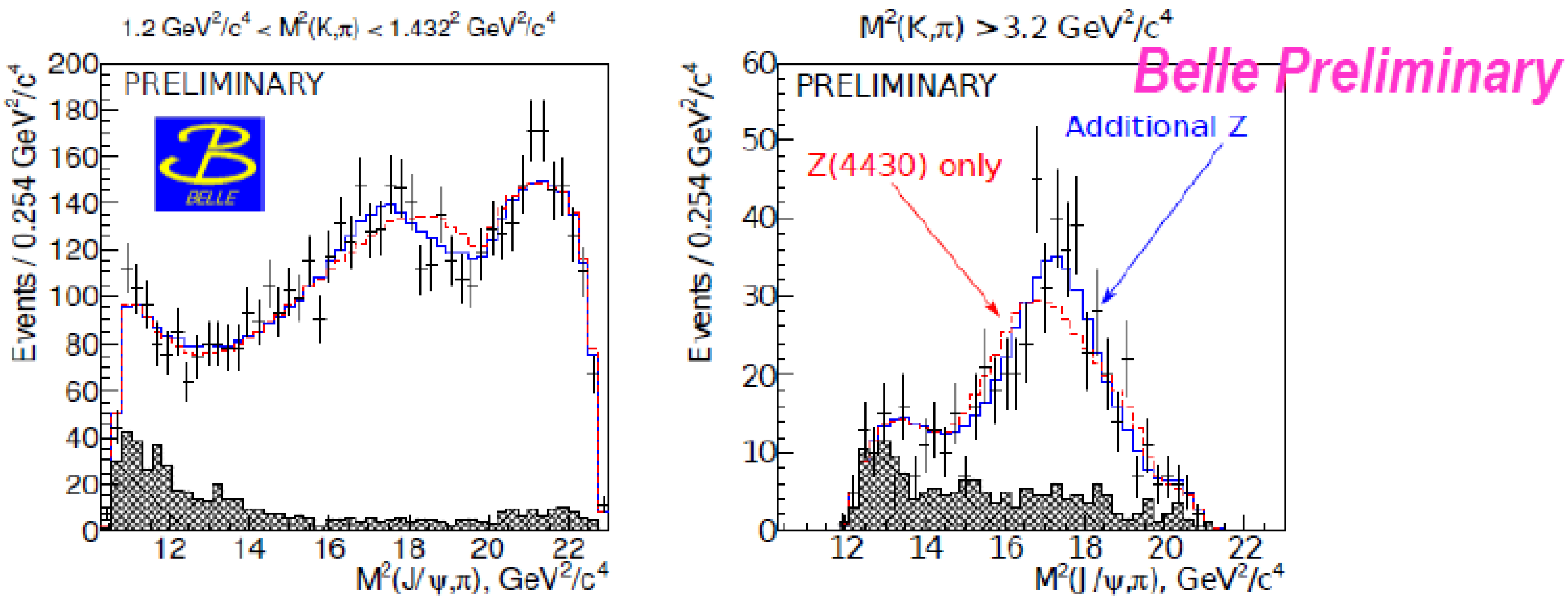
$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV; $\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

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

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

arXiv:1308.2760 submitted to PRL

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



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

$$M = 4196^{+31+17}_{-29-6}\ \mathrm{MeV}/c^2,\ \Gamma = 370^{+70+70}_{-70-85}\ \mathrm{MeV}.$$

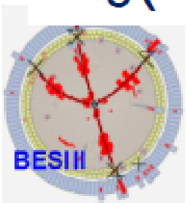
- Exclusion levels ($J^P=0^-, 1^-, 2^-, 2^+$) : 6.7σ , 7.7σ, 5.2σ, 7.6σ
- $Z_c(4430)$ is also found (4σ) , $\frac{\mathcal{B}(Z_c(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+)} \sim 10$

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

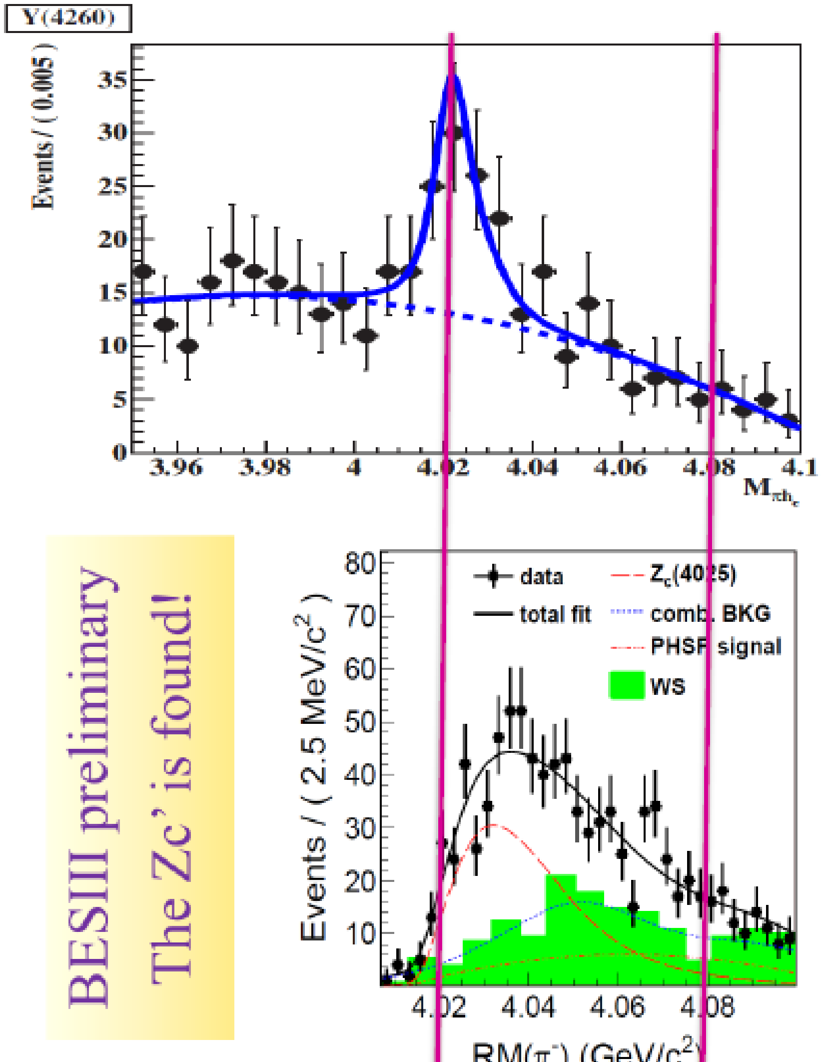
A new $Z_c(4430)$ decay mode?

Need confirmation!

$Z_c(3885) = Z_c(3900)$ => the same question?



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



BESIII preliminary
The Zc' is found!

- M(4020) = 4021.8±1.0±2.5 MeV
- M(4025) = 4026.3±2.6±3.7 MeV
- Γ(4020) = 5.7±3.4±1.1 MeV
- Γ(4025) = 24.8±5.6±7.7 MeV

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

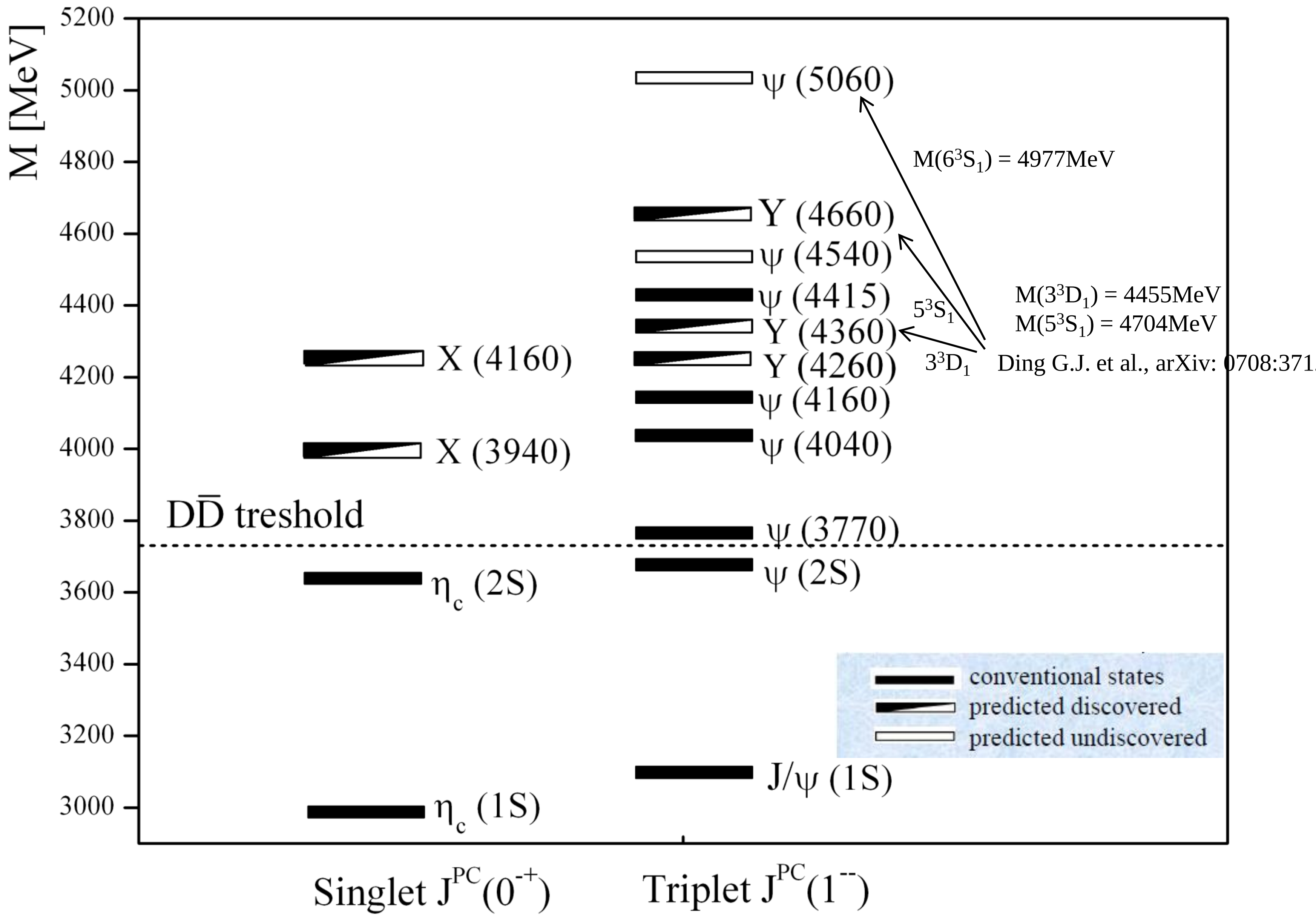
Mass consistent with each other but width ~2σ difference

Interference with other amplitudes may change the results

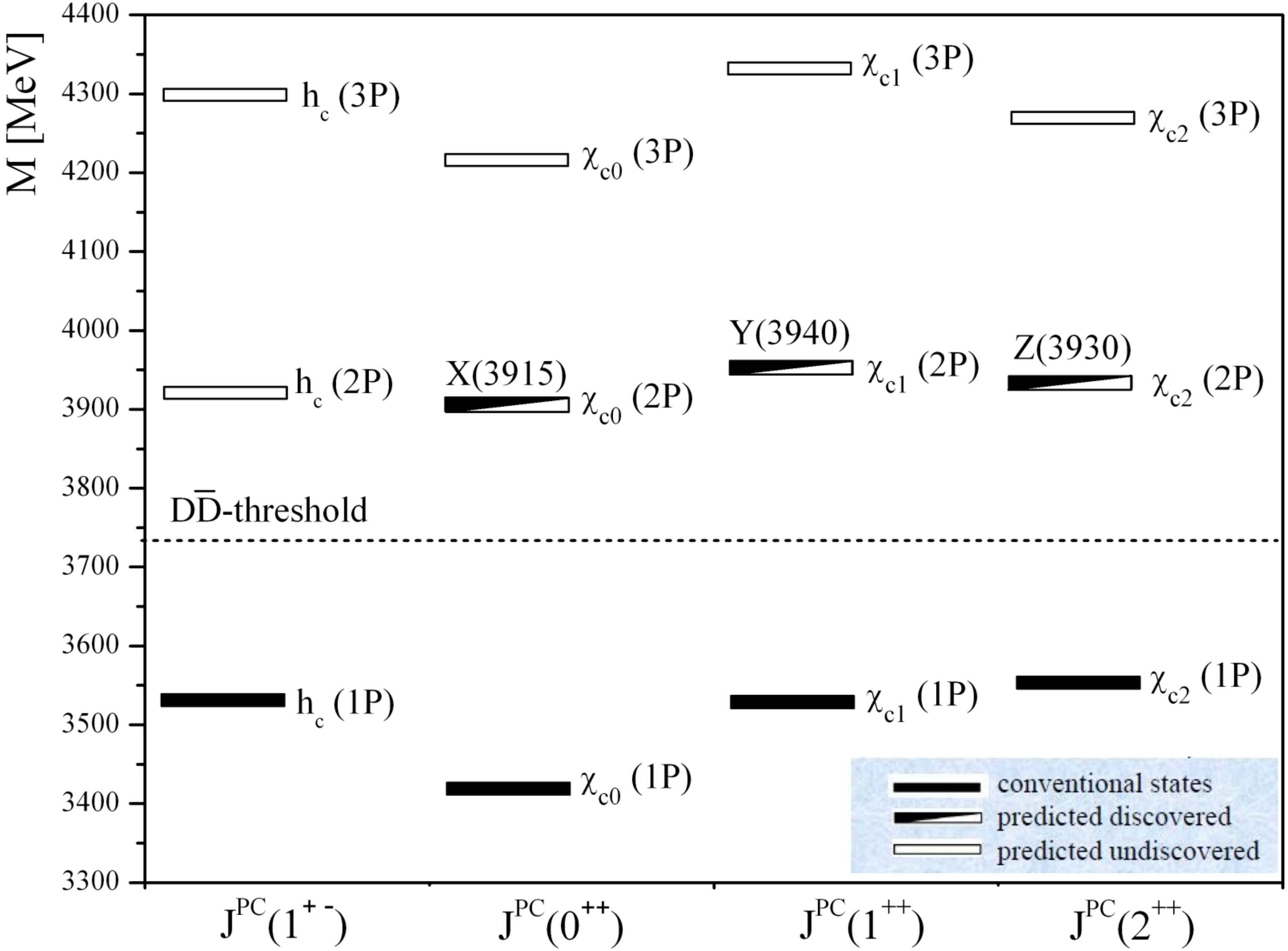
Coupling to $\bar{D}^*D^*$ is much larger than to πh_c if they are the same state

Will fit with Flatte formula

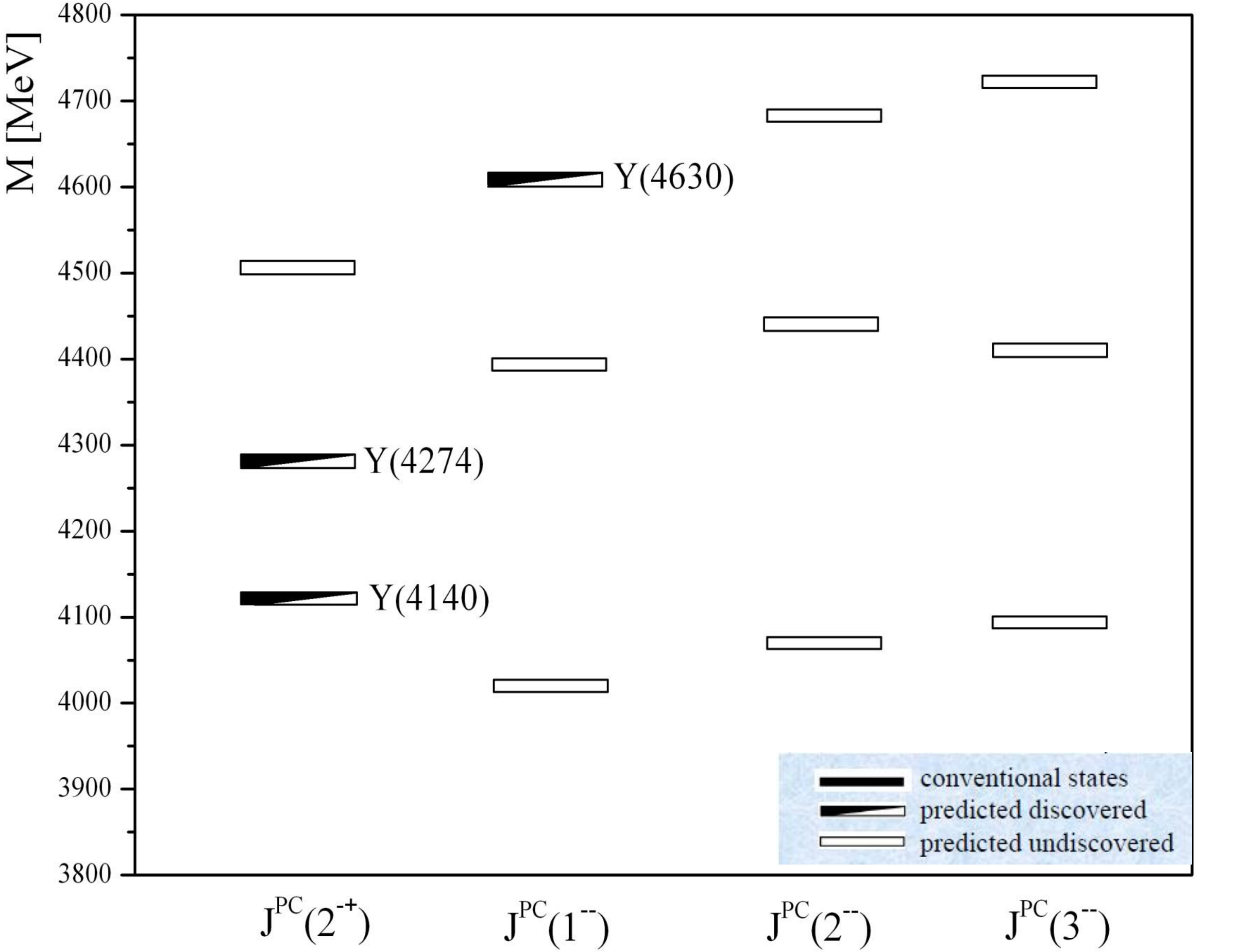
THE SPECTRUM OF SINGLET ($^1S_0$) AND TRIPLET ($^3S_1$) STATES OF CHARMONIUM



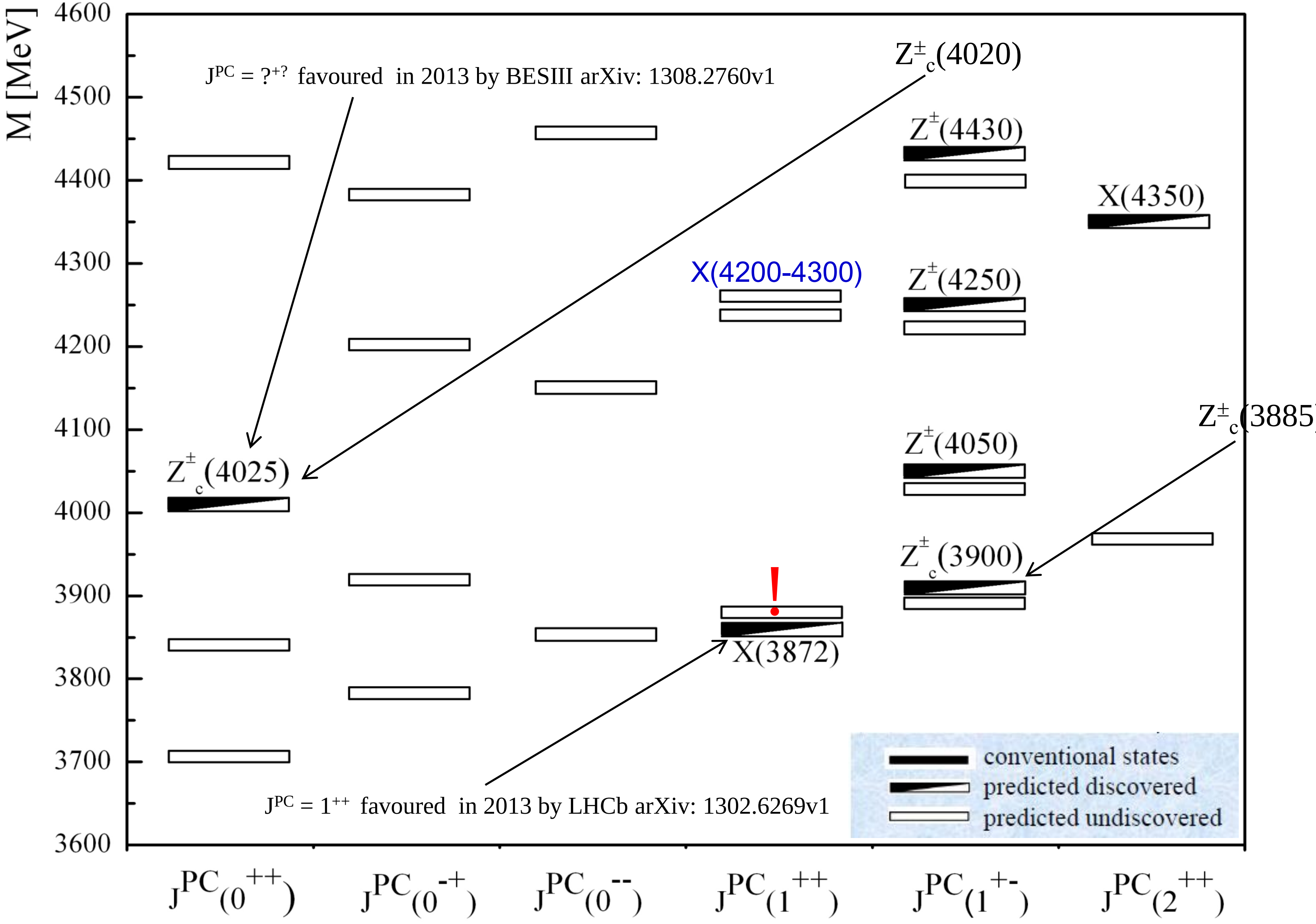
THE SPECTRUM OF SINGLET ($^1P_1$) AND TRIPLET (^3P_J) STATES OF CHARMONIUM



THE SPECTRUM OF SINGLET $^1D_2$ AND TRIPLET ^3D_J STATES OF CHARMONIUM



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.

AD Polosa with L Maiani, F Piccinini,V Riquer

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):

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

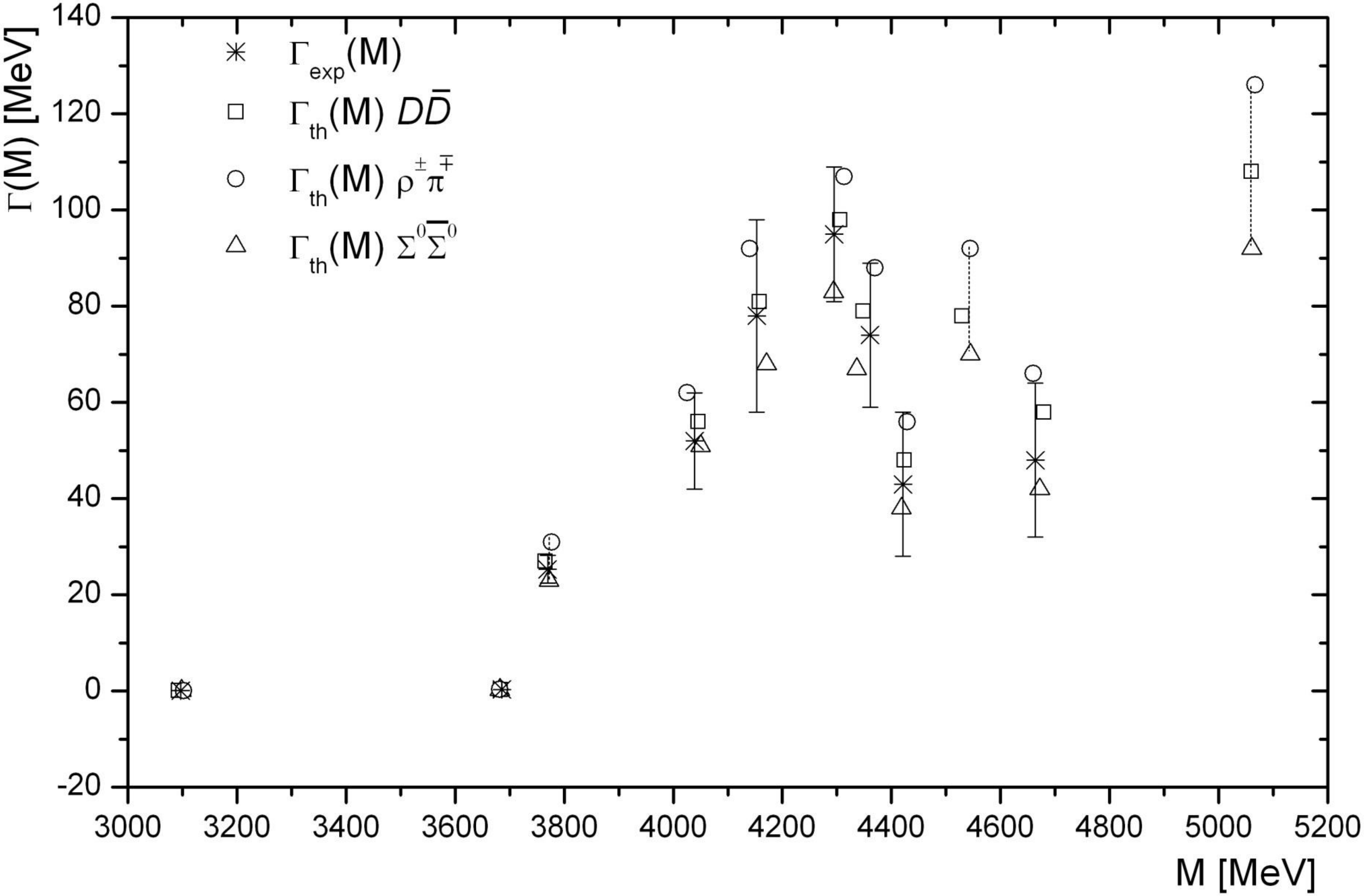
$$(r < R): \int_0^R |\phi_L(r)|^2 \, dr = 1$$

where

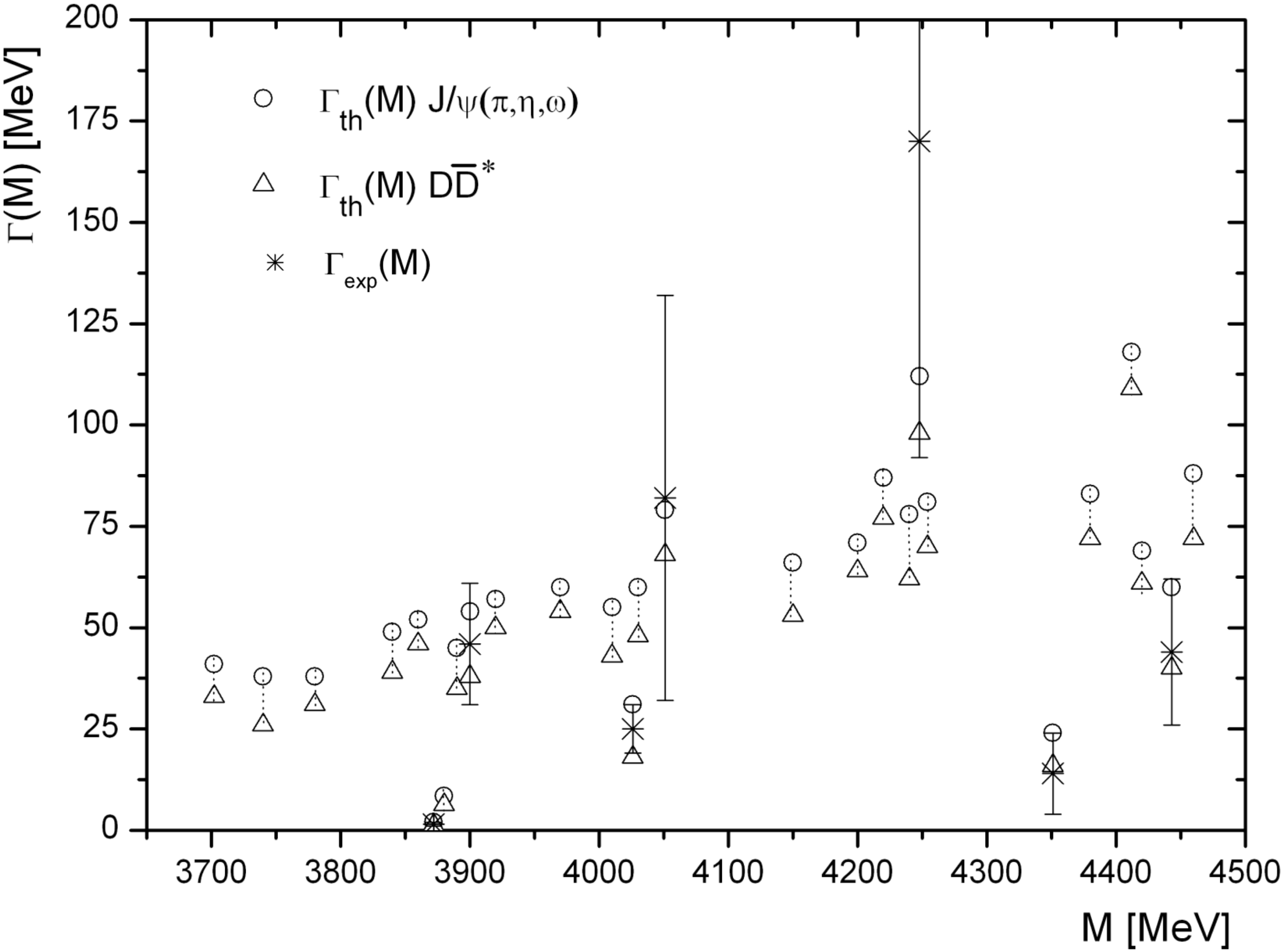
where $F_L(r)$ – is the regular decision in the $V_2(r)$ potential, normalized on the energy delta-function; $\phi_{L(}r)$ – normalized wave function of the resonance state. This wave function transforms into irregular decision in the $V_2(r)$ potential far away from the internal turning point.

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 TRIPLET $^3S_1$ CHARMONIUM STATES



THE WIDTHS OF TETRAQUARKS WITH THE HIDDEN CHARM

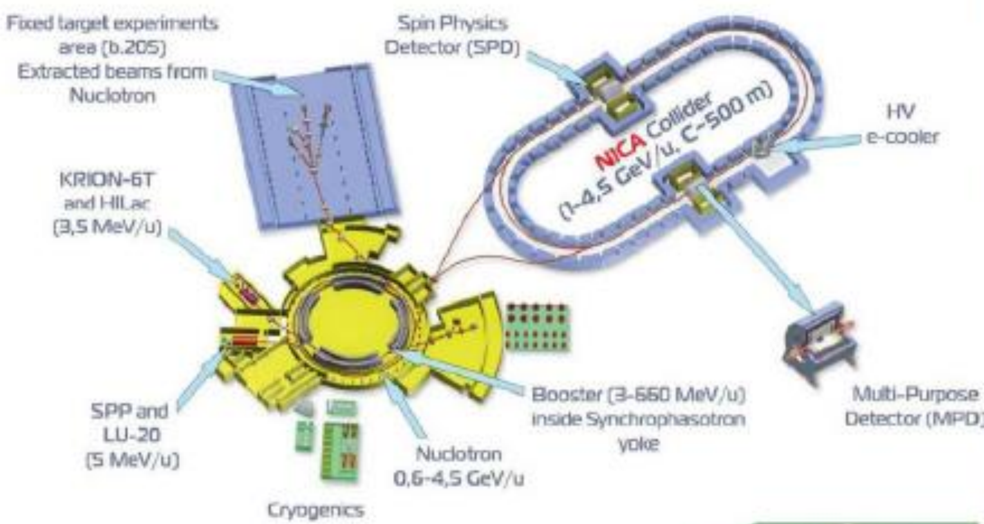


Multi-Purpose Detector (MPD) at NICA

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 $\sqrt{S_{NN}}$ = 4-11 GeV до протон-протонных столкновений при энергии $\sqrt{S_{pp}}$=20 GeV.

Superconducting accelerator complex NICA
(Nuclotron based Ion Collider fAcility)

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



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 $\bar{s}sg$, $\bar{c}cg$ 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 Ω^0_c, Ξ_c, Ξ'_c, Ξ^+_{cc}, Ω^+_{cc}, Σ^*_b, Ω^-_b, Ξ^0_b, Ξ^-_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 η, η', h, h', ω, φ, 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, Λ-hyperon decays).

Summary

- The most promising decay channels of charmonium (decays into light hadrons, particle-antiparticle, decays with J/Ψ, Ψ' 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.
- 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 ten as tetraquarks (two neutral and eight charged). Charge/neutral tetraquarks are awaited to 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 values of branching ratios 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 at FAIR & NICA 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

Prof. Dr. Stephen Olsen

Prof. Dr. Vladimir Nikitin

Thank You!