PROBING OF CHARMONIUM AND EXOTICS WITH HADRON AND HEAVY ION COLLISIONS

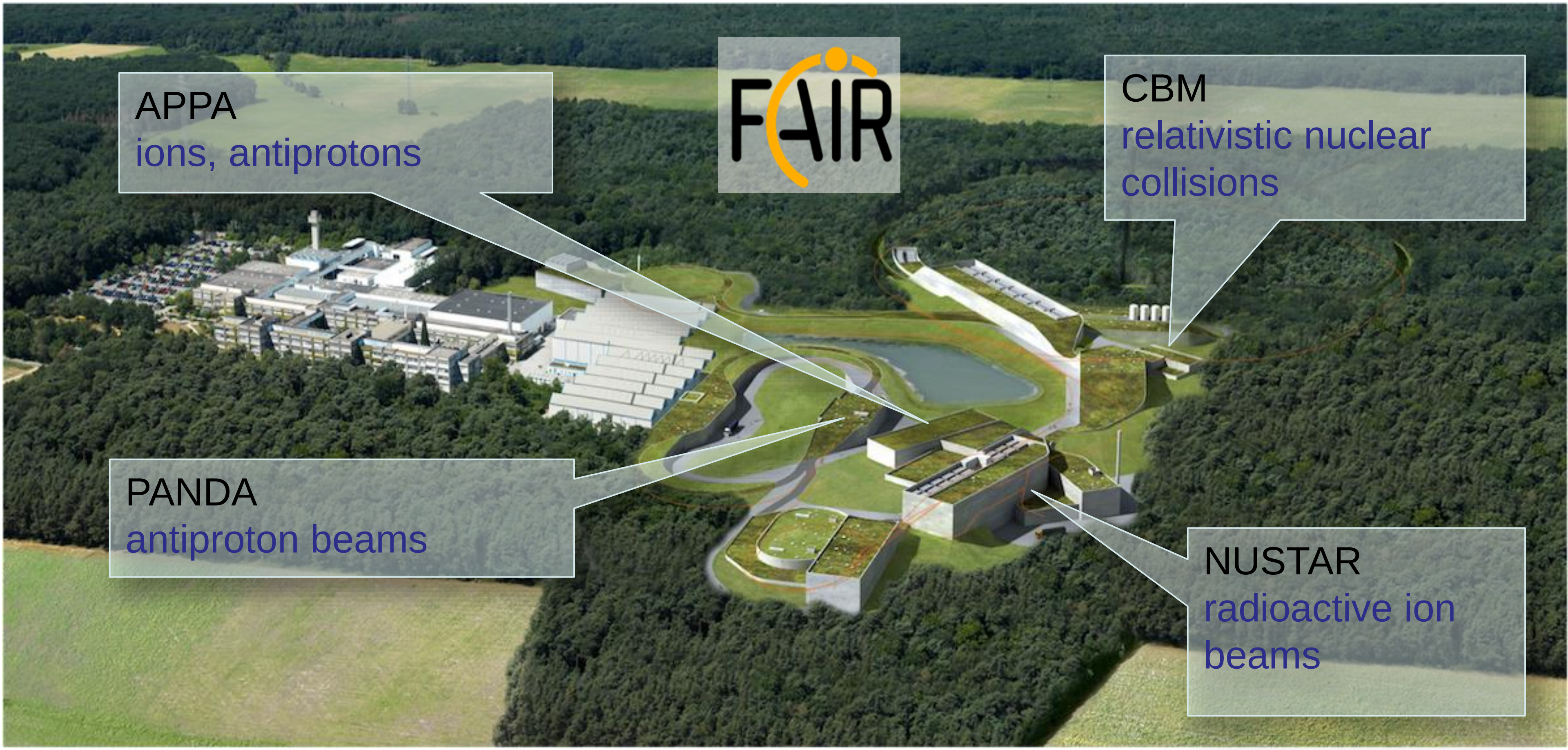
Mikhail Barabanov, Alexander Vodopyanov

(Joint Institute for Nuclear Research, Dubna, Russia)

in collaboration with

Stephen Olsen
(University of the Chinese Academy of Science,
Beijing, People's Republic of China)
&
(Institute for Basic Science, Daejeon, Republic of Korea)

FAIR complex



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~ 2×10^{32} cm^{-2}s^{-1}
- Beam cooling (stochastic & electron)

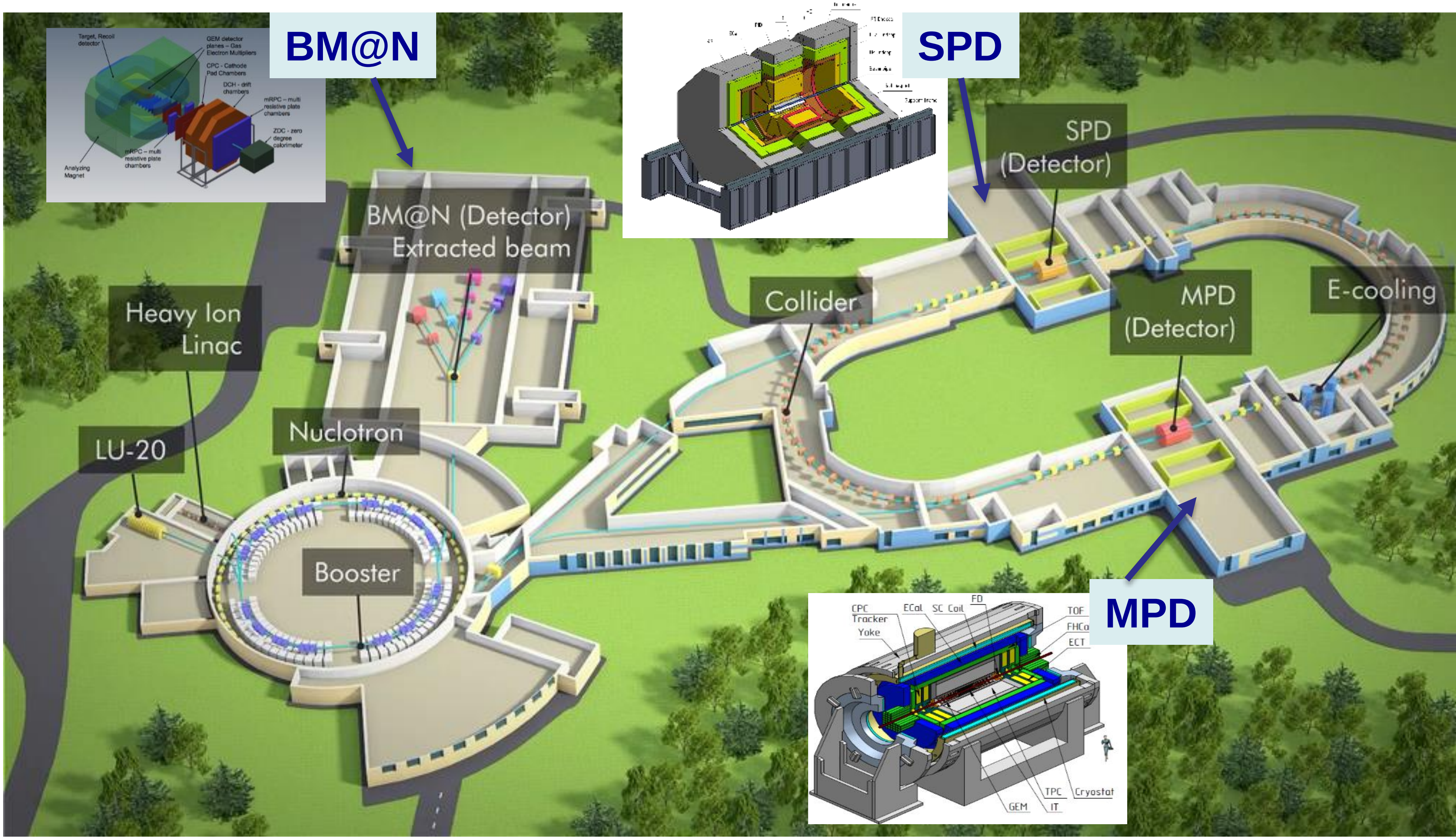
$\sqrt{s} \approx 5.5$ GeV

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

NICA complex

Collider basic requirements: beams from *p* to *Au*

L ~ 10^{27} cm^{-2}c^{-1}(*Au*) $\sqrt{S_{NN}}$= 4-11 GeV; L ~ 10^{32} cm^{-2}c^{-1}(*p*) $\sqrt{S_{pp}}$=12-27 GeV



OUTLINE

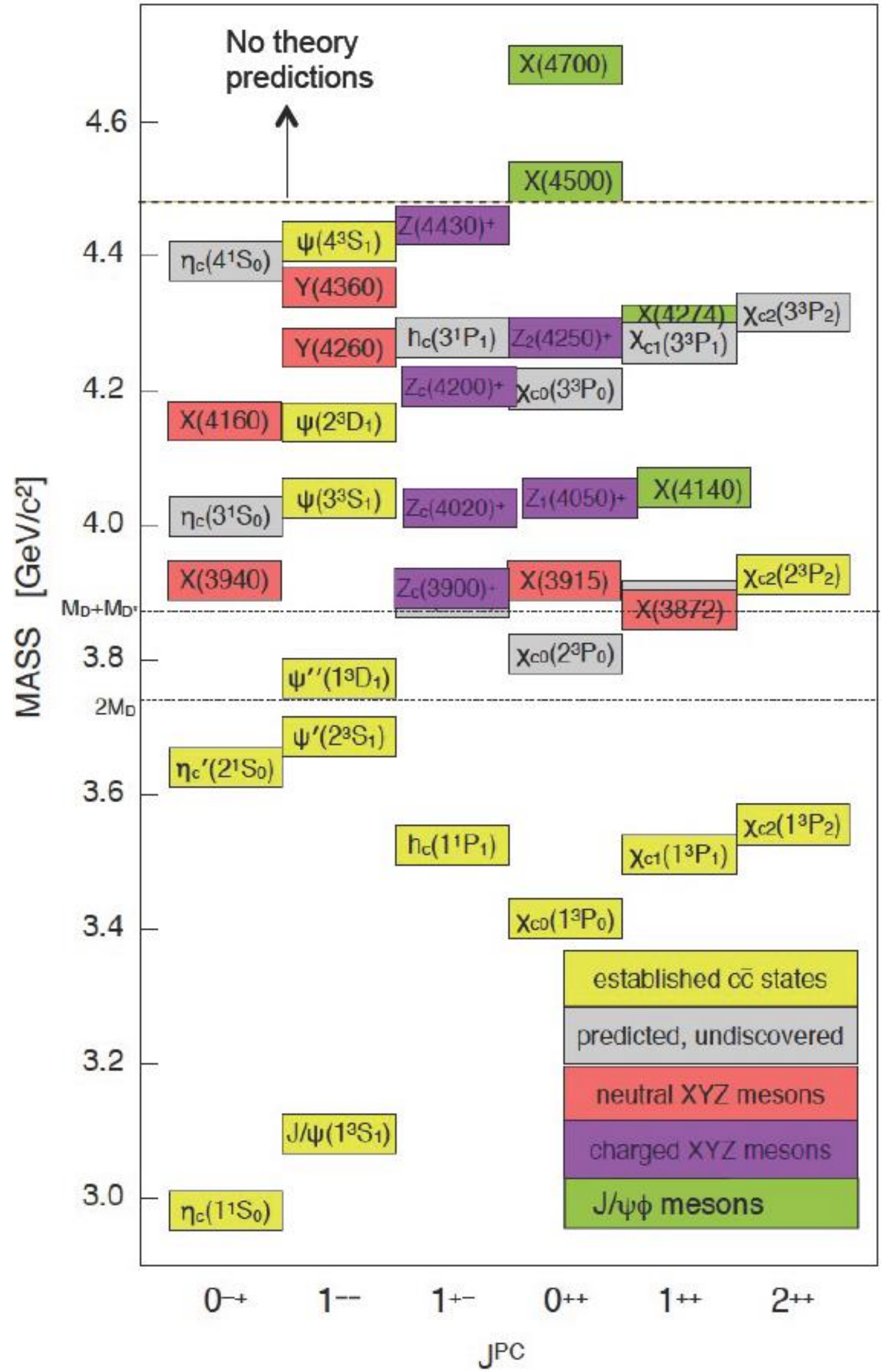
- Physics case & motivation
- Conventional & exotic hadrons
- Recent experimental review
- Physics analysis & results (*pp* & *pA* collisions)

MOTIVATION

To look for different charmonium-like states (conventional and exotic) in *pp* and *pA* collisions to obtain complementary results to the ones from *e+e-* interactions, *B*-meson decays and *pp\bar* interactions

Motivation

- Predicted neutral charmonium states compared with found $c\bar{c}$ states, & both neutral & charged exotic candidates
- Based on Olsen [arXiv:1511.01589]
- Added 4 new $J/\psi\phi$ states



Charmonium-like states possess 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;

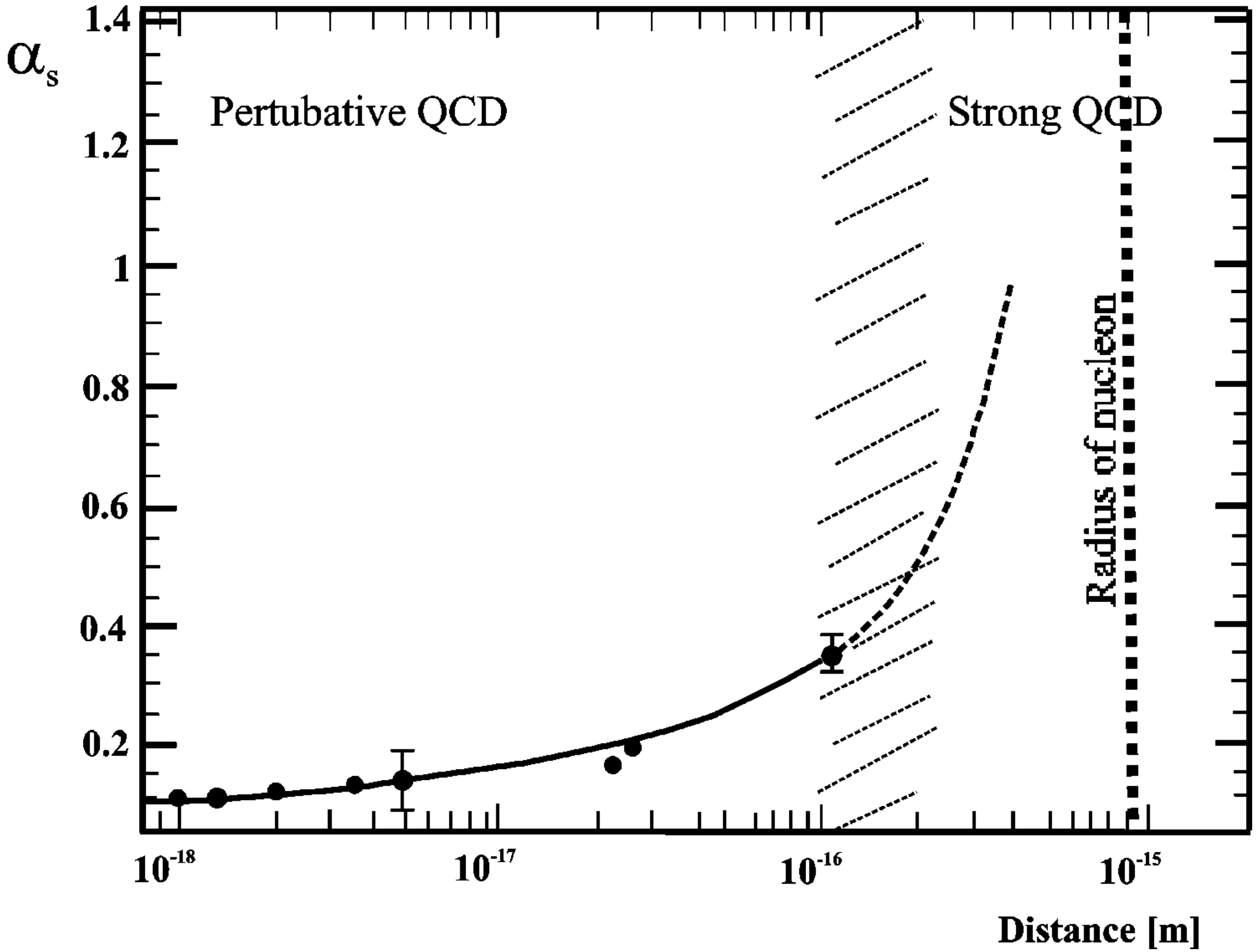
- quark motion velocities in charmonium-like systems are non-relativistic (the coupling constant, $\alpha_s \approx 0.3$ is not too large, and relativistic effects are manageable ($v^2/c^2 \approx 0.2$));

- 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;

<u>Therefore</u>:

♦ charmonium-like studies are promising for understanding the dynamics of quark interaction at small distances;

♦ charmonium-like spectroscopy represents itself 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 $\langle v^2/c^2 \rangle \approx 0.2$.

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:

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

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 $V_{spin\text{-}dep}$ 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) .*

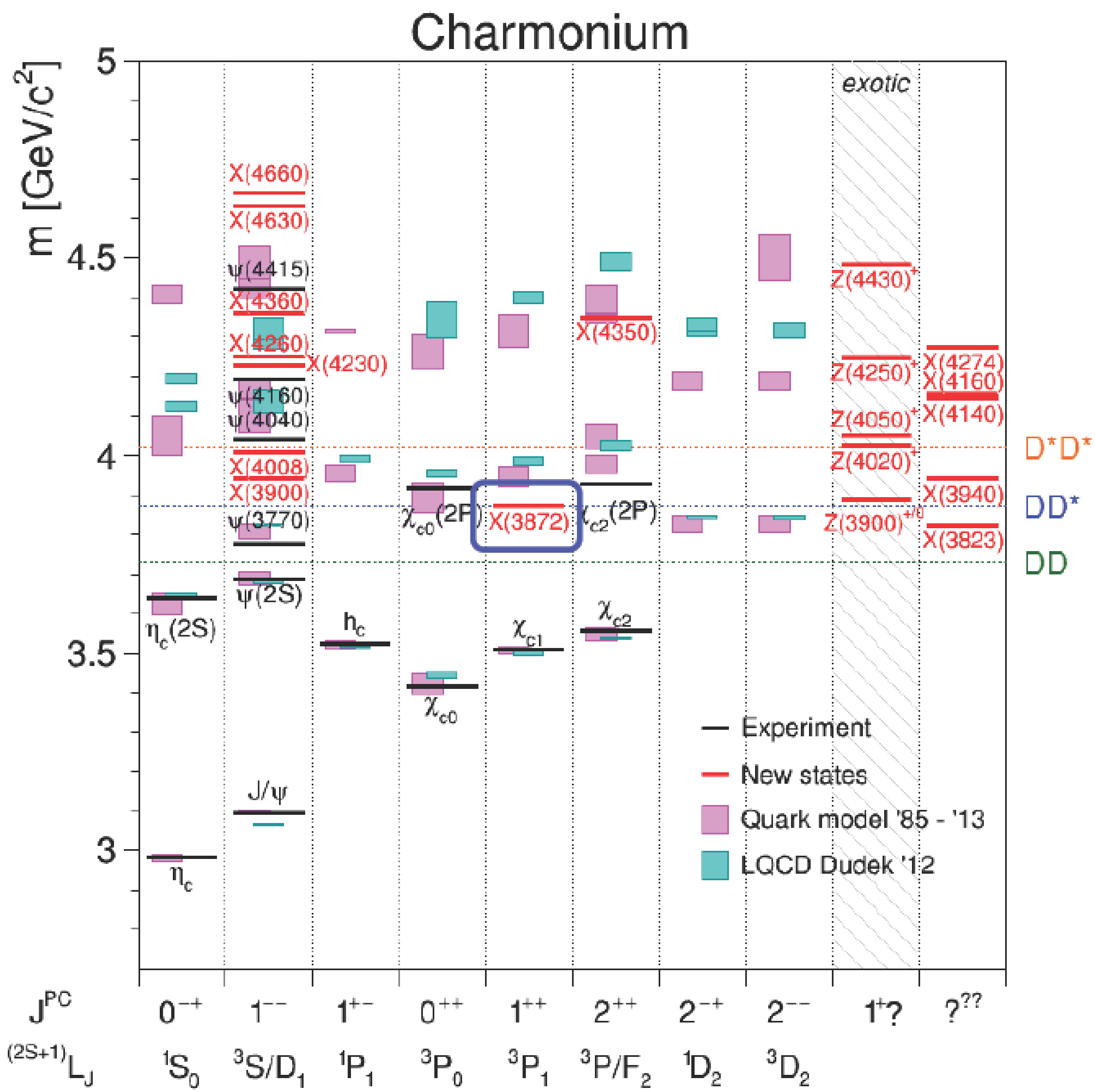
$$\Delta V_N(\vec{r}) = \text{const}\ G_N^{-1/2}(r)\delta(\vec{r}), \qquad V_N(r) = V_0\int D(r)R^{1-N}(r)dr/r,\ V_0 = \text{const} > 0.$$

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

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 $G_{\mu\nu}(r)$.



Charmonium
m [GeV/c²]
5
4.5
4
3.5
3
exotic
X(4660)
X(4630)
ψ(4415)
X(4360)
X(4260)
X(4230)
ψ(4160)
ψ(4040)
X(4008)
X(3900)
ψ(3770)
ψ(2S)
J/ψ
η_c(2S)
η_c
h_c
χ_c0(2P)
χ_c0
X(3872)
χ_c1
χ_c2(2P)
χ_c2
X(4350)
Z(4430)⁺
Z(4250)⁺
Z(4050)⁺
Z(4020)⁺
Z(3900)^{+/0}
X(4274)
X(4160)
X(4140)
X(3940)
X(3823)
D*D*
DD*
DD
Experiment
New states
Quark model '85 - '13
LQCD Dudek '12
J^PC
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
2⁻⁺
2⁻⁻
1⁺?
???
^(2S+1)L_J
¹S₀
³S/D₁
¹P₁
³P₀
³P₁
³P/F₂
¹D₂
³D₂

The $\overline{c}c$ 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 $\overline{p}p$-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 should be determined**
- **little 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 $D\overline{D}$ – threshold (*S, P, D*,….)**
- **many recently discovered states above $D\overline{D}$ - threshold (*XYZ*-states) expect their verification and explanation (their interpretation now is far from being obvious).**

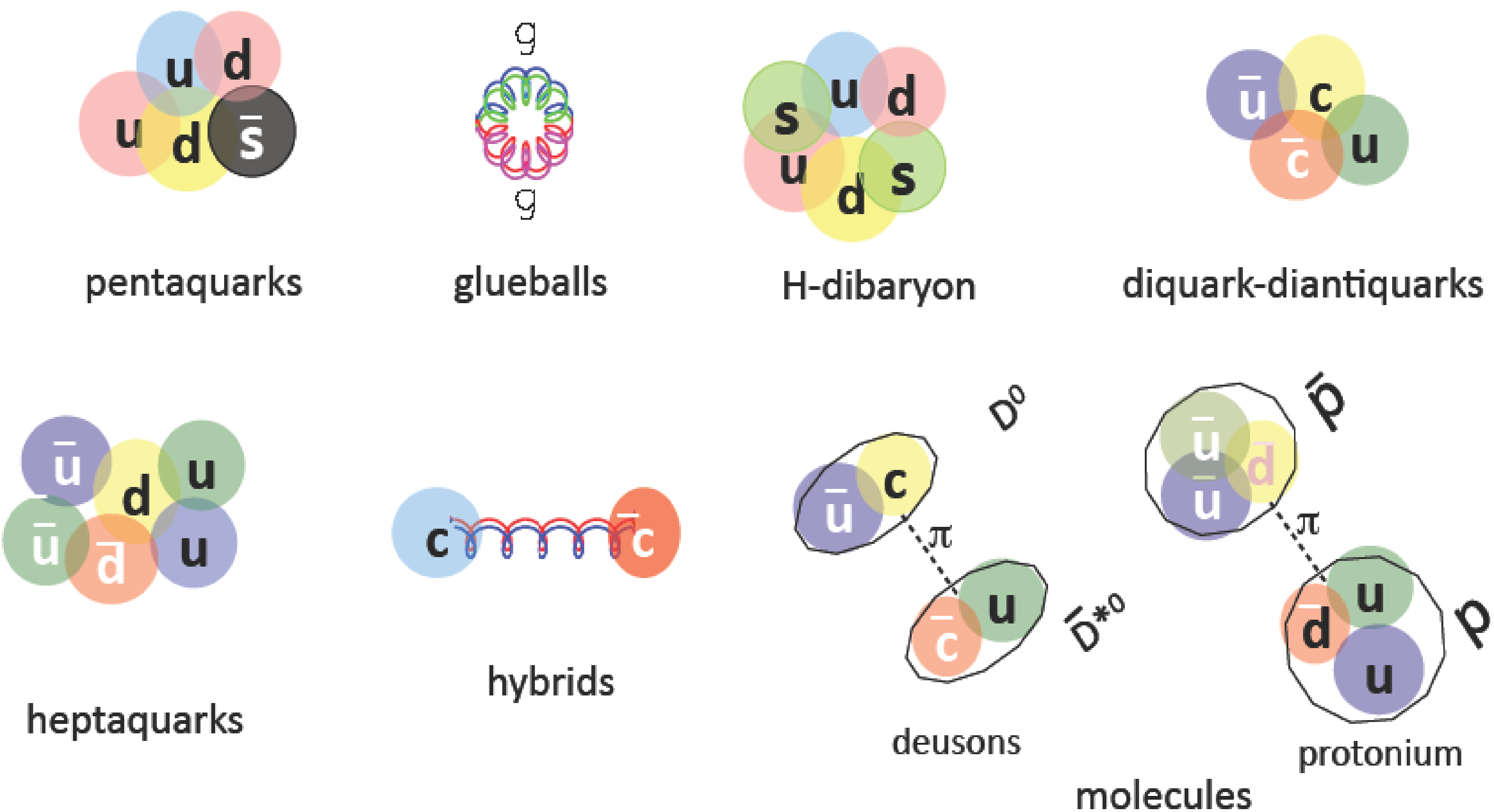
IN GENERAL ONE CAN IDENTIFY FOUR MAIN CLASSES OF CHARMONIUM DECAYS:

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

$\overline{c}c \to \Psi' + X \Rightarrow \overline{c}c \to \Psi'\, \pi^+\pi^-$, $\overline{c}c \to \Psi'\, \pi^0\pi^0$; $\overline{c}c \to h_c + X \Rightarrow \overline{c}c \to h_c\, \pi^+\pi^-$, $\overline{c}c \to h_c\, \pi^0\pi^0$

non-standard hadrons

non-$q\bar{q}$ & non-qqq color-singlet combinations



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

Multiquark states have been discussed since the 1st page of the quark model

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

Where are they??

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" [1-3], we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone [4]. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

Two different kinds of experiments to study exotics:

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

The low laying charmonium hybrid states:

	Gluon	
$(q\overline{q})_8$	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-like exotics (hybrids, tetraquarks) predominantly decay via electromagnetic and hadronic transitions and into the open charm final states:

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

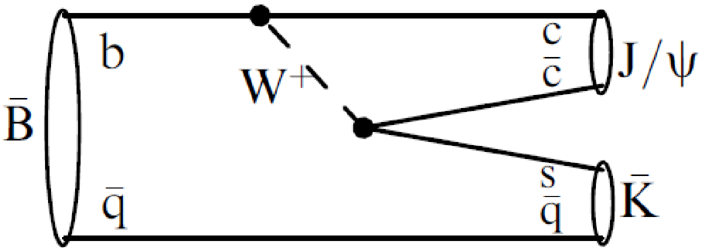
The most interesting and promising decay channels of charmed hybrids have been, in particular, analyzed:

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

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

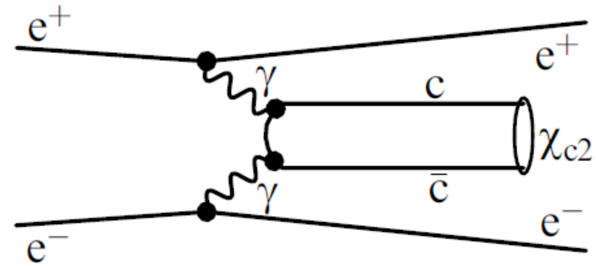
CHARMONIUM – LIKE PRODUCTION MECHANISMS RELEVANT TO THE *XYZ* – STATES

B-decays



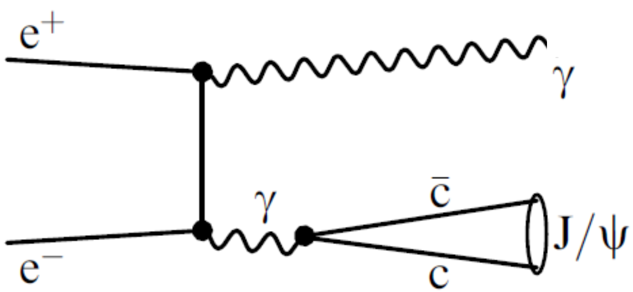
Any quantum numbers are possible

γγ fusion



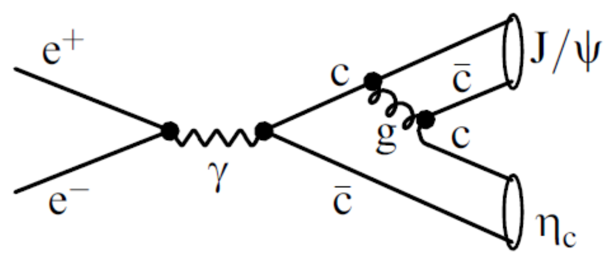
J^{PC}=0 $^{-+}$, 0 $^{++}$, 2 $^{-+}$, 2^{++}

annihilation with initial state radiation



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

double charmonium production



in association with J/ψ only J ^{PC} = 0^{-+}, 0^{++} seen

CHARMONIUM PRODUCTION MECHANISMS RELEVANT TO THE *XYZ* – STATES (*XYZ* - PARTICLES)

$$B \to K(c\overline{c}) \Rightarrow J^{PC} = 0^{-+}, 1^{--}, 1^{++}, 2^{-+} \quad \beta \approx 2 \times 10^{-3}.\ B^+ = u\overline{b},\ B^0 = d\overline{b},\ B^- = \overline{u}b.$$

***B*-decays to final states containing $c\overline{c}$ mesons.** At the quark level, the dominant decay mechanism is the weak interaction transition of a *b* quark to *c* quark accompanied by the emission of a virtual W^- boson, the mediator of the weak interaction. Approximately half of the time, the W^- boson matirializes as a $\overline{s}c$ pair. So, almost half of all *B*-meson decays result in a final state that contains *c* and $\overline{c}$ quarks. When these final-state *c* and $\overline{c}$ quarks are produced close to each other in phase space, they can coalesce to form a $c\overline{c}$ meson. The simplest charmonium producing *B*-meson decays are those where the *s* quark from the W^- combines with the parent *B*-meson's $\overline{u}$ or $\overline{d}$ quark to form a *K*-meson ($K^+ = u\overline{s}$; $K^0 = d\overline{s}$).

♦ **Production of $J^{PC} = 1^{--}$ charmonium states via initial state radiation (ISR).** In e^+e^- collisions at a cm energy of 10580 MeV the initial-state e^+ or e^- occasionally radiates a high-energy γ-ray (γ_{ISR} = 4000 MeV – 5000 MeV), and e^+ and e^- subsequently annihilate at a reduced cm energy that correspond to the range of mass values of charmonium mesons. Thus, the ISR process can directly produce charmonium states with $J^{PC} = 1^{--}$.

♦ **Charmonium associated production with J/Ψ in e^+e^- annihilation. $J^{PC} = 0^{-+}$ and 0^{++}.** In studies of e^+e^- annihilations at cm energies near 10580 MeV => Belle discovered that in inclusive annihilation process => $e^+e^- \to J/\Psi + (c\overline{c}) \Rightarrow J/\Psi + \eta_c$ or $J/\Psi + \chi_{c0}$ (J=0≠1≠2).

♦ **Two photon collisions.** In high energy e^+e^- machines, photon-photon collisions are produced when both an incoming e^+ and e^- radiate photons that subsequently interact with each other. Two photon interactions can directly produce particles with **J^{PC}=0^{-+}, 0^{++}, 2^{-+}, 2^{++}.**

Candidate exotic hadrons

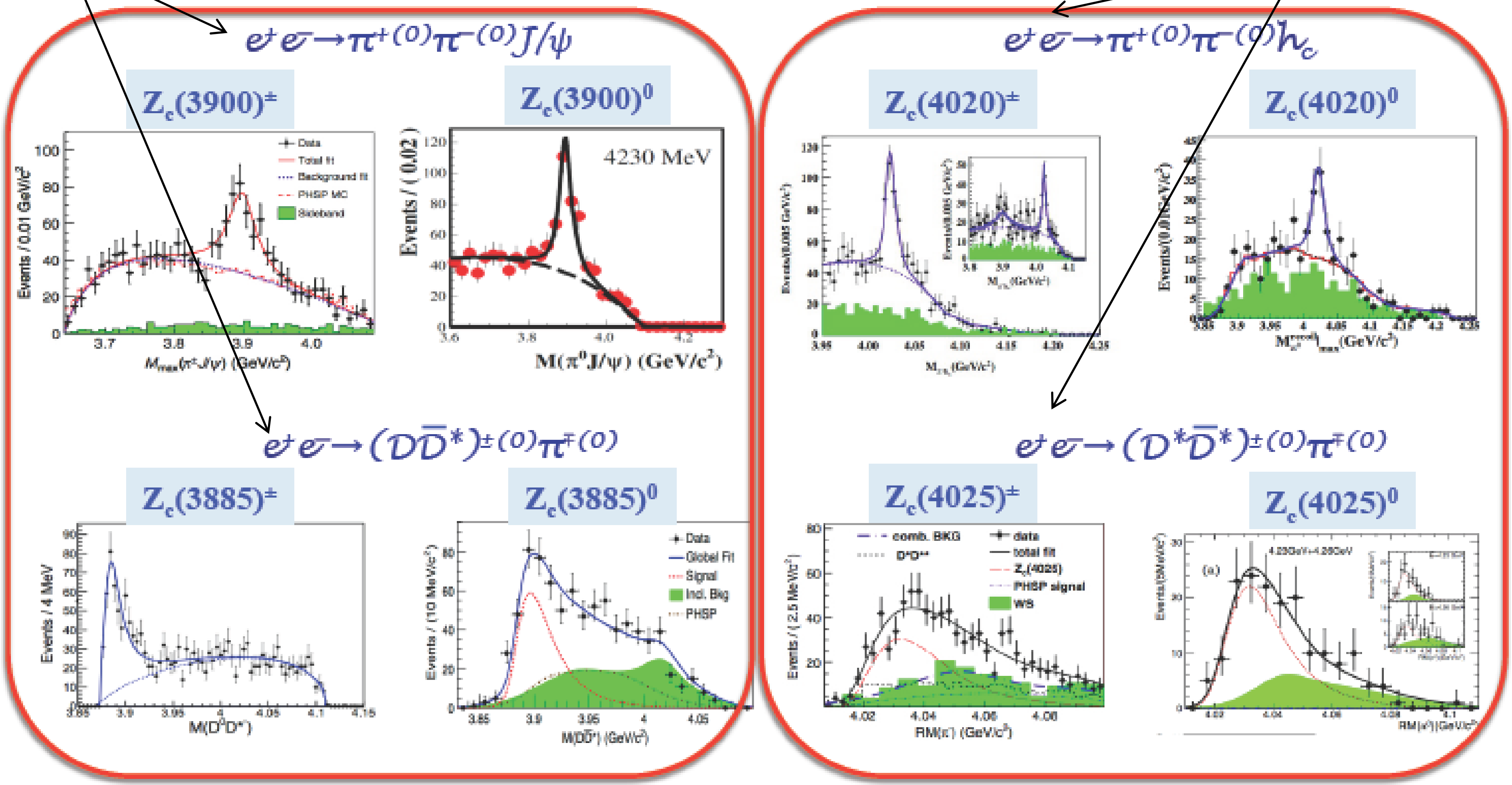
	State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
Light quark sector	$\pi_1(1400)$	1354 ± 25	330 ± 25	1^{-+}	$\pi^- p \to (\eta\pi^-)p$	MPS, Compass
					$p\bar{p} \to \pi^0(\pi^0\eta)$	Xtal Barrel
	$X(1835)$	$135.7^{+5.0}_{-3.2}0$	99 ± 50	0^{-+}	$J/\psi \to \gamma(p\bar{p})$	BESII, CLEOc, BESIII
					$J/\psi \to \gamma\,(\pi^+\pi^-\eta')$	BESII, BESIII
Charmonium-like	$X(3872)$	3871.68 ± 0.17	<1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle, BaBar, LHCb
					$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$	CDF, D0
					$B \to K + (J/\psi\,\pi^+\pi^-\pi^0)$	Belle, BaBar
					$B \to K + (D^0\bar{D}^0\pi^0)$	Belle , BaBar
					$B \to K + (J/\psi\,\gamma)$	BaBar, Belle , LHCb
					$B \to K + (\psi'\,\gamma)$	BaBar, Belle , LHCb
					$pp \to (J/\psi\,\pi^+\pi^-) + \ldots$	LHCb, CMS
	$X(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K + (J/\psi\,\omega)$	Belle , BaBar
					$e^+e^- \to e^+e^- + (J/\psi\,\omega)$	Belle , BaBar
	$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle , BaBar
	$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle
					$e^+e^- \to J/\psi + (\ldots)$	Belle
	$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar, Belle
	$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	Belle
	$Y(4140)$	$4146.5^{+6.4}_{-5.3}$	$83^{+30}_{-25}9$	1^{++}	$B \to K + (J/\psi\,\phi)$	CDF, CMS, LHCb
	$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0(?)^{-(?)+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle
	$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	BaBar, CLEO, Belle
					$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO, BESIII
					$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO, BESIII
	$Y(4274)$	4273^{+19}_{-9}	56 ± 16	1^{++}	$B \to K + (J/\psi\,\phi)$	CDF, CMS, LHCb
	$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle
	$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	BaBar, Belle
	$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle
	$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi'\,\pi^+\pi^-)$	Belle
Charged charmonium-like	$Z_c^+(3900)$	3890 ± 3	33 ± 10	1^{+-}	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII, Belle
					$Y(4260) \to \pi^- + (D\bar{D}^*)^+$	BESIII
	$Z_c^+(4020)$	4024 ± 2	10 ± 3	$1(?)^{+(?)-}$	$Y(4260) \to \pi^- + (h_c\,\pi^+)$	BESIII
					$Y(4260) \to \pi^- + (D^*\bar{D}^*)^+$	BESIII
	$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle, BaBar
	$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^{+-}	$B \to K + (J/\psi\,\pi^+)$	Belle, LHCb
	$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K + (\chi_{c1}\,\pi^+)$	Belle, BaBar
	$Z^+(4430)$	4477 ± 20	181 ± 31	1^{+-}	$B \to K + (\psi'\,\pi^+)$	Belle, LHCb
					$B \to K + (J\psi\,\pi^+)$	Belle
Hidden charmed pentaquarks	$P_c^+(4380)$	4380 ± 30	205 ± 88	$(3/2)^-$	$\Lambda_b^+ \to K + (J/\psi\,p)$	LHCb
	$P_c^+(4450)$	4449.8 ± 3.0	39 ± 20	$(5/2)^+$	$\Lambda_b^+ \to K + (J/\psi\,p)$	LHCb
b-quark sector	$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle
	$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle
					"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle
					"$\Upsilon(5S)$" $\to \pi^- + (B\bar{B}^*)^+$, $n=1,2$	Belle
	$Z_b^0(10610)$	10609 ± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n=1,2,3$	Belle
	$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	"$\Upsilon(5S)$" $\to \pi^- + (\Upsilon(nS)\,\pi^+)$, $n=1,2,3$	Belle
					"$\Upsilon(5S)$" $\to \pi^- + (h_b(nP)\,\pi^+)$, $n=1,2$	Belle
					"$\Upsilon(5S)$" $\to \pi^- + (B^*\bar{B}^*)^+$, $n=1,2$	Belle

!

SUMMARY on Zc from BES III

Are these states the same?!

Are these states the same?!



- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?

THE LHCb NEW RESONANCES

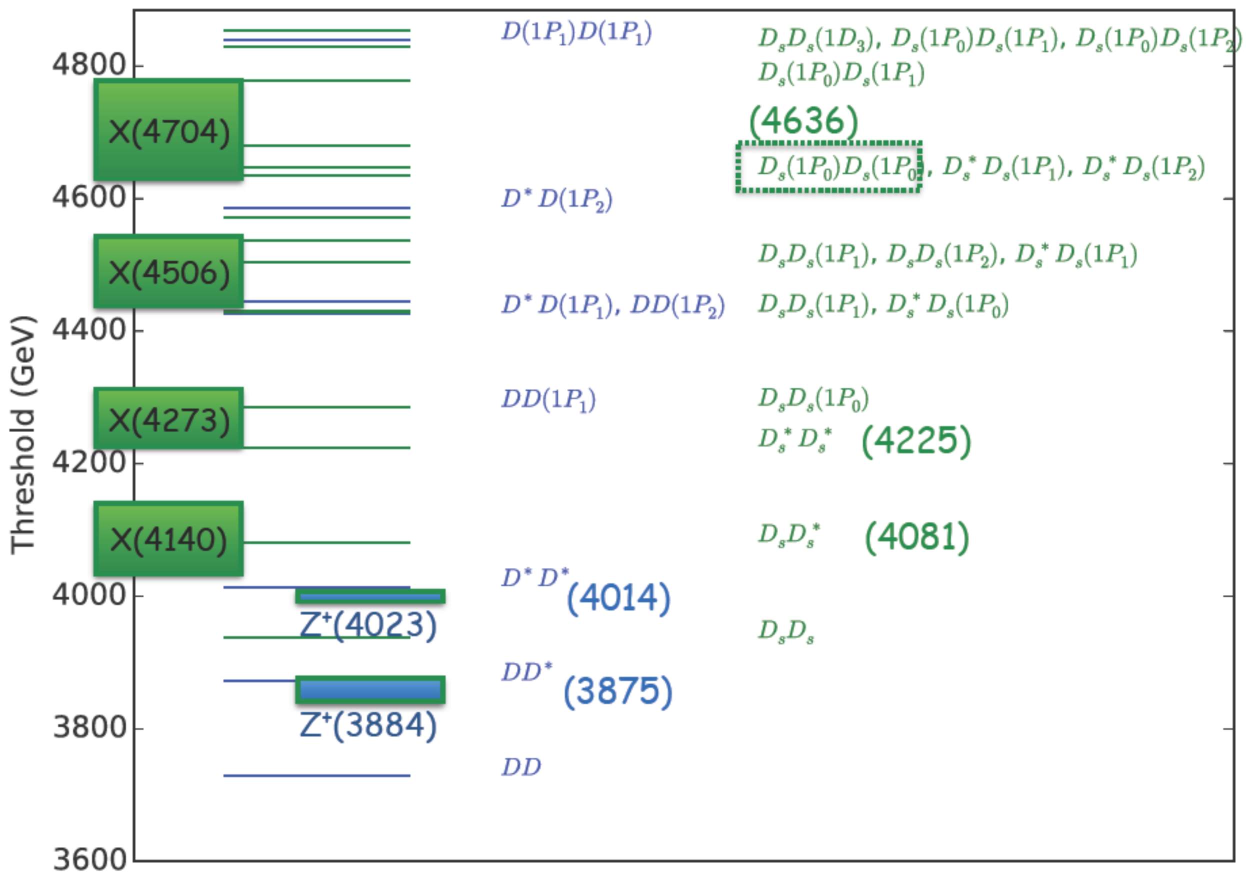
In 2016 LHCb measured 4 new resonances with an amplitude analysis on $B^+ \to J/\Psi\phi K^+$ decay

- The $X(4140)\ 1^{++}$ state, Phys. Rev. Lett. 118, 022003 (2017), Phys. Rev. D 95, 012002 (2017)
  - Not seen by Belle, and BaBar
  - Seen by CDF and D0
  - The 1^{++} quantum numbers ruled out most of the multiquark models.
- The $X(4274)\ 1^{++}$, Phys. Rev. Lett. 118, 022003 (2017), Phys. Rev. D 95, 012002 (2017)
  - Seen by CDF and CMS and Belle with a higher mass.
- The $X(4500)\ 0^{++}$ and $X(4700)\ 0^{++}$, Phys. Rev. D 95, 012002 (2017)

NEW STATES WITH ZERO STRANGENESS from LHCb

- strangeness zero states - charmonium ($c\bar{s}s\bar{c}$) structures
- SU(3) symmetry suggests new X_s states near the thresholds:
  $D D_s^*$, $D_s D^*$, $D_s^* D_s^*$: observable in B decays?

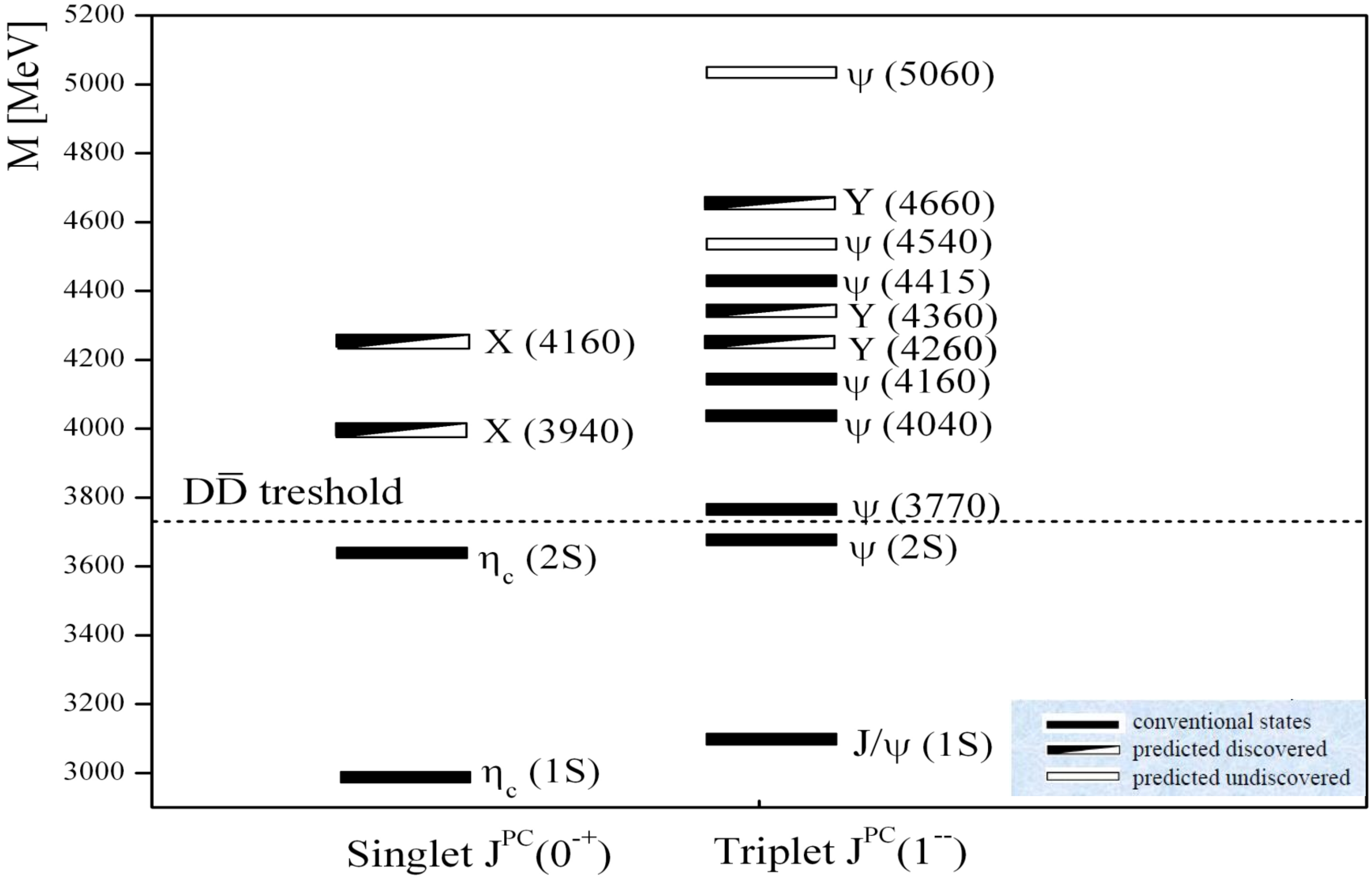
B -> X K: M_X < 4785 MeV



- No evidence in preliminary LQCD studies for ($c\bar{s}s\bar{c}$) tetraquark states.

Motivation

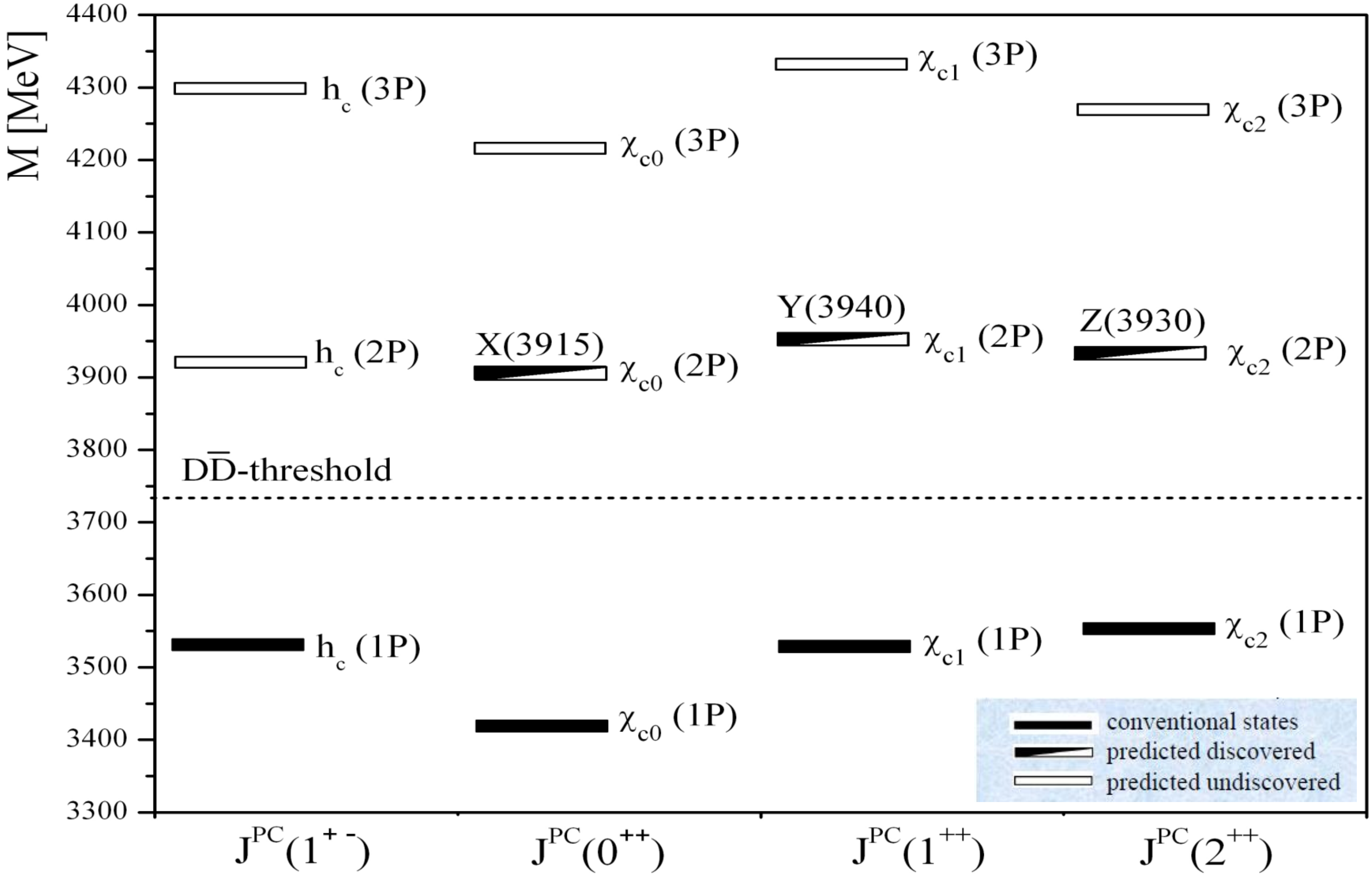
THE SPECTRUM OF SINGLET ($^1S_0$) AND TRIPLET ($^3S_1$) STATES OF CHARMONIUM



M.Yu. Barabanov, A.S. Vodopyanov, S.L. Olsen, Yadernaya Fizica, V.77, N.1, pp. 1 - 5 (2014) / Phys. At. Nucl., V.77, N.1, pp. 126 -130 (2014)

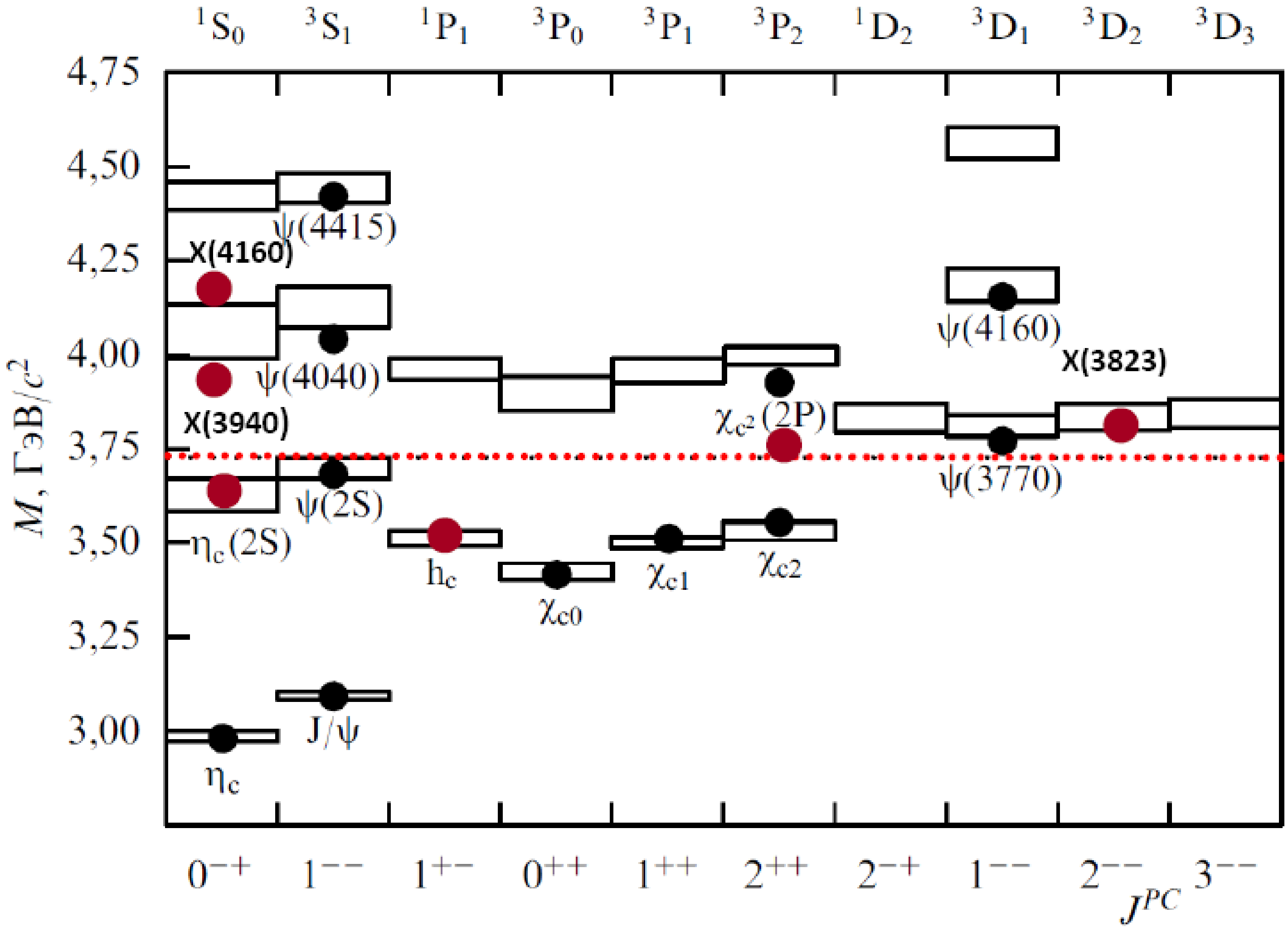
Motivation

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



M.Yu. Barabanov, A.S. Vodopyanov, S.L. Olsen , Yadernaya Fizica, V.77, N.1, pp. 1 - 5 (2014) / Phys. At. Nucl., V.77, N.1, pp. 126 -130 (2014)

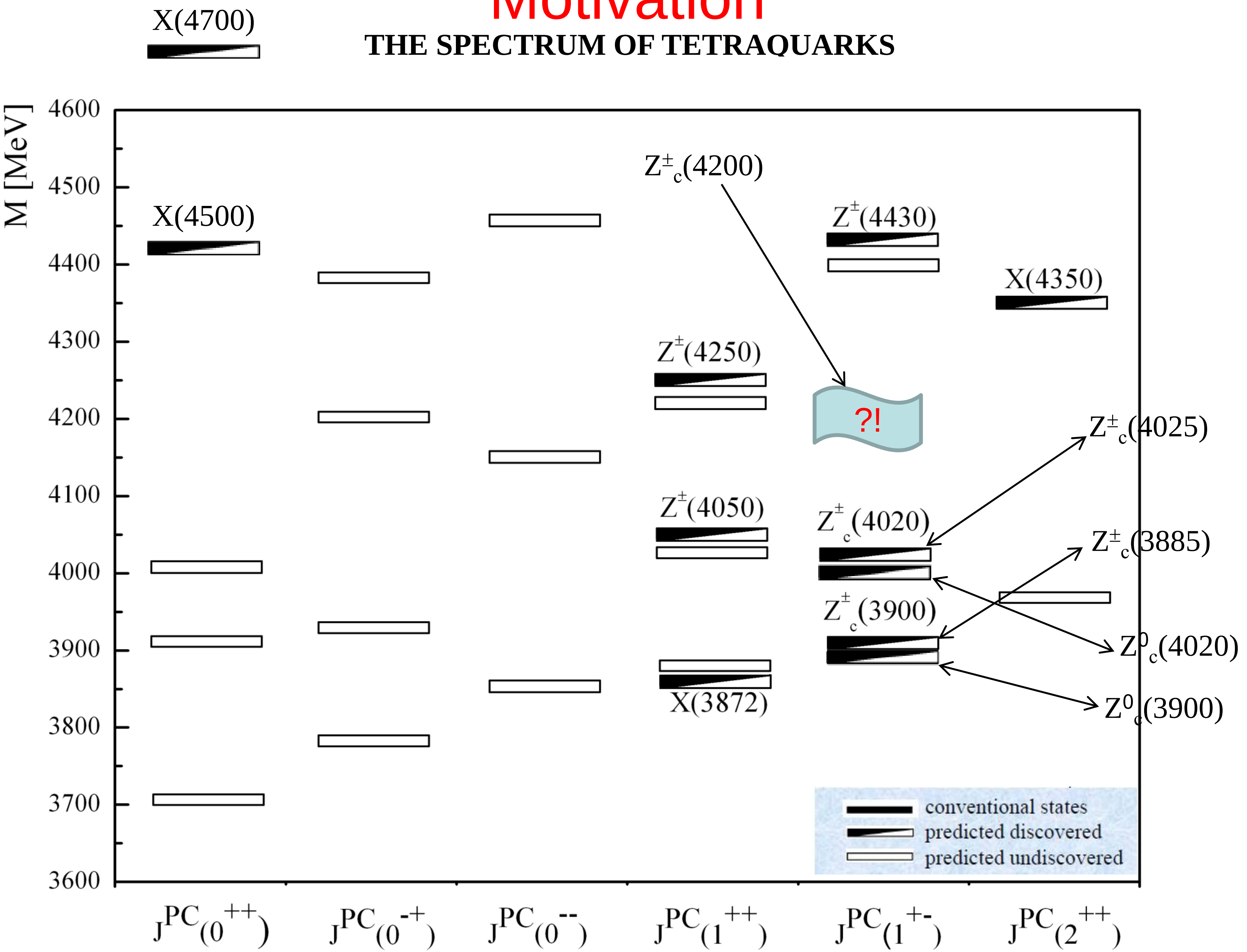
6 observed states can fit* into charmonium table



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

What about others?

Motivation



M.Yu. Barabanov, A.S. Vodopyanov, A.I. Zinchenko, *Nuovo Cimento C*, V. 42, N. 2-3, pp.110-113 (2019)

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

TETRAQUARK STATES

There are indications of structures in $J/\psi\,\phi$ of the kind $[cs]_0[\bar{c}\bar{s}]_1 + [cs]_1[\bar{c}\bar{s}]_0$ — FROM LHCb.

SPECTRUM

0^{++} $+\kappa$ 4270

1^{+-} $+\kappa$

2^{++} $+\kappa$ 4270

1^{++} 4140

1^{+-} $-\kappa$

0^{++} -3κ

and 4500 0^{++}
4700 0^{++}
(RADIAL EXCITATIONS LIKE Z(4430)?)

PROBLEM: 4270 seems at the moment a 1^{++} !!

PHYSICS WITH *pp* & *pA* COLLISIONS:

• 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-like states cc, *i.e.* $pp \to \overline{c}c\, pp$; $pp \to \overline{c}qcq'\, pp \quad (q, q' = u, d, s)$

• spectroscopy of baryons and mesons with strangeness and charm:

$$\Omega^0{}_c\,,\ \Xi_c\,,\ \Xi'_c\,,\ \Xi^+{}_{cc}\,,\ \Omega^+{}_{cc} \quad i.e.\quad pp \to \Lambda_c X\,;\ pp \to \Lambda_c pX\,;\ pp \to \Lambda_c pD_s$$

• 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

Running conditions

1. $p+p$ at $\sqrt{s} = 25$ GeV

2. Luminosity $L = 10^{29}\ cm^{-2}c^{-1} - 10^{31}\ cm^{-2}c^{-1}$

3. Running time 10 weeks:

   integrated luminosity $L_{int} = 604.8\ nb^{-1} - 60.48\ pb^{-1}$

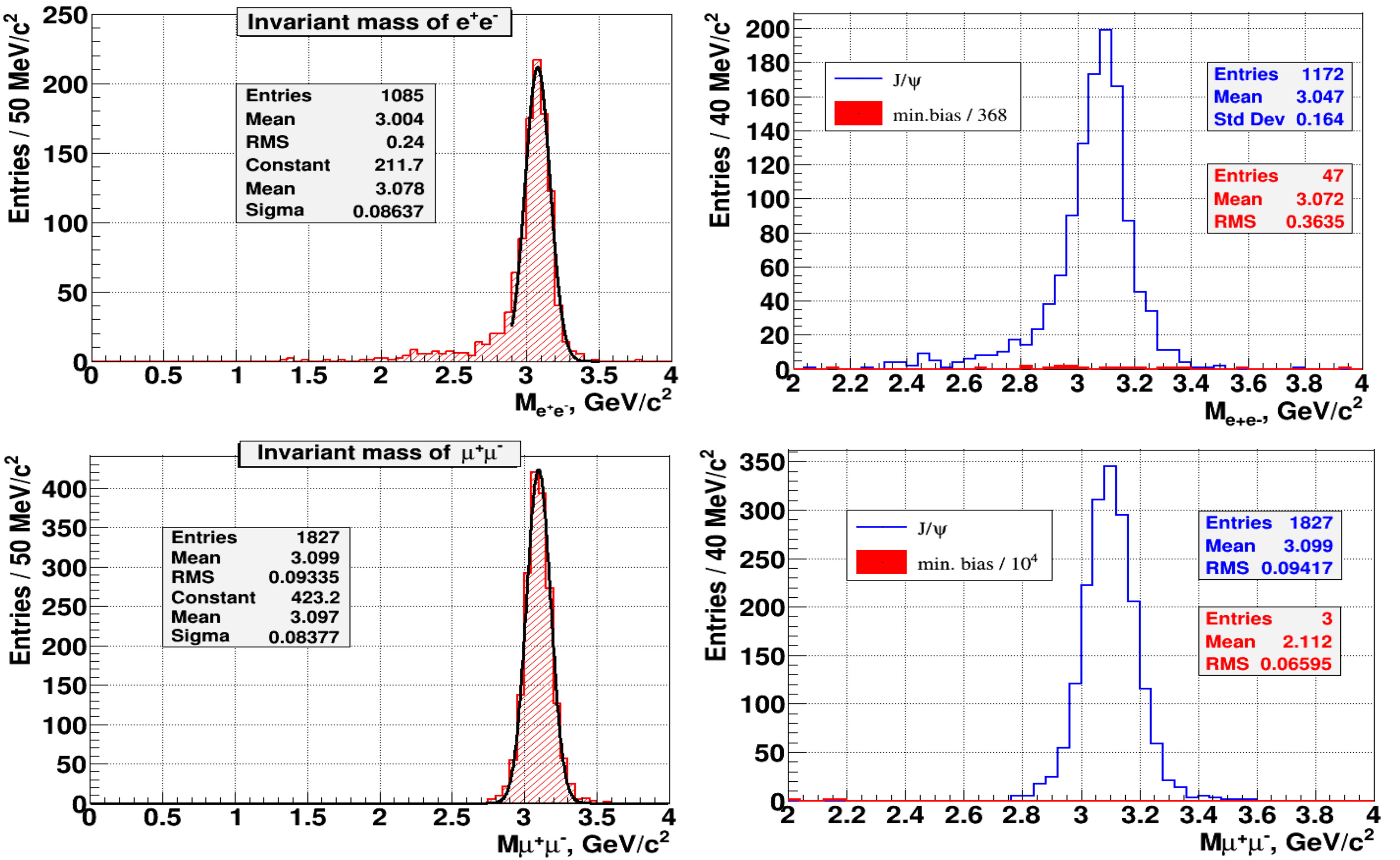
Expectations for J/ψ

1. X-section $\sigma_{J/\psi}$ from Pythia8 108.7 nb

2. Statistics: $N_{J/\psi} = L_{int} \cdot \sigma_{J/\psi} \cdot Br_{J/\psi \to e+e-} \cdot Eff._{\Delta\eta=\pm 1.5} =$

$604.8 \cdot 108.7 \cdot 0.06 \cdot 0.8 = 3156$

Invariant mass: $e^- + e^+$ or $\mu^- + \mu^+$



Reconstructed invariant mass $J/\psi\pi^+\pi^-$ (from CDF)

VOLUME 93, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2004

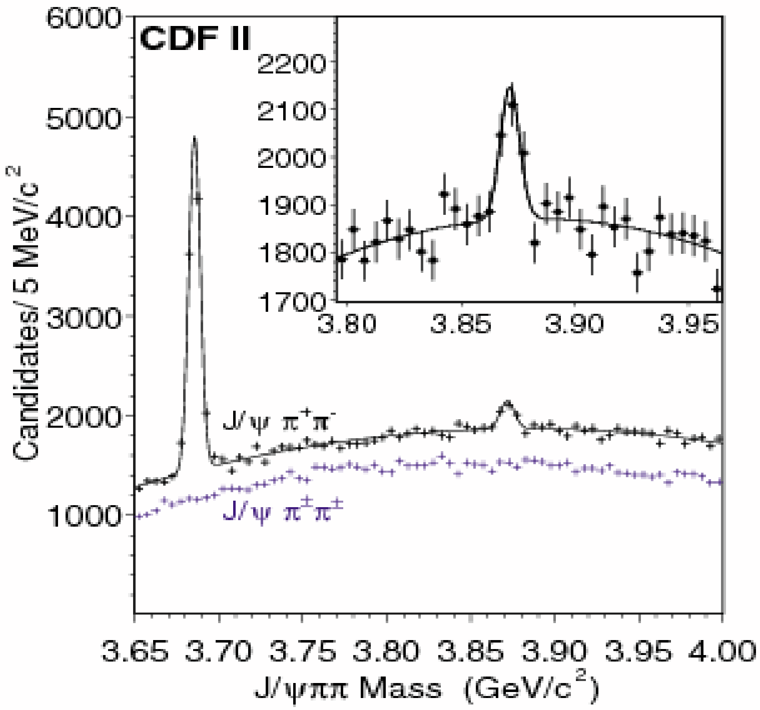


FIG. 1 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ and $J/\psi\pi^\pm\pi^\pm$ candidates passing the selection described in the text. A large peak for the $\psi(2S)$ is seen in the $J/\psi\pi^+\pi^-$ distribution as well as a small signal near a mass of 3872 MeV$/c^2$. The curve is a fit using two Gaussians and a quadratic background to describe the data. The inset shows an enlargement of the $J/\psi\pi^+\pi^-$ data and fit around 3872 MeV$/c^2$.

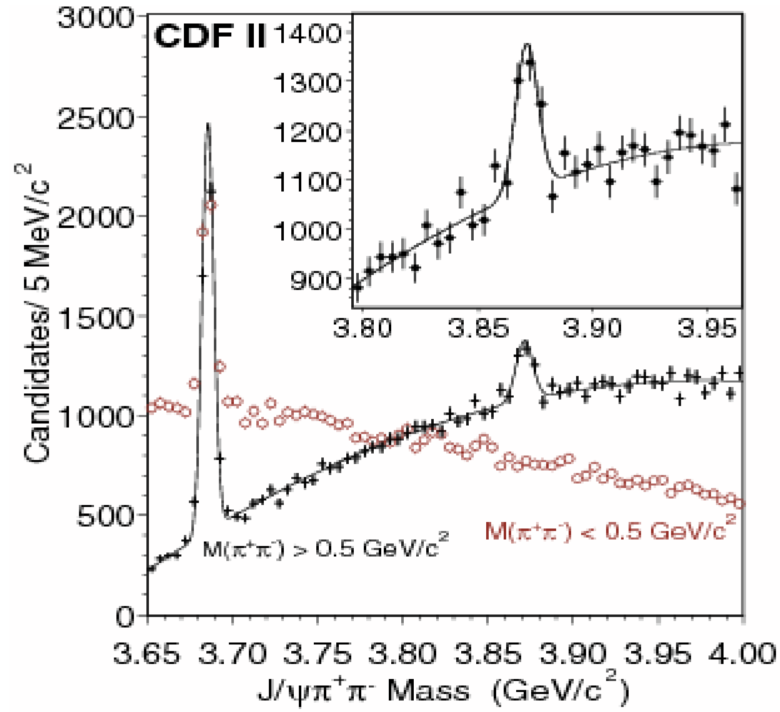


FIG. 2 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ candidates with $m(\pi^+\pi^-) > 0.5$ GeV$/c^2$ (points) and $m(\pi^+\pi^-) < 0.5$ GeV$/c^2$ (open circles). The curve is a fit with two Gaussians and a quadratic background. The inset shows an enlargement of the high dipion-mass data and fit.

Requiring $M(\pi^+\pi^-) > 0.5$ MeV$/c^2$ reduces the back-

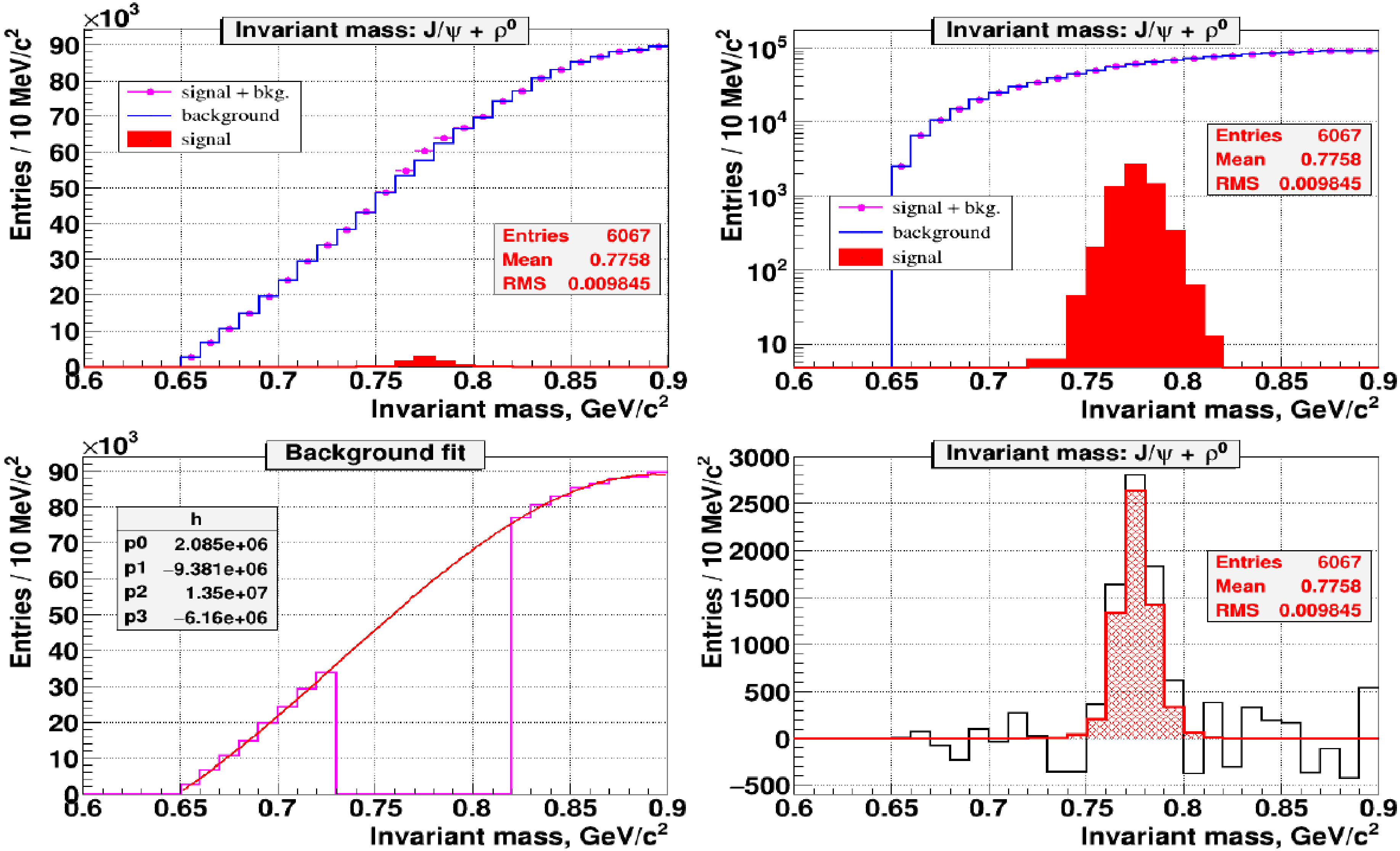
X(3872) state

1. X-section in Pythia8 for X(3872) is 4 nb ($X(3872) \equiv \psi(3770)$ with mass 3.872 GeV)

2. Br ($X3872 \rightarrow J/\psi\ \rho^0$) = 5.0%
   Br ($X3872 \rightarrow e+e-\ \pi+\pi-$) = 0.3% $\rightarrow$ X-section = 12.2 pb
   1000 events at $L = 10^{31}$ $cm^{-2}s^{-1}$: 95 days
   10^{32} $cm^{-2}s^{-1}$ and 10 months: 31600 events

$X(3872) \rightarrow J/\psi + \rho^0$

Using mass combination: $M_{e+e-\pi+\pi-} - M_{e+e-}$



Probing the X(3872) meson structure with near-threshold pp and pA collisions at NICA

M.Yu. Barabanov[1], S.-K. Choi[2], S.L. Olsen[3†], A.S. Vodopyanov[1] and A.I. Zinchenko[1]

(1) *Joint Institute for Nuclear Research, Joliot-Curie 6 Dubna Moscow region Russia 141980*
(2) *Department of Physics, Gyeongsang National University, Jinju 660-701, Korea*
(3) *Center for Underground Physics, Institute for Basic Science, Daejeon 34074, Korea*

Pythia8 predictions for X(3872)

1. *X-section of $\psi(3770)$ with m = 3.872 GeV at pp 12.5+6.5 GeV: 1.3 nb*

2. *X-section at pCu: 1.3 * A (=63) = 81.9 nb*

3. *Br $(X(3872) \to J/\psi\ \pi+\pi-)$ = 5.00%*
   Br $(X(3872) \to D^+D^-)$ = 40.45%
   Br $(X(3872) \to D^0D^{*0}bar)$ = 54.55% $\Rightarrow$ $D^0D^0bar\pi^0$ = 35.29%

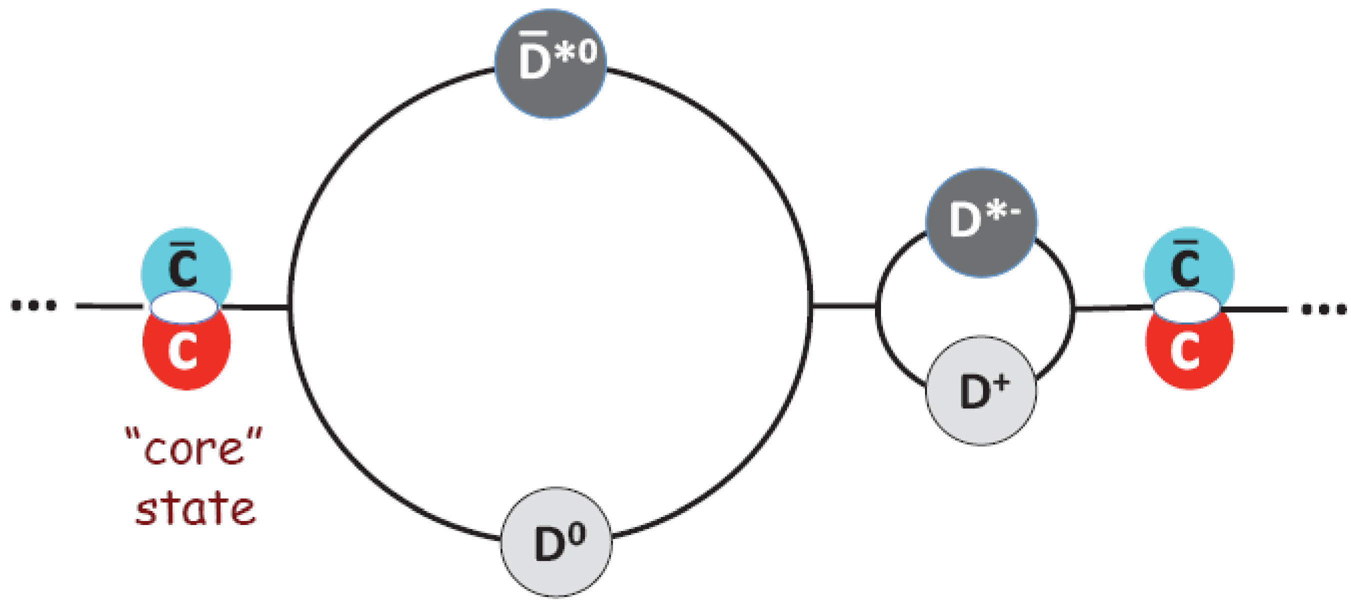
4. *Br $(D+ \to K-\pi+\pi+)$ = 9.2%, Br $(D0 \to K-\pi+)$ = 3.8%*

5. *$\sigma(pCu)$ * Br$(J/\psi\ \pi+\pi-)$ * Br(e+e-) = 81.9 * 0.05 * 0.06 = 0.246 nb*
   *$\sigma(pCu)$ * Br(D+D-) * Br$(K\pi\pi)^2$ = 81.9 * 0.4045 * 0.092 * 0.092 = 0.280 nb*
   *$\sigma(pCu)$ * Br$(D^0D^0bar\pi^0)$ * Br$(K\pi)^2$ = 81.9 * 0.3529 * 0.039 * 0.039 = 0.044 nb*

0.280 nb => L = 5.9 x 10^{29} (1000 events / 10 weeks)

Can the X(3872) structure be probed?

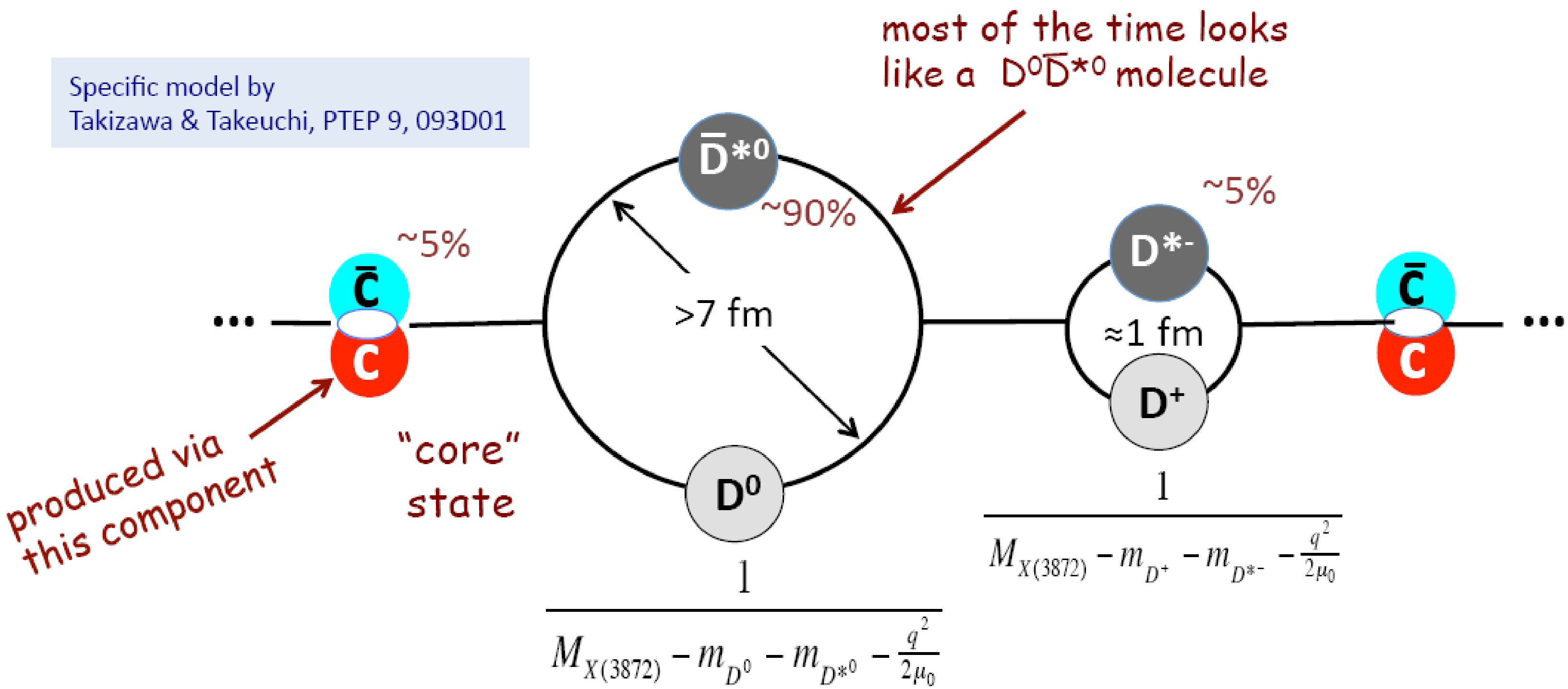
Takizawa & Takeuchi, PTEP 9, 093D01



$$\left|X(3872)\right\rangle = 0.94\left|D^0\overline{D}^{*0}\right\rangle + 0.23\left|D^+D^{*-}\right\rangle - 0.24\left|c\overline{c}\right\rangle$$

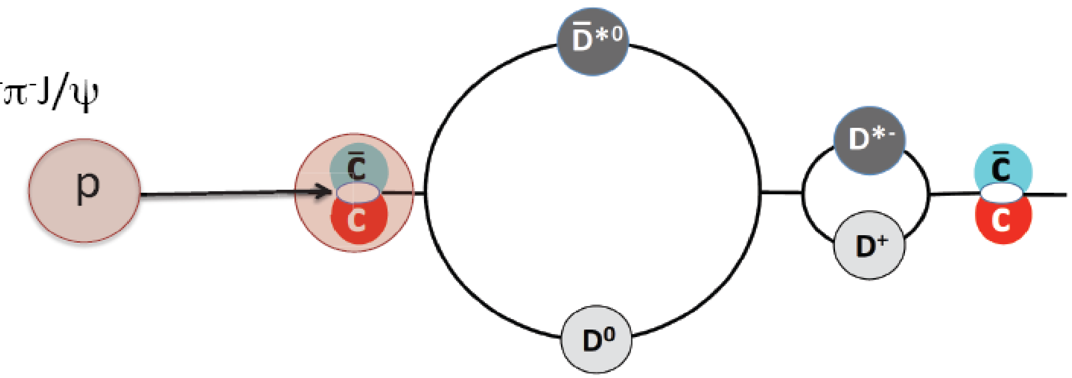
Probably a mixture of $D\bar{D}^*$ & a $c\bar{c}$ “core”

Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01

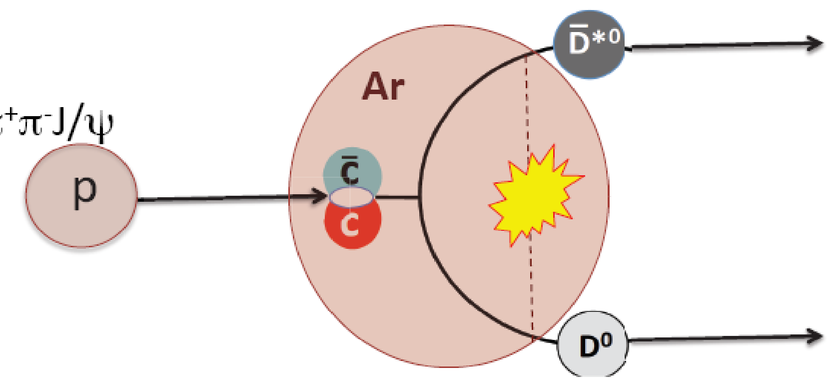


Near-threshold prod. via pp & pA

$pp \rightarrow X(3872) \rightarrow \pi^+\pi^- J/\psi$



$pAr \rightarrow X(3872) \rightarrow \pi^+\pi^- J/\psi$



Strong quenching
for A~40 nuclei??

$$\sqrt{s_{pN}} \simeq 8 \text{ GeV}$$

Summary / Conclusions

♦ Many observed states remain puzzling and can not be explained for many years. This stimulates and motivates for new searches and ideas to obtain their nature.

♦ A combined approach based on quarkonium potential model and confinement model has been proposed and applied to study charmonium-like states, i.e. charmoinum and tetraquarks.

♦ The most promising production channels of charmonium-like states have been analyzed. Different states above DD\bar are expected to exist in the framework of the combined approach.

♦ Physics analysis for the *pp* & *pA* collisions is in progress nowadays. Preliminary results have been obtained. The experiments with *pp* & *pA* collisions can obtain some valuable information on the charm production.

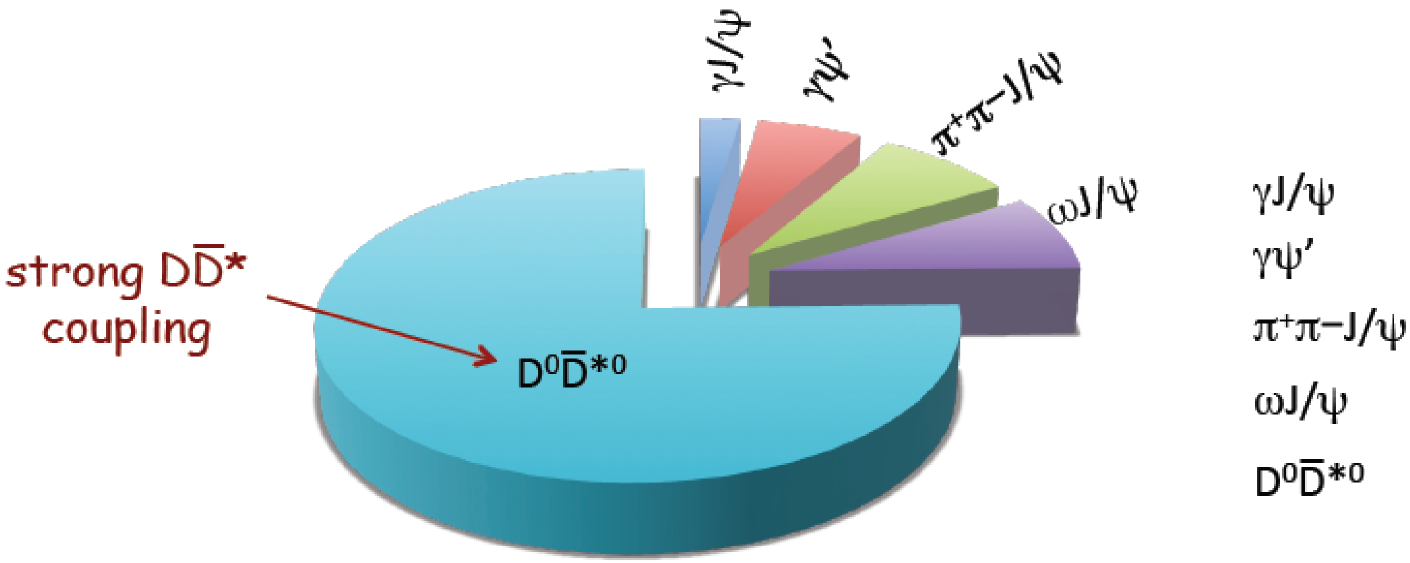
♦ Measurements of charmonium-like states can be considered as one of the “pillars” of *pp* & *pA* program. The detector should provide good opportunities for the reconstruction and identification of charged and neutral particles.

THANK YOU!

and

WELCOME FOR COLLABORATION…

X(3872) decay channels



$\Gamma_{\text{“tot”}} \approx 15\ \Gamma(X(3872) \to \pi^+\pi^- J/\psi)$

$\Gamma(X(3872) \to \pi^+\pi^- J/\psi) < 80\ \text{keV}$

$\Gamma(X(3872) \to p\bar{p}) < 0.002\Gamma(\pi^+\pi^- J/\psi) < 160 eV$