PROBING OF MULTIQUARK STRUCTURE WITH HADRON AND HEAVY ION COLLISIONS

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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 $L \sim 2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$
- Beam cooling (stochastic & electron)

$\sqrt{s} \approx 5.5 \text{ GeV}$

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
Collider basic parameters: beams: from p to Au; 
$L \sim 10^{27} \text{ cm}^{-2} \text{ c}^{-1} \text{ (Au)}, \sqrt{s_{NN}} = 4-11 \text{ GeV}; \sim 10^{32} \text{ cm}^{-2} \text{ c}^{-1} \text{ (p)}, \sqrt{s} = 12-26 \text{ GeV};$

**NICA collider major parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring circumference, m</td>
<td>503.04</td>
</tr>
<tr>
<td>$\beta, m$</td>
<td>0.35</td>
</tr>
<tr>
<td>Energy range for Au$^{79+}$: $\sqrt{s_{NN}}$, GeV</td>
<td>4 - 11</td>
</tr>
<tr>
<td>r.m.s. $\Delta p/p$, $10^{-3}$</td>
<td>1.6</td>
</tr>
<tr>
<td>Peak luminosity for Au$^{79+}$, cm$^{-2}$ s$^{-1}$</td>
<td>$1 \times 10^{27}$</td>
</tr>
</tbody>
</table>

**polarized particles**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. energy for polarized p, GeV</td>
<td>27</td>
</tr>
<tr>
<td>Peak luminosity for p, cm$^{-2}$ s$^{-1}$</td>
<td>$1 \times 10^{32}$</td>
</tr>
</tbody>
</table>
Outline

• Physics case & motivation
• Conventional & exotic hadrons
• Review of recent experimental data
• Physics analysis & results
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 $pp\bar{p}$ 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 ($1.27 \pm 0.07$ GeV) compared to the masses of $u$, $d$ & $s$ ($\sim 0.1$ GeV) quarks, that makes it plausible to attempt a description of the dynamical properties of charmonium-like system in terms of non-relativistic potential models and phenomenological models;

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

• the size of charmonium-like systems is of the order of less than 1 Fm ($R_{cc} \sim \alpha_s \cdot m_q$) 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 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 $\alpha_s$ is $\approx 0.1$, 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:

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

where $\delta_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$ 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.


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

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

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

Izmeestev 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).

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

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

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

$$\cotg(r/a) \approx a / r - r / 3a,$$

we get:

$$\left. V(r) \right|_{r \to 0} \sim 1/r, \quad \quad \left. V(r) \right|_{r \to \infty} \sim kr$$

where $R(r)$, $D(r)$ and $G_N(r)$ are scaling factor, gauging and determinant of metric tensor $G_{\mu\nu}(r)$.
The $\bar{c}c$ system has been investigated in great detail first in $e^+e^-$-reactions, and afterwards on a restricted scale ($E_p \leq 9$ GeV), but with high precision in $\bar{p}p$-annihilation (the experiments R704 at CERN and E760/E835 at Fermilab).

The number of unsolved questions related to charmonium has remained:

- singlet $1D_2$ and triplet $3D_J$ charmonium states are not determined yet;
- 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 $D\bar{D}$ – threshold ($S$, $P$, $D$, ...);
- 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 FOUR MAIN CLASSES OF CHARMONIUM DECAYS:**

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

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

- pentaquarks
- glueballs
- H-dibaryon
- diquark-diantiquarks
- heptaquarks
- hybrids
- deusons
- molecules
- protonium
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

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...
Two different kinds of experiments to study exotics:

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

The low laying charmonium hybrid states:

<table>
<thead>
<tr>
<th>Gluon</th>
<th>(q\bar{q})_8</th>
<th>1^- (TM)</th>
<th>1^+ (TE)</th>
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<tbody>
<tr>
<td>$^1S_0, 0^{--}$</td>
<td>$1^{++}$</td>
<td>$1^{--}$</td>
<td></td>
</tr>
<tr>
<td>$^3S_1, 1^{--}$</td>
<td>$0^{+-} \leftarrow$ exotic</td>
<td>$0^{--}$</td>
<td></td>
</tr>
<tr>
<td>&amp; $1^{+-}$</td>
<td>$1^{++} \leftarrow$ exotic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&amp; $2^{+-} \leftarrow$ exotic</td>
<td>$2^{--}$</td>
<td></td>
<td></td>
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</tbody>
</table>

Charmonium-like exotics (hybrids, tetraquarks) predominantly decay via electromagnetic and hadronic transitions and into the open charm final states:

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

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

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

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

<table>
<thead>
<tr>
<th>State</th>
<th>( M ) (MeV)</th>
<th>( \Gamma ) (MeV)</th>
<th>( J^{PC} )</th>
<th>Process (decay mode)</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+ (1400) )</td>
<td>1354±25</td>
<td>330±25</td>
<td>1++</td>
<td>( \pi^+ p \rightarrow (n\pi^+) p )</td>
<td>MPS, Compress</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Xtal Barrel</td>
</tr>
<tr>
<td>( X(1835) )</td>
<td>135.7±3.0</td>
<td>89±50</td>
<td>0++</td>
<td>( J/\psi \rightarrow \gamma (\rho \rho) )</td>
<td>BESIII, CLEOc, BESIII</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BESIII, BESIII</td>
</tr>
<tr>
<td>( X(3872) )</td>
<td>3871.68±0.17</td>
<td>&lt; 1.2</td>
<td>1++</td>
<td>( B \rightarrow K + (J/\psi \pi^+ \pi^-) )</td>
<td>Belle, BaBar, LHCb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CDF, D0, LHCb</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>Belle, BaBar</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>Belle, BaBar, Belle, LHCb</td>
</tr>
<tr>
<td>( \chi_{c2}(2P) )</td>
<td>3927.2±6.4</td>
<td>26±4.6</td>
<td>2++</td>
<td>( e^+ e^- \rightarrow e^+ e^- (J/\psi \omega) )</td>
<td>Belle, BaBar</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Belle, BaBar</td>
</tr>
<tr>
<td>( X(3940) )</td>
<td>3942.0±1.9</td>
<td>37±3.7</td>
<td>0(0)(^{-})(^{+})</td>
<td>( e^+ e^- \rightarrow J/\psi + (\gamma \rho \rho) )</td>
<td>Belle, BaBar</td>
</tr>
<tr>
<td>( G(3900) )</td>
<td>3913±21</td>
<td>52±11</td>
<td>1−</td>
<td>( e^+ e^- \rightarrow \gamma + (DD) )</td>
<td>BaBar, Belle</td>
</tr>
<tr>
<td>( Y(4008) )</td>
<td>4008±21</td>
<td>226±97</td>
<td>1−</td>
<td>( e^+ e^- \rightarrow (J/\psi \pi^+ \pi^-) )</td>
<td>Belle, BaBar</td>
</tr>
<tr>
<td>( Y(4140) )</td>
<td>4146.5±13.4</td>
<td>83±29</td>
<td>1++</td>
<td>( B \rightarrow K + (J/\psi \phi) )</td>
<td>CDF, CMS, LHCb</td>
</tr>
<tr>
<td>( X(4160) )</td>
<td>4150.5±20</td>
<td>139±46</td>
<td>1−</td>
<td>( e^+ e^- \rightarrow J/\psi + (\gamma \rho \rho) )</td>
<td>BaBar, CLEO, Belle</td>
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<tr>
<td>( Y(4260) )</td>
<td>4263±14</td>
<td>95±14</td>
<td>1−</td>
<td>( e^+ e^- \rightarrow (J/\psi \pi^+ \pi^-) )</td>
<td>CLEO, BESIII</td>
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<tr>
<td>( Y(4274) )</td>
<td>4273±10</td>
<td>66±16</td>
<td>1++</td>
<td>( B \rightarrow K + (J/\psi \phi) )</td>
<td>CLEO, BESIII</td>
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<tr>
<td>( X(4360) )</td>
<td>4360±8</td>
<td>13.8±10.0</td>
<td>0/2++</td>
<td>( e^+ e^- \rightarrow e^+ e^- (J/\psi \phi) )</td>
<td>Belle, BaBar</td>
</tr>
<tr>
<td>( Y(4360) )</td>
<td>4361±13</td>
<td>74±18</td>
<td>1++</td>
<td>( e^+ e^- \rightarrow \phi + (\Lambda_c \Lambda_c^*) )</td>
<td>BaBar, Belle</td>
</tr>
<tr>
<td>( X(4660) )</td>
<td>4664±12</td>
<td>48±15</td>
<td>1−</td>
<td>( e^+ e^- \rightarrow (J/\psi \phi \pi^+ \pi^-) )</td>
<td>Belle, BaBar</td>
</tr>
<tr>
<td>( Z_0^+(4680) )</td>
<td>4680±0</td>
<td>53±10</td>
<td>1++</td>
<td>( Y(4260) \rightarrow \pi^+ + (DD)^* )</td>
<td>BESIII, Belle</td>
</tr>
<tr>
<td>( Z_+^{*}(4020) )</td>
<td>4024±2</td>
<td>10±3</td>
<td>1(0)(^{+})(^{−})</td>
<td>( Y(4260) \rightarrow \pi^+ + (\rho \rho \rho)^* )</td>
<td>BESIII</td>
</tr>
<tr>
<td>( Z_+^{*}(4050) )</td>
<td>4051±24</td>
<td>82±11</td>
<td>1++</td>
<td>( Y(4260) \rightarrow \pi^+ + (\rho \rho \rho)^* )</td>
<td>BESIII</td>
</tr>
<tr>
<td>( Z_0^+(4200) )</td>
<td>4200±10</td>
<td>370±80</td>
<td>1−</td>
<td>( B \rightarrow K + (n\pi^+ \pi^-) )</td>
<td>BaBar, Belle, Belle, LHCb</td>
</tr>
<tr>
<td>( Z_0^{*}(4250) )</td>
<td>4250±20</td>
<td>177±32</td>
<td>1−</td>
<td>( B \rightarrow K + (\rho \rho \rho)^* )</td>
<td>Bell, LHCb</td>
</tr>
<tr>
<td>( Z_0^+(4430) )</td>
<td>4477±20</td>
<td>181±31</td>
<td>1−</td>
<td>( B \rightarrow K + (\rho \rho \rho)^* )</td>
<td>Belle, LHCb</td>
</tr>
<tr>
<td>( P_0^+(4380) )</td>
<td>4380±30</td>
<td>205±88</td>
<td>(3/2)(^{+})</td>
<td>( \Lambda_c \rightarrow K + (J/\psi \rho) )</td>
<td>LHCb</td>
</tr>
<tr>
<td>( P_0^{*}(4450) )</td>
<td>4459±8.0</td>
<td>39±20</td>
<td>(5/2)(^{+})</td>
<td>( \Lambda_c \rightarrow K + (J/\psi \rho) )</td>
<td>LHCb</td>
</tr>
<tr>
<td>( Y_0(1089) )</td>
<td>10888.4±30.7</td>
<td>5078±15.0</td>
<td>( \pi^+ \pi^- )</td>
<td>( e^+ e^- \rightarrow (\gamma (nS) \pi^+ \pi^-) )</td>
<td>Belle</td>
</tr>
<tr>
<td>( Z_0^+(10610) )</td>
<td>10607.2±20</td>
<td>18.4±24</td>
<td>1++</td>
<td>( \gamma (5S) \rightarrow \pi^+ + (\gamma (nS) \pi^+ \pi^-) ), ( n = 1, 2, 3 )</td>
<td>Belle</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \gamma (5S) \rightarrow \pi^- + (\gamma (nS) \pi^+ \pi^-) ), ( n = 1, 2, 3 )</td>
</tr>
<tr>
<td>( Z_0^+(10610) )</td>
<td>10609±6</td>
<td>( \gamma (5S) \rightarrow \pi^+ + (\gamma (nS) \pi^+ \pi^-) ), ( n = 1, 2, 3 )</td>
<td>Belle</td>
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<td>( \gamma (5S) \rightarrow \pi^- + (\gamma (nS) \pi^+ \pi^-) ), ( n = 1, 2, 3 )</td>
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<td></td>
<td>( \gamma (5S) \rightarrow \pi^- + (\gamma (nS) \pi^+ \pi^-) ), ( n = 1, 2, 3 )</td>
</tr>
</tbody>
</table>

**Light quark sector**

**Charmonium-like**

**Charged charmonium-like**

**Hidden charmed pentaquarks**

**b-quark sector**
SUMMARY on $Z_c$ from BES III

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 $B^+ \rightarrow J/\Psi\phi K^+$ decay

  - Not seen by Belle, and BaBar
  - Seen by CDF and D0
  - The $1^{++}$ quantum numbers ruled out most of the multiquark models.

  - 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 (\(\bar{c}s\bar{s}c\)) 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?

\[B \rightarrow X K: \quad M_X < 4785 \text{ MeV}\]

- No evidence in preliminary LQCD studies for (\(\bar{c}s\bar{s}c\)) tetraquark states.
THE SPECTRUM OF TETRAQUARKS

Motivation

X(4700)

X(4500)

Z⁺(4200)

Z⁺(4430)

Z⁺(4250)

Z⁺(4050)

Z⁺(4020)

Z⁺(3900)

Z⁺(3872)

Z⁺(3885)

Z⁺(4025)

Z⁺(3900)

X(4350)

X(4500)

Z±(4020)

Z±(3885)

Z±(4025)

Z0_c(4020)

Z0_c(3885)

Z0_c(3900)

Z0_c(3900)

M [MeV]

3600

3700

3800

3900

4000

4100

4200

4300

4400

4500

4600

JPC (0++)

JPC (0+-)

JPC (0--)

JPC (1++)

JPC (1+-)

JPC (2++)

conventional states

predicted discovered

predicted undiscovered
What to look for

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

(L.Maiani, A.D.Polosa, V.Riquer, 0708.3997)
There are indications of structures in $J/\psi$ of the kind $[cc][\bar{c}\bar{s}], [\bar{c}s][c\bar{s}], c\bar{s}J_0$ — from LHCb.

**Spectrum**

$$
\begin{align*}
0^{++} & \quad -k \\
4270 & \\
1^{++} & \quad 1^{+-} - k \\
4140 & \\
0^{++} & \quad -3k \\
\end{align*}
$$

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 $gg, ggg, \bar{Q}Qg, Q^3g$ in mass range from 1.3 to 5.0 GeV. Especially pay attention at the states $\bar{ss}g, \bar{cc}g$ in mass range from $1.8 - 5.0$ GeV.

- charmonium-like states $cc$, i.e. $pp \rightarrow \bar{cc} pp$; $pp \rightarrow \bar{cc} qq' pp$ $(q, q' = u, d, s)$

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

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

  $pp \rightarrow \Lambda_c X$; $pp \rightarrow \Lambda_c pX$; $pp \rightarrow \Lambda_c pD_s$  $pp \rightarrow \Lambda_b X$, $pp \rightarrow \Lambda_b pX$; $pp \rightarrow \Lambda_b pB_s$

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

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

- $D$-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 $\sigma_{J/ψ}$ from Pythia8 108.7 nb

2. Statistics: $N_{J/ψ} = L_{int} \cdot \sigma_{J/ψ} \cdot Br_{J/ψ \rightarrow e^+e^-} \cdot Eff_{Δη=±1.5} = 604.8 \cdot 108.7 \cdot 0.06 \cdot 0.8 = 3156$
Invariant mass: $e^- + e^+ \text{ or } \mu^- + \mu^+$

7 weeks

**Invariant mass of $e^+e^-$**
- Entries: 1085
- Mean: 3.004
- RMS: 0.24
- Constant: 211.7
- Mean: 3.078
- Sigma: 0.08637

**Invariant mass of $\mu^+\mu^-$**
- Entries: 1827
- Mean: 3.099
- RMS: 0.09335
- Constant: 423.2
- Mean: 3.097
- Sigma: 0.08377

**Histograms:**
- $J/\psi$
- min.bias / 368
- Entries: 1172
- Mean: 3.047
- Std Dev: 0.164
- Entries: 47
- Mean: 3.072
- RMS: 0.3635
- Entries: 1827
- Mean: 3.099
- RMS: 0.09417
- Entries: 3
- Mean: 2.112
- RMS: 0.06595
1. X-section in Pythia8 for $X(3872)$ is 4 nb ($X(3872) \equiv \psi(3770)$ with mass 3.872 GeV)

2. $\text{Br} (X_{3872} \rightarrow J/\psi \, \rho^0) = 5.0\%$
   $\text{Br} (X_{3872} \rightarrow e^+e^- \, \pi^+\pi^-) = 0.3\% \rightarrow X$-section $= 12.2 \text{ pb}$
   1000 events at $L = 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ : 95 days
   $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and 10 months: 31600 events
$X(3872) \rightarrow J/\psi + \rho^0$

Using mass combination: $M_{e^+e^−\pi^+\pi^-} - M_{e^+e^-}$
Can the $X(3872)$ structure be probed?

\[ |X(3872)\rangle = 0.94 \left| D^0 \bar{D}^{*0} \right\rangle + 0.23 \left| D^+ D^{*-} \right\rangle - 0.24 \left| c\bar{c} \right\rangle \]
Probably a mixture of $\bar{D}\bar{D}^*$ & a $\bar{c}\bar{c}$ "core"

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

\[
\frac{1}{M_{X(3872)} - m_{D^0} - m_{D^{*0}} - \frac{q^2}{2\mu_0}}
\]
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$\sim$40 nuclei??

$\sqrt{s_{pN}} \simeq 8$ GeV
Many observed states remain puzzling and can not be explained for many years. This stimulates and motivates for new searches and ideas to obtain the nature of multiquark states.

A combined approach based on quarkonium potential model and confinement model has been proposed and applied to study charmonium and multiquark states.

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

Physics analysis for the proton-proton and proton-nuclear 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.
THANK YOU!

AND

WELCOME FOR
COLLABORATION...
$\chi(3872)$ decay channels

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

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

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