



PROBING OF CHARMONIUM AND EXOTICS WITH HADRON AND HEAVY ION COLLISIONS

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in collaboration with

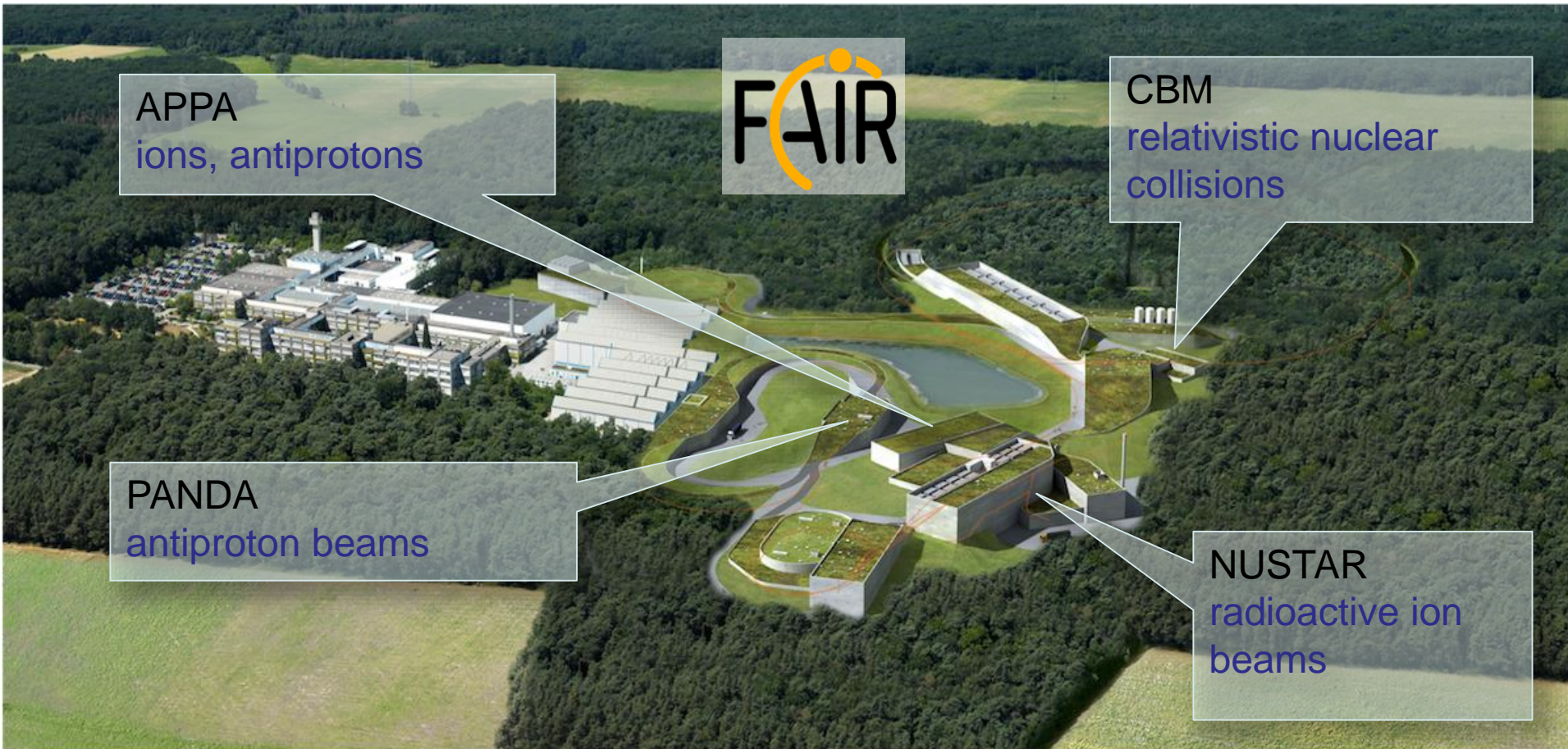
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FAIR complex



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

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

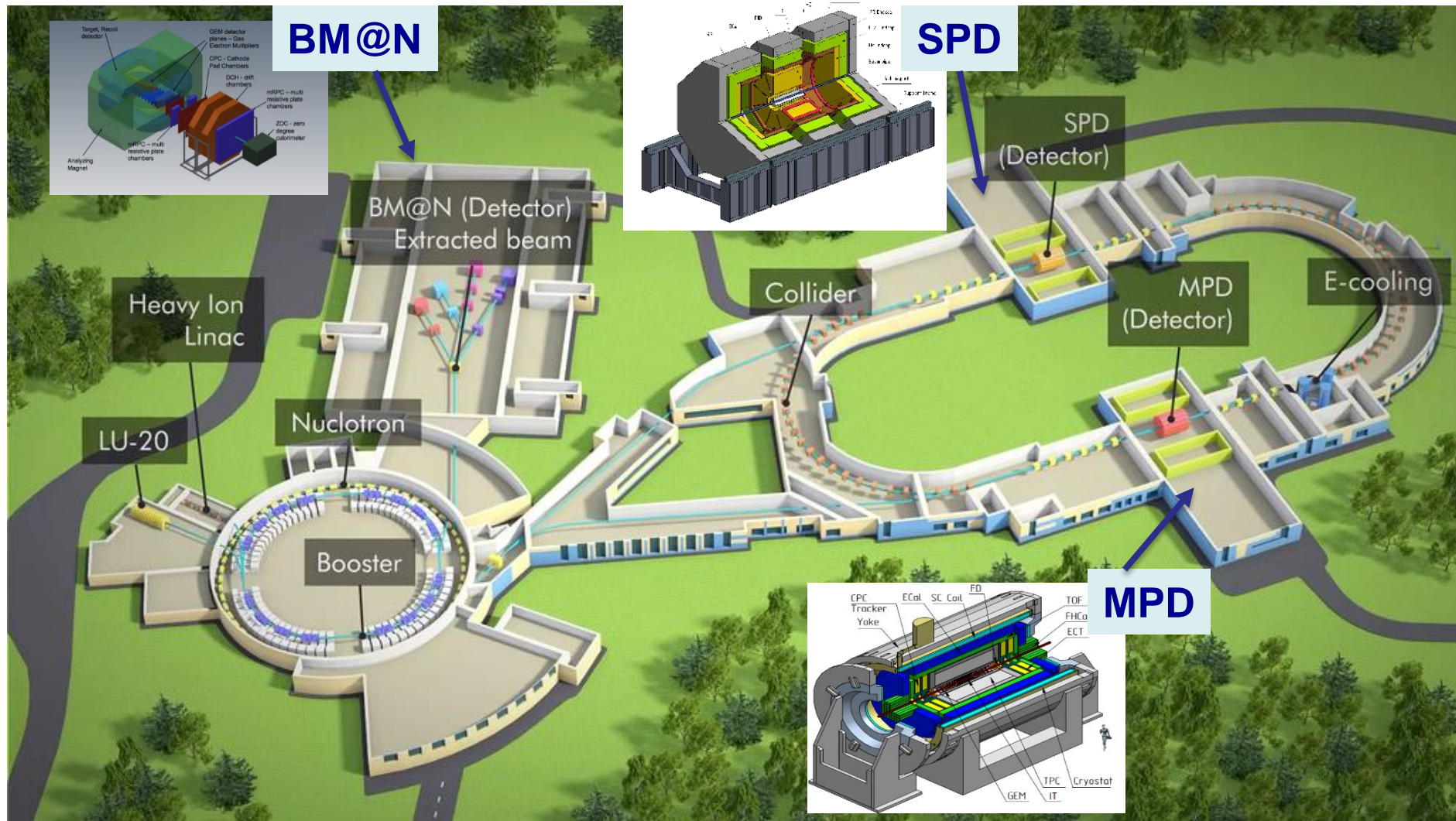
Antiproton production

- 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

NICA complex

Collider basic requirements: beams from p to Au

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



OUTLINE

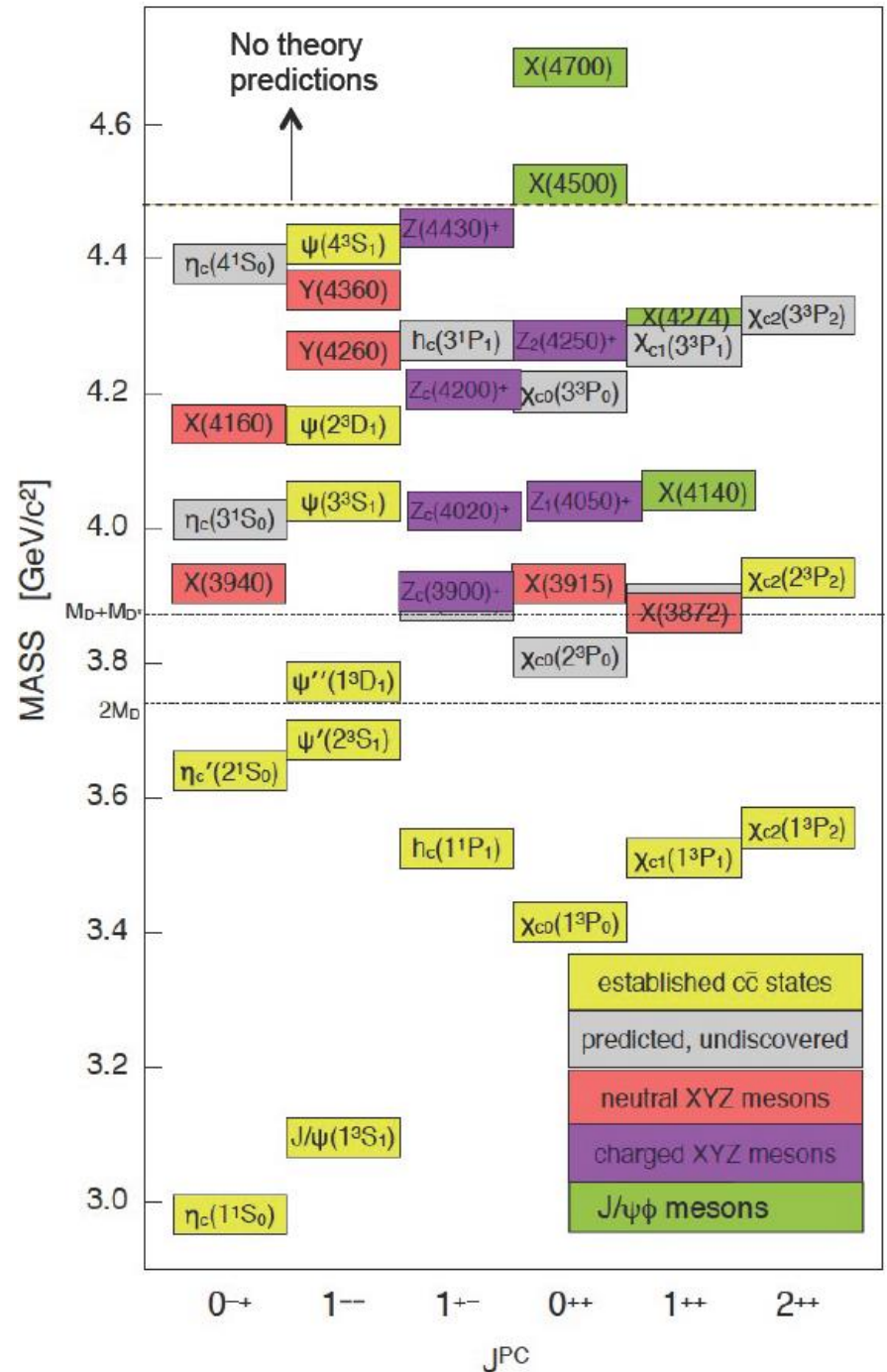
- Physics case & motivation
- Conventional & exotic hadrons
- Recent experimental review
- Physics analysis & results (pp & pA collisions)

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 $pp\bar{b}$ interactions

Motivation

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

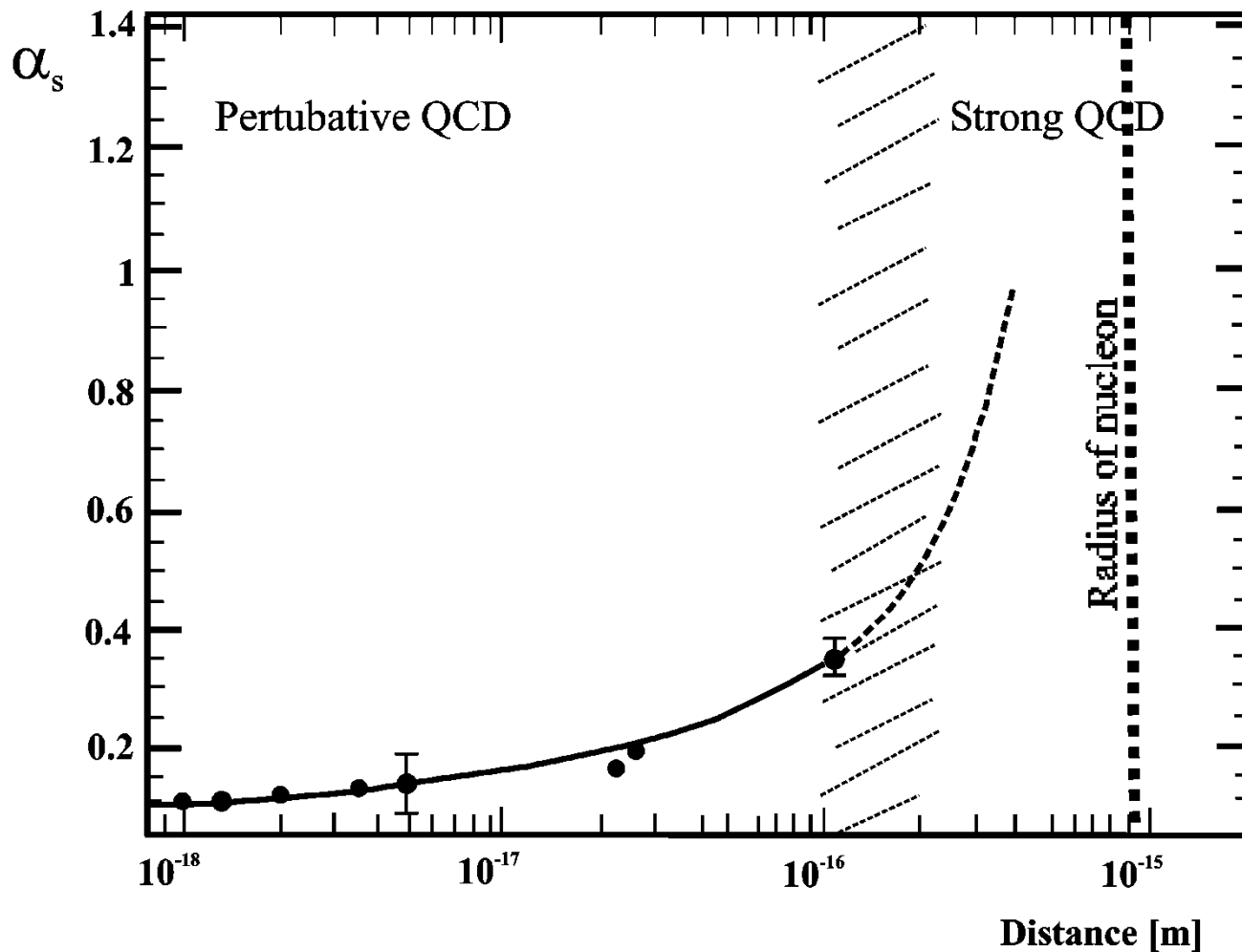


Charmonium-like states possess some well favored characteristics:

- 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;

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

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

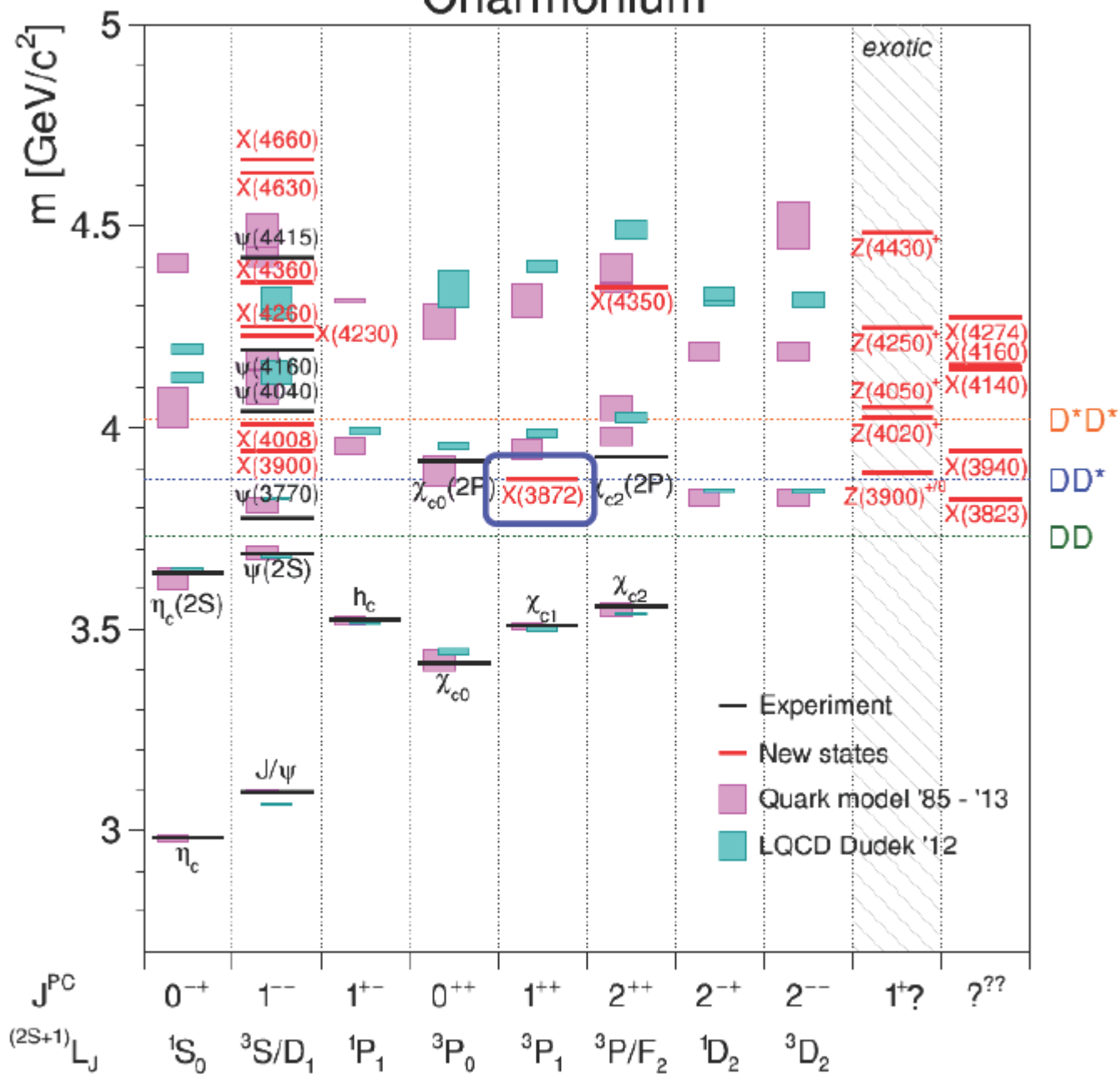
where α_s - coupling constant, b - string tension, σ - hyperfine interaction smear parameter.

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).

$$\begin{aligned} \Delta V_N(\vec{r}) &= \text{const } G_N^{-1/2}(r) \delta(\vec{r}), & V_N(r) &= V_0 \int D(r) R^{1-N}(r) dr / r, \quad V_0 = \text{const} > 0. \\ R(r) &= \sin(r/a), \quad D(r) = r/a, & V_3(r) &= -V_0 \text{ctg}(r/a) + B, \quad V_0 > 0, \quad B > 0. \end{aligned}$$

When cotangent argument in $V_3(r)$ is small: $r^2/a^2 \ll \pi^2$, $\left\{ \begin{array}{l} V(r)|_{r \rightarrow 0} \sim 1/r \\ V(r)|_{r \rightarrow \infty} \sim kr \end{array} \right.$
we get: $\text{ctg}(r/a) \approx a/r - r/3a$, \longrightarrow
where $R(r)$, $D(r)$ and $G_N(r)$ are scaling factor, gauging and determinant of metric tensor $G_{\mu\nu}(r)$.

Charmonium



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 should be determined
- little is known about partial width of 1D_2 and 3D_J charmonium states
- higher lying singlet 1S_0 , 1P_1 and triplet 3S_1 , 3P_J charmonium states are poorly investigated
- only few partial widths of 3P_J -states are known (some of the measured decay widths don't fit theoretical schemes and additional experimental check or reconsideration of the corresponding theoretical models is needed, more data on different decay modes are desirable to clarify the situation)

AS RESULT :

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

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

- decays into particle-antiparticle or $D\bar{D}$ -pair: $\bar{c}c \rightarrow (\Psi, \eta_c, \chi_{cJ}, \dots) \rightarrow \Sigma^0 \bar{\Sigma}^0, \Lambda \bar{\Lambda}, \Sigma^0 \bar{\Sigma}^0 \pi, \Lambda \bar{\Lambda} \pi$
- decays into light hadrons: $\bar{c}c \rightarrow (\Psi, \eta_c, \dots) \rightarrow \rho \pi; \bar{c}c \rightarrow \Psi \rightarrow \pi^+ \pi^-, \bar{c}c \rightarrow \Psi \rightarrow \omega \pi^0, \eta \pi^0, \dots$
- radiative decays: $\bar{c}c \rightarrow \gamma \eta_c, \gamma \chi_{cJ}, \gamma J/\Psi, \gamma \Psi', \dots$
- decays with J/Ψ , Ψ' 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

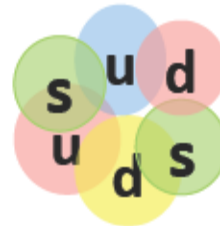
non- $q\bar{q}$ & non- qqq color-singlet combinations



pentaquarks



glueballs



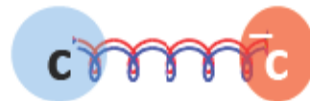
H-dibaryon



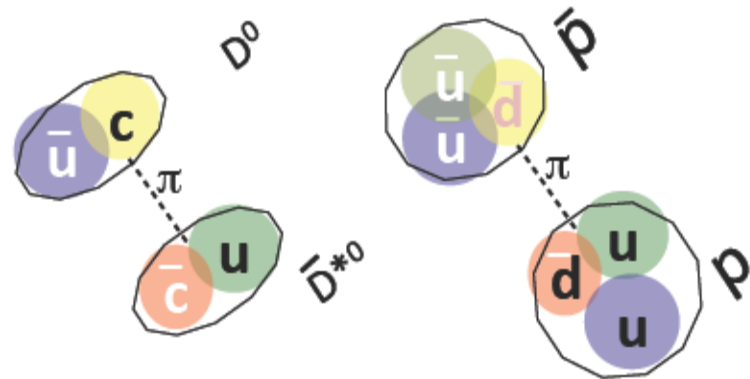
diquark-diantiquarks



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 *

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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

where are they??
 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 (qqq) , $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) 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 – $\bar{c}cg \rightarrow X + M$, where $M = \pi, \eta, \omega, \dots$ (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:

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

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

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

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

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

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

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^{-+} | $\pi^- p \rightarrow (\eta \pi^-) p$ $p \bar{p} \rightarrow \pi^0 (\pi^0 \eta)$ | MPS, Compass Xtal Barrel |
| | $X(1835)$ | $135.7^{+5.0}_{-3.2} 0$ | 99 ± 50 | 0^{-+} | $J/\psi \rightarrow \gamma (p \bar{p})$ $J/\psi \rightarrow \gamma (\pi^+ \pi^- \eta')$ | BESII, CLEOc, BESIII BESII, BESIII |
| Charmonium-like | $X(3872)$ | 3871.68 ± 0.17 | < 1.2 | 1^{++} | $B \rightarrow K + (J/\psi \pi^+ \pi^-)$ $p \bar{p} \rightarrow (J/\psi \pi^+ \pi^-) + \dots$ $B \rightarrow K + (J/\psi \pi^+ \pi^- \pi^0)$ $B \rightarrow K + (D^0 \bar{D}^0 \pi^0)$ $B \rightarrow K + (J/\psi \gamma)$ $B \rightarrow K + (\psi' \gamma)$ $pp \rightarrow (J/\psi \pi^+ \pi^-) + \dots$ | Belle, BaBar, LHCb CDF, D0 Belle, BaBar Belle, BaBar BaBar, Belle, LHCb BaBar, Belle, LHCb LHCb, CMS |
| | $X(3915)$ | 3917.4 ± 2.7 | 28^{+10}_{-9} | 0^{++} | $B \rightarrow K + (J/\psi \omega)$ $e^+ e^- \rightarrow e^+ e^- + (J/\psi \omega)$ | Belle, BaBar Belle, BaBar |
| | $\chi_{c2}(2P)$ | 3927.2 ± 2.6 | 24 ± 6 | 2^{++} | $e^+ e^- \rightarrow e^+ e^- + (D \bar{D})$ | Belle, BaBar |
| | $X(3940)$ | 3942^{+9}_{-8} | 37^{+27}_{-17} | $0(?)^{-(?) +}$ | $e^+ e^- \rightarrow J/\psi + (D^* \bar{D})$ $e^+ e^- \rightarrow J/\psi + (\dots)$ | Belle Belle |
| | $G(3900)$ | 3943 ± 21 | 52 ± 11 | 1^{--} | $e^+ e^- \rightarrow \gamma + (D \bar{D})$ | BaBar, Belle |
| | $Y(4008)$ | 4008^{+121}_{-49} | 226 ± 97 | 1^{--} | $e^+ e^- \rightarrow \gamma + (J/\psi \pi^+ \pi^-)$ | Belle |
| | $Y(4140)$ | $4146.5^{+6.4}_{-5.3}$ | $83^{+30}_{-25} 9$ | 1^{++} | $B \rightarrow K + (J/\psi \phi)$ | CDF, CMS, LHCb |
| | $X(4160)$ | 4156^{+20}_{-25} | 139^{+113}_{-65} | $0(?)^{-(?) +}$ | $e^+ e^- \rightarrow J/\psi + (D^* \bar{D})$ | Belle |
| | $Y(4260)$ | 4263^{+8}_{-9} | 95 ± 14 | 1^{--} | $e^+ e^- \rightarrow \gamma + (J/\psi \pi^+ \pi^-)$ $e^+ e^- \rightarrow (J/\psi \pi^+ \pi^-)$ $e^+ e^- \rightarrow (J/\psi \pi^0 \pi^0)$ | BaBar, CLEO, Belle CLEO, BESIII CLEO, BESIII |
| | $Y(4274)$ | 4273^{+10}_{-9} | 56 ± 16 | 1^{++} | $B \rightarrow K + (J/\psi \phi)$ | CDF, CMS, LHCb |
| | $X(4350)$ | $4350.6^{+4.6}_{-5.1}$ | $13.3^{+18.4}_{-10.0}$ | $0/2^{++}$ | $e^+ e^- \rightarrow e^+ e^- (J/\psi \phi)$ | Belle |
| | $Y(4360)$ | 4361 ± 13 | 74 ± 18 | 1^{--} | $e^+ e^- \rightarrow \gamma + (\psi' \pi^+ \pi^-)$ | BaBar, Belle |
| | $X(4630)$ | 4634^{+9}_{-11} | 99^{+41}_{-32} | 1^{--} | $e^+ e^- \rightarrow \gamma (\Lambda_c^+ \Lambda_c^-)$ | Belle |
| | $Y(4660)$ | 4664 ± 12 | 48 ± 15 | 1^{--} | $e^+ e^- \rightarrow \gamma + (\psi' \pi^+ \pi^-)$ | Belle |
| Charged charmonium-like | $Z_c^+(3900)$ | 3890 ± 3 | 33 ± 10 | 1^{+-} | $Y(4260) \rightarrow \pi^- + (J/\psi \pi^+)$ $Y(4260) \rightarrow \pi^- + (D \bar{D}^*)^+$ | BESIII, Belle BESIII |
| | $Z_c^+(4020)$ | 4024 ± 2 | 10 ± 3 | $1(?)^{+(?) -}$ | $Y(4260) \rightarrow \pi^- + (h_c \pi^+)$ $Y(4260) \rightarrow \pi^- + (D^* \bar{D}^*)^+$ | BESIII BESIII |
| | $Z_1^+(4050)$ | 4051^{+24}_{-43} | 82^{+51}_{-65} | $?^{?+}$ | $B \rightarrow K + (\chi_{c1} \pi^+)$ | Belle, BaBar |
| | $Z^+(4200)$ | 4196^{+35}_{-32} | 370^{+99}_{-140} | 1^{+-} | $B \rightarrow K + (J/\psi \pi^+)$ | Belle, LHCb |
| | $Z_2^+(4250)$ | 4248^{+185}_{-45} | 177^{+321}_{-72} | $?^{?+}$ | $B \rightarrow K + (\chi_{c1} \pi^+)$ | Belle, BaBar |
| Hidden charmed pentaquarks | $Z^+(4430)$ | 4477 ± 20 | 181 ± 31 | 1^{+-} | $B \rightarrow K + (\psi' \pi^+)$ $B \rightarrow K + (J/\psi \pi^+)$ | Belle, LHCb Belle |
| | $P_c^+(4380)$ | 4380 ± 30 | 205 ± 88 | $(3/2)^-$ | $\Lambda_b^+ \rightarrow K + (J/\psi p)$ | LHCb |
| | $P_c^+(4450)$ | 4449.8 ± 3.0 | 39 ± 20 | $(5/2)^+$ | $\Lambda_b^+ \rightarrow K + (J/\psi p)$ | LHCb |
| b-quark sector | $Y_b(10890)$ | 10888.4 ± 3.0 | $30.7^{+8.9}_{-7.7}$ | 1^{--} | $e^+ e^- \rightarrow (\Upsilon(nS) \pi^+ \pi^-)$ | Belle |
| | $Z_b^+(10610)$ | 10607.2 ± 2.0 | 18.4 ± 2.4 | 1^{+-} | $^4\Upsilon(5S)'' \rightarrow \pi^- + (\Upsilon(nS) \pi^+), n = 1, 2, 3$ $^4\Upsilon(5S)'' \rightarrow \pi^- + (h_b(nP) \pi^+), n = 1, 2$ $^4\Upsilon(5S)'' \rightarrow \pi^- + (B \bar{B}^*)^+, n = 1, 2$ | Belle Belle Belle |
| | $Z_b^0(10610)$ | 10609 ± 6 | | 1^{+-} | $^4\Upsilon(5S)'' \rightarrow \pi^0 + (\Upsilon(nS) \pi^0), n = 1, 2, 3$ | Belle |
| | $Z_b^+(10650)$ | 10652.2 ± 1.5 | 11.5 ± 2.2 | 1^{+-} | $^4\Upsilon(5S)'' \rightarrow \pi^- + (\Upsilon(nS) \pi^+), n = 1, 2, 3$ $^4\Upsilon(5S)'' \rightarrow \pi^- + (h_b(nP) \pi^+), n = 1, 2$ $^4\Upsilon(5S)'' \rightarrow \pi^- + (B^* \bar{B}^*)^+, n = 1, 2$ | Belle Belle Belle |



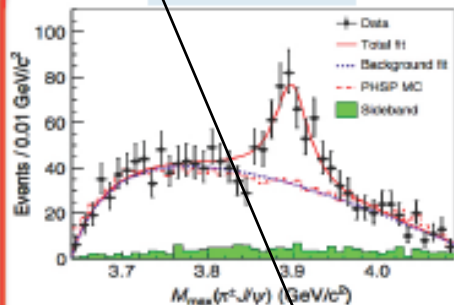
Are these states
the same?!

SUMMARY on Z_c from BES III

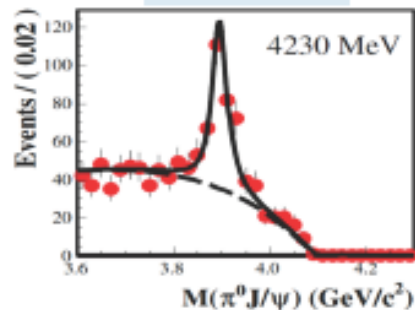
Are these states
the same?!

$$e^+e^- \rightarrow \pi^{+(0)}\pi^{-(0)}J/\psi$$

$Z_c(3900)^\pm$

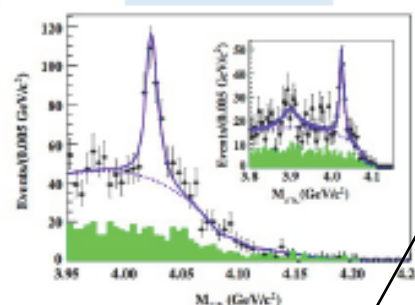


$Z_c(3900)^0$

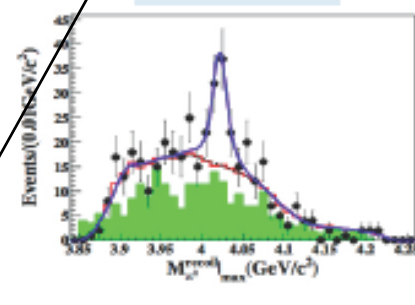


$$e^+e^- \rightarrow \pi^{+(0)}\pi^{-(0)}h_c$$

$Z_c(4020)^\pm$

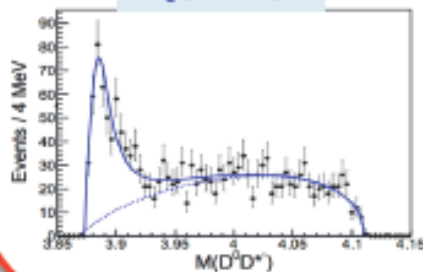


$Z_c(4020)^0$

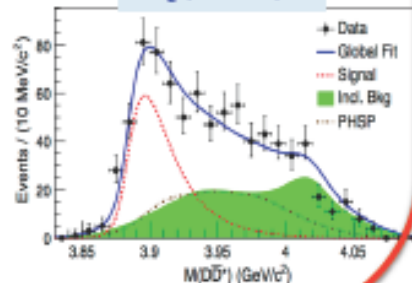


$$e^+e^- \rightarrow (D\bar{D}^*)^\pm(0)\pi^\mp(0)$$

$Z_c(3885)^\pm$

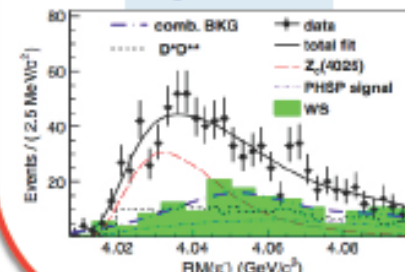


$Z_c(3885)^0$

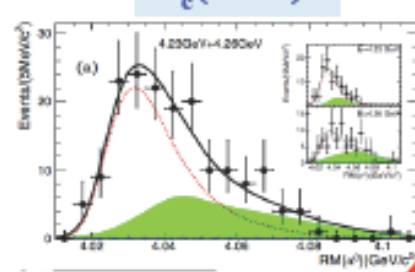


$$e^+e^- \rightarrow (D^*\bar{D}^*)^\pm(0)\pi^\mp(0)$$

$Z_c(4025)^\pm$



$Z_c(4025)^0$



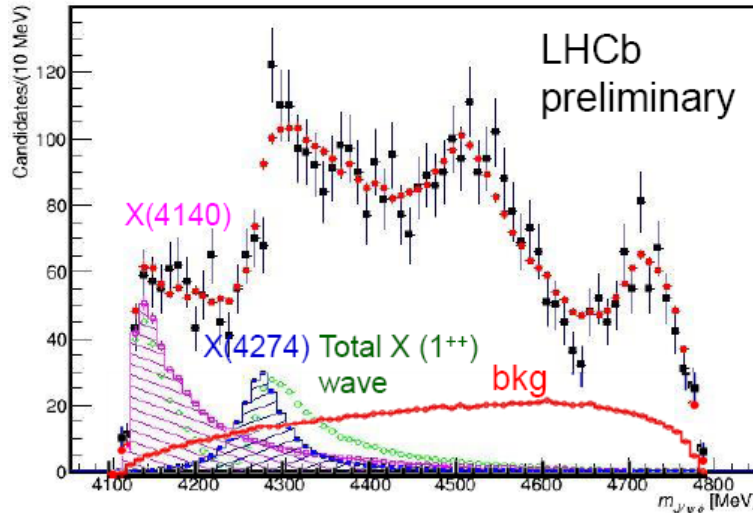
- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?

THE LHCb NEW RESONANCES

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

- 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)

$X(1^{++})$

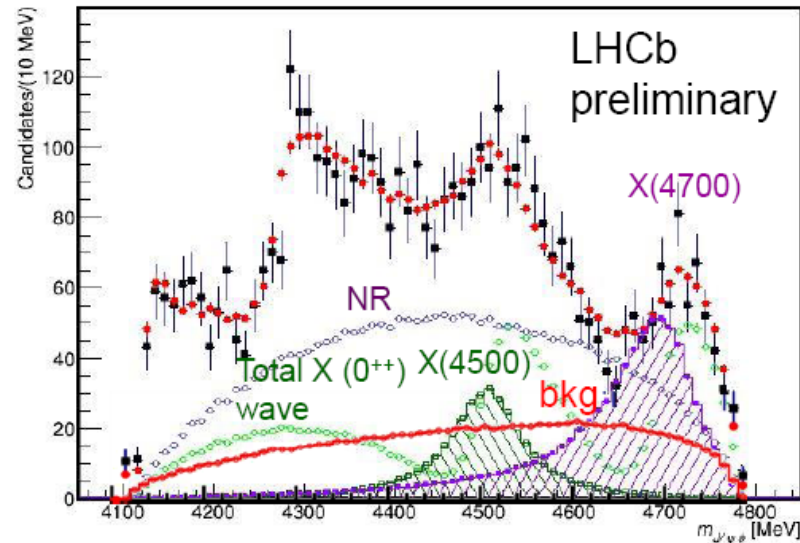


| Contri- bution | sign. or Ref. | M_0 MeV | Γ_0 MeV | Fit results F.F. % |
|-------------------|------------------|------------------------------------|----------------------------|--------------------------------|
| All $X(1^+)$ | | | | 16 ± 3 $^{+6}_{-2}$ |
| $X(4140)$ | 8.4σ | 4146.5 ± 4.5 $^{+4.6}_{-2.8}$ | 83 ± 21 $^{+21}_{-14}$ | 13 ± 3.2 $^{+4.8}_{-2.0}$ |
| ave. | | 4146.9 ± 2.3 | 17.8 ± 6.8 | |
| $X(4274)$ | 6.0σ | 4273.3 ± 8.3 $^{+17.2}_{-3.6}$ | 56 ± 11 $^{+8}_{-11}$ | 7.1 ± 2.5 $^{+3.5}_{-2.4}$ |
| CDF | | 4274.4 $^{+8.4}_{-6.7} \pm 1.9$ | 32 $^{+22}_{-15} \pm 8$ | |
| CMS | | $4313.8 \pm 5.3 \pm 7.3$ | 38 $^{+30}_{-15} \pm 16$ | |

- Significant $X(4140)$ 8.4σ ,
 - mass consistent with the previous measurements, but the width substantially larger
 - $J^{PC}=1^{++}$ determined at 5.7σ including systematic errors
- Significant $X(4274)$ 6.0σ ,
 - Consistent with the unpublished CDF results. First significant claim for this structure.
 - $J^{PC}=1^{++}$ determined at 5.8σ including systematic errors



$X(0^{++})$



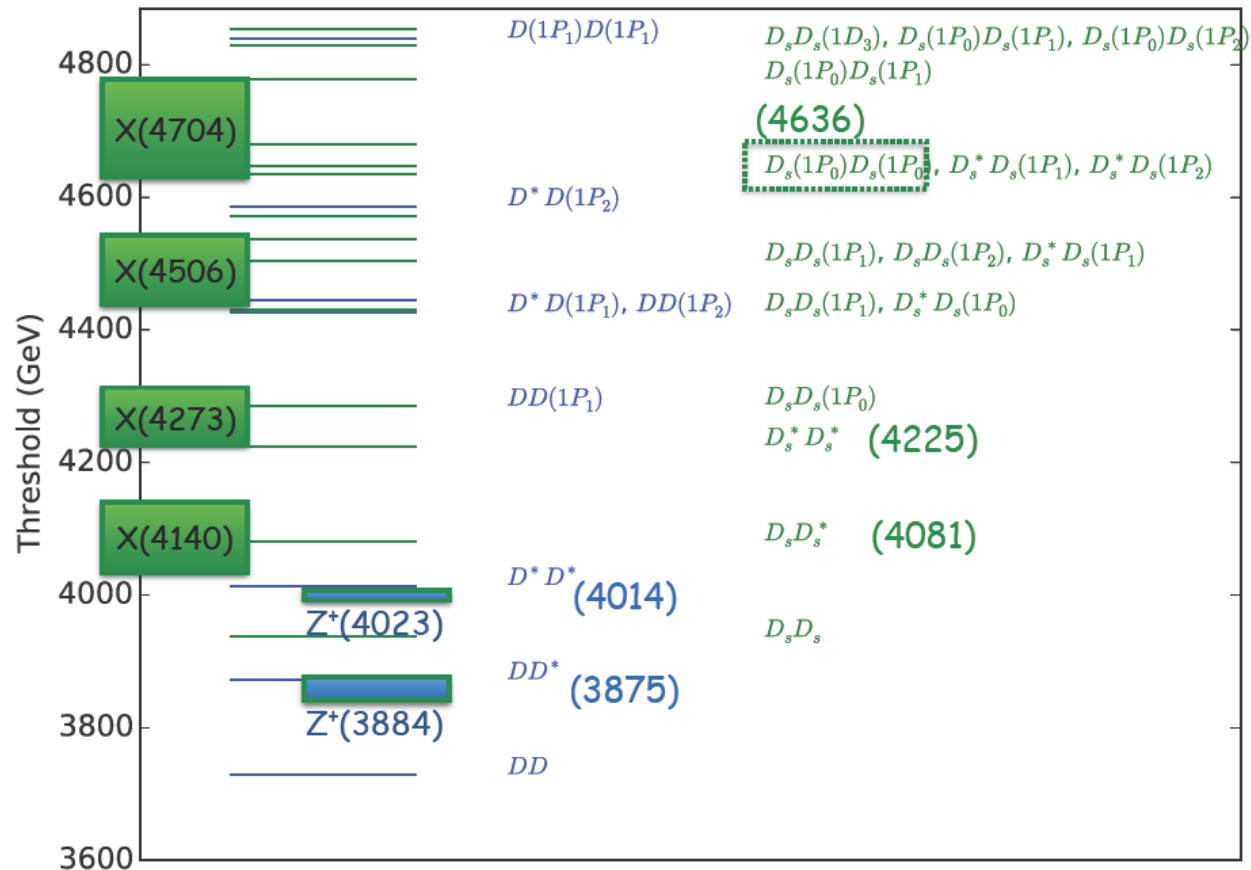
| Contri- bution | sign. | Fit results | | |
|--------------------|-------------|---------------------------|--------------------------|-----------------------------|
| | | M_0 MeV | Γ_0 MeV | F.F. % |
| All $X(0^+)$ | | | | $28 \pm 5^{+7}_{-7}$ |
| NR $_{J/\psi\phi}$ | 6.4σ | | | $46 \pm 11^{+11}_{-21}$ |
| $X(4500)$ | 6.1σ | $4506 \pm 11^{+12}_{-15}$ | $92 \pm 21^{+21}_{-20}$ | $6.6 \pm 2.4^{+3.5}_{-2.3}$ |
| $X(4700)$ | 5.6σ | $4704 \pm 10^{+14}_{-24}$ | $120 \pm 31^{+42}_{-33}$ | $12 \pm 5^{+9}_{-5}$ |

- Significant structures at higher masses, best described by two new 0^{++} resonances $X(4500), X(4700)$:
 - Significances of $6.1\sigma, 5.6\sigma$
 - $J^{PC}=0^{++}$ determined at $4.0\sigma, 4.5\sigma$, respectively

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?

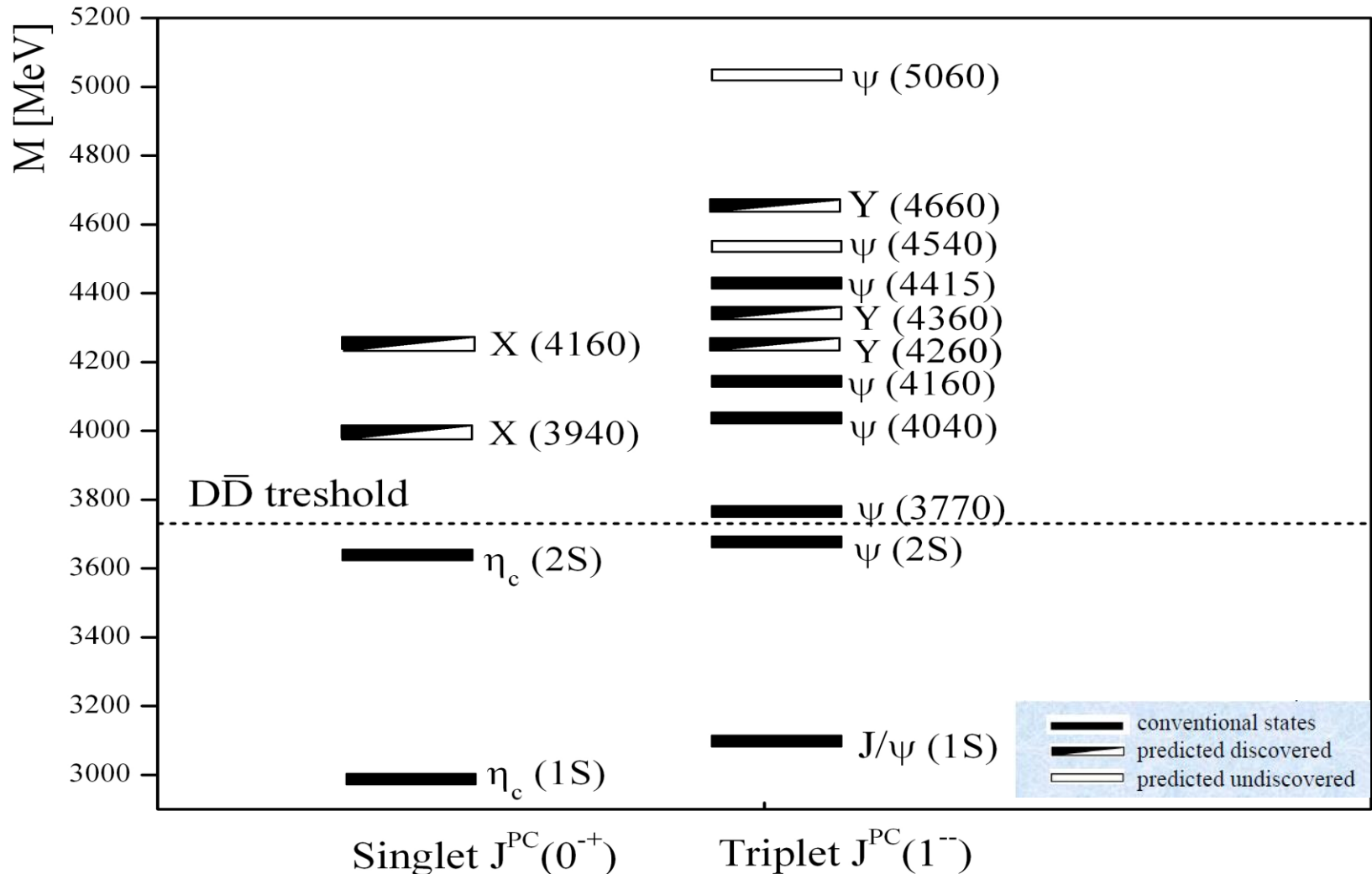
$B \rightarrow X K$: $M_X < 4785 \text{ MeV}$



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

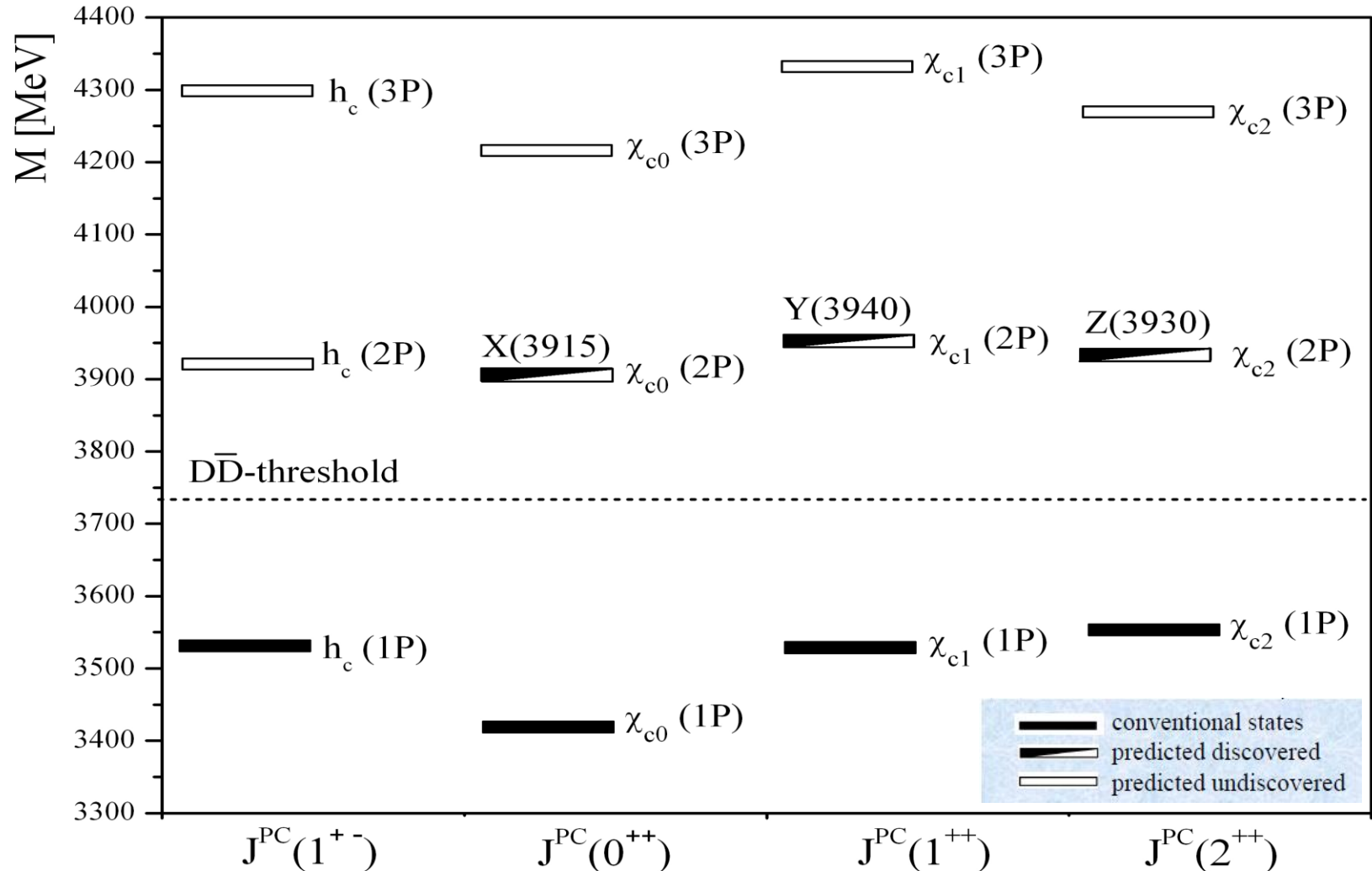
Motivation

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



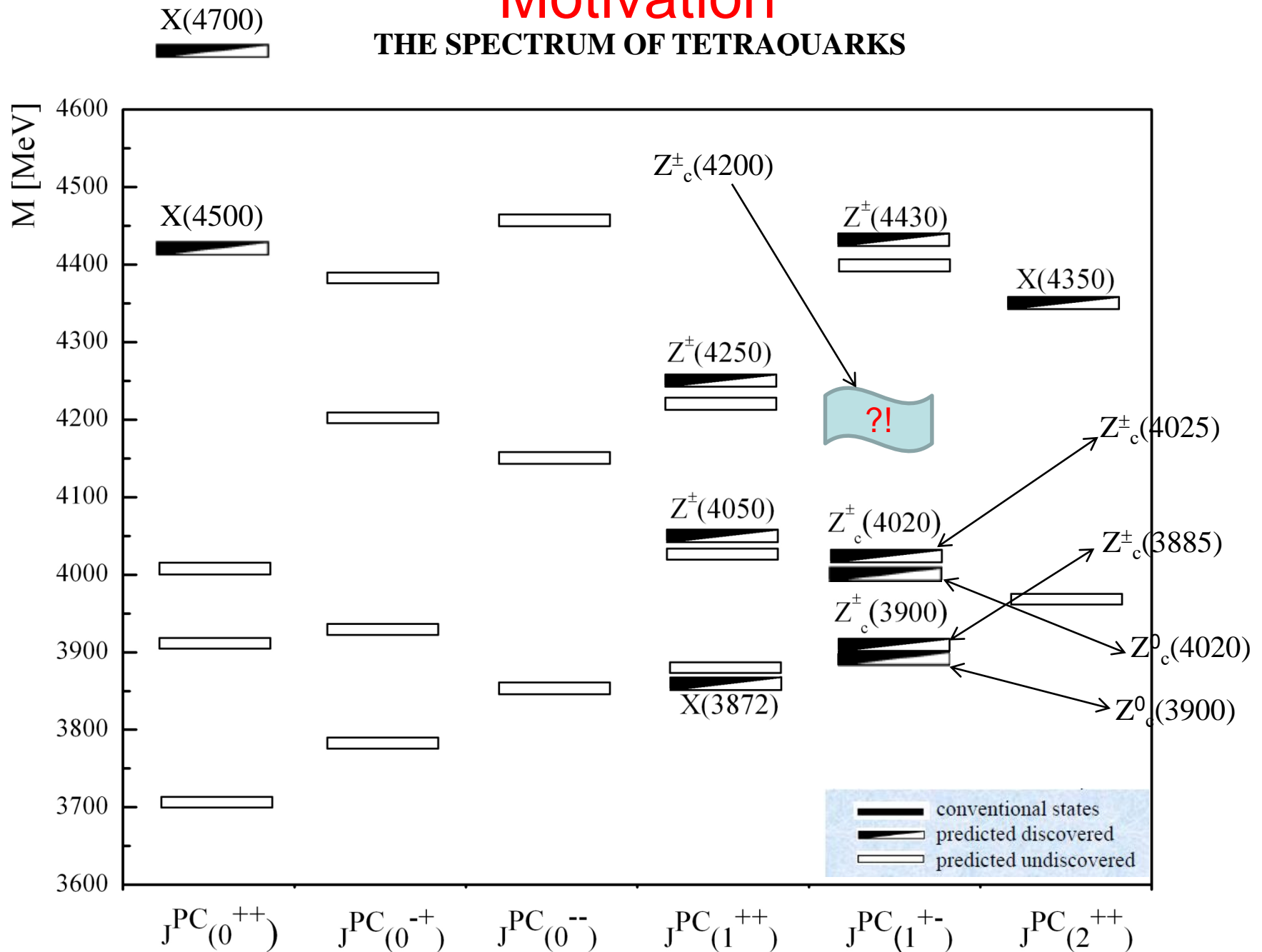
Motivation

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



Motivation

THE SPECTRUM OF TETRAQUARKS



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 ≈ 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.

TETRAQUARK STATES

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

SPECTRUM

$$\frac{0^{++}}{4270} + K$$

$$\frac{1^{+-}}{+K}$$

$$\frac{2^{++}}{4270} + K$$

$$\frac{1^{++}}{4140}$$

$$\frac{1^{+-}}{-K}$$

$$\frac{0^{++}}{-3K}$$

and 4500 0^{++}
4700 0^{++}

(RADIAL EXCITATIONS
LIKE $Z(4430)?$)

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

CALCULATION OF WIDTHS

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

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

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

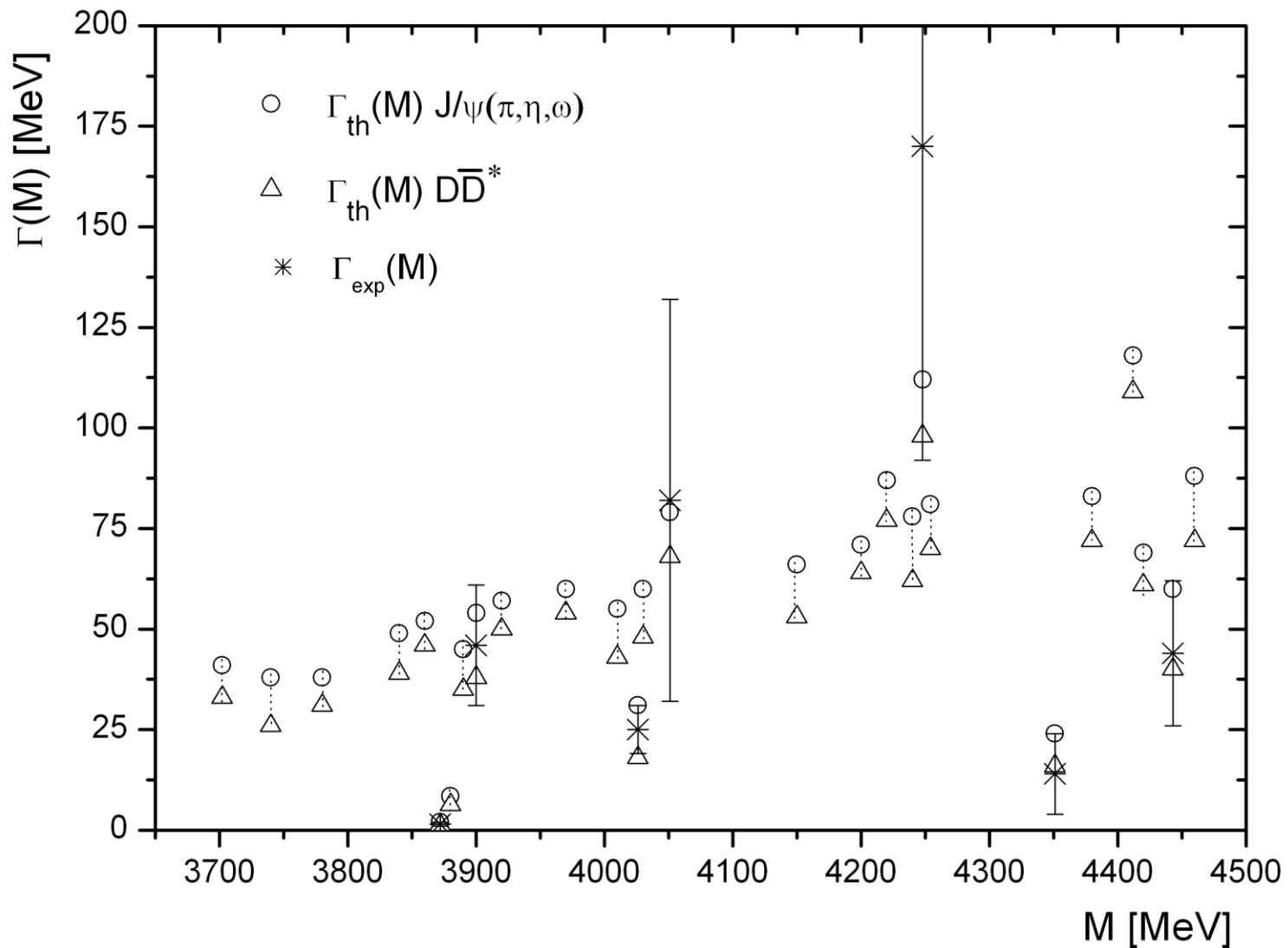
$$(r < R): \int_0^R |\phi_L(r)|^2 dr = 1$$

where

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

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

THE WIDTHS OF TETRAQUARKS WITH THE HIDDEN CHARM



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 $\bar{s}s g, \bar{c}c g$ in mass range from 1.8 – 5.0 GeV.

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

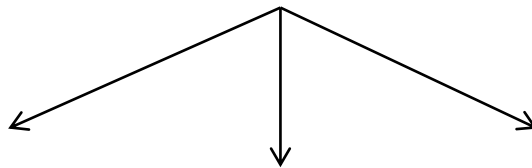
- spectroscopy of baryons and mesons with strangeness and charm:

$$\Omega_c^0, \Xi_c, \Xi'_c, \Xi_{cc}^+, \Omega_{cc}^+ \text{ i.e. } pp \rightarrow \Lambda_c X; pp \rightarrow \Lambda_c p X; pp \rightarrow \Lambda_c p D_s$$

- 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 $\sqrt{s} = 25 \text{ GeV}$

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

3. Running time 10 weeks:

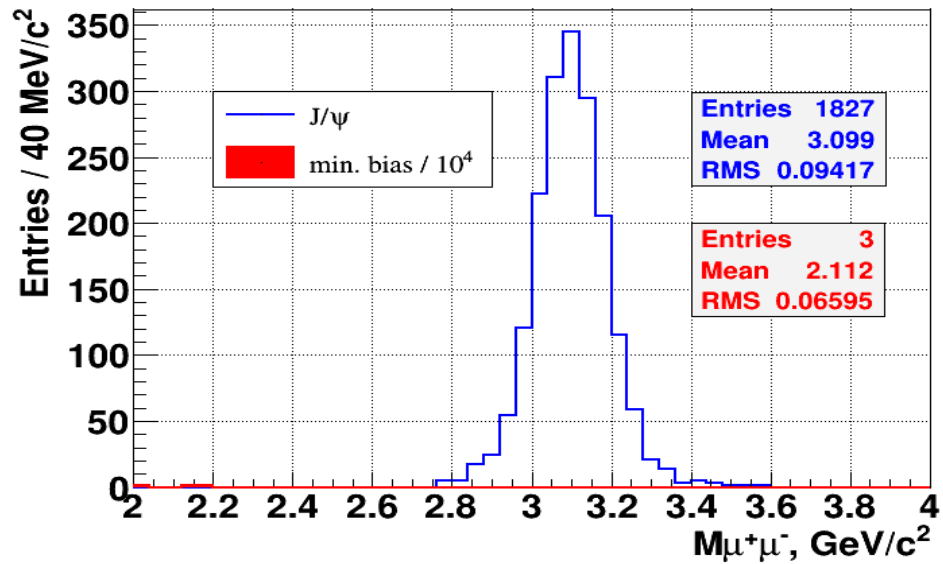
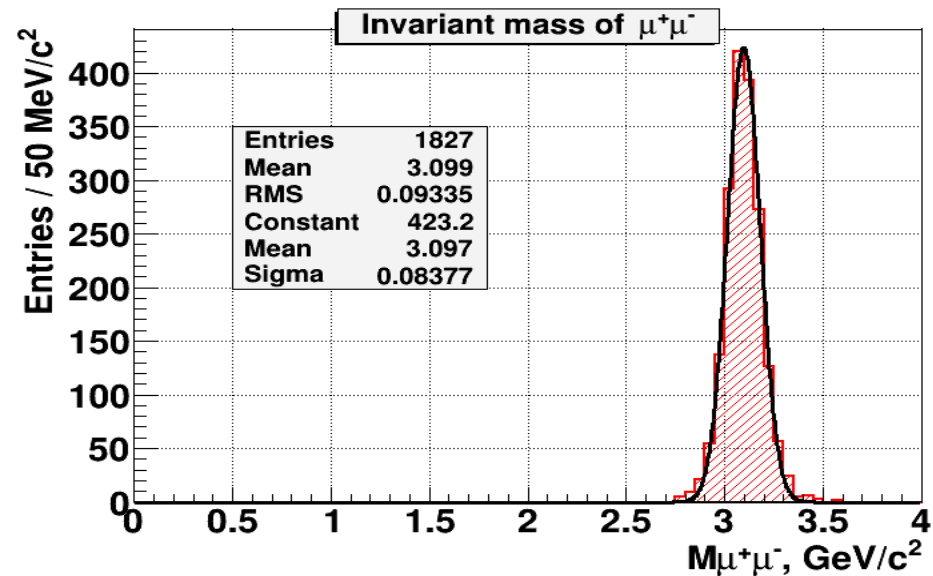
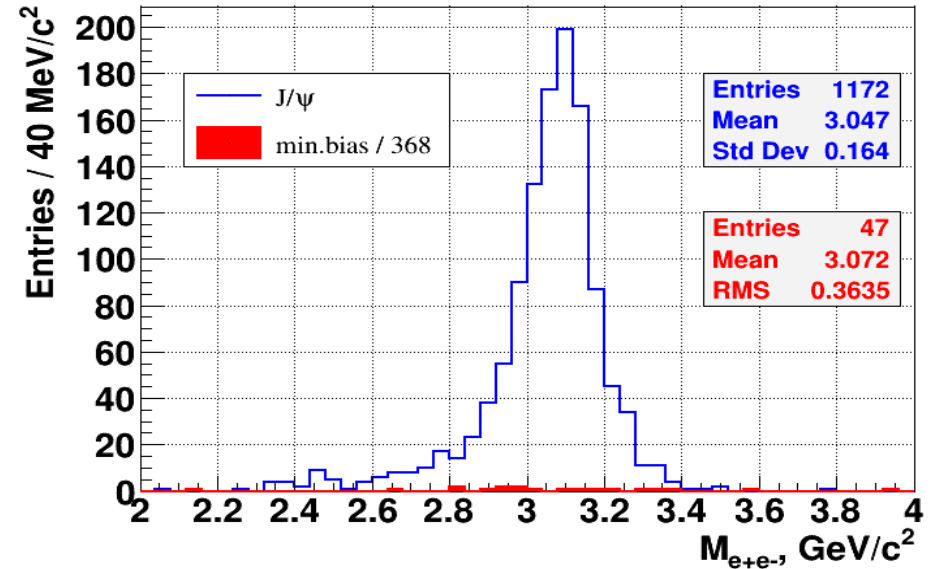
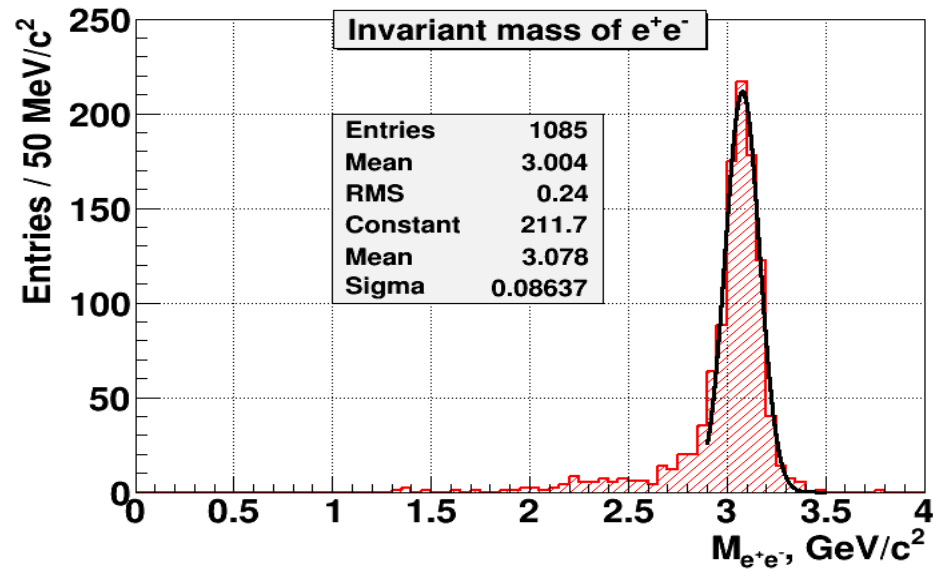
integrated luminosity $L_{\text{int}} = 604.8 \text{ nb}^{-1} - 60.48 \text{ pb}^{-1}$

Expectations for J/ψ

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

2. Statistics: $N_{J/\psi} = L_{\text{int}} \cdot \sigma_{J/\psi} \cdot Br_{J/\psi \rightarrow e^+e^-} \cdot \text{Eff.}_{\Delta\eta=\pm 1.5} =$
 $604.8 \cdot 108.7 \cdot 0.06 \cdot 0.8 = 3156$

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



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

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PHYSICAL REVIEW LETTERS

week ending
13 AUGUST 2004

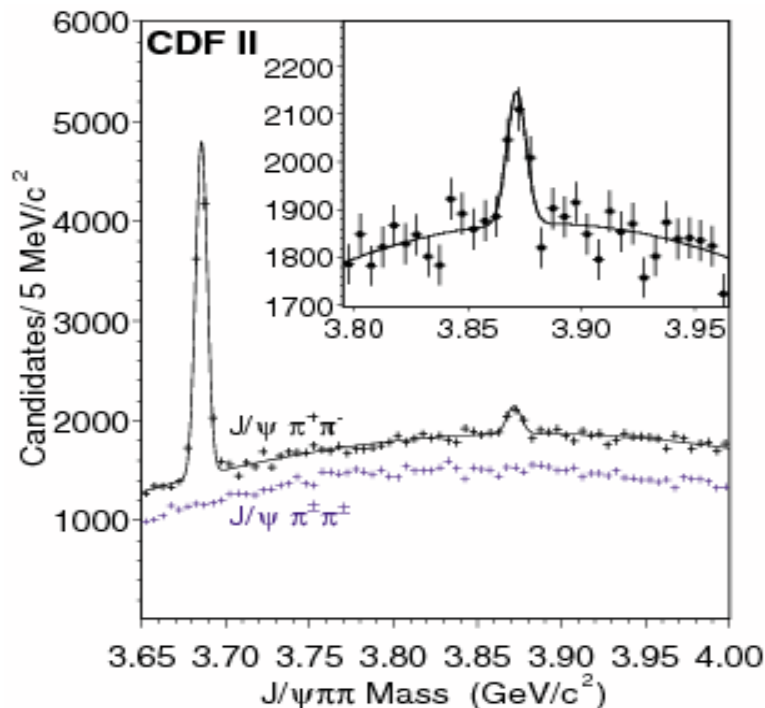


FIG. 1 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ and $J/\psi\pi^+\pi^+$ candidates passing the selection described in the text. A large peak for the $\psi(2S)$ is seen in the $J/\psi\pi^+\pi^-$ distribution as well as a small signal near a mass of $3872 \text{ MeV}/c^2$. The curve 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 $3872 \text{ MeV}/c^2$.

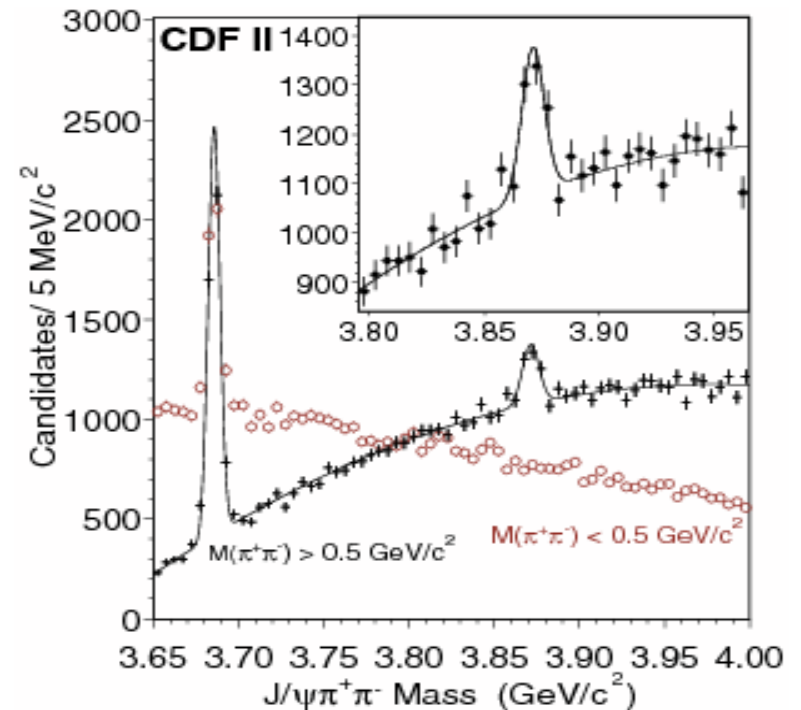


FIG. 2 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ candidates with $m(\pi^+\pi^-) > 0.5 \text{ GeV}/c^2$ (points) and $m(\pi^+\pi^-) < 0.5 \text{ GeV}/c^2$ (open circles). The curve is a fit with two Gaussians and a quadratic background. The inset shows an enlargement of the high dipion-mass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

Requiring $M(\pi^+\pi^-) > 0.5 \text{ MeV}/c^2$ 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. $Br(X3872 \rightarrow J/\psi \rho^0) = 5.0\%$

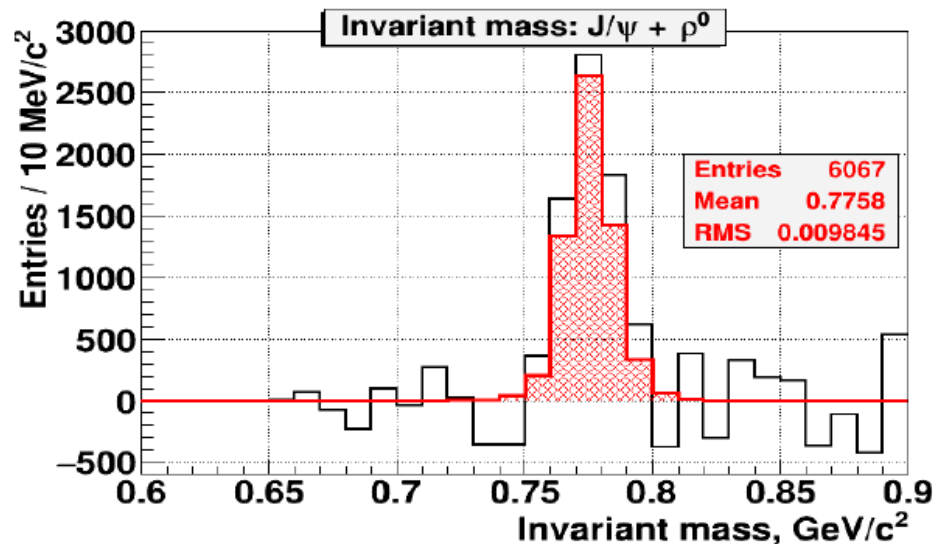
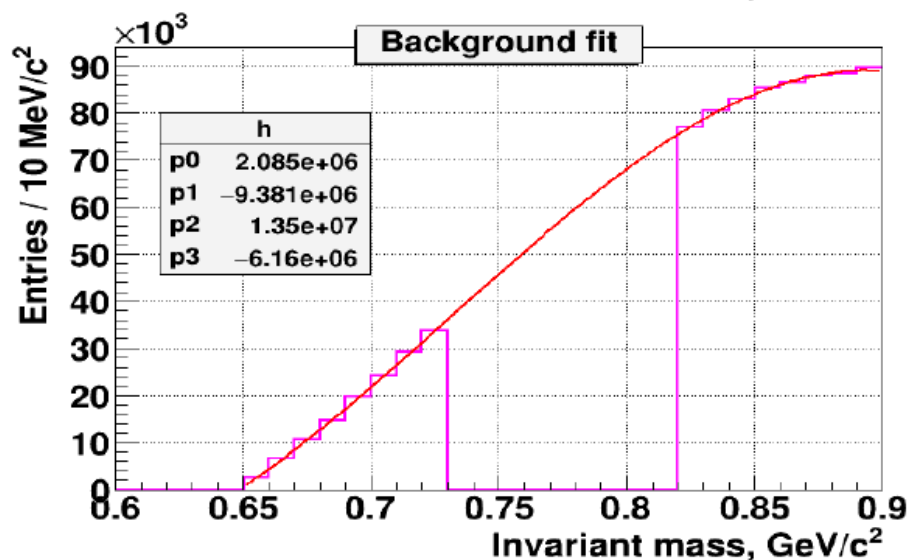
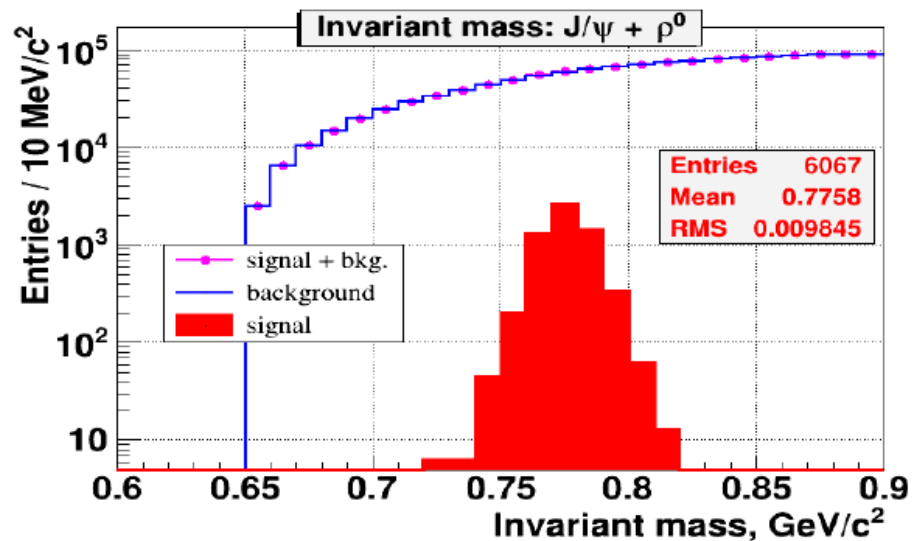
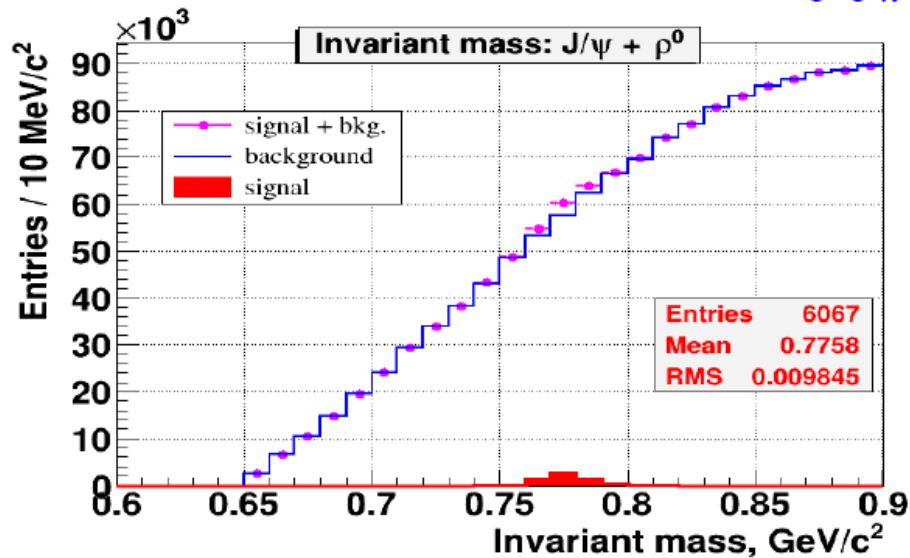
$Br(X3872 \rightarrow e^+e^- \pi^+\pi^-) = 0.3\% \rightarrow X\text{-section} = 12.2 \text{ pb}$

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: $M_{e^+e^-\pi^+\pi^-} - M_{e^+e^-}$



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

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(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. $Br(X(3872) \rightarrow J/\psi \pi^+ \pi^-) = 5.00\%$

$Br(X(3872) \rightarrow D^+ D^-) = 40.45\%$

$Br(X(3872) \rightarrow D^0 D^{*0} \bar{\pi}^0) = 54.55\% \Rightarrow D^0 D^0 \bar{\pi}^0 = 35.29\%$

4. $Br(D^+ \rightarrow K^- \pi^+ \pi^+) = 9.2\%$, $Br(D^0 \rightarrow K^- \pi^+) = 3.8\%$

5. $\sigma(pCu) * Br(J/\psi \pi^+ \pi^-) * Br(e^+ e^-) = 81.9 * 0.05 * 0.06 = 0.246$ nb

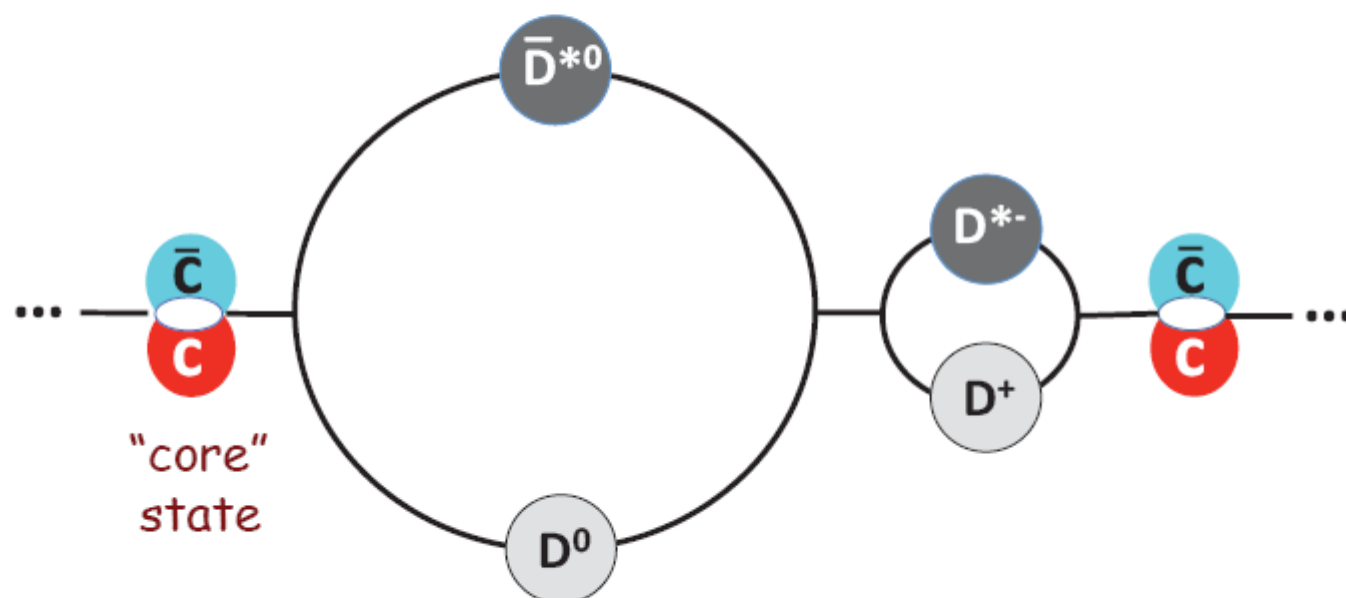
$\sigma(pCu) * Br(D^+ D^-) * Br(K \pi \pi)^2 = 81.9 * 0.4045 * 0.092 * 0.092 =$
0.280 nb

$\sigma(pCu) * Br(D^0 D^0 \bar{\pi}^0) * Br(K \pi)^2 = 81.9 * 0.3529 * 0.039 * 0.039 =$
0.044 nb

0.280 nb $\Rightarrow L = 5.9 \times 10^{29}$ (1000 events / 10 weeks)

Can the X(3872) structure be probed?

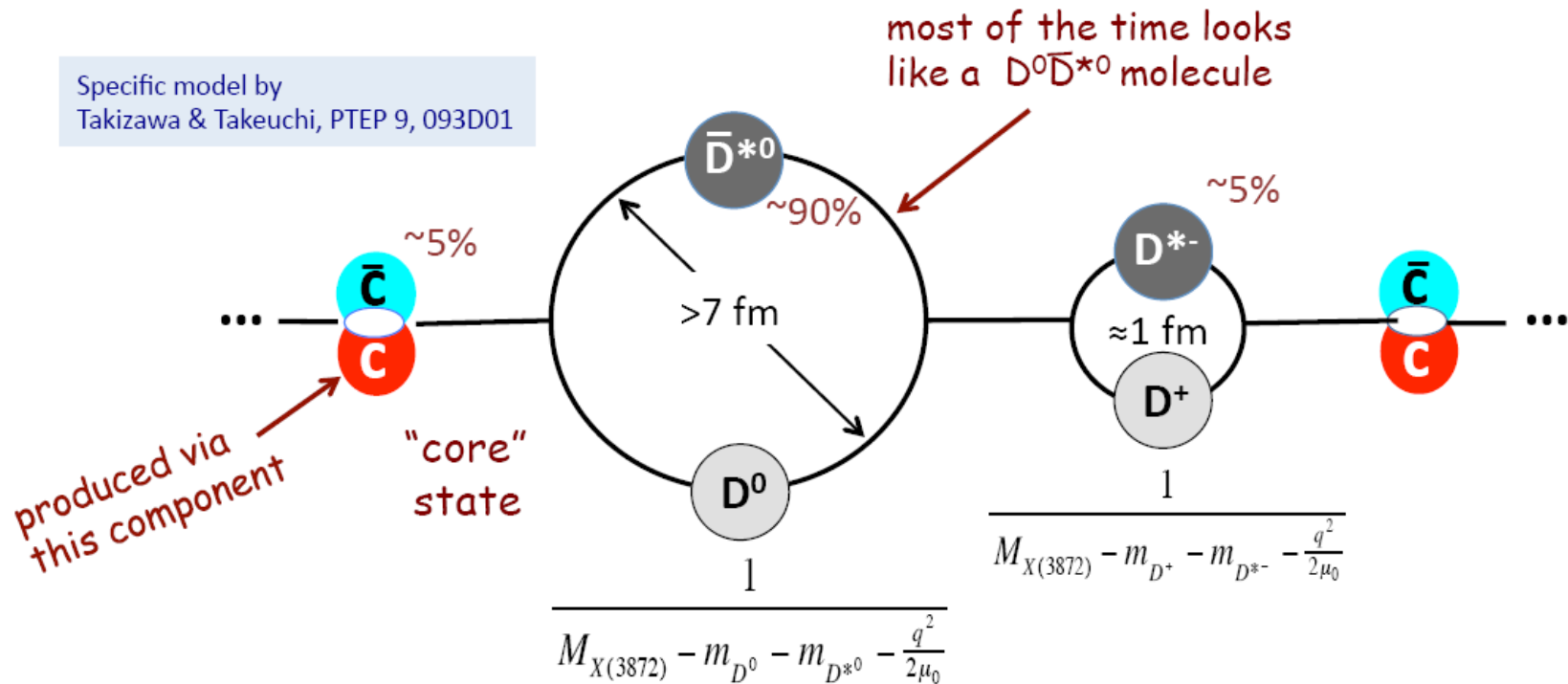
Takizawa & Takeuchi, PTEP 9, 093D01



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

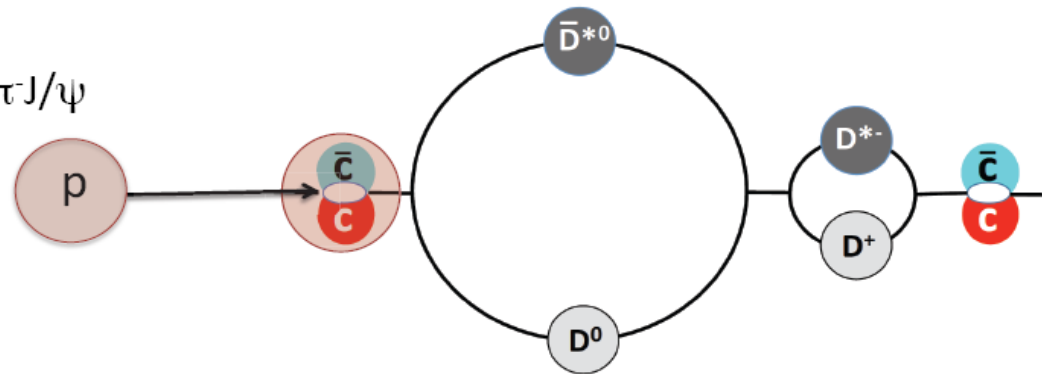
Probably a mixture of $D\bar{D}^*$ & a $c\bar{c}$ “core”

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

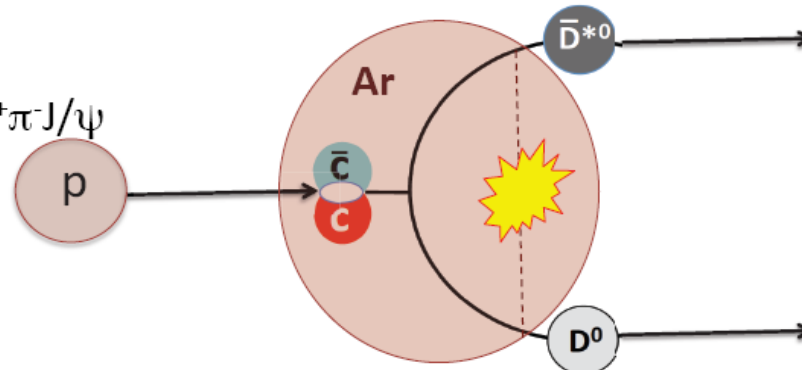


Near-threshold prod. via pp & pA

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



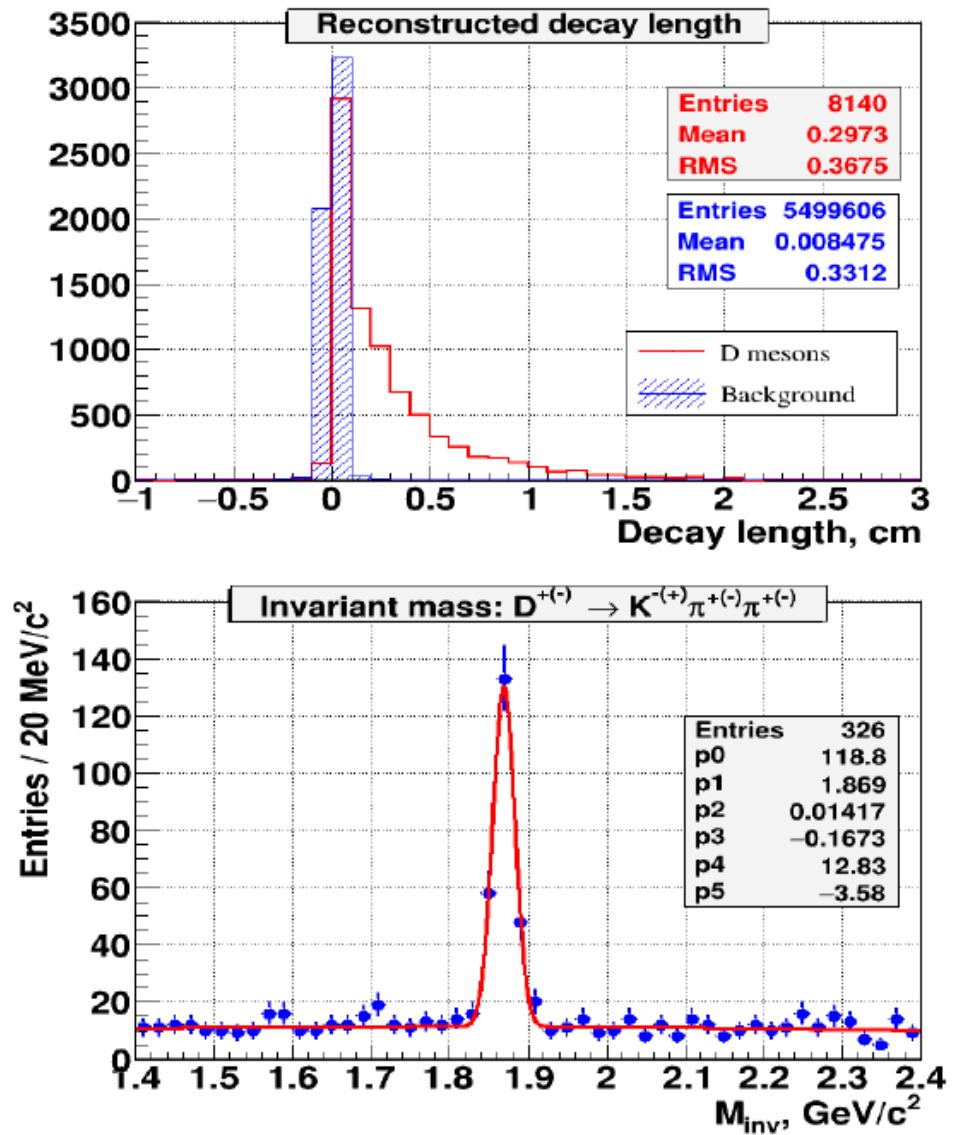
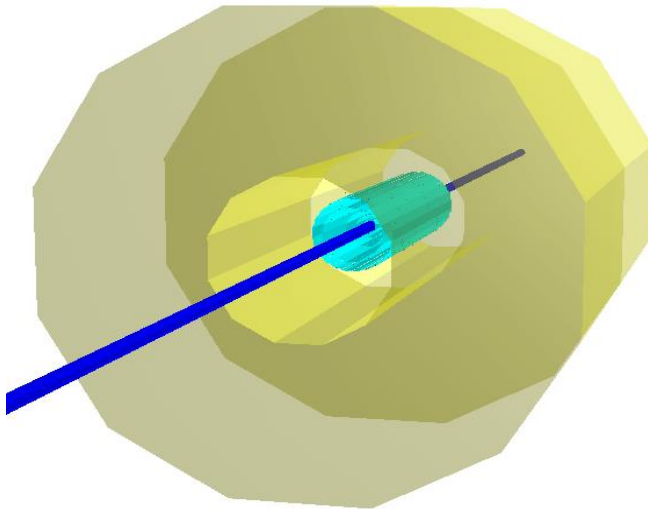
$$p\text{Ar} \rightarrow X(3872) \rightarrow \pi^+ \pi^- J/\psi$$



Strong quenching
for $A \sim 40$ nuclei??

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

Vertex detector / Inner tracker



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 and tetraquarks.
- ◆ The most promising decay channels of charmonium-like states have been analyzed. Different charmonium-like states above $D\bar{D}$ 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 detectors should provide good opportunities for the reconstruction and identification of charged and neutral particles.
- ◆ For hadronic decays the silicon ITS should greatly enhance the research potential (reconstruction and selection).

PERSECTIVES AND FUTURE PLANS

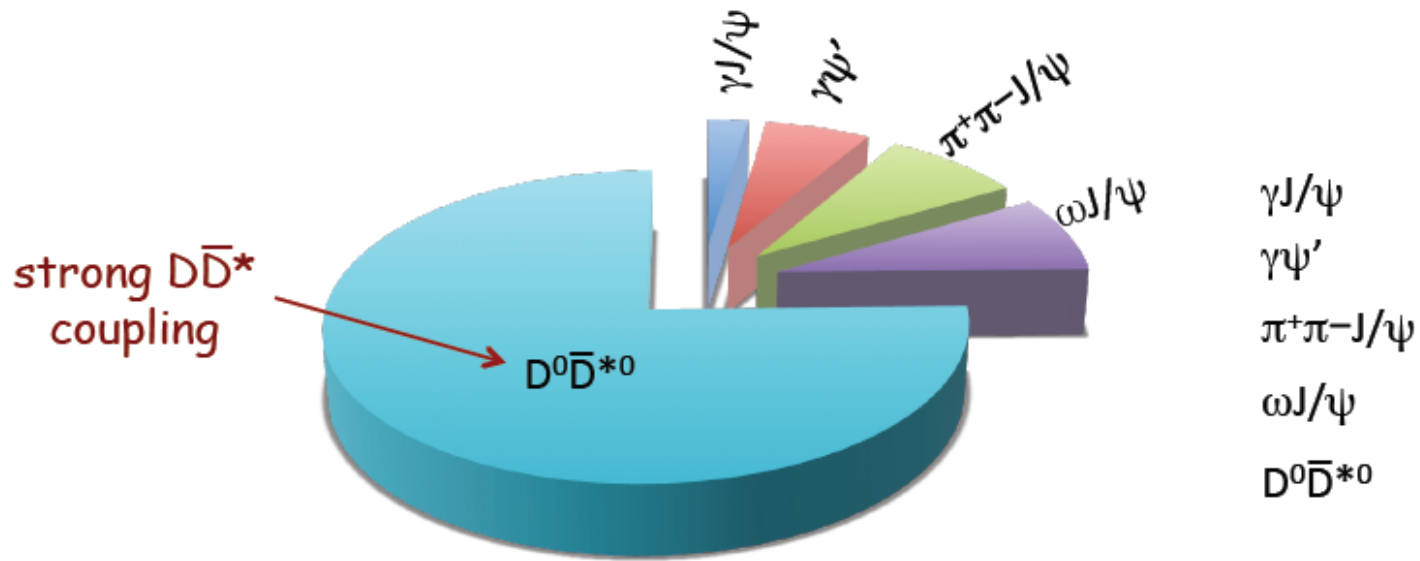
- *D*-meson spectroscopy:
 - *CP*-violation
 - Flavour mixing
 - Rare decays
- Baryon spectroscopy:
 - Strange baryons
 - Charmed baryons

THANK YOU!

and

**WELCOME FOR
COLLABORATION...**

X(3872) decay channels



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

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

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