STUDY OF STRONG INTERACTIONS AND HADRONIC MATTER IN HADRON AND HEAVY ION COLLISIONS

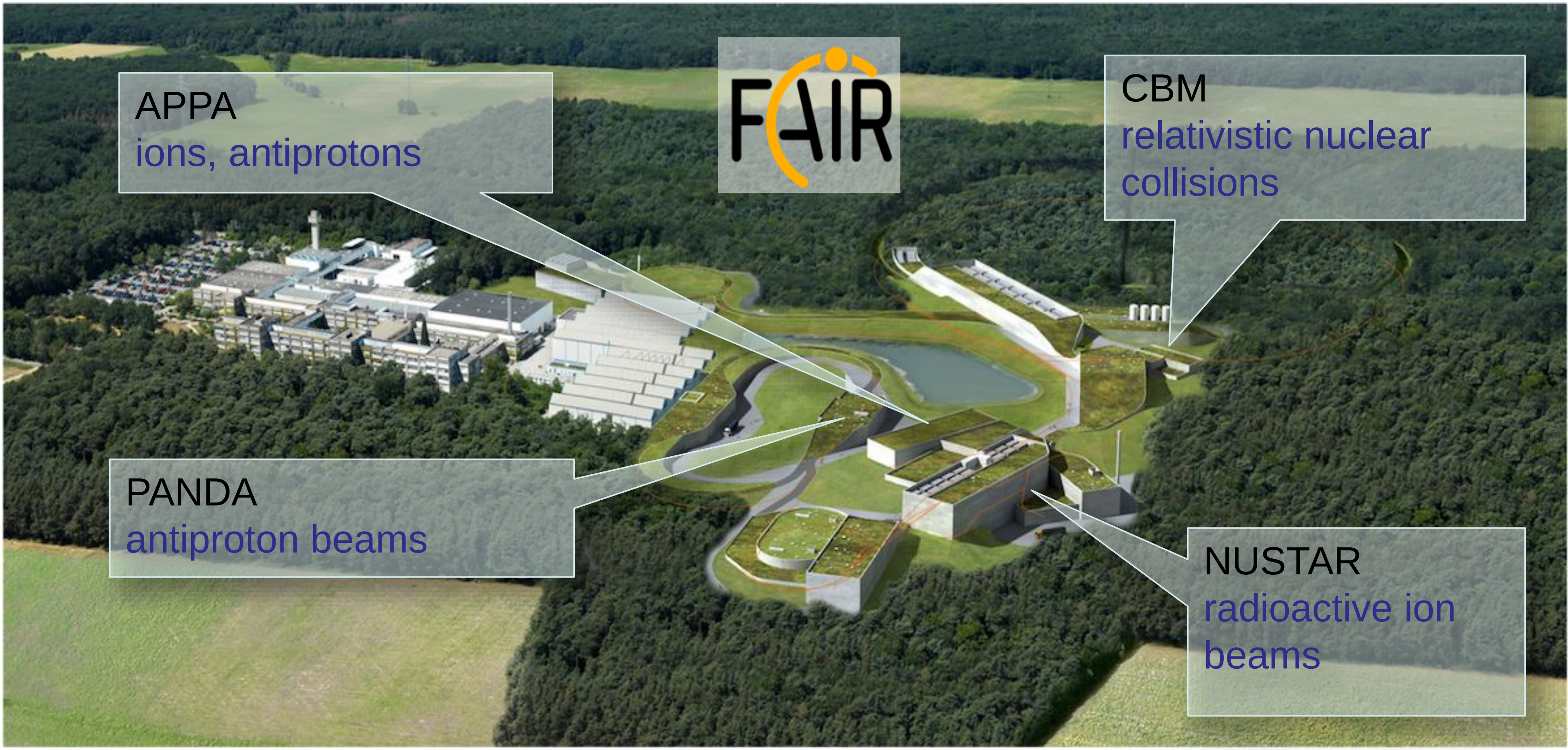
Mikhail Barabanov, Alexander Vodopyanov

(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



APPA
ions, antiprotons

CBM
relativistic nuclear collisions

PANDA
antiproton beams

NUSTAR
radioactive ion beams

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

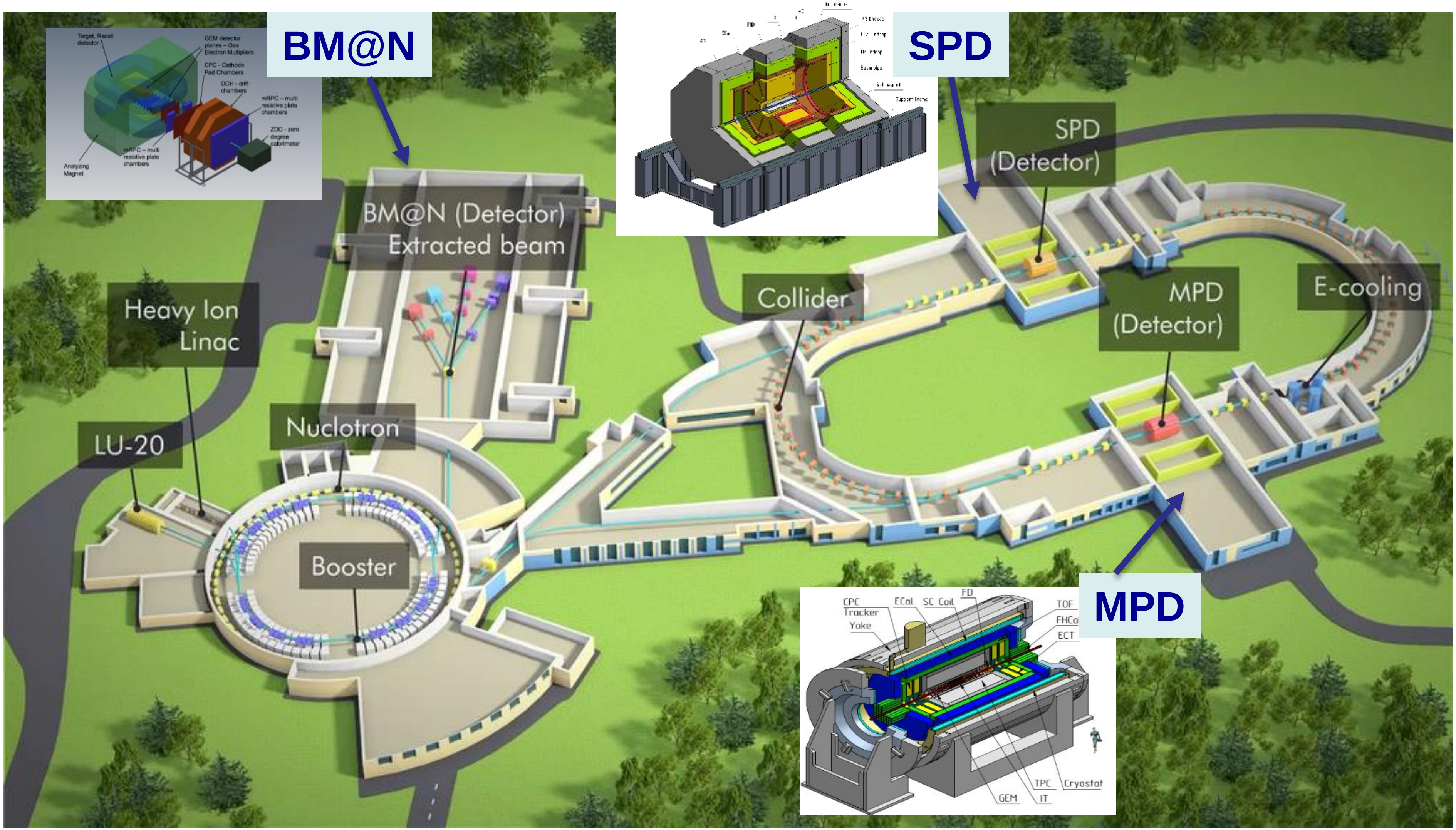
Antiproton production

- 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*

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

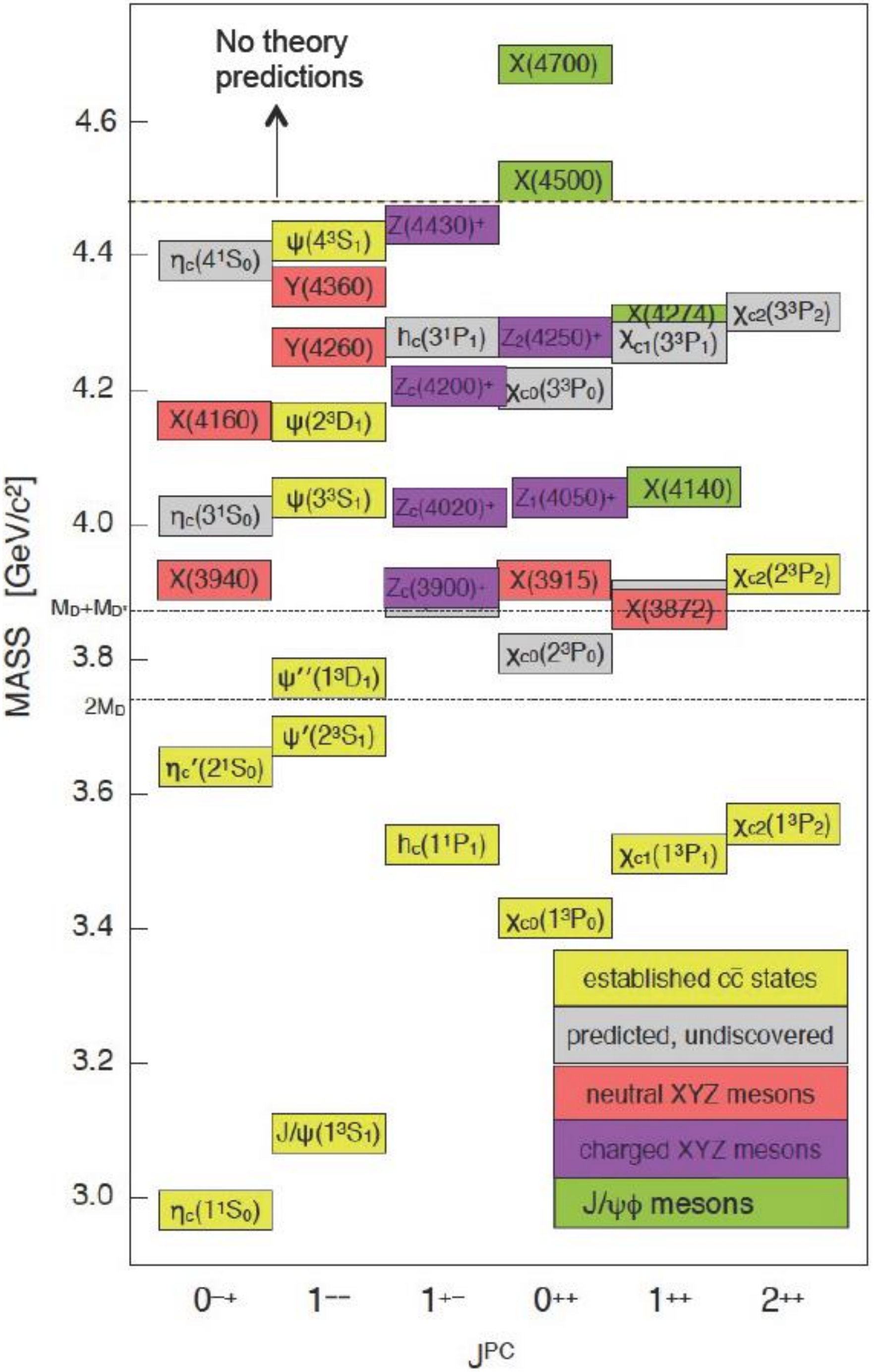


MOTIVATION

To look for different conventional and exotic charmonium-like states 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

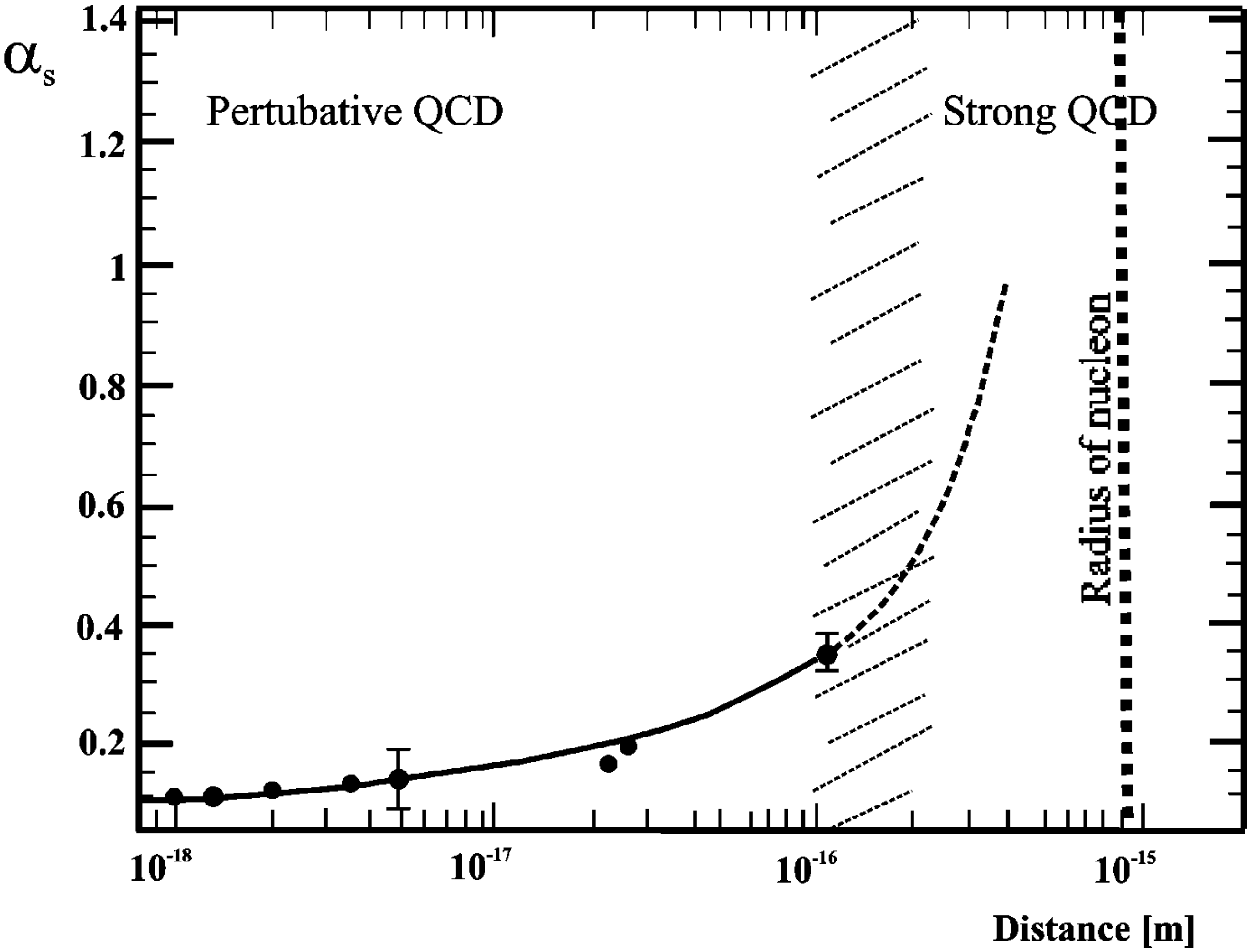


Charmonium-like states possess some well favored characteristics:

- 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 $<v^2/c^2> \approx 0.2$.

The quark potential models have successfully described the charmonium spectrum, which generally assumes short-range coulomb interaction and long-range linear confining interaction plus spin dependent part coming from one gluon exchange. The zero-order potential is:

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

where $\tilde{\delta}_\sigma(r) = (\sigma/\sqrt{\pi})^3 e^{-\sigma^2 r^2}$ defines a gaussian-smeared hyperfine interaction.

Solution of equation with $H_0 = p^2/2m_c + V_0^{(c\bar{c})}(r)$ gives zero order charmonium wavefunctions.

**T. Barnes, S. Godfrey, E. 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:

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

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

Izmestev A. has shown ** Nucl. Phys., V.52, N.6 (1990) & *Nucl. Phys., V.53, N.5 (1991)* that in the case of curved coordinate space with radius *a* (confinement radius) and dimension *N* at the dominant time component of the gluonic potential the quark-antiquark potential defines via Gauss equations. If space of physical system is compact (sphere S^3), the harmonic potential assures confinement: ** Advances in Applied Clifford Algebras, V.8, N.2, p.235 - 270 (1998) .*

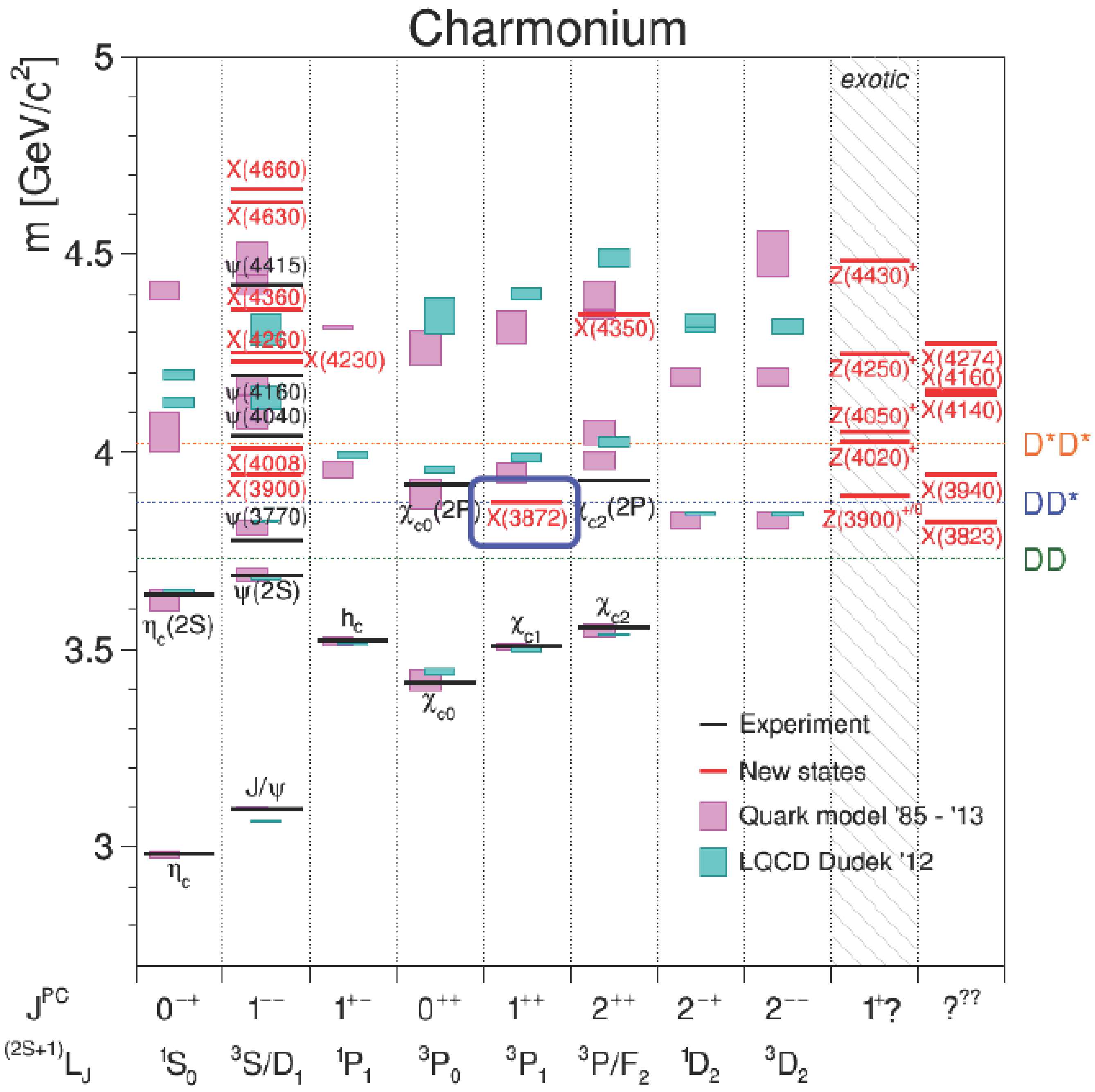
$$\Delta V_N(\vec{r}) = \mathrm{const}\ G_N^{-1/2}(r)\delta(\vec{r}), \qquad V_N(r) = V_0\int D(r)R^{1-N}(r)dr/r,\ V_0 = \mathrm{const} > 0.$$

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

When cotangent argument in V$_3$(r) is small: $r^2/a^2 << \pi^2,$

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

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/c^2]
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$_J$
^{1}S$_0$
^{3}S/D$_1$
^{1}P$_1$
^{3}P$_0$
^{3}P$_1$
^{3}P/F$_2$
^{1}D$_2$
^{3}D$_2$

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

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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

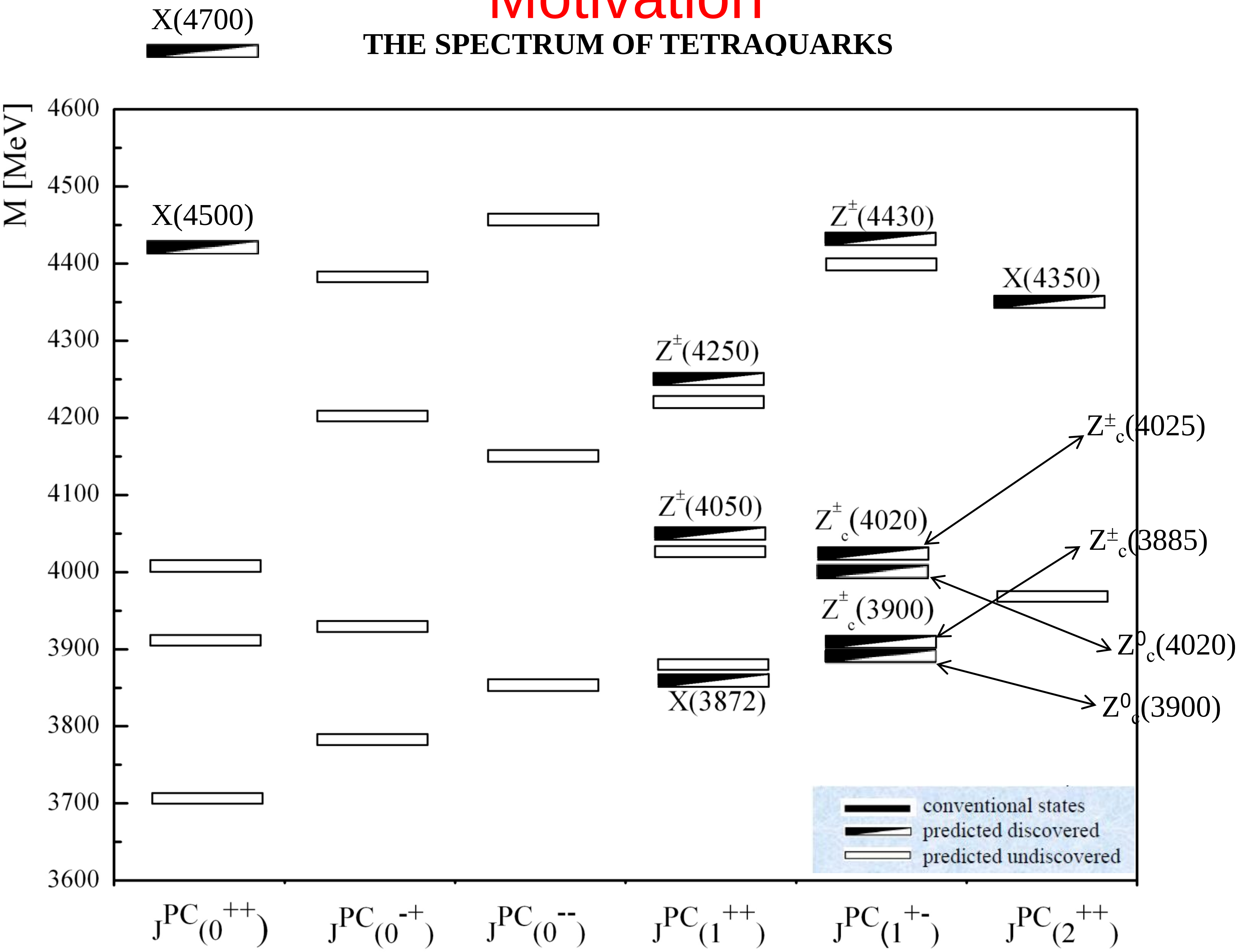
ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^-, s^-, u^0 and b^0 exhibit a parallel with the leptons.

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**.

Where are they??

Motivation

THE SPECTRUM OF TETRAQUARKS



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

What to look for

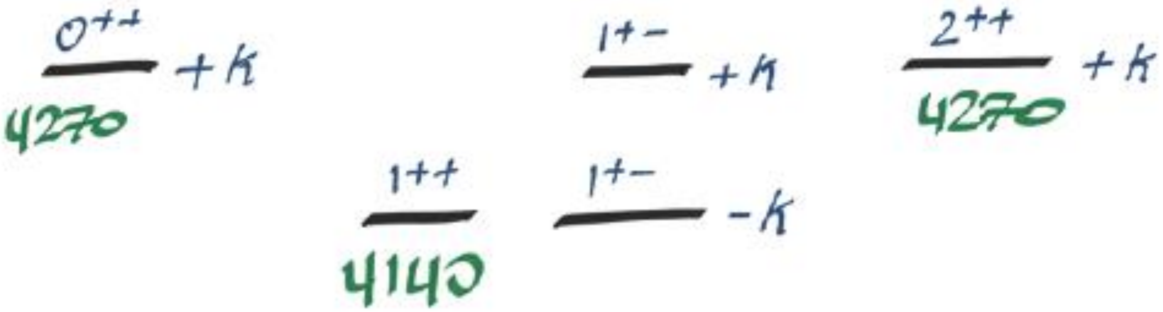
- Does the Z(4433) exist??
- Better to find charged X !
- Neutral partners of Z(4433)~X(1^{+-},2S) should be close by few MeV and decaying to $\psi(2S)$ π/η or $\eta_c(2S)$ ρ/ω
- What about X(1^{+-},1S)? Look for any charged state at ≈ 3880 MeV (decaying to $\psi\pi$ or $\eta_c\rho$)
- Similarly one 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.

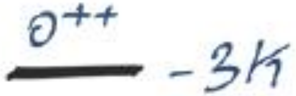
(L.Maiani, A.D.Polosa, V.Riquer, 0708.3997

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





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

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

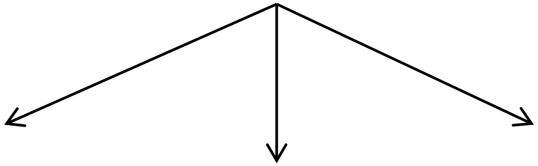
A.D. Polosa, “Bound states in QCD and beyond II”, Germany, 20th - 23rd Feb, 2017

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 $\bar{s}sg$, $\bar{c}cg$ in mass range from 1.8 – 5.0 GeV.
- charmonium-like states cc, i.e. $pp \to \bar{c}c\, pp$; $pp \to \overline{cq}cq'\, pp$ $(q, q' = u, d, s)$
- spectroscopy of baryons and mesons with strangeness and charm:

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

- 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

Software

1. *MpdRoot as a framework*
2. *Pythia8, UrQMD3.3 generators*
3. *MpdRoot Geant3 transport*
4. *MpdRoot TPC Kalman filter – based track and vertex reconstruction*

UrQMD model base on QCD for hadrons production – Very rare mesons decay probably does not exist in this model - **We should implement PLUTO model for UrQMD+PLUTO calculation** (ex. CBM in Darmstadt)

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

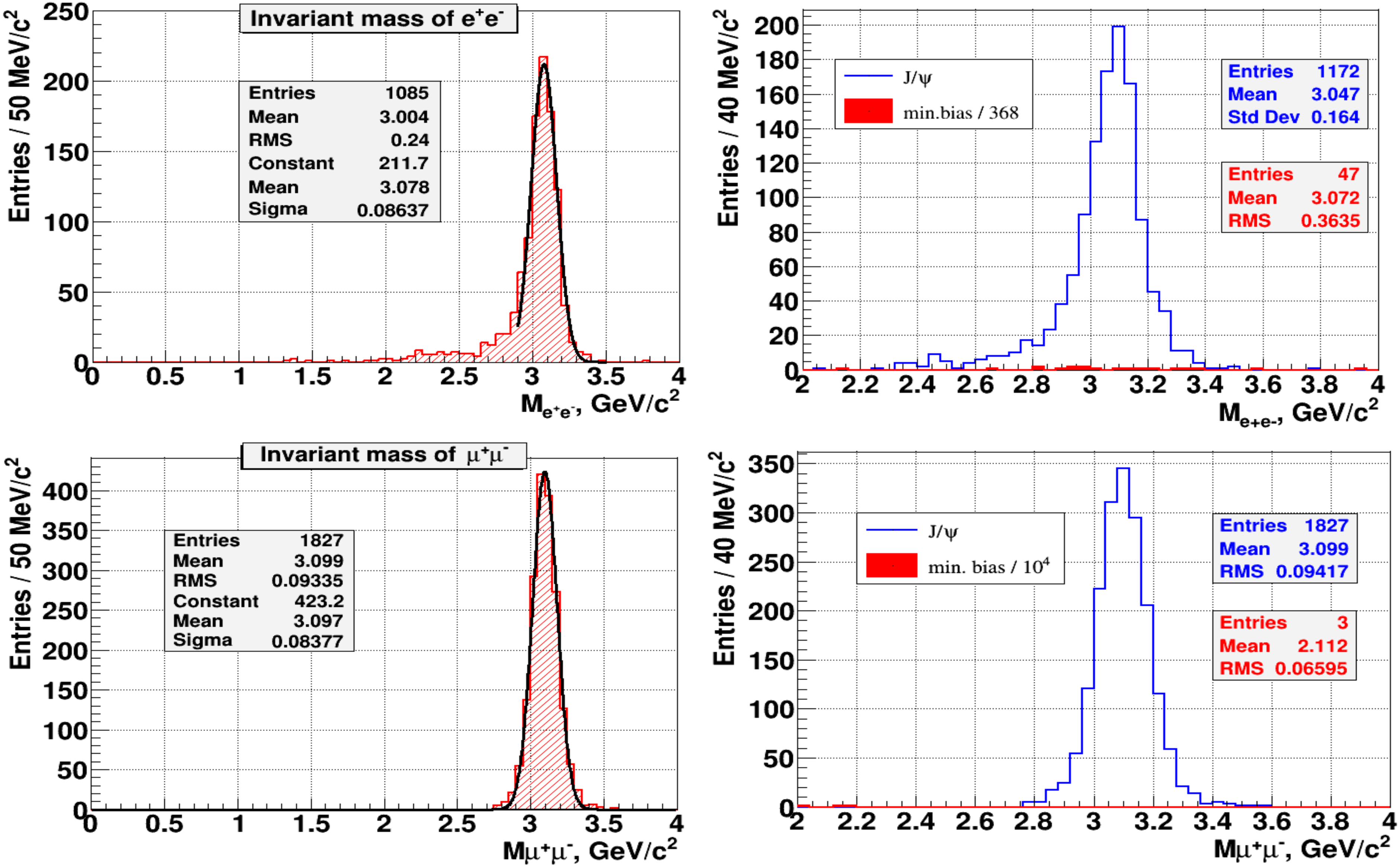
Expectations for J/ψ

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

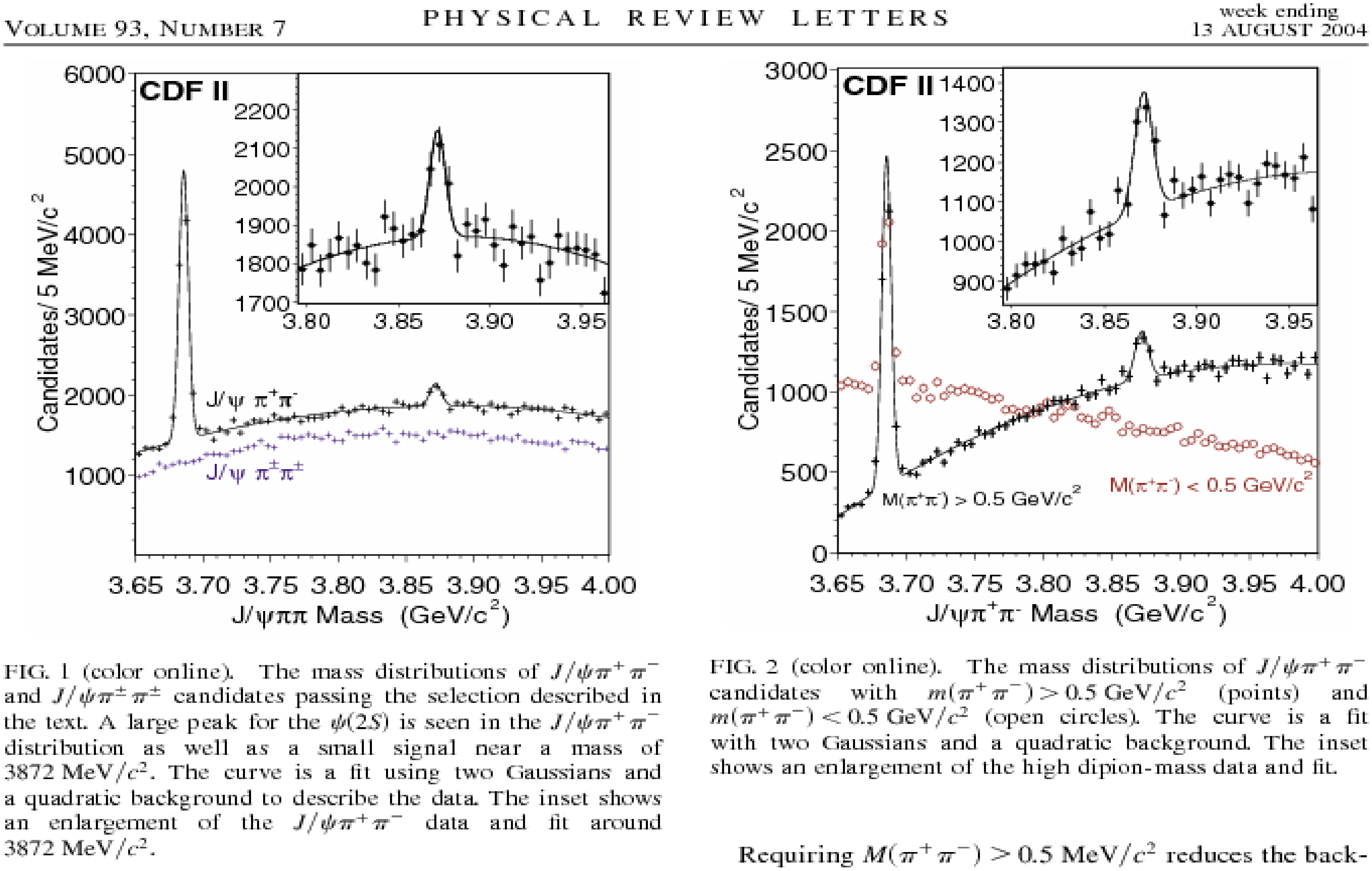
2. Statistics: $N_{J/\psi} = L_{int} \cdot \sigma_{J/\psi} \cdot Br_{J/\psi \rightarrow e+e-} \cdot Eff._{\Delta\eta=\pm 1.5} =$

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

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

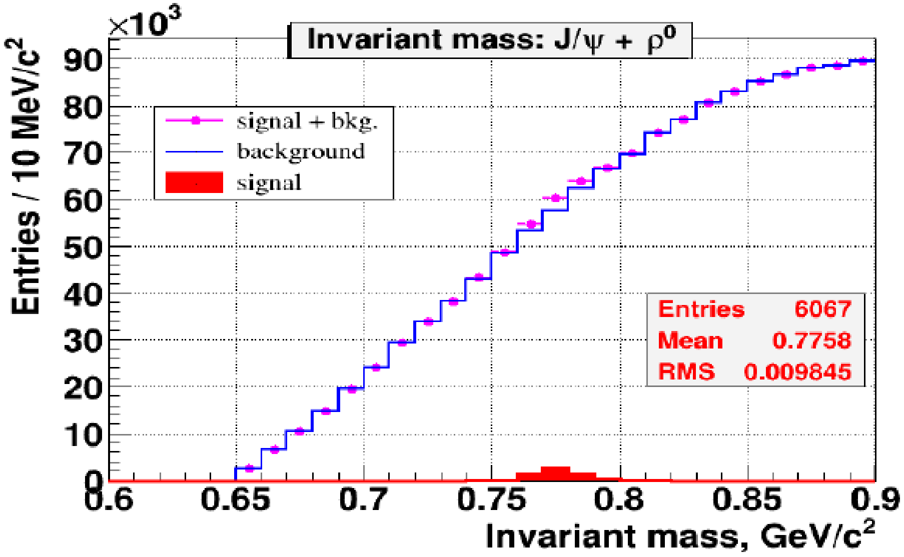
FIG. 1 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ and $J/\psi\pi^\pm\pi^\pm$ candidates passing the selection described in the text. A large peak for the $\psi(2S)$ is seen in the $J/\psi\pi^+\pi^-$ distribution as well as a small signal near a mass of 3872 MeV$/c^2$. The curve is a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

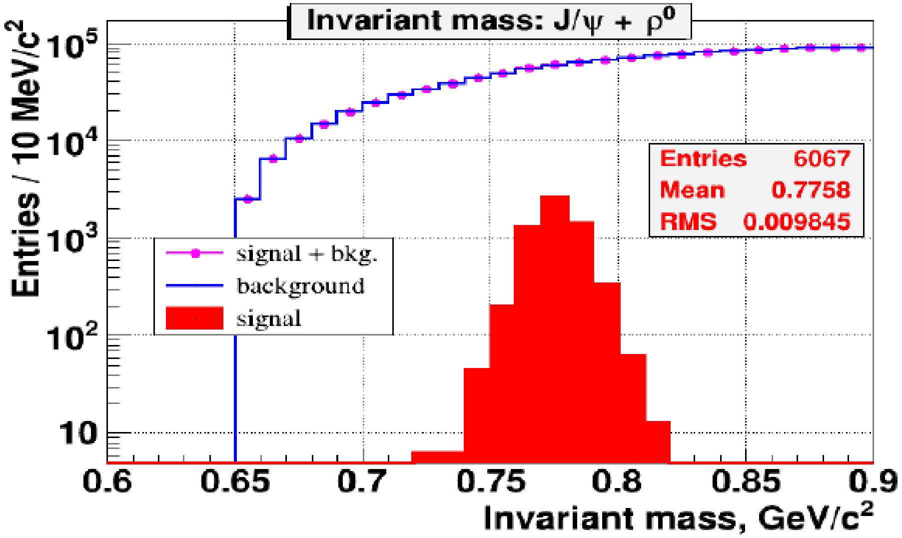
FIG. 2 (color online). The mass distributions of $J/\psi\pi^+\pi^-$ candidates with $m(\pi^+\pi^-) > 0.5$ GeV$/c^2$ (points) and $m(\pi^+\pi^-) < 0.5$ GeV$/c^2$ (open circles). The curve is a fit with two Gaussians and a quadratic background. The inset shows an enlargement of the high dipion-mass data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

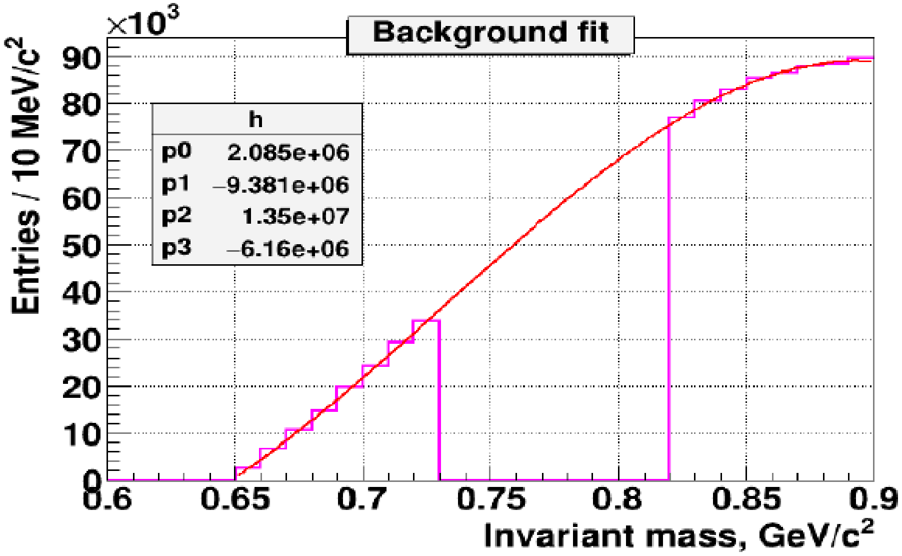
Requiring $M(\pi^+\pi^-) > 0.5$ MeV$/c^2$ reduces the back-

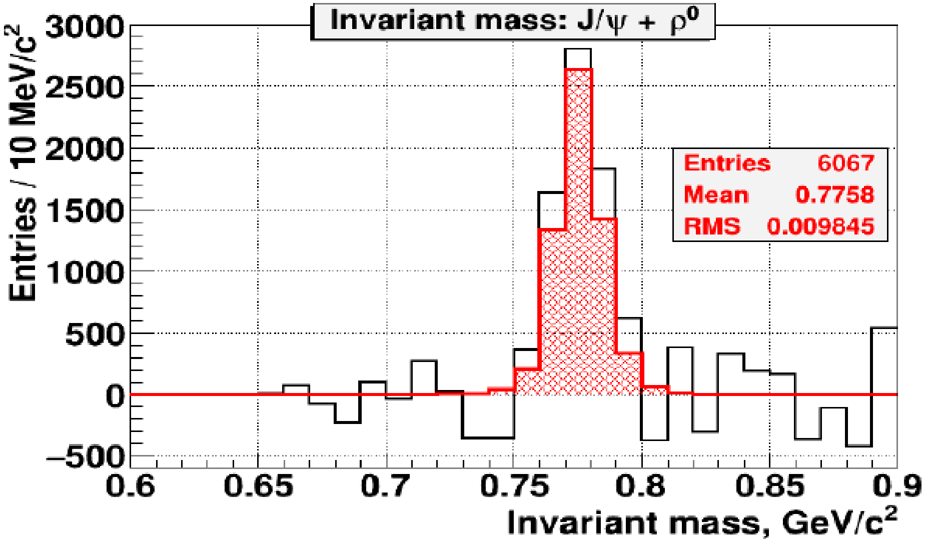
$X(3872) \rightarrow J/\psi + \rho^0$

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 ψ(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)→J/ψ π+π–) = 5.00%
Br (X(3872)→D^+D^-) = 40.45%
Br (X(3872)→D^0D^{*0}bar) = 54.55% ⇒ D^0D^0barπ^0 = 35.29%

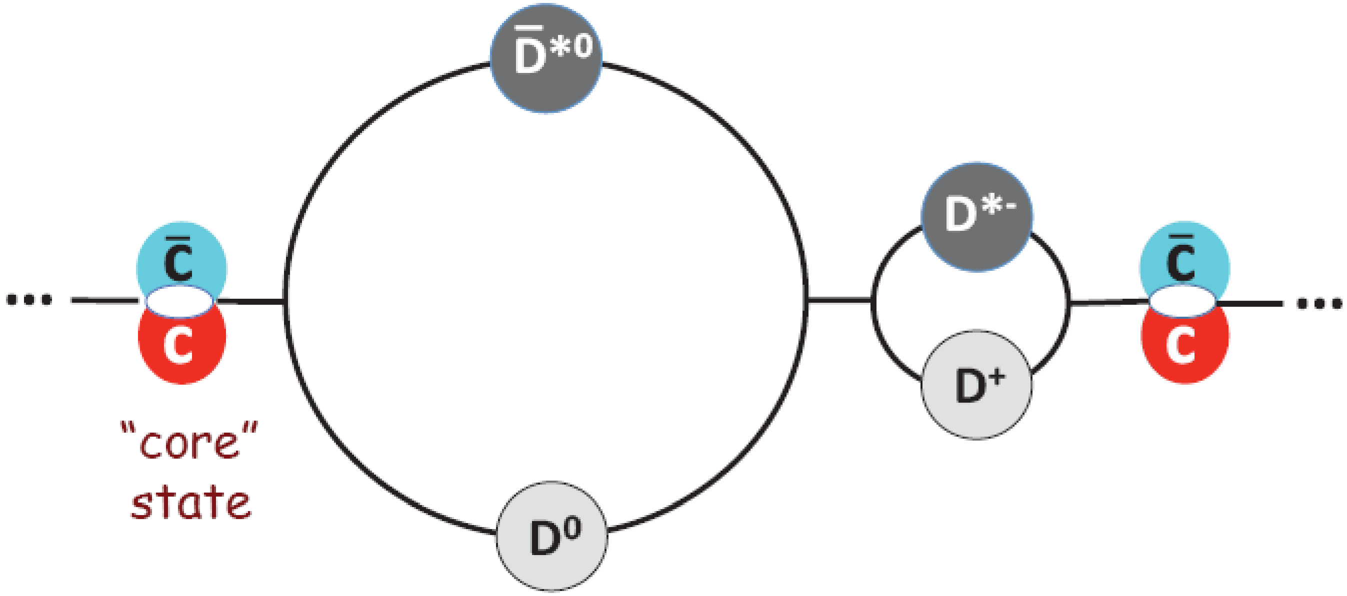
4. Br (D+->K-π+π+) = 9.2%, Br (D0->K-π+) = 3.8%

*5. σ(pCu) * Br(J/ψ π+π–) * Br(e+e-) = 81.9 * 0.05 * 0.06 = 0.246 nb*
*σ(pCu) * Br(D+D-) * Br$(K\pi\pi)^2$ = 81.9 * 0.4045 * 0.092 * 0.092 = 0.280 nb*
*σ(pCu) * Br(D^0D^0barπ^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

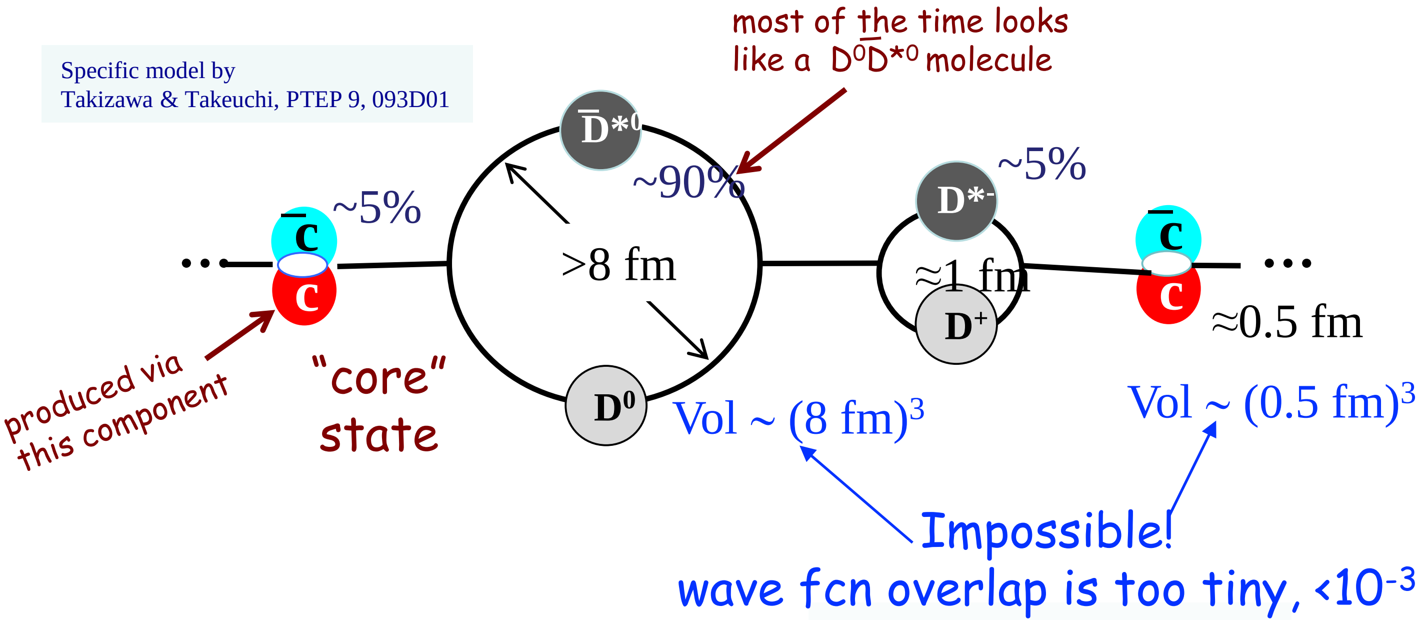


"core" state

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

X(3872) as a D$\bar{D}$* molecule + a c$\bar{c}$-“core” mixture?

-- “consensus” opinion (?) --



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

most of the time looks like a $D^0\bar{D}^{*0}$ molecule

produced via this component

Vol ~ $(8\ \text{fm})^3$

Vol ~ $(0.5\ \text{fm})^3$

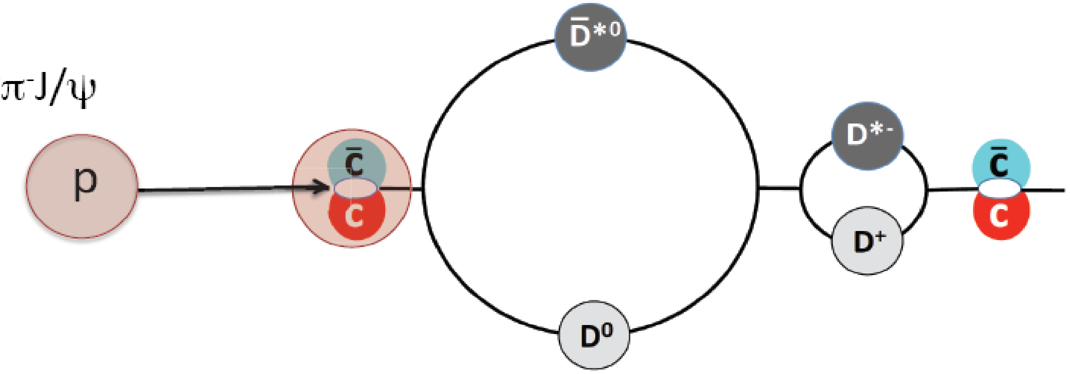
Impossible!

wave fcn overlap is too tiny, $<10^{-3}$

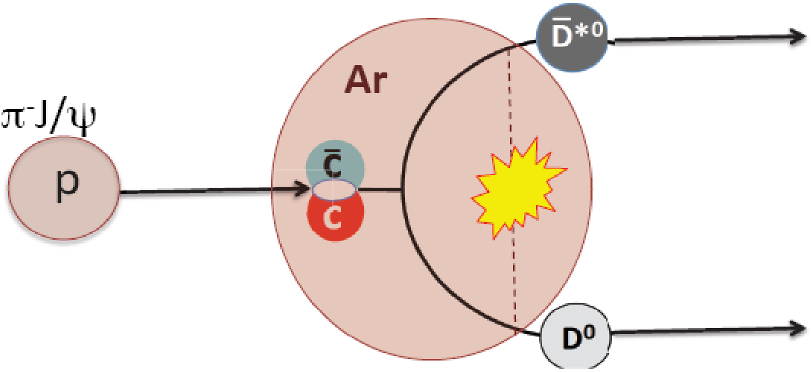
Polosa: “Multiquark Hadrons,” pg 56
Achasov: MPLA 30, 1550181 (2015)

Near-threshold prod. via pp & pA

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



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

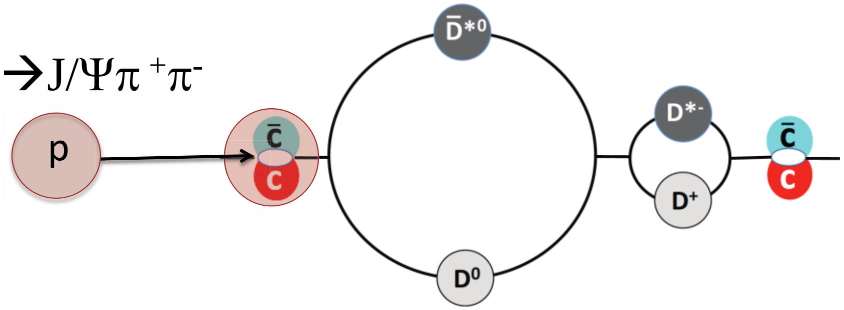


Strong quenching
for A~40 nuclei??

The production experiments with proton-proton and proton-nuclei collisions with $\sqrt{S_{pN}} \geq 8$ GeV planned at NICA may be well suited to test the structure of *X(3872)* and, possibly, other more heavier *XYZ* mesons.

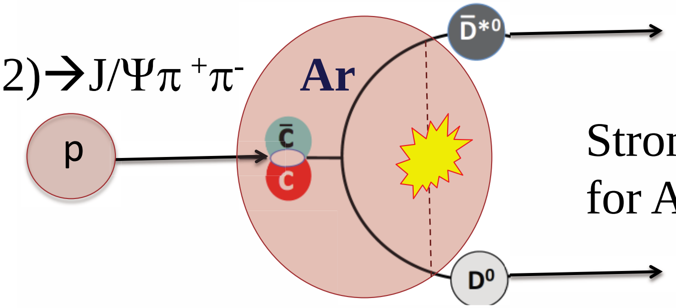
compare production ratio for pp with that for pA

pp→X(3872)→J/Ψ$\pi^+\pi^-$



$$\frac{X(3872)\rightarrow\pi^+\pi^- J/\psi}{\psi'\rightarrow\pi^+\pi^- J/\psi}\approx 5\%$$

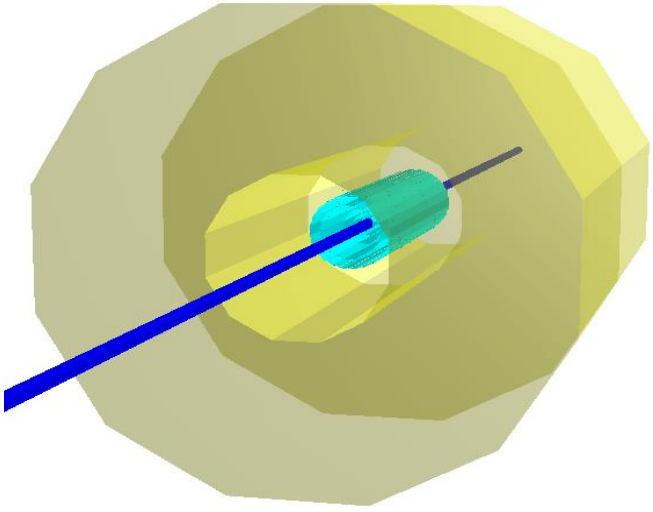
pAr→X(3872)→J/Ψ$\pi^+\pi^-$

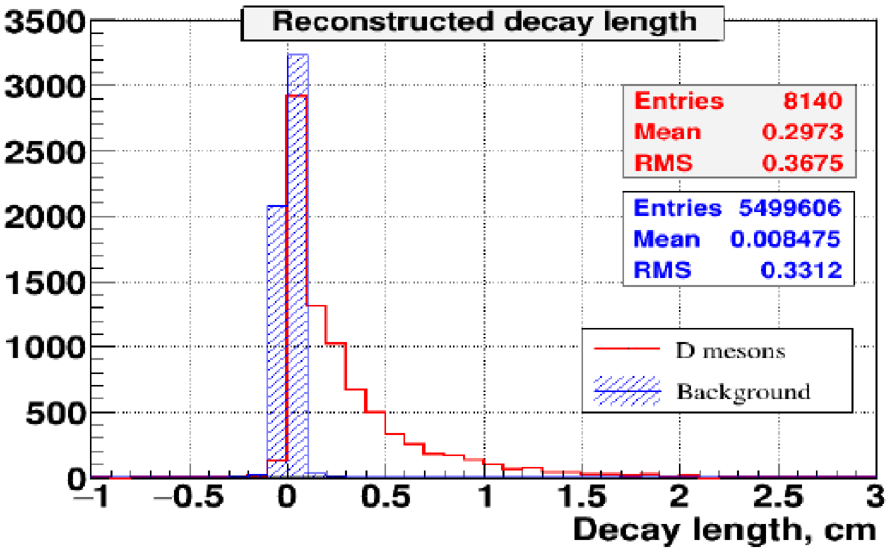


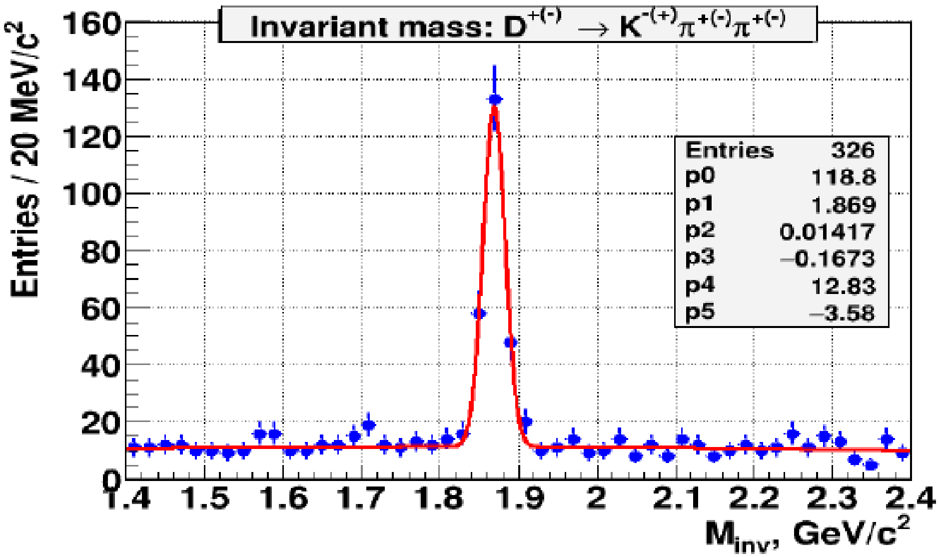
Strong quenching
for A~40 nuclei??

$$\frac{X(3872)\rightarrow\pi^+\pi^- J/\psi}{\psi'\rightarrow\pi^+\pi^- J/\psi} = ???$$

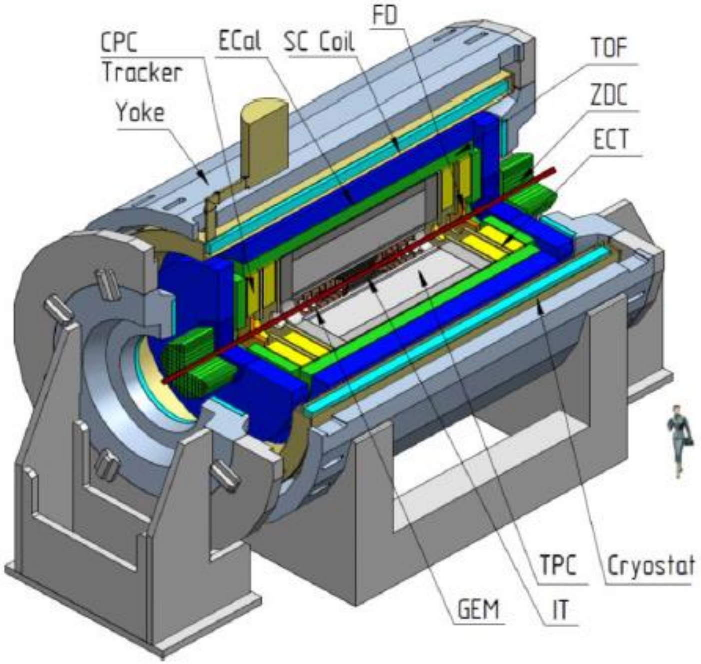
Vertex detector / Inner tracker

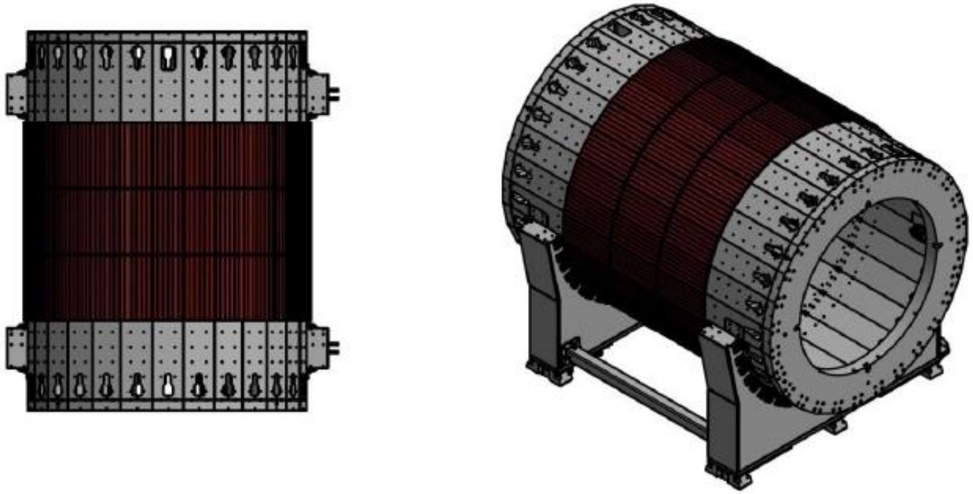


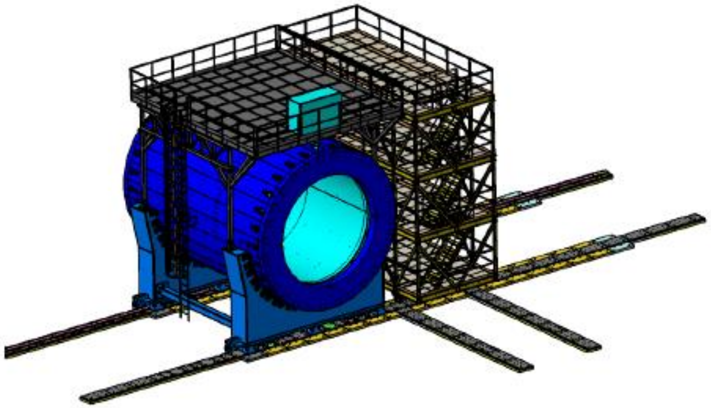




MCORD AND MPD







MCORD - One surface on full circumference

- FD Forward detector
- Superconductor solenoid (SC Coil)
- Inner Tracker (IT)
- Straw-tube Tracker (ECT)
- **Time-projection chamber (TPC)**
- **Time-of-Flight system (TOF)**
- **Electromagnetic calorimeter (EMC - ECal)**
- Zero degree calorimeter (ZDC).
- Cosmic Ray Detector (MCORD)

Marcin Bielewicz et el.

Motivation for the study of muon production in nucleus-nucleus interactions with MCORD at NICA.

In the existing NICA program the study of e^+e^- dileptons is mentioned as one of important goals. When the available energy in the process is larger than the two muon mass ($2 \cdot 105 = 210$ MeV/c^2), the lepton universality lead to the production of muonic dileptons.

The major sources of dileptons are:

1. The decays of light scalar (η, η' …) and vector (ρ, ω , φ ..) mesons.
2. Open charm meson decays.
3. Drell-Yan processes.
4. Thermal muon pairs from dense, hot matter.
5. Possible decays of new, beyond SM, "dark" particles (dark photon and Higgs-like particles).
6. Charmonium and exotics $\mu\mu$-decays may be…?

Advantages
- Very high resolution (track and time)
- Determination of the possible source (High tracking capabilities)
- Unique for horizontal events
- Detector with magnetic field (Muon momentum spectrum and charge rate)
- Work in cooperation with TPC and TOF

Disadvantages
- Rather small size of the detector
- Ground level location
- Only muons and hadrons detection (no e,γ)

Marcin Bielewicz et el.

Summary / Conclusions

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

◆ The experiments with *pp & pA* collisions can obtain some valuable information on the charm production.

◆ Measurements of charmonium-like exotic 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 IT should greatly enhance the research potential (reconstruction and selection).

◆ The MCORD can be useful for detection of rare processes of muonic dilepton production. It can be helpful for better calibration of subdetectors. The opportunity of the precise measurement of atmospheric muon multiplicity distributions as a function of the zenith angle, up to nearly horizontal showers is foreseen.

THANK YOU!

AND

WELCOME FOR COLLABORATION...