PROBING OF EXOTIC MULTIQUARK STATES WITH HADRON AND HEAVY ION COLLISIONS

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Baldin ISHEPP XXV
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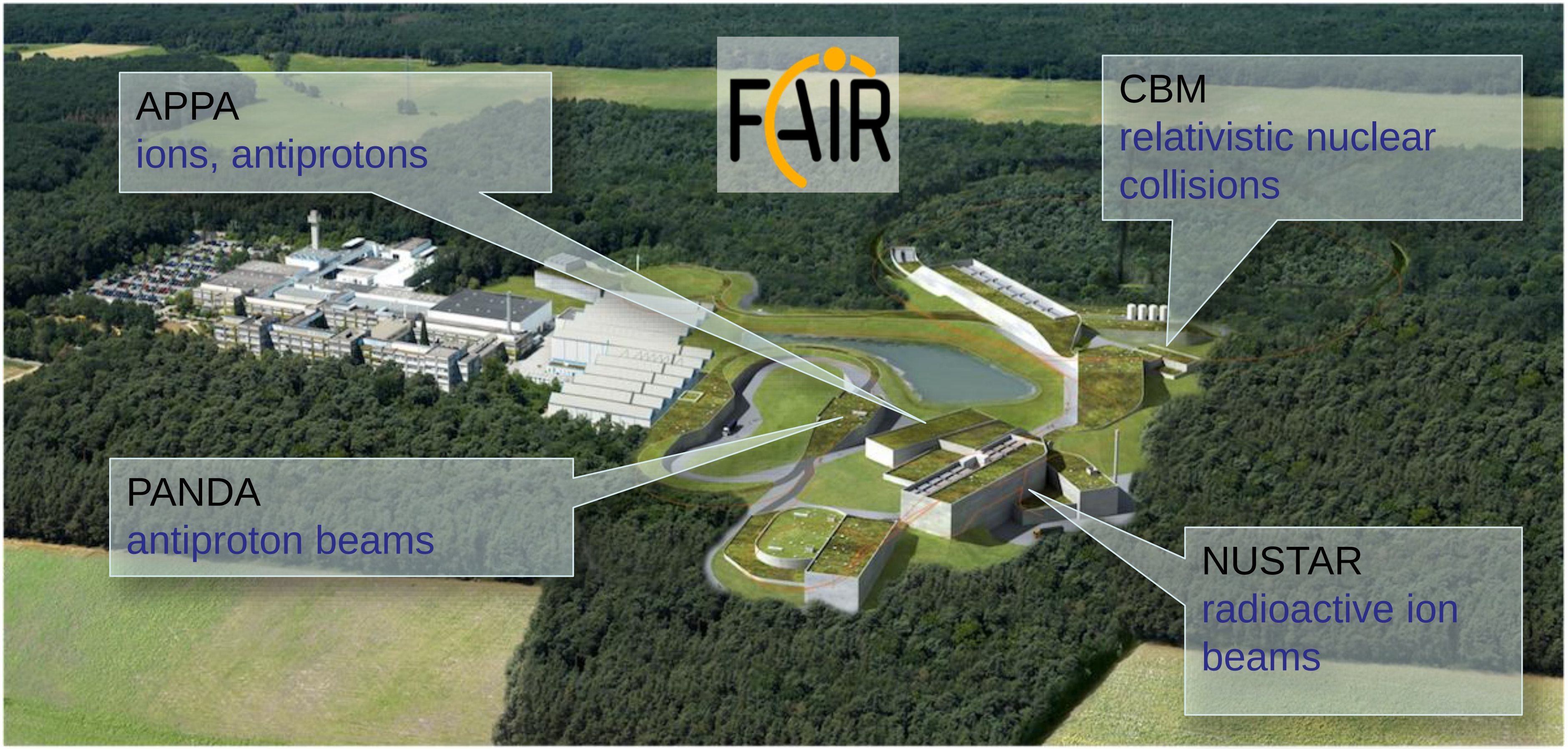
FAIR COMPLEX



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

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

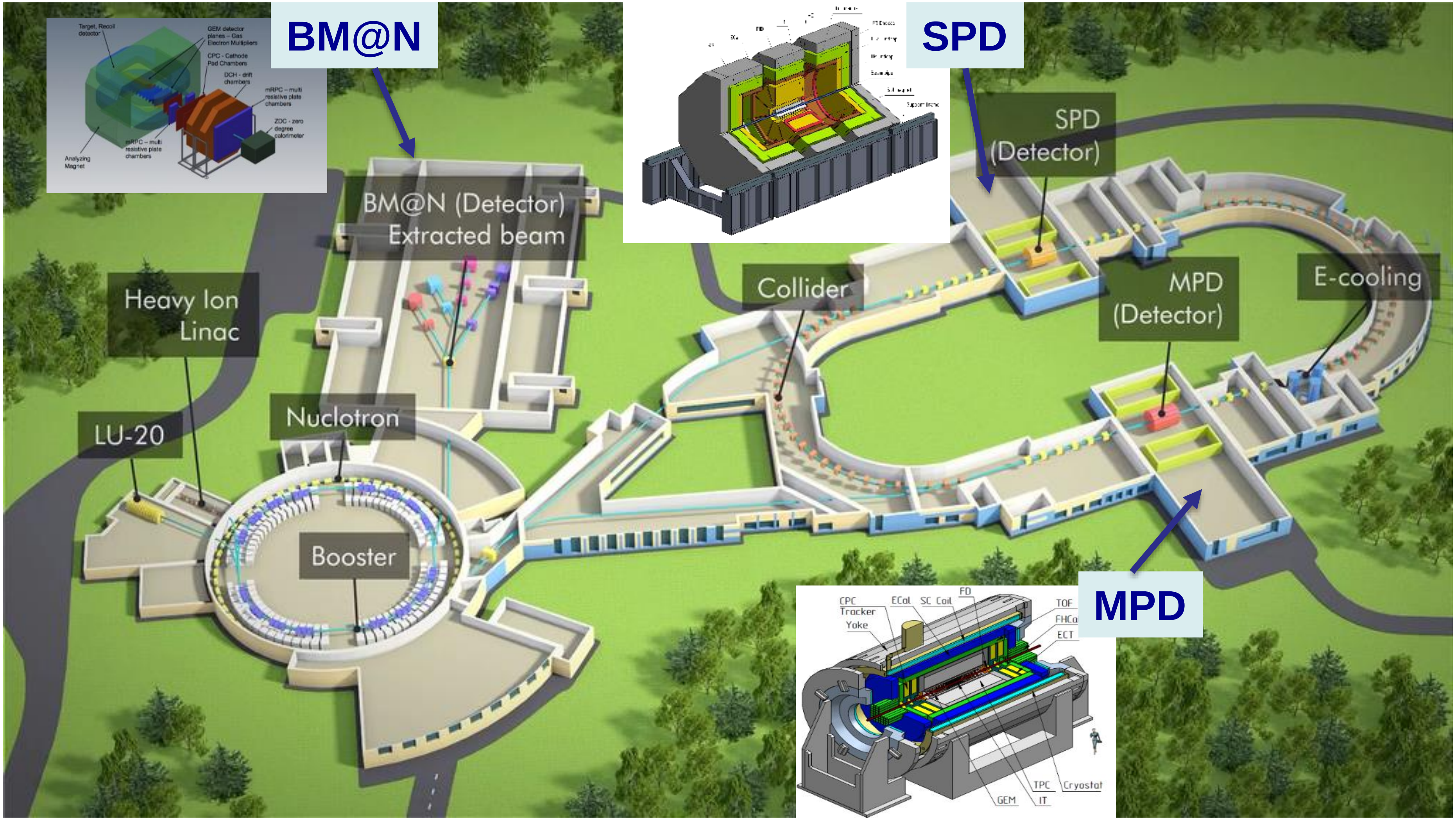
Antiproton production

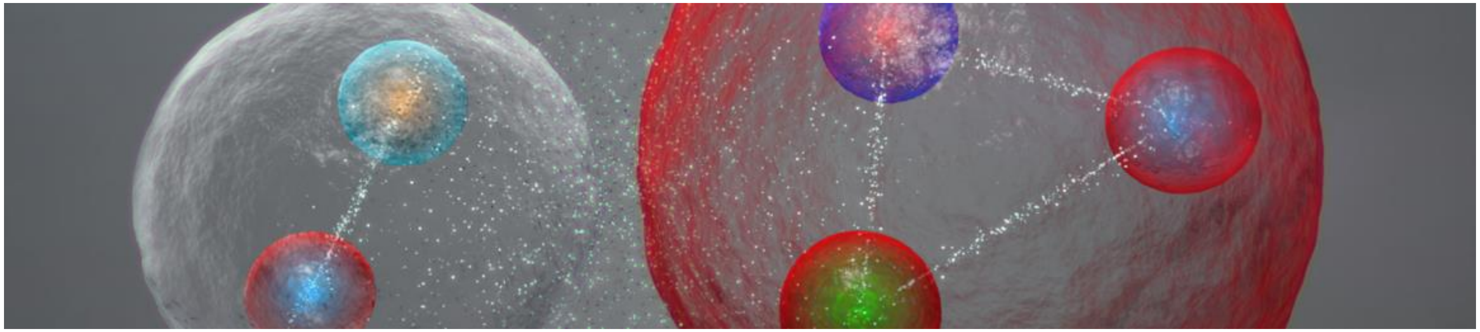
- Proton Linac 70 MeV
- Accelerate p in SIS18 / 100
- Produce $\bar{p}$ on Cu target
- Collection in CR, fast cooling
- Accumulation in RESR
- Storage and usage in HESR

NICA COMPLEX

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

L ~ 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





THE PRESENT AND FUTURE OF HEAVY FLAVOUR AND EXOTIC HADRON SPECTROSCOPY

Munich, Germany, 8 May - 2 June 2023

https://munich-iapbp.de/heavyflavour

ORGANIZERS:

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Mikhail Mikhasenko (ORIGINS Excellence Cluster)

MOTIVATION

To look for different flavor hadrons together with charmonium-like states (conventional and exotic) in *pA* and *AA* collisions to obtain complementary results to the ones from *e+e-* interactions, *B*-meson decays and pp\bar interactions (on a restricted scale of energy)

HADRONIC PHYSICS BEFORE AND AFTER 2003

Consensus before 2003:

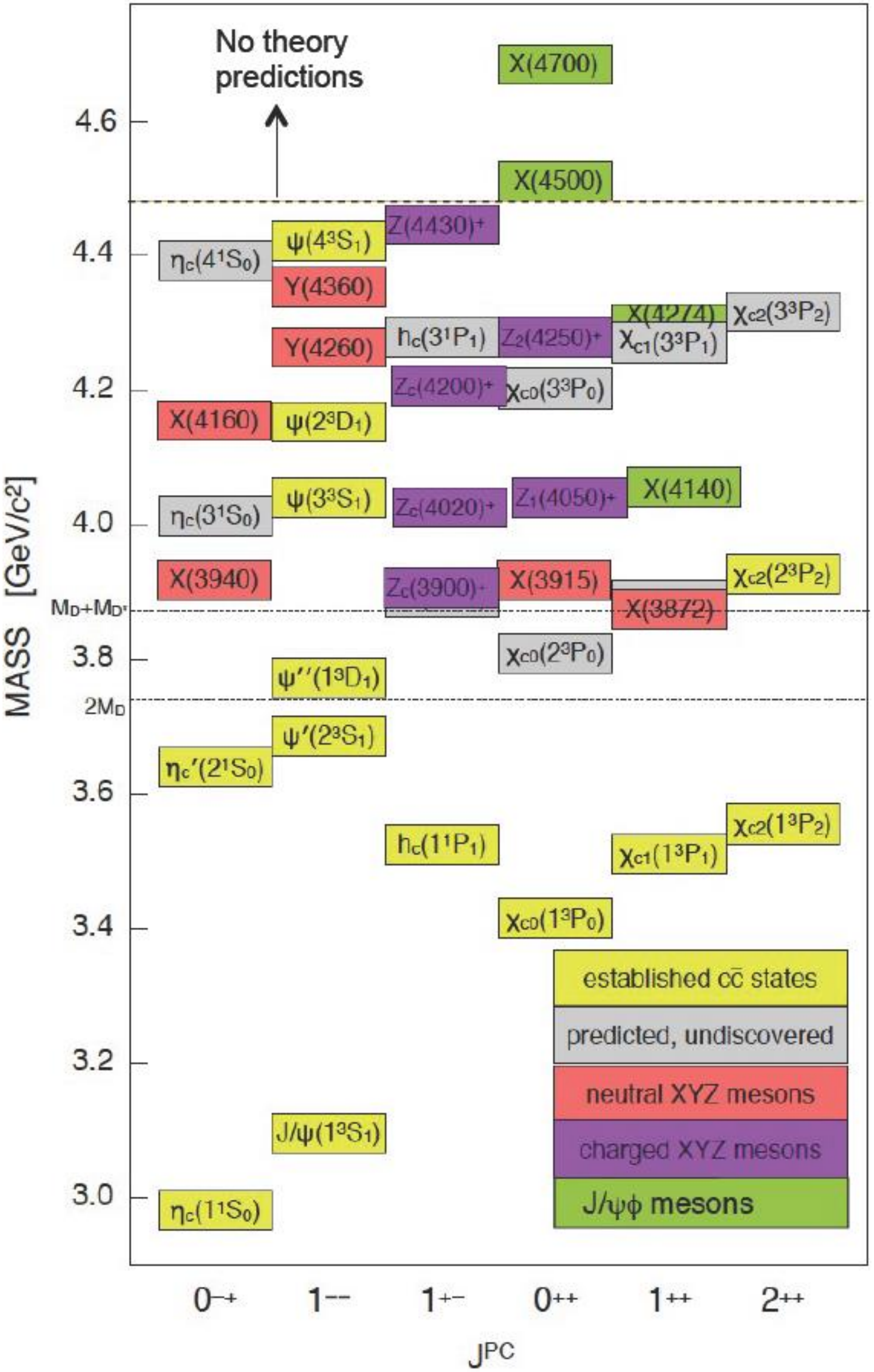
- Quark model provides a decent description of low-lying hadrons
- Quark model works surprisingly well even for light flavours
- Heavy flavours (c and b) comply with nonrelativistic theory
- Relatisitc corrections improve the description
- Experiment gradually fills "missing states"
- Lattice provides additional/alternative source of information

Situation after 2003:

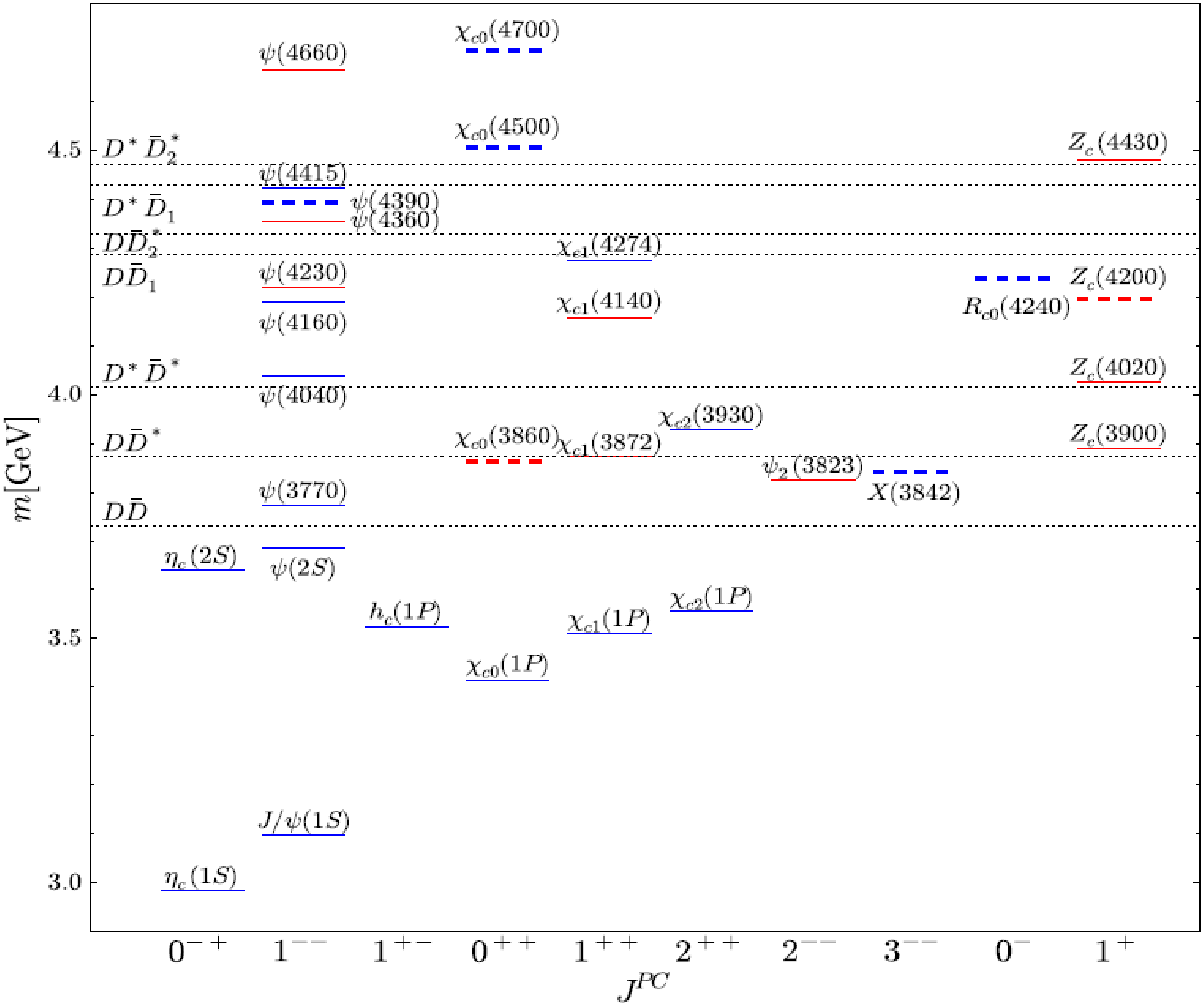
- $X(3872)$ observed by Belle with properties at odds with quark model
- Number of such unconventional hadrons with heavy quarks grows fast
- New branch of hadrons spectroscopy — exotic XYZ states

QUARKONIUM-LIKE STATES

- 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/ψφ states

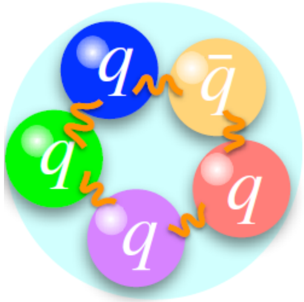


QUARKONIUM-LIKE STATES

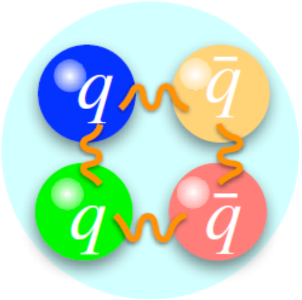


NON-STANDARD EXOTIC HADRONS

Evidence for QCD exotic states is a missing piece
of knowledge about the nature of strong QCD

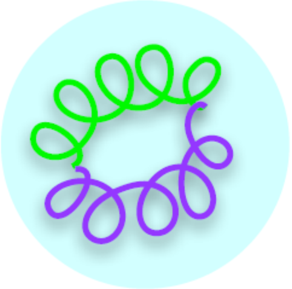


Pentaquarks
4 quarks and 1 antiquark

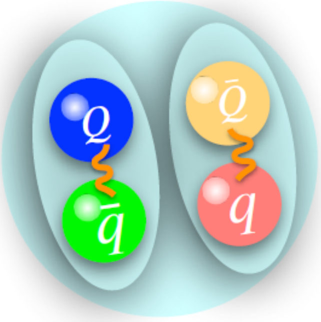


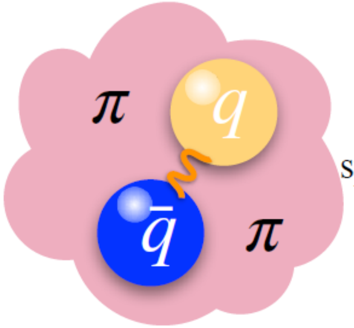
Tetraquarks
2 quarks and 2 antiquarks

Glueball
only gluons, no quarks

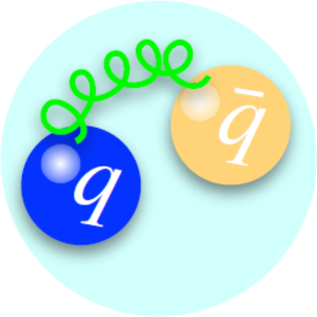


Hadronic molecule
2 loosely bound heavy mesons





Hadroquarkonium
specific quarkonium core “coated” by
excited light-hadron matter



Hybrid
states with excited gluonic
degrees of freedom

threshold effects should also be taken into account

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.

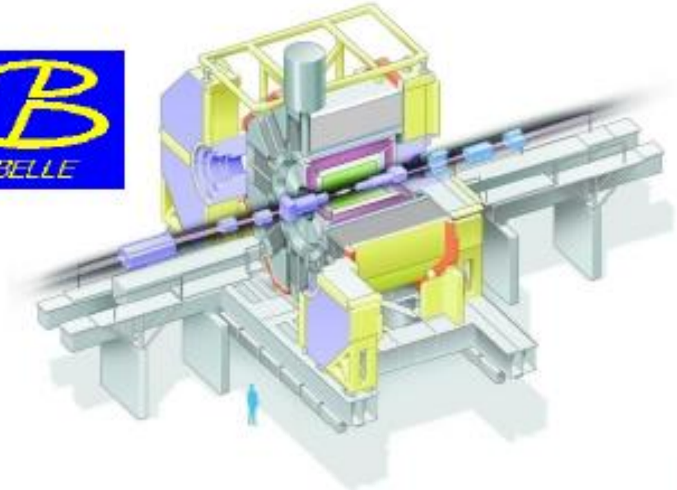
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

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.

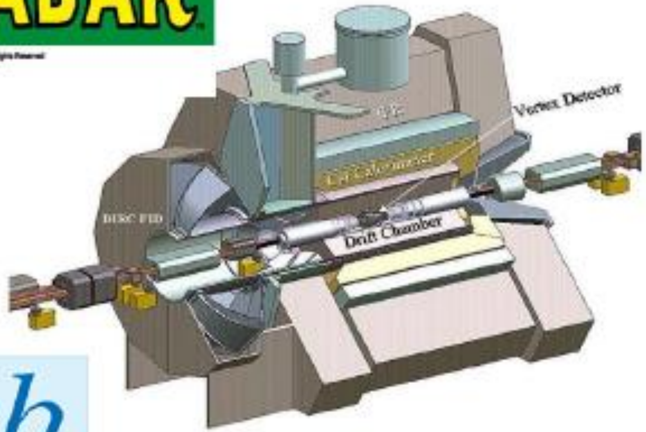
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the 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**.

RESULTS WERE OBTAINED FROM THESE EXPERIMENTS

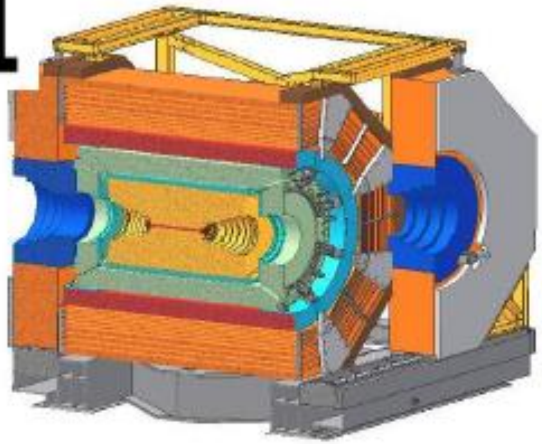
BELLE



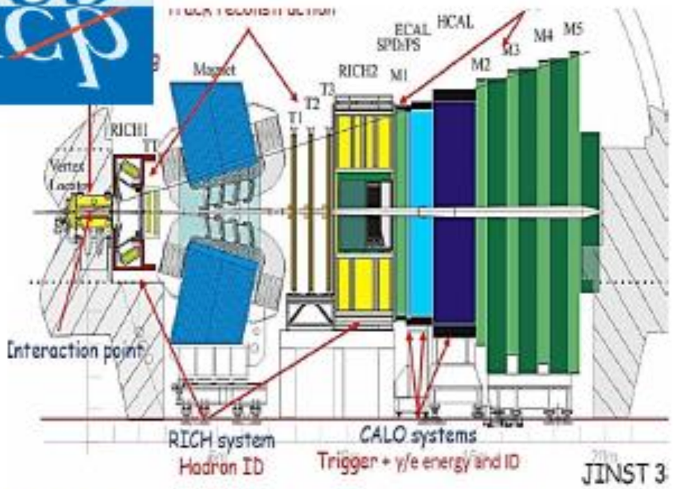
BABAR



BESIII

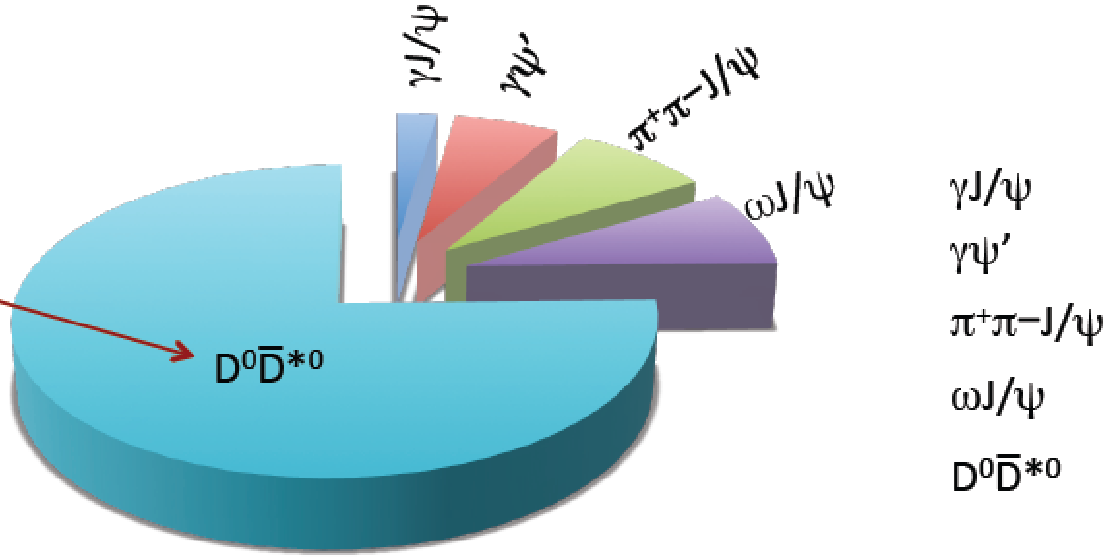


LHCb



+ CLEOc, CDF, CMS/ATLAS …

X(3872) decay channels



strong $D\bar{D}^*$ coupling

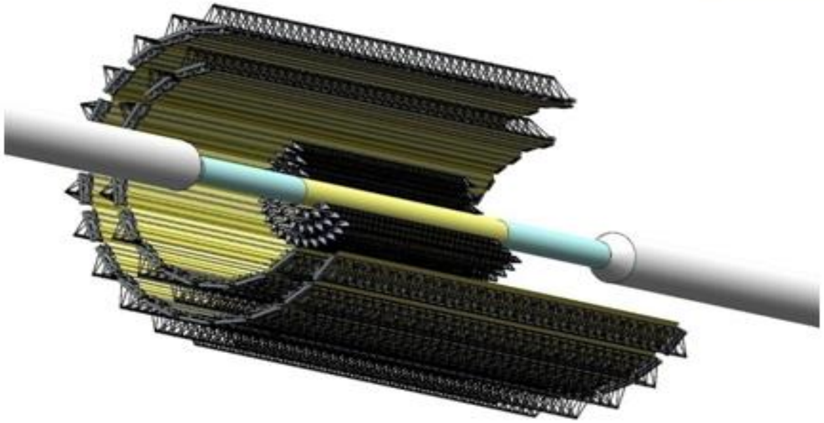
$$\Gamma_{\text{“tot”}} \approx 15\,\Gamma(X(3872)\rightarrow\pi^+\pi^- J/\psi)$$

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

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

MPD INNER TRACKING SYSTEM BASED ON MAPS

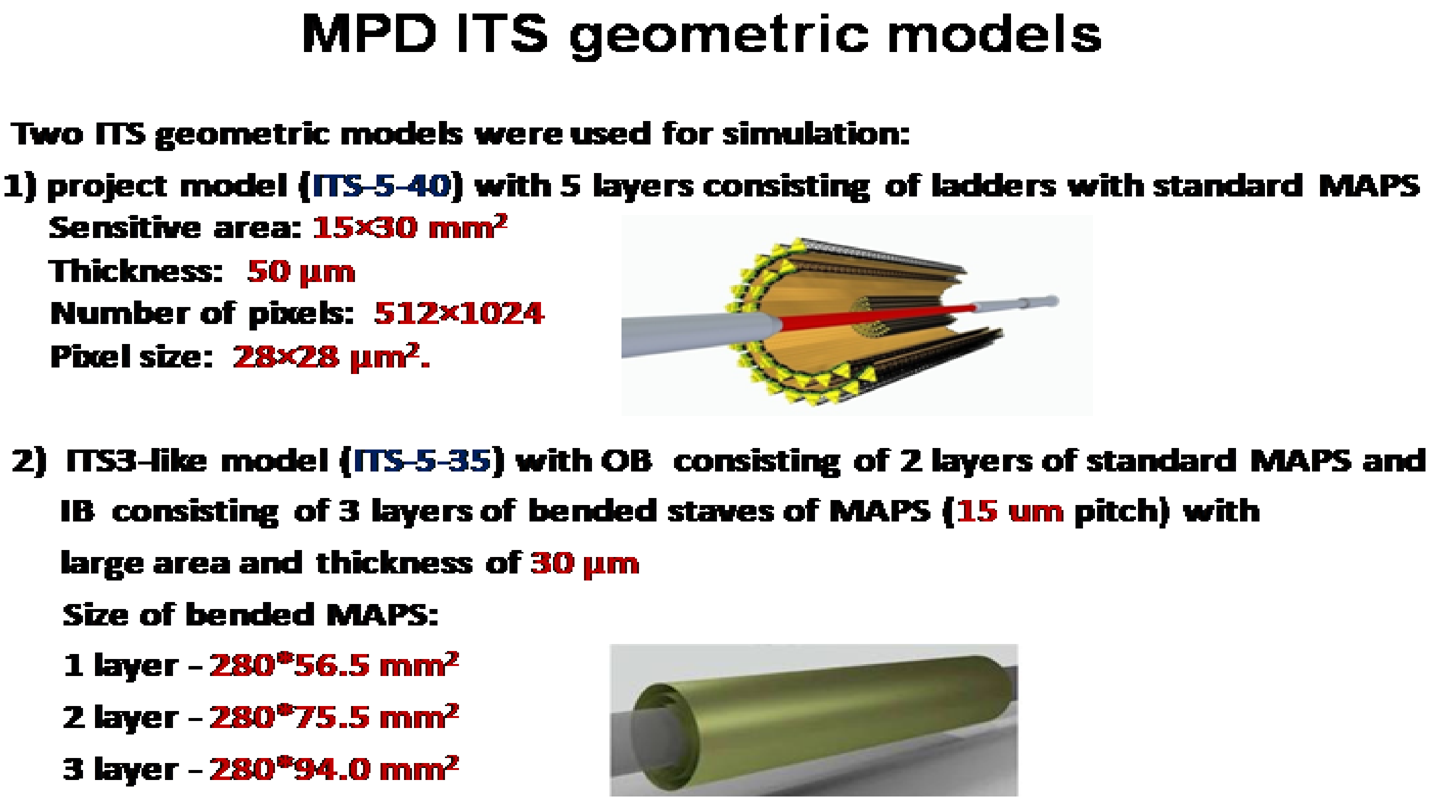
Reconstruction of charmed particles in Au+Au central collisions with MPD ITS3+TPC tracking system



Open charm studies: exclusive decays ⟶ Inner tracking System (ITS). Dedicated track reconstruction methods ("Vector Finder").

mpd.jinr.ru/doc/mpd-tdr

MPD INNER TRACKING SYSTEM BASED ON MAPS



MPD ITS geometric models

Two ITS geometric models were used for simulation:

1) project model (ITS-5-40) with 5 layers consisting of ladders with standard MAPS

Sensitive area: 15×30 mm^2

Thickness: 50 µm

Number of pixels: 512×1024

Pixel size: 28×28 µm^2.

2) ITS3-like model (ITS-5-35) with OB consisting of 2 layers of standard MAPS and IB consisting of 3 layers of bended staves of MAPS (15 um pitch) with large area and thickness of 30 µm

Size of bended MAPS:

1 layer - 280*56.5 mm^2

2 layer - 280*75.5 mm^2

3 layer - 280*94.0 mm^2

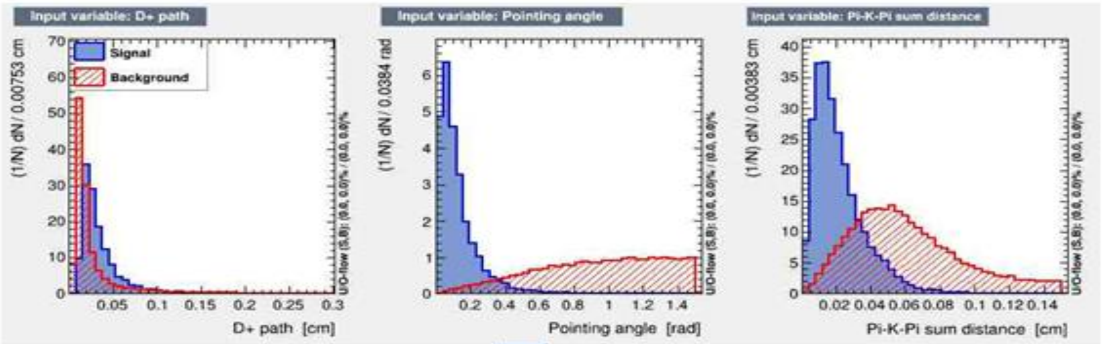
mpd.jinr.ru/doc/mpd-tdr

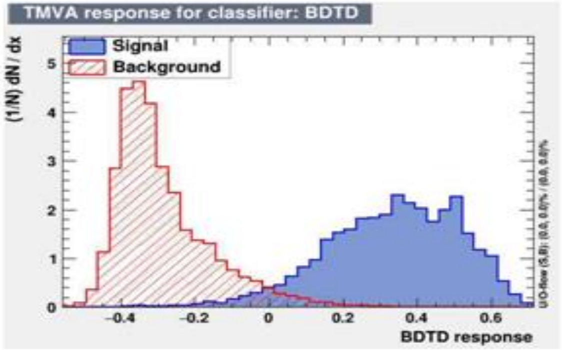
D+ RECONSTRUCTION

D^+ reconstruction in ITS-5-35 + TPC using VF + TMVA

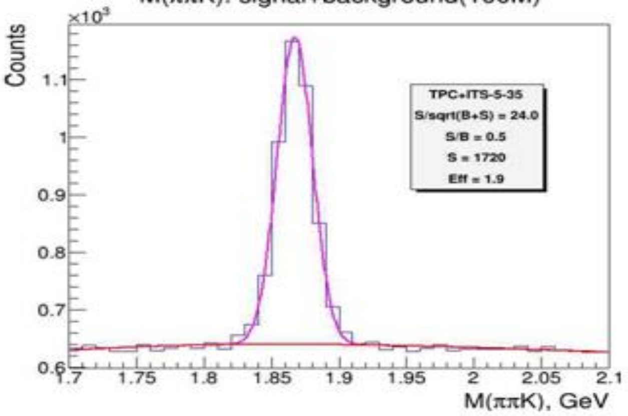
dca(π), dca(K), dist(πK), λ(D^+), θ(D^+) cuts

BDT cut





M(ππK): signal+background(100M)



D^+ reconstruction efficiency obtained: ε=1.9%

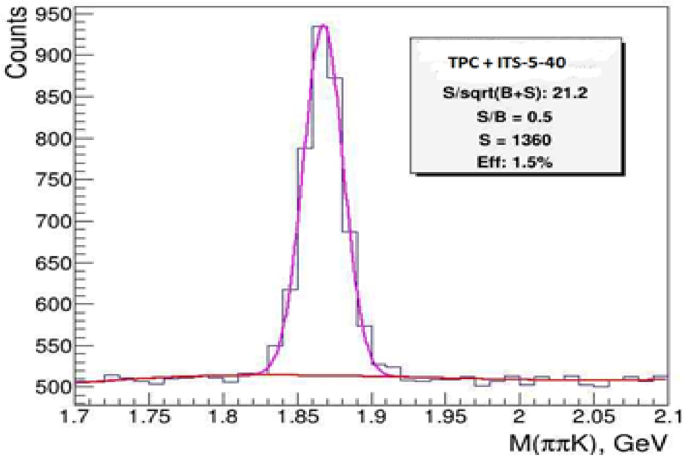
V. Kondratev

D$^+$ RECONSTRUCTION

D$^+$ reconstruction efficiency with two ITS models

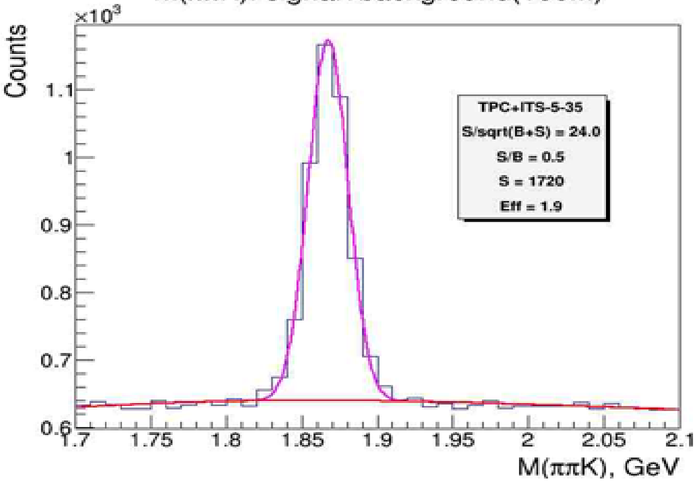
Project model

M(ππK): signal+background(100M)



ITS3-like model

M(ππK): signal+background(100M)



ITS	S	S/B	$S/\sqrt{S+B}$	ε, %
ITS-5-40	1360	0.50	21.2	1.5
ITS-5-35	1720	0.50	24.0	1.9

The reconstruction efficiency increases by 25% when using ITS with an Internal Barrel built on the base of a new type of sensors (bended MAPS with large area)

V. Kondratev

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

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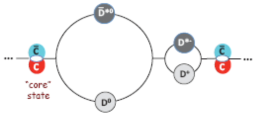
The spectroscopy of charmonium-like mesons with masses above the $2m_D$ open charmed threshold has been full of surprises and remains poorly understood [1]. The currently most compelling theoretical descriptions of the mysterious XYZ mesons attributes them to hybrid stucture with a tightly bound $c\bar{c}$ diquark [2] or a $c\bar{c}q\bar{q}'$ tetraquark [3] core that strongly couples to S-wave $D^{(*)}\bar{D}^{(*)}$ molecule-like structures. In this picture, the production of an XYZ particle in high energy hadron collisions and its decays to light hadron + charmonium final states proceed via the core component of the meson, while decays to pairs of open-charmed mesons proceed via the $D^{(*)}\bar{D}^{(*)}$ component.

These ideas have been applied with some success to the $X(3872)$ [2], where a detailed calculation finds a $c\bar{c}$ core component that is only about 5 percent of the time, with the $D\bar{D}^*$ component (mostly $D^0\bar{D}^{*0}$) accounting for the rest. In this picture, illustrated in cartoon form in Fig. 1, the $X(3872)$ is composed of three rather disparate components: a small charmonium-like $c\bar{c}$ core with $r_{\rm rms} < 1$ fm, a larger D^+D^{*-} component with $r_{\rm rms} = \hbar/\sqrt{2\mu_+ B_+} \simeq 1.5$ fm and a dominant $D^0\bar{D}^{*0}$ component with a huge, $r_{\rm rms} = \hbar/\sqrt{2\mu_0 B_0} > 9$ fm spatial extent. Here μ_+ (μ_0) and B_+ (B_0) denote the reduced mass for the D^+D^{*-} ($D^0\bar{D}^{*0}$) system and the relevant *binding energy*: $|(m_D + m_{D^*}) - M_{X(3872)}|$ ($B_+ = 8.2$ MeV and $B_0 < 0.3$ MeV). The different amplitudes and spatial distributions of the D^+D^{*-} and $D^0\bar{D}^{*0}$ components ensure that the $X(3872)$ is not an isospin eigenstate; instead it is mostly $I = 0$, but has a significant (~ 25 percent) $I = 1$ component.



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

Figure 1: The $X(3872)$ in a hybrid picture. The numerical values come from ref. [2].

In the hybrid scheme, an $X(3872)$ is produced in high-energy pN collisions via its compact ($r_{\rm rms} < 1$ fm) charmonium-like structure and this rapidly mixes (in a time $t \sim \hbar/\delta M$) into huge and fragile, mostly $D^0\bar{D}^{*0}$, molecule-like structure; δM is the difference between the $X(3872)$ mass and that of the nearest $c\bar{c}$ mass pole core state, which we take to be that of the the $\chi_{c1}(2P)$ pure charmonium state that is expected to lie about $20 \sim 30$ MeV above $M_{X(3872)}$ [4]. In this case, the mixing time, $c\tau_{\rm mix} = 5 \sim 10$ fm, is much shorter than the the lifetime of the $X(3872)$, which is $c\tau_{X(3872)} > 150$ fm [5].

The NICA superconducting collider is uniquely well suited to test this picture for the $X(3872)$ (and, possibly, other XYZ mesons). In near-threshold production experiments in the $\sqrt{s_{pN}} \simeq 8$ GeV energy range, $X(3872)$ mesons can be produced with typical c.m.s. kinetic energies of a few hundred MeV (*i.e.*, with $\gamma\beta \simeq 0.3$). In the case of the $X(3872)$, its decay length will be greater than 50 fm while the distance scale for the $c\bar{c} \to D^0\bar{D}^{*0}$ transition would be $2 \sim 3$ fm. Since the survival probability of an $r_{\rm rms} \sim 9$ fm "molecule" inside nuclear matter should be very small, $X(3872)$ meson production on a nuclear target with $r_{\rm rms} \sim 5$ fm or more ($A \sim 60$ or larger) should be strongly quenched (see Fig. 2). Thus, if this hybrid picture is correct, the atomic number dependence of $X(3872)$ production at fixed $\sqrt{s_{pN}}$ should have a dramatically different behaviour than that of the ψ', which is a long-lived compact charmonium state.

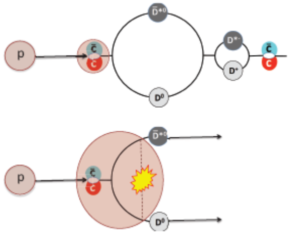


Figure 2: **(Top)** $X(3872)$ production on a proton target ($r_{\rm rms} \simeq 1$ fm). Here the $X(3872)$ escapes the target region before it establishes a significant $D\bar{D}^*$ component. **(Bottom)** $X(3872)$ production on a nuclear target. Here the presence nuclear material disrupts the (< 200 keV) coherence between the well separated D^0 and D^{*0} (represented by the dashed line).

In this talk I will summarize the current experimental status of the XYZ mesons and hidden-charm pentaquark candidates and present simulations of what we might expect from an A-dependence of $X(3872)$ mesons at NICA.

References

[1] See, for example, S.L. Olsen, Front. Phys. **10**, 101401 (2015).

[2] S. Takeuchi, K. Shimizu and M. Takizawa, Prog. Theor. Exp. Phys. **2015**, 079203 (2015).

[3] A. Esposito, A. Pilloni and A.D. Polosa, arXiv:1603.07667 [hep-ph].

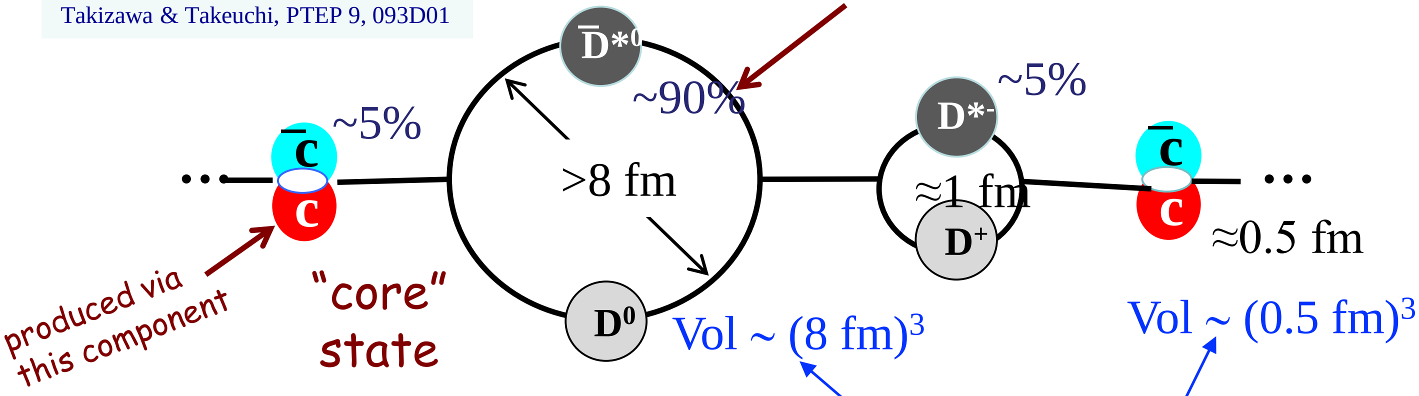
[4] Here we use $\chi_{c2}(2P)$-$\chi_{c1}(2P)$ mass splitting from S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985) and scale the $\chi_{c1}(2P)$ mass from the measured $\chi_{c2}(2P)$ mass reported in K.A. Olive *et al.* (PDG), Chin. Phys. C **38**, 090001 (2014).

[5] The width of the $X(3872)$ is experimentally constrained to be $\Gamma_{X(3872} < 1.2$ (90% CL) in S.-K. Choi *et al.* (Belle Collaboration), Phys. Rev. D **84**, 052004 (2011).

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

$\sim$90%

>8 fm

$\sim$5%

$\approx$1 fm

$\sim$5%

$\approx$0.5 fm

"core" state

produced via this component

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

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

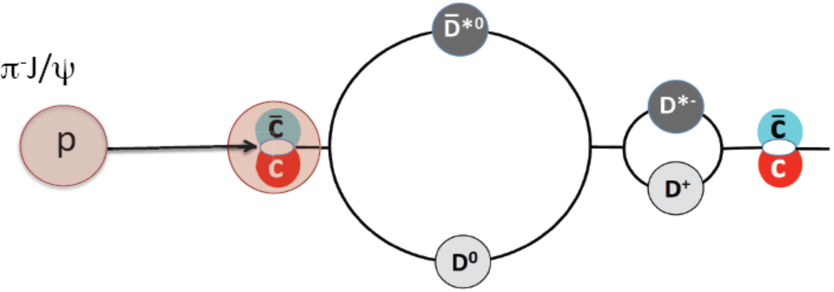
Impossible!

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

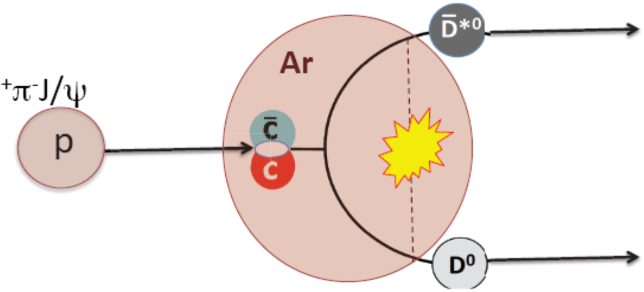
Polosa: “Multiquark Hadrons,” pg 56
Achasov: MPLA 30, 1550181 (2015)

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??

Use NICA, a new pp/pA/AA collider at JINR (Dubna)?

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

In near threshold production experiments with the $\sqrt{S_{pN}} \approx 8$ GeV energy range, *XYZ* mesons can be produced with typical low kinetic energies of a few hundred MeV.

Since the survival probability of such “molecular” inside nuclear matter should be very small, *XYZ* meson production on a nuclear target with A ~ 40 or larger should be strongly quenched.

Thus, if this hybrid picture is correct, the atomic number dependence of X(3872) production at fixed $\sqrt{S_{pN}}$ for A ~ 40 or larger should have a dramatically different behavior than that of the *Ψ‘*, which is a long-lived compact charmonium state.

SUMMARY

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

♦ Modern facilities with hadron and heavy ion collisions should provide good opportunities for identification of charged and neutral particles and shed light on the nature of exotics.

♦ The experiments with *pp* and *pA* collisions at NICA can obtain some valuable information on the charm production. For hadronic decays the ITS should greatly enhance the research potential (reconstruction and selection).

♦ Measurements of charmonium-like states may be considered as one of the “pillars” of the *pp* and *pA* program at NICA.

THANK YOU!

and

WELCOME FOR COLLABORATION…

Toolkit for MultiVariate Analysis

TMVA is a ROOT package for training, testing and performances evaluation of multivariate classification techniques.

Analysis is generally organized in 2 steps :

- ☐ **Training phase**

  At this stage the variables from the signal and background samples are trained according the classifier chosen by the user. The results of the classification is written into weight files, traducing the initial **N** input variables **V** to one dimensional variable **R** (response) :

  $$\mathbf{V^N \rightarrow R}$$

- ☐ **Application phase**

  At this stage the data classification, reading from the weight files, is applied to the data to be analyzed.

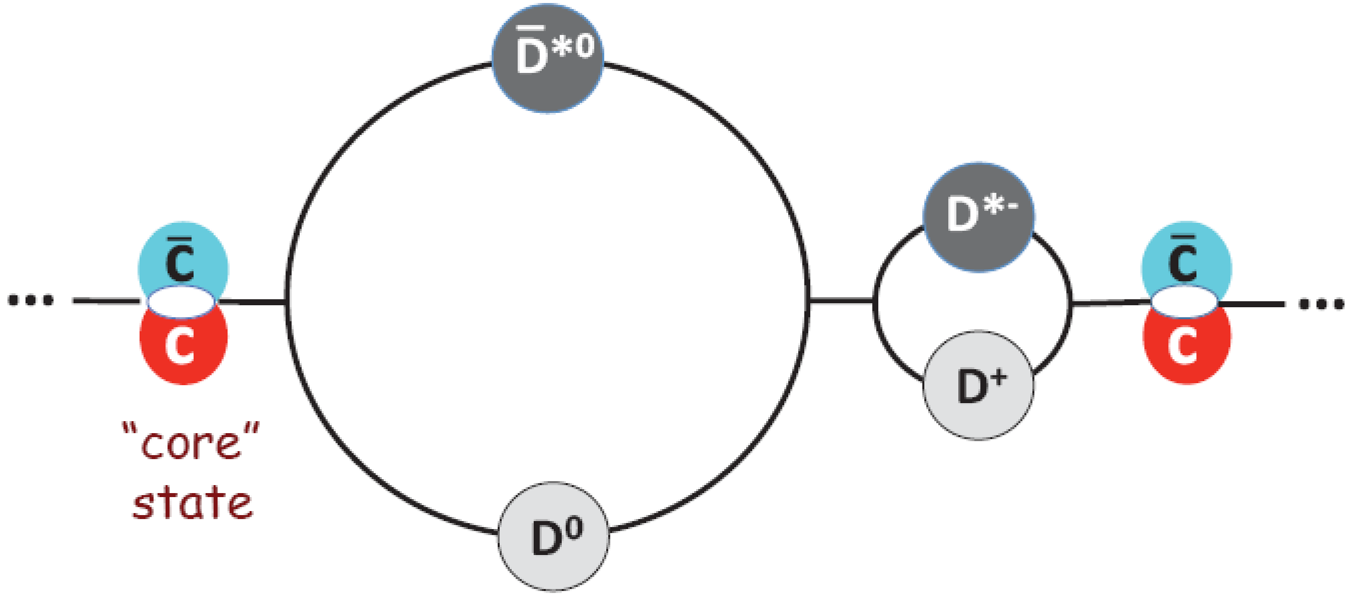
The classifier BDT (Boosted Decision Trees) has been chosen for the analysis phase when reconstructing D mesons

Charm in AA

1. *J/ψ polarization studies*
2. *Open charm selection via hadronic decays*

Can the X(3872) structure be probed?

Takizawa & Takeuchi, PTEP 9, 093D01



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