PERSPECTIVES OF CHARMONIUM AND EXOTICS STUDIES WITH pp & pA COLLISIONS at NICA

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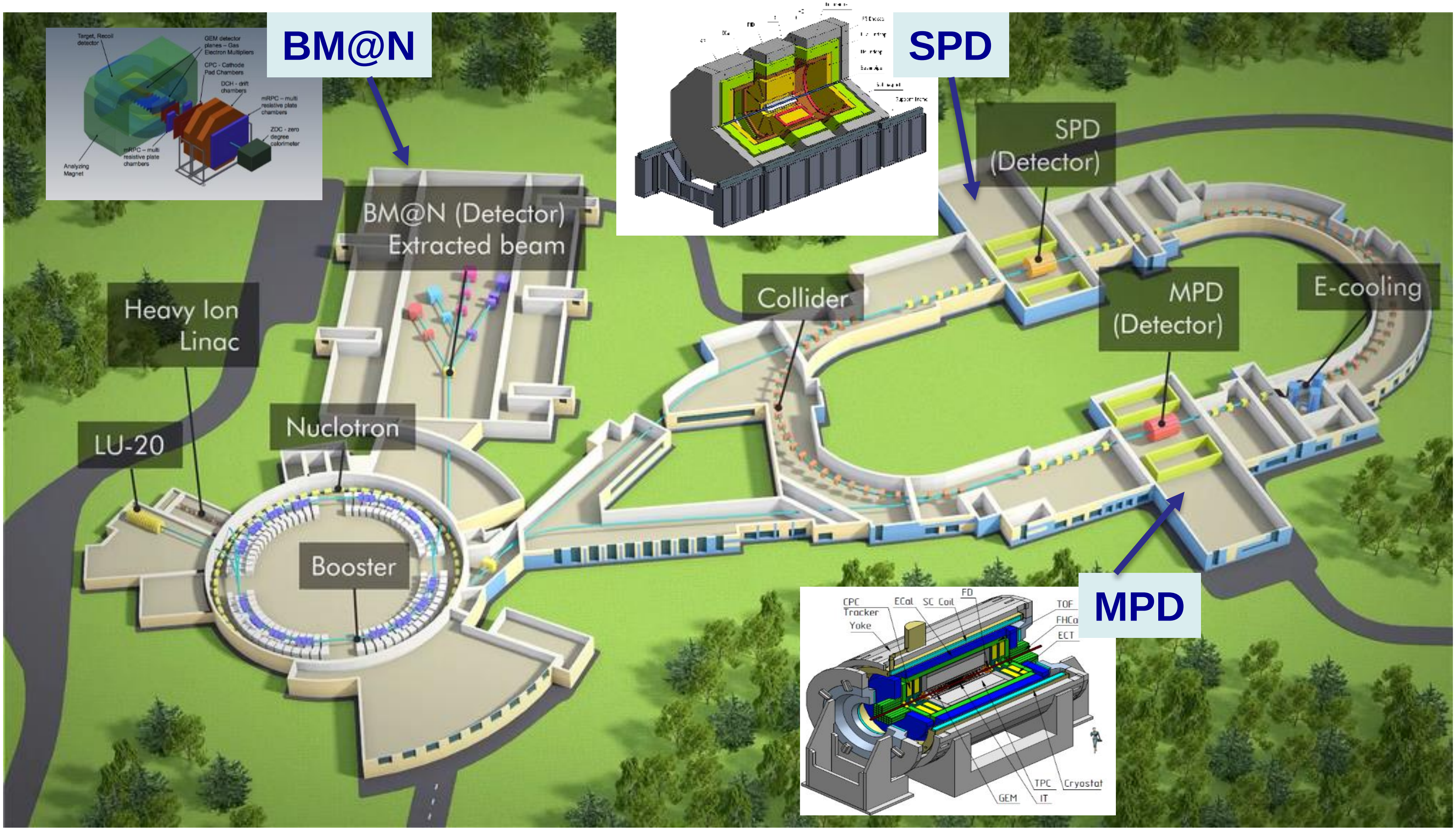
NICA complex

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

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



OUTLINE

- Physics case & motivation
- Recent review of exotic hadrons
- Physics analysis & results
- Future perspectives

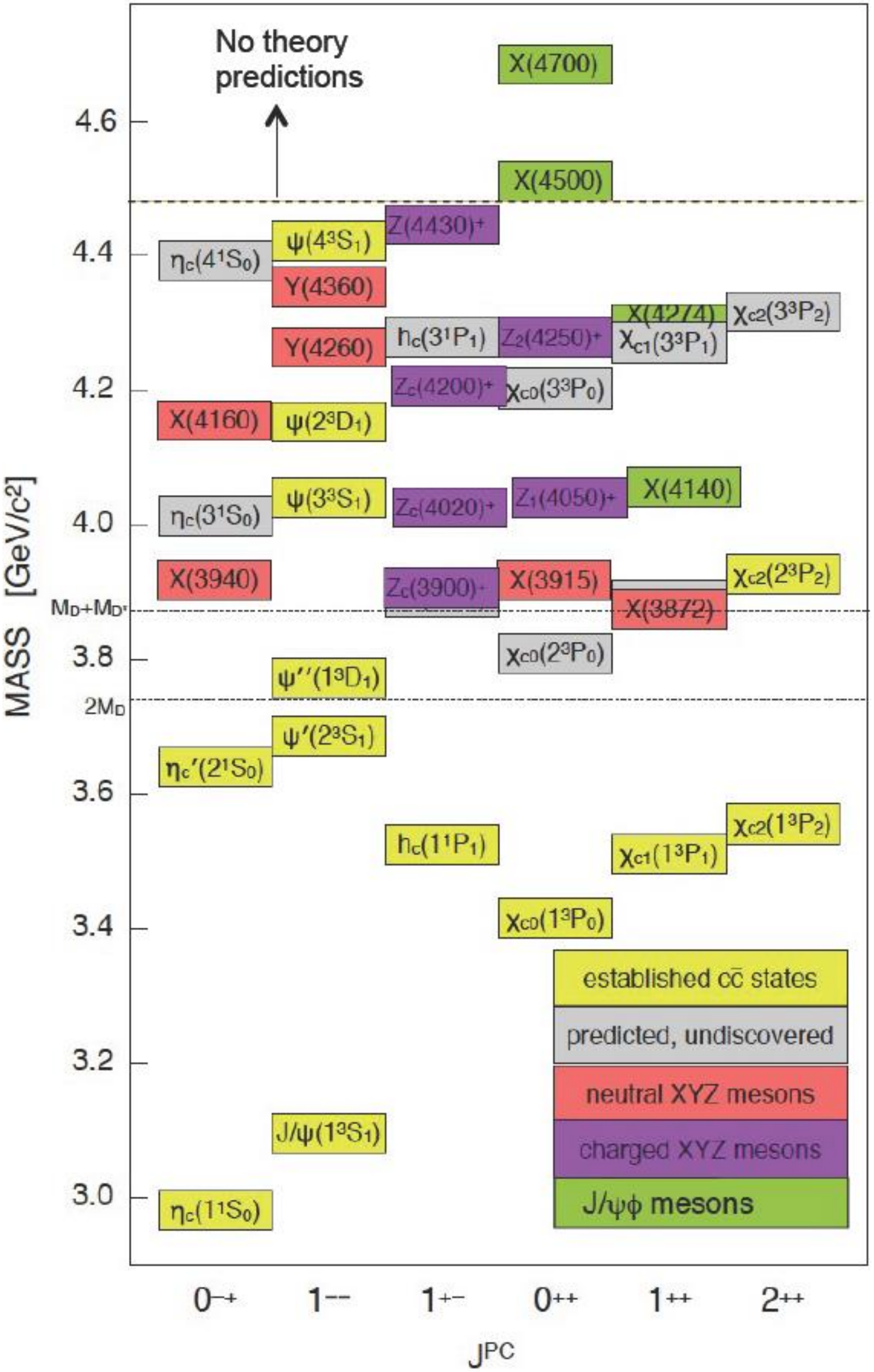
MOTIVATION

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

Motivation

CHARMONIA AND CHARMONIUM-LIKE EXOTICS

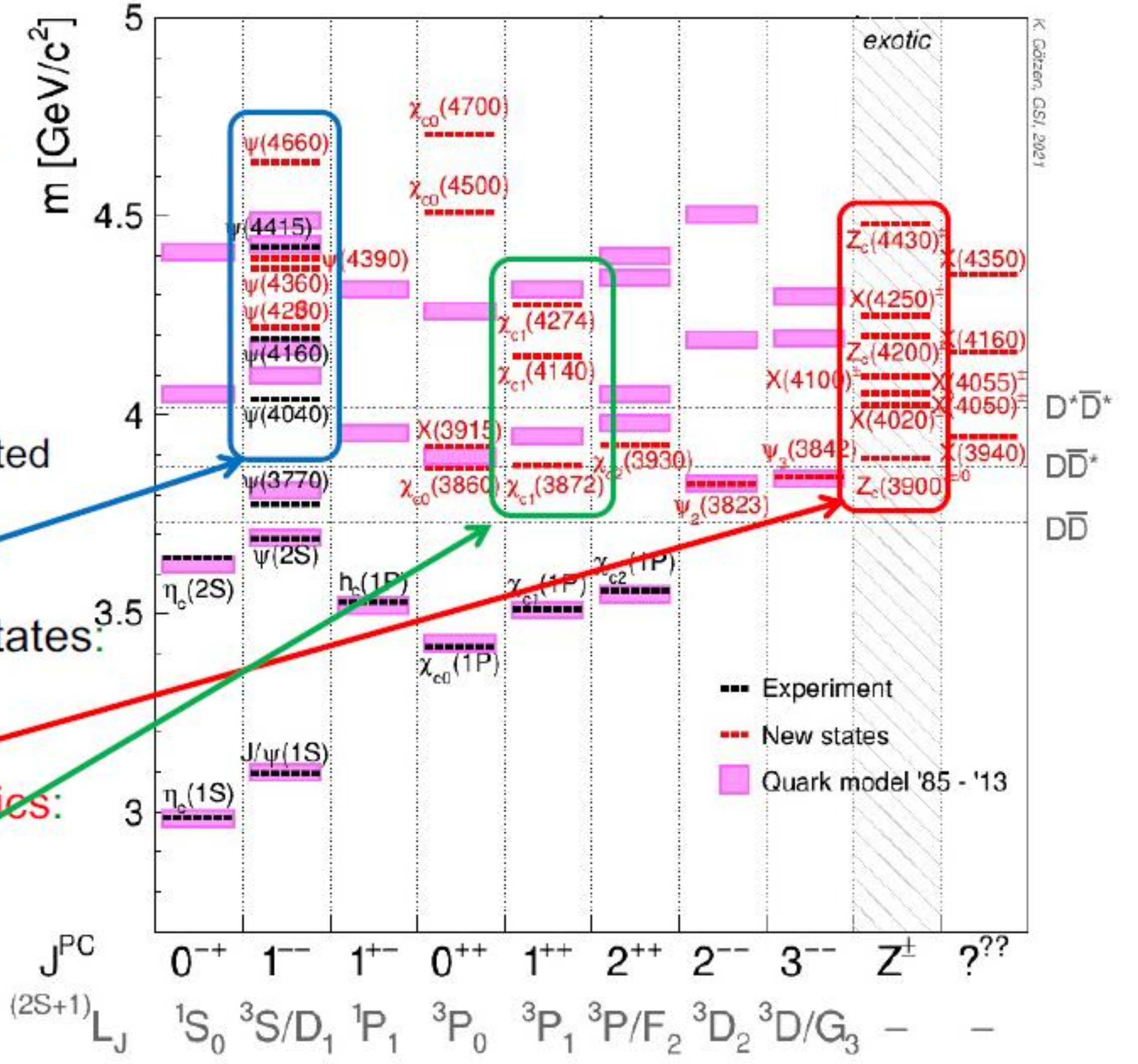
- Predicted neutral charmonium states compared with found $c\bar{c}$ states, & both neutral & charged exotic candidates
- Based on Olsen [arXiv:1511.01589]
- Added 4 new $J/\psi\phi$ states



MOTIVATION

Charmonium-like spectrum

- Before 2003:
  - Good agreement between theory and experiment, particularly beneath open charm thresholds
- After 2003:
  - Severe mismatch between predicted and observed spectrum
- Several supernumerary vector states: Y(4260), ..., Y(4660)
- Several charged manifestly exotics: $Z_c(3900)^{+/-}$, ..., $Z_c(4430)^{+/-}$
- The X states – the $\chi_{c1}(3872)$ was the first observed in 2003



The $\overline{cc}$ system has been investigated in great detail first in e^+e^--reactions, and afterwards on a restricted scale ($E_{\bar{p}} \leq 9$ GeV), but with high precision in $\overline{pp}$-annihilation (the experiments R704 at CERN and E760/E835 at Fermilab).

The number of unsolved questions related to charmonium has remained:

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

AS RESULT :

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

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

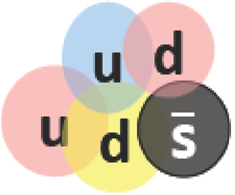
- decays into particle-antiparticle or $D\overline{D}$-pair: $\overline{cc} \rightarrow (\Psi, \eta_c, \chi_{cJ},..) \rightarrow \Sigma^0\overline{\Sigma}^0$, $\Lambda\overline{\Lambda}$, $\Sigma^0\overline{\Sigma}^0\pi$, $\Lambda\overline{\Lambda}\pi$
- decays into light hadrons: $\overline{cc} \rightarrow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

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

non-standard hadrons

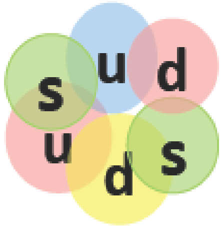
Hadrons beyond the conventional QM and…

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

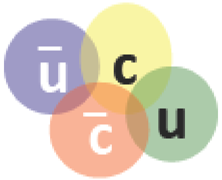


pentaquarks

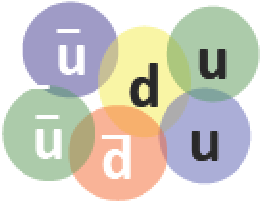
glueballs



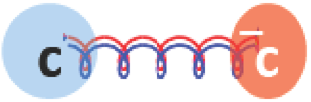
H-dibaryon



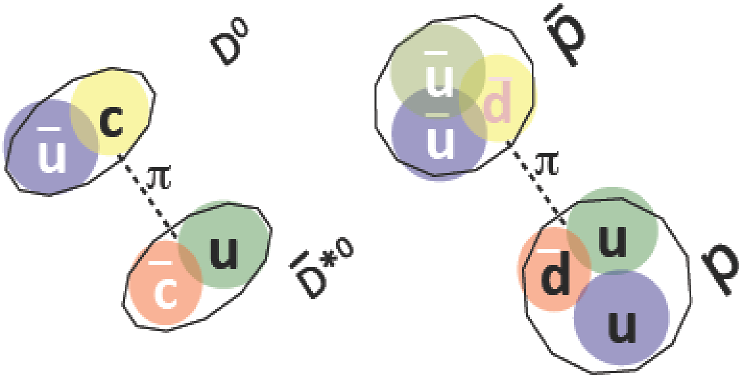
diquark-diantiquarks



heptaquarks



hybrids



deusons

protonium

molecules

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

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

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A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
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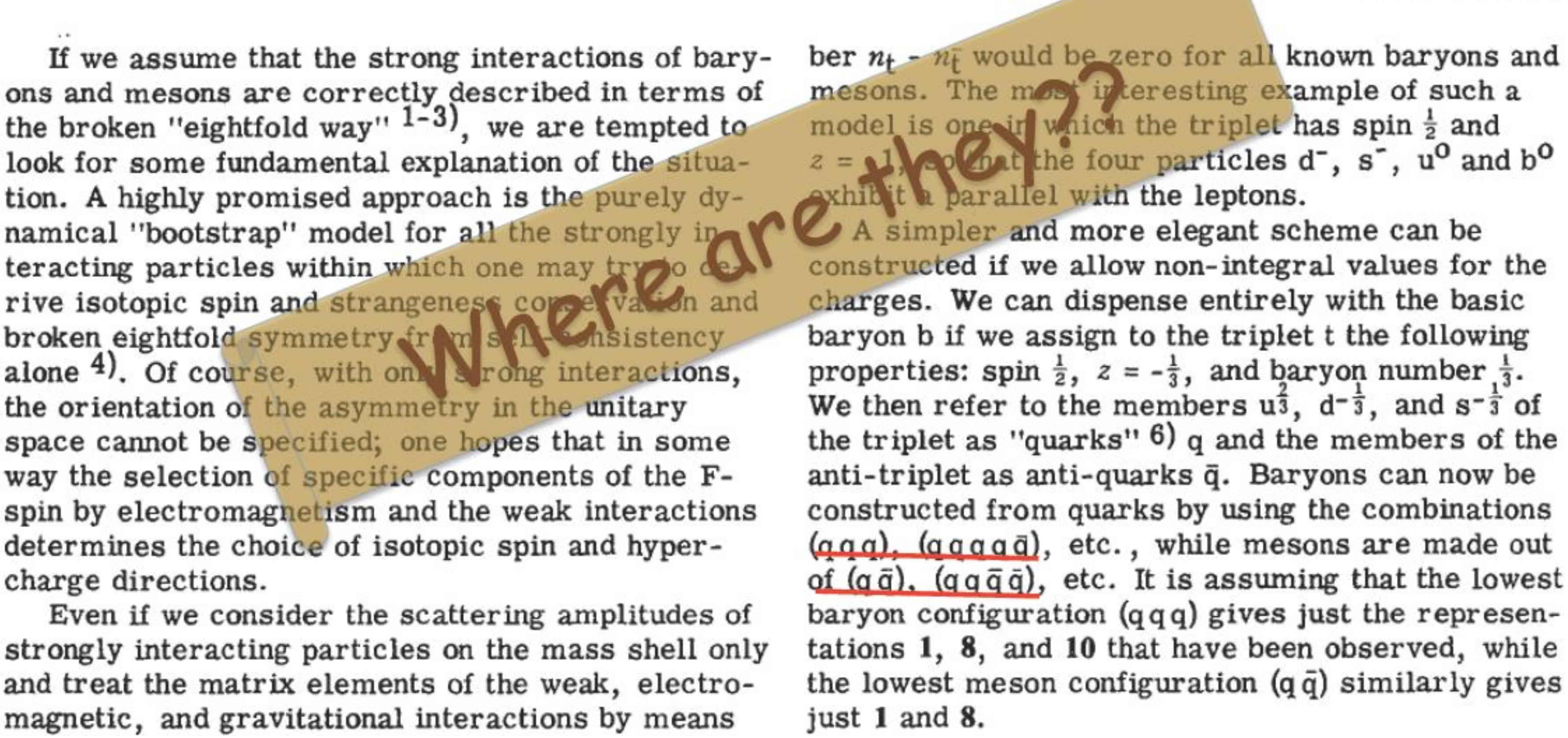
Received 4 January 1964



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.

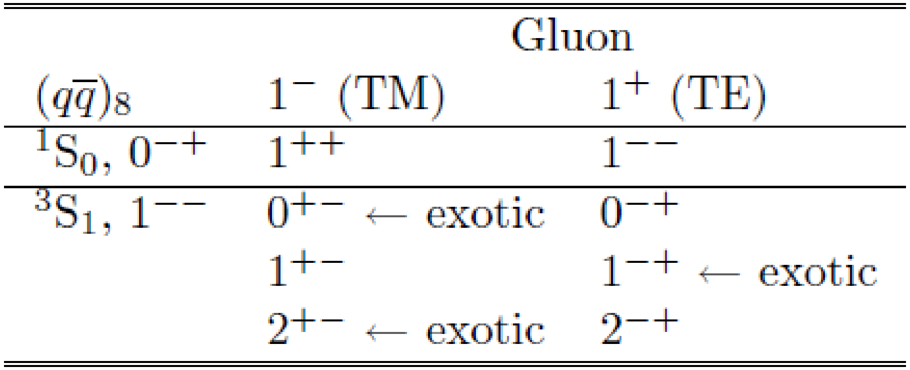
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the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

Two different kinds of experiments to study exotics:

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

The low laying charmonium hybrid states:



	Gluon	
$(q\overline{q})_8$	1^- (TM)	1^+ (TE)
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-} ← exotic	0^{-+}
	1^{+-}	1^{-+} ← exotic
	2^{+-} ← exotic	2^{-+}

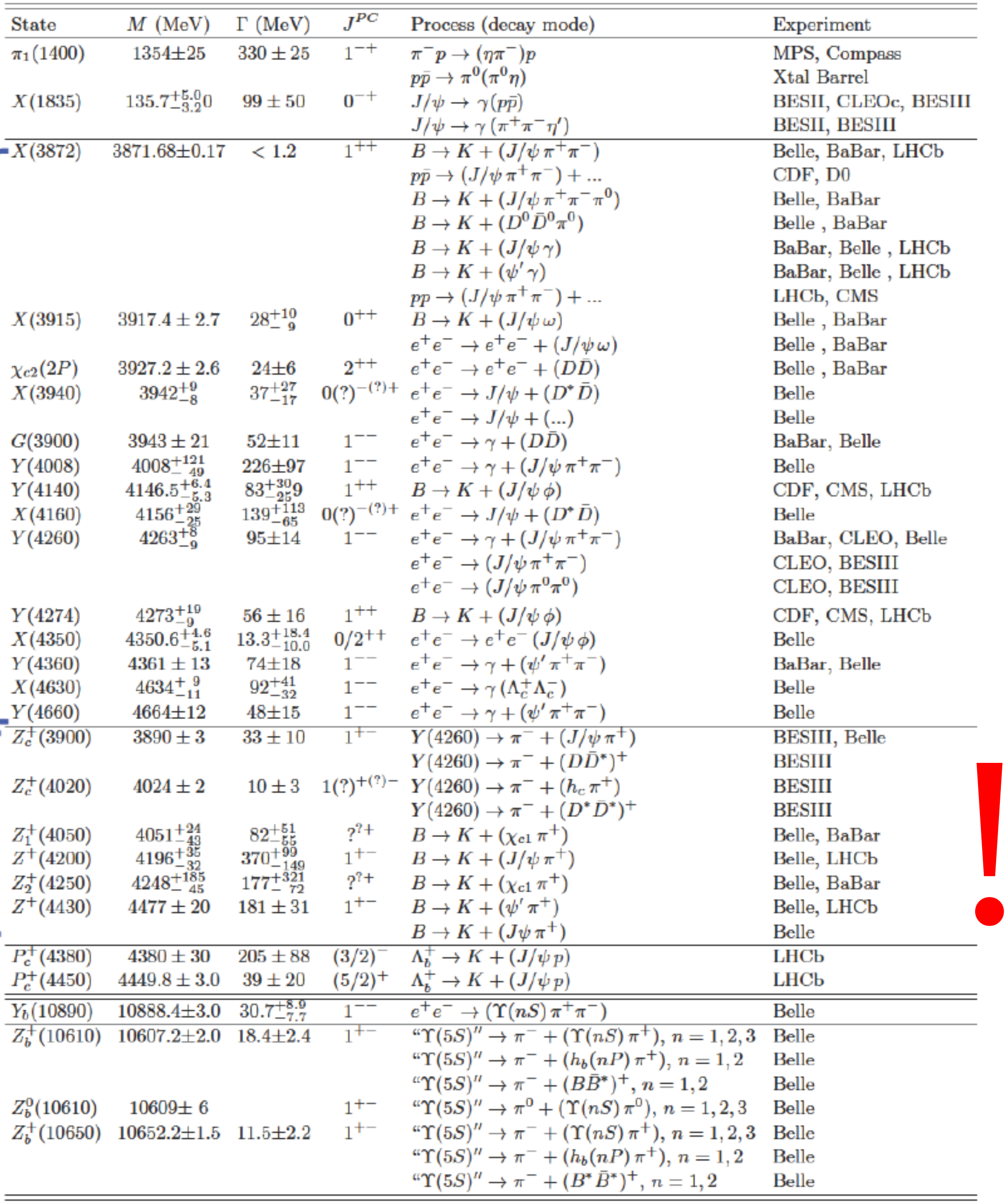
Charmonium-like exotics (hybrids, tetraquarks) predominantly decay via electromagnetic and hadron transitions and into the open charm final states:

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

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

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

Candidate exotic hadrons



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

!

Z_c States

State	M (MeV/c^2)	Γ (MeV)	J^{PC}	Process	Experiment
$Z_c(3900)^{(\pm,0)}$	3888.4 ± 2.5	28.3 ± 2.5	1^{+-}	$e^+e^- \to \pi^{(+,0)}(\pi^{(-,0)}J/\psi)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)}(D\bar{D}^*)^{(-,0)}$	BESIII
				$H_b \to X\pi^+(\pi^- J/\psi)$	D0
				$e^+e^- \to \pi^+(\eta_c\rho^-)$	BESIII
$Z_c(4020)^{(\pm,0)}$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e^- \to \pi^{(+,0)}(\pi^- h_c)$	BESIII, Belle
				$e^+e^- \to \pi^{(+,0)}(D^*\bar{D}^*)^{(-,0)}$	BESIII
$Z(4050)^\pm$	4051^{+24}_{-40}	82^{+50}_{-28}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4055)^\pm$ 3.5σ	4054 ± 3.2	45 ± 13	$?^{?-}$	$e^+e^- \to \pi^+(\pi^-\psi(2S))$	Belle
$Z(4100)^\pm$ 3.4σ	4096 ± 28	152^{+80}_{-70}	$?^{??}$	$B^0 \to K^+(\pi^-\eta_c)$	LHCb
$Z(4200)^\pm$	4196^{+35}_{-32}	370^{+100}_{-150}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle, LHCb
$Z(4250)^\pm$	4248^{+190}_{-50}	177^{+320}_{-70}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle
$Z(4430)^\pm$	4478^{+15}_{-18}	181 ± 31	1^{+-}	$B^0 \to K^+(\pi^-\psi(2S))$	Belle, LHCb
first/2008				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle
$R_{c0}(4240)$	4239^{+50}_{-21}	220^{+120}_{-90}	0^{--}	$B^0 \to K^+\pi^-\psi(2S)$	LHCb
$Z_{cs}(3985)^\pm$	$3982.5^{+2.8}_{-3.4}$	$12.8^{+6.1}_{-5.3}$	?	$e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$	BESIII
$Z_{cs}(4000)^\pm$	4003^{+7}_{-15}	131 ± 30	1^+	$B^+ \to \phi(J/\psi K^+)$	LHCb
$Z_{cs}(4220)^\pm$	4216^{+49}_{-38}	233^{+110}_{-90}	1^+	$B^+ \to \phi(J/\psi K^+)$	LHCb

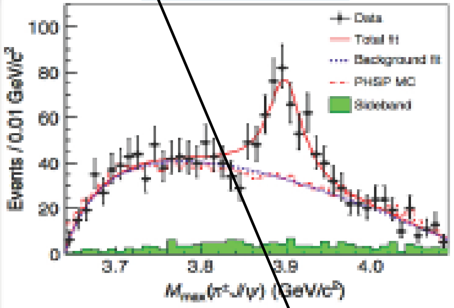
Are these states the same?!

SUMMARY on Z_c from BES III

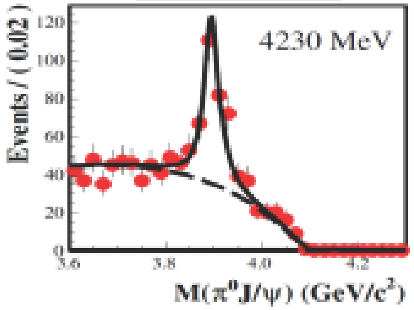
Are these states the same?!

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

$Z_c(3900)^\pm$

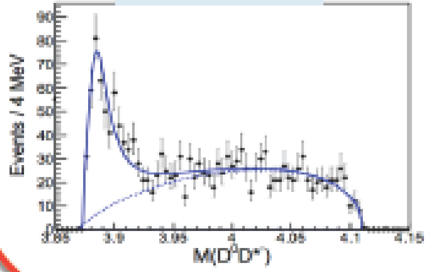


$Z_c(3900)^0$

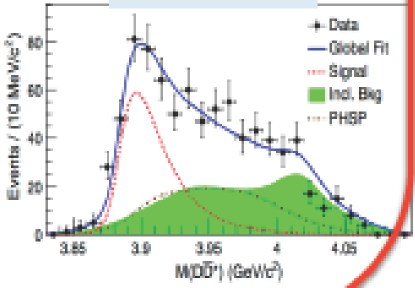


$e^+e^- \to (D\bar{D}^*)^{\pm(0)}\pi^{\mp(0)}$

$Z_c(3885)^\pm$

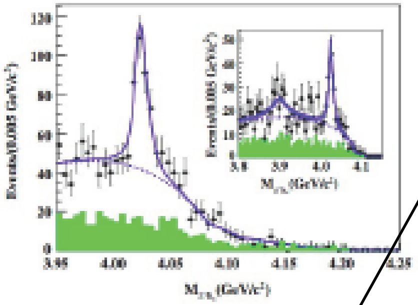


$Z_c(3885)^0$

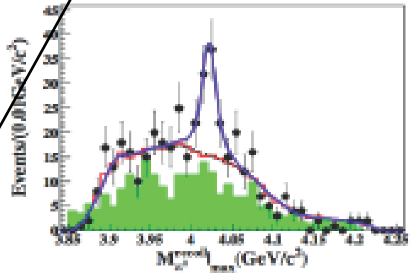


$e^+e^- \to \pi^{+(0)}\pi^{-(0)} h_c$

$Z_c(4020)^\pm$

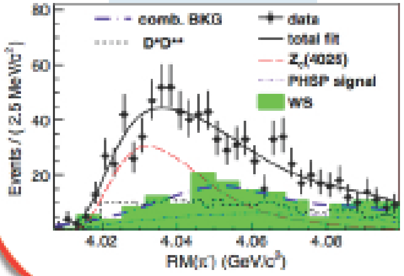


$Z_c(4020)^0$

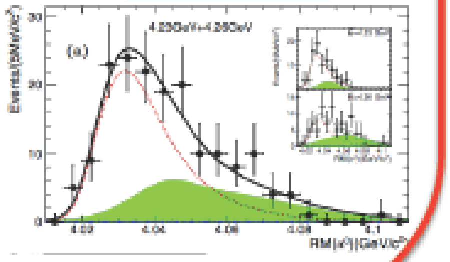


$e^+e^- \to (D^*\bar{D}^*)^{\pm(0)}\pi^{\mp(0)}$

$Z_c(4025)^\pm$



$Z_c(4025)^0$



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

THE LHCb NEW RESONANCES

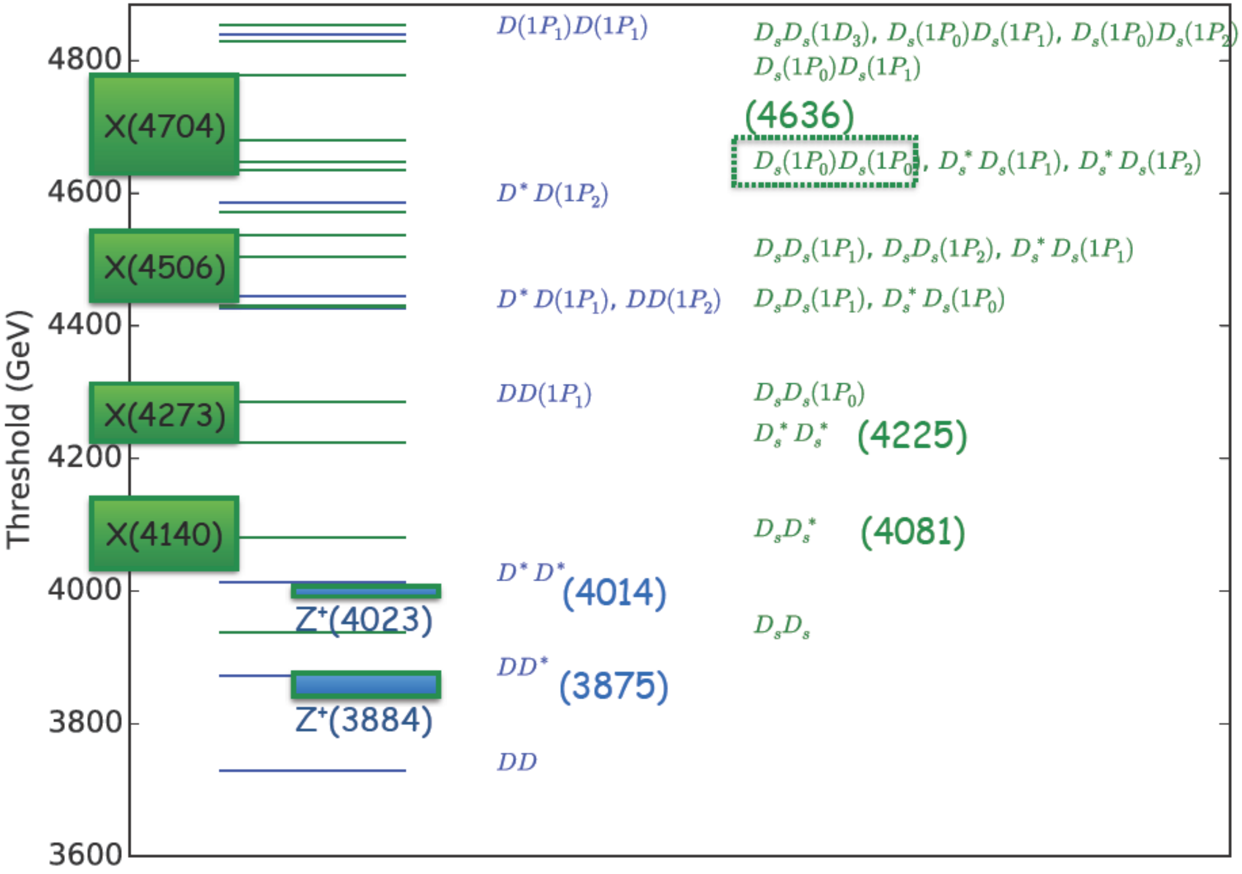
In 2016 LHCb measured 4 new resonances with an amplitude analysis on $B^+ \to J/\Psi \phi K^+$ decay

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

NEW STATES WITH ZERO STRANGENESS from LHCb

- strangeness zero states - charmonium ($c\bar{s}\bar{s}c$) 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 -> X K: $M_X < 4785$ MeV



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

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.* $pp \to \bar{c}c\; pp$; $pp \to \bar{c}qcq'\; pp$ $\quad (q, q' = u, d, s)$
- spectroscopy of baryons and mesons with strangeness and charm:

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

- 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*

Running conditions

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

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

3. Running time 10 weeks:

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

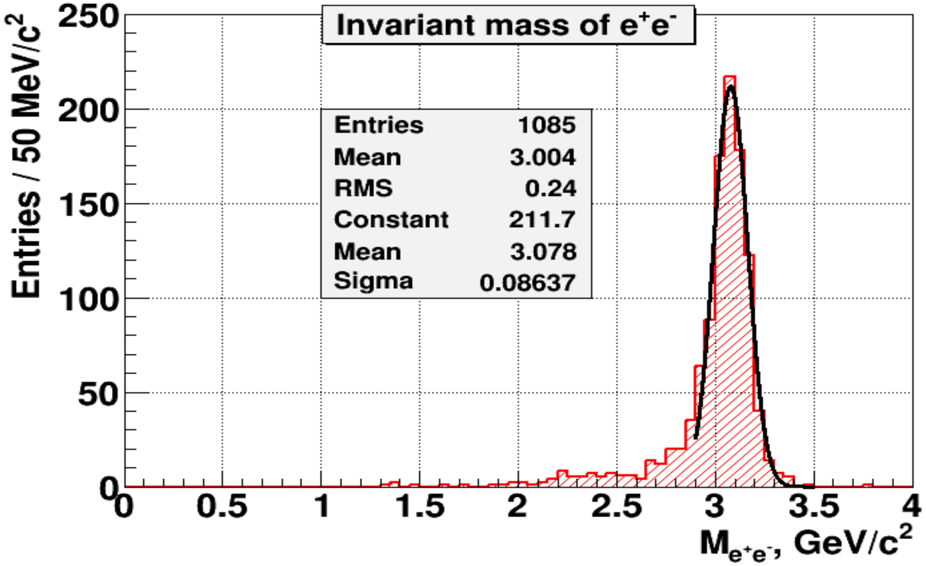
Expectations for J/ψ

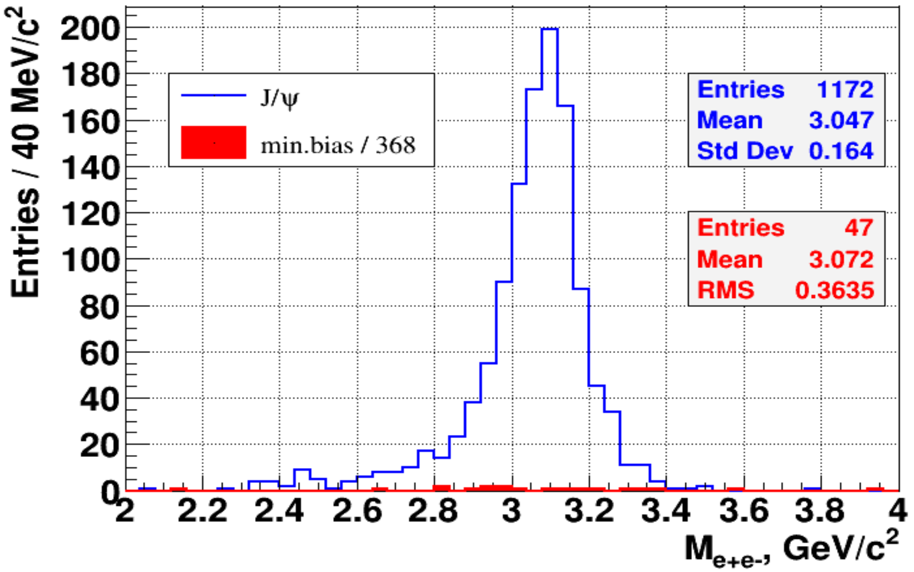
1. X-section $\sigma_{J/\psi}$ from Pythia8 108.7 nb

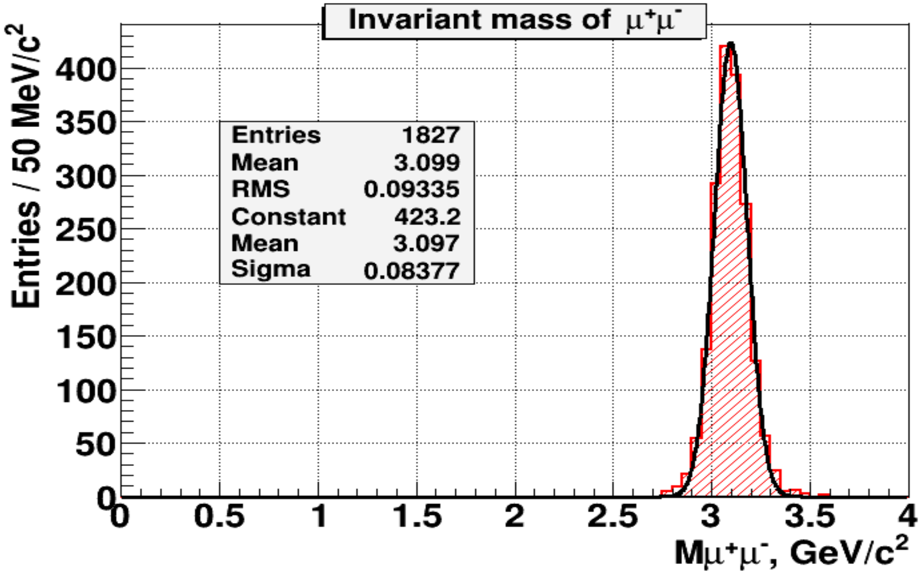
2. Statistics: $N_{J/\psi} = L_{int} \cdot \sigma_{J/\psi} \cdot Br_{J/\psi \to e+e-} \cdot Eff._{\Delta\eta=\pm1.5} =$

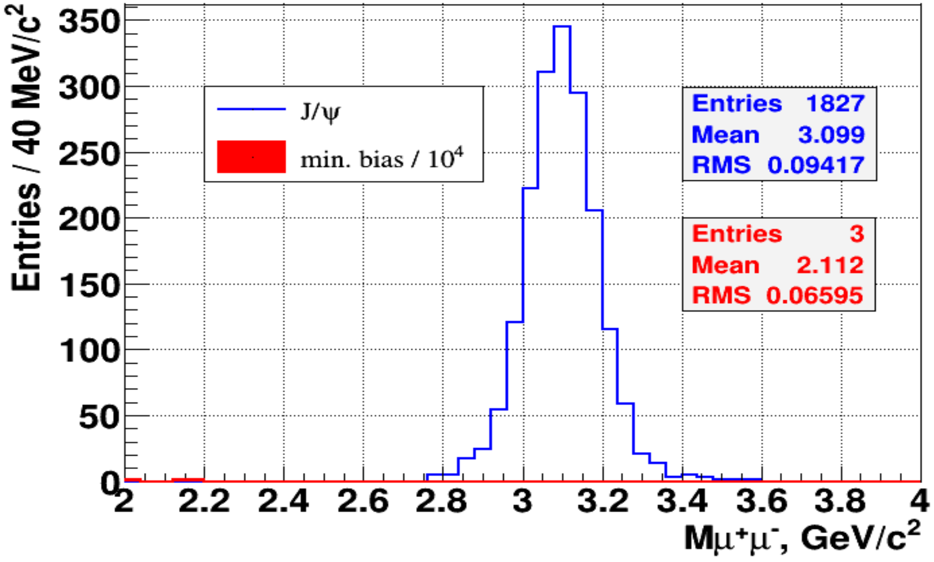
$604.8 \cdot 108.7 \cdot 0.06 \cdot 0.8 = 3156$

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









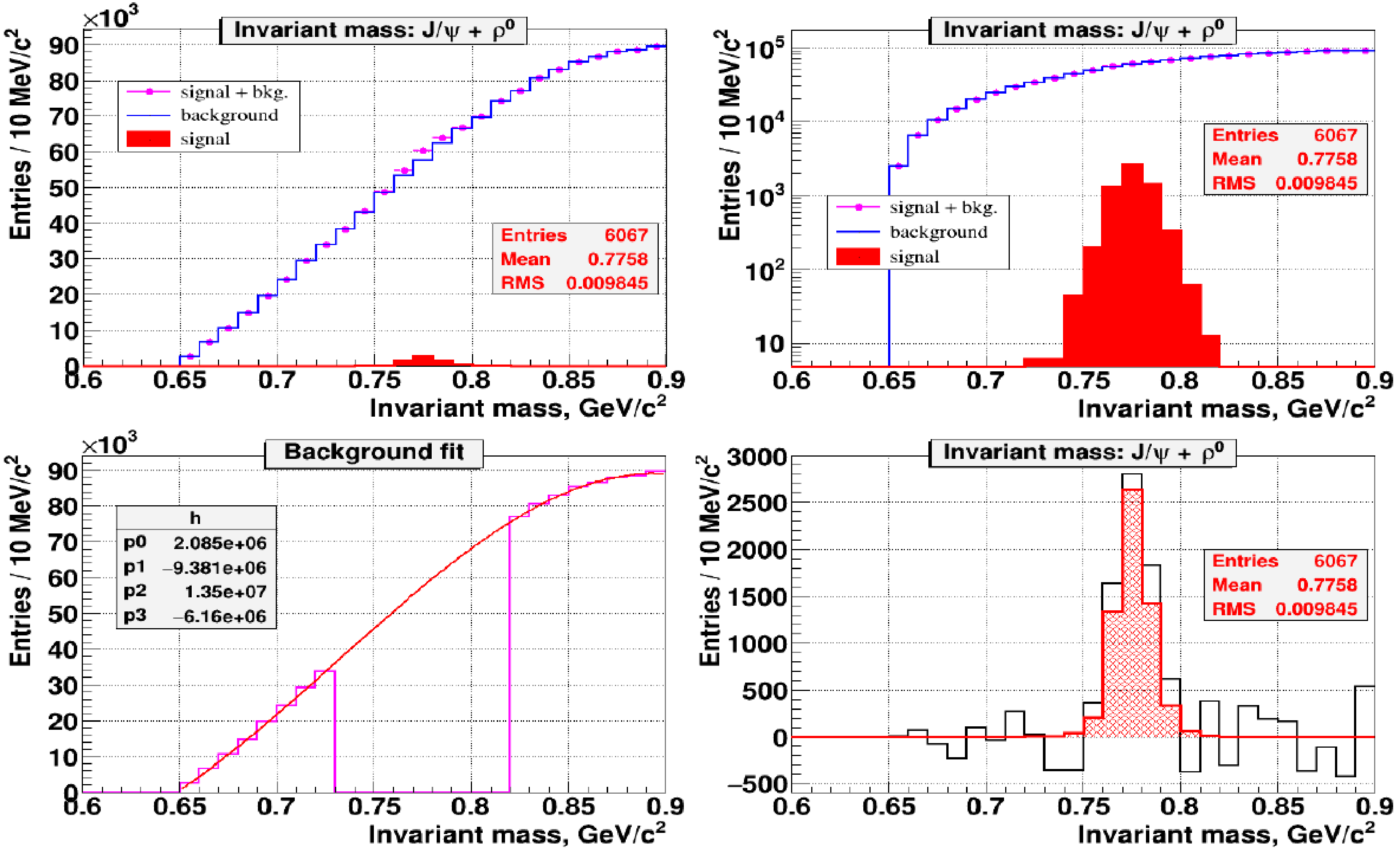
X(3872) state

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

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

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



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

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

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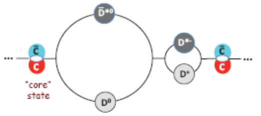
The spectroscopy of charmonium-like mesons with masses above the $2m_D$ open charmed threshold has been full of surprises and remains poorly understood [1]. The currently most compelling theoretical descriptions of the mysterious XYZ mesons attributes them to hybrid stucture with a tightly bound $c\bar{c}$ 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.

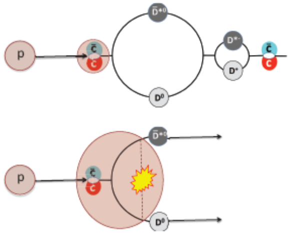


Figure 2: **(Top)** $X(3872)$ production on a proton target ($r_{\rm rms} \simeq 1$ fm). Here the $X(3872)$ escapes the target region before it establishes a significant $D\bar{D}^*$ component. **(Bottom)** $X(3872)$ production on a nuclear target. Here the presence nuclear material disrupts the (< 200 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].

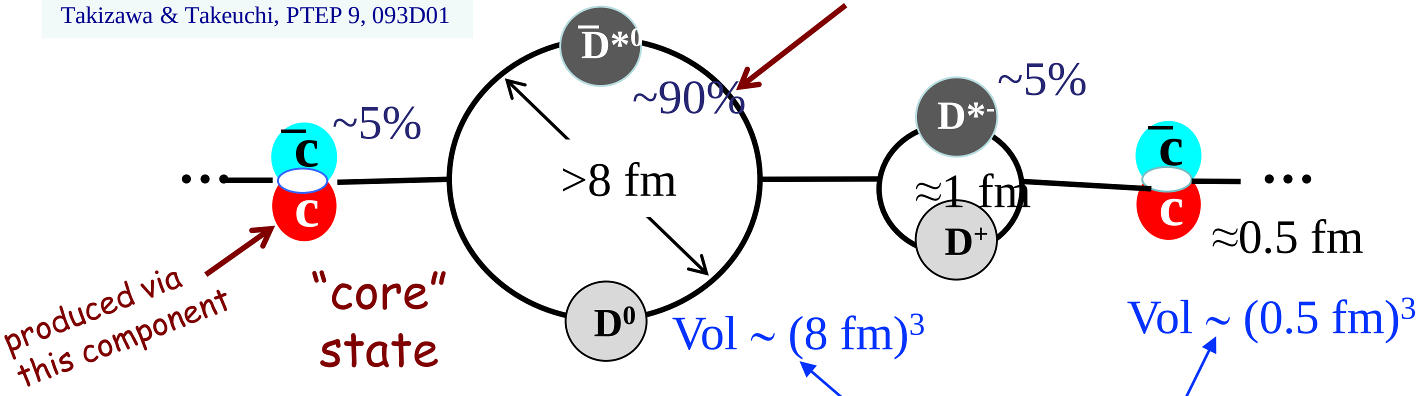
[4] Here we use $\chi_{c2}(2P)$-$\chi_{c1}(2P)$ mass splitting from S. Godfrey and N. Isgur, Phys. Rev. D **32**, 189 (1985) and scale the $\chi_{c1}(2P)$ mass from the measured $\chi_{c2}(2P)$ mass reported in K.A. Olive *et al.* (PDG), Chin. Phys. C **38**, 090001 (2014).

[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

produced via this component

“core” state

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

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

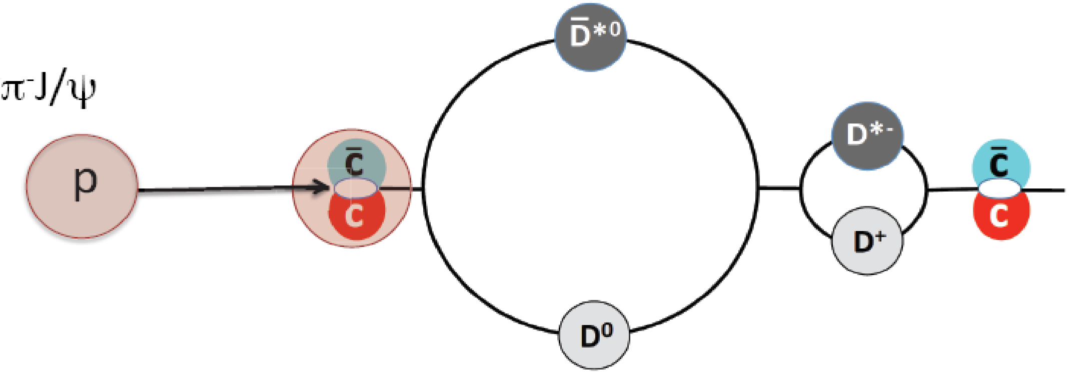
Impossible!

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

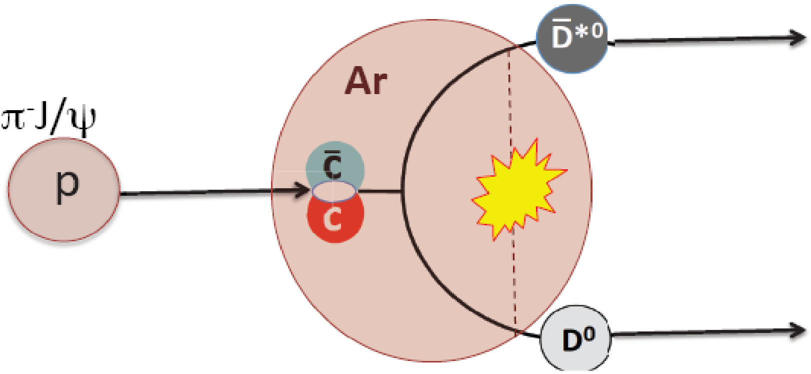
Polosa: “Multiquark Hadrons,” pg 56
Achasov: MPLA 30, 1550181 (2015)

Near-threshold prod. via pp & pA

pp→X(3872)→$\pi^+\pi^-J/\psi$



pAr→X(3872)→$\pi^+\pi^-J/\psi$



Strong quenching
for A~40 nuclei??

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

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 behavior than that of the Ψ', which is a long-lived compact charmonium state.

Pythia8 predictions for X(3872)

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

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

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

4. Br $(D+ \text{->} K-\pi+\pi+) = 9.2\%$, Br $(D0 \text{->} K-\pi+) = 3.8\%$

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

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

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Review

Diquark correlations in hadron physics: Origin, impact and evidence

M.Yu. Barabanov [1], M.A. Bedolla [2], W.K. Brooks [3], G.D. Cates [4], C. Chen [5], Y. Chen [6,7], E. Cisbani [8], M. Ding [9], G. Eichmann [10,11], R. Ent [12], J. Ferretti [13], R.W. Gothe [14], T. Horn [15,12], S. Liuti [4], C. Mezrag [16], A. Pilloni [9], A.J.R. Puckett [17], C.D. Roberts [18,19,*], P. Rossi [12,20], G. Salmé [21], E. Santopinto [22], J. Segovia [23,19], S.N. Syritsyn [24,25], M. Takizawa [26,27,28], E. Tomasi-Gustafsson [16], P. Wein [29], B.B. Wojtsekhowski [12]

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ОБЪЕДИНЕННЫЙ ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ
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М. Ю. Барабанов, А. С. Водопьянов, А. Кищель

Перспективы изучения ароматных адронов и экзотических мультикварковых состояний в современной физике

Главной задачей физики сильных взаимодействий является понимание природы адронов, из которых состоит окружающая материя. Основная исследовательская активность связана с двумя фундаментальными вопросами: из чего состоят адроны и как они рождаются в рамках квантовой хромодинамики и сильновзаимодействующей компоненты Стандартной модели. Для решения этих вопросов адронная спектроскопия является ценным и проверенным временем инструментом, поскольку позволяет понять структуру мезонов, барионов и экзотических состояний и процесс их образования. В таком контексте открытие большинства новых адронных состояний, в частности наблюдаемое изобилие экзотических состояний X, Y, Z [1], действительно впечатляет, поскольку эти объекты бросают вызов общепринятому представлению об адронах как о кварк-антикварковых или трехкварковых цветовых синглетных состояниях.

Экспериментальные исследования структуры и спектра адронов представлены с помощью процессов адрон-адронного рассеяния, фото- и электророждения на нуклонах или распадов тяжелых мезонов на мировых ускорительных комплексах. За последнее десятилетие в этих исследованиях получен большой объем данных, которые улучшили осведомленность о спектре барионов и мезонов и позволили установить существование новых состояний наряду с эмпирическим определением их углового момента, структуры и спина. Недавние достижения связаны с наблюдением мультикварковых состояний, которые не укладываются в общепринятую классификацию адронов. Их можно интерпретировать как давно востребованные физическим сообществом системы пента- и тетракварков [2, 3].

Однако определение новых состояний и их фундаментальных свойств, таких как масса, ширина, спин

M. Yu. Barabanov, A. S. Vodopyanov, A. Kisiel

The Perspective Study of Flavour Hadrons and Exotic Multiquark States in Modern Physics

The major goal in strong-interaction physics is to understand the nature of hadrons that make up visible matter. The main research activity revolves around two fundamental questions: what are hadrons made of and how does quantum chromodynamics, the strong-interaction component of the Standard Model, produce them? Although these questions are simple, the answers still have not been found. To address these questions, hadron spectroscopy is a valuable and time-honored tool, as it enables us to understand the structure of mesons, baryons and exotics and how they are produced. In this context, the recent discovery of many new hadronic states, in particular, the abundance of observed X, Y, Z exotic states [1], is exciting, as these objects challenge the common-place view of hadrons as either quark–antiquark or three-quark color-singlet states.

Experimental studies of the hadron structure and spectrum are performed via hadron–hadron scattering processes, photo- and electroproduction by nucleons or, more recently, by means of heavy-meson decays at worldwide accelerator facilities. In the last decade, these studies have yielded an enormous amount of data, which have already improved our knowledge of the baryon and meson spectrum, and enabled us to establish the existence of new states, together with an empirical determination of their angular momentum, content and spin. Recent highlights are observations of multiquark states outside our well-known hadronic pictures. The states are interpreted as the penta- and tetraquark systems long sought after by physics community [2, 3].

However, identifying new states and their fundamental properties, such as mass, width, spin and parity, requires complex analysis, which is often subject to model assumptions. For many of the new states, we still do not know the value of their spin and parity. Different theoretical models for the structure of the new states give different predictions of their quantum numbers. Therefore, the composition of many states remains controversial. Indeed, some of these newly discovered hadrons seem to fit the picture of compact multiquark states, while others can be classified as molecular states or both, i.e., the superposition of a constituent-quark core and a meson cloud. Thus, one of the main goals of modern physics is to discuss how to distinguish them.

SUMMARY

♦ 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.

♦ Exotics have been suggested by theorists since the onset of QCD. One encounters several new, interesting, difficult and unsolved problems when modeling tetraquark resonances.

♦ Modern facilities with hadron and heavy ion collisions should provide good opportunities for identification of charged and neutral particles. These experiments may shed light on the nature of *XYZ* exotic states.

♦ The ***pp* & *pA* collisions** can obtain some valuable information on the charm production. Measurements of charmonium-like states may be considered as one of the “pillars” of the ***pp* and *pA* program at NICA.**

♦ New scientific program: “THE PRESENT AND FUTURE OF HEAVY FLAVOUR AND EXOTIC HADRON SPECTROSCOPY”, Munich, Germany, 8 May - 2 June 2023.

ORGANIZERS:

Mikhail Barabanov, Bruno El-Bennich, Stephan Paul, Elena Santopinto, Laura Tolos.

THANK YOU!

and

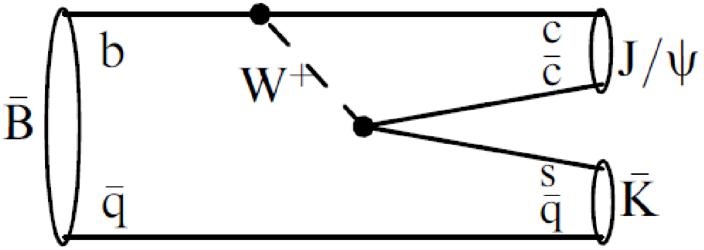
WELCOME FOR COLLABORATION…

Charm in AA

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

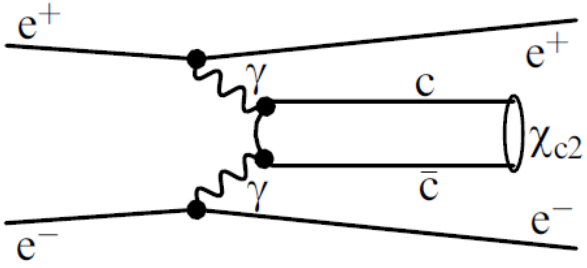
CHARMONIUM-LIKE PRODUCTION MECHANISMS RELEVANT TO THE XYZ EXOTIC STATES

B-decays



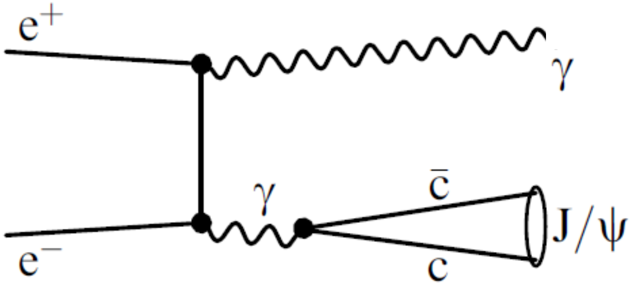
Any quantum numbers are possible

γγ fusion



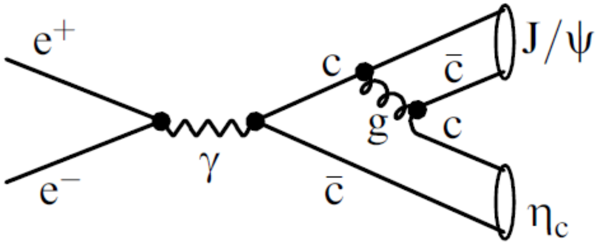
$J^{PC}=0^{-+}, 0^{++}, 2^{-+}, 2^{++}$

annihilation with initial state radiation



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

double charmonium production



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

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

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

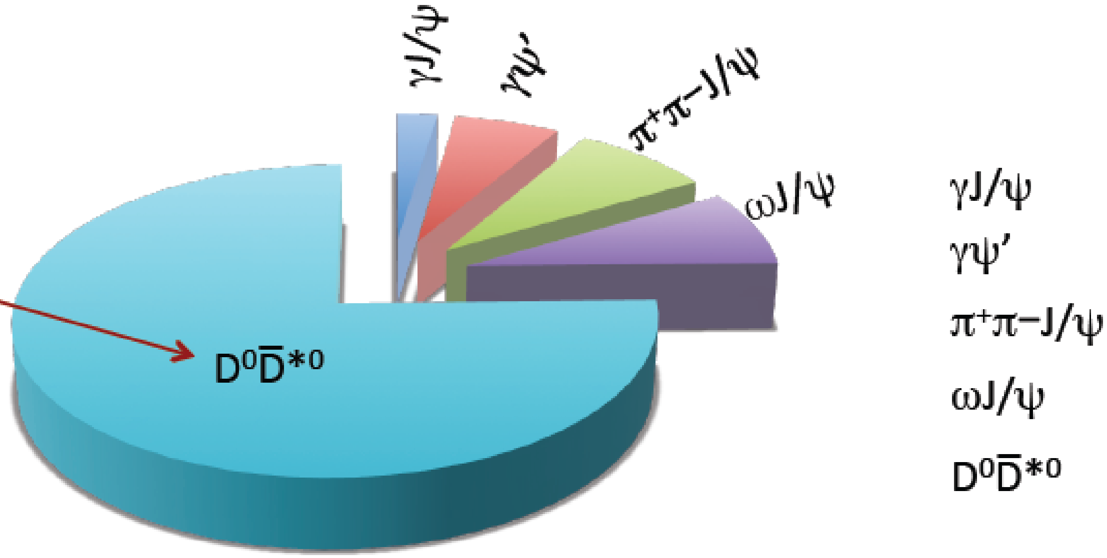
***B*-decays to final states containing $c\bar{c}$ mesons.** At the quark level, the dominant decay mechanism is the weak interaction transition of a *b* quark to *c* quark accompanied by the emission of a virtual W^{-} boson, the mediator of the weak interaction. Approximately half of the time, the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

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

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

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

X(3872) decay channels



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

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

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

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

MPD Inner Tracking System (ITS)

MAPS (Monolithic Active Pixel Sensors)