PERSPETIVE STUDY OF CHARMONIUM-LIKE EXOTICS IN *pp*\bar ANNIHILATION AND *pp* COLLISIONS

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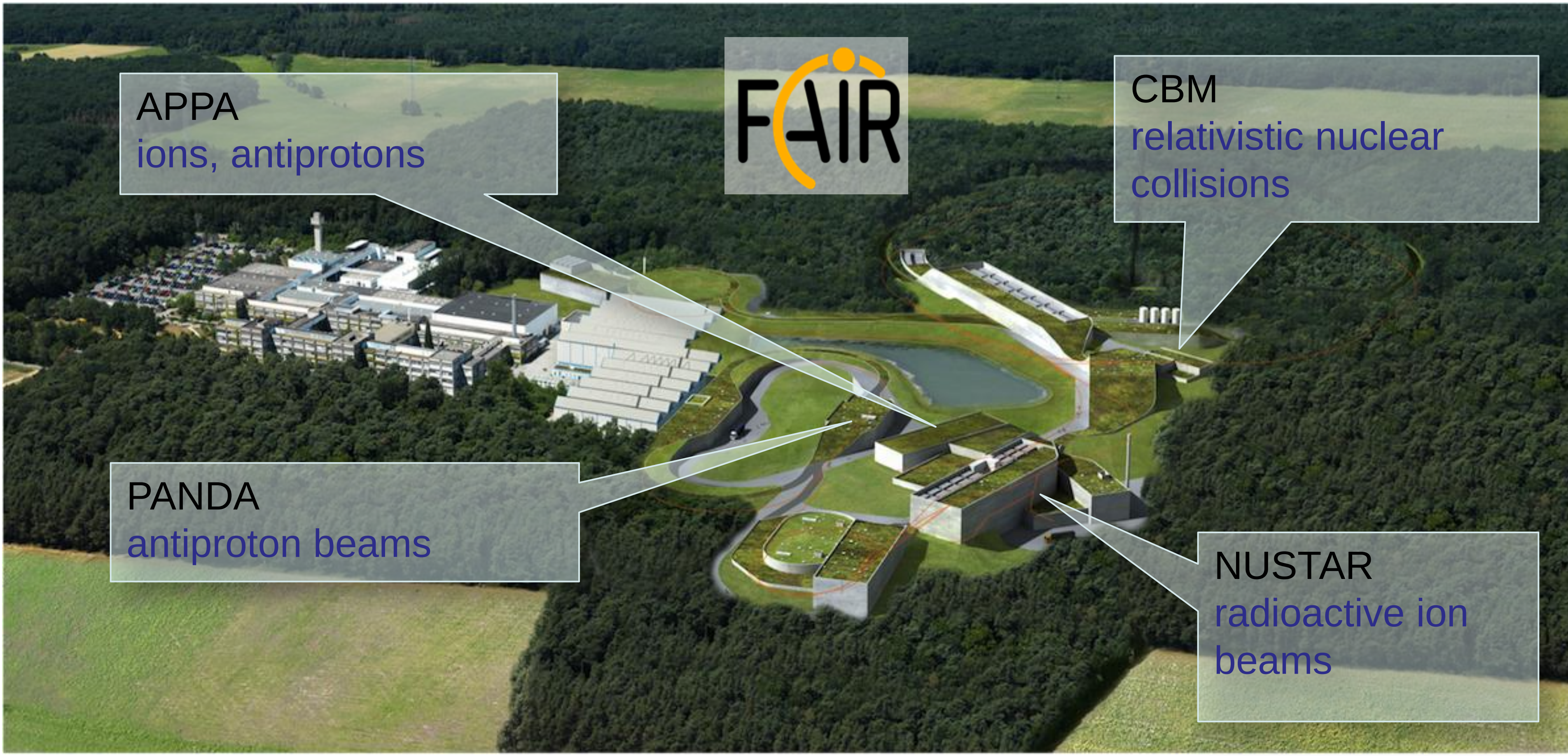
Complex FAIR



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)

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

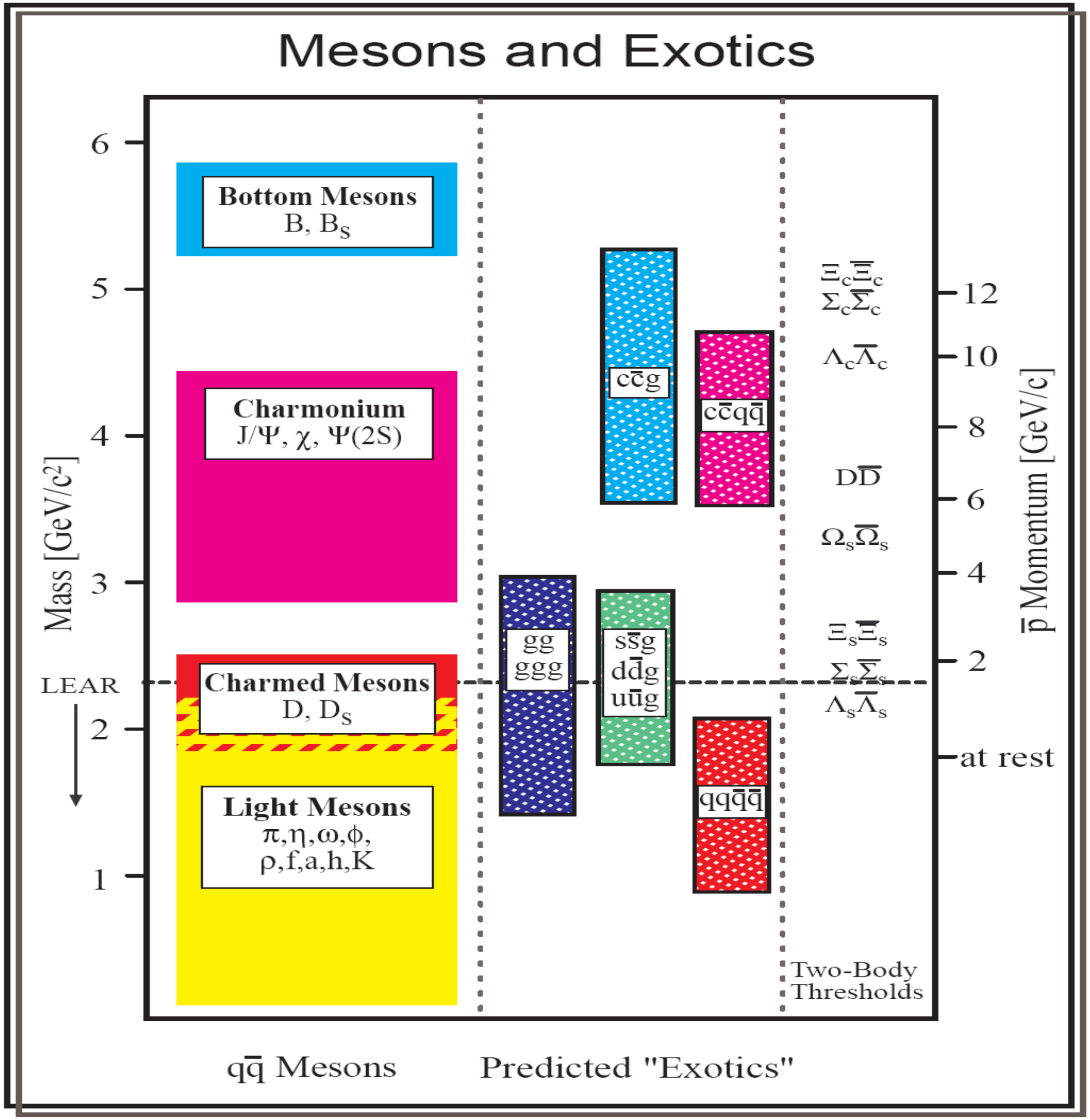
Complex NICA

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

NICA collider major parameters

Ring circumference, m	**503.04**
heavy ions	
β, m	**0.35**
energy range for ***Au^{79+}***: $\sqrt{S_{NN}}$, GeV	**4 - 11**
r.m.s. $\Delta p/p$, 10^{-3}	**1.6**
peak Luminosity for ***Au^{79+}***, cm^{-2} s^{-1}	1×10^{27}
polarized particles	
max. energy for polarized ***p***, *Gev*	**27**
peak Luminosity for ***p***, cm^{-2} s^{-1}	1×10^{32}

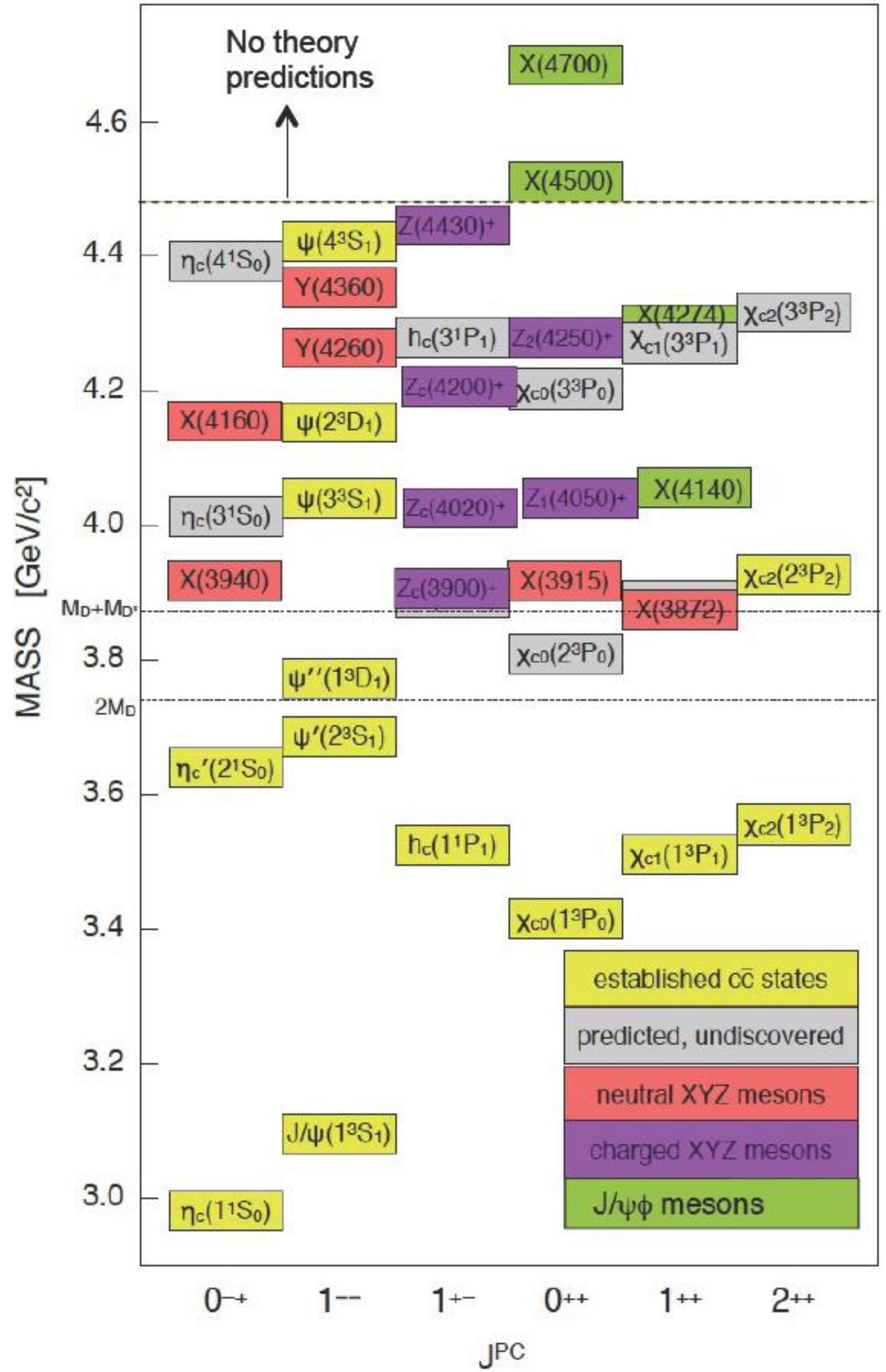
WHY WE CONCENTRATE ON PHYSICS WITH ANTIPROTONS AND PROTONS



Expected masses of $\overline{qq}$-mesons, glueballs, hybrids and two-body production thresholds.

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



Outline

- Physics case
- Conventional & exotic hadrons
- Review of recent experimental data
- Analysis & results
- Summary & perspectives

Why is charmonium-like (with a hidden charm) state chosen!?
Charmonium-like state possesses some well favored characteristics:

- is the simplest two-particle system consisting of quark & antiquark;

- is a compact bound system with small widths varying from several tens of keV to several tens of MeV compared to the light unflavored mesons and baryons

- charm quark *c* has a large mass (1.27 $\pm$ 0.07 GeV) compared to the masses of *u, d* & *s* (~ 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 ($v^2/c^2 \approx 0.2$));

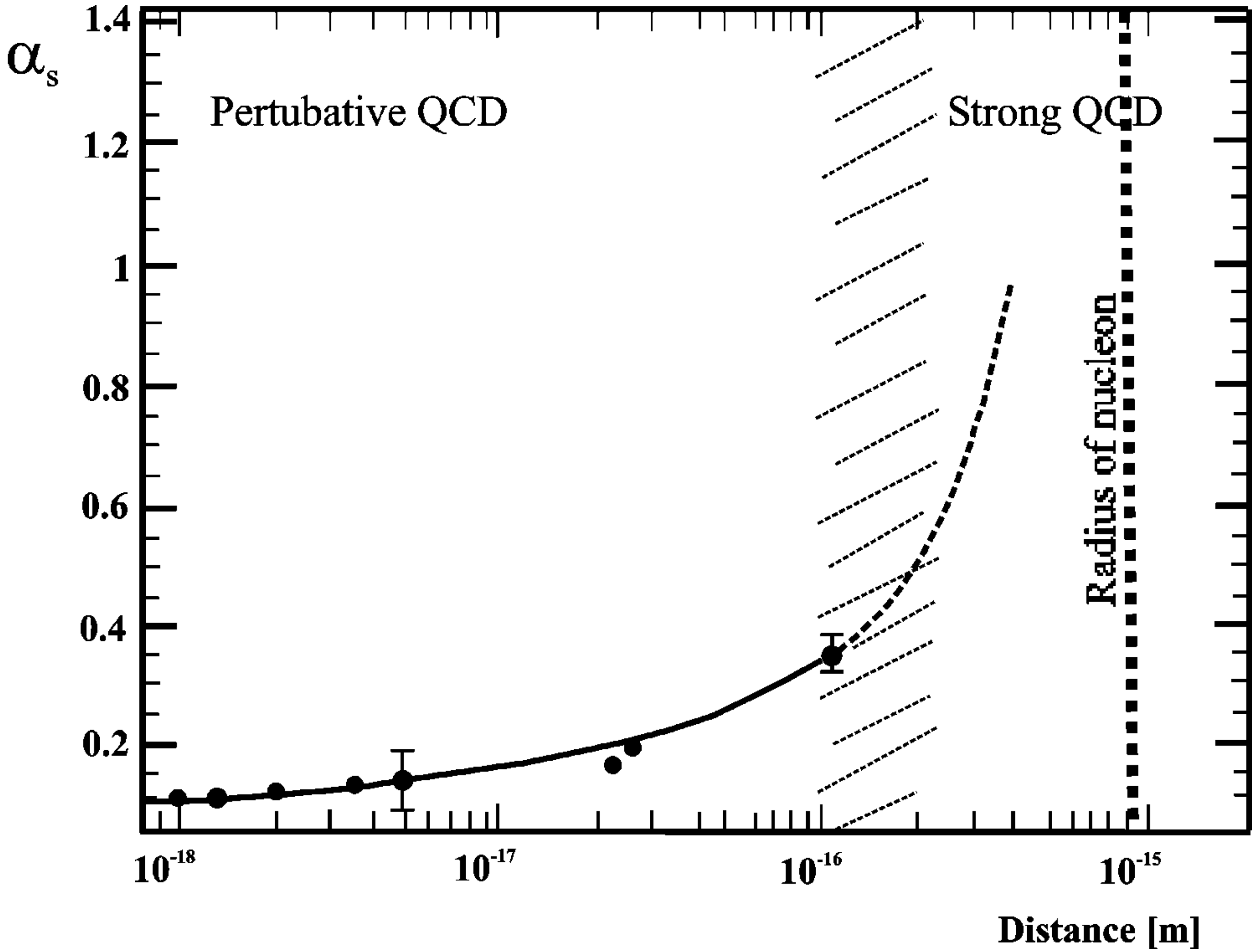
- the size of charmonium-like systems is of the order of less than 1 Fm $(R_{c\bar{c}} \sim \alpha_s \cdot m_q)$ so that one of the main doctrines of QCD – asymptotic freedom is emerging;

Therefore:

♦ charmonium-like studies are promising for understanding the dynamics of quark interaction at small distances;

♦ charmonium-like spectroscopy is 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 $\langle v^2/c^2 \rangle \approx 0.2$.

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. Swangon, 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:

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

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) .*

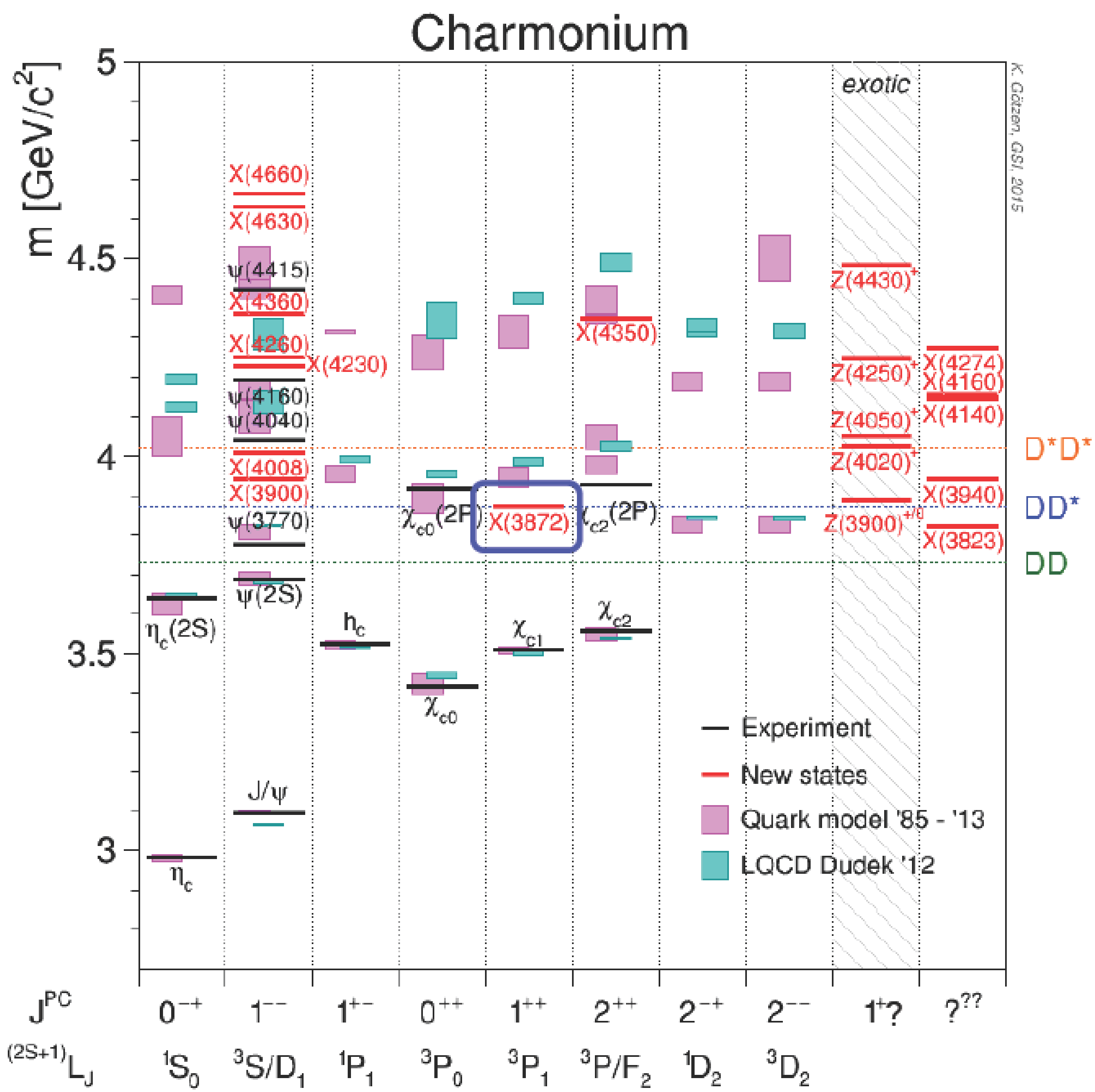
$$\Delta V_N(\vec{r}) = \text{const}\, G_N^{-1/2}(r)\delta(\vec{r}), \qquad V_N(r) = V_0\int D(r)R^{1-N}(r)dr/r,\ V_0 = \text{const} > 0.$$

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

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

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

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/c²]
5
4.5
4
3.5
3
exotic
K. Götzen, GSI, 2015
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
X(4350)
χ_c2(2P)
χ_c2
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
¹S₀
³S/D₁
¹P₁
³P₀
³P₁
³P/F₂
¹D₂
³D₂

The $c\bar{c}$ 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 $\bar{p}p$-annihilation (the experiments R704 at CERN and E760/E835 at Fermilab).

The number of unsolved questions related to charmonium has remained:

- **singlet $^1D_2$ and triplet ^3D_J charmonium states are not determined yet;**
- **nothing is known about partial width of $^1D_2$ and ^3D_J charmonium states.**
- **higher laying singlet $^1S_0$, $^1P_1$ and triplet $^3S_1$, ^3P_J – charmonium states are poorly investigated;**
- **only few partial widths of ^3P_J-states are known** (some of the measured decay widths don't fit theoretical schemes and additional experimental check or reconsideration of the corresponding theoretical models is needed, more data on different decay modes are desirable to clarify the situation)**;**

AS RESULT :

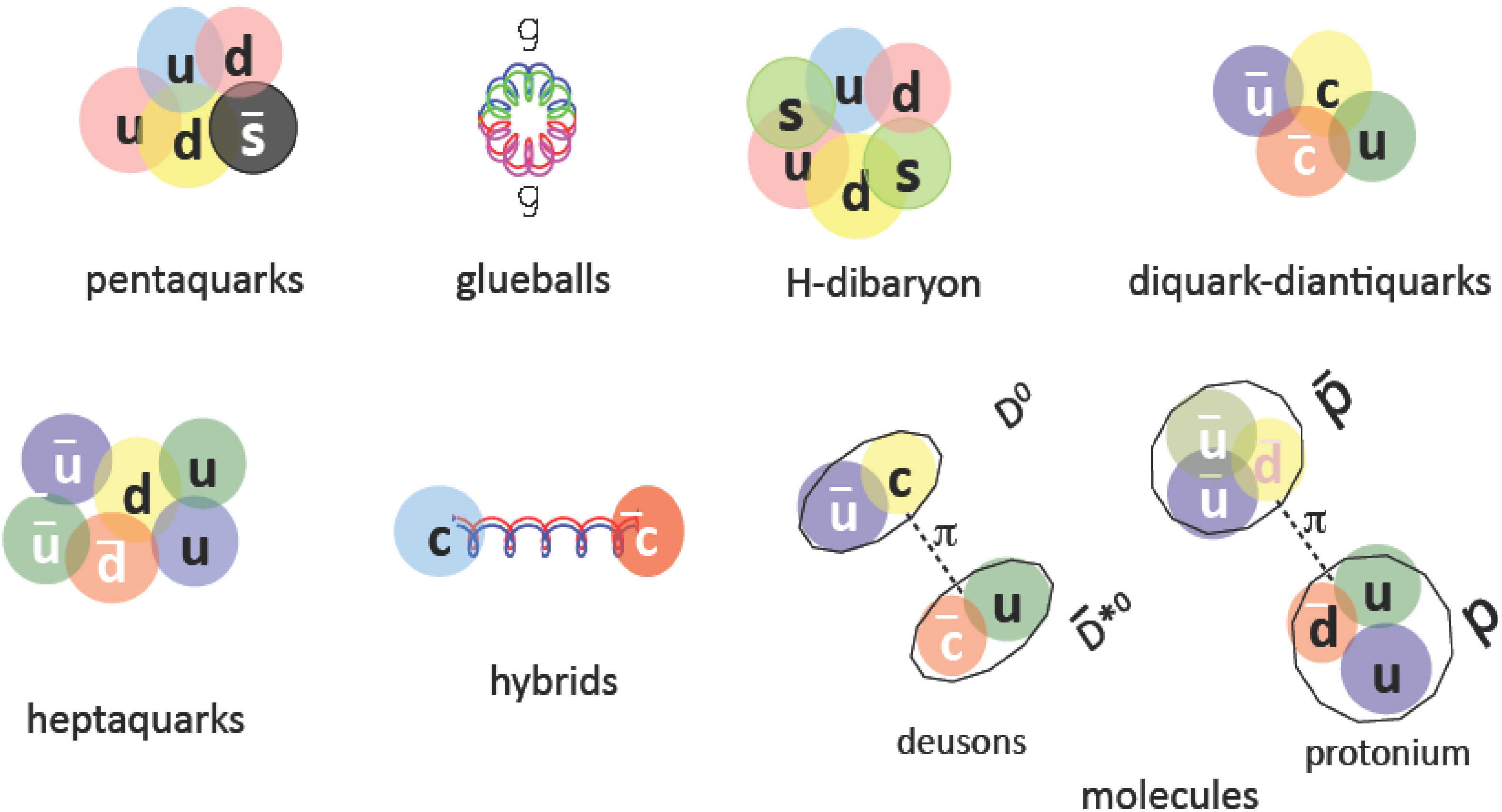
- **little is known on charmonium states above the the $D\bar{D}$ – threshold ($S, P, D,\ldots$);**
- **many recently discovered states above $D\bar{D}$ - threshold (XYZ-states) expect their verification and explanation (their interpretation now is far from being obvious).**

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

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

non-standard hadrons

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



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

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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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**.

Two different kinds of experiments:

- production experiment – $\bar{p}p \to X + M$, where $M = \pi, \eta, \omega, \ldots$ (conventional states plus states with exotic quantum numbers)
- formation experiment (annihilation process) – $\bar{p}p \to X \to M_1 M_2$ (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^{--}
${}^3S_1,\ 1^{--}$	$0^{+-} \leftarrow$ exotic	0^{-+}
	1^{+-}	$1^{-+} \leftarrow$ exotic
	$2^{+-} \leftarrow$ exotic	2^{-+}

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

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

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

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

According the constituent quark model tetraquark states are classified in terms of the diquark and diantiquark spin S_{cq}, $S_{\overline{cq}'}$, total spin of diquark-diantiquark system S, total angular momentum J, spacial parity P and charge conjugation C. The following states with definite quantum numbers J^{PC} are expected to exist:

- two states with $J = 0$ and positive P-parity $J^{PC} = 0^{++}$ *i.e.*, $|\, 0_{cq}, 0_{\overline{cq}'}\,; S = 0, J = 0\,\rangle$ and $|\, 1_{cq}, 1_{\overline{cq}'}\,; S = 0, J = 0\,\rangle$;
- three states with $J = 0$ and negative P-parity *i.e.*, $|A\,\rangle = |\, 1_{cq}, 0_{\overline{cq}'}\,; S = 1, J = 0\,\rangle$; $|B\,\rangle = |\, 0_{cq}, 1_{\overline{cq}'}\,; S = 1, J = 0\,\rangle$; $|C\,\rangle = |\, 1_{cq}, 1_{\overline{cq}'}\,; S = 1, J = 0\,\rangle$. State $|C\,\rangle$ is even under charge conjugation. Taking symmetric and antisymmetric combinations of states $|A\,\rangle$ and $|B\,\rangle$ we obtain a C-odd and C-even state respectively; therefore we have one state with $J^{PC} = 0^{--}$ *i.e.*, $|\,0^{--}\,\rangle = \frac{1}{\sqrt{2}}\left(|A\,\rangle + |B\,\rangle\right)$ and two states with $J^{PC} = 0^{-+}$ *i.e.*, $|\,0^{-+}\,\rangle_1 = \frac{1}{\sqrt{2}}\left(|A\,\rangle - |B\,\rangle\right)$; $|\,0^{-+}\,\rangle_2 = |\,C\,\rangle$.
- three states with $J = 1$ and positive P-parity *i.e.*, $|D\rangle = |\, 1_{cq}, 0_{\overline{cq}'}\,; S = 1, J = 1\,\rangle$; $|E\rangle = |\, 0_{cq}, 1_{\overline{cq}'}\,; S = 1, J = 1\,\rangle$; $|F\rangle = |\, 1_{cq}, 1_{\overline{cq}'}\,; S = 1, J = 1\,\rangle$. State $|F\,\rangle$ is odd under charge conjugation. Operating $|D\rangle$ and $|E\rangle$ in the same way as for states $|A\,\rangle$ and $|B\,\rangle$ we obtain one state with $J^{PC} = 1^{++}$ state *i.e.*, $|\,1^{++}\,\rangle = \frac{1}{\sqrt{2}}\left(|D\,\rangle + |E\,\rangle\right)$ and two states with $J^{PC} = 1^{+-}$ *i.e.*, $|\,1^{+-}\,\rangle_1 = \frac{1}{\sqrt{2}}\left(|D\,\rangle - |E\,\rangle\right)$; $|\,1^{+-}\,\rangle_2 = |F\rangle$.
- one state with $J = 2$ and positive P-parity $J^{PC} = 2^{++}$ *i.e.*, $|\, 1_{cq}, 1_{\overline{cq}'}\,; S = 1, J = 2\,\rangle$.

    - $\bar{p}p \to X \to J/\Psi\,\rho \to J/\Psi\,\pi\pi$; $\bar{p}p \to X \to J/\Psi\,\omega \to J/\Psi\,\pi\pi\pi$, $\bar{p}p \to X \to \chi_{cJ}\,\pi$ (decays into J/Ψ, Ψ', χ_{cJ} and light mesons);
    - $\bar{p}p \to X \to D\overline{D}^* \to D\overline{D}\,\gamma$; $\bar{p}p \to X \to D\overline{D}^* \to D\overline{D}\,\eta$ (decays into $D\overline{D}^*$-pair).

Candidate exotic hadrons

S. Olsen, Front. Phys. (Beijing) **10**, 121 (2015)

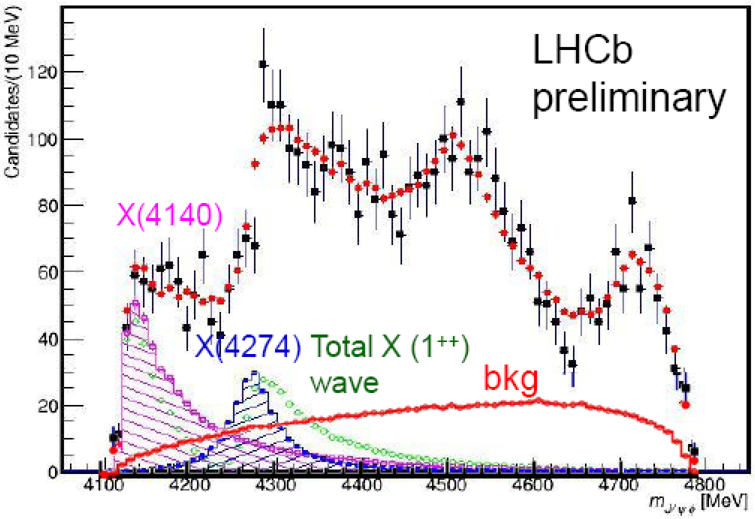
Sector	State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
Light quark sector	$\pi_1(1400)$	1354 ± 25	330 ± 25	1^{-+}	$\pi^- p \to (\eta\pi^-)p$	MPS, Compass
					$p\bar{p} \to \pi^0(\pi^0\eta)$	Xtal Barrel
	$X(1835)$	$135.7^{+5.0}_{-3.2}0$	99 ± 50	0^{-+}	$J/\psi \to \gamma(p\bar{p})$	BESII, CLEOc, BESIII
					$J/\psi \to \gamma(\pi^+\pi^-\eta')$	BESII, BESIII
Charmonium-like	$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K + (J/\psi\,\pi^+\pi^-)$	Belle, BaBar, LHCb
					$p\bar{p} \to (J/\psi\,\pi^+\pi^-) + \ldots$	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
					$pp \to (J/\psi\,\pi^+\pi^-) + \ldots$	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 ± 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
					$e^+e^- \to J/\psi + (\ldots)$	Belle
	$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	BaBar, Belle
	$Y(4008)$	4008^{+121}_{-49}	226 ± 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 ± 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 ± 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 ± 12	48 ± 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 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle
	$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 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 ± 6		1^{+-}	"$\Upsilon(5S)$" $\to \pi^0 + (\Upsilon(nS)\,\pi^0)$, $n=1,2,3$	Belle
	$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 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

SUMMARY on Zc from BES III

State]	Mass (MeV/c^2)	Width (MeV)	Decay	Process	[Ref]
$Z_c(3900)^{\pm}$	3899.0±3.6±4.9	46±10±20	$\pi^{\pm}J/\psi$	$e^+e^- \to \pi^+\pi^-J/\psi$	[1]
$Z_c(3900)^0$	3894.8±2.3±2.7	29.6±8.2±8.2	$\pi^0 J/\psi$	$e^+e^- \to \pi^0\pi^0 J/\psi$	[2]
$Z_c(3885)^{\pm}$	3883.9±1.5±4.2 Single D tag	24.8±3.3±11.0 Single D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$	[3]
	3881.7±1.6±2.1 Double D tag	26.6±2.0±2.3 Double D tag	$(D\bar{D}^*)^{\pm}$	$e^+e^- \to (D\bar{D}^*)^{\pm}\pi^{\mp}$	[4]
$Z_c(3885)^0$	$3885.7^{+4.3}_{-5.7}$±8.4	35^{+11}_{-12}±15	$(D\bar{D}^*)^0$	$e^+e^- \to (D\bar{D}^*)^0\pi^0$	[5]
$Z_c(4020)^{\pm}$	4022.9±0.8±2.7	7.9±2.7±2.6	$\pi^{\pm}h_c$	$e^+e^- \to \pi^+\pi^-h_c$	[6]
$Z_c(4020)^0$	4023.9±2.2±3.8	fixed	$\pi^0 h_c$	$e^+e^- \to \pi^0\pi^0 h_c$	[7]
$Z_c(4025)^{\pm}$	4026.3±2.6±3.7	24.8±5.6±7.7	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^{\pm}\pi^{\mp}$	[8]
$Z_c(4025)^0$	$4025.5^{+2,0}_{-4.7}$±3.1	23.0±6.0±1.0	$D^*\bar{D}^*$	$e^+e^- \to (D^*\bar{D}^*)^0\pi^0$	[9]

[1] PRL,110,252001; [2] PRL 115, 112003; [3] PRL,112, 022001; [4] PRD 92, 092006
[5] PRL 115, 222002; [6] PRL,110, 252001; [7] PRL,113,212002; [9] PRL,112, 132001
[9] arXiv:1507.02404

X(1^{++})

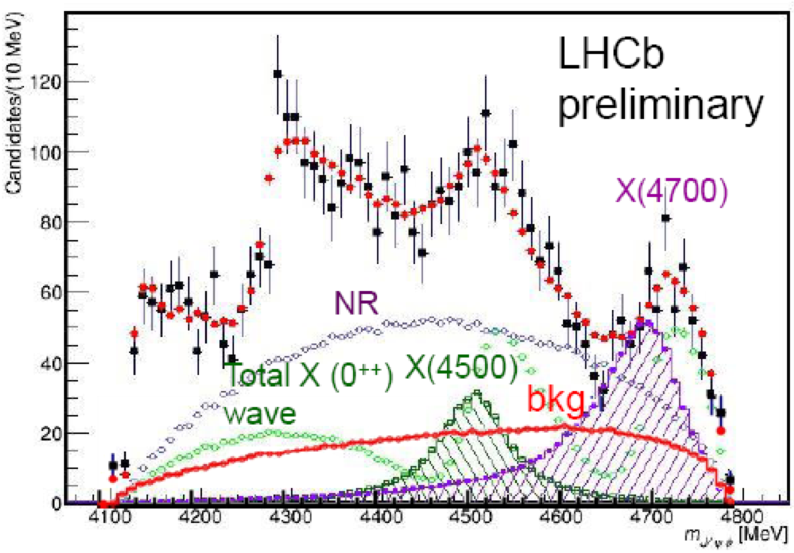


Tetra- and Penta-quarks in LHCb, T. Skwarnicki Meson 2016

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

$X(0^{++})$



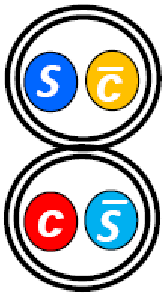
Tetra- and Penta-quarks in LHCb, T. Skwarnicki Meson 2016

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 6.1σ, 5.6σ
  - $J^{PC}=0^{++}$ determined at 4.0σ, 4.5σ, respectively

THEORETICAL INTERPRETATIONS OF X(4140) & X(4274)

Molecular models

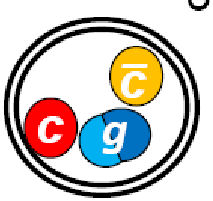


- The determination of the quantum numbers of X(4140) as $J^{PC}=1^{++}$ rules out many interpretations. Namely, 0^{++} or 2^{++} $D_s^{*}\overline{D}_s^{*}$ molecules. The large width is also not expected for true molecular bound states.

- However, X(4140) may be a 1^{++} $D_s\overline{D}_s^{*}$ cusp (form of rescattering)

Hybrid models

- Hybrid charmonium states proposed for X(4140) would have $J^{PC}=1^{-+}$. Thus they are also ruled out.

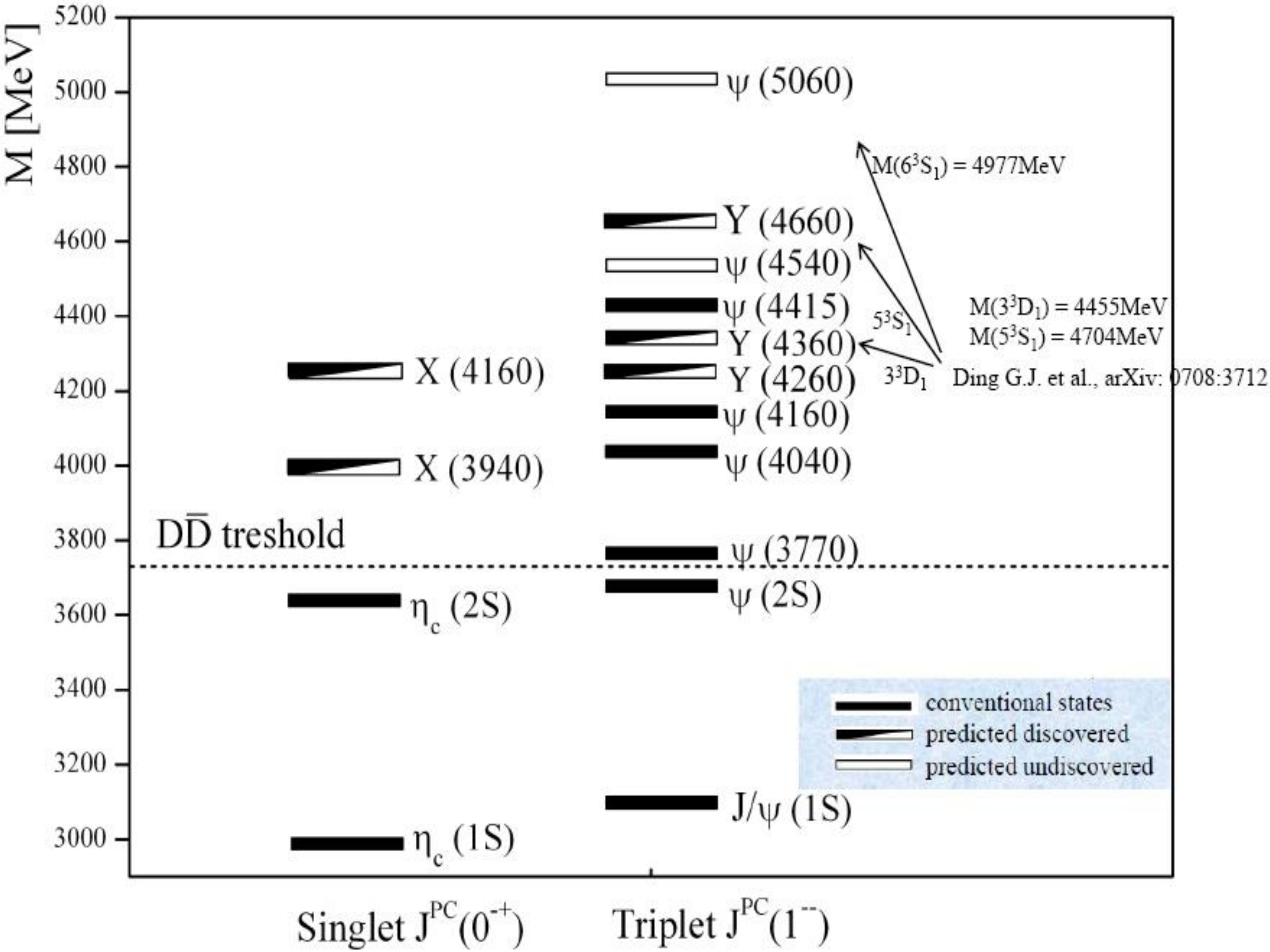


Tightly-bound tetraquark models

- There are tetraquark models which predict states with $J^{PC}=0^{-+}$, 1^{-+} or 0^{++}, 2^{++} near X(4140); these can be ruled out.

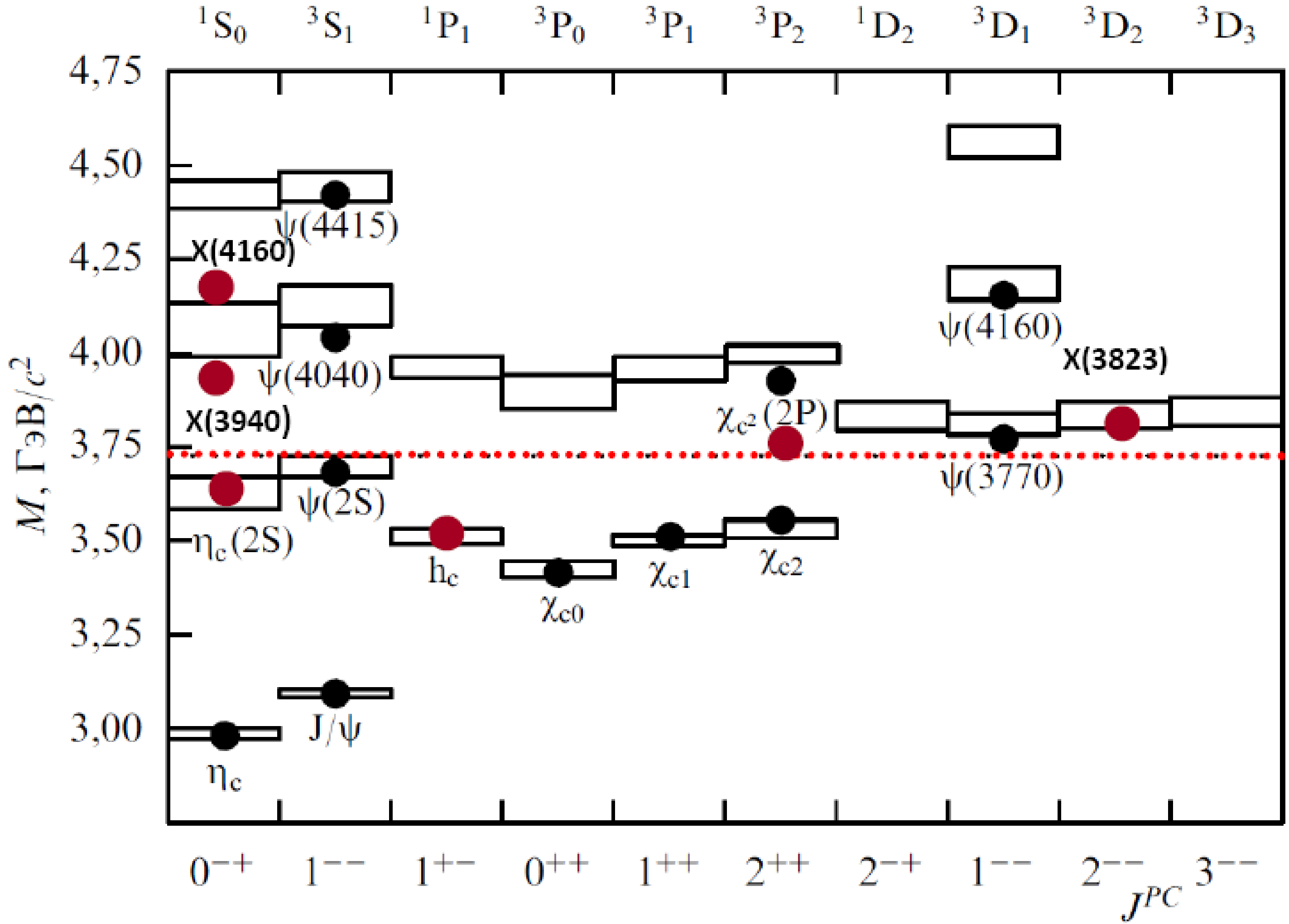
- A tetraquark model implemented by Stancu [JP G37, 075017 (2010), arXiv:0906.2485] correctly assigns 1^{++} to X(4140) and predicts a second 1^{++} state at a mass not much higher than X(4274)

- A Lattice calculation by Padmanth et al [PRD92, 034501 (2015)], based on a diquark tetraquark model, found no evidence for a 1^{++} tetraquark below 4.2 GeV



M [MeV]
5200
5000
4800
4600
4400
4200
4000
3800
3600
3400
3200
3000
ψ (5060)
M(6³S₁) = 4977MeV
Y (4660)
ψ (4540)
ψ (4415)
5³S₁
M(3³D₁) = 4455MeV
M(5³S₁) = 4704MeV
Y (4360)
Y (4260)
3³D₁
Ding G.J. et al., arXiv: 0708:3712
X (4160)
ψ (4160)
X (3940)
ψ (4040)
DD̄ treshold
ψ (3770)
ψ (2S)
η_c (2S)
conventional states
predicted discovered
predicted undiscovered
J/ψ (1S)
η_c (1S)
Singlet J^PC(0^-+)
Triplet J^PC(1^--)

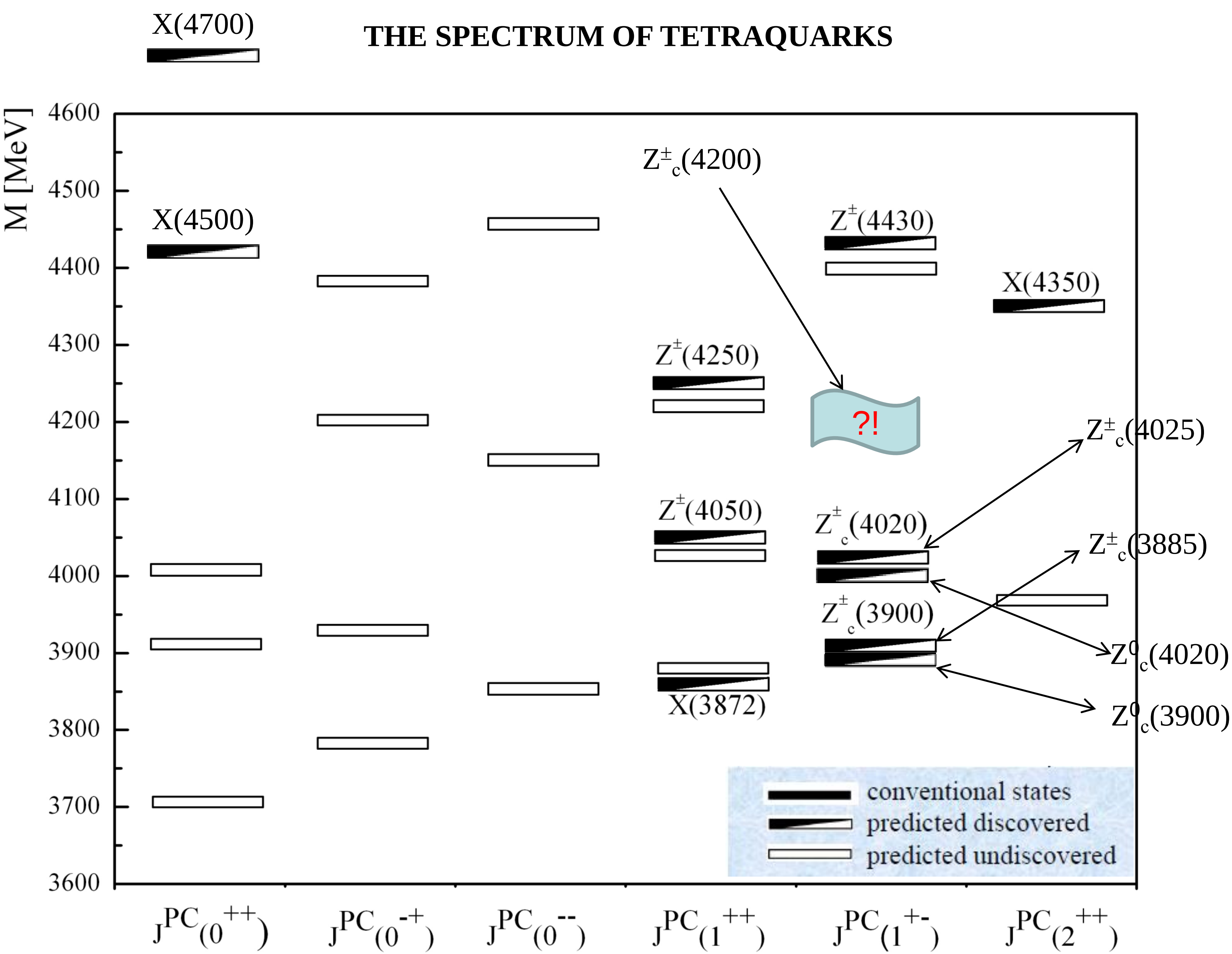
6 observed states can fit* into charmonium table



* However, not easily: potential models need to be elaborated to describe new masses

What about others?

THE SPECTRUM OF TETRAQUARKS



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 $\psi(2S)\ \pi/\eta$ 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~4200-4300: $X(1^{++},2S)\to D^{(*)}D^{(*)}$
- 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

0^{++} $+\kappa$ 4270

1^{+-} $+\kappa$

2^{++} $+\kappa$ 4270

1^{++} 4140

1^{+-} $-\kappa$

0^{++} -3κ

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):

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

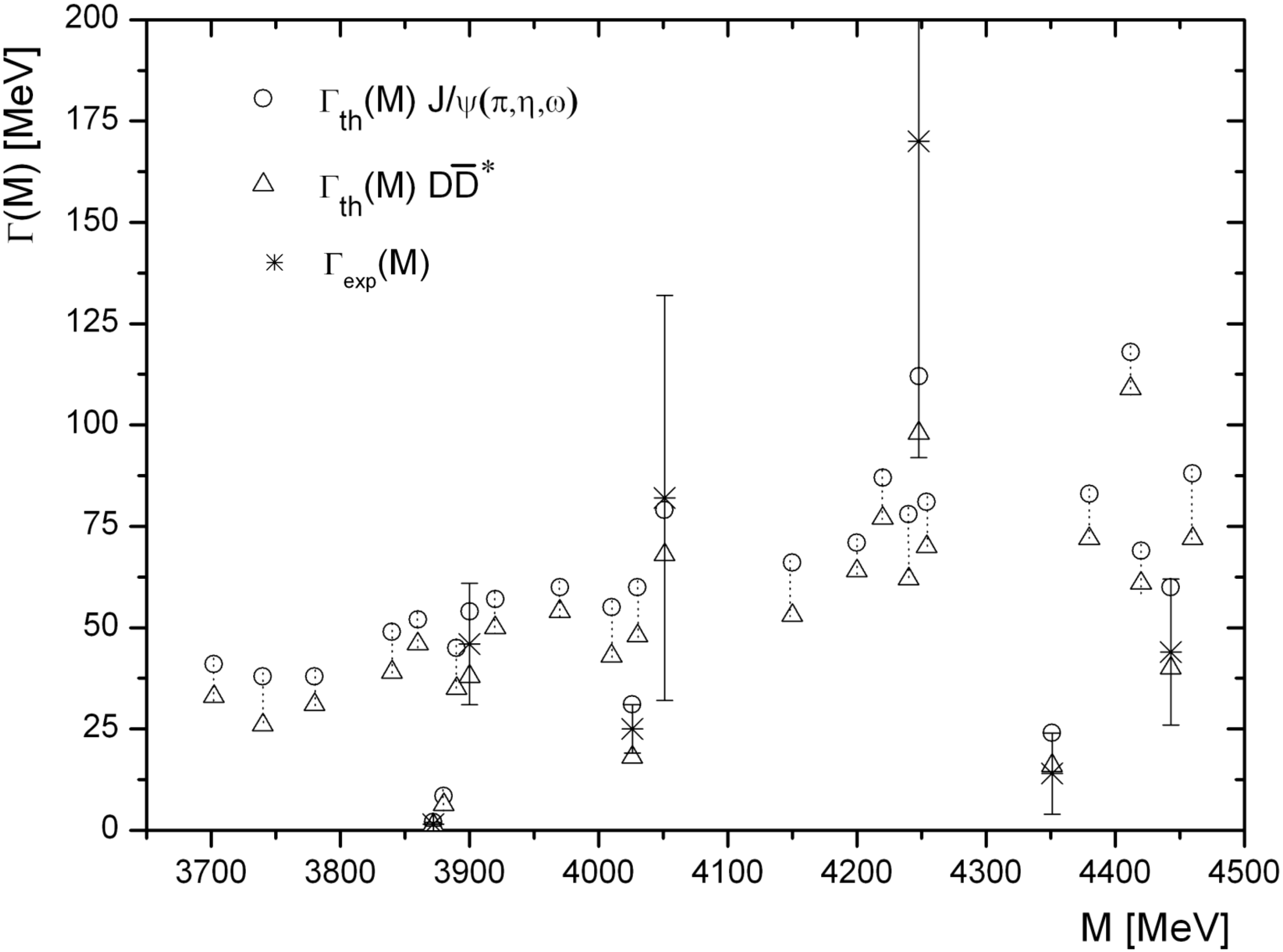
$$(r < R): \int_0^R |\phi_L(r)|^2 \, dr = 1$$

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 PROTON - PROTON COLLISIONS:

• search for the bound states with gluonic degrees of freedom: glueballs and hybrids of the type gg, ggg, $\overline{Q}Qg$, Q^3g in mass range from 1.3 to 5.0 GeV. Especially pay attention at the states $\overline{s}sg$, $\overline{c}cg$ in mass range from 1.8 – 5.0 GeV.

• charmonium-like spectroscopy $\overline{c}c$, *i.e.* $pp \to \overline{c}c\, pp$ (threshold $\sqrt{s} \approx 5$ GeV)

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

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

$$pp \to \Lambda_c X;\ pp \to \Lambda_c pX;\ pp \to \Lambda_c pD_s \qquad pp \to \Lambda_b X,\ pp \to \Lambda_b pX;\ pp \to \Lambda_b pB_s$$

• 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

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 Pythia6 41.5 nb (factor ~2 below experiment)

2. Decay channel $J/\psi \rightarrow e^+e^-$ (branching ratio ~6%)

3. Statistics: $N_{J/\psi} = L_{int} \cdot \sigma_{J/\psi} \cdot Br_{J/\psi \rightarrow e+e-} \cdot Eff_{\Delta\eta=\pm 1,5} =$
$604.8 \cdot 41.5 \cdot 0.06 \cdot 0.8 = 1205$

Y(4260) state

1. *X-section in Pythia6 for heavy flavours with default PDF and $Y(4260) \equiv \chi_{c2}(4260)$ is 81.3 nb*

2. *X-section for Y(4260) 9.1 nb*

3. *Y(4260) decay table as for $\psi(2S)$:*

   $Br\ (Y4260 \to J/\psi\ \pi+\pi-) = 32.4\%$
   $Br\ (Y4260 \to e+e-\ \pi+\pi-) = 1.9\% \to$ X-section = 0.18 nb
   1000 events for 10 weeks: $L = 9.2 \cdot 10^{29}\ cm^{-2}s^{-1}$

   $Br\ (Y4260 \to J/\psi\ K+K-) = 7.8\%$
   $Br\ (Y4260 \to e+e-\ K+K-) = 0.5\% \to$ X-section = 0.045 nb
   1000 events for 10 weeks: $L = 3.7 \cdot 10^{30}\ cm^{-2}s^{-1}$

   $Br\ (Y4260 \to \chi_{c1}\ \gamma) = 8.7\%$
   $Br\ (\chi_{c1} \to \gamma\ J/\psi) = 27.3\%$
   $Br\ (Y4260 \to e+e-\ \gamma\gamma) = 0.14\% \to$ X-section = 0.013 nb
   1000 events for 10 weeks: $L = 1.3 \cdot 10^{31}\ cm^{-2}s^{-1}$

X(3872) state

1. *X-section in Pythia6 for heavy flavours with default PDF and $X(3872) \equiv \chi_{c2}(3872)$ is 92.9 nb*

2. *X-section for X(3872) 20.9 nb*

3. *X(3872) decay table as for $\psi(2S)$:*

   $Br\ (X3872 \to J/\psi\ \pi+\pi-) = 32.4\%$
   $Br\ (X3872 \to e+e-\ \pi+\pi-) = 1.9\% \to$ *X-section = 0.42 nb*
   1000 events for 10 weeks: $L = 3.9 \cdot 10^{29}\ cm^{-2}s^{-1}$

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*

* ISHEPP 2016, JINR Dubna Sept 23 , 2016

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 ($\psi(3770) \rightarrow J/\psi\ \pi+\pi-$) = 0.34%
Br ($\psi(3770) \rightarrow D^+D^-$) = 42.4%
Br ($\psi(3770) \rightarrow D^0D^0$bar) = 57.2%

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

*5. σ(pCu) * Br(D+D-) * Br(K$\pi\pi$) = 81.9 * 0.424 * 0.092 * 0.092 = 0.294 nb*
*σ(pCu) * Br(D0D0) * Br(Kπ) = 81.9 * 0.572 * 0.038 * 0.038 = 0.068 nb*

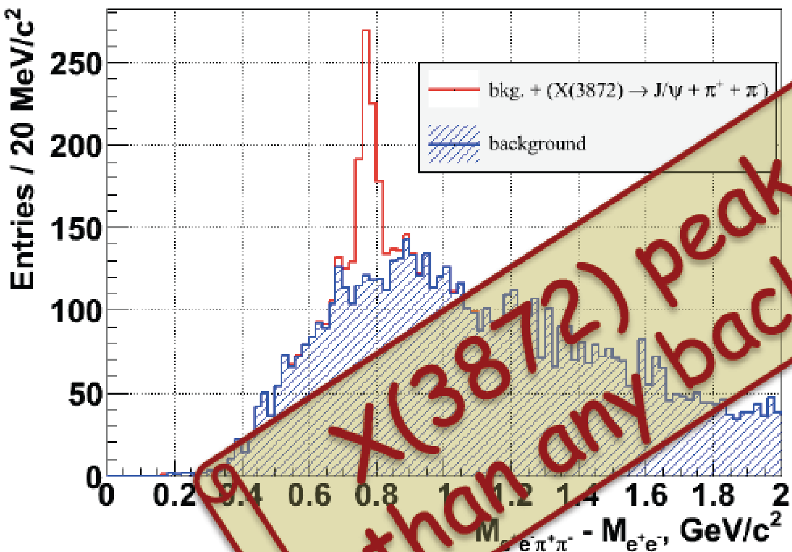
0.294 + 0.068 = 0.362 nb => L = 4.6 x 10^{29} (1000 events / 10 weeks)

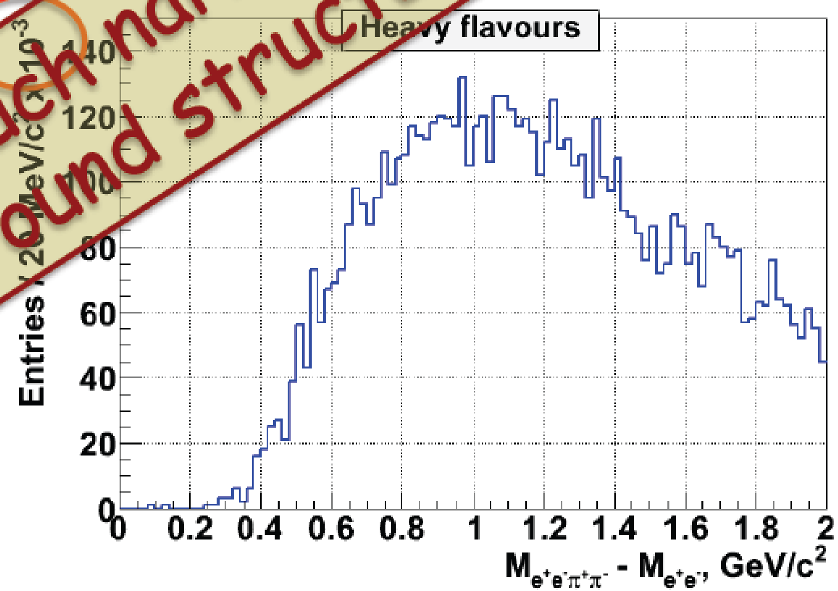
M(π⁺π⁻J/ψ) @ MPD/NICA

-- Challenge: start with S/N ≈ 10^{-3}!! --

Signal MC ~100% effic.

Heavy flavor Bkg MC ~100% effic.



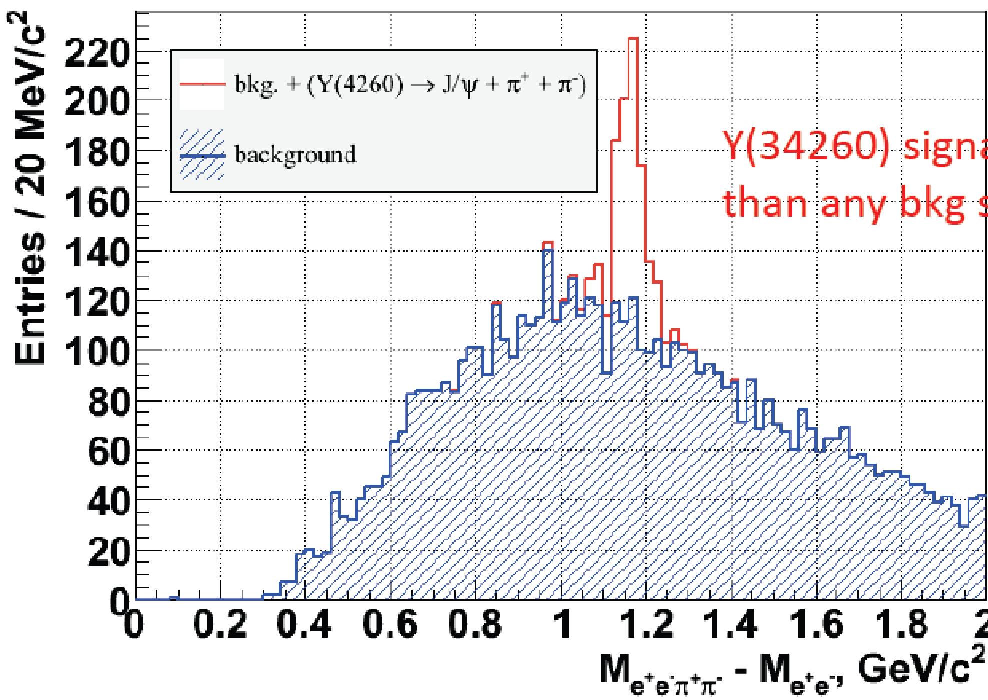


X(3872) peak much narrower than any background structure

Lots of work to do!!!

Is the "Y(4260)" produced on pp collisions?

-- possibility for NICA?? --



Y(34260) signal is narrower than any bkg structure

S/N problem the same as for the X(3872)

Conclusions

The MPD detector provides good opportunities for the reconstruction and identification of charged and neutral particles.

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

PERSECTIVES AND FUTURE PLANS

- *D*-meson spectroscopy:

-*CP*-violation
-Flavour mixing
-Rare decays

- Baryon spectroscopy:

-Strange baryons
-Charmed baryons

in progress!

Summary

- Many observed states remain puzzling and can not be explained for many years. This stimulates and motivates for new searches and ideas. New theoretical models are needed to obtain the nature of charmonium-like states.
- A combined approach based on quarkonium potential model and confinement model has been proposed and applied to study charmonium and exotics.
- Different charmonium-like states are expected to exist in the framework of the combined approach.
- The most promising decay channels of charmonium-like states have been analyzed.
- It is expected that charge / neutral tetraquarks with hidden charm must have neutral / charge partners with mass values which differ by few tens of MeV.
- Using the integral approach for the hadron resonance decay, the widths of the expected states of charmonium & tetraquarks were calculated; they turn out to be relatively narrow; most of them are of order of several tens of MeV.
- The branching ratios of charmonium-like states were calculated. Their values are of the order of $\beta \approx 10^{-1} – 10^{-2}$ dependent of their decay channel.
- NICA & FAIR can provide important complimentary information and new discoveries. The necessity for further charmonium and exotics research has been demonstrated.

THANK YOU!