The relevant overlaps presented in figure J in masso. The pattern of states appears to rule out the flux-tube model which does not predict two such states so close in mass.

The observation of two 3\(^P_0\) states nearly degenerate with 3\(^P_1\), 3\(^P_2\) states is not the pattern expected in the flux-tube model. The P-wave quasiparticle gluon approach is suggested to be dominantly hybrid in character if it has a relatively large overlap onto an S-wave excitation and the ground state in charmonium is comparable to that in the light meson.

To explore this hypothesis of a lightest hybrid multiplet further, we follow references to the quantum numbers of gluonic excitation. As in figure 39, or more generally where a quark-antiquark pair in S-wave is coupled to a non- trivial chromomagnetic gluonic field with a mass slightly above this. Not shown on the figures, an excited 1\(^2S_0\) state is suggested to be dominantly hybrid in character if it has a relatively large overlap onto an S-wave. We note that within QCD non-exotic hybrids can mix with conventional charmonia.

By considering operator-state overlaps, we identify candidate hybrid mesons. A state is predicted to form the lightest hybrid supermultiplet in the bag model. The observation that there are four hybrid candidates nearly degenerate with the 0\(^2S_0\) level suggests that the four hybrid candidates have slightly above this. Not shown on the figures, an excited 1\(^2S_0\) state is suggested to be dominantly hybrid in character if it has a relatively large overlap onto an S-wave.

Established

New States

Potential Theory

**Lattice calculations**

HYBRID CHARMONIUM?


Hadron Spectrum Collaboration

JHEP 1207, 126 (2012)
terra incognita: QCD exotics?

ONGOING: 2x500 pb⁻¹ data being taken at 4260 & 4360 MeV
A quark model state with $J^{PC} = 1^{--}$ has:

- **even** $L$ (since $P = (-1)^{L+1}$) and
- **odd** $S$ (since $C = (-1)^{L+S}$).

So $J^{PC} = 1^{--}$ and $S = 0$

$\Rightarrow$ a non-quark model state
Resonance parameters
- details confinement potential
- line shape studies
- exotic resonances/XYZ

Miscellaneous
- e.m. formfactors
- rare/forbidden decays
- beyond SM physics

Open charm \( (D_s) \)
- \( f_D \) decay constant
- quark mixing matrix
- \( D_s \) spectroscopy

Transitions & decays
- test validity pQCD
- quark masses
- strong coupling constant
- constrain EFTs

Light hadron spectroscopy
- light glueball&hybrid searches
- baryon&meson spectroscopy

Tau physics
- decays & mass
A few BESIII highlights

Resonance parameters:
- details confinement potential
- line shape studies
- exotic resonances/XYZ

Open charm:
- f_D decays
- hadronic formfactors
- spectroscopy

Miscellaneous:
- e.m. formfactors
- rare/forbidden decays
- beyond SM physics

Transitions & decays:
- test validity pQCD
- quark masses
- strong coupling constant
- constrain EFTs

Light glueball searches:
- light glueballs? PWA in progress...

CP/P-violation tests in decay of pseudoscalar mesons

New states discovered: glueballs? PWA in progress...

Precise hyperfine measurements

Mass scan: feasible and heading for precision

Importance of virtual DD pair contribution in decays

Open charm hadronic formfactors!
The next generation charmonium spectroscopy

**BESIII at IHEP, China**

- electron+positron
- couples to $J^{PC}=1^{--}$ states
- clean environment

**PANDA at FAIR, Germany**

- **anti-proton**+proton or light nuclei
- couples to all $J^{PC}$ states
- hadronic environment, background
The next generation charmonium spectroscopy

Scanning with cooled anti-protons: mass and width determination

$X(3872)$

MC simulations

Input Width $\Gamma_{X(3872)} = 100$ keV

M. Galuska, S. Lange
Giessen Group
QWG 2011

PANDA at FAIR, Germany

$\textbf{PANDA: 2018-??}$

$\textbf{\textgreater}$ anti-proton + proton or light nuclei

$\textbf{\textgreater}$ couples to all $J^{PC}$ states

$\textbf{\textgreater}$ hadronic environment, background
Charmonium Physics - probing the strong force & beyond

The strong force fascinates: confinement & generation of hadron mass

Charmonium provides a unique window to study the dynamics of the strong force

Since its discovery in 1974, charmonium spectroscopy has become a precision field

New discoveries are emerging with todays BESIII, and near future experiments such as PANDA, Belle2, ...

“This could be the discovery of the century. Depending, of course, on how far down it goes.”
BESIII collaboration: >300 physicists, 51 institutions from 10 countries
Confirmation of $X(1835)$ and Observation of two new structures

$\sigma=\pm\pm$  
$\gamma=\pm\pm$  

(Stat. sig. ~ 7.7)

$1833.7\pm 6.1(\text{stat})\pm 2.7(\text{syst})\text{MeV}$

BESII result

$PRL\ 95,\ 262001(2005)$

$f_1(1510)$

two news!

$J/\Psi \rightarrow \gamma + X(1835)$

BESIII

terra incognita: QCD exotics?

exploit radiative decay of “charmonium” to study light hadronic matter:

search for gluon-rich matter!
X(1835): $0^+$ glueball, excited $\eta'$?

X(2120), X(2370): ?

\[ J/\Psi \to \gamma + X(1835) \]

Re-discovery of the X(1835)

What’s the nature of this pseudoscalar?

Partial-wave analysis with more data in progress....
Excellent tracking and calorimetry with a uniform acceptance:

- tracks: $\sigma_p/p = 0.5\%$ at 1 GeV/c
- photons: $\sigma_E/E = 2.5\%$ at 1 GeV
PANDA, the challenges
PANDA, the challenges

Cross section (mb)

100 mb
10 mb
1 mb
100 μb
10 μb
1 μb
100 nb
10 nb
1 nb

Glueballs

η_c
X_c2
X_c(3872)
η_cπ^0
X_c0
Hybrids
The PANDA Detector

pp, pA collisions
1.5\rightarrow15 \text{ GeV/c (p momentum)}
The PANDA Detector

PANDA is a modular multi-purpose device:

- nearly $4\pi$ solid angle (partial wave analysis)
- high reaction rate capability ($2 \cdot 10^7$ annihilations/s)
- high data rate capability (200 GB/s)
- good PID ($\gamma, e, \mu, \pi, K, p$)
- momentum resolution (~1%)
- vertex info for $D, K^0_s, \Lambda$ ($c_\tau = 317 \, \mu m$ for $D^\pm$)
- efficient, software trigger ($e, \mu, K, D, \Lambda$)
- modular design (Hypernuclei experiments)
BESIII@BEPCII - breaking all records

(+data taken at 3.65 GeV and resonance scans)

~2.9 fb$^{-1}$
~106 million (+more)

~225 million (+more)

~10-20x previous generation charmonium factories
BESIII@BEPCII - breaking all records

(+data taken at 3.65 GeV and resonance scans)

\~2.9 fb\(^{-1}\)
\~106 million (+more)

0.5 fb\(^{-1}\) @4010 MeV
0.5 fb\(^{-1}\) @4260 MeV
0.5 fb\(^{-1}\) @4360 MeV (ongoing!)

\~225 million (+more)

\~10-20x previous generation charmonium factories
The proton revisited

"naive"

\[ M_{\text{proton}} \approx 3 \times M_{\text{quark}} \approx 10 \text{ MeV}/c^2 \]

“reality”

\[ M_{\text{proton}} = 938 \text{ MeV}/c^2 \]

Strong interaction = mass!