Prospects of Spectroscopy at Future Facilities

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Outline

1. General
2. Hadrons of light quarks
3. Hadrons with heavy quarks
4. Conclusions
Instead of Introduction


“This nearly total disconnect between the hadrons that we observe in experiments and the quarks and gluons that appear in the theory is a problem of large proportions in particle physics. This is what we refer to as the “QCD dilemma.” In addition to the intellectual dissatisfaction with a theory that is not directly applicable to the particles that are used and detected in experiments, there is also a practical problem in that many SM tests and searches for new physics (NP) involve strongly interacting hadrons in the initial and/or final states of the associated measurements.”

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As Frank Wilczek put it in a recent interview (Wilczek, 2016): “We have something called a standard model, but its foundations are kind of scandalous. We have not known how to define an important part of it mathematically rigorously,…”
Models of Hadron Production

MODELS FOR NONSTANDARD HADRONS
(from Olsen, Sikwarrick, and Ziembinska, REVIEW OF MODERN PHYSICS, VOLUME 90, JANUARY-MARCH 2018)

QCD-color-motivated models

QCD diquarks

+QCD hybrids (also glueballs)

Other models

+Kinematically induced resonance-like mass peaks (such as, e.g. threshold cusps)

HADRON19, Guilin
August 16-21, 2019

S.Eidelman, BINP/LPI
• What is behind the nice pictures above: how distinguish different possibilities experimentally - a question to theory?

• Strong interaction was deprived attention lately compared to $CP$ violation, $\nu$ physics, astroparticle physics

• In the light meson sector:
  Many “extra” states (e.g. scalars), which of them are “exotic”? 
  Mesons between 2 and 3 GeV, high-spin states 
  Rather old (LASS) studies of strange mesons

• In the heavy meson sector a variety of new states with exotic properties among heavy quarkonia, but scarce knowledge of open-flavour mesons ($D^{**}$, $D_{sJ}$, $B^{**}$, $B_{sJ}$)

• Situation with baryons is far from satisfactory
VEPP-2000 will run in the c.m. energy range 0.3-2 GeV for another 7-10 years

Cross sections of $e^+e^- \rightarrow$ hadrons as an input for the $(g - 2)_\mu$ problem

Dynamics of multihadronic production of mesons $\rho$, $\omega$, $\phi$ and their excitations

Cross sections near the $N\bar{N}$ threshold
Strong interaction of nucleons in the Paris potential convolved with c.m. energy spread of 0.95 MeV and radiative corrections explains all $\sigma$’s


Is the effect $\propto B$ in $p\bar{p}$ annihilation?

The effect of strong interaction of $N\bar{N}$ near threshold is common for $e^+e^-, J/\psi, D$ and $B$ decays

S.Eidelman, BINP/LPI
BESIII Detector

The c.m. energy range: 2-4.6(4.9) for BESIII, 9-11.02 (?) for BelleII

Study of dynamics in multihadronic processes using ISR, vector meson decays in the $\psi$ and $\Upsilon$ families, baryons of light quarks, some baryons with charm

S. Eidelman, BINP/LPI
BelleII and BESIII will strongly improve the BaBar measurements
$e^+e^-$ Colliders – V ($R$ measurement at KEDR)

1.84-3.05 GeV  \[ R = 2.225 \pm 0.020 \pm 0.047 \quad (R_{\text{PQCD}} = 2.18 \pm 0.02) \]


3.05-3.72 GeV  \[ R_{uds} = 2.204 \pm 0.013 \pm 0.030 \quad (R_{\text{PQCD}} = 2.16 \pm 0.01) \]

V.V. Anashin et al., Phys. Lett. B753, 533 (2016); B788, 42 (2019)

Total (syst. error) 3.9\% (2.4\%) at low, 2.6\% (1.9\%) at high $\sqrt{s}$

$R$ measurement from 5 to 7 GeV in progress

Confirmation by BESIII awaited impatiently


V.V. Anashin et al., Phys. Lett. B753, 533 (2016); B788, 42 (2019)
Lepto- and Hadroproduction

VES

COMPASS
**τ lepton as a Source of Resonances**

- A pure laboratory to test Standard Model
- All three basic interactions are probed:
  - electromagnetic production in $e^+e^- \rightarrow \tau^+\tau^-$, weak decay,
  - strong form factors in hadronic decays
- Low decay multiplicity $\Rightarrow$ smaller combinatorial BG
- Each hadronic decay is saturated by a single resonance: $2\pi$, $4\pi$, $\eta\pi\pi - \rho + \rho' + \ldots$, $3\pi - a_1(1260) + a'_1$ etc.
- At $\Upsilon(4S)$ $\sigma(e^+e^- \rightarrow \tau^+\tau^-) \approx 0.9$ nb, so $1$ ab$^{-1}$ gives $\approx 10^9$ $\tau^+\tau^-$ pairs
- BelleII will collect a data sample
  - 3 orders of magnitude higher than CLEO
Current values of mass and width show a high scatter of values caused by different parameterizations.

Determination of decay dynamics ($\rho\pi$, $\sigma\pi$, $KK^*$, ...)

More light on $a_1(1420)$ and possible $a_1'$ at 1640 MeV
What can be learned about the $\eta\pi$ and $\eta'\pi$ systems from the combined analysis of the $\eta(\eta')\pi^+\pi^-$ system in $e^+e^-$ (CMD-3, SND, BESIII), photoproduction (GlueX) and $\tau$ decays (BelleII)?

Properties of excited vector mesons ($\rho'$, $\omega'$, $\phi'$) are known badly.

Strong evidence for the $\rho'$ at 2.2 GeV, Is $\phi(2170)$ normal? $\omega'$

S.Eidelman, BINP/LPI
The $M_{K\pi}$ spectrum is well described by the $K^*(892)$, $K^*_0(700)$ ($\kappa$) and $K^*_0(1430)$ (or $K^*(1410)$)

$M(K^*(892)^-) = (895.47 \pm 0.20 \pm 0.44 \pm 0.59) \text{ MeV}$

$\Gamma(K^*(892)^-) = (46.2 \pm 0.6 \pm 1.0 \pm 0.7) \text{ MeV}$

Are masses of $K^{*\pm}$ and $K^{*0}$ different?

### Spectroscopy of $K^*$’s

About 3.5% of $\tau$ decays are with kaons.

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>Mass, MeV</th>
<th>Width, MeV</th>
<th>Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_0^*(700)(\kappa)$</td>
<td>$0^+$</td>
<td>$824 \pm 30$</td>
<td>$470 \pm 50$</td>
<td>$K\pi$</td>
</tr>
<tr>
<td>$K^*(892)$</td>
<td>$1^-$</td>
<td>$891.66 \pm 0.26$</td>
<td>$50.8 \pm 0.9$</td>
<td>$K\pi$</td>
</tr>
<tr>
<td>$K_1(1270)$</td>
<td>$1^+$</td>
<td>$1272 \pm 7$</td>
<td>$90 \pm 20$</td>
<td>$K\pi\pi$</td>
</tr>
<tr>
<td>$K_1(1400)$</td>
<td>$1^+$</td>
<td>$1403 \pm 7$</td>
<td>$174 \pm 13$</td>
<td>$K\pi\pi$</td>
</tr>
<tr>
<td>$K^*(1410)$</td>
<td>$1^-$</td>
<td>$1414 \pm 15$</td>
<td>$232 \pm 21$</td>
<td>$K\pi\pi, K\pi$</td>
</tr>
<tr>
<td>$K_0^*(1430)$</td>
<td>$0^+$</td>
<td>$1425 \pm 50$</td>
<td>$270 \pm 80$</td>
<td>$K\pi$</td>
</tr>
<tr>
<td>$K_2^*(1430)$</td>
<td>$2^+$</td>
<td>$1425.6 \pm 1.5$</td>
<td>$98.5 \pm 2.9$</td>
<td>$K\pi, K\pi\pi$</td>
</tr>
<tr>
<td>$K(1460)$</td>
<td>$2^+$</td>
<td>$1482.40 \pm 3.58 \pm 15.22$</td>
<td>$335.60 \pm 6.20 \pm 8.65$</td>
<td>$K^*\pi, K\rho$</td>
</tr>
<tr>
<td>$K_2(1580)$</td>
<td>$2^-$</td>
<td>$\approx 1580$</td>
<td>$\approx 110$</td>
<td>$K^<em>\pi, K_2^</em>(1430)\pi$</td>
</tr>
<tr>
<td>$K_1(1650)$</td>
<td>$1^+$</td>
<td>$1650 \pm 50$</td>
<td>$150 \pm 50$</td>
<td>$K\phi$</td>
</tr>
<tr>
<td>$K^*(1680)$</td>
<td>$1^-$</td>
<td>$1718 \pm 18$</td>
<td>$322 \pm 110$</td>
<td>$K\pi, K\rho, K^*\pi$</td>
</tr>
</tbody>
</table>

12 more resonances from 1780 to 3100 MeV are badly studied.
$K^0_L$ Factory (KLF) at JLAB
Measurement with KLF will reduce:
Uncertainty in the mass by a factor of two!
Uncertainty in the width by a factor of five!
Hadrons with Heavy Quarks
In addition to BESIII, Belle/BelleII, LHCb, ATLAS and CMS, there are also Super-c-τ factories and PANDA

\[ p\bar{p} \to c\bar{c} \] has high potential (all \( J^P \) accessible)

Two difficulties – one should know the precise mass of a narrow state, and PANDA can start too late (close to 2030?) after BelleII and LHCb
Analyses of the first data are in progress, the first paper on luminosity measurement will be soon submitted to CPC
LHCb upgrade - I
LHCb upgrade - II

<table>
<thead>
<tr>
<th>Year</th>
<th>LS2</th>
<th>LS3</th>
<th>LS4</th>
<th>Run 5, 6,...</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Run 2</td>
<td>Run 3</td>
<td>Run 4</td>
<td></td>
</tr>
</tbody>
</table>

- Install LHCb Upgrade (Phase I)
- Potential ‘stepping stone’ projects to prepare for Phase II
- HL-LHC: Phase II upgrade

Current detector:
- $\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- 1.1 visible interactions / crossing
- 8 fb$^{-1}$ collected

Phase-I Upgrade:
- $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ (5x)
- 5.5 visible interactions / crossing
- 50 fb$^{-1}$ collected

Phase-II?
- $\mathcal{L} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (50x)
- 55 visible interactions / crossing
- 300 fb$^{-1}$ collected
### LHCb upgrade - III

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>LHCb 23 fb(^{-1})</th>
<th>LHCb 50 fb(^{-1})</th>
<th>LHCb 300 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^+ \to X(3872)(\to J/\psi \pi^+\pi^-)K^+)</td>
<td>14k</td>
<td>30k</td>
<td>180k</td>
</tr>
<tr>
<td>(B^+ \to X(3872)(\to \psi(2S)\gamma)K^+)</td>
<td>500</td>
<td>1k</td>
<td>7k</td>
</tr>
<tr>
<td>(B^0 \to \psi(2S)K^-\pi^+)</td>
<td>340k</td>
<td>700k</td>
<td>4M</td>
</tr>
<tr>
<td>(B_c^+ \to D_s^+D^0\bar{D}^0)</td>
<td>10</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>(\Lambda_b^0 \to J/\psi pK^-) ([*])</td>
<td>680k</td>
<td>1.4M</td>
<td>8M</td>
</tr>
<tr>
<td>(\Xi_b^- \to J/\psi \Lambda K^-)</td>
<td>4k</td>
<td>10k</td>
<td>55k</td>
</tr>
<tr>
<td>(\Xi_{cc}^{++} \to \Lambda_c^+K^-\pi^+\pi^+)</td>
<td>7k</td>
<td>15k</td>
<td>90k</td>
</tr>
<tr>
<td>(\Xi_{bc}^+ \to J/\psi \Xi_c^+)</td>
<td>50</td>
<td>100</td>
<td>600</td>
</tr>
</tbody>
</table>
$M_{Z(4430)^-} = 4475$ MeV
$\Gamma_{Z(4430)^-} = 172$ MeV
Dots – good old guys, Dots – new states matching Quark Model
Dots – neutral, triangles – charged states, exotic?
Rectangulars – potential model predictions
Exotic because of the too large number of states with given \( I^G J^{PC} \)
or unexpected decay pattern \( (J/\psi \pi^+ \pi^- \text{ instead of open charm}) \)
Study of Charmonium-(like) States – II

Huge data samples needed to perform a coupled-channel analysis resulting in a consistent set of resonance parameters
From a controversial $Y(4140)$ of CDF to $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ of LHCb

Once again about importance of full amplitude analysis!

**X(3872) Production at ATLAS**

Cross section of prompt $X(3872)$ in $pp$-collision (LHC experiment)

**ATLAS**

$\sqrt{s}=8$ TeV, 11.4 fb$^{-1}$

Prompt $X(3872)$

- Inconsistent with pure molecular interpretation
- Support $D\bar{D}^* - \chi_{c1}(2P)$ mixture state.
  - Need further information about production and decay
- Current $X(3872)$ total width:
  \[ \Gamma_{\text{tot}} < 1.2 \text{ MeV} \]
Determination of the $X(3872)$ Width at BelleII

With 50 ab$^{-1}$ for $D^0\bar{D}^0\pi^0$
the toy-MC gives for $\Gamma_{\text{tot}}$:
UL at 90%CL 180 keV
3$\sigma$ sign. 280 keV
5$\sigma$ sign. 570 keV

Talk of H. Hirata
PANDA: $\Gamma/\Delta\Gamma > 5$ at $\Gamma > 50\ldots120$ keV
**General View of the Novosibirsk c-τ Factory**

**Super Charm-Tau factory project at BINP**

Beam energy from 1.0 to 2.5 GeV
Luminosity ~1E35 at 2 GeV
Crab waist collisions

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c-tau factory project status:
- CDR completed in 2013
- Discussion with government and potential collaborators
- Project recently re-energized (Aug 2016) with the **International Advisory Committee** created
Two projects of Super-charm-tau factories

**Novosibirsk:** 2-6 GeV, $L$ from 0.63 (1 GeV) to 1 (4 GeV) $10^{35} \text{cm}^{-2}\text{s}^{-1}$

**Hefei:** 2-7 GeV, $L$ from 0.5 (Phase I) to 1 (Phase II) $10^{35} \text{cm}^{-2}\text{s}^{-1}$

Both have longitudinal polarization of the initial $e^{-}$ beam
Detector for Novosibirsk SCTF

Counting rate 300 kHz  Good energy and momentum resolution
High efficiency for soft tracks  Very high identification quality
Conventional Charmonia

<table>
<thead>
<tr>
<th>State</th>
<th>$J/\psi$</th>
<th>$\psi(2S)$</th>
<th>$\psi(3770)$</th>
<th>$\psi(4040)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$, MeV</td>
<td>0.093</td>
<td>0.294</td>
<td>27</td>
<td>84</td>
</tr>
<tr>
<td>$\int Ldt$, fb$^{-1}$</td>
<td>800</td>
<td>250</td>
<td>400</td>
<td>10</td>
</tr>
<tr>
<td>$N$</td>
<td>$10^{12}$</td>
<td>$10^{11}$</td>
<td>$2 \cdot 10^9$</td>
<td>$10^8$</td>
</tr>
</tbody>
</table>

- Even for the $J/\psi$ and $\psi(2S)$ full decay pattern is unclear
- Is the $\psi(3770)$ a $D\bar{D}$ factory?
- $20$ ($25$) fb$^{-1}$ needed to produce $10^8 \psi(4160)$ ($\psi(4415)$) mesons
- $\sim 10^{10} \chi_{cJ}$ and $\eta_c(1S)$ in radiative decays of the $J/\psi$ and $\psi(2S)$
- About $10^8 h_c$ mesons in $\psi(2S) \rightarrow h_c\pi^0$
- $\eta_c(2S)$ mesons can be produced in $\psi(2S) \rightarrow \eta_c(2S)\gamma$ or $\gamma\gamma$ collisions
- Although believed to be conventional, these states are not well enough studied
Unconventional charmonia

- All $\psi(Y)$ states with $J^{PC} = 1^{--}$ will be directly produced at $\sqrt{s} = M_Y$: $\psi(4260/4230)$, $\psi(4360)$, $\psi(4660)$

- Charged $Z_c$ states can be produced by scanning the $\sqrt{s}$ range and studying the $J/\psi\pi\pi$, $h_c\pi\pi$, $D(\ast)\bar{D}(\ast)$ final states

- Neutral $c\bar{c}$ states with other quantum numbers can be studied in the recoil to $\pi\pi$, $\pi^0$, $\eta$, $\omega$ final states

- $C = +1$ states can be also produced in $\gamma\gamma$ collisions

- Between 6 and 7 GeV double $c\bar{c}$ production?
Mesons with open flavour

- 12 $D^{**}$ are known
- 9 $D_{sJ}$ are known, what are $D_{s0}^*(2317)$ and $D_{s1}(2460)$?
- 6 $B^{**}$ are known
- Only 3 $B_{sJ}$ observed,
  there is also $X(5568)$ decaying to $B_s \pi^\pm$ claimed by D0, but not seen by ATLAS, CDF, CMS and LHCb

More efforts from both experiment and theory needed
The $B_c$ is well established and its parameters are dominated by LHCb:

\[ M = 6274.9 \pm 0.8 \text{ MeV}, \quad \tau = (0.510 \pm 0.009) \times 10^{-12} \text{s} \]

The $B_c(2S)$ decaying to $B_c\pi^+\pi^-$ is expected to be narrow. ATLAS claims it at $6842 \pm 4 \pm 5 \text{ MeV}$
CMS and LHCb have consistent, more precise results at 29 MeV higher mass.

It would be interesting to search for $B_c(nP)$ as well as $B_c^* \rightarrow B_c\gamma$

The “Last Meson” definitely deserves more attention.
LHCb – doubly charm baryon

- Consistent mass measurements

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>3621.40</td>
<td>± 0.72 ± 0.27 ± 0.14 ($\Lambda_c^+$)</td>
</tr>
<tr>
<td>3620.56</td>
<td>± 1.5 ± 0.4 ± 0.3 ($\Xi_c^+$)</td>
</tr>
<tr>
<td>3621.24</td>
<td>± 0.65 ± 0.31</td>
</tr>
</tbody>
</table>

Mass difference: $m(\Xi^{++}_{cc})_{\text{LHCb}} - m(\Xi^{++}_{cc})_{\text{SLEEX}} = 103 ± 2$ MeV

- Inconsistent with being isospin partners

- $\tau_{\Xi^{++}_{cc}} = (256^{+24}_{-22} ± 14)$ fs

- Confirms it is a weakly decaying $J = 1/2$ ground state

- A challenging search for $\Xi^{++}_{cc}$ and $\Omega^{++}_{cc}$ in future
For the $\Omega_c(css)$ five narrow states are predicted with mass around 3000 MeV and splittings about 30 MeV, two $1/2^-$, two $3/2^-$ and one $5/2^-$. The $s\bar{s}$ diquark is ripped apart and made narrow. Not clear what is what.

LHCb: R. Aaij et al., PRL 118, 182001 (2017)
### Promising energy regions

<table>
<thead>
<tr>
<th>Particles</th>
<th>Threshold, GeV/c^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^{(*)} \bar{B}^{**}$</td>
<td>11.00 – 11.07</td>
</tr>
<tr>
<td>$B_{s}^{(*)} \bar{B}_{s}^{**}$</td>
<td>11.13 – 11.26</td>
</tr>
<tr>
<td>$\Lambda_b \bar{\Lambda}_b$</td>
<td>11.24</td>
</tr>
<tr>
<td>$B^{<strong>} \bar{B}^{</strong>}$</td>
<td>11.44 – 11.49</td>
</tr>
<tr>
<td>$B_{s}^{<strong>} \bar{B}_{s}^{</strong>}$</td>
<td>11.48 – 11.68</td>
</tr>
<tr>
<td>$\Lambda_b \bar{\Lambda}_b^{**}$</td>
<td>11.53 – 11.54</td>
</tr>
<tr>
<td>$\Sigma_b^{(<em>)} \bar{\Sigma}_b^{(</em>)}$</td>
<td>11.62 – 11.67</td>
</tr>
<tr>
<td>$\Lambda_b^{<strong>} \bar{\Lambda}_b^{</strong>}$</td>
<td>11.82 – 11.84</td>
</tr>
</tbody>
</table>

At the moment it is 11.02 GeV or slightly higher
Circular Electron Positron Collider (CEPC)

Unique number of hadrons produced under clean conditions,
a study of various correlations

<table>
<thead>
<tr>
<th>Operation mode</th>
<th>Z factory</th>
<th>WW threshold</th>
<th>Higgs factory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>91.2</td>
<td>160</td>
<td>240</td>
</tr>
<tr>
<td>Run time (year)</td>
<td>2</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Instantaneous luminosity $(10^{34}\text{cm}^{-2}\text{s}^{-1})$</td>
<td>16–32</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Integrated luminosity $(\text{ab}^{-1})$</td>
<td>8–16</td>
<td>2.6</td>
<td>5.6</td>
</tr>
</tbody>
</table>

Higgs boson yield $\rightarrow 10^6$
$W$ boson yield $\rightarrow 10^7$ $10^8$
$Z$ boson yield $10^{11}–10^{12}$ $10^8$ $10^8$

Lepton Universality – How large is $\mathcal{B}(W^+ \rightarrow \tau^+ \nu_\tau)$?
Conclusions

Already now and more in close future there are excellent possibilities to study strong interactions.

Complementarity of different approaches, both at the facility and analysis level, is crucial.