Current Experiments

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Outline

- Current challenges (with a spectroscopy bias)
- Some results that showcase current experiments
Reaction Products (?)
Meson Spectrum from Lattice QCD


FIG. 11 (color online). Isoscalar (green and black) and isovector (blue) meson spectrum on the $m_{\pi} = 391$ MeV, $24^3 \times 128$ lattice. The vertical height of each box indicates the statistical uncertainty on the mass determination. States outlined in orange are the lowest-lying states having dominant overlap with operators featuring a chromomagnetic construction—their interpretation as the lightest hybrid meson supermultiplet will be discussed later.
**Precision Experiment**

\[ \frac{J/\psi}{\gamma\pi^0\pi^0} \]

**Events / 15 MeV/c**

**Total Intensity**

**BESIII Collaboration, arXiv:1506.00546**

\[ D \rightarrow K_S\pi^+\pi^- \]

**Belle Collaboration, PRD 73, 112009 (2006)**
Challenges of Precision Analysis

\[ \pi^- \quad X \quad \pi^+ \]

or

\[ \pi^- \quad X \quad \pi^- \]

\[ \pi^- \quad X \quad \pi^- \]

\[ \pi^- \quad X \quad \pi^- \]
Theme

- advances in theory continue to sharpen and frame questions about QCD that can be addressed by experiment
- advances in experiment and technology have positioned us to address questions using data with unprecedented precision
- goal of this school: foster and share advances in phenomenology that help connect the two points above
A Selection of Recent Results

that showcase a variety of experiments and emphasize the need for understanding reaction theory
e^+e^- \rightarrow \text{hadrons}

BaBar at PEP-II SLAC (Menlo Park, CA)
Belle at KEK (Tsukuba, Japan)
BESIII at BEPCII (Beijing, China)
Charmonium Landscape

- Key players:
  - $Y(4260)$: ???
  - $J/\psi$: $S_q=1\; L=0, J^{PC} = 1^{--}$
  - $h_c$: $S_q=0\; L=1, J^{PC} = 1^{+-}$

- Key transitions:
  - $Y \to \pi\pi J/\psi$
  - $Y \to \pi\pi h_c$

- Study of $Y(4260)$ led to discovery of charged $Z(3900)^\pm$ and $Z(4020)^\pm$ structures

Quark Model Prediction:
Barnes et al., PRD 72, 054026 (2005)
(approximate — not all XYZ candidates shown!)
The $Y(4260)$

- $I^-\bar{I}$ state produced in $e^+e^-$

- Mass greater than $2M(D)$ so we expect OZI favored decay:

$$\frac{\mathcal{B}(Y(4260) \to D\bar{D})}{\mathcal{B}(Y(4260) \to \pi\pi J/\psi)} < 4$$

compare with $\approx 500$ for $\psi(3770)$

CLEO Collaboration, PRD 80, 072001 (2009)
Charmonium from Lattice QCD

L. Liu et al. [Hadron Spectrum Collab.], JHEP07 126 (2012)

Figure 16. Charmonium spectrum up to around 4.5 GeV showing only $J^{PC}$ channels in which we identify candidates for hybrid mesons. Red (dark blue) boxes are states suggested to be members of the lightest (first excited) hybrid supermultiplet as described in the text and green boxes are other states, all calculated on the 24$^3$ volume. As in Fig. 14, black lines are experimental values and the dashed lines indicate the lowest non-interacting $D\bar{D}$ and $D_s\bar{D}_s$ levels.

7.2 Exotic mesons and hybrid phenomenology

In Fig. 16 we show the charmonium spectrum for the subset of $J^{PC}$ channels in which, by considering operator-state overlaps, we identify candidate hybrid mesons. A state is suggested to be dominantly hybrid in character if it has a relatively large overlap onto an operator proportional to the commutator of two covariant derivatives, the field-strength tensor. We note that within QCD non-exotic hybrids can mix with conventional charmonia. We find that the lightest exotic meson has $J^{PC}=1^{--}$ and is nearly degenerate with the three states observed in the negative parity sector suggested to be non-exotic hybrids, $(0^{-}, 2^{-}), (0^{-}, 1^{-}), (1^{-}, 1^{-})$. Higher in mass there is a pair of states, $(0^{-}, 2^{-}), (1^{-}, 2^{-})$, and a second $2^{++}$ state slightly above this. Not shown on the figures, an excited $1^{++}$ appears at around 4.6 GeV, there is an exotic $3^{++}$ state at around 4.8 GeV and the lightest $0^{++}$ exotic does not appear until above 5 GeV.

The observation that there are four hybrid candidates nearly degenerate with $J^{PC}=(0^{-}, 1^{-}, 2^{-})$, coloured red in Fig. 16, is interesting. This is the pattern of states predicted to form the lightest hybrid supermultiplet in the bag model [38, 39] and the P-wave quasiparticle gluon approach [40], or more generally where a quark-antiquark pair in S-wave is coupled to a $1^{++}$ chromomagnetic gluonic excitation as shown Table 5. This is not the pattern expected in the flux-tube model [41] or with an S-wave quasigluon. In addition, the observation of two $2^{++}$ states, with one only slightly heavier than the other, appears to rule out the flux-tube model which does not predict two such states so close in mass.

The pattern of $J^{PC}$ of the lightest hybrids is the same as that observed in light meson sector [11, 31]. They appear at a mass scale of 1.2-1.3 GeV above the lightest conventional – 25 –
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at $E_{cm} = 4260$ MeV

- $J/\psi$ is cleanly identified in dilepton decay modes

- Structure in $\pi^+J/\psi$ mass that does not arise from $\pi^+\pi^-$ interactions

BESIII Collaboration, PRL 110, 252001 (2013)
\[ Z(3900)^\pm \rightarrow \pi^{\pm} J/\psi \]

- Narrow (\( \approx 50 \) MeV) and charged
- Not conventional charmonium: tetraquark?
- Evidence of neutral partner
  \[ \text{[T. Xiao et al., PLB 727, 366 (2013)]} \]
What is $Z(3900)$?

$J^P = 1^+$

How is it connected to $Y(4260)$?

$D^*$

$L=0$

$J^P = 1^-$

$\bar{D}$

$c$

$J^P = 0^-$

$\bar{D}$

$c$

$u$

$\bar{c}$

$\bar{d}$

$u$

$\bar{c}$

$\bar{d}$
What is a Resonance?

\[ \begin{align*}
\pi & \quad \rho \\
\pi & \quad \pi
\end{align*} \]

\[ M_\rho = 775 \text{ MeV} \quad \Gamma_\rho = 148 \text{ MeV} \]

\[ M \propto \frac{1}{M^2 - s - i\sqrt{s}\Gamma} \]

pole: \[ \sqrt{s} = M - i\Gamma/2 \]

Expt.: \[ s = [M(\pi\pi\pi)]^2 \text{ (real)} \]
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics 6, 139 (2013) | DOI: 10.1103/Physics.6.139

Physics looks back at the standout stories of 2013.

As 2013 draws to a close, we look back on the research covered in Physics that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the Physics staff, we wish everyone an excellent New Year.

– Matteo Rini and Jessica Thomas

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed Z₃(3900), are possible, the “tetraquark” interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.

Strangers from Beyond our Solar System

Detector experiments hunting for rare events can go years and never see anything out of the ordinary. So it was cause for excitement when IceCube, a giant neutrino telescope at the South Pole, reported the detection of two neutrinos with energies of around 1000 tera-electron-volts (TeV), roughly a billion times more energetic than those arriving from the Sun. Scientists at IceCube have since further analyzed their data and reported 26 more neutrinos with energies above 30 TeV. Researchers will need to
Y(4260) hybrid test?

- Lattice QCD predicts the hybrid $1^{- -}$ state to have spin $S = 0$

Using LQCD Dudek et al. predict [PRD 79, 094504 (2009)]

$$Y_{\text{hybrid}} \rightarrow \gamma \eta_c$$

rate is comparable or larger than

$$Y_{\text{hybrid}} \rightarrow \gamma \chi_{c0}$$

Potential “hybrid test” for $Y(4260)$, but no experimental sensitivity…yet

Two decays that we can attempt to compare instead:

$$Y(4260) \rightarrow \pi \pi h_c$$

$$Y(4260) \rightarrow \pi \pi J/\psi$$
The plot shows the Dalitz plot of the \( \psi(4S) \) candidate events summed over all energies. The individual signal and sideband distributions are taken from the BESIII Collaboration, PRL 111, 242001 (2013).

The cross section \( \sigma(\pi^+ \pi^- h_c) \) is plotted versus the center-of-mass energy \( E_{cm} \). The tail in the high mass region is depicted, and the detection efficiency, the ISR correction factor, and the fit are measured by using large angle Bhabha events, and the integrated luminosity at each energy point is estimated in the same way as described in Refs. [11, 13].

The fit is applied to the 16 data sets at 4.23, 4.26, and 4.36 GeV, and the detection efficiency, the ISR correction factor, and the fit range are estimated by varying the number of signal events (mainly come from the luminosity measurement, the contrast to the observed energy dependence in the cross section appears to be constant above 4.2 GeV with a possible local maximum at around 4.23 GeV). This is in contrast to the predicted, undiscovered, and unpredicted, discovered results.

The branching fraction is measured by using large angle Bhabha events, and the detection efficiency, the ISR correction factor, and the fit are measured by using large angle Bhabha events, and the integrated luminosity at each energy point is estimated in the same way as described in Refs. [11, 13].
$Z(4020)^\pm \rightarrow \pi^\pm h_c$

- No $Y(4260)$-like peaking structure in $\pi^+\pi^- h_c$ cross section, which is comparable to peak in $\sigma(\pi^+\pi^- J/\psi)$
- Very narrow charged $\pi^\pm h_c$ structure near $DD^*$ threshold
- Not conventional charmonium
What about $b$ quarks?

- Same story, heavier characters
- $\Upsilon(4260) \to \Upsilon$ or $\Upsilon(10860)$
- $J/\psi \to \Upsilon$
- $h_c \to h_b$
- at 10890 MeV: peak in $\pi\pi\pi$ transitions to $\Upsilon(nS)$ states
- Study $\pi\Upsilon$ and $\pi h_b$ structure in transitions
Observation of $Z_b(10610)^\pm$ and $Z_b(10650)^\pm$

- Belle observes two charged states in the bottomonium spectrum
- couple to $\pi^\pm h_b$ and $\pi^\pm Y$
- consistent masses and widths in five different decay modes
- masses at or just above $BB^*$ and $B^*B^*$ thresholds
- decays to $B^{(*)}\overline{B}^*$: [Belle Collaboration arXiv:1209.6450]
Decays of B Mesons

LHCb at the LHC
BaBar at PEP-II SLAC (Menlo Park, CA)
Belle at KEK (Tsukuba, Japan)
Charmonium in B Decay

- Hadronic decays of the B meson ($M(B) = 5.27$ GeV) can be used to study the charmonium spectrum
  - useful tool at hadron colliders
- Recent hot topics:
  - charged states: $Z(4430)$ and $Z(4200)$ in $\pi^\pm \psi(\prime)$
  - narrow neutral state: $X(4140)$ in $\Phi J/\psi$

\[ \begin{align*}
\eta_c(1^1S_0) & \quad \psi(2^3D_1) \\
Y(4260) & \quad \psi(4^3S_1) \\
X(4140) & \quad \chi_{c2}(3^3P_2)
\end{align*} \]
**Z(4430)⁰⁺ → ψ’π⁺**

- Examine ψ’π⁺ produced in B→ψ’Kπ⁺
- need to understand Kπ structure
- Z(4430) reported initially by Belle [PRL 100, 142001 (2008)], but not confirmed by BaBar [PRD 79, 112001 (2009)]
- Z(4430) recently confirmed with 10x more data at LHCb
- established J^P = 1⁺
- not S-wave D*(2007)D₁(2420) or D*(2007)D₂*(2460)
- Broad structure: Γ tot ≈ 200 MeV
- LHCb: second structure around 4200 at 6σ; resonant nature inclusive
**B → KπJ/ψ**

- Belle reports evidence for $Z(4430) \rightarrow π J/ψ$
  - about 10x smaller than $Z(4430) \rightarrow π J/ψ'$
- Belle: $Z(4200)^{\pm} \rightarrow π J/ψ$ at 6.2σ
  - broad: $Γ_{\text{tot}} \approx 400$ MeV
  - $J^P = 1^+$ favored
  - compatible with “structure” in LHCb analysis of $π J/ψ'$
- No evidence for the $Z(3900)$ that is correlated with $Y(4260)$ decay
  - production mechanism dependence?
  - $Z(3900)$ is fundamentally different from $Z(4200)$ and $Z(4430)$?
Comments/Questions

• $e^+e^- \rightarrow \text{hadrons}$
  • Similar physics in both bottom and charm systems
  • Experimentally significant narrow peaks in the mass spectrum
    • resonances?

• Decays of B Mesons
  • Additional charged states observed in B decay
    • significantly broader
    • one appears to have phase motion of a resonance
π Beam Data

COMPASS at CERN
In this case we take all three quark flavors to be mass degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU(3) flavor symmetry, we characterize mesons in terms of their SU(3)F representation, octet (8) or singlet (1), and compute correlation matrices using the basis in Eq. (5).

The octet correlators feature only connected diagrams while the singlets receive an additional contribution from a disconnected diagram. Since the strange quarks are now no heavier than the "light" quarks, any splitting between states in the octet and singlet spectra is purely due to the disconnected diagrams and thus to "annihilation dynamics." In Fig. 13 we present the spectra extracted on two lattice volumes.

D. Quark mass and volume dependence

Figures 14–16 show the quark mass and volume dependence of the extracted isoscalar and isovector spectra. In general, the extracted spectrum is fairly consistent across quark masses. There are some cases, such as the second level in 3+/C0, that are not cleanly extracted at the lowest pion mass. We refrain from performing extrapolations of the masses to the limit of the physical quark masses, since, as we have already pointed out, we expect most excited states to be unstable resonances. A suitable quantity for extrapolation might be the complex resonance pole position, but we do not obtain this in our simple calculations using only single-hadron operators.

We discuss the specific case of the 0/C0+ and 1/C0/C0 systems in the next subsections.

E. The low-lying pseudoscalars:

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the 25 and 17 mesons are exactly stable and 170 is rendered stable since its isospin conserving 25/25 decay mode is kinematically closed. Because of this, many of the caveats presented in Sec. III B do not apply. Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass,

\[ m_{\text{eff}} = \frac{1}{1 + \log(t)/21} \frac{t}{t + 1/4} \]

for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

Figure 18 indicates the detailed quark mass and volume dependence of the 17 and 170 mesons. We have already commented on the unexplained sensitivity of the 170 mass to the spatial volume at \( m_{\pi} = 391 \text{ MeV} \), and we note that...
Hybrid Mesons

\[ J = L + S \quad P = (-1)^{L+1} \quad C = (-1)^{L+S} \]

**Allowed** \( J^{PC} \): 0\(^{-+} \), 0\(^{++} \), 1\(^{--} \), 1\(^{+-} \), 2\(^{++} \), ...

**Forbidden** \( J^{PC} \): 0\(^{-} \), 0\(^{+} \), 1\(^{+} \), 2\(^{+} \), ...

Lightest Hybrids

\[ S_{q\bar{q}} = 1 \quad S_{q\bar{q}} = 0 \]

\[ J^{PC} : \quad 0^{-}, 1^{-+}, 2^{-} \quad 1^{--} \]

“exotic hybrid”

“constituent gluon”

\[ (J^{PC})_g = 1^{+-} \]

mass \( \approx 1.0 - 1.5 \text{ GeV} \)
\( \pi^- p \rightarrow \eta' \pi^- p \)

- Data collected from COMPASS using a 190 GeV pion beam
- \( \eta' \pi^- \) in a P-wave: \( L=1 \)
  - parity: -
  - \( G: - \)
  - isospin: 1
  - \( J^{PC} \) of neutral isovector is 1\(^{-+} \) (exotic!)
We confirm the presence of a broad structure in the wave an additional incoherent flat, phase-space-like component. This resonance is also visible in the 3D distribution. This resonance can be fitted with a single-channel relativistic Breit-Wigner shape underestimates the density of this structure by a single-channel relativistic Breit-Wigner shape. E852 found the much broader resonance in the 3D distribution. E852 fits the intensity of the positive-reflectivity waves. From left to right: 

**Left graph:**
- COMPASS 2008
- $\pi p \rightarrow \pi \eta' p$
- $D_+ (J^{PC} = 2^{++})$ intensity

**Central graph:**
- COMPASS 2008
- $\pi p \rightarrow \pi \eta' p$
- $G_+ (J^{PC} = 4^{++})$ intensity

**Right graph:**
- COMPASS 2008
- $\pi p \rightarrow \pi \eta' p$
- $P_+ (J^{PC} = 1^{++})$ intensity

The results for the intensity of the positive-reflectivity waves are shown in Fig. 3. The fit with a single-channel relativistic Breit-Wigner shape underestimates the density of this structure. A fit to the intensity of the positive-reflectivity waves shows the apparent onset of double-Regge behavior. The results for the intensity of the positive-reflectivity waves are shown in Fig. 3. The fit with a single-channel relativistic Breit-Wigner shape underestimates the density of this structure. A fit to the intensity of the positive-reflectivity waves shows the apparent onset of double-Regge behavior.
$\pi^+\pi^-\pi^+\pi^-$ from 190 GeV $\pi$ on Pb


$\pi^+\pi^-\pi^+$ from 190 GeV $\pi$ on p

$\pi^-\pi^+\pi^-$ (COMPASS 2008)

F. Krinner, POS (Bormio 2014), 031
The biggest is not the most important

Exotic Quantum Numbers

In this case we take all three quark flavors to be mass-degenerate, with the mass we have tuned to correspond to the physical strange quark. Here, because there is an exact SU$_3$ flavor symmetry, we characterize mesons in terms of their SU$_3$ representation, octet (8) or singlet (1), and compute correlation matrices using the basis in Eq. (5).

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We discuss the specific case of the $^0/C_0$ and $^1/C_0/C_0$ systems in the next subsections.

E. The low-lying pseudoscalars:

In lattice calculations of the type performed in this paper, where isospin is exact and electromagnetism does not feature, the $^2/C_0$ and $^1/C_0$ mesons are exactly stable and $^0/C_0$ is rendered stable since its isospin conserving $^0/C_0/C_0/C_0$ decay mode is kinematically closed. Because of this, many of the caveats presented in Sec. III B do not apply.

Figure 17 shows the quality of the principal correlators from which we extract the meson masses, in the form of an effective mass, $m_{\text{eff}} = \frac{1}{2} \log \left( \frac{t}{t + \frac{1}{14}} \right)$; (16) for the lightest quark mass and largest volume considered. The effective masses clearly plateau and can be described at later times by a constant fit which gives a mass in agreement with the two exponential fits to the principal correlator that we typically use.

Figure 18 indicates the detailed quark mass and volume dependence of the $^1/C_0$ and $^0/C_0$ mesons. We have already commented on the unexplained sensitivity of the $^0/C_0$ mass to the spatial volume at $m/C_0 = 391$ MeV, and we note that...
Two sides of the same coin?

F. Krinner, POS (Bormio 2014), 031
See also: COMPASS Collab., arXiv:1501.05732
Comments

• Excellent data in hand with amazing statistical precision
• Modeling of the reaction in analysis seems to be the dominant systematic error when interpreting data
• The ability to make major discoveries depends on the ability to quantify and limit this systematic uncertainty
Current and Future Opportunities

hadron probes

electromagnetic probes

completed/analysis
ongoing/future
ongoing/future
completed/analysis

colliding beam

fixed target
I2 GeV Upgrade to JLab

- Upgrade maximum electron energy from 6 GeV to 12 GeV with addition of cryomodules
- New Hall D and upgrades to existing Hall
- Project completion: Spring 2017
  - *Accelerator upgrade is complete*
  - *Hall D facility and associated experimental equipment are complete*
GlueX in Hall D

- high intensity, linearly-polarized photoproduction experiment: 9 GeV photons
- core program: light meson spectroscopy - access to everything up to around 3 GeV
- unique and complementary to hadron beam data, e.g., COMPASS
Hall D/GlueX Polarized Photon Beam

data collected on May 2, 2015

\[ \gamma p \rightarrow \rho^0 p \rightarrow \pi^+ \pi^- p \]

\[ \frac{d\sigma}{d\psi} \propto (1 + P \cos 2\psi) \]

Polarization \( P \) is preserved in \( \rho \) production.

- Diamond
- Amorphous

Energy of Beam with Different Radiators for \( \gamma p \rightarrow \rho p \) Events

Spring 2015 Commissioning (a few hours of beam)

coh. bremsstrahlung peak has high degree of linear polarization

γ Photon Beam Polarization Plane

Polarization Plane

ρ Decay Plane

\( \psi \)

\( \pi^+ \)

\( \pi^- \)

\( \rho \)

\( \gamma \)
Conclusions

- Exciting developments in experimental studies of spectroscopy in the last ten years
  - understanding underlying reaction dynamics is critical
  - data will keep coming: new experiments studying different reactions are starting now
- Advances in technology and sociology
  - statistically precise data for many related reactions
  - high-performance analysis machinery
  - new (old) ideas about theory and experiment collaboration
- Ability to draw firm conclusions from the data depends on having a good understanding of underlying reaction dynamics