The HASPECT Project
HAdron SPEctroscopy CenTer(s)

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Outline
✦ Hadron spectroscopy
✦ Old and new challenges
✦ A road-map for future analysis
Why hadron spectroscopy

- Quantitative understanding of quark and gluon confinement
- Revealing the nature of the mass of the hadrons
- See the QCD degrees of freedom at work
- Validate lattice-QCD predictions

<table>
<thead>
<tr>
<th>Perturbative</th>
<th>Transition</th>
<th>Non- Perturbative</th>
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<tbody>
<tr>
<td>High energy</td>
<td>Asymptotic freedom</td>
<td>Low energy</td>
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<tr>
<td>Small distance</td>
<td></td>
<td>Large distance</td>
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- **pQCD** << 0.1 fm
- Effective degrees of freedom (models) 0.1 – 1 fm
- Confinement > 1 fm

- Mesons
- & Baryons
The light quark meson spectrum

Constituent Quark Model

- Quark-antiquark pairs with total spin \( S=0,1 \) and orbital angular momentum \( L \)

\[
S = S_1 + S_2 \quad J = L + S \\
P = (-1)^{L+1} \quad C = (-1)^{L+S}
\]

Not all the \( J^{PC} \) combinations are allowed:
\[
0^{++} \quad 0^{-+} \quad 0^{--} \quad 1^{++} \quad 1^{-+} \quad 1^{--} \quad 2^{++} \quad 2^{-+} \quad 2^{--} \quad 3^{++} \quad 3^{-+} \quad 3^{--} \quad 3^{-+} \quad 3^{--} \quad \ldots
\]

- SU(3) flavor symmetry
  \( \rightarrow \) nonet \((8 \oplus 1)\) of degenerate states

\[
J^{PC} = 0^{-+} \quad \Rightarrow (\pi, K, \eta, \eta') \\
1^{-} \quad \Rightarrow (\rho, K^*, \omega, \Phi) \\
1^{++} \quad \Rightarrow (b_1, K_1, h_1, h_1')
\]

... 

- Great success in describing the lower mass states
- A number of predicted states is not experimentally observed and assignments are uncertain

Consider light quarks: \( u, d, s \)
**The gluons and the meson spectrum**

- Understanding gluonic excitations of mesons and the origin of confinement
- At high energy experimental evidence is found in jet production
- At lower energies the hadron spectrum carries information about the gluons that bind quarks
- Can we find hints of the glue in the meson spectrum?

**Search for non-standard states with explicit gluonic degrees of freedom**

- Not-allowed $J^{PC} = 0^-, 0^{+-}, 1^{+-}, 2^{+-} ...$

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states
Gluonic excitation models

**Flux tube model**
- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay

**Bag model**
- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

**CQM + constituent gluon**
- qq + massive transverse quasi-gluon ($J_g^{PgCg}$)
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave
- Repulsive 3-body force selects $J_g^{PgCg}= l^+$ in relative P-wave added to a qq pair is S-wave or P-wave

**Normal meson:**
- Flux tube in ground state
- $m=0$
- $CP=(-1)^{s+l}$

**Hybrid meson:**
- Flux tube in excited state
- $m=1$
- $CP=(-1)^s$

**Lightest multiplet**
- $(0,1,2)^+,(0,1,2)^+,1^-$, $l^+, l^{++}$
- $(0,1,2)^+,1^-$, $l^+, l^{++}$
- $(0,1,2)^+,1^-$, $l^-, l^{++}$

- $qq$ in S-wave + $J_g^{PgCg}= l^-$ in S-wave
  - Lightest multiplet
  - $(0,1,2)^+,1^-$

- $qq$ in P-wave + $J_g^{PgCg}= l^-$ in S-wave
  - Lightest multiplet
  - $(0,1,2)^-,1^-$

- $qq$ in S-wave + $J_g^{PgCg}= l^+$ in P-wave
  - Lightest multiplet
  - $(0,1,2)^+,1^-$

- $qq$ in P-wave + $J_g^{PgCg}= l^+$ in P-wave
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- $qq$ in S-wave + $J_g^{PgCg}= l^-$ in S-wave
  - Lightest multiplet
  - $(0,1,2)^-,1^-$

- $qq$ in P-wave + $J_g^{PgCg}= l^-$_{S-wave} + $J_g^{PgCg}= l^+$ in P-wave
  - Lightest multiplet
  - $(0,1,2)^-,1^-$

- $qq$ in S-wave + $J_g^{PgCg}= l^+$ in P-wave
  - Lightest multiplet
  - $(0,1,2)^+,1^-$

- $qq$ in P-wave + $J_g^{PgCg}= l^+$ in P-wave
  - Lightest multiplet
  - $(0,1,2)^+,1^-$
Hybrids decay modes

- Decays can only be calculated within models:
  - $^3P_0$: $M \rightarrow qq$ with $J^{PC}=0^{++}$

- Flux-tube model: $\pi b_1: \pi f_1: \pi \rho: \eta \pi: \eta' \pi$
  - $170$: $60: 5-20: 0-10: 0-10$

- Some hints:
  - hybrids with vector $qq$ quantum number
  - pairs of not identical mesons
  - pairs of $L=0$ mesons suppressed
  - pairs of $(L=0)(L=1)$ favored

- Lattice QCD
  - sparse results (so far)
  - width overestimates (compared to other models)

To define the experimental program we need to have reliable prediction of hybrids decay
Lattice QCD calculations

- Interpretation in term of CQM + Gluon field
- Dependence on Lattice size
- Dependence on pion mass

in blue: overlap with $J^{\pi C}=1^{-+}$ operator interpreted as $q\bar{q}$ in S-wave + $J_g^{P_gC_g}=1^{-+}$ in P-wave

Pion mass = 700 MeV

An example of lattice QCD/models interpretation

Lightest and first-excited hybrid supermultiplet in charmonium spectrum

- Coulomb Gauge QCD predictions
- confirmed by LQCD calculations
- 201X experimental confirmation?

**CHARMONIUM HYBRIDS**

- Quarks in an S-wave
  \[ q\bar{q}_{8c} \left[ ^1S_0 \right] G_{8c}^* \left[ B \right] \] \[ \rightarrow 1_{\text{hyb}}^{-} \]
  \[ q\bar{q}_{8c} \left[ ^3S_1 \right] G_{8c}^* \left[ B \right] \] \[ \rightarrow (0, 1, 2)_{\text{hyb}}^{-+} \]

- Quarks in a P-wave
  \[ q\bar{q}_{8c} \left[ ^1P_1 \right] G_{8c}^* \left[ B \right] \] \[ \rightarrow (0, 1, 2)_{\text{hyb}}^{++} \]
  \[ q\bar{q}_{8c} \left[ ^3P_{0,1,2} \right] G_{8c}^* \left[ B \right] \] \[ \rightarrow (0, 1^3, 2^2, 3)_{\text{hyb}}^{+-} \]

**2008**

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Heavy quarkonium hybrids from Coulomb gauge QCD

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Using the nonrelativistic reduction of Coulomb gauge QCD we compute a spectrum of the low mass hybrid mesons containing a heavy quark-antiquark pair. The gluon degrees of freedom are treated in the mean field approximation calibrated to the glueball spectrum. We discuss the role of the non-Abelian nature of the QCD Coulomb interaction in the ordering of the spin-parity levels.
From the data to the spectrum: Partial Wave Analysis

- Parametrize the cross section in term of partial waves
- Fit to data to extract amplitudes
- A model is needed to parametrize amplitudes: Isobar Model, Dispersion Relations, ...

Is this adequate for current and future experiments?

- Exotics, if exist, are tiny: how to deal with the background?
- How to go beyond the Isobar Model?
- Do the amplitudes incorporate all the necessary constraints?
- Are experimental data precise and abundant enough to constraint PWA?

... not every bump is a resonance and not every resonance is a bump!
Why a hadron spectroscopy analysis center?

New high statistics and precise data NEEDS and adequate analysis

A modern experiment for an old problem:

the $\pi_1(1600)$

- exotic $1^{-+}$ waves in $\rho\pi$, $\eta'\pi$, $f_1\pi$
- non-resonant and resonant contributions
- A dependence of $M=1$ production

Brookhaven E852 1997

$P$-wave $\rho\pi$ ($\pi^-\pi^-\pi^+$)

Exotic signal

Re-analysis

$\pi^+\pi^-\pi^0 \rightarrow P$ Pb

COMPASS 2004
The HASPECT project

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50M on H₂ vs 0.4M on Pb

New reliable analysis

- Independent t-bins PWA
- Checks of systematics (different sets of waves)
- s-binning to disentangle production mechanisms

To claim new physics, we need a widely accepted analysis framework
DATA ANALYSIS and THEORY
Meson spectroscopy with photons at JLab-12 GeV

- Determination of $J^{PC}$ of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

**Hall-D - GlueX Detector**

- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

**Hall-B - CLAS12 Detector**

- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance
Why a hadron spectroscopy analysis center?

GlueX- Hall D $\gamma p \rightarrow (n) \pi^+ \pi^+ \pi^-$ X (exotic) $\rightarrow \rho \pi^+ \rightarrow \pi^+ \pi^+ \pi^-$

MesonEx - Hall B $\gamma p \rightarrow \pi \pi \pi p$

Present:
- $e^+e^-$: BESIII and KLOE
- B decay: LHCb
- Belle, CLEO, BABAR

Future:
- Photoproduction at JLab:
  - $p p$-bar at GSI: PANDA

We all need a sound analysis fw!
How to develop a strong analysis framework?

★ Implementing reliable amplitudes
  • Back to classics from 60’ and 70’
  • Check amplitudes with existing data

Prepare the framework for future experiments

★ Developing common tools and procedures:
  • Common PWA framework across different experiments (eg AmpTools)
  • Wider data access and distribution (see recent CLAS Nuclear Physics Working Group effort)
  • Plugin for amplitudes and methods to judge the quality of the fit
  • Computing: fitting procedures, GPUs, etc.

Establish shared procedures and tests to claim a discovery of new physics

★ Learning & teaching
  • Promote exchanges between experimentalists and theorists
  • Write two handbooks: “HS data analysis for dummies” and “HS theory revealed”
  • Workshops and schools to share expertise and establish common rules

Promote a two-ways communication EXP-THE
Future initiatives:

★ ECT* Workshop in December
★ GGI School in summer 2014
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HASPECT as a possible example for the HS community

• Stable work group in Genova + satellites
• Weekly phone/skype meetings
• “HASPECT weeks”
The HASPECT way: a proposal for the analysis of future experiments

★ The unprecedented statistic and data quality requires an adequate analysis
★ PWA is on the boundary between experiment and theory
★ We need to develop a strong analysis framework

★ Beyond Isobar-Model
    coupled-channel analysis
★ Analyze existing photoproduction data:
    \( \pi, \eta, \eta', \pi\pi, \pi\eta, \pi\eta', \omega \pi \ldots \)
★ Include baryon vertex in the amplitude description
    \( N\pi, N\eta, N\eta', N\pi\pi, N\pi\eta, N\pi\eta', N\omega \pi \ldots \)
★ Use Regge theory to parametrize amplitude properties:
    analyticity, unitarity, FSI
★ Use a combination of:
    • Regge Born with low partial wave removed
    • Explicit resonance parametrization in low waves
    • FESR to constrain parametrized waves
★ Exploit the high statistics and accuracy of new data set
★ PWA in \( s \) and \( t \) bins + polarization observables (+≠ beams)
★ Effective Lagrangians can be used now to provide a microscopic interpretation

The goal: compare results to LQCD predictions using model to understand the underlying physics
A first attempt ...

\[ \gamma p \rightarrow p \pi \pi \]

\( M(\pi^+\pi^-) \) spectrum below 1.5 GeV:
- P-wave: \( \rho \) meson
- D-wave: \( f_2(1270) \)
- S-wave: \( \sigma, f_0(980) \) and \( f_0(1320) \)

\[ \langle Y_{\lambda \mu}(E_\gamma, t, M) = \frac{1}{\sqrt{4\pi}} \int d\Omega_\pi \frac{d\sigma}{tdM d\Omega_\pi} Y_{\lambda \mu}(\Omega_\pi) \]

Amplitude parametrization (Dispersion relation)
Related to \( \pi \pi \) scattering matrix: phase-shift, inelasticity, S-P-D-F amplitude in 0.4 GeV < \( M_{\pi\pi} \) < 1.4 GeV

\[ a_{lm,t}(s) = \frac{1}{2} [U + S_{lm,t}(s)] \tilde{a}_{lm,t}(s) - \frac{1}{\pi} D_{lm,t}^{-1}(s) \text{PV} \int ds \frac{N_{lm,t}(s')}p(s')\tilde{a}_{lm,t}(s') \]

\[ \tilde{a}_{lm,t} = [\mathcal{A} + \mathcal{B}s + Cs^2 + \cdots][k] \]

Expanded in a Taylor series: coefficient fit to the experimental moment

First observation of the \( f_0(980) \) in a photoproduction experiment
Work in progress

\[ \gamma p \to p k k \]
- S.Lombardo (IU)
- Full analysis from g11 CLAS6 data set
- S-P interference in 2k system

\[ \gamma p \to p \pi \eta \]
- A.Celentano (Genova) PhD Thesis
- Amplitudes provided by V.Mathieu (ECT*) and A.Szczepaniak (IU&JLab)
- Preliminary analysis on CLAS6 data to fix parameters
- Full projection on CLAS12 and PWA

\[ \gamma p \to p \pi \eta' \]
- Theoretical support:
  A.Szczepaniak, V.Mathieu, E.Santopinto (INFN-GE), A.Vassallo (GE), J.Ferretti (UMAS)
- Experimental Analysis:
  S.Fegan (INFN-GE), A. Filippi (INFN-TO), S.Hughes (Edinburgh), S. Lewis (Glasgow),
  S.Lombardo (IU), A.Rizzo (RomaTV), L.Zana (Edinburgh)
HASPECT: Act locally but think globally!

Global strategy:

✶ Creation of twin and parallel centers for both analysis and theory development
✶ Collaboration and exchanges: personnel, short visits, ...
✶ Coordination via JLab Pysics Analysis Center
✶ Creation of a “Hadron spectrum” working group

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Common funding plans:

✶ European-FP7 (EU calls and local): HPH, Synergy grants
✶ DOE-Topical -collaboration proposals
✶ Helmholtz Virtual-Institutes
Conclusions

✴ Recent LQCD results renew interest in Meson Spectroscopy
✴ Models are used to understand and interpret Lattice data
✴ Comprehensive meson spectroscopy program at existent (COMPASS, BES, BELLE, LHCb) and near-future facilities (JLAB, PANDA, SUPER-BELLE, BES-III)
✴ Expected abundant and precise data requires a solid PWA analysis framework
✴ Global effort that includes: theoretically-motivated analysis, technological solutions and learning/teaching exchange between theory and experiment
✴ Coupled channel analysis, 3-body corrections, FSI, … require a new theoretical approach
✴ HASPECT and the other twin centers (JPAC, BES, GSI, Julich) want to meet the challenge
Back up
Regge phenomenology in a nut-shell

- Exploit the analytical structure of the amplitude

\[ A(s, t) = 16\pi \sum_\ell (2\ell + 1) A_\ell(t) P_\ell(z_\ell) \]

\[ A(s, t) \propto \sum_e \beta_e(t) \frac{s^{\alpha_e(t)}}{\sin \pi \alpha_e(t)} \]

- Implement crossing symmetry

\[ \pi N \to \pi N \quad (s > 0, t < 0) \]

\[ \pi\pi \to N\bar{N} \quad (s < 0, t > 0) \]

- Regge trajectories

- Efficient and theoretically correct way to parametrize Amplitudes
- Good agreement to total xsec, differential xsec, spin observables
- Many different reactions (probes) and channels
- Regge theory can be used to parametrize Amplitudes (resonance and BG)