

### HADRON SPECTROSCOPY WITH PHOTONS AT CLAS AND CLAS12



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### Outline

- Hadron spectroscopy: open problems in the meson and baryon spectrum
- Hadron spectroscopy in photoproduction reactions
  - With real photons: CLAS6
    - Some selected results
  - With virtual photons: CLAS12
    - On-going data taking, recently started
    - New results awaited soon
- Summary and conclusions

### Hadron spectroscopy: a tool to understand QCD

- The dynamics of the QCD confinement are responsible for most of the mass of hadrons: dominant manifestation of strong force
  - Only 1% due to quark masses
- How to understand these effects?
  - Perturbative QCD effects still largely unknown
    - Study of the phenomenology of hadrons and their spectrum
      - Identify the relevant degrees of freedom
      - Understand the role of gluons and the origin of confinement



### Meson vs baryon spectroscopy

#### Meson spectroscopy

- Light quark spectroscopy (u,d,s)
  - Probes the strong force at large distances (confinement)
  - Sensitive to chiral symmetry breaking and vacuum condensate
    - Non perturbative regime
- Heavy quark spectroscopy (b, c, t)
  - Probes the strong force at small distances
  - Perturbative approaches can be applied
  - The spectrum can be described by nonrelativistic quark models



#### Baryon spectroscopy

- SU(6)xO(3) symmetry, fundamental for the development of QCD
  - Multiplet structure → starting point for non-relativistic Quark Models
  - Microscopic structure → colored quarks



### LQCD expectations for the meson spectrum





Remarkable agreement of LQCD calculation with the expected meson spectrum the lightest exotic of the spectrum now expected at 1600 MeV ( $1^{-+}$ ) and 2 GeV ( $0^{++}$ ) s

### LQCD expectations for N\* and $\Delta$ excitations



R.G. Edwards et al., PR **D84** (2011) 074508

- SU(6)xO(3) symmetry respected, consistency with non-relativistic quark model expectations
- New observed states fit with LQCD predictions (many of them with larger masses)
- No parity doubling foreseen
- Some problems still unsolved!

Clas

### **Hybrid baryons**

- q<sup>3</sup>G objects
  - Same quantum numbers of q<sup>3</sup> ordinary baryons
  - More extended
- Lowest mass hybrid: expected N\* state at ~2.2 GeV, J<sup>P</sup> = ½<sup>+</sup>
  - A cluster of several states in the same mass region is expected  $(J^P = \frac{1}{2} + and \frac{3}{2})$
- Study of transition form factors as a function of Q<sup>2</sup> to disentangle hybrids/conventional baryons production
  - Similar to what is done for the characterization of the Roper resonance

J.J. Dudek and R.G. Edwards, PR D85 (2012) 054016  $N^*$ LQCD  $\frac{1}{2}^+$   $\frac{3}{2}^+$   $\frac{5}{2}^+$   $\frac{7}{2}^+$  3.0 2.5 2.5 2.01.3 GeV

1.5

1.0



### HADRON SPECTROSCOPY IN PHOTOPRODUCTION REACTIONS

### Hadron spectroscopy with e.m. probes

- The electromagnetic interaction is weaker than the strong one and can be calculated perturbatively with high precision (based on well-known QED)
  - Scattering: one-photon exchange approximation



 Meson photoproduction: high probability of spin-1 meson production from photons



- Expected production rate for exotics and conventional mesons: comparable
- ss coupling to the photon relatively large (beam spin vector)





# CLAS @ 6 GeV









## Photoproduction experiments at JLAB today

- High intensity real and virtual photon beams
- Able to measure exclusively the production reactions and the decays of the emitted particles
- Requirements:
  - Good acceptance, momentum resolution, particle id capabilities



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



- Good resolution
- Good pID
- Resonable hermeticity
- NON-Uniform acceptance

### **CLAS12 and The Forward Tagger**

#### The CLAS12 detector







- FT-Cal: PbWO<sub>4</sub> calorimeter
- FT-Hodo: scintillator tiles
- FT-Tracker: MicroMegas



Clas



## FT: low Q<sup>2</sup> quasi-real photoproduction



$E_{scattered}$	0.5 - 4.5 GeV
$\theta$	$2.5^{\circ} - 4.5^{\circ}$
$\phi$	0° - 360°
ν	6.5 - 10.5 GeV
$Q^2$	$0.01 - 0.3 \text{ GeV}^2 \ (< Q^2 > 0.1 \text{ GeV}^2)$
W	3.6 - 4.5 GeV



- Electron scattering at "0" deg (2.5°-4.5°)
  - Low  $Q^2$  virtual photon  $\Rightarrow$  quasi-real
- Photon tagging: detection of electron at small angles
  - High energy photons: 6.5 10.5 GeV
  - To be accomplished by a "Forward Tagger"
- Quasi real photons: linearly polarized
  - Polarization: 70%-10%, measured event by event
- High luminosity:  $N_{\gamma} \sim 5 \times 10^8$ , L  $\sim 10^{35}$  cm<sup>-2</sup>s<sup>-1</sup> on 5 cm LH<sub>2</sub> target
  - Thin targets can be used

#### The CLAS12 hadron spectroscopy program



Identification of exotic configuration via PWA

electron beam

### New data with CLAS12: first performances



Charged particle detection by Time of Flight

Photon detection in the Forward Calorimeter



### MESON SPECTROSCOPY IN PHOTOPRODUCTION REACTIONS: EXPERIMENTAL RESULTS FROM CLAS



CLAS Collaboration, PRC97, 025203 (2018)

#### Physics case: search for a scalar glueball in its kaonic decay

- K<sub>S</sub>K<sub>S</sub> system: J<sup>PC</sup> = (even)<sup>++</sup>
- light scalar sector: several candidates, too many states for the nonet
  - f<sub>0</sub>(600), f<sub>0</sub>(980), f<sub>0</sub>(1370), **f<sub>0</sub>(1500)**, f<sub>0</sub>(1700), ...
- no study yet in photoproduction reactions
- CLAS6 g12 data set:
  - $E_{\gamma} = (2.7-3) \&\& (3.1-5.1) \text{ GeV}$
  - $4\pi$  detected in CLAS, p reconstructed by missing mass
  - High correlation between  $K_s$  pairs
- Selection in t ranges
  - Low t: resonance production in t-channel
  - Wider t range for s-channel production



## The $K_sK_s$ system: $\gamma p \rightarrow pK_sK_s$



- Clean signal of f<sub>0</sub>(1500) for |t| < 1 GeV<sup>2</sup>, no indication for |t|>1 GeV<sup>2</sup>
  - t-channel process
  - Good glueball candidate??
- Low acceptance at fw/bw angle: no PW analysis possible
- Angular analysis of Gottfried-Jackson distributions, comparison with simulations
  - S-wave dominance, small D-wave contribution above 1550 MeV



CLAS Collaboration, PRC97, 025203 (2018)

## The KK $\pi$ system: $\gamma p \rightarrow pK^0K^{\pm}\pi^{\mp}$

CLAS Collaboration, PRC93, 065202 (2016)

## Physics case: superimposition of several axial/scalar states in the 1.3-1.5 GeV mass range with decay in $K\overline{K}\pi$

- $J^{P} = (odd)^{+} \text{ or } J^{P} = (even)^{-}$
- $\eta$ -like pseudoscalars **0**<sup>-+</sup>: all of them decay to  $K\overline{K}\pi$ , K\*K,  $a_0(980)\pi$
- axial states 1++:
  - f<sub>1</sub>(1285): not seen in K\*K
  - $f_1(1420)$ : favored candidate as hybrid  $q\bar{q}g$ , or 4q state, or K\*K molecule
  - other: f<sub>1</sub>(1510), isovector a<sub>1</sub>(1420)...
- CLAS6 g11a data set:
  - $E_{\gamma} = (3-3.8) \text{ GeV}$
  - − p, K<sup>±</sup>,  $\pi^{\mp}$  detected in CLAS, K<sup>0</sup> from missing mass
  - Kaon identification by TOF
  - Study of the  $p\pi^+\pi^-\eta$  and  $p\pi^+\pi^-\gamma$  channels on the same sample



## The K $\overline{K}\pi$ system: $\gamma p \rightarrow pK^{0}K^{\pm}\pi^{\mp}$

CLAS Collaboration, PRC93, 065202 (2016)





- No evidence found for higher mass η(1405), η(1470), f<sub>1</sub>(1420), f<sub>1</sub>(1510)
- First observation in photoproduction at ~1280 MeV, studied in  $\pi^+\pi^-\eta$ 
  - M = (1281.0  $\pm$  0.8) MeV
  - Γ = (18.4 ± 1.4) MeV
    - More compatible with  $f_1(1285)$  than  $\eta(1295)$
  - Differential cross sections: flatter trend as compared to η<sup>(958)</sup>



## Search for "new" strangeonia with CLAS12: $\gamma p \rightarrow p \phi \pi^{\Theta}$



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#### Search for "new" strangeonia with CLAS12: $\gamma p \rightarrow p \phi \eta$

- Smoking gun decay modes for ss̄ states:
  ηφ, η'φ, φφ
  - $-\eta\phi$ : identification of C = -1 s $\overline{s}$  candidates
  - Small branching fraction to non-strange final states
- Acceptance evaluation of  $\gamma p \rightarrow p \phi (1850) \rightarrow p \eta \phi \rightarrow p K^+(K^-)_{miss} \gamma \gamma$  events with CLAS12+FT (lab emission angle distribution)
  - Good acceptance for neutrals, sizeably increased by FT calorimeter: overall acceptance > 10%



Expected cross section for strangeonia production: O(10 nb)



### $3\pi$ system study in CLAS



- Purpose: confirmation of the signal (hybrid?) observed by COMPASS in 3π
- First study on CLAS-g12 data set
  - Several resonances observed
  - No confirmation for the hybrid 1<sup>-+</sup> in (ρπ) P-wave



A. Tsaris, FSU, 2016

### The $3\pi$ system analysis: projections for CLAS12

- PWA analysis simulation: to what extent the detector acceptance and resolution distort the reaction mechanisms?
- Events generated using a realistic differential cross section, filtered through the full reconstruction chain, and fitting them with a set of partial waves in bins of kinematic variables (m, t)
- Benchmark reaction:

 $\gamma \mathbf{p} \rightarrow \pi^+ \pi^+ \pi^- \mathbf{p}$ 

- sum of 8 isobar channels, in S, P, D
  wave + exotic signal
- CLAS12 acceptance projected and fitted
- The results are stable against acceptance distortions
- PWA is feasible in CLAS12!





### BARYON SPECTROSCOPY IN PHOTOPRODUCTION REACTIONS: EXPERIMENTAL RESULTS FROM CLAS

### The updated spectrum of baryon resonances

- No new baryon resonances in PDG until 2010, all based on πN scattering or π photoproduction only
- Now all new photoproduction reactions results are included
- Complex multichannel models for PWA analyses exploited (Bonn-Gatchina, ...)

	Particle Data Group 2010	BnGa <b>analyses</b>	Particle Data Group 2012
N(1860)5/2+		*	**
N(1875)3/2-		***	***
N(1880)1/2+		**	**
N(1895)1/2-		**	**
N(1900)3/2+	**	***	***
N(2060)5/2-		***	**
N(2150)3/2-		**	**
∆ <b>(1940)3/2</b> <sup>−</sup>	*	*	**

Study of Helicity Asymmetry E in  $\gamma p \rightarrow \pi^+ n$ 

Many quality new data: finer binning, tighter constraints for PWA analysis

#### CLAS Collaboration, PLB750 (2015) 53



## **Search for parity doublets**

- High mass mesons and baryons are often observed in parity doublets with the same spin, opposite parities and about the same mass
  - Chiral symmetry is restored in highly excited resonances?
  - $\Delta^*$  spectrum:

$\Delta(1910)1/2^+$	Δ(1920)3/2 <sup>+</sup>
$\Delta(1900)1/2^{-1}$	Δ(1940)3/2 <sup>-</sup>
$\Delta(1905)5/2^+$	$\Delta(1950)7/2^+$ (****)
$\Delta(1930)5/2^{-1}$	$\Delta(2200)7/2^-$ (*)

- Evidence for  $\Delta(2200) 7/2^{-}$  (\*) from coupled-channel analysis

(Bn-Ga on CLAS+CBELSA /TAPS data)

- m = 2180 MeV
- Mass, width and decay modes disprove chiral symmetry restoration



### **Q<sup>2</sup> evolution of the transition form factor**

- Electroproduction can be used to explore hadron structure at different wavelengths (Q<sup>2</sup>)
- Hybrid model predictions:
  - Steeper drop in the transverse helicity amplitude A<sub>1/2</sub>
  - Suppressed longitudinal amplitude S<sub>1/2</sub>
- Electro-couplings of "Roper" N(1440)1/2+ 80  $A_{1/2} (10^{-3} GeV^{-1/2})$ <sup>5</sup>GeV<sup>-1/2</sup>) nrQM nπ<sup>+</sup> 50 60 pπ<sup>+</sup>π<sup>-</sup> F ROM 40 40 20  $S_{1/2}$ 20 q<sup>3</sup>G 10 -20 nπ<sup>+</sup> -40 0 q<sup>3</sup>G pπ<sup>+</sup>π<sup>-</sup> -10 -60 -20 -80 1 2 3 2 3  $Q^2 (GeV^2)$  $Q^2 (GeV^2)$
- Hybrid model inconsistent with experimental results
  - Internal consistency of N $\pi$  and N $\pi\pi$  data
  - nrQM fails to reproduce low Q<sup>2</sup> behaviour
  - A<sub>1/2</sub> changes sign and has large magnitude
  - N(1440)1/2<sup>+</sup>: interplay of the q<sup>3</sup> core (first radial excitation) and the outer meson-baryon cloud



CLAS Collaboration, PRC 80, 055203 (2009) CLAS Collaboration, PRC 86, 035203 (2012)

### New strange baryons at CLAS

• Study of  $\Xi$  and excited states in  $\gamma p \rightarrow K^+K^+X$ ,  $K^+K^+\pi^-X$ 

5.5

- g11a run:
  - clean signals for  $\Xi(1320)$  and  $\Xi(1530)$ , 10:1 ratio
- g12 run:
  - total production  $\Xi$  cross section (3.5-5.4 GeV).
    - − Only Ξ(1530) significant
    - Upper limits for  $\Xi$  excitations production:
      - » Ξ(1630): 0.78 nb
      - » Ξ(1690): 0.97 nb
      - » Ξ(1820): 1.09 nb



### 

CLAS Collaboration, PRC 76, 205208 (2007)





### CLAS12: the "Very strange baryon" program

- Goals: high statistics measurements of Ω<sup>-</sup> and Ξ excitations in photoproduction reactions
  - Strange quarks multiple production from the sea
  - Helicity asymmetries
  - $\Xi^{-}$  polarization
  - N\*, Y\* excitations properties
  - Excited cascades and  $\Omega^{-}$
- Equipment: CLAS12 + Forward Tagger
- Reactions of interest:
  - $\ \gamma p \longrightarrow K^+ K^- p$
  - $\gamma p \rightarrow K^{+} \Lambda \pi^{0}$
  - $\gamma p \to K^+ K^- \Xi^-, \ \Xi^- \to \Lambda \pi^-$



	Detected particles	Measured Decays	Overall Efficiency	Rate/hr	Total Detected
$\Omega^-$	$K^+K^+K^0$		~3.9%	~3.6	$\sim 7k$
$\Omega^-$	$K^+K^+K^0K^-$	$\Omega^{-}$	~0.5%	~0.5	$\sim 1k$
Ξ-	Κ+Κ+π-	Ξ	~9.3%	~440	~0.9M
<b>Ξ</b> <sup>-</sup> (1530)	$K^+K^+\pi^-$	Ξ-(1530)	~7.4%	~140	~270K
Ξ-(1820)	K <sup>+</sup> K <sup>+</sup> K <sup>-</sup> p	Ξ-(1820)Λ	~0.63%	~6	~12K

#### projections for 80 beam days @ half field

### **Summary and conclusions**

- Still many open problems in light hadron spectroscopy
  - Mesons:
    - the scalar/pseudoscalar/axial sector
    - radial excitations with open/hidden strangeness
    - existence of exotics, ...
  - Baryons:
    - N\* and  $\Delta^*$  missing resonances
    - parity doublets
    - (very) strange baryons excitations
    - Baryonic hybrids and exotics
    - transition form factors, ...
- At JLAB: high intensity, linearly polarized real (by brehmsstrahlung, Hall D) and virtual (by low Q<sup>2</sup> electron scattering, Hall B) photon beams
- CLAS12: excellent PID and momentum resolution ⇒ high performance detector
- Abundant and high quality data expected to perform solid PW analyses ⇒ robust analysis framework (tested on older data by CLAS)
- First class quality data and results expected soon!