HADRON SPECTROSCOPY WITH PHOTONS AT CLAS AND CLAS12

Alessandra Filippi
INFN Torino, Italy

WTPLF2018, Genova, December 10, 2018

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

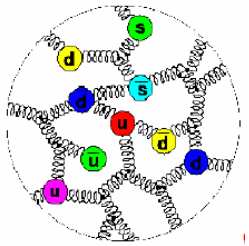
- The dynamics of the QCD confinement are responsible for most of the mass of hadrons: dominant manifestation of strong force
  - Only 1% due to quark masses

- 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

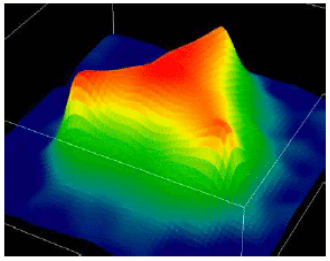
Perturbative
High energy
Small distance
Asymptotic freedom

Transition

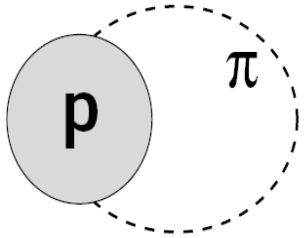
Non- Perturbative
Low energy
Large distance
Confinement



pQCD



Effective degrees of freedom (models)



Mesons & Baryons

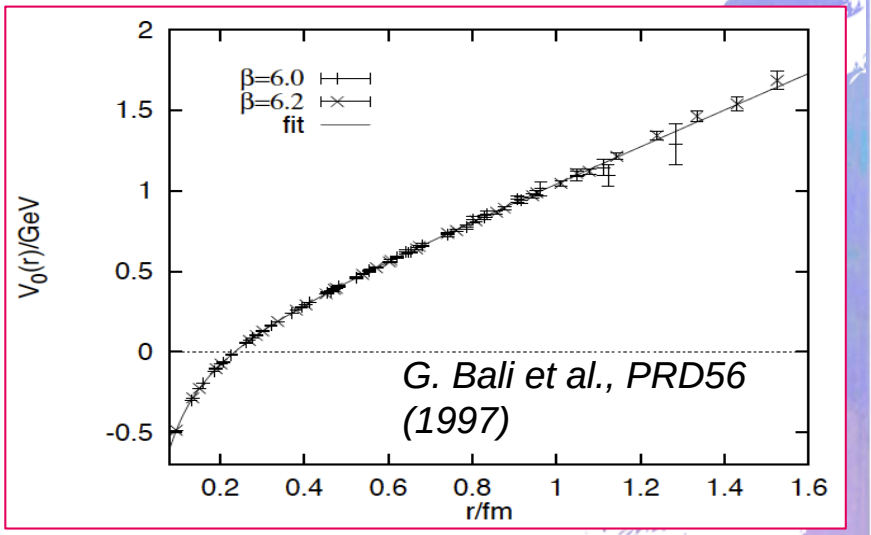
<< 0.1 fm

0.1 – 1 fm

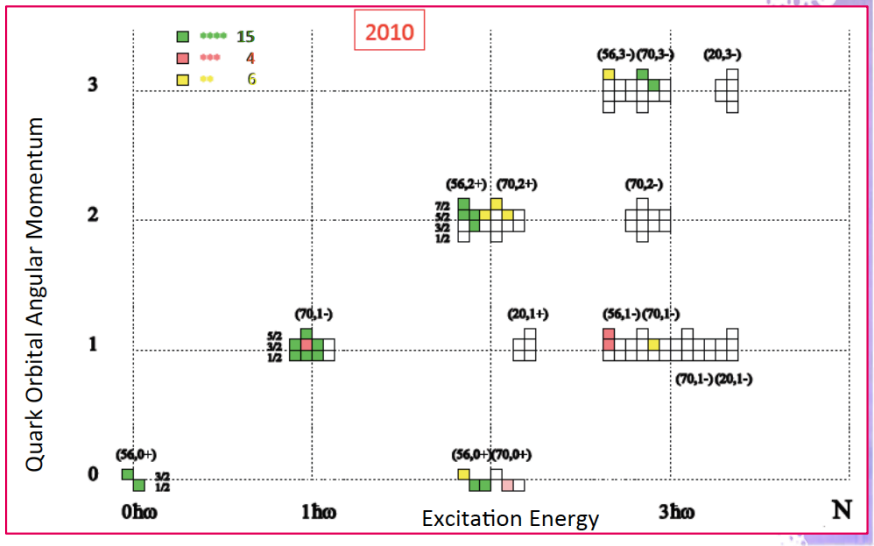
> 1 fm

Meson vs baryon spectroscopy

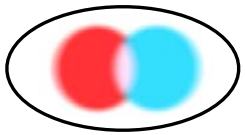
- **Meson spectroscopy**
  - **Light quark spectroscopy (u,d,s)**
    - Probes the strong force at large distances (confinement)
    - Sensitive to chiral symmetry breaking and vacuum condensate
      - Non perturbative regime
  - **Heavy quark spectroscopy (b, c, t)**
    - Probes the strong force at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



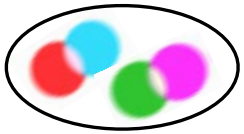
- **Baryon spectroscopy**
  - SU(6)xO(3) symmetry, fundamental for the development of QCD
    - Multiplet structure → starting point for non-relativistic Quark Models
    - Microscopic structure → colored quarks



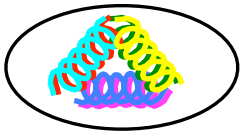
LQCD expectations for the meson spectrum



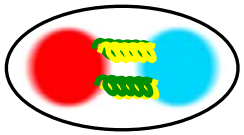
ordinary mesons



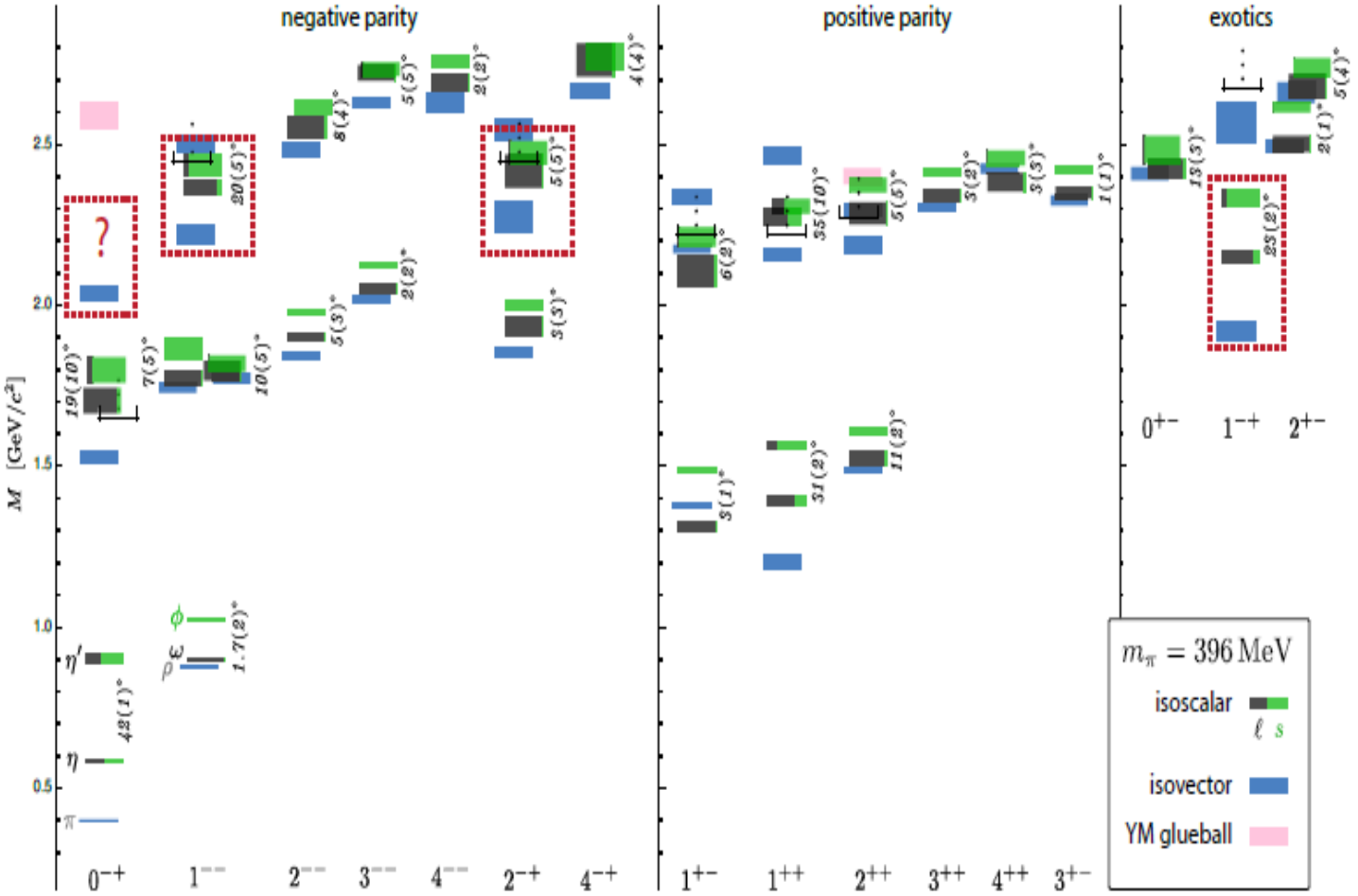
tetraquarks



glueballs



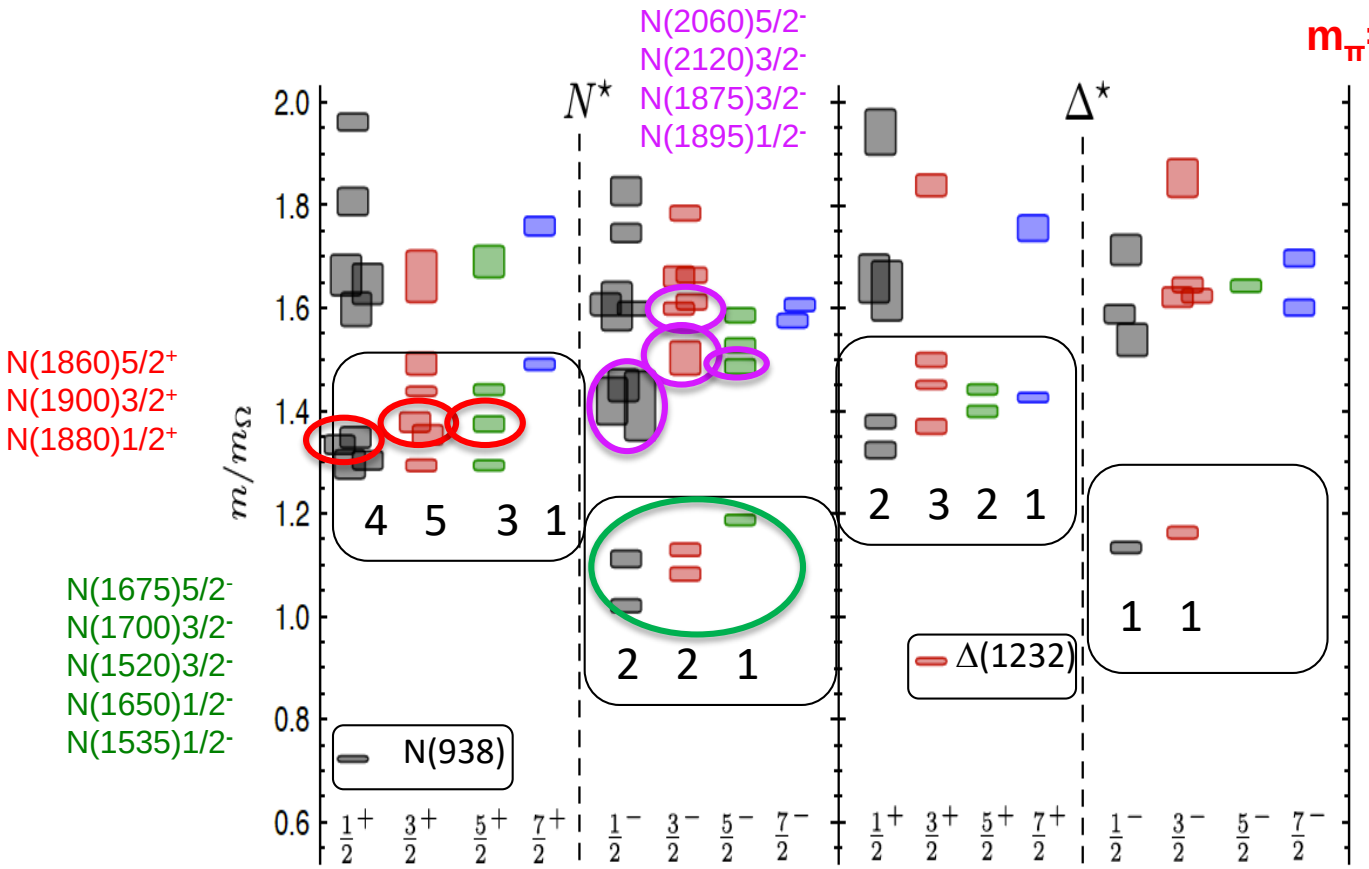
hybrids



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^{+-})

LQCD expectations for N* and Δ excitations



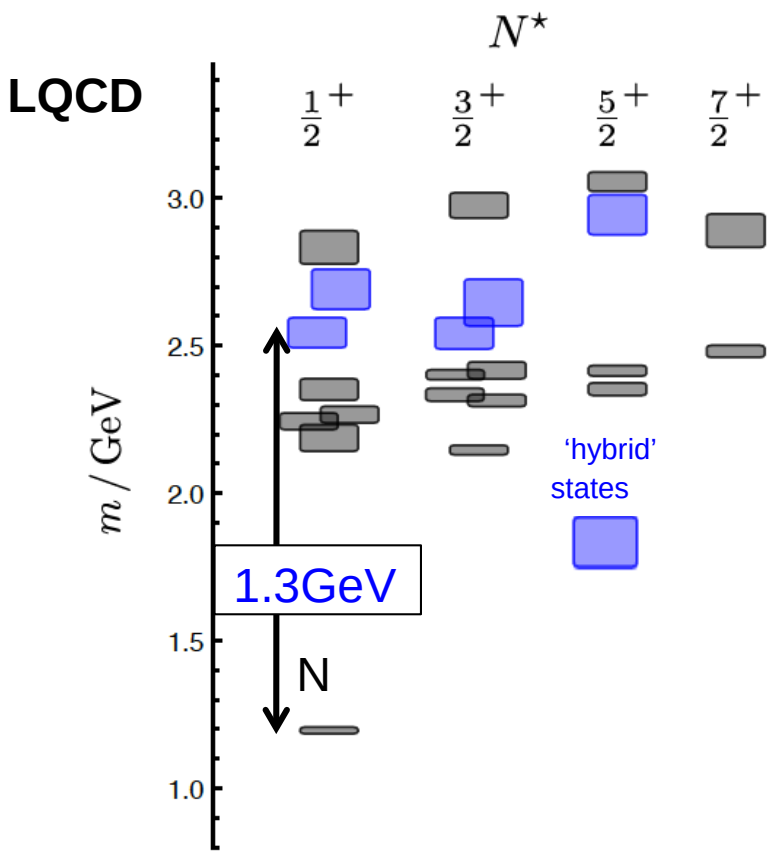
R.G. Edwards et al., PR **D84** (2011) 074508

- 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!

Hybrid baryons

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

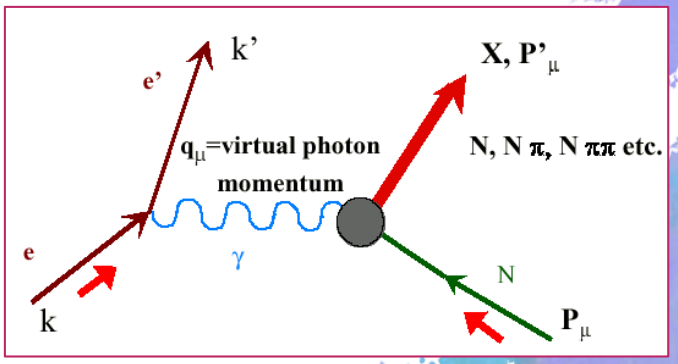
J.J. Dudek and R.G. Edwards, PR **D85** (2012) 054016



HADRON SPECTROSCOPY IN PHOTOPRODUCTION REACTIONS

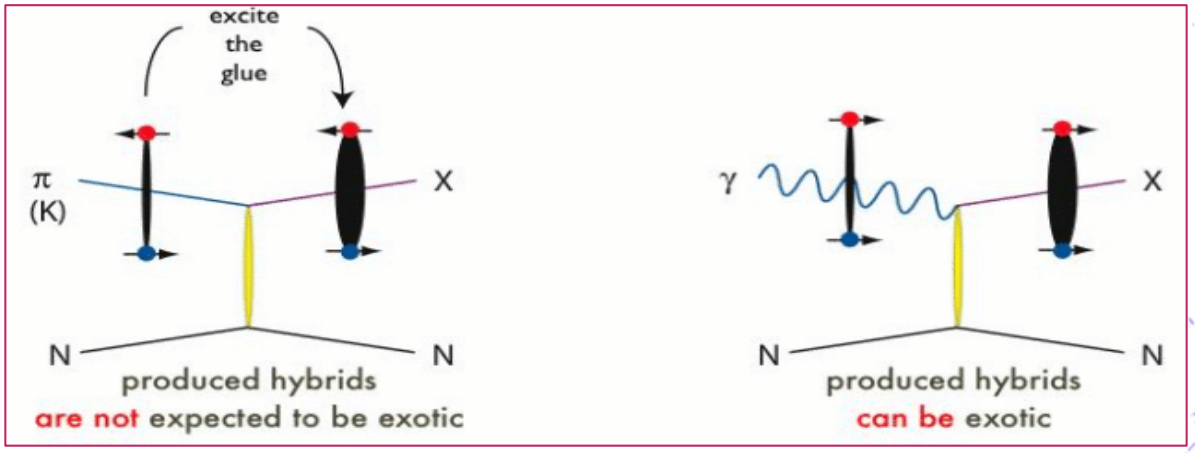
Hadron spectroscopy with e.m. probes

- 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**

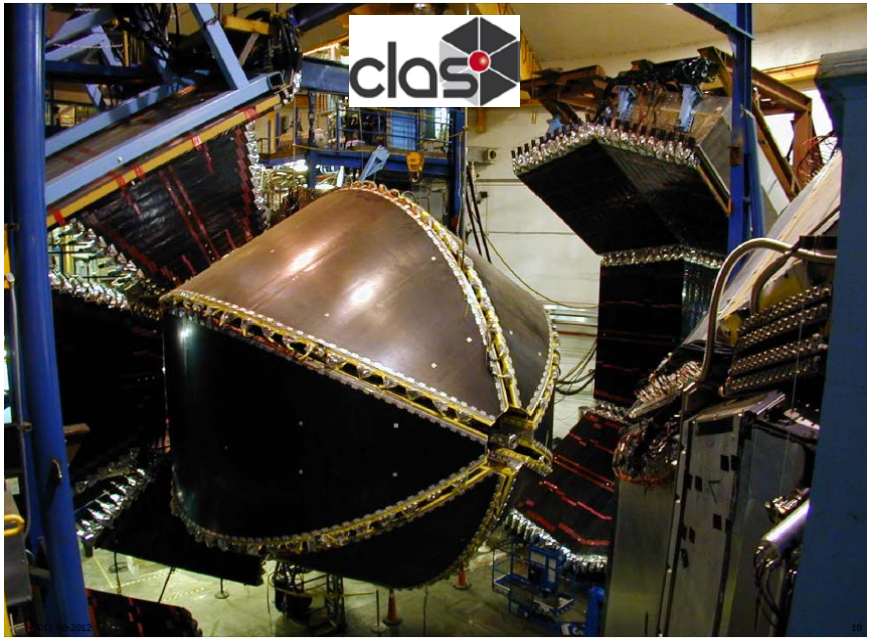
π (K)N: Need spin-flip for exotic quantum number

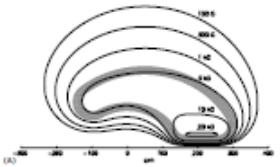


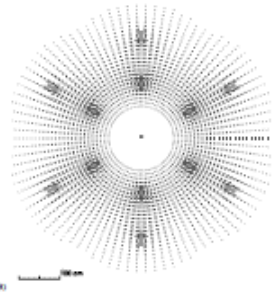
γN: No spin-flip for exotic quantum number

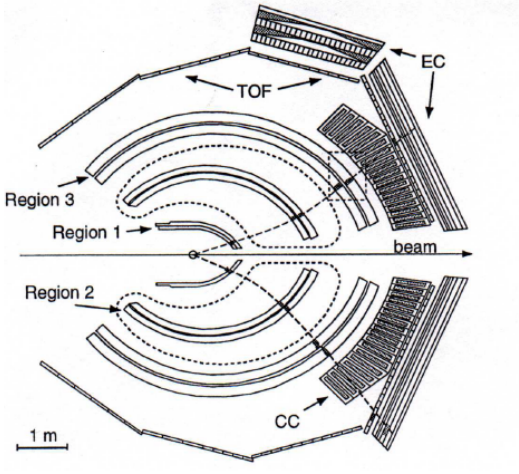
  - Expected production rate for exotics and conventional mesons: comparable
- **$\bar{s}s$ coupling to the photon relatively large (beam spin vector)**

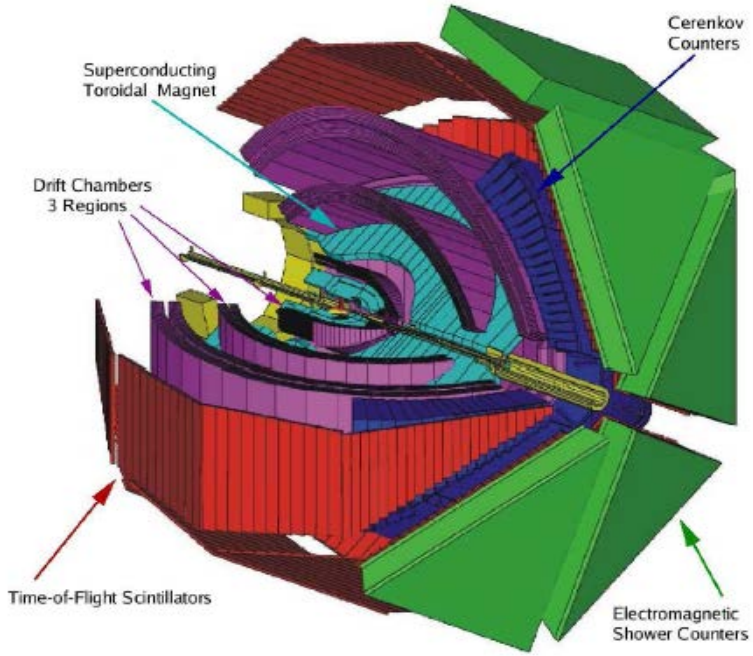
CLAS @ 6 GeV


clas

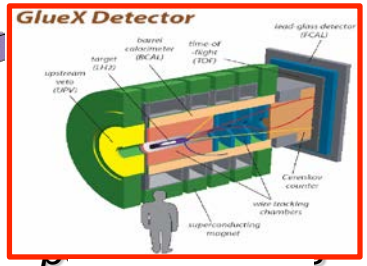




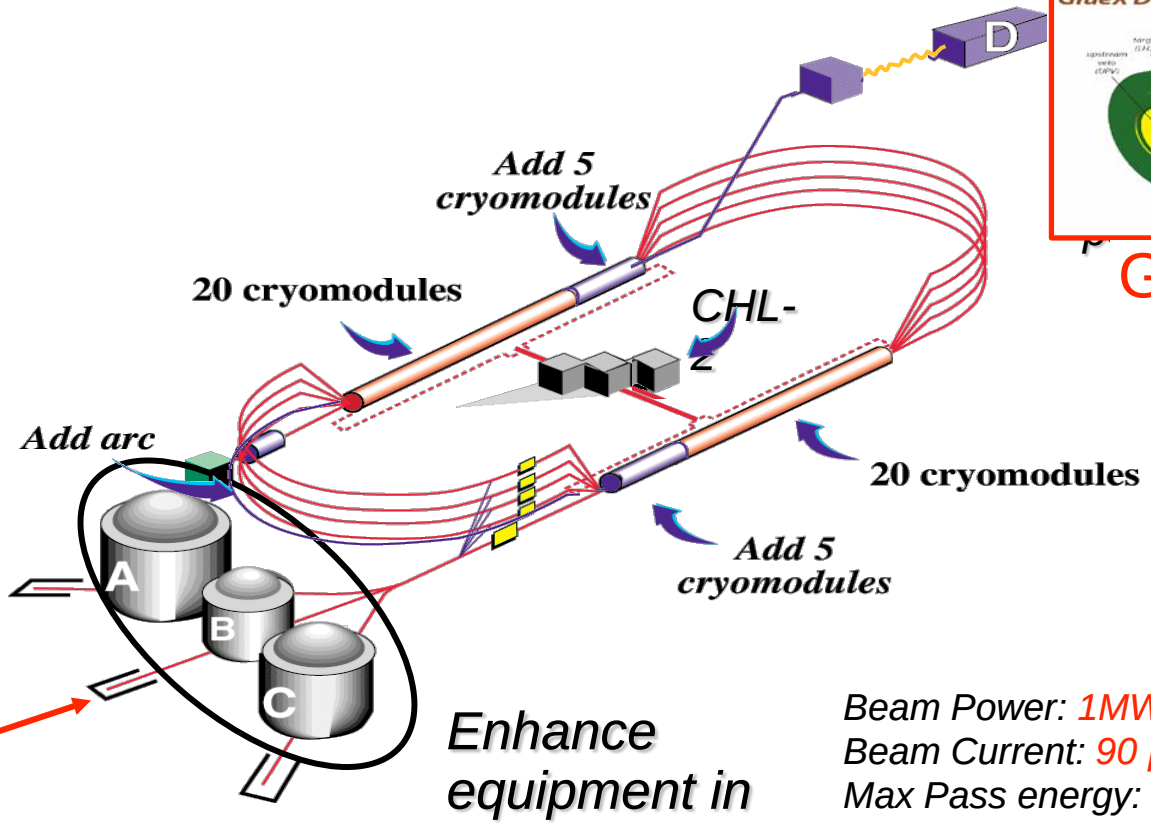

EC
TOF
Region 3
Region 1
beam
Region 2
CC
1 m

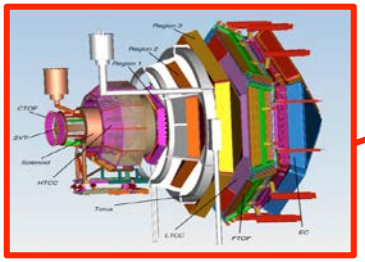

Cerenkov
Counters
Superconducting
Toroidal Magnet
Drift Chambers
3 Regions
Time-of-Flight Scintillators
Electromagnetic
Shower Counters

CEBAF @12 GeV:
the new electron machine at JLAB



GlueX





CLAS12

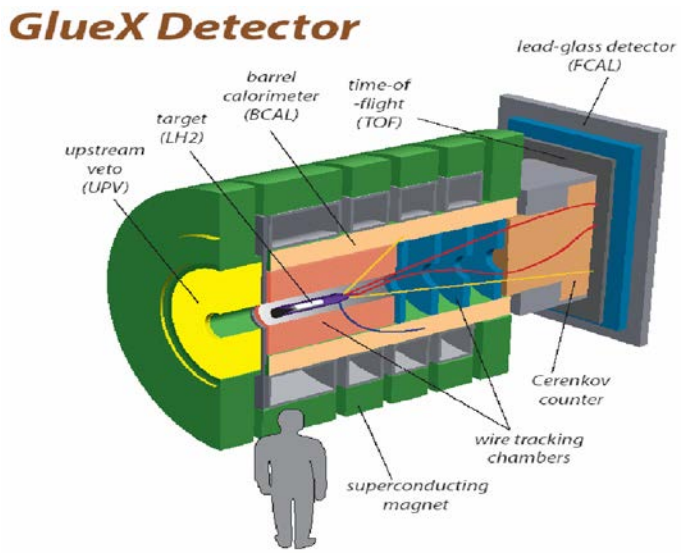
Enhance equipment in existing halls

Beam Power: 1MW
Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

Photoproduction experiments at JLAB today

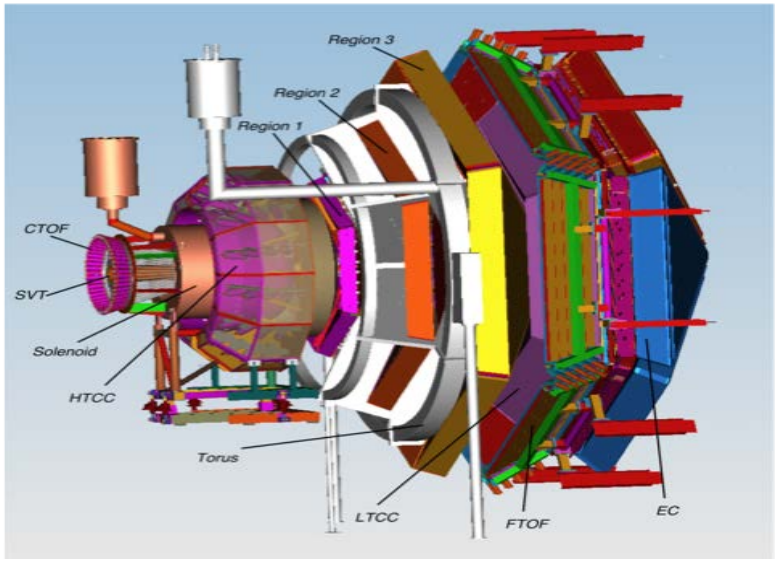
- High intensity real and virtual photon beams
- Able to measure exclusively the production reactions and the decays of the emitted particles
- Requirements:
  - Good acceptance, momentum resolution, particle id capabilities

Hall-D - GlueX Detector



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

Hall-B - CLAS12 Detector

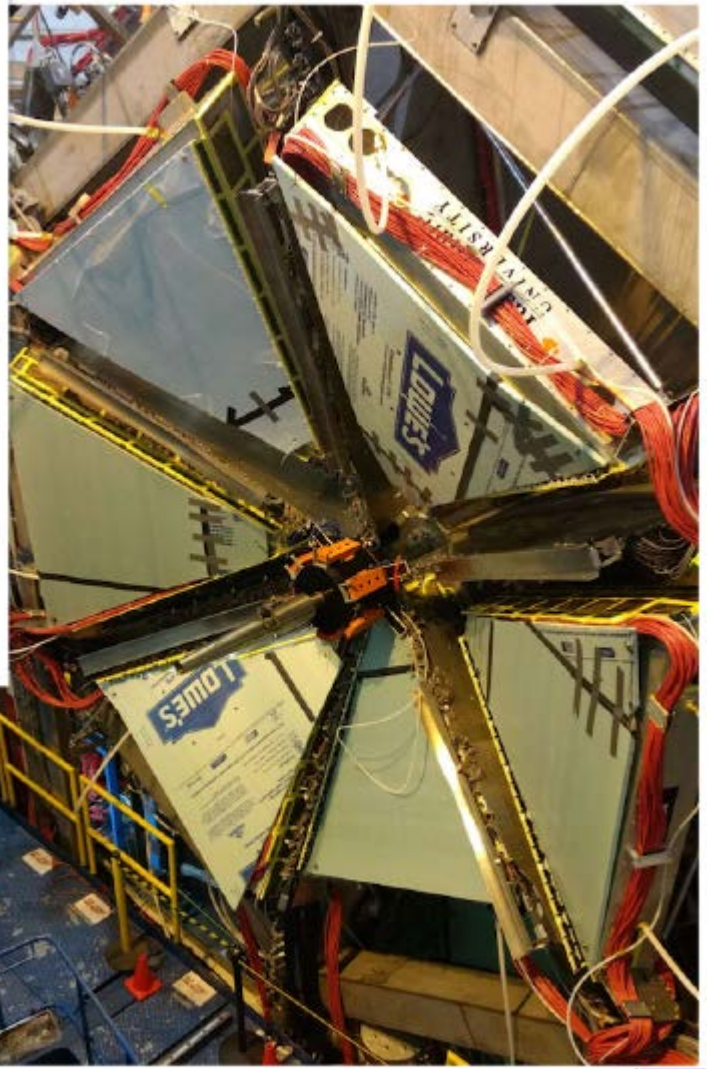


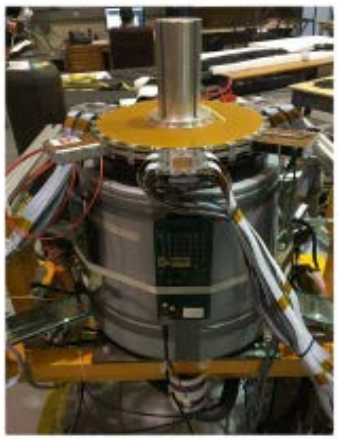
- Good resolution
- Good pID
- Resonable hermeticity
- NON-Uniform acceptance

CLAS12 and The Forward Tagger

The CLAS12 detector

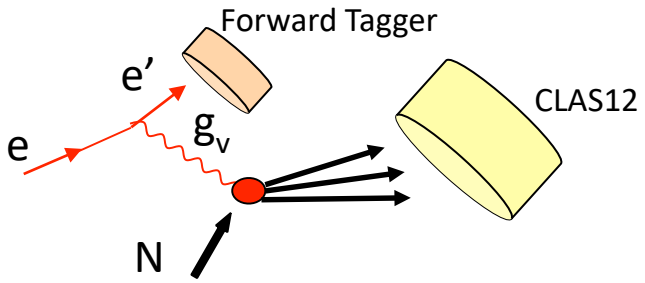
The FT installed in CLAS12



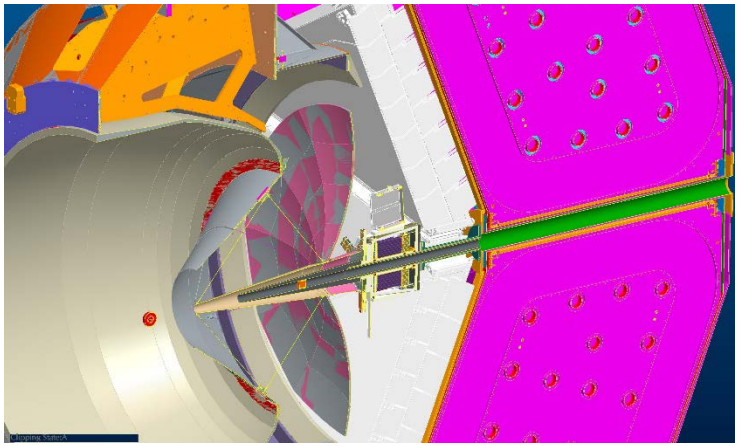


- FT-Cal: $PbWO_4$ calorimeter
- FT-Hodo: scintillator tiles
- FT-Tracker: MicroMegas

FT: low Q^2 quasi-real photoproduction



$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0^o - 360^o
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 > 0.1$ GeV^2)
W	3.6 - 4.5 GeV



- Electron scattering at "0" deg (2.5°-4.5°)
  - **Low Q^2 virtual photon ⇒ 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**: $N_\gamma \sim 5\times10^8$, $L \sim 10^{35}$ $cm^{-2}s^{-1}$ on 5 cm LH_2 target
  - Thin targets can be used

The CLAS12 hadron spectroscopy program

Photoproduction of hyperons with CLAS12

Exp-12-008 "Very Strange Experiment"

Search for missing excited hyperon states

- Excited cascades
  - Hyperon spectrum less know wrt N*
  - How quark masse change the effective degrees of freedom in hadron spectra
  - $\Xi(1530)$, $\Xi(1820)$
  - $K^+K^+\pi^-$, $K^+K^+K^-p$
- Ω^- photoproduction
  - 3 s quarks systemPoorly know
  - Quantum number poorly known
  - $K^+K^+K^0$, $K^+K^+K^0K^-$
- Quantum numbers and production dynamics determination
  - Parity and polarisation measurement of $\Xi(1820)$
  - Ω^- cross section

- Excellent K identification
- Excellent resolution to use missing mass technique
- Decay and production of multi kaon systems

Requirements

1) 4π detector
2) High intensity 6-10 GeV

Meson spectroscopy with photons in CLAS12

Exp-11-005 "MesonEx"

Study the meson spectrum in the 1-3 GeV mass range to identify gluonic excitation of mesons (hybrids) and other quark configuration beyond the CQM

- Hybrid mesons and Exotics
  - Search for hybrids looking at many different final states
  - Charged and neutral-rich decay modes
  - $\gamma p \rightarrow p\,3\pi$, $\gamma p \rightarrow p\,\eta\,\pi$, ...
- Hybrids with hidden strangeness and strangeonia
  - Intermediate mass of s quarks links long to short distance QCD potencial
  - Good resolution and kaon Id required
  - $\gamma p \rightarrow p\,\phi\,\pi$, $\gamma p \rightarrow p\,\phi\,\eta$, $\gamma p \rightarrow p\,2K\,\pi$, ...
- Scalar mesons
  - Poorly know f_0 and a_0 mesons in the mass range 1-2 GeV
  - Theoretical indications of unconventional configurations (qqqq or gg)
  - $\gamma p \rightarrow p\,2\pi$, $\gamma p \rightarrow p\,2K$, ...

- Decay and production of exclusive reactions, different final states (charged/neutral)
- Detector requirements: good acceptance, energy resolution, particle Id
- a PWA

Requirements

1) 4π detector
2) High intensity 6-10 GeV photon beam

Light Meson Decay

Exp-12-06-108b "LMD"

Transition Form Factor of the eta' Meson with CLAS12

- Transition form factor of the eta' meson
  - hadronic light-by-light (HLBL) contribution to the muon anomalous magnetic moment a_μ
  - Dalitz decays of η' mesons, $\eta' \rightarrow \gamma e^+ e^-$
  - η' produced in $e\,p \rightarrow e\,p\,\eta'$
  - 0.5% statistical uncertainties (disregarding higher order effects)

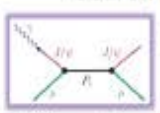
- Studied in g12 (CLAS6)
- Detector requirements: high luminosity, lepton trigger capability, large angle acceptance
- External photon pair production background suppressed by exploiting the 1 mm vertex resolution

LHCb Pentaquark with C

Exp-12-12-001a "Pentaquark"

Near threshold J/psi photoproduction and s pentaquarks with CLAS12

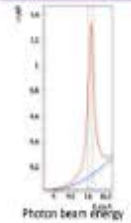
Search for LHCb Pentaquark



$\gamma + p \rightarrow P_c \rightarrow J/\psi + p$

$J/\psi \rightarrow e^+e^-$

$J/\psi \rightarrow \mu^+\mu^-$



$BR(P_c \rightarrow J/\psi p) = 1\%$ $L = 10^{33}\,cm^{-2}s^{-1}$

	$P_c(4380)$		$P_c(4450)$	
	Minimum	Maximum	Minimum	Maximum
Untagged mode	48	500	70	220
Tagged mode	20	600	28	880
Total	68	1100	98	1100

98 events/day for narrow $P_c(4450)$ pentaquark state at nominal CLAS12 luminosity

Nucleon resonances studies with CLAS12

Exp-12-009 "N" and Exp-12-06-108a "KY"*

Study the baryon spectrum to map the Q2 evolution of excited states in an unexplored domain

- Single and multi pions Xsec
  - Extended kinematic coverage in the unexplored Q^2 region between 5-10 GeV
  - Precise and abundant data for many final states
- Hyperon electroproduction
  - Natural extension to single and multi K final states
- Photocoupling extraction
  - Mapping the NN* transition form factors to pin down the underlying dynamics
  - Phenomenological models to parametrize the data, and PWA for full interpretation
  - Well established analysis procedure tested with CLAS data

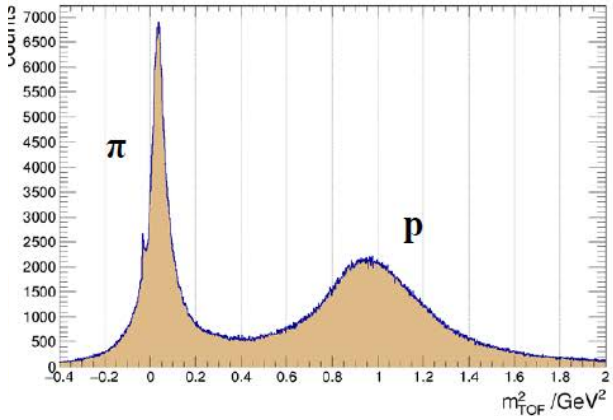
- Isobar model and beyond
- Detector requirements: good acceptance, energy resolution, particle Id
- Identification of exotic configuration via PWA

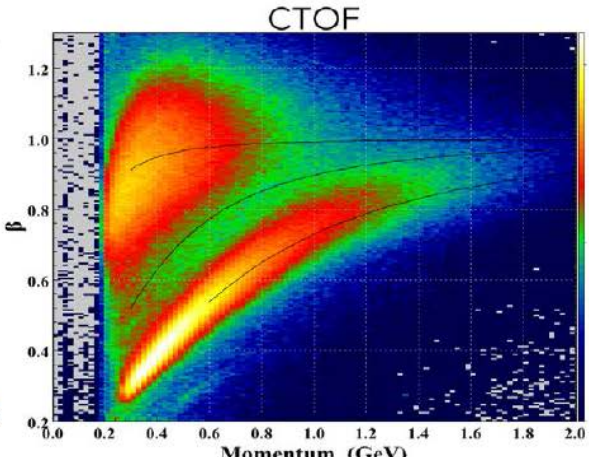
Requirements

1) 4π detector
2) High intensity 10 GeV electron beam

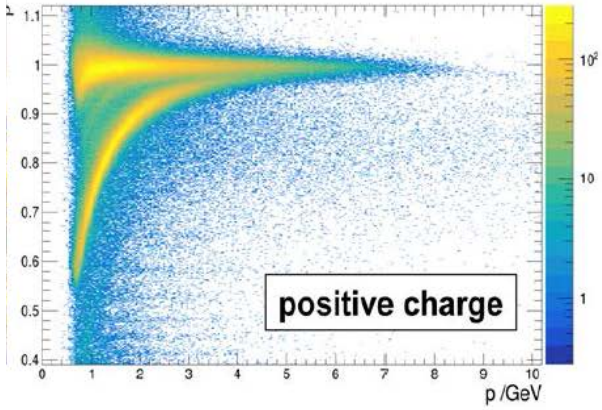
New data with CLAS12: first performance

Central time-of-flight

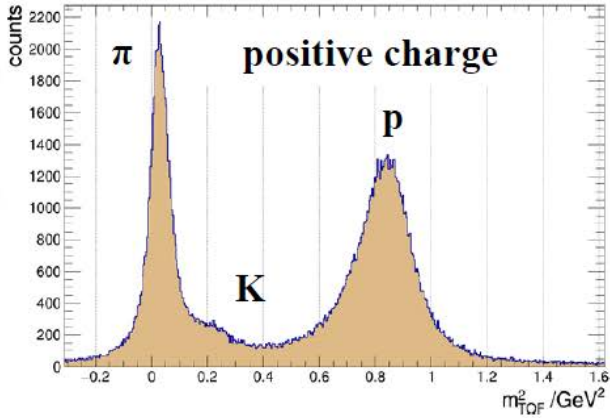




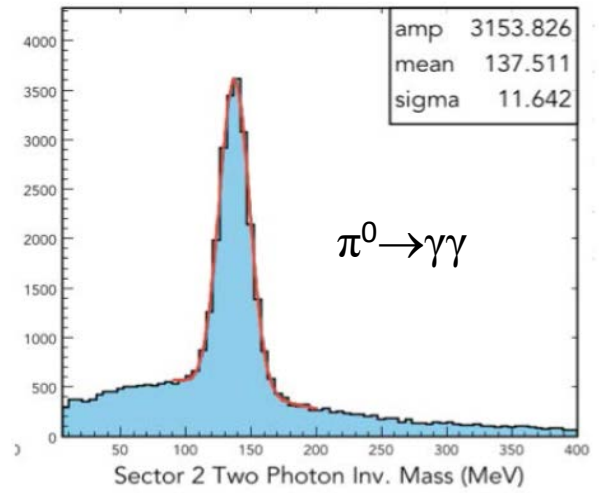
Forward time-of-flight

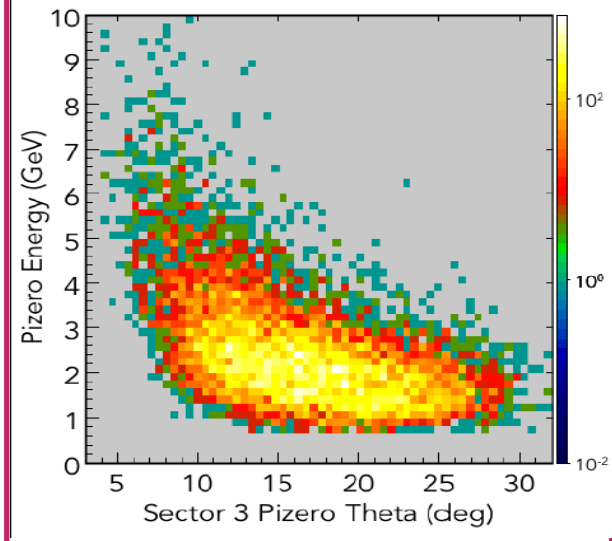


δT within 20% of specs



Charged particle detection by Time of Flight





Photon detection in the Forward Calorimeter

MESON SPECTROSCOPY IN PHOTOPRODUCTION REACTIONS: EXPERIMENTAL RESULTS FROM CLAS

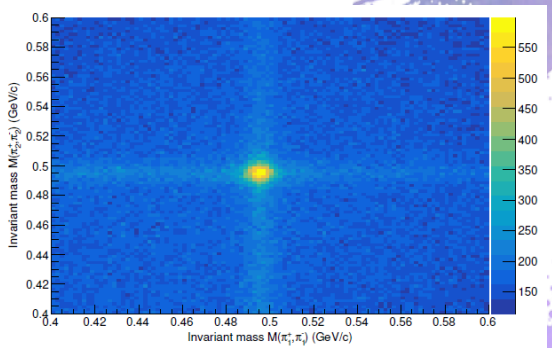
The K_SK_S system: $\gamma p \rightarrow pK_SK_S$

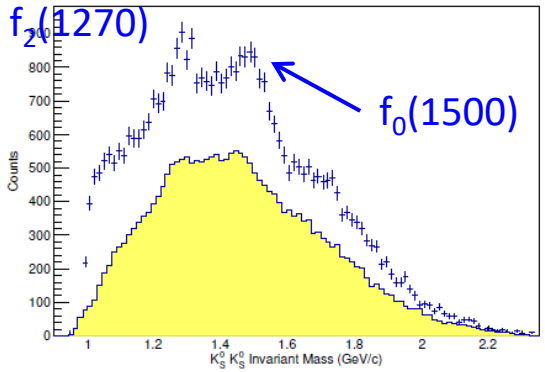
CLAS Collaboration, PRC97, 025203 (2018)

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

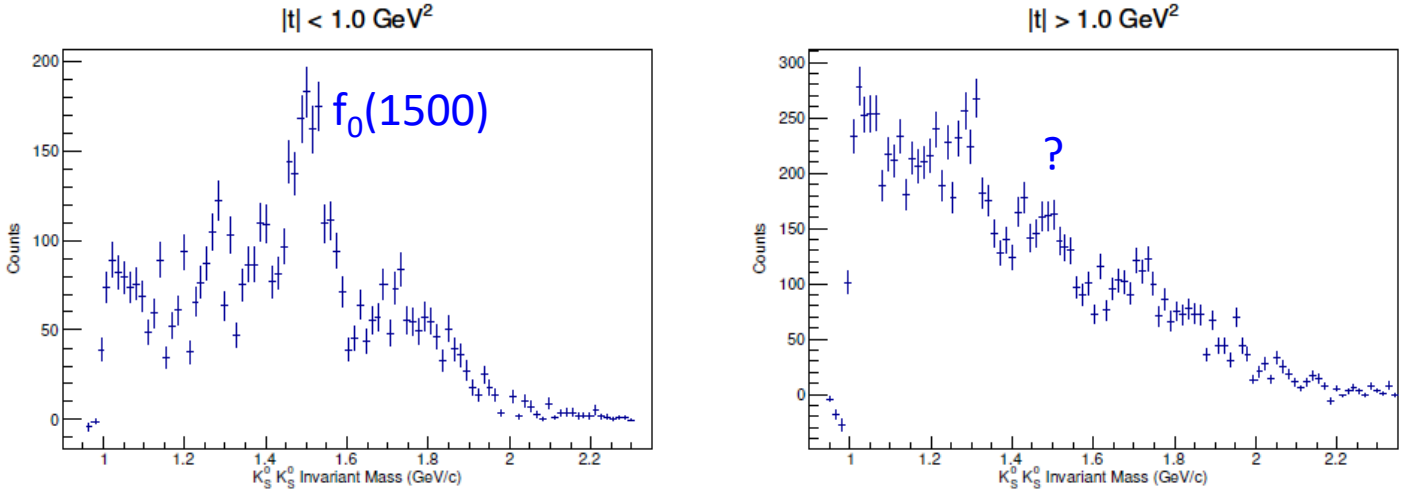
- K_SK_S system: $J^{PC} = (\text{even})^{++}$
- light scalar sector: several candidates, too many states for the nonet
  - $f_0(600)$, $f_0(980)$, $f_0(1370)$, **$f_0(1500)$**, $f_0(1700)$, …
- no study yet in photoproduction reactions

- CLAS6 g12 data set:
  - E_γ = (2.7-3) && (3.1-5.1) GeV
  - 4π 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

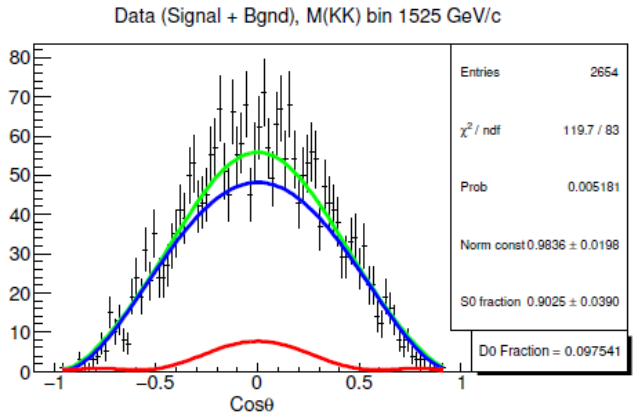




The K_SK_S system: $\gamma p \rightarrow pK_SK_S$



- Clean signal of $f_0(1500)$ for $|t| < 1$ GeV^2, no indication for $|t| > 1$ GeV^2
  - 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)

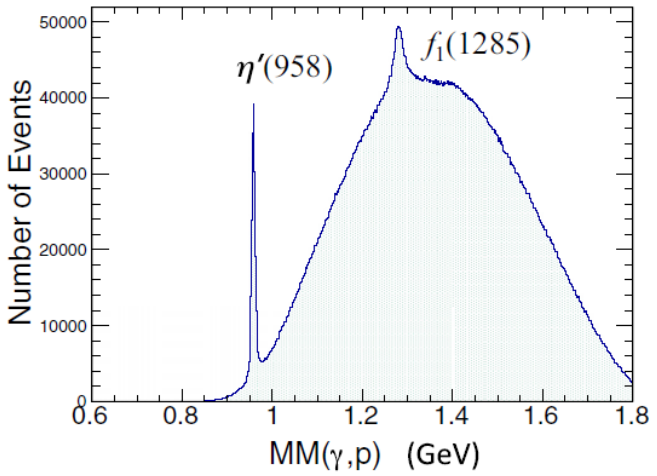
The $K\bar{K}\pi$ system: $\gamma p \rightarrow pK^0K^{\pm}\pi^{\mp}$

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 $K\bar{K}\pi$

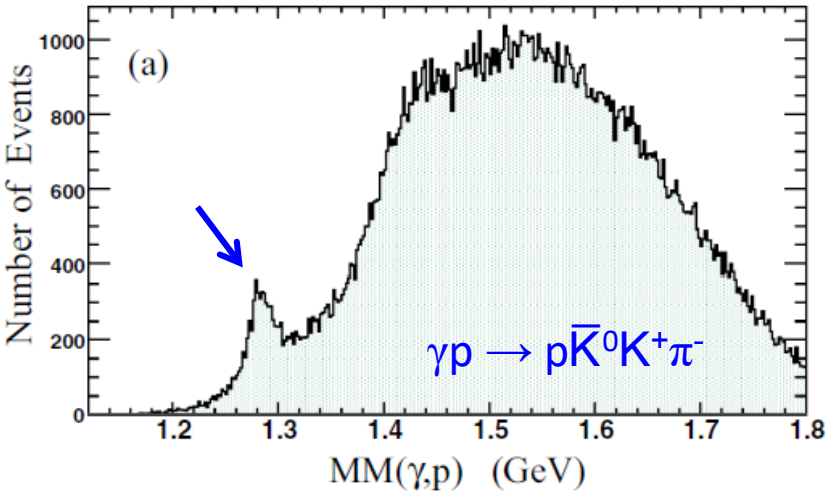
- $J^P = (odd)^+$ or $J^P = (even)^-$
- η-like pseudoscalars $\mathbf{0^{-+}}$: all of them decay to $K\bar{K}\pi$, K^*K, $a_0(980)\pi$
- axial states $\mathbf{1^{++}}$:
  - $f_1(1285)$: not seen in K^*K
  - $f_1(1420)$: favored candidate as hybrid $q\bar{q}g$, or 4q state, or K^*K molecule
  - other: $f_1(1510)$, isovector $a_1(1420)$…

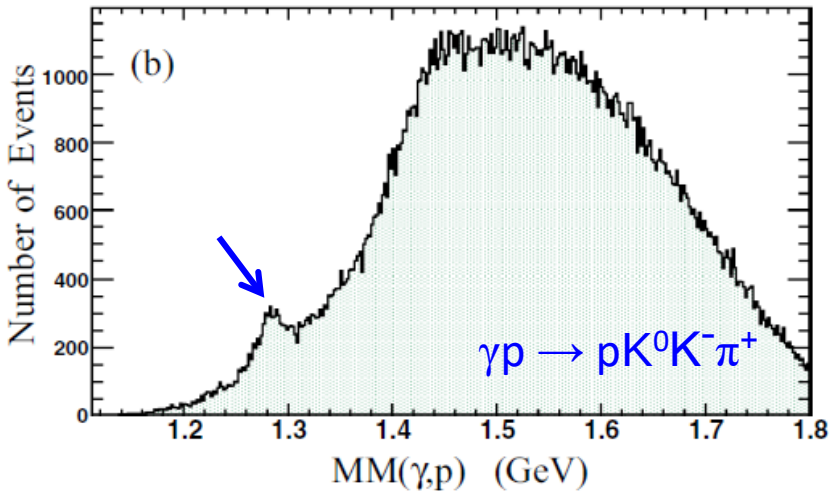
- CLAS6 g11a data set:
  - E_γ = (3-3.8) GeV
  - p, $K^{\pm}$, $\pi^{\mp}$ detected in CLAS, K^0 from missing mass
  - Kaon identification by TOF
  - Study of the $p\pi^+\pi^-\eta$ and $p\pi^+\pi^-\gamma$ channels on the same sample



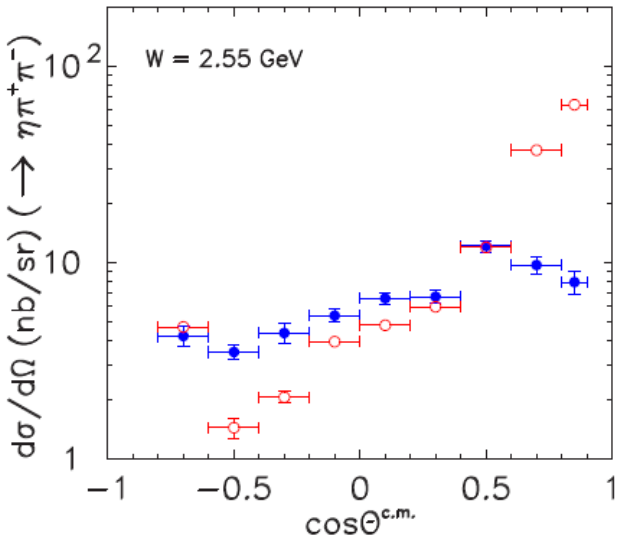
The $K\bar{K}\pi$ system: $\gamma p \rightarrow pK^0K^{\pm}\pi^{\mp}$

CLAS Collaboration, PRC93, 065202 (2016)

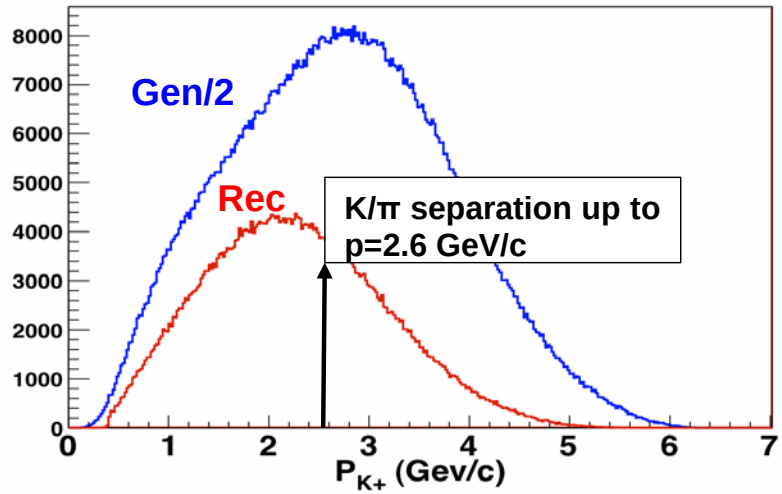




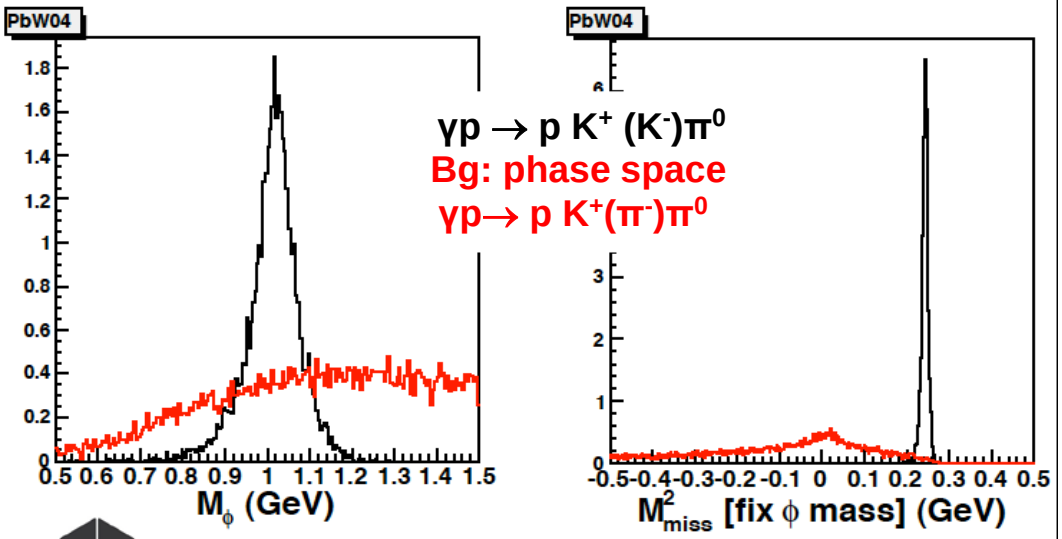
- No evidence found for higher mass $\eta(1405)$, $\eta(1470)$, $f_1(1420)$, $f_1(1510)$
- First observation in photoproduction at ~1280 MeV, studied in $\pi^+\pi^-\eta$
  - $M = (1281.0 \pm 0.8)$ MeV
  - $\Gamma = (18.4 \pm 1.4)$ MeV
    - More compatible with $f_1(1285)$ than $\eta(1295)$
  - Differential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

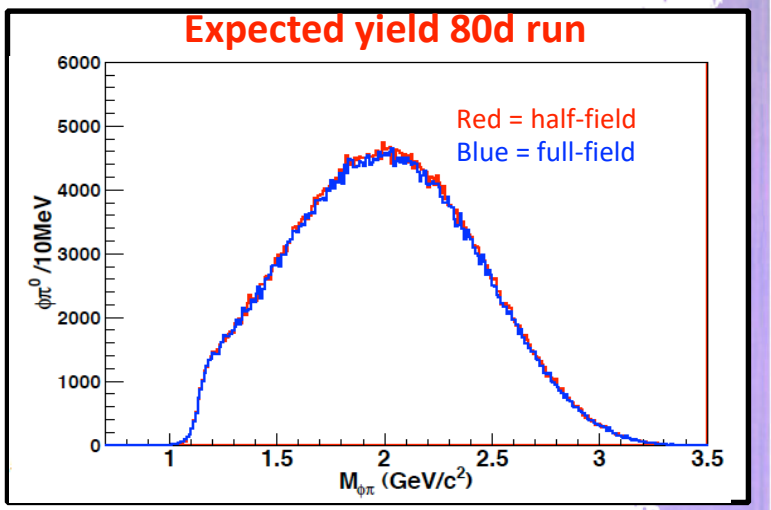


Search for "new" strangeonia with CLAS12: $\gamma p \rightarrow p\phi\pi^0$



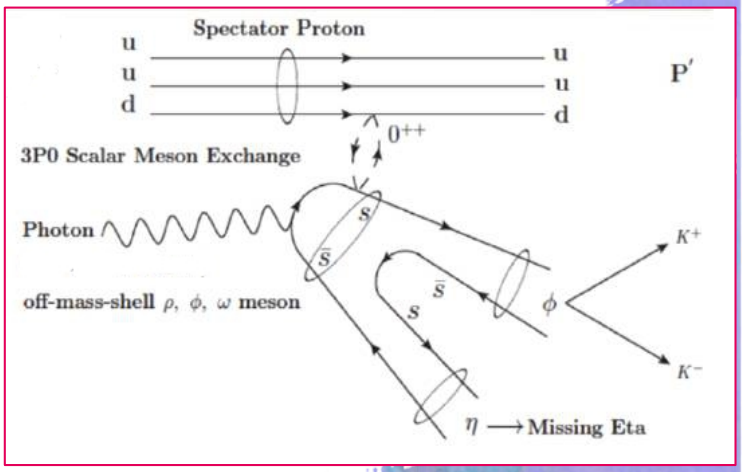
- Production cross section: 10 nb
- CLAS12 acceptance: ~10%
- Good π/K separation power required for momenta up to 2.6 GeV/c
- Simulation: **good background rejection capabilities using kin. fit and pid** of CLAS12
- Expected events in 80 data taking days @ full luminosity: ~ 3000 evts/mass bin
- Expected trigger rate: < 10 kHz





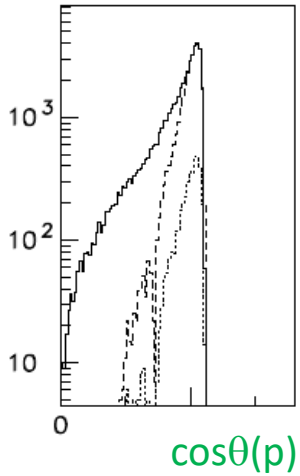
$\gamma p \rightarrow \varphi\pi^0 p$

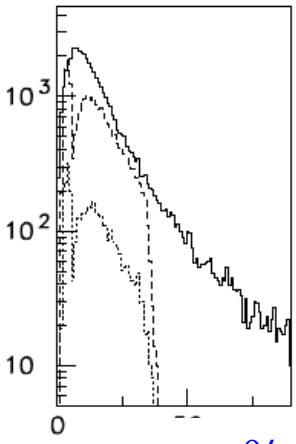
Search for "new" strangeonia with CLAS12: $\gamma p \rightarrow p\phi\eta$

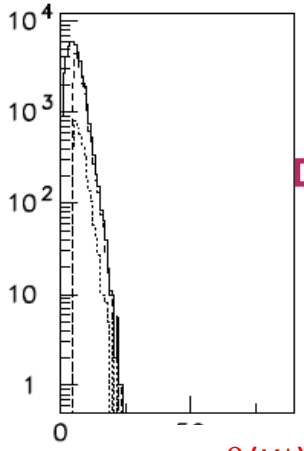


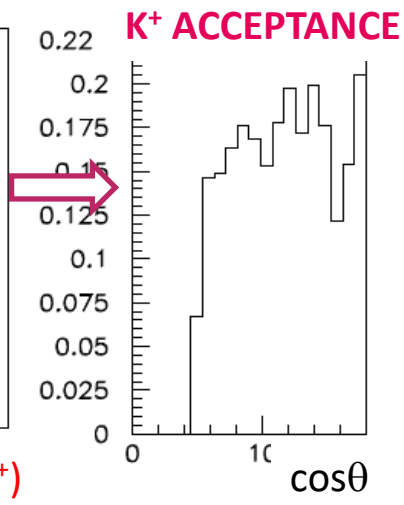
- **Smoking gun** decay modes for $s\bar{s}$ states: $\eta\phi$, $\eta'\phi$, $\phi\phi$
  - $\eta\phi$: identification of C = -1 $s\bar{s}$ candidates
  - Small branching fraction to non-strange final states

- Acceptance evaluation of $\gamma p \rightarrow p\phi(1850) \rightarrow p\eta\phi \rightarrow pK^+(K^-)_{miss}\gamma\gamma$ events with CLAS12+FT (lab emission angle distribution)
  - Good acceptance for neutrals, sizeably increased by FT calorimeter: overall acceptance > 10%



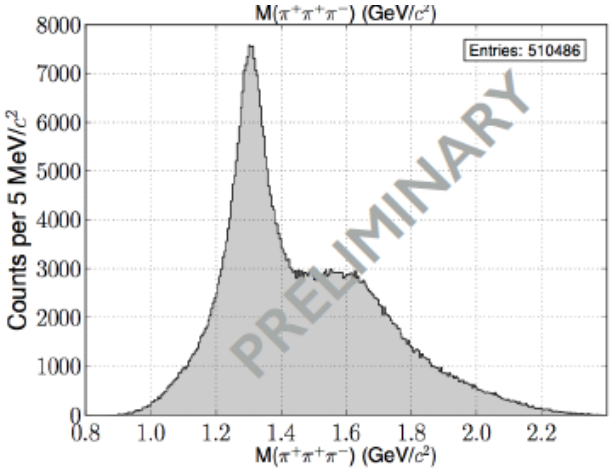


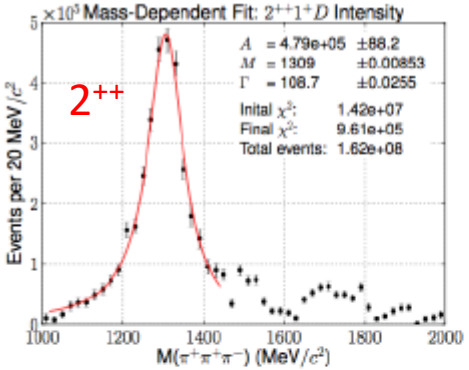


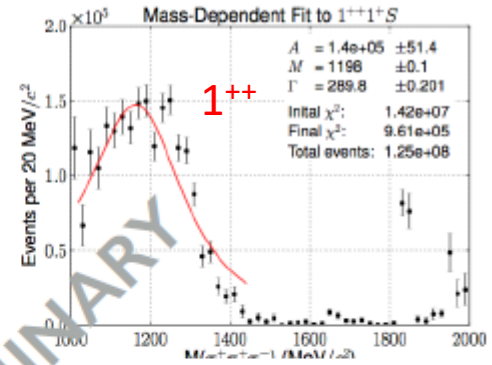


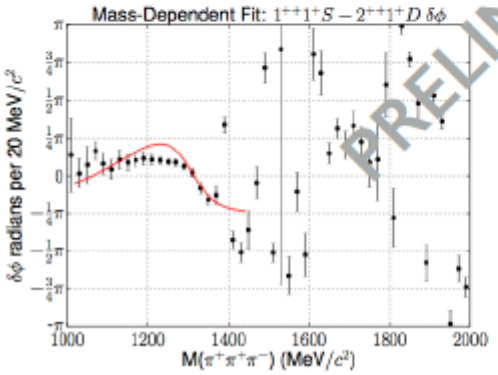
- Expected cross section for strangeonia production: **O(10 nb)**

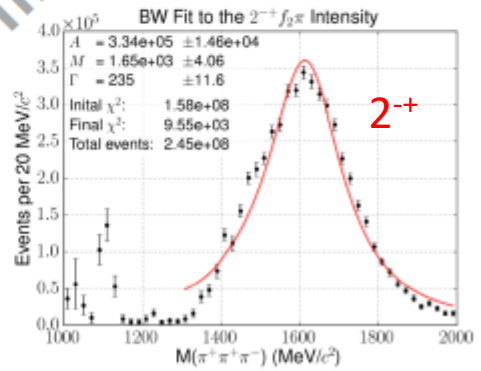
3π system study in CLAS

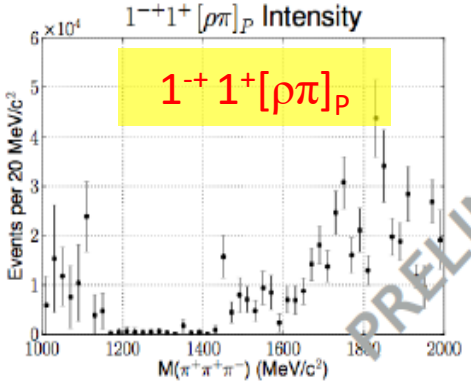


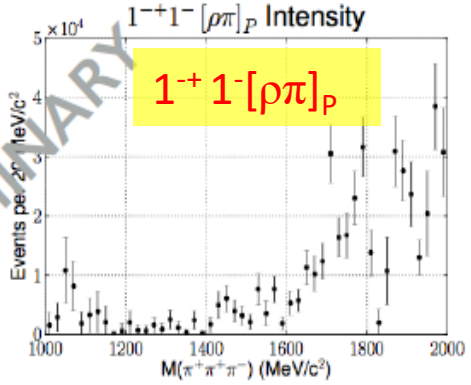












- Purpose: confirmation of the signal (hybrid?) observed by COMPASS in 3π

- First study on CLAS-g12 data set
  - Several resonances observed
  - No confirmation for the hybrid 1^{-+} in (ρπ) P-wave

A. Tsaris, FSU, 2016

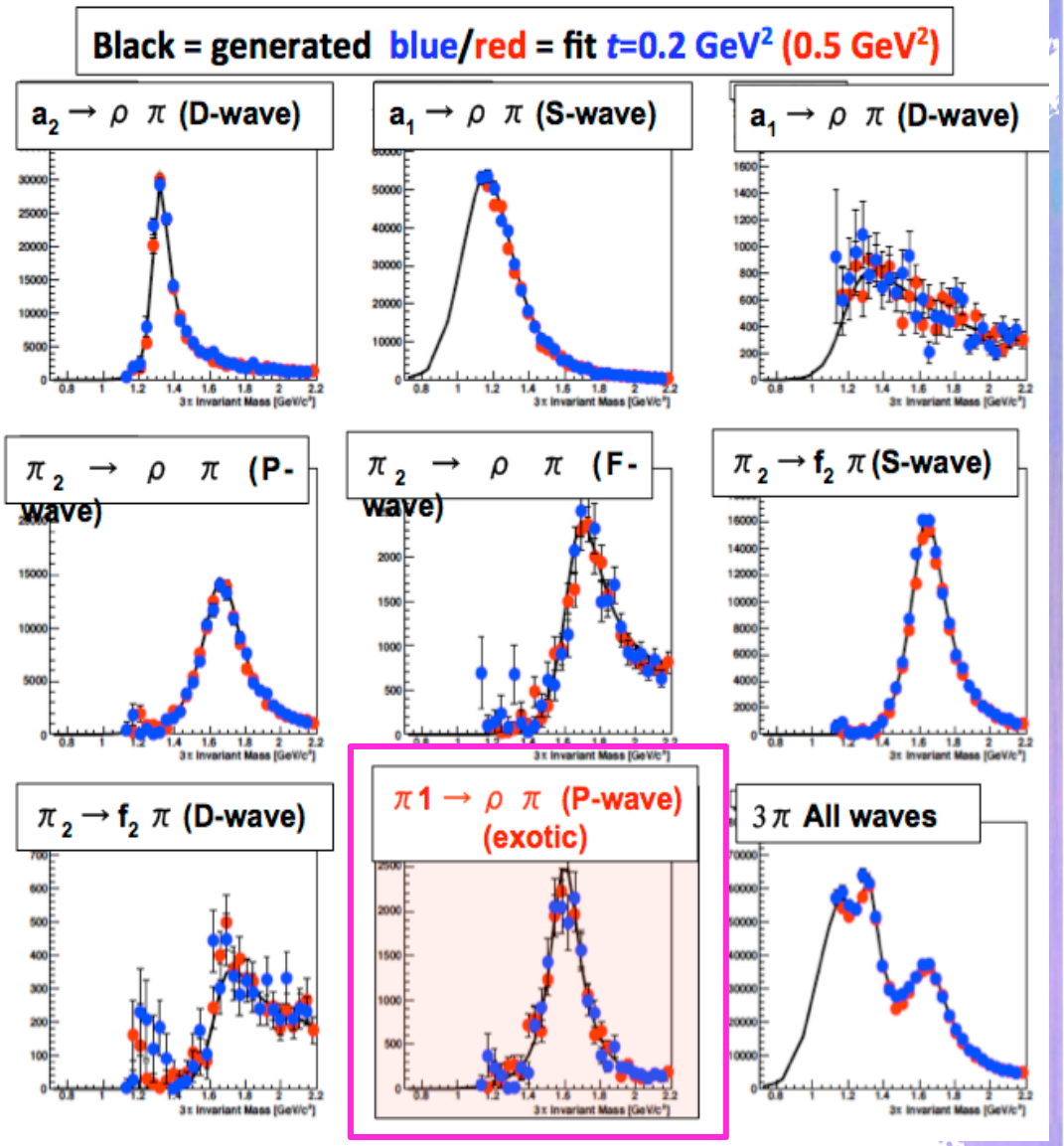
The 3π system analysis: projections for CLAS12

- 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:

  $\gamma p \rightarrow \pi^+\pi^+\pi^- p$

  - 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!**



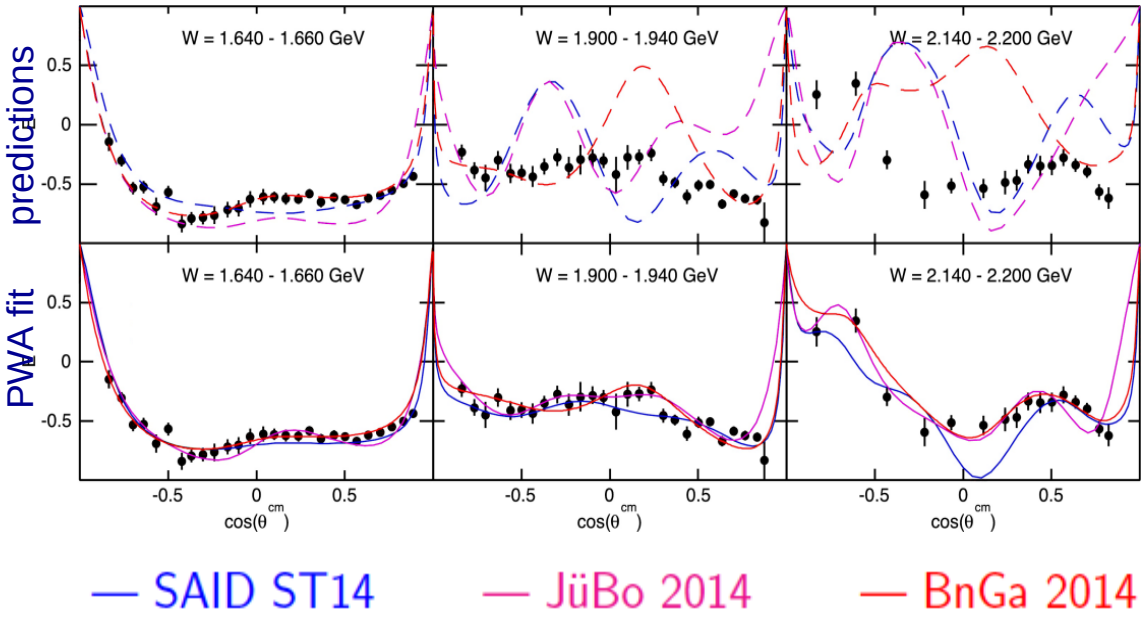
BARYON SPECTROSCOPY IN PHOTOPRODUCTION REACTIONS: EXPERIMENTAL RESULTS FROM CLAS

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 analyses	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$^-$		**	**
Δ(1940)3/2$^-$	*	*	**

CLAS Collaboration, PLB750 (2015) 53



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

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

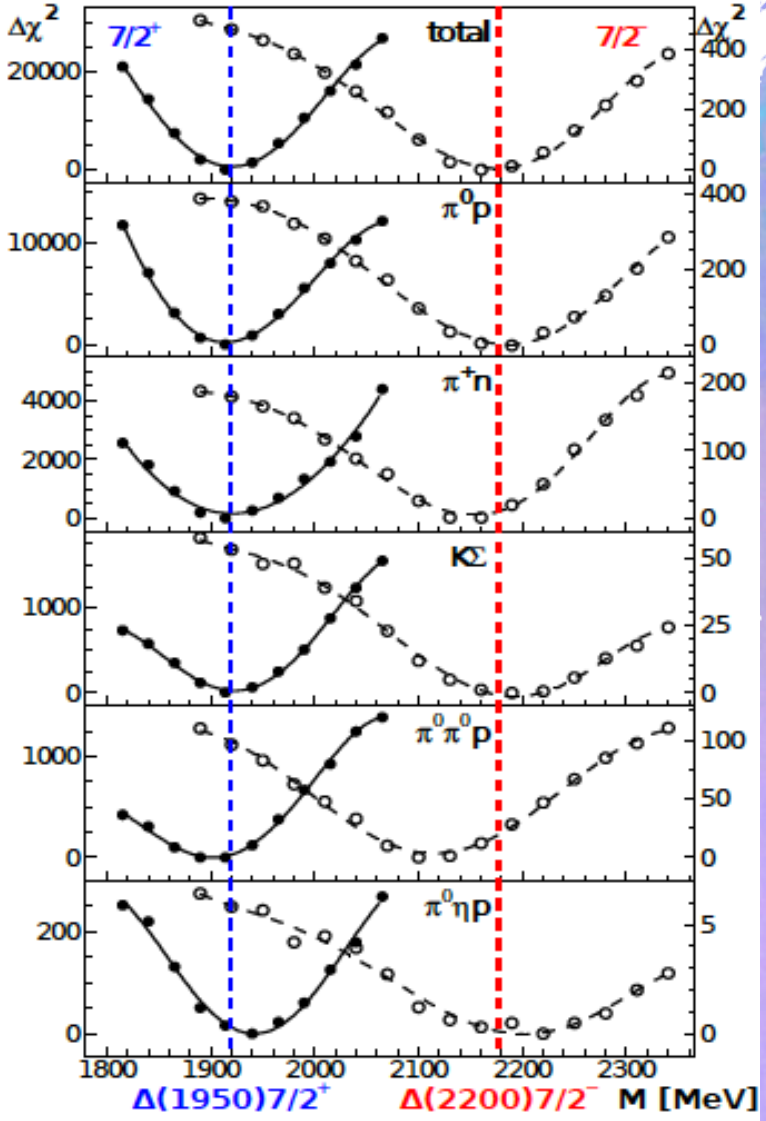
Search for parity doublets

- 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?
  - Δ^* spectrum:

$\Delta(1910)1/2^+$	$\Delta(1920)3/2^+$
$\Delta(1900)1/2^-$	$\Delta(1940)3/2^-$
$\Delta(1905)5/2^+$	$\Delta(1950)7/2^+$ (****)
$\Delta(1930)5/2^-$	$\Delta(2200)7/2^-$ (*)

  - 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



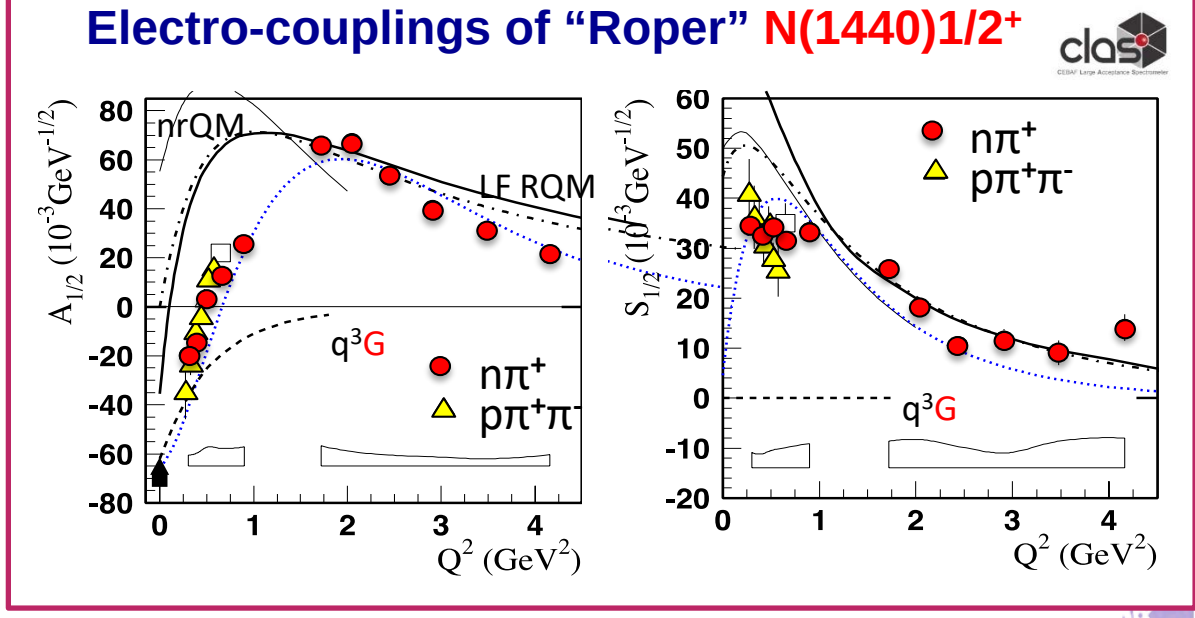
A.V. Anisovich et al, PL B766 (2017), 357

Q^2 evolution of the transition form factor

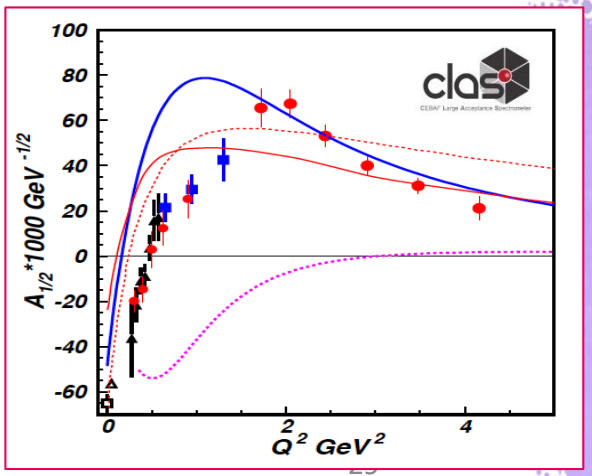
CLAS Collaboration, PRC 80, 055203 (2009)
CLAS Collaboration, PRC 86, 035203 (2012)

- Electroproduction can be used to explore hadron structure at different wavelengths (Q^2)

- Hybrid model predictions:
  - Steeper drop in the transverse helicity amplitude $A_{1/2}$
  - Suppressed longitudinal amplitude $S_{1/2}$



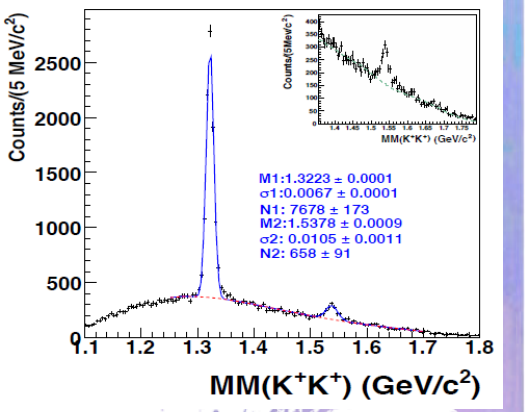
- Hybrid model inconsistent with experimental results
  - Internal consistency of Nπ and Nππ data
  - nrQM fails to reproduce low Q^2 behaviour
  - $A_{1/2}$ changes sign and has large magnitude
  - $N(1440)1/2^+$: interplay of the q^3 core (first radial excitation) and the outer meson-baryon cloud

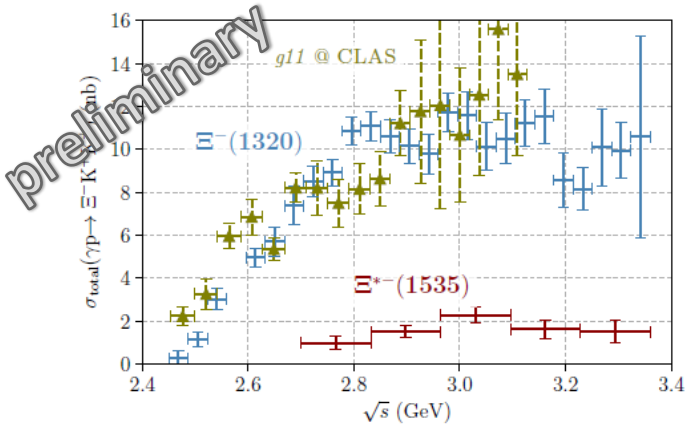


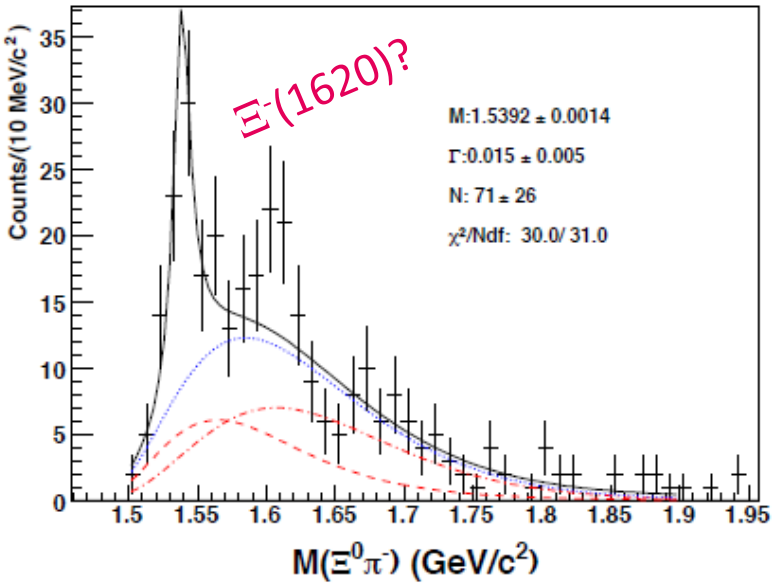
New strange baryons at CLAS

- Study of Ξ and excited states in $\gamma p \rightarrow K^+K^+X$, $K^+K^+\pi^-X$
  - g11a run:
    - clean signals for Ξ(1320) and Ξ(1530), 10:1 ratio
  - g12 run:
    - total production Ξ cross section (3.5-5.4 GeV).
      - Only Ξ(1530) significant
      - Upper limits for Ξ excitations production @90% C.L.:
        - » Ξ(1690): 0.75 nb
        - » Ξ(1820): 1.01 nb
        - » Ξ(1950): 1.58 nb

CLAS Collaboration, PRC **76**, 205208 (2007)







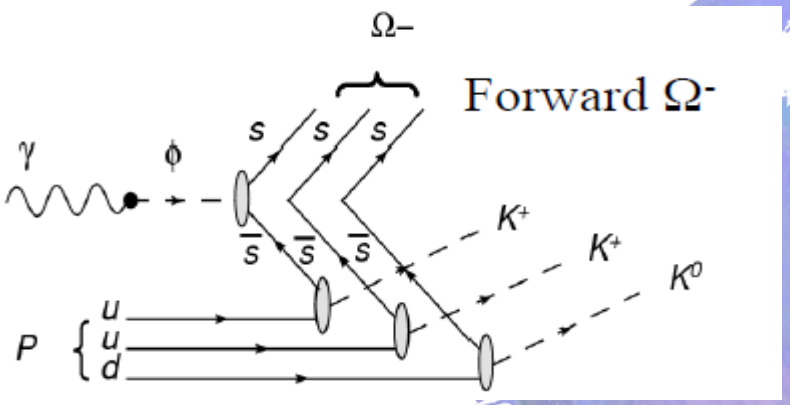
CLAS Collaboration, arXiv:1809.00074

CLAS12: the "Very strange baryon" program

- Goals: high statistics measurements of Ω^- and Ξ excitations in photoproduction reactions
  - Strange quarks multiple production from the sea
  - Helicity asymmetries
  - Ξ^- polarization
  - N*, Y* excitations properties
  - Excited cascades and Ω^-

- Equipment: CLAS12 + Forward Tagger

- Reactions of interest:
  - $\gamma p \rightarrow K^+K^-p$
  - $\gamma p \rightarrow K^+\Lambda\pi^0$
  - $\gamma p \rightarrow K^+K^-\Xi^-$, $\Xi^- \rightarrow \Lambda\pi^-$



	Detected particles	Measured Decays	Overall Efficiency	Rate/hr	Total Detected
Ω^-	$K^+K^+K^0$		~3.9%	~3.6	~7k
Ω^-	$K^+K^+K^0K^-$	Ω^-	~0.5%	~0.5	~1k
Ξ^-	$K^+K^+\pi^-$	Ξ^-	~9.3%	~440	~0.9M
$\Xi^-(1530)$	$K^+K^+\pi^-$	$\Xi^-(1530)$	~7.4%	~140	~270K
$\Xi^-(1820)$	$K^+K^+K^-p$	$\Xi^-(1820)\Lambda$	~0.63%	~6	~12K

projections for 80 beam days @ half field

Summary and conclusions

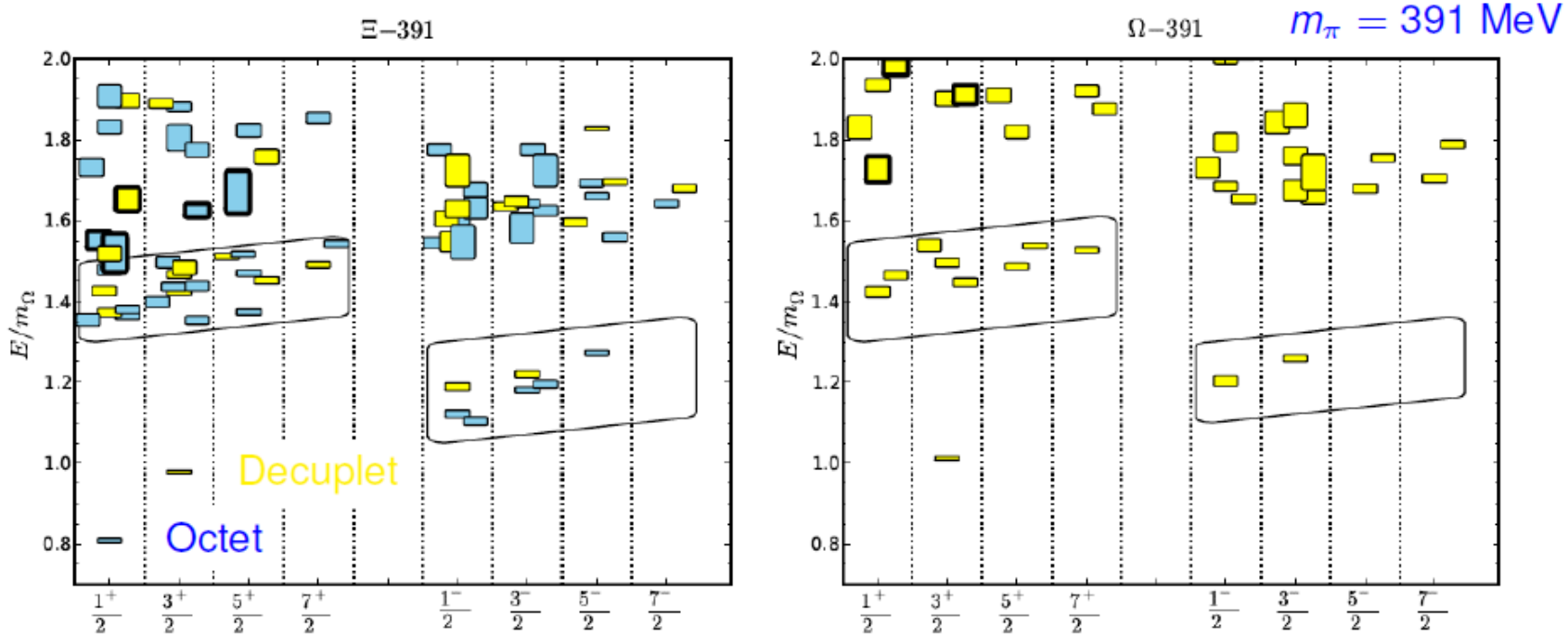
- Still many open problems in light hadron spectroscopy
  - Mesons:
    - the scalar/pseudoscalar/axial sector
    - radial excitations with open/hidden strangeness
    - existence of exotics, …
  - Baryons:
    - N* and Δ* missing resonances
    - parity doublets
    - (very) strange baryons excitations
    - Baryonic hybrids and exotics
    - transition form factors, …

- **At JLAB**: **high intensity**, linearly polarized real (by brehmsstrahlung, Hall D) and virtual (by low Q^2 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!**

Backup slides

Ξ and Ω spectrum from LQCD

R. Edwards *et al.*, Phys. Rev. D **87**, no. 5, 054506 (2013)



- Number of expected states of each flavor and spin consistent with QM for the lowest negative and positive parity bands
- (Roughly) same features as expected from SU(6)xO(3) symmetry

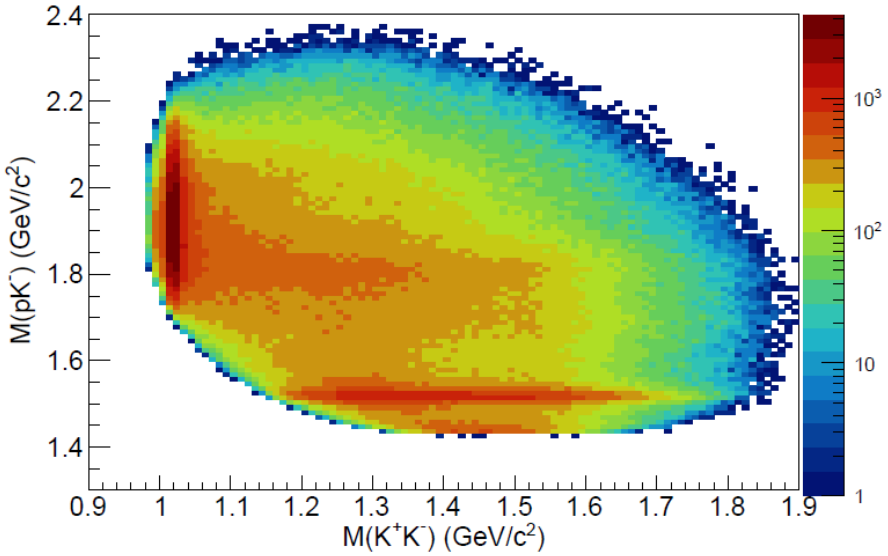
The K^+K^- system: $\gamma p \rightarrow pK^+K^-$

Physics case: investigation of light meson resonance spectrum

- $\phi(1020)$ main decay mode
- possible sub-threshold decay of $f_0(980)$ and $a_0(980)$ scalars
- issues: σ production? Other scalars? $f_0(980)$ coupling to $\pi\pi/K\bar{K}$?

- CLAS6 g11 data set:
  - E_γ = (3-3.8) GeV
  - -t: (0.6-1.3) GeV^2
  - p and K^+ detected in CLAS, K^- reconstructed by missing mass
    - π/K misidentification: 10-15%
- Low mass region selected
  - $m_{pK^-} > 1.6$ GeV
  - Baryonic resonance contributions ($\Lambda(1520)$) removed, no overlap

CLAS Collaboration, PRD98 (2018), 052009



The K^+K^- system: $\gamma p \rightarrow pK^+K^-$

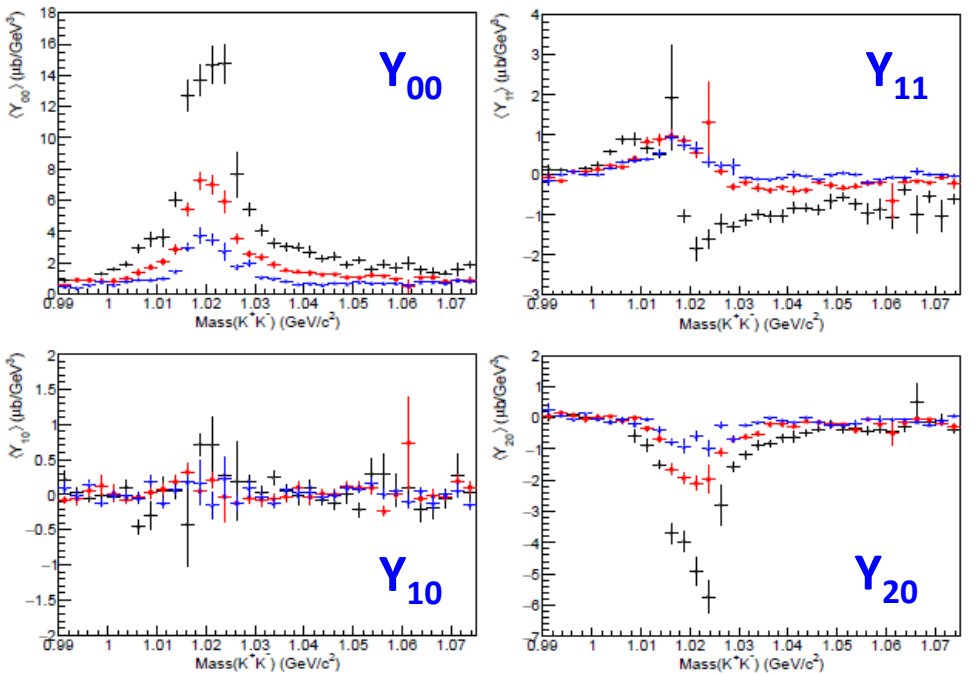
- Study of S-P wave interplay in the $K\bar{K}$ system
  - Cross-sections extraction in each partial wave through likelihood fits

- Method: moments analysis

$$\langle Y_{LM} \rangle = 4\pi \int d\Omega_K \frac{d\sigma}{dt dM_{KK} d\Omega_K} Y_{LM}(\Omega_K)$$

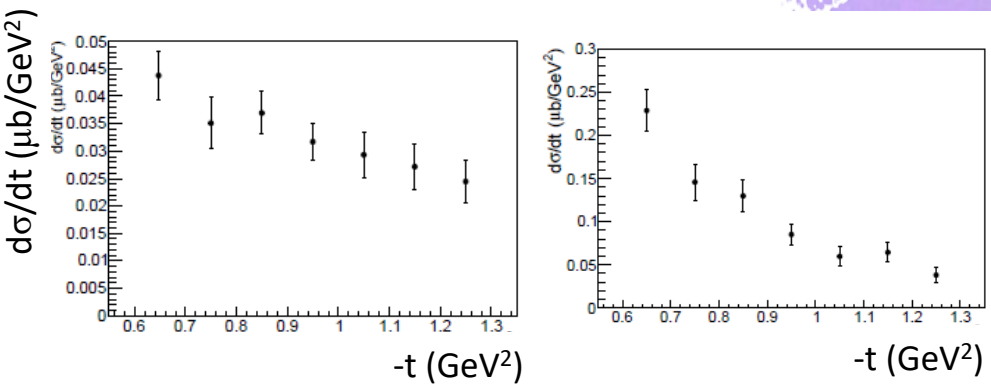
  - Moments can be expressed as bilinear combination of partial waves, depending on L, M and photon and proton helicities
  - Amplitude parameterizations:
    - S wave: ρ, ω exchange in t-channel
    - P-wave: Pomeron exchange

CLAS Collaboration, PRD98 (2018) 052009



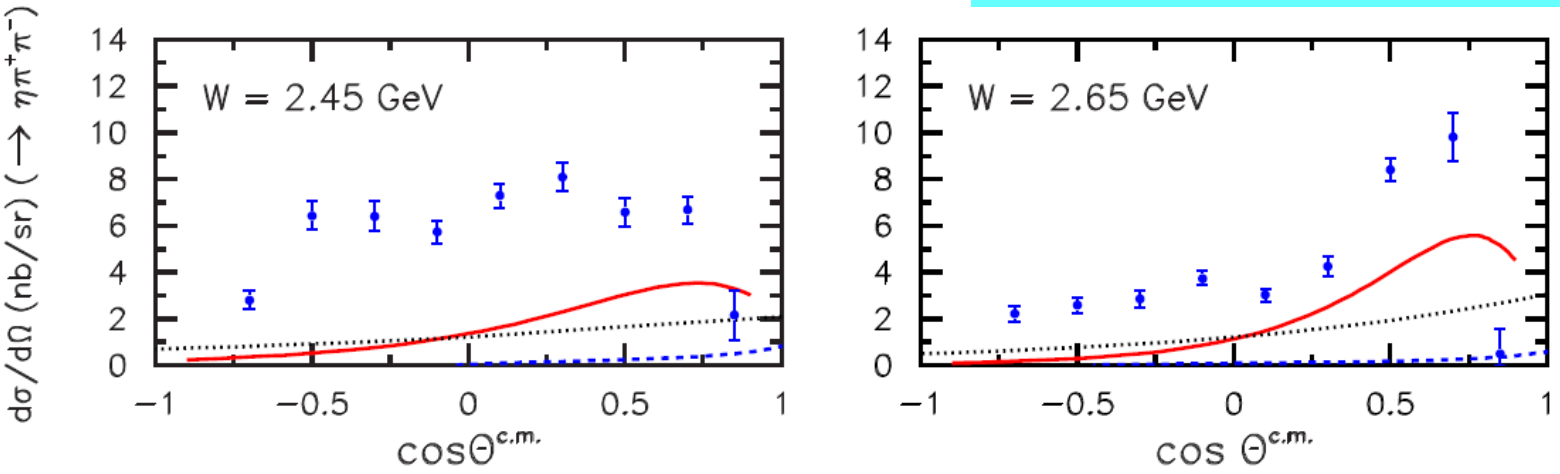
S-wave diff. cross section

P-wave diff. cross section



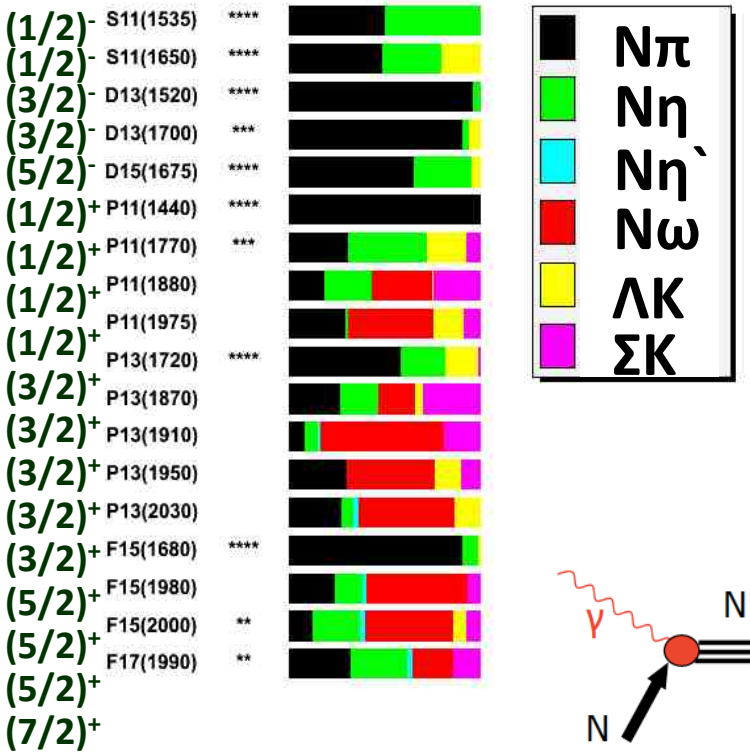
The $K\bar{K}\pi$ system: $\gamma p \rightarrow pK^0K^{\pm}\pi^{\mp}$

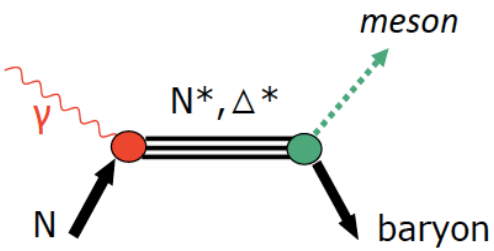
CLAS Collaboration, PRC93, 065202 (2016)



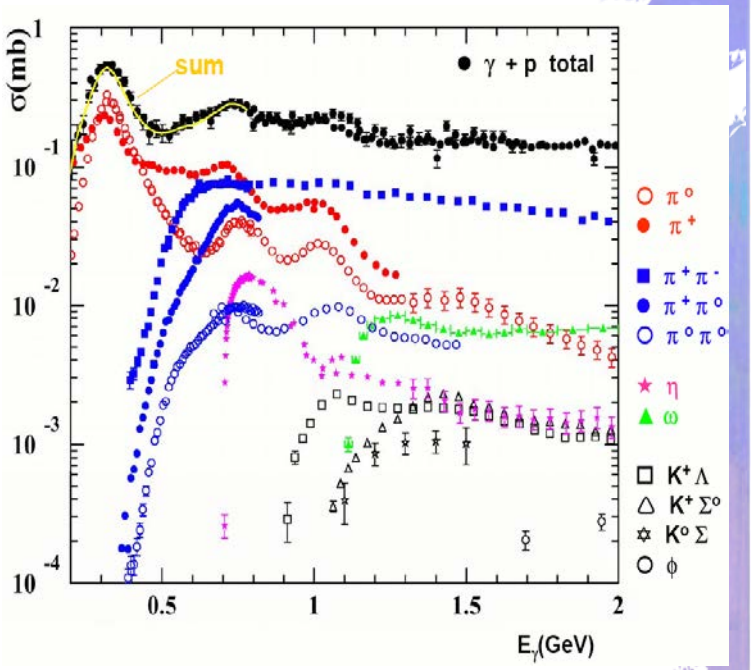
- Poor match of the differential cross sections with expectations from t-channel models
  - s-channel substantial contribution?
  - Dynamically produced state via s-channel involving N* excitations or KK* molecular interactions?
  - Larger support for $f_1(1285)$ identification
- First determination of the relative branching ratio: $\Gamma(K\bar{K}\pi)/\Gamma(\eta\pi\pi) = 0.216 \pm 0.032$
  - Consistent with PDG value : 0.171 ± 0.013
  - Not known for η(1295)

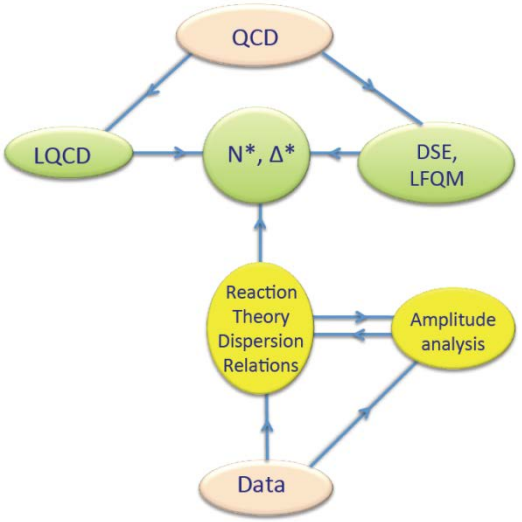
Search for missing N* and Δ* resonances





Photonuclear cross sections





- Necessary: precision measurements of photoproduction reactions in wide kinematic ranges and all possible channels
- Key measurements: **polarization observables**
- Coupled channels analysis + dispersion relations techniques to extract s-channel resonances