Meson Spectroscopy at CLAS and CLAS12

An overview of selected results

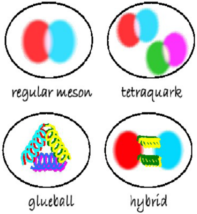
Andrea Celentano
CLAS Collaboration

INFN-Genova

Introduction

Exotic mesons

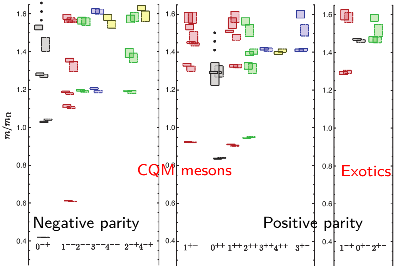
QCD does not prohibit the existence of unconventional meson states such as hybrids ($q\bar{q}g$), tetraquarks ($q\bar{q}q\bar{q}$), and glueballs.



Exotic quantum numbers: $J^{PC} \neq q\bar{q}$

The discovery of states with manifest gluonic component, behind the CQM, would be the opportunity to directly "look" inside hadron dynamics. **Exotic quantum numbers** would provide an **unambiguous** evidence of these states.

Lattice QCD calculations[1] provided a first hint on the spectrum and mass range of exotics.
Mass range: 1.4 GeV - 3.0 GeV
Lightest exotic is a 1^{-+} state.

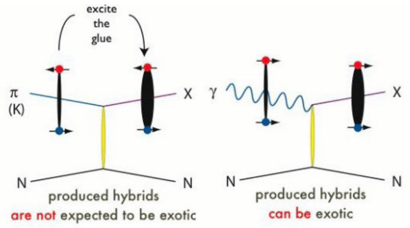


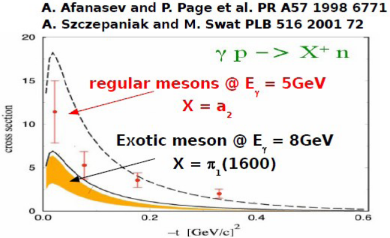
[1] J. J. Dudek et al, Phys. Rev. D82, 034508 (2010)

Exotic mesons photoproduction

Traditionally, meson spectroscopy was studied trough different experimental techniques: **peripheral hadron production**, $N\overline{N}$ annihilation, ...
Photo-production measurements were limited by the lack of high-intensity, high-energy, high-quality photon beams.
Today, this limitation is no longer present.
Advantages:

- Photon spin: exotic quantum numbers are more likely produced by $S = 1$ probe
- Linear polarization: acts like a filter to disentangle the production mechanisms and suppress backgrounds
- Production rate: for exotics is expected to be comparable as for regular meson



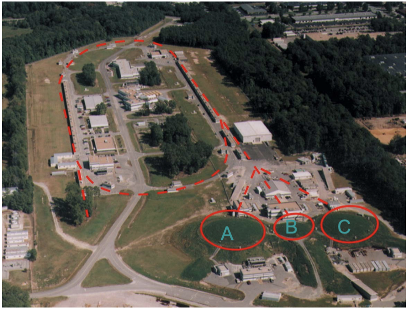


Jefferson Laboratory

Home of the Continuous Electron Beam Accelerator Facility (CEBAF)

Until 2012: 6-GeV e^- machine based on superconducting technology.

- 3 experimental Halls: A, B, C
- Max. current: $\simeq 200\mu$A / Hall (A and C)
- CW beam, $\simeq 100\%$ duty-cycle
- Beam polarization $\simeq 80\%$

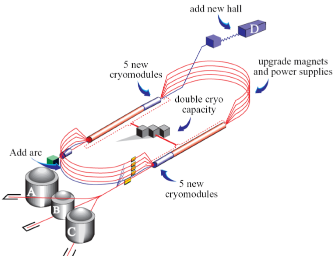


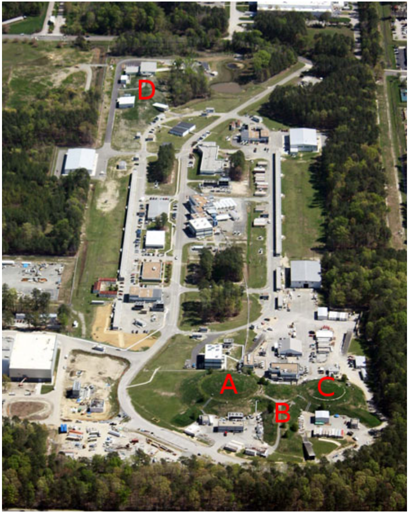
Jefferson Laboratory

Home of the Continuous Electron Beam Accelerator Facility (CEBAF)

Today: 12-GeV e^- machine based on superconducting technology.

- 4 experimental Halls: A, B, C, D
- Multi-pass acceleration scheme, 2.2 GeV / pass
- Max. current: $\simeq 100\mu$A / Hall (A and C)
- CW beam, $\simeq 100\%$ duty-cycle
- Beam polarization $\simeq 80\%$



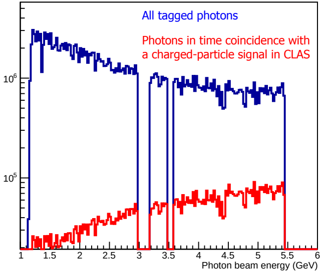


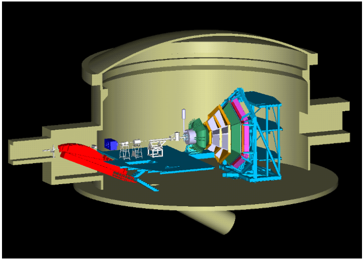
The CLAS-g12 experiment

High-energy, high-statistics breammstrahlung photon-beam experiment on lH_2 target

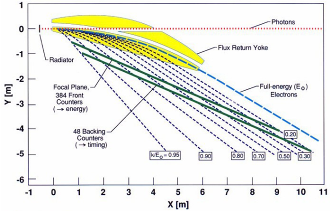
The g12 run period

- Summer 2008, $E_{e^-} = 5.715$ GeV, $I_{e^-} \simeq 60$ nA
- Tagged Bremsstrahlung photon-beam: 0.3-5.4 GeV, $L_{rad} = 10^{-4} X_0$
- 40-cm long LH_2 target
- Total number of recorded events $\simeq 26 \cdot 10^8$





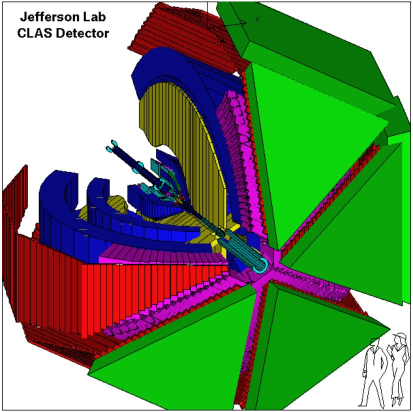
CLAS photon tagger



CLAS detector

CLAS detector in Hall B at Jefferson Laboratory: almost 4π detector optimized for multi-particle final states

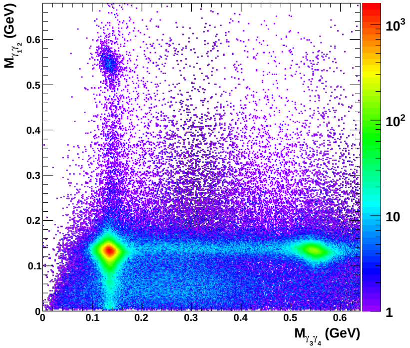
- Toroidal magnetic field (6 supercond. coils)
- Drift chambers (3 layers)
- Time-of-flight counters
- Electromagnetic calorimeters
  - $\sigma_E/E \simeq 10\%/\sqrt{E}$
  - Angular coverage: $5° \leq \theta \leq 45°$
- Charged particle performances:
  - Acceptance: $8° < \theta < 142°$
  - Resolution: $\delta p/p \simeq 1\%$, $\delta\theta < 1$ mrad



First measurement of the photoproduction reaction $\gamma p \to p a_2(1320)$

The $\gamma p \to p\pi^0\eta$ is a "golden channel" in meson spectroscopy: any $P-$wave resonance would unambiguously carry $J^{PC} = 1^{-+}$ *exotic* quantum numbers. A first measurement of this reaction in the multi-GeV energy range was recently completed using data from CLAS-g12.

- Both mesons were identified via their two-photons decay. A 4C kinematic fit was applied to the reaction $\gamma p \to p4\gamma$ events to ensure exclusivity.
- The $_s\mathcal{P}lot$ technique was applied to isolate the reaction $\gamma p \to \pi^0\eta p$, using the invariant mass of the two photons from the η as control variable.
- The differential cross section $d^2\sigma/dtdM_{\pi^0\eta}$ was extracted in different E_γ and $-t$ kinematic bins



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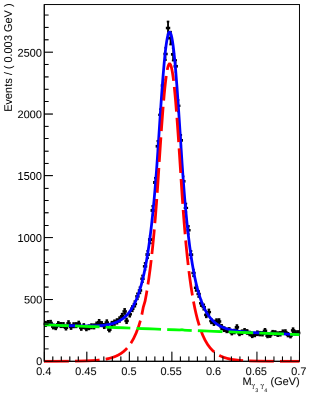

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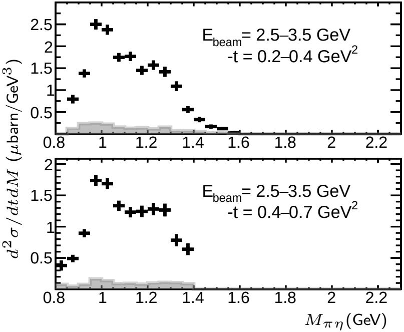

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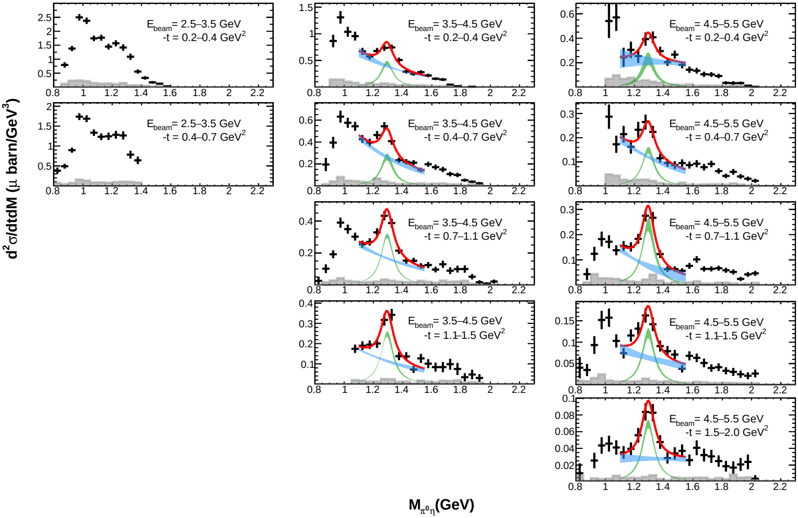


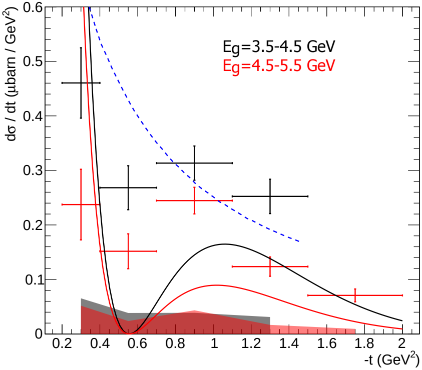
First measurement of the photoproduction reaction $\gamma p \to p a_2(1320)$

The limited statistics and acceptance prevented a full PWA of the final state. The dominant contribution of the $a_2(1320)$ to the total photo-production cross section was extracted in each E_γ and $-t$ kinematic bin through a fit to the $d^2\sigma/dtdM_{\pi^0\eta}$ observable via a resonance (a_2) + background model.

Most peculiar cross-section feature: dip at $-t \simeq 0.55$ GeV^2 for both beam energies. From Regge phenomenology, considering the dominant ρ and ω exchanges (Mathieu, PRD 102, 2020):

$$A_{a_2} \propto (1 + \tau e^{i\pi\alpha(t)})\Gamma(1-\alpha(t))$$

Our data also rule out other predictions for the $\gamma p \to p a_2$ photo-production cross section, based on other assumptions concerning the a_2 nature (for example, Xie et al. PRC 93, 2016)

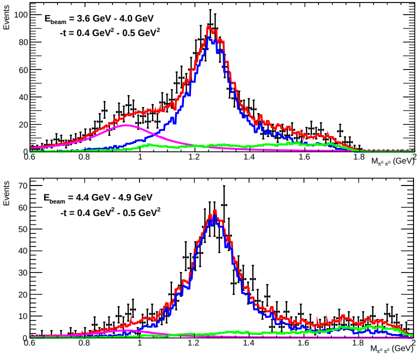


$f_2(1270)$ photoproduction and decay via two π^0 channel

Exploiting the same $\gamma p \to p4\gamma$ CLAS-g12 dataset, a high-statistics measurement of the $f_2(1270)$ photoproduction cross section on the proton was performed, exploiting the $f_2 \to \pi^0\pi^0$ neutral decay channel. This acts as a "PWA-filter": no P-wave signals (i.e. no background from ρ production).

- In each E_{beam} and $-t$ beam, the f_2 yield was extracted from the $M_{\pi\pi}$ spectrum, performing a template fit to the f_2 signal and to the background (phase-space + f_0 tail)
- The cross section was determined from the measured f_2 yield, accounting for the CLAS acceptance/efficiency and for the luminosity.
- Results were compared with a prediction from a Regge-based model, finding a good agreement.

M. Carver, Ohio University



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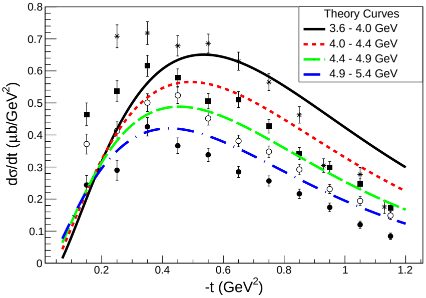


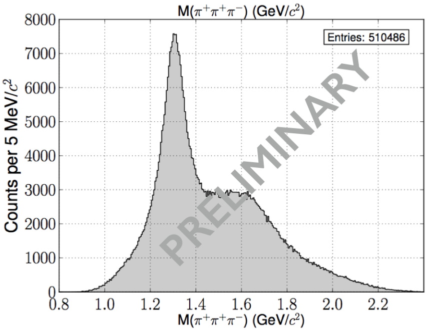
Parameter-free theory prediction, scaled by arbitrary factor 0.6 for comparison.

Full PWA of $\gamma p \to n\pi^+\pi^+\pi^-$

Reaction $\gamma p \to \pi^+\pi^+\pi^-(n)$ - neutron identified via missing mass technique.
Focus on $E_\gamma > 4.4$ GeV to enhance meson resonances production.

- Clean 3π spectrum showing peaks of dominant resonances $a_2(1320)$ and $\pi_2(1670)$.
- Full PWA (17 waves): first time observation of $a_1(1260)$ in photoproduction.
- No signal of $\pi_1(1600)$ photoproduction.

C.Bookwalter (FSU)



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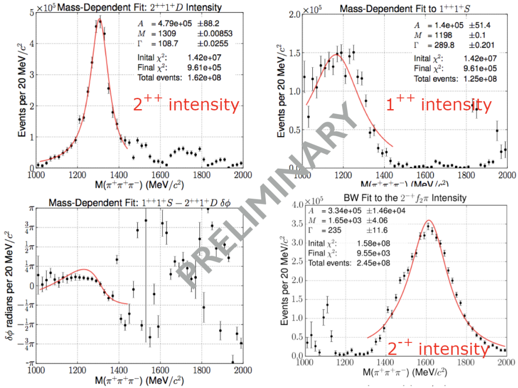

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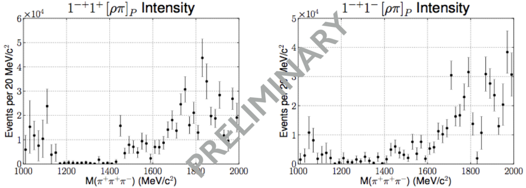
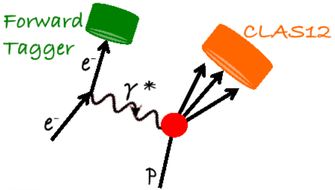


From C. Bookwalter (FSU) PhD thesis. Full paper (A. Tsaris et al) submitted to PRL.

MesonEx (E12-12-005) in Hall-B at Jefferson Laboratory

Meson Spectroscopy program with quasi-real photons: low Q^2 electron scattering on a hydrogen target.

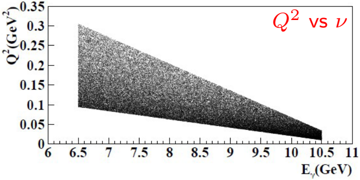


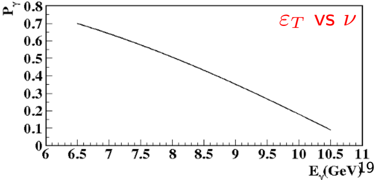
Goals:

- Measure the light-quarks mesons spectrum in the mass range 1.0 - 3.0 GeV
- Determine masses and properties of rare $q\bar{q}$ states
- Search for **exotic mesons**

Low Q^2 electron scattering:

- Provides a high-flux of high-energy, linearly polarized, quasi-real photons.
- Complementary and competitive to real photo-production
- Virtual photon kinematics and polarization determined event-by-event measuring scattered electron variables





Experimental technique: coincidence measurement between CLAS12 (final state hadrons) and Forward Tagger facility (low-angle scattered electron)

CLAS12 / Forward tagger detectors

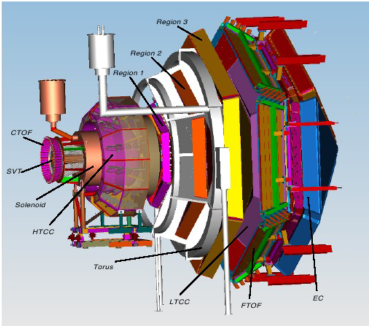
CLAS12: multi-purpose, large acceptance, detector optimized for multi-particles final states (charged/neutrals)

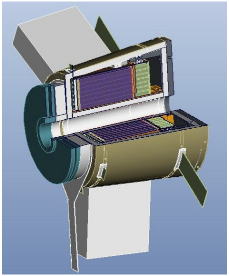
- Nominal luminosity: $\mathcal{L} = 10^{35} cm^{-2} s^{-1}$
- Charged particles tracking: toroidal magnet + drift chambers system
- Particle ID: TOF, Cerenkov, RICH
- Neutral particles: lead/plastic scintillator calorimeter

Forward tagger: forward spectrometer optimized for detection of e^- scattered at low angle.

- **Lead-tungstate calorimeter (FT-Cal):** measure scattered electrons energy ($\sigma_E \simeq \%$)
- **Hodoscope (FT-Hodo):** distinguish photons from electrons.
- **Tracker (FT-Trck):** determine the electron scattering plane.

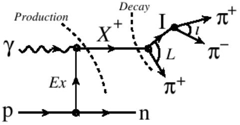
Nominal acceptance: $2.5° < \theta_e < 4.5°$, $0.5 < E_e(GeV) < 4.5$





MesonEx: expected results. Benchmark reaction: $\gamma p \to n\pi^+\pi^+\pi^-$ MC study

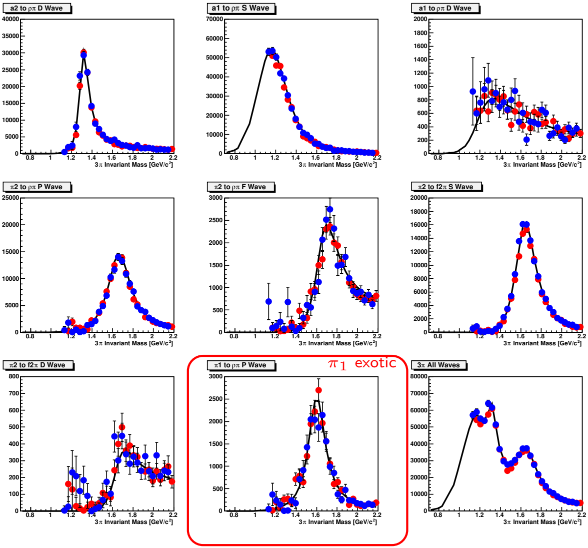
Isobar model for 3-pions production, $\sigma_{Tot} \simeq 10\ \mu$barn



State	J^{PC}	L	Decay Mode
$a_1\,(1260)$	1^{++}	D	$\rho\pi$
$a_2\,(1320)$	2^{++}	D	$\rho\pi$
$\pi_2\,(1670)$	2^{-+}	P	$\rho\pi$
$\pi_2\,(1670)$	2^{-+}	F	$\rho\pi$
$\pi_2\,(1670)$	2^{-+}	S	$f_2\pi$
$\pi_2\,(1670)$	2^{-+}	D	$f_2\pi$
$\pi_1\,(1600)$	1^{-+}	P	$\rho\pi$

- 3π channel PWA feasible in MesonEx
- Sensitivity to $\pi_1(1600)$: $\sigma \geq 0.01\sigma_{Tot}$
- Leakage contribution to exotic waves from others: $< 1\%$

Black: generated, Red: t=-0.5 GeV^2, Blue: t=-0.2 GeV^2 (D. Glazier, U. Glasgow)



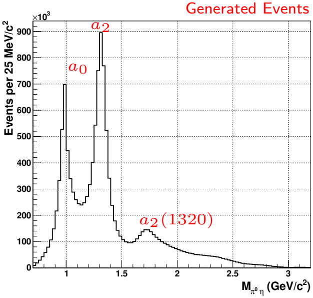
MesonEx: expected results. Benchmark reaction $\gamma p \to p\pi^0\eta$ MC study

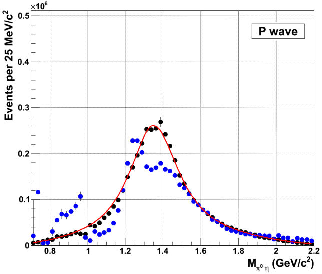
Ad-hoc model for reaction cross-section:

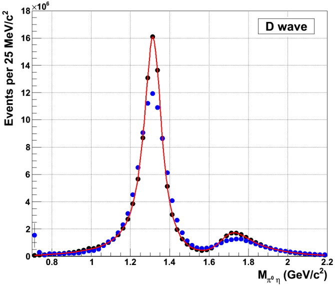
- Known resonances: $a_0(980)$, $a_2(1320)$, $a_2(1700)$
- Exotic contribution: $\pi_1(1400)$
- Large-$M_{\pi^0\eta}$: double-Regge exchange

Results:

- Non-exotic contributions properly reconstructed from PWA procedure
- Sensitivity to $\pi_1(1400)$ signal down to 5% of dominant $a_2(1320)$ signal







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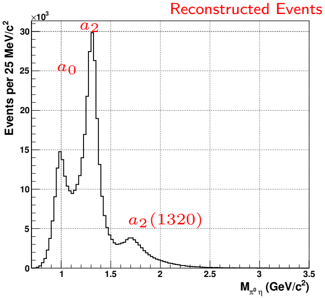
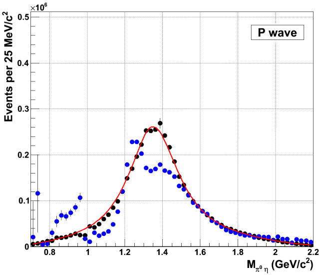
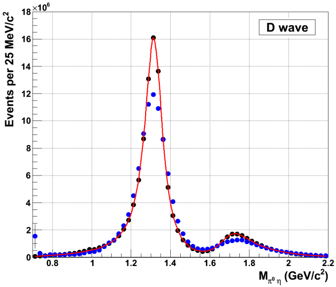




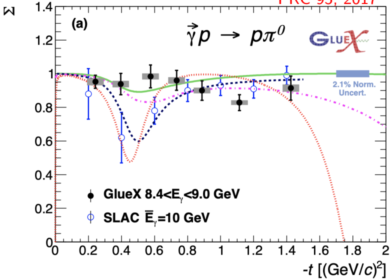


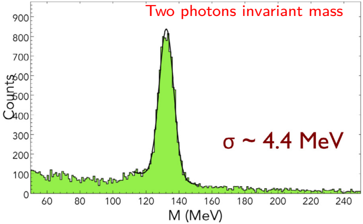
MesonEx: π^0 photo-production

Motivation: day-0 analysis, involving only the FT detector. This will allow to solve the SLAC/GlueX tension on Σ.

- Reaction: $ep \to e'\pi^0(p)$: measure e' and two photons in FT, reconstruct proton via missing mass. $E_e = 10.6$ GeV
- Observables: Σ, $d\sigma/dt$ (also vs Q^2), σ_{TL} (not available in photoproduction.
- Status: analysis in progress exploiting the full CLAS12 RG-A 2018/2019 dataset (L. Biondo, Messina U.).

PRC 95, 2017

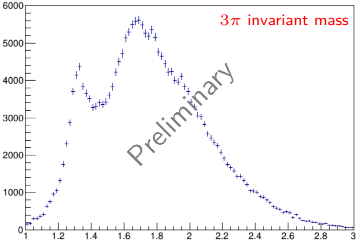


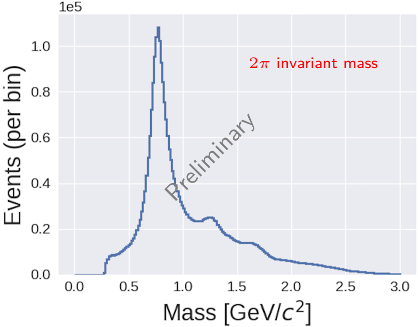


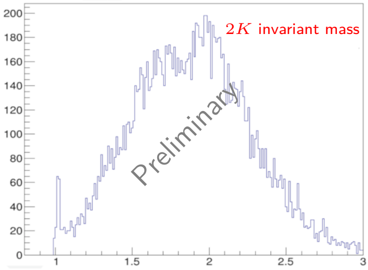
MesonEx: multi-particle final states

Day-1 analysis, core MesonEx program. All analysis are currently "work-in-progress".

- 2π analysis (A. Thornton, Glasgow U.): $ep \to e'\pi^+\pi^-(p)$
- 3π analysis (R. Wishart, Glasgow U.): $ep \to e'\pi^+\pi^+\pi^-(n)$
- $2K$ analysis (M. Nicol, York U.): $ep \to e'pK^+K^-(p)$







LHCB hidden-charm pentaquark

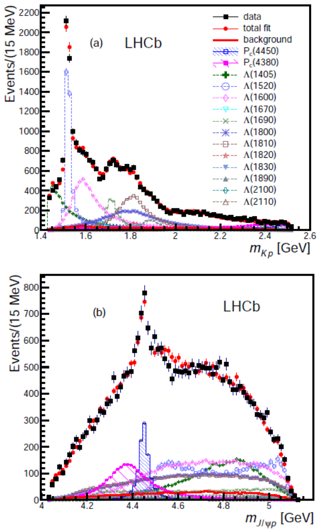
LHCb in 2015 announced[2] the discovery of two exotic structures in the J/ψ - p channel: $P_c(4380)$ and $P_c(4450)$, by measuring the decay $\Lambda_b^0 \to pJ/\psi K^-$.
They claimed that the minimum quark content is $c\bar{c}uud$.
Widths:

- $P_c(4450)$: $\Gamma = 39$ MeV
- $P_c(4380)$: $\Gamma = 205$ MeV

Quantum numbers (PWA most probable solution)

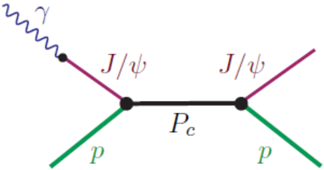
- $P_c(4450)$: $J_P = \frac{5}{2}^-$
- $P_c(4380)$: $J_p = \frac{3}{2}^+$

Altough: *"Acceptable solutions are also found for additional cases with opposite parity"*



[2] Phys. Rev. Lett. **115**, 072001 (2015)

Hidden-charm pentaquark photo-production



A p-J/ψ resonance would apper as an $s - channel$ resonance in the direct photo-production reaction: $\gamma p \to pJ/\psi$. $M_R = \sqrt{s} = M^2 + 2E_\gamma M$

$M_R \simeq 4.4$ GeV $\to E_\gamma \simeq 10.1$ GeV

"Naive" cross-section estimate ingredients[3]:

- Breit-Wigner *elastic* cross-section
- Vector Meson Dominance

$$\sigma(W) = \frac{2J+1}{4}\frac{4\pi}{k_i^2}\frac{B_{in}B_{out}\Gamma^2/4}{(W-M_R)^2+\Gamma^4/4}$$

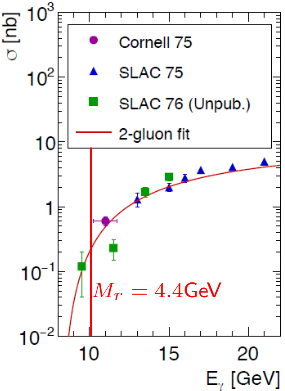
Vector Meson Dominance:

$$B_{in} = (e/f_V)^2 B_{out}(k_{in}/k_{out})^{2L+1}$$

Cross-section estimate:

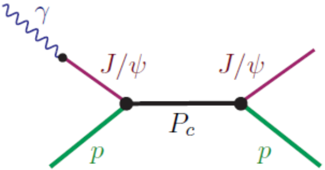
$P_c(4380)$: 1.5 μbarn $< \sigma_0/(B^2_{out}) <$ 50 μbarn

$P_c(4450)$: 12 μbarn $< \sigma_0/(B^2_{out}) <$ 360 μbarn



[3] M. Karliner and J.L. Rosnerbz, arXiv:1508.01496

Hidden-charm pentaquark photo-production



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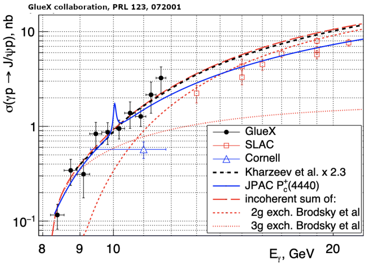


Recent result from GlueX collaboration: no p-J/ψ resonance seen at $M = 4.44$ GeV

[3] M. Karliner and J.L. Rosnerbz, arXiv:1508.01496

Hall-B measurement

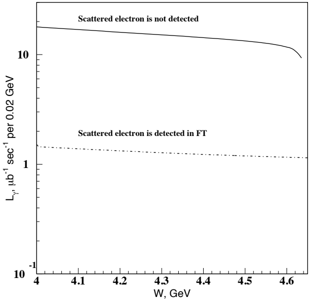
Use CLAS12 + Forward tagger detector for p-J/ψ quasi-real photo-production with two **complementary** techniques:

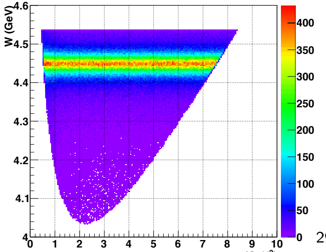
Untagged photo-production

- Scattered electron at $\theta_e \simeq 0^\circ$ not detected
- Measure final state p and e^+e^- from J/ψ decay with CLAS12
- Higher luminosity, lower W resolution.

Tagged photo-production

- Scattered electron detected in Forward Tagger, $2.5^\circ < \theta_e < 4.5^\circ$
- Measure in coincidence final state p and/or and e^+e^- from J/ψ decay with CLAS12
- p-J/ψ invariant mass W measured as missing mass on scattered e^- in Forward Tagger
- Lower luminosity, higher W resolution.



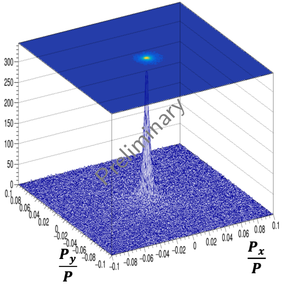


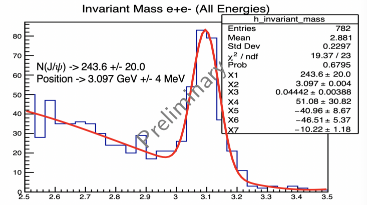
Hall-B measurement: untagged production

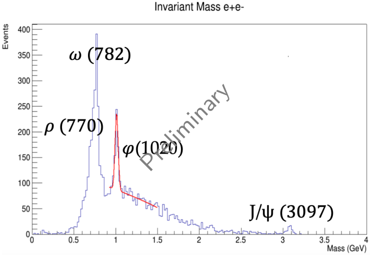
Reaction: $ep \to pe^+e^-(e')$ - scattered e' at $\theta \simeq 0^\circ$, undetected.

- Selection cuts based on transverse missing momentum, Q^2, and missing mass. Optimal cut values determined using a boosted decision tree-based ML method.
- Clear evidence for light vector mesons production (ρ, ω, ϕ) - will be used as reference to check normalization and validate results.
- J/ψ signal is well visible: $\simeq$ 240 exclusive events (full RG-A data)

J. Newton, Old Dominion University







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R. Tyson, Glasgow U.

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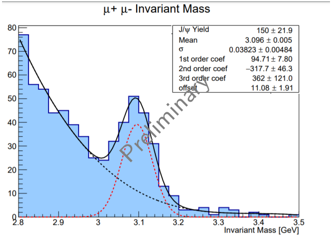
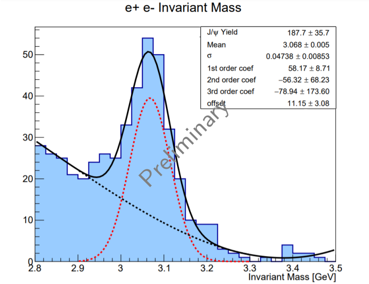
Other on-going analysis exploiting the $\mu^+\mu^-$ channel and the e^+e^- channel on deuteron.





Conclusions

- Experimental investigation of "exotic" hadrons is a powerful technique to answer to fundamental questions in QCD:
  - What is the origin of color confinement?
  - What is the role of gluons inside hadrons?
- Photoproduction is a very valuable technique to produce exotic mesons: unique role of fixed-target, high-acceptance, medium-energy experiments.
- CLAS at 6 GeV performed a first set of photo-production measurements - recent results from neutral channels (a_2, f_2), full PWA of 3π final state submitted for publication.
- CLAS12 - MesonEx program: low-Q^2 electroproduction as a source of a high-intensity quasi-real photon beam. Starting from simple π^0 exclusive production, moving forward to multi-particle final states.

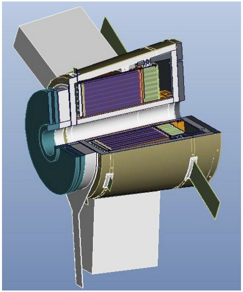
Backup slides

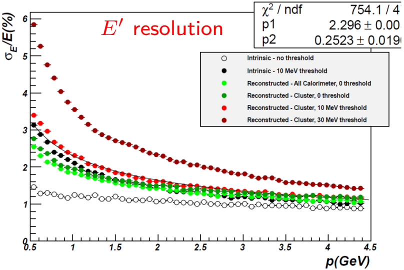
3 components:

- **Lead-tungstate calorimeter (FT-Cal):** measure the energy of scattered electrons with few % resolution.
- **Hodoscope (FT-Hodo):** distinguish photons from electrons.
- **Tracker (FT-Trck):** determine the electron scattering plane.

Nominal design parameters:

	Range
$E_{e'}$	0.5 - 4.5 GeV
$\theta_{e'}$	2.5^o - 4.5^o
$\phi_{e'}$	0° - 360°
E_γ	6.5 - 10.5 GeV
P_γ	70 - 10 %
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV





The Forward Tagger Facility

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