Photoproduction of exotic hadrons

Exotic mesons photoproduction + photoproduction of LHCB pentaquarks

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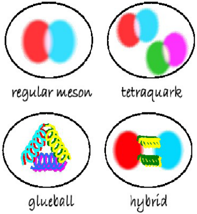
Introduction

Exotic mesons

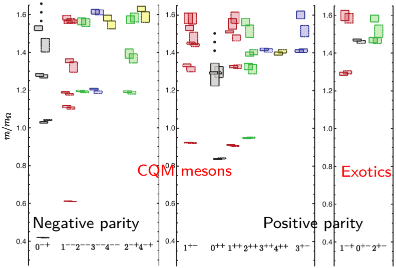
QCD does not prohibit the existence of unconventional meson states such as hybrids ($q\bar{q}g$), tetraquarks ($q\bar{q}q\bar{q}$), and glueballs.



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.

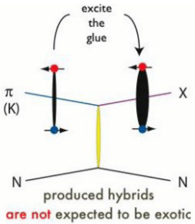


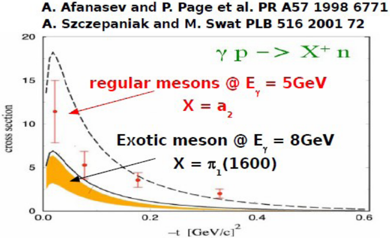
[1] J. J. Dudek et al, Phys. Rev. D82, 034508 (2010)

Exotic mesons photoproduction

Traditionally, meson spectroscopy was studied trough different experimental techinques: **peripheral hadron production**, $N\overline{N}$ annihiliation, ...
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





Results from past experiments

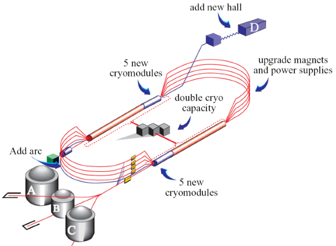
See P. Eugenio talk on Thursday!

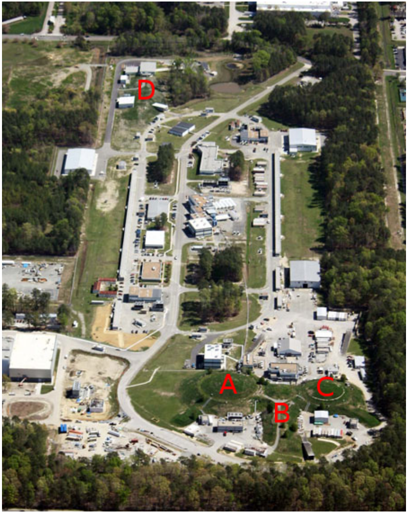
Jefferson Laboratory

Jefferson Laboratory (Newport News, VA, USA): home of the Continuous Electron Beam Accelerator Facility (CEBAF)

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 $\simeq 80\%$





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.

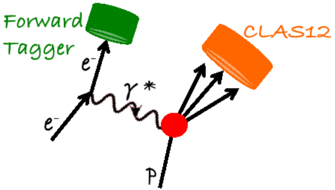
Goals:

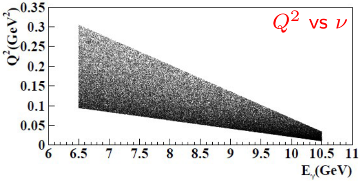
- Measure the light-quarks mesons spectrum in the mass range 1.0 - 3.0 GeV
- Determine masses and properties of rare $q\overline{q}$ states
- Search for **exotic mesons**

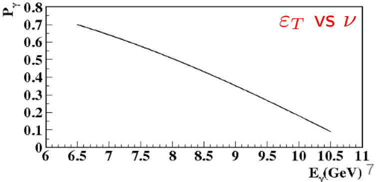
Low Q^2 electron scattering:

- 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

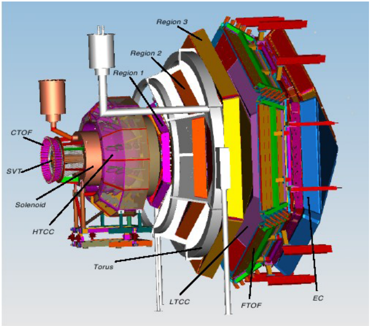
CLAS12: multi-purpouse, large acceptande, detector optimized for multi-particles final states (charged/neutrals)

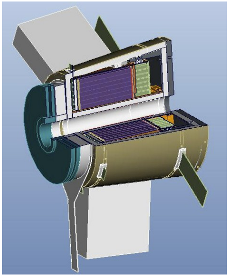
- Nominal luminosity: $\mathcal{L} = 10^{35} cm^{-2} s^{-1}$
- Charged particles tracking: toroidal magnet + drift chambers system
- Particle ID: TOF, Cerenkov, RICH
- Neutral particles: lead/plastic scintillator calorimeter

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.

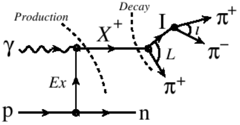
Nominal acceptance: $2.5^\circ < \theta_e < 4.5^\circ$, $0.5 < E_e(GeV) < 4.5$





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

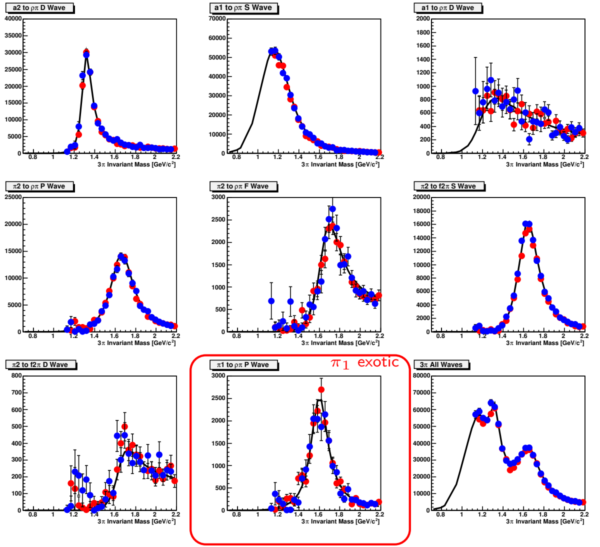
Isobar model for 3-pions production, $\sigma_{Tot} \simeq 10\ \mu$barn



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



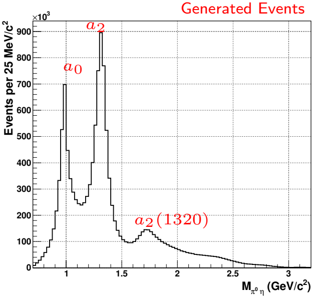
MesonEx: expected results. Benchmark reaction $\gamma p \to p\pi^0\eta$ MC study

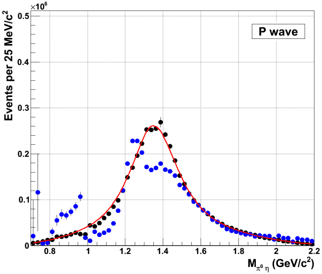
Ad-hoc model for reaction cross-section, $\sigma_{tot} \simeq 1\mu barn$:

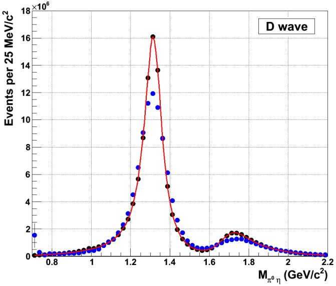
- Known resonances: $a_0(980)$, $a_2(1320)$, $a_2(1700)$
- Exotic contribution: $\pi_1(1400)$
- Large-$M_{\pi^0\eta}$: double-Regge exchange

Results:

- Average acceptance: 3%, 180 k events/day
- 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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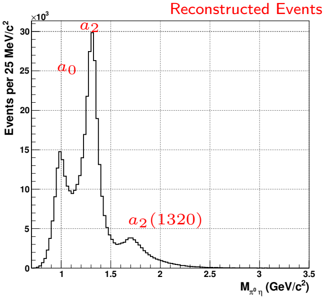
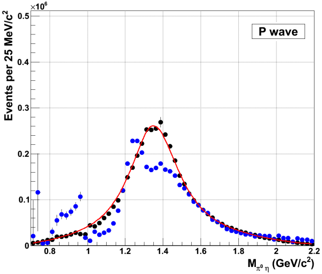
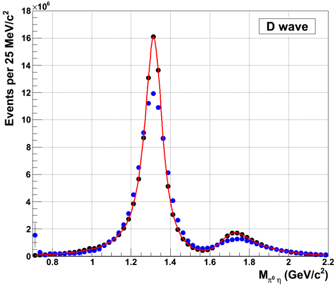




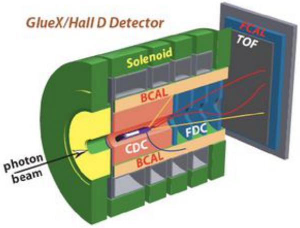


The GlueX experiment in Hall-D at Jefferson Laboratory

Photo-production experiment (real photons) on a fixed LH_2 target

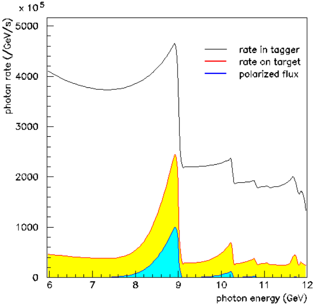
GlueX detector:

- Hermetic detector optimized for multi-particle final state measurement
- Charged particle tracking: 2.2 T solenoidal field + drift chambers (central/forward)
- Calorimetry: FCAL (lead glass) / central (lead + fibers)
- Particle ID: Time of flight, Start counter (future upgrade: DIRC detector)



Hall-D photon beam: coherent Bremmstrahlung on diamond target

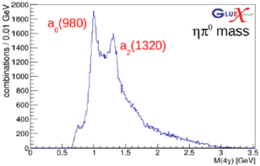
- 12 GeV e^- beam, 0.05 - 2.2 μA
- Coherent peak 8.4 - 9 GeV, $\mathcal{P} \simeq 40\%$
- Tagger spectrometer (Elbek-type) $\sigma_E/E \simeq 0.1\%$
- Pair spectrometer: $\sigma_\mathcal{P}/\mathcal{P} \simeq 5\%$

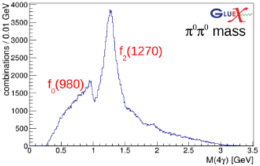


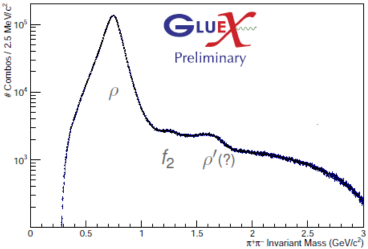
GlueX recent results[2]

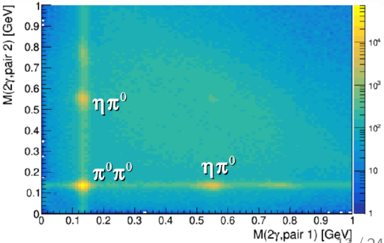
GlueX 2016 spring run: 12 GeV beam - 60 days GlueX engineering run. Data for early physics results. Promising preliminary results for exotic mesons spectroscopy:

- $\pi\pi$ spectroscopy
- Multi-photon final states (golden channel $\pi^0\eta$: 4γs)









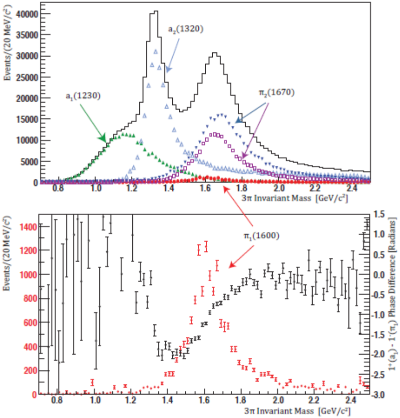
[2] Plots from A. Austregelsilo talk at PWA8/Athos4

GlueX future perspectives

GlueX physics runs:

- GlueX-I: 2017-2018. Started in February, 10x more data than 2016 planned: data for physics analysis.
- GlueX-II: 2019+. Upgraded detector (better PID), higher luminosity

MC study of benchmark reaction $\gamma p \to n\pi^+\pi^+\pi^-$



- PWA MC study performed with exotic state strenght: $\sigma_{\pi 1} = 1.6\% \cdot \sigma_{3\pi}$
- Thanks to the high acceptance and good resolution of the GlueX detector a complete Partial Wave Analysis is feasible.
- The contribution of small signals to the invariant mass spectrum can be clearly isolated and measured.

LHCB hidden-charm pentaquark

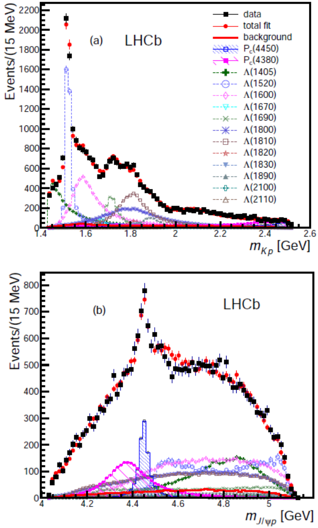
LHCb in 2015 announced[3] the discovery of two exotic structures in the J/ψ - p channel: P_c(4380) and P_c(4450), by measuring the decay $\Lambda_b^0 \rightarrow pJ/\psi K^-$.
They claimed that the minimum quark content is $c\bar{c}uud$.
Widths:

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

Quantum numbers (PWA most probable solution)

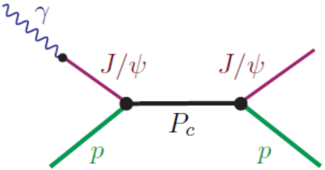
- P_c(4450): $J_P = \frac{5}{2}^-$
- P_c(4380): $J_p = \frac{3}{2}^+$

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



[3] 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: $\gamma p \to pJ/\psi$. $M_R = \sqrt{s} = M^2 + 2E_\gamma M$
$M_R \simeq 4.4\text{GeV} \to E_\gamma \simeq 10.1\text{GeV}$

"Naive" cross-section estimate ingredients[4]:

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

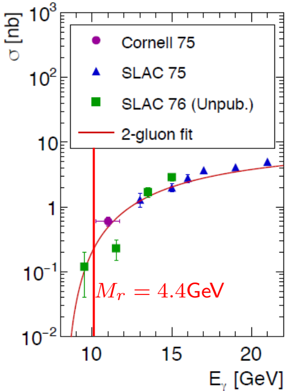
$$\sigma(W) = \frac{2J+1}{4}\frac{4\pi}{k_i^2}\frac{B_{in}B_{out}\Gamma^2/4}{(W-M_R)^2+\Gamma^4/4}$$

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

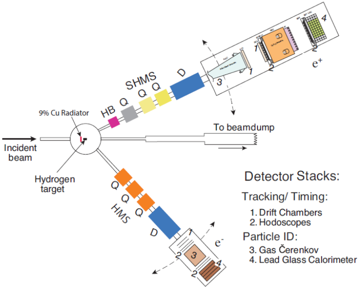


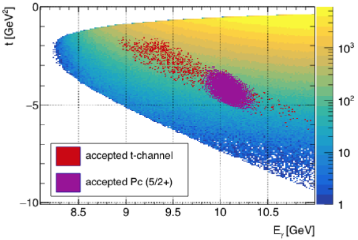
[4] M. Karliner and J.L. Rosnerbz, arXiv:1508.01496

Hall-C proposal[5]

Measure the **elastic** J/ψ photo-production on a hydrogen target trough an **untagged** real photon beam

- Bremmstrahlung photon beam: 11 GeV, 50 μA e^- beam impinging on a 9% copper radiator.
- e^+e^- pairs from J/ψ decay measured in coincidence trough the two high-momentum spectrometers, HMS and SHMS. Spectrometers settings optimized to enanhce $s-$channel resonance production over $t-$channel diffractive background
- Invariant mass W of p-J/ψ system reconstructed assuming elastic production.





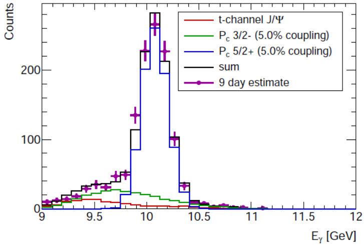
[5] PR12-16-007, Z. E. Meziani *et al.*

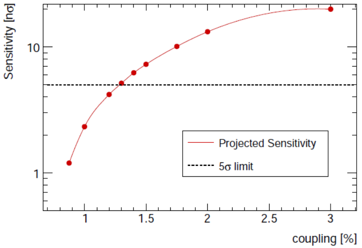
Hall-C proposal

Expected results from 9 days of running:

- J/ψ mass reconstructed with $\sigma \simeq 5$ MeV, p-J/ψ invariant mass W resolution $\sigma_W \simeq 10$ MeV
- Discovery sensitivity for $BR(P_c(4450) \to pJ/\psi) > 1.25\%$, for $J^P = 5/2^+$
- The Hall-C experiment can measure the resonance line-shape (W-scan), but can't determine uniquely J^P quantum numbers due to the very limited angular acceptance

Proposal approved as "high-impact" experiment by JLab PAC44 (2016), with "A" rating.





Hall-B proposal

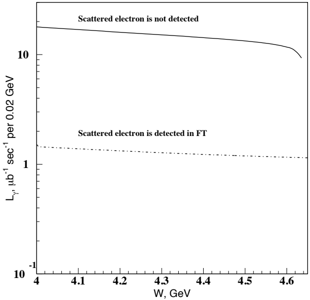
Use CLAS12 + Forward tagger detector for p-J/ψ quasi-real photo-production with two **complementary** techniques:

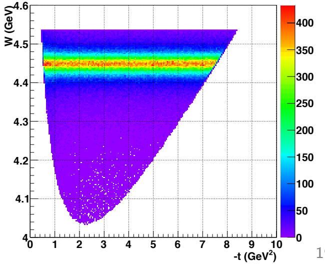
Untagged photo-production

- 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.



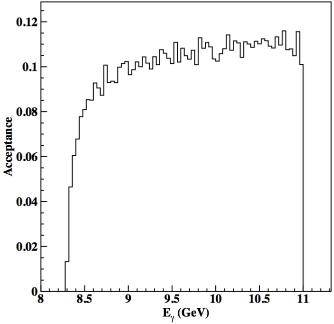


Hall-B proposal

Full simulation of reaction performed considering $J/\psi \to e^+e^-$ decay, for un-tagged and tagged measurement

Results:

- Un-tagged measurement: CLAS12 acceptance for p, e^+, e^- measurement is $\simeq 10\%$. Resolution: $\sigma_W \simeq 14$ MeV
- Tagged measurement: different measurement strategies are possible. Acceptance for measurement of any two charged particles is $\simeq 50\%$. Resolution: $\sigma_W \simeq 4$ MeV
- On-going studies to exploit other J/ψ decay modes in tagged measurement, selecting J/ψ via proton missing mass



Experiment status:

- p-J/ψ photo-production measurement included in physics program of already-approved experiments: E12-12-001 and E12-11-005 (MesonEx)
- Results of detailed studies summarized in run-group proposal, submitted to JLab PAC45

Foreseen P_c yield, for BR($P_c \to p - J/\psi = 1\%$)

	Un-tagged	Tagged	Tagged (all)
$P_c(4380)$	24-750	10-330	130-3900
$P_c(4450)$	35-1100	14-440	180-5700

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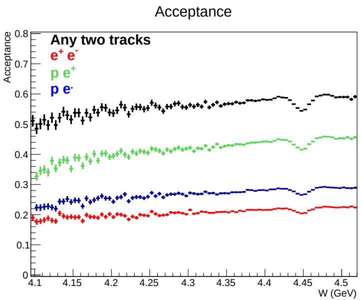

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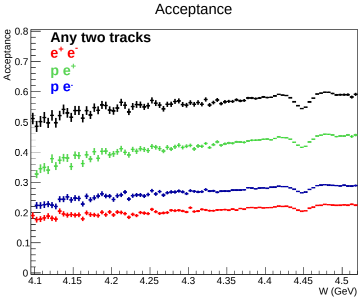

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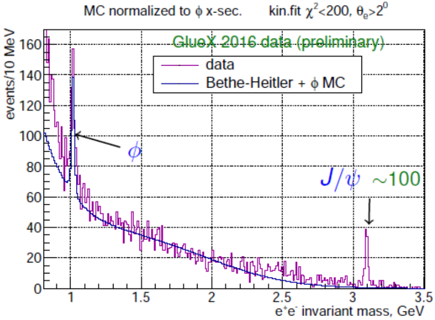
Hall-D recent results[6]

GlueX recently released preliminary results for the measurement of J/ψ photo-production near threshold

- Full 2016 statistics
- Exclusive events, pe^+e^-.
  Lepton-PID trough EM calorimeters

Future plans: add the 2017 data and study the energy-depedence of cross-section to search for LHC$_b$ pentaquarks



[6] From E. Chudakov talk at ECT*, Trento, April 2017

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?
- With the advent of the 12 GeV era at Jefferson Laboratory a new generation of meson spectroscopy experiments starts: **GlueX** in Hall D and **MesonEx** in HallB.
- The goal of both is to use (quasi)-real photo-production to investigate the meson spectrum in the GeV energy range, looking for rare $q\bar{q}$ and non-CQM states.
- Recent LHC$_b$ claim of hidden-charm pentaquarks in the $p - J/\psi$ system triggered the idea of studying these resonances in $s-$channel photoproduction: complementary measurements will be performed in Hall-B, Hall-D and Hall-C.

Backup slides

Rates

Low Q^2 limit $\rightarrow$ the unpolarized reaction cross-section is: $d\sigma(\Omega', E') = \sigma_\gamma(\nu) \cdot d\Gamma$

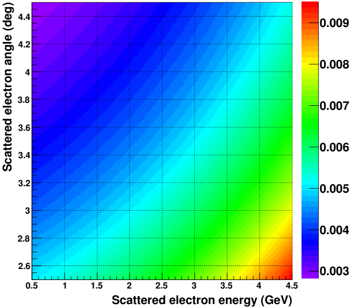
Virtual photon flux:

$$d\Gamma(\Omega', E') = \frac{\alpha}{4\pi^2} \frac{E'}{E_0} \frac{\nu}{Q^2} \left[\frac{(2E_0 - \nu)^2}{\nu^2} + 1 \right] d\Omega' \, dE'$$

Integration over FT acceptance:

- $2.5^\circ < \theta_e < 4.5^\circ$
- $0.5 < E_e(GeV) < 4.5$
- Assuming constant $\sigma(\nu)$

$$\Gamma \simeq 0.04$$

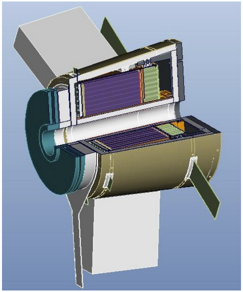


Equivalent photon flux at $\mathcal{L} = 10^{35} cm^{-2} s^{-1}$: need to assume a certain target lenght for photo-production case. Consider $d = 50$ cm. Then:

$$\begin{aligned} R_{electron} &= \mathcal{L} \cdot \Gamma \cdot \sigma(\nu) \\ R_{photon} &= \Phi_\gamma \cdot N_{Av} \rho \cdot d \cdot \sigma(\nu) \\ \Phi_\gamma &\simeq 10^9 \gamma / s \end{aligned}$$

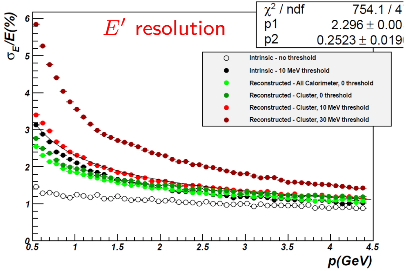
3 components:

- **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



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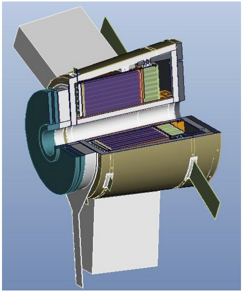

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