Hall D Spectroscopy

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JLab, 2012

Jefferson Lab

Hall D

- Hall D - a new hall
  - Under construction, funded by the DOE 12 GeV Upgrade project
- Physics with high intensity polarized photon beams
  - *Experiment GlueX: search for exotic hybrid mesons*
  - Radiative widths of pseudoscalars
  - Other topics in preparation
- A new beamline and a new large acceptance detector
  - Coherent Bremsstahlung $\Rightarrow$ linearly polarized photons
  - Large solenoidal spectrometer $\Rightarrow$ a uniform acceptance
  - Fully pipelined electronics $\Rightarrow$ very high trigger/DAQ rate

Outline

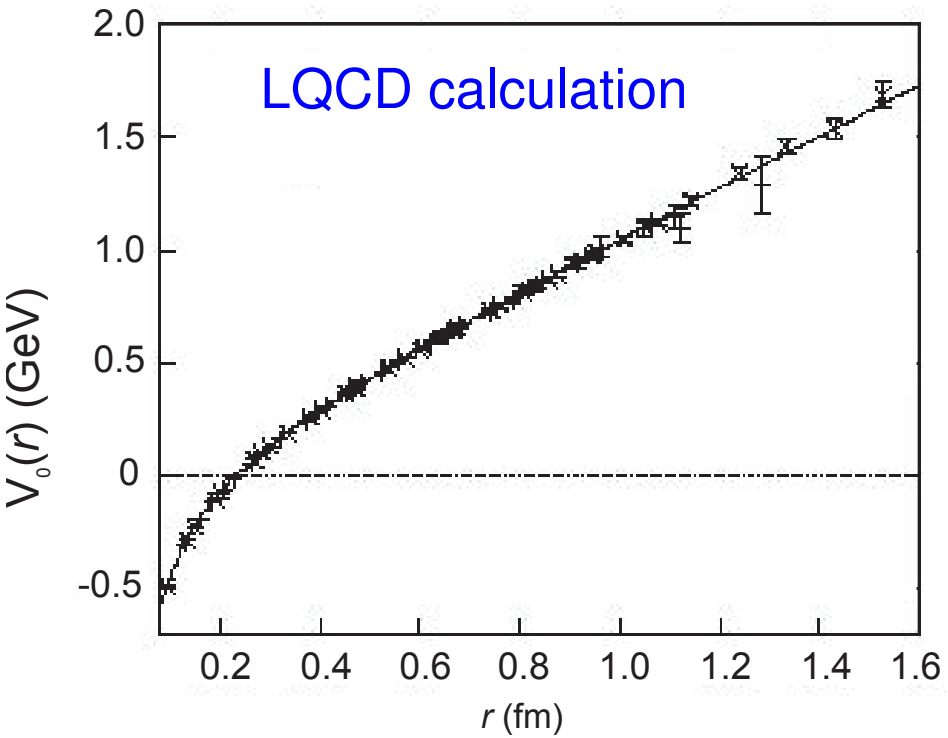
1. Spectroscopy of hypothetical hybrid mesons
   - Theoretical motivations
   - Experimental status
2. Experimentt GlueX in Hall D
   - Approach, requirements
   - Hall D construction status

Gluonic Field in a $\overline{q}q$ pair

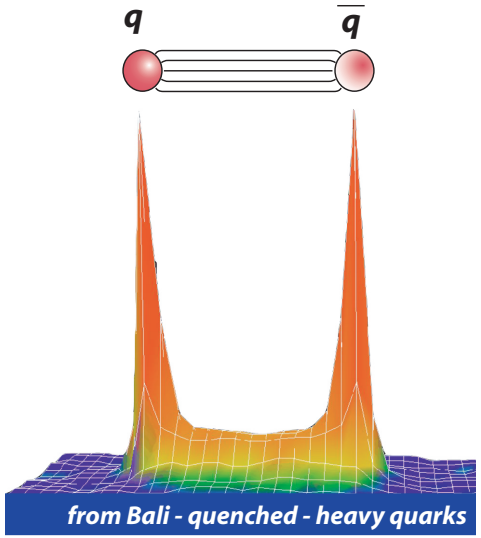
$\overline{c}c$ spectra suggested a QCD potential:

$$V(r) \propto -\frac{a}{r} + \kappa r$$

Linear term $\Rightarrow$ *confinement*



LQCD quenched and unquenched reproduce the shape of the potential



Quenched LQCD, heavy quarks

- Gluons are self-interacting
- Flux tube model
  Nambu 1970, Isgur, Paton 1983
  Bernard et al. 2004 and others
- $V(r) = \kappa r$
- Non-perturbative
- Explanation of confinement

$\overline{q}q$ quantum numbers

Naive quark model:

- Mesons are $\overline{q}q$, quarks are $J = 1/2$ fermions
- No gluonic degrees of freedom
- Restrictions on the quantum numbers: J^{PC}:
  $P = (-1)^{L+1}$, $C = (-1)^{L+S}$

J	$--$	$++$	$-+$	$+-$
0		0^{++}	0^{-+}	
1	1^{--}	1^{++}		1^{+-}
2	2^{--}	2^{++}	2^{-+}	
3	3^{--}	3^{++}		3^{+-}

$q\overline{q}$ QN "exotic" QN

$\overline{q}q$ quantum numbers

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2	2^{--}	2^{++}	2^{-+}	$\mathbf{2^{+-}}$
3	3^{--}	3^{++}	$\mathbf{3^{-+}}$	3^{+-}

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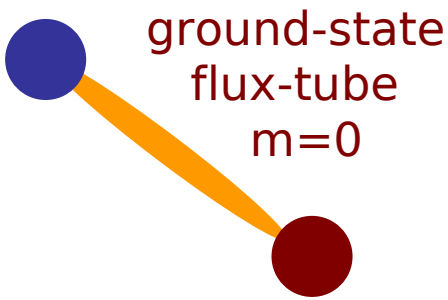
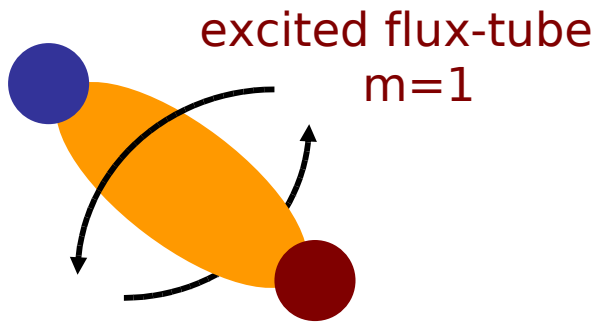
Gluonic excitations and meson quantum numbers





J^{PC}

$P = (-1)^{L+1}$, $C = (-1)^{L+S}$

The lowest tube excitation $L = 1$:

J^{PC} : 1^{+-} or 1^{-+}

Conventional mesons

Regular quantum numbers:

0^{-+}	$S = 0, L = 0$	π, η, K
1^{--}	$S = 1, L = 0$	ρ, ω, ϕ, K^*
1^{+-}	$S = 0, L = 1$	h_1, b_1, K_1..
0^{++}	$S = 1, L = 1$	$a_\circ, f_\circ, K^*_\circ$
1^{++}	$S = 1, L = 1$	a_1, f_1, K^*_{1A}
2^{++}	$S = 1, L = 1$	a_2, f_2, K^*_2

etc.

Hybrid mesons

Regular quantum numbers:

1^{++}	$S = 0, L = 0$ ...	
1^{--}	$S = 0, L = 0$ ...	

Exotic quantum numbers:

1^{-+}	$S = 1, L = 0$	π_1, η_1...
2^{+-}	$S = 1, L = 0$	b_2, h_2...
0^{+-}	$S = 1, L = 0$	$b_\circ, h_\circ$...

etc.

Are there hybrids mesons?

Do they exist and are they detectable?

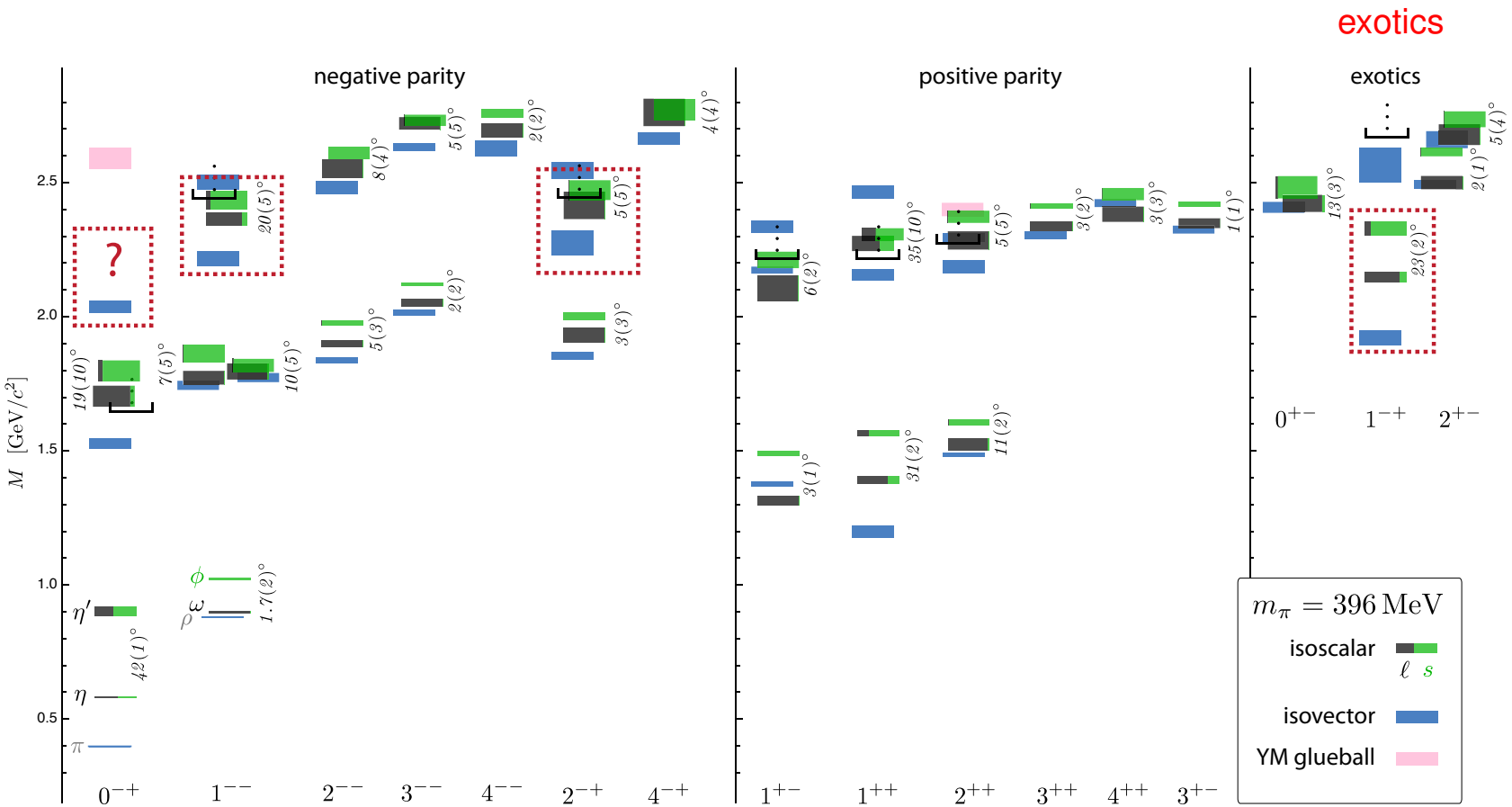
- Signatures ?
  - Exotic quantum numbers: - an excellent signature!
  - Regular quantum numbers: most likely difficult to identify a hybrid
  - Experimental identification of the QN:
    Partial Wave Analysys (PWA)
    Positive identification as a hybrid is still not trivial, mapping out a number of states would be required
- Masses ?
- Full widths ?

Predictions for hybrid masses and widths

- Mass spectra
  - *Flux-Tube Model*: 8 degenerate nonets $\sim 1.9 GeV/c^2$
    $\underbrace{1^{++}, 1^{--}}_{S=0}, \quad \underbrace{0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}}_{S=1}$
  - *Bag Model*: 1^{-+} lightest multiplet $\sim 1.2 - 1.4 GeV/c^2$
    $1_g^{+-}, 1_g^{-+}$ TE and TM gluons
  - *Constituent gluon*: $1^{-+} \sim 2.1 - 2.4 GeV/c^2$
    1_g^{--} added to $\bar{q}q$ in P state: 1^{-+}, 0^{--}-*unique to this model*
  - *Lattice QCD*: 2011 - rich spectra exotic multiplets $1.8 - 2.8 GeV/c^2$
    more on the results later
- Full widths
  - $1/N_c$ *expansion* T.Cohen PL 427B (1998): similar to regular mesons
  - *Various models*: $0.1 - 0.5 GeV/c^2$
  - *LQCD early esimate* UKQCD PRD 73(2006): $\sim 0.5 GeV/c^2$

Lattice QCD calculations: recent progress

Identifying hybrids in LQCD: *J.Dudek et al PRD 83 (2011); J.Dudek PRD 84 (2011)*

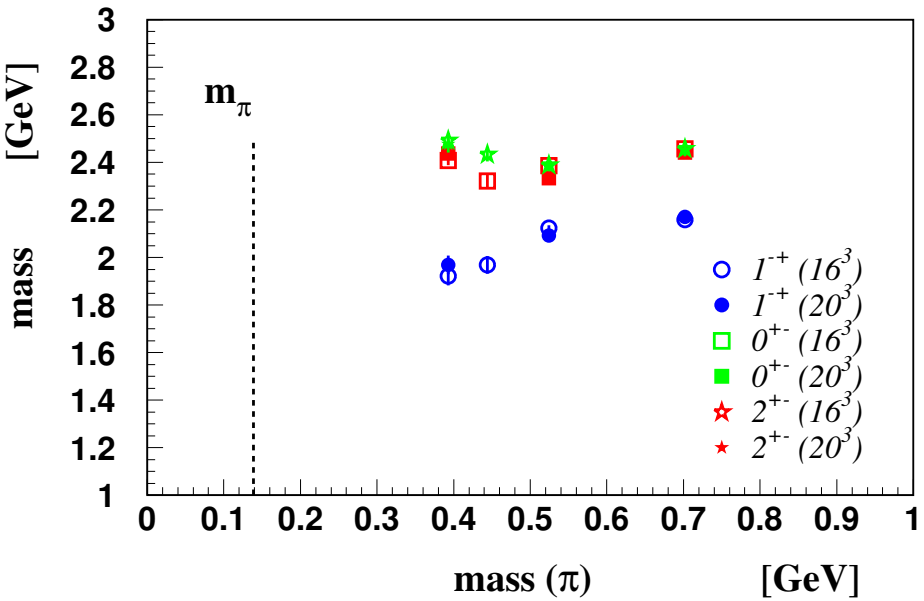


Calculations for $m_\pi \sim 400 MeV$

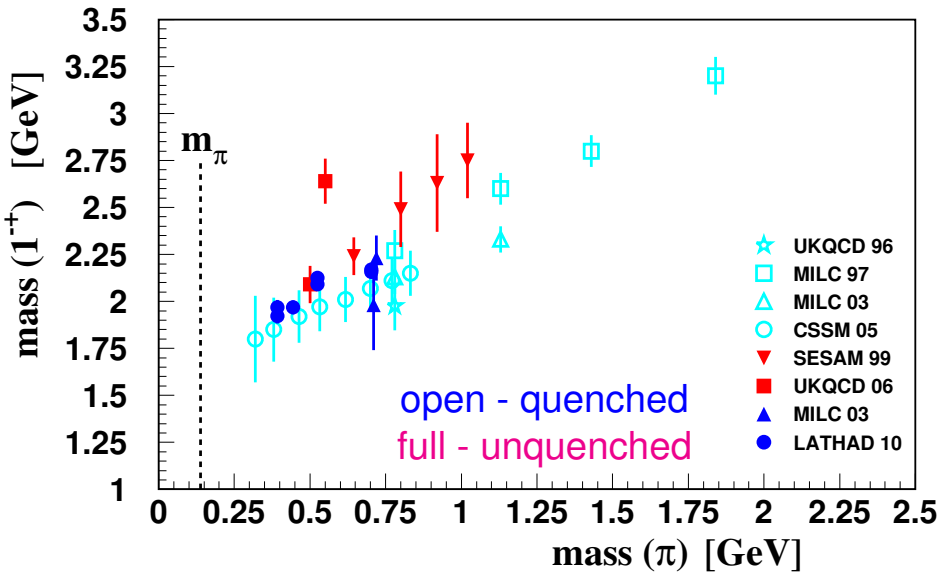
Red boxes - lightest hybrids

Lattice QCD calculations: exotic hybrids

$1^{-+}, 0^{+-}, 2^{+-}$ *Unquenched*



1^{-+} *Quenched and unquenched*



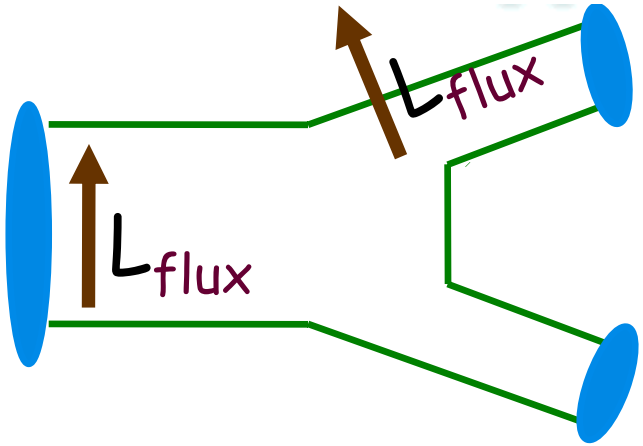
Lattice calculations: nonet 1^{-+} is the lightest ~ 2 GeV/c^2

0^{+-} is the heaviest < 2.8 GeV/c^2 $\Rightarrow$ $E_{beam} > 8$ GeV

No calculations for the decays widths or cross sections so far.

One may expect a progress in a few years!

Flux Tube Model: Decays of Hybrids



The angular momentum of the flux tube stays in one of the daughter mesons.
Rule: 2-body decay to $L = 1$ and $L = 0$

Exotic quantum numbers

1^{-+} $\pi_1 \rightarrow b_1\pi,\ f_1\pi,\ \rho\pi,\ a_1\eta$
1^{-+} $\eta_1 \rightarrow \pi(1300)\pi,\ a_1\pi$

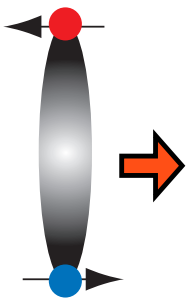
2^{-+} $b_2 \rightarrow a_1\pi,\ h_1\pi,\ \omega\pi,\ a_2\pi$
2^{-+} $h_2 \rightarrow b_1\pi,\ \rho\pi,\ \omega\pi$

0^{+-} $b_\circ \rightarrow \pi(1300)\pi,\ h_1\pi$
0^{+-} $h_\circ \rightarrow b_1\pi,\ h_1\pi$

Mass, model-dependent predictions

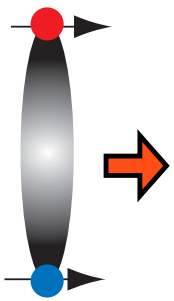
Final states in GlueX:
$(p, n) + 3\pi,\ 4\pi,\ 3\pi\eta,\ 4\pi\eta...$
70% $\geq 1\pi^\circ$
50% $\geq 2\pi^\circ$

Production of Hybrids



$J^{PC} = 1^{--}$ *or* 1^{++}

$\vec{L} = 0,\ \vec{S} = 0$



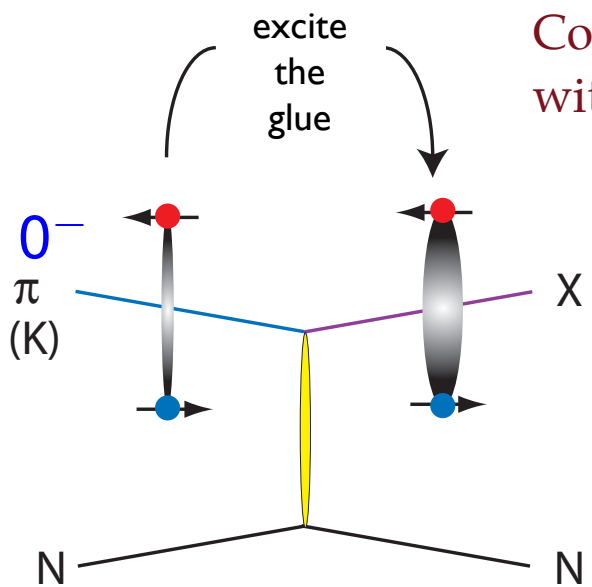
$J^{PC} = 0^{-+}, 1^{+-}, 2^{-+}$

$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$

exotic

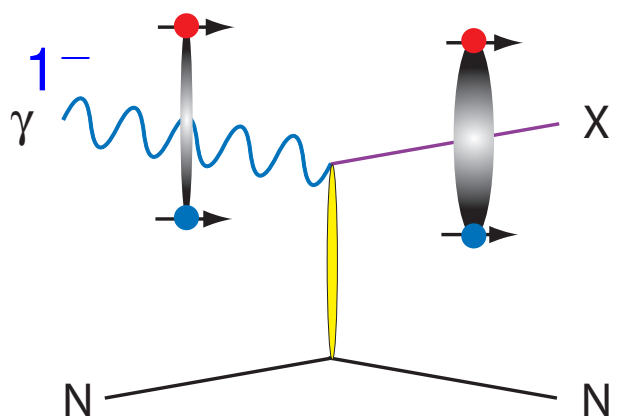
$\vec{L} = 0,\ \vec{S} = 1$

Combine excited glue QN ($J^{PC} = 1^{+-}$ *or* 1^{-+}) with those of the quarks:



produced hybrids

are not expected to be exotic



produced hybrids

can be exotic

Photoproduction and Linear Polarization

Beam: γ vs π

- γ: *exotic* QN without spin flip
- γ: allows linear polarization

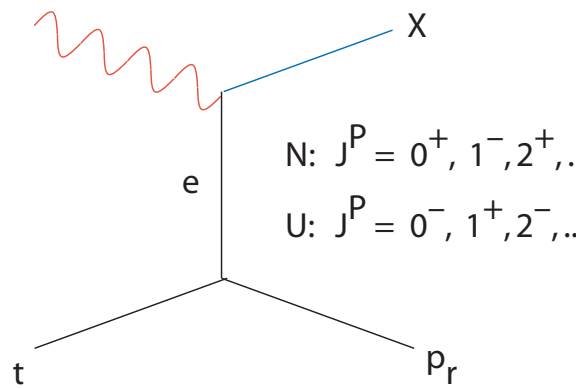
Photon Polarization - how?

- Coherent Bremsstrahlung
- Diamond radiator
- Photon collimation
- Energy selection

Electron energy at JLab

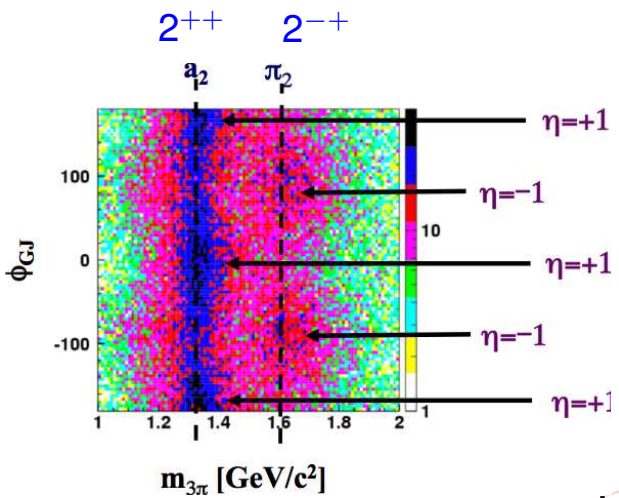
- $E_\gamma > 8$ GeV to see $M_X \sim 2.8$ GeV
- $E_e > 12$ GeV to have $\mathcal{P} > 40\%$

Beam Polarization Effect



Filter on the *naturality*

MC simulation $\gamma p \to 3\pi p$



Experimental Evidence for Exotic Hybrids 1^{-+}

mass	reaction	experiment	mass	width
1400	$\pi^- p \to \eta\pi^\circ n$	GAMS, 100 GeV 1988	1406±20	180± 20
	$\pi^- p \to \eta\pi^- p$	BKEI, 6 GeV 1993	1320± 5	140± 10
	$\pi^- p \to \eta\pi^- p$	MPS, 18 GeV 1997	1370±60	380±100
	$\pi^- p \to \eta\pi^\circ n$	E-852, 18 GeV 2007	1260±40	350± 60
	$\bar{p}p \to \eta\pi^\circ\pi^\circ$	CBAR, 0 GeV 1999	1360±25	360± 80
	$\bar{p}n \to \eta\pi^\circ\pi^-$	CBAR, 0 GeV 1998	1400±30	220± 90
1600	$\pi^- A \to \pi^+\pi^-\pi^- A$	VES, 37 GeV 2000	1610±20	290± 30
		VES, 37 GeV 2005	*none*	
	$\pi^- p \to \pi^+\pi^-\pi^- p$	E-852, 18 GeV 2002	1590±40	170± 60
		E-852, 18 GeV 2006	*none*	
	$\pi^- A \to \pi^+\pi^-\pi^- A$	COMPASS, 190 GeV 2009	1660±60	270± 60
	$\gamma p \to \pi^+\pi^+\pi^- n$	CLAS, 5. GeV 2008	*none*	
	$\pi^- p \to \pi^-\pi^\circ\pi^\circ p$	E-852, 18 GeV 2006	*none*	
	$\pi^- p \to \eta'\pi^- p$	E-852, 18 GeV 2001	1600±40	340± 50
	$\pi^- A \to \eta'\pi^- A$	VES, 37 GeV 2005	1600	300
		GAMS, 100 GeV 2005	1600	300
	$\pi^- p \to \eta\pi^+\pi^-\pi^- p$	E-852, 18 GeV 2004	1710±60	400± 90
	$\pi^- p \to \omega\pi^-\pi^\circ p$	E-852, 18 GeV 2005	1660±10	190± 30
	$\pi^- A \to \omega\pi^-\pi^\circ A$	VES, 18 GeV 2005	1600	300
2000	$\pi^- p \to b_1\pi, f_1\pi$	E-852, 18 GeV 2005	2010±25	230± 80

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	$\pi^- p \to \eta\pi^-$			100
	$\pi^- p \to \eta\pi^\circ$			60
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Signal: solid, seen by several experiments
Interpretation: unclear, but not a hybrid:
1400 dynamic origin; 4-quark state

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Signal: 3π - controversial - leakage from 2^{-+}
new confirmation from COMPASS
$\eta'\pi^-$ - promising
Interpretation: may be a hybrid
1600 needs more analysis and data

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	$\gamma p \to \pi^+\pi^+\pi$			
	$\pi^- p \to \pi^-\pi^\circ\pi$			
	$\pi^- p \to \eta'\pi^-$			
	$\pi^- A \to \eta'\pi^- A$	VES, 37 GeV 2005	1600	300
		GAMS, 100 GeV 2005	1600	300
	$\pi^- p \to \eta\pi^+\pi^-$			400± 90
	$\pi^- p \to \omega\pi^-\pi$			190± 30
	$\pi^- A \to \omega\pi^-\pi$			300
2000	$\pi^- p \to b_1\pi, f$			230± 80

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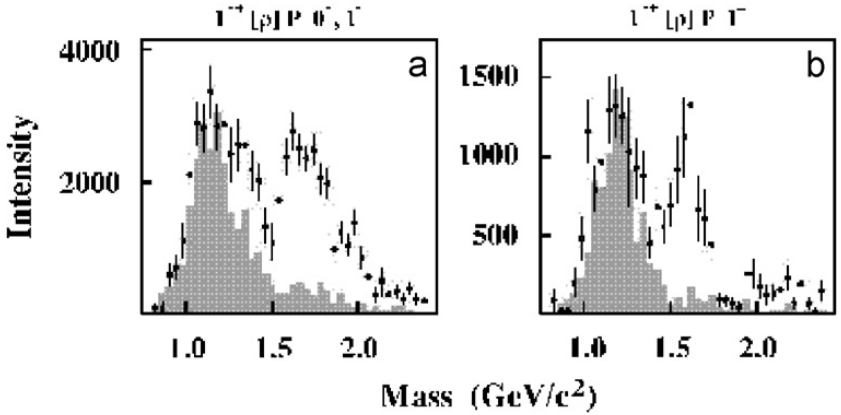
Signal: weak - one experiment only
Interpretation: may be a hybrid
expected decay modes
2000 needs more data

BNL E-852 18 GeV $\pi^- p$ Results on 1^{-+} $\pi_1(1600) \rightarrow \rho\pi$

S.U.Chung et al, PRD65, 2000

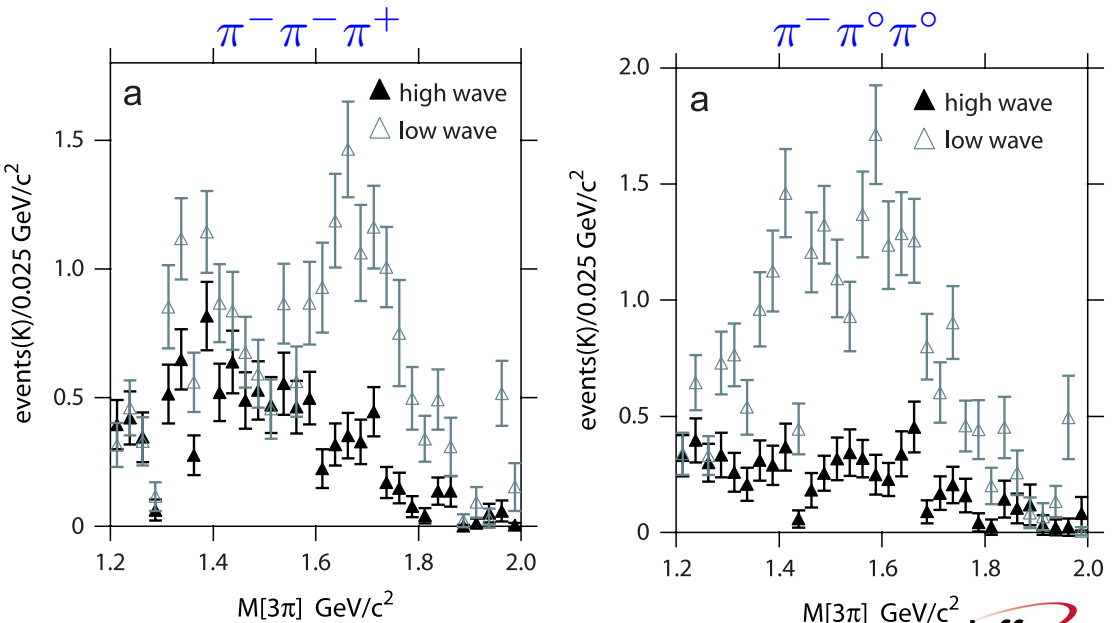
- 250k $\pi^-\pi^-\pi^+$ events
- M=1.59±0.03, Γ=0.17±0.03 GeV/c^2



A. Dzierba et al, PRD73, 2006

- 2.6M $\pi^-\pi^-\pi^+$ events
- 3.0M $\pi^-\pi^\circ\pi^\circ$ events
- "Low" - 20 waves
- "High" - 35 waves
- *no signal*

leakage from $\pi_2(1670)$ 2^{-+}

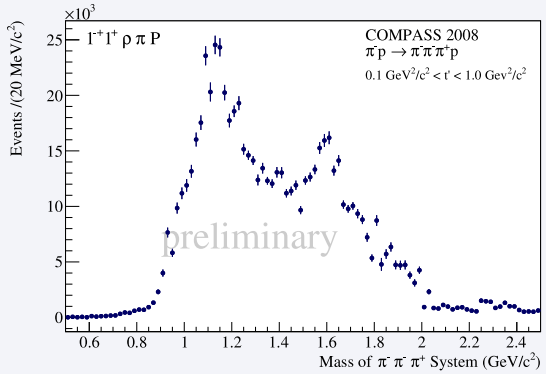


Preliminary: COMPASS 2008 run 190GeV π^-p $\pi_1(1600) \longrightarrow \pi^-\pi^-\pi^+, \eta'\pi^-$

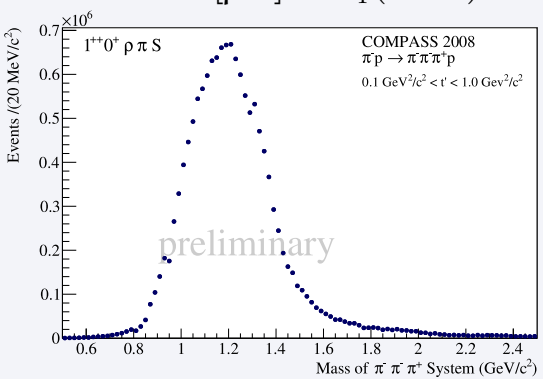
Large statistics: 100M $\pi^-\pi^-\pi^+$

B.Grube PANIC-2011:

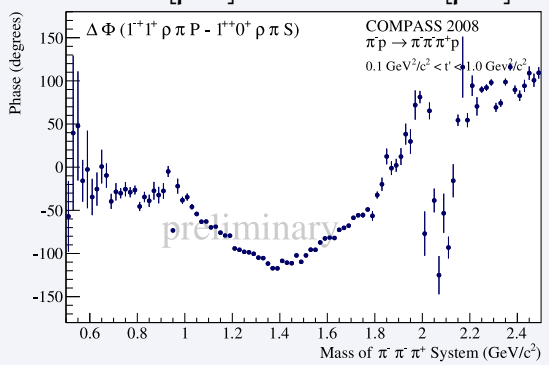
Spin-exotic $1^{-+}\,1^+\,[\rho\pi]$P



$1^{++}\,0^+\,[\rho\pi]$S : $a_1(1260)$



$1^{-+}\,1^+\,[\rho\pi]$P $-$ $1^{++}\,0^+\,[\rho\pi]$S



- Structure around 1.1 GeV/c^2 unstable w.r.t. fit model
- Stable enhancement around 1.6 GeV/c^2
- Phase motion w.r.t. to tail of $a_1(1260)$
- Phase locked w.r.t. $\pi_2(1670)$
- Ongoing analysis

B.Grube DPG March 2012: These plots not shown: complications

1^{-+} in $\eta'\pi^-$ confirmed

What to Conclude from Existing Evidence

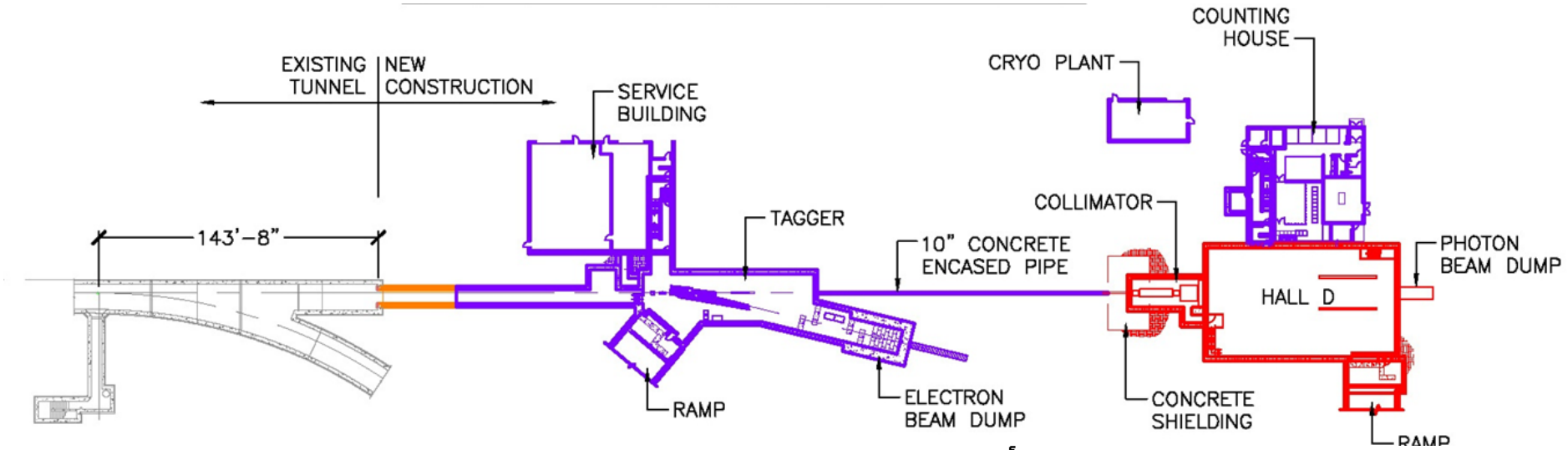
Hybrids with exotic quantum numbers:

- Predicted by LQCD and models
- Masses evaluated by LQCD, production/decays by models
- Experimental evidence is tantalizing but not strong
- Evidence for unusual states in the heavy-quark sector
- Experimental improvements essential to move forward:
  - Improved hermeticity and resolution
  - All potentially important decay modes must be analyzed
  - Amplitude analysis must be well understood and controlled
  - Perhaps pions are not the optimal probe to produce exotic hybrids
    Photoproduction - few data so far
- New generation of experiments: COMPASS, *GlueX, BESIII, PANDA...*

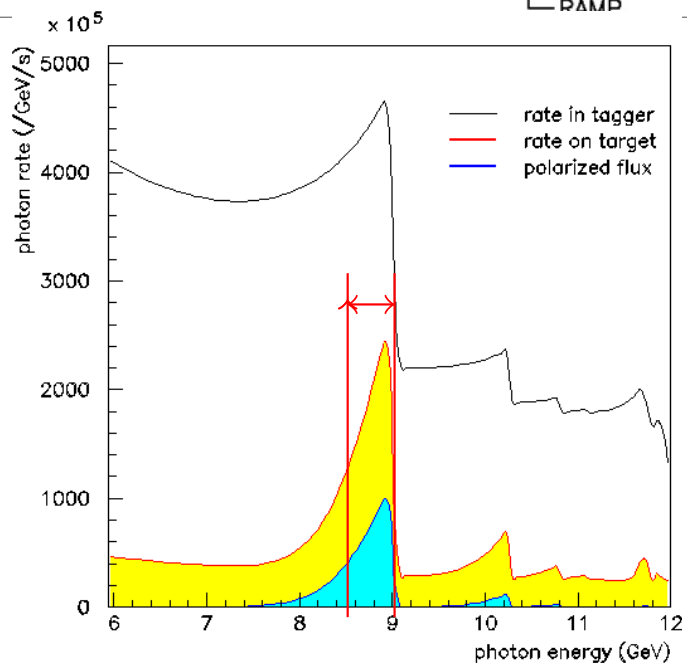
GlueX: approach and requirements

- Photon Beamline
  - Linear polarization using coherent Bremsstrahlung:
    $\Rightarrow$ small angles $\Rightarrow$ collimating at large distance
  - End point 12 GeV
  - Tagging to $\sigma_E \sim 0.1\%$ at a high rate $\sim$ 100 MHz/GeV
- Spectrometer
  - Detecting of charged particles and photons with a few % energy resolution
  - Hermiticity: $1^\circ < \theta < 120^\circ$
  - Particle identification
  - Wide variety of final states:
    soft trigger for photoproduction of hadrons $\Rightarrow$ high DAQ rate

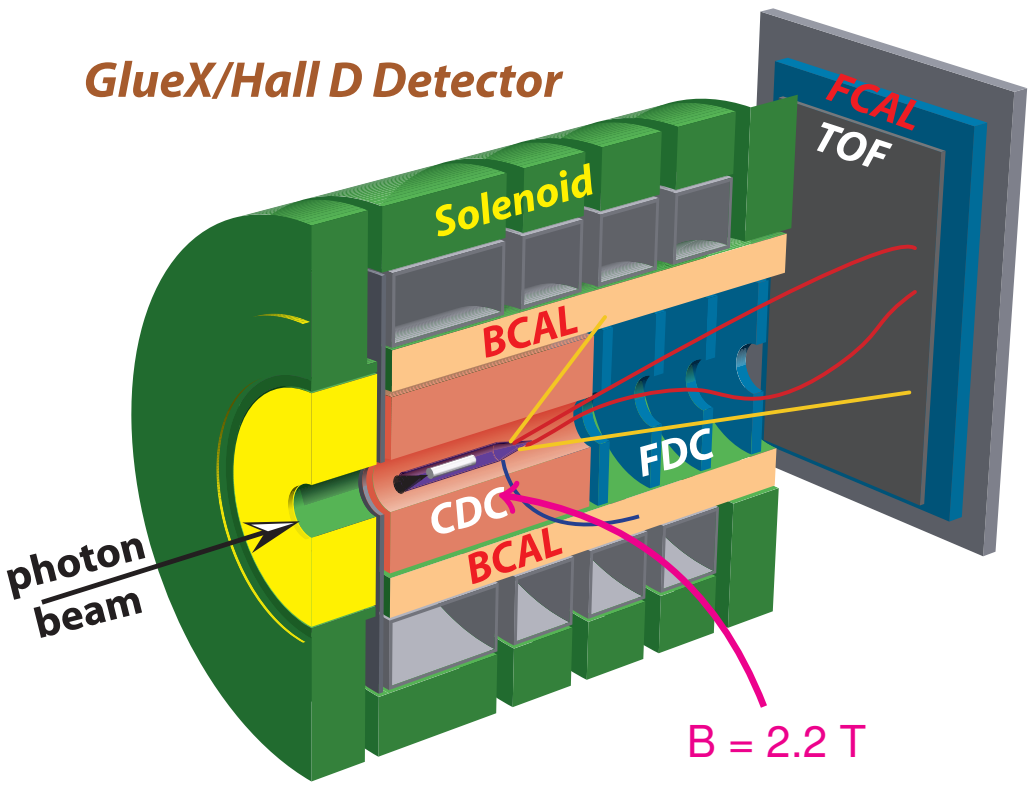
Hall D and the Photon Beamline



- 12 GeV e^- beam 2.2 μA
- 20 μm diamond: coherent $<$25 μrad
- Collimation r $<$1.8 mm at $\sim$ 80 m
- Coherent peak 8.4 – 9.0 GeV
  photons: 100 MHz $\quad \mathcal{P} \sim 40\%$
- Energy/polarization measured:
  - Tagger spectrometer
  - Pair spectrometer



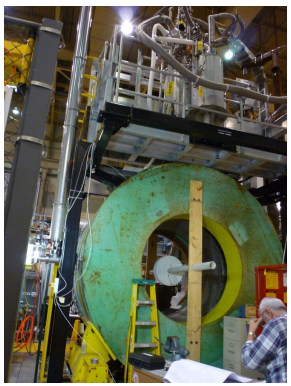
Spectrometer



- Liquid H target - 30 cm long
- Solenoid: 2.24 T, bore 2 m
- Tracking (inside solenoid):
  - Start counter
  - Central Drift Chamber (CDC)
  - Forward Drift Chamber (FDC)
- Calorimetry
  - Barrel Calorimeter (BCAL)
  - Forward Calorimeter (FCAL)
- Time-of-flight wall (ToF)
- pipeline electronics
  front-end $\sim$ 200 kHz L1 triggers
  to tape $\sim$ 20kHz
  trigger using FADCs

Progress with construction: about 40% done

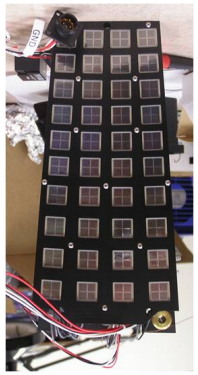
Solenoidal Magnet: tested at 1500 A



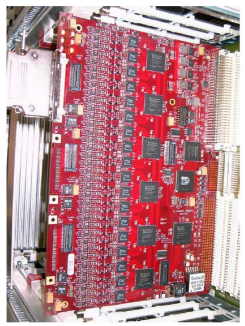
CDC: all 3500 wires strung

FDC: 60% done

BCAL: All 48 modules built



FCAL: all 3000 lead glass and PMTs



Electronics: 70% ordered

Summary

- Hall D - a new facility for physics with photon beam < 12 GeV, polarized at $\sim$9 GeV
- Spectrometer with a large and uniform acceptance for charged particles and photons
- Very high DAQ rate - minimum bias trigger
- Physics program:
  - Search and mapping out the spectra of hybrid mesons with exotic quantum numbers
  - Measurements of 2-photon coupling of pseudoscalers
  - Other topics are discussed

The Hall D/Gluex collaboration

- Jefferson Lab (CDC, FDC, BCal, beamline, software)
- Carnegie Mellon (CDC)
- Catholic University (Tagger hod.)
- Christopher Newport (Trigger)
- Florida International (start-counter)
- Florida State (ToF wall)
- Indiana University (FCal, software)
- IUCF (FDC, Solenoid)
- University of NC, A&T (PS)
- University of NC, Wilmington (PS)
- University of Connecticut (beamline)
- University of Athens (BCal)
- University of Pennsylvania (ASIC for CDC, FDC)
- University of Regina (BCal)
- University Santa Maria (Chile) (BCal readout)
- University of Massachusetts (targets, electronics)
- Yerevan (beamline)
- MIT(Cherenkov) - *in progress*
- University of Arizona(beamline) - *in progress*