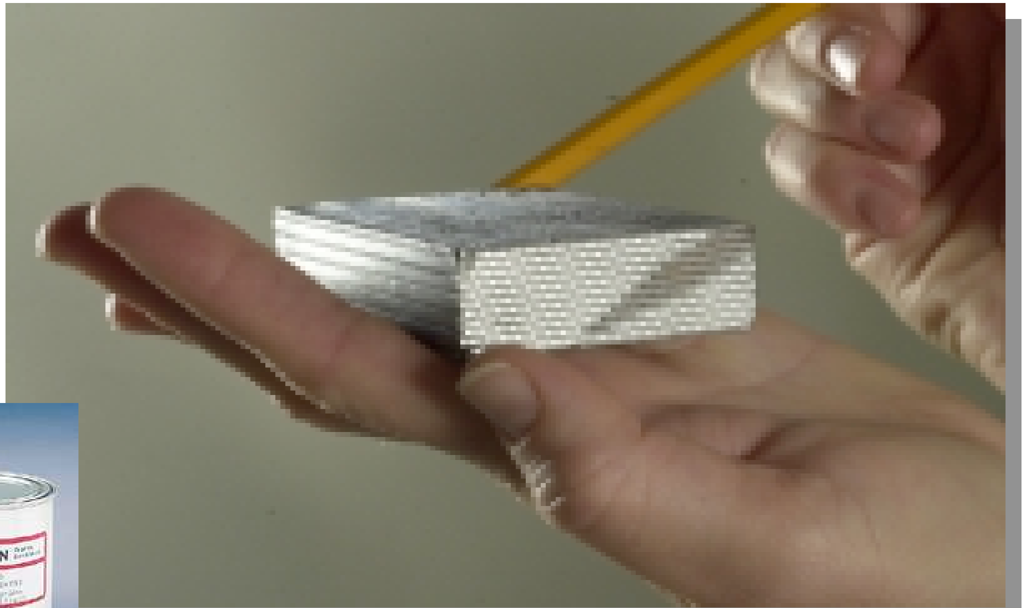
It takes glue to study the "Glue"



Spaghetti Calorimetry

Zisis Papandreou
Dept. of Physics
University of Regina

Frascati Physics Seminar
May 21, 2003

100 Physicists
(including 16 theorists)
from 6 countries
including 10 states + D. of C.

- Australia
- Canada
- Poland
- Russia
- Scotland
- USA

FIFA Rules

Canadians:
Regina, Carleton

GlueXcitations eXperiment

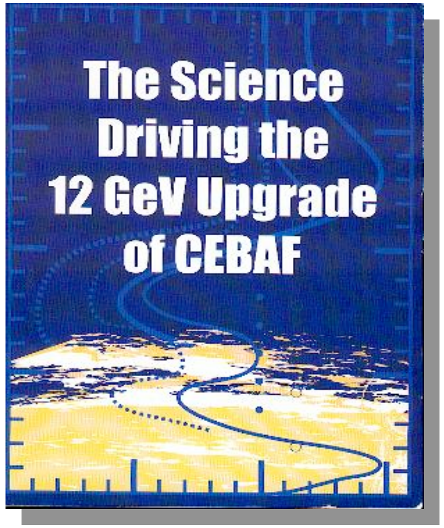
Hall D at Jefferson Lab
www.gluex.org

References

Nov 2002

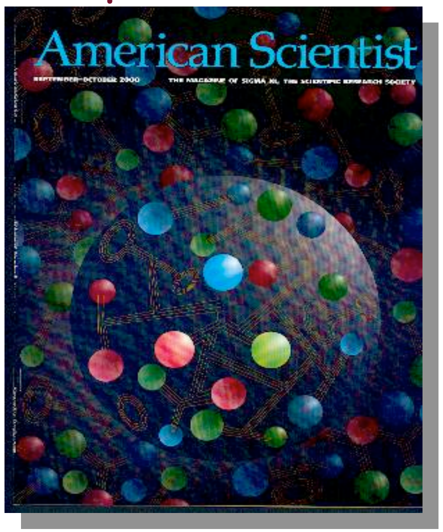
Design Report

Feb 2001



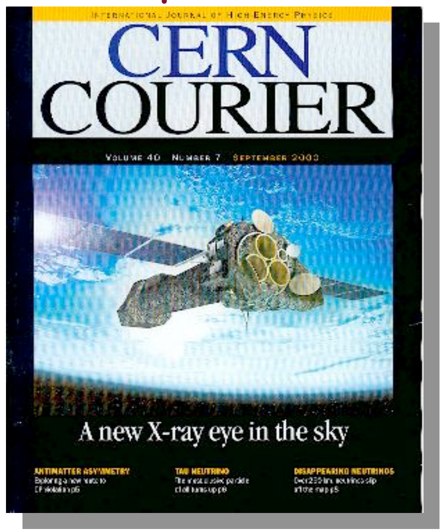
JLab whitepaper

Sept/Oct 2000



Cover story article
on exotics and Hall D

Sept 2000



Article
on exotics and Hall D

All can be
downloaded from
the Hall D website

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www.gluex.org

Scientific Goals and Means

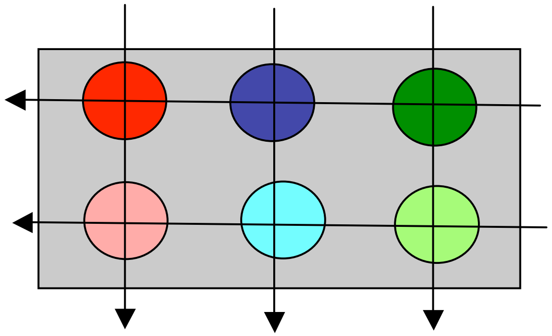
- Definitive and detailed mapping of **hybrid meson spectrum**
- Quantitative understanding of **confinement mechanism** in Quantum Chromodynamics (QCD).
- Search for smoking gun signature of **exotic J^{PC} hybrid mesons**; these do not mix with qq states
- **Tools for the GlueX Project:**
  - Accelerator: 12 GeV electrons, 9 GeV linearly polarized photons with high flux
  - Detector: **hermiticity**, resolution, charged and neutrals, R&D
  - PWA Analysis: each reaction has multi-particle final states
  - Computing power: **1 Pb/year data** collection, data grids, distributed computing, web services…

QCD is the theory of quarks and gluons

$$L_{QCD} = \bar{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - 1/2\, tr(G^{\mu\nu}G_{\mu\nu})$$

qqq

white

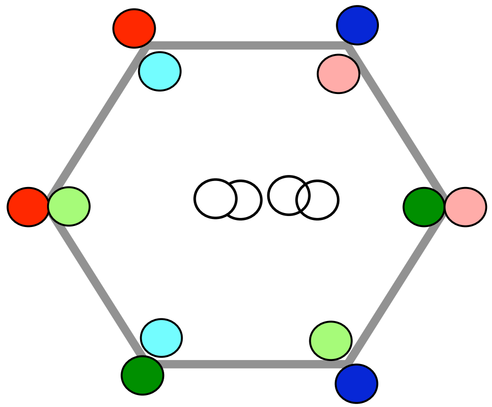


3 Colors

3 Anti-colors

$q\bar{q}$ white (colorless objects)

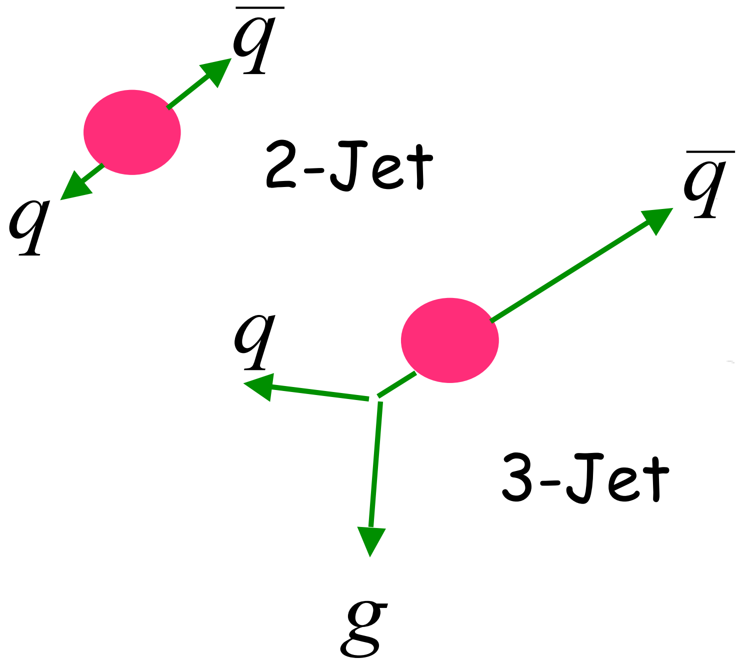
confinement

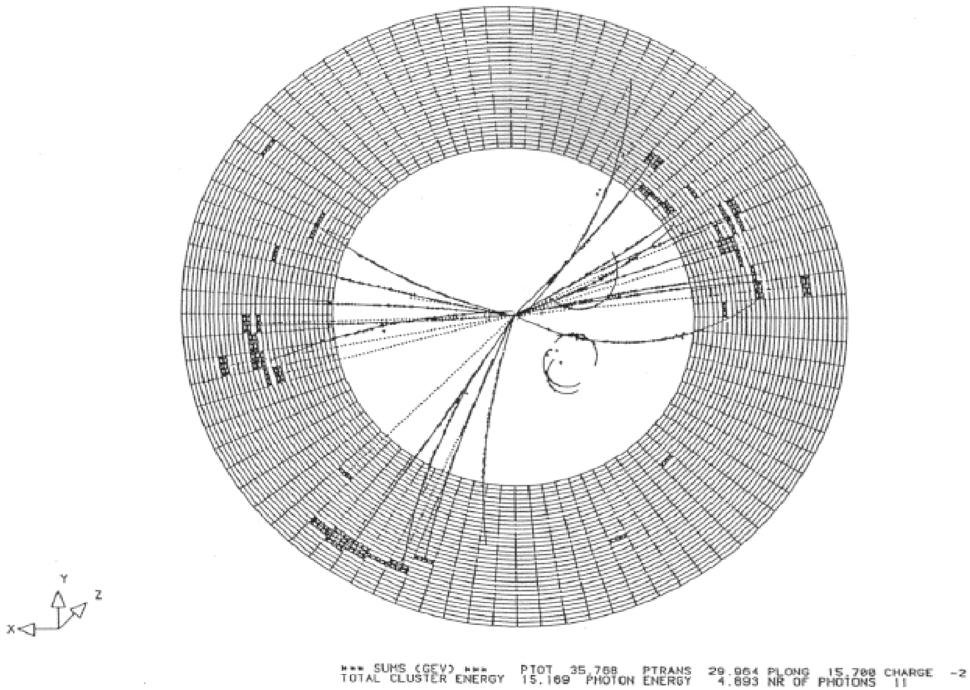


8 Gluons, each with a color and an anti-color charge.

Jets at High Energy

Direct evidence for gluons come from high energy jets.
But this doesn't tell us anything about the "static" properties of glue. We learn something about α_s.

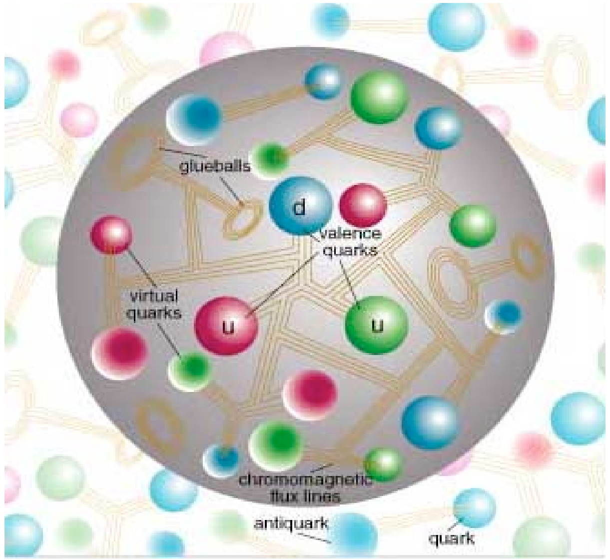




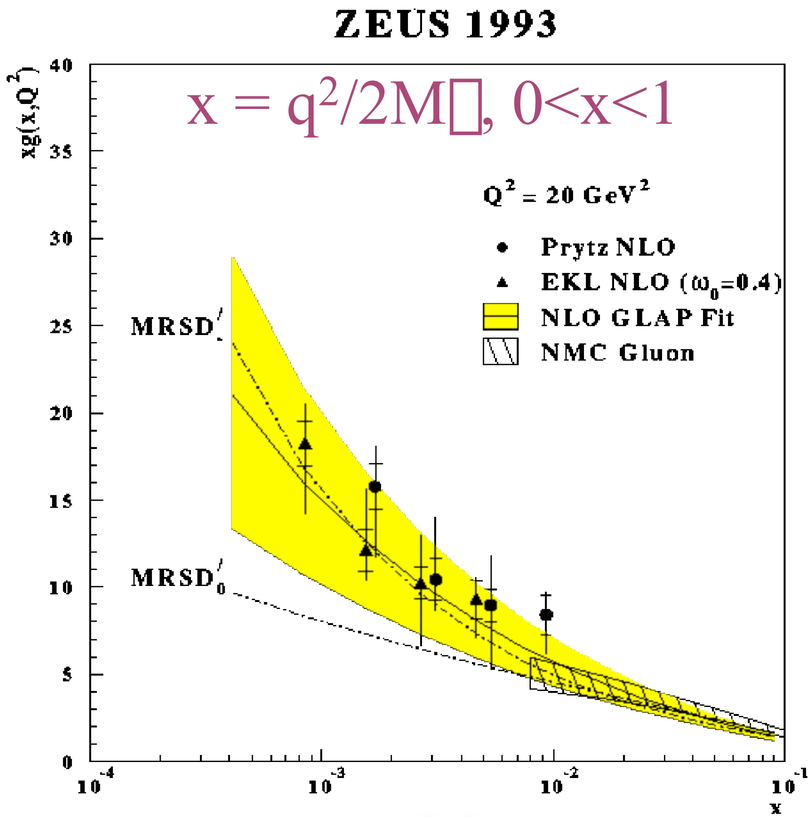
gluon bremsstrahlung $\quad q(\bar{q}) \to q(\bar{q})g$

Deep Inelastic Scattering

As the nucleon is probed to smaller and smaller x, the gluons become more and more important. Much of the nucleon momentum and most of its spin is carried by gluons!



Glue is important to hadronic structure.



Asymptotic Freedom

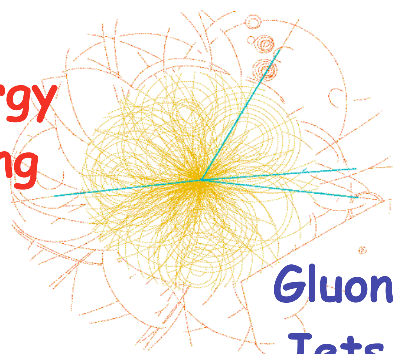
Small Distance
High Energy

Confinement

Large Distance
Low Energy

Perturbative Regime

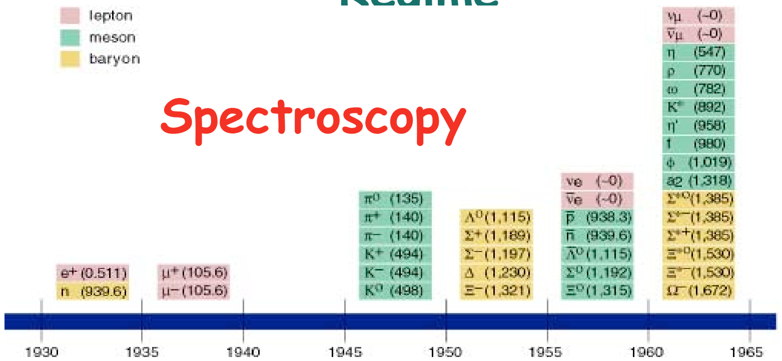
High Energy Scattering



Gluon Jets Observed

Non-Perturbative Regime

Spectroscopy



Gluonic Degrees of Freedom Missing

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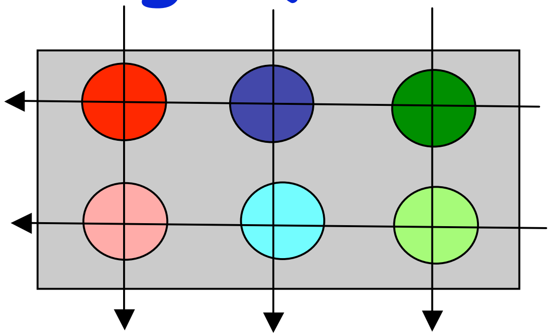
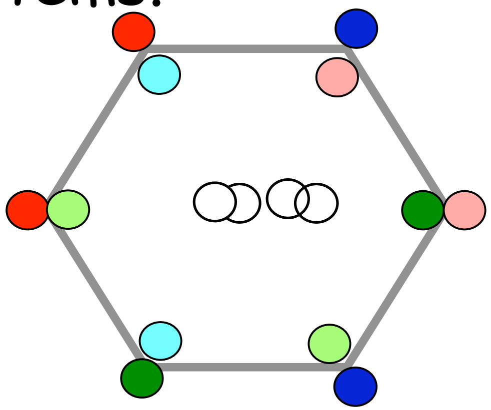
Strong QCD: See $q\bar{q}$ and qqq systems.

white



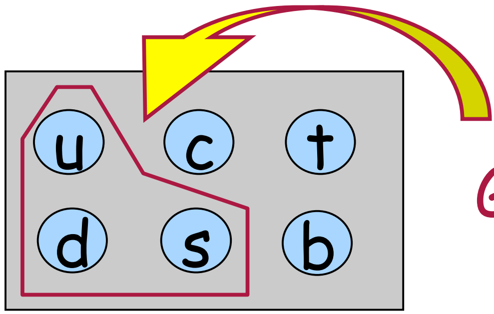
white

Nominally, glue is not needed to describe hadrons.



Allowed systems: $\underbrace{gg\,,\,ggg}_{\text{Glueballs}}$ $\underbrace{\boxed{q\bar{q}g}}_{\text{Hybrids}}$ $\underbrace{q\bar{q}q\bar{q}}_{\text{Molecules}}$

Glueballs, Hybrids: Gluonic Excitations

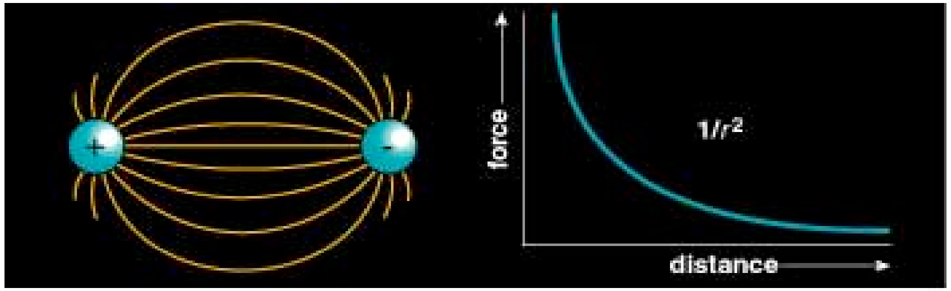


GlueX Focus: “light-quark mesons”

Six Flavors of quarks

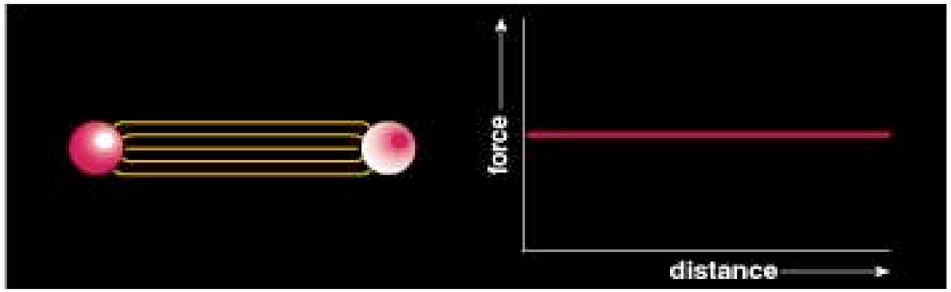
QED vs. QCD

Dipole



- 1 electric charge
- □ carries no charge

Flux Tube



- 3 Color charges
- g carry charge

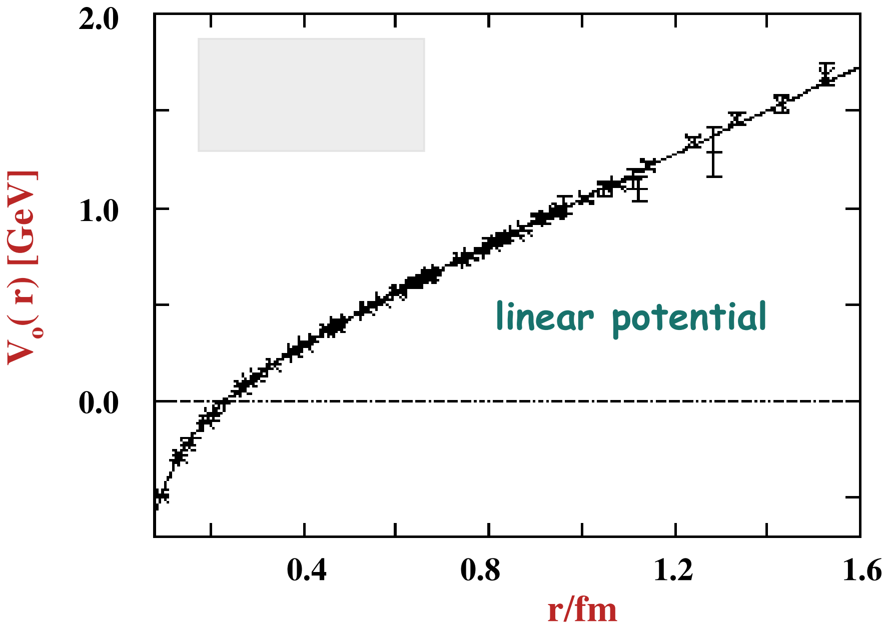
Color Field: Gluons possess color charge: they couple to each other!

Notion of flux tubes comes about from model-independent general considerations: observed linear dependence of m^2 on J. Idea originated with Nambu in the '70s.

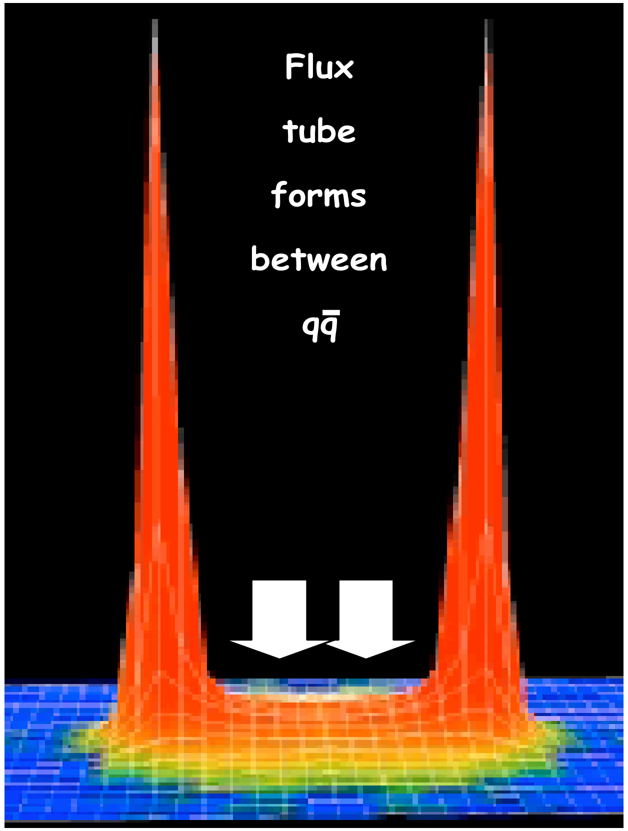
Lattice QCD

Flux tubes realized

From G. Bali



Lattice "measurement"
of quenched static potential



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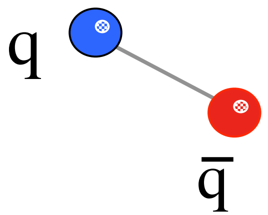
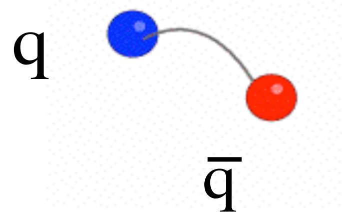
"Pluck" the Flux Tube

How do we look for gluonic degrees of freedom in spectroscopy?

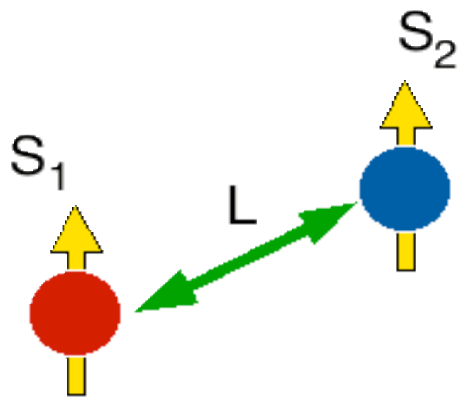
Normal meson:
flux tube in ground state



Hybrid meson:
flux tube in excited state



There are two degenerate first-excited transverse modes with J=1
– clockwise and counter-clockwise –
and their linear combinations lead to $J^{PC} = 1^{-+}$ or $J^{PC}=1^{+-}$ for the excited flux-tube



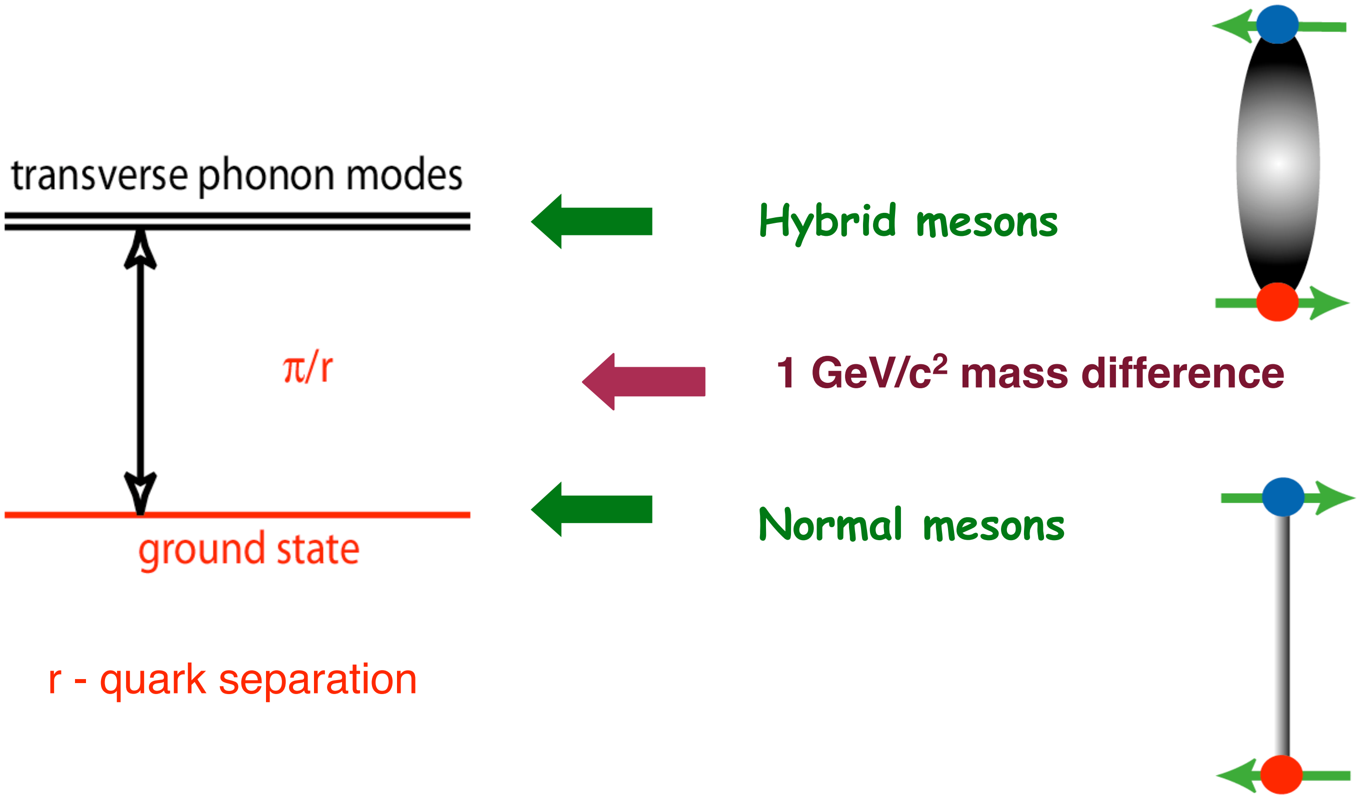
$S = S_1 + S_2$

$J = L + S$

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

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

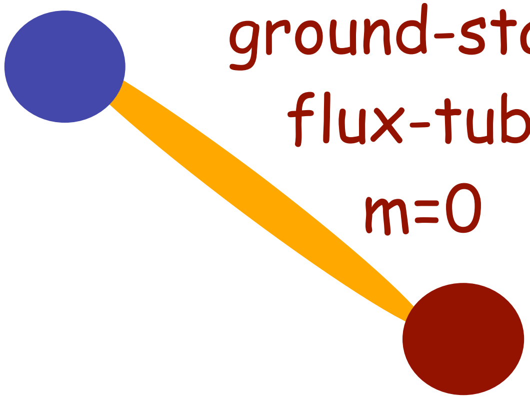
Mass Difference



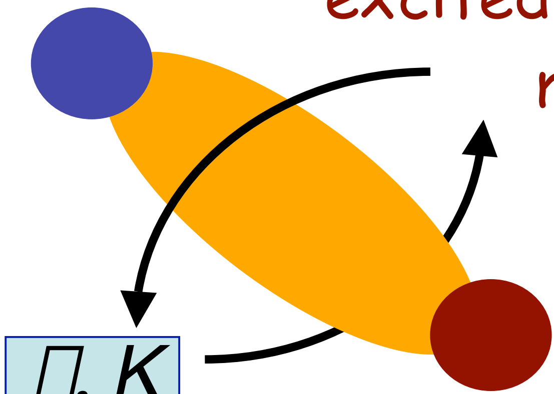
Hybrid Mesons

built on quark-model mesons

ground-state
flux-tube
m=0



excited flux-tube
m=1
1^{-+} or 1^{+-}



normal mesons

$$CP=\{(-1)^{L+S}\}\{(-1)^{L+1}\}$$
$$=\{(-1)^{S+1}\}$$

Flux-tube Model

m=0 $CP=(-1)^{S+1}$

m=1 $CP=(-1)^{S}$

□, K

S=0,L=0,m=1

J=1 CP=+

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

non exotic

□, □, □

S=1,L=0,m=1

J=1 CP=-

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

exotic $1^{-+},1^{+-}$

$2^{-+},2^{+-}$

GlueX Exotic Citations Experiment

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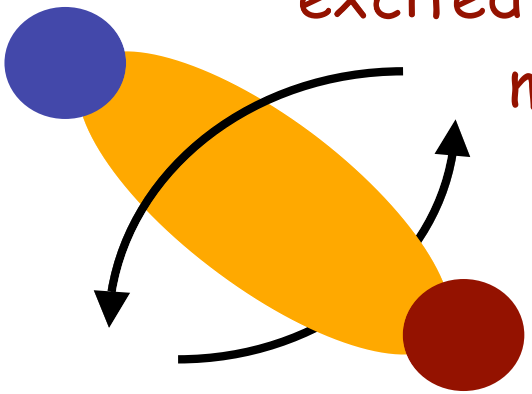
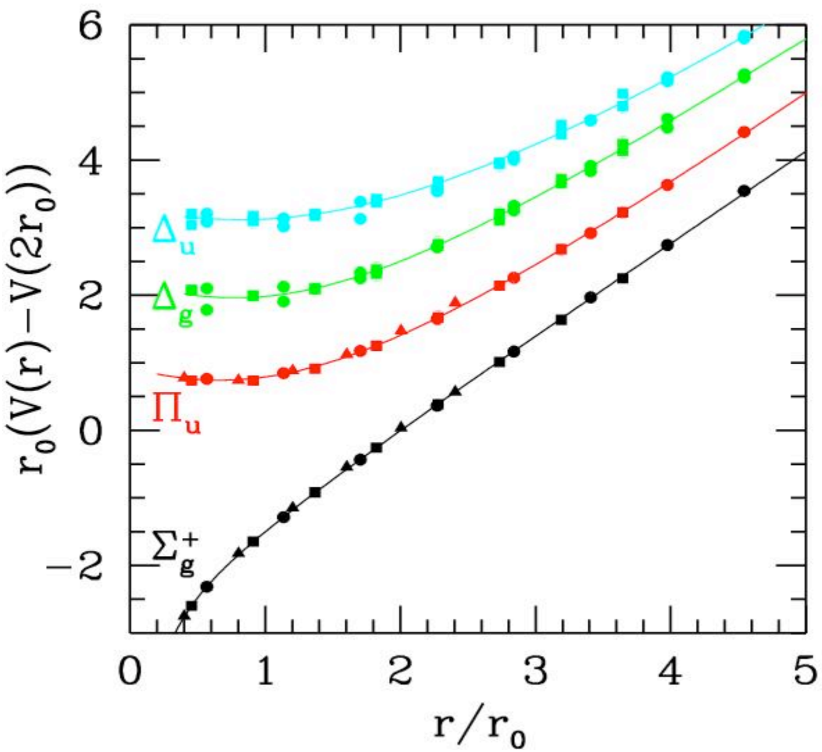
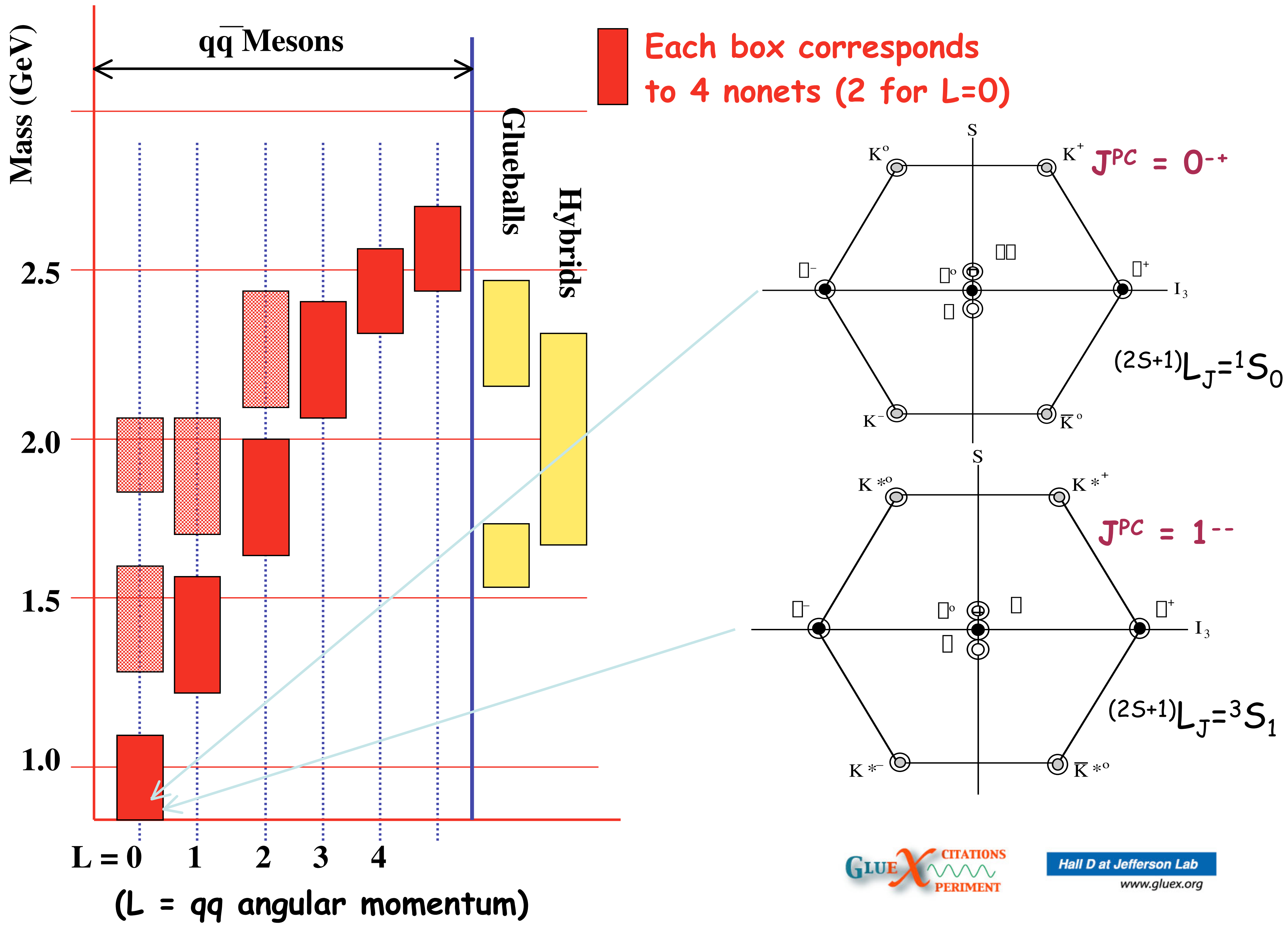
QCD Potential



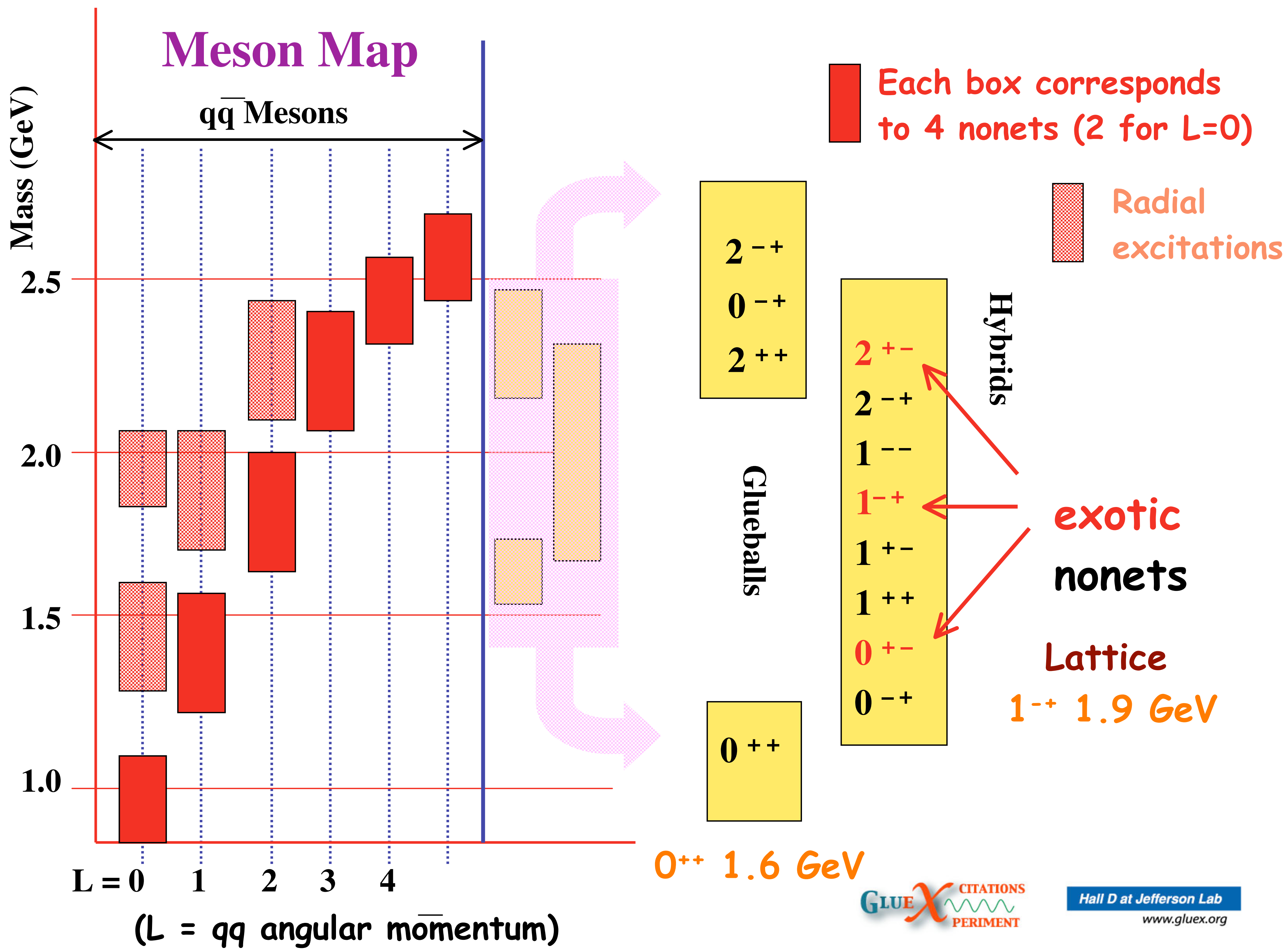


Gluonic Excitations provide an experimental measurement of the excited QCD potential.

Observations of exotic quantum number nonets are the best experimental signal of gluonic excitations.



Mass (GeV)
qq Mesons
Each box corresponds to 4 nonets (2 for L=0)
Glueballs
Hybrids
2.5
2.0
1.5
1.0
L = 0 1 2 3 4
(L = qq angular momentum)
S
K°
K+
$J^{PC} = 0^{-+}$
I3
$^{(2S+1)}L_J = {}^1S_0$
K−
$\bar{K}$°
K*°
K*+
$J^{PC} = 1^{--}$
$^{(2S+1)}L_J = {}^3S_1$
K*−
$\bar{K}$*°



Meson Map
qq Mesons
Mass (GeV)
2.5
2.0
1.5
1.0
L = 0
1
2
3
4
(L = qq angular momentum)
Each box corresponds to 4 nonets (2 for L=0)
Radial excitations
2 −+
0 −+
2 ++
Glueballs
0 ++
0++ 1.6 GeV
2 +−
2 −+
1 −−
1−+
1 +−
1 ++
0 +−
0 −+
Hybrids
exotic nonets
Lattice
1-+ 1.9 GeV
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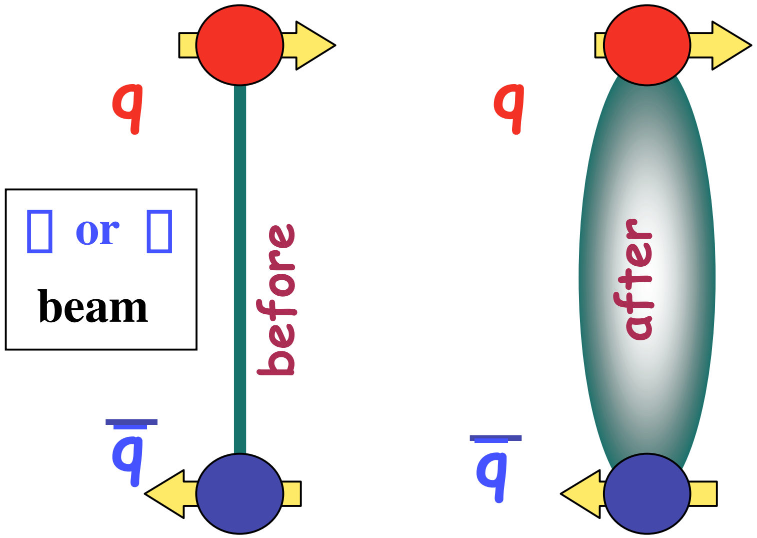
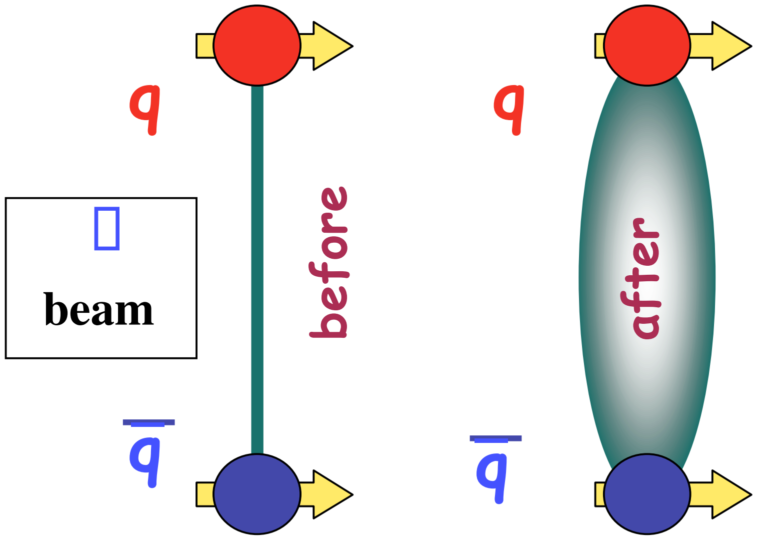
Production of Exotics



Quark spins anti-aligned

A pion or kaon beam,
when scattering occurs,
can have its flux tube excited

Much data in hand with some
evidence for gluonic excitations
(exotic hybrids are suppressed)

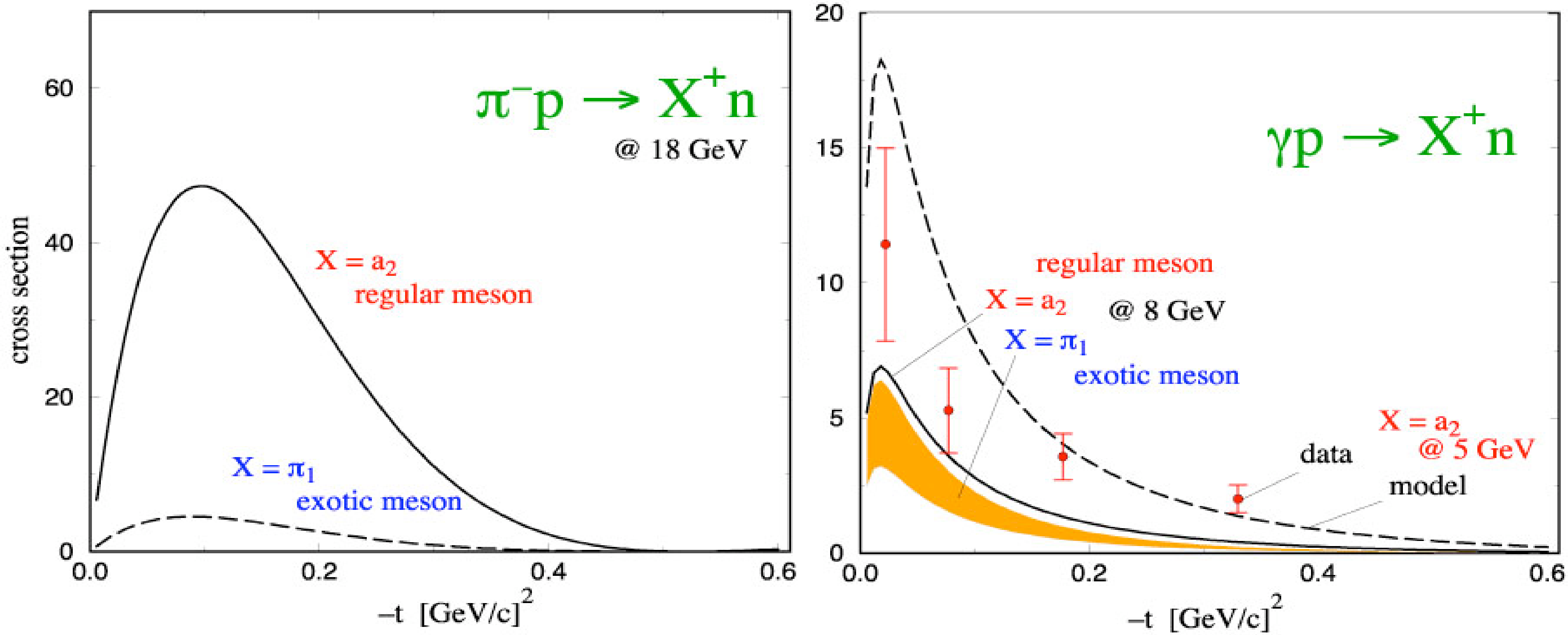


Quark spins aligned

Almost no data in hand
in the mass region
where we expect to find exotic hybrids
when flux tube is excited

Phenomenology

Model predictions for regular vs exotic meson prodution with pion (S=0) and photon (S=1) probes



Szczepaniak & Swat

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Partial Wave Analysis (PWA)

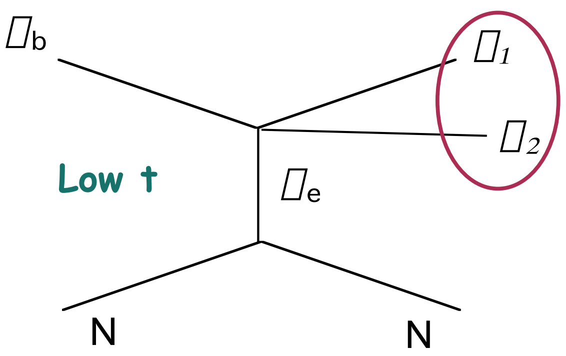
- Identify the J^{PC} of a meson
- Determine production amplitudes & mechanisms
- Include polarization of beam, target, spin and parity of resonances and daughters, relative angular momentum.

A simple example - identifying states which decay into □□

Decay into □$^+$□$^□$ implies J=L, P=(-1)^L and C=(-1)^L

Line shape and phase consistent with Breit-Wigner line shape

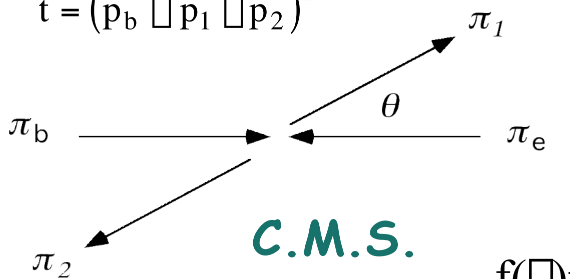
□$^□$p □ □$^+$□$^□$n



production

$$m_{□□} = (p_1 + p_2)^2$$

$$t = (p_b □ p_1 □ p_2)^2$$



C.M.S.

Production and decay point the way

$$\frac{dN}{d(\cos □)} \quad |Y_J^0|^2$$

$$d□ = |f(□)|^2 d□$$

$$f(□) = (1/k)□ (C_l/l)\sin□_l P_l(\cos□)$$

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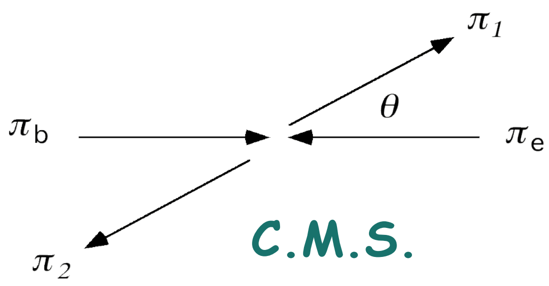
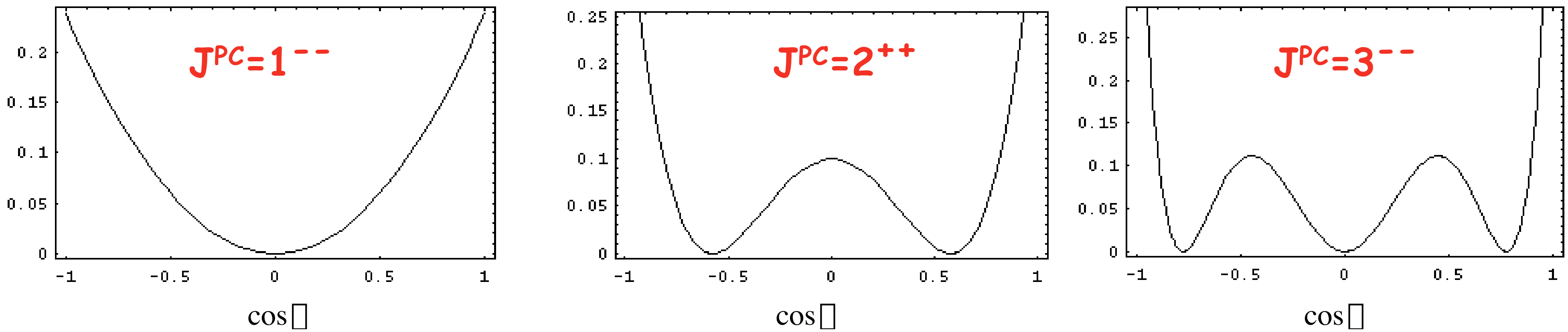
Decay Angular Distributions



$$\frac{dN}{d(\cos\theta)} \quad \left|Y_J^0\right|^2$$



Place PWA tools on firm footing, years before experiment

- effects of polarized and unpolarized beam
- detector acceptance (hermetic)
- Leakage of non-exotics into exotic signal

GlueX uses two parallel PWA codes for cross-checking!

PWA Exercise

GlueX Test

The J ^{PC} exotic was in the mix with other waves at the level of 2.5%

$J^{PC}=1^{-+}\square_1$

The generated mass and width are compared with those from PWA fits:

Mass

Input: 1600 MeV
Output: 1598 +/- 3 MeV

Width

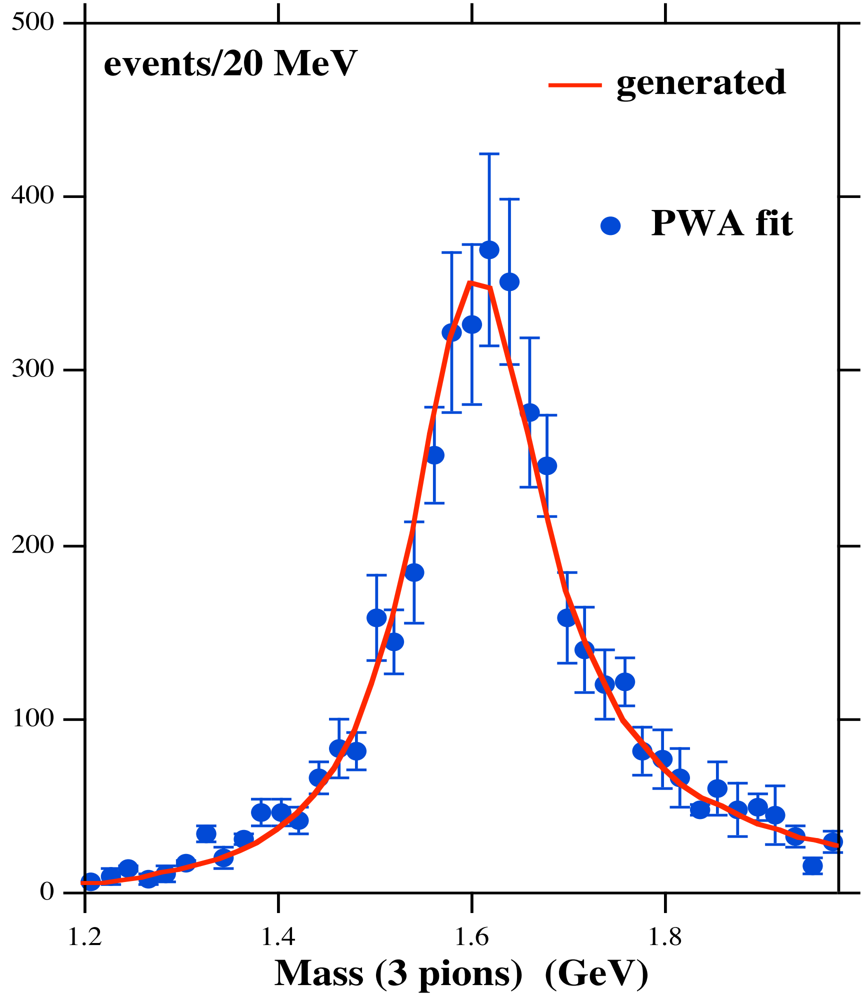
Input: 170 MeV
Output: 173 +/- 11 MeV

Statistics correspond to a few days of running

$\square p \square \square^+\square^+\square^{\square} n$

Double-blind MC exercise

Finding the Exotic Wave



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What is Needed for the GlueX Experiment?

Linearly Polarized, CW Photon Beam:

- Linear Polarization is required by the PWA
- At least 12 GeV electrons
- Small spot size and superior emittance
- CW beam minimizes detector deadtime, permitting much higher rates

Hermetic Detector:

- PWA requires that the entire event be kinematically identified - all particles detected, measured and identified. It is also important that there be sensitivity to a wide variety of decay channels to test theoretical predictions for decay modes.

The detector should be hermetic for neutral and charged particles, with excellent resolution and particle identification capability. The way to achieve this is with a solenoidal-based detector.

Why a 12 GeV Electron Beam?

The mass reach of GlueX is up to about 2.5 GeV/c^2 so the photon energy must at least be 5.8 GeV. Energy must be higher than this so that:

1. Mesons have enough boost so decay products are detected and measured with sufficient accuracy.
2. Line shape distortion for higher mass mesons is minimized.
3. Meson and baryon resonance regions are kinematically distinguishable.
4. Linear polarization is optimal.

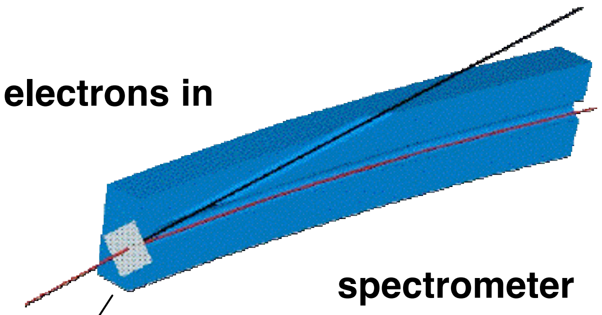
But the photon energy should be low enough so that:

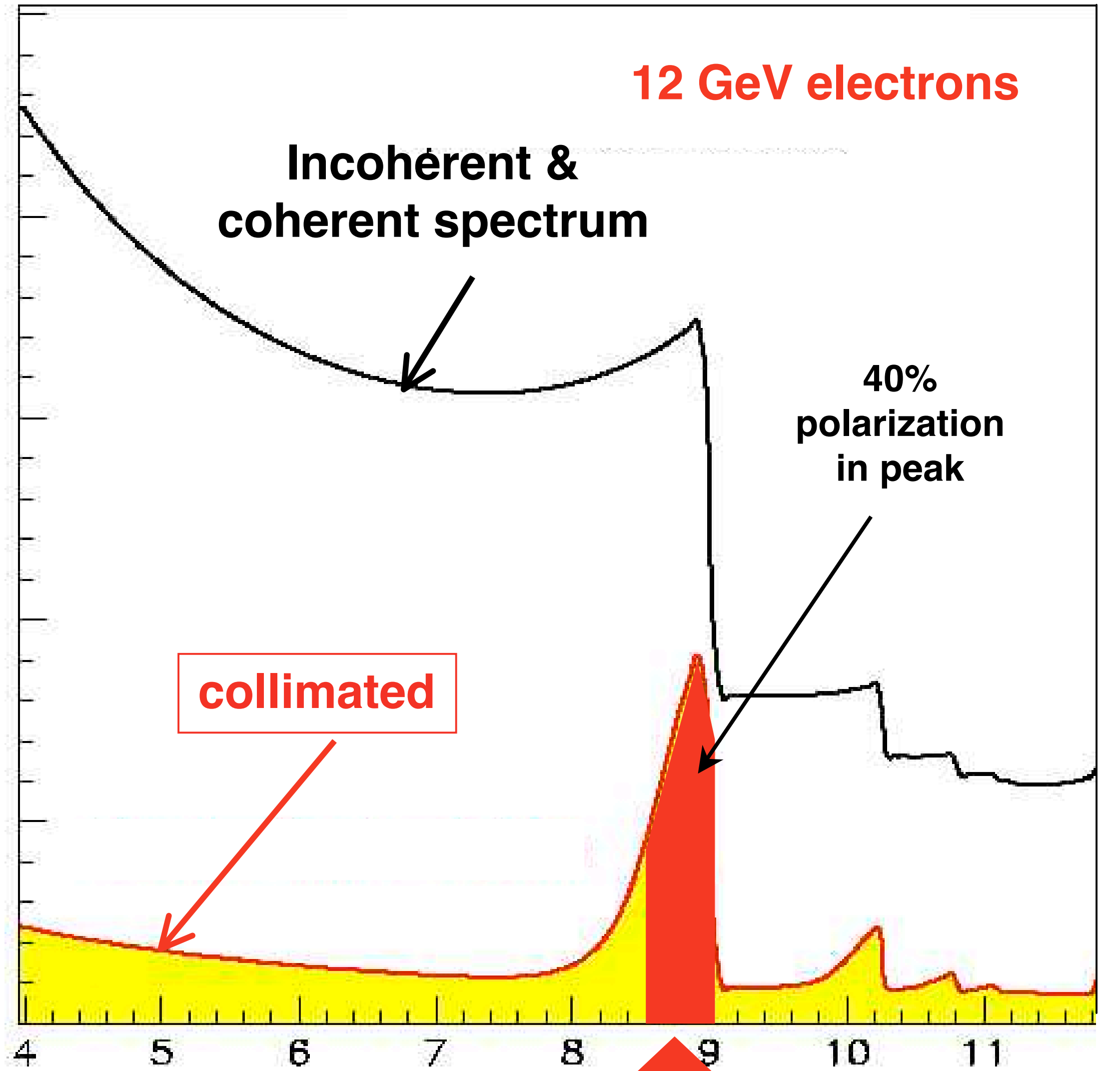
1. An all-solenoidal geometry (ideal for hermeticity) can still measure decay products with sufficient accuracy.
2. Background processes are minimized.

$\Rightarrow$ 9 GeV photons ideal

Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization





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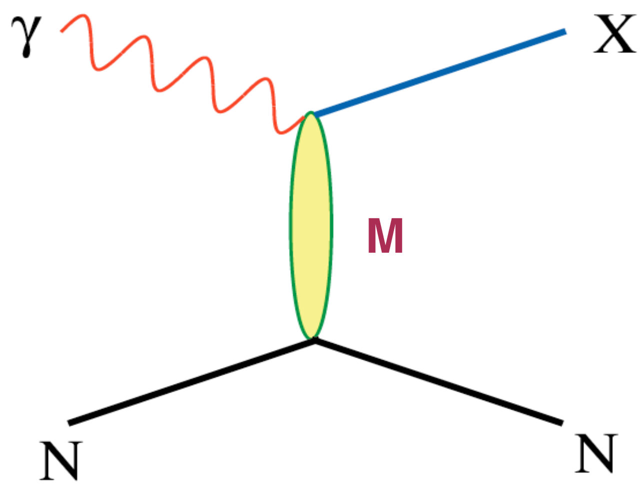
Linear Polarization

Linear polarization is:

- ✓ Essential to isolate the production mechanism (M) if X is known
- ✓ A J^{PC} filter if M is known (via a kinematic cut)
- ✓ Degree of polarization is directly related to required statistics
- ✓ Linear polarization separates natural and unnatural parity

States of linear polarization are eigenstates of parity. States of circular polarization are not.



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How GlueX Compares to Existing Data

Experiment	a_2 yield	Exotic Yield
SLAC	10^2	--
BNL (published)	10^4	250
BNL (in hand - to be analyzed)	10^5	2500
GlueX	10^7	5x 10^6

More than 10^4 increase

GlueX estimates are based on 1 year of low intensity running (10^7 photons/sec)

Even if the exotics were produced at the suppressed rates measured in π-production, we would have 250,000 exotic mesons in 1 year, and be able to carry out a full program of hybrid meson spectroscopy

Computational Challenge

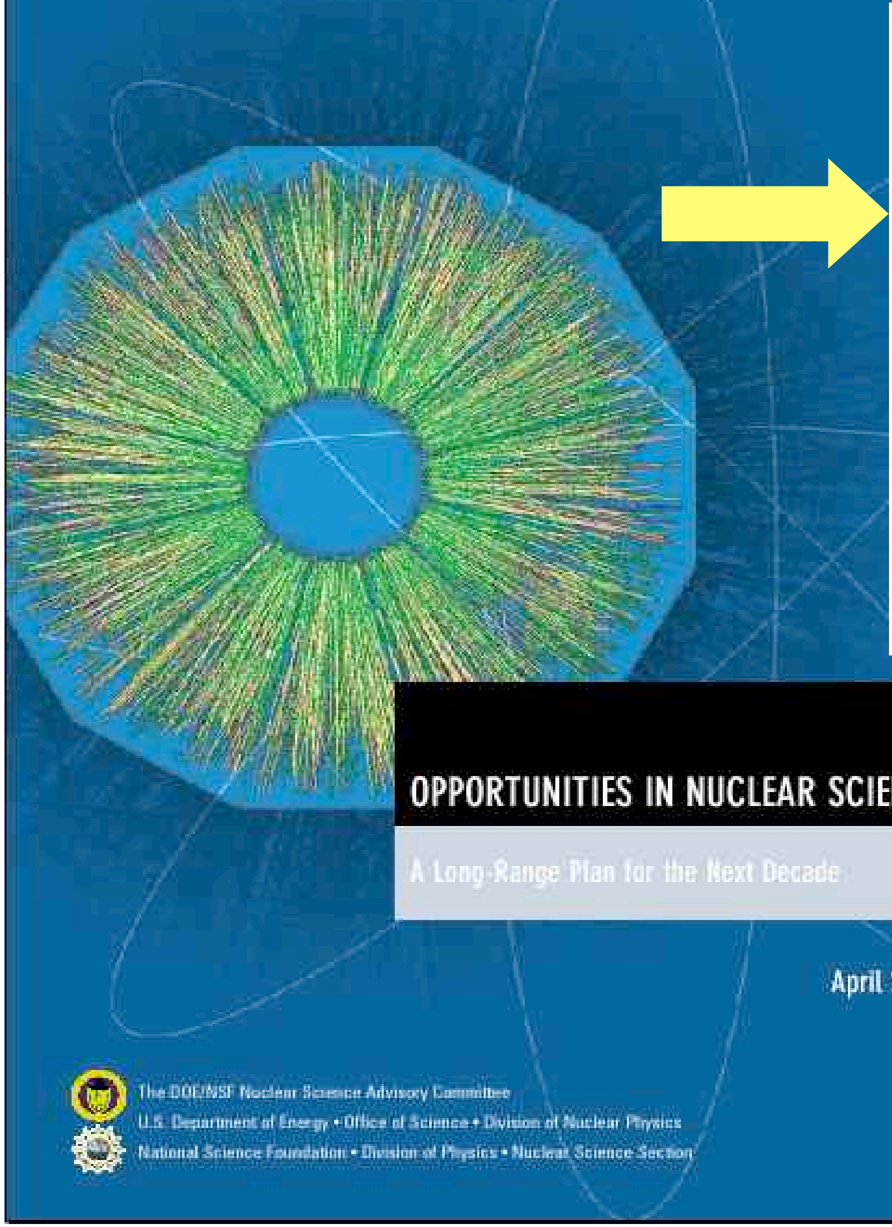
- GlueX will collect data at 100 MB/sec or 1 Petabyte/year - comparable to LHC-type experiments.

- GlueX will be able to make use of much of the infrastructure developed for the LHC including the multi-tier computer architecture and the seamless virtual data architecture of the Grid.

- To get the physics out of the data, GlueX relies entirely on an amplitude-based analysis - PWA – a challenge at the level necessary for GlueX. For example, visualization tools need to be designed and developed. Methods for fitting large data sets in parallel on processor farms need to be developed.

- Close collaboration with computer scientists has started and the collaboration is gaining experience with processor farms.

www.nscl.msu.edu/future/lrp2002.html



RECOMMENDATION 4

We strongly recommend the upgrade of CEBAF at Jefferson Laboratory to 12 GeV as soon as possible.

The 12-GeV upgrade of the unique CEBAF facility is critical for our continued leadership in the experimental study of hadronic matter. This upgrade will provide new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of matter, and the nature of quark confinement.

NSAC Long Range Plan

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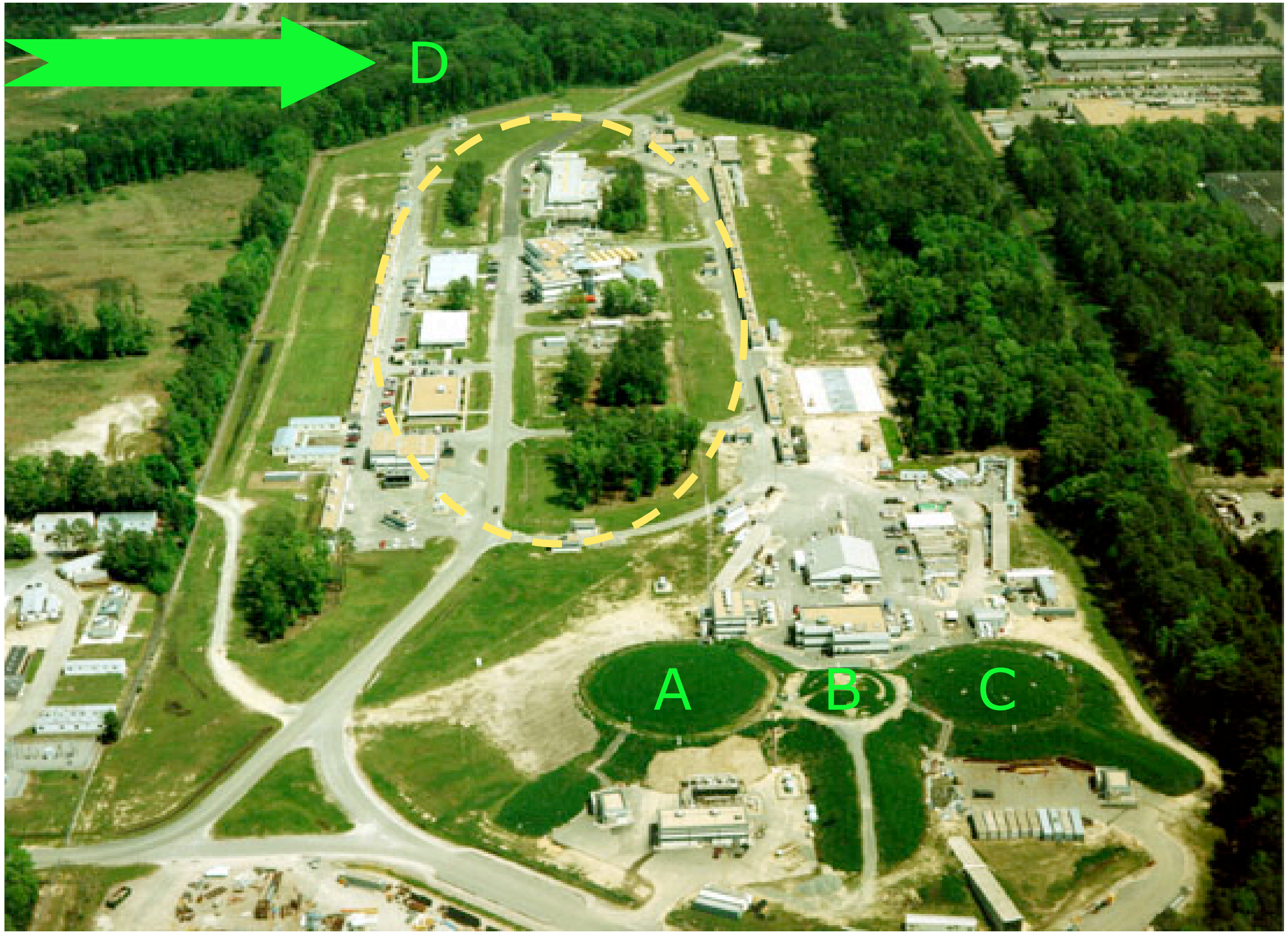
Jefferson Lab Facility

Newport News, Virginia

Hall D will be located here



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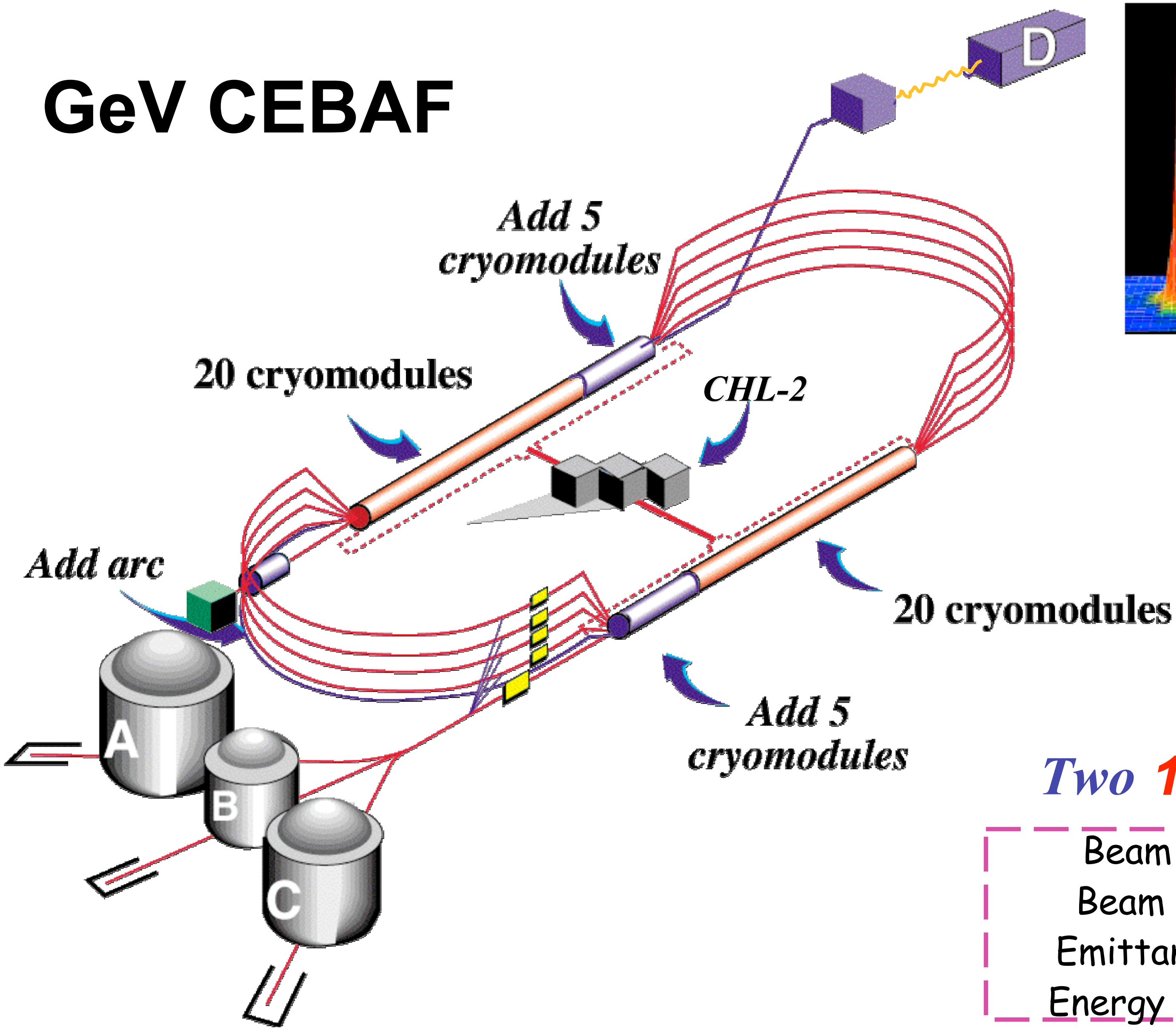
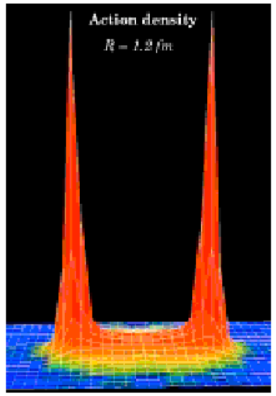
12 GeV CEBAF





*Two **1.1** GV linacs*

Beam Power: 1MW
Beam Current 5 μA
Emittance: 10 nm-rad
Energy Spread: 0.02%

GLUEX CITATIONS PERIMENT

Hall D at Jefferson Lab
www.gluex.org

GlueX Collaboration

A. Dzierba (Spokesperson) - IU
C. Meyer (Deputy Spokesperson) - CMU
E. Smith (JLab Hall D Group Leader)

Collaboration Board

L. Dennis (FSU)
J. Kellie (Glasgow)
G. Lolos (Regina) (chair)
R. Jones (U Conn)
A. Klein (ODU)
A. Szczepaniak (IU)

US Experimental Groups

- Carnegie Mellon University
- Catholic University of America
- Christopher Newport University
- University of Connecticut
- Florida International University
- Florida State University
- Indiana University
- Jefferson Lab
- Los Alamos National Lab
- Norfolk State University
- Old Dominion University
- Ohio University
- University of Pittsburgh
- Renssalaer Polytechnic Institute

Other Experimental Groups

- University of Glasgow
- Institute for HEP - Protvino
- Moscow State University
- Budker Institute - Novosibirsk
- University of Regina

100 collaborators
25 institutions

Theory Group

- CSSM & University of Adelaide
- Carleton University
- Carnegie Mellon University
- Insitute of Nuclear Physics - Cracow
- Hampton University
- Indiana University
- Los Alamos
- North Carolina Central University
- University of Pittsburgh
- University of Tennessee/Oak Ridge

GLUEX CITATIONS PERIMENT
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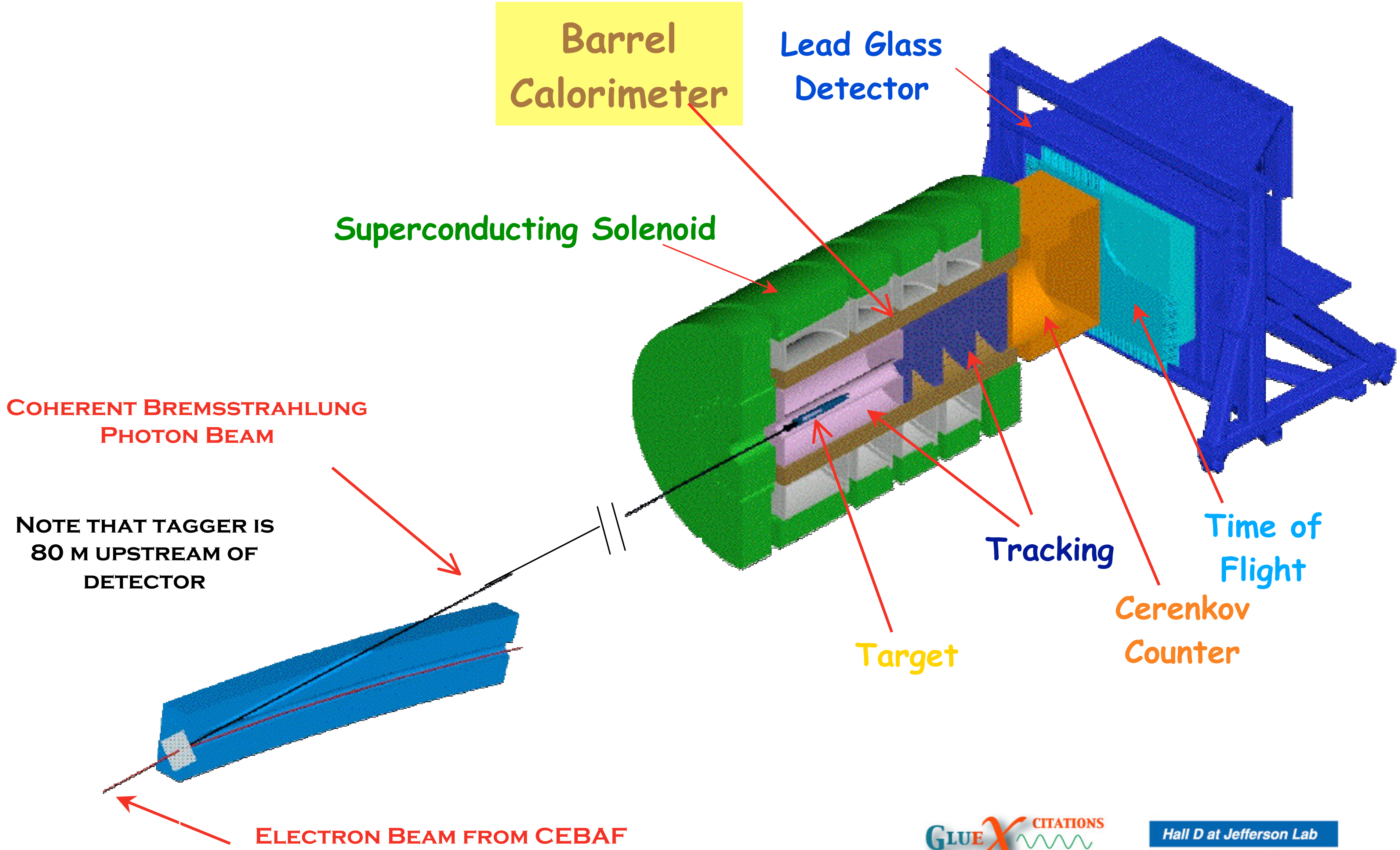
The impact of sparro

Subatomic Physics At Regina with Research Offshore

- Chair of Collaboration board: **George Lolos**
- Hardware working group co-leader: **Zisis Papandreou**
- Software working group co-leader : **Ed Brash**
- Most recent Hall D Collaboration meeting was held at UofR.
- SPARRO has been tasked with the design and construction of the full barrel calorimeter: weight of 30 tons, 5,000 km of fibers, and a price tag of US$4,000,000.
- Initial R&D is ongoing at Regina; JLab discretionary funds
- Assembly and machining of full modules in Edmonton.

GlueX Detector



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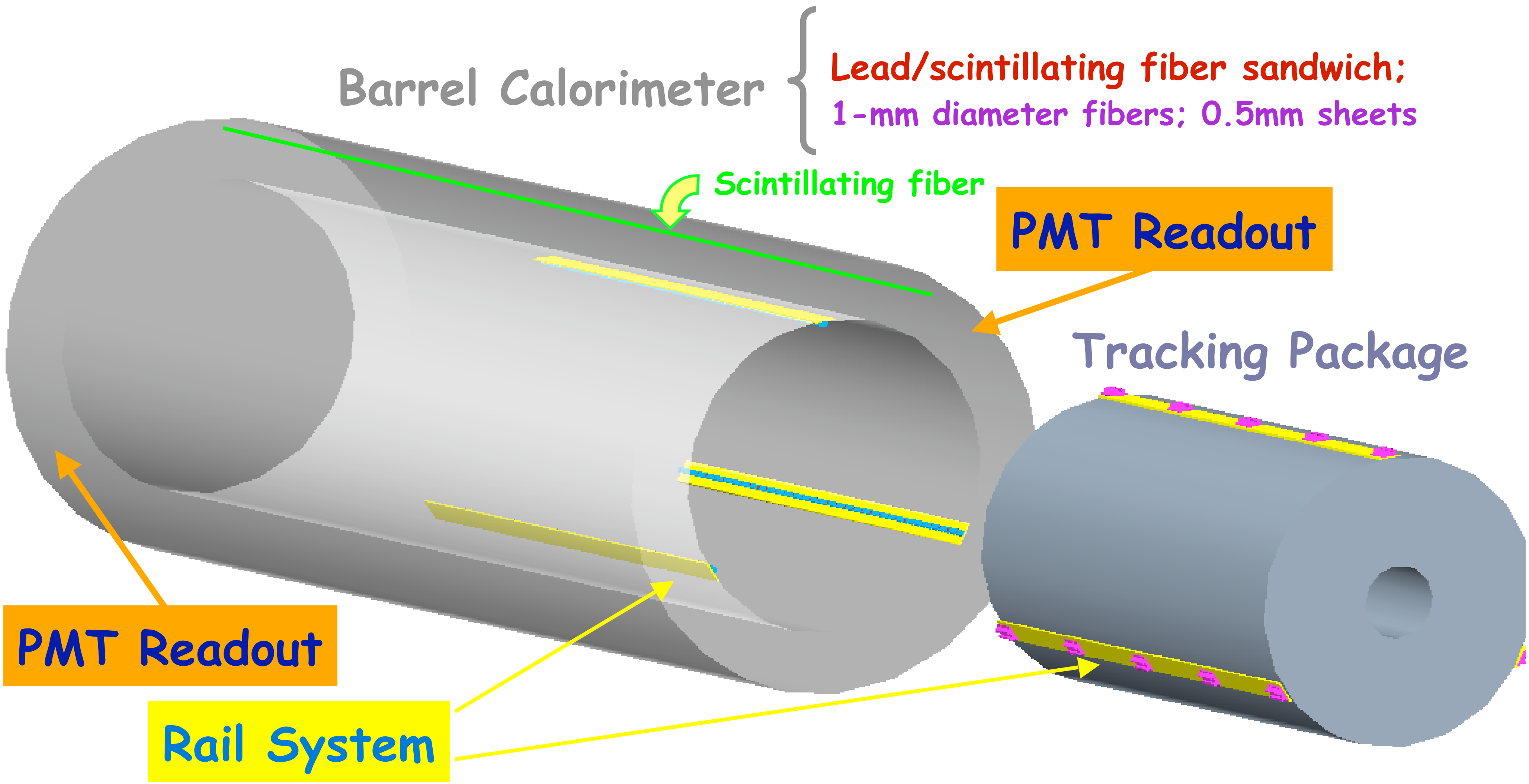

Barrel Calorimeter
Lead/scintillating fiber sandwich;
1-mm diameter fibers; 0.5mm sheets
Scintillating fiber
PMT Readout
Tracking Package
PMT Readout
Rail System

Barrel Calorimeter Design Issues

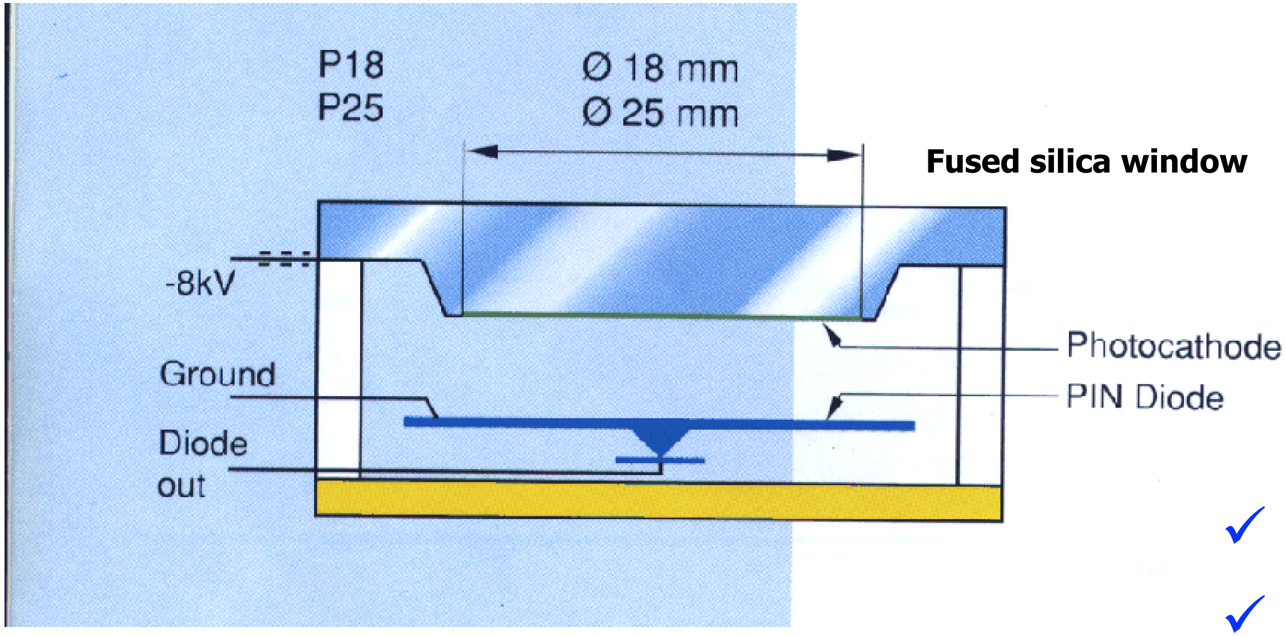
- Length of device (> 4 m)
- Shower containment/radiation lengths: ~16Xo
- Azimuthal granularity vs. PMT geometry & light collection
- Minimum energy deposition threshold: 20 MeV
- Neutral energy resolution balance (vs. FCAL)
  - Fiber diameter & Pb thickness: uniform throughout?
- Charged vs. Neutral energy resolution balance
- Timing resolution vs. other subsystems
- Mechanical issues: **manufacturing, inner detector mounting**

R&D at Regina:

•Monte Carlo

•Hardware: Readout, fibers, Pb/SciFi Matrix

What's a Hybrid?



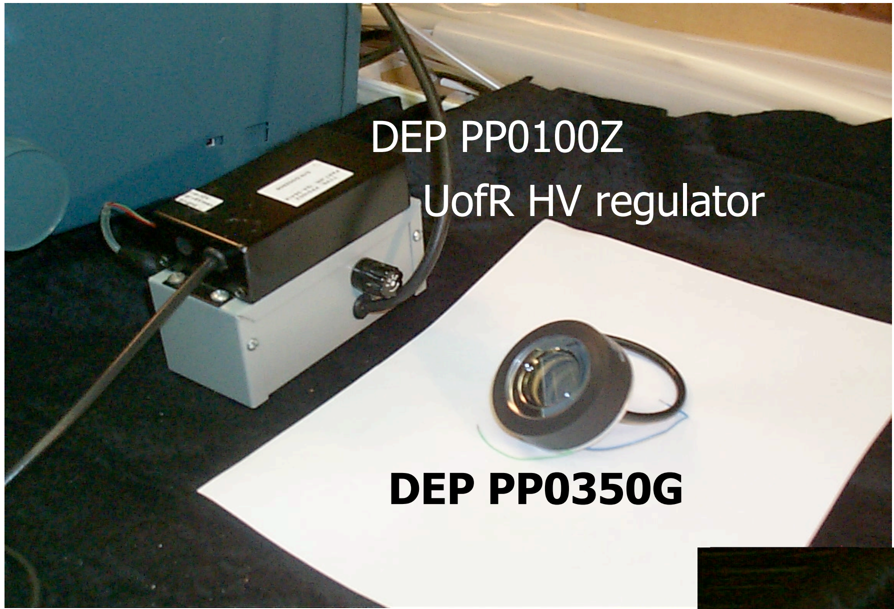
2 Tesla Central Field means HPMTs or 20m fiber light guides

- Proximity-focused vacuum tube
- Fast rise- and fall-time (2, 12 ns)
- High QE for UV, Gain is 10^5
- Insensitive to high magnetic fields

✓ HV: -8kV
✓ Bias: -80V
✓ Pre-amp
✓ Shaper

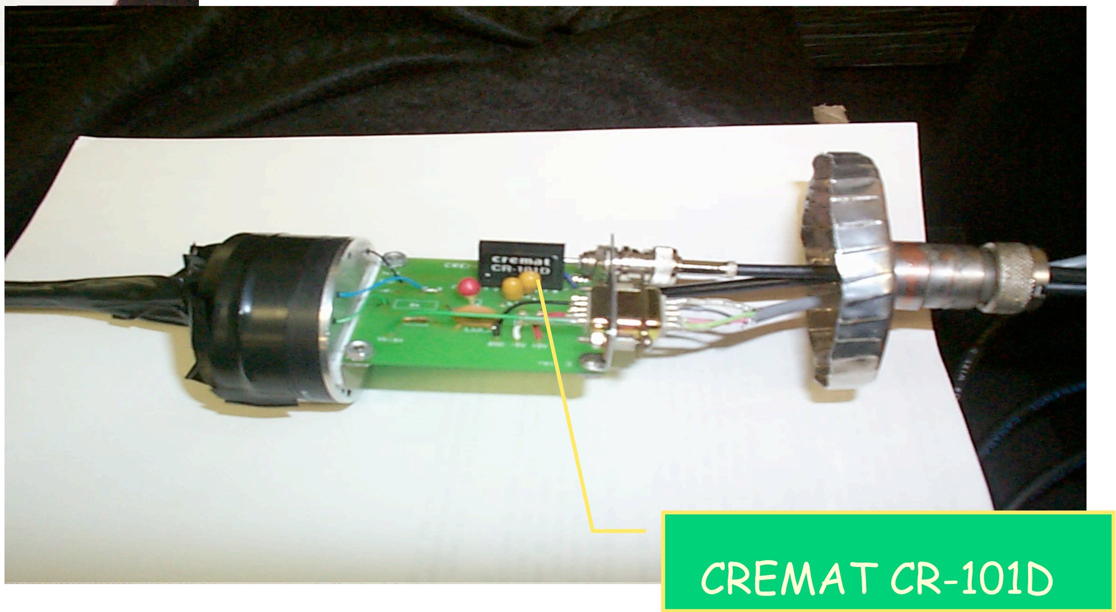
GlueX Citations Periment — Hall D at Jefferson Lab www.gluex.org

Hybrid PMT



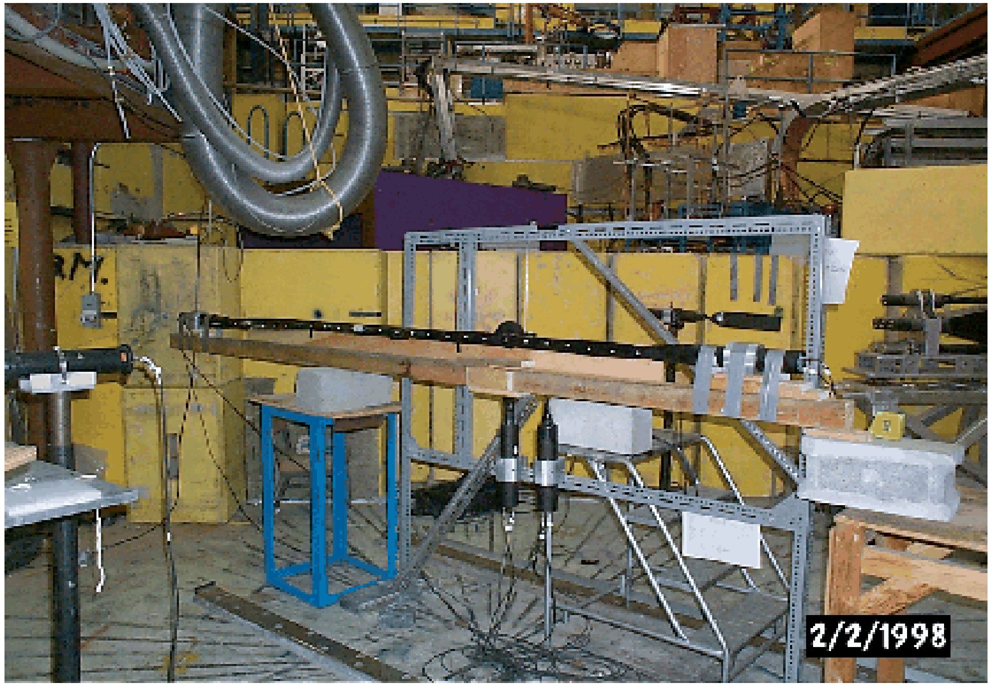
- R&D:
  - NaI detector
  - Scintillator
- Parameters measured

- System works:
  - Pre-amp
  - R&D on circuit
  - Price issue



Optical Fiber Tests with 100MeV pions

- Properties:
  - Light collection efficiency (cladding)
  - Scintillation light production (doping)
  - Light attenuation coefficient
  - Timing resolution
- Fibers Types (single-, double-clad)
  - Kuraray SCSF-81
  - Pol.Hi.Tech. 0046
  - Bicron (too expensive)



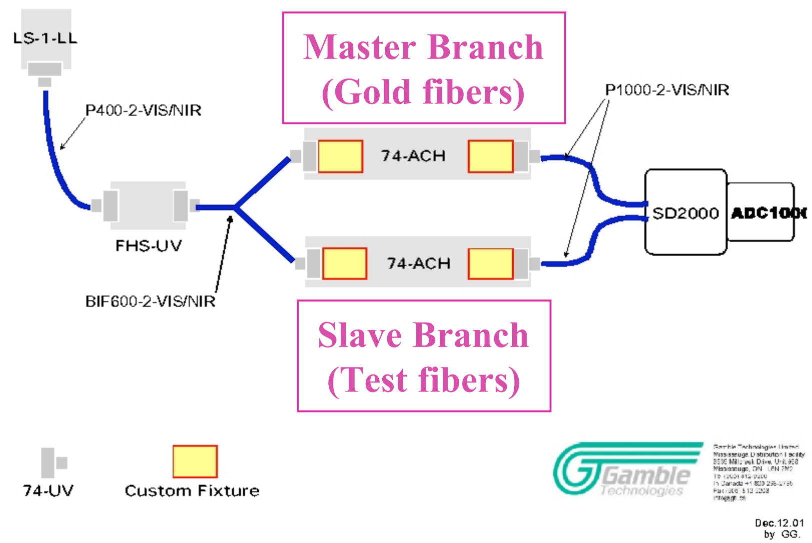
M11 Experimental Area at TRIUMF
August 2001

Attenuation: ~3m (Kuraray)

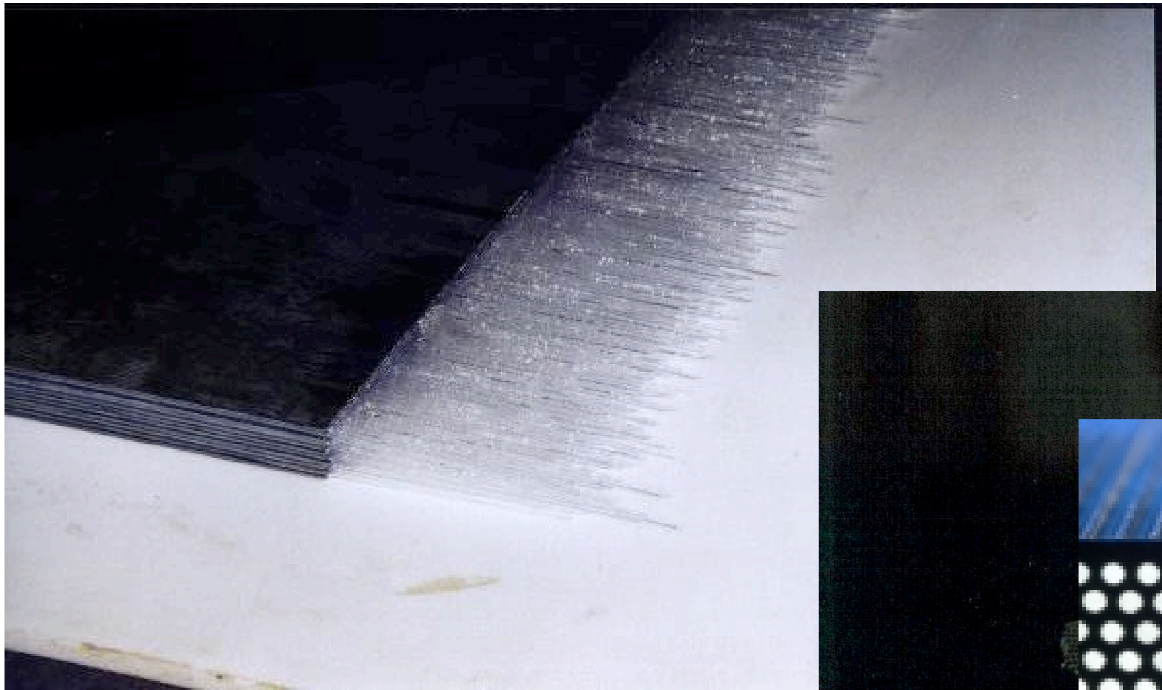
Performance/Price: (Pol.Hi.Tech.)

Fiber Optical Properties

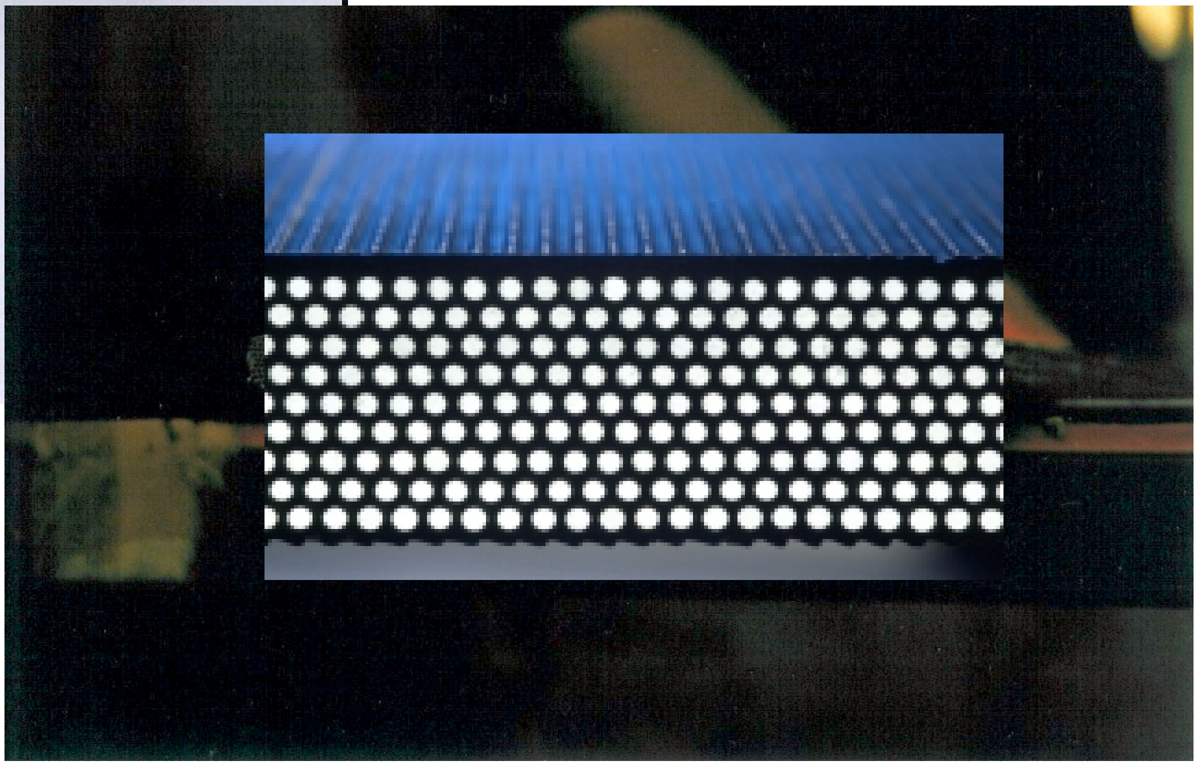
- **Quality Control of Fibers**
  - **Quick, reliable, reproducible**
- Commercial system was used
- Components: SD2000 spectrometer, ADC1000USB, laptop, fibers, neutral density filters, connectors, lenses, optical grease, light source.
- Kuraray, PHT fibers have been tested for transmission and attenuation.



Prototype Pb/SciFi Modules



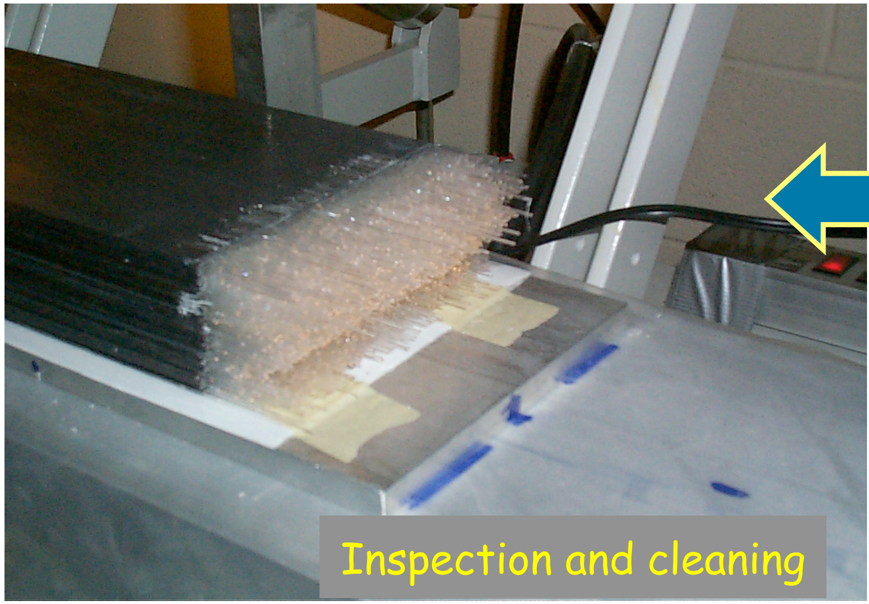
Frascati Module



Build in May 2002
with help from
KLOE Folks
P. Campana
F. Cervelli
e Technici

Prototype Module Construction

B. Klein, J. Kushniryk,
T.Summers, G. Williams



$96 \times 13 \times 10\ \mathrm{cm}^3$

70 kg

1-m “Baby” Module

Conclusions

- An outstanding and fundamental question is the nature of confinement of quarks and gluons in QCD.
- Lattice QCD and phenomenology strongly indicate that the gluonic field between quarks forms flux-tubes and that these are responsible for confinement.
- The excitation of the gluonic field leads to an entirely new spectrum of mesons and their properties are predicted by lattice QCD.
- But data are needed to validate these predictions.
- Only now are the tools in place to carry out the definitive experiment and JLab – with the energy upgrade – is unique for this search.
- If exotic hybrids are there, we will find them!

The right people are in place - ready to make this happen

We are eagerly awaiting CD-0 from the DOE.