University of Massachusetts, Nov. 20 2009

Hadron Physics
with polarized photons at 9 GeV with GlueX

Searching for gluonic excitations in the light meson spectrum using photoproduction

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Outline

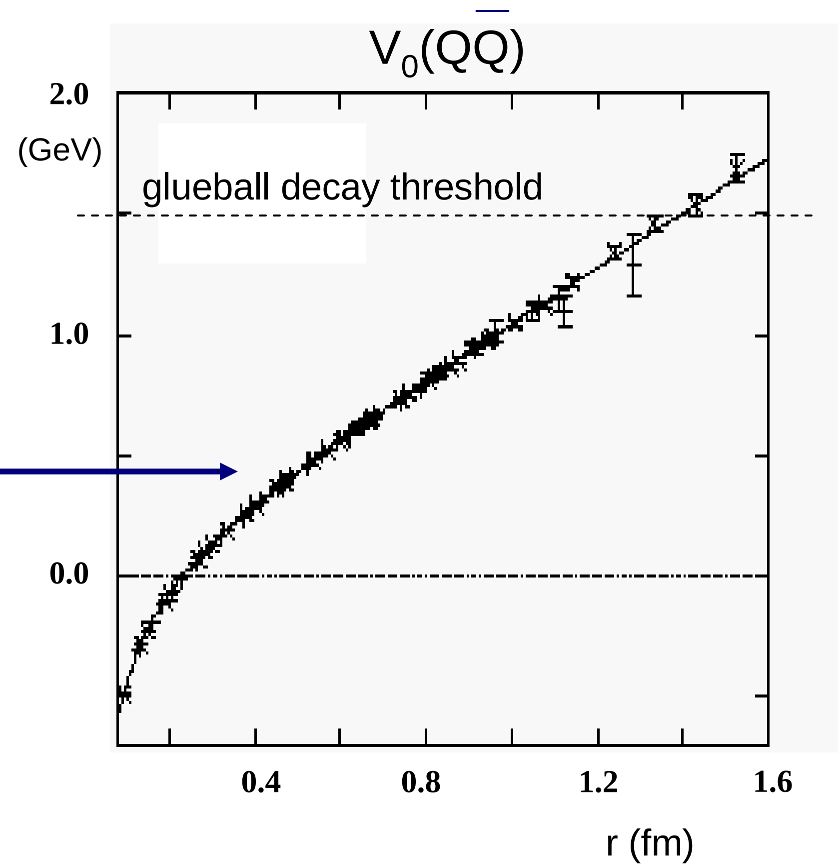
- Motivation
  - gluonic excitations in QCD
  - exotics in the light meson spectrum
  - photoproduction of hybrid mesons
- Gluex at Jefferson Lab @ 12 GeV
  - 9 GeV polarized photon beam
  - photon beam source and instrumentation
  - other physics addressed by Gluex
- Summary

Motivation: the hadron mass spectrum in QCD

Consider QCD with only heavy quarks:

Data from Lattice QCD show :

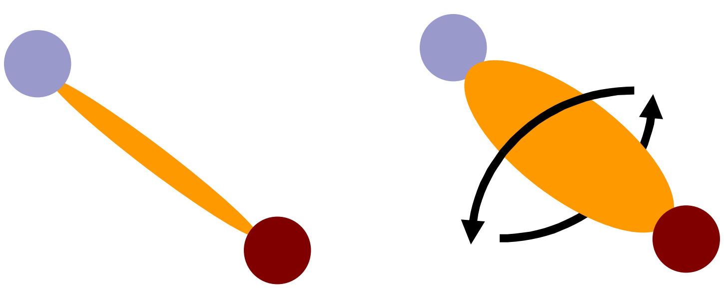
- the light mesons are glueballs
- $\bar{q}q$ mesons have the conventional positronium low-energy spectrum
- spectrum is distorted at higher excitations by a linear potential
- for r > 0.5 fm a tube of gluonic flux forms between $\bar{q}$ and q



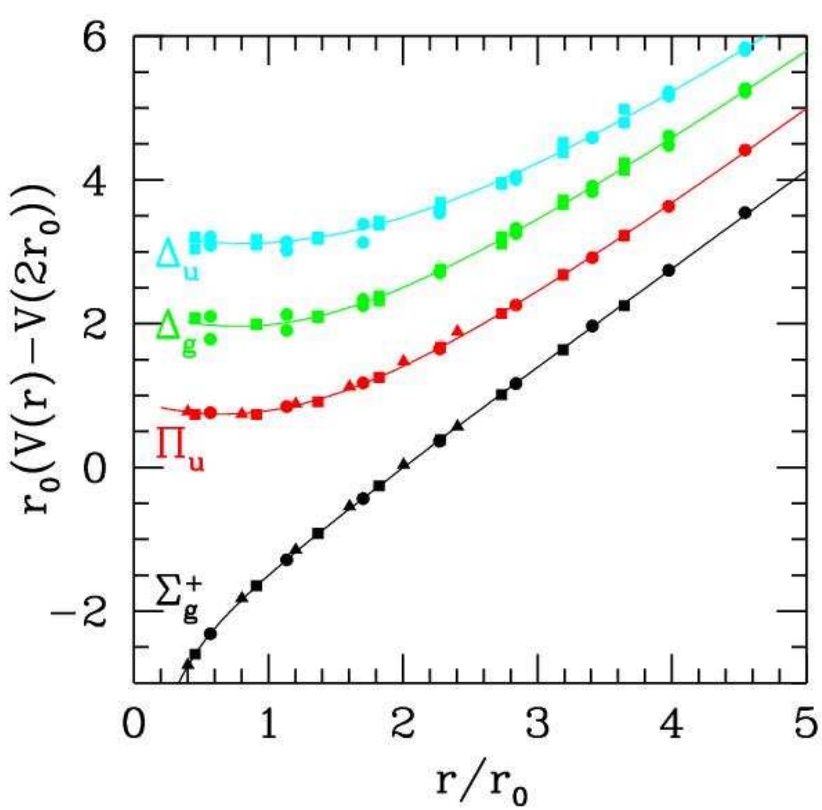
Motivation: the hadron mass spectrum in QCD

Consider QCD with only heavy quarks:

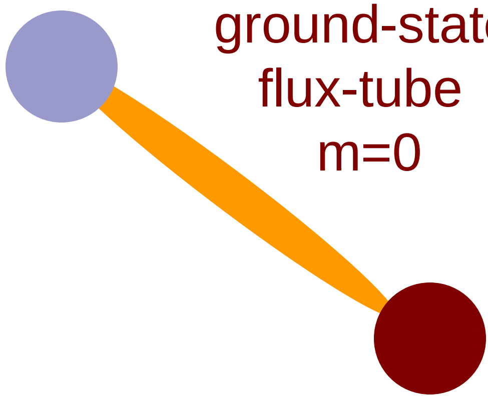
- gluonic excitations give rise to new potential surfaces
- for r >> r_0 gluonic excitations behave like flux tube oscillations

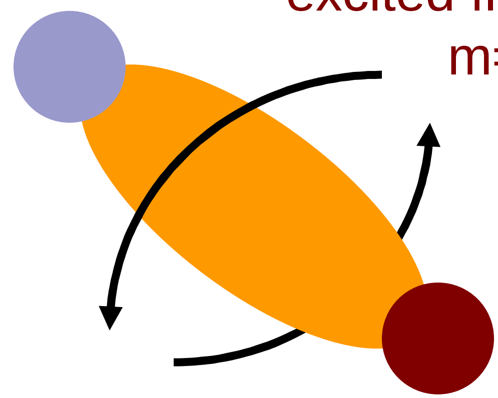


- inspires the **flux tube model**



Motivation: conventional *vs* hybrid mesons





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

Flux-tube Model

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

S=0, L=0

J=1 CP=+

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

(not exotic)

S=1, L=0

J=1 CP=-

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

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

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

exotic

Motivation: extrapolation to light quarks

- Does the flux-tube picture still make sense for light quarks?
  - quarks are relativistic
  - Fock subspaces mix ($q\bar{q}$, $q\bar{q}q\bar{q}$, …)
  - excited mesons are unstable (decays)
  - gluon fields modified by dynamical quarks (loops)

- Can experiments actually observe exotic states?
  - resonances may be broad – difficult to observe individually
  - configurations mix – exotic identification may be ambiguous
  - hybrids are embedded in a continuum of lighter 2-meson states
    - $q\bar{q}$ selection rules do not apply to 2-meson states
    - strong mixing may occur

Accounted for in quenched lattice studies, flux tube model

Requires unquenched lattice studies, advanced methods

Motivation: conventional *vs* hybrid mesons

Flux-tube model: 8 degenerate nonets

$1^{++}, 1^{--}$ (S=0) $0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$ (S=1) **~1.9 GeV/c^2**

Lattice calculations – 1^{-+} nonet is the lightest

UKQCD (97)	1.87 ± 0.20	GeV/c^2
MILC (97)	1.97 ± 0.30	GeV/c^2
MILC (99)	2.11 ± 0.10	GeV/c^2
Lacock (99)	1.90 ± 0.20	GeV/c^2
Mei(03)	2.01 ± 0.10	GeV/c^2
Bernard (04)	1.79 ± 0.14	GeV/c^2

~1.8 - 2.0 GeV/c^2

1^{-+}, 0^{+-}: Splitting $\approx$ 0.20 GeV/c^2

2^{+-}

In the charmonium sector:

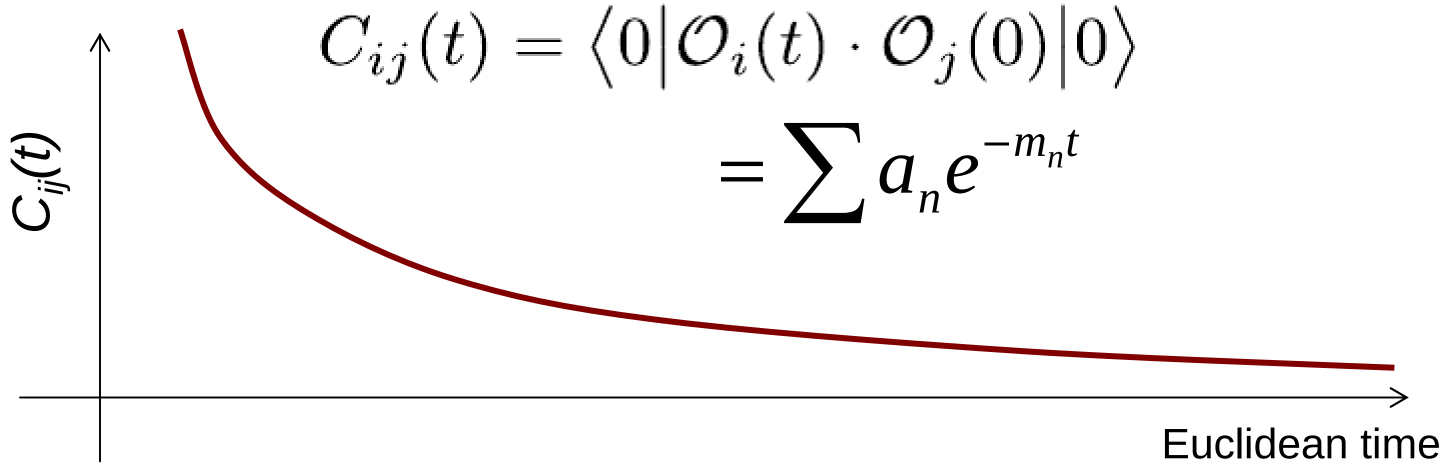
1-+	4.39 ± 0.08	GeV/c^2
0+-	4.61 ± 0.11	GeV/c^2

Splitting = 0.20 GeV/c^2

Recent results with unquenched lattices

- How excited state masses are extracted from LQCD data

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t) \cdot \mathcal{O}_j(0) | 0 \rangle$$
$$= \sum a_n e^{-m_n t}$$



- Jo Dudek *(INT workshop 11/2009)*

  "This fit is very unstable for all but the lowest mass in a given multiplet."

Recent results with unquenched lattices

- How excited state masses are extracted from LQCD data
- Dudek et.al. *(INT workshop 11/2009)*
  - QCD gives a choice of many operators with the same J^{PC} (made from γ matrices remixed as spherical tensors)

Note: All of these operators have the same $q\bar{q}$ character, different angular momentum and gluonic content.

$\bar{\psi}\Gamma\psi$ **J = 0,1**

$\langle 1, m_1; 1, m_2 | J, m\rangle \; \bar{\psi}\Gamma_{m_1} \overleftrightarrow{D}_{m_2}\psi$ **J = 0,1,2**

$\langle 1, m_1; J_D, m_D | J, m\rangle \langle 1, m_2; 1, m_3 | J_D, m_D\rangle \; \bar{\psi}\Gamma_{m_1} \overleftrightarrow{D}_{m_2} \overleftrightarrow{D}_{m_3}\psi$ **J = 0,1,2,3**

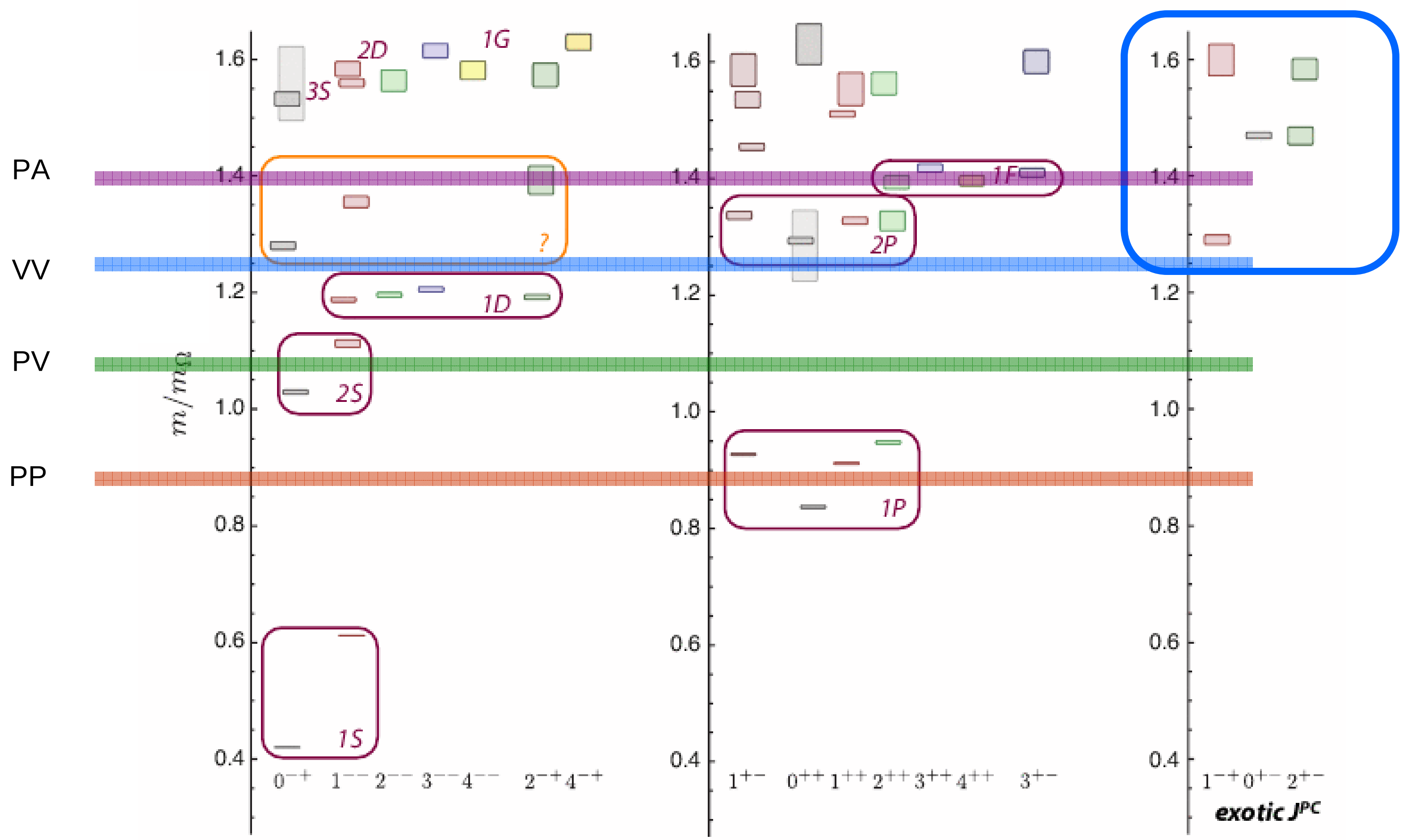
$$C_{ij}(t) = \sum_{\mathfrak{n}} \langle 0|\mathcal{O}_i(0)|M_{\mathfrak{n}}\rangle\langle M_{\mathfrak{n}}|\mathcal{O}_j(0)|0\rangle e^{-m_{\mathfrak{n}}t}$$

$$C_{ij}(t) = \sum Z_i^{\mathfrak{n}} Z_j^{\mathfrak{n}*} e^{-m_{\mathfrak{n}}t}$$

Diagonalize this coupling matrix, each operator will have only one exponential

Recent results with unquenched lattices

Dudek et.al., preliminary results @ pion mass 700 MeV/c²



Recent results with unquenched lattices

Dudek et.al., preliminary results @ pion mass 700 MeV/c²

- **Question: where are all the continuum states?**

  suggested answer:
  - $q\bar{q}$ operator set incomplete
  - variational method for diagonalizing ZZ* matrix can miss weak signals
  - plans – try again with a larger operator set, look at energy shifts with box size

$\omega\pi$ continuum near b_1 resonance

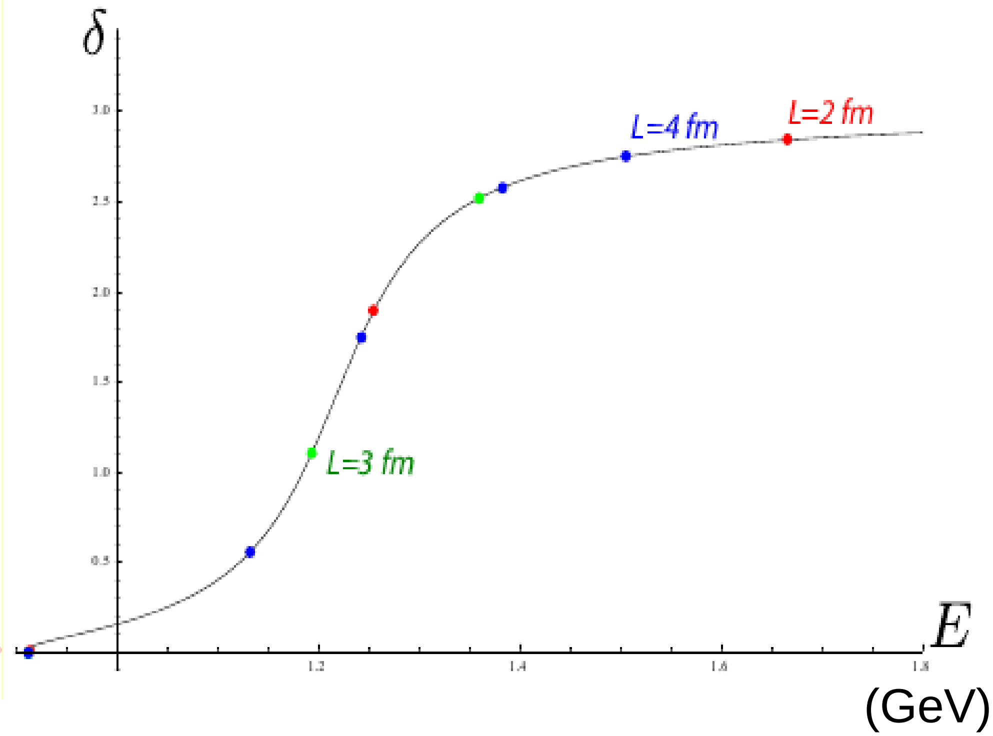
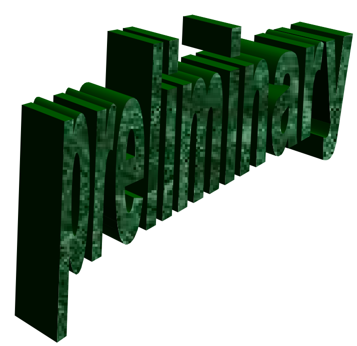


Illustration of Luscher's method

Motivation: summary so far

- QCD with only heavy quarks:
  - hierarchy of hadrons with gluonic excitations
  - mesons have a much simpler spectrum than baryons
  - some gluonic mesons have exotic quantum numbers – “hybrids”
  - lightest hybrid exotic multiplet is 1^{-+}, followed by 0^{+-} , 2^{+-}

- QCD with light(er) quarks:
  - requires unquenched LQCD, advanced techniques
  - mass splitting exotic—conventional states unchanged
  - mixing of $q\bar{q}$ and $q\bar{q}g$ states with continuum is weak
  - ***should be accessible to experiments !***



Experiment: hybrid searches

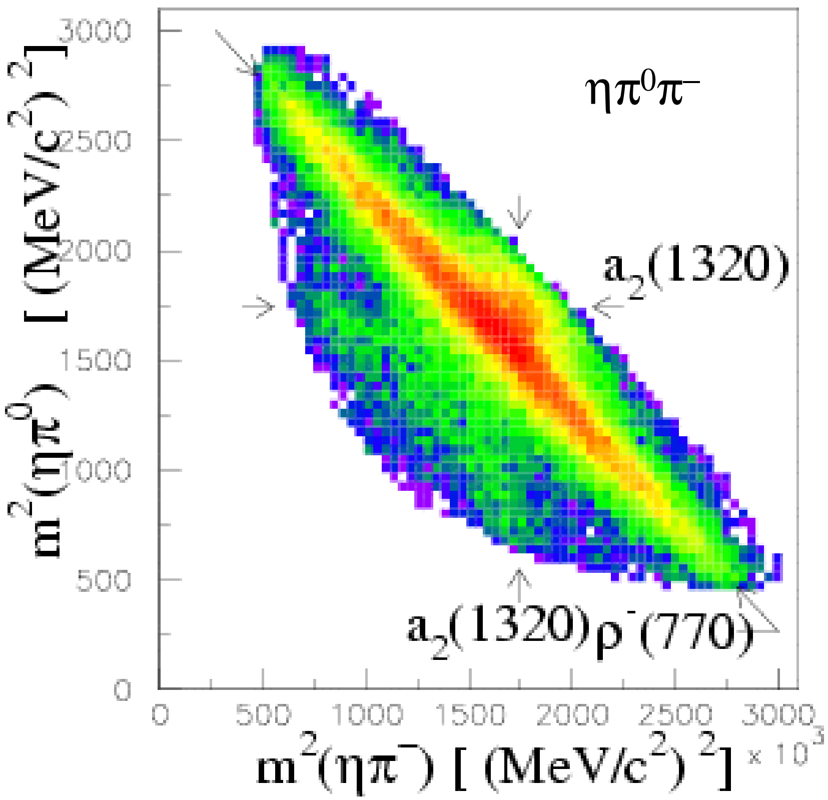
- Most of the attention is focused on 3 observed states:
  - $\pi_1(1400)$ – seen in $\eta\pi$ — E852, Crystal Barrel
  - $\pi_1(1600)$ – seen in $\rho\pi$, $f_1\pi$, $b_1\pi$, $\eta'\pi$ — VES, E852, Compass
  - $\pi_1(2000)$ – seen in $f_1\pi$, $b_1\pi$ — E852
- General observations regarding these analyses
  - all experiments (except CB) use pion beams
  - exotic intensities are typically 1/10 dominant ones
  - requires access to complex multi-particle final states
  - requires large samples (~10^6 in exclusive channels)
  - requires good acceptance (uniform and well-understood)

Experiment: $\pi_1(1400)$ from Crystal Barrel

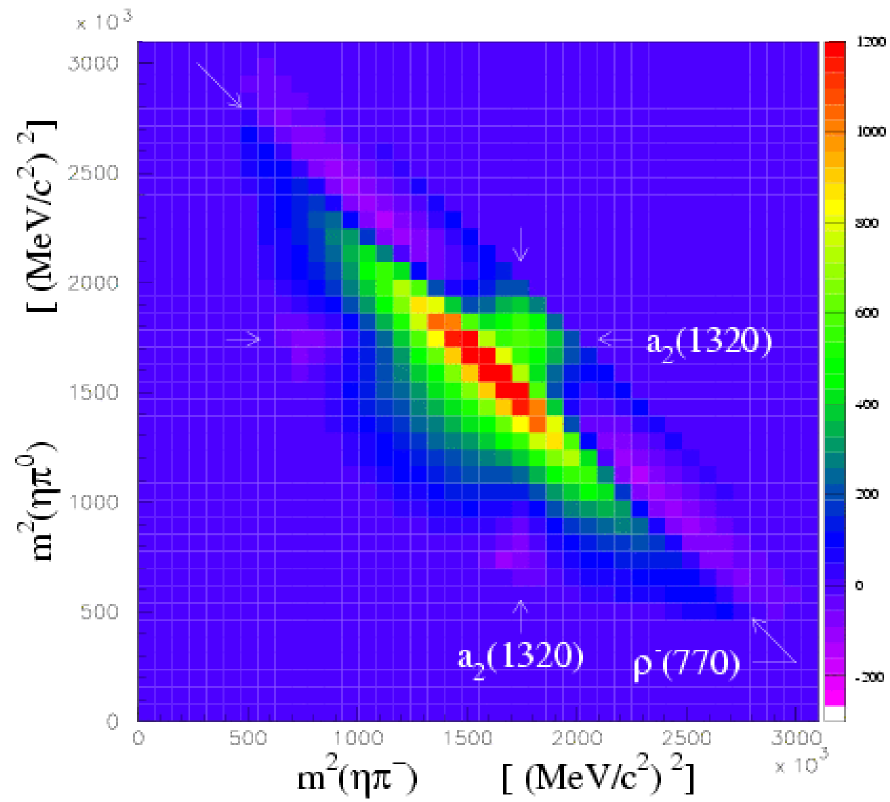
Mass = 1400 +- 20 +- 20 MeV/c^2

Width = 310+-50$^{+50}_{-30}$ MeV/c^2

without π_1 χ^2/dof = 3, with = 1.29



PWA fit to Dalitz plot:
π_1 wave needed with same strength as the a_2

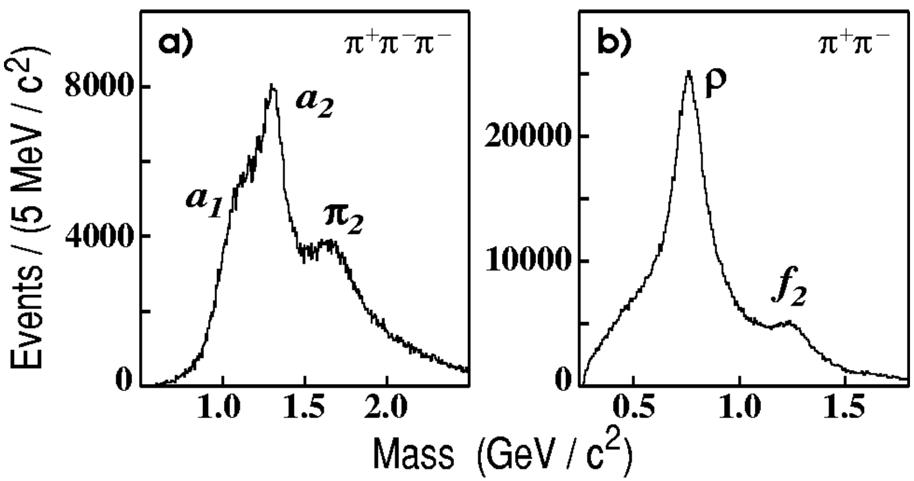


Experiment: $\pi_1(1600)$ from BNL-852

Mass = 1598 ±8+29-47 MeV/c^2
Width = 168±20+150-12 MeV/c^2

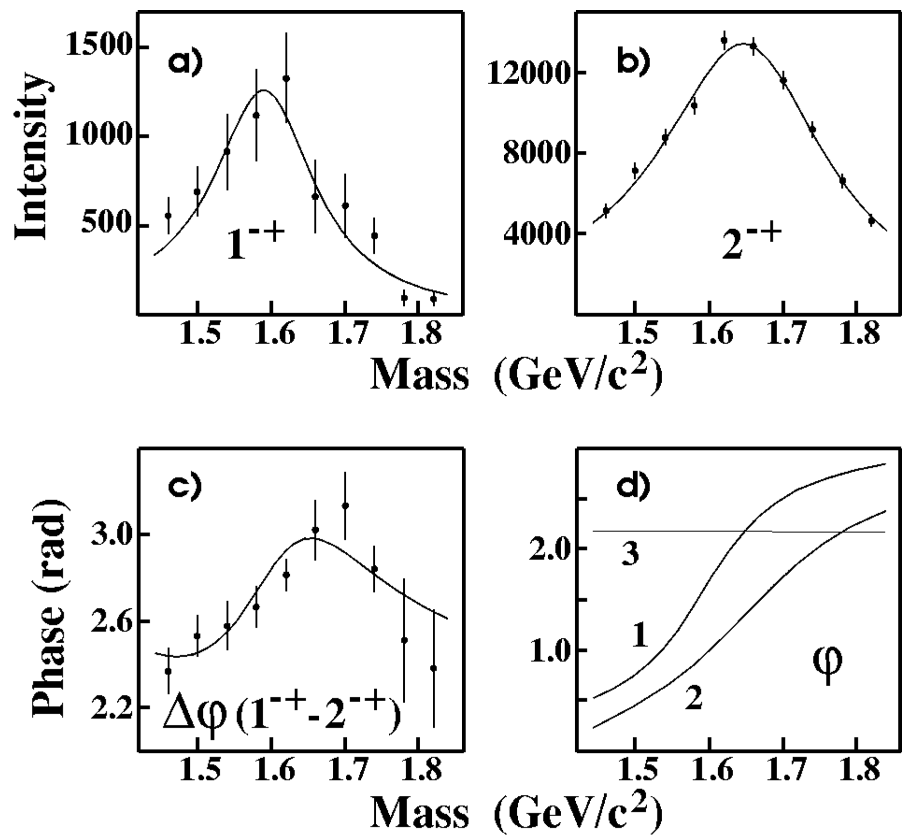
$$\pi^- p \to \pi^- \pi^- \pi^+ p$$

(~250,000 Events)



Partial Wave Analysis

$\pi_1(1600) \to \rho\pi$



Experiment: $\pi_1(1600)$ from BNL-852

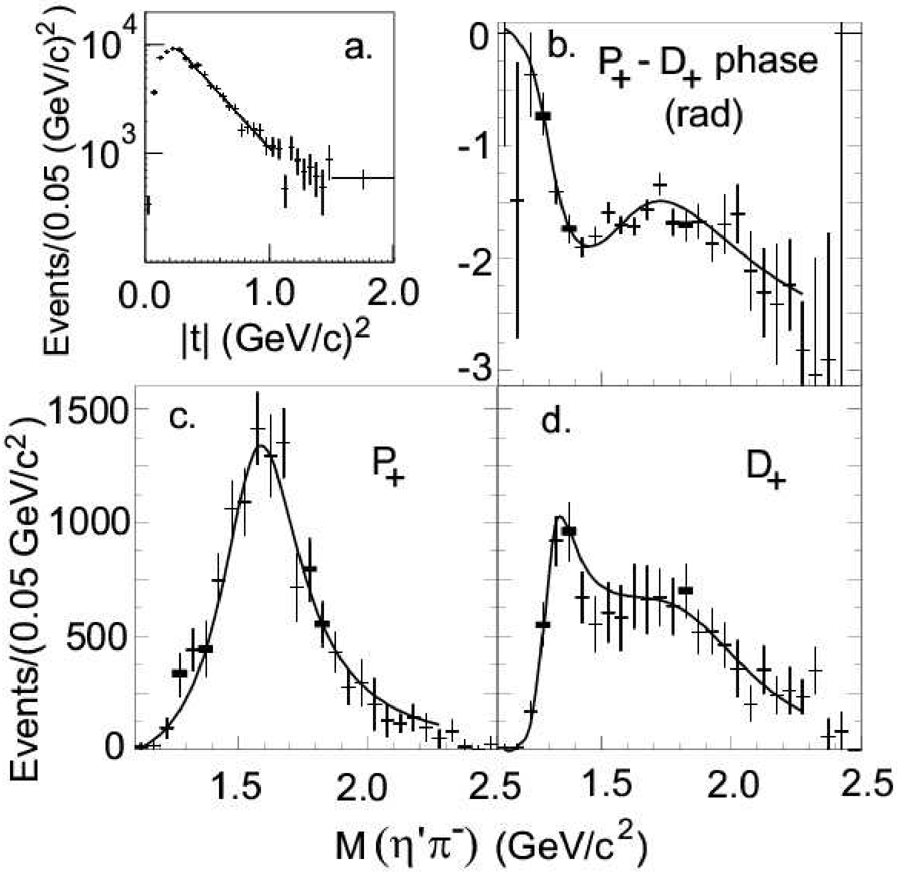
Mass = 1597±10+45-10 MeV/c^2
Width = 340±40±50 MeV/c^2

$\pi^- p \rightarrow \eta' \pi^- p$

The exotic wave is the dominant wave in this channel.

Partial Wave Analysis

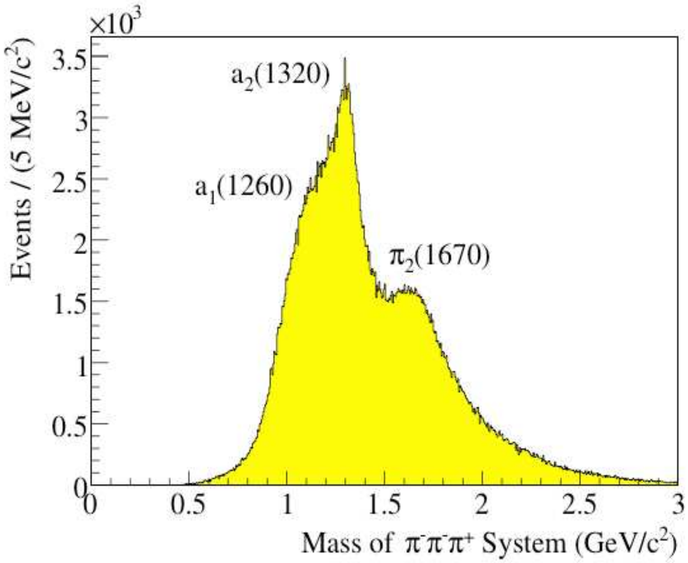
(~6000 Events)



Experiment: π_1(1600) from Compass

Mass = 1660 MeV/c^2
Width = 269 MeV/c^2

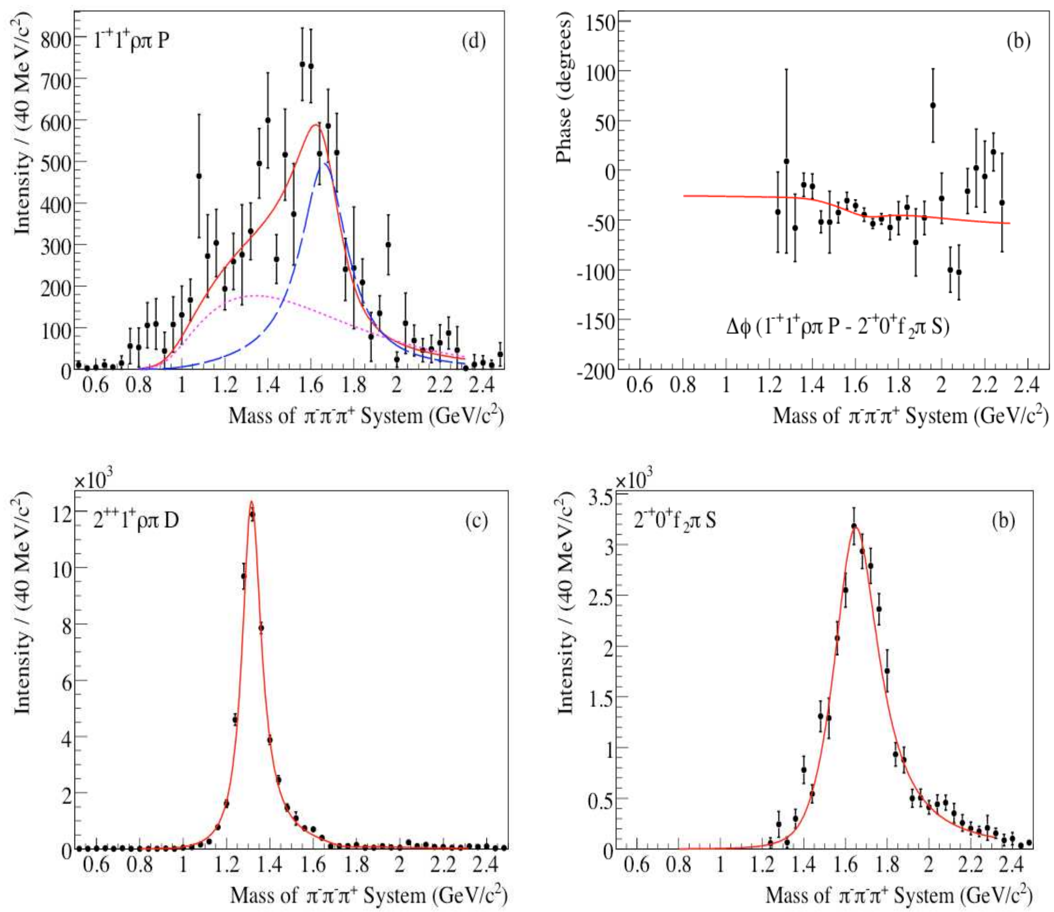
$$\pi^- Pb \rightarrow \pi^+\pi^-\pi^-(Pb)$$



(180 GeV pions, 420,000 events)

Partial Wave Analysis, preliminary

arXiv:0910.5842 – unpublished



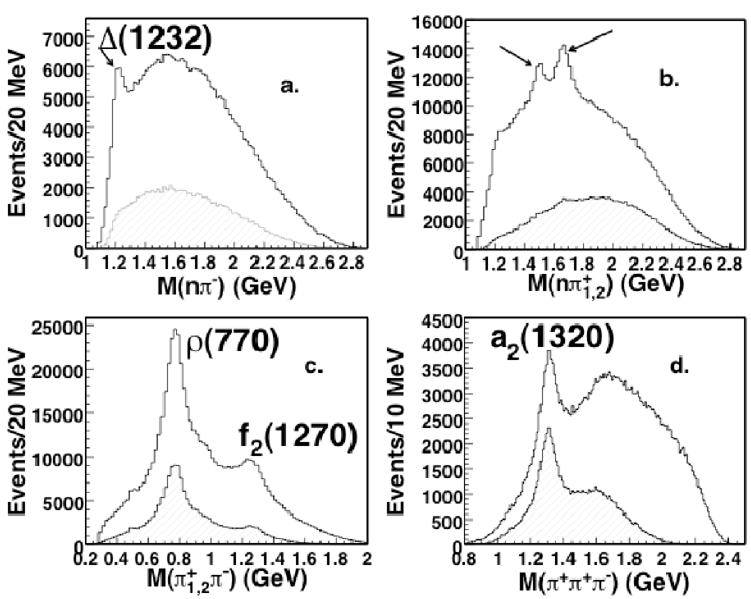
Experiment: $\pi_1(1600)$ from CLAS ?

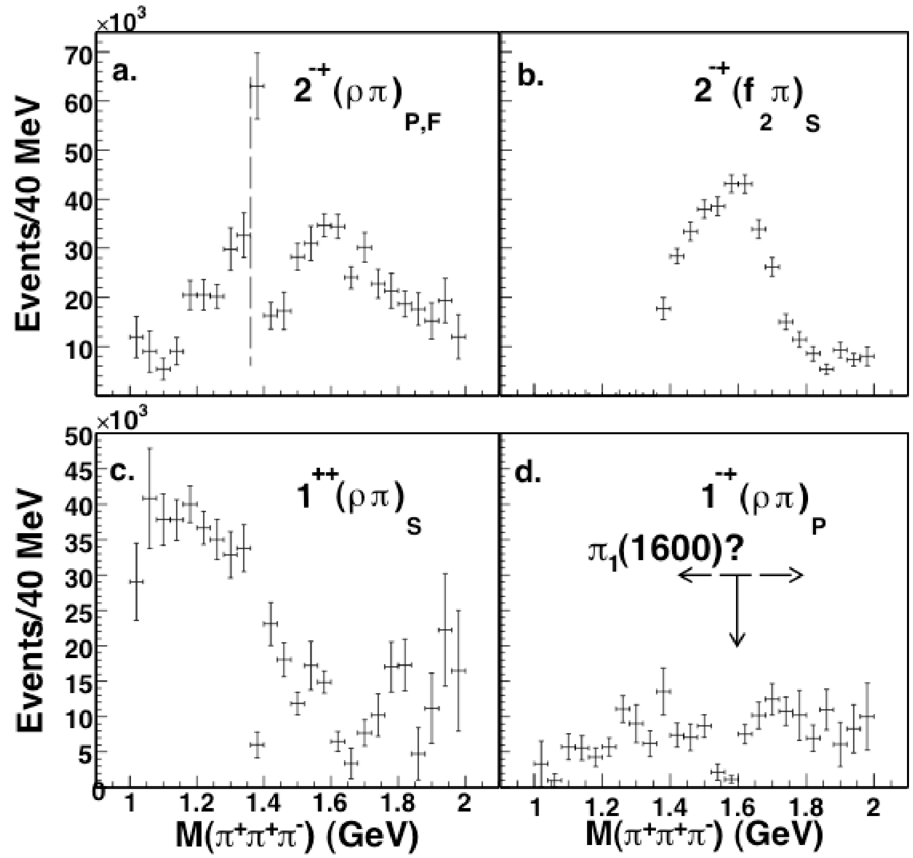
No evidence of $\pi_1(1600) \rightarrow \rho\pi$, (13.5 nb upper limit).

$E_\gamma = 4.8 - 5.4$ GeV
83000 events after all cuts
final acceptance < 5%

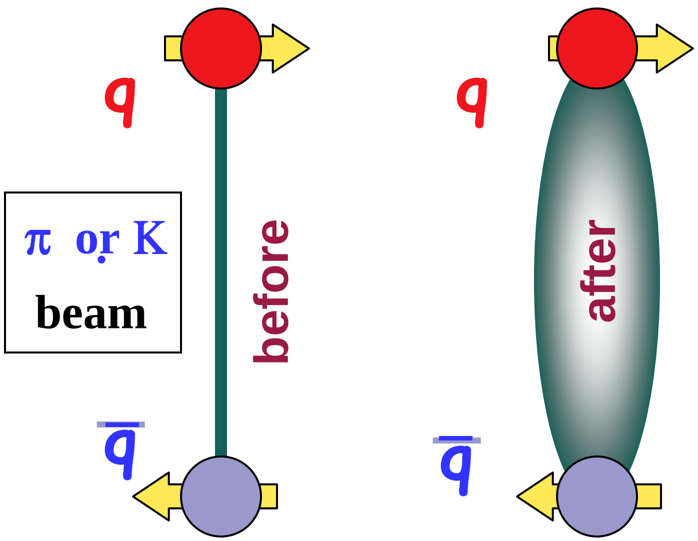
$\gamma p \rightarrow n\pi^+\pi^+\pi^-$

Baryons "removed" by hard kinematic cuts.





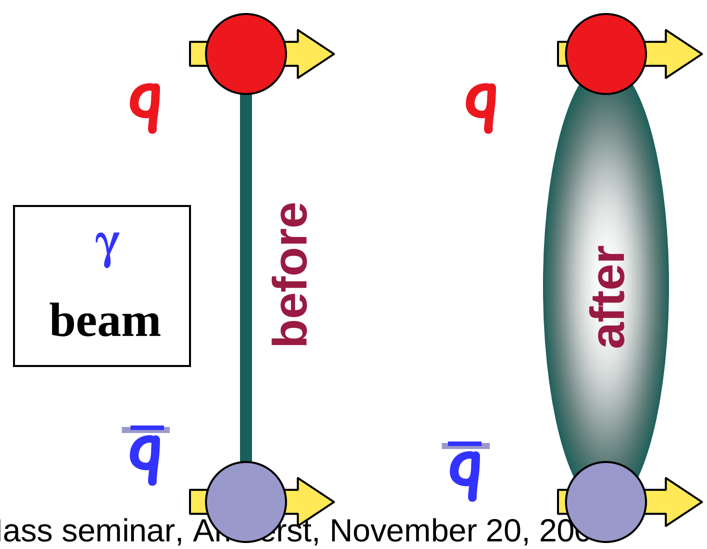
Argument: hybrid photoproduction



Quark spins anti-aligned

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

Data from these reactions show
evidence for gluonic excitations
(small part of cross section)

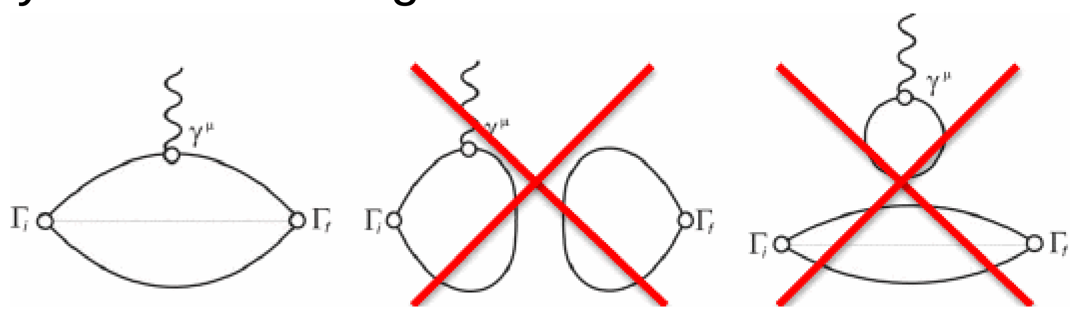


Quark spins aligned

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

Hybrid photon couplings on the lattice

- very little is known
- preliminary results for charmonium 1^{-+} hybrid
  Dudek, Edwards, Thomas PRD79 094504 (2009)
  - quenched (only charmed quarks)
  - only one lattice volume, one lattice spacing
  - only connected diagrams



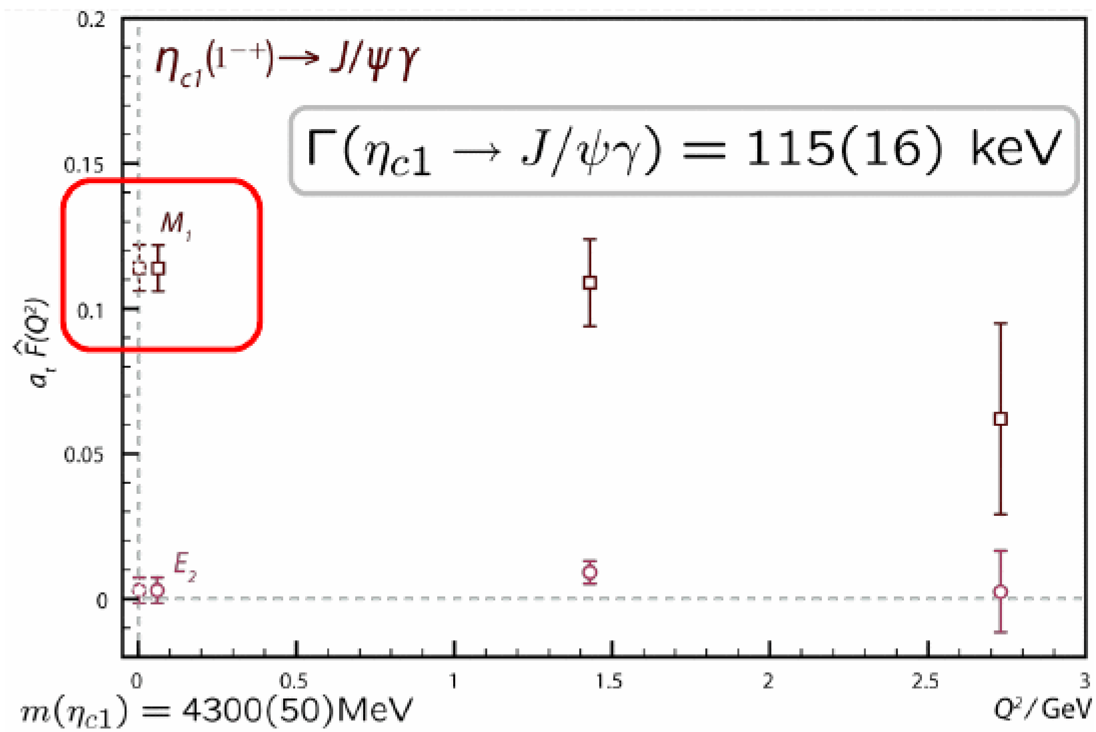
  - disconnected diagrams may be suppressed by OZI rule

Hybrid photon couplings on the lattice

- very little is known
- preliminary results for charmonium 1^{-+} hybrid
  Dudek, Edwards, Thomas PRD79 094504 (2009)

authors comment:

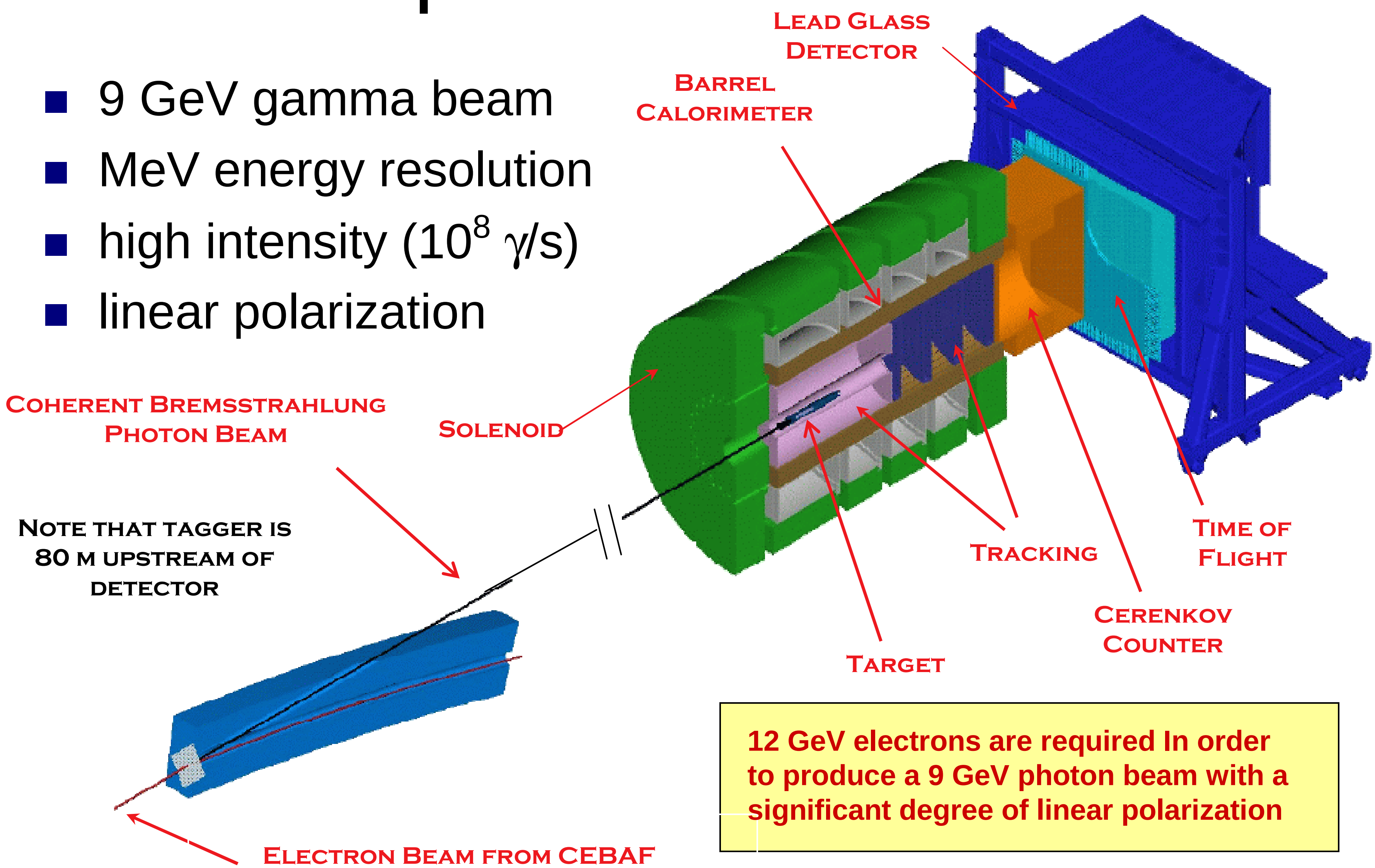
- same scale as many measured EM transitions to conventional cc states
- very large for M1 – eg. $\Gamma(J/\psi \to \gamma\eta_c) \sim 2$ KeV consistent with spin-triplet configuration for hybrid.
- no suppression of photocouplings for hybrids



GlueX Experiment

www.gluex.org

- 9 GeV gamma beam
- MeV energy resolution
- high intensity (10^8 γ/s)
- linear polarization



12 GeV electrons are required In order to produce a 9 GeV photon beam with a significant degree of linear polarization

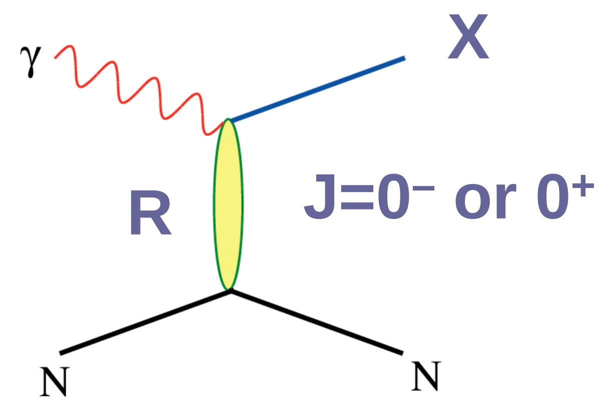
GlueX Experiment: beam polarization

Gottfried-Jackson frame

for R with J = 0

$$L = 0,\ 1,\ \text{or}\ \ 2$$

$$P_V = P_\gamma \cdot P_X \cdot (-1)^L$$



Suppose we want to distinguish the exchange: O^+ from 0^- (A^N from A^U)

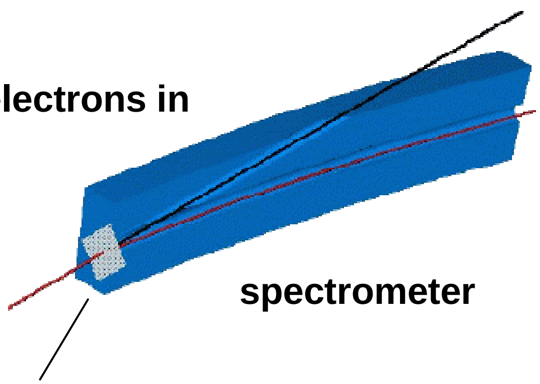
- With linear polarization we can isolate A^N from A^U
- Circular polarization gives access to their interference

For circular polarization:

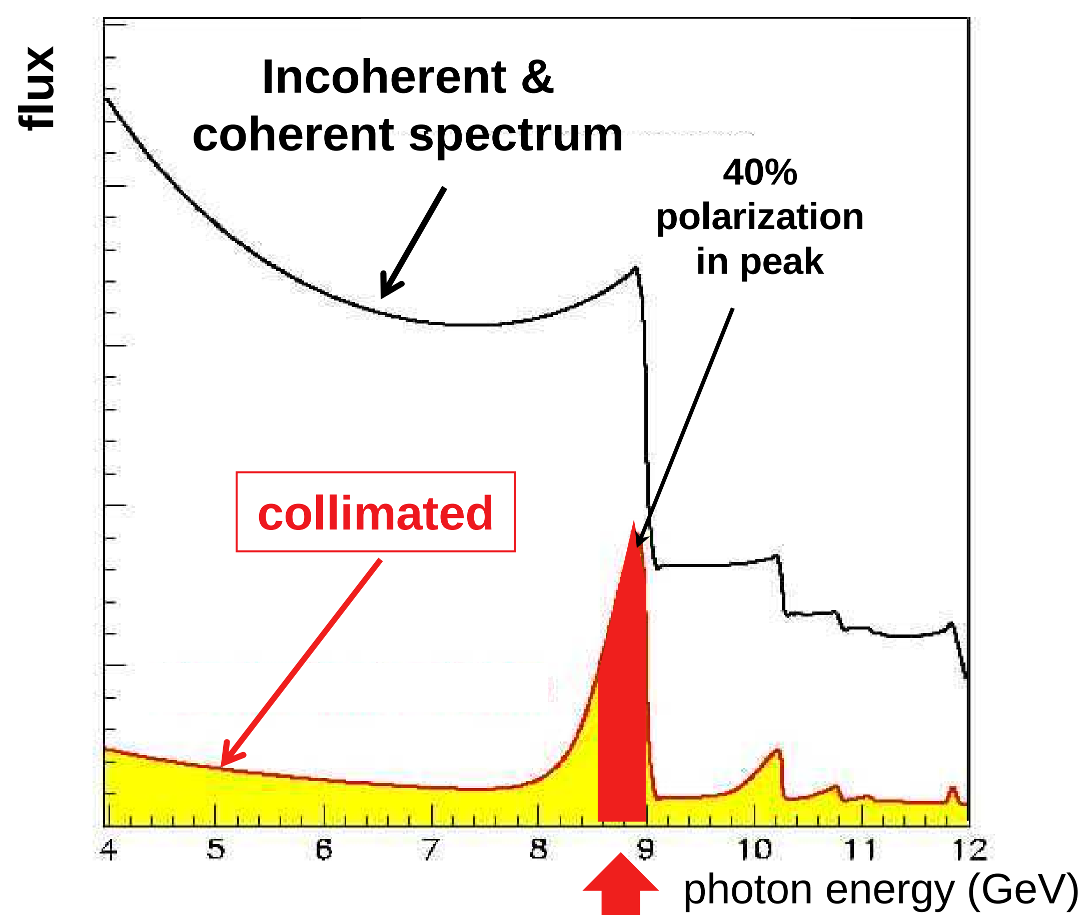
	photon		V = vector	
$\lvert R\rangle$		m = 1		$A^N + A^U$
$\lvert L\rangle$		m = -1		$A^N - A^U$

GlueX Experiment: photon beam

The coherent bremsstrahlung technique provides requisite energy, flux and polarization



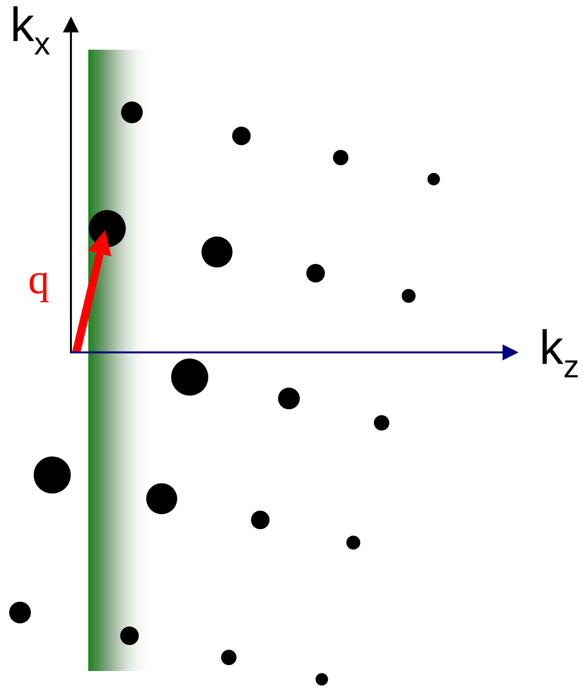
12 GeV electrons



tagged
with 0.1% resolution

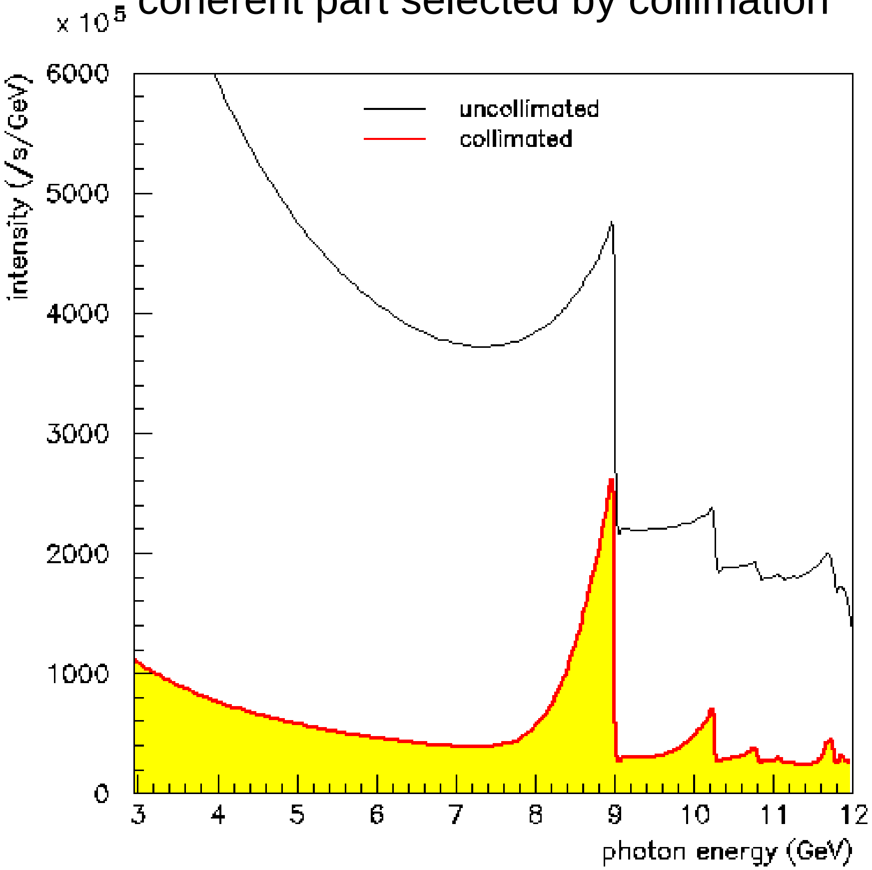
coherent bremsstrahlung

in k-space



large coherent gain

coherent part selected by collimation



What sets the scale for the maximum achievable coherent gain?

coherent bremsstrahlung

- coherent scattering: rate ~ (target thickness)^2
- limited by something => "coherence length"
  - "duration" of bremsstrahlung radiative process
  - Landau-Pomeranchuk-Migdal effect

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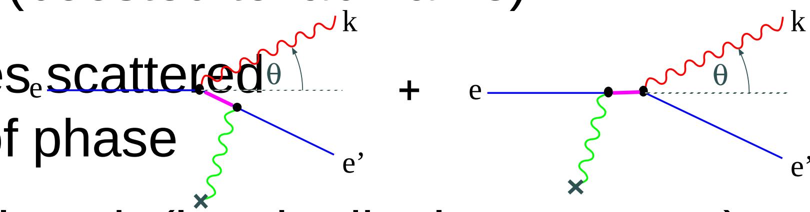
1. In an infinite crystal, radiation of a hard photon is localized (somewhat)

- HUP for off-shell electron (boosted to lab frame)
- distance over which waves scattered earlier and later drift out of phase



- momentum transfer wavelength (longitudinal component)

All three of these amount to the same thing!

$\sim \frac{E-k}{k}$ for E=12 GeV, k=9 GeV, cl = 6 nm, about 20 diamond unit cells

coherent bremsstrahlung

- coherent scattering: rate ~ (target thickness)^2
- limited by something => "coherence length"
  - "duration" of bremsstrahlung radiative process
  - Landau-Pomeranchuk-Migdal effect

---

2. In an infinite crystal, the coherence length cuts off at the mean distance between radiation events – the LPM effect

   - radiation rate diverges at long wavelengths – always present!
   - for 9 GeV photons, 12 GeV electrons:

cl < 50 cm (due to LPM cutoff)

- so what *does* place physical limits on radiator thickness?

  1. ***multiple scattering***
  2. ***radiation damage***

Gluex Photon Beam Collimation Geometry

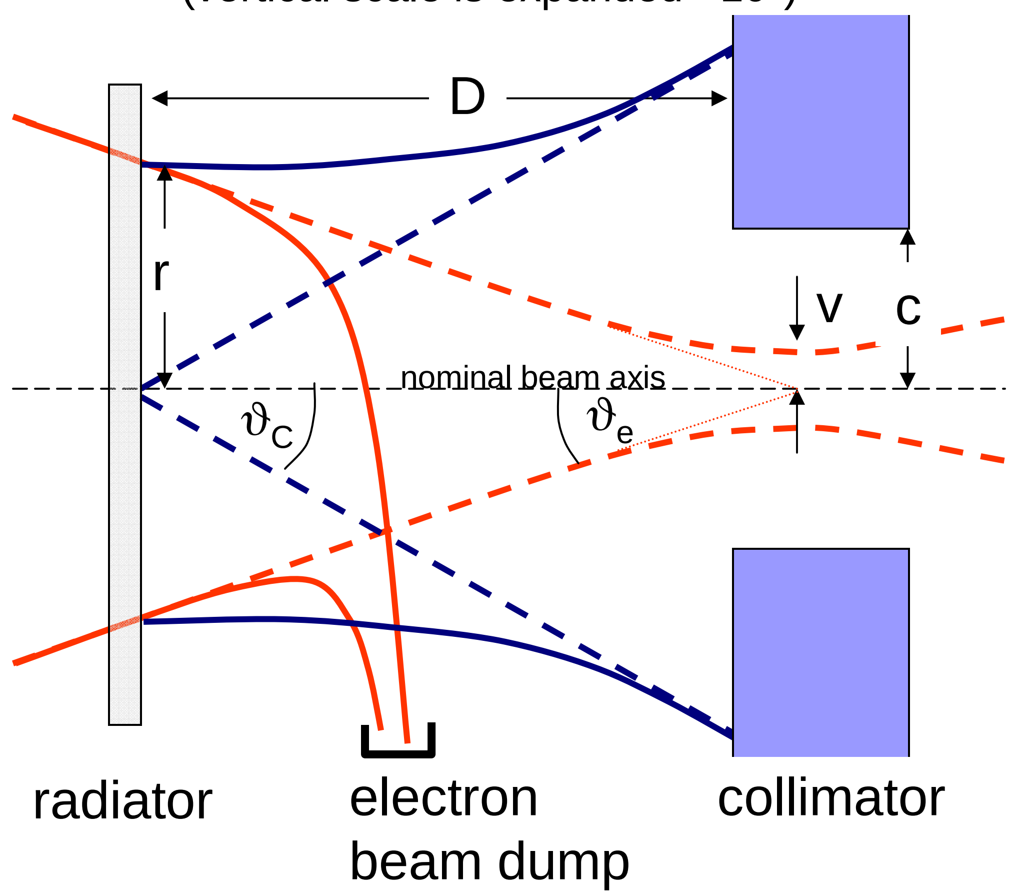
ε: beam emittance (rms)
ϑ_e : electron beam divergence angle
ϑ_C: characteristic bremsstralung angle

(1) $\varepsilon = v\,\vartheta_e$
(2) $r = D\,\vartheta_e$
(3) $c = D\,\vartheta_C / 2$

$v \ll c \longrightarrow \varepsilon \ll r\,\vartheta_C / 2$

$\varepsilon \ll 3 \times 10^{-8}$ m.r

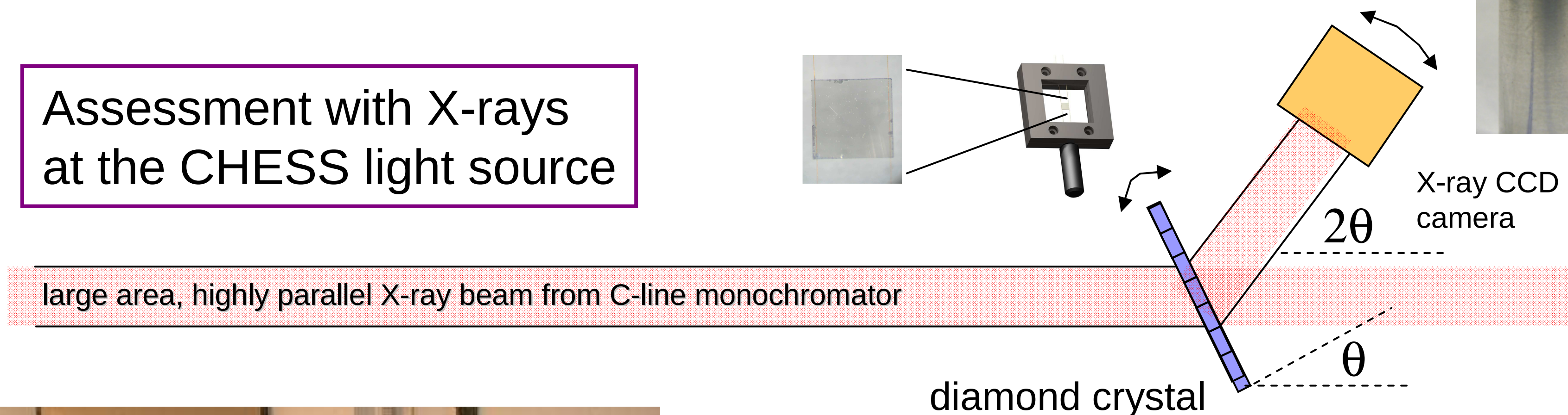
(vertical scale is expanded ~10^5)

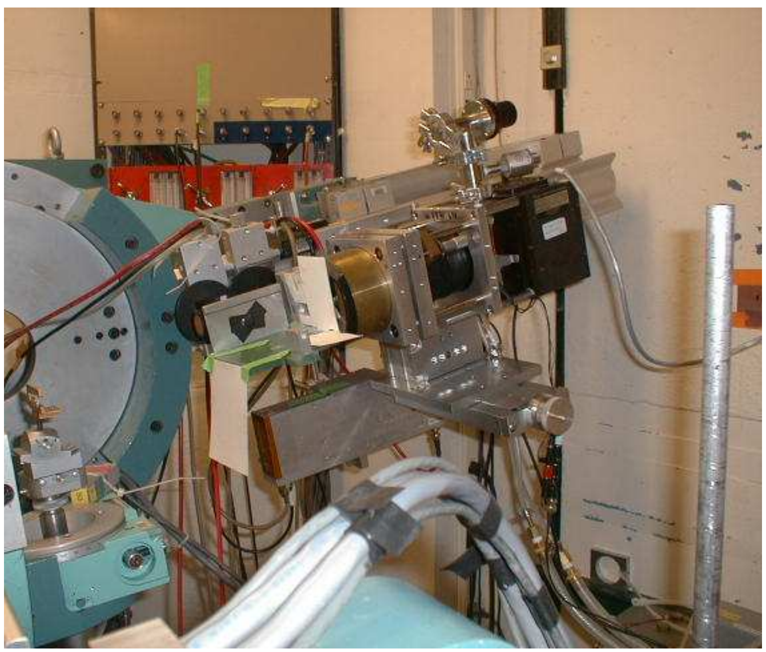


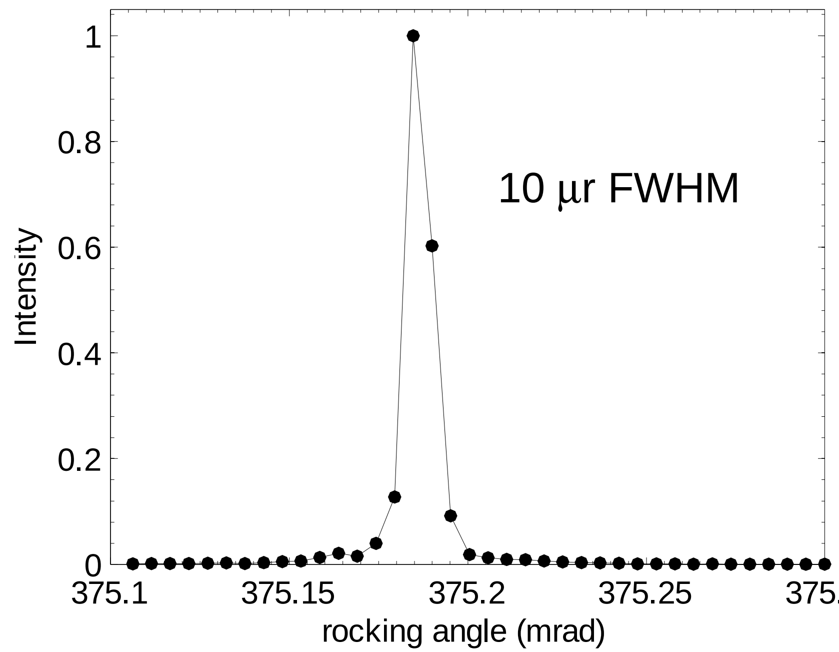
must include multiple scattering => limits radiator thickness to 20μm

Diamond radiators for Gluex

Assessment with X-rays at the CHESS light source







Diamond crystal requirements: lifetime

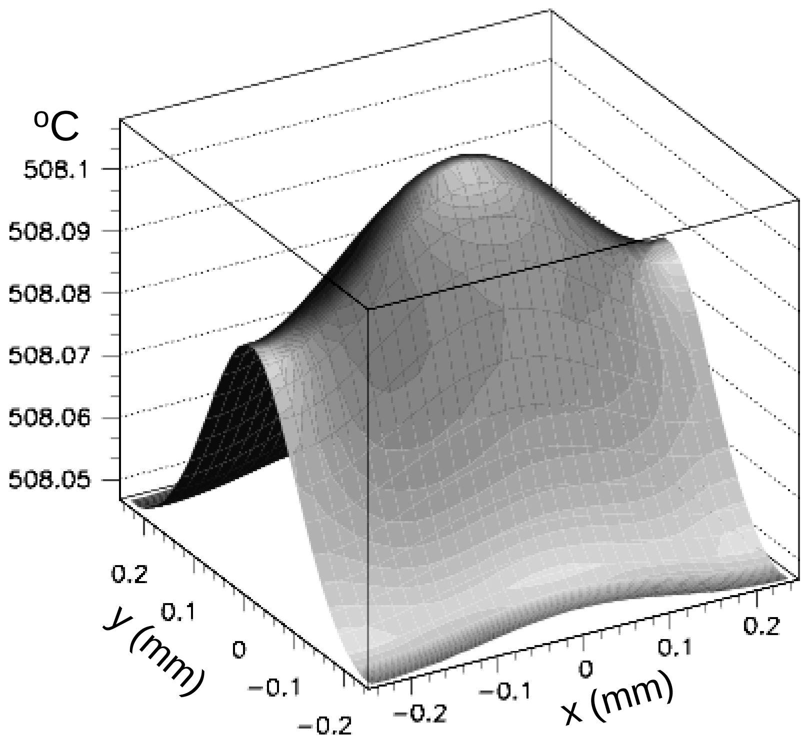
- conservative estimate (SLAC) for useful lifetime (before significant degradation):

0.25 C / mm²

- conservative estimate: **3-6 crystals / year** of full-intensity running

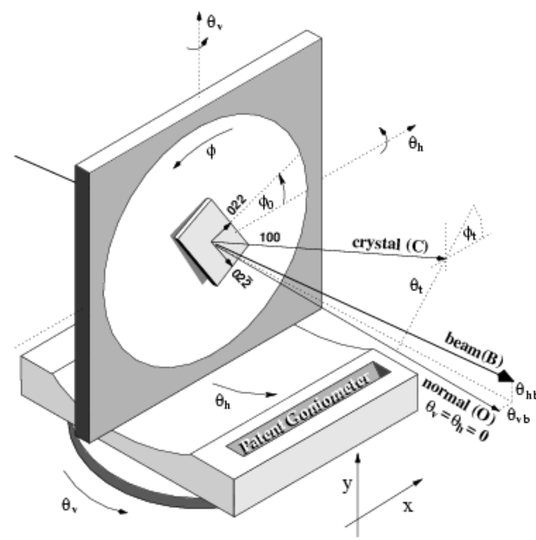
Diamond crystal requirements: mounting

temperature profile of crystal
at full intensity, radiation only



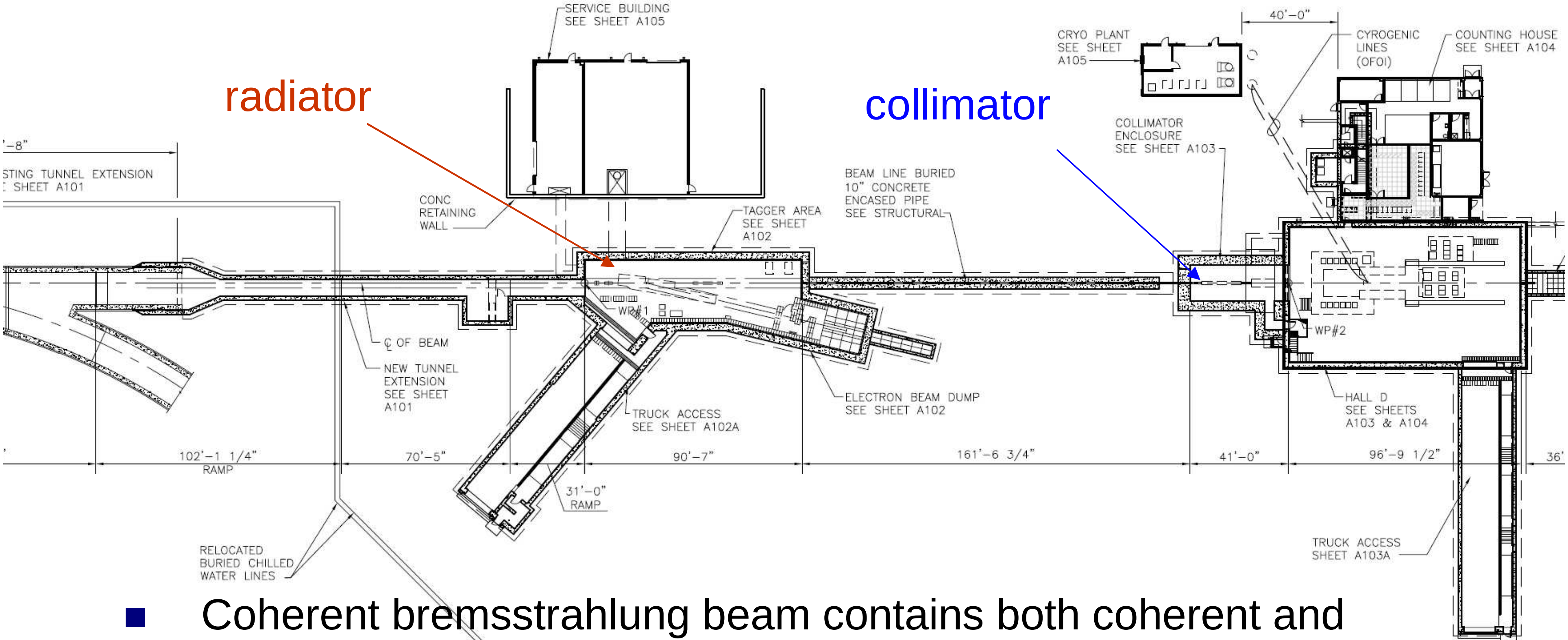
diamond-graphite transition sets in ~1200°C

Heat dissipation specification for the mount is not required.



translation step:	200 μm horizontal 25 μm target ladder (fine tuning)
rotational step:	1.5 μrad pitch and yaw 3.0 μrad azimuthal rotation

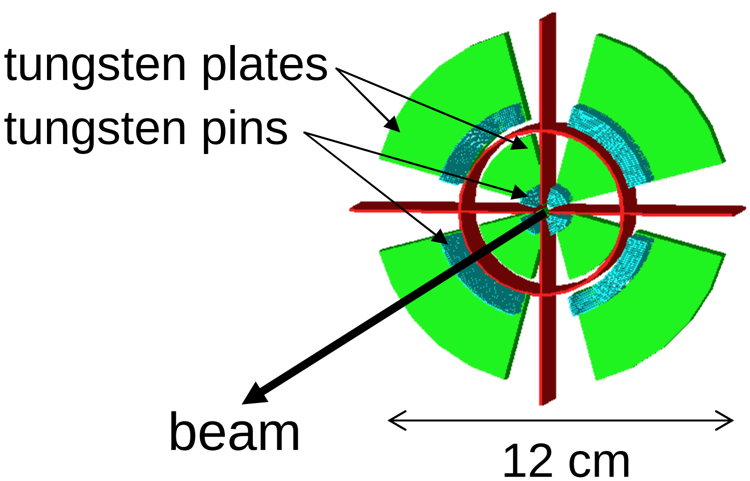
Hall D Beam Line



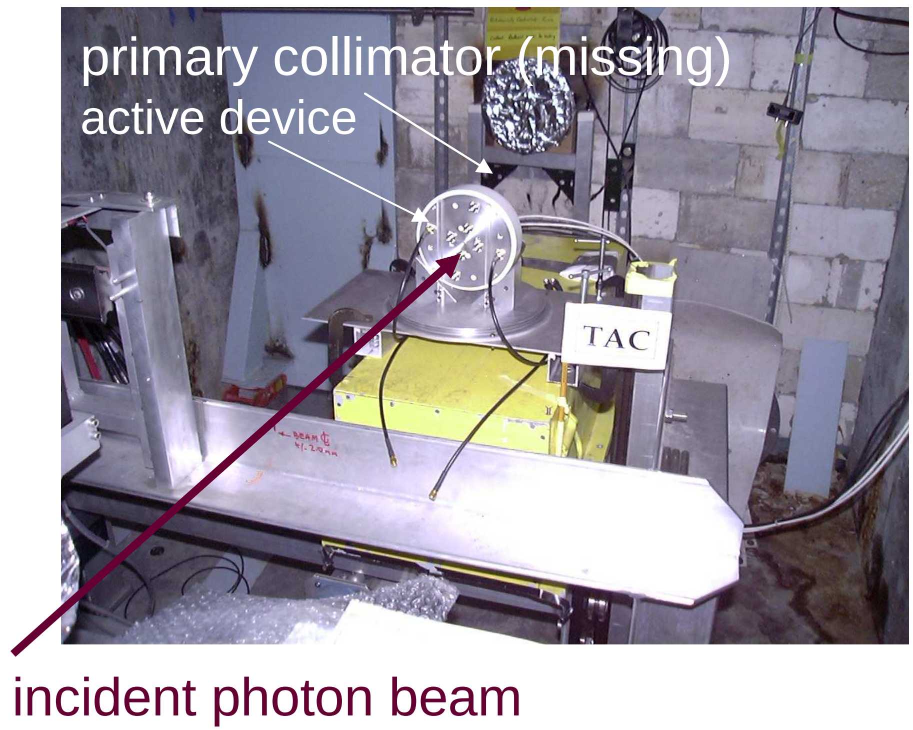
- Coherent bremsstrahlung beam contains both coherent and incoherent components.
- Only the coherent component is polarized.
- Incoherent component is suppressed by narrow collimation.

Active Collimator Design

- [Tungsten pin-cushion detector]
  - reference: **Miller and <u>Walz</u>, NIM 117 (1974) 33-37**
  - measures current due to knock-ons in EM showers



beam test in Hall B in April 2007

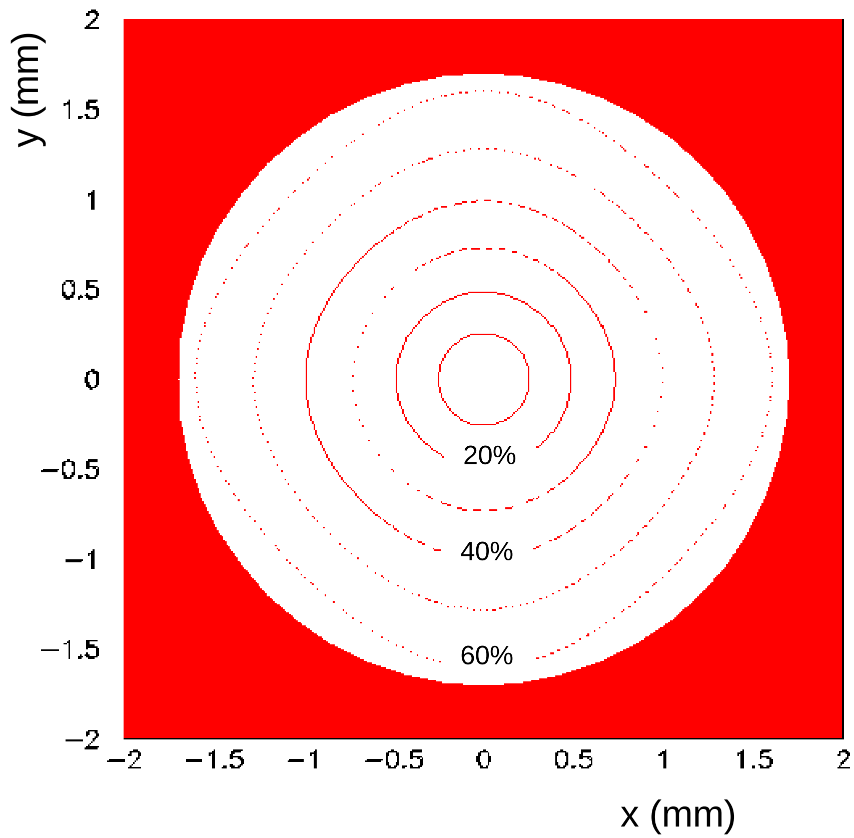


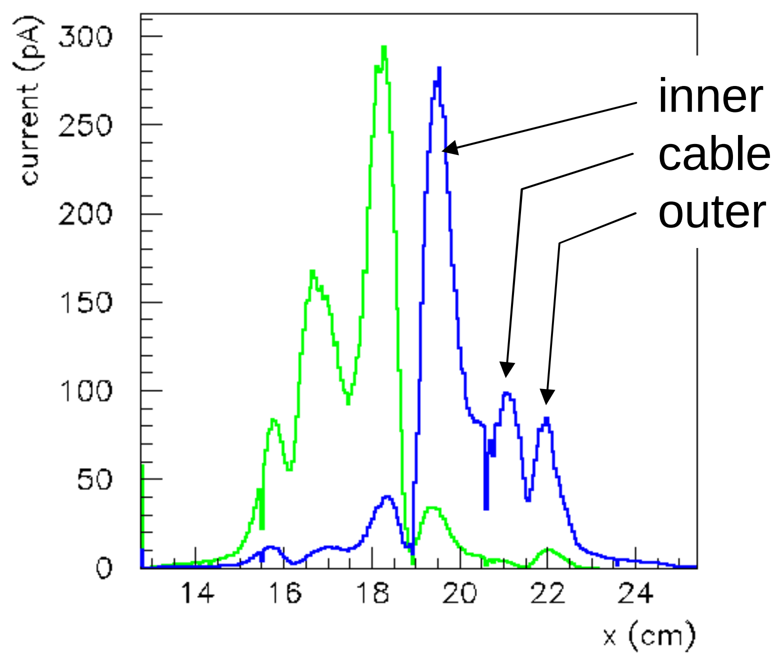
Active Collimator Sensitivity

Monte Carlo simulation

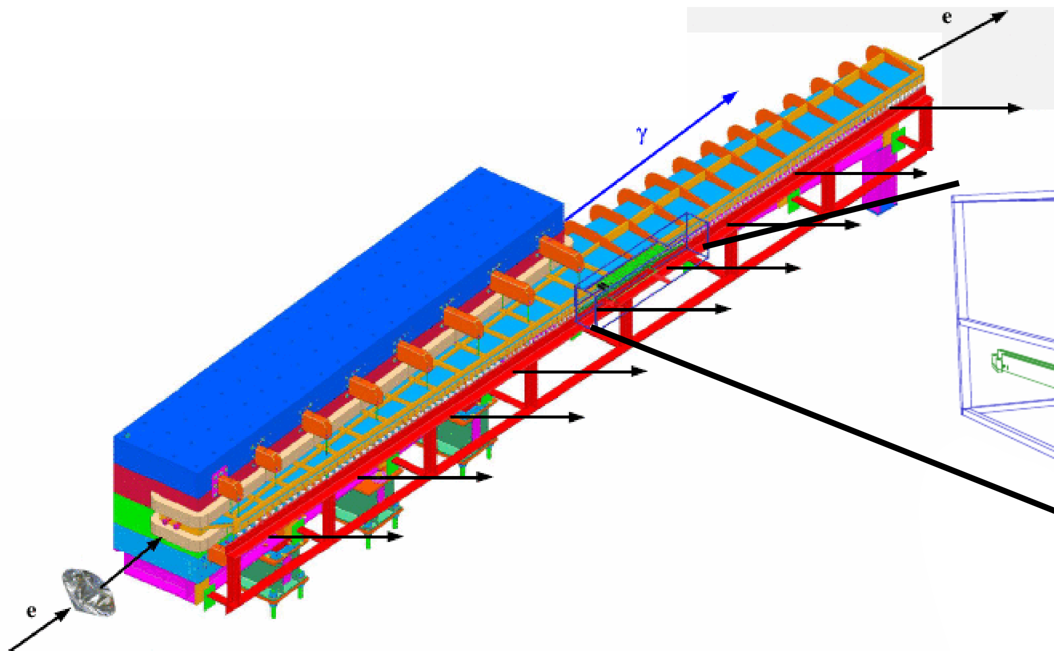
test beam data (raw)

current asymmetry vs. beam offset

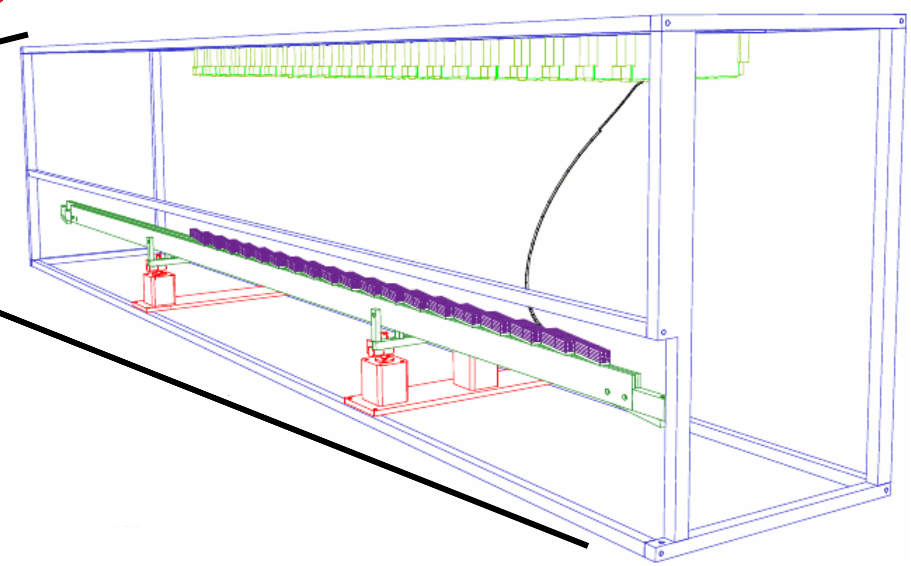




Photon tagging detector



Tagger “microscope”



- 1.5 T dipole, 6 m long, 30 mm pole gap
- Deflects electrons (13.4°= 12 GeV)
- 190 Hodoscopes: scintillator + PMTs (12 m long) → 3 - 11.7 GeV

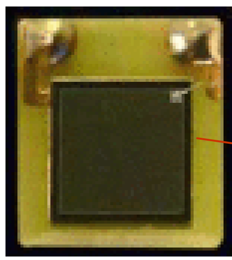
scintillating fibers
read out with SiPM’s

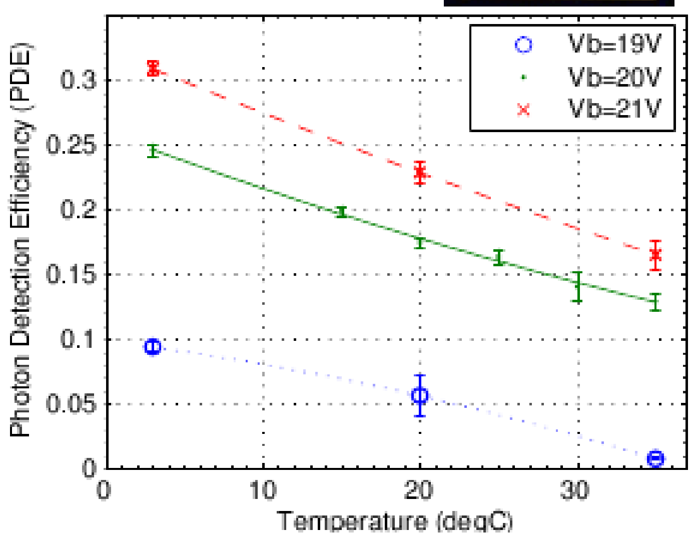
Photon tagging detector

- 8 MeV tagging channel width
- 200 ps time resolution
- 4 MHz/fiber

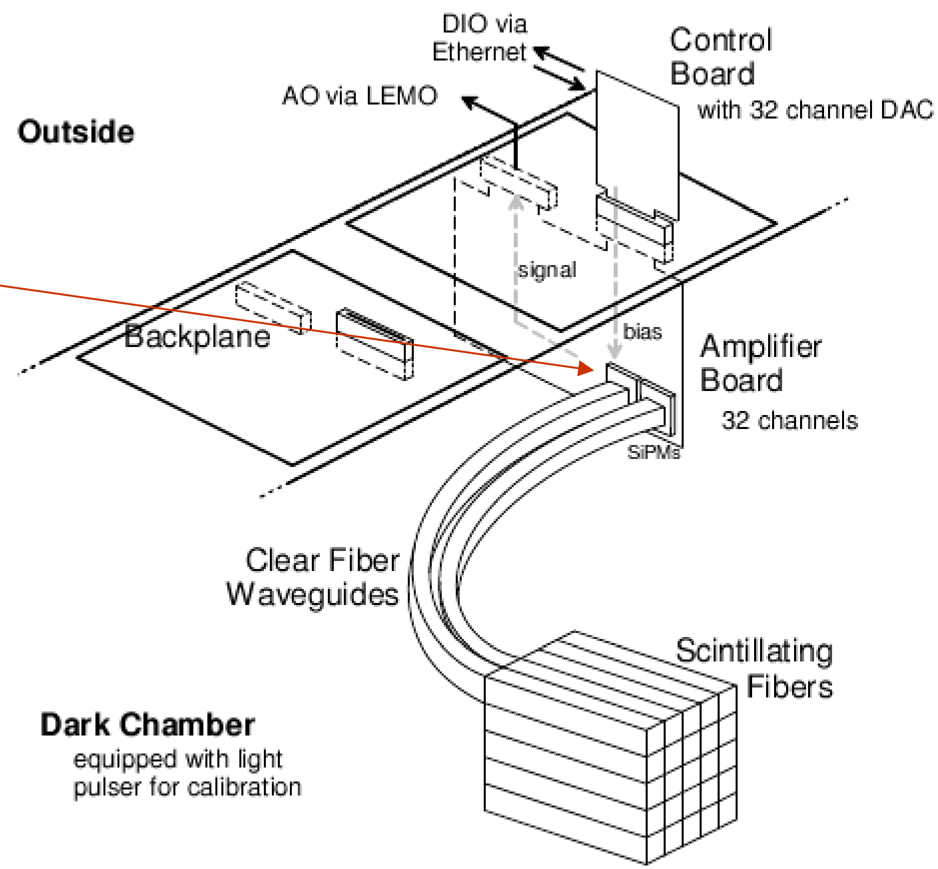
“Silicon PMT” (multi-pixel APD in Geiger mode)

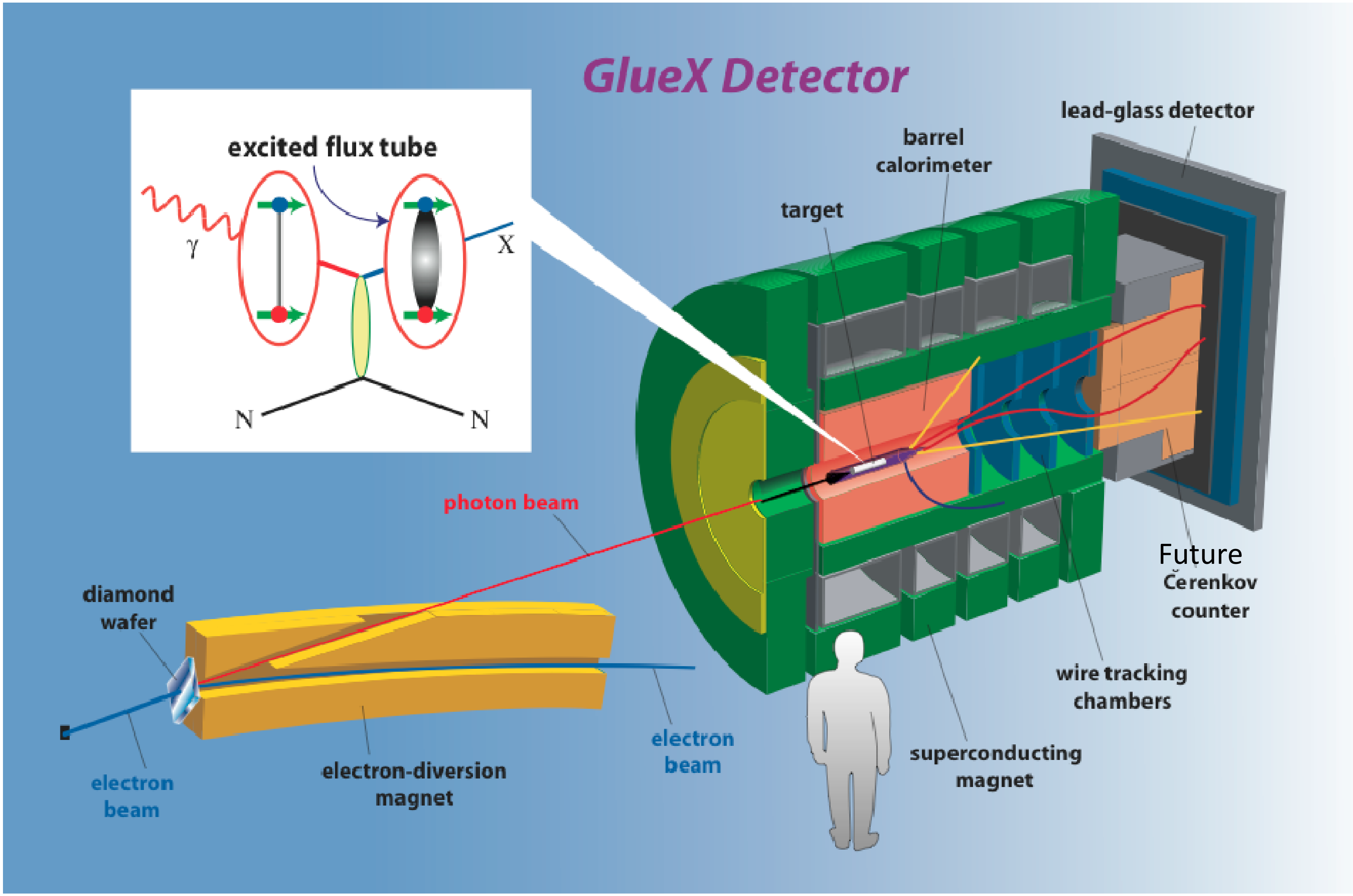
2mm



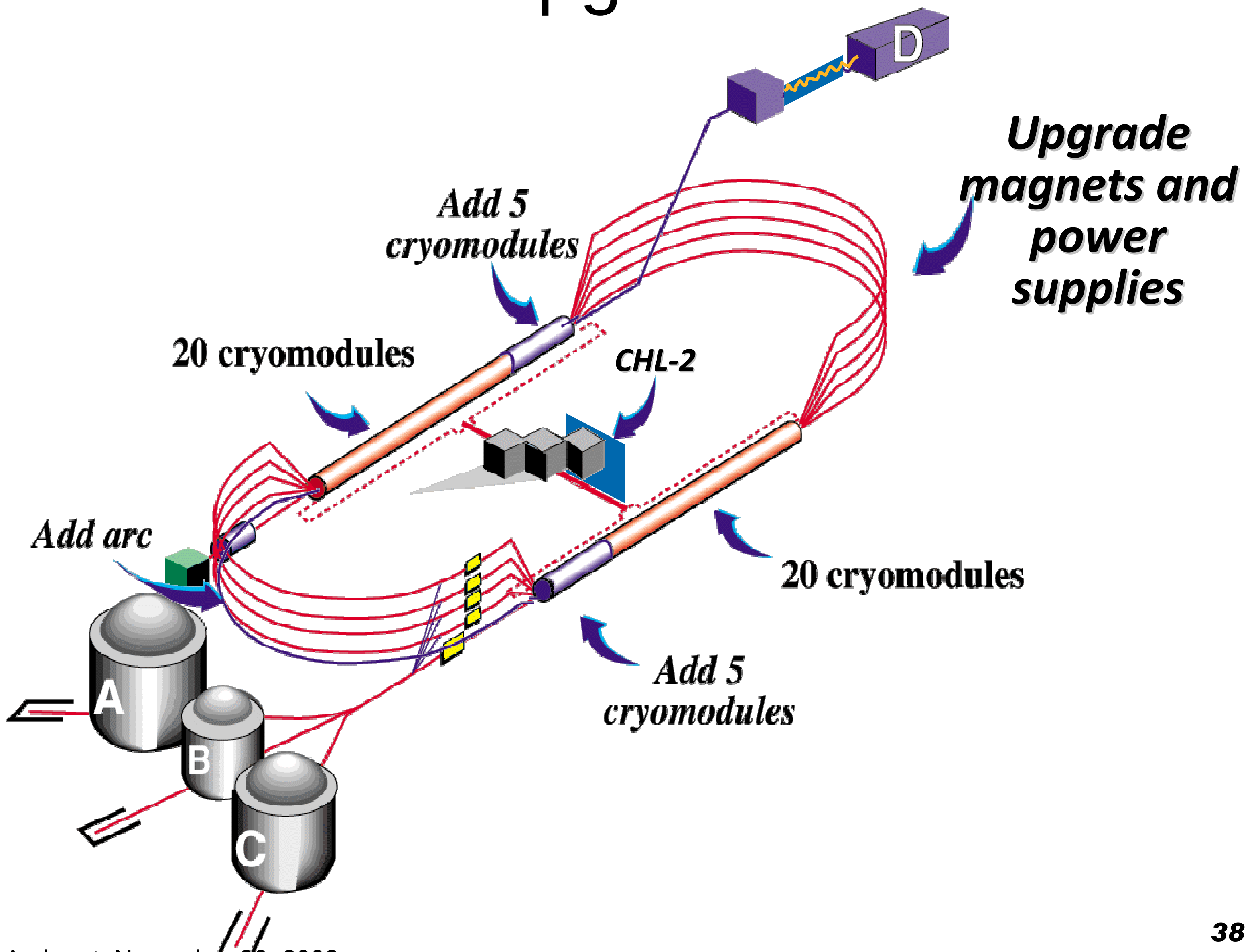


scintillating fiber readout scheme




GlueX Detector
excited flux tube
γ
X
N
N
lead-glass detector
barrel
calorimeter
target
photon beam
diamond
wafer
electron
beam
electron-diversion
magnet
electron
beam
Future
Čerenkov
counter
wire tracking
chambers
superconducting
magnet

12 GeV CEBAF Upgrade



Construction of Hall D is underway

Ground breaking in April 2009

Live webcam feed of Hall D site

Current plans call for the first beam in HallD/GlueX in late 2014.

The Gluex collaboration

- ~40 physicists from 10 universities + Jefferson Lab (Canada, Chile, China, Greece, UK, USA)

- other physics topics to be addressed (beside hybrids):
  - Primakov measurement of eta, eta' lifetime
  - rare eta decays
  - hadron formation in nuclear medium
  - inverse deeply virtual Compton scattering
  - threshold J/ψ production
  - cascade baryon spectroscopy

- recently welcomed new collaborators from UMass !

Summary

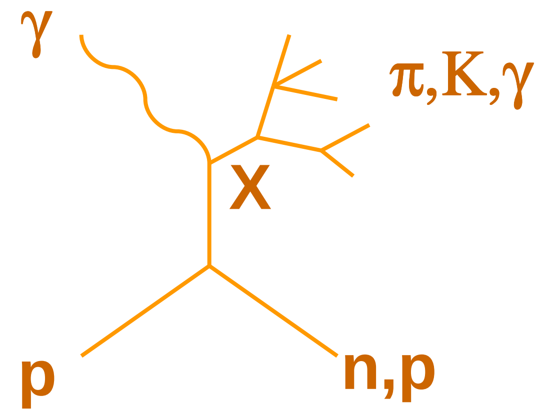
- QCD predicts that states with explicit gluonic degrees of freedom play a role in the hadron spectrum.
- Recent results from lattice QCD suggest that these states should be experimentally accessible (without requiring a complete solution to the n-meson scattering problem).
- … that these states should have photon couplings as large as ordinary $q\bar{q}$ mesons.

- The Gluex collaboration is mounting a major effort at Jefferson Lab to find these states in photoproduction in the region where the lattice says they should be found.
- A state-of-the-art photon beam (and detector) are under construction to accomplish this ambitious goal.

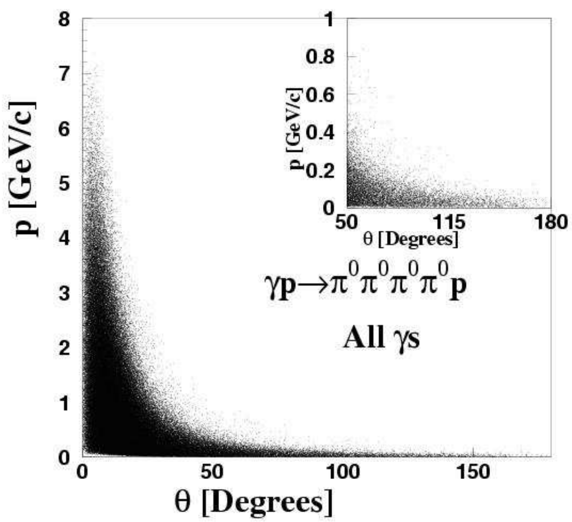
GlueX Experiment: topologies

t-channel meson photoproduction

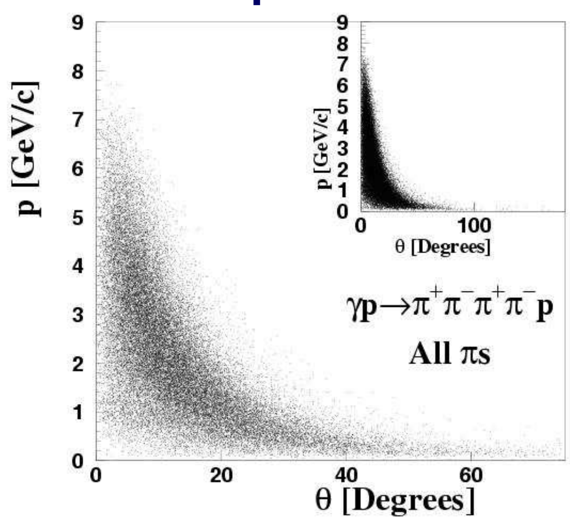
$$\sigma(t) \sim e^{-\alpha t}$$



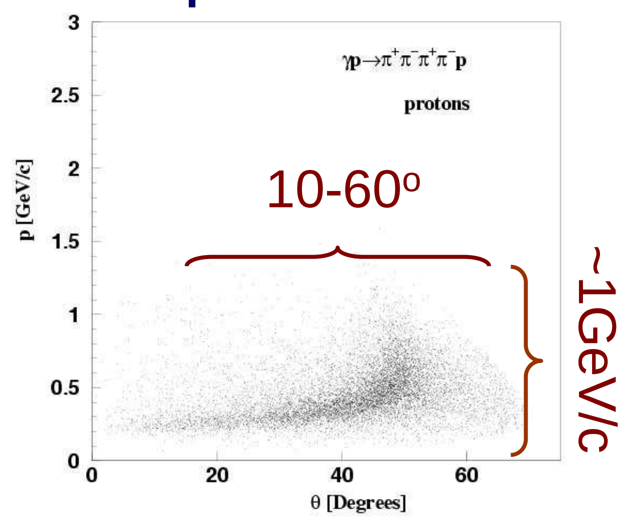
photons



pions



protons



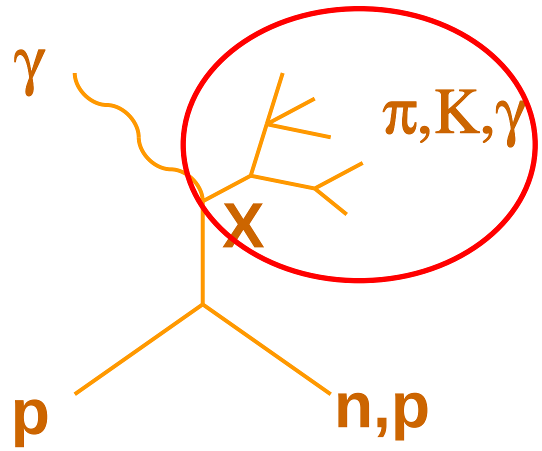
GlueX Experiment: detector design

The GlueX detector design has been driven by the need to carry out amplitude analysis.

π_1 η_1 η'_1 — 1^{-+}

b_2 h_2 h'_2 — 2^{+-}

b_0 h_0 h'_0 — 0^{+-}



$\eta_1 \rightarrow a^+_1\pi^- \rightarrow (\rho^o\pi^+)(\pi^-) \rightarrow \pi^+\pi^-\pi^+\pi^-$

all charged

$h_0 \rightarrow b^o_1\pi^o \rightarrow (\omega\pi^o)\gamma\gamma \rightarrow \pi^+\pi^-\gamma\gamma\gamma\gamma\gamma$

many photons

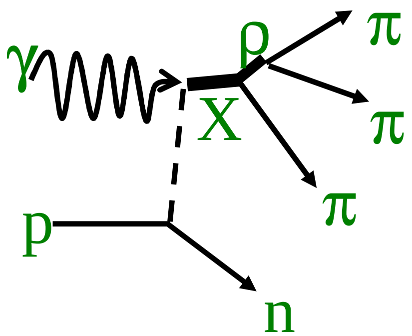
$h'_2 \rightarrow K^+_1K^- \rightarrow \rho^o K^+ K^- \rightarrow \pi^+\pi^-K^+K^-$

strange particles

Final state particles: $\pi^\pm$ $K^\pm$ γ p n K_L

GlueX Analysis: test of PWA

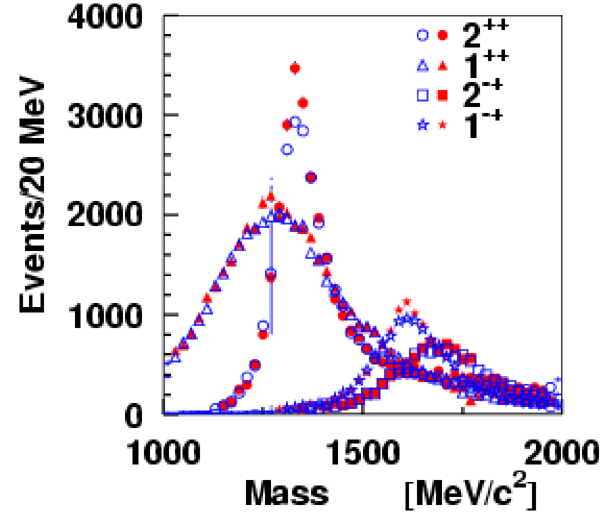
Double-blind study of 3π final states

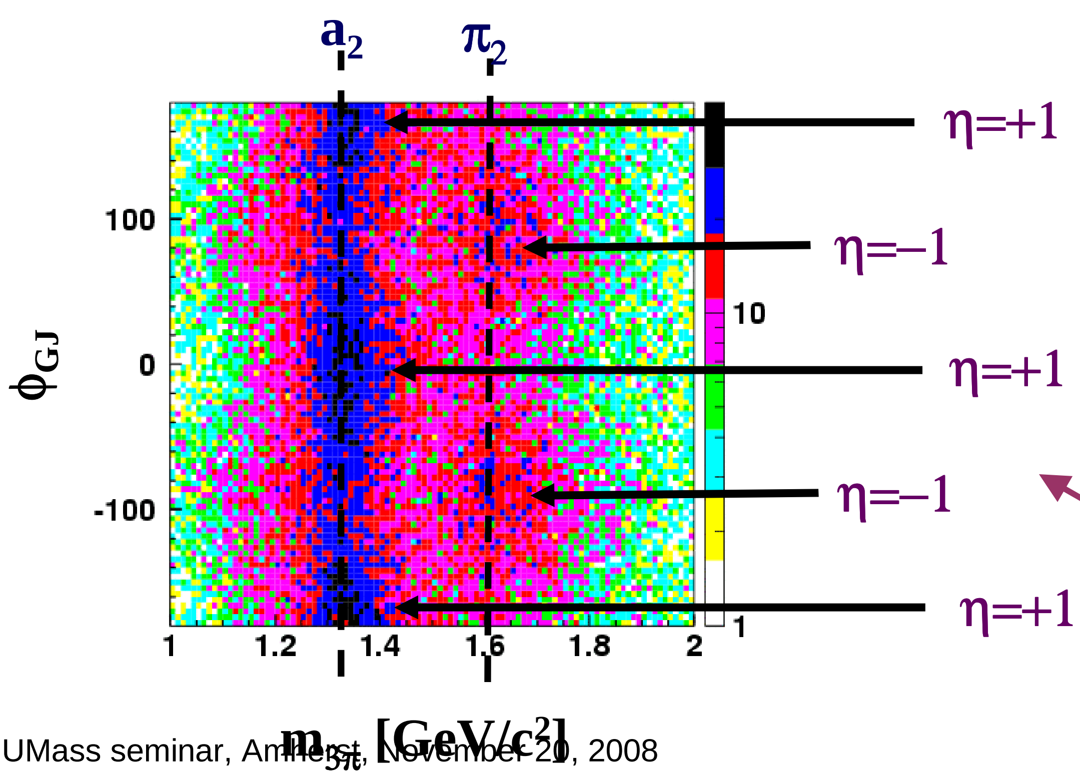


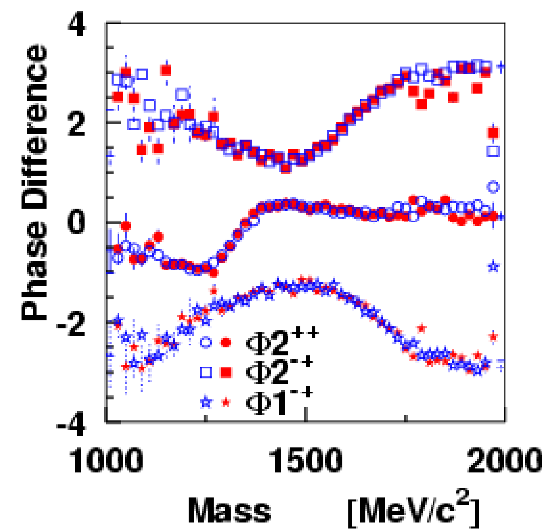
GlueX Monte Carlo

$\gamma\, p \rightarrow \pi_1^+ n \rightarrow \pi^+\pi^+\pi^- n$

$\rightarrow \pi^+\pi^0\pi^0 n$







Polarization effects!

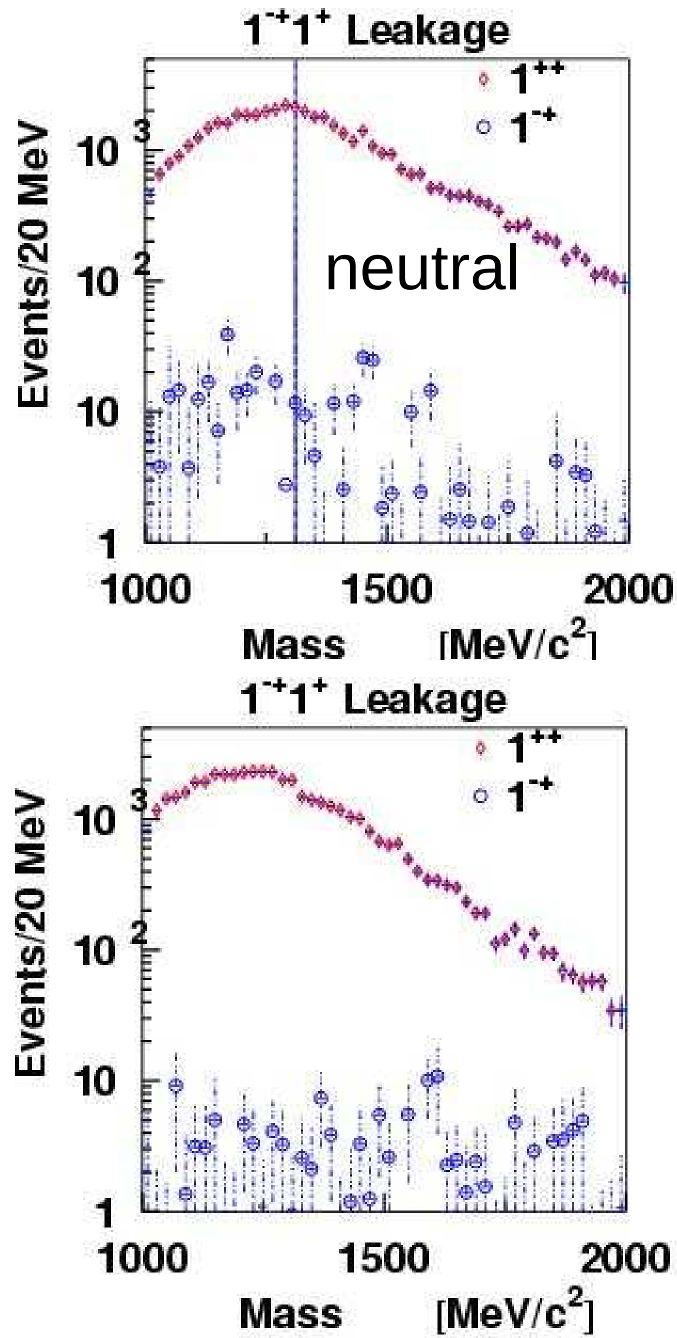
GlueX Analysis: test of PWA

If acceptance is not well understood, the PWA will "leak" one wave into another.

Break the GlueX detector in MC:

- distort B-field
- degrade resolution
- change hole sizes
- distort beam energy

Largest leakage is ~ 1/2% of a strong signal: $a_1(1^{++}) \rightarrow \pi_1(1^{-+})$



coherent bremsstrahlung

- requirements for a crystal radiator
  1. low-Z (large atomic form factor at q_{min})
  2. large S-factor (dense packing in unit cells)
  3. large Debye temperature (coherent yield)

element	*best reciprocal lattice vector*	*P/P(diamond)*
diamond	2 2 0	**1.00**
beryllium	0 0 2	**0.86**
boron	2 0 8	**0.38**
silicon	2 2 0	**0.19**