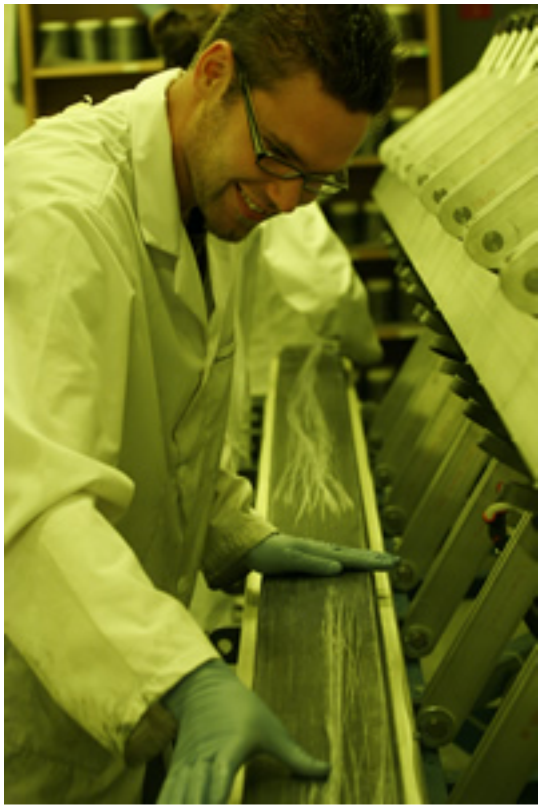
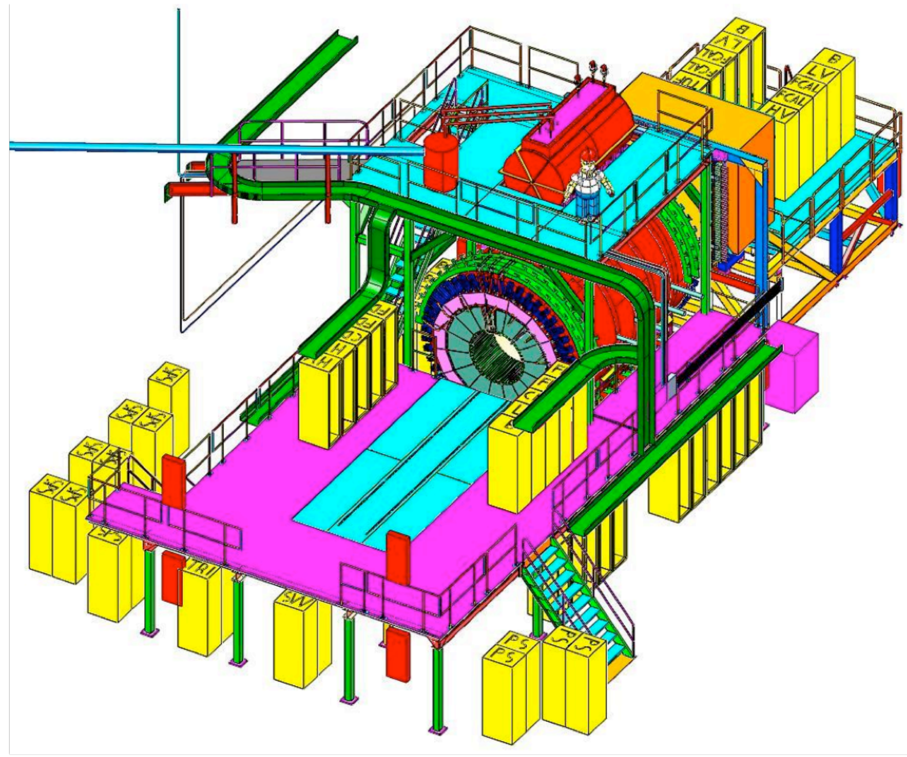
The GlueX Experiment: construction is under way





University of Regina

Jefferson Lab
Exploring the Nature of Matter

GlueX Scientific Goals and Means

- **GlueX Physics**
  - Elucidate the phenomenon of confinement in QCD
  - Definitive and detailed mapping of hybrid meson spectrum
  - Search for smoking gun signature of exotic J^{PC} hybrid mesons; no mixing with $q\bar{q}$
  - Test photo-couplings and phenomenology
  - $s\bar{s}$ and baryon spectroscopy, Primakoff effect, rare eta decays, etc…
- **Tools for the GlueX Project at Jefferson Lab**
  - 12 GeV electrons, 9 GeV tagged, linearly polarized photons with high flux
  - Detector: hermiticity, resolution, charged and neutrals
  - Spin-Amplitude Analysis of multi-particle final states
  - Computing power: Pb/year data collection, distributed computing, grid tools,…
- **Key detector subsystem**: **BCAL**
  - Pb-Scintillating Fibre sampling calorimeter
  - 70% of decay photons are captured by BCAL
  - 40 MeV – 3.5 GeV operating range; high magnetic field, tight space
  - **Recent results: fibre testing and readout, construction status quo**

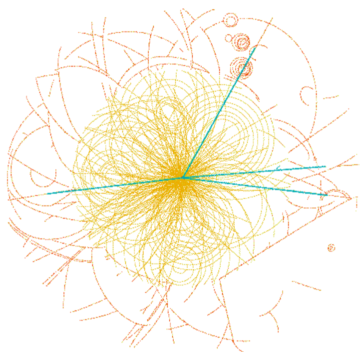
Perturbative | Non-Perturbative

Asymptotic Freedom | Confinement

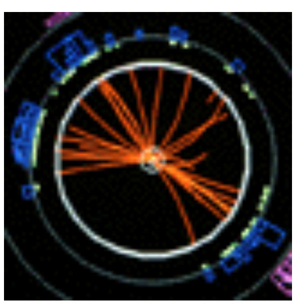
Small Distance
High Energy

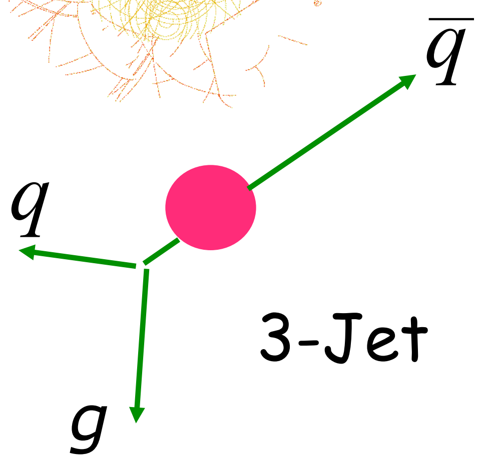
Large Distance
Low Energy

High Energy
Scattering

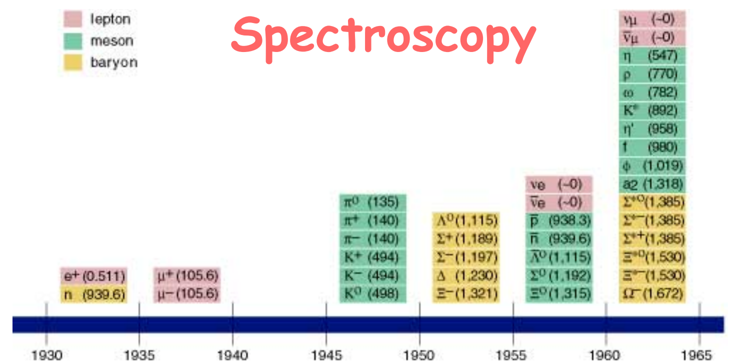


Gluon
Jets
Observed

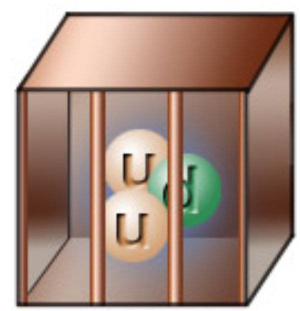




Spectroscopy



Gluonic
Degrees of Freedom
Missing

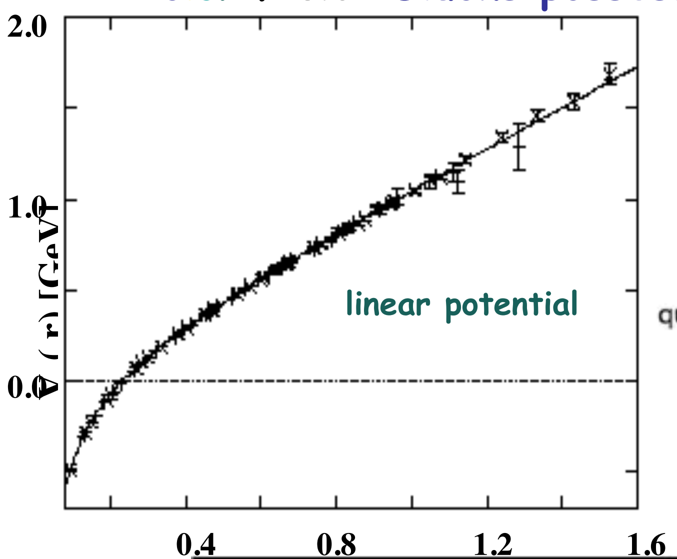


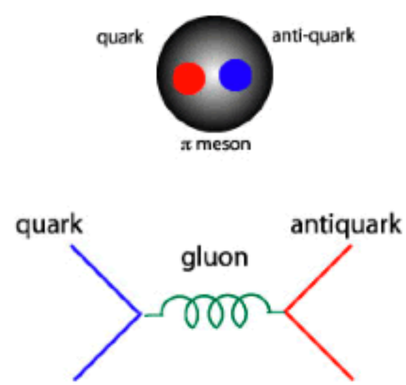
Flux Tubes - LQCD & Models

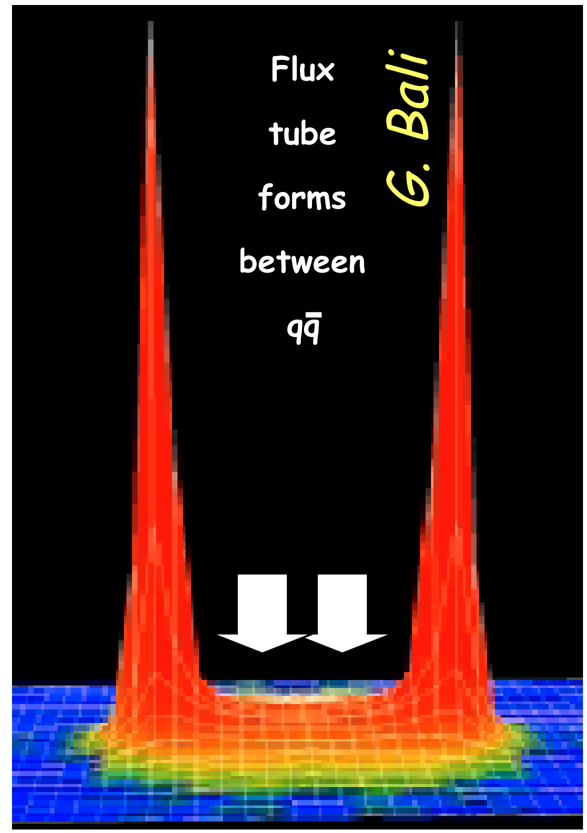
In the simple quark model, glue is not needed to describe hadrons.

But in QCD: Allowed systems: gg, ggg, $q\bar{q}g$, $q\bar{q}q\bar{q}$
Glueballs | Hybrids | Molecules

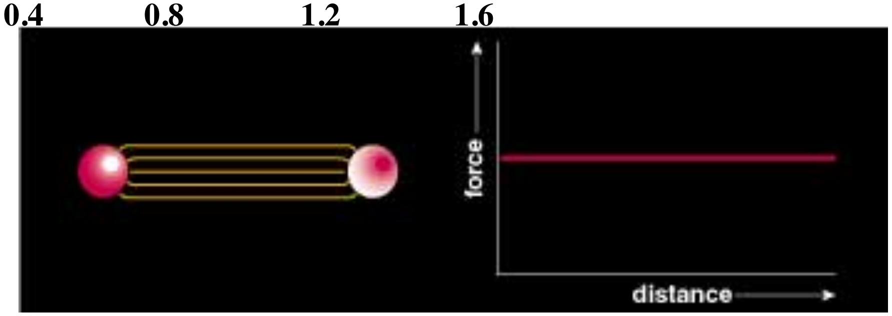
Color Field: Gluons possess color charge: they couple to each other!





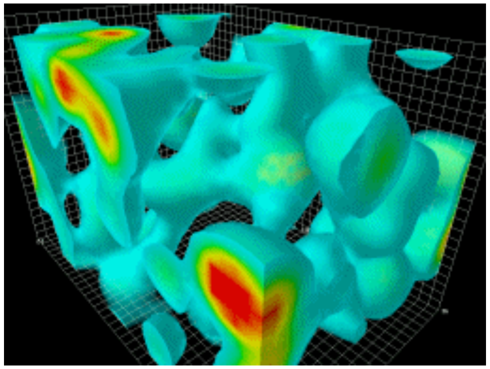


F L U X T U B E

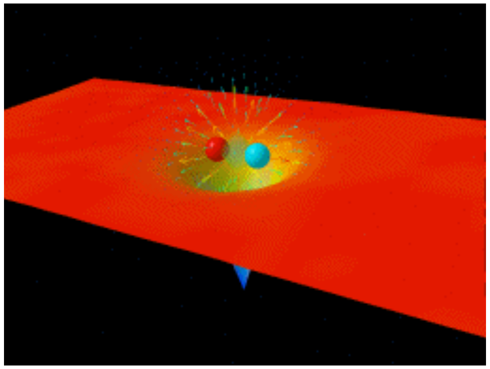


Quark-Gluon Activity

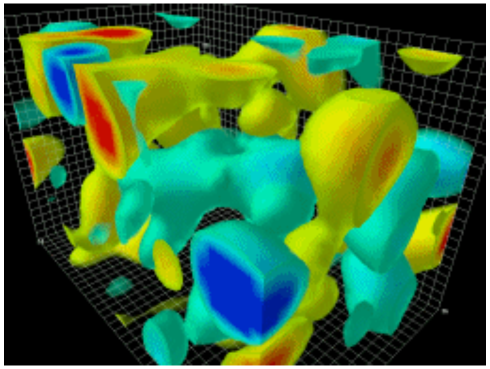
Action Density



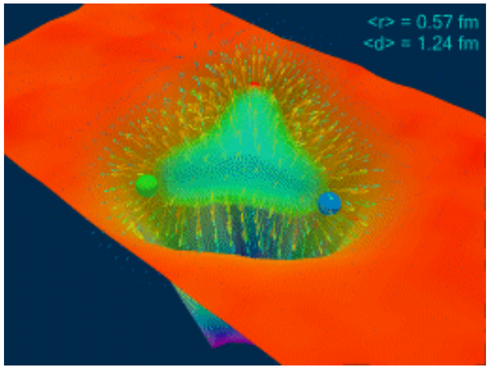
Meson



Charge Density



Baryon

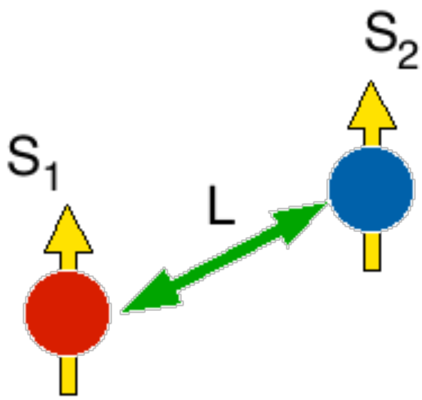


D. Leinweber

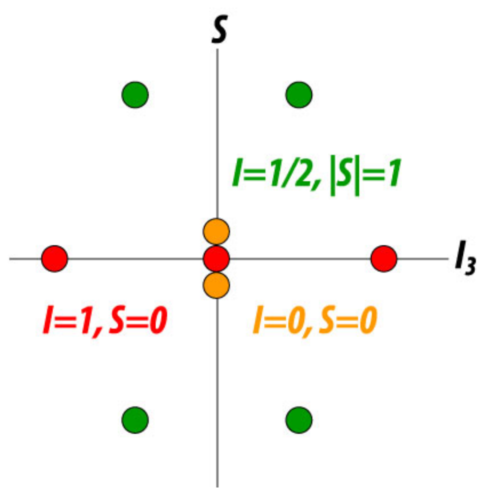
Flux Tube Quantum Numbers

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

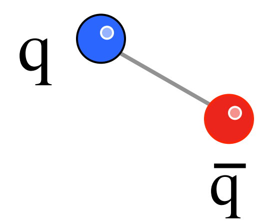
Nonets characterized by given J^{PC}



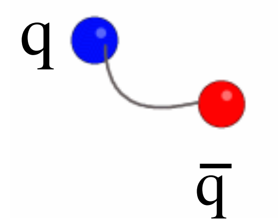
$$S = S_1 + S_2$$
$$J = L + S$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$



Normal meson:
flux tube in ground state
m=0
$CP=(-1)^{S+1}$

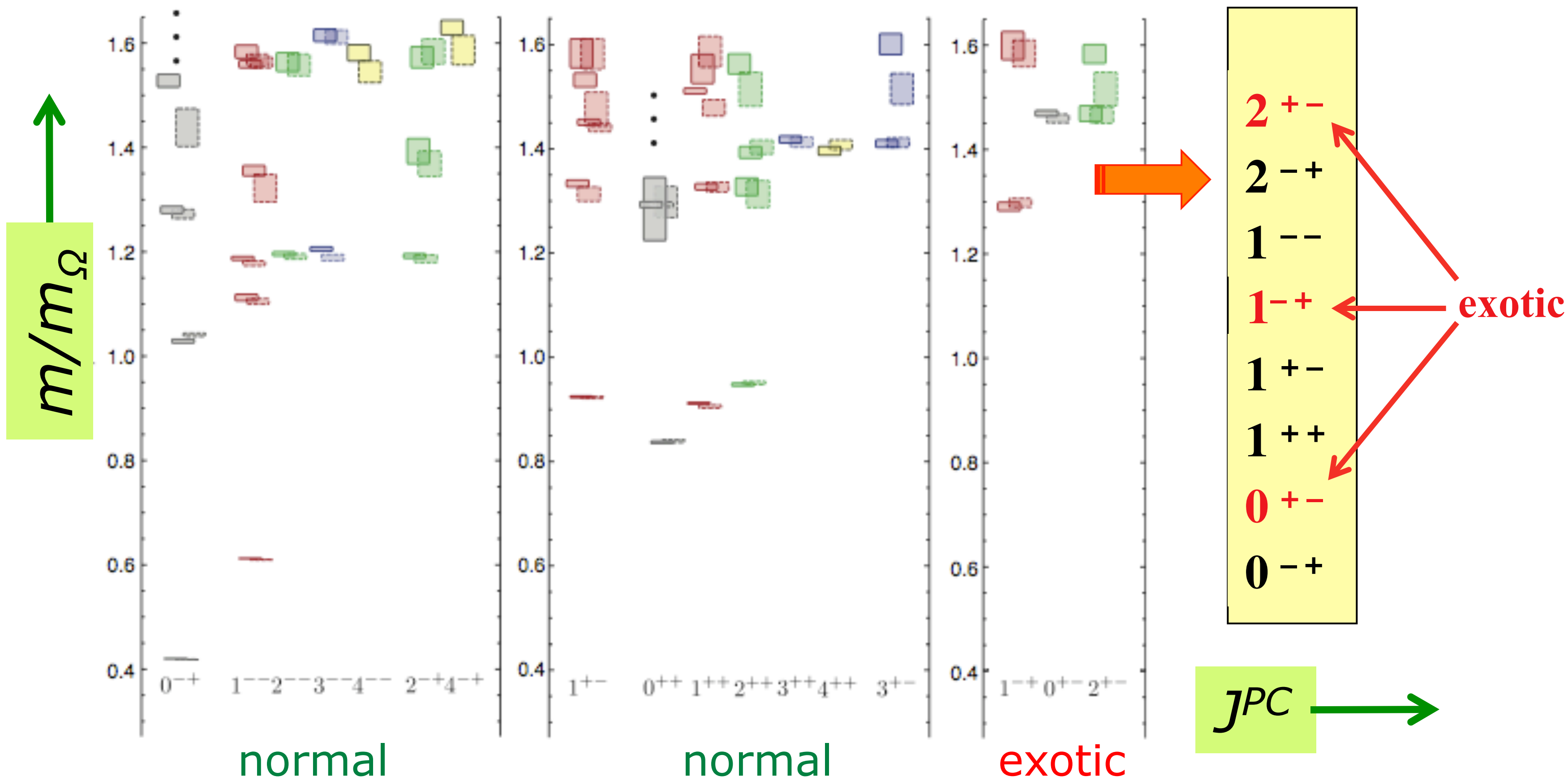


Hybrid meson:
flux tube in excited state
m=1
$CP=(-1)^{S}$



In the first-excited state we have two degenerate 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

Isovector Meson Map from LQCD

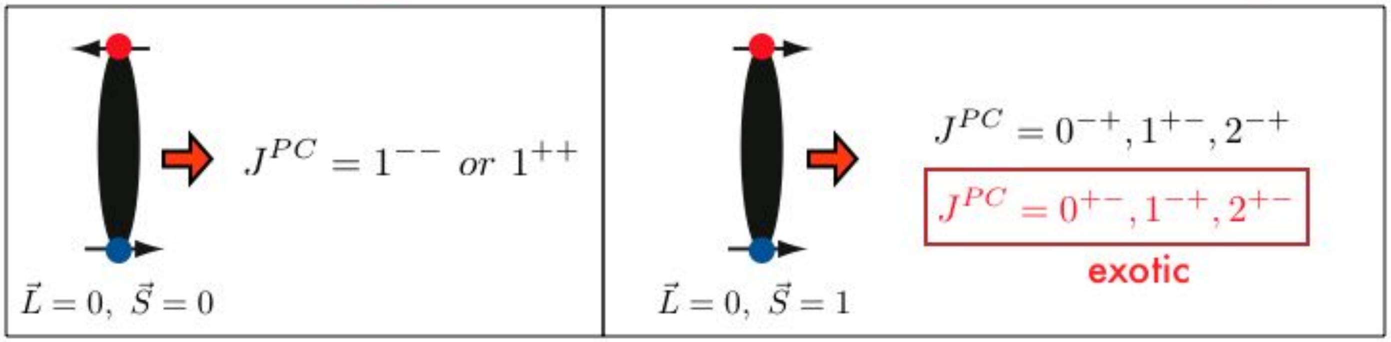


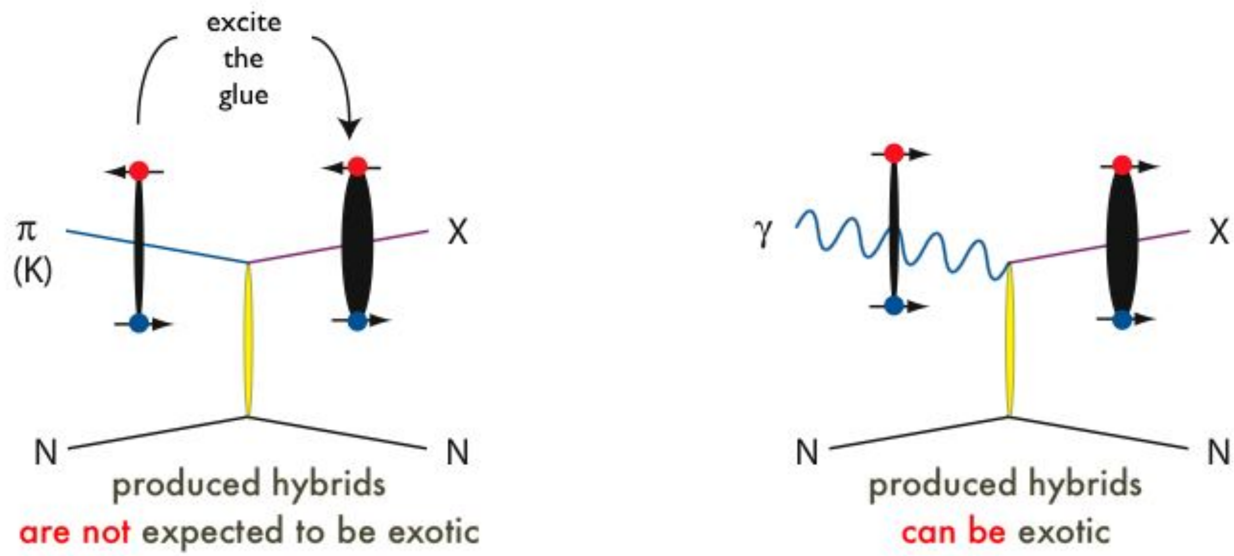
-390-700 MeV pion mass
-colour denotes spin
- no lattice volume effect

J. Dudek et al., submitted to PRD
(unquenched, light quarks)

Production of Hybrid Mesons

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





Evidence for Exotic Hybrids

Data Candidates & Issues

State	Mass (GeV)	Width (GeV)
$\pi_1(1400)$	1.351 ± 0.03	0.313 ± 0.040
$\pi_1(1600)$	1.662 ± 0.015	0.234 ± 0.050
$\pi_1(2015)$	2.01 ± 0.03	0.28 ± 0.05
State	**Production**	**Decays**
$\pi_1(1400)$	$\pi^- p, \bar{p}n$	$\pi^-\eta', \pi^0\eta'$
$\pi_1(1600)$	$\pi^- p, \bar{p}p$	$\eta'\pi, b_1\pi, f_1\pi, \rho\pi'$
$\pi_1(2015)$	$\pi^- p$	$b_1\pi, f_1\pi$
State	**Experiments**	
$\pi_1(1400)$	E852, CBAR	
$\pi_1(1600)$	E852, VES, COMPASS, CBAR	
$\pi_1(2015)$	E852	

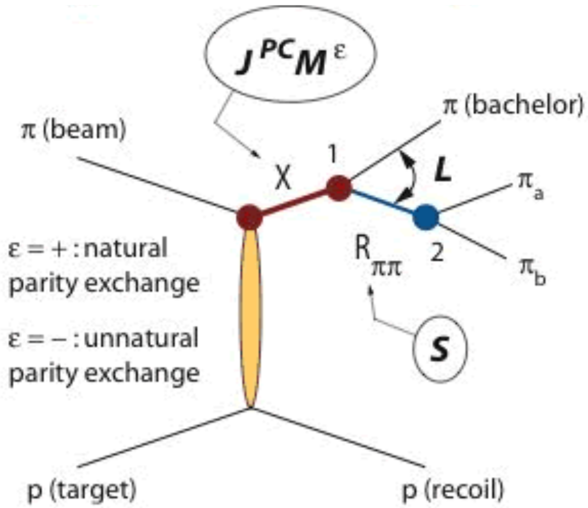
- Low statistics
- Possible leakage due to acceptance issues or insufficient number of wave sets
- Interpretation of line shapes and phases
- Inconsistencies in production
- Controversial decay channels

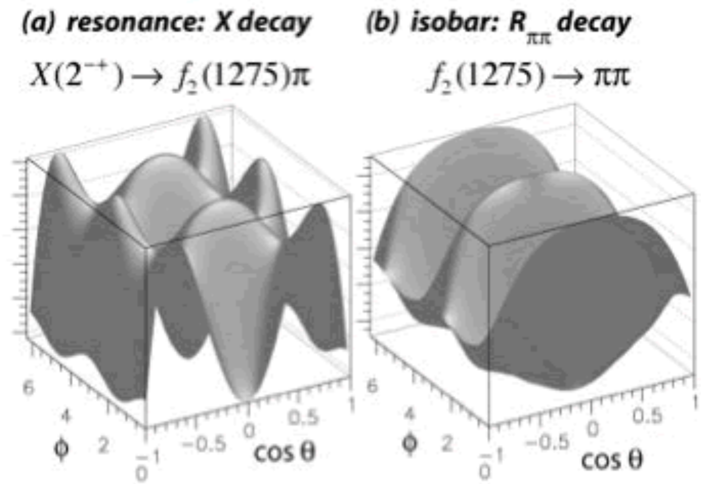
LQCD Hybrid Predictions

Name	J^{PC}	Total Width MeV PSS	IKP	Large Decays
π_1	1^{-+}	$81 - 168$	117	$b_1\pi$, $\rho\pi$, $f_1\pi$, $a_1\eta$
η_1	1^{-+}	$59 - 158$	107	$a_1\pi$, $f_1\eta$, $\pi(1300)\pi$
η'_1	1^{-+}	$95 - 216$	172	$K_1^m K$, $K_1^l K$, $K^* K$
b_0	0^{+-}	$247 - 429$	665	$\pi(1300)\pi$, $h_1\pi$
h_0	0^{+-}	$59 - 262$	94	$b_1\pi$, $h_1\eta$, $K(1460)K$
h'_0	0^{+-}	$259 - 490$	426	$K(1460)K$, $K_1^l K$, $h_1\eta$
b_2	2^{+-}	$5 - 11$	248	$a_2\pi$, $a_1\pi$, $h_1\pi$
h_2	2^{+-}	$4 - 12$	166	$b_1\pi$, $\rho\pi$
h'_2	2^{+-}	$5 - 18$	79	$K_1^m K$, $K_1^l K$, $K_2^* K$

- PSS and IKP models
- Different masses for hybrids
- Width ranges vary

Amplitude Analysis (PWA)





The analysis is based on the ***isobar model*** *that assumes an intermediate 2π resonance*

- *Bump hunting in cross section data is inadequate to the task*
- *Need PWA:*
  - *Identify the J^{PC} of a meson using intensity and phase motion analysis*
  - *Determine production amplitudes & mechanisms*
  - *Include polarization of beam, target, spin and parity of resonances and daughters, relative angular momentum.*
- *GlueX experience:*
  - *E852, Crystal Barrel, CLAS; new independent code has been developed*

False Signals

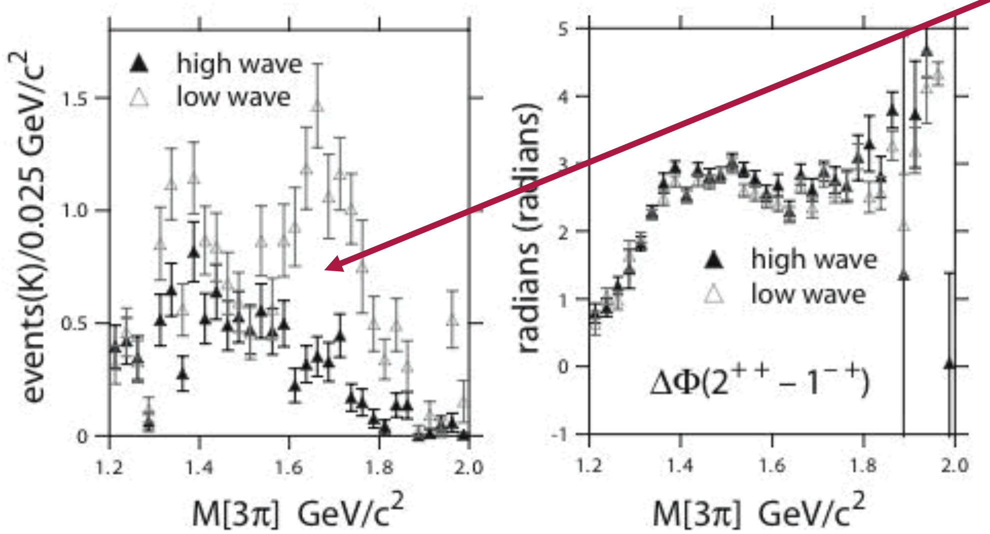
Revisiting $\pi_1(1600) \to \rho\pi$

A. R. Dzierba et al, Phys. Rev. **D73** (2006) 072001

A new analysis of E852 data based on larger statistics and two different 3π modes comes to another conclusion. This new analysis is similar to the previous analysis but included additional waves.

E852@Brookhaven $\pi^- p \to \begin{array}{l} \pi^-\pi^-\pi^+ p \\ \pi^-\pi^0\pi^0 p \end{array}$ (1) 2.6 M events (2) 3.0 M events

Oops!



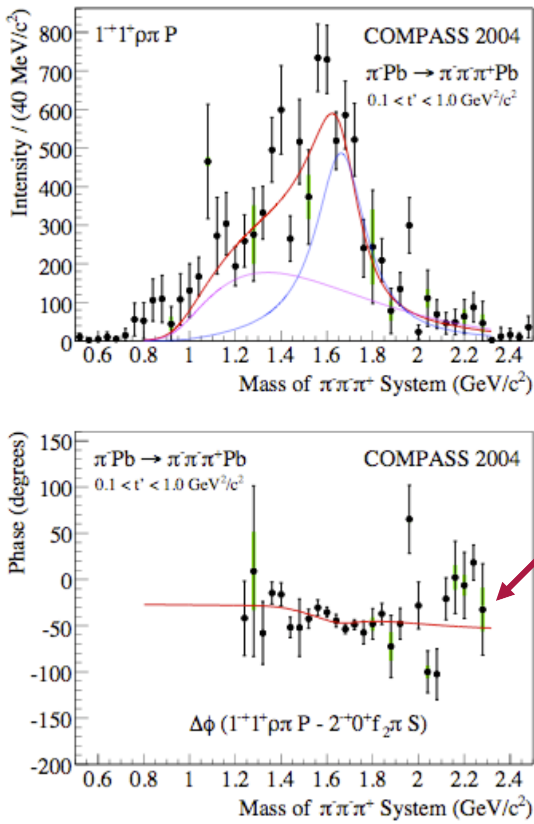
$1^{-+}1^+$ P-wave ρπ ($\pi^-\pi^-\pi^+$)

Low-wave set is the same as in the earlier E852 analysis while the high-wave set includes additional waves.

Conclusion: *Structure in the exotic wave disappears when one includes additional waves corresponding to decays of the $\pi_2(1670)$*

Controversial Signal

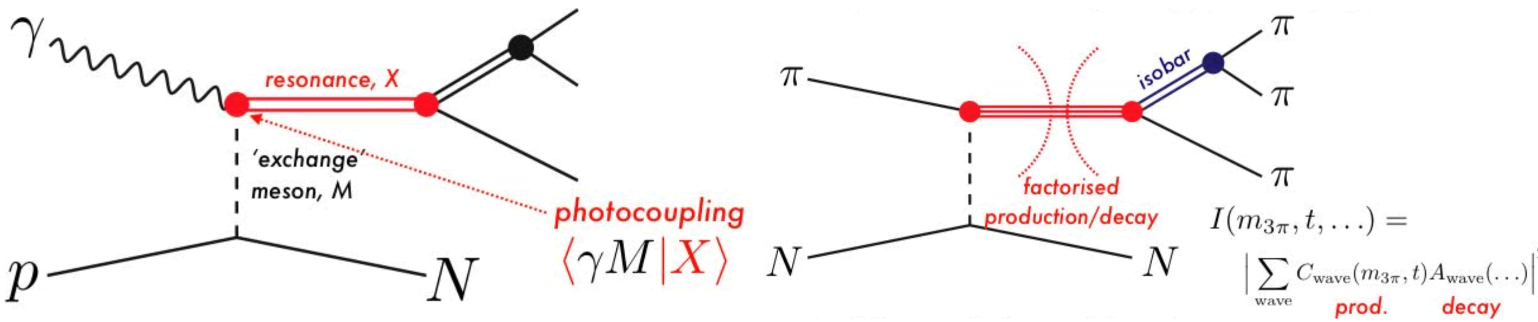
COMPASS@CERN



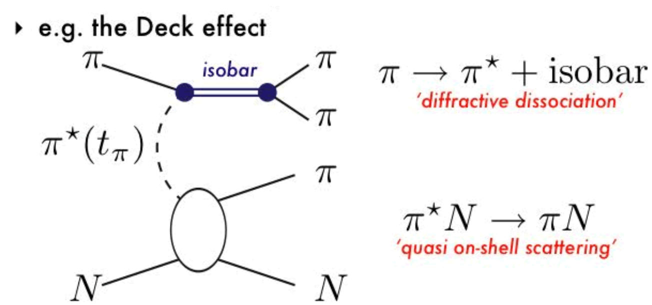
Oops!

- Intensity:
  - Breit-Wigner plus unknown background
- Phase difference:
  - Flat motion!
- $\pi_1(1600)$, $\pi_2(1670)$:
  - Same mass and width!
- Feed-through into 1600 from stronger 1670 due to isobar model

Photocouplings & Phenomenology



- Couplings virtually unknown even for conventional mesons
- Testbed: by the time GlueX runs expect all predictions to be tested by Lattice QCD



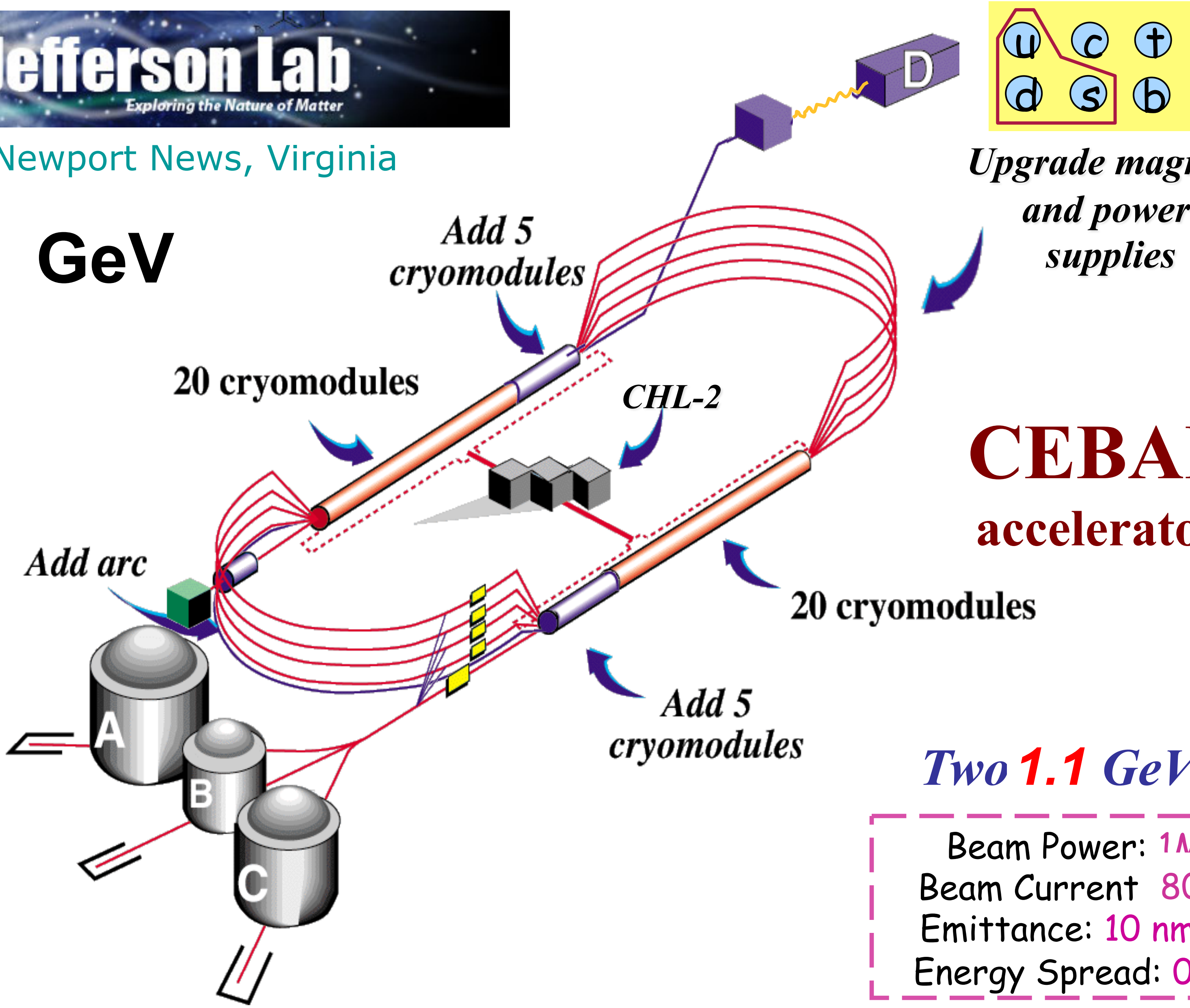
- Phenomenology:
  - isobar model widely used in multi-particle πN→ πππN states; it is not completely general
  - factorized approach has limitations: e.g. Deck effect where we get a threshold peak in isobar π S-wave

Jefferson Lab
Exploring the Nature of Matter

Newport News, Virginia

12 GeV

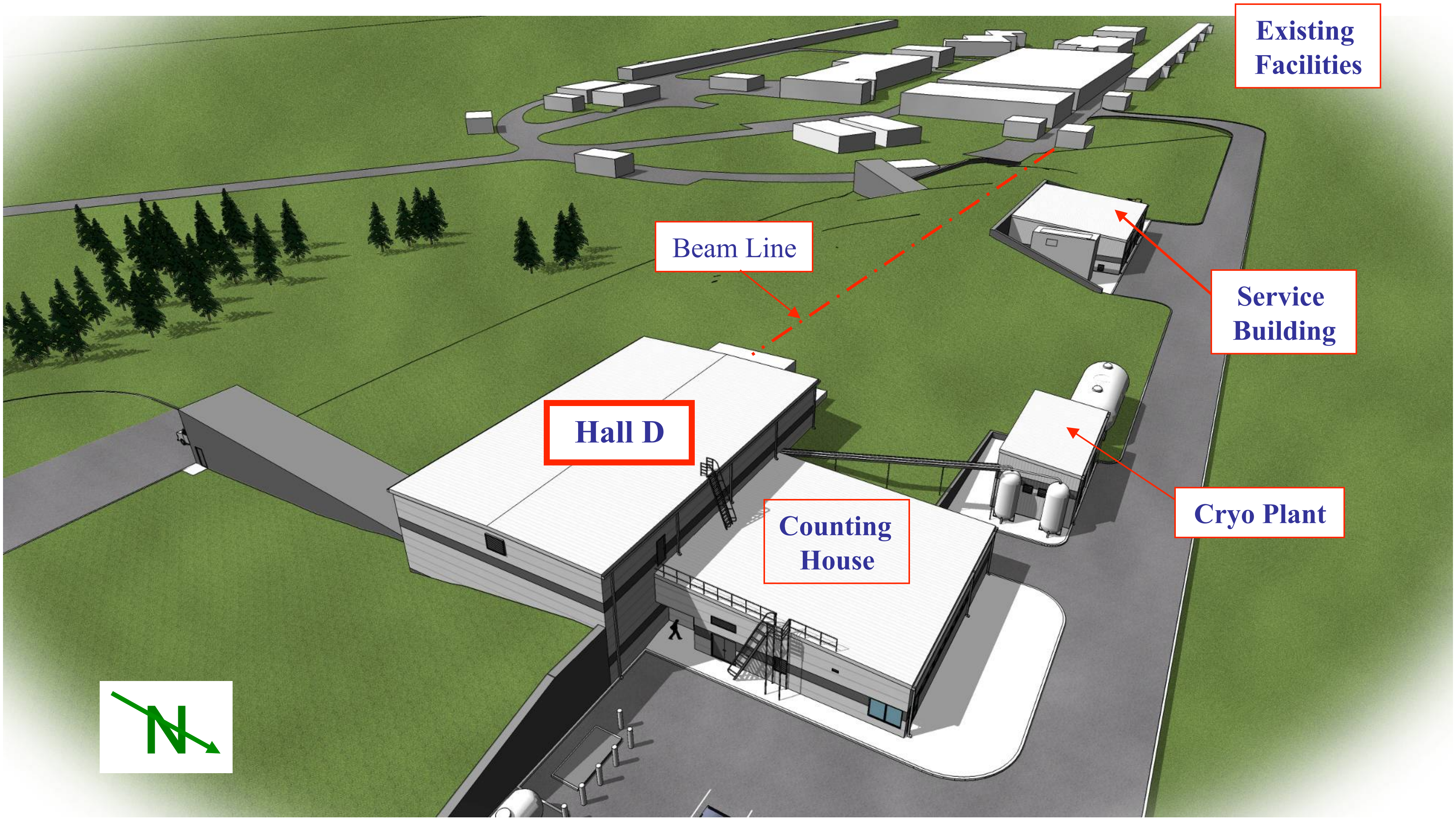
CEBAF accelerator



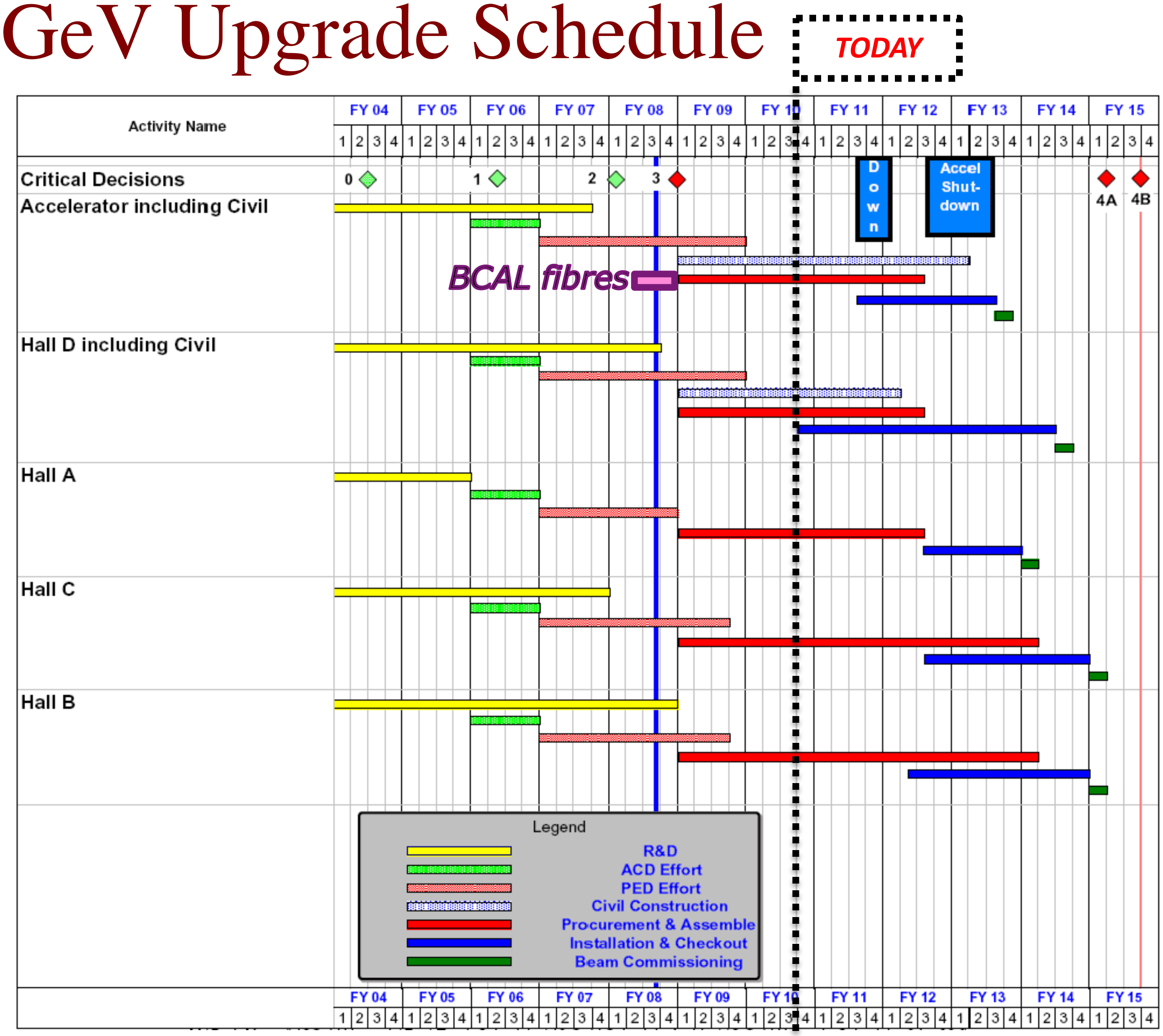
Two **1.1** *GeV linacs*

Beam Power: 1MW
Beam Current 80 μA
Emittance: 10 nm-rad
Energy Spread: 0.02%

Hall D Complex - Overhead View



12 GeV Upgrade Schedule

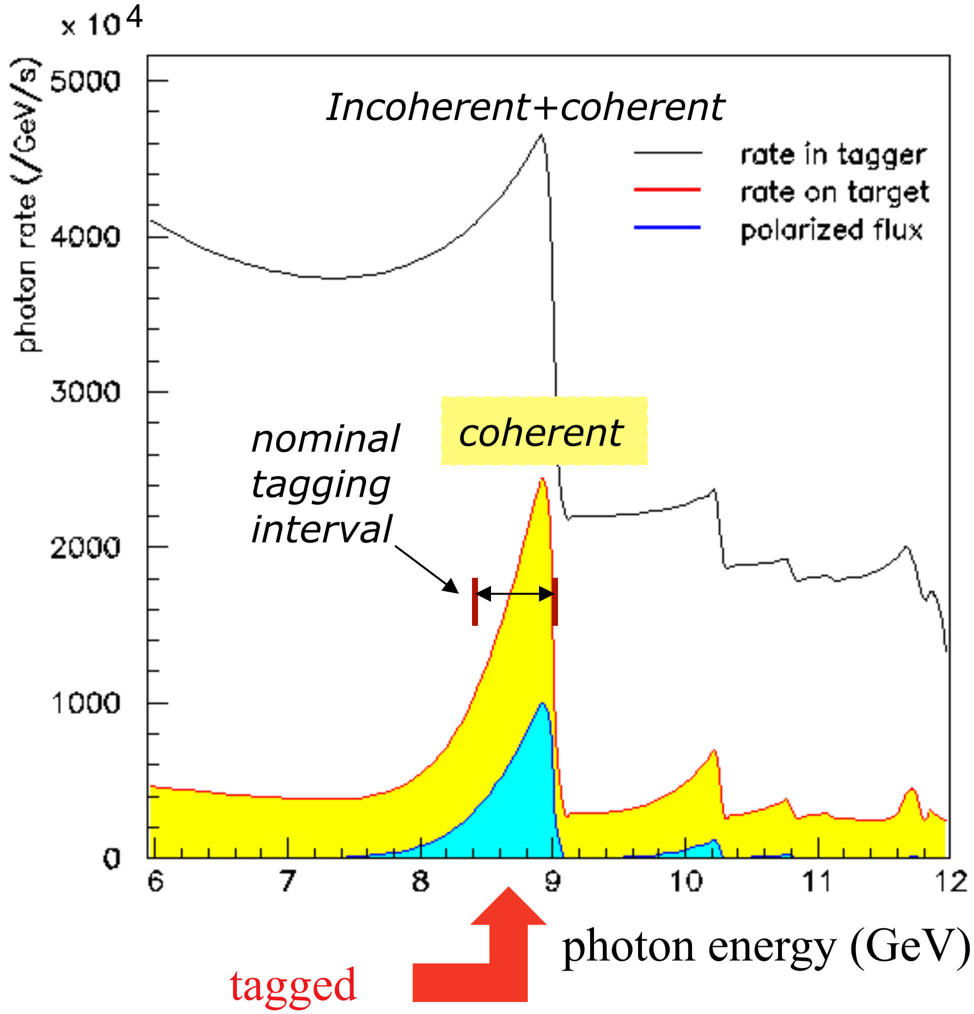


16

Hall-D: Linearly Polarized Photon Beam

12 GeV endpoint, 9 GeV γ's
- 20 μm diamond crystal
- 300 nA electron beam
- diamond – collimator: 76 m
- collimator diameter: 3.5 mm
- $\delta E/E = 0.1\%$, Pol = 40%

10^7 γ/s on target → 10^8 γ/s

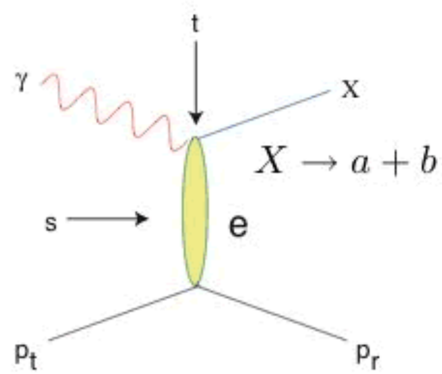


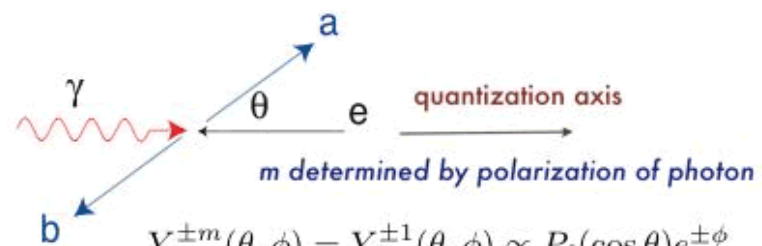
Linear Polarization

States of linear polarization are eigenstates of parity.

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

assume that X decays into two spin-less mesons: a and b and that e is also spin-less





$$Y_\ell^{\pm m}(\theta,\phi) = Y_\ell^{\pm 1}(\theta,\phi) \propto P_\ell(\cos\theta)e^{\pm\phi}$$

For circularly polarized photons: m = +1 or m = −1 ➡ $W(\theta,\phi) \propto |P_\ell(\cos\theta)|^2$

For unpolarized photons:
equal mixture of m = +1 and m = −1 ➡ $W(\theta,\phi) \propto |P_\ell(\cos\theta)|^2$

For x - linear polarization: ➡ $W(\theta,\phi) = |Y_\ell^{+1} - Y_\ell^{-1}|^2 \propto |P_\ell(\cos\theta)|^2 \sin^2\phi$

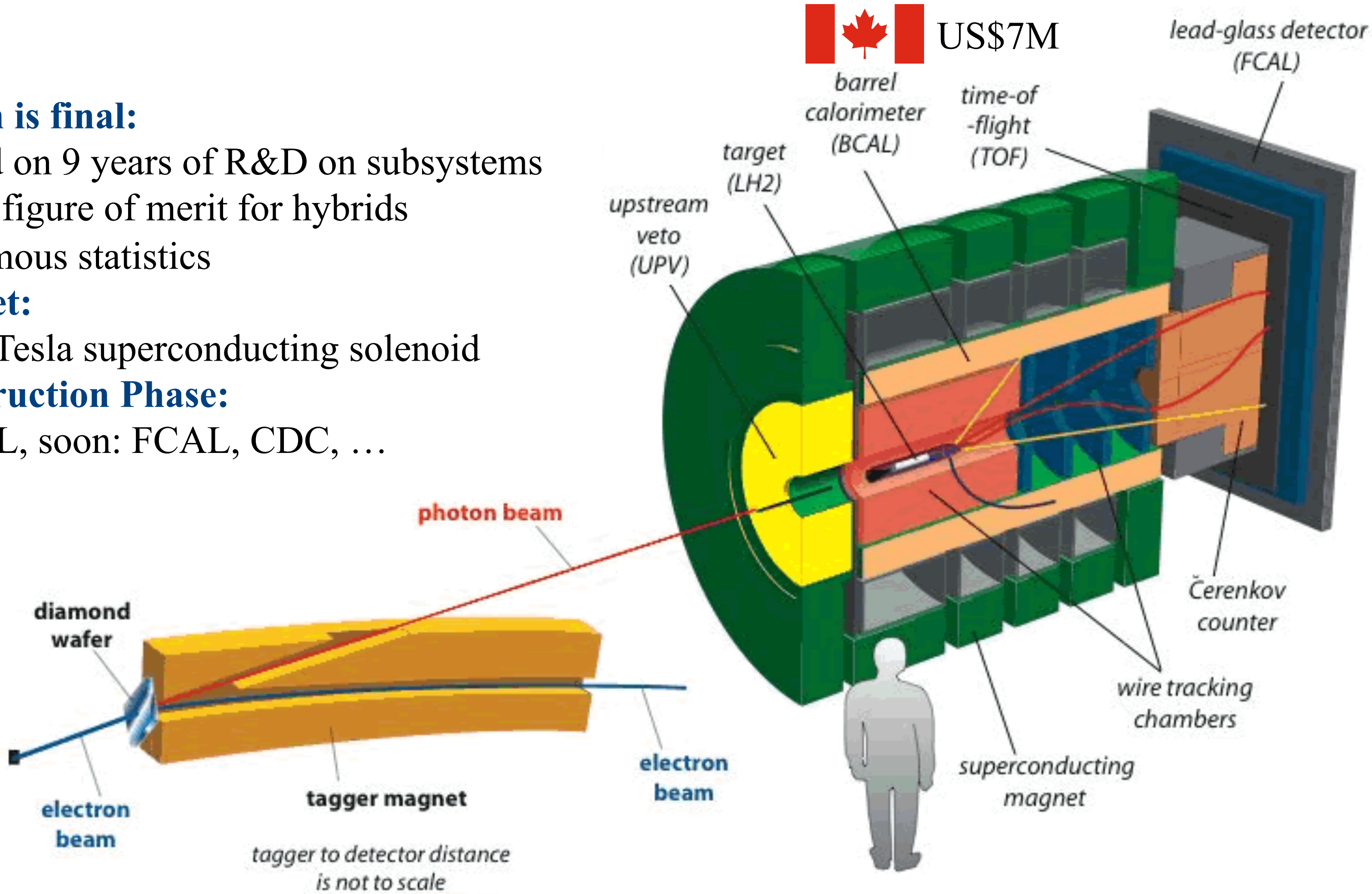
For y - linear polarization: ➡ $W(\theta,\phi) = |Y_\ell^{+1} + Y_\ell^{-1}|^2 \propto |P_\ell(\cos\theta)|^2 \cos^2\phi$

The GlueX Detector

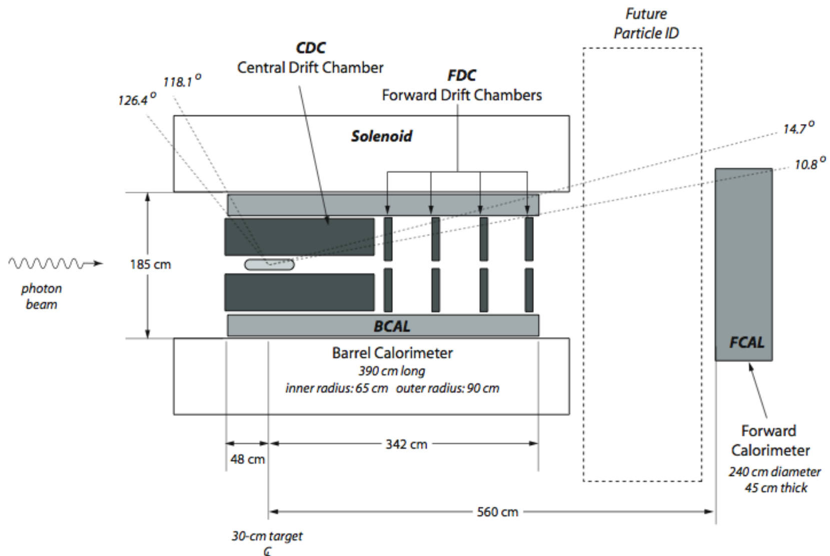
Design is final:
- based on 9 years of R&D on subsystems
- large figure of merit for hybrids
- enormous statistics

Magnet:
- 2.24 Tesla superconducting solenoid

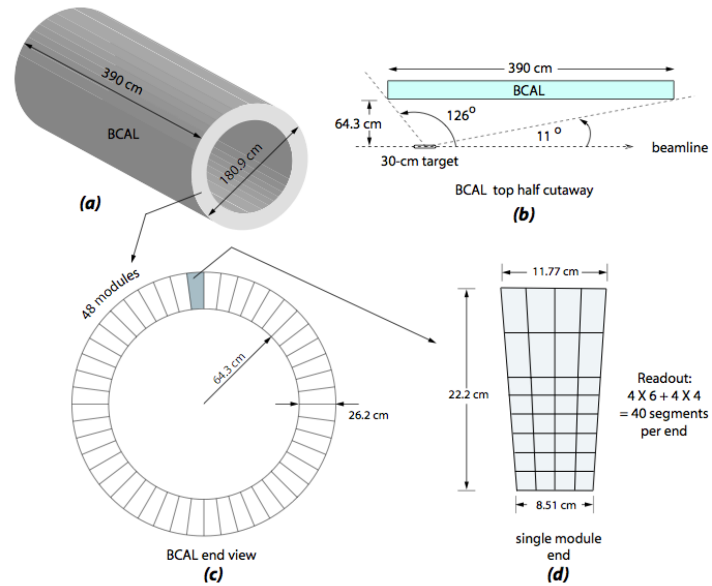
Construction Phase:
- BCAL, soon: FCAL, CDC, …

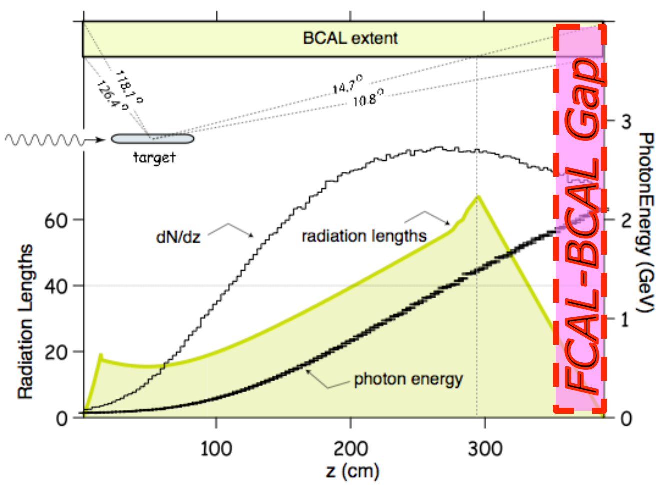


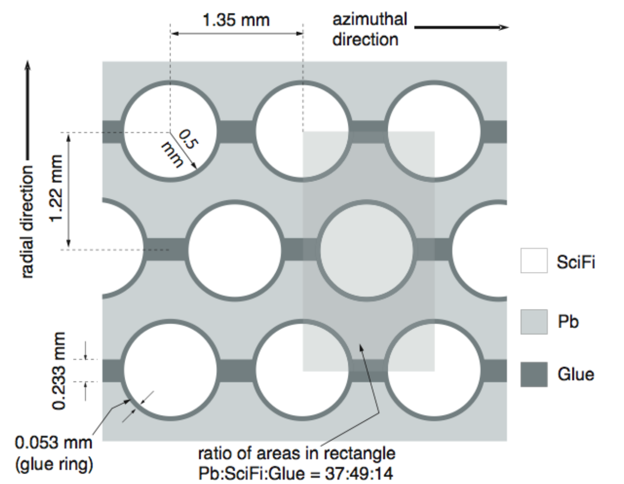
BCAL Schematics



GlueX Detector







BCAL Highlights

Key component of the GlueX detector

• Crucial for reconstructing γ from π^0 and η resulting from decay mesons

• Provides timing information (neutrals/charged)

• With the CDC it provides charged particle PID

• It supplies secondary dE/dx

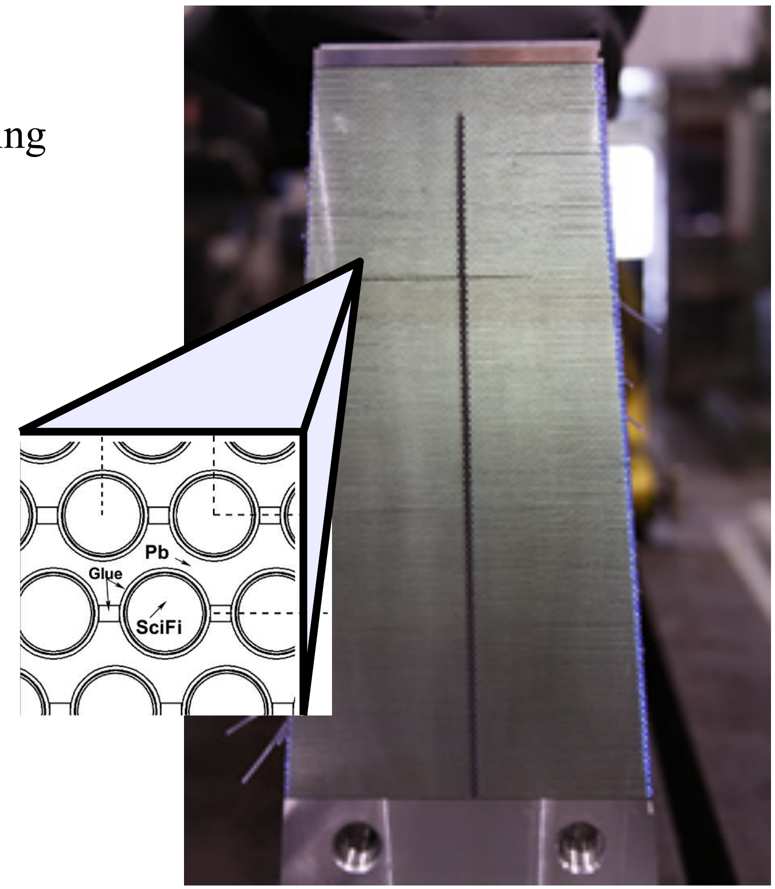
Geometry & Configuration

• Sampling calorimeter (11% sampling fraction)

• Based on KLOE Emcal design

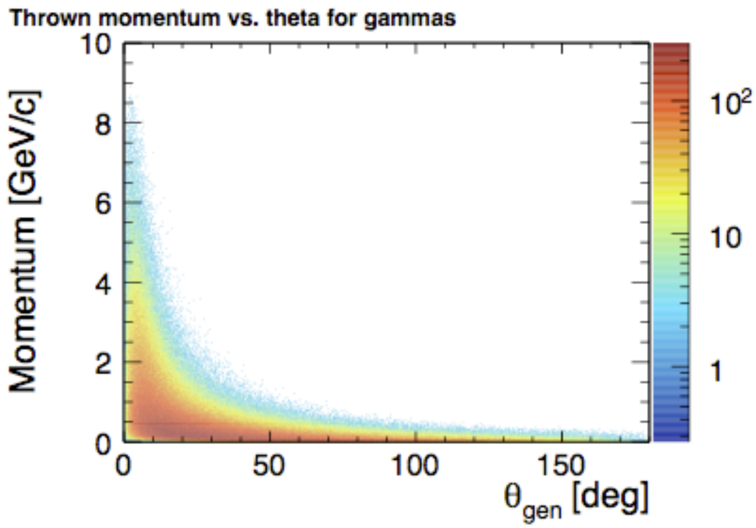
• BCAL: ~25 tonnes

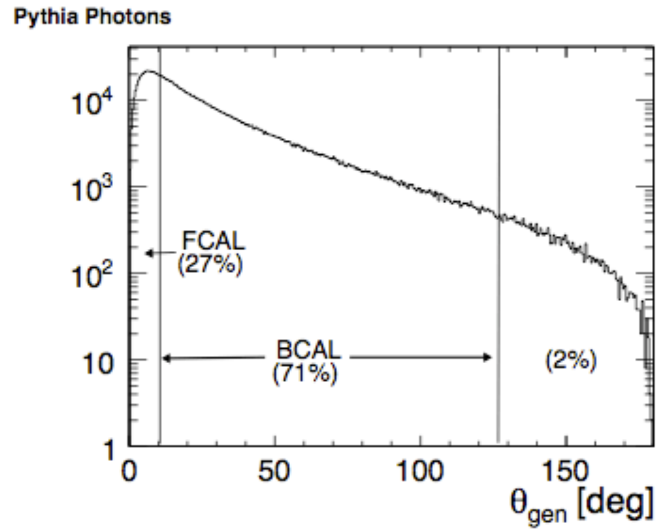
• The scintillating fibres have a polystyrene core which produces 8000 photons/MeV (***disputed***) and are blue-green, double clad (increases light captured by ~50%).

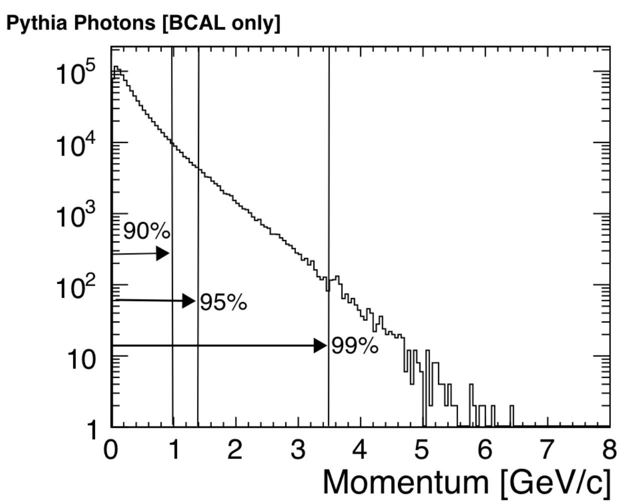


Machined module:
15,000 fibres

Decay Photon Distributions

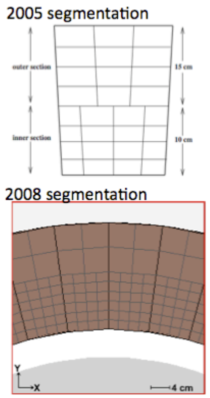






- Pythia simulations
  - 27% of photons in FCAL
  - 71% of decay photons are captured by BCAL
  - 50% of BCAL ones have energies < 300 MeV
- Dynamic range: 0.04-3.5 GeV
- FCAL-BCAL: gap at 11^0

Reconstruction Software



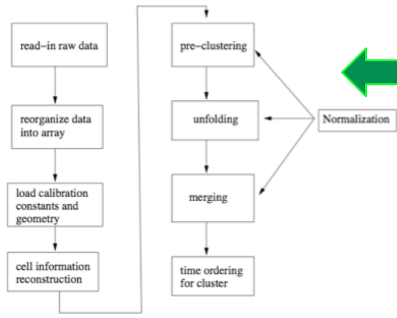
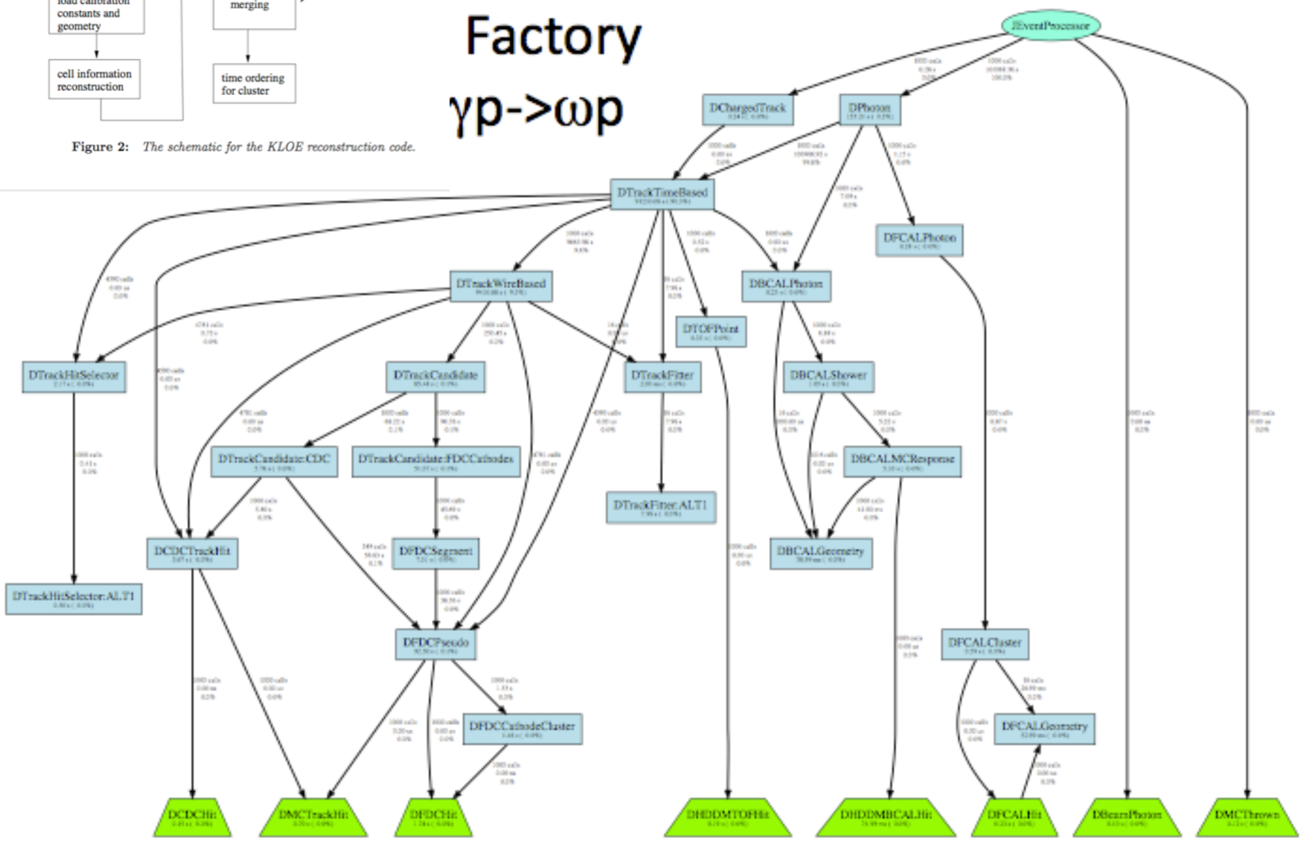


Figure 2: *The schematic for the KLOE reconstruction code.*

Original code KLOE->Regina

Factory

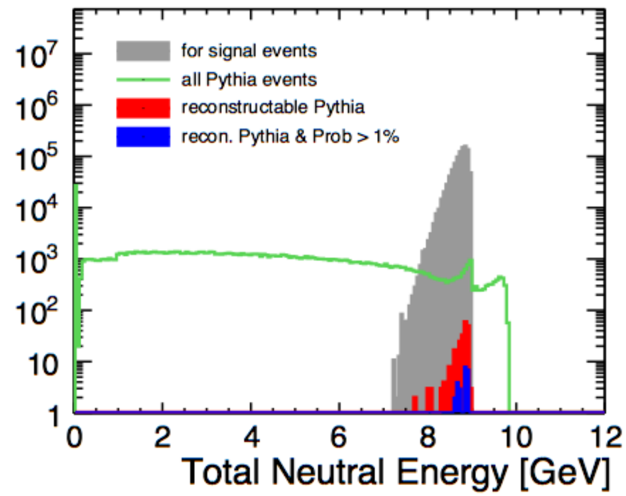
γp->ωp

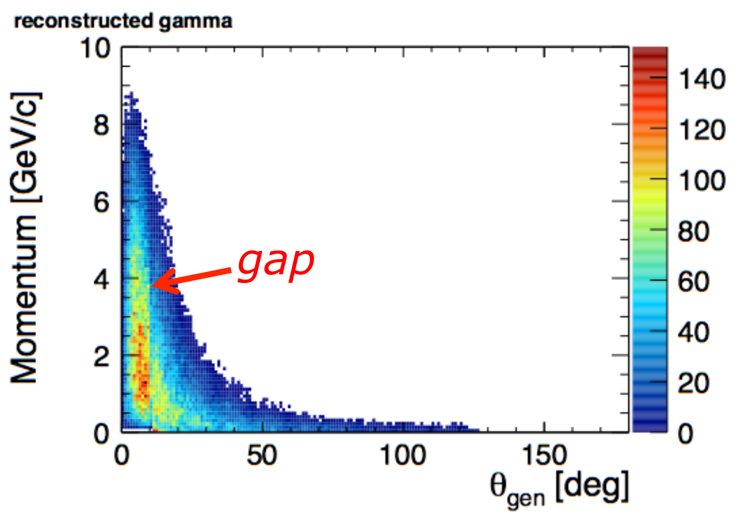


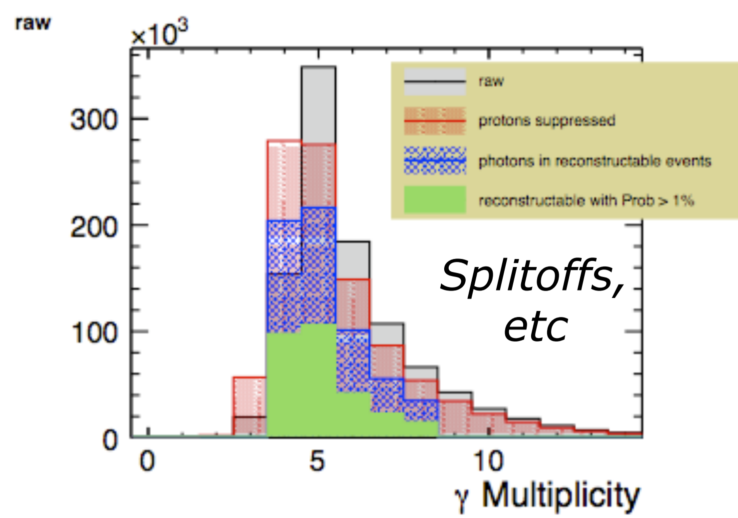
All Neutral Reconstruction

(by B.D. Leverington, UofR, now LNF!)

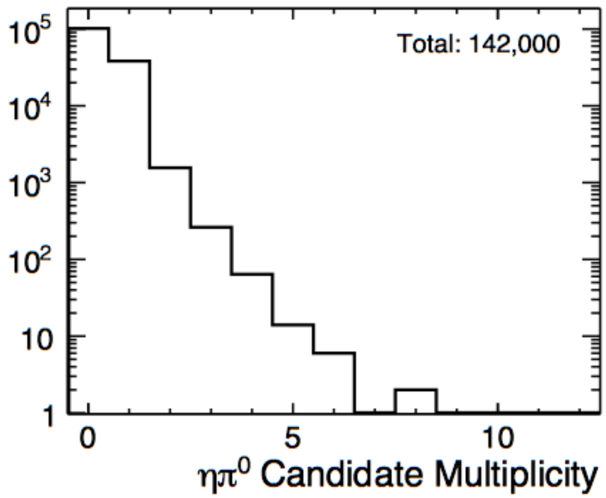
- Pythia background
- **$\eta\pi^0 \rightarrow 4\gamma$ signal events**
- Normalized by cross section
- 7.5 GeV<E<9.0 GeV
- Mesons decay to their final states
- Reconstruction
- Probability cuts

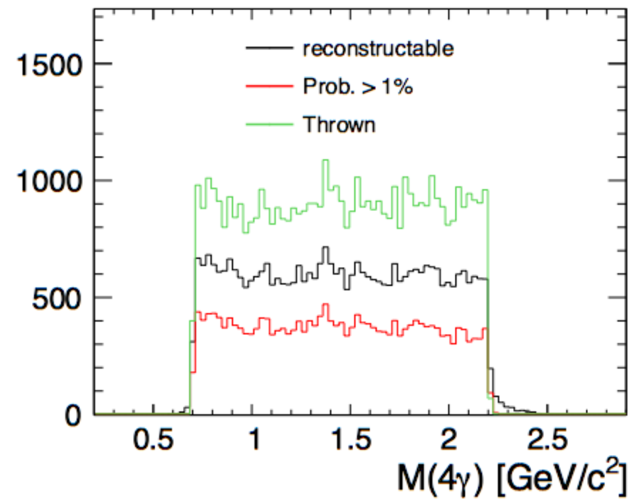


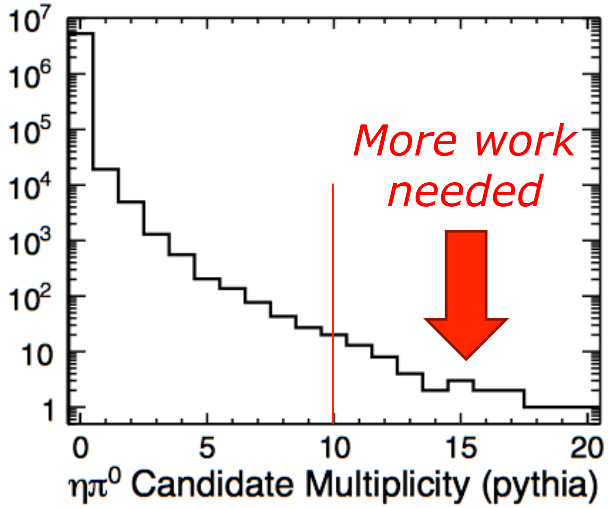


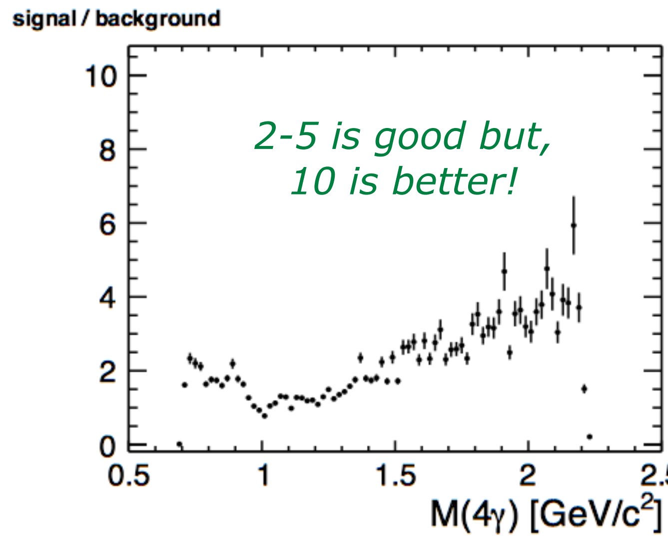


First Reconstruction Pass

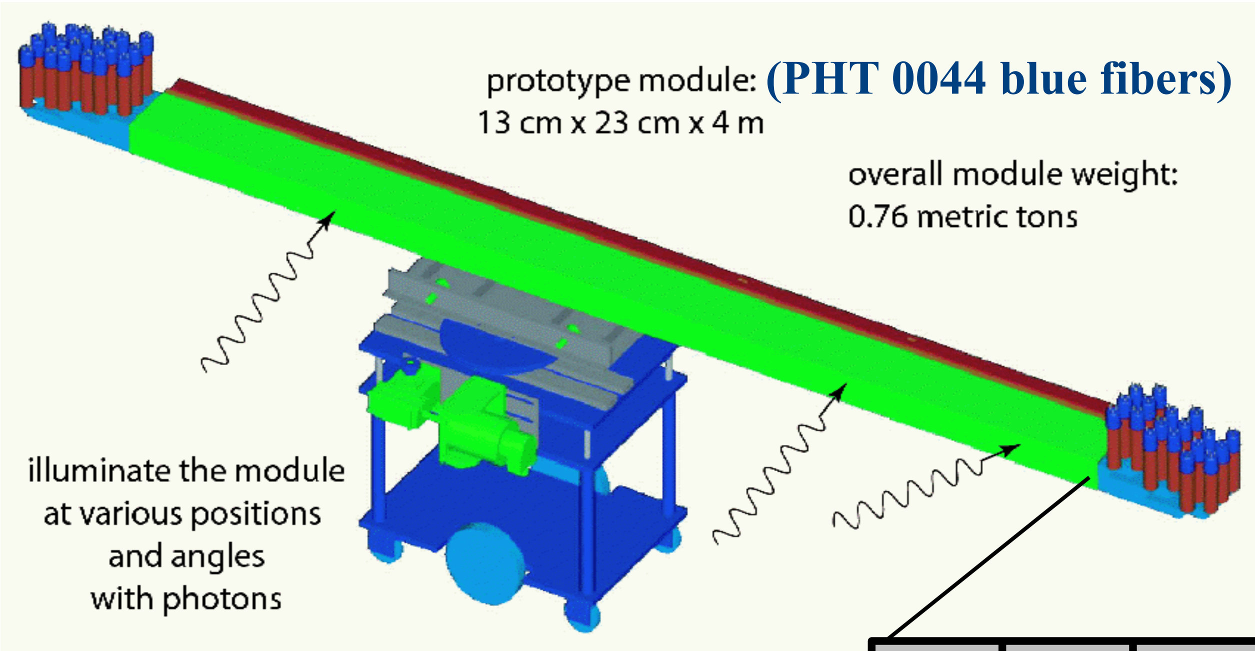








Beam Test at Hall B - Sep 2006

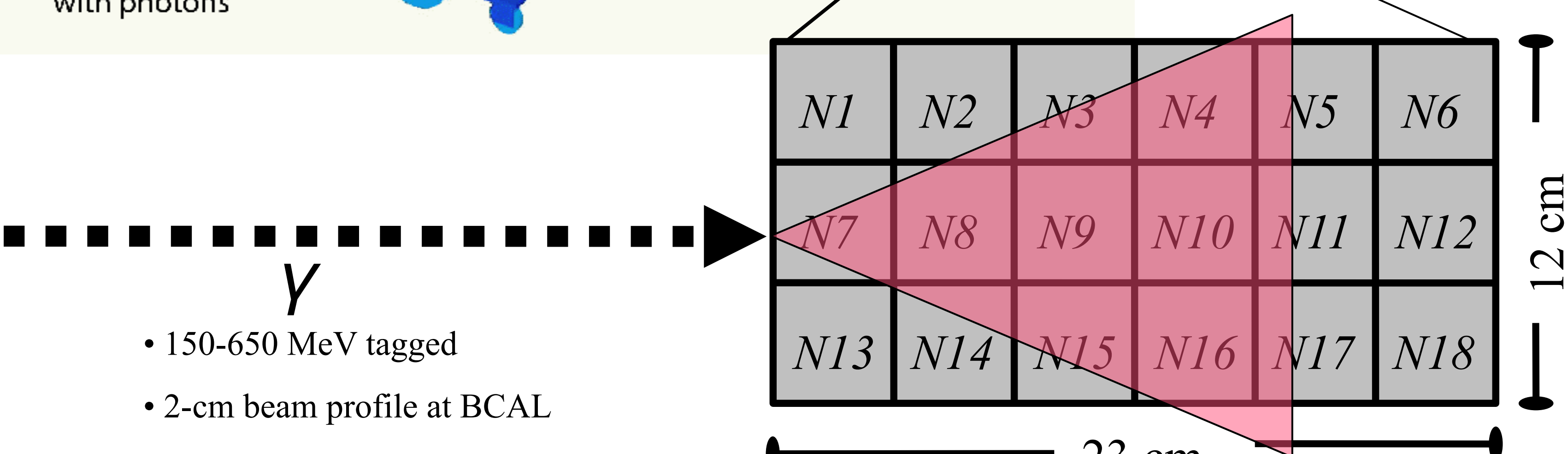


Verify

- Construction
- Fiber light output

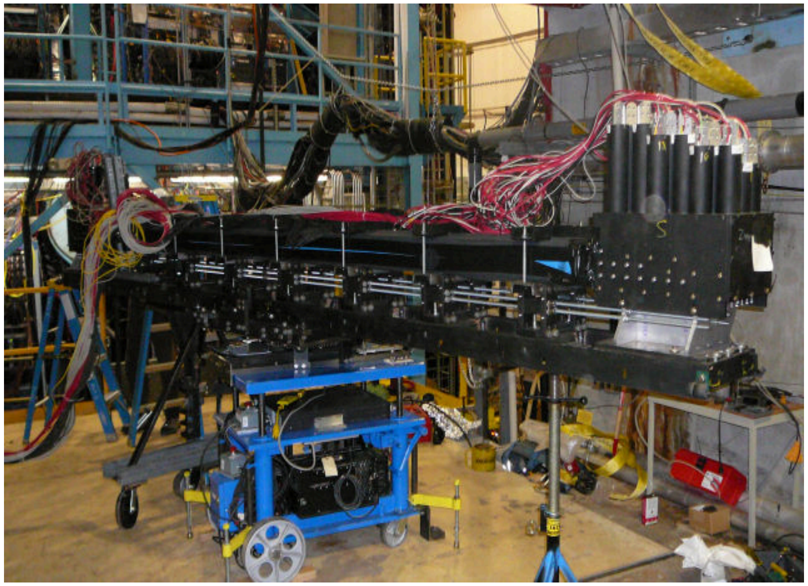
Measure

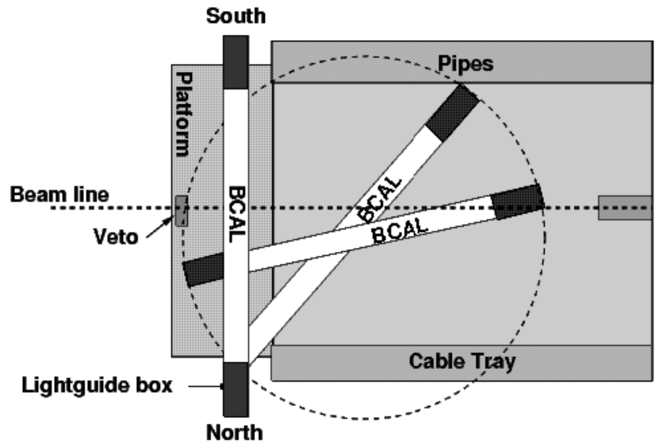
- Energy resolution
- Timing resolution
- No. of p.e.

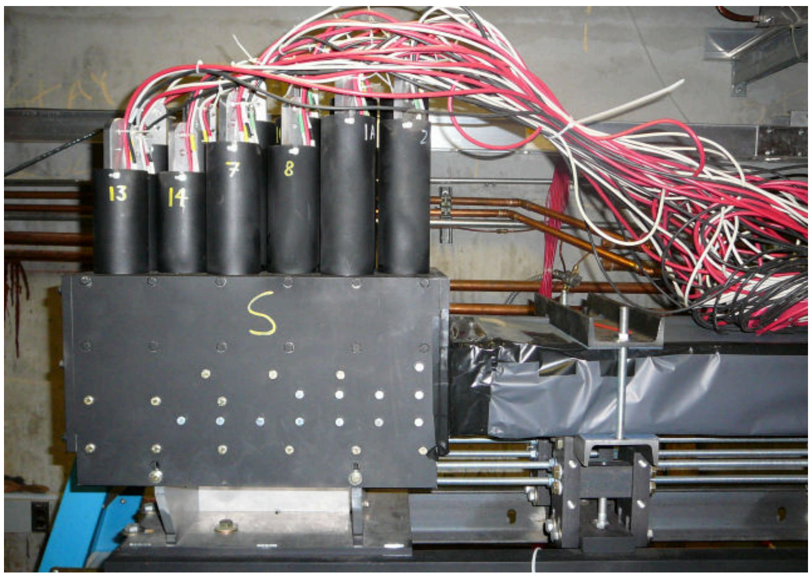


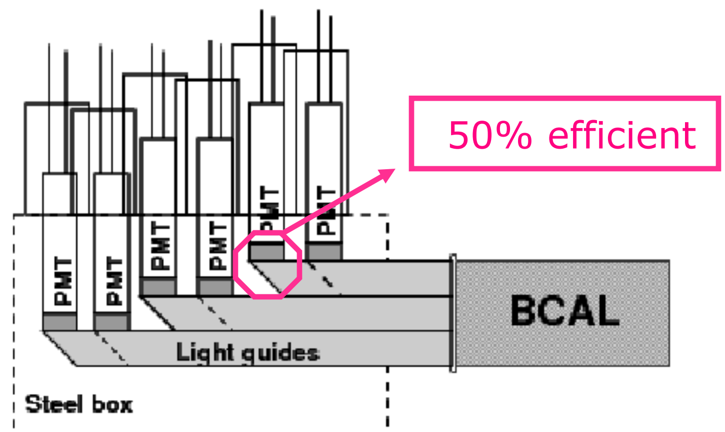
- 150-650 MeV tagged
- 2-cm beam profile at BCAL

Setup Photos



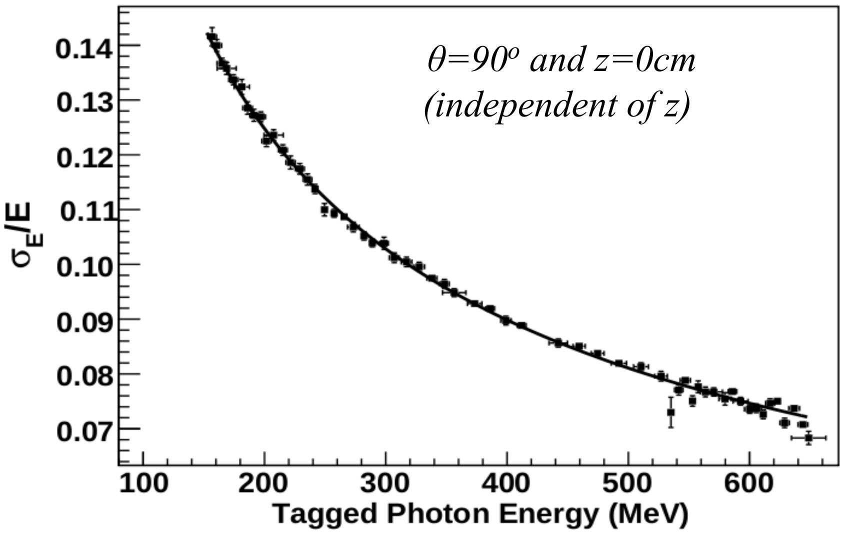


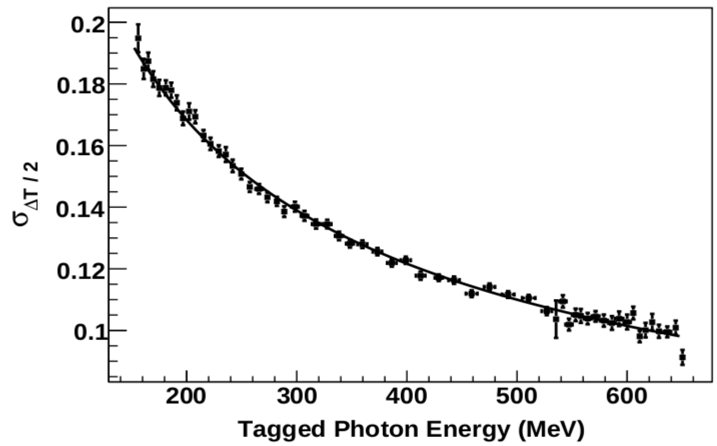




Energy, Timing Resolution & No of p.e.

Beam Test in 2006





$$\frac{\sigma_E}{E} = \frac{5.5 \pm 0.1\%}{\sqrt{E}} \oplus 2.4 \pm 1\%$$

time difference resolution

$$\sigma_{\Delta T/2} = \frac{70\,ps}{\sqrt{E(GeV)}}$$

$$KLOE \quad \left(\frac{\sigma_E}{E} = \frac{5.4\%}{\sqrt{E}} \oplus 0.7\% \right)$$

$$KLOE \quad \left(\sigma_t = \frac{72\,ps}{\sqrt{E}} \right)$$

BCAL: 660 pe/GeV vs KLOE: 700 pe/GeV
- single clad fibers, better light guides

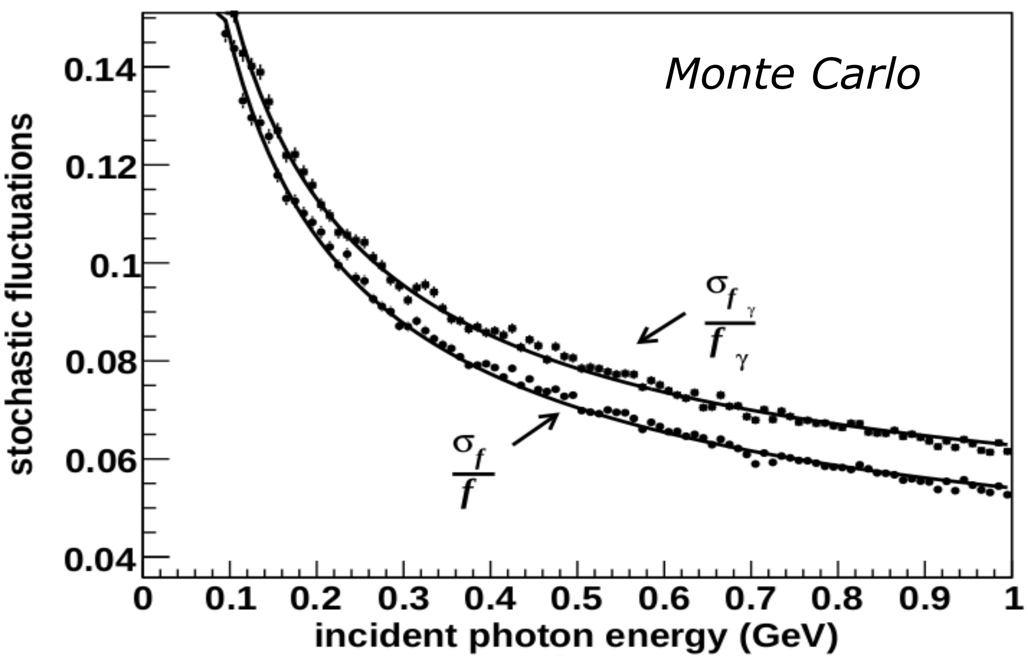
NIMA 48874 (2008)
http://dx.doi.org/10.1016/j.nima.2008.08.137

Contributions to Energy Resolution

- The dominant contribution to the energy resolution is the fluctuations in the energy sampling by the scintillating fibres.

- The properties of the scintillating fibres and coupling will affect the photon statistics contribution to the resolution.

$$\frac{\sigma_E}{E} = \frac{\sigma_f}{f(E)} \oplus \frac{\sigma_{pe}}{E}$$



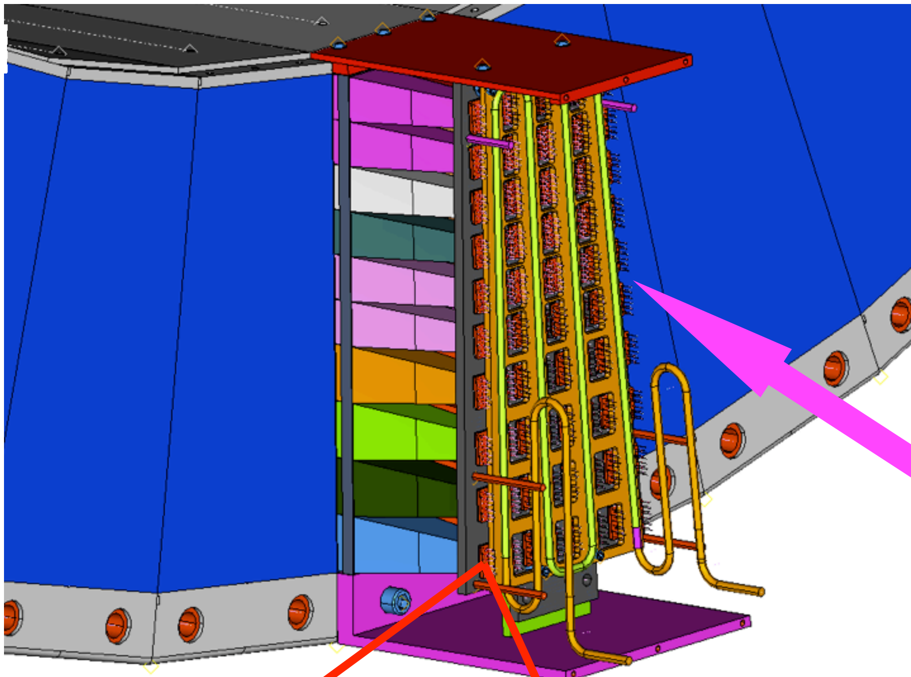
sampling fluctuations

$$\frac{\sigma_f}{f(E)} = \frac{4.1\%}{\sqrt{E(GeV)}} \oplus 1\%$$

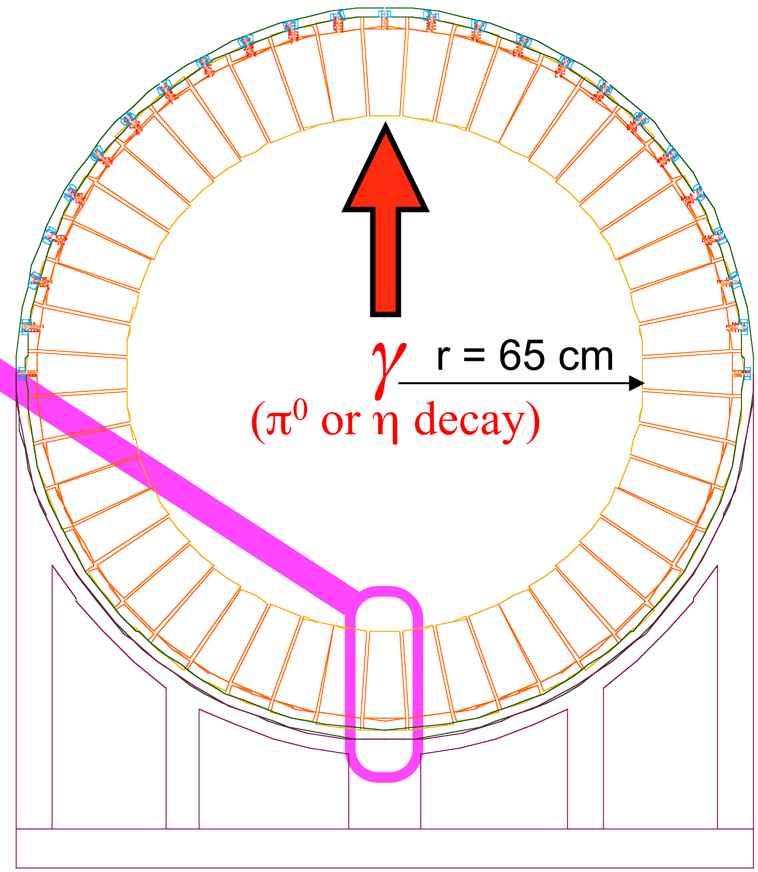
photoelectron statistics

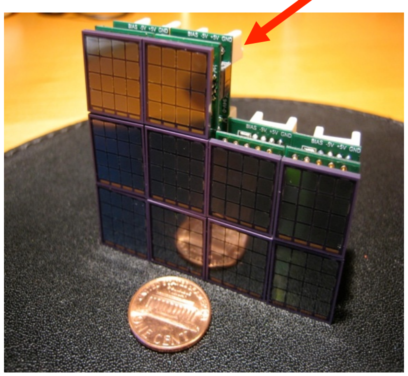
$$\frac{\sigma_{pe}}{E} = \frac{3.1\%}{\sqrt{E(GeV)}}$$

BCAL Readout: GlueX sets SiPM Array Standard!

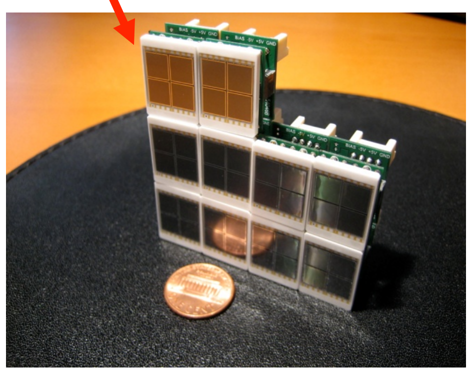


48 modules (phi sectors)





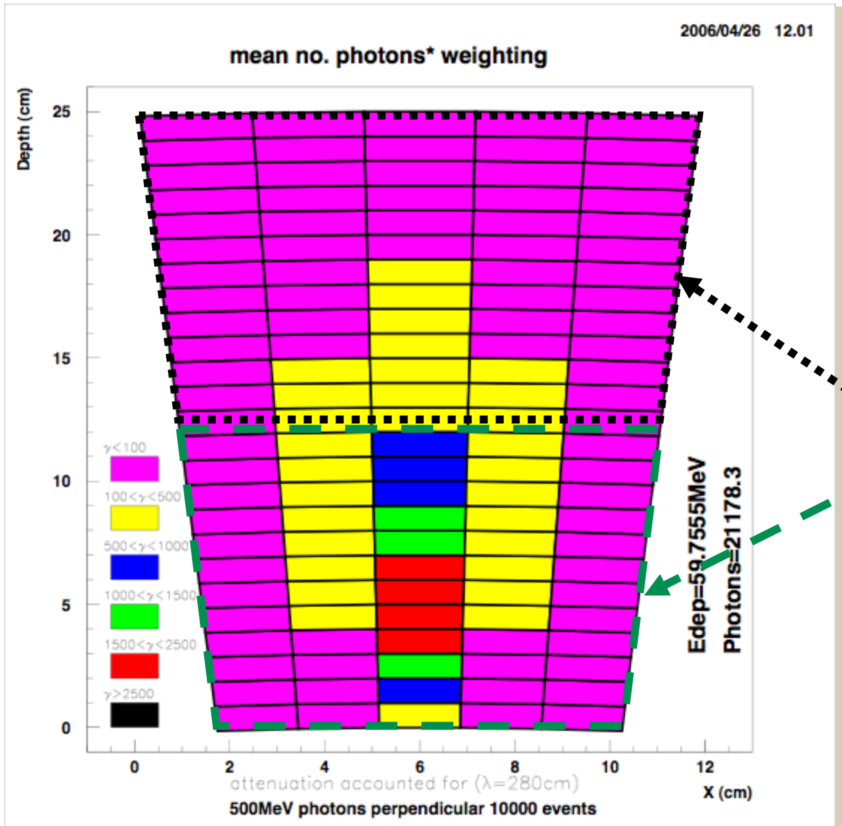
SensL SPMArray

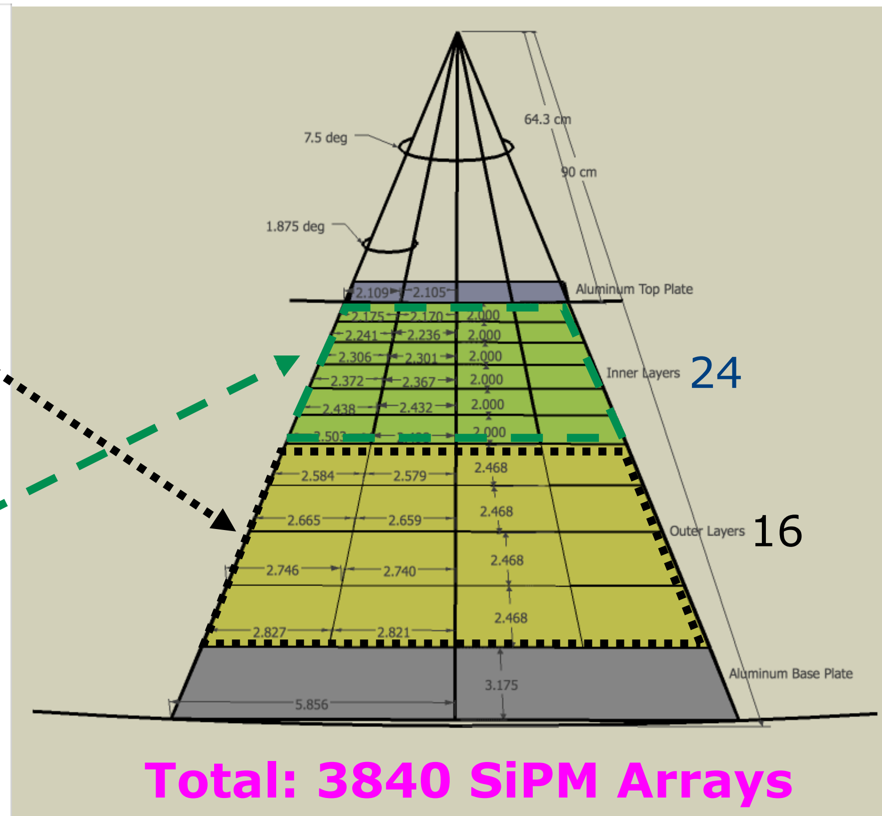


Hamamatsu MPPC

- $16X_0$ thick
- Sampling Fraction = 11%

Readout Segmentation



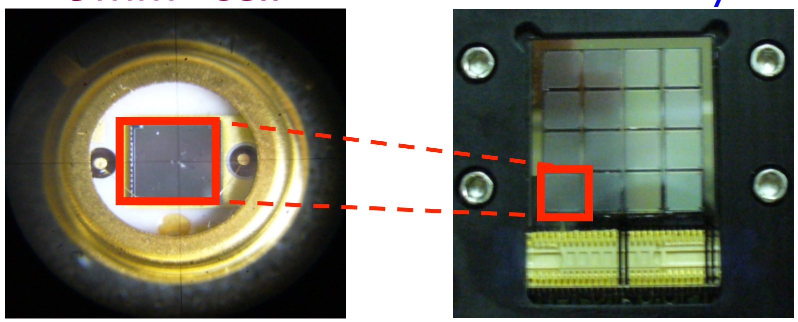


Simulation

Design

SiPM Highlights – 2006-9

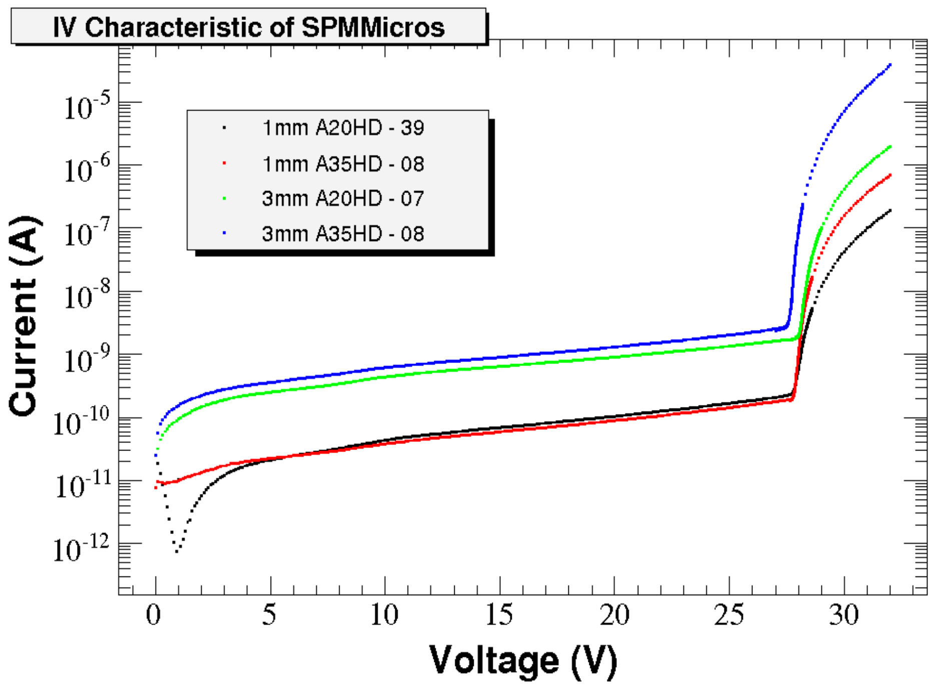
Features of SiPMs:
- High gain APD (10^6)
- Low bias voltage (~28V)
- Compact and stable
- Insensitive to magnetic fields
- Tolerant to excess light



Evolution at Regina/Jefferson Lab:

1x1mm^2 …→ 3x3mm^2 (A35HD, η_{FF}=59%, 3640 microcells) …→ Arrays

Micro Mini Array



Extracting PDE - 2009

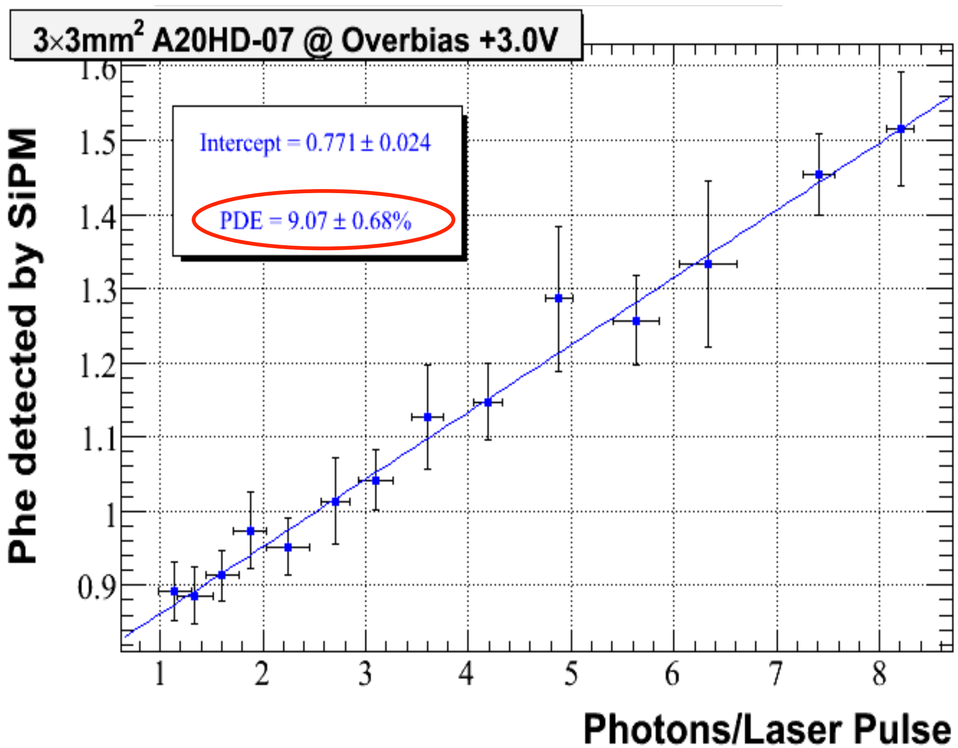
$$PDE = Q_E \times F \times \alpha_p$$

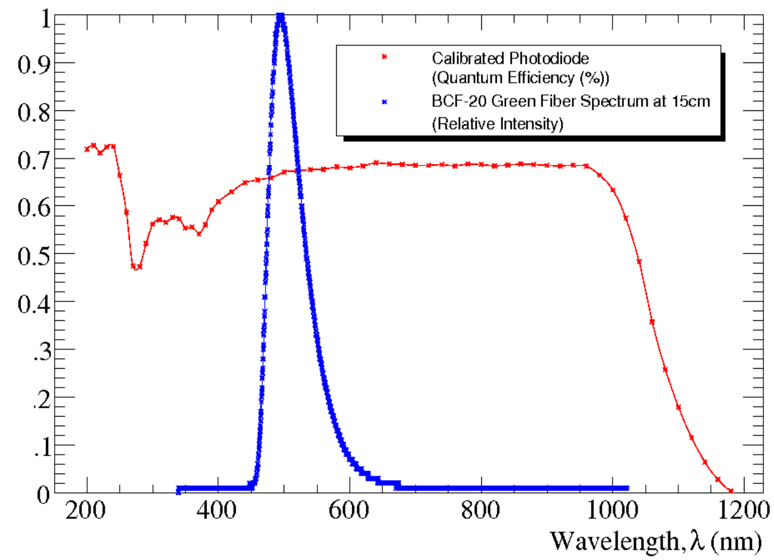
PDE = Photon Detection Efficiency

Q_E = quantum efficiency (pixels)

F = "fill factor" = fraction of actual photosensitive surface

α_p = avalanche probability = $f\,[V-V_{br}]$

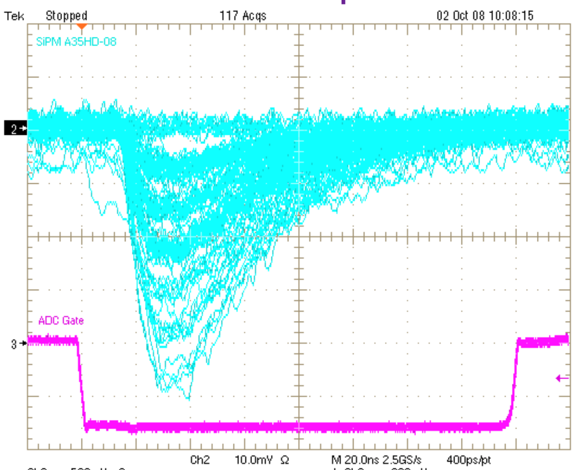




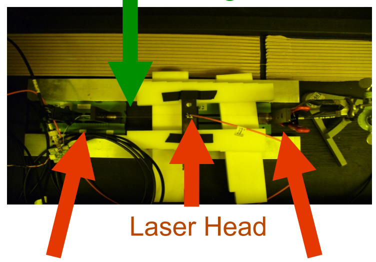
Photons/Pulse = I/(E•S•f)
where
I=photodiode current
E=3.97x10^{19} J/photons
S=270 mA/W
f = 2.5 MHz

SiPMMicro Performance - 2009

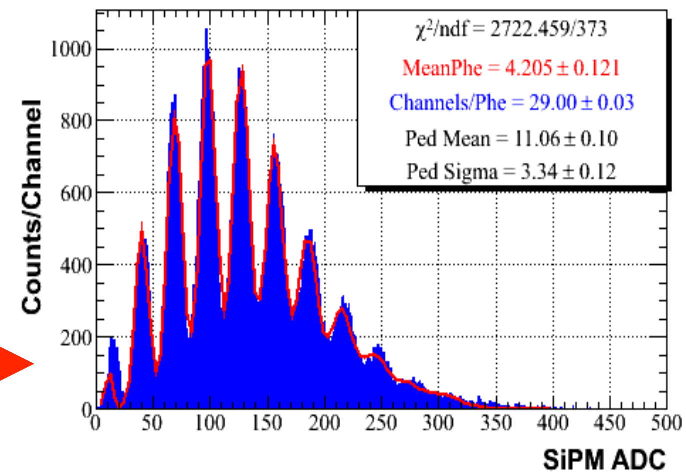
Individual Photoelectron Bands in Scope Traces

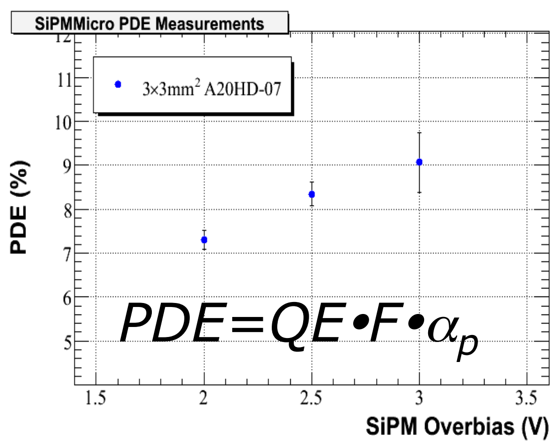


~30cm BCF20 green Sci/Fi



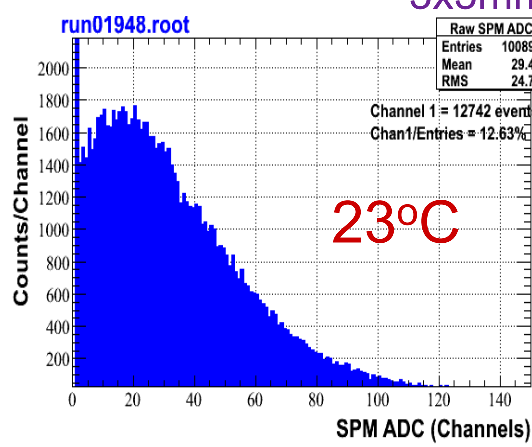
1x1mm^2 A20HD

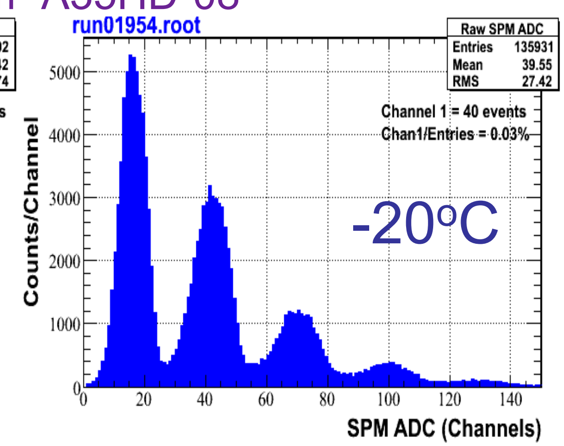




$PDE = QE \bullet F \bullet \alpha_p$

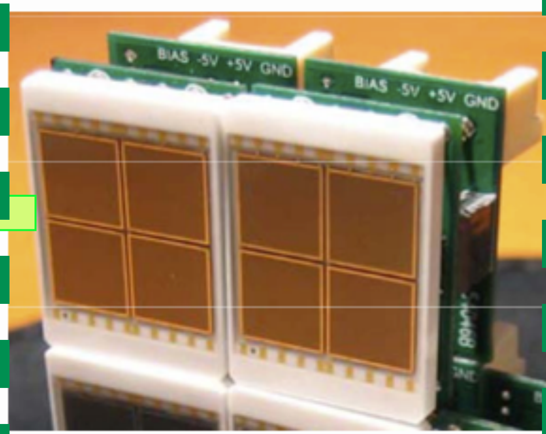
3x3mm^2 A35HD-08



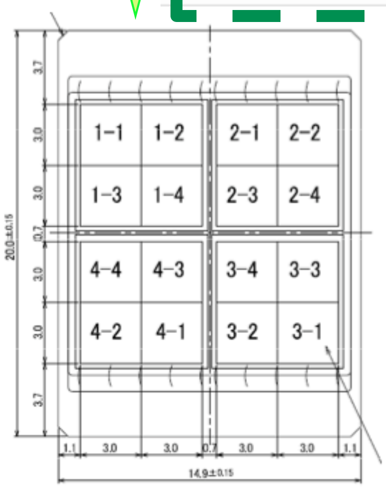


..and then there were TWO - 2010

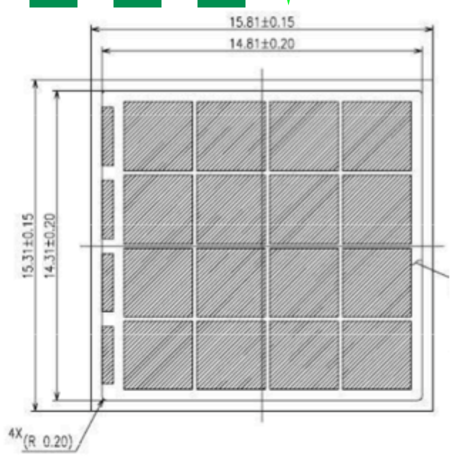
Hamamatsu MPPC



SensL SiPM4



- Cells (2x2): 4x3x3 mm²
- Photosensitive: 3x3 mm²
- 700 μm gaps

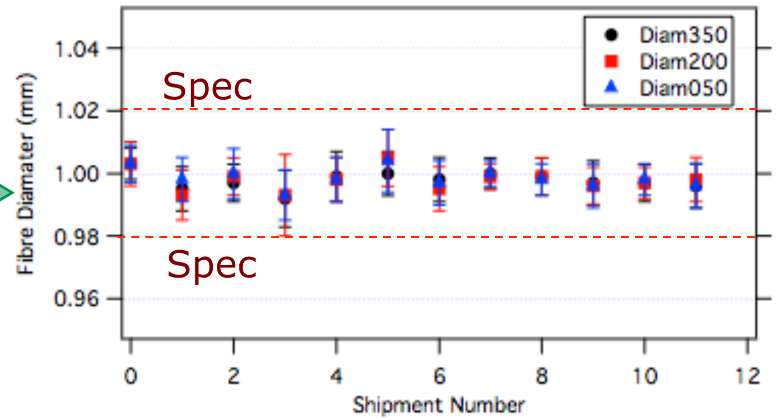


- Cells (16): 3.16x3.16 mm²
- Photosensitive: 2.85 x 2.85 mm²
- 200 μm gaps

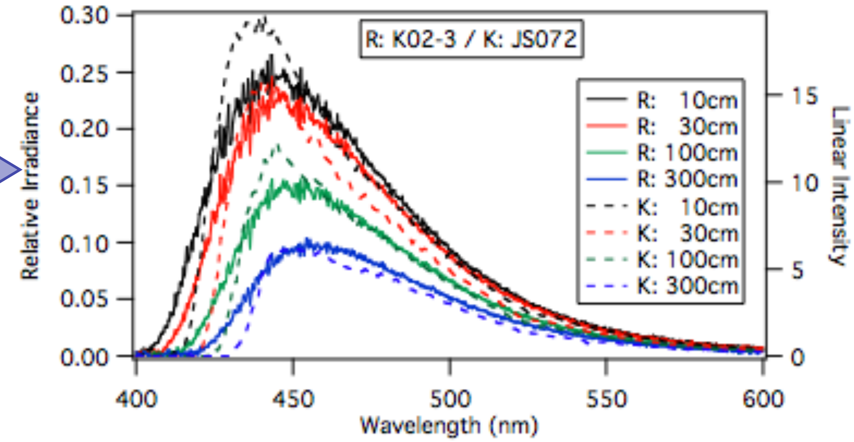
	SensL	Hamamatsu
Pixel size (μm)	35	50
N_{pixels} / cell	3640	3600
PDE	10-20%	> 20%
Fill Factor	59%	61.5%
Dark Rate (per cell)	8Mhz	5-6 Mhz
V_{op}	30 V	70 V
Gain	$> 10^6$	$> 10^6$
Eff. Area	75%	89%

BCAL Construction QC/QA: Fibres

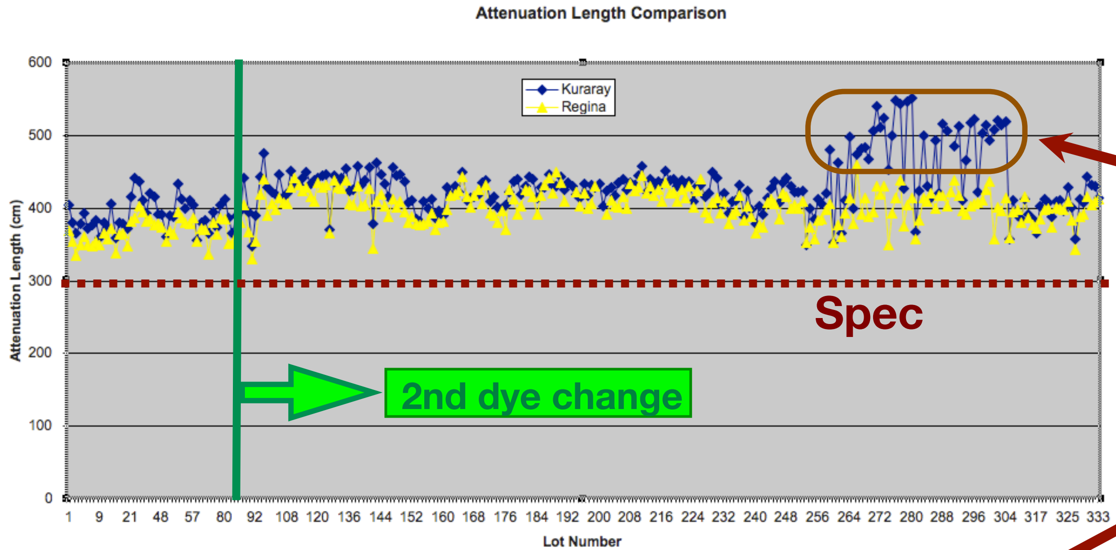
- Kuraray SCSF-78MJ (780,000 fibres); chosen in late 2008
- diameters: within specs



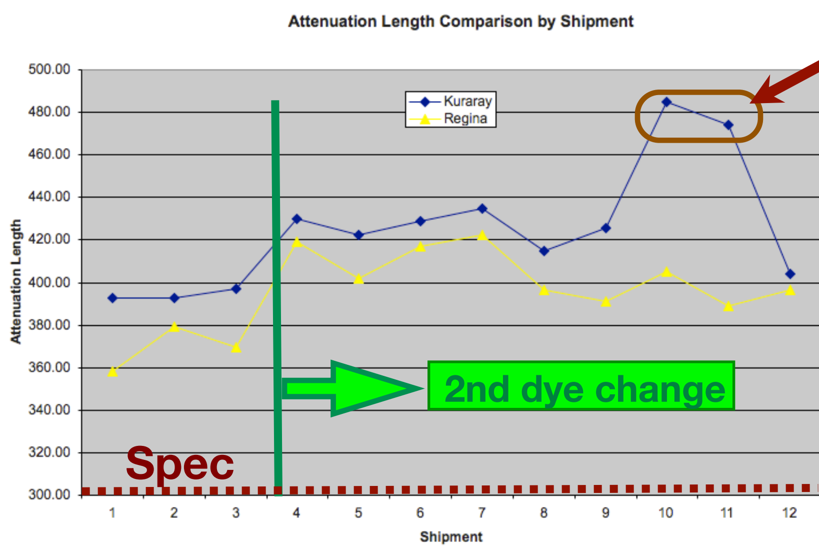
- Spectra measured at Regina qualitatively agree with Kuraray's
- integrals are close, but shapes are different; response is acceptable and scales by distance in a similar fashion



Fibre Attenuation Length



Shipments 10&11; Resolved!



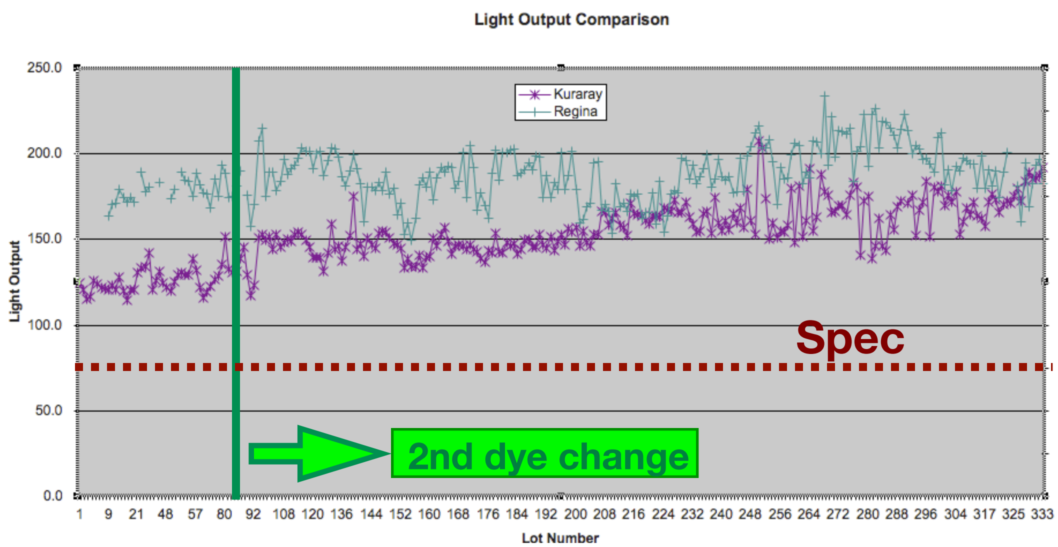
Lot-to-lot variation and Shipment-to-shipment change

Kuraray and Regina results track each other

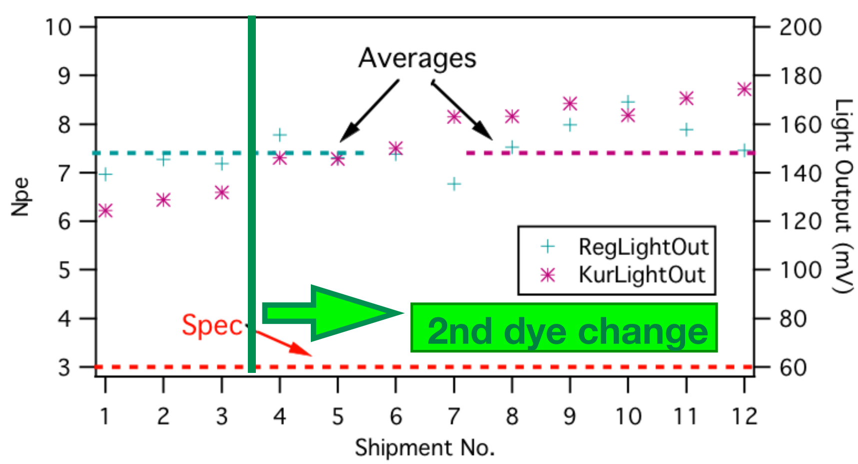
... and fibres meet specs

(cumulative RMS<9.7%)

Fibre Light Output



Methods are very different:
- K: scope
- R: Npe w. 90Sr



Lot-to-lot variation and Shipment-to-shipment change

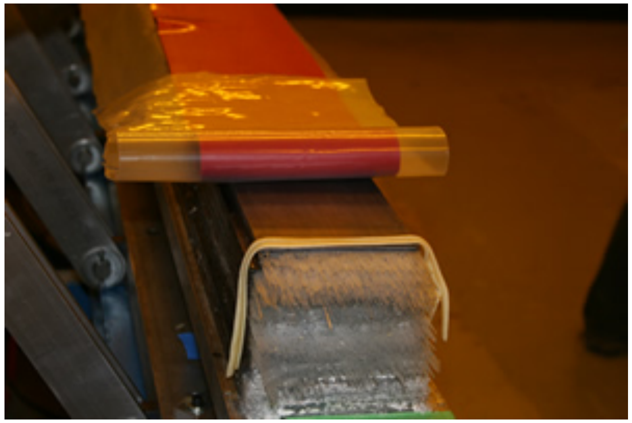
Kuraray and Regina results differ somewhat

... but fibres meet specs

(cumulative RMS<12.2%)

Matrix Construction Facility @ Regina

ROLLING



GLUING

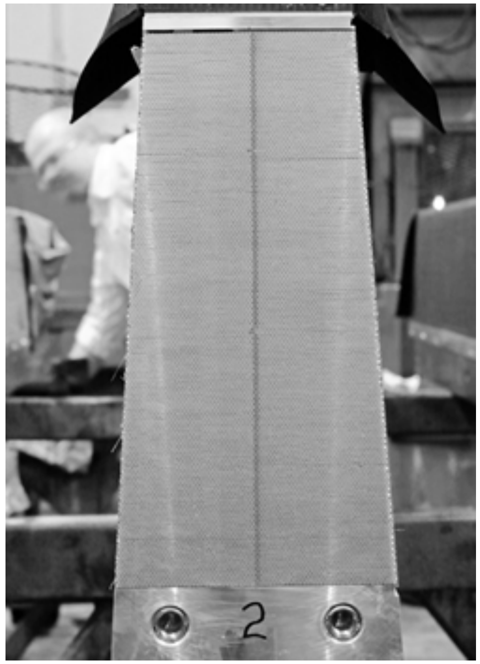
QUALITY CONTROL AT EVERY STEP

SWAGGING

PRESSING

Machined Modules 01-04

01



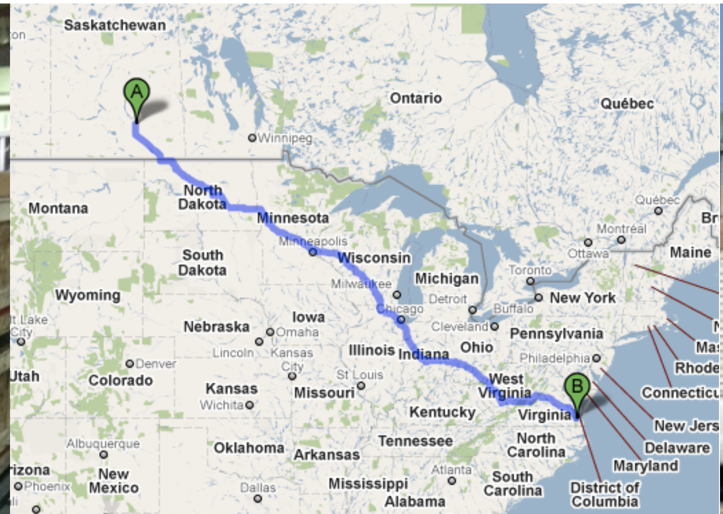
02

03

04

- Excellent finish of end faces & transmission uniformity
- Eight more modules have been built & are being machined

Module Delivery to JLab



41

~3,300 km

Ready to leave Regina
(April 22)

Arrived at JLab
(April 26)

Modules 01-04: 1st detector delivery for 12 GeV program!

Modules 05-08: arrive at Jlab tomorrow

Summary

• The nature of confinement is an outstanding and fundamental question of quarks and gluons in QCD.
• LQCD and phenomenology suggest flux-tubes as the explanation.
• The excitation of the gluonic field leads to an entirely new spectrum of mesons as predicted by LQCD. Data are needed.
• PWA and improved theoretical understanding is required.
• The definitive experiment for this search will be GlueX at the energy-upgraded JLab. If exotic hybrids are there, we will find them!

- BCAL construction is on schedule; completion in spring of 2012.
- Detector integration in 2013.
- Engineering data in 2014, Physics data in 2015.

We welcome new collaborators and students!

Acknowledgements

- **Group members**:
  - K. Janzen, S. Katsaganis, B. Leverington, G. Lolos, Z. Papandreou, A. Semenov, I. Semenova, D. Kolybaba, plus **many undergraduates**
- A. Dzierba, Indiana University
- C. Meyer, Carnegie Mellon University
- J. Dudek, Jefferson Lab/ODU
- Bali, U. Glasgow
- D. Leinweber, CSSM / U. Adelaide
- Particle Adventure
- **portal.gluex.org**
- **www.halld.org**
- **www.gluex.org**

Regina & University

Regina
- *781 km from Edmonton*
- *200,000 pop.*
- *Negligible traffic*
- *Home of the Riders*

UofR
- *12000 full+part time*
- *Facilities growth*
- *Subatomic Physics Dept*

Backup Slides

Moments and PWA

Moments provide an arbiter for wave set sufficiency

$$H(LMN) = \int I(\Omega) D^L_{MN}(\Omega) d\Omega$$

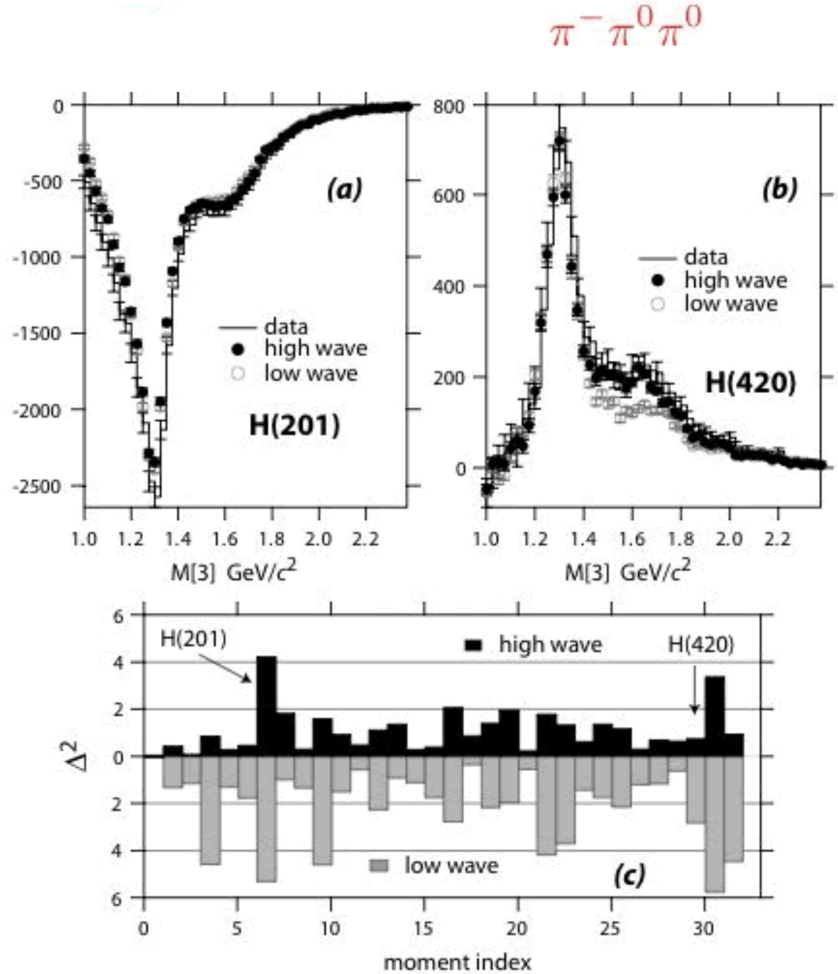
compare moments calculated from data and from PWA

$$\Delta^2 = \frac{1}{n}\sum_i^n \frac{(H_D - H_P)^2}{\sigma_D^2 + \sigma_P^2}$$

Number of waves used in old analysis - 21 waves (low-wave set)

Number of waves used in new analysis - 35 waves (high-wave set)

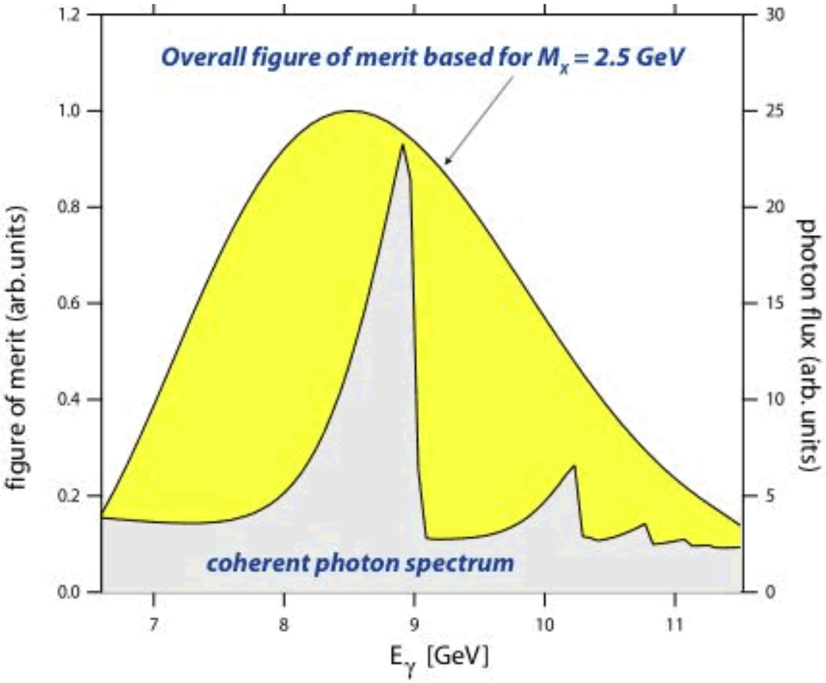
Agreement with moments better with high wave set.

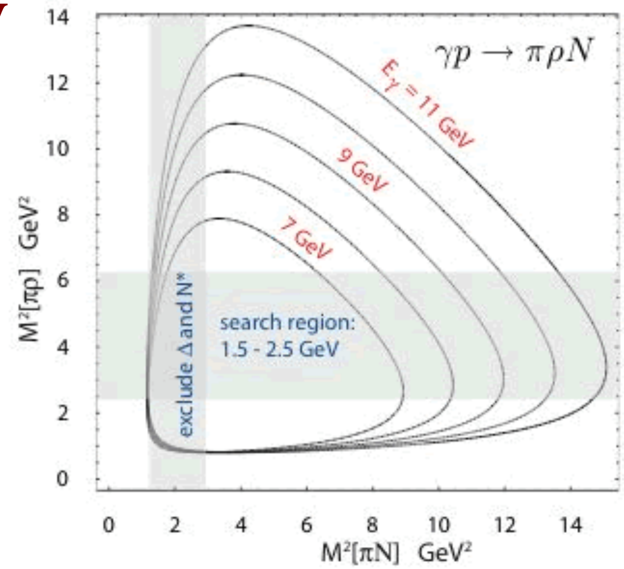


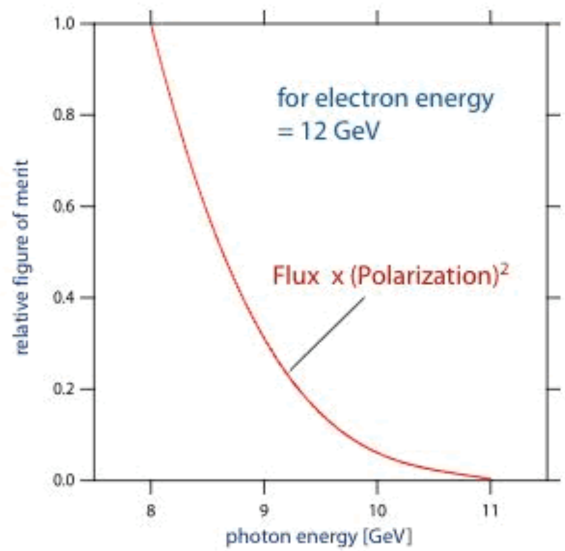
Ideal Photon Beam Energy

Figure of Merit:

- *Start with 12 GeV electrons*
- *Meson yield for high mass region*
- *Separate meson from baryon resonances*
- *Balance beam flux/polarization*
- *Coherent bremsstrahlung, tagger, collimator*







Gain Balancing and Calibration

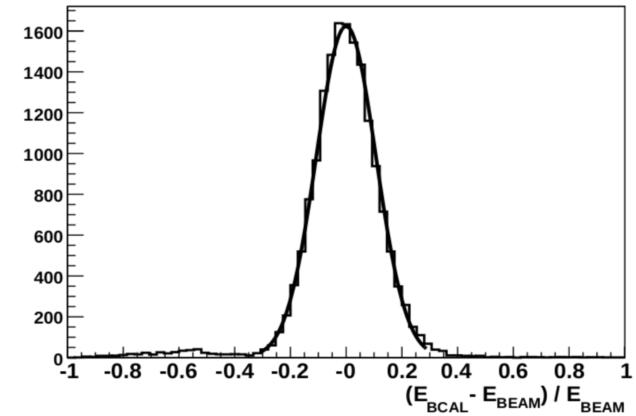
Important step: Gain balance all 36 PMTs

✓Online: the means of the cosmic ADC spectra were balanced to within 10% during setup

✓Offline:

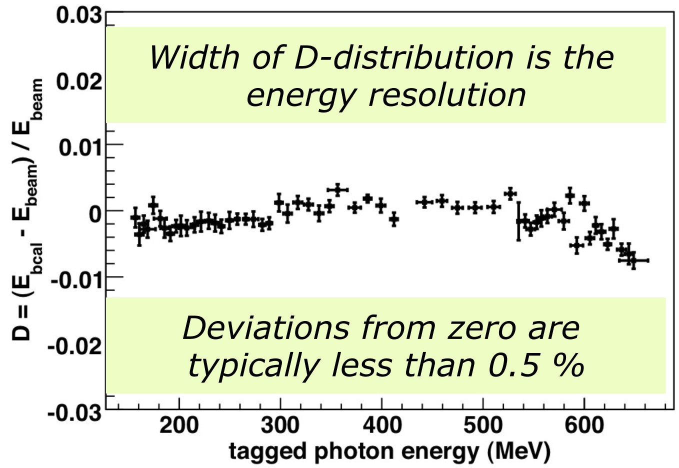
- gain balance using dedicated cosmics runs
- energy calibration
- minimize the width of the difference between the tagged beam energy, E_{beam} and the reconstructed energy in the BCAL, E_{bcal}

$$D = \frac{E_{beam} - E_{bcal}}{E_{beam}}$$



$$C_{N,i} = \frac{N_{ADC,i}}{N_{ADC,7}}$$

$$E_{BCAL} = K \cdot \sqrt{\left(\sum_{i=1}^{18} \frac{N_{ADC,i}}{C_{N,i}}\right) \cdot \left(\sum_{i=1}^{18} \frac{S_{ADC,i}}{C_{S,i}}\right)}$$



Number of Photo-Electrons

No. of photoelectrons important:

- Low energies: threshold
- SiPM versus FM PMTs (readout)

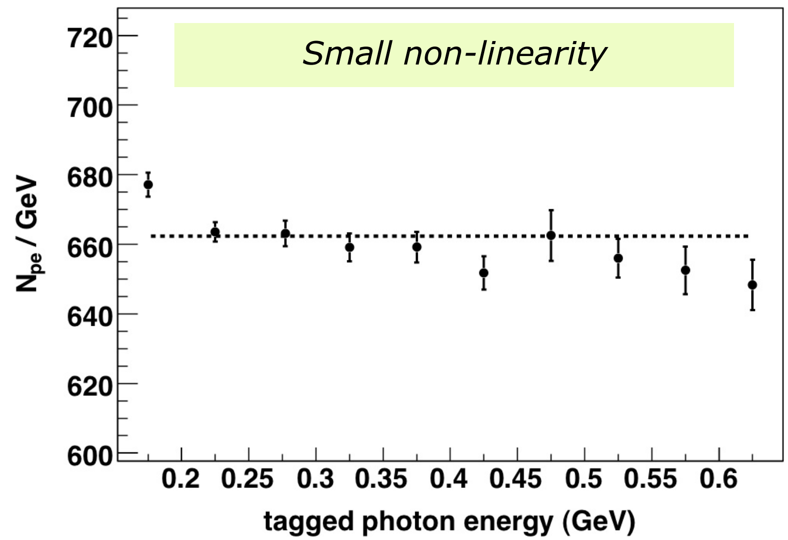
$$R(E_j) = \frac{\sum_{i=1}^{18} E_{N,i;j}}{\sum_{i=1}^{18} E_{S,i;j}}$$

Calibrated energies:
i^{th} segment, j^{th} energy bin

$$f(r) \approx \int P\left(x, N_{pe} \cdot \sqrt{R}\right) \cdot \frac{1}{r} \cdot P\left(\frac{x}{r}, \frac{N_{pe}}{\sqrt{R}}\right)\left[\frac{x}{r} dx\right]$$

Poisson-shape for amplitude spectra
(r=N/S amplitude, R=N/S average)

z=0 cm & θ=90°



KLOE: 700 pe/GeV

- single clad fibers
- better light guides

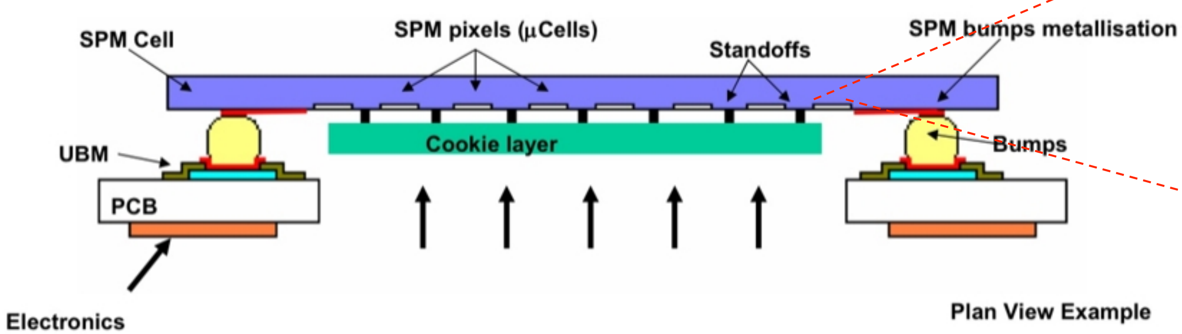
Silicon Photo-Multipliers (SiPM)

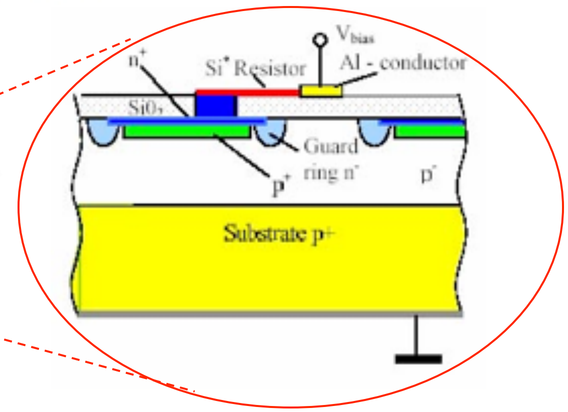
Approach Pursued

SensL
The Low Light Sensing Company

Option#4: Thru. PCB – front side illumination – flip-chip.

Pixel: independent photon micro-counter in limited Geiger mode

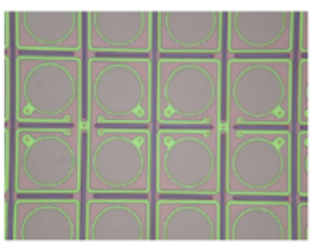




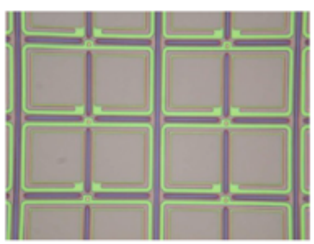
Plan View Example

Breakdown bias: 25-30V

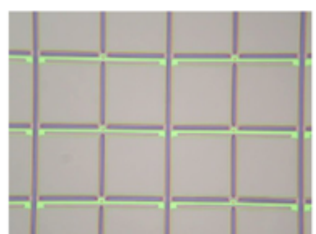
Gain: >10^6



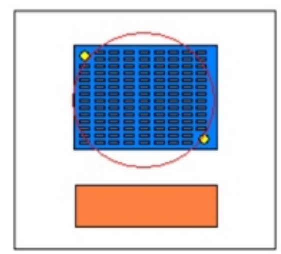
C20
17%FF



A20L
34%FF



A20H
43%FF
848 pixels
PDE=9% (+2V)



Goal: A35H chip

Physics Plans

- Detector commissioning
- Physics commissioning: density matrices, $a_2(1320)$
- Exotic hybrid search

Particle	J^{PC}	I	G	Possible Modes[a]
b_0	0^{+-}	1	+	
h_0	0^{+-}	0	−	$b_1\pi$
π_1	1^{-+}	1	−	$\rho\pi$, $b_1\pi$
η_1	1^{-+}	0	+	$a_2\pi$
b_2	2^{+-}	1	+	$a_2\pi$
h_2	2^{+-}	0	−	$\rho\pi$, $b_1\pi$

[a]Assuming the $G = +$ channel $2\pi\eta$ or the $G = -$ channels 3π or $2\pi\omega$.

- $s\bar{s}$ physics, baryon spectroscopy, …