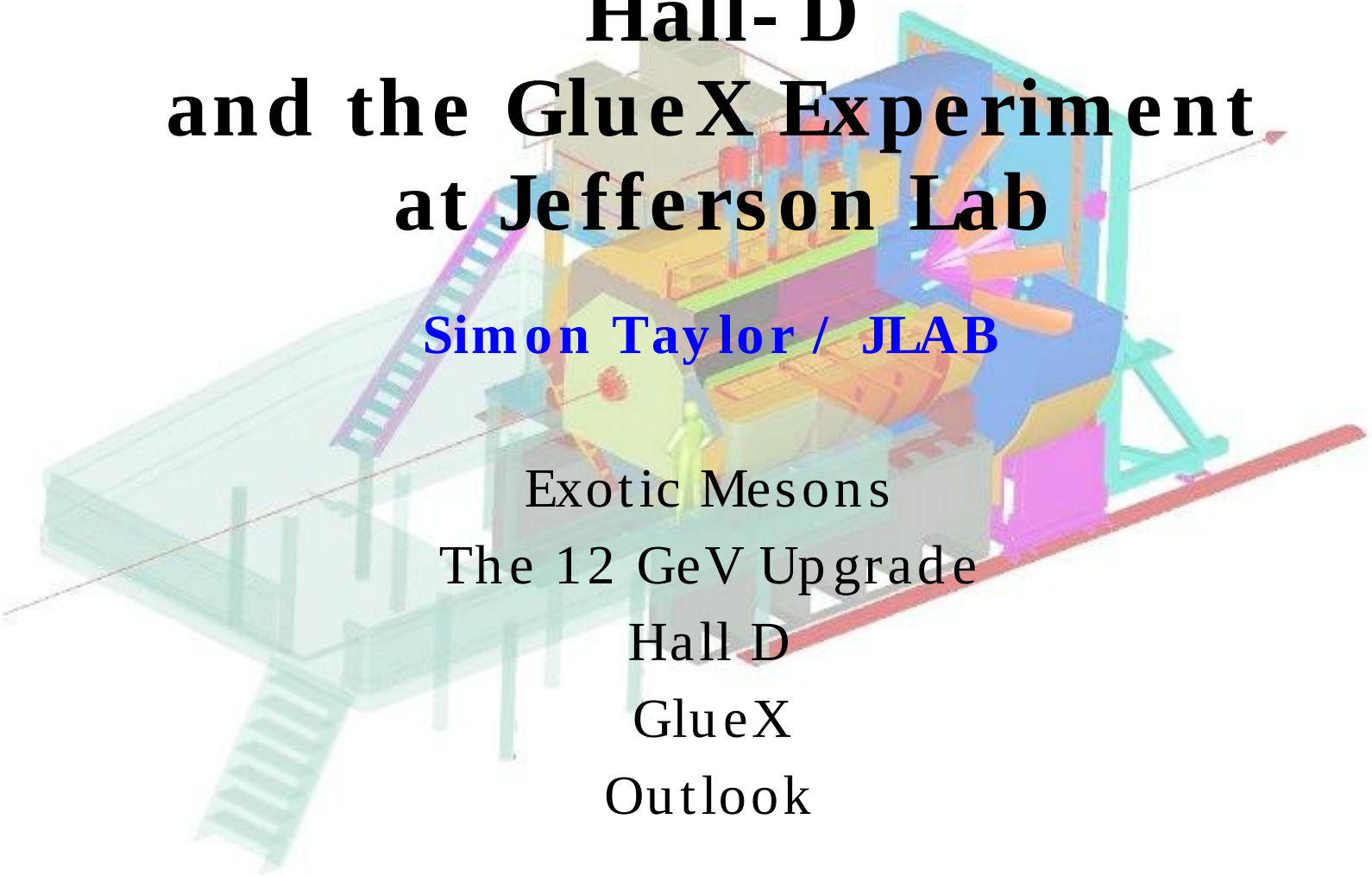
Hall- D and the GlueX Experiment at Jefferson Lab

Simon Taylor / JLAB



Exotic Mesons

The 12 GeV Upgrade

Hall D

GlueX

Outlook

Gluonic Degrees of Freedom

Perturbative

Non-Perturbative

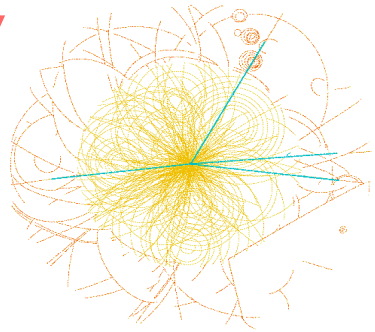
Asymptotic Freedom

Confinement

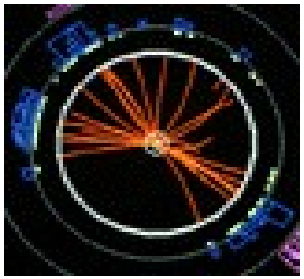
Small Distance
High Energy

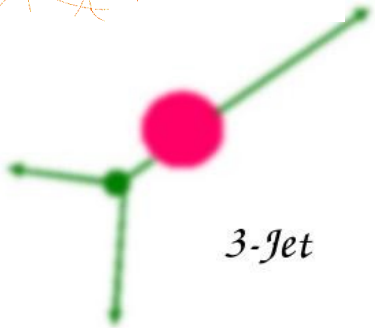
Large Distance
Low Energy

High Energy Scattering



Gluon Jets Observed



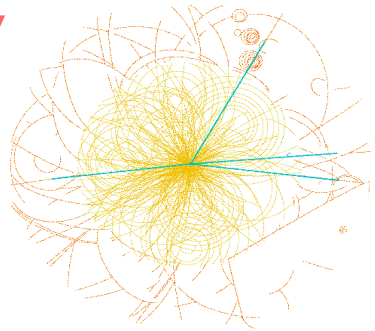


Gluonic Degrees of Freedom

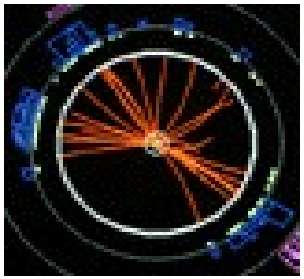
Perturbative — **Asymptotic Freedom** — **Small Distance, High Energy**

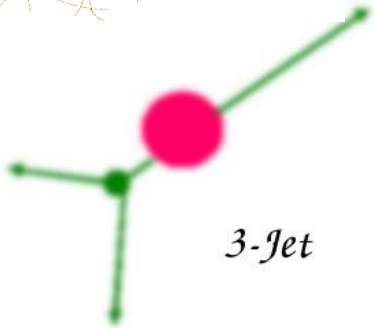
Non-Perturbative — **Confinement** — **Large Distance, Low Energy**

High Energy Scattering

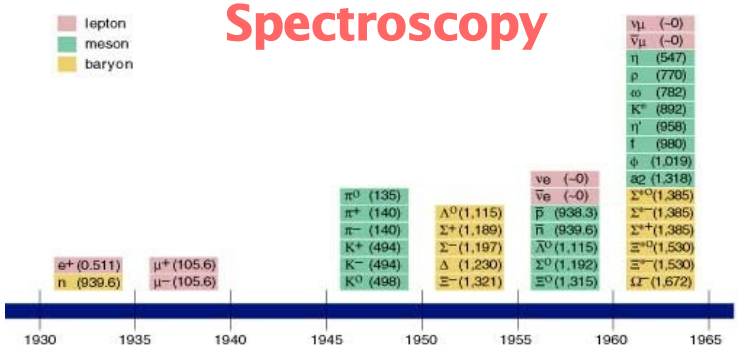


Gluon Jets Observed





Spectroscopy



Gluonic Degrees of Freedom Missing

Quark Pairs and Triplets and Glue?

- Conventional hadrons: $q\bar{q}$ or qqq
  - Strong force mediated by gluons...
    ... but glue not needed to describe these states (quark model)...
- Gluons carry color charge → can couple to each other

Allowed systems: gg, ggg, $q\bar{q}g$, $q\bar{q}q\bar{q}$

Glueballs Hybrids Molecules

Gluonic Excitations

Excitation of glue can lead to exotic quantum numbers J^{PC} not possible in simple quark model

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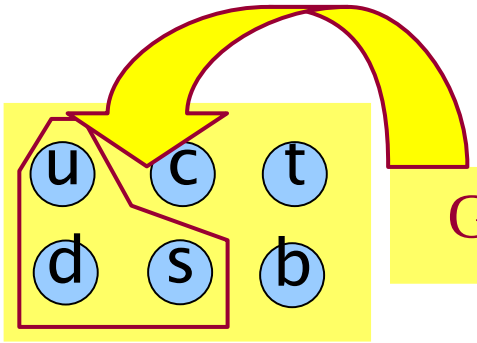
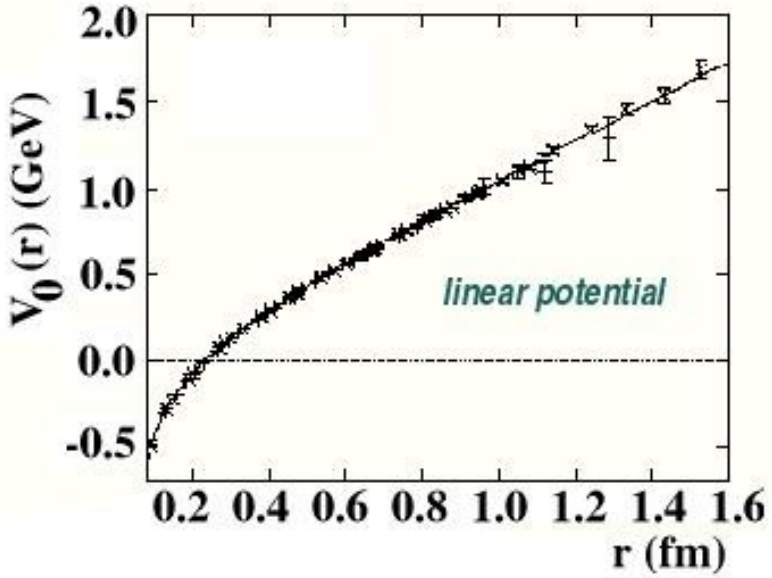
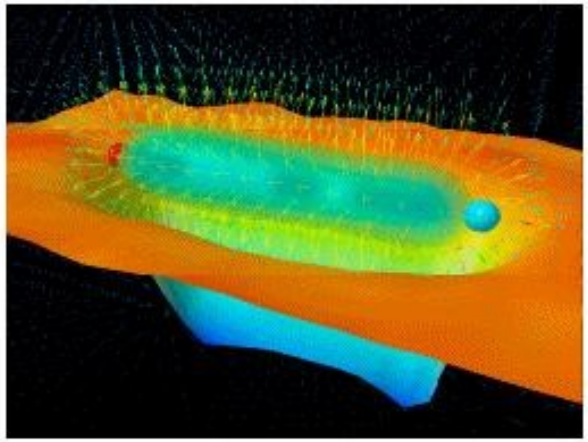


GlueX Focus: light-quark mesons

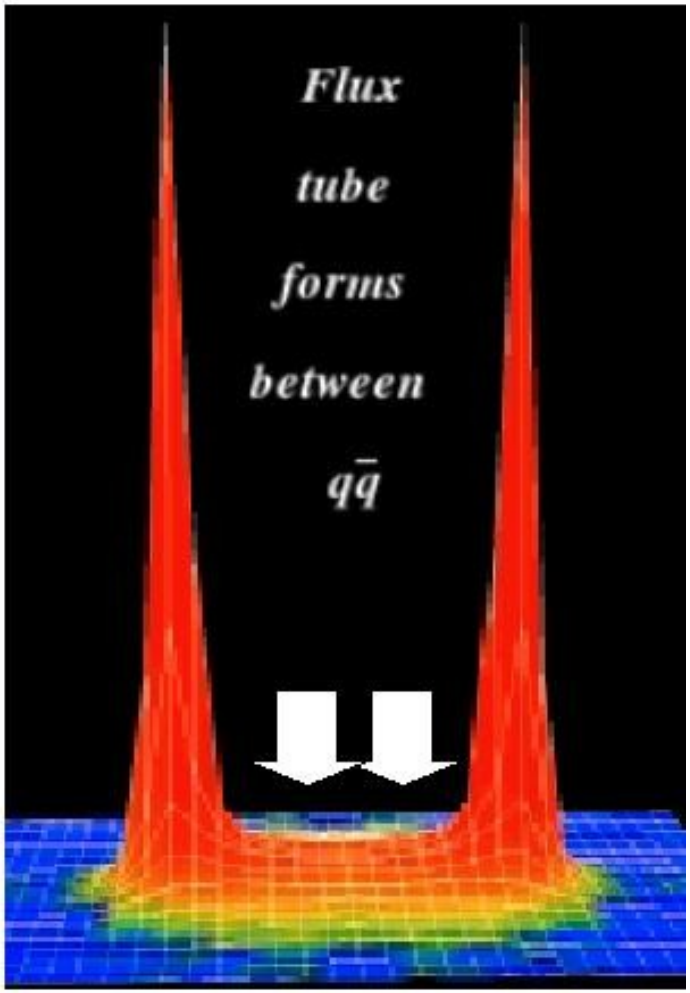
Lattice Calculations





D. Leinweber

Flux tubes realized in LQCD

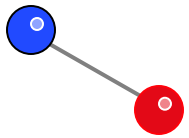


G. Bali

Plucking the Flux Tube

- Looking for gluonic degrees of freedom in spectroscopy

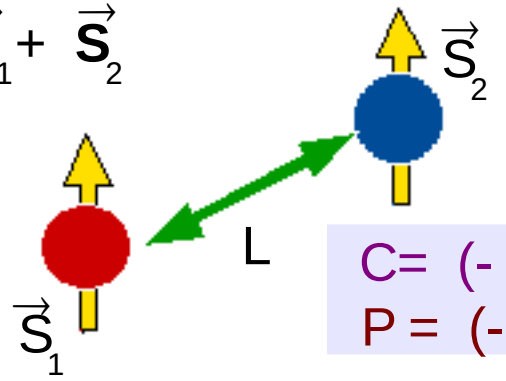
Normal meson:
flux tube in ground state
$m=0$
$CP=(-1)^{S+1}$



Nonets characterized by given J^{PC}

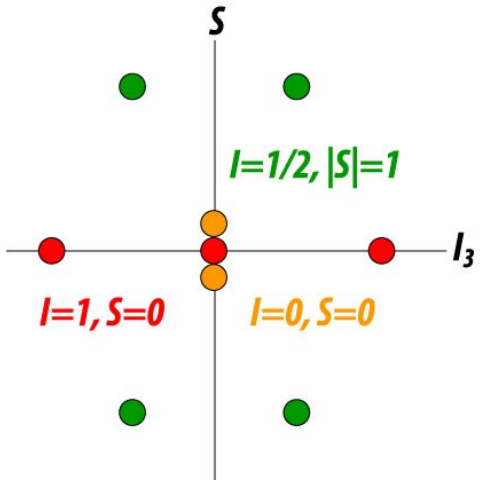
$\vec{J} = \vec{L} + \vec{S}$

$\vec{S} = \vec{S}_1 + \vec{S}_2$



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

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



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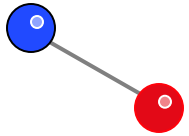
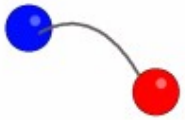


Hybrid meson:
flux tube in excited state
$m=1$
$CP=(-1)^{S}$



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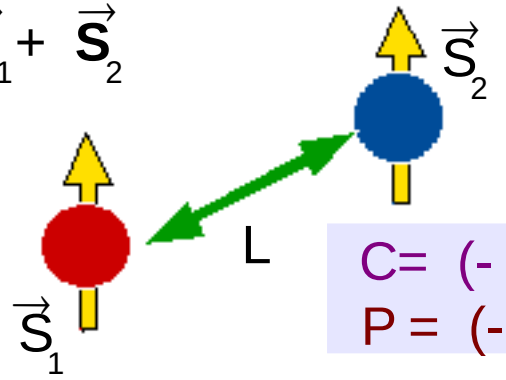
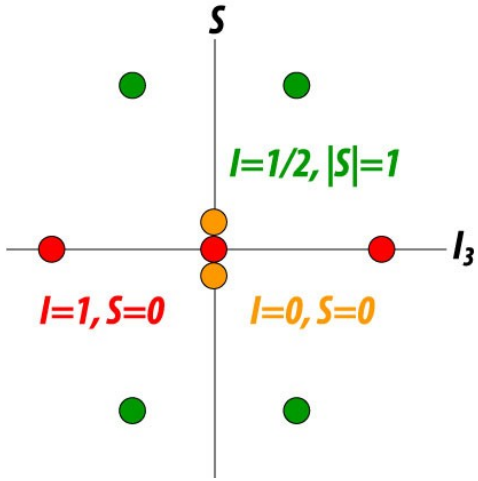


$C = (-1)^{L+S}$

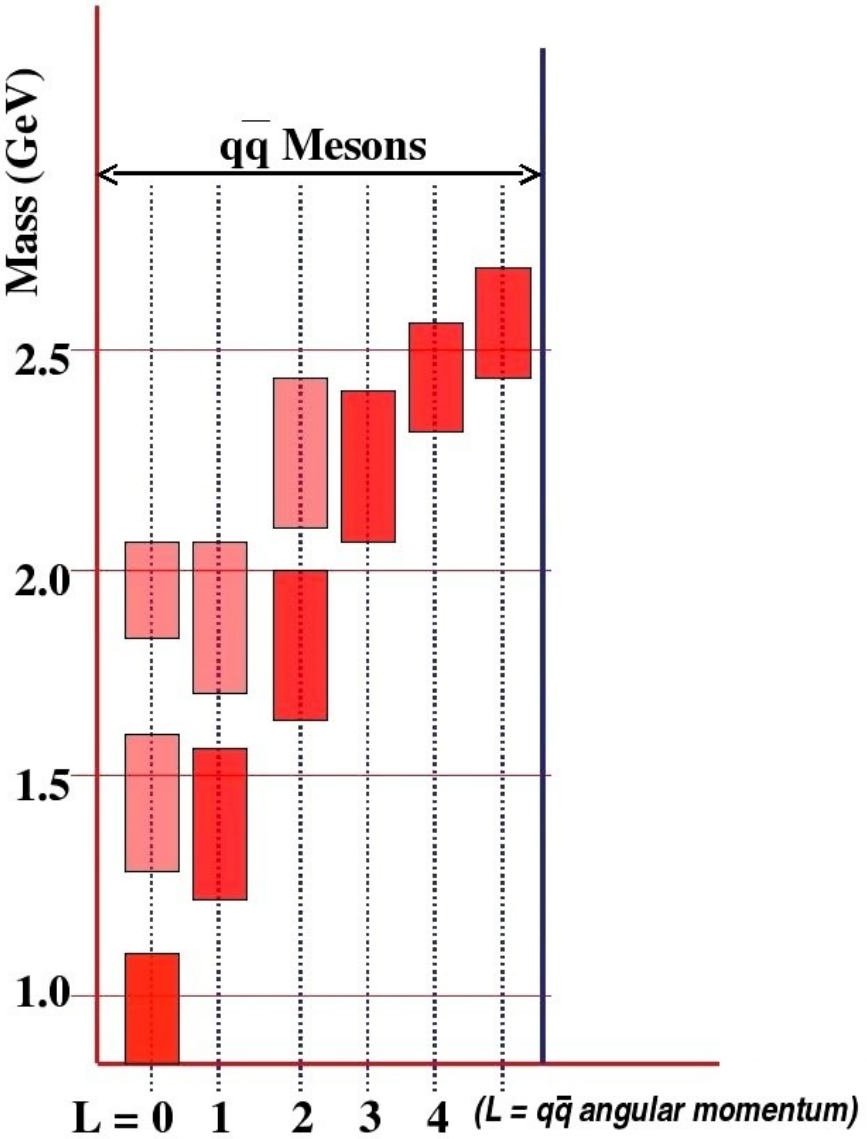
$P = (-1)^{L+1}$

First excited state:

- Two degenerate transverse modes with $J=1$ (clockwise and counter-clockwise)
- Linear combinations lead to $J^{PC}=1^{-+}$ or $J^{PC}=1^{+-}$ for excited flux tube



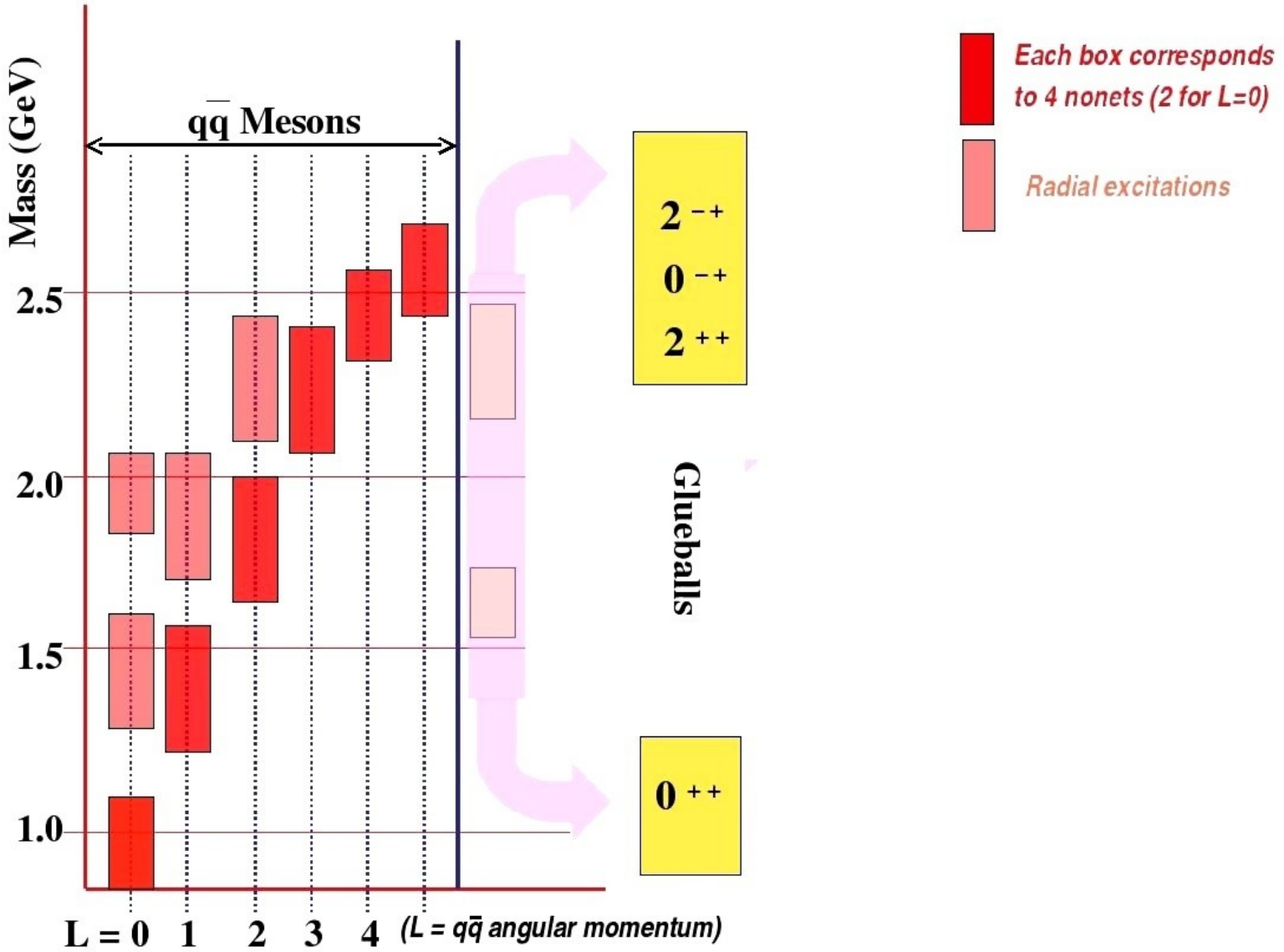
Meson Map



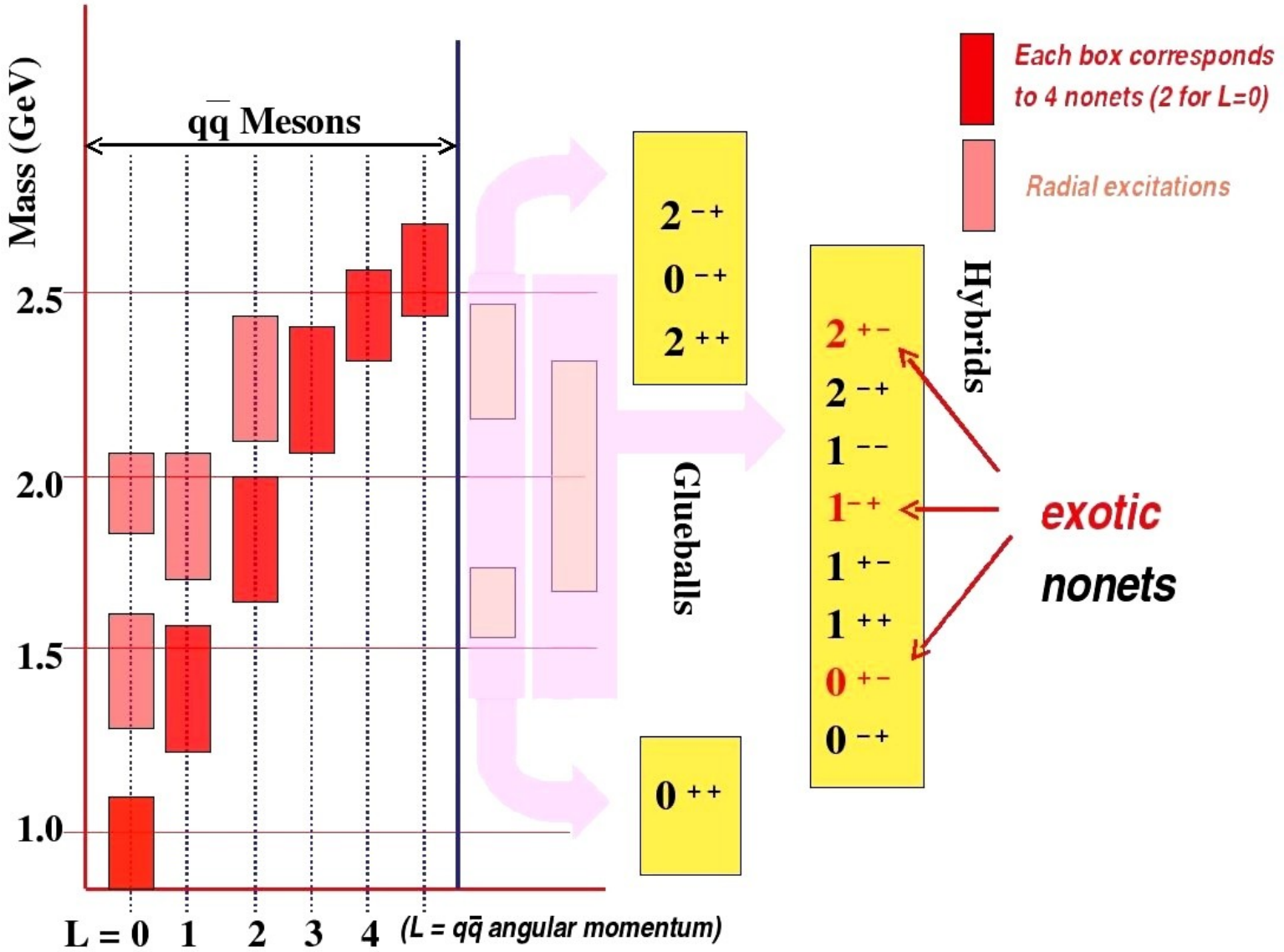
Each box corresponds to 4 nonets (2 for L=0)

Radial excitations

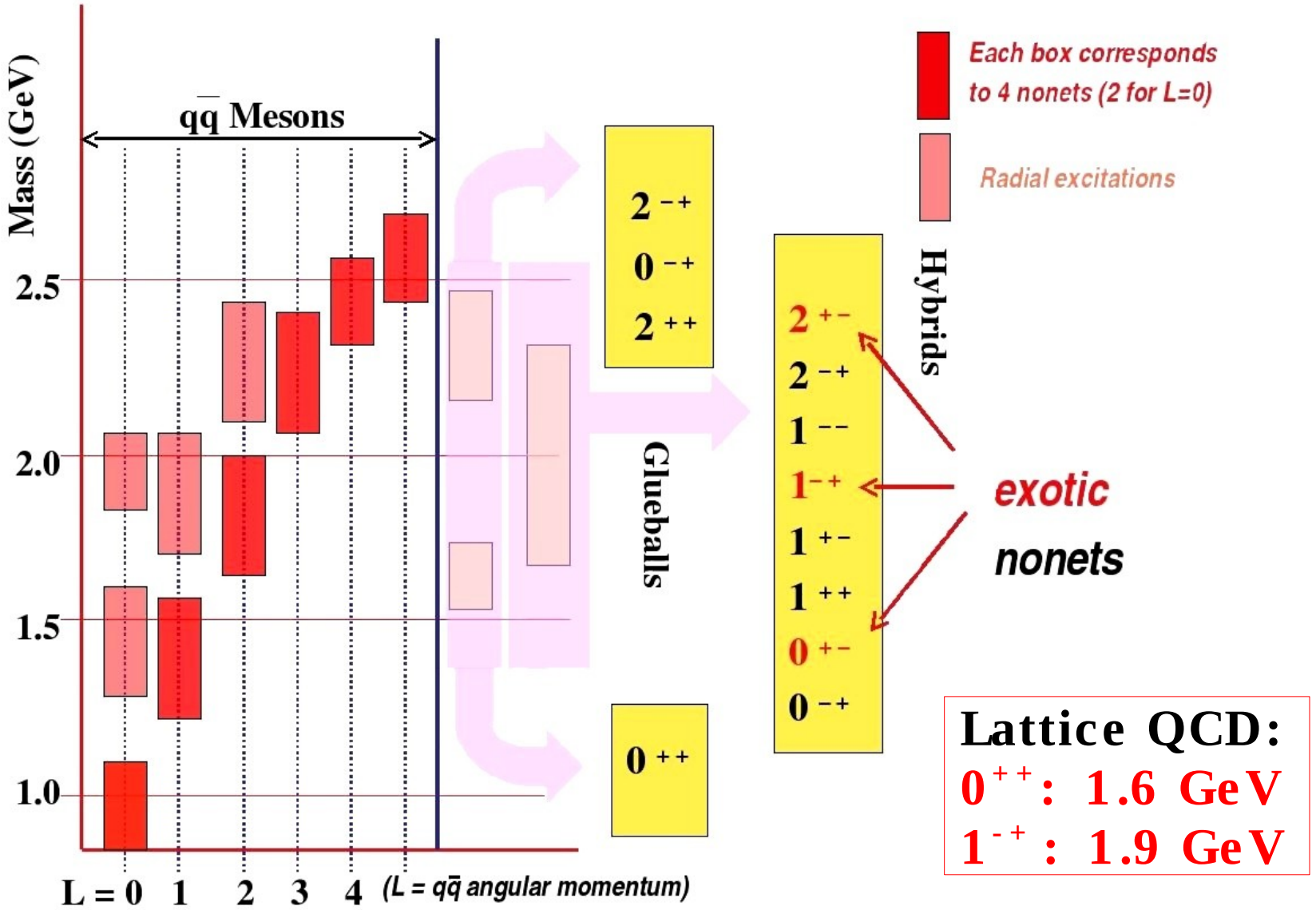
Meson Map


Mass (GeV)
2.5
2.0
1.5
1.0
qq̄ Mesons
L = 0
1
2
3
4
(L = qq̄ angular momentum)
2 −+
0 −+
2 ++
0 ++
Glueballs
Each box corresponds to 4 nonets (2 for L=0)
Radial excitations

Meson Map


Mass (GeV)
2.5
2.0
1.5
1.0
$q\bar{q}$ Mesons
L = 0 1 2 3 4 (L = $q\bar{q}$ angular momentum)
Each box corresponds to 4 nonets (2 for L=0)
Radial excitations
Hybrids
Glueballs
2^{-+}
0^{-+}
2^{++}
0^{++}
2^{+-}
2^{-+}
1^{--}
1^{-+}
1^{+-}
1^{++}
0^{+-}
0^{-+}
exotic
nonets

Meson Map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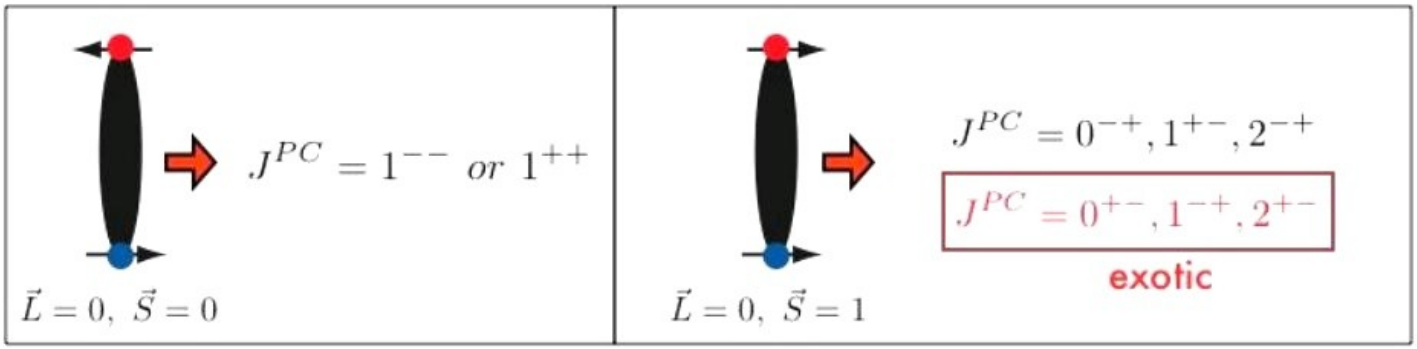
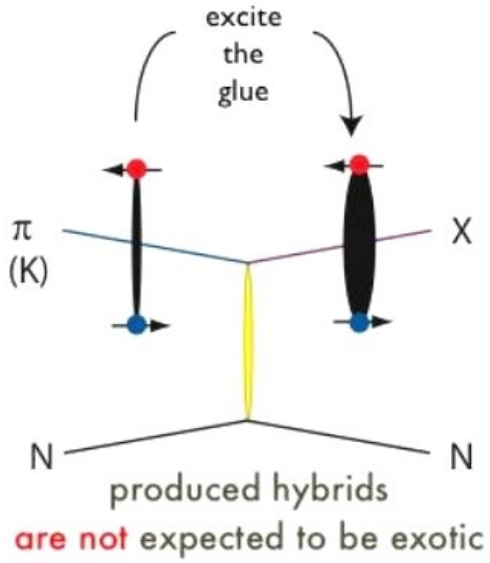
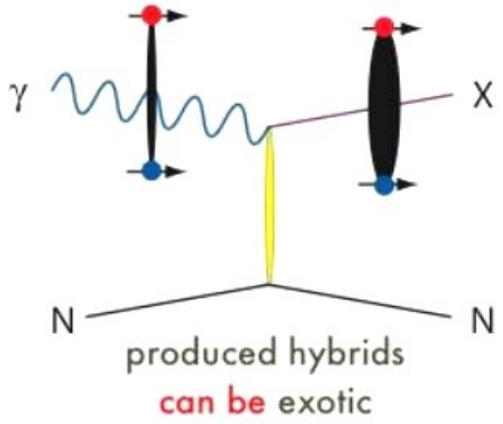
Glueballs
Each box corresponds to 4 nonets (2 for L=0)
Radial excitations
Hybrids
2 +−
2 −+
1 −−
1−+
1 +−
1 ++
0 +−
0 −+
exotic nonets
Lattice QCD:
0++: 1.6 GeV
1-+: 1.9 GeV

Production of Exotic Mesons

- Choice of probe may determine accessible quantum numbers
  - Photon beam increases chance for producing mesons with exotic quantum numbers







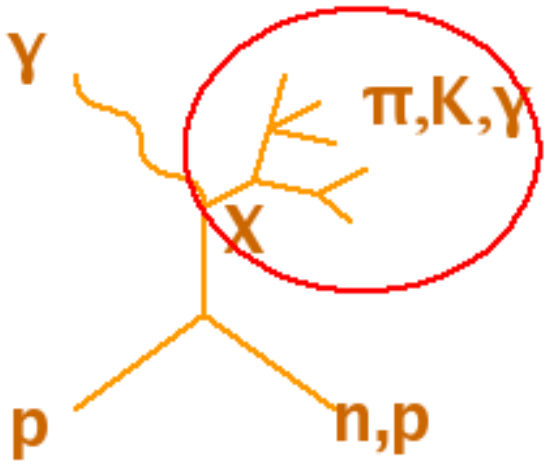
QCD Exotic Topologies

The GlueX Detector Design has been driven by the need to carry out Amplitude analysis.

π_1 η_1 η'_1 b_2 h_2 h'_2 b_0 h_0 h'_0

1^{-+} 2^{+-} 0^{+-}

Mass scale ~ 2 GeV



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

all charged

QCD Exotic Topologies

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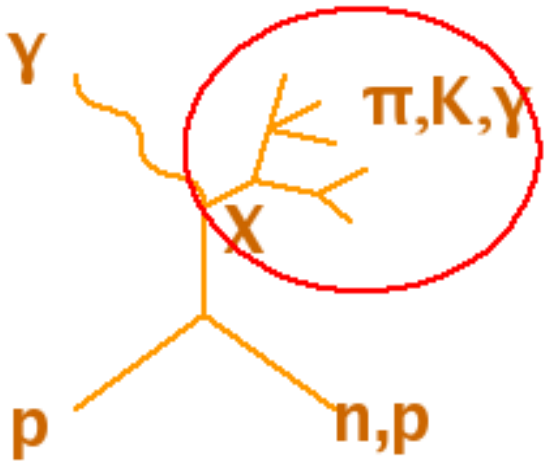


$\eta_1 \rightarrow a^+_1\pi^- \rightarrow (\rho^o\pi^+)(\pi^-) \rightarrow \pi^+\pi^-\pi^+\pi^-$

all charged

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

many photons

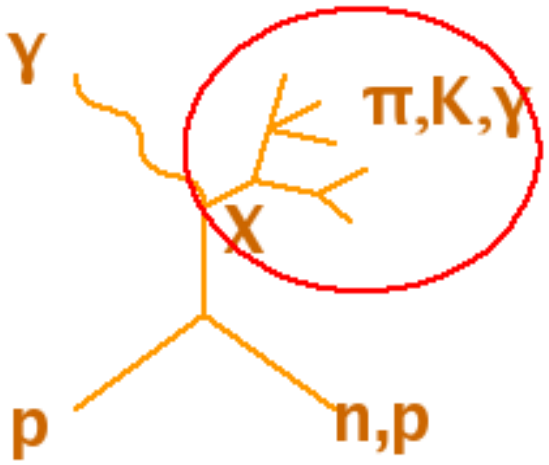
QCD Exotic Topologies

The GlueX Detector Design has been driven by the need to carry out Amplitude analysis.

π_1 η_1 η'_1 b_2 h_2 h'_2 b_0 h_0 h'_0

1^{-+} 2^{+-} 0^{+-}

Mass scale ~ 2 GeV



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all charged

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

many photons

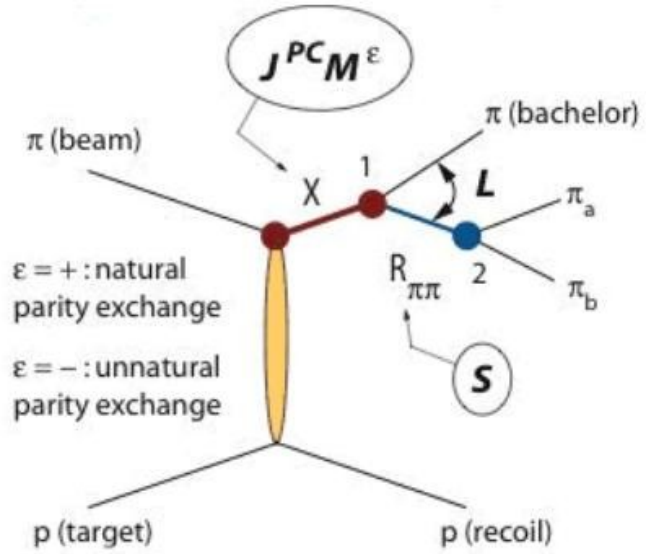
$h'_2 \rightarrow K^+_1K^- \rightarrow \rho^o K^+ K^- \rightarrow \pi^+\pi^-K^+K^-$

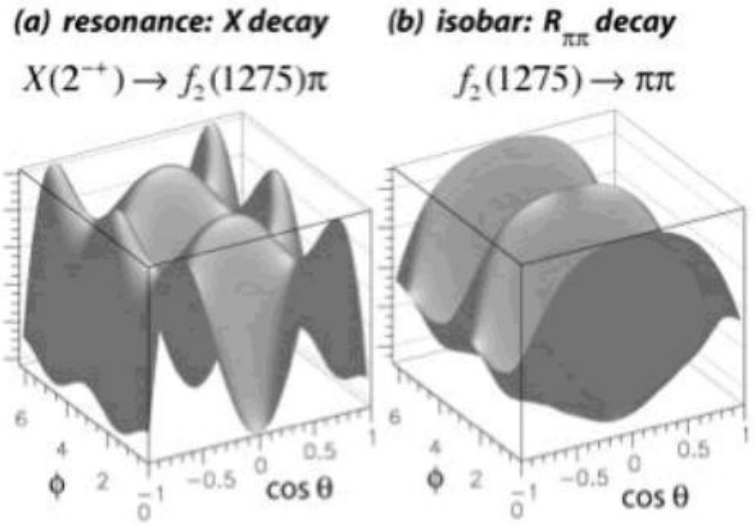
strange particles

Final state particles $\pi^\pm$ $K^\pm$ γ p

Partial Wave Analysis

- States expected to be broad with multi-particle final states
  - Bump hunting in cross section data not expected to be sufficient
- Need 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





Evidence for Exotic Mesons

State	Processes
$\pi_1(1400) \to \eta\pi$	$\pi^- N$ Interactions $\bar{p}N$ Annihilations
$\pi_1(1600) \to \eta'\pi$	
$\pi_1(1600) \to \rho\pi$	$\pi^- N$ Interactions
$\pi_1(1600) \to b_1\pi$ $\pi_1(1600) \to f_1\pi$	
$\pi_1(2000) \to b_1\pi$ $\pi_1(2000) \to f_1\pi$	

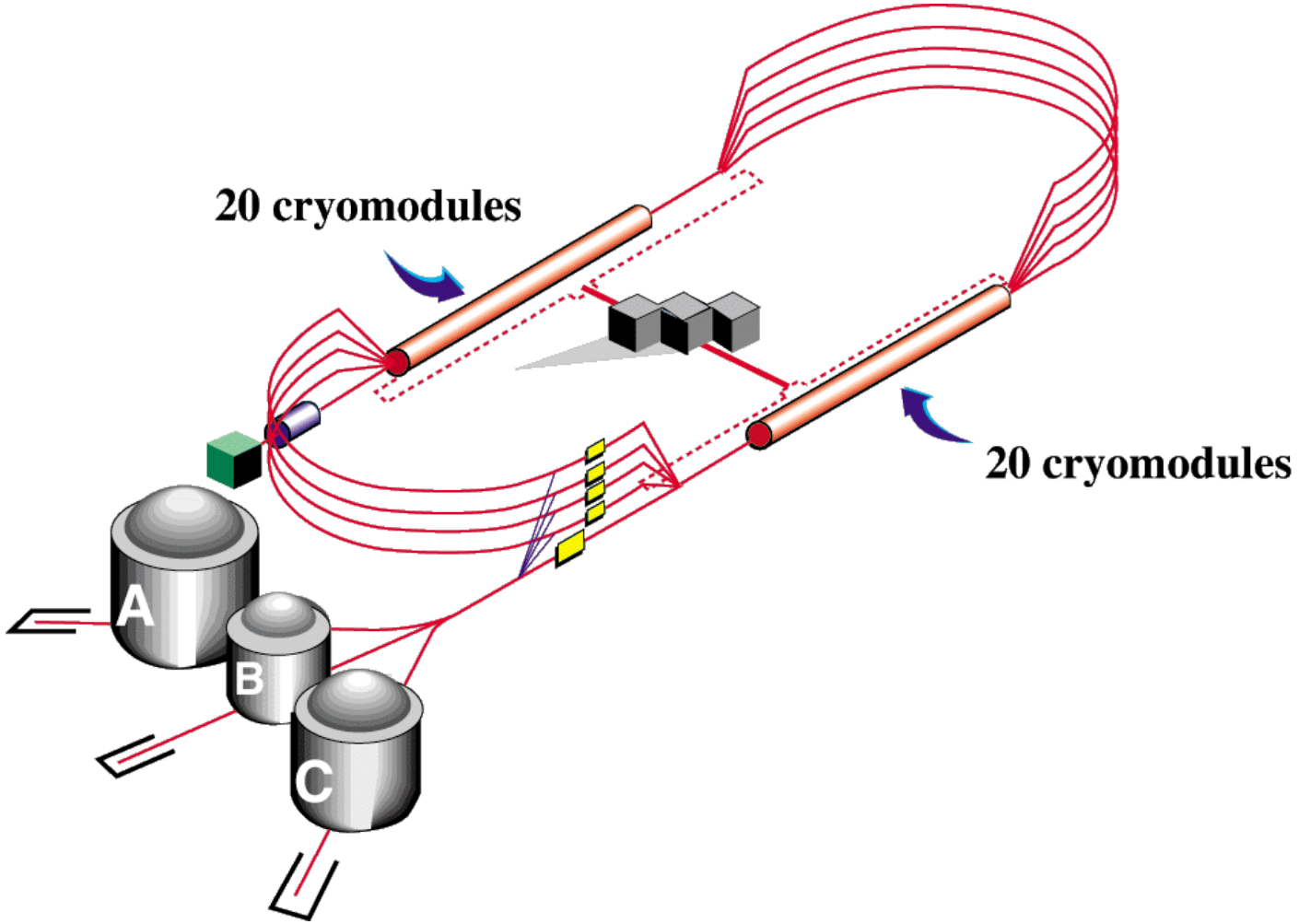
- Candidates with $J^{PC} = 1^{-+}$
- States are controversial → issues with amplitude analysis
  - Possible leakage due to acceptance or insufficient wave sets
  - Problems with interpretation of line shapes and phases
- Physics interpretation as hybrids (instead of $q\bar{q}q\bar{q}$ states?) open to question
- $\pi_1(2000)$ needs confirmation

The GlueX Experiment

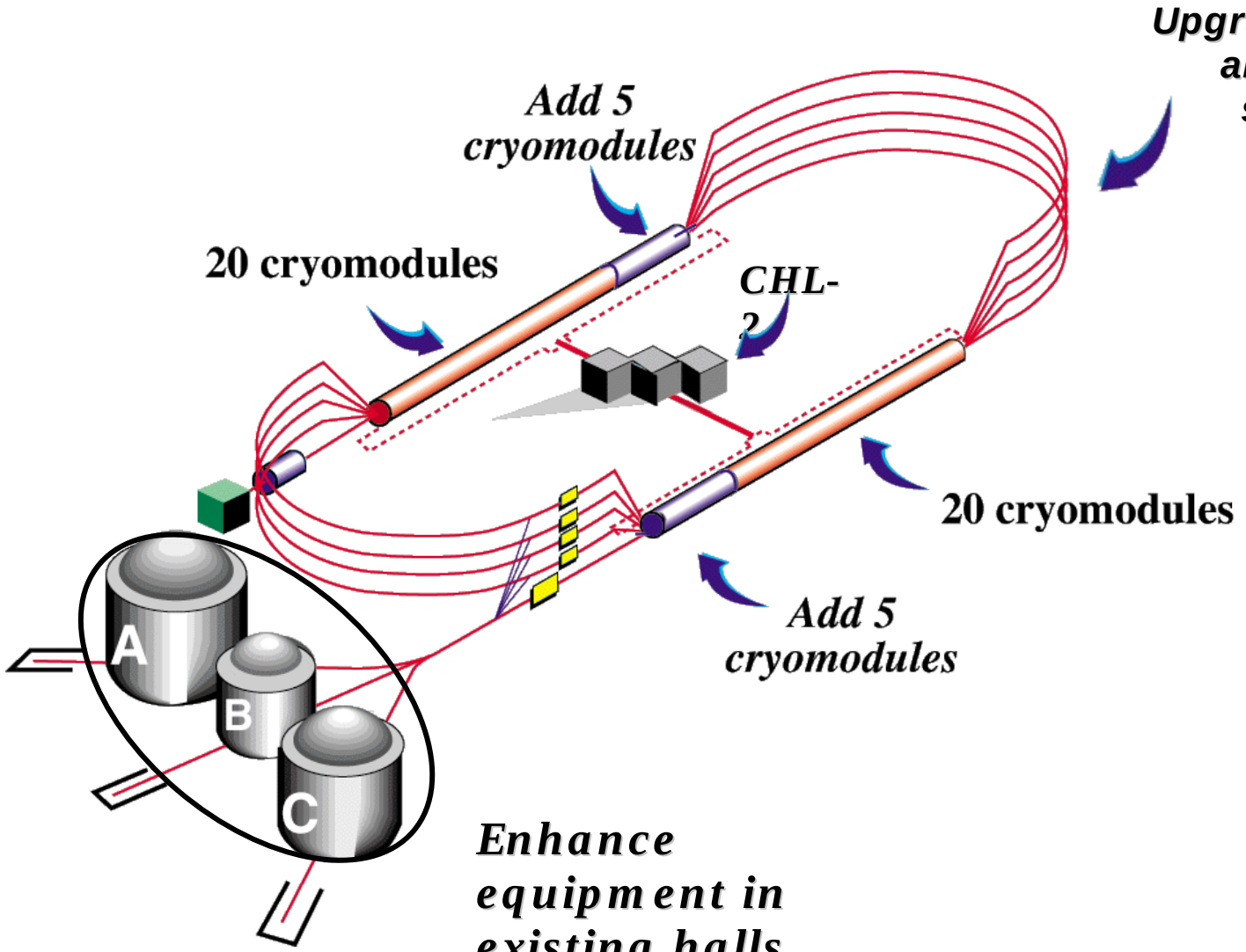
- Goal: definitive and detailed mapping of hybrid meson spectrum
  - Search for smoking gun signature of exotic J^{PC} hybrid mesons
    - Exotics do not mix with $q\bar{q}$ mesons
  - Plans for $s\bar{s}$ and baryon spectroscopy

- Tools for the GlueX Project:
  - Accelerator: 12 GeV electrons, 9 GeV tagged, linearly polarized photons with high flux
  - Detector: hermeticity, ability to detect both charged and neutral particles with good resolution
  - Partial-Wave Analysis: spin-amplitude of multi-particle final states
  - Computing power: 1 Pb/year data collection, databases, distributed computing, grid services…

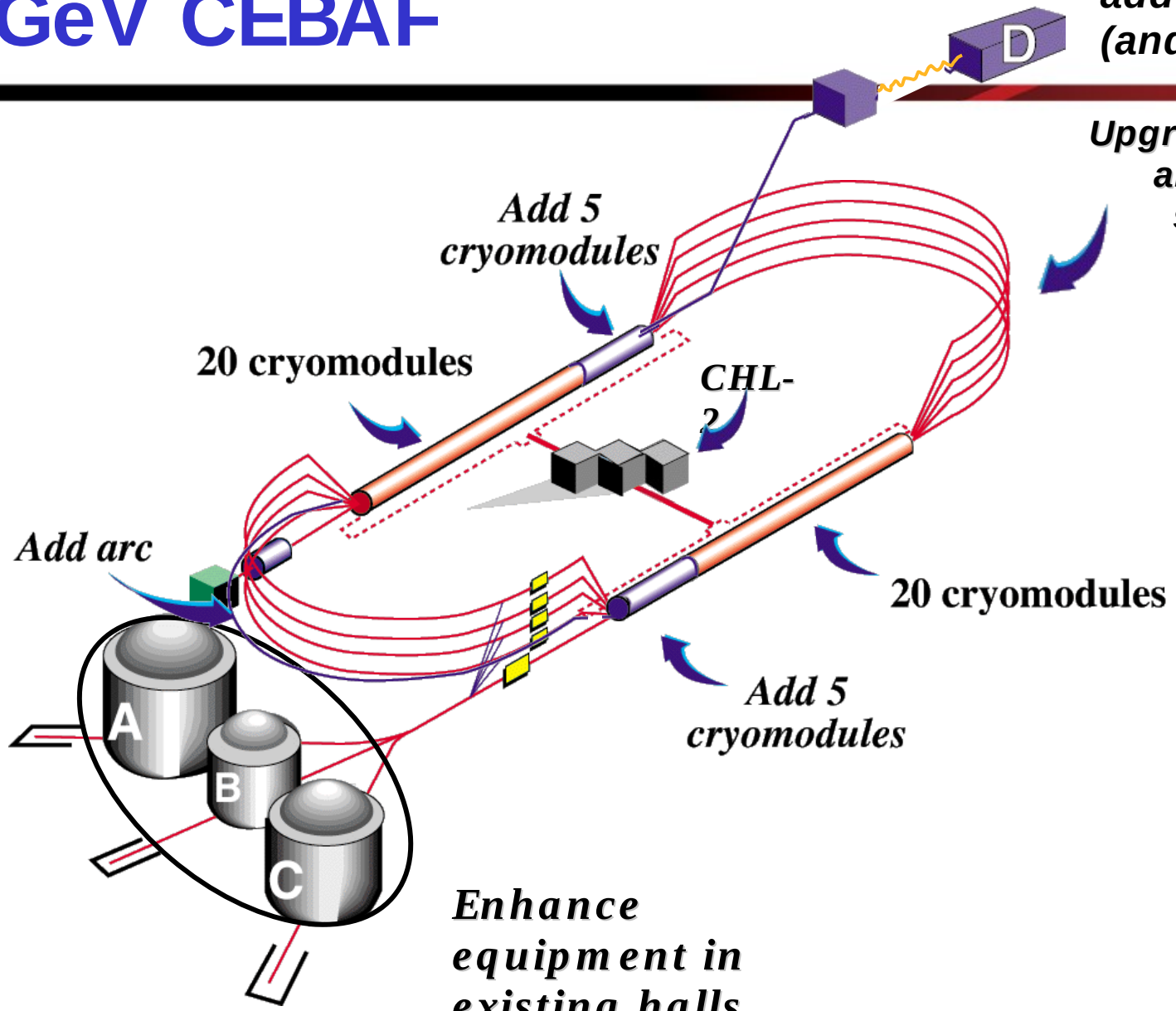
6 GeV CEBAF



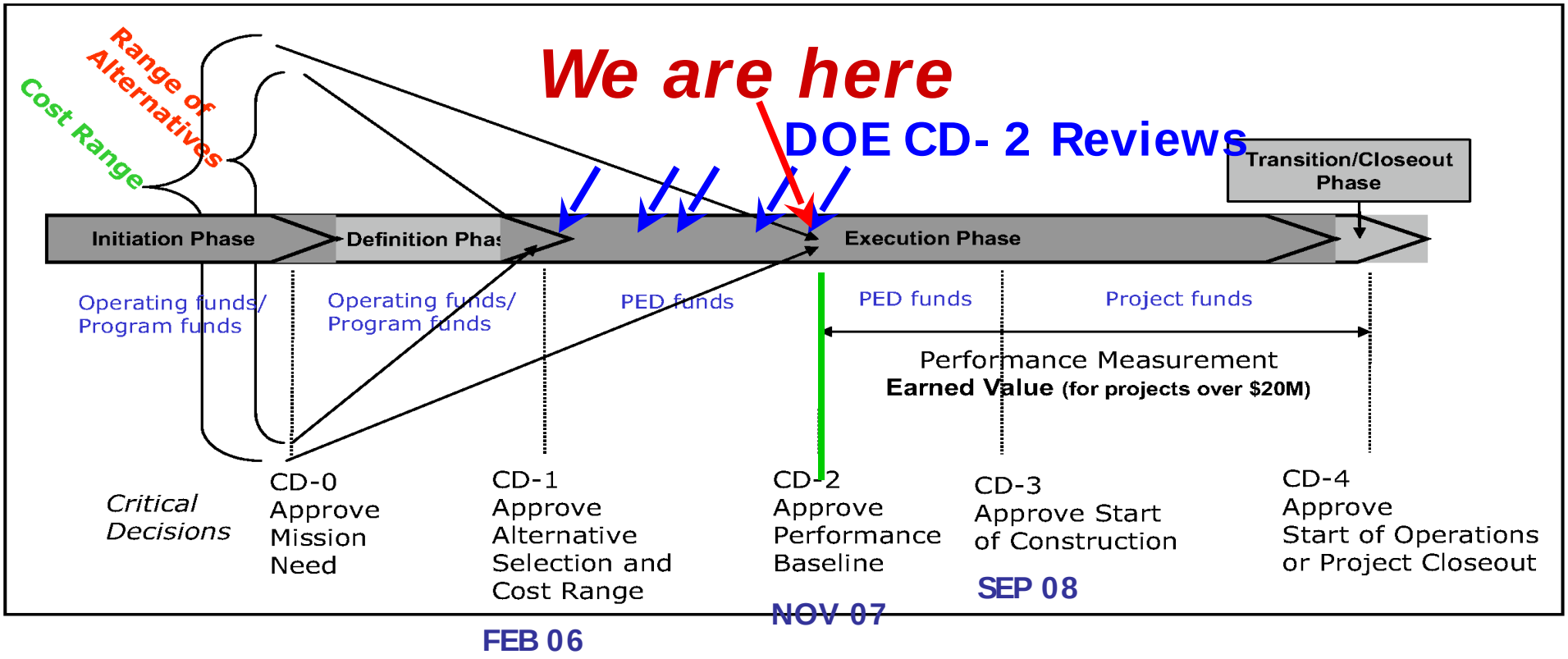
11 GeV CEBAF


Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
20 cryomodules
Add 5 cryomodules
A
B
C
Enhance equipment in existing halls

12 GeV CEBAF

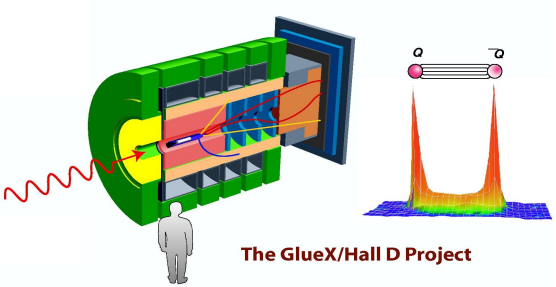

D
add Hall D
(and beam line)
Upgrade magnets
and power
supplies
Add 5
cryomodules
20 cryomodules
CHL-
2
Add arc
20 cryomodules
Add 5
cryomodules
A
B
C
Enhance
equipment in
existing halls

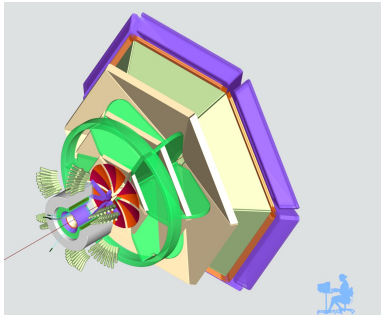
DOE Generic Project Timeline



Overview of 12 GeV Physics

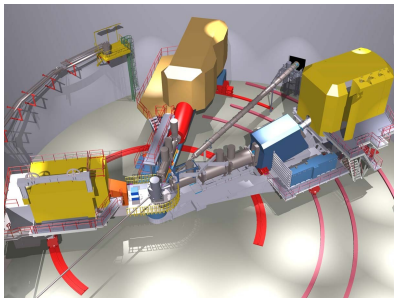
Hall D exploring origin of confinement by studying exotic mesons

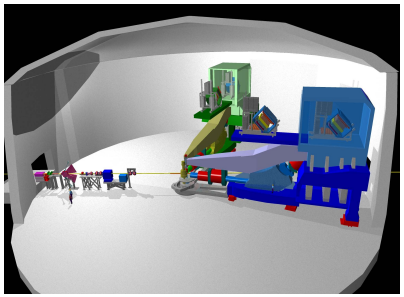




Hall B understanding nucleon structure via generalized parton distributions

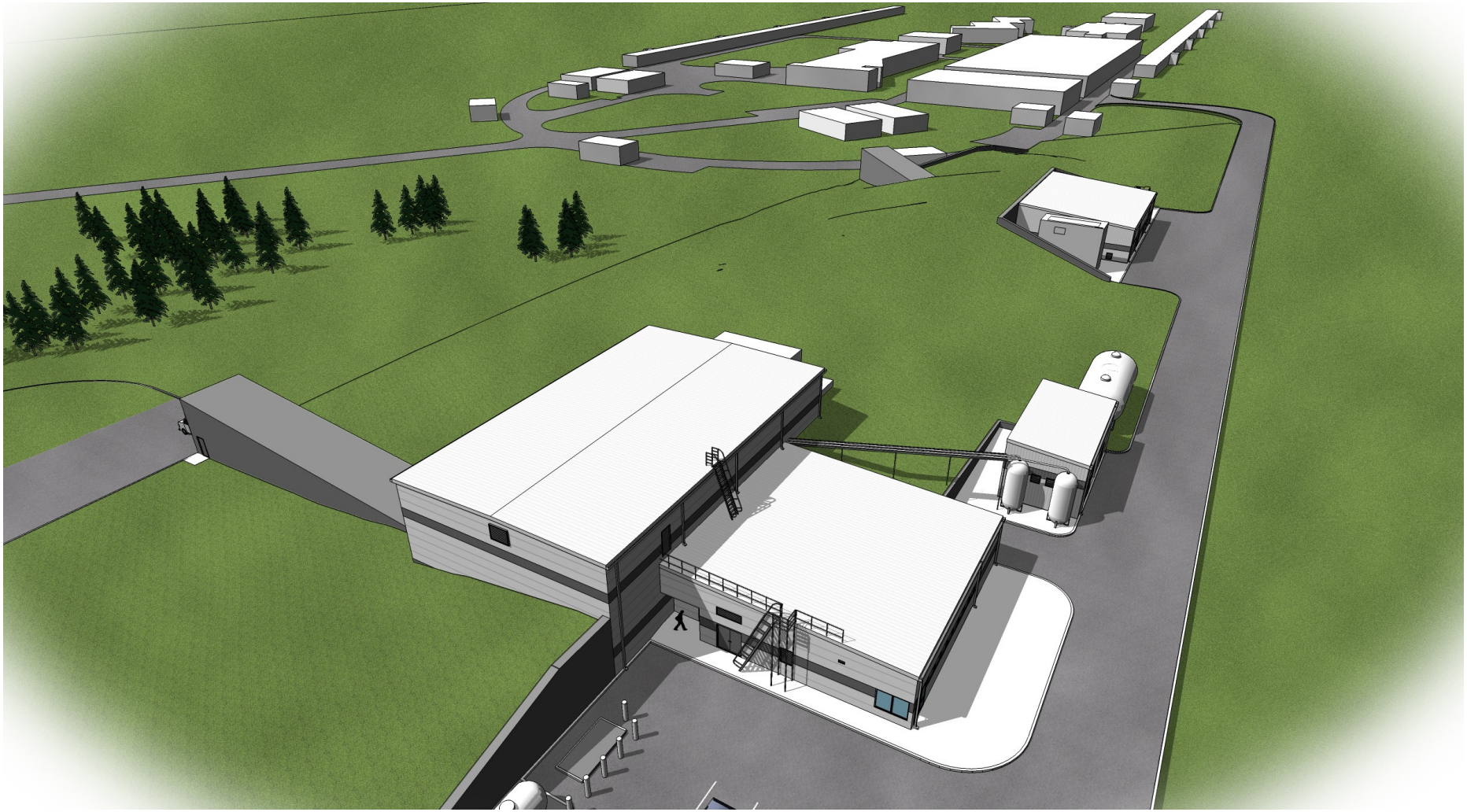
Hall C precision determination of valence quark properties in nucleons and nuclei



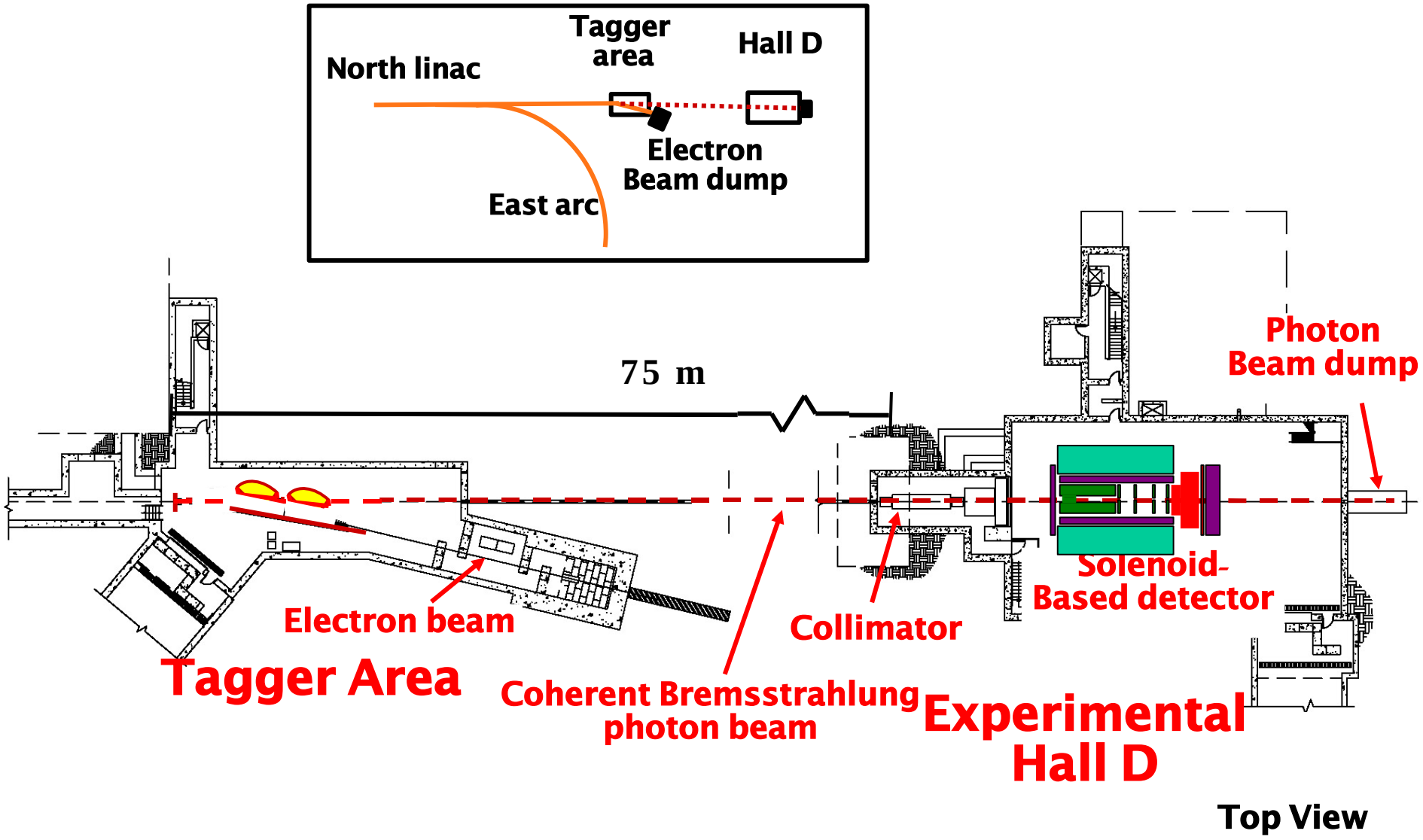


Hall A short range correlations, form factors, hyper- nuclear physics, future new experiments

Architect's rendering of Hall-D Complex



The Hall- D Complex

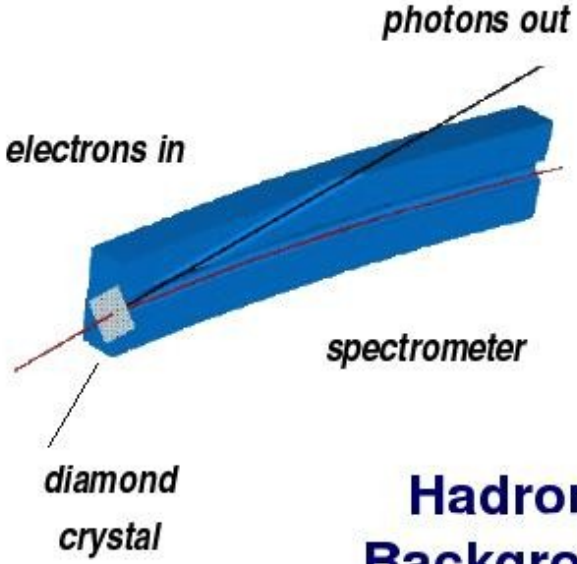


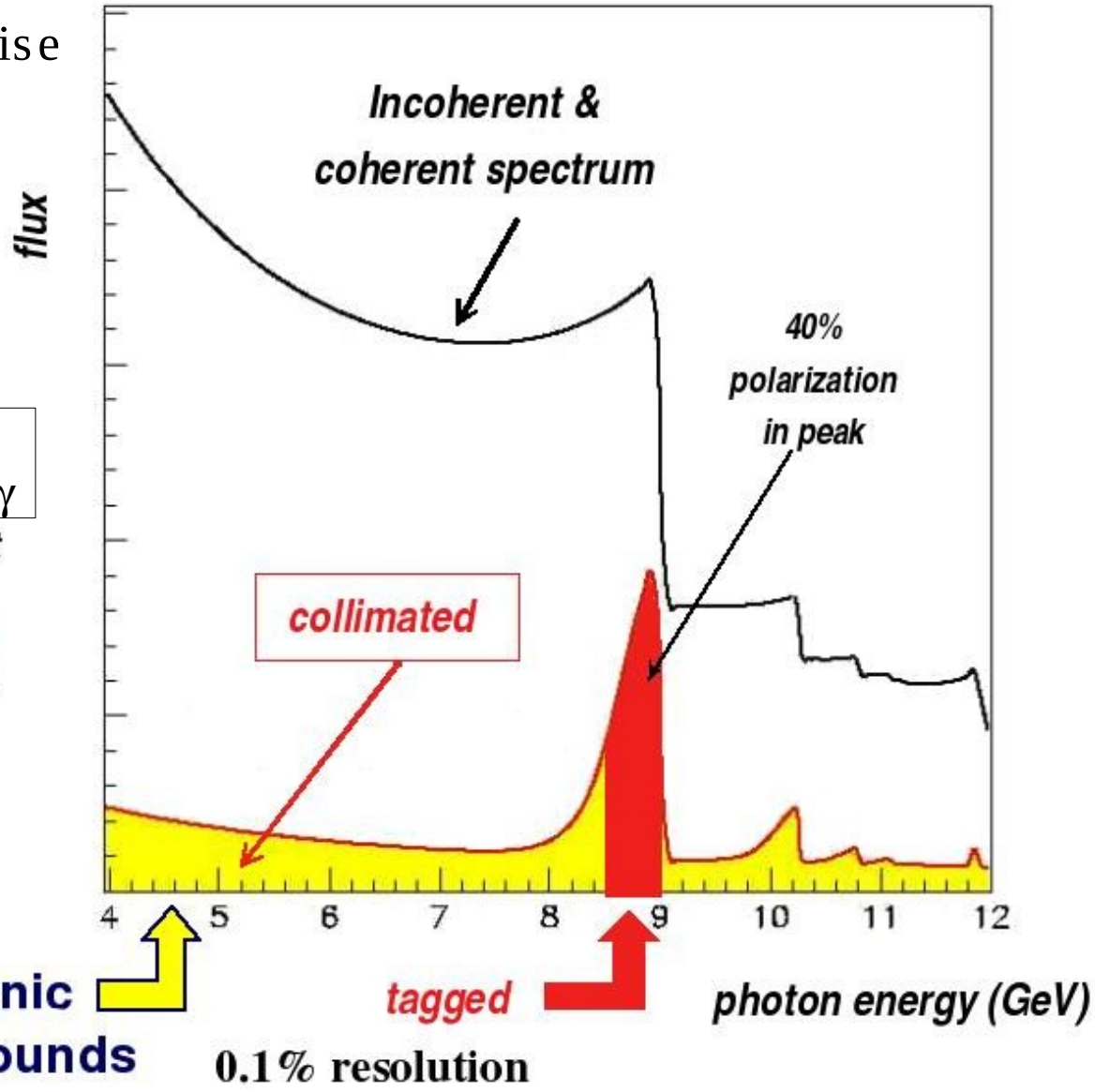
Coherent Bremsstrahlung Beam

- γ-beam energy compromise between polarization and meson mass coverage

- Diamond radiator:

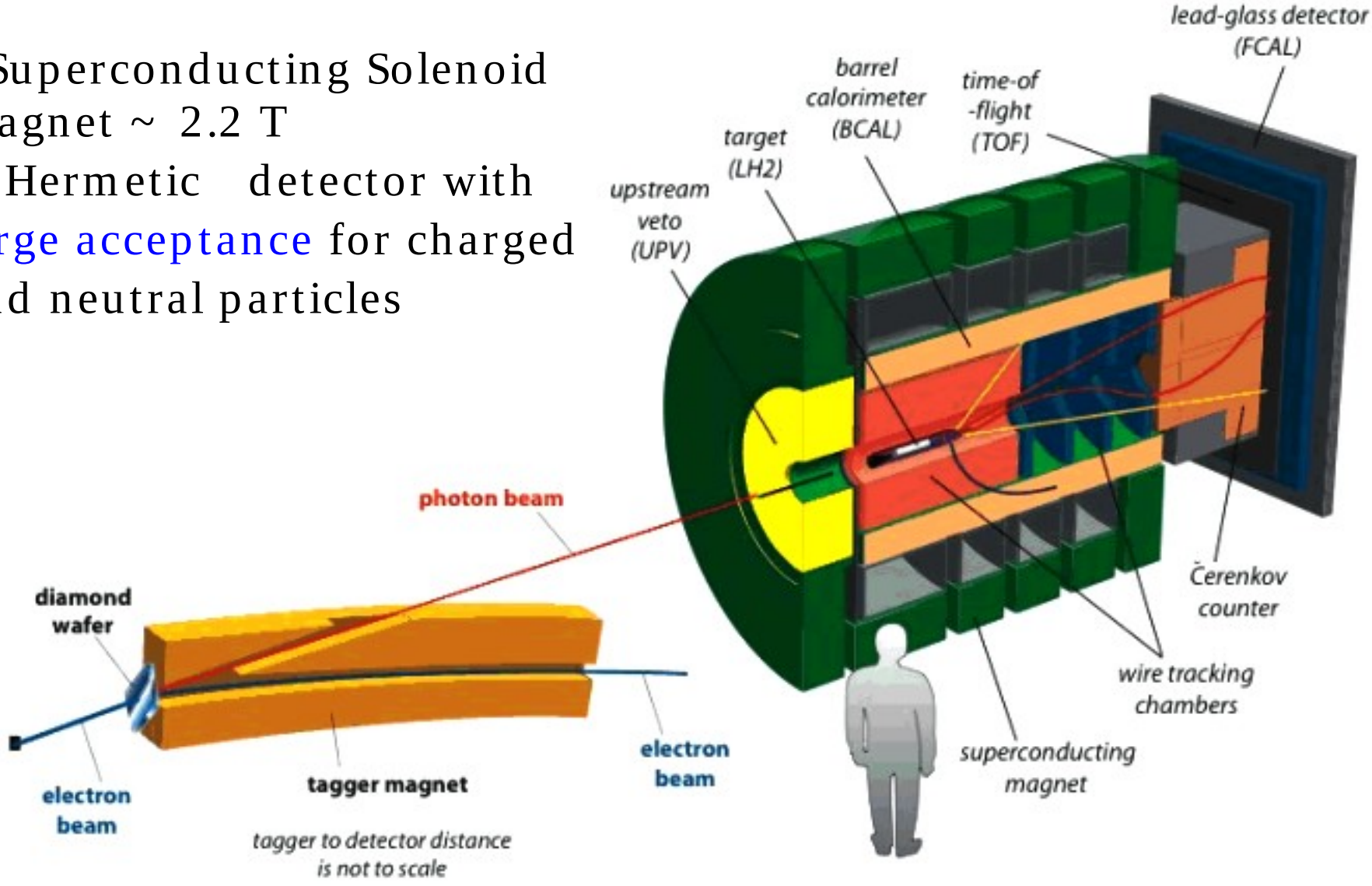
Orientation of crystal planes
→linearly-polarized γ





The GlueX Detector

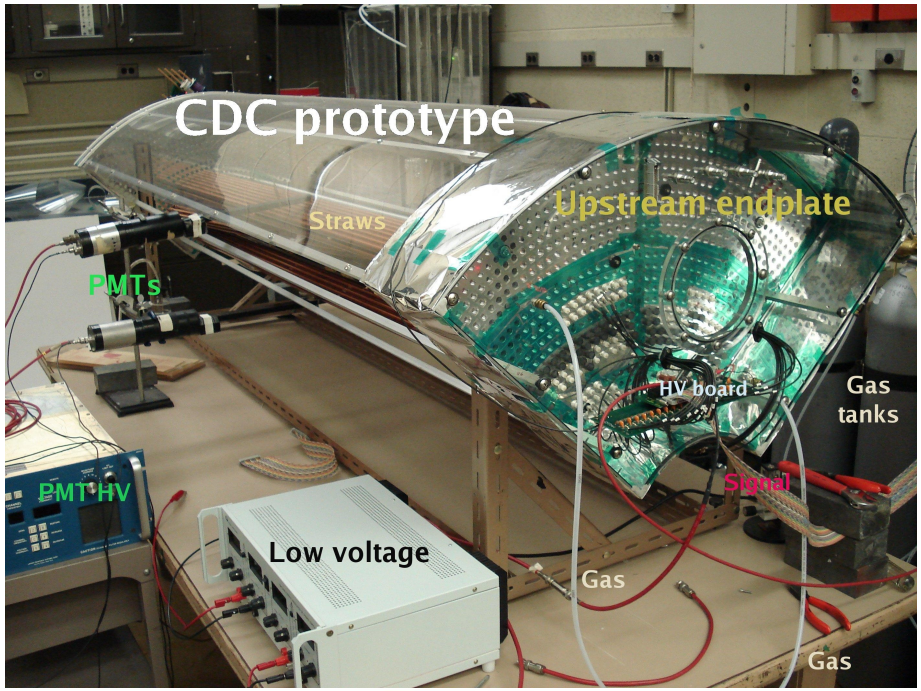
- Superconducting Solenoid magnet ~ 2.2 T
- Hermetic detector with large acceptance for charged and neutral particles

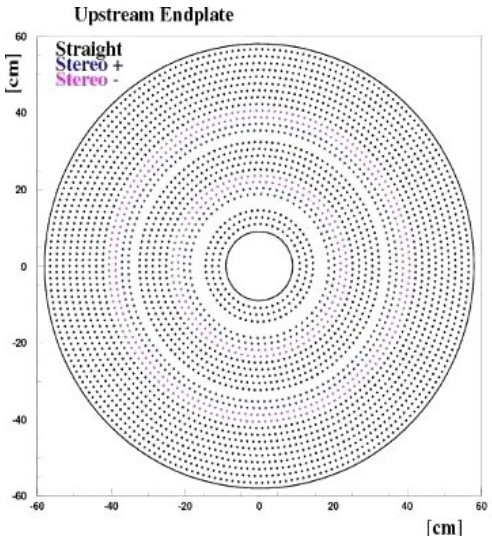


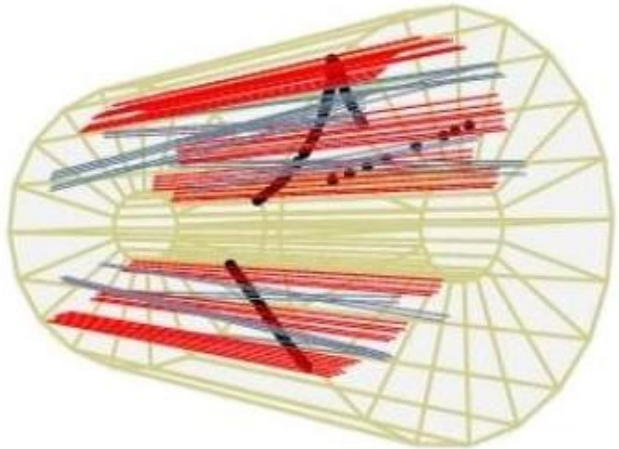
Central Drift Chambers

- Track charged particles in central region ($140^\circ < \theta < 20^\circ$)
- 25 radial layers of straw tubes
  - 17 straight layers
  - 4 $+6^\circ$ stereo layers
  - 4 -6° stereo layers
  - dE/dx capability for $p < 450$ MeV/c

→identify protons

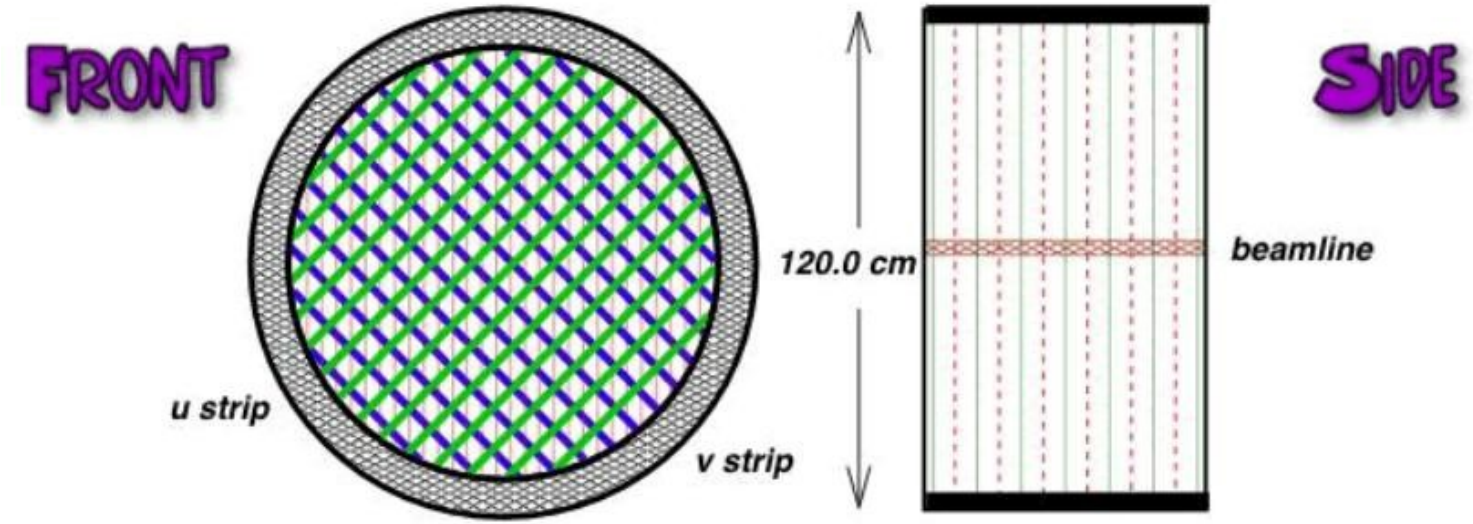






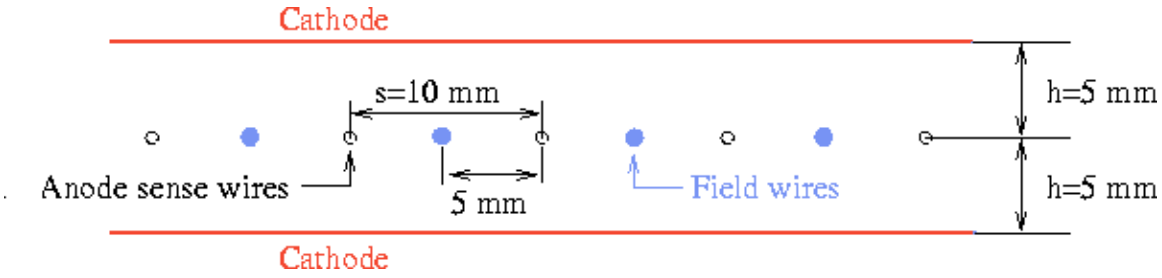
Forward Drift Chambers

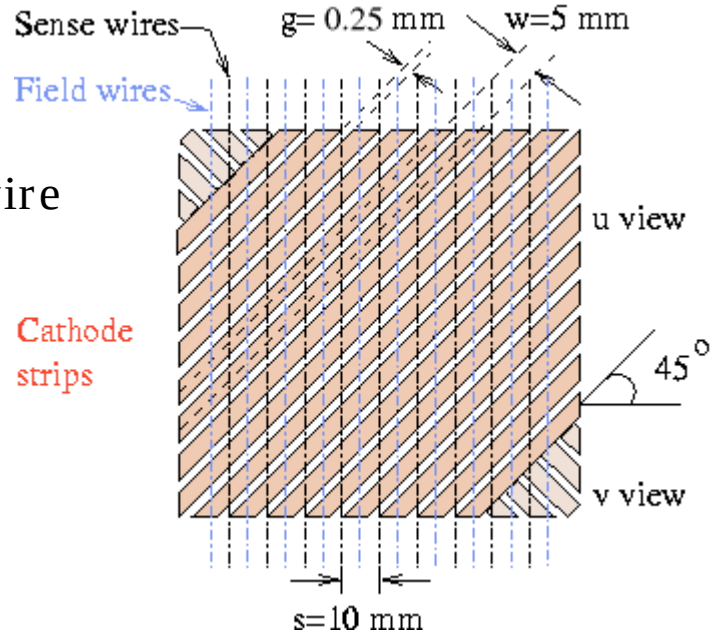
- Purpose: track forward-going ($\theta < 20^\circ$) charged particles
- Design: 4 packages each containing 6 cathode strip chambers
  - Cathode strip chamber: cathode plane / wire plane / cathode plane
    - Drift chambers with cathode readout
    - Cathode planes divided into strips oriented at $\pm 75^\circ$ with respect to wires
  - Each chamber rotated with respect to its neighbor by 60°
  - Position resolution goal < 200 μm

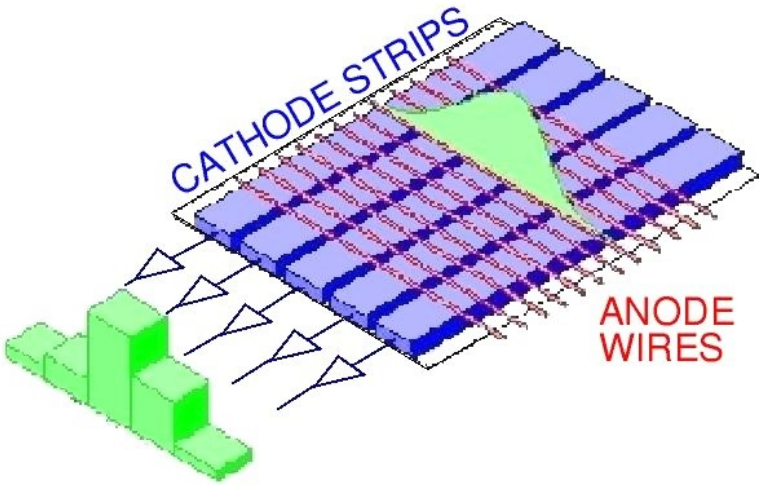


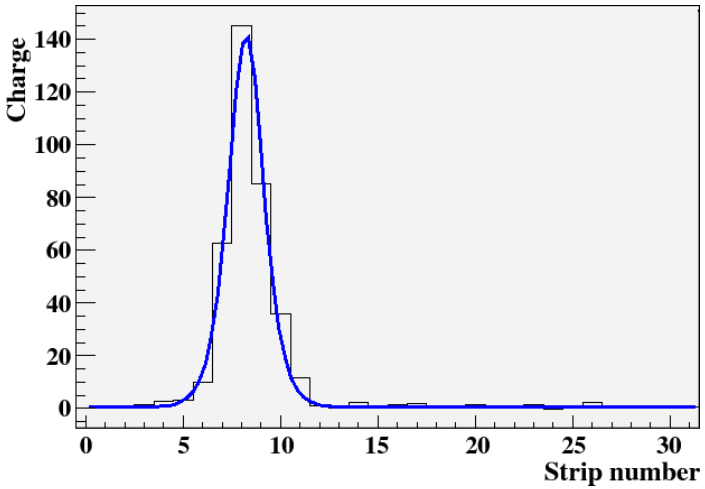
Cathode Strip Chambers

- 3D space point at each wire plane
  - Drift time → coordinate away from wire
  - Strip centroids → avalanche position along wire

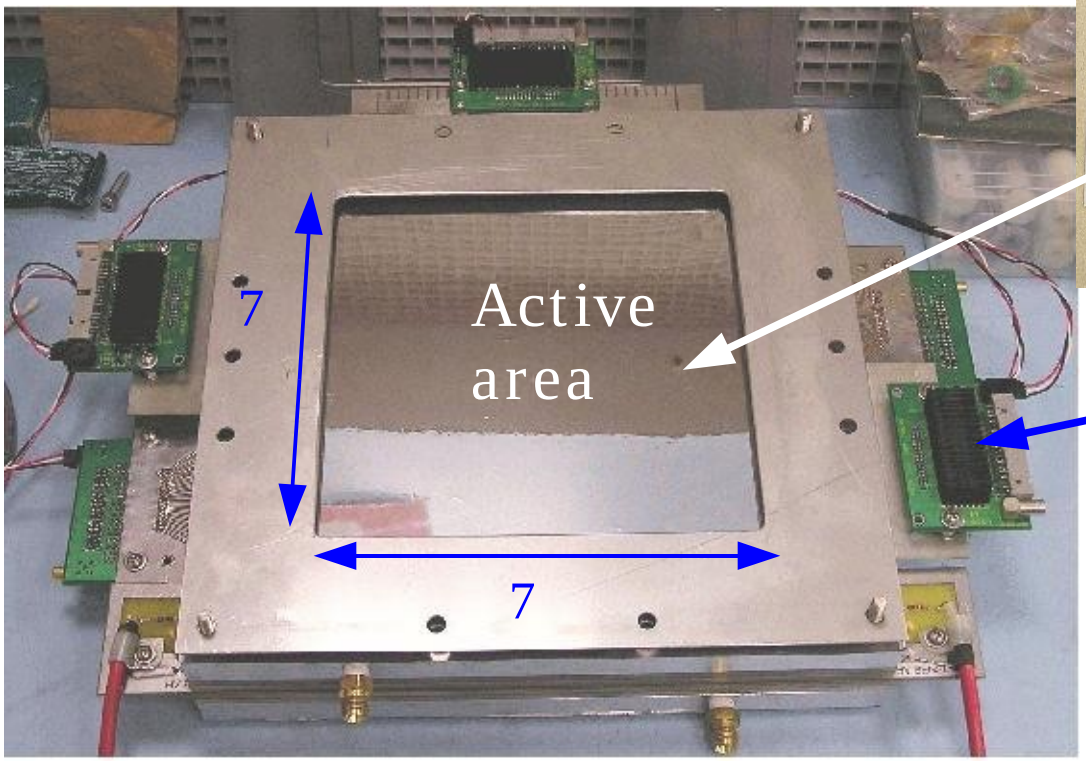


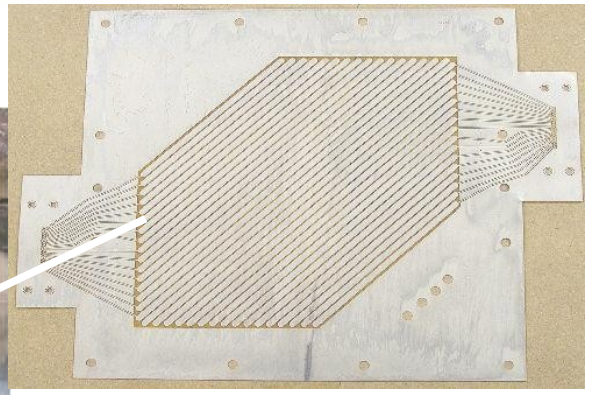






Small-scale prototype



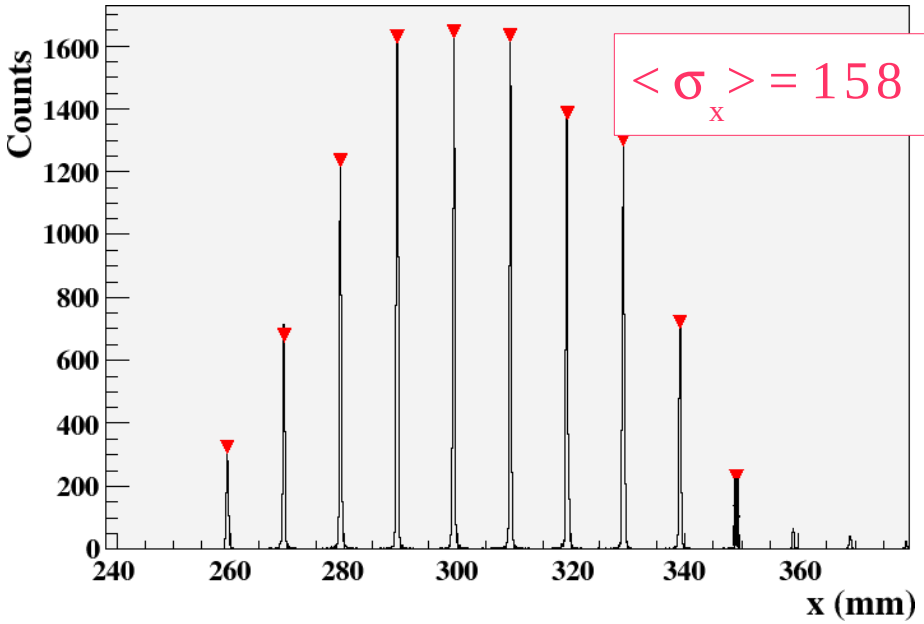


- Preamplifier boards: SIPs
  - Gain ~2.3 mV/μA
  - No pulse shaping
  - No tail-cancellation
- Gas mixture:
  40% Ar / 60% CO_2

- Readout for cathode strips: CAEN V792 charge-integrating ADCs
- Readout for sense wires: CAMAC discriminator / F1 TDC

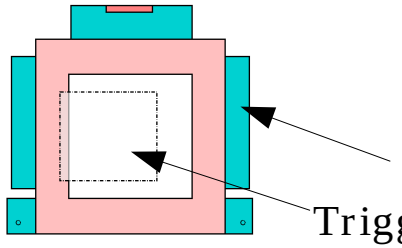
Imaging the wires

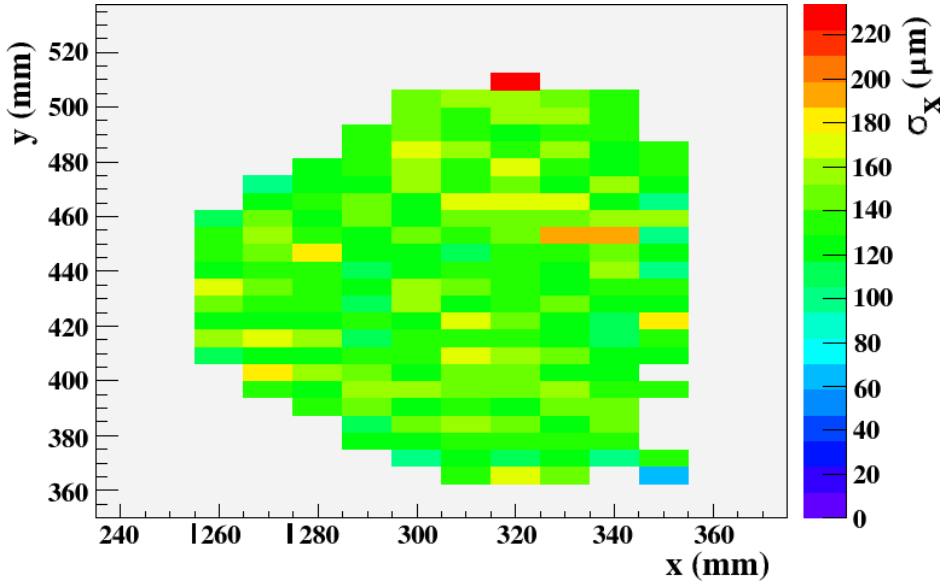
- Use centroids on both views to reconstruct wire positions
  - Avalanche occurs near wire → x-positions quantized
  - $x_{wire} \propto 1/\sqrt{2}\,(\langle u\rangle + \langle v\rangle)$ using cathode data only
  - Gaussian fits to reconstructed wire positions → resolution



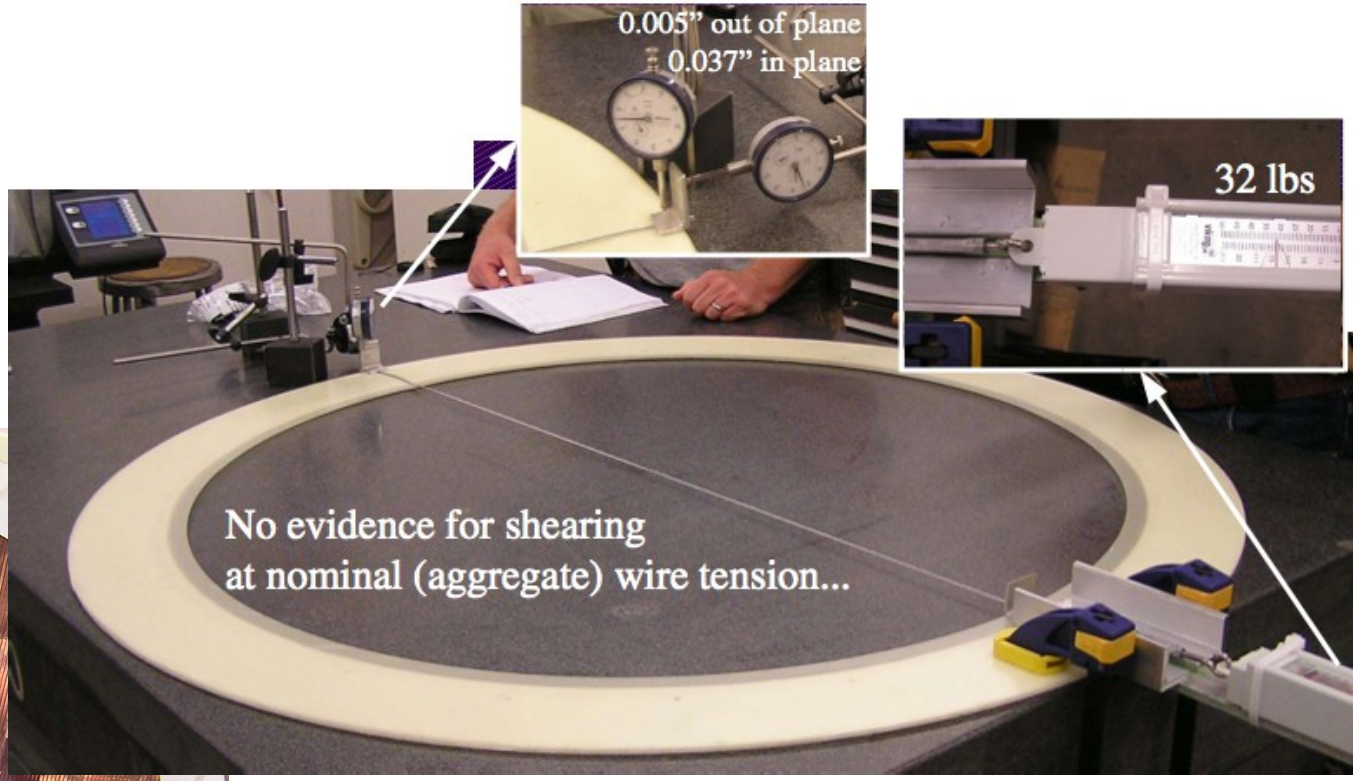
$\langle \sigma_x \rangle = 158 \pm 3\ \mu m$

Strip lengths vary between 12.8 cm and 27.8 cm



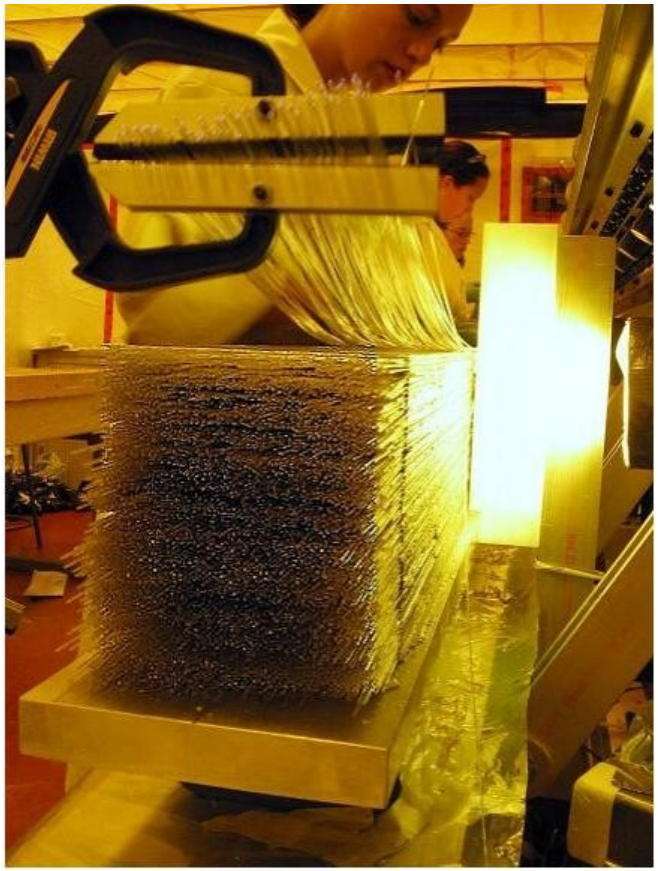


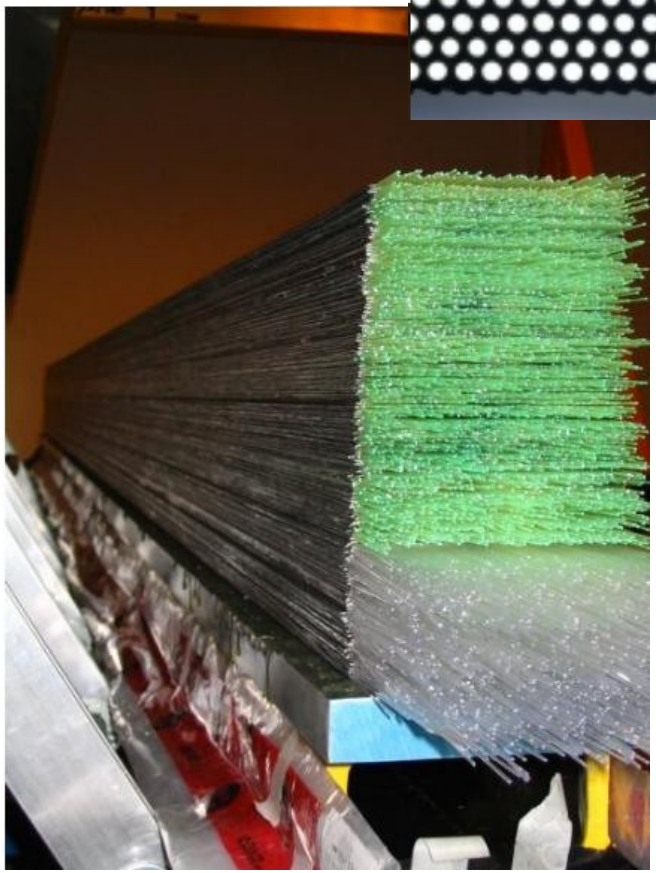
Toward a Full- Scale FDC Prototype



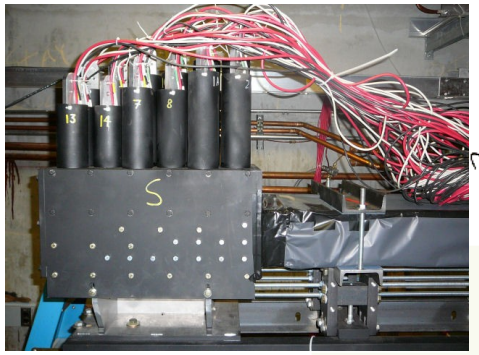
Barrel Calorimeter

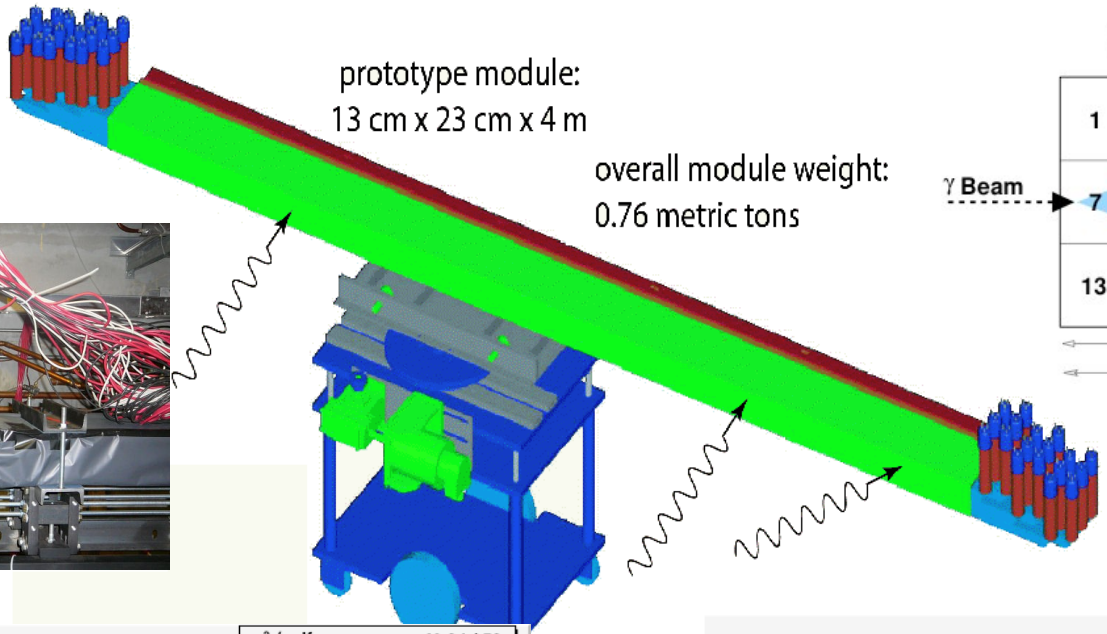
- Photon detection in central region
- Alternating lead + scintillating fiber layers
  - Sampling Fraction = ~12%

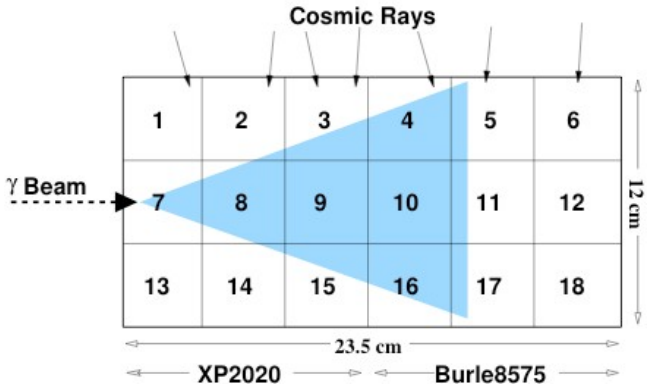


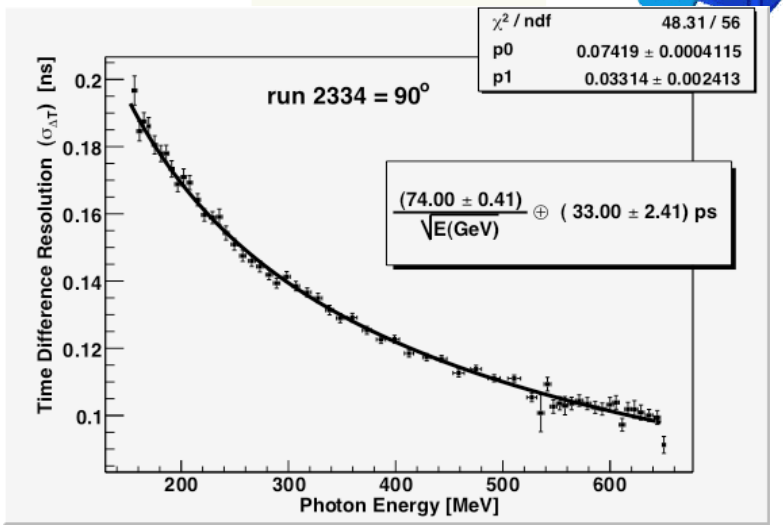


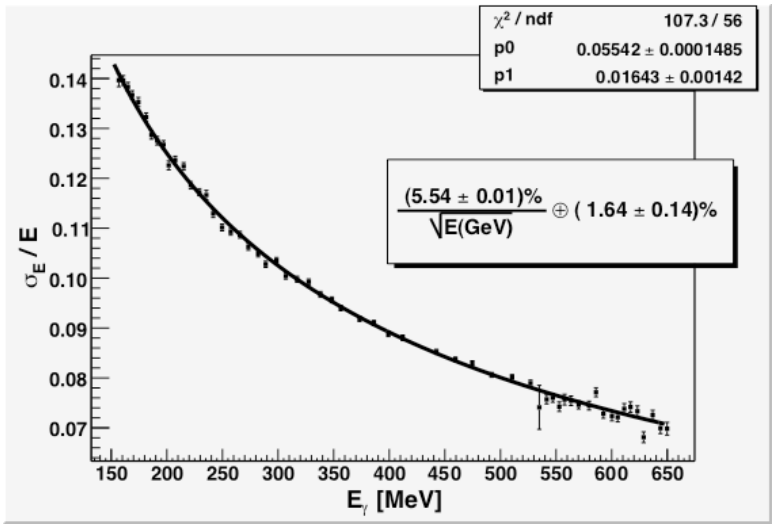
BCAL in Test Beam



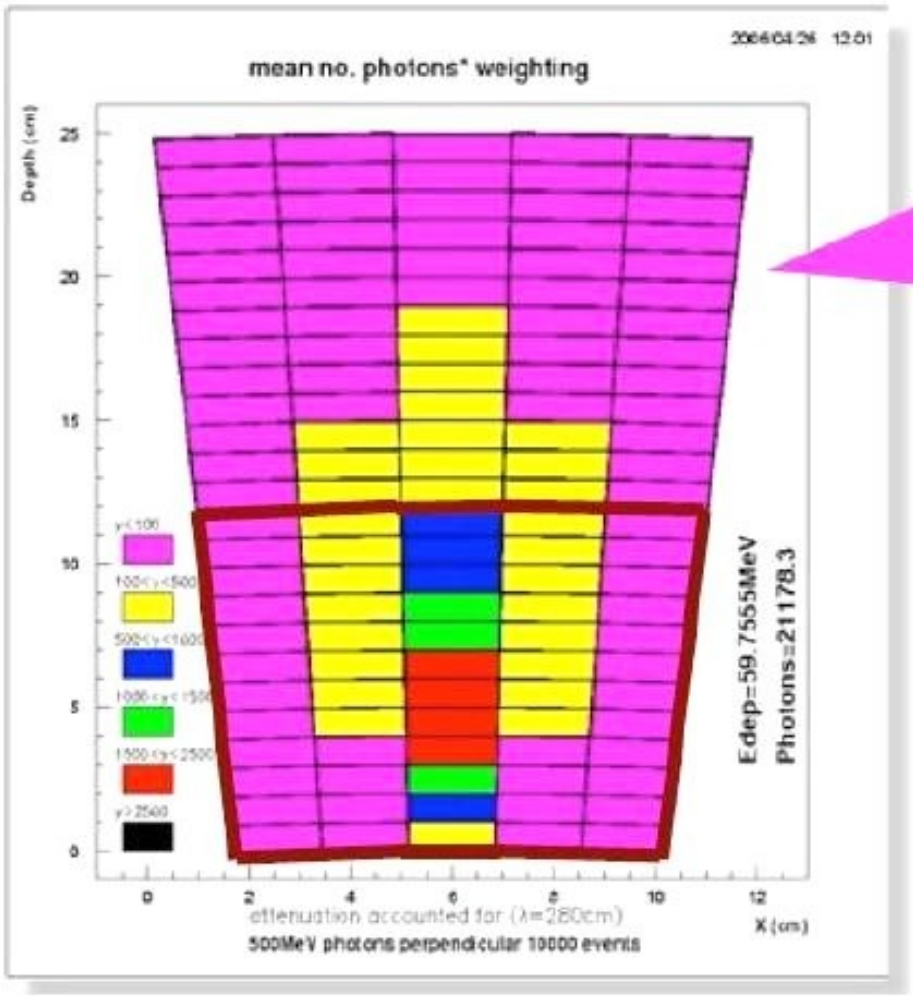


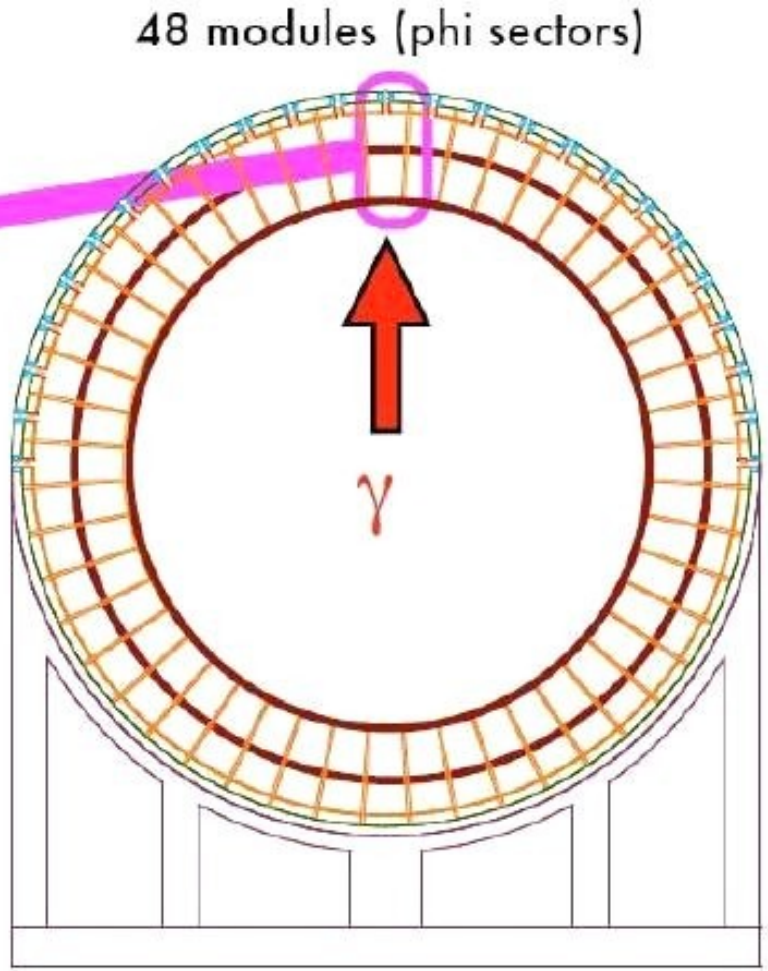




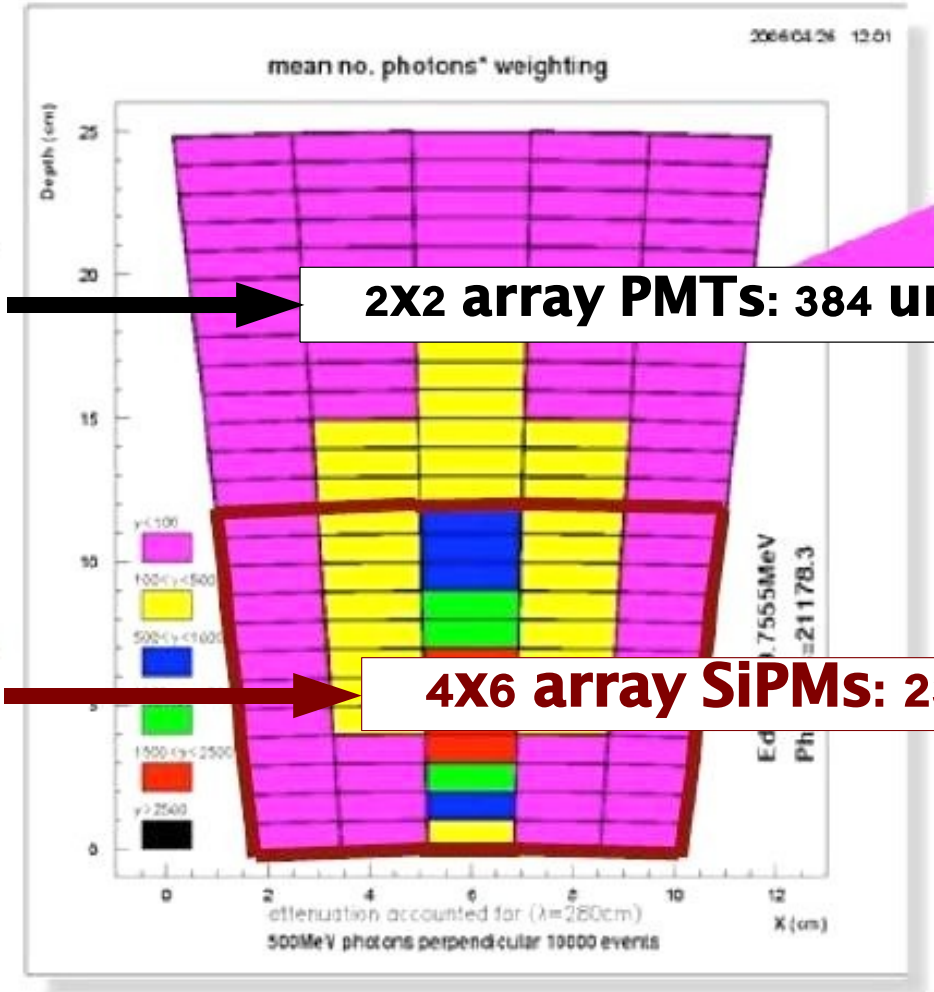


Barrel Calorimeter Configuration





Barrel Calorimeter

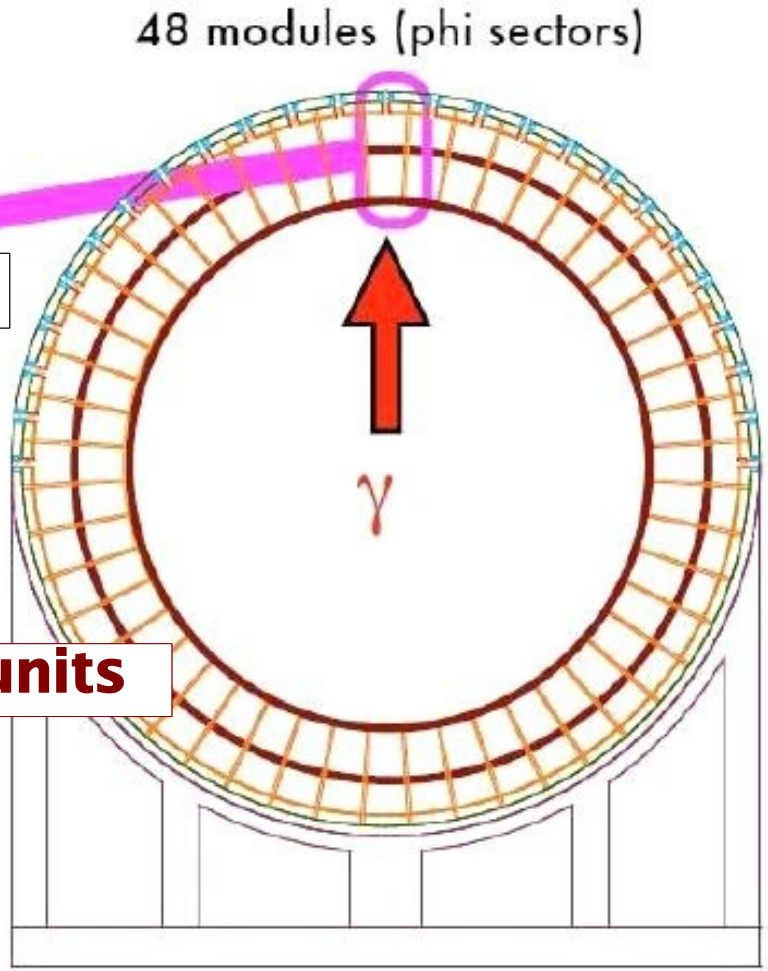


Outer Layers

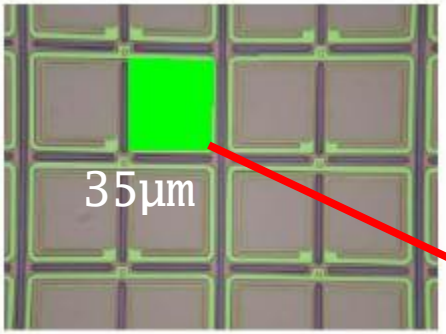
Inner Layers

2X2 array PMTs: 384 units

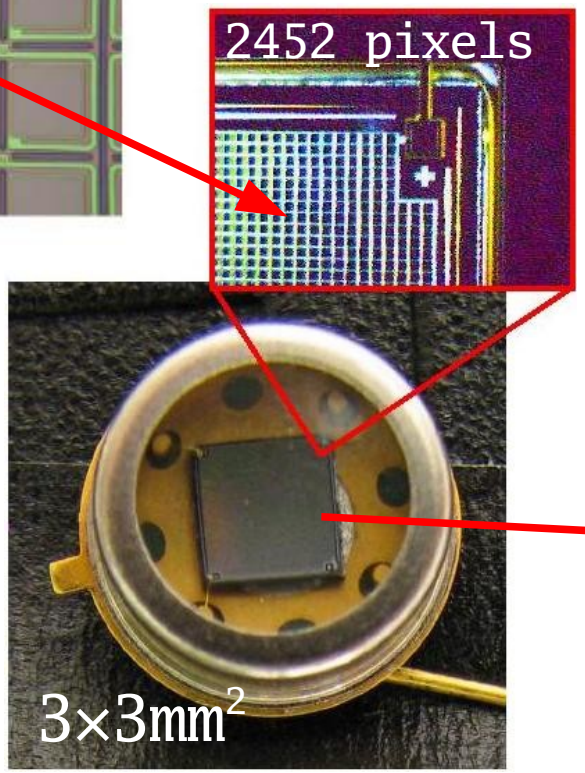
4X6 array SiPMs: 2304 units

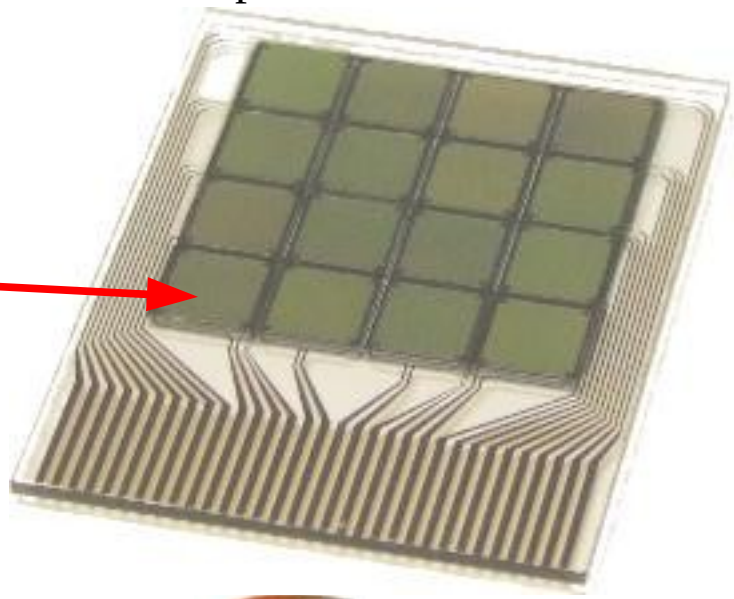


Silicon Photomultipliers



- Technology choice for readout of inner layers
  - Avalanche photodiode (APD) matrix of semiconductor photon sensitive devices
  - Each pixel operates in Geiger mode
  - Gain comparable to conventional PMT

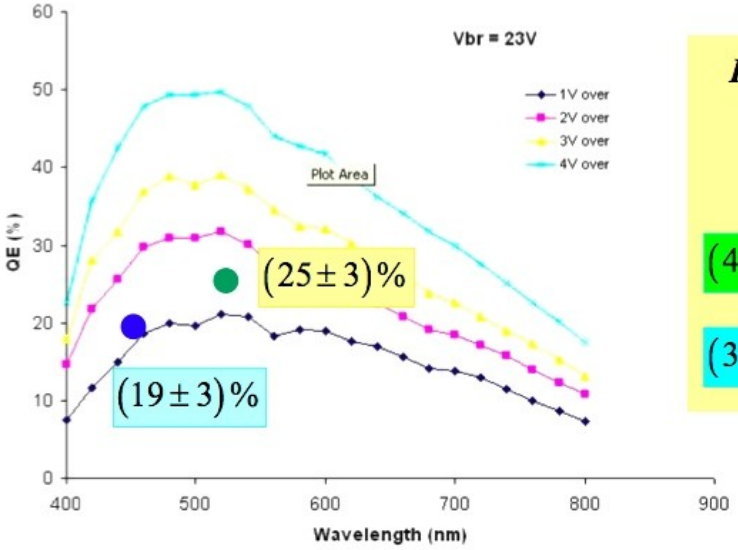




Immune to magnetic fields…

SensL
The Low Light Sensing Company

SiPM Measurements



$F = 0.178$

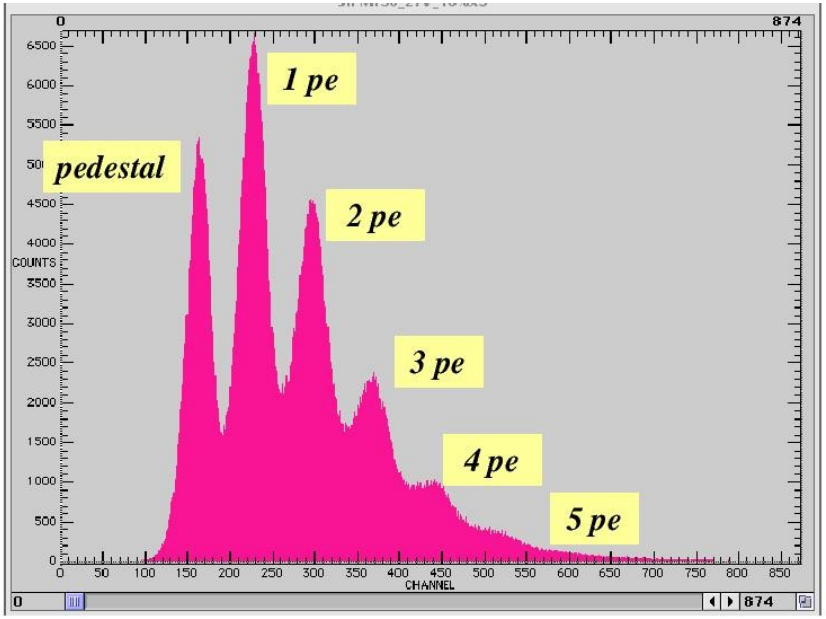
PDE

$(4.4 \pm 0.5)\%$

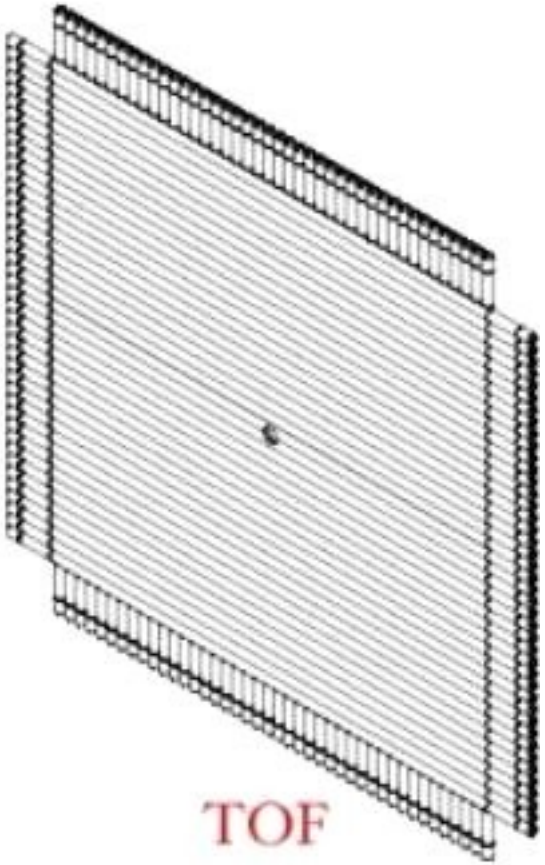
$(3.4 \pm 0.5)\%$

- Sensitivity to green wavelengths ⇒ good match to BCAL fibers

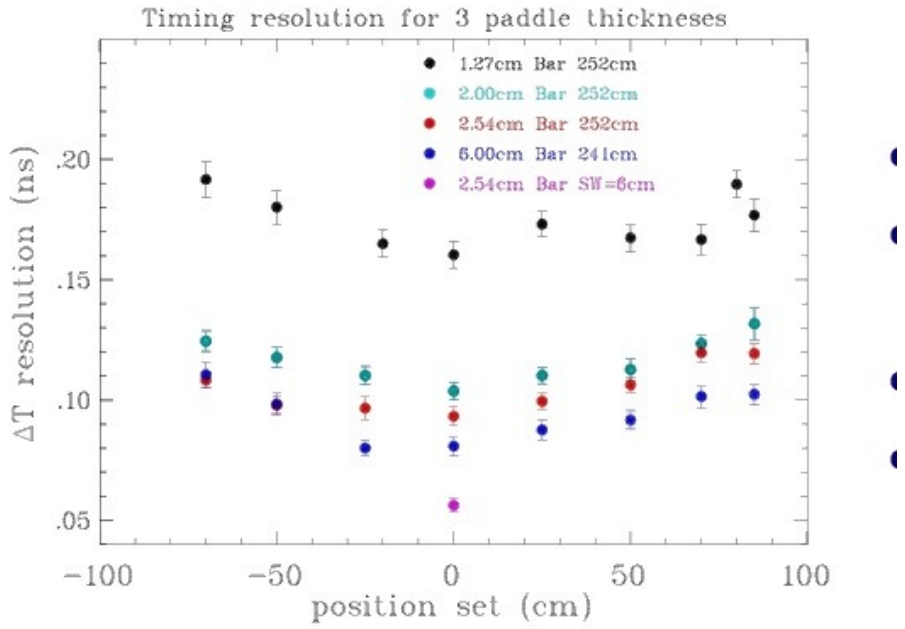
- Clean photo-electron spectrum observed for 35 μm pixel, 3×3 mm^2 sensor at -20°C
  - Would prefer to run near room temperature…



Time-of-flight Detectors

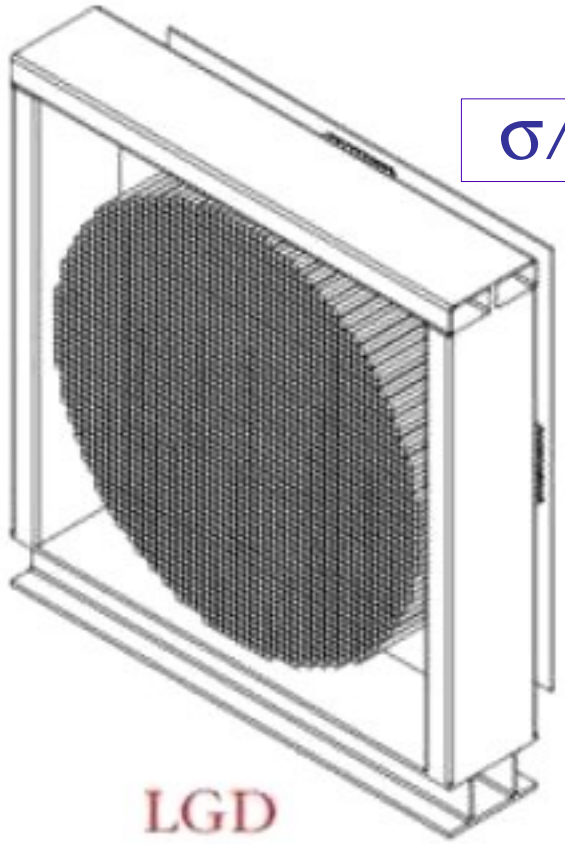


- Particle identification for forward-going charged tracks
- Two layers of scintillating plastic
  - 250×6×2.54 cm^3 bars
  - ~168 channels
  - Timing resolution goal $\sigma < 100$ ps

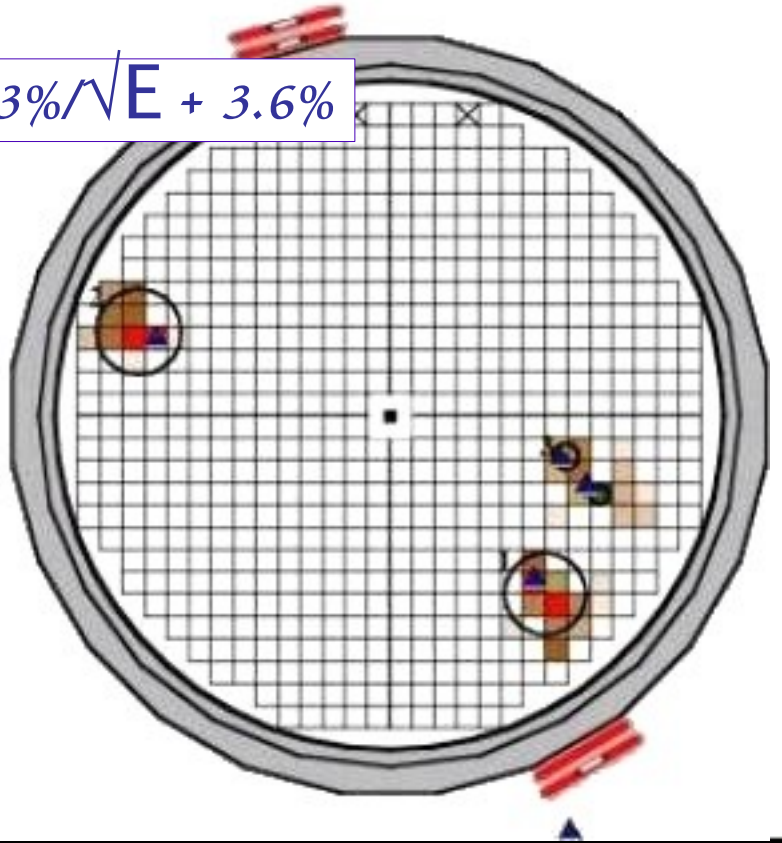


Forward Calorimeter

- Detect photons in the forward direction
- Array of $4 \times 4 \times 45$ cm^3 lead glass blocks (~ 2800 channels)
  - Crystals already in hand (recycled from E852 and RadPhi)

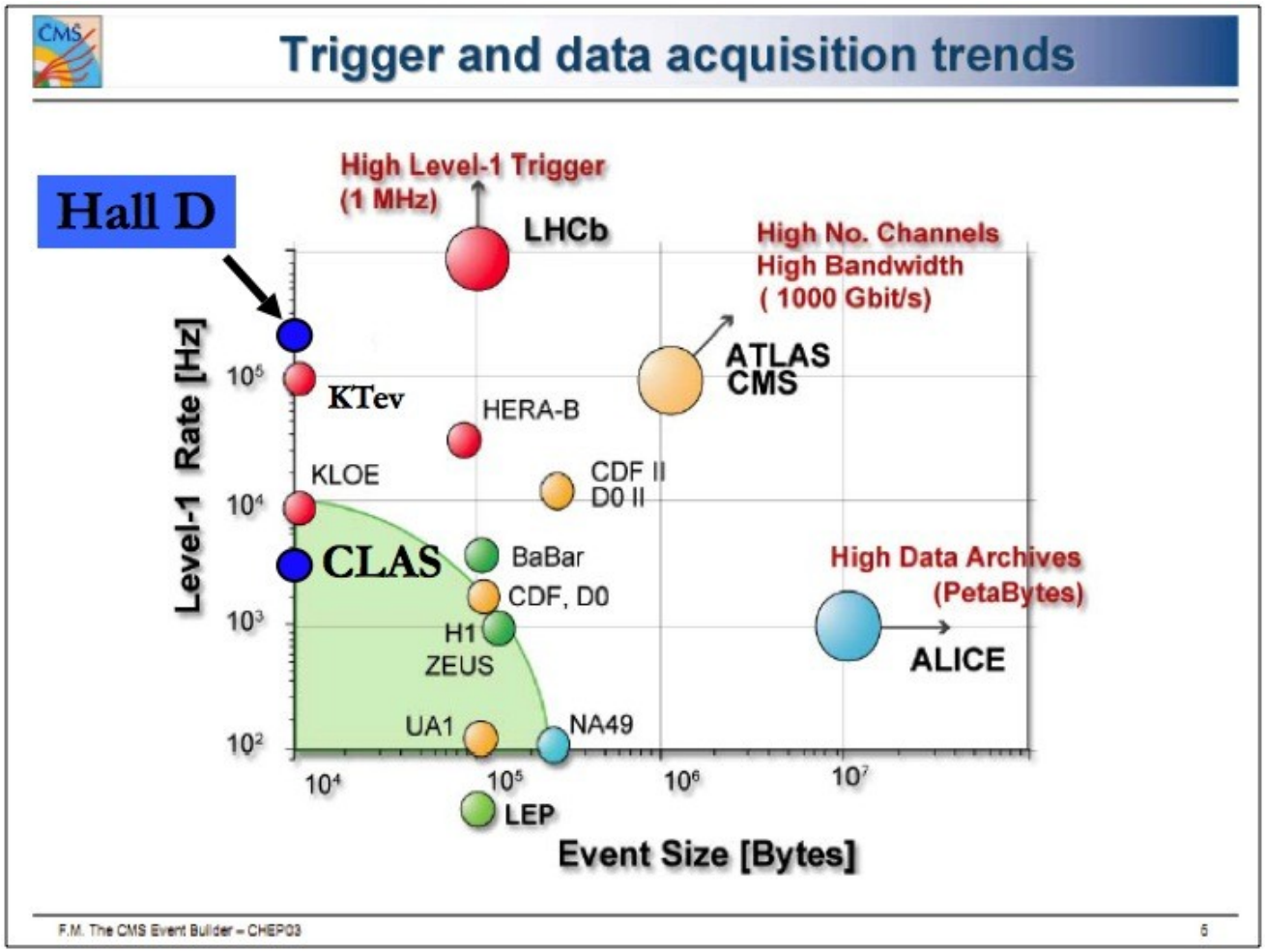


$\sigma/E = 7.3\%/\sqrt{E} + 3.6\%$



DAQ and Trigger

- Trigger rate: 200 kHz, Data rate: 100 MB/s
- No dead time ⇒ pipelined electronics...

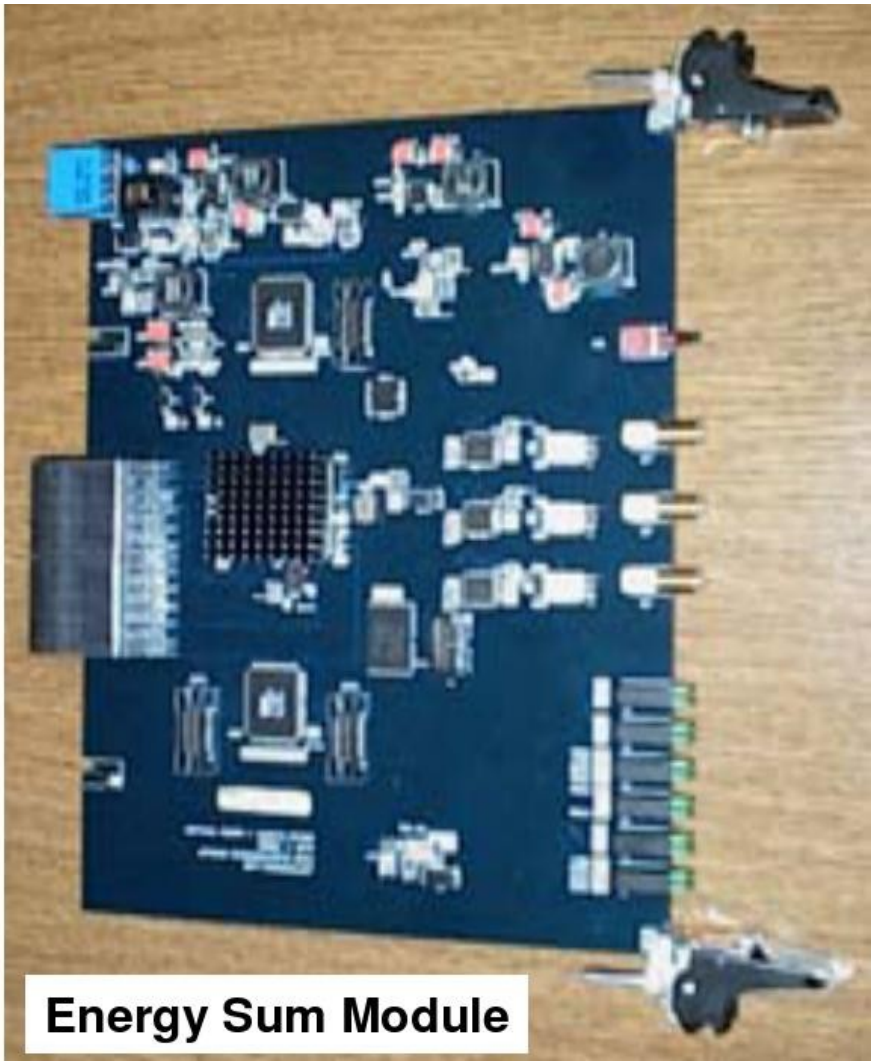


Electronics

- Custom electronics in VME-64X/VXS

16 channel 250 Msps Flash ADC

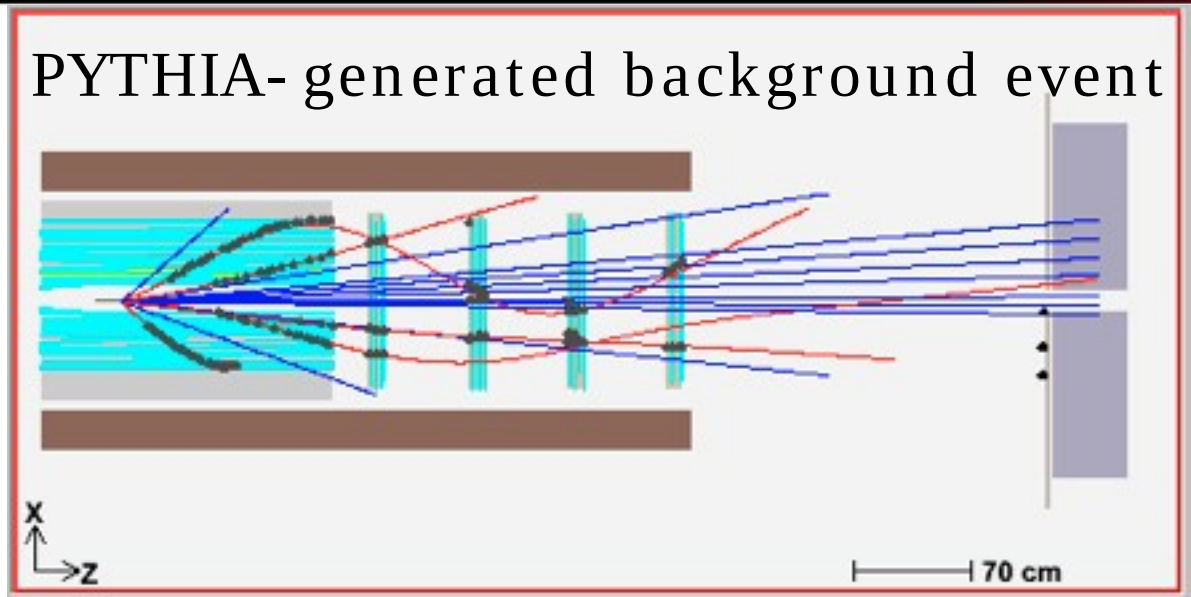
VXS
High Speed
Serial
Backplane

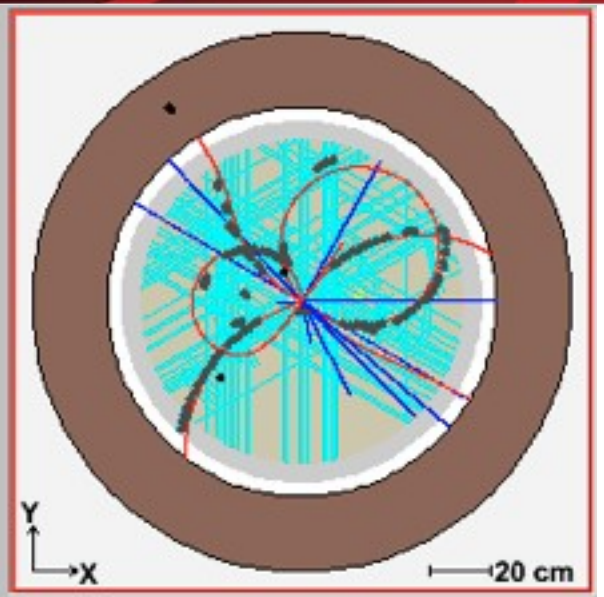


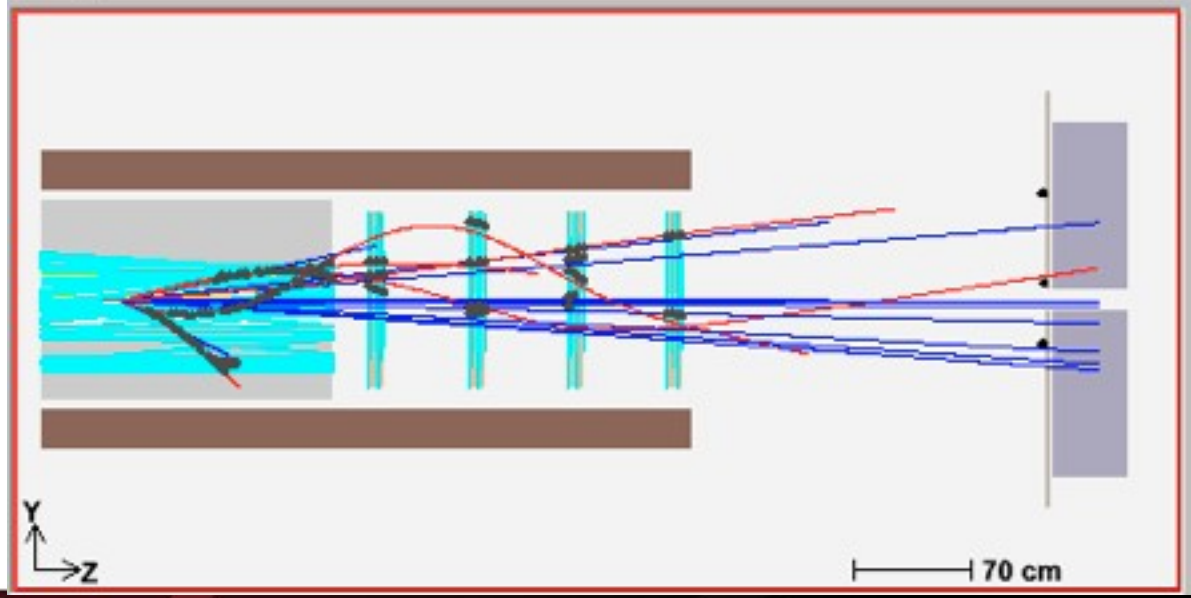
Energy Sum Module

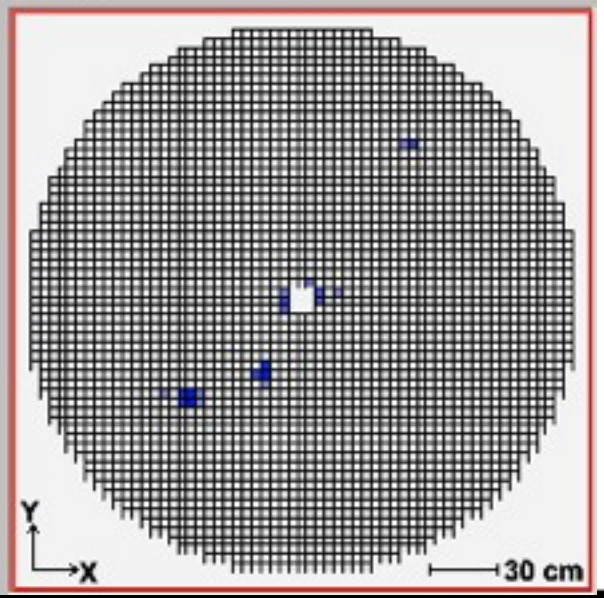
Event Simulation

PYTHIA-generated background event

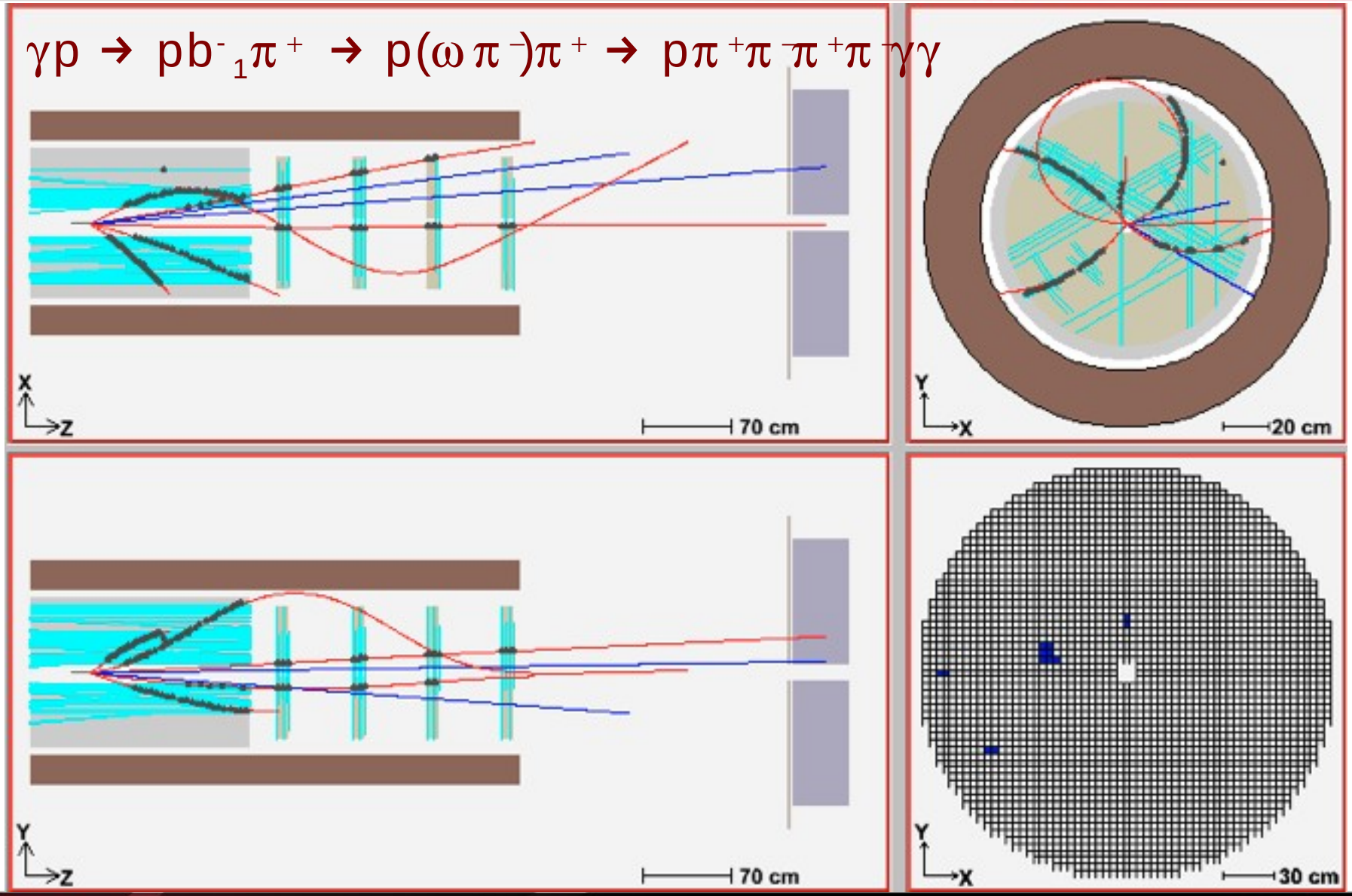








Sample Signal Event



Summary and Outlook

- The 12 GeV upgrade project has passed a major milestone
  - DOE awarded CD-2 in November (3rd out of 5 CD levels)
- The GlueX experiment is a major part of the upgrade
  - Goal is to map out spectrum of hybrid mesons
  - Major construction project with brand-new hall and detector
    - Detectors are in design and prototype stage
    - ... there's still a lot of work to do!
- CD-3 (Approval to start construction) is expected next year

We welcome new collaborators!

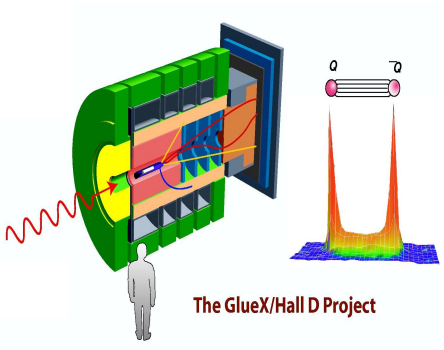
Hall D Workshop

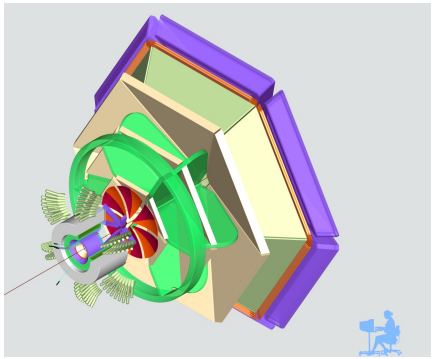
"Photon-hadron physics with GlueX in Hall D"
Jefferson Lab, March 6-8, 2008

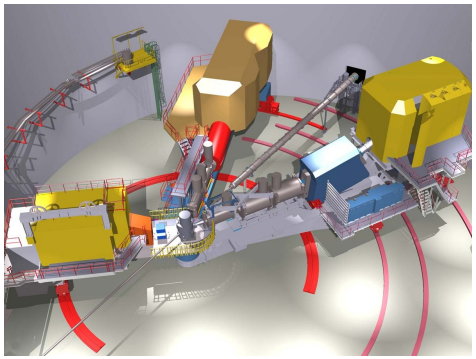
- Topics include:
  - Chiral anomaly and Primakoff effect
  - Charm production near threshold
  - Exclusive reactions at high momentum transfer
  - Nuclear effects in photo-production
  - Meson and Baryon Spectroscopy
  - Detector upgrades

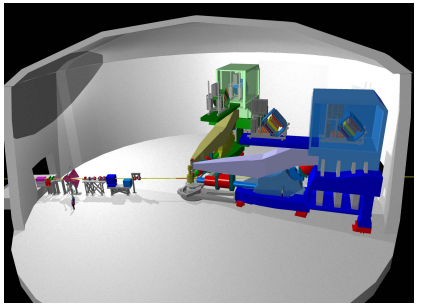
Additional Slides

Overview of Technical Performance Requirements









Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10×10^{34}	energy reach	installation space
polarized photons	hermeticity	precision	
$E_\gamma \sim 8.5-9$ GeV	11 GeV beamline		
10^8 photons/ s	target flexibility		
good momentum/ angle resolution	excellent momentum resolution		
high multiplicity reconstruction	luminosity up to 10^{38}		
particle ID			

Design Parameters

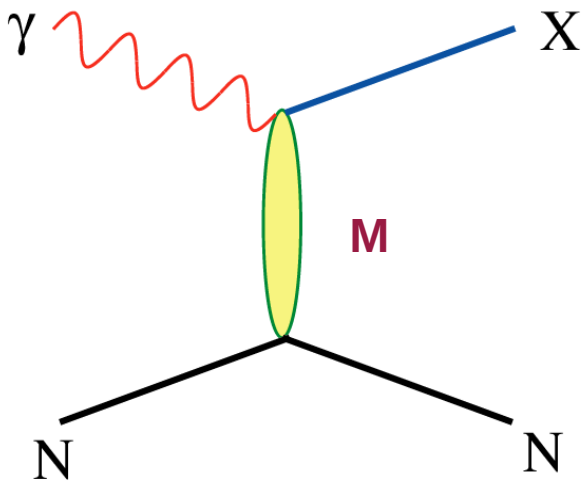
Capability	Quantity	Range
Charged particles	Coverage	$1^\circ < \theta < 140^\circ$
	Momentum Resolution (5°-140°)	$\sigma_p/p = 1 - 3\%$
	Position resolution	$\sigma \sim 150\text{-}200\ \mu m$
	dE/dx measurements	$20 < \theta < 140^\circ$
	Time-of-flight measurements	$\sigma_t < 80$ ps
	Cerenkov and π/K separation	$\theta < 14^\circ$
	Barrel time resolution	$\sigma_t < (150 + 50/\sqrt{E})$ ps
Photon detection	Energy measurements	$2 < \theta < 120^\circ$
	Veto capability	$120 < \theta < 170^\circ$
	LGD energy resolution (E > 100 MeV)	$\sigma_E/E = (3.6 + 7.3/\sqrt{E})\%$
	Barrel energy resolution (E > 40 MeV)	$\sigma_E/E = (2 + 5/\sqrt{E})\%$
	LGD position resolution	$\sigma_{x,y,} \sim 1$ cm
	Barrel position resolution	$\sigma_z \sim 4$ cm
DAQ/trigger	Level 1	200 kHz
	Level 3 event rate to tape	15 kHz
	Data rate	100 MB/s
Electronics	Fully pipelined	Flash ADCs, multi-hit TDCs
Photon Flux	Initial: 10^7 γ/s rate	Final: 10^8 γ/s

Linear Polarization

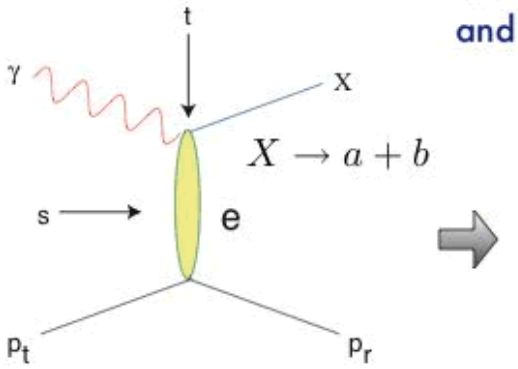
Linear polarization is:

- ✓ **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**

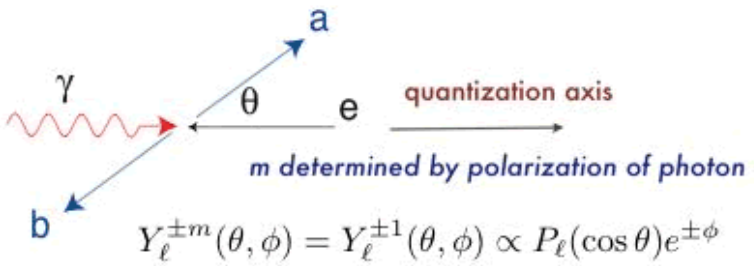
States of linear polarization are eigenstates of parity. States of circular polarization are not.



Linear Polarization



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



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