Searching for Interesting Bound States of QCD with the GlueX Experiment at Jefferson Lab

Strong Interactions in the 21st Century
TIFR, Mumbai
February 10-12, 2010

(Mumbai is much warmer than home!)

Matthew Shepherd
Indiana University

Gluon Dynamics in QCD

- QCD has interesting properties
  - confinement: force is strong at large distances
  - gluon-gluon interactions
- *How do these properties exhibit themselves in experimental data?*
  - What are the fundamental degrees of freedom that make up hadrons?
  - Can we observe evidence for gluonic degrees of freedom in the spectrum of meson states?
  - What role do gluons play in the structure of matter?
  - Does QCD predict *experimentally observable* gluonic excitations?

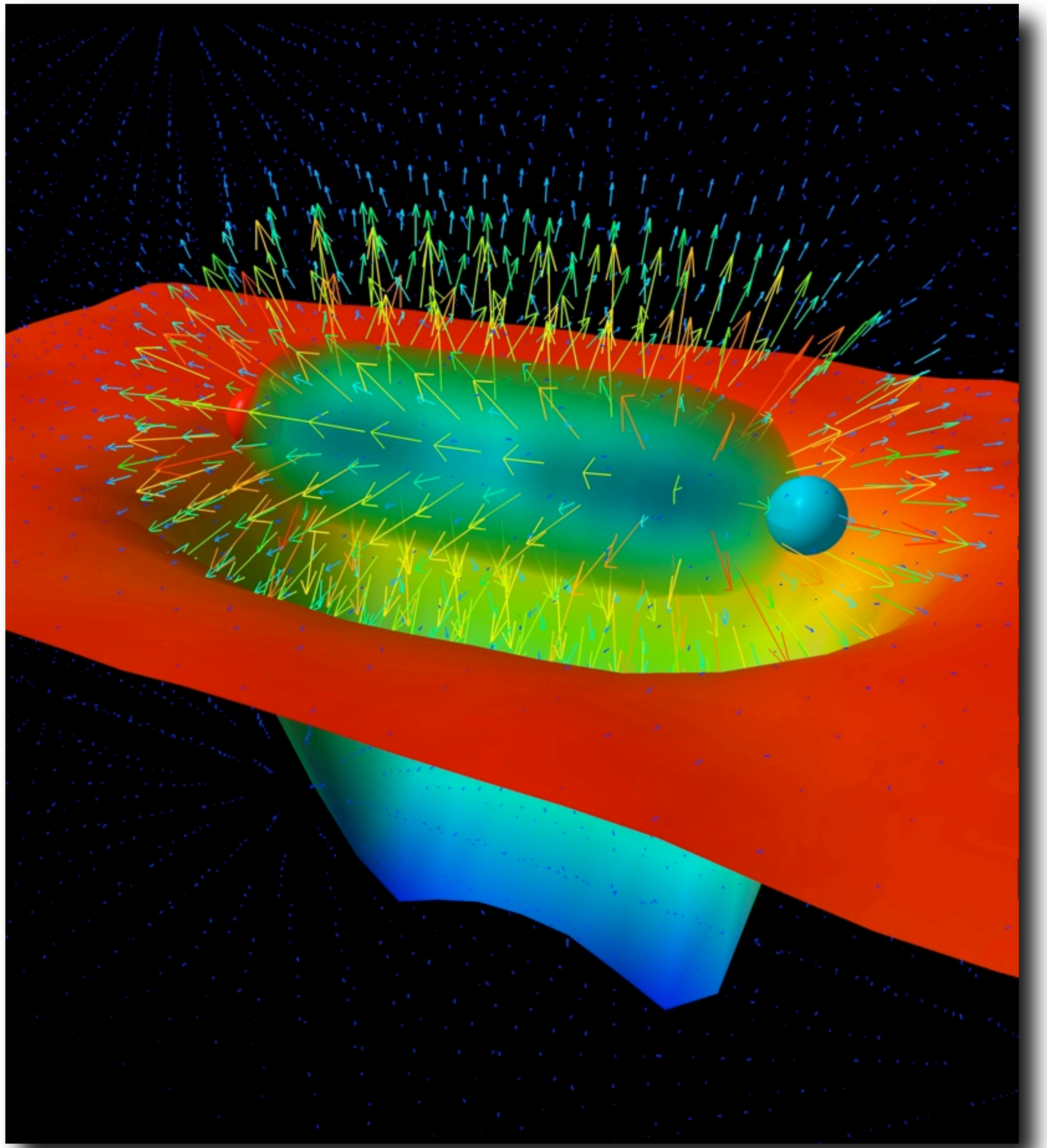
Outline

- Motivation: What drove the design of the GlueX experiment?
(the 20th century inspiration)

- Recent developments: Why is GlueX particularly exciting now?
(the 21st century context)

- Analysis/Data Handling challenges: How does one extract exotics?
(the 21st century technology)

- Status: When can we expect data from GlueX?
(the 21st century results)

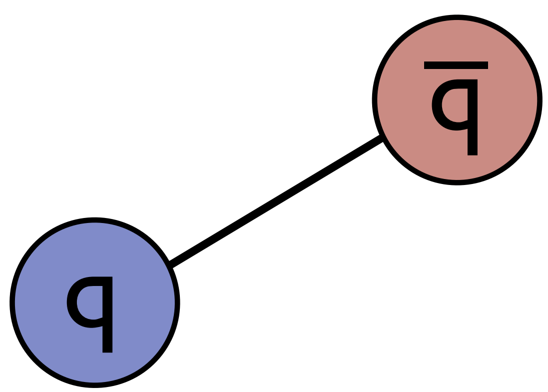


D. Leinweber
U. of Adelaide

Exotic Hybrid Mesons

a tool for exploring gluonic degrees of freedom in QCD

Conventional Mesons



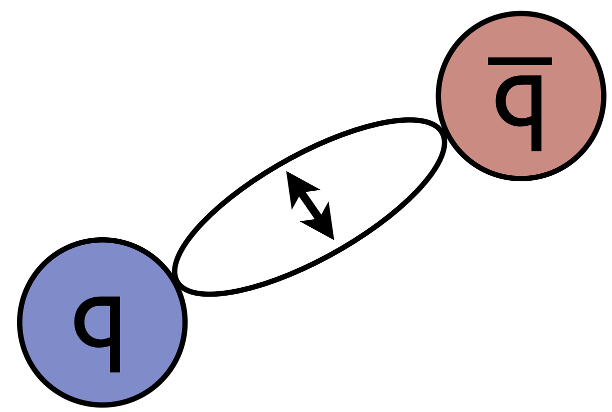
$$J = L + S$$

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

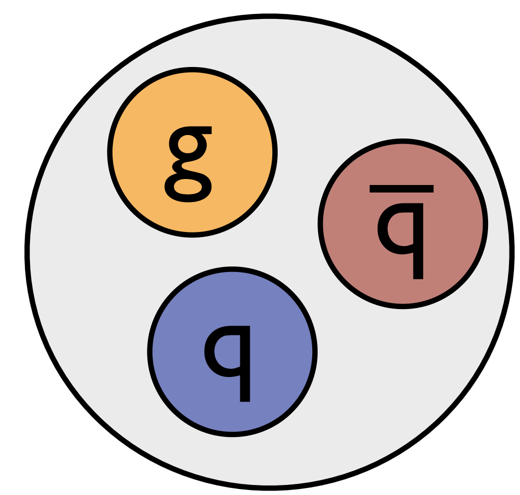
$$C=(-1)^{L+S}$$

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

Hybrid Mesons



or



Additional degrees of freedom from constituent gluons can result in formation of exotic J^{PC}

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

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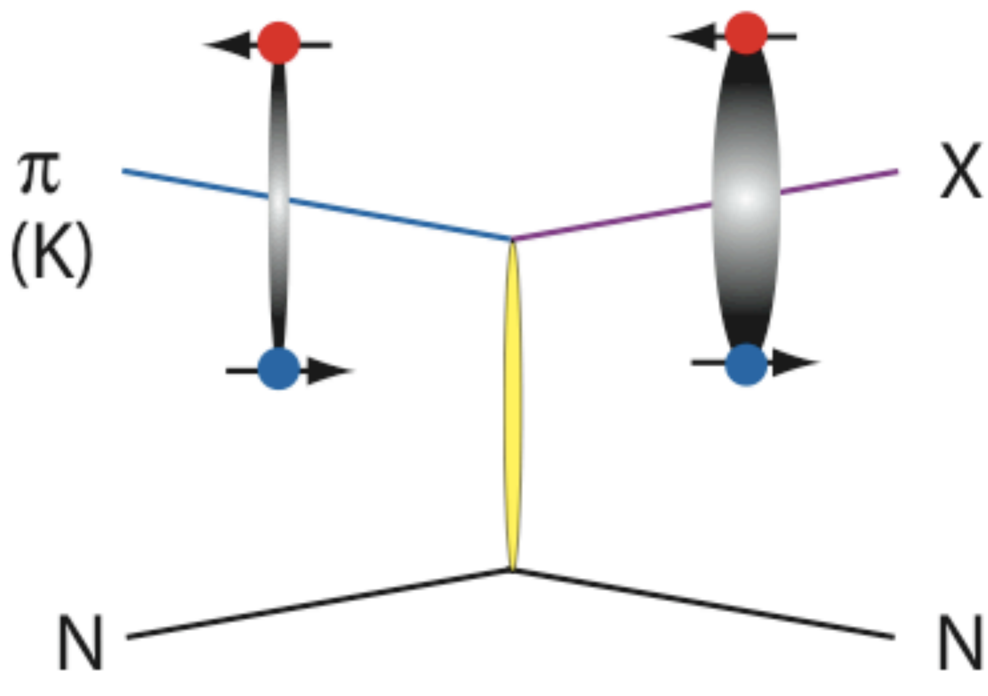
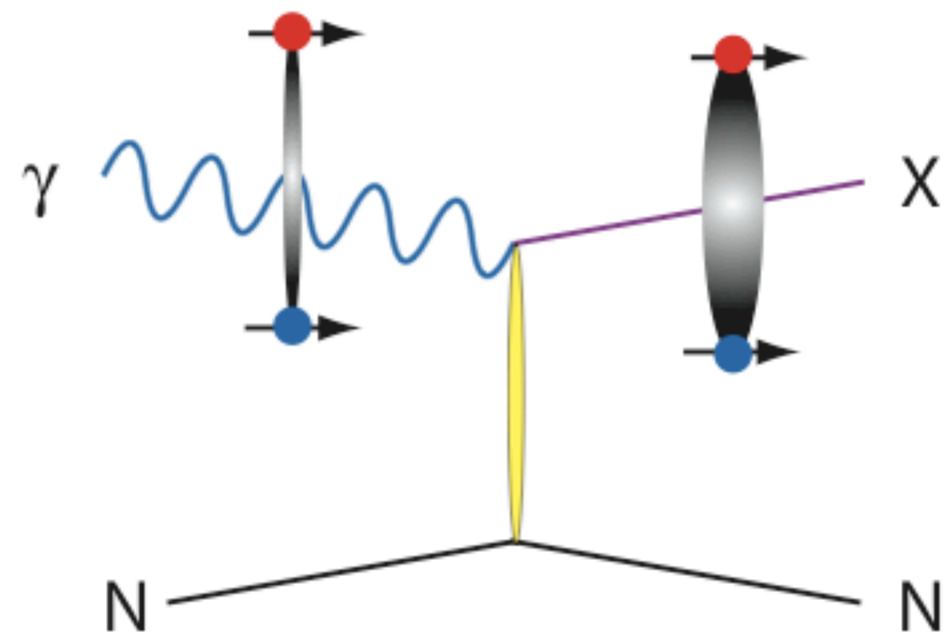
Exotic Photoproduction





Fluxed tube model predicts first excitation to have glue in $J^{PC} = 1^{+-}, 1^{-+}$

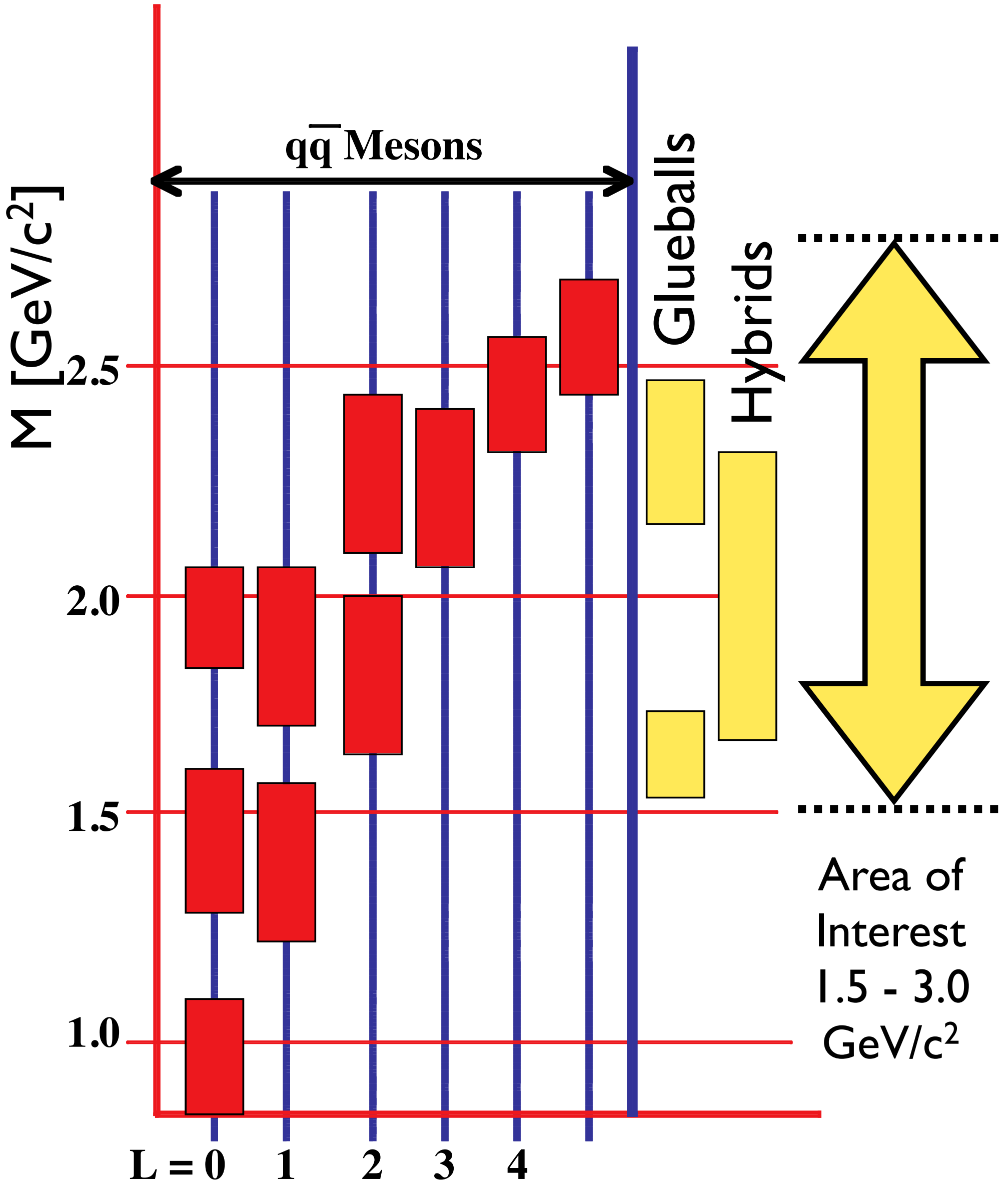
Combined with 0^{-+} (π,K)
yields
$J^{PC} = 1^{++}$ and 1^{--}

Combined with 1^{--} (ρ,ω,Φ)
yields
$J^{PC} = 0^{+-}, 0^{-+}, 1^{+-}, 1^{-+}, 2^{+-}$, and 2^{-+}

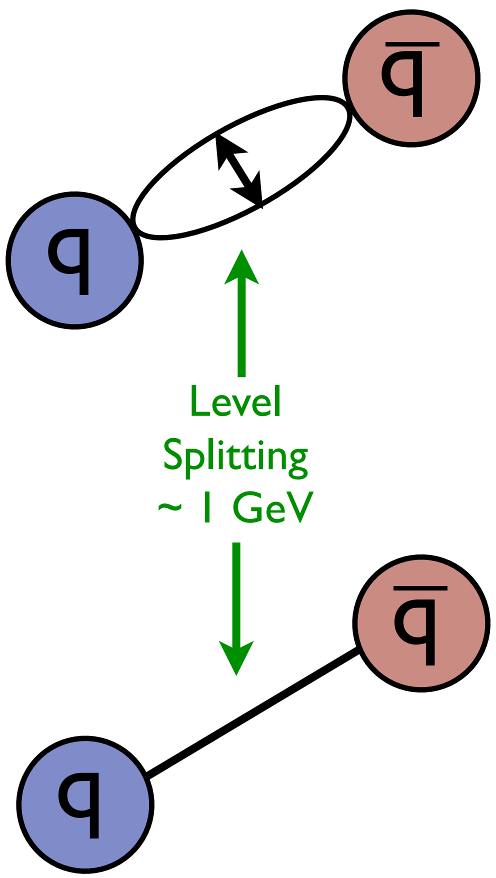
Exotics!

Photon beam is ideal for production of exotics.

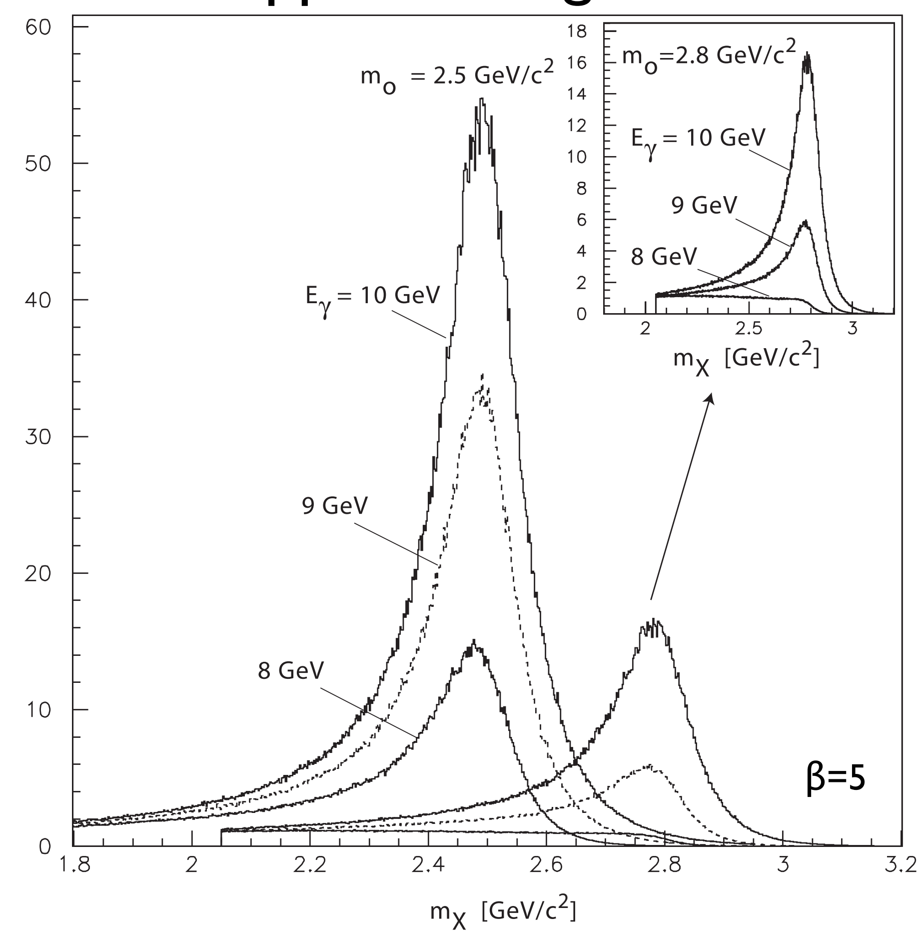
Expected Masses



(model dependent picture)



t dependence in production suppresses high mass

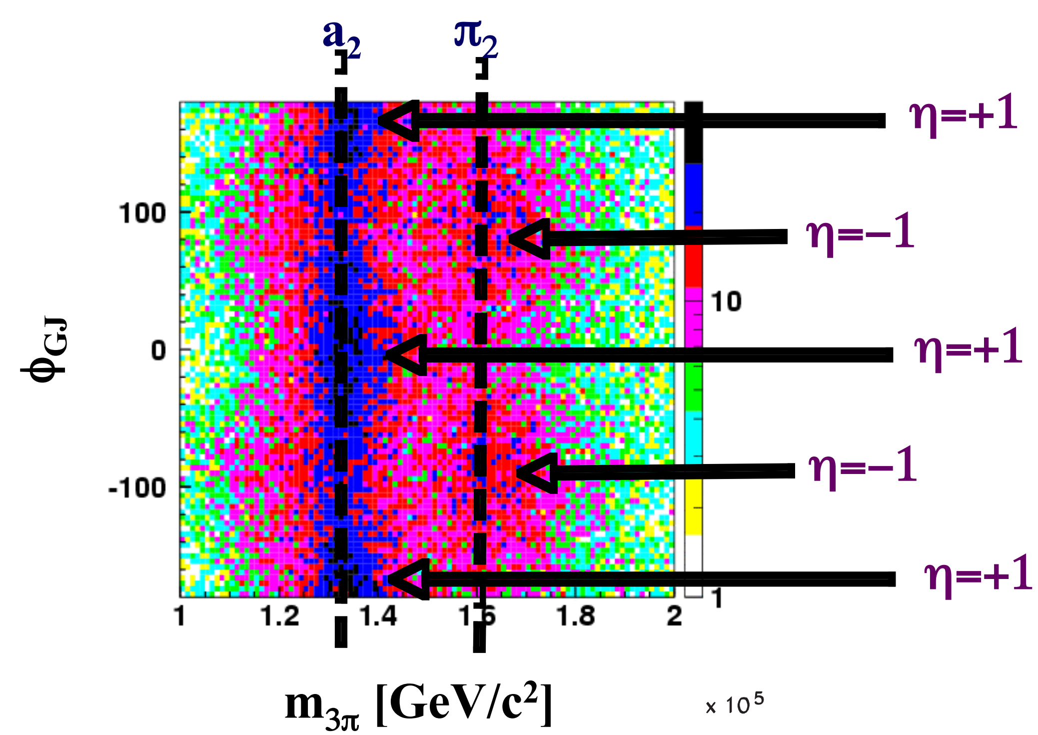


$$\frac{dN}{d|t|} \propto e^{-\beta|t|}$$

9 GeV photons provide sufficient mass reach
(This sets 12 GeV scale for electron beam.)

Linear Polarization

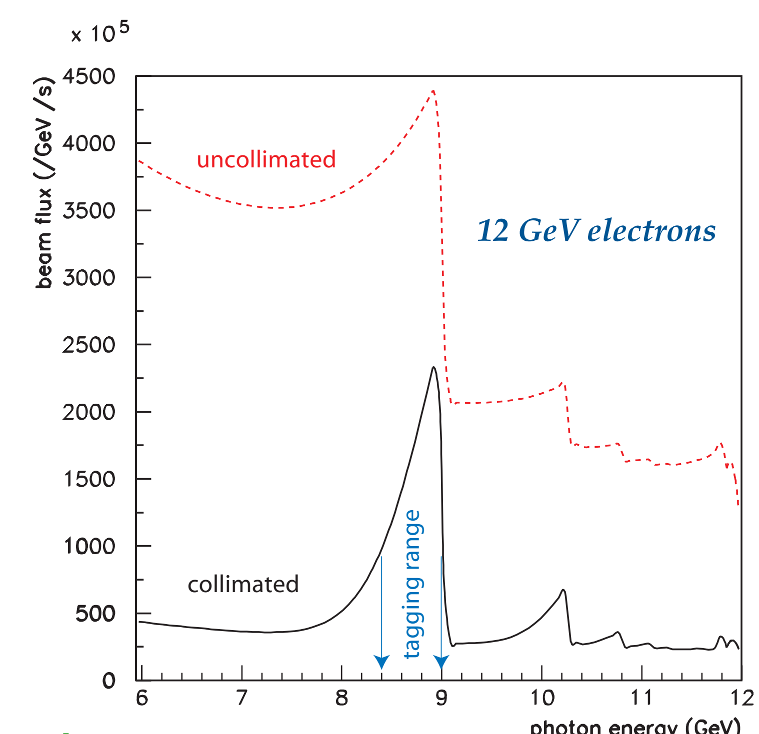
- Coherent bremsstrahlung technique produces 9 GeV linearly polarized photons from 12 GeV electrons using a thin diamond wafer
- Linear polarization encodes the spin/parity of exchanged particle in the azimuthal angle of decay products
- Critical extra handle in spin/parity analysis of final state
- Can be used to increase sensitivity to exotics



parity-dependent azimuthal distribution

Simulated GlueX Analysis

$$\gamma p \to 3\pi n$$



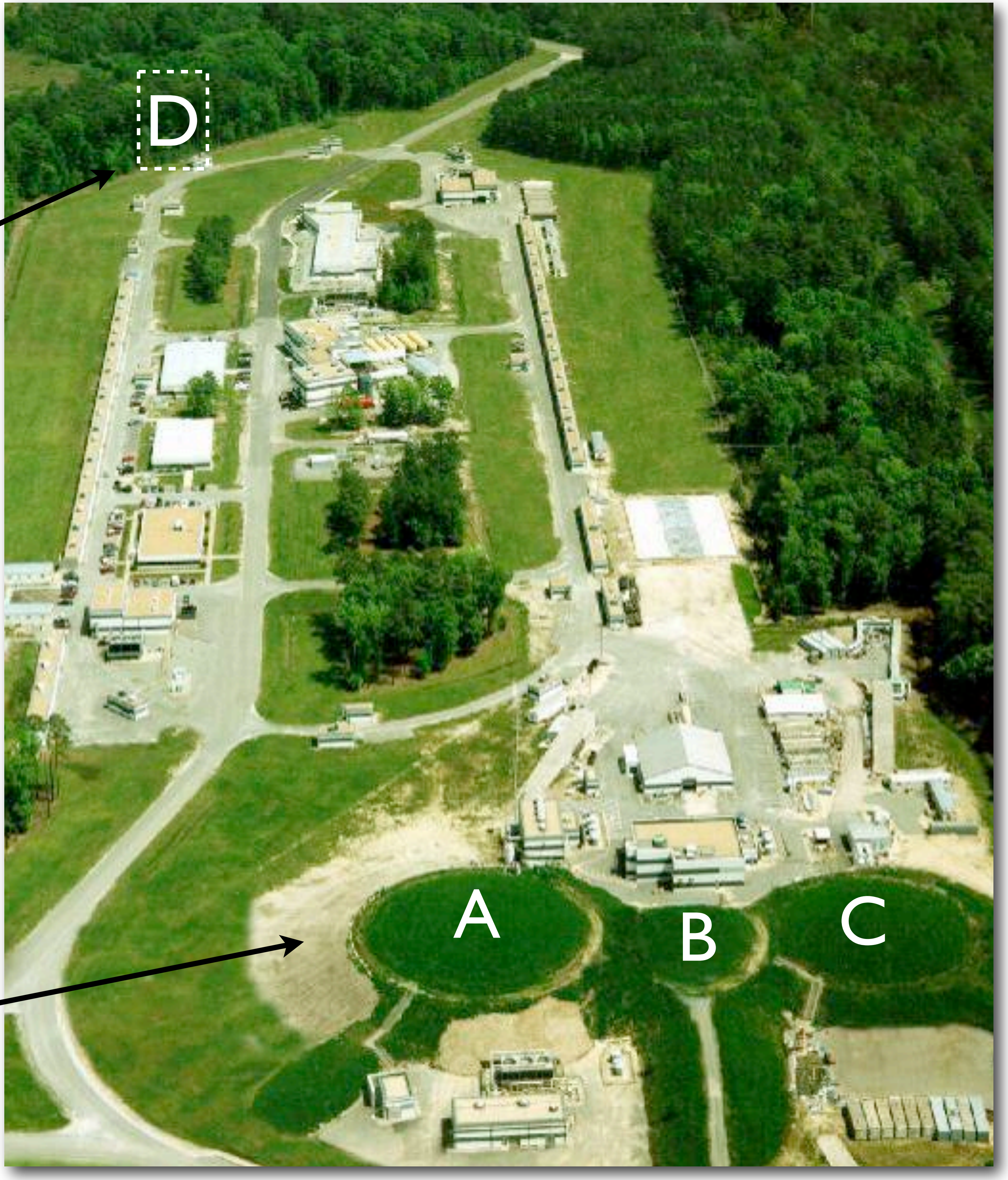
A linearly polarized 9 GeV photon beam is ideal

Jefferson Lab (Newport News, VA)

Future Site of Hall D

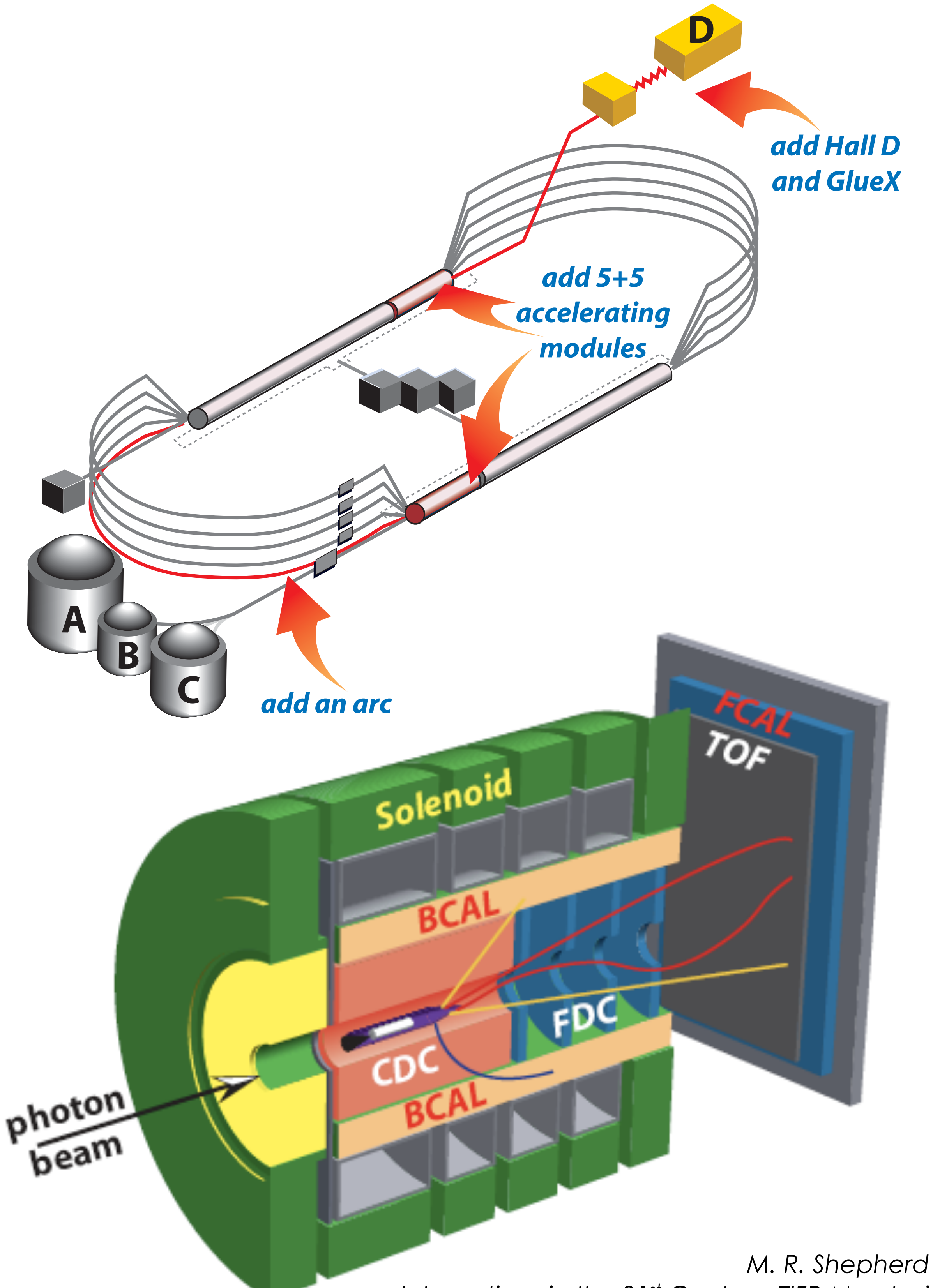
- currently 6 GeV electron beam
  - three existing fixed target experimental halls
- Hall D:
  - part of 12 GeV upgrade
  - 9 GeV tagged polarized, energy-tagged photons, produced from 12 GeV electron
  - new multi-purpose spectrometer

Existing Experimental Halls



GlueX in Hall D

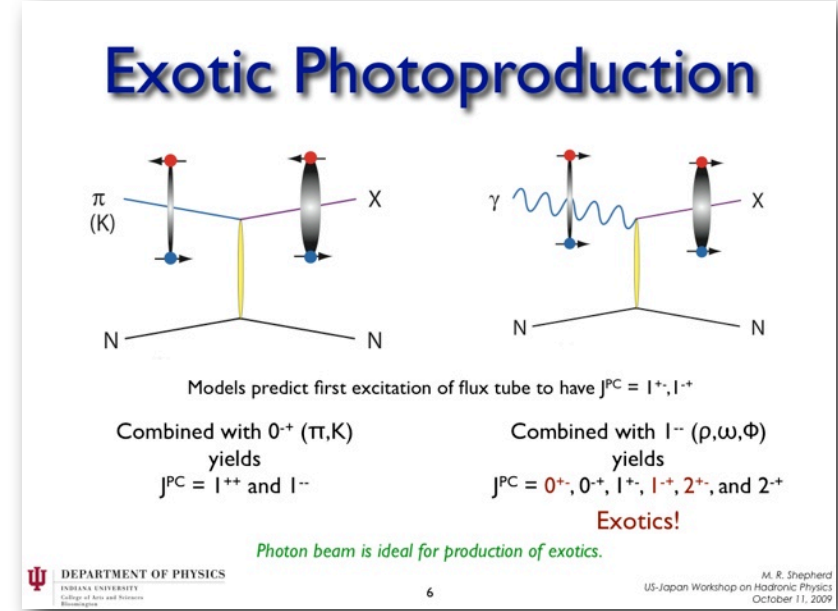
- part of $310M 12 GeV upgrade to Jefferson Lab
- core physics motivation:
    - light hybrid spectroscopy
    - complementary to BES III, PANDA, COMPASS, and others
- exploring other possibilities: $\Gamma_{\gamma\gamma}$ via Primakoff, baryon spectroscopy, inverse DVCS, ...
- 9 GeV linearly *polarized* photons incident on proton target -- polarization enhances spin-parity analysis
- hermetic multi-particle spectrometer, optimized for amplitude analysis -- expect multi-particle final states
- ~60 physicists
- Collaboration founded around 1998



Why is GlueX particularly exciting *now*?

(the 21st century context)

New Lattice Calculations of Photon-Hybrid Couplings



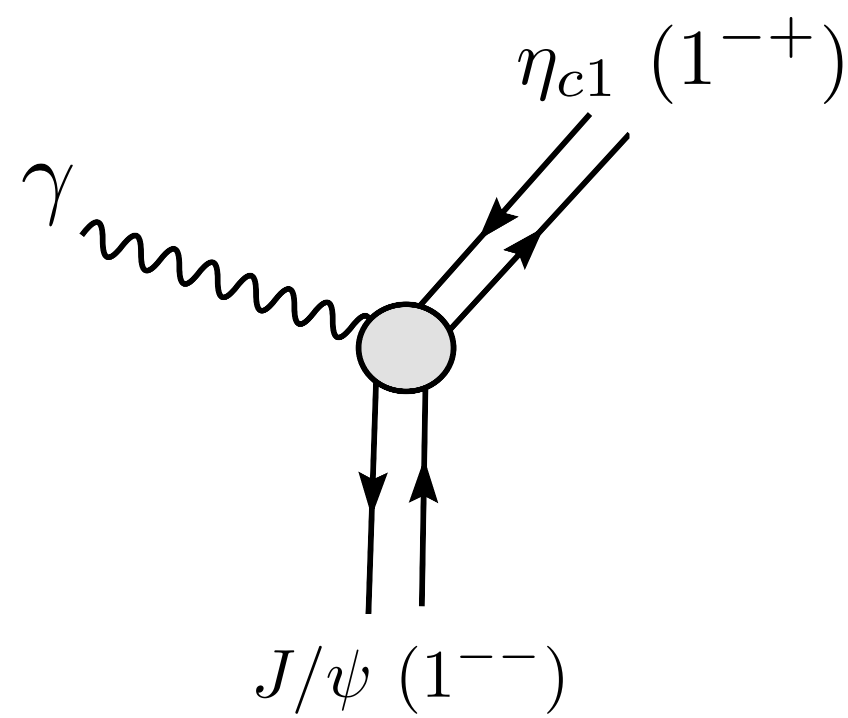
- Use radiative transitions in charmonia as a test bed for calculations of hybrid photo-couplings (measurable at CLEO-c and BES III)
- Calculate magnetic-dipole transitions:

$$\Gamma(J/\psi \to \gamma\eta_c) = (2.51 \pm 0.08)\ \mathrm{keV}$$

agrees w/expt. -- suppressed by heavy quark spin flip

$$\Gamma(\eta_{c1} \to \gamma J/\psi) = (115 \pm 16)\ \mathrm{keV}$$

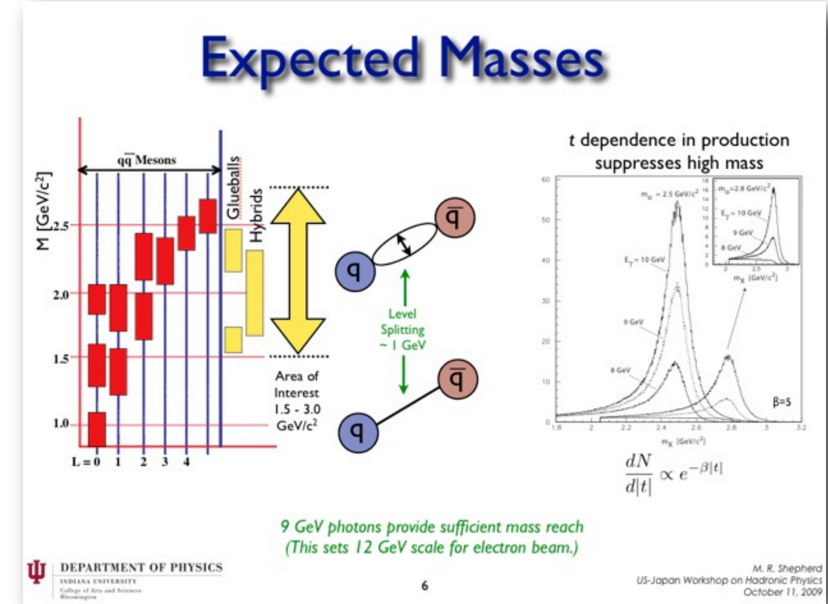
much larger -- can proceed without spin flip

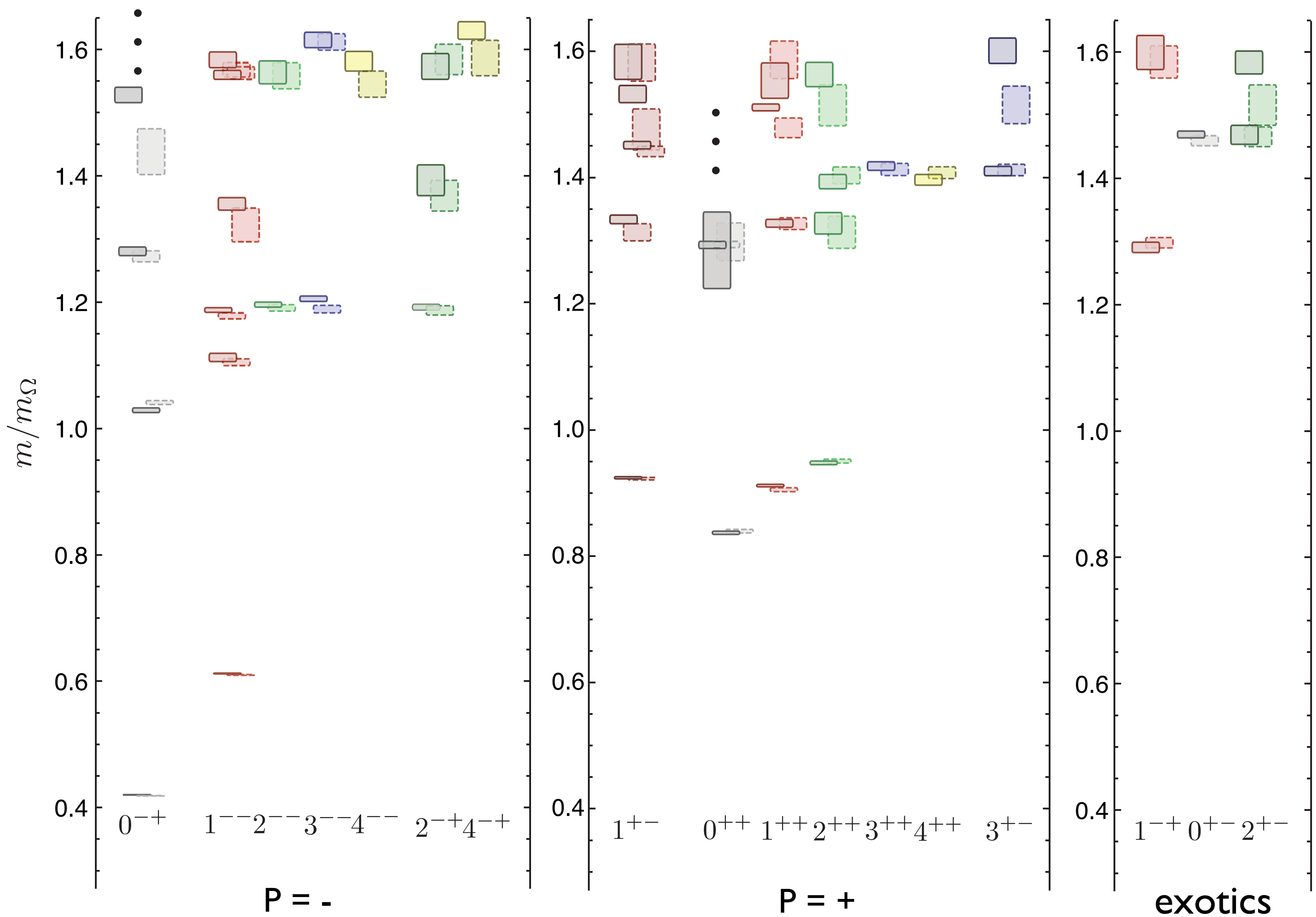


- *Interesting... does this trend hold in the light quark sector?*

Dudek, Edwards, and Thomas
Phys. Rev. D 79, 094504 (2009)

New Lattice Calculations of Light Meson Spectra





3 quark flavors
unquenched

all light quarks at
strange quark mass
(SU(3) flavor)

Beautifully rich spectrum of states that supports model predictions!

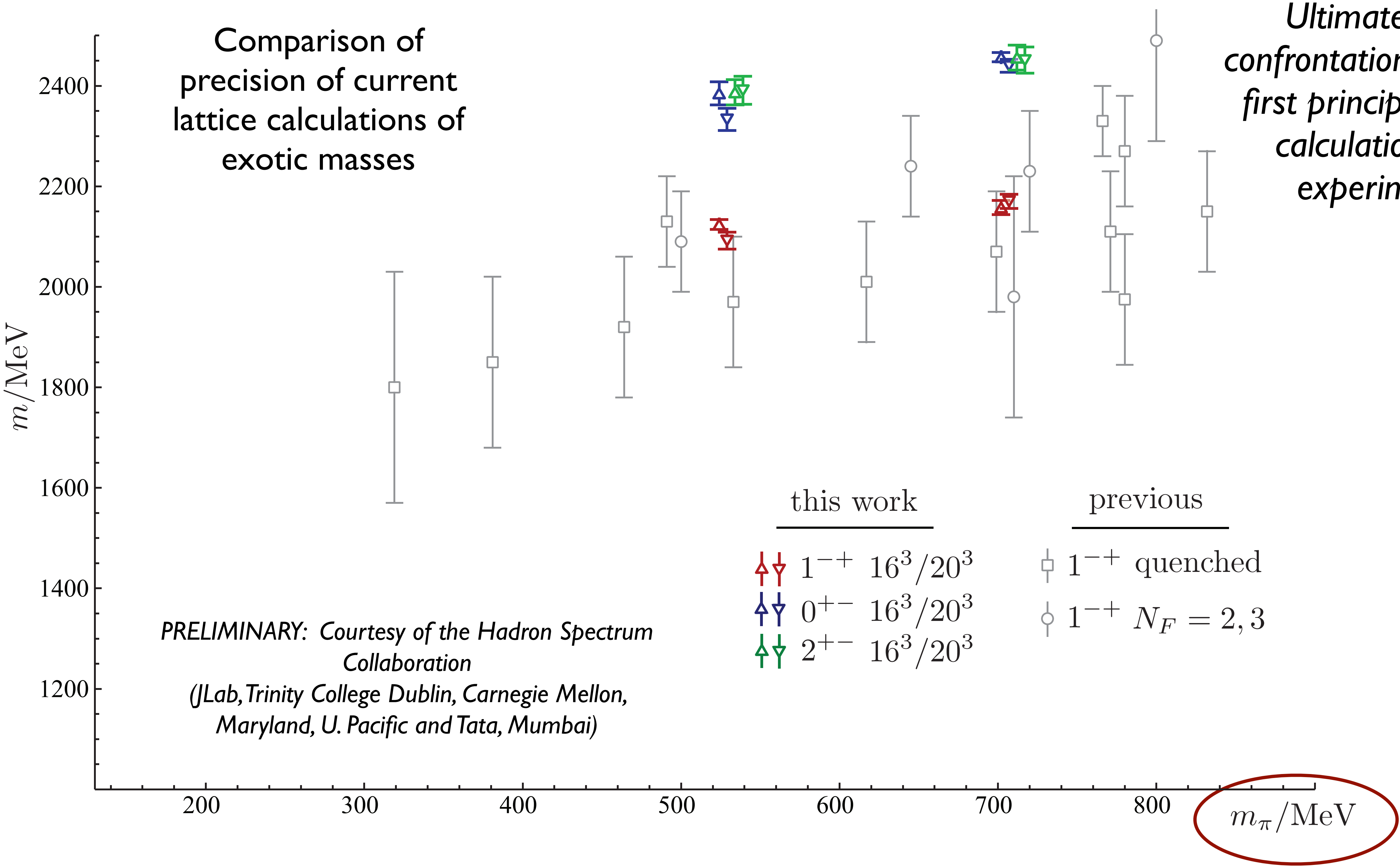
Dudek et al.
[The Hadron Spectrum Collaboration]
Phys.Rev.Lett.103:262001 (2009)

Exotic Masses from Lattice QCD

GlueX "Discovery Range"

Comparison of precision of current lattice calculations of exotic masses

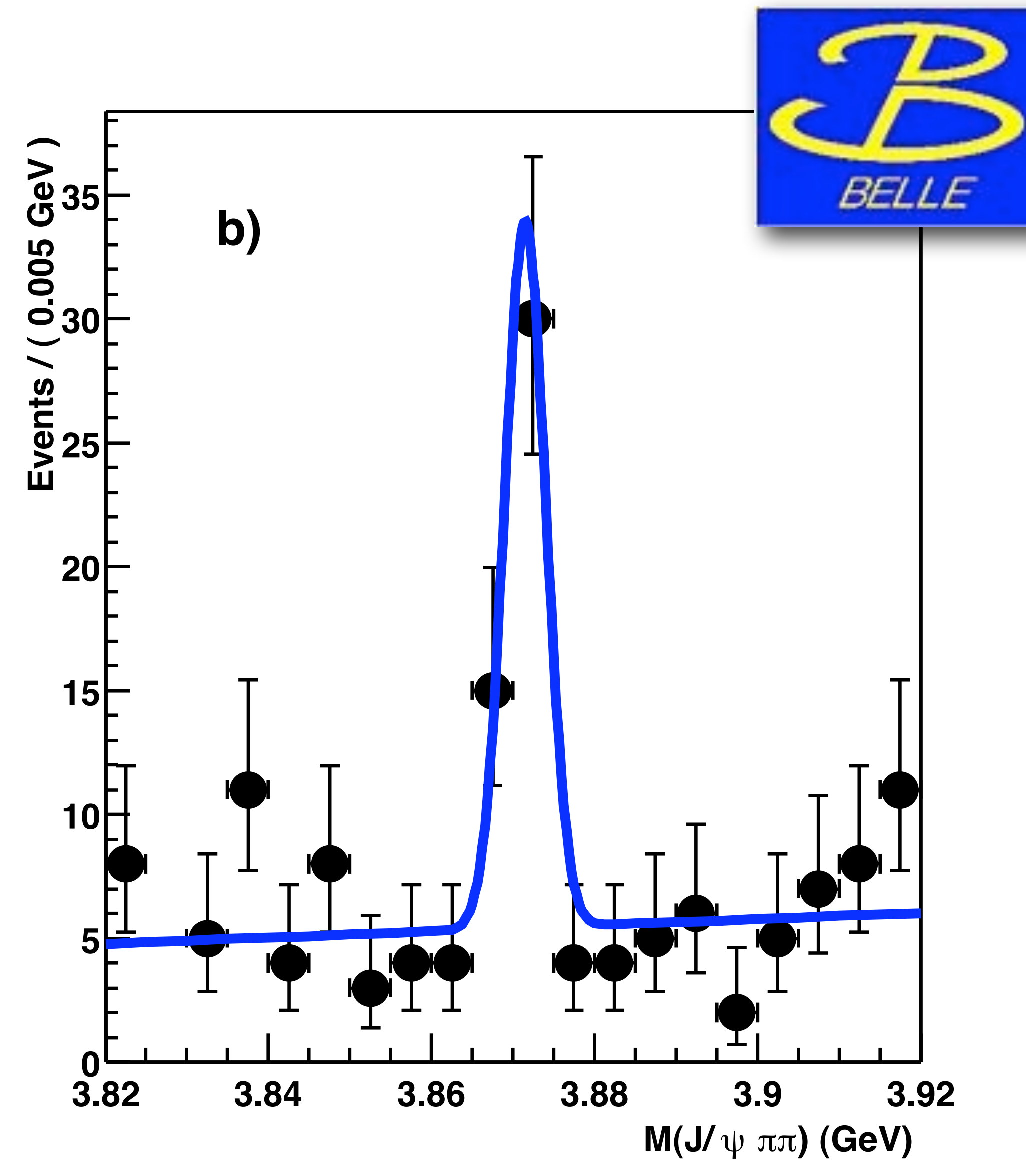
Ultimate goal: confrontation between first principles QCD calculation and experiment!



PRELIMINARY: Courtesy of the Hadron Spectrum Collaboration (JLab, Trinity College Dublin, Carnegie Mellon, Maryland, U. Pacific and Tata, Mumbai)

A Revolution in Charmonium Spectroscopy

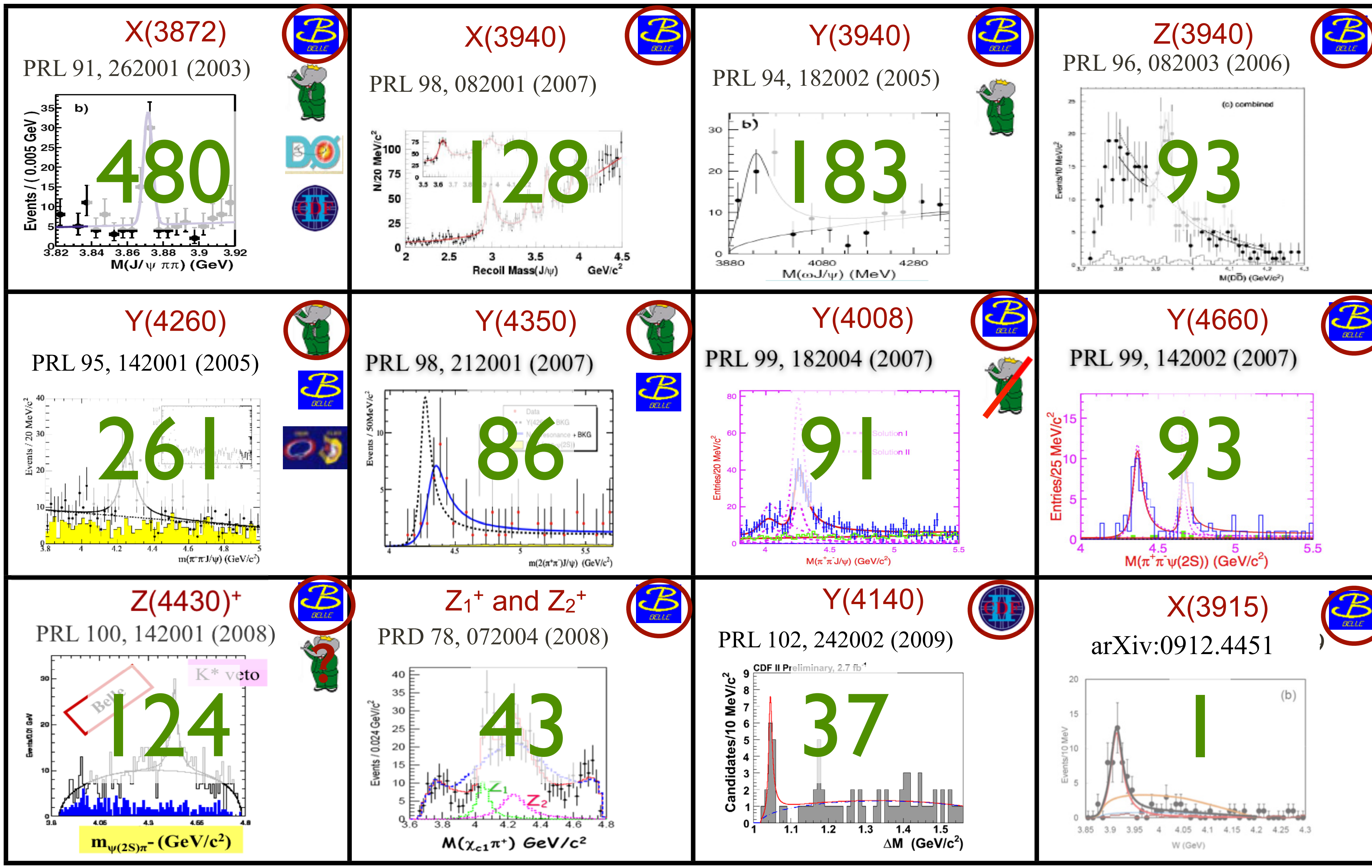
- In the past five years, over ten new states have been discovered in charmonium region.
- Driven by enormous data sets at *B* factories: Belle and BaBar
  - production in *B* meson decay
  - ISR production allows systematic exploration of vector states below 10 GeV
- Some results surprising: narrow resonances above $D\bar{D}$ threshold -- if conventional charmonium, expect OZI favored $\Gamma(X \to D\bar{D})$ to be large
- These have generated an incredible amount of excitement in the spectroscopy community



See Kam Seth's talk tomorrow!

PRL 91, 262001 (2003)

What is the nature of these states?
What are the implications for the light quark sector?

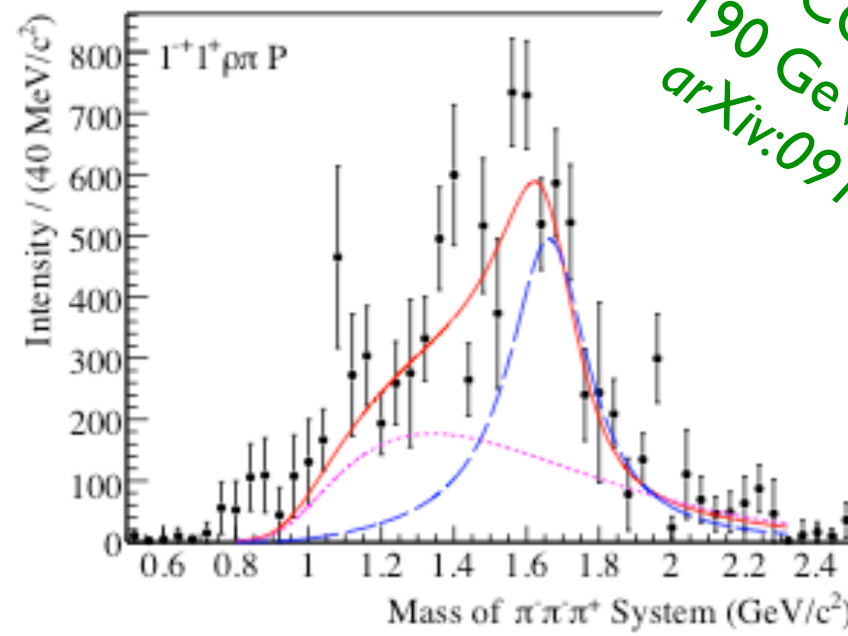


Citation count of initial "discovery papers" as of Feb. 8, 2010

scorecard format from:
G. Cibinetto (CIPANP 09)

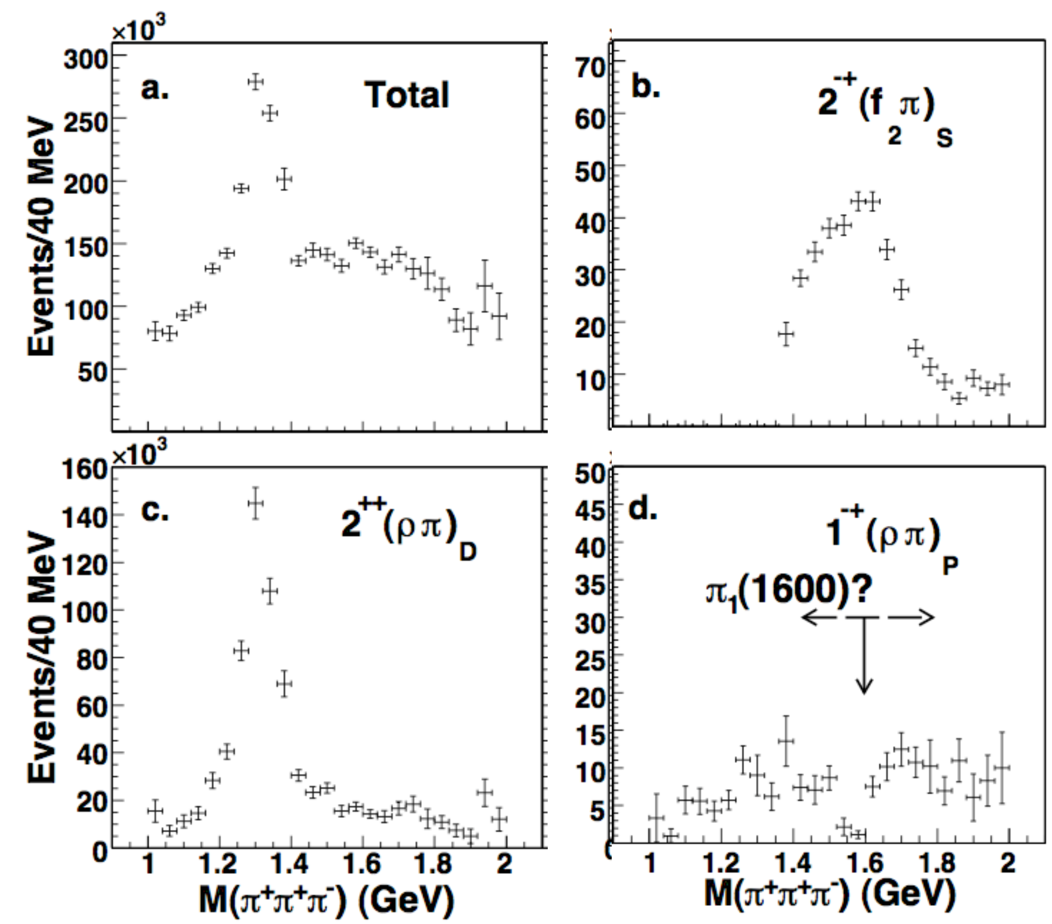
Interesting Progress in the Light Quark Sector

- Several candidates for the π_1 (1^{-+}) in the literature at 1400, 1600, and 2000 GeV -- some reported by multiple experiments
  - interpretation of data has received much discussion in community
- New high statistics data using pion beams at COMPASS
- We are also getting our first glimpses of photo-production from CLAS at 5 GeV



COMPASS
190 GeV π^- beam
arXiv:0910.5842

CLAS: $\gamma p \rightarrow \pi^+\pi^+\pi^- n$ at ~5 GeV
(PRL 102, 102002)



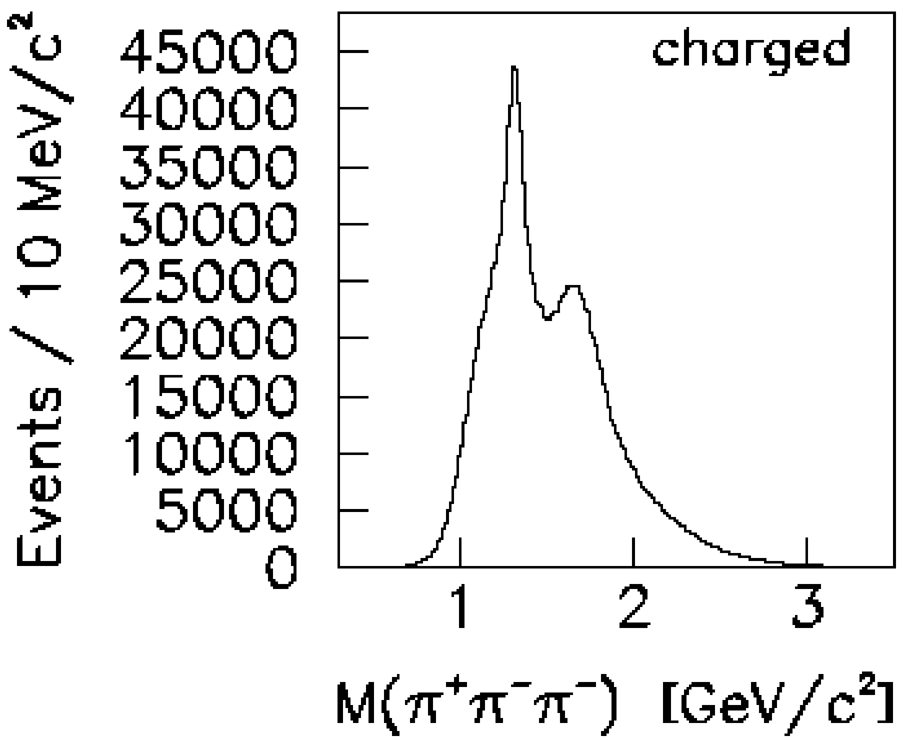
Analysis Techniques

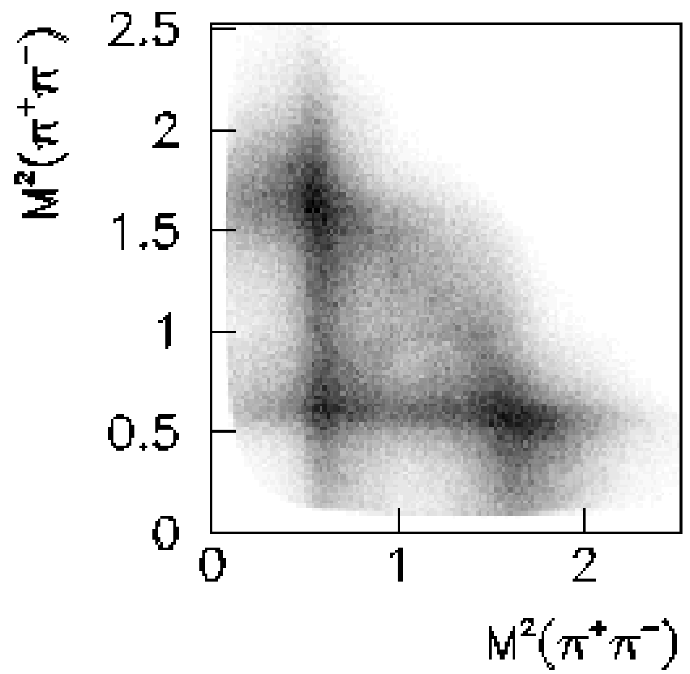
How to be certain we have correctly measured J^{PC}?

(computational challenges for the 21^{st} century)

Amplitude Analysis

- An illustrative example:
  $\pi^- p \to \pi^+\pi^-\pi^- p$ at 18 GeV/c
  from E852 at
  (PRD 73, 072001 (2006))
- E852 ran at 18 GeV/c π^- beam line at Brookhaven National Lab, detector provided both charged and neutral tracking
- Analysis includes well over 1M events
- How to separate various overlapping resonances?



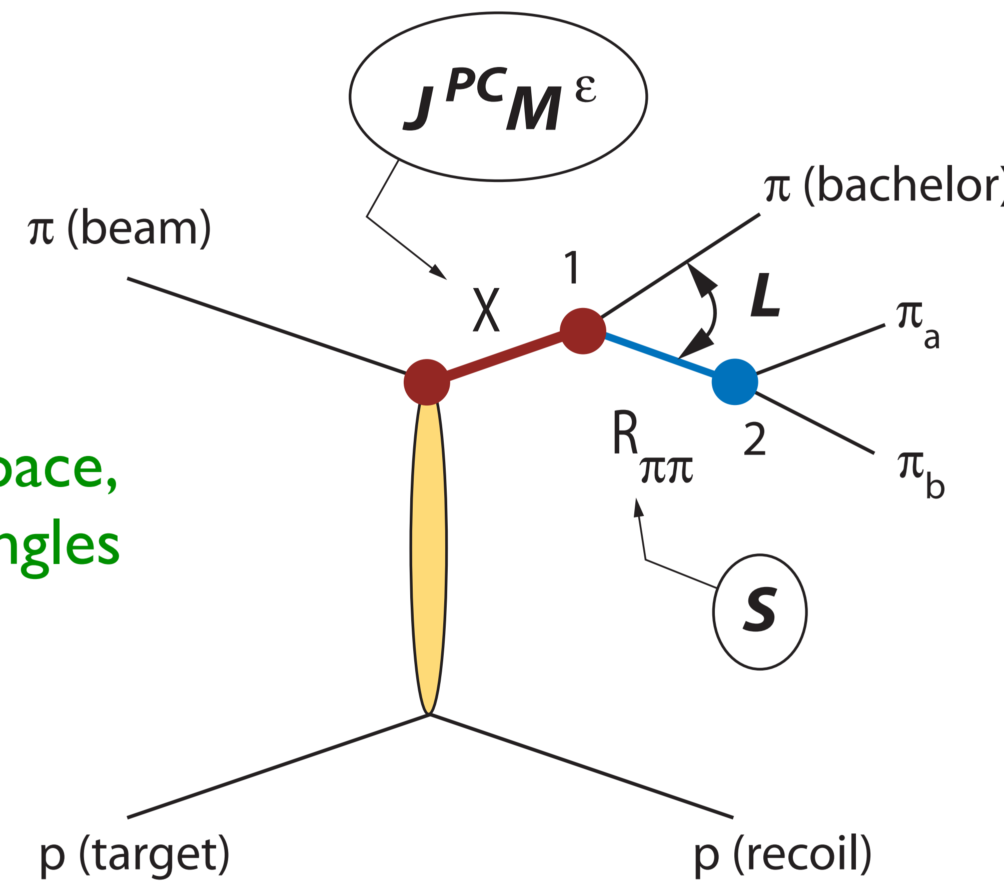


Dalitz plot shows clear f_2 and ρ

3π Amplitudes

Within the "Isobar Formalism"

- Write detector intensity as a coherent sum of products of production amplitude and decay amplitudes



$$I(\Omega) = \left| \sum_{\alpha} V_{\alpha} A_{\alpha}(\Omega) \right|^2$$

location in phase space, kinematics, decay angles

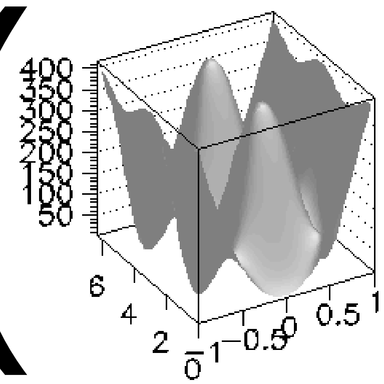
production amplitudes (fit parameters)

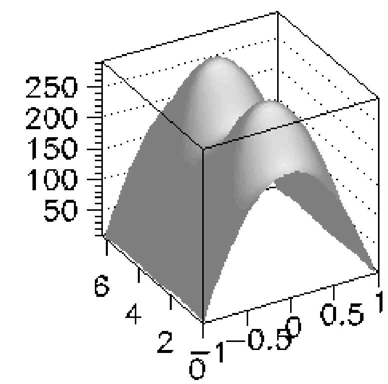
decay amplitudes "basis states" form depends on J^{PC}MLS of 3-body decay choose a complete set to describe the physics

More Pictorially

(Although Somewhat Incorrect)

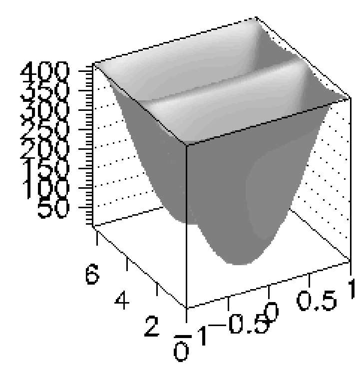
$2^{++}1^{+}\rho\pi(D)$

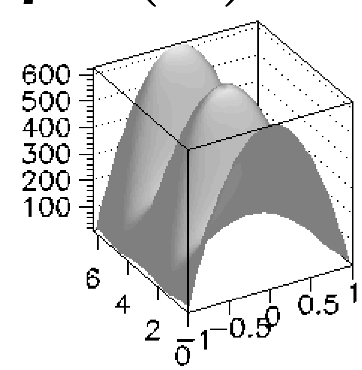
Detector Data $= \Big| V_1 \Big($ 



$\Big) +$

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

$V_2 \Big($ 



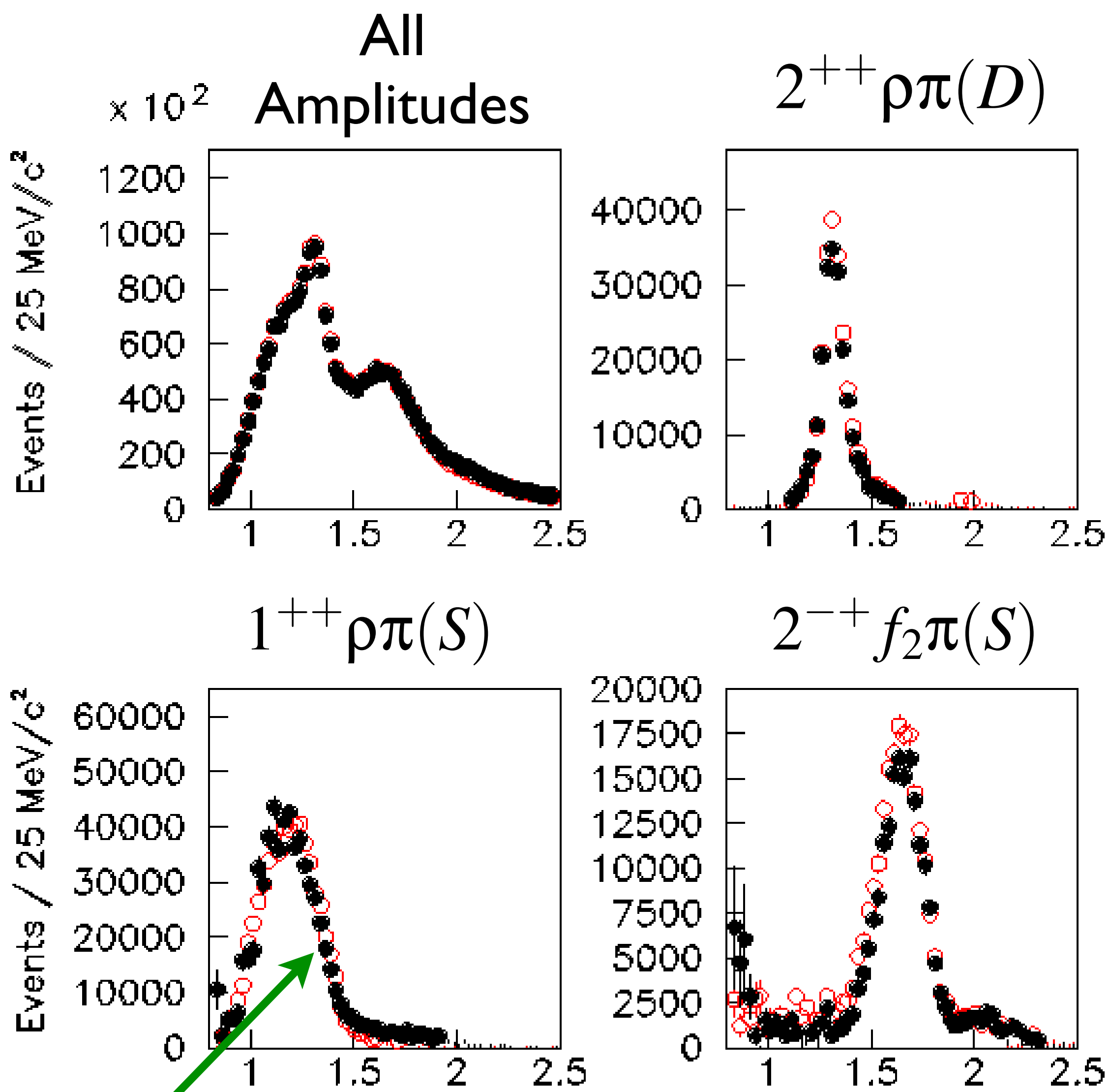
$\Big) +$

$\ldots \Big|^2$

Good angular acceptance critical for distinguishing amplitudes!

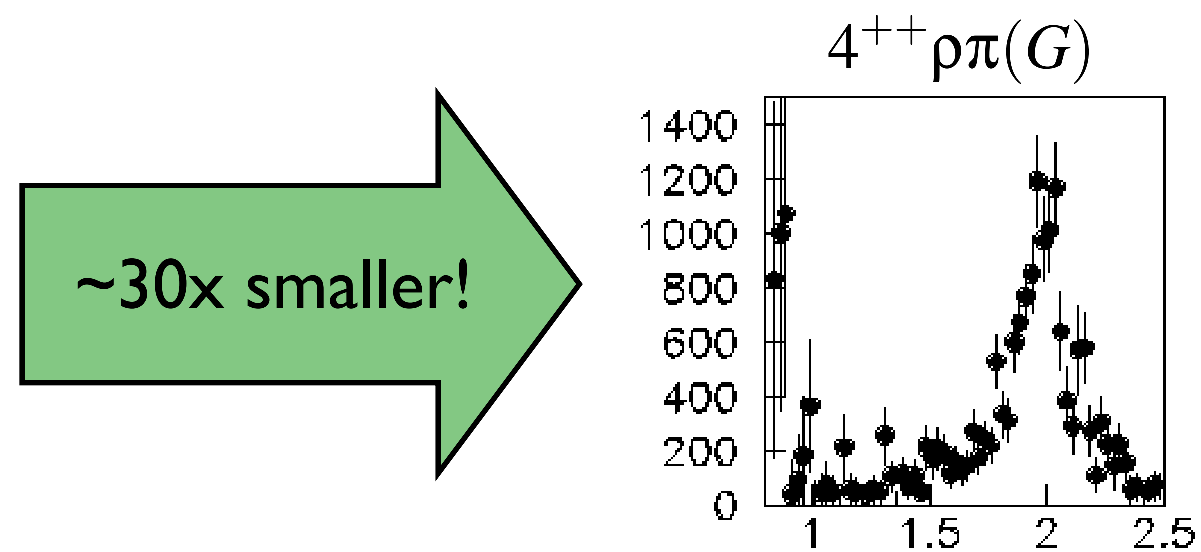
For 3 body processes, key angles are θ and Φ in the helicity frames of each isobar

The Power of Amplitude Analysis



each point:
$\int I(\Omega)d\Omega$

Dominant resonances
are clearly visible



- Amplitude Analysis allows sensitivity to much rarer processes
- Relative phases of amplitudes are measured by the fit -- valuable input to resonance interpretation
- Due to multi-dimensional character and complicated angular distributions, fit requires an unbinned maximum likelihood approach (computationally intensive)

The tool for searching for rare
states with unique quantum numbers!

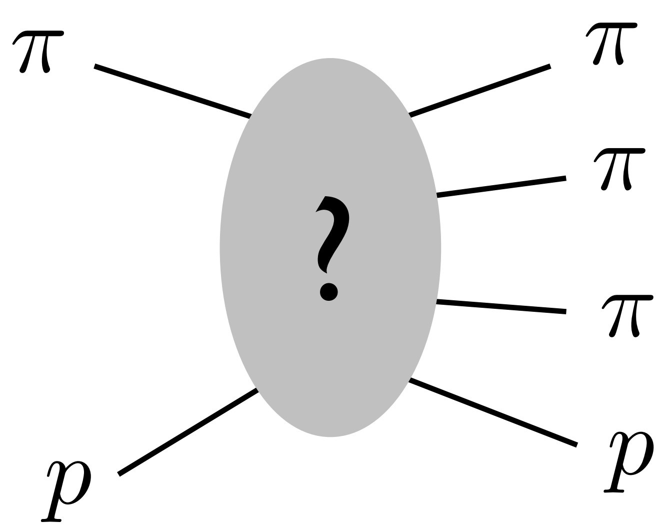
Fitting Challenges

Multi-Dimensional Probability Distribution Function = Detector Acceptance (evaluate with Monte Carlo integration) X Physics Model (Parameters to Interpret)

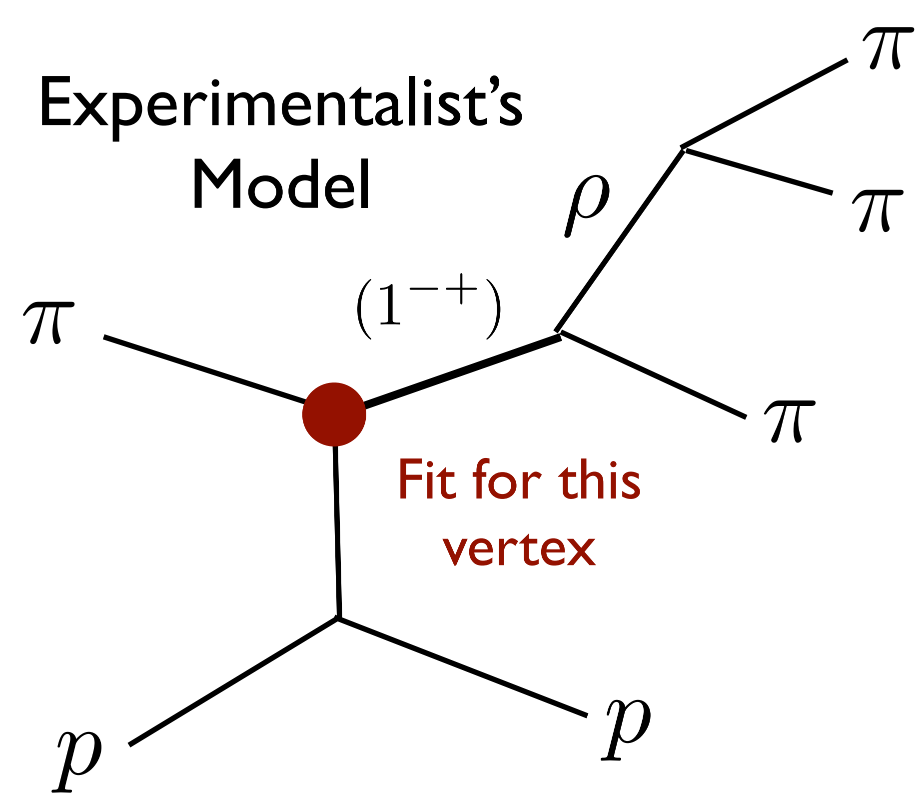
Evaluate this for every event and vary parameters to maximize likelihood

Huge computational expense -- especially for complicated models

Theorist's Reality



Experimentalist's Model



GlueX will collect tens of millions of events in some channels -- greatly enhanced computational ability is needed in order to fully explore the theoretical model space.

GPU (Graphics Processing Unit) Computing

120 x 1.6 GHz cores
60 GB RAM
25,000 Watts
$200,000

(20th century solution)

240 cores / multiple clocks (0.7 -1.5 GHz)
1 GB RAM
200 Watts
$400

(21st century solution)

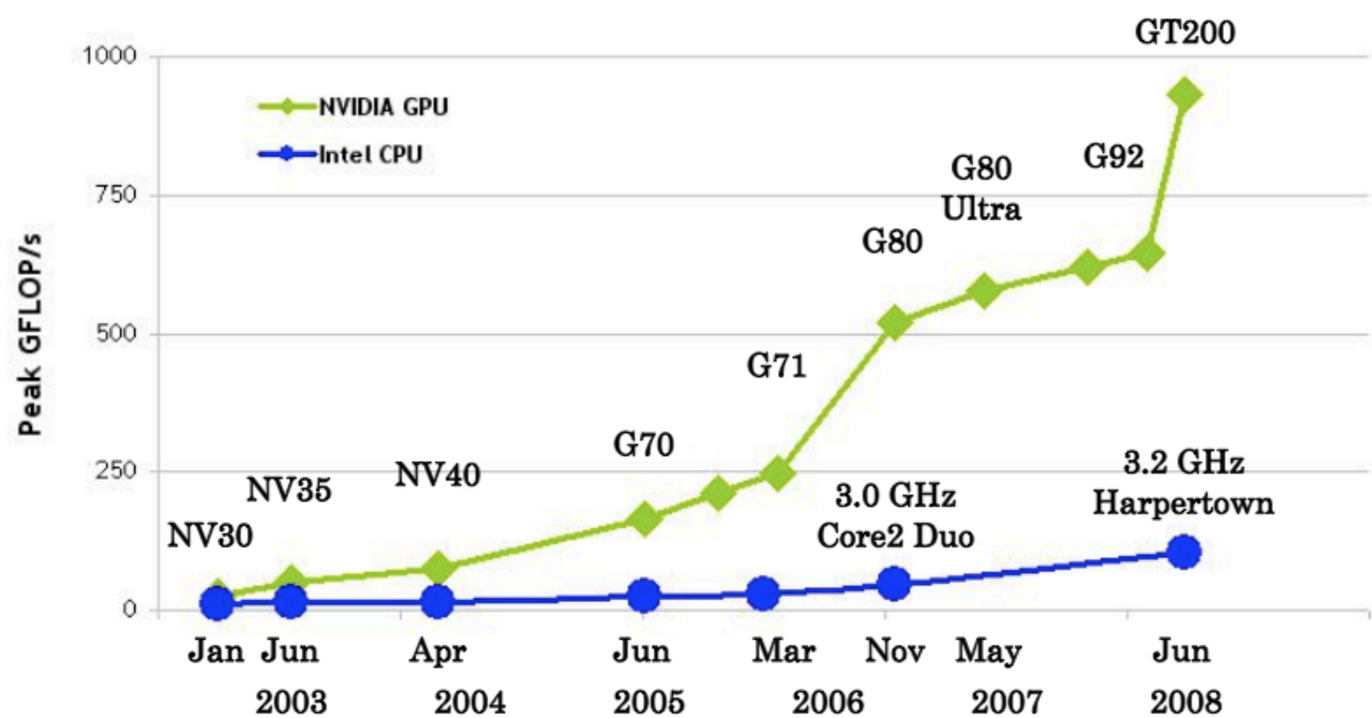
Advances in Analysis Technology

- Massively parallel architecture of GPU is ideal for likelihood fitting -- much more efficient than a cluster of parallel CPUs
- Key goal: enhance collaboration between theory and experiment by separating physics from computational and experimental details
- Develop (experiment independent) fitting algorithms capable of handling massive statistics and complicated theoretical models
    - parallelized fitting for multiple processors, machines
    - graphics hardware acceleration -- *potential for at least 1-2 orders of magnitude speed gain*
- Software is being prototyped now on data from CLEO-c and BES III experiments

Raw Amplitude Calculation

(preliminary benchmarks)

Sample	CPU Intel Core i7 (1 core)	GPU nVidia GTX 285 (240 cores)
8M evts.; 3 Amps	48 s	0.29 s
8M evts.; 1 Amp	16 s	0.10 s



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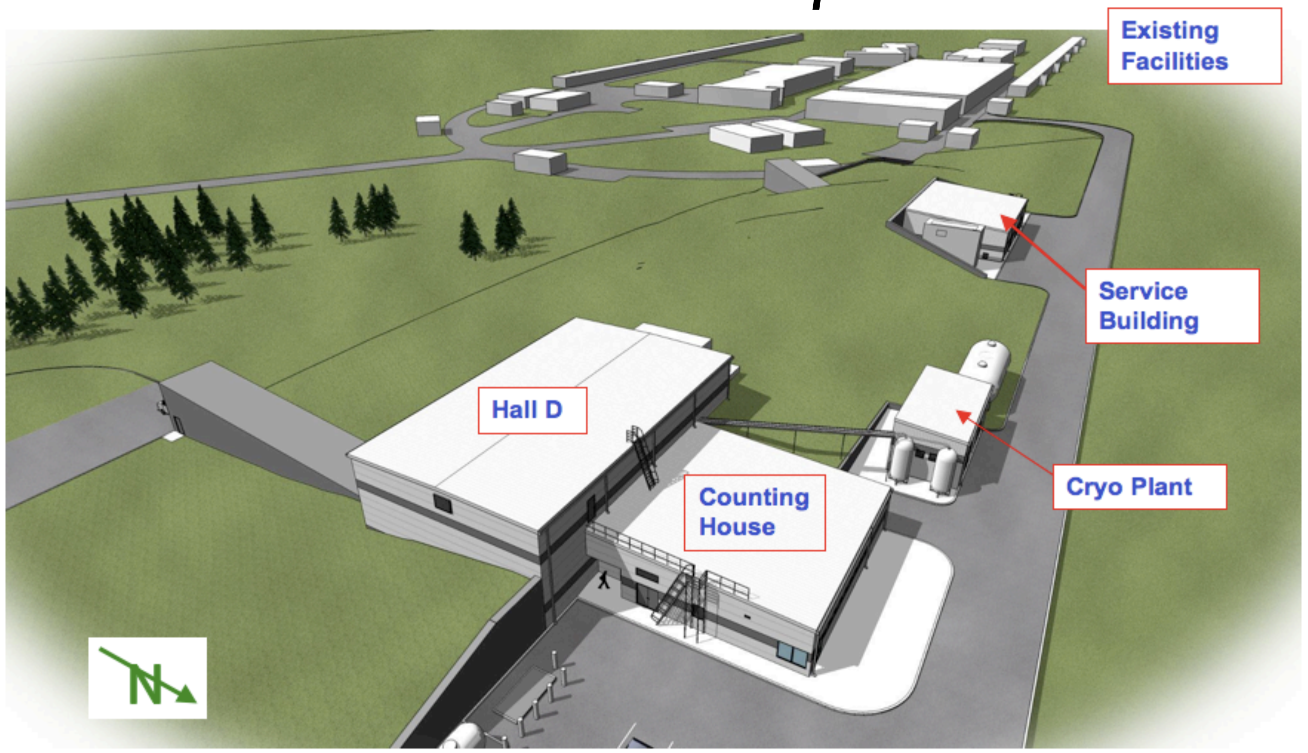
The Present Status of Hall D and GlueX

Construction is Underway!

- Groundbreaking for the new experimental Hall D was last April
- Construction of detector components has begun at collaborating universities
  - we have ordered 2,000 miles of scintillating fiber for GlueX barrel calorimeter and construction has started (This is the first new detector of JLab 12 GeV upgrade.)
  - central drift chamber and forward calorimeter construction to start in 1-2 months
- Plan to start putting detectors on the floor in Hall D around 2012
- On track for first beam around 2014

The Hall D Complex



BCAL Fabrication at the University of Regina, Saskatchewan

- Civil construction of Hall D is ongoing.
- The concrete foundation for the hall was completed about two weeks ago.

Hall D Construction Live View

mms://jlabvid.jlab.org/HallDConstruction

Summary

- Hall D and GlueX will offer a unique opportunity to explore the spectrum of mesons and search for exotic hybrid mesons.
- There have been many recent developments in both theory and experiment that have renewed excitement in meson spectroscopy as a experimental test of QCD.
- Construction is underway -- we hope to be analyzing data in 5 years!
- *The study of strong interactions is off to an exciting start in the 21st century.*

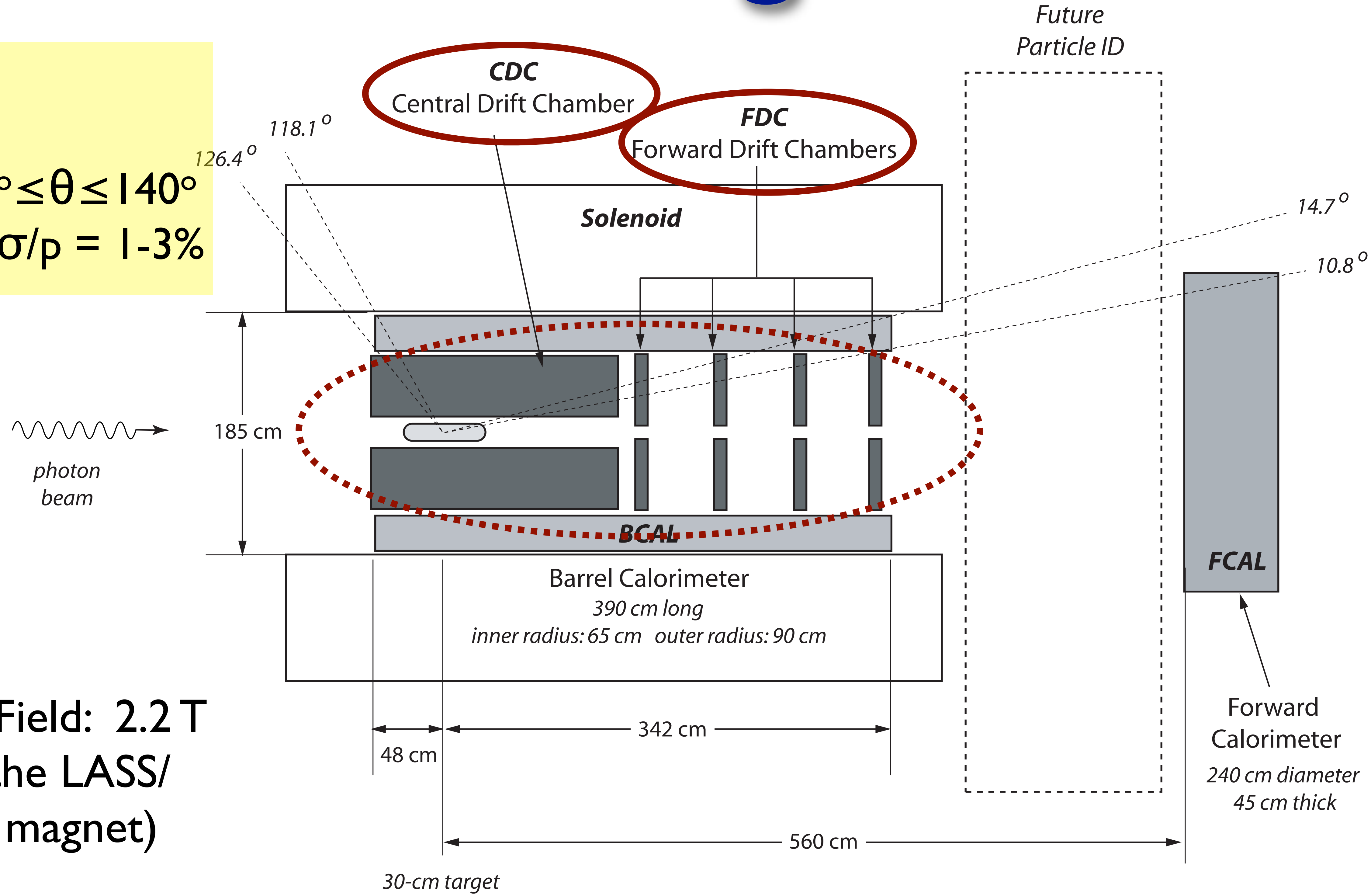
www.gluex.org

Detector Slides

Tracking

Goals

coverage: $1° \leq \theta \leq 140°$
resolution: σ/p = 1-3%



Solenoid Field: 2.2 T
(reuse the LASS/
MEGA magnet)

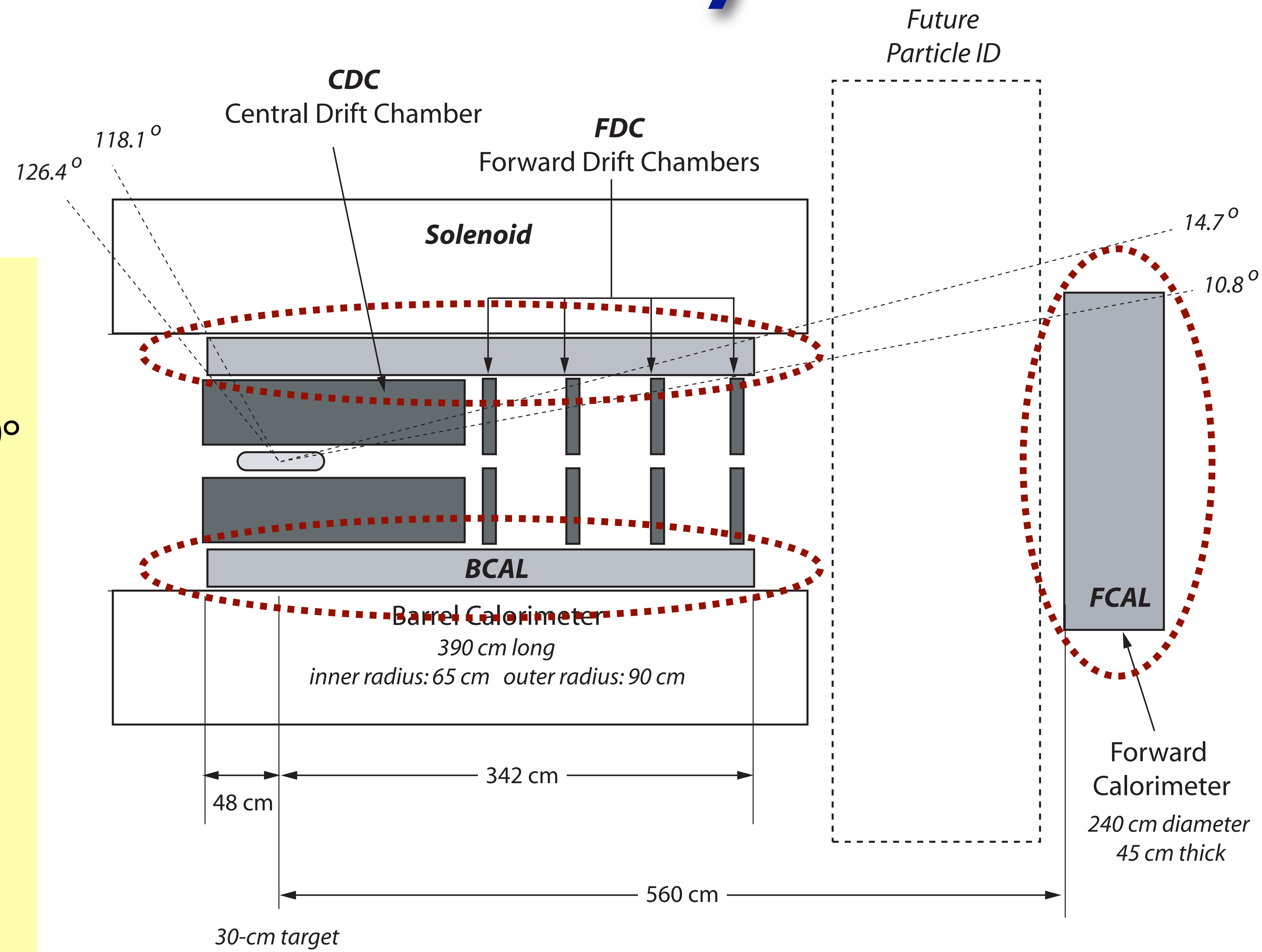
Calorimetry

Goals

coverage: $2° \leq \theta \leq 120°$

average approximate resolution:
$\sigma/E = 6\%/\sqrt{E} + 2\%$

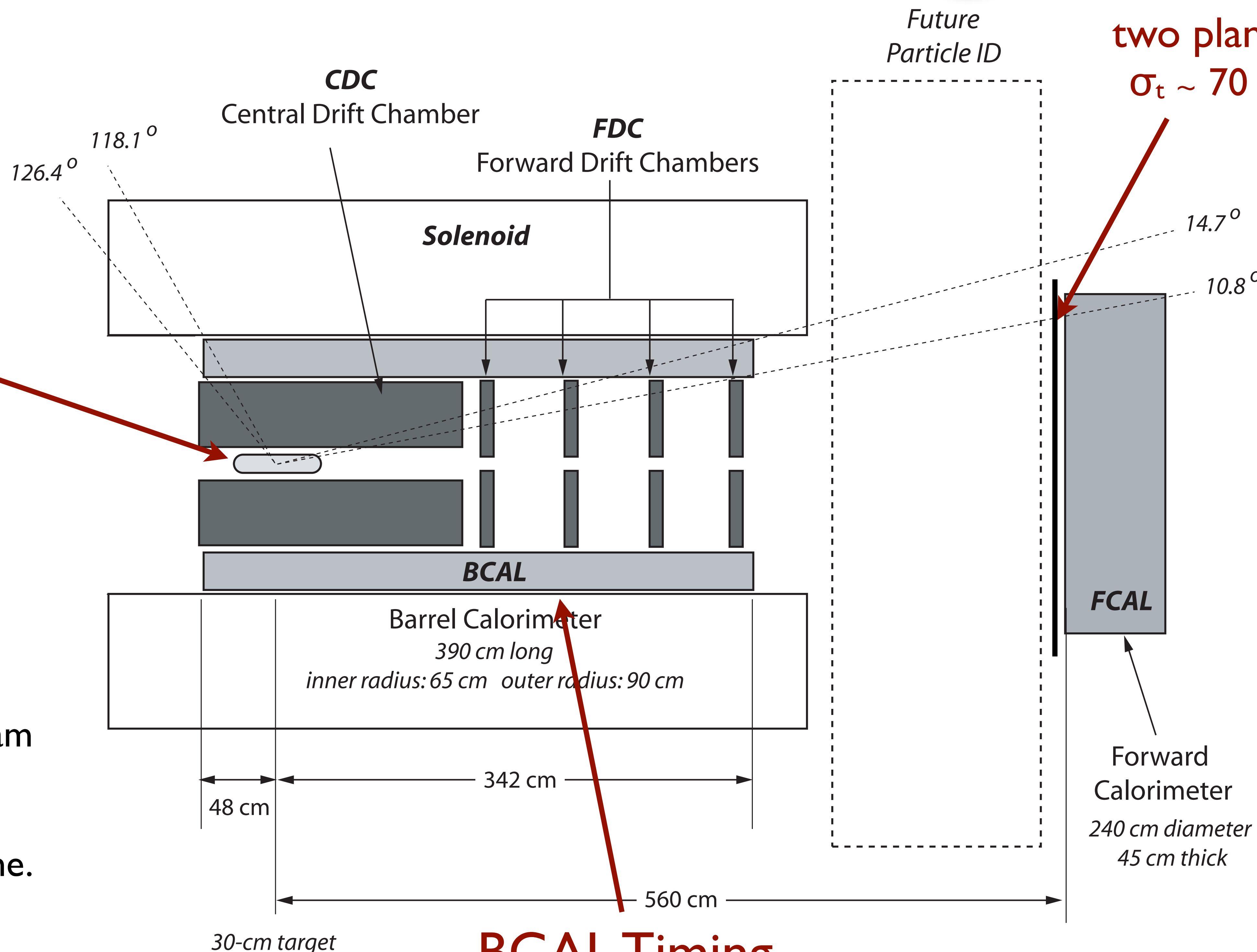
low energy threshold:
forward: 80 MeV
barrel: 30 MeV



Particle ID/Timing

Start Counter
segmented scintillator around target
$\sigma_t \sim 250$ ps

TOF Wall
scintillator, two planes,
$\sigma_t \sim 70$ ps



BCAL Timing

We need to identify beam bunch to select the correct tagger hit and determine the event time.