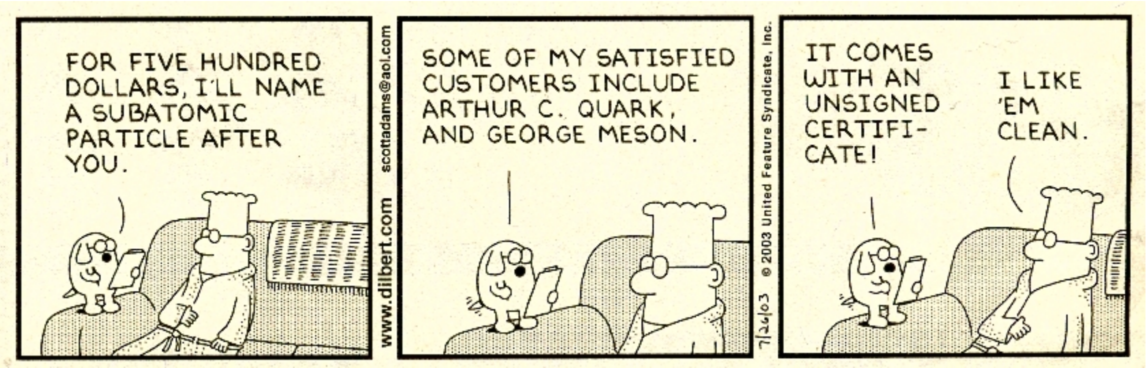
Spectroscopy



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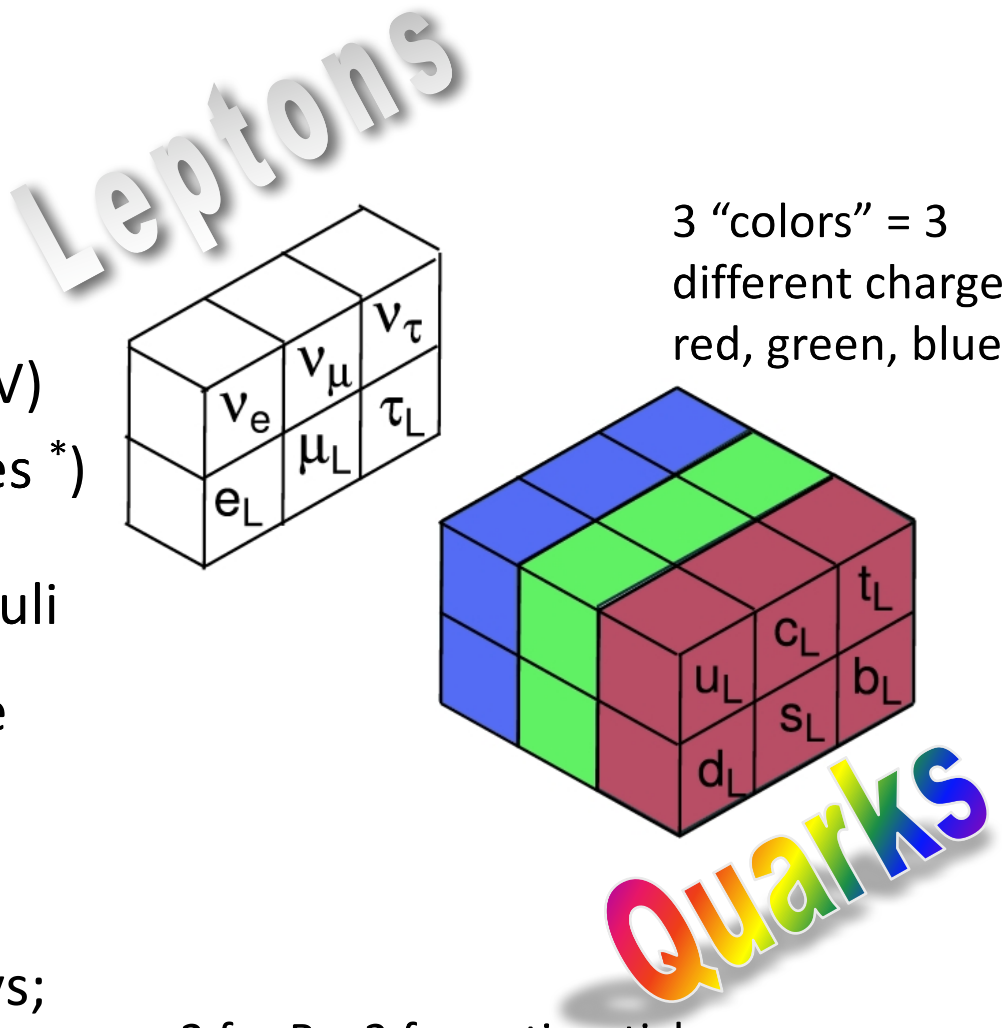
Matter Particles

- Make up visible matter
- Pointlike ($<10^{-18}$ m), Fundamental *)
- Have mass (from < ½ eV to 178,000,000,000 eV = 178 GeV)
- Distinct from their antiparticles *)
- Fermions (Spin ½) ⇒ they "defend" their space (Pauli Principle) and can only be created in particle-antiparticle pairs
- Can be "virtual", but make up matter being (nearly) "real"
- "stable" (against strong decays; lifetimes from ∞ to 10^{-24} s)



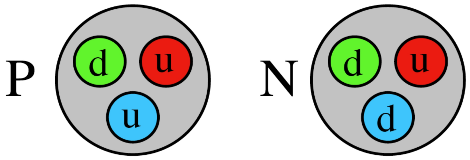
3 "colors" = 3 different charges: red, green, blue

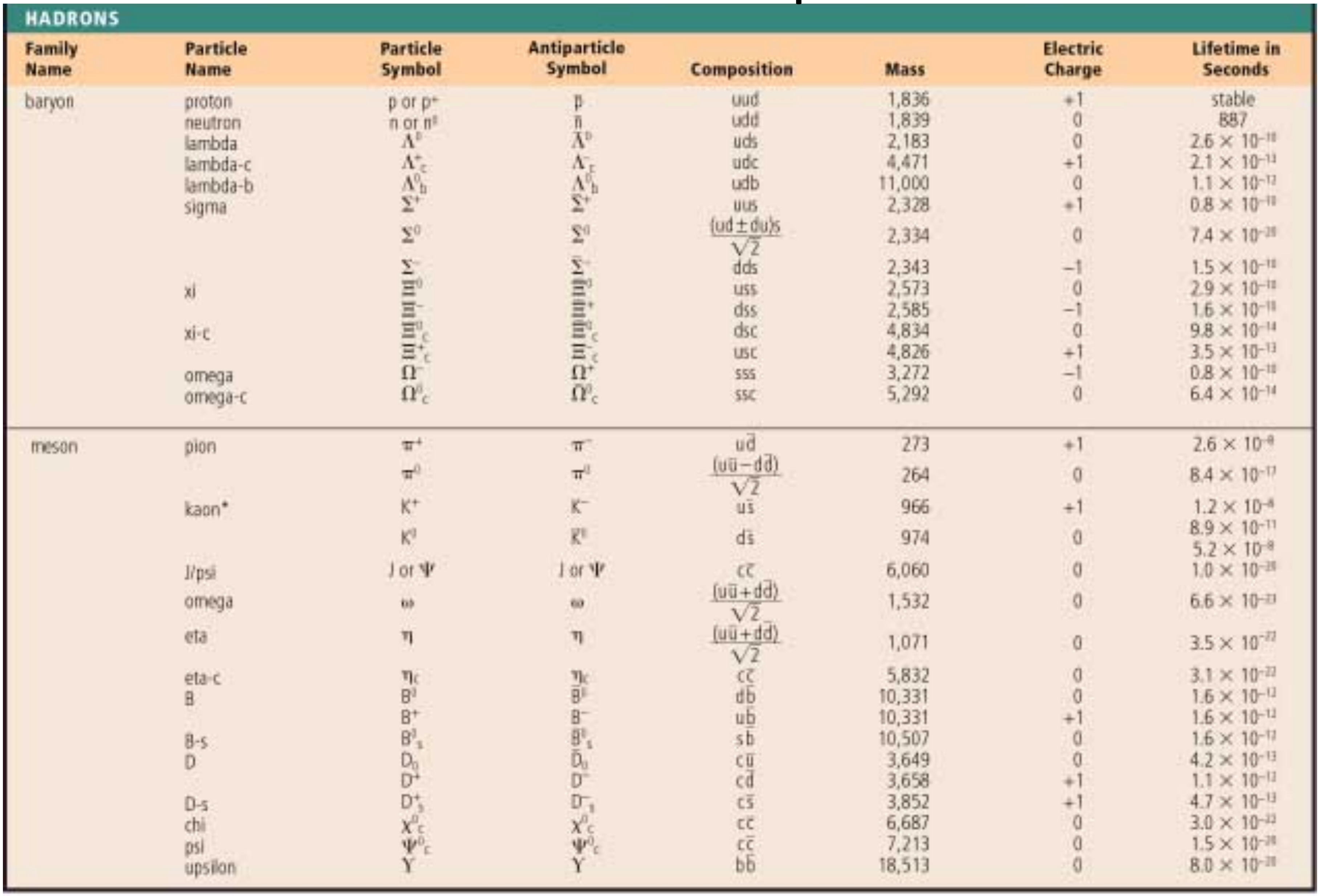
x2 for R, x2 for antiparticles

*) Until further notice

Hadronic Particle Zoo

- what can one build from quarks?





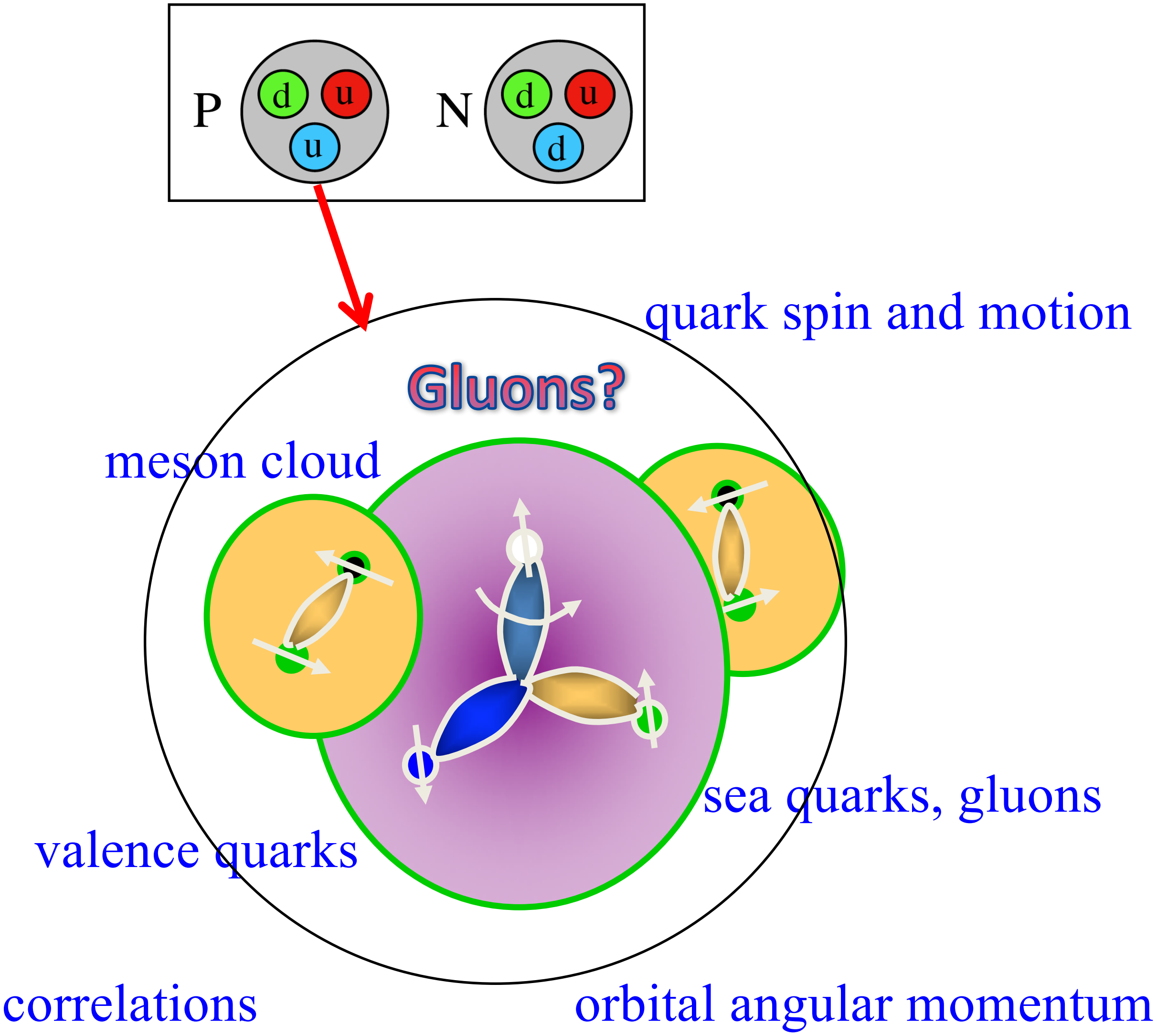
HADRONS

Family Name	Particle Name	Particle Symbol	Antiparticle Symbol	Composition	Mass	Electric Charge	Lifetime in Seconds
baryon	proton	p or p^+	$\bar{p}$	uud	1,836	+1	stable
	neutron	n or n^0	$\bar{n}$	udd	1,839	0	887
	lambda	Λ^0	$\bar{\Lambda}^0$	uds	2,183	0	2.6×10^{-10}
	lambda-c	Λ^+_c	$\bar{\Lambda}^-_c$	udc	4,471	+1	2.1×10^{-13}
	lambda-b	Λ^0_b	$\bar{\Lambda}^0_b$	udb	11,000	0	1.1×10^{-12}
	sigma	Σ^+	$\bar{\Sigma}^+$	uus	2,328	+1	0.8×10^{-10}
		Σ^0	$\bar{\Sigma}^0$	$\frac{(ud \pm du)s}{\sqrt{2}}$	2,334	0	7.4×10^{-20}
		Σ^-	$\bar{\Sigma}^-$	dds	2,343	−1	1.5×10^{-10}
	xi	Ξ^0	$\bar{\Xi}^0$	uss	2,573	0	2.9×10^{-10}
		Ξ^-	$\bar{\Xi}^+$	dss	2,585	−1	1.6×10^{-10}
	xi-c	Ξ^0_c	$\bar{\Xi}^0_c$	dsc	4,834	0	9.8×10^{-14}
		Ξ^+_c	$\bar{\Xi}^-_c$	usc	4,826	+1	3.5×10^{-13}
	omega	Ω^-	$\bar{\Omega}^+$	sss	3,272	−1	0.8×10^{-10}
	omega-c	Ω^0_c	$\bar{\Omega}^0_c$	ssc	5,292	0	6.4×10^{-14}
meson	pion	π^+	π^-	$u\bar{d}$	273	+1	2.6×10^{-8}
		π^0	π^0	$\frac{(u\bar{u} - d\bar{d})}{\sqrt{2}}$	264	0	8.4×10^{-17}
	kaon*	K^+	K^-	$u\bar{s}$	966	+1	1.2×10^{-8}
		K^0	$\bar{K}^0$	$d\bar{s}$	974	0	8.9×10^{-11} 5.2×10^{-8}
	J/psi	J or Ψ	J or Ψ	$c\bar{c}$	6,060	0	1.0×10^{-20}
	omega	ω	ω	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,532	0	6.6×10^{-23}
	eta	η	η	$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$	1,071	0	3.5×10^{-22}
	eta-c	η_c	η_c	$c\bar{c}$	5,832	0	3.1×10^{-22}
	B	B^0	$\bar{B}^0$	$d\bar{b}$	10,331	0	1.6×10^{-12}
		B^+	B^-	$u\bar{b}$	10,331	+1	1.6×10^{-12}
	B-s	B^0_s	$\bar{B}^0_s$	$s\bar{b}$	10,507	0	1.6×10^{-12}
	D	D_0	$\bar{D}_0$	$c\bar{u}$	3,649	0	4.2×10^{-13}
		D^+	D^-	$c\bar{d}$	3,658	+1	1.1×10^{-12}
	D-s	D^+_s	D^-_s	$c\bar{s}$	3,852	+1	4.7×10^{-13}
	chi	χ^0_c	χ^0_c	$c\bar{c}$	6,687	0	3.0×10^{-23}
	psi	Ψ^0_c	Ψ^0_c	$c\bar{c}$	7,213	0	1.5×10^{-20}
	upsilon	Υ	Υ	$b\bar{b}$	18,513	0	8.0×10^{-20}

*The neutral kaon is composed of two particles; the average lifetime of each particle is given.

Hadron Structure

- Simple-most (constituent quark) model of nucleons (protons and neutrons)
- … becomes much more complicated once we consider the full relativistic quantum field theory called QCD



quark spin and motion

Gluons?

meson cloud

sea quarks, gluons

valence quarks

correlations

orbital angular momentum

How Do We Study Hadron/Nuclear Structure?

- Energy levels: Nuclear and particle (baryon, meson) masses, excitation spectra, excited state decays -> Spectroscopy
  (What states exist?)
- Elastic and inelastic scattering, particle production, Reactions
  (*How do they interact?*)
- Probing the internal structure directly
  Imaging, “Tomography” and “Holography”
  (*Shape and Content?*)

Open Questions:

- What excited states of the nucleon have we missed so far?
- Excited strange baryons?
- ”Exotic” States:
  - $qq\bar{q}\bar{q}$
  - $qqqq\bar{q}$
  - qqG
  - qqqG
  - GG

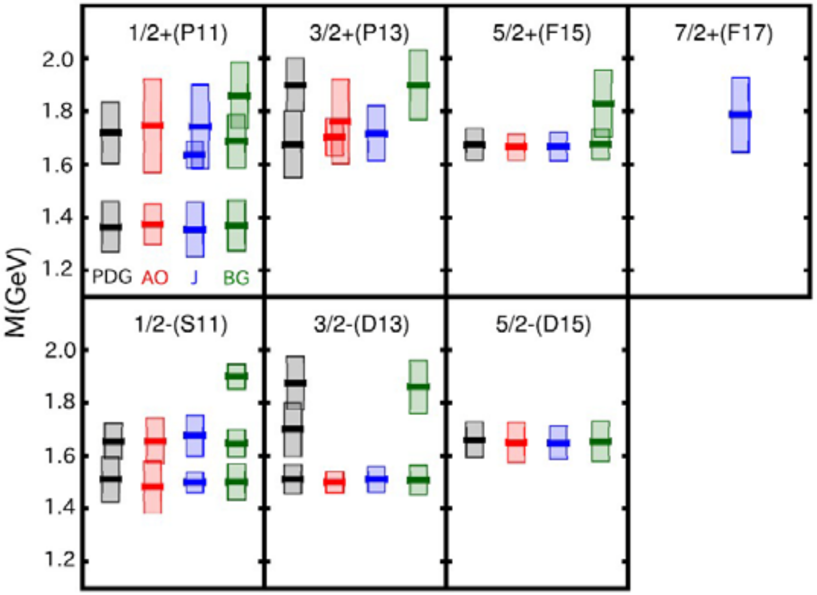


Figure 15 – Three- and four-star nucleon resonance masses as listed by the Particle Data Group[128] and as extracted in three separate analyses: Argonne-Osaka,[190] Jülich[191] and Bonn-Gatchina.[189] For each resonance, Re(M_R) together with the Re(M_R) ± Im(M_R) band is plotted. The four values only agree well in the low-mass region. At higher masses, the differences are large, an outcome that can mainly be attributed to the fact that the available πN and γN data for $W \geq 1.7$-GeV reactions are insufficient to determine the partial-wave-amplitudes model independently. Naturally, differences in the analysis methods and the data included in each analysis could also lead to disagreements.

⇒ Our 1D View of the Nucleon

(depends on energy ν and wave length of the virtual photon ~ 1/Q^2)

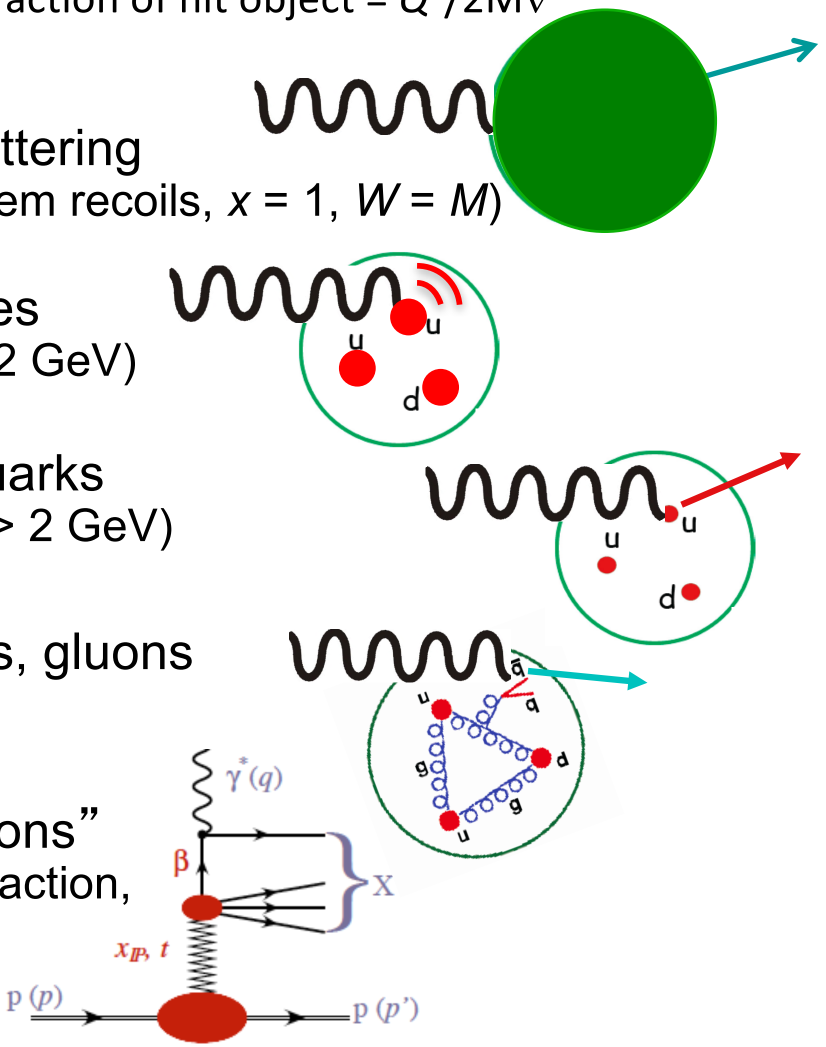
W = final state invariant mass = $\sqrt{M^2+2M\nu-Q^2}$

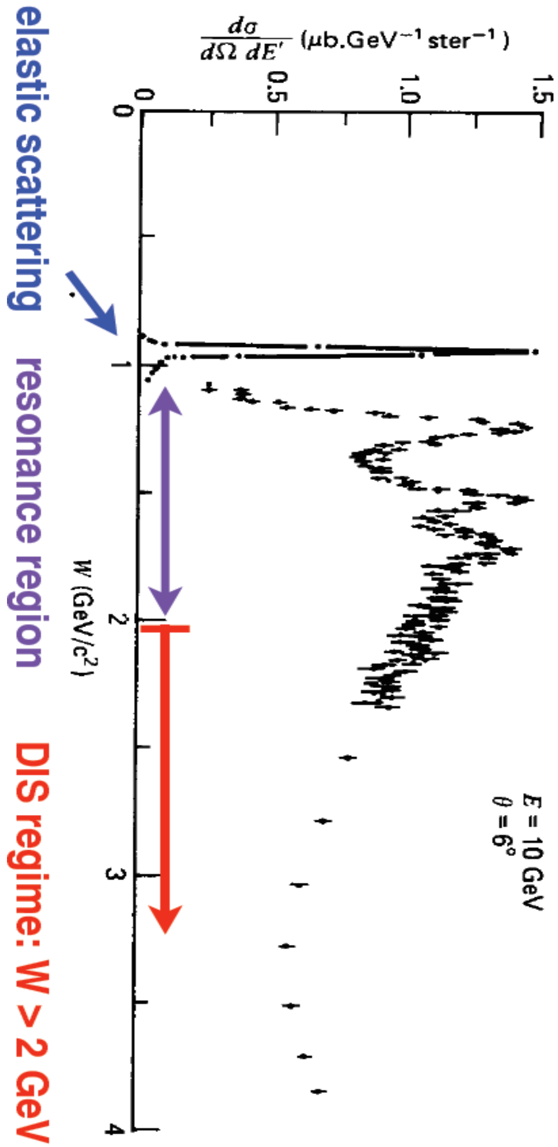
x = energy fraction of hit object = $Q^2/2M\nu$

JLab

DIS

- Elastic scattering
  (Whole system recoils, x = 1, W = M)
- Resonances
  (x < 1, W < 2 GeV)
- Valence quarks
  (x ≥ 0.3, W > 2 GeV)
- Sea quarks, gluons
  (x < 0.3)
- "Wee Partons"
  ($x \to 0$, Diffraction, Pomerons)





From “The Science and Experimental Equipment for The 12 GeV Upgrade of CEBAF” (2005)

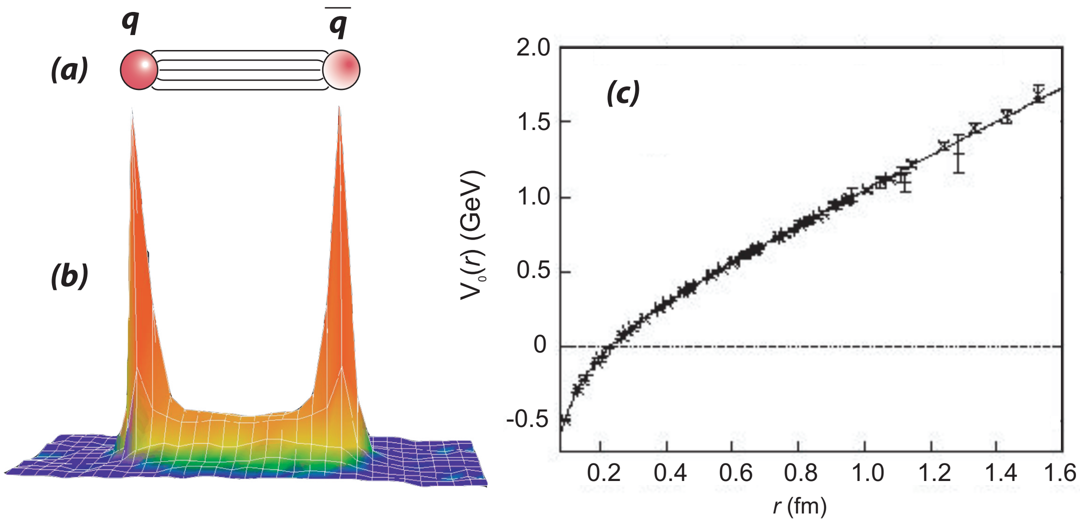


Figure 1: (a) The flux of chromo-electric field lines between a quark (q) and anti-quark ($\bar{q}$) is confined to a flux-tube; (b) LQCD prediction (from G. Bali) of the action density in the color field in the space surrounding a q and $\bar{q}$ showing the energy density peaking at the position of the quarks and confined to a flux tube between the quarks; (c) The corresponding potential (also from Bali) between the q and $\bar{q}$ as a function of separation r. For large r the potential is linear while for small r it is Coulombic. The LQCD calculation by Bali is for heavy quarks in the quenched approximation. Recent unquenched calculations reach the same conclusions.

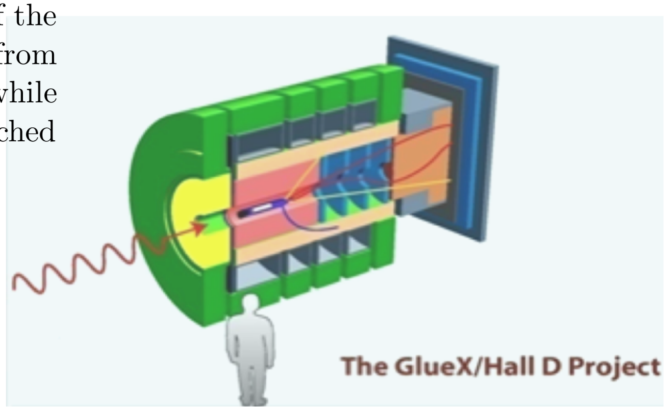
qq mesons:

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

$\vec{J} = \vec{L} + \vec{S}$, $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

Exotic Mesons:

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



Sidebar 2.1: Solving the Structure of Hadrons and Light Nuclei with Lattice QCD

The building blocks of nuclei, protons and neutrons, are comprised of quarks and gluons. Quantum chromodynamics (QCD), the theory describing the interactions of quarks and gluons, is well known, and its equations can be written down in an elegant manner. QCD has had tremendous successes, for example, it allows direct comparisons of its predictions with experiments at high energies, where "deep inelastic scattering experiments" have beautifully revealed the quark and gluon substructure of protons, neutrons, and nuclei. However, precise descriptions of many low-energy properties of even the simplest systems, such as protons and neutrons, have remained elusive. A top priority of nuclear physics has been to develop first-principles predictive capabilities for low-energy processes described by QCD.

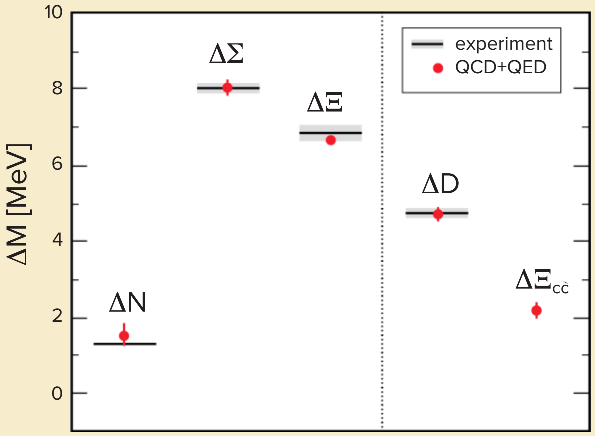


Figure 1: *Shown are the mass differences between "isospin pairs" of baryons, such as a proton and a neutron (ΔN), and other unstable isospin pairs. Experimental values (gray bands) are compared with LQCD, including electromagnetic effects (red points). It is remarkable that differences in these baryon masses at the level of one part in a thousand can now be precisely calculated from first principles.*

To achieve predictive capability, a numerical technique to perform QCD calculations has been developed: lattice QCD (LQCD). LQCD combines breathtaking advances in high-performance computing, innovative algorithm and software development, and conceptual breakthroughs in nuclear theory. In LQCD, space and time are described as points on a grid. Quarks and gluons are also defined on this grid, and their interactions with one another can be calculated numerically. Next, a widely used set of approaches to computer simulations, known as Monte Carlo methods, is employed. Basically, a large number of computer-generated configurations of the quantum fields are created and analyzed, and out of this process the true behavior of the quarks and gluons emerges. In principle, any level of accuracy can be obtained, limited only by computational resources and available work force.

The progress in LQCD calculations since the 2007 Long Range Plan has been dramatic. For the first time, calculations are being performed using the physical quark masses rather than the artificially increased masses that were needed previously. The effects of electromagnetism are being included as well. In Figure 1, the impressive agreement of calculated and measured mass differences between isospin partners amongst the hadrons confirms that QCD provides an accurate description of strongly interacting matter.

Underscoring this huge progress, LQCD plays an essential role in guiding experimental work. GlueX at JLab, one of the flagship experiments of the 12-GeV Upgrade, is designed to search for exotic particles where the "glue" is in an energetically excited state. Initial LQCD calculations motivated the experiment and guided its design. Recent LQCD results confirm the mass range of the predicted particles. And in the future, LQCD calculations of hadron dynamics will play a critical role in the analysis of the data.

Tremendous progress has been made in the calculation of hadron-hadron scattering probabilities. Phase shifts and mixings describing the low-energy scattering behavior have been successfully calculated for elastic pion-pion scattering, including mapping out the shape of the rho resonance, and, recently, for multi-channel scattering. The mixing is highlighted in the extraction of resonance information in pion-kaon scattering when the inelastic eta-kaon channel also contributes. These studies illustrate the practicality of extracting physical scattering (S-matrix) elements from LQCD and have opened a whole new era of lattice computations of hadron dynamics.

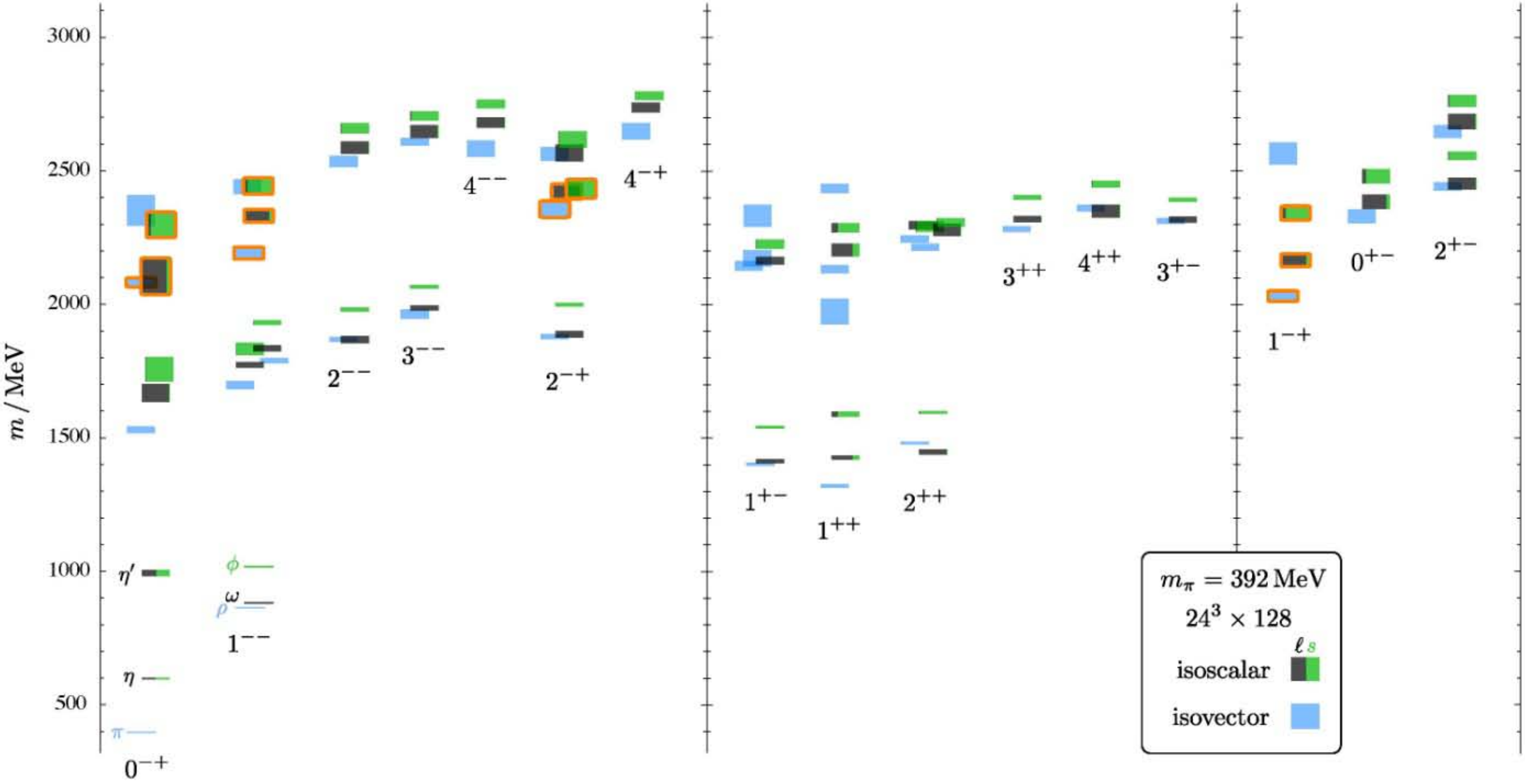


Figure 2 – Isoscalar (green and black) and isovector (blue) meson spectrum obtained with $m_\pi \sim 400$ MeV in a numerical simulation of lattice-regularized QCD. The vertical height of each box indicates the statistical uncertainty on the mass determination. Orange boxes are used to highlight the lowest-lying hybrid states, based on their gluonic field content; and the three rightmost towers of states carry exotic quantum numbers.

Resonance Hunting: Separate different final state J^P quantum numbers through spin and angular distributions; follow phase shift as function of mass -> resonance

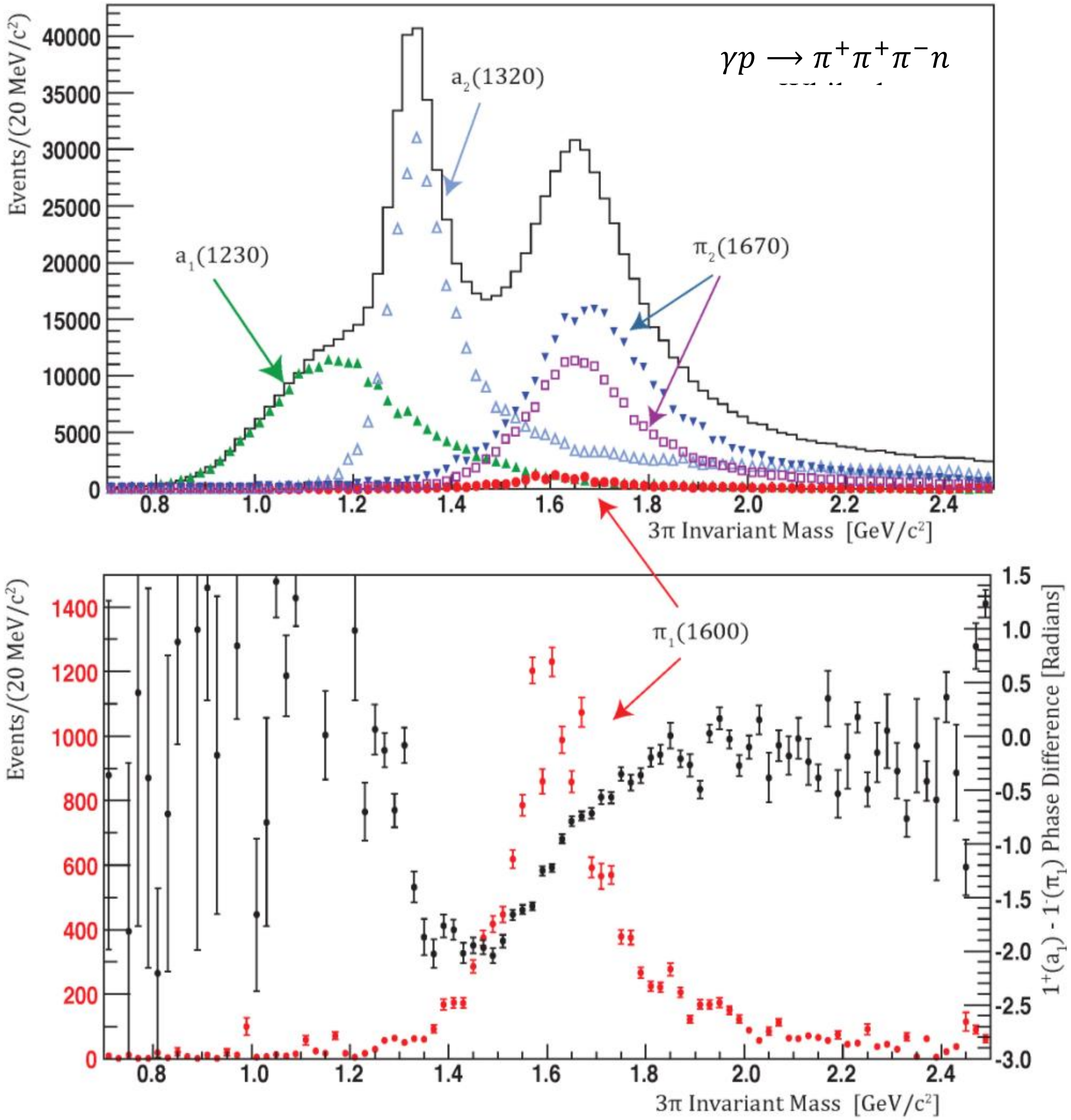
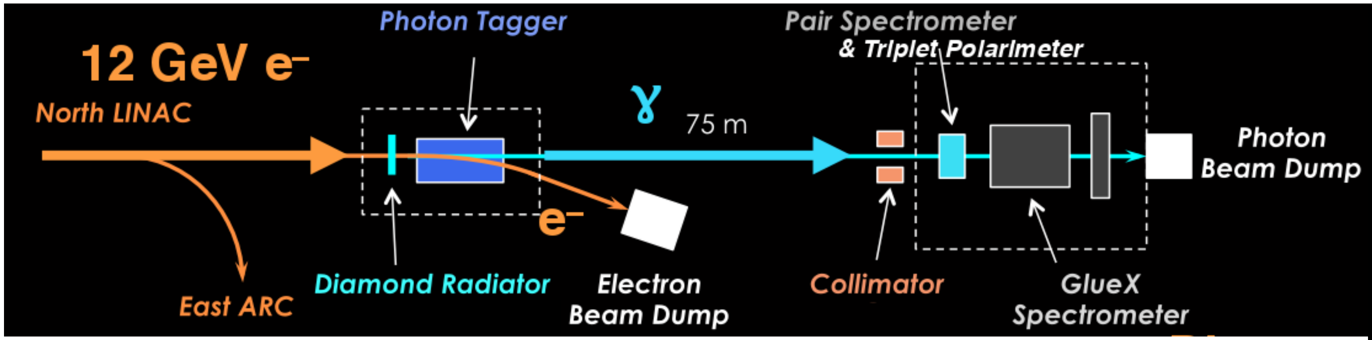
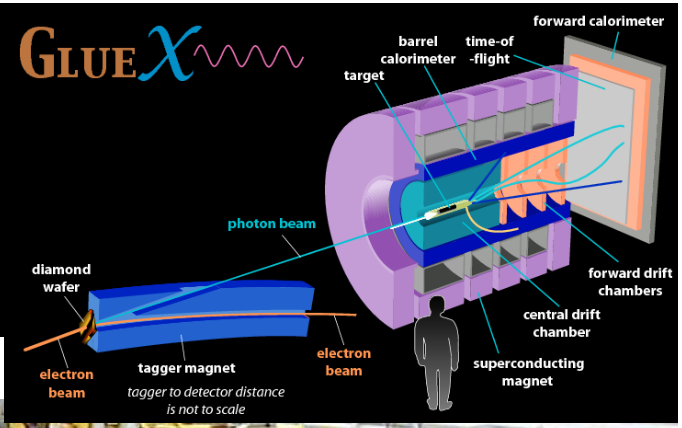


Figure 2.4: An amplitude analysis carried out using the full GlueX software suite showing a small exotic signal being cleanly extracted from the much stronger conventional signals in the data. The top plot shows the total cross section (solid curve) and the extracted intensities of several partial waves. Of note is the reproduction of a very small signal for an exotic π_1(1600). The strength of this wave, which may be large in actual photoproduction, is chosen to be small in the simulation to test the sensitivity of the analysis methodology. The bottom plot shows the weak exotic signal on a large scale as well as the observed phase motion between the signal and one of the stronger waves. Such an extracted phase motion would be clear evidence for resonant behavior of the signal.

Hall D


12 GeV e^-
North LINAC
East ARC
Photon Tagger
Diamond Radiator
e^-
Electron Beam Dump
γ
75 m
Pair Spectrometer & Triplet Polarimeter
Collimator
GlueX Spectrometer
Photon Beam Dump


GlueX
forward calorimeter
barrel calorimeter
time-of -flight
target
photon beam
forward drift chambers
central drift chamber
superconducting magnet
diamond wafer
electron beam
tagger magnet
electron beam
tagger to detector distance is not to scale