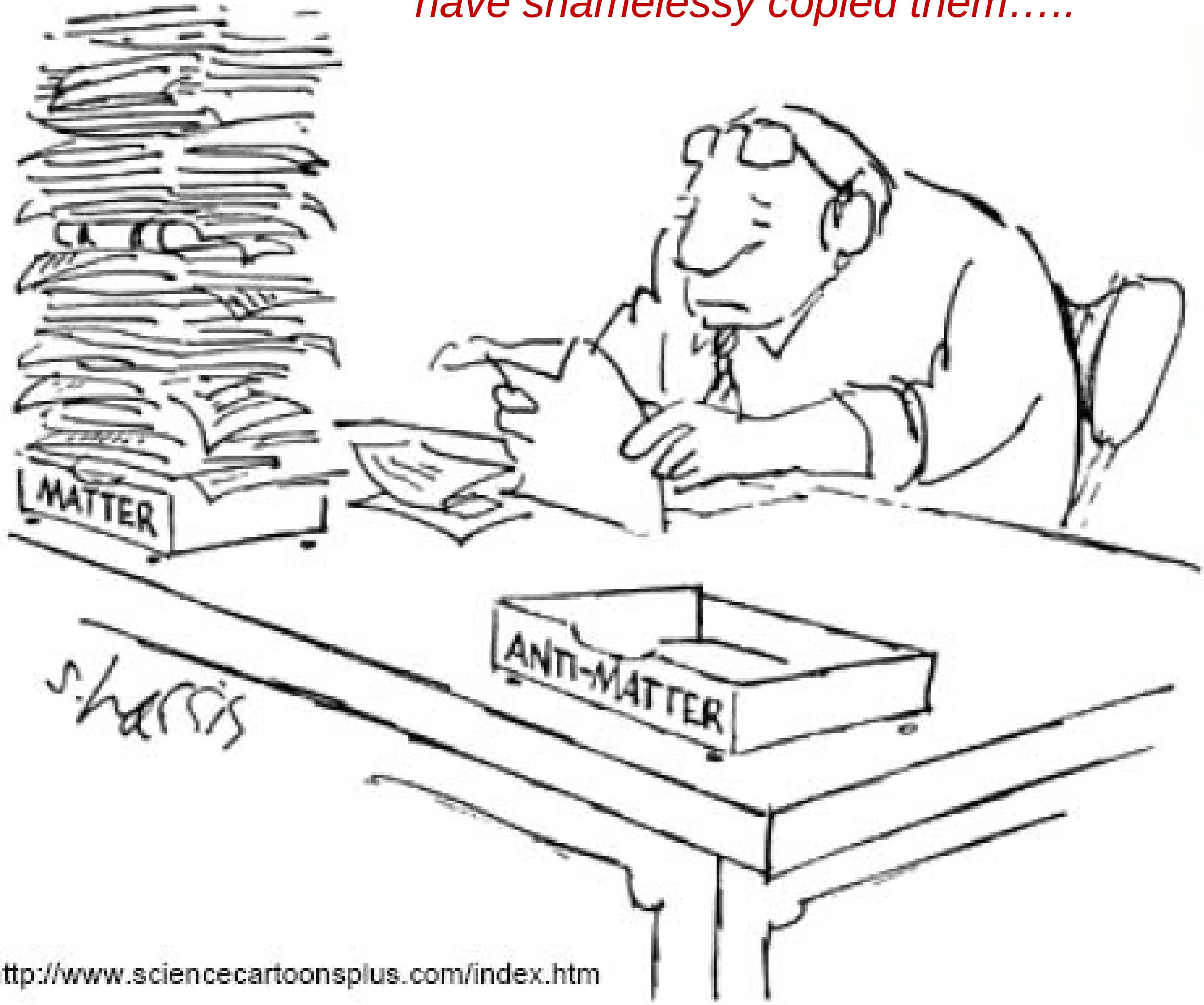
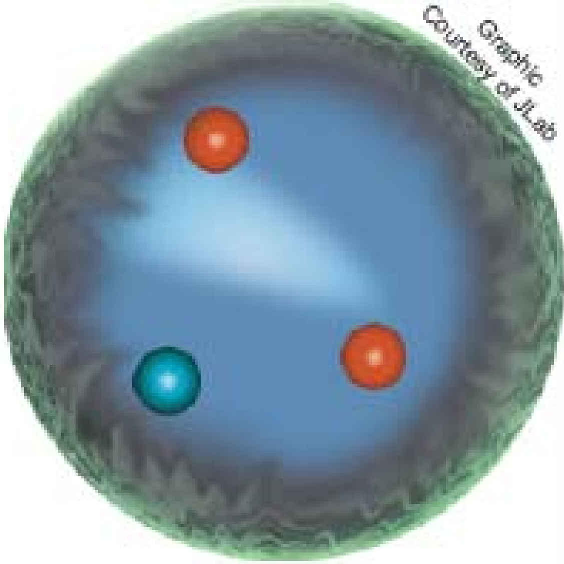
What's in the proton?

Paul Reimer showed these two slides at the Jlab User's Group meeting: I have shamelessy copied them…..



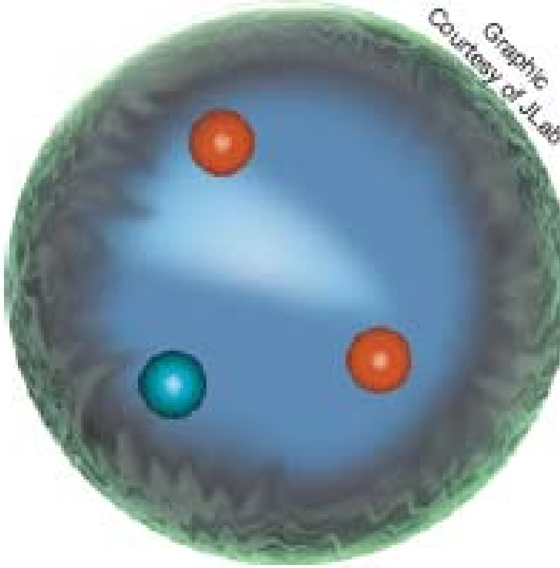
http://www.sciencecartoonsplus.com/index.htm



- Just three valence quarks?

What's in the proton?

http://www.sciencecartoonsplus.com/index.htm


Graphic Courtesy of JLab

- Just three valence quarks?
- NO!!

Hadron Physics

Topics I will attempt to cover:

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons as laboratories (and other miscellaneous topics)

caveats

I am an experimentalist! I will focus on what we know and how we measure it
I will not give a rigorous presentation of the theory by any stretch.

I am not an expert on most of these topics: I will borrow heavily from the work of others. In particular presentations from recent conferences and past summer schools. Recent Conferences are:

Workshop of the APS Topical Group on Hadronic Physics (GHP): Denver, 2009
http://www.fz-juelich.de/ikp/ghp2009/Program.shtml

Conference on the Intersections between Nuclear and Particle Physics (CIPANP), San Diego 2009
http://groups.physics.umn.edu/cipanp2009/program.html

Jefferson Lab Users Annual Meeting, June 2009
http://conferences.jlab.org/ugm/program.html

some references

Halzen & Martin: Quarks and Leptons
F.E. Close: An Introduction to Quarks and Partons
Perkins: Introduction to High Energy Physics
Cahn and Goldhaber: The Experimental Foundations of Particle Physics

Xiangdong Ji: Graduate nuclear physics lecture notes
http://www.physics.umd.edu/courses/Phys741/xji/lecture_notes.htm

Lectures from the Hampton University Graduate School (HUGS):
http://www.jlab.org/hugs/archive/

Lectures from past Nuclear Physics Summer Schools (most are available online) and I have shamelessly borrowed material from wherever I could find it.

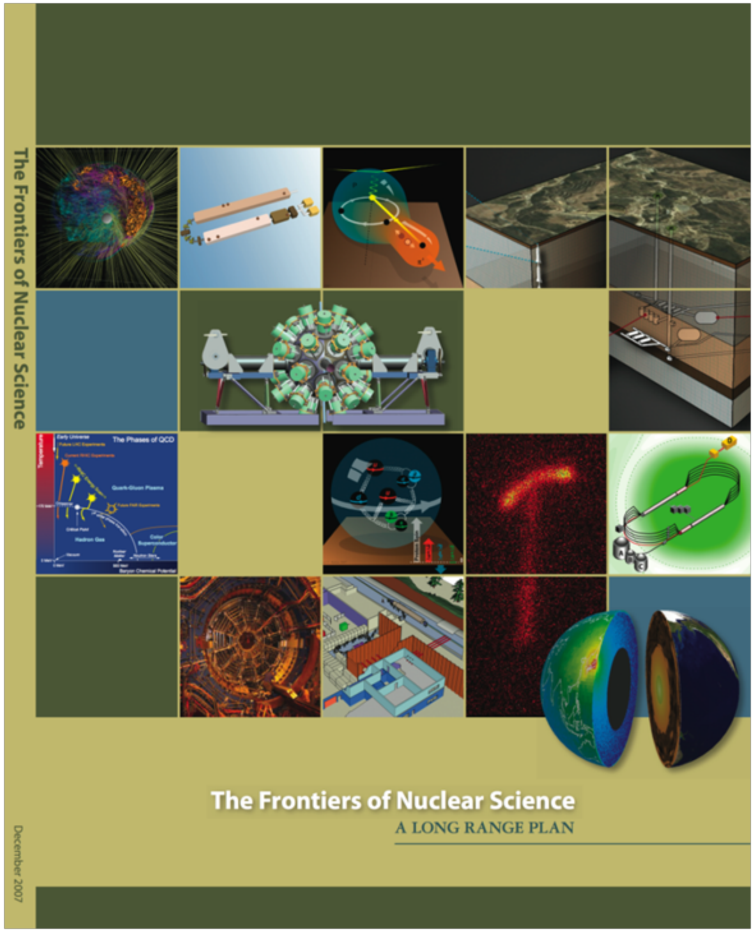
Special thanks to (for nice review slides)
Zein-Eddine Meziani, Temple University (spin, DIS)
Naomi Makins, University of Illinoisn (spin, transversity)
Volker Burkert, Jefferson Lab (N physics)*
Volker Crede, Florida State University (glueballs)

The big picture

What are the questions?

What are the connections between this topic and other areas of nuclear physics?

The Questions of the 2007 Long Range Plan



The Frontiers of Nuclear Science

The Frontiers of Nuclear Science
A LONG RANGE PLAN

December 2007

http://www.sc.doe.gov/np/nsac/nsac.html

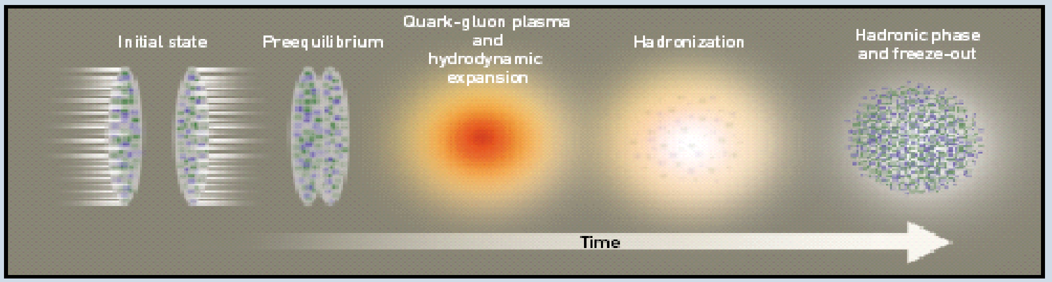
- Quantum ChromoDynamics
  - What are the phases of strongly interacting matter?
  - What is the internal landscape of nucleons?
  - What governs the transition of quarks and gluons into nucleons and pions?
- Nuclei and Nuclear Astrophysics
  - What is the nature of the nuclear force?
  - What is the origin of simple patterns in complex nuclei?
  - What is the origin of the elements in the cosmos?
- Symmetries and Neutrinos
  - What is the nature of neutrinos?
  - Why is there now more visible matter than antimatter?
  - *… and of course more….*

Landscape of Nuclear Physics

stable and radioactive beams

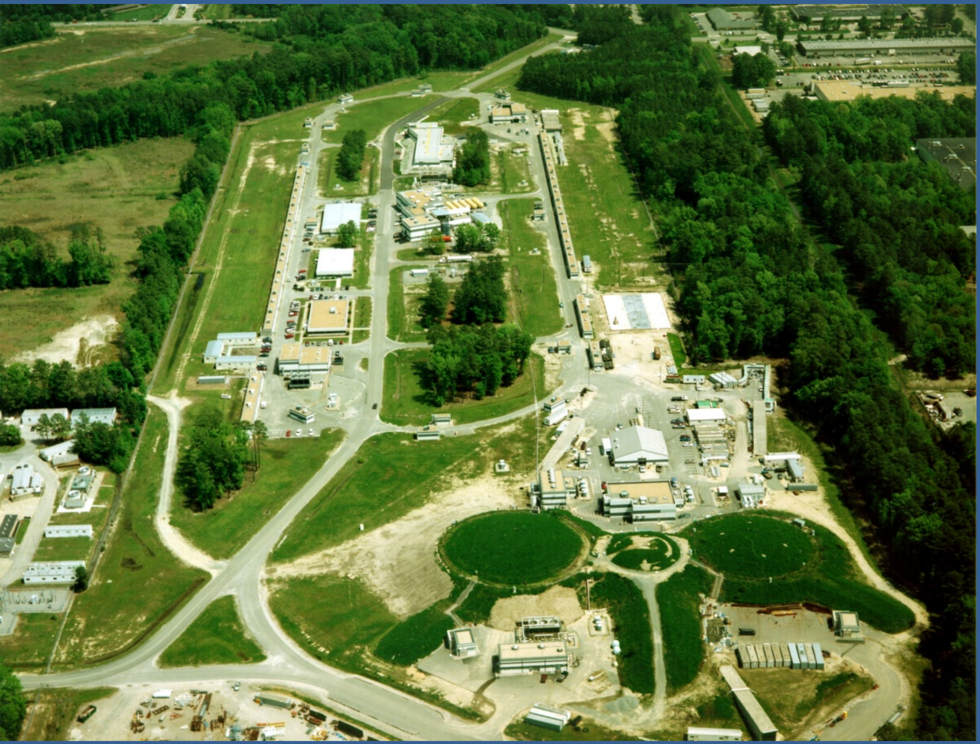
electron scattering

relativistic heavy ions



From W. Nazarewicz, ORNL

Jefferson Laboratory (Newport News, VA)



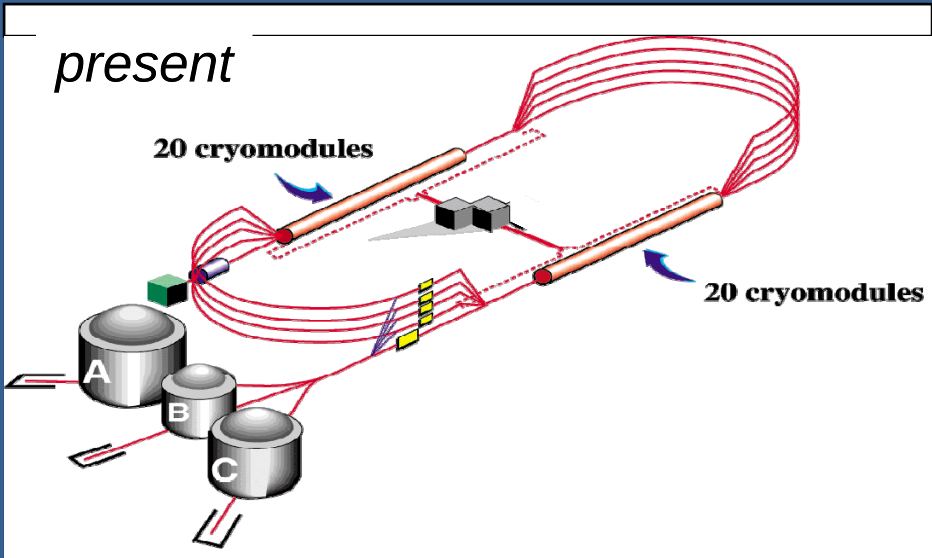
E ~ 6 GeV

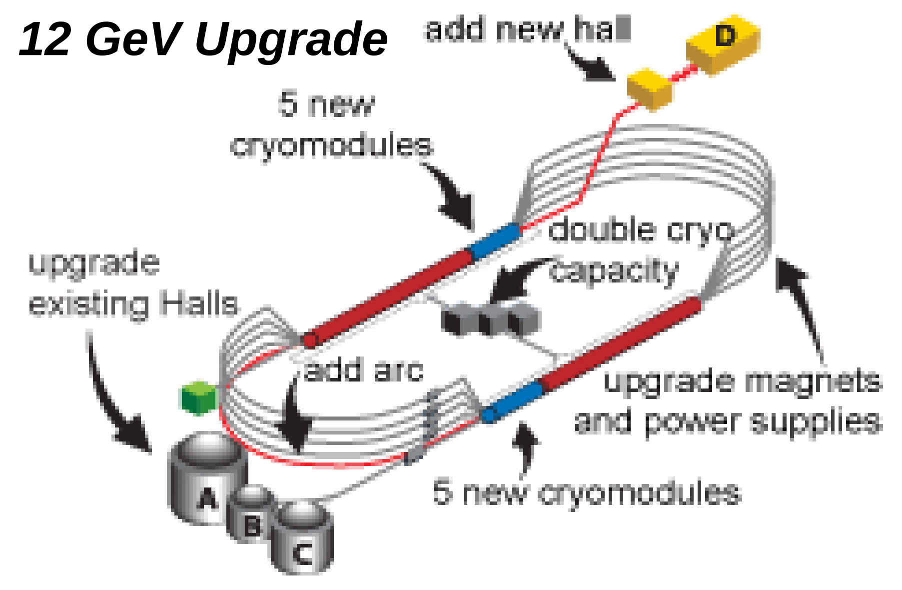
Continuous Polarized Electron Beam

> 100 μA

up to 85% polarization

concurrent to 3 Halls





Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

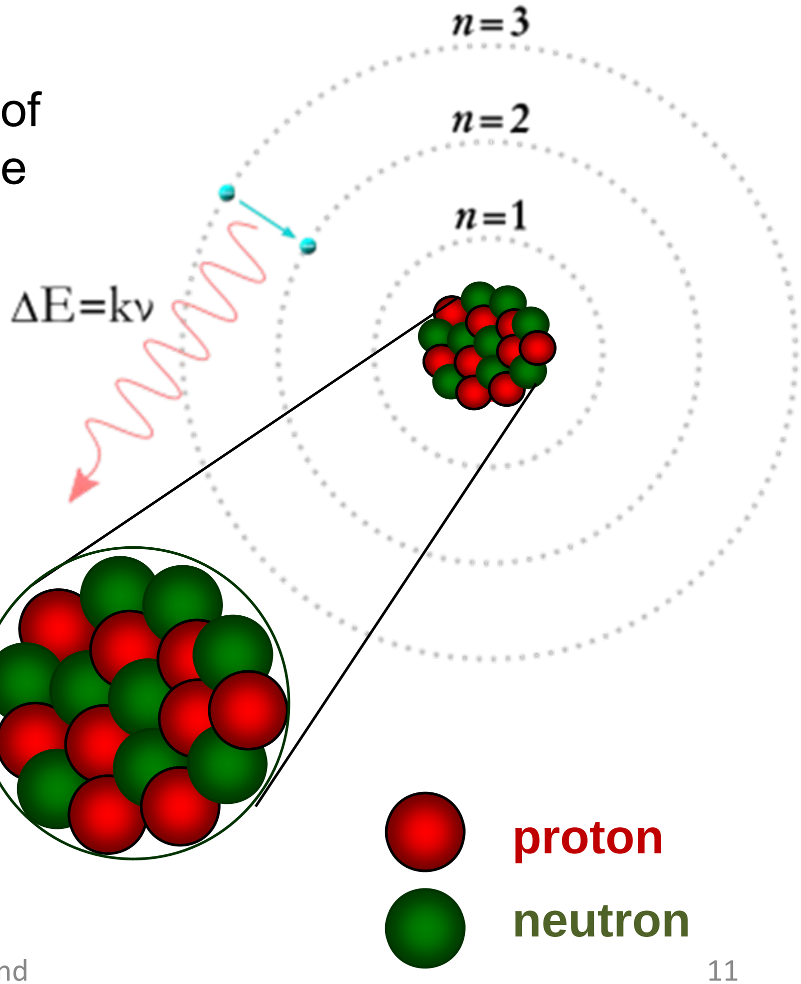
Lecture #4: Hadrons as laboratories (and other miscellaneous topics)

The atom

(slide from R. DeVita, AAAS meeting, Feb 2008)

Our present knowledge on the atomic structure of matter was obtained through a series of experimental observations and theoretical advances

- In 1803 J. Dalton postulated the existence of chemical elements introduced to explain the variety of known compounds
- Discovery of the electron by J.J. Thomson in 1867 and its studies on isotopes destroy the concept of the atom as indivisible particle
- The "gold foil" experiment by E. Rutherford and the development of Quantum Mechanics led to the modern models of atomic structure



FERMIONS

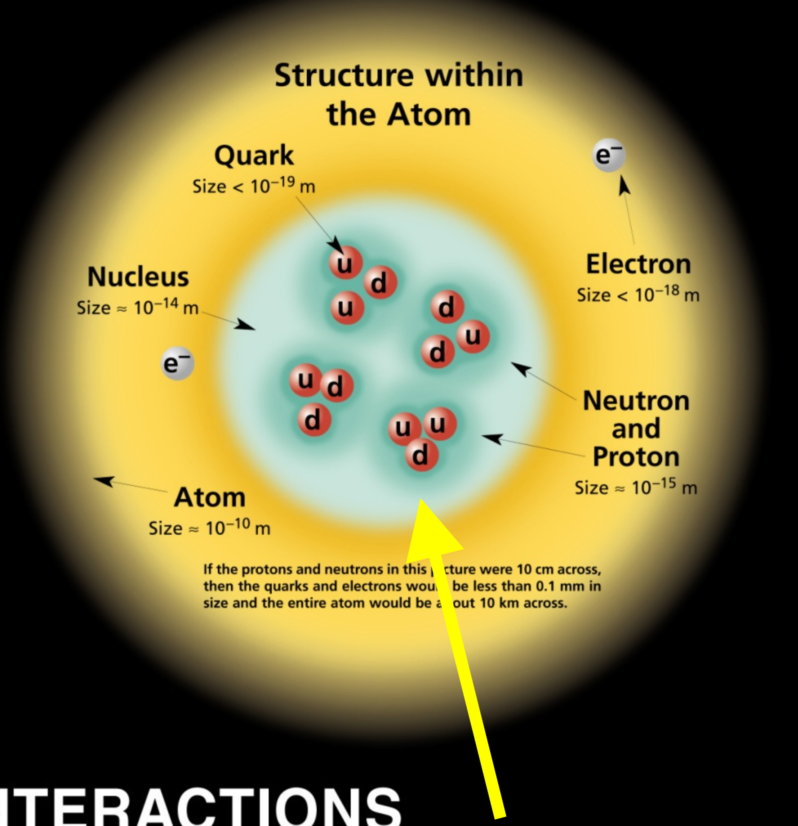
matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

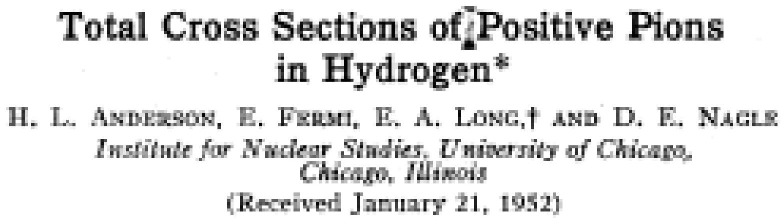


If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

observation of hadron states



Total Cross Sections of Positive Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

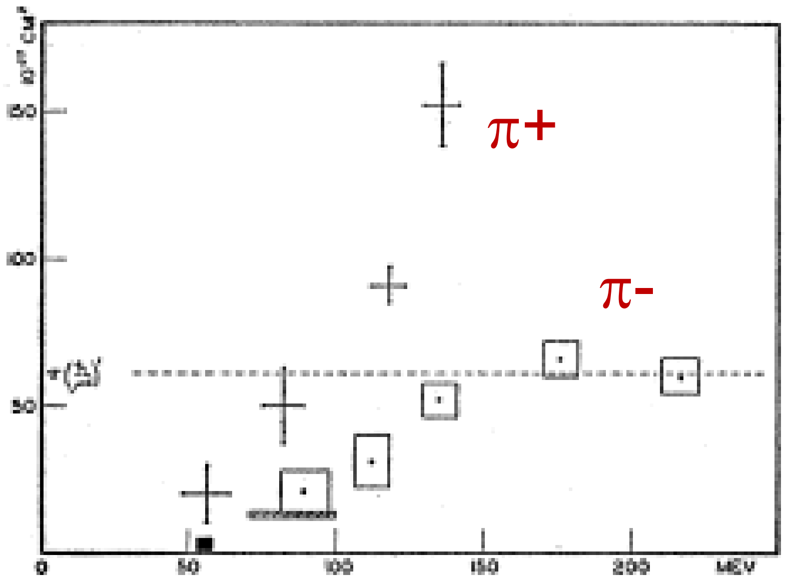


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

Chicago Cyclotron: beams of π+ and π– from 50-180 MeV

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

$$\pi^- p \to \pi^0 n$$

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

ratio of production cross sections (9:2:1) consistent with all three processes going through a single common resonance with Isospin 3/2. The authors suggest looking at the angular distribution in order to determine the state's total angular momentum….

angular distributions

Pion-Proton Scattering at 150 and 170 Mev*

J. Ashkin, J. P. Blaser, F. Feiner,† and M. O. Stern
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received August 5, 1955)

From "phase shift analysis", assuming only S and P waves, found that resonance was associated with I=3/2, J=3/2

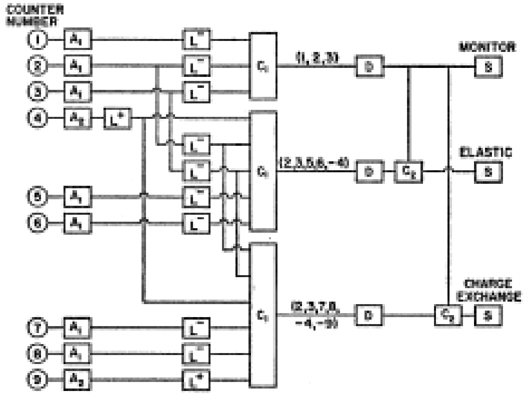


Fig. 2. Block diagram of the electronics. A_1—100-Mc band-width amplifier; A_2—40-Mc band width amplifier; L^- limiter and clipper; L^+ limiter; C_1 fast diode coincidence circuit of approximately 5-mμsec resolving time; D fast discriminator and univibrator pulse shaper; C_2 semi-fast coincidence circuit of approximately 20-mμsec resolving time; S fast 0.1-μsec scaler.

(early example of electronics diagram in a paper!)

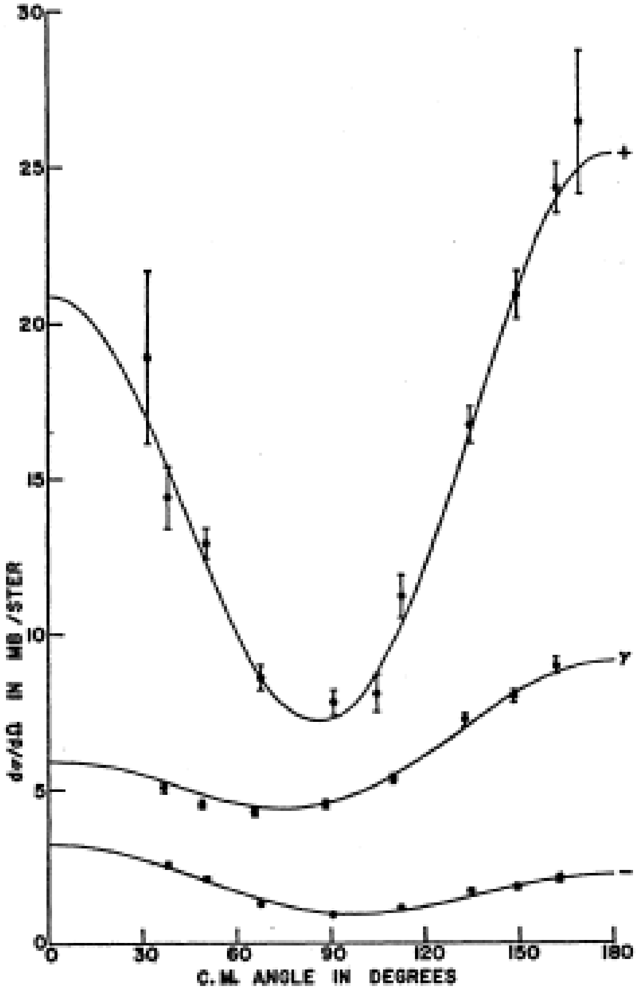


Fig. 4. 150-Mev pion-proton differential scattering cross sections. The curves represent the cross sections given by the phase shifts: $\alpha_3=-10°$, $\alpha_{33}=51.5°$, $\alpha_{31}=-5°$, $\alpha_1=9°$, $\alpha_{13}=2°$, $\alpha_{11}=2°$. The experimental points are plotted with the scale factors: $(+)\times 0.97$, $(-)\times 1.00$, $(\gamma)\times 1.00$ (see Sec. VIII).

(slide from R. DeVita, AAAS meeting, Feb 2008)

strangeness: The V particle

EVIDENCE FOR THE EXISTENC OF NEW UNSTABLE ELEMENTARY PARTICLES
G.D. Rochester and C.C. Butler, Nature 160 (1947) 855.

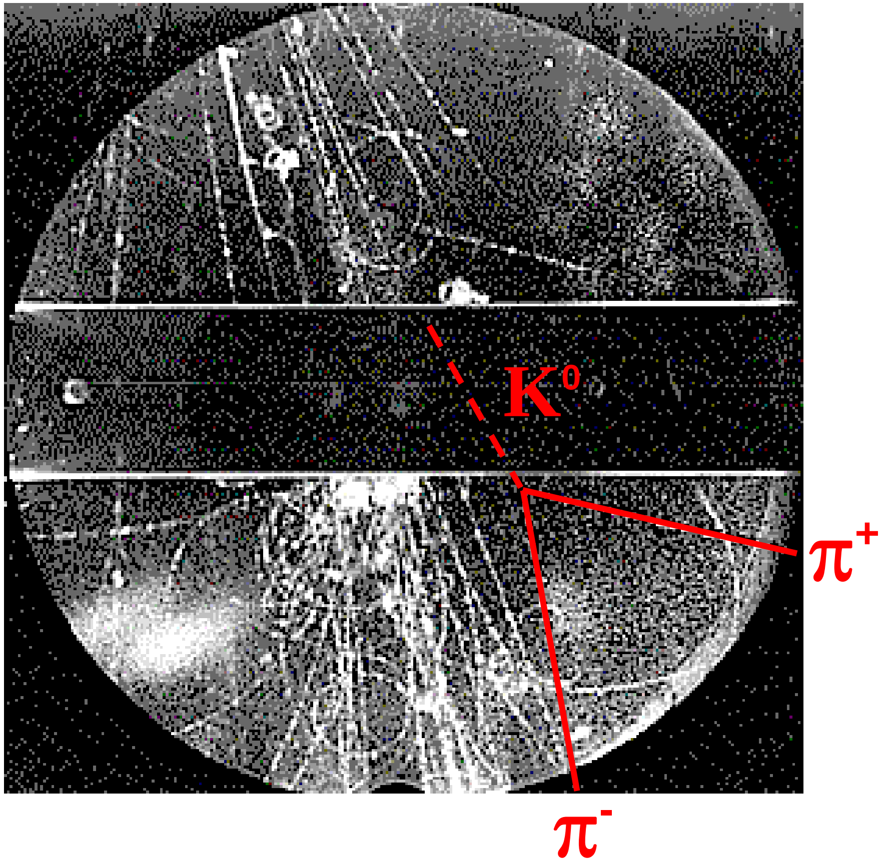
Tracks observed in a cloud chamber photographs, exposed to cosmic rays

2 photographs out of 5000 showed forked tracks

Surprisingly long life time (10^{-10} s) compared w/ typical production reactions: → weak decay

masses of outgoing tracks could only be estimated, but < proton mass.

New property called *strangeness* was introduced: conserved in strong interactions but violated in weak interactions.



Experiments

Experimental requirements for hadron spectroscopy:

energy (accelerators provide the luminosity)

mass/charge measurement: magnetic field

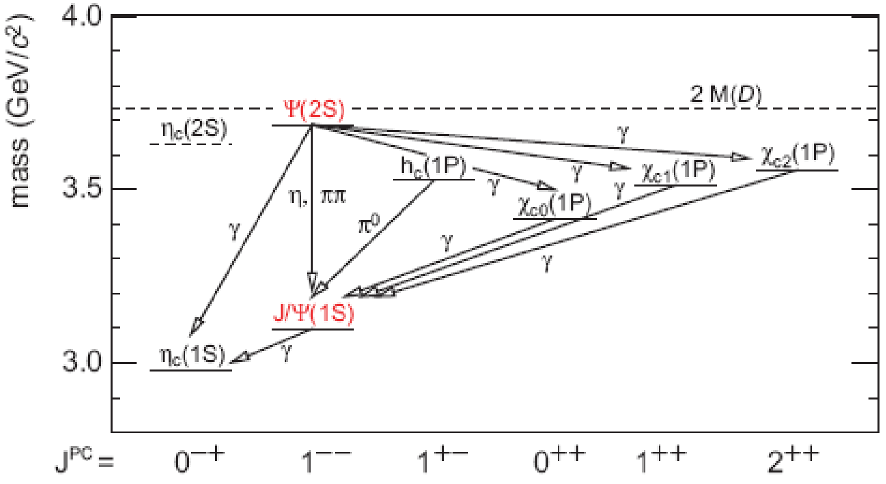
solid angle: need to detect *all* the outgoing products to completely reconstruct the decays

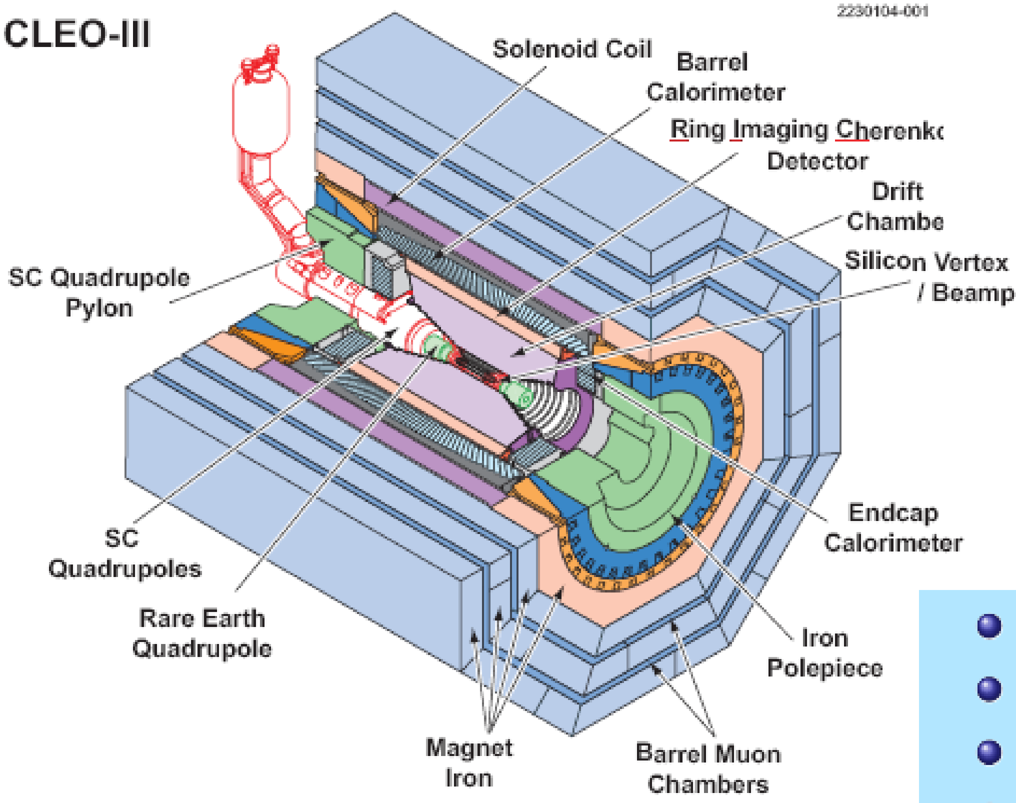
"hermetic" detector (cloud chamber, bubble chamber)

track resolution needed both for particle ID and for vertex reconstruction

CLEO-c: charm quark spectroscopy at Cornell (CESR: e^+e^- collider)

$$e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$$





- Excellent Calorimeter
- Excellent Tracking
- RICH and dE/dx for PID
- Muon Chambers

the quark model

1950-1970:

explosion of discovery of new “particles”, including antibaryons

concepts of *isospin*, *strangeness*, baryon number, became useful as organizing/classification scheme

charge: $Q = I_3 + (B+S)/2$ (hypercharge = $B+S$)

Quark hypothesis (Gell-Mann and Zweig, 1964): up, down, and strange

Flavor	B	J	I	I3	S	charge
u	1/3	½	½	+1/2	0	2/3
d	1/3	½	½	-1/2	0	-1/3
s	1/3	½	0	0	-1	-1/3

what are the quark masses? Can we understand them from the spectrum of observed particles?

hadrons in QCD

The strong interaction is defined by the property “color”. This is required to produce bound states with the appropriate symmetry properties (fermion/boson statistics)

- The strong interaction is (approximately) flavor independent *(same for all quarks, thus, e.g., same for n and p)*

- There are 3 types of “color”

- The bound states of QCD are only “color neutral”: individual constituents cannot be observed → *confinement*

- The exchange particles (gluons) carry the property of color (and thus can interact with themselves)

- The interaction strength *decreases* with increasing energy
  → *asymptotic freedom*

u and d only: SU(2) flavor symmetry

$$\begin{pmatrix} u \\ d \end{pmatrix}$$

$$q\bar{q}: \quad 2 \otimes \bar{2} = 3 \oplus 1$$

symmetric

$$\left(\pi^{+}, \pi^{0}, \pi^{-}\right)$$

antisymmetric

$$\eta$$

$$qqq: \quad 2 \otimes 2 \otimes 2 = \left(3 \otimes 2\right) \oplus \left(1 \otimes 2\right) = 4 \oplus \underbrace{2 \oplus 2}$$

symmetric

$$\left(\Delta^{++}, \Delta^{+}, \Delta^{0}, \Delta^{-}\right)$$

mixed symmetry:
combine with spin
part of wave fn to
get antisymmetric
state: *p and n*

e.g.,

$$\left|\Delta^{++}\right\rangle = \underbrace{\left|3/2, 3/2\right\rangle_{I} \otimes \left|3/2, 3/2\right\rangle_{S} \otimes \left|L=0\right\rangle}_{\text{symmetric}} \otimes \left|\psi\right\rangle_{color}$$

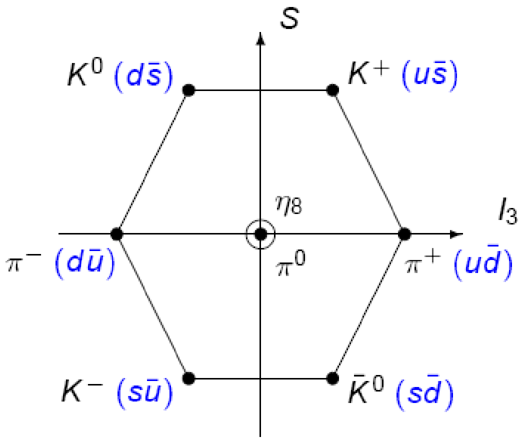
color “neutral”: antisymmetric

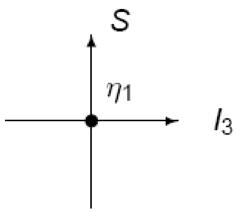
SU(3) and s quarks

Mesons: $q\bar{q}$

$$3 \otimes \bar{3} = 8 \oplus 1$$

figure from V. Crede, FSU





$$|\,\pi^0\,\rangle = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}\,)$$

$$|\,\eta_8\,\rangle = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s}\,) \qquad |\,\eta_1\,\rangle = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}\,)$$

Baryons: qqq

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$

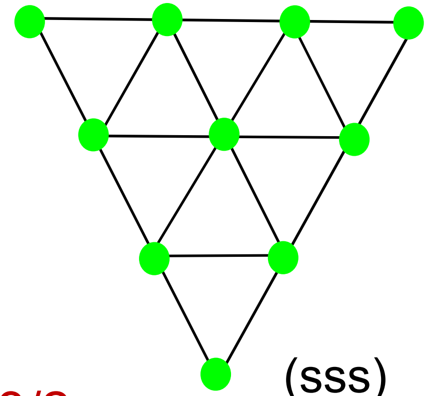
S

$\Delta^-, \Delta^0, \Delta^+, \Delta^{++}$

$\Sigma^{*-}, \Sigma^{*0}, \Sigma^{*+}$

$\Xi^{*-}\,, \Xi^{*0}$

Ω^-



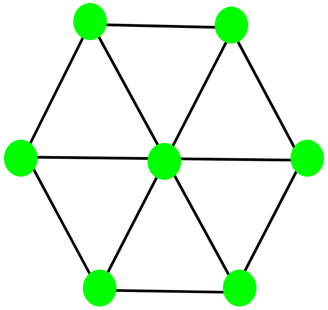
(sss)

J^P=3/2+

p, n

$\Sigma^-, \Sigma^0, \Sigma^+$

$\Xi^-\,, \Xi^0$



● Λ^0

(uds)

J^P=1/2+

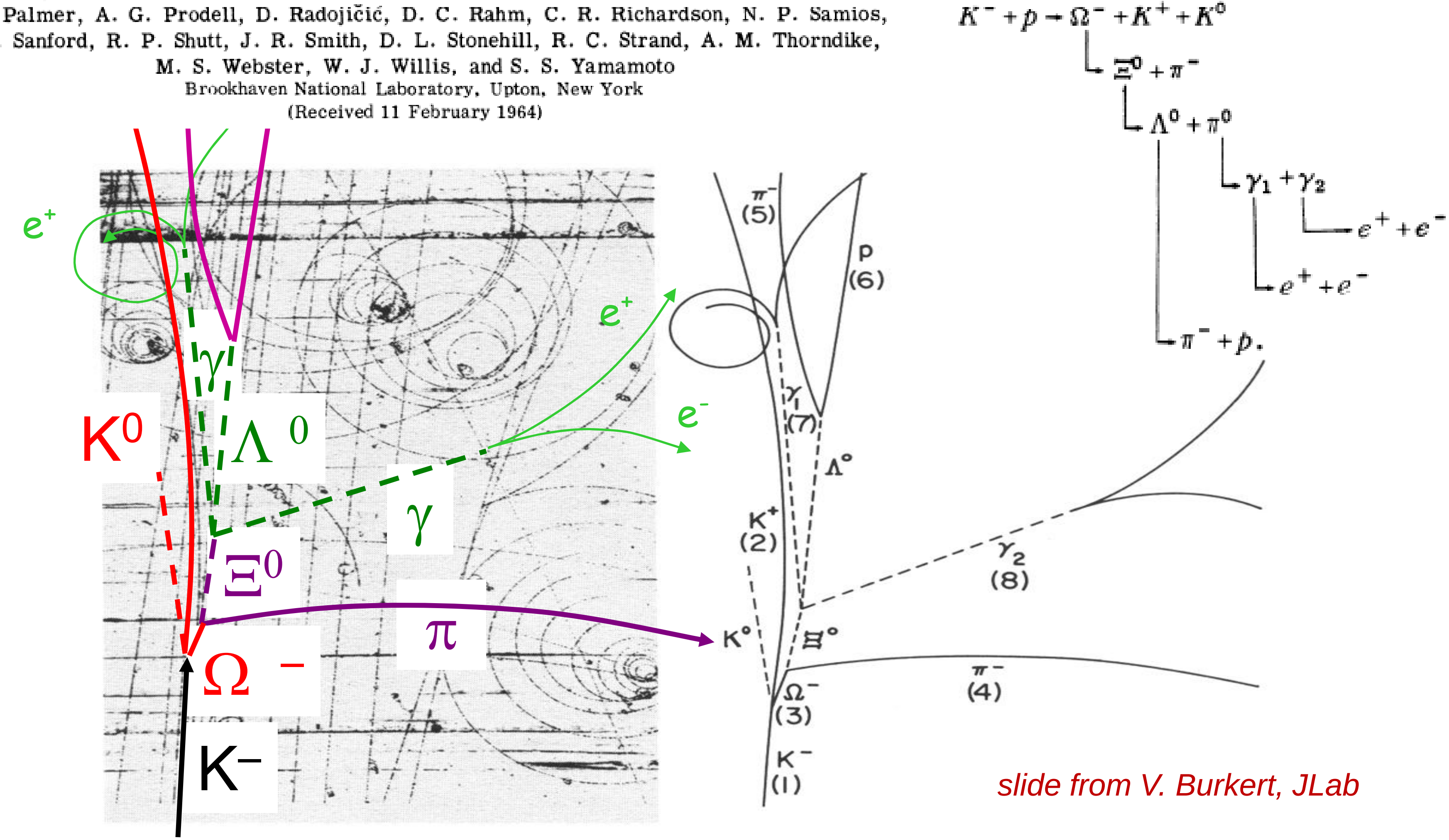
sss: the Ω^-

Phys. Rev. Lett. 12, 204 (1964)

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney,
W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen,
J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren,
R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, C. R. Richardson, N. P. Samios,
J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike,
M. S. Webster, W. J. Willis, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York

(Received 11 February 1964)



slide from V. Burkert, JLab

FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

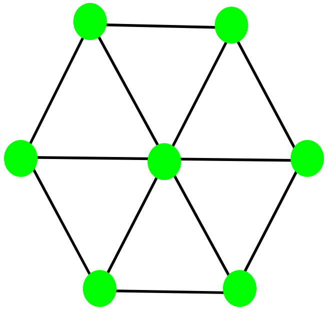
masses and magnetic moments

The “constituent quark” model can predict these pretty well.

$$M_\Lambda - M_N = 177 \text{ MeV}$$

$$M_\Sigma - M_N = 254 \text{ MeV}$$

$$M_\Xi - M_\Lambda = 203 \text{ MeV}$$



p, n

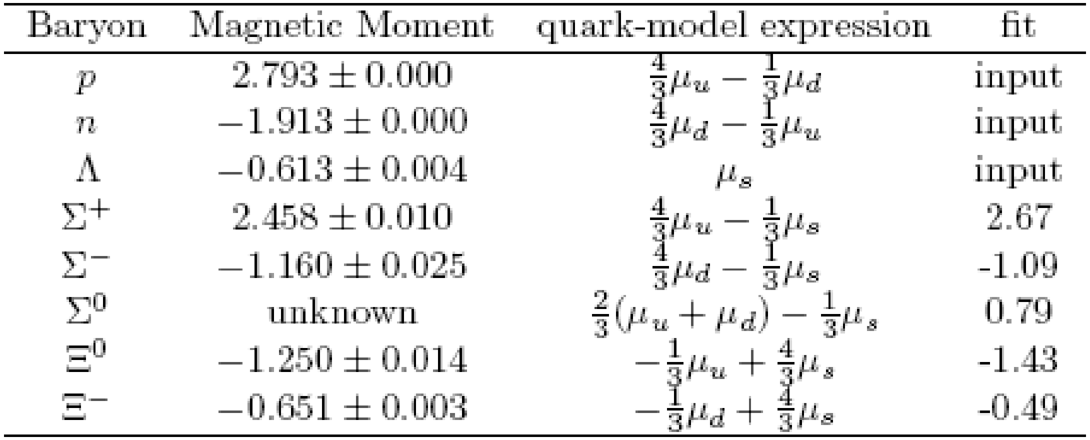
$\Sigma^-, \Sigma^0, \Sigma^+$

Ξ^-, Ξ^0

● Λ^0

(uds)

Similar relationships for the J^P=3/2+ baryons. These get modified a little by q-q hyperfine structure. Result in “constituent quark” masses:



Baryon	Magnetic Moment	quark-model expression	fit
p	2.793 ± 0.000	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_d$	input
n	-1.913 ± 0.000	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_u$	input
Λ	-0.613 ± 0.004	μ_s	input
Σ^+	2.458 ± 0.010	$\frac{4}{3}\mu_u - \frac{1}{3}\mu_s$	2.67
Σ^-	-1.160 ± 0.025	$\frac{4}{3}\mu_d - \frac{1}{3}\mu_s$	-1.09
Σ^0	unknown	$\frac{2}{3}(\mu_u + \mu_d) - \frac{1}{3}\mu_s$	0.79
Ξ^0	-1.250 ± 0.014	$-\frac{1}{3}\mu_u + \frac{4}{3}\mu_s$	-1.43
Ξ^-	-0.651 ± 0.003	$-\frac{1}{3}\mu_d + \frac{4}{3}\mu_s$	-0.49

Table 3.3: The magnetic moment of the octet baryons and quark model fit.

$$m_u \approx m_d \approx \tfrac{1}{3} M_N = 300 \text{ MeV}$$

$$m_s \approx 450 \text{ MeV}$$

$$\mu_q \approx \frac{q_q \hbar}{2 m_q c}$$

$$\mu_u = -2\mu_d$$

heavy quark bound states

quark analog of positronium

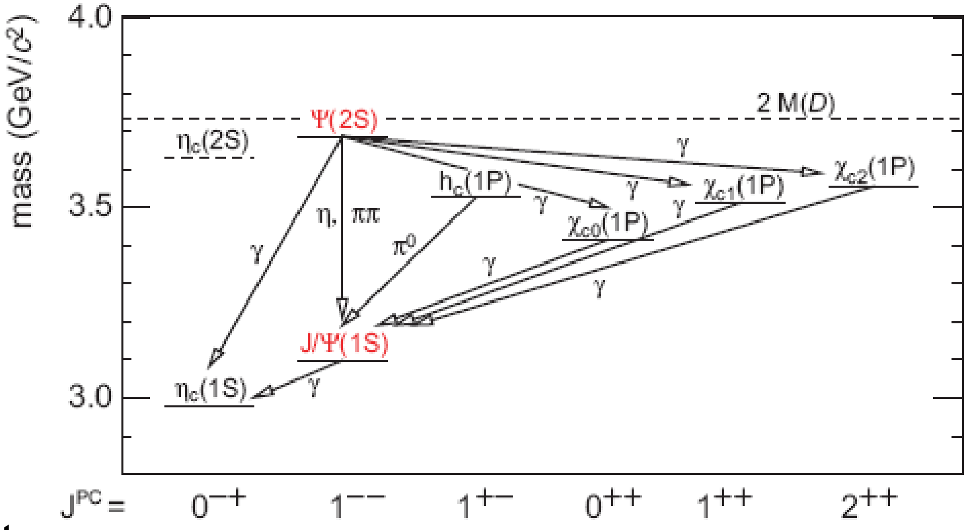
- short range
- nonrelativistic
- perturbative QCD is not bad

e.g. Charmonium: (J/Ψ)

- states are very narrow
- excellent lab to search for
- exotic and hydbrid bound states

(very active: BaBar, Belle, CDF, D0, …)

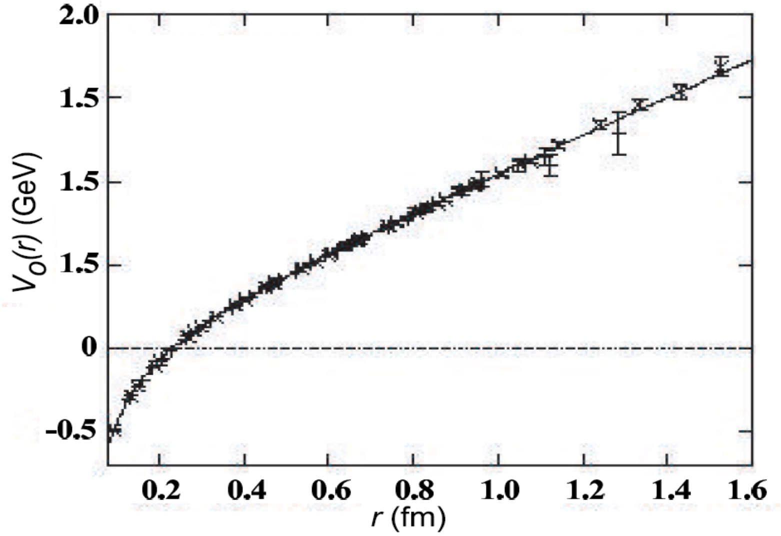
$e^+e^- \rightarrow \gamma^* \rightarrow c\bar{c}$



$$V_{QCD}(r) \propto -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

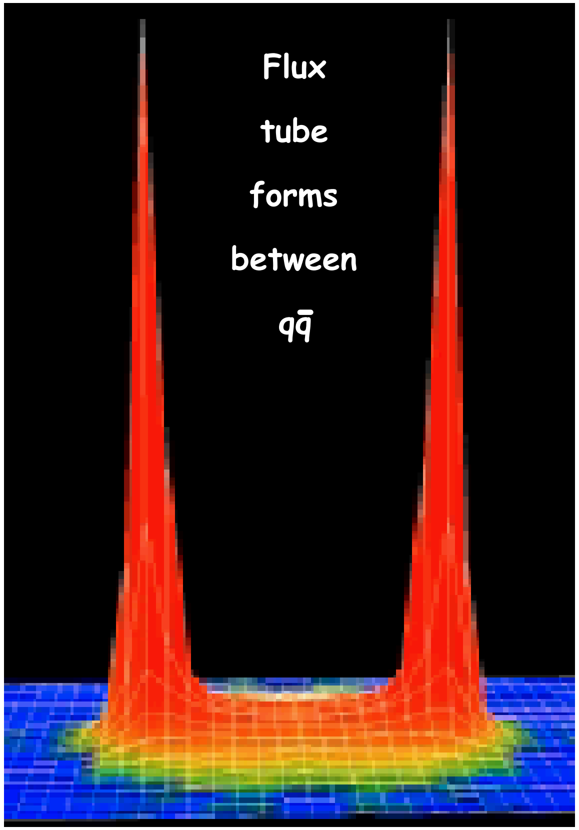
“Coulombic”

confining

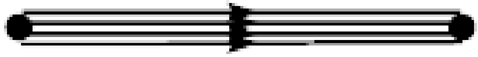


Lattice QCD

Flux tubes in LQCD

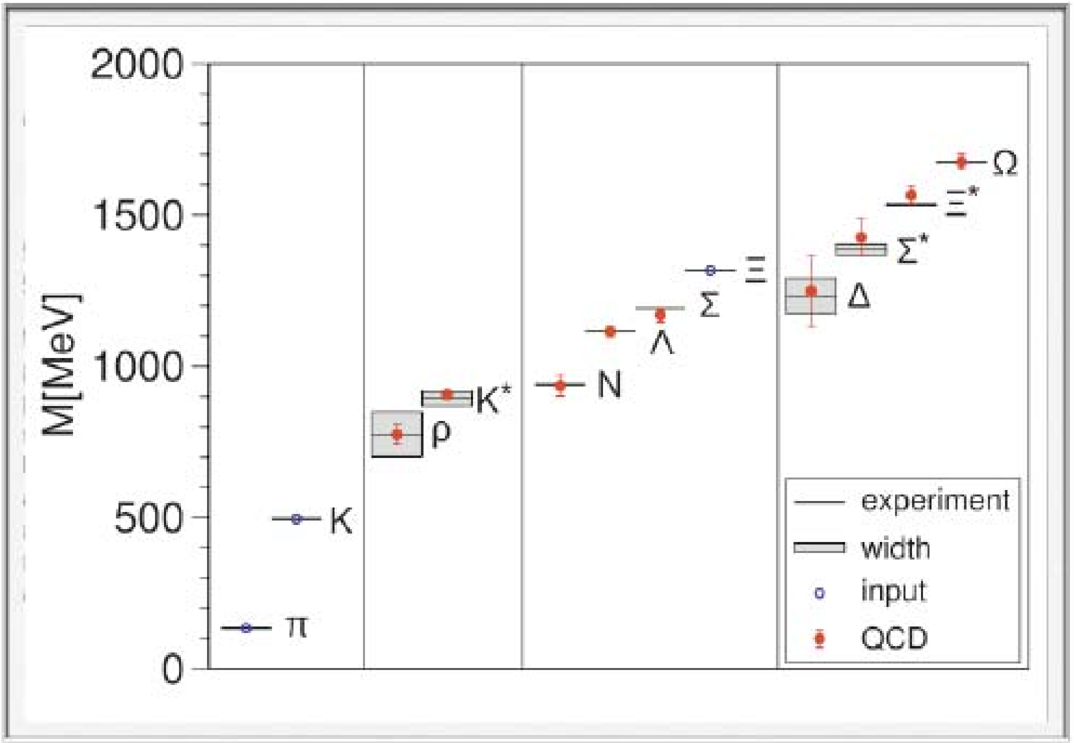


G. Bali



ab initio computation of Baryon masses

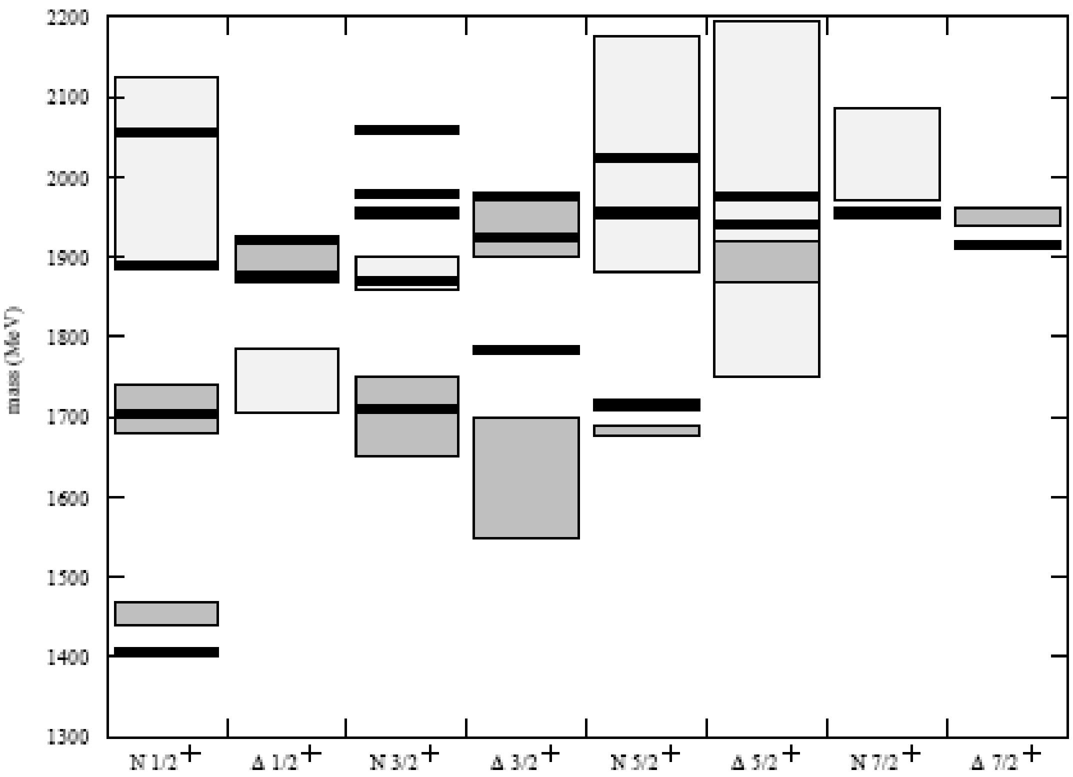
S. Dürr, et al *Science* 21 November 2008: 1224-1227.



Excited baryons

simple quark model: harmonic oscillator + some hyperfine splitting…

$$H_0 = \frac{1}{2m}\left(\vec{p}_2^{\,2} + \vec{p}_1^{\,2}\right) + \frac{1}{2m'}\vec{p}_3^{\,2} + \frac{1}{2}k\sum_{i<j}\left(\vec{r}_i - \vec{r}_j\right)^2 + V_{ij}$$



more states predicted than have been found. Are these the correct degrees of freedom?

▬ predicted

▨ PDG 3-4 ***

☐ PDG 1-2 ***

see X. Ji, U Md Phys 741 lecture notes

see also Capstick& Roberts PRD 58 (1998) 074011

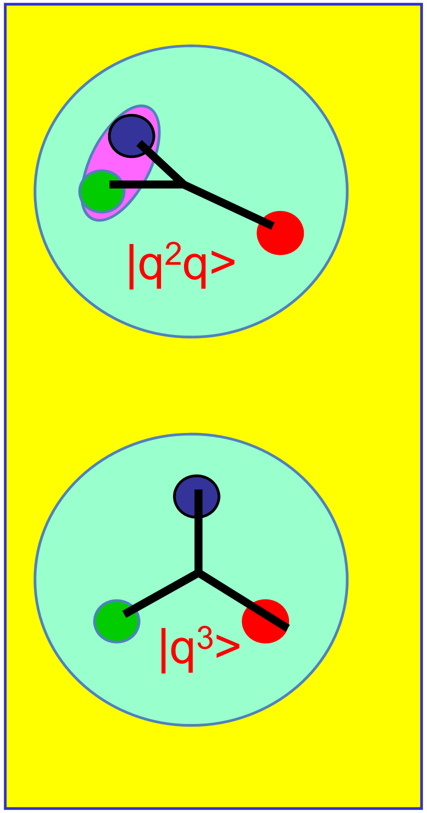
“Missing” Baryon States

Quark models with underlying SU(6)xO(3) symmetry predict many states, not observed in either hadronic experiments or in meson photo- and electro-production.

Possible solutions:

1. States don’t exist, e.g. di-quark model predicts fewer states, with different underlying symmetry group

2. States exist but have not been found.



Possible reason: they do not couple to πN final states…

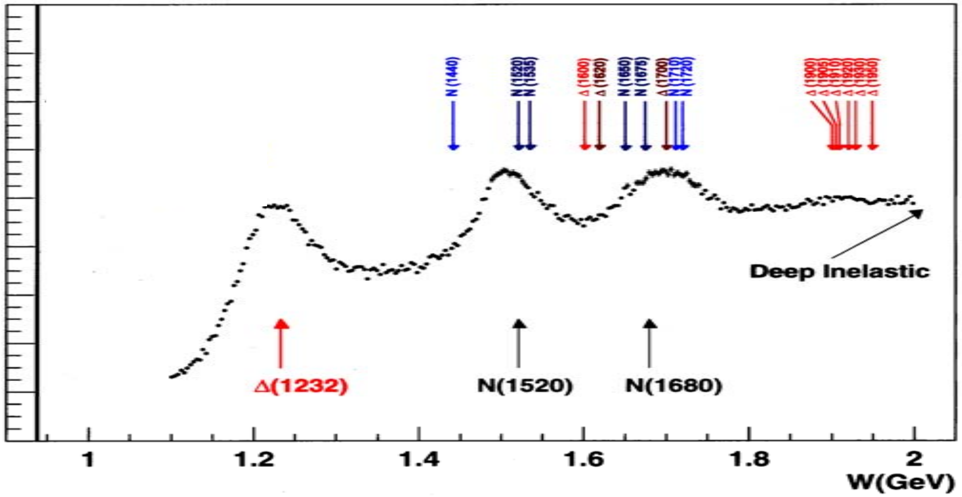
Maybe they decay to other channels:

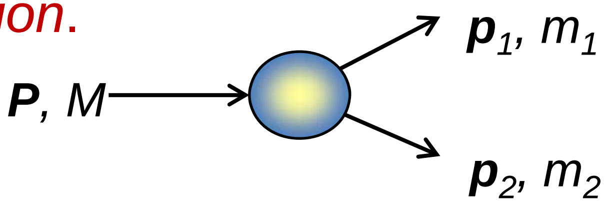
$K\Lambda$, $K\Sigma$, $p\omega$

adapted slide from V. Burkert, JLab

Searches for resonances

2-body decay: look at the *invariant mass distribution*.

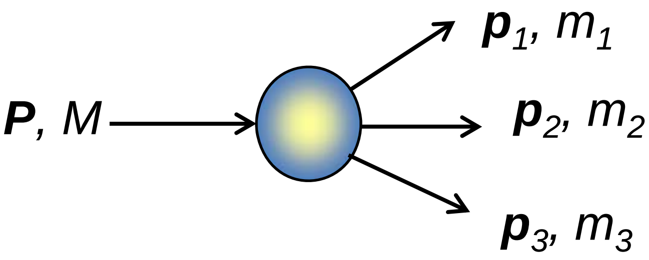


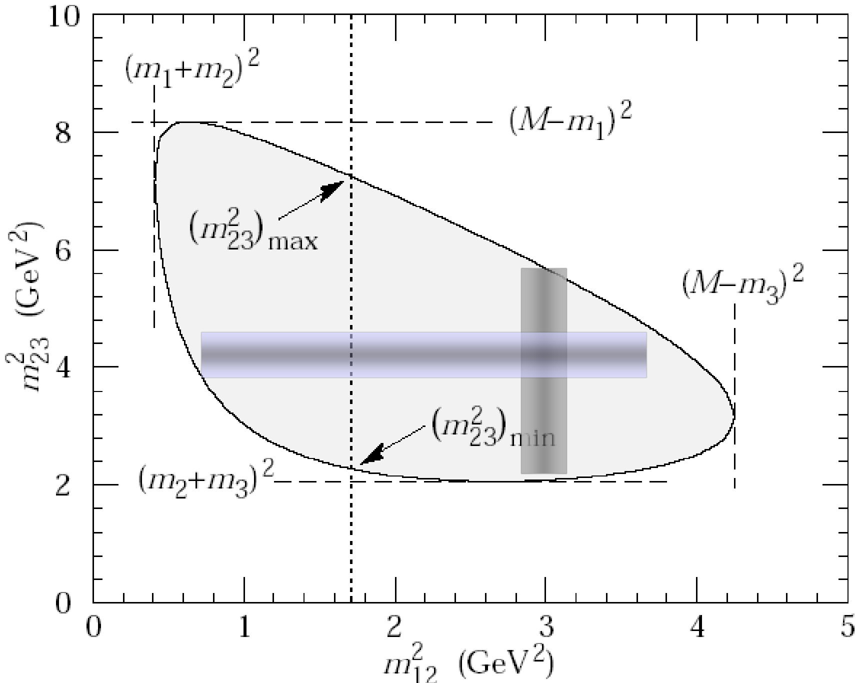


$$W^2 = M^2 = (p_1 + p_2)^2$$

doesn't tell you about the quantum #'s
Sometimes they overlap

3-body decay: Dalitz plot



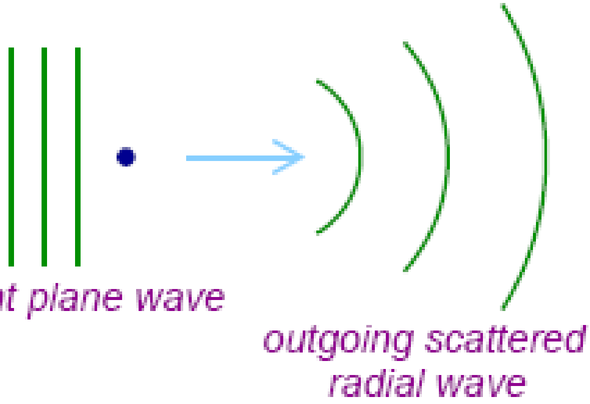


beware of artifacts…..

slide from V. Burkert, JLab

Partial Wave Analysis II

See Dan Carman's seminar from see last year's Summer School



$$\psi(r,\theta,\phi) \longrightarrow e^{ikz} + f(\theta,\phi)\frac{e^{ikr}}{r}$$

$$f(\theta,\phi) = \text{scattering amplitude}$$

- Differential cross section: $\dfrac{d\sigma}{d\Omega} = |f(\theta,\phi)|^2$

$$f(\theta,\phi) = \frac{-m}{2\pi\hbar^2}\int d\vec{r}\,e^{i\vec{q}\cdot\vec{r}/\hbar}V(\vec{r})$$

Fourier transform of potential

(First Born approximation)

- More generally,

phase shifts

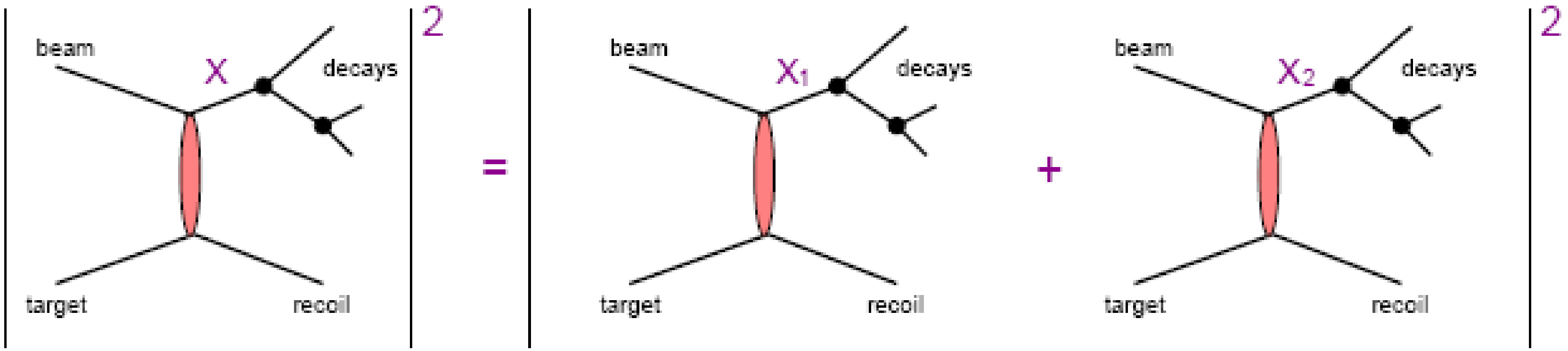
$$\psi_s = \psi_f - \psi_i = \boxed{\frac{1}{k}\sum_{l=0}^{\infty}(2l+1)\frac{\eta_l e^{2i\delta_l}}{2i}P_l(\cos\theta)}\frac{e^{ikr}}{r}$$

scattering amplitude

See Dan Carman's seminar from see last year's Summer School

Partial Wave Analysis IV

- Amplitude analysis:



CAVEATS:

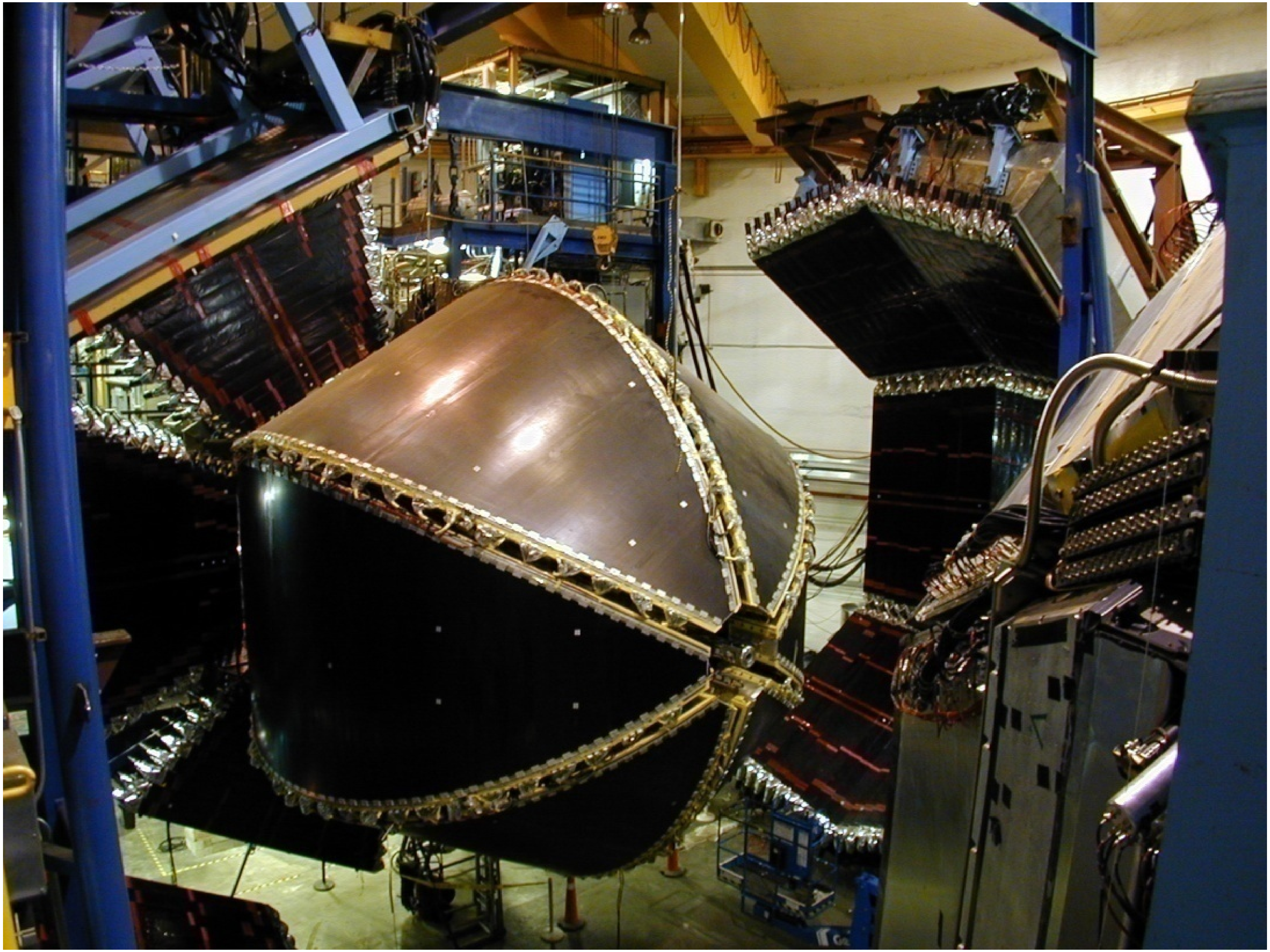
The number of counts in a given bin must account for the Poisson fluctuation probability in the number of events.

The true number of counts is not just what we see in the detector. We must count up everything.

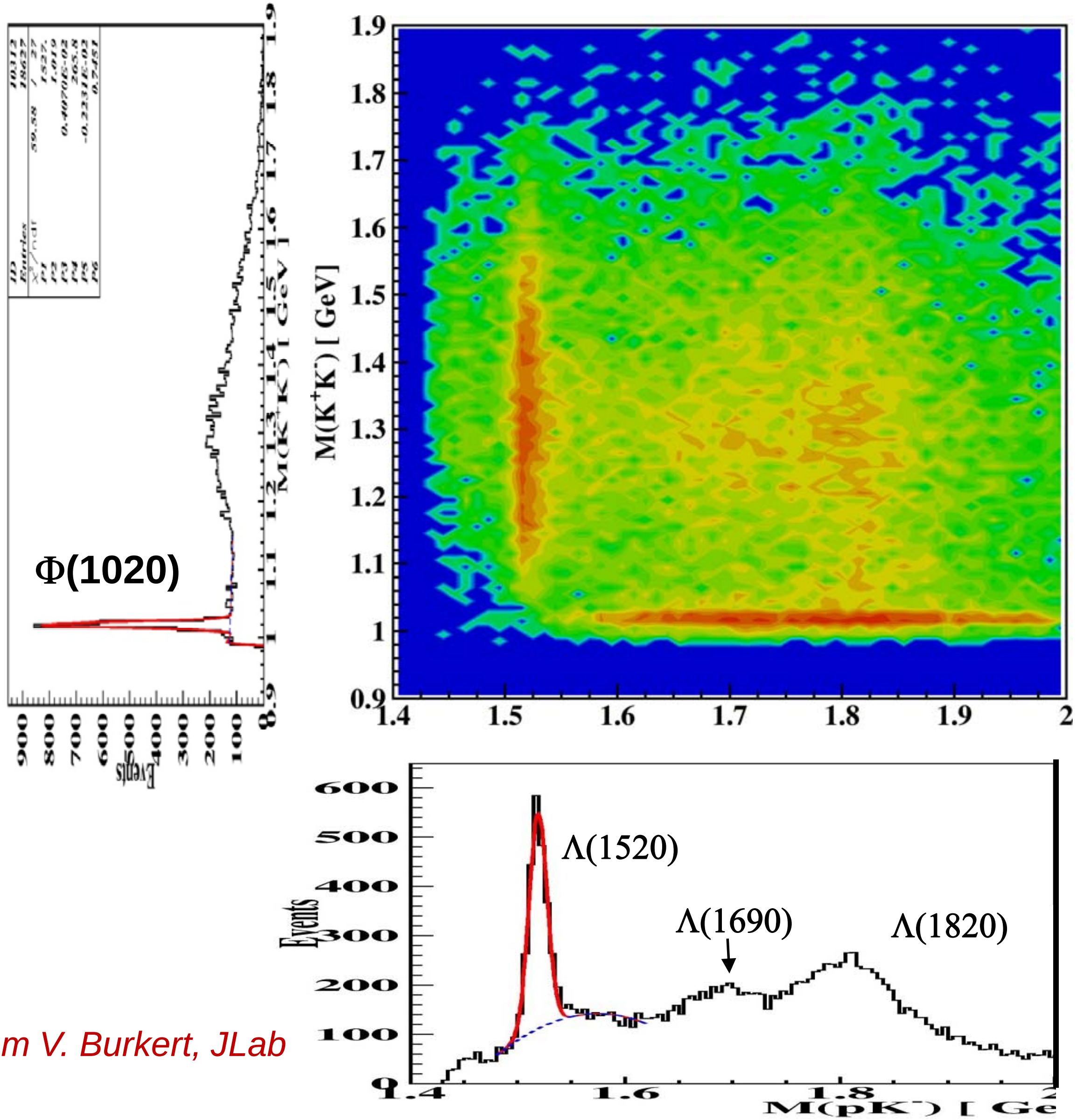
account for acceptance of detector and all inefficiencies

(the larger the detector acceptance, the smaller the corrections)

The CLAS Detector at JLab



example of Dalitz Plot: $\gamma p \longrightarrow pK^+K^-$

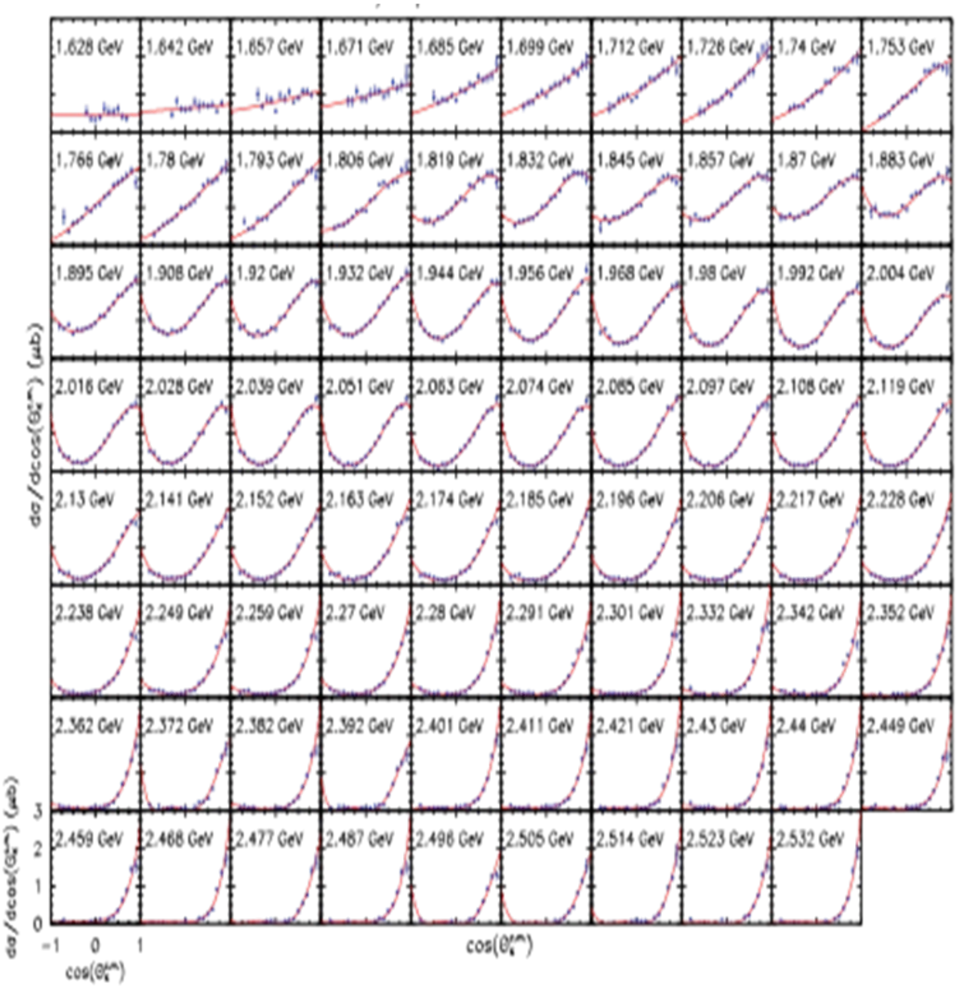


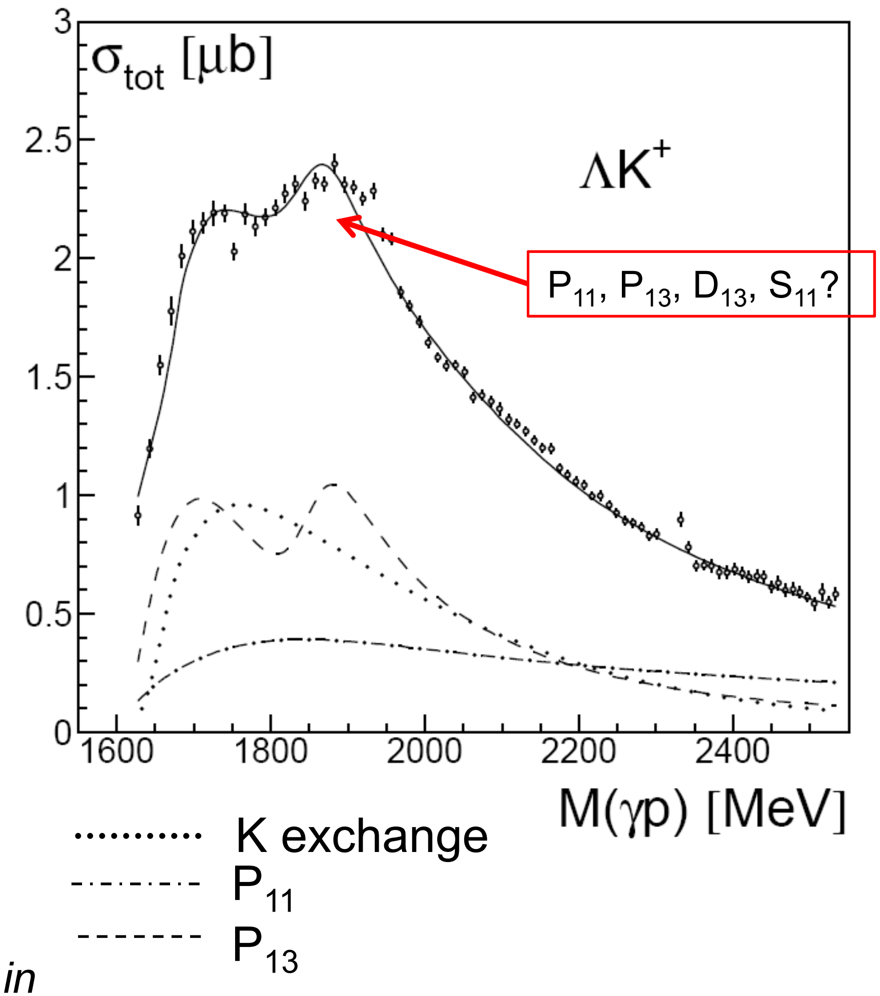
$E\gamma$ = 1.6-3.5 GeV

from the CLAS detector in Hall B at JLab

slide from V. Burkert, JLab

CLAS Differential & total cross section of $\gamma p \rightarrow K^+\Lambda$



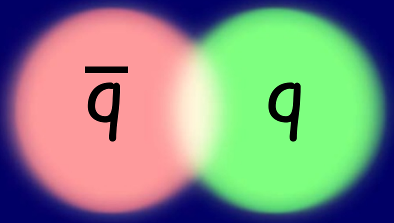


Needs polarization observables and measurement in other channels for more definite conclusions.

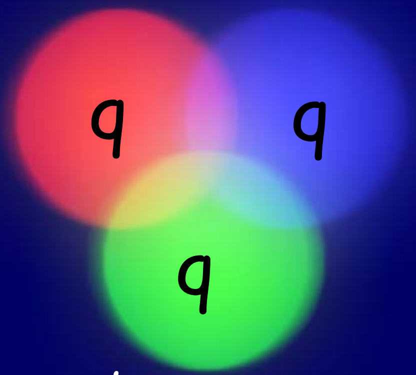
Beyond the Quark Model: Hybrids and Exotics

slide from R. deVita, AAAS meeting, Feb 2008

Quarks combine to “neutralize” color force

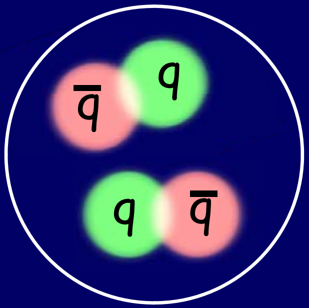


mesons

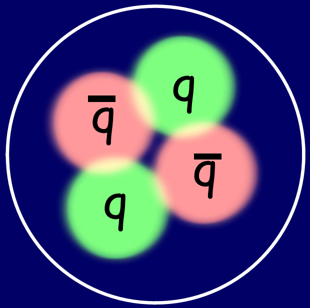


baryons

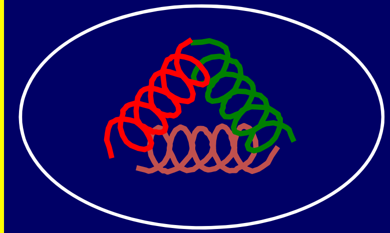
Other quark-gluon configurations can give colorless objects



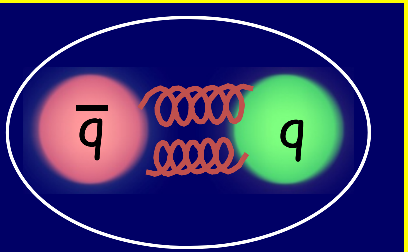
molecule



tetraquark



glueball meson



hybrid meson

pure glue

from V. Crede, FSU

- Glueballs: $g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$
- Hybrids: $q \otimes \bar{q} \otimes g = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus 1$ ➜ $\boxed{(q\bar{q})^{l}((q)^{3})^{m}(g)^{n}}$,

  $l + m \geq 1$ for $n = 1$

③ States with hidden exotic properties

$\Rightarrow$ Problem: predicted glueballs can mix with ordinary $q\bar{q}$ states

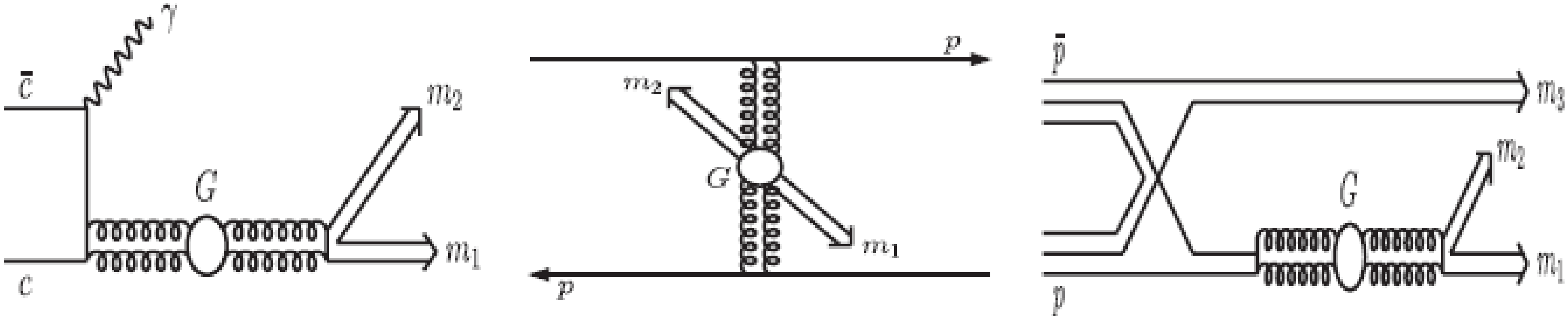
$f_0(1500)\ \}\ J^{PC} = 0^{++}$

In summary: Is there evidence for glueballs?

- Lightest 0^{++} glueball: possible ... $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
- Lightest 0^{-+} glueball: maybe ... $\eta(1295)$, $\eta(1405)$, $\eta(1490)$
- Lightest 2^{++} glueball: well, there is not even a candidate ...

Glue-Rich Environments

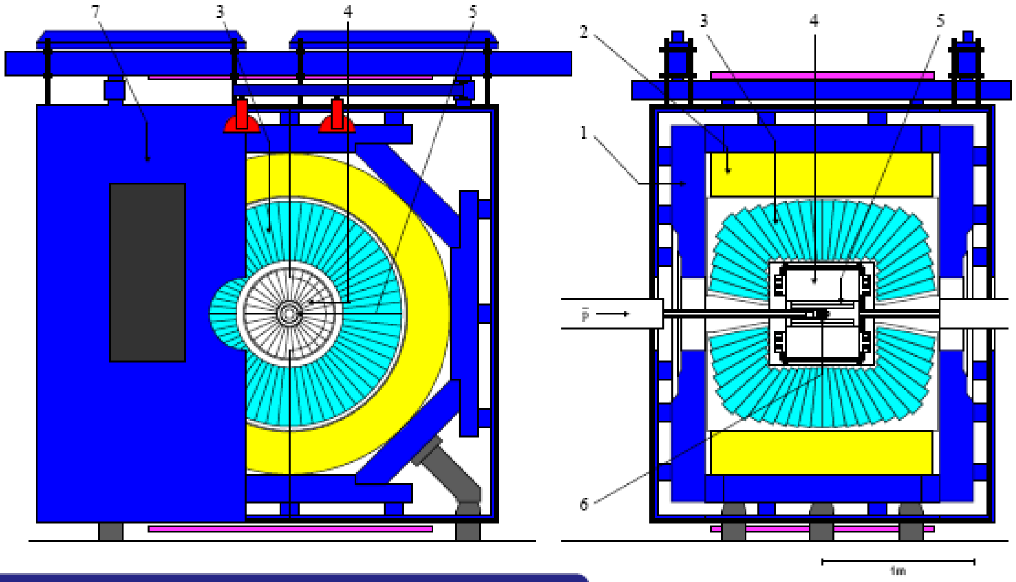
from V. Crede, FSU



Different Production Mechanisms

1. J/ψ may convert into two gluons and a photon.
2. In central production, two hadrons scatter diffractively; no valence quarks are exchanged.
3. In $p\bar{p}$ annihilation, quark-antiquark pairs annihilate into gluons forming glueballs.

The Crystal-Barrel Experiment *from V. Crede, FSU*



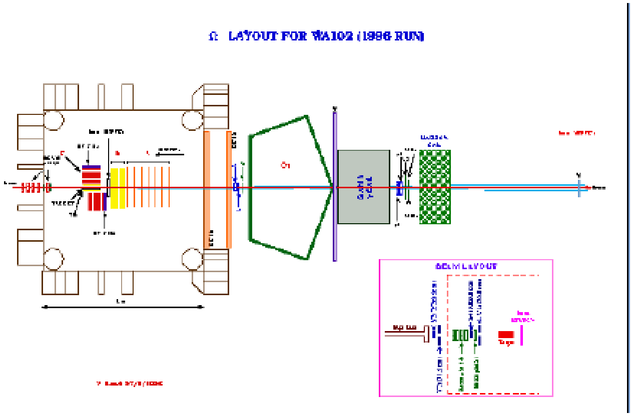
$p+\bar{p}$

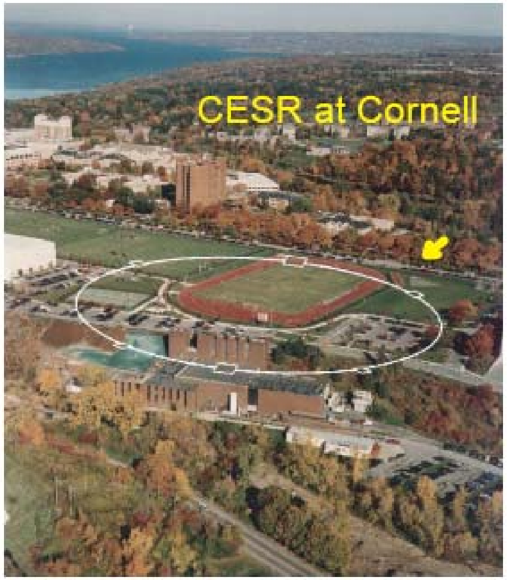
1989 - 1996

Proton-Antiproton Physics at LEAR, CERN

$p+p$

Combination of WA76 and GAMS-4000 detector ...

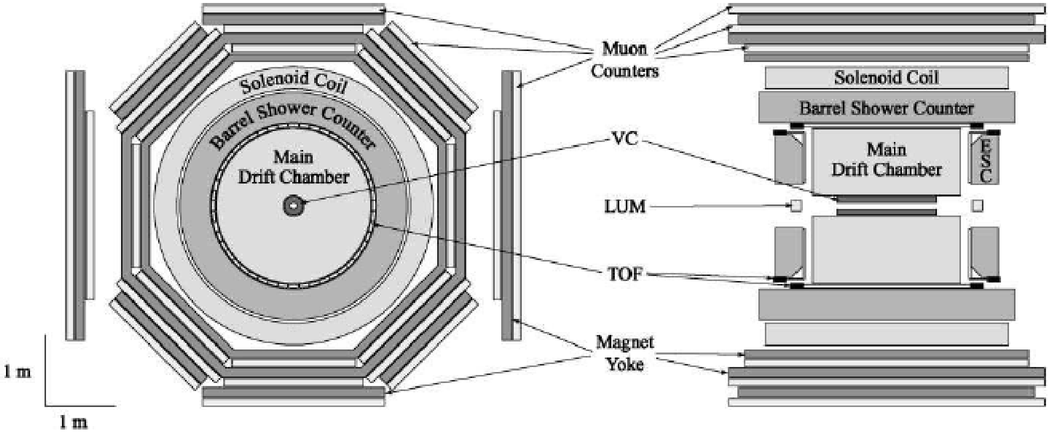




$e^+ + e^-$

The BES-II Experiment at IHEP, Beijing

Operation started in 1989 ...



from V. Crede, FSU

Do glueballs exist in nature?

I don't know ... `http://dx.doi.org/10.1016/j.ppnp.2009.03.001`

① The tensor glueball

➡ No evidence so far.

② The pseudoscalar glueball

➡ Very weak evidence, not likely.

③ The scalar glueball

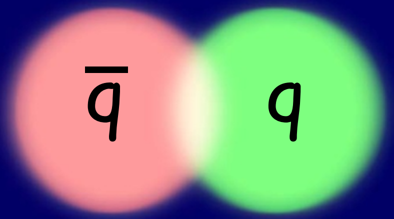
➡ Best evidence, but no clear state. Physical states can mix:

$$\begin{pmatrix} |\, f_0(1370) \,\rangle \\ |\, f_0(1500) \,\rangle \\ |\, f_0(1710) \,\rangle \end{pmatrix} = \begin{pmatrix} M_{1n} & M_{1s} & M_{1g} \\ M_{2n} & M_{2s} & M_{2g} \\ M_{3n} & M_{3s} & M_{3g} \end{pmatrix} \cdot \begin{pmatrix} |\, n\bar{n} \,\rangle \\ |\, s\bar{s} \,\rangle \\ |\, G \,\rangle \end{pmatrix}$$

Beyond the Quark Model: Hybrids and Exotics

slide from R. deVita, AAAS meeting, Feb 2008

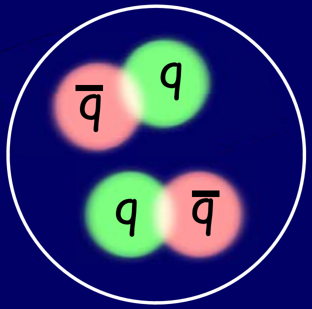
Quarks combine to “neutralize” color force



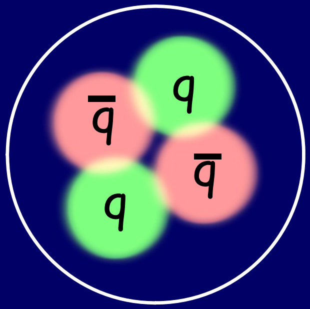
mesons

baryons

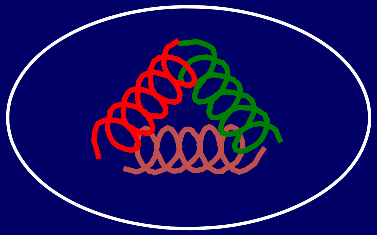
Other quark-gluon configurations can give colorless objects



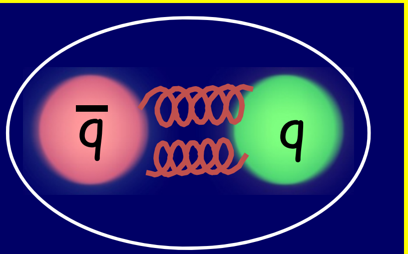
molecule



tetraquark



glueball meson



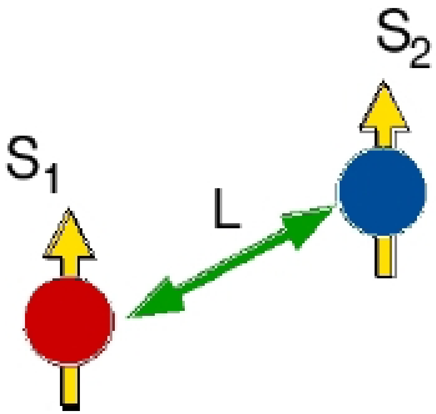
hybrid meson

See Dan Carman's seminar from see last year's Summer School

"Ordinary" Meson Properties

- Spin/angular momentum configurations and radial excitations generate the known spectrum of light quark mesons.

Starting with u, d, s quarks, we expect to find mesons grouped in nonets, each characterized by a given J, P, and C.

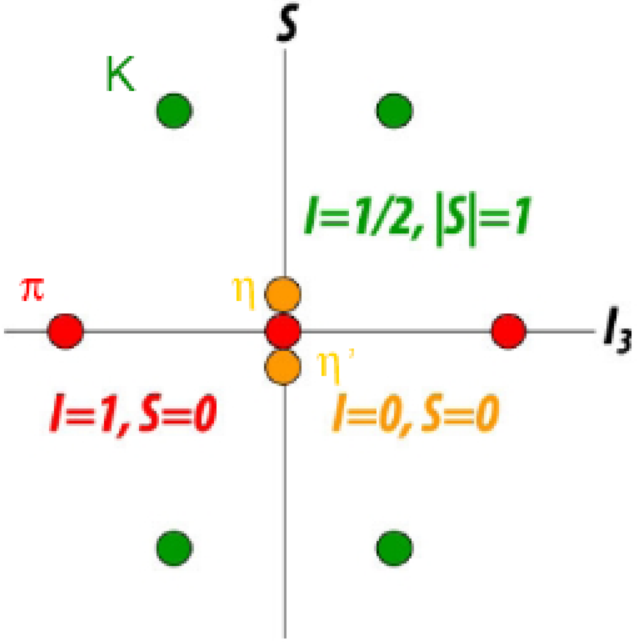


$S = S_1 + S_2$

$J = L + S$

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

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



$q\bar{q}$ color singlet bound states

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

Allowed combinations

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

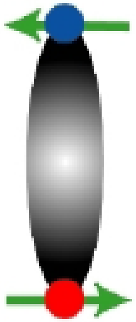
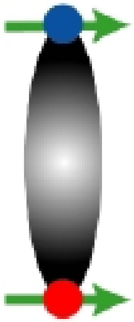
Not-allowed: exotic

No need for gluons here!

Hybrid Mesons

See Dan Carman’s seminar from see last year’s Summer School

Hybrids are quark−antiquark states with excitation energy in the gluonic flux tube.

Quarks	⊕	**Excited Flux Tube**	→	**Hybrid Meson**
S = 0 L = 0 $J^{PC} = 0^{-+}$ **like** π, K		$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$		$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$
S = 1 L = 0 $J^{PC} = 1^{--}$ **like** γ, ρ		$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$		**Exotic** $J^{PC} = \begin{cases} 0^{-+} & \boxed{1^{-+}} & 2^{-+} \\ \boxed{0^{+-}} & 1^{+-} & \boxed{2^{+-}} \end{cases}$

Flux tube excitation (and parallel quark spins) lead to exotic J^{PC}

Exotic Mesons

See Dan Carman's seminar from see last year's Summer School

Data Set Overview

- Existing data for the evidence of exotic mesons has come from a number of sources.

1). **Brookhaven National Laboratory**: E852 - 18 GeV $\pi^- p$ reactions

2). **Crystal Barrel at CERN**: $\bar{p}p$, $\bar{p}d$ reactions at 1–2 GeV

3). **VES at IHEP**: $\pi^- p$ at 37 GeV

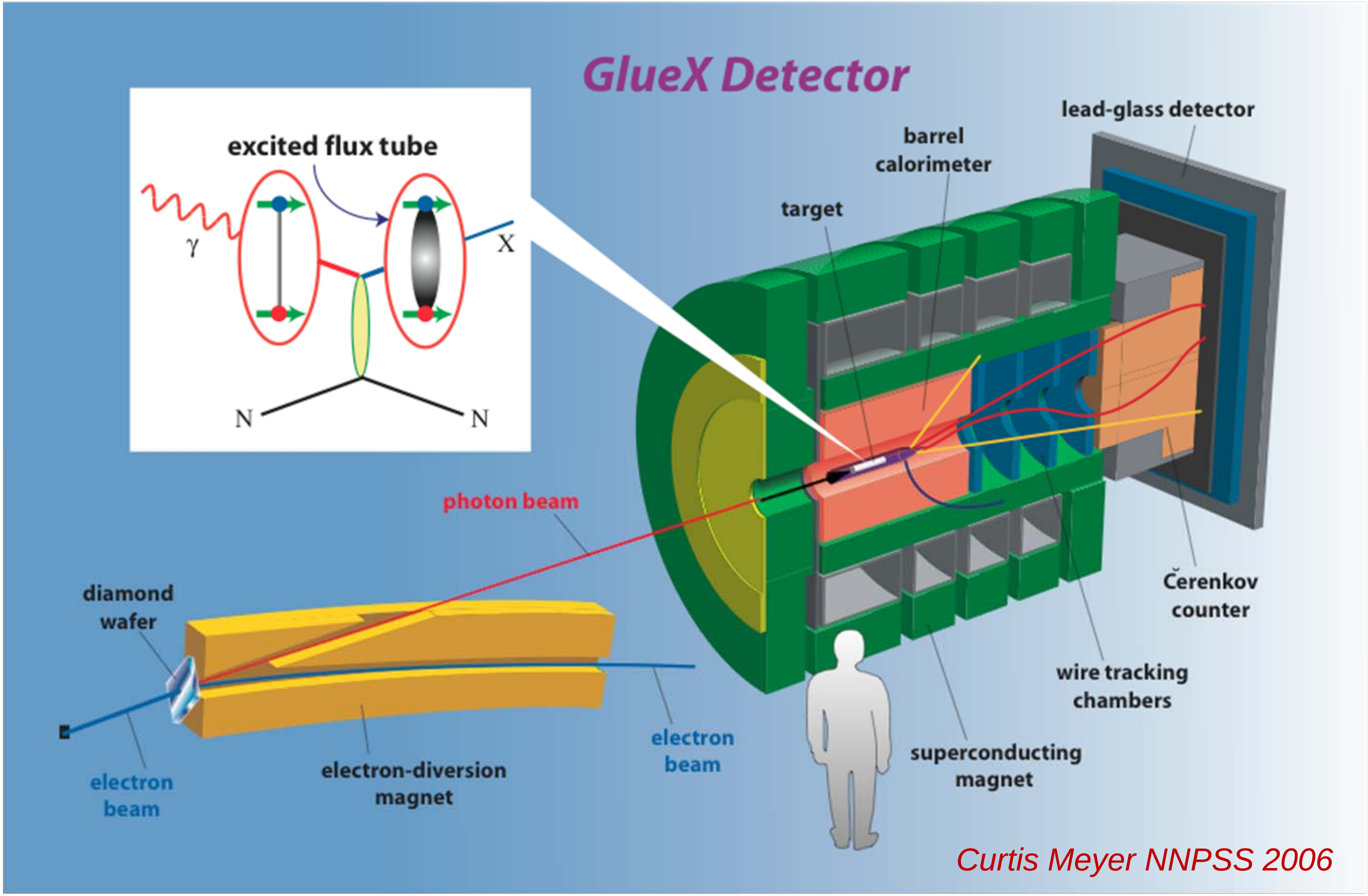
4). **GAMS at Serpukhov**: $\pi^- p$ at 40 GeV

5). **KEK at Japan**: $\pi^- p$ at 6 GeV

6). **Smattering of photoproduction data**: SLAC (old) and JLab/CLAS

Each experiment has its own limitations, not the least of which is relatively small statistics!

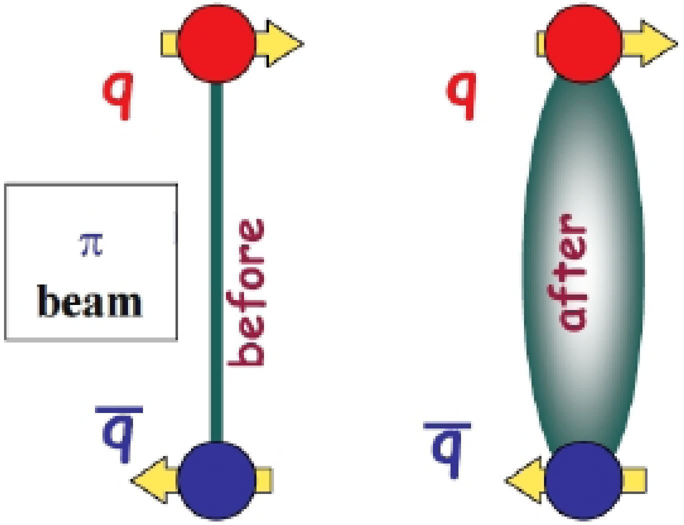
The GlueX Experiment (w/ JLab 12 GeV upgrade)



Curtis Meyer NNPSS 2006

Photoproduction Experiment

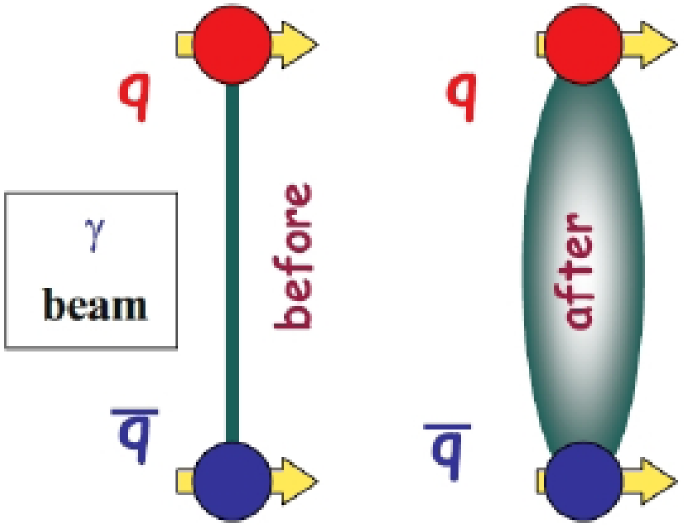
See Dan Carman's seminar from
see last year's Summer School



Quark spins anti-aligned

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

Much data in hand but little
evidence for gluonic excitations
(and not expected)



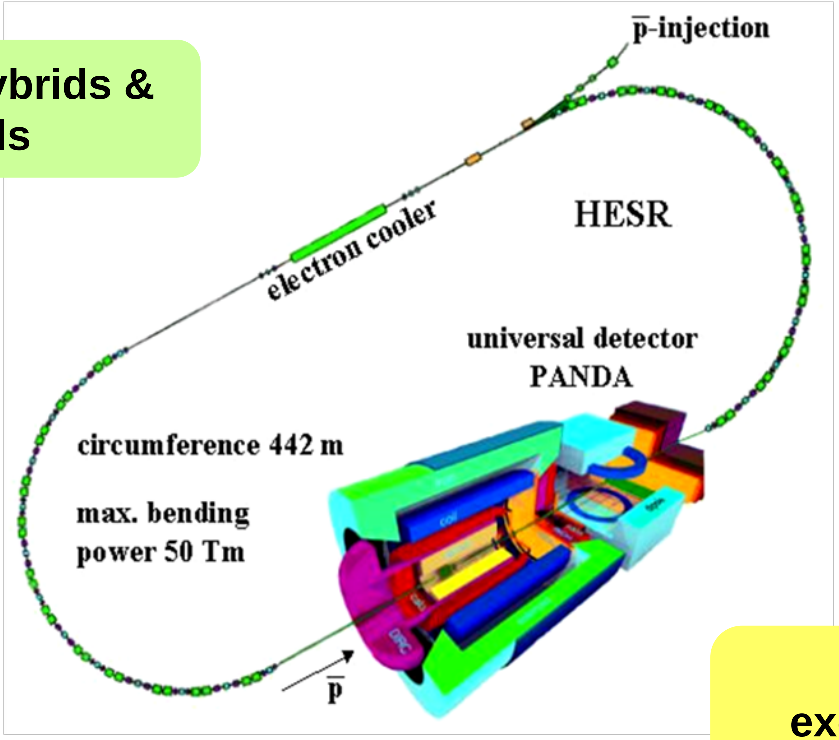
Quark spins aligned

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

CROSS SECTIONS SHOULD BE SIZEABLE!

GSI Helmholtz Center and FAIR

PANDA Physics Program at the FAIR Facility in Germany



Charmonium spectroscopy

Exotics: charmed hybrids & heavy glueballs

Time-like form factors

Medium modifications of charmed mesons

Drell-Yan processes

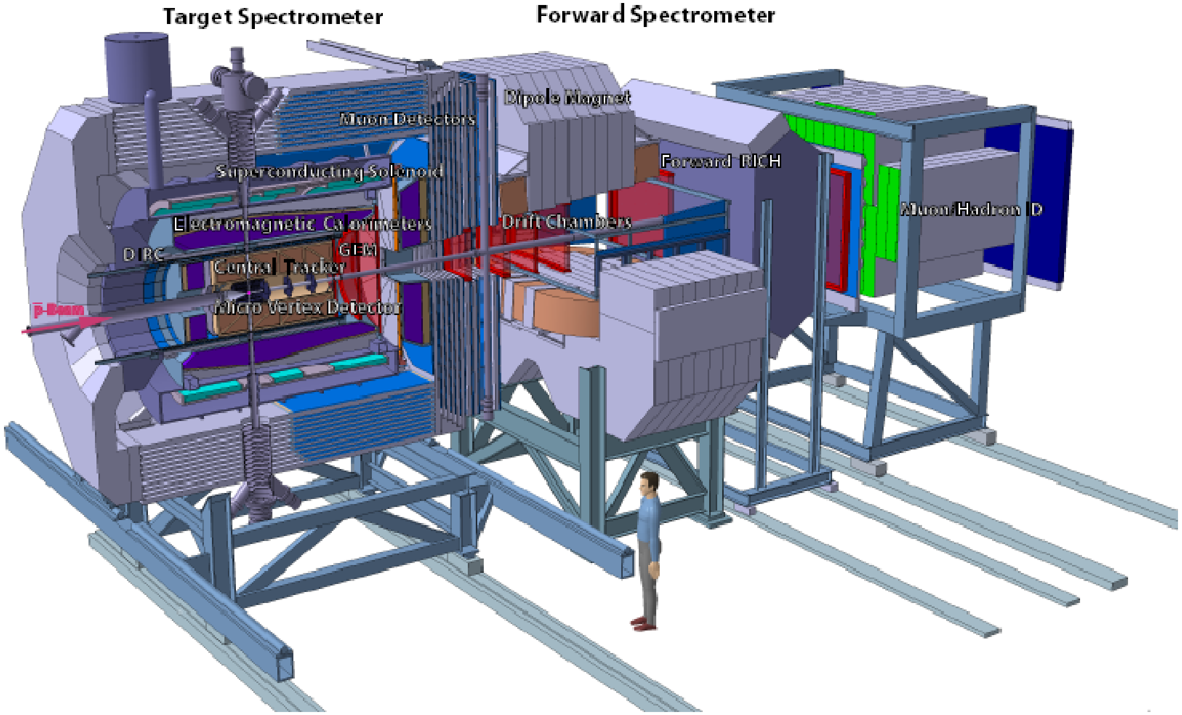
CP-violation (D & Λ - sector)

Hard exclusive processes

Hypernuclei

D. Bettoni, GHP 2009

PANDA detector



http://www.gsi.de/panda

Detector Requirements

- (Nearly) 4π solid angle coverage (partial wave analysis)
- High-rate capability (2×10^7 annihilations/s)
- Good PID (γ, e, μ, π, K, p)
- Momentum resolution ($\approx$ 1 %)
- Vertex reconstruction for D, K^0_s, Λ
- Efficient trigger
- Modular design
- Pointlike interaction region
- Lepton identification
- Excellent calorimetry
  - Energy resolution
  - Sensitivity to low-energy photons

Summary of this section

The quark model laid the groundwork for QCD.

The basic spectroscopy of the more easily identifiable bound states of meson and baryon can be characterized by a set of quantum #'s described by the quark model.

Searching for new bound states tests the limits, perhaps revealing something deeper about QCD and confinement.

Difficult task! Need lots of data taken together with close connection to theory.

Opportunities are abundant!

Hadron Physics

Lecture #1: The quark model, QCD, and hadron spectroscopy

Lecture #2: Internal structure of hadrons: momentum and spin

Lecture #3: Internal structure of hadrons: charge, magnetism, polarizability

Lecture #4: Hadrons as laboratories (and other miscellaneous topics)