JLab: Probing Hadronic Physics with Electrons and Photons

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Jefferson Lab

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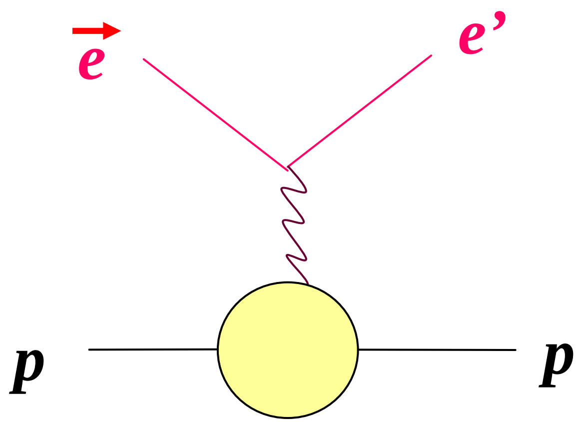
Introduction to JLab

The shape of the proton

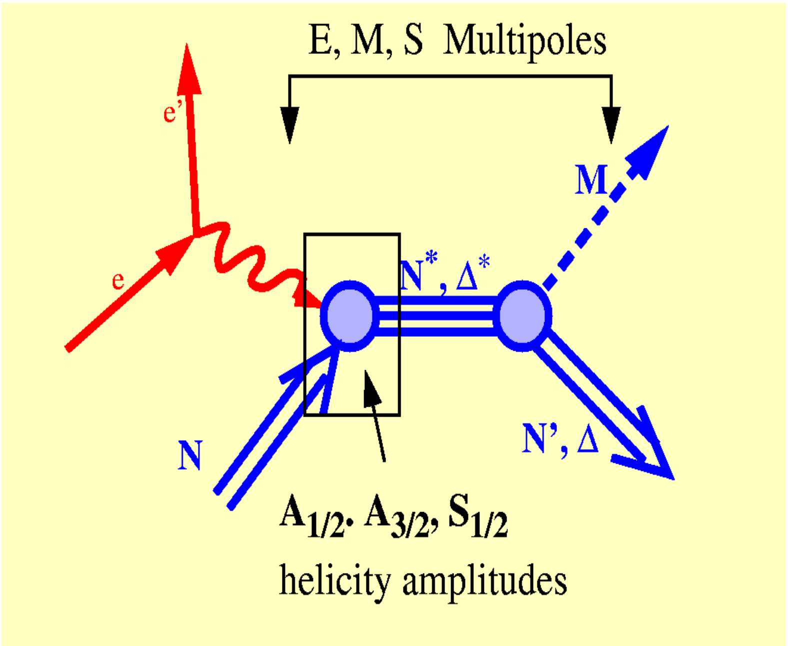
Pentaquarks

Why use electron and photon probes?

Electromagnetic interaction is well-known



F(Q^2)



Elastic Form Factors

Inelastic transitions

Size probed ~ $1/\sqrt{Q^2}$

CEBAF @ JLab Today

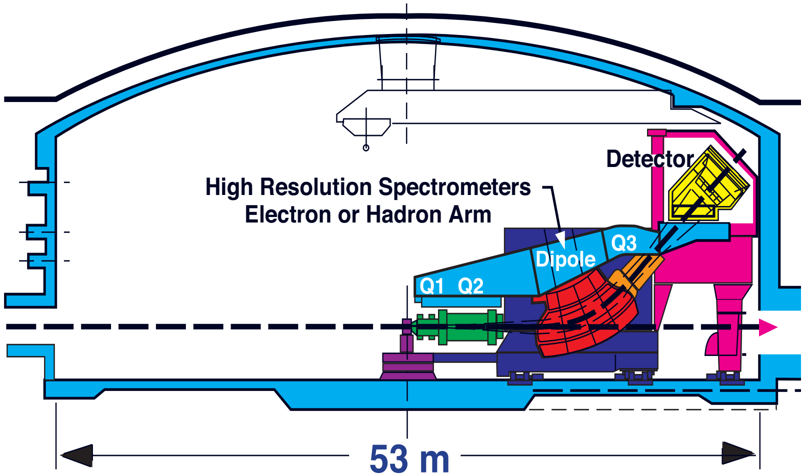
- Main physics programs
  - nucleon electromagnetic form factors (including strange form factors)
  - N $\rightarrow$ N* electromagnetic transition form factors
  - spin structure functions of the nucleon
  - form factors and structure of light nuclei

- Superconducting recirculating electron accelerator
  - max. energy 5.7 GeV
  - max current 200 μA
  - e polarization 80%

- Simultaneous operation in 3 halls — $L[cm^{-2}s^{-1}]$
  - A: Two High Resolution Spectrometers (p_{max}=4 GeV/c — 10^{39}
  - B: Large Acceptance Spectrometer for e and γ induced reactions — 10^{34}
  - C: Two spectrometers (p_{max}= 7 and 1.8 GeV/c) + special equipment — 10^{39}

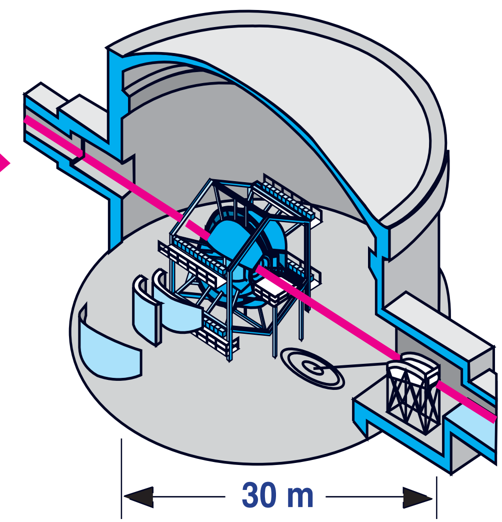
CEBAF accelerator site

Three Experimental End-Stations



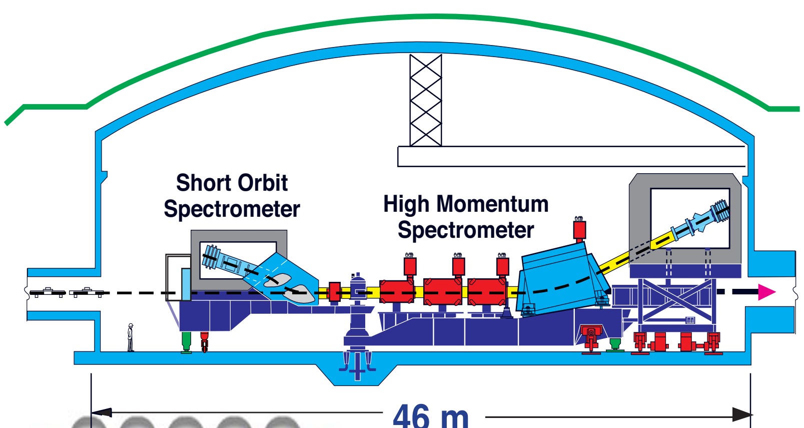
HALL A

Pair of identical High Resolution Spectrometers (HRS^2)



HALL B

CEBAF's Large Acceptance Spectrometer (CLAS) and Bremsstrahlung Photon Tagger



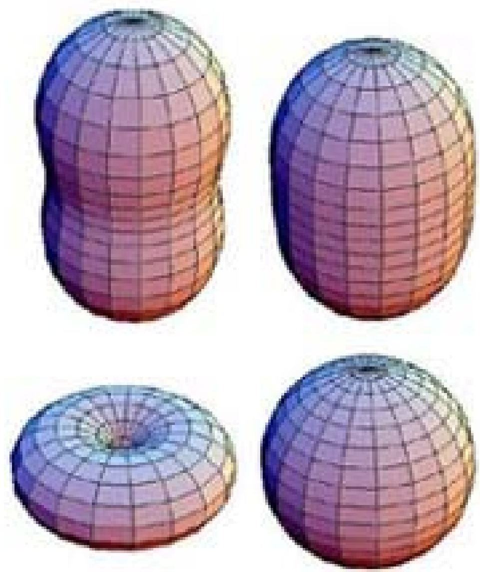
HALL C

High Momentum Spectrometer (HMS) and Short Orbit Spectrometer (SOS)

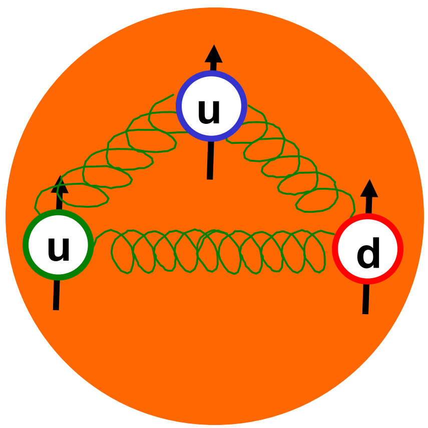
G_{Ep}: Electric form factor of the proton

Goal: Determine the charge and current distributions inside the proton

NY Times "Is a proton round?"



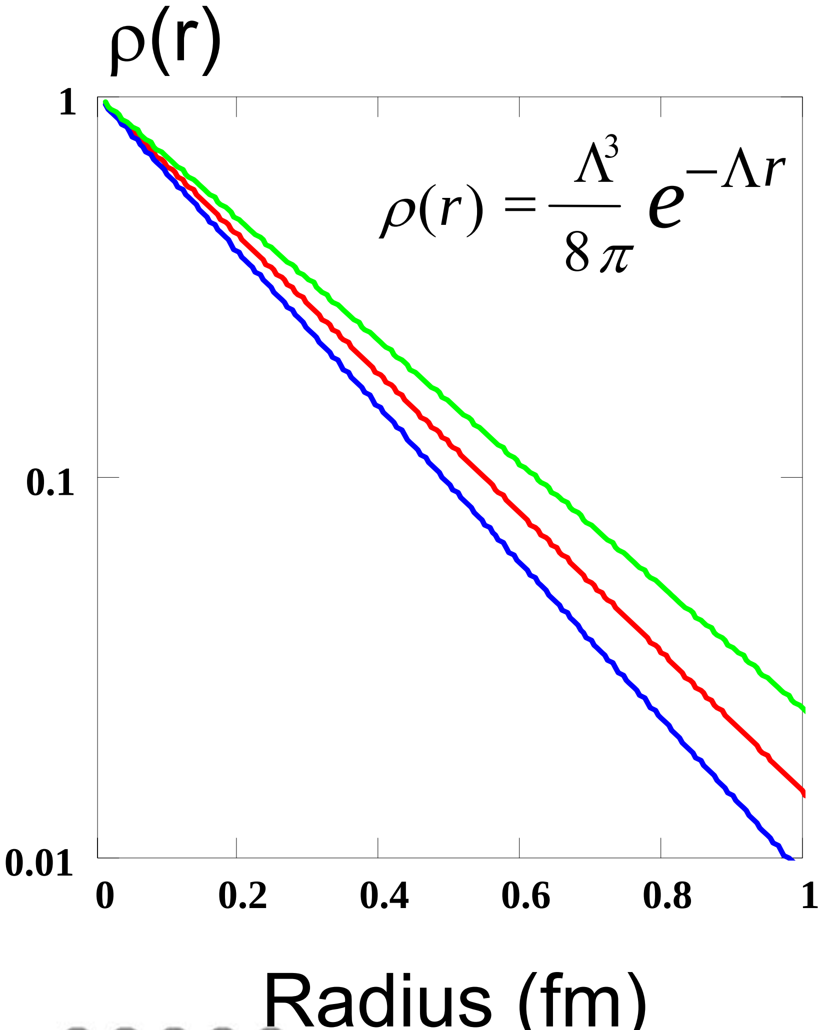
from G.A. Miller

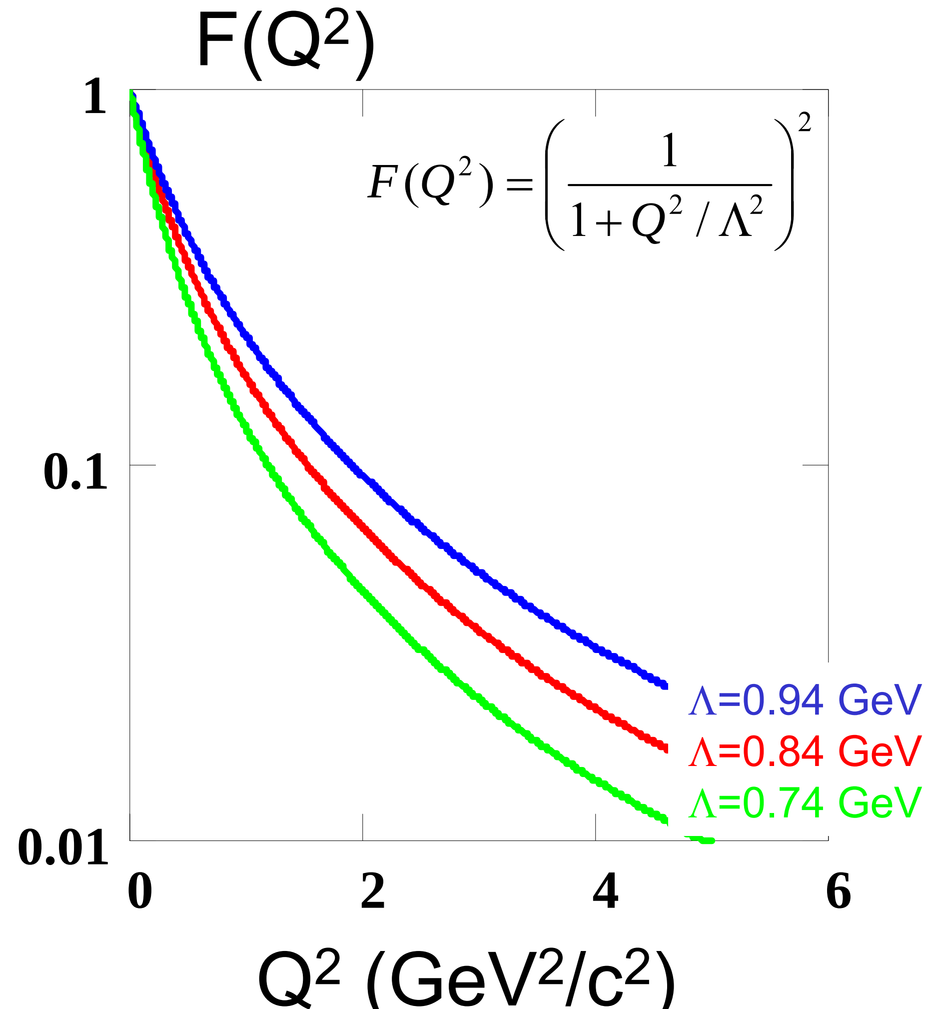


Naïve expectation is that the charge and currents are determined from the spatial distribution of quark charges and spins.

Charge distribution and Form Factors

$$\rho(r) = \int d^3q\, F(q^2)\, e^{-i\vec{q}\cdot\vec{r}}$$





Charge Distributions and Form Factors

point	$f(r) = \delta(r - r_o)$	$F(Q^2) = 1$	**unity**
exponential	$f(r) = \dfrac{\Lambda^3}{8\pi} e^{-\Lambda r}$	$F(Q^2) = \left(\dfrac{1}{1 + Q^2/\Lambda^2} \right)^2$	**dipole**
Yukawa	$f(r) = \dfrac{\Lambda^2}{4\pi r} e^{-\Lambda r}$	$F(Q^2) = \dfrac{1}{1 + Q^2/\Lambda^2}$	**pole**
Gaussian	$f(r) = \left(\dfrac{\Lambda^2}{2\pi} \right) e^{-\left(\frac{1}{2} \Lambda^2 r^2 \right)}$	$F(Q^2) = e^{-\frac{1}{2}\left(Q^2/\Lambda^2 \right)}$	**Gaussian**

Decomposition of the elastic cross section

$$\frac{d\sigma}{d\Omega} = \sigma_{ns} \left(\frac{G_{Ep}^2 + \tau G_{Mp}^2}{1+\tau} + 2\tau G_{Mp}^2 \tan^2(\vartheta_e/2) \right)$$

$$\sigma_{ns} = \frac{\alpha^2 \cos^2(\vartheta_e/2)}{4E^2 \sin^4(\vartheta_e/2)} \frac{E'}{E} \qquad \tau = \frac{Q^2}{4M_p^2}$$

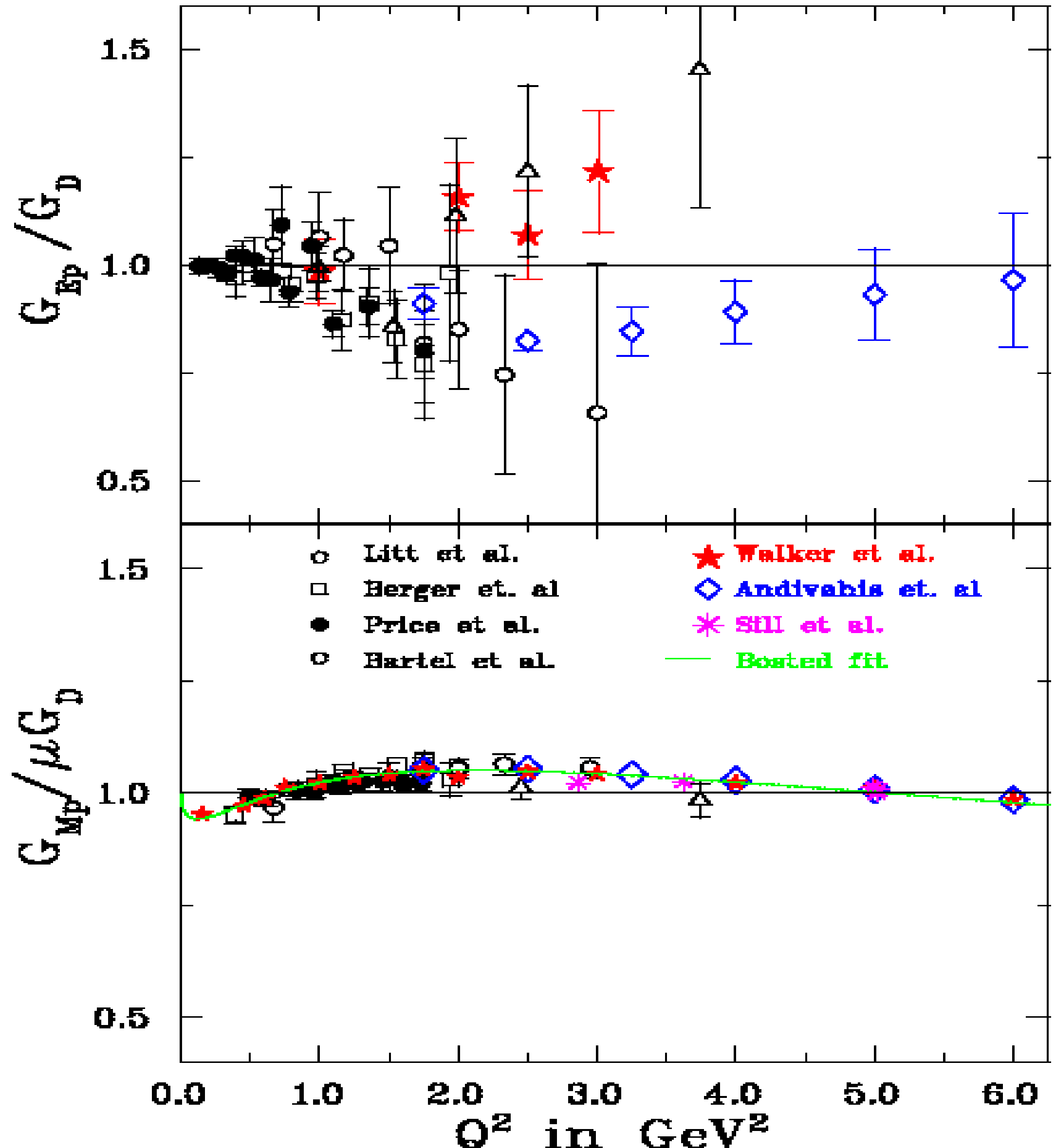
$$\sigma_R = \frac{d\sigma}{d\Omega} \frac{(1+\tau)\varepsilon}{\sigma_{ns}\tau} = \frac{\varepsilon}{\tau} G_{Ep}^2(Q^2) + G_{Mp}^2(Q^2)$$

$$\varepsilon = \{1 + 2(1+\tau)\tan^2(\vartheta_e/2)\}^{-1}$$

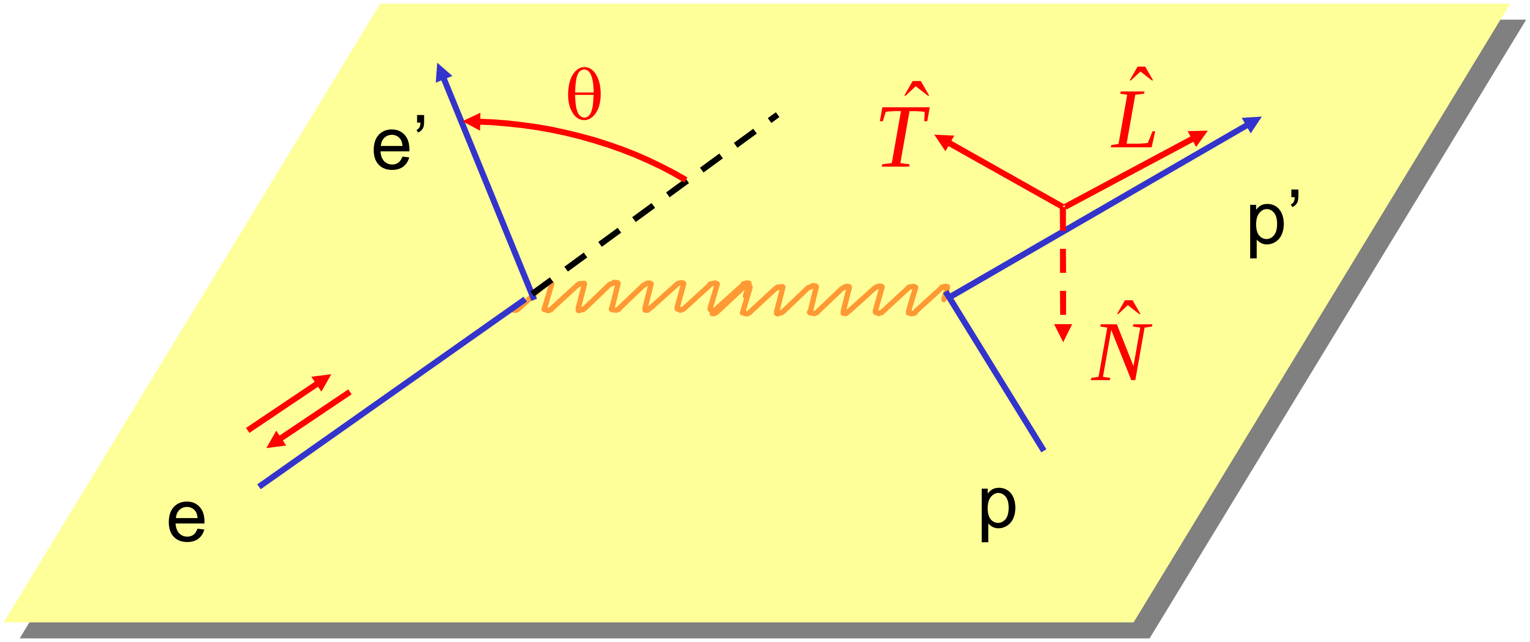
Proton Form Factors pre-1998

$$G_{Ep} \sim \frac{G_{Mp}}{\mu} \sim G_D$$

$$G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2}$$

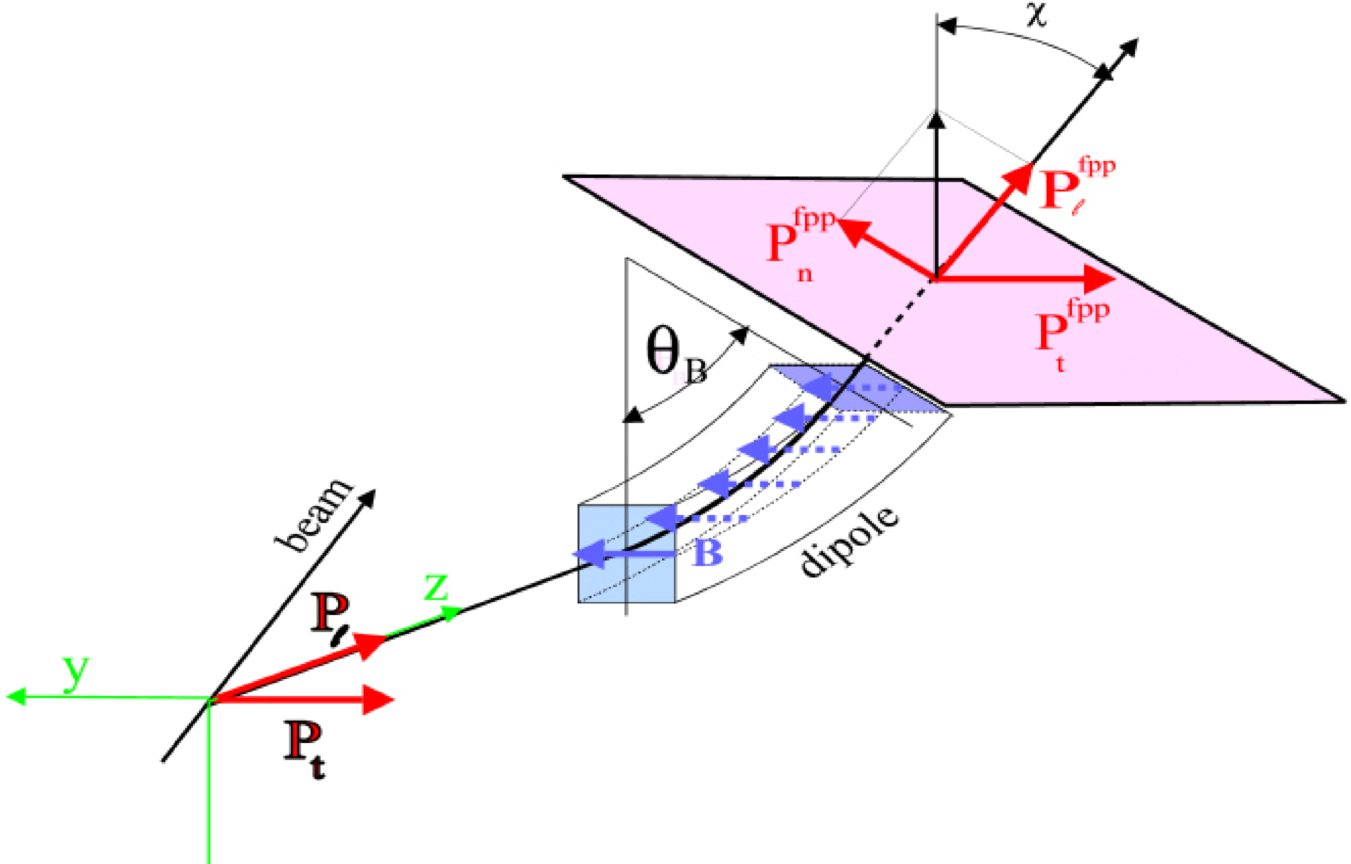


Spin transfer reaction $\vec{e}\,p \rightarrow e\,\vec{p}$



$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_l}\,\frac{E_e + E_{e'}}{2M}\tan(\vartheta_e/2)$$

Transport through magnet

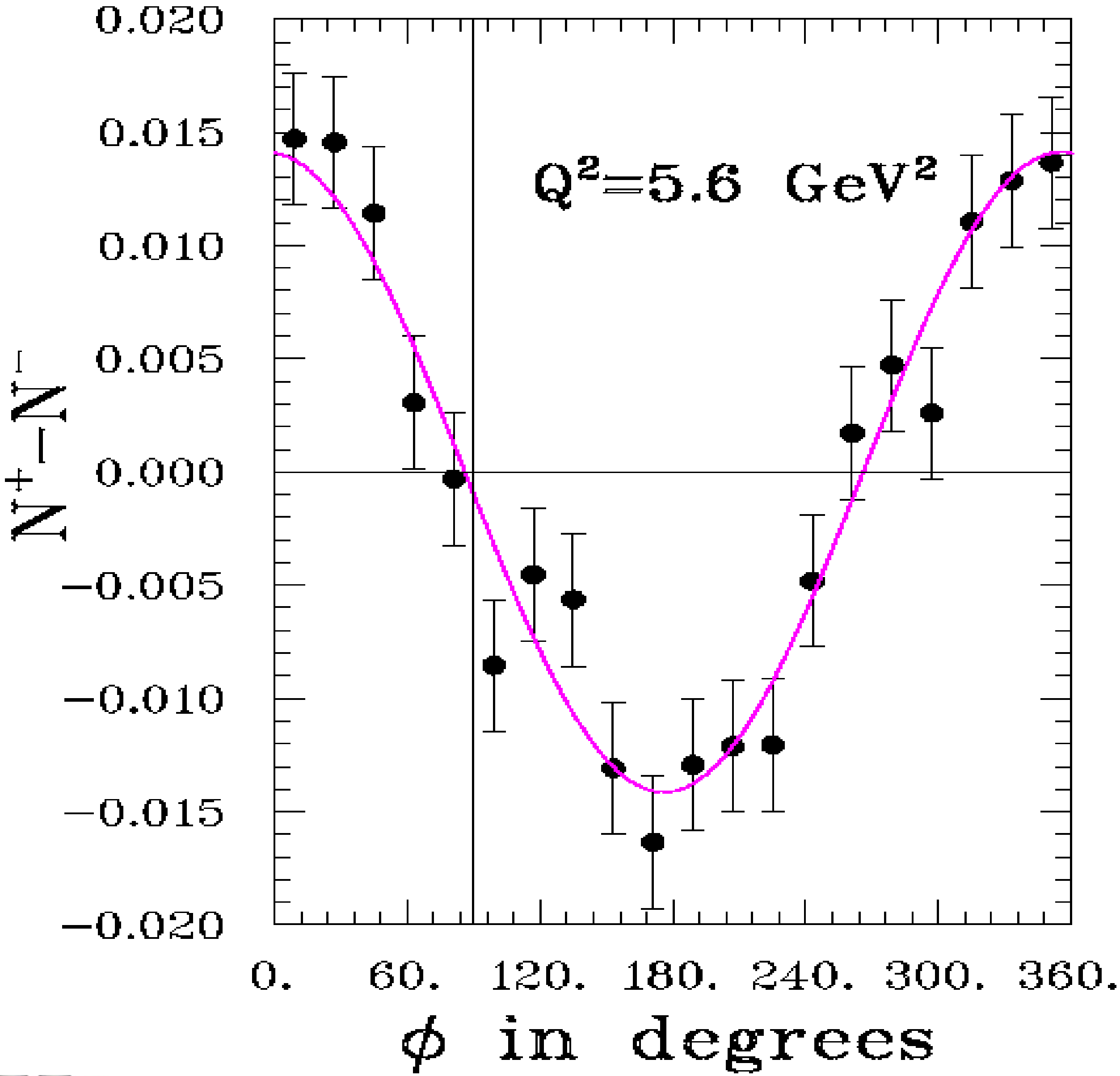


$$\chi = \gamma\, \theta_B (\mu_p - 1)$$

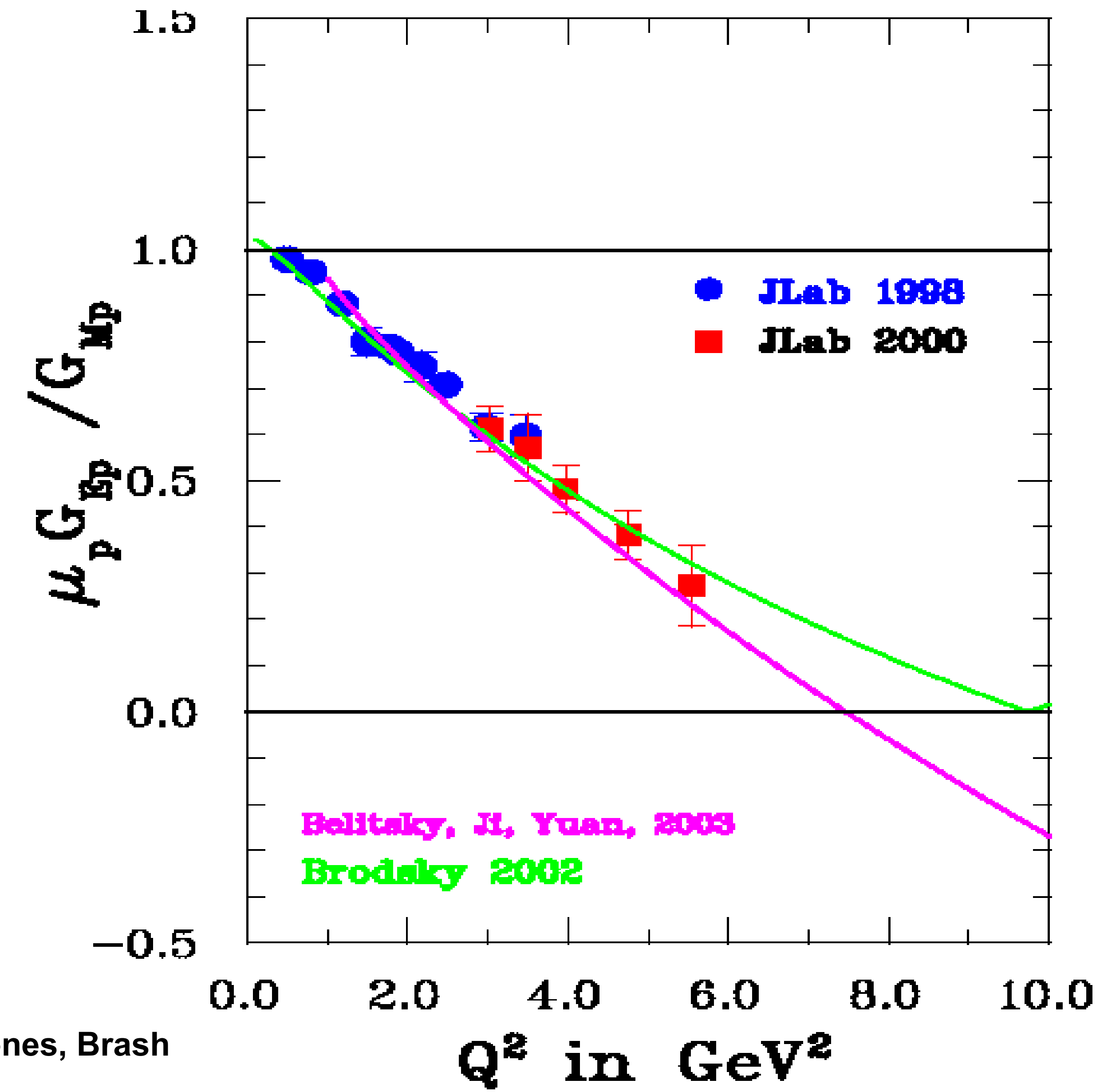
$$P_t^{fpp} = P_t$$

$$P_\ell^{fpp} = P_\ell \sin \chi$$

Azimuthal asymmetry in the polarimeter

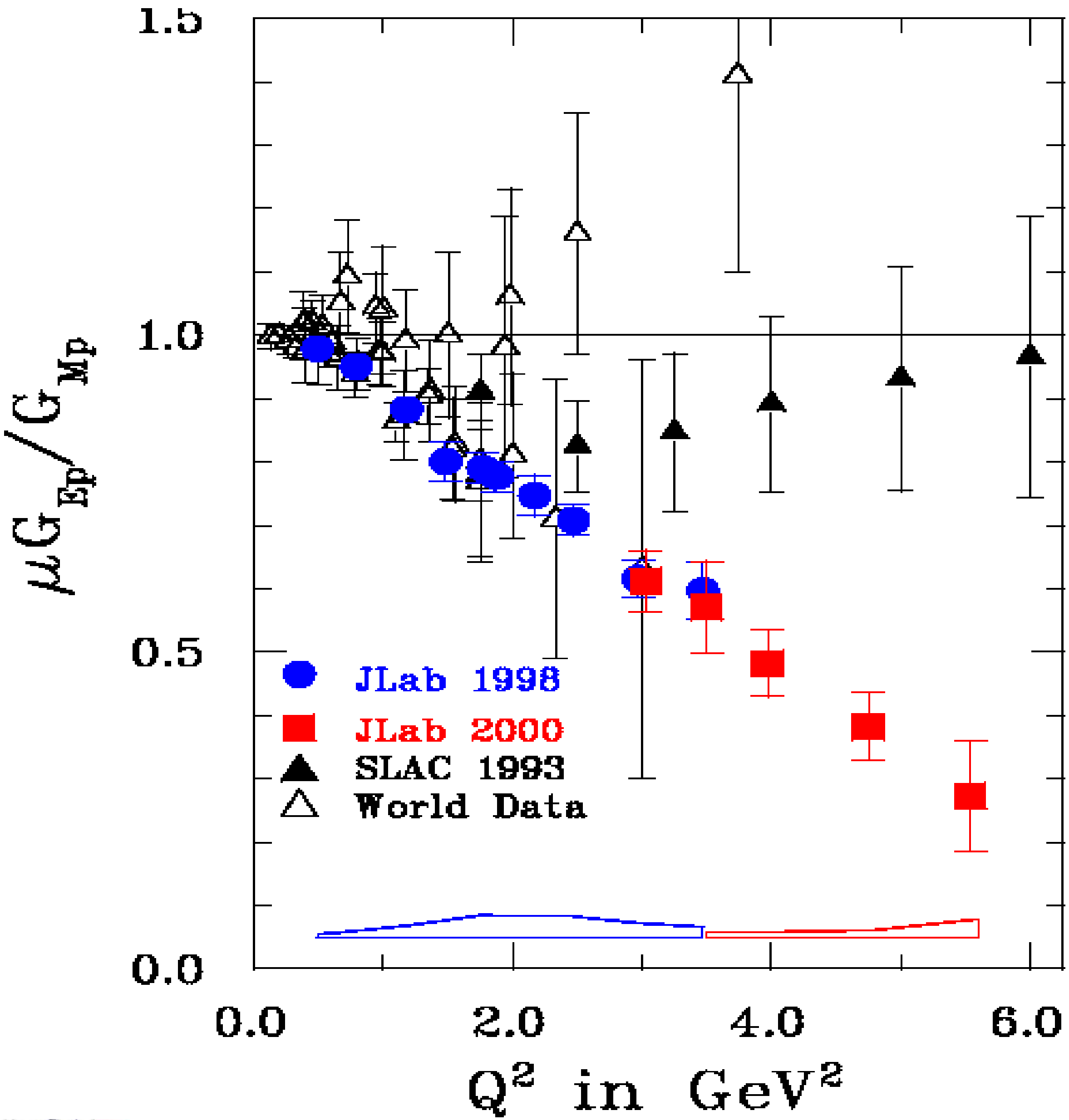


G_{Ep} from polarization transfer



E93-027, E99-007
Perdrisat, Punjabi, Jones, Brash

World data for G_{Ep}



Interpretation of new data

$F_2(Q^2)$ is a spin-flip transition

$$\langle P'_{\uparrow} | J^{\mu} | P_{\downarrow} \rangle \sim F_2(Q^2) \bar{u}_{\uparrow}(P') \frac{i\sigma^{\mu\nu} q_{\alpha}}{2M} u_{\downarrow}(P)$$

In the absence of quark angular momentum

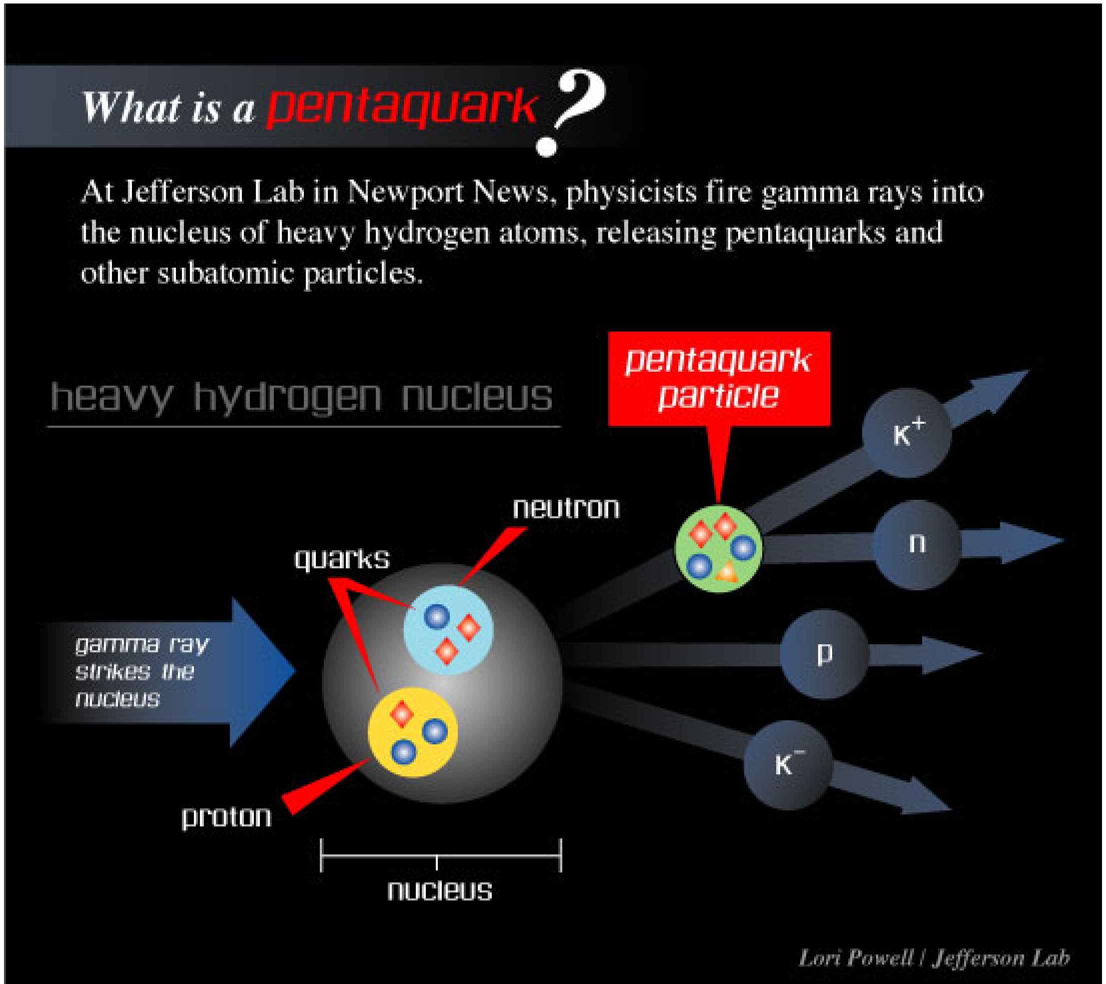
$$Q^2 \frac{F_2}{F_1} \sim m_q M \xrightarrow[m_q \to 0]{} 0$$

Quark orbital angular momentum essential to describe data

$$Q \frac{F_2}{F_1} \sim \frac{1}{Q} \log^2\left(\frac{Q^2}{\Lambda^2}\right) \sim const$$

Pentaquark: Baryon with five quarks

Goal: Determine quark content of colorless hadrons

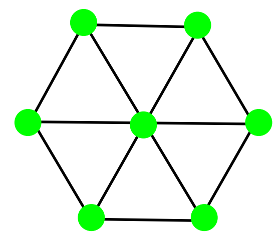


Expectation from the quark model is that the properties of baryons are determined by three valence quarks (qqq)

Hadron multiplets

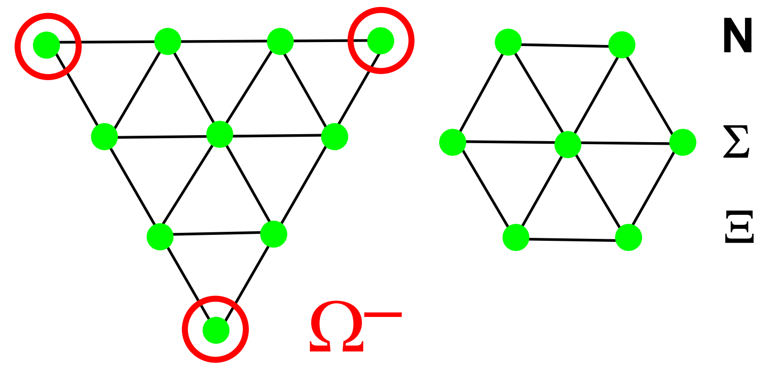
Mesons $q\bar{q}$

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



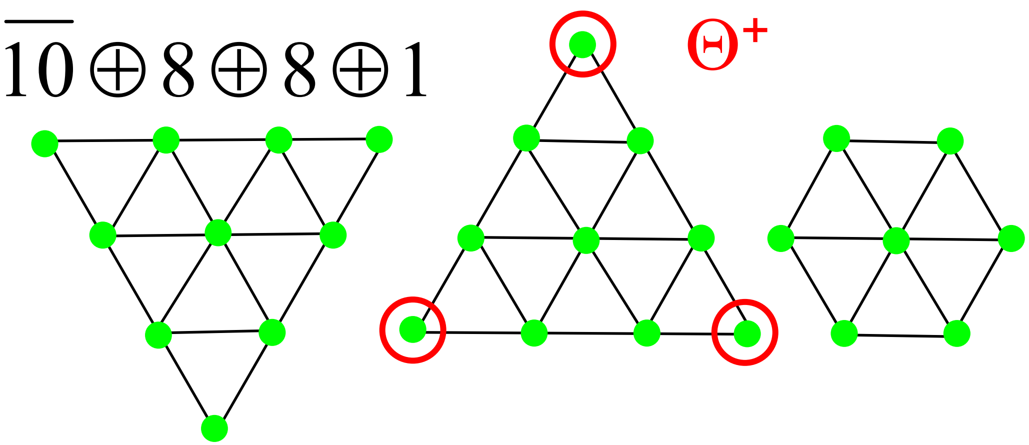
Baryons qqq

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

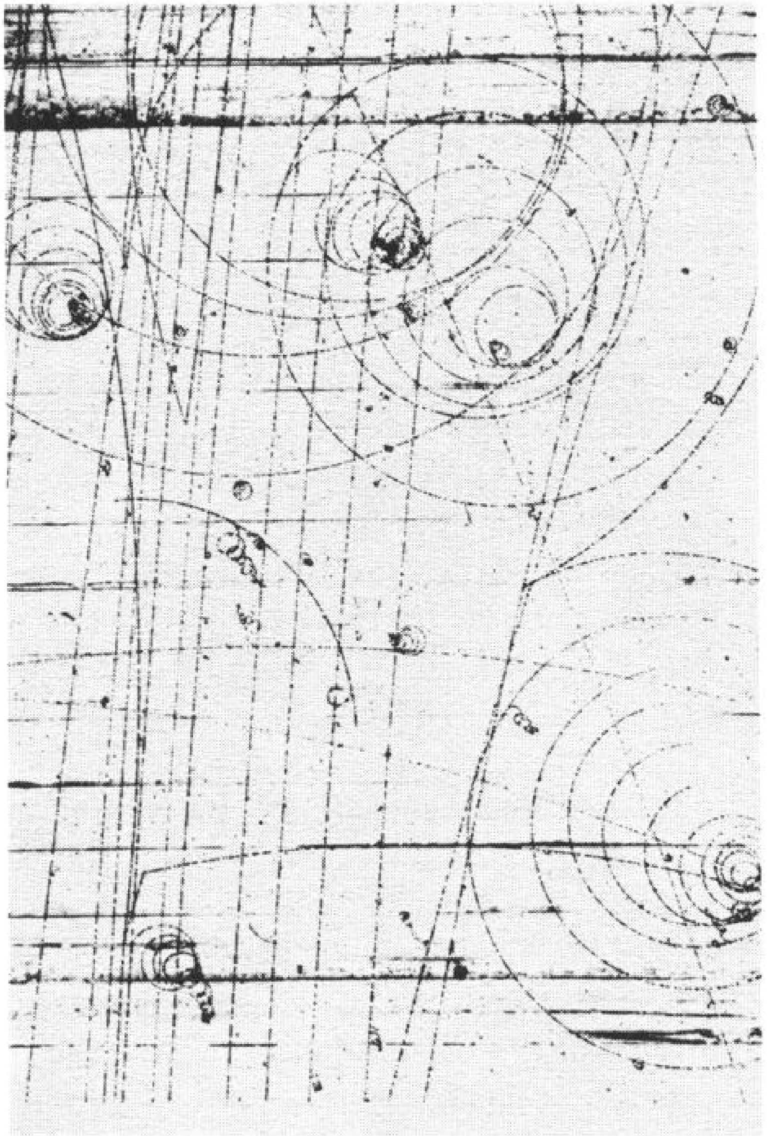


Baryons built from meson-baryon basis

$$8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$$



Production and decay of $\Omega^- \rightarrow \Xi^o \pi^-$



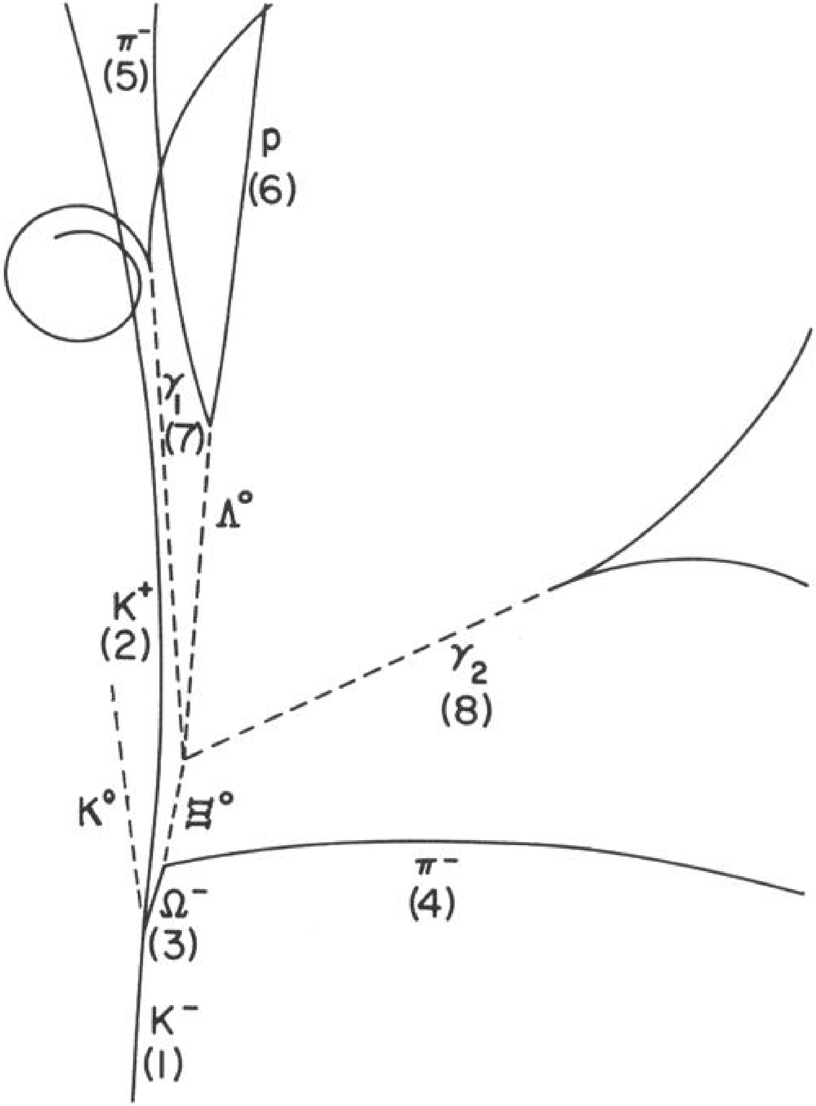


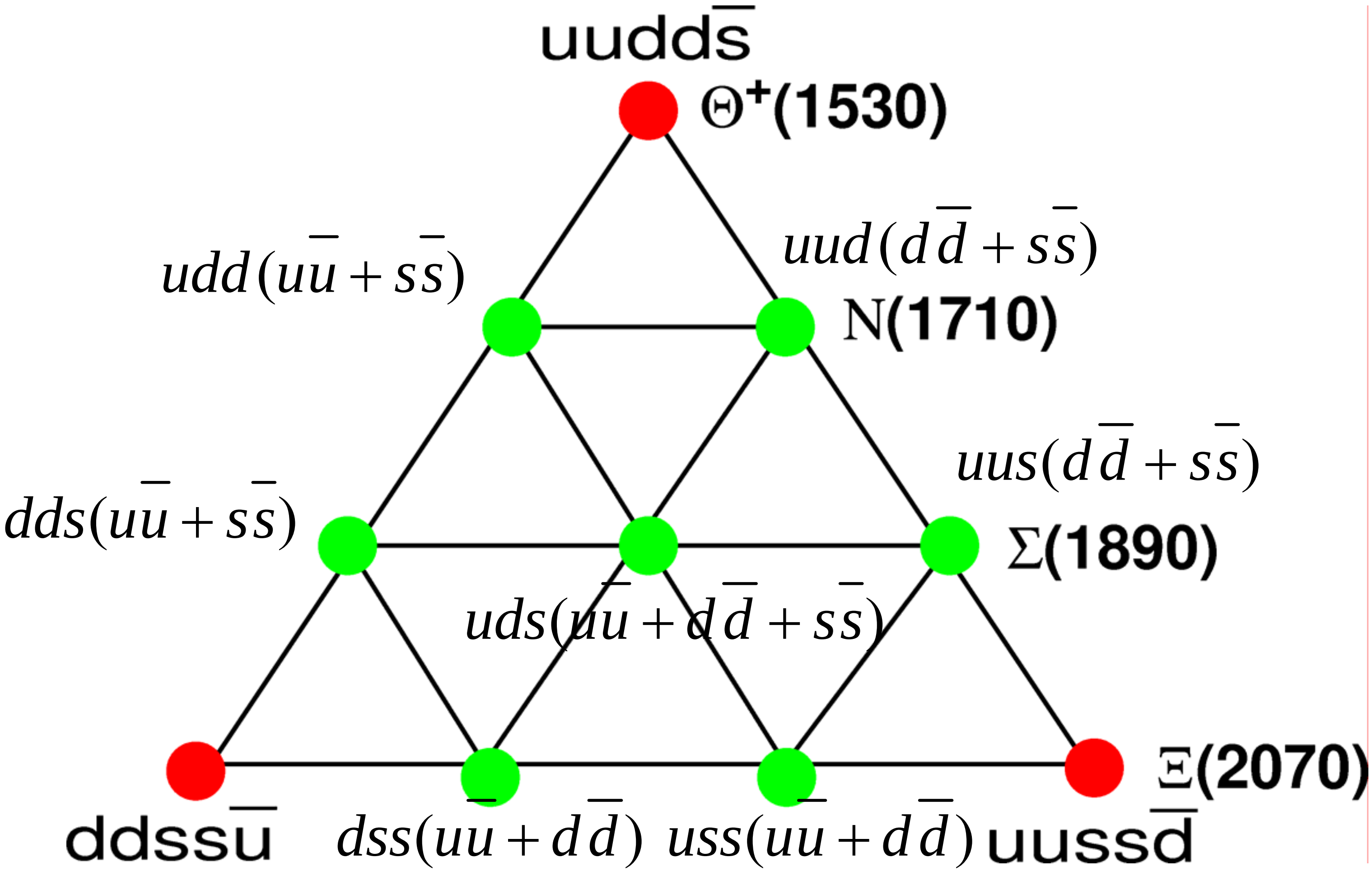
FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

What are pentaquarks?

- Minimum quark content is 5-quarks.
- Anti-quark has different flavor than any of 4-quarks ($qqqq\overline{Q}$).
- Quantum numbers can not be defined by 3-quarks.

- General idea of a five-quark states has been around since late 60's.
- However, searches did not give any conclusive results.
- PDG dropped the discussion on pentaquark searches after 1988.

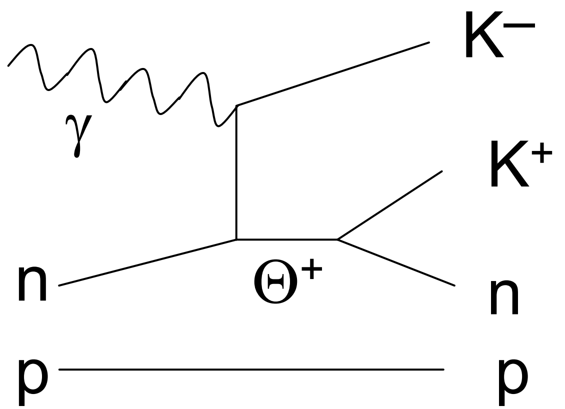
The Anti-decuplet predicted by Diakonov et al.



Reactions on deuterium

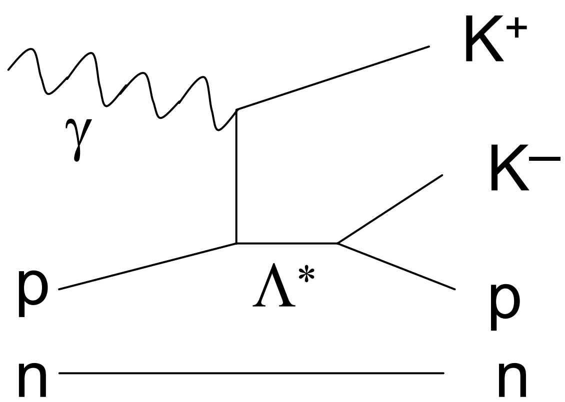
$$\gamma n\,(p) \rightarrow \Theta^{+} K^{-}\,(p)$$

$$\Theta^{+} \rightarrow K^{+} n$$



$$\gamma p\,(n) \rightarrow \Lambda^{*}(1520) K^{+}\,(n)$$

$$\Lambda^{*}(1520) \rightarrow K^{-} p$$



$$\gamma N \rightarrow \phi(1020)\, N \rightarrow K^{+} K^{-} N$$

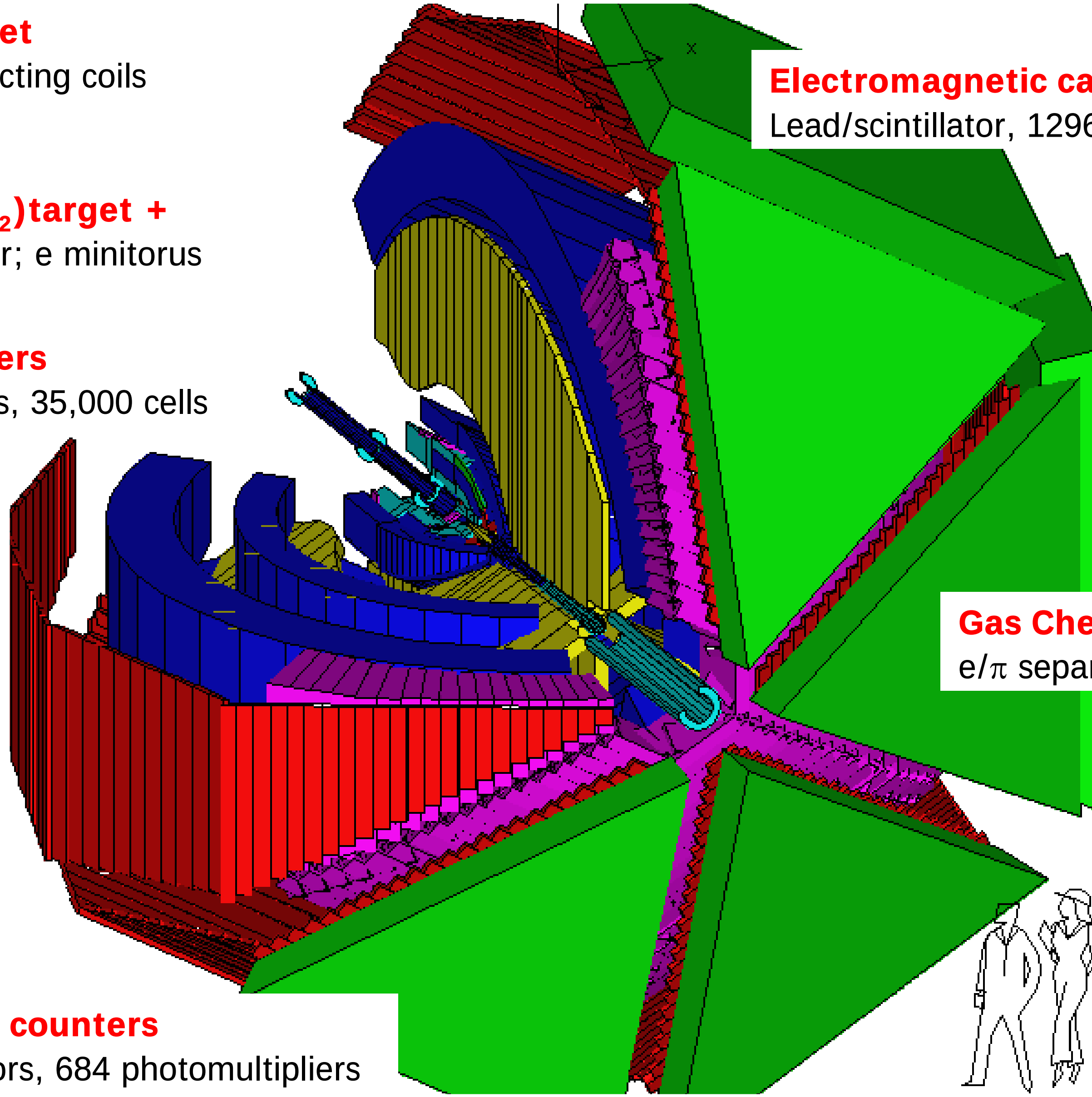
CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

Liquid D_2 (H_2)target +
γ start counter; e minitorus

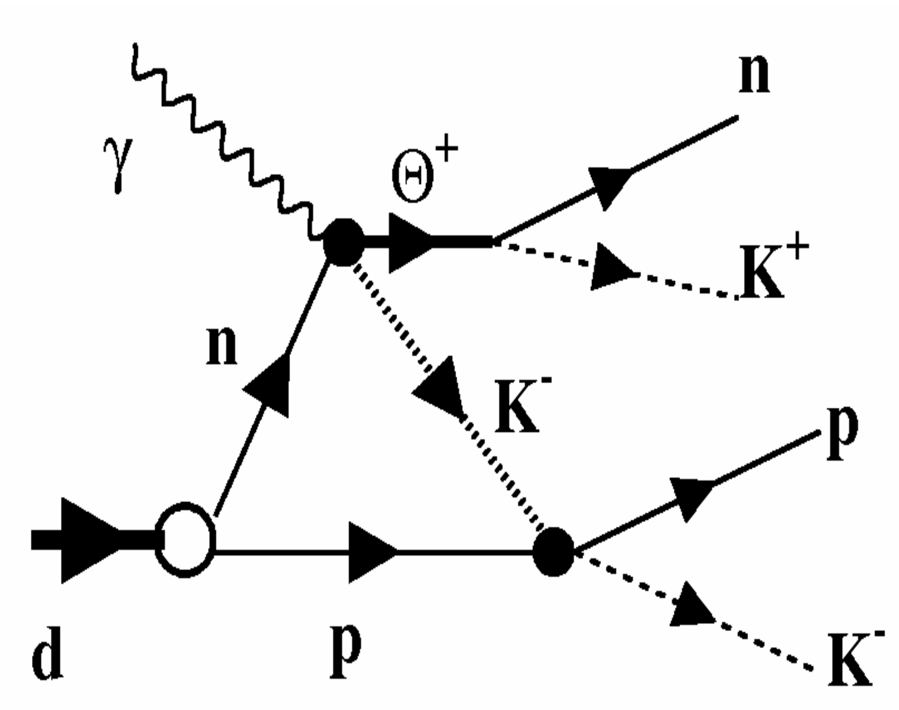
Drift chambers
argon/CO_2 gas, 35,000 cells



Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 684 photomultipliers

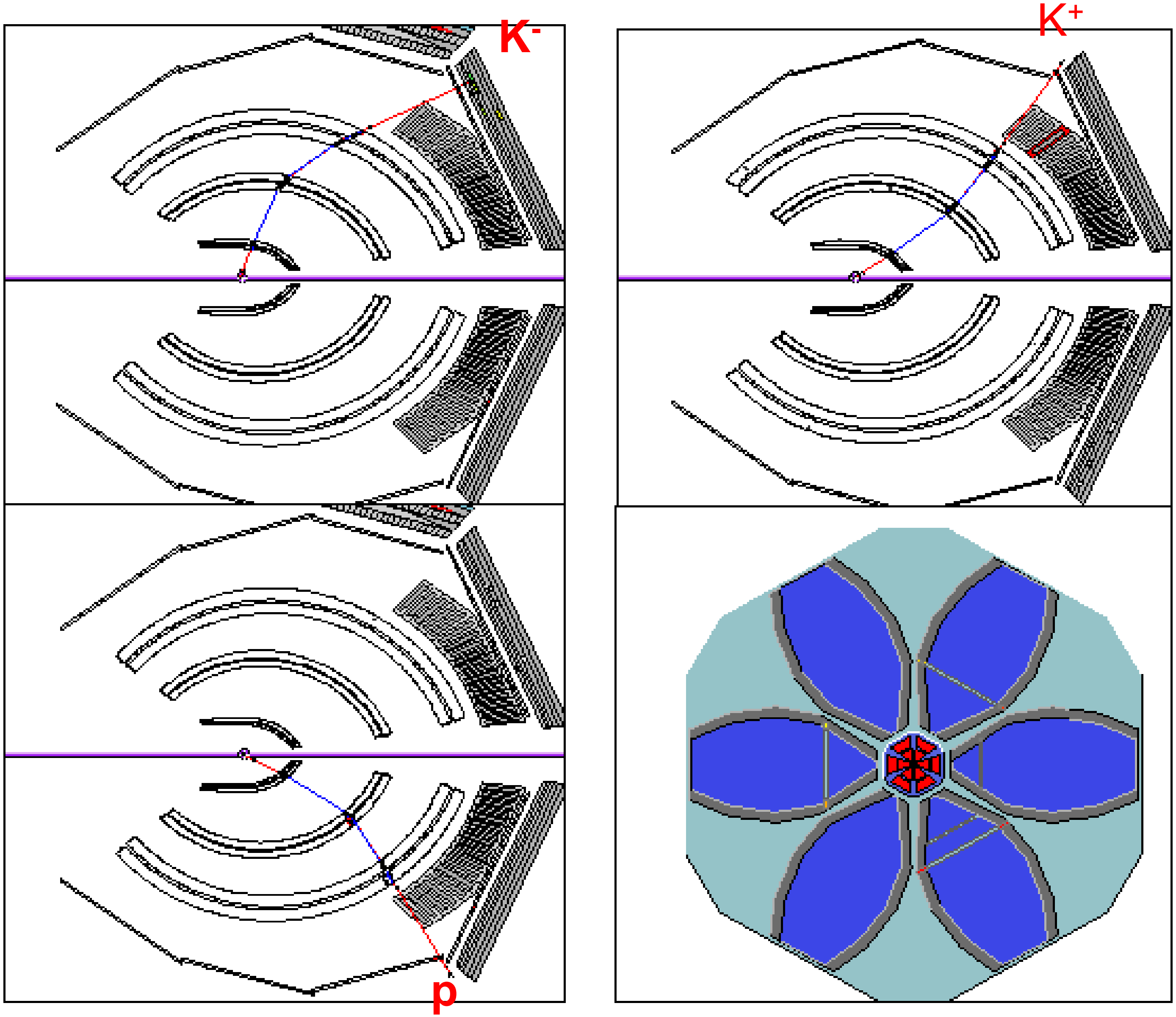
Exclusive measurement using γd reactions



CLAS Collaboration (S. Stepanyan, K. Hicks, *et al.*), hep-ex/0307018

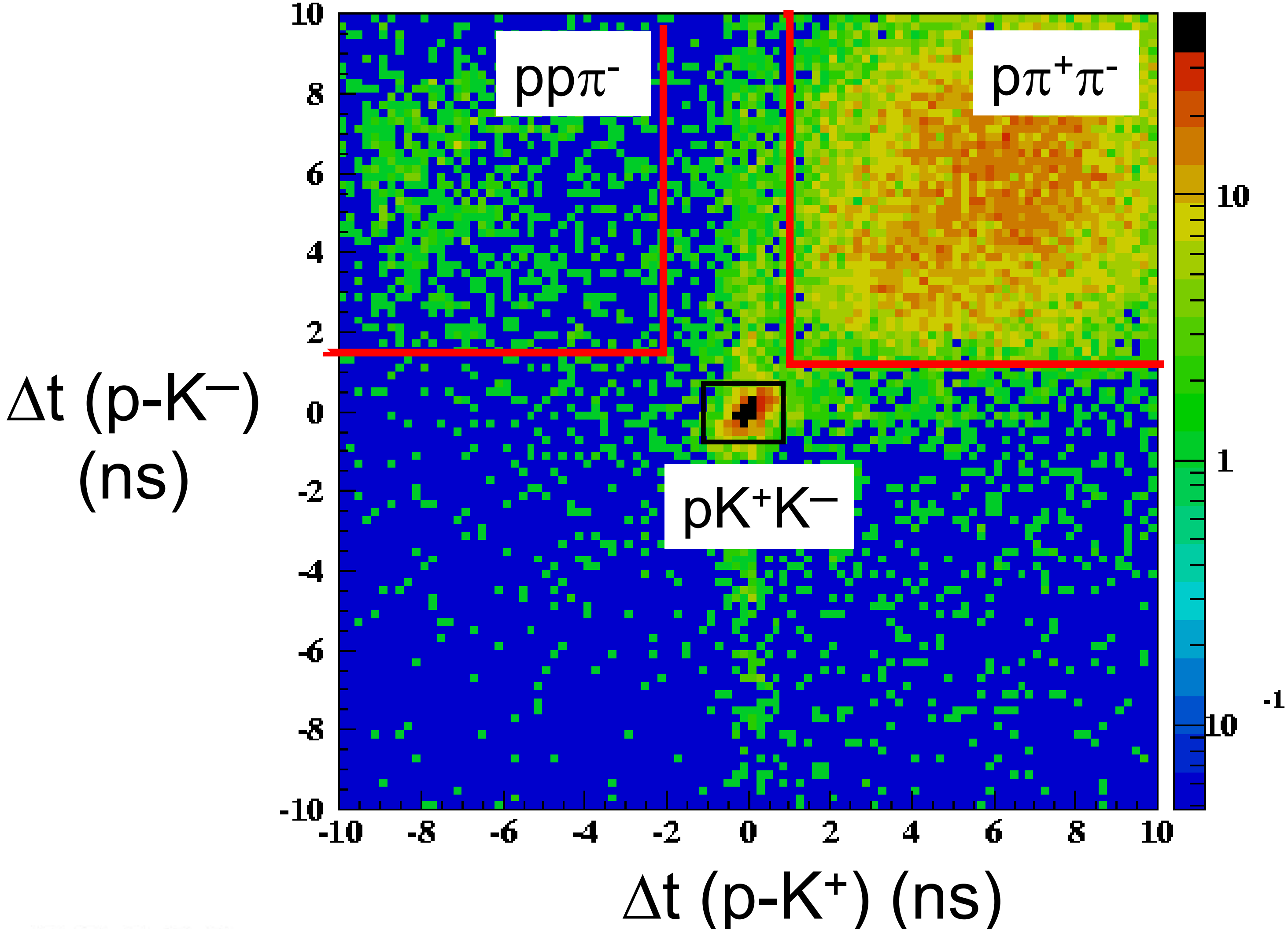
- Requires FSI – both nucleons involved
  - No Fermi motion correction necessary
  - FSI puts K^- at larger lab angles: better CLAS acceptance
  - FSI not rare: in ~50% of $\Lambda^*(1520)$ events both nucleons detected with $p > 0.15$ GeV/c

$\gamma d \rightarrow p K^+K^- (n)$ in CLAS



Kaon times relative to proton

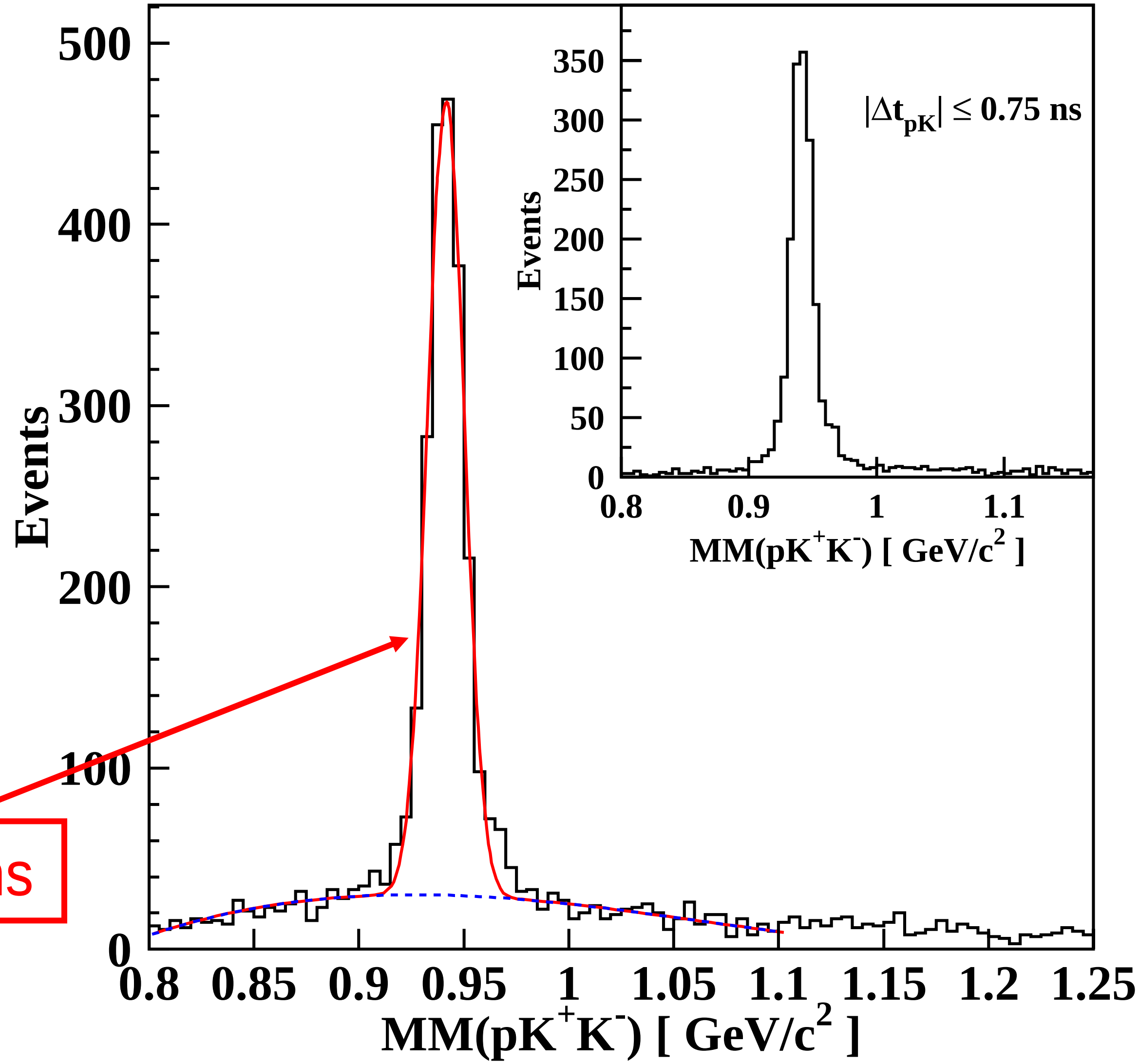
$$\Delta t_K = t - \frac{R}{\beta_c \cdot c}; \beta_c = \frac{p}{\sqrt{p^2 + m_K^2}}$$



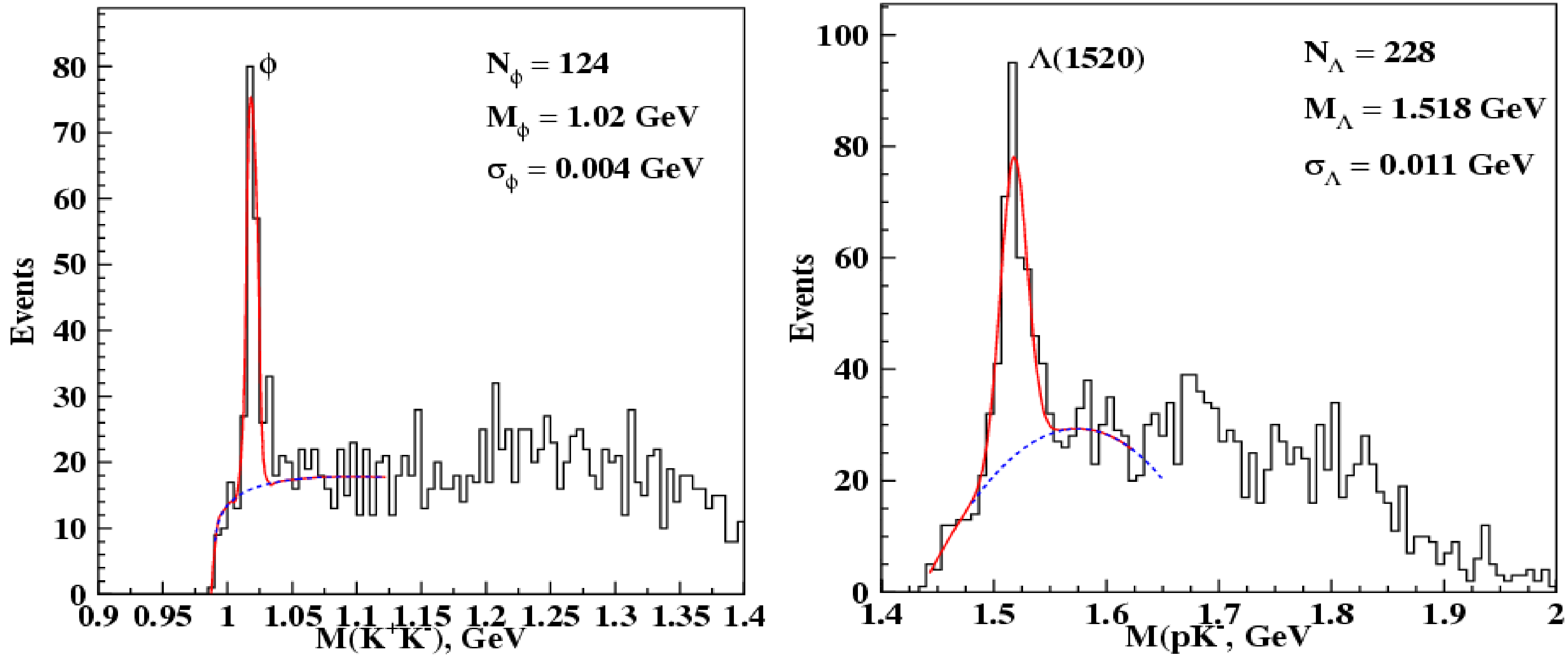
Reaction $\gamma d \rightarrow pK^+K^-(n)$

- Clear peak at neutron mass.
- 15% non pKK events within ±3σ of the peak.
- Almost no background under the neutron peak after event selection with tight timing cut.

Reconstructed Neutrons

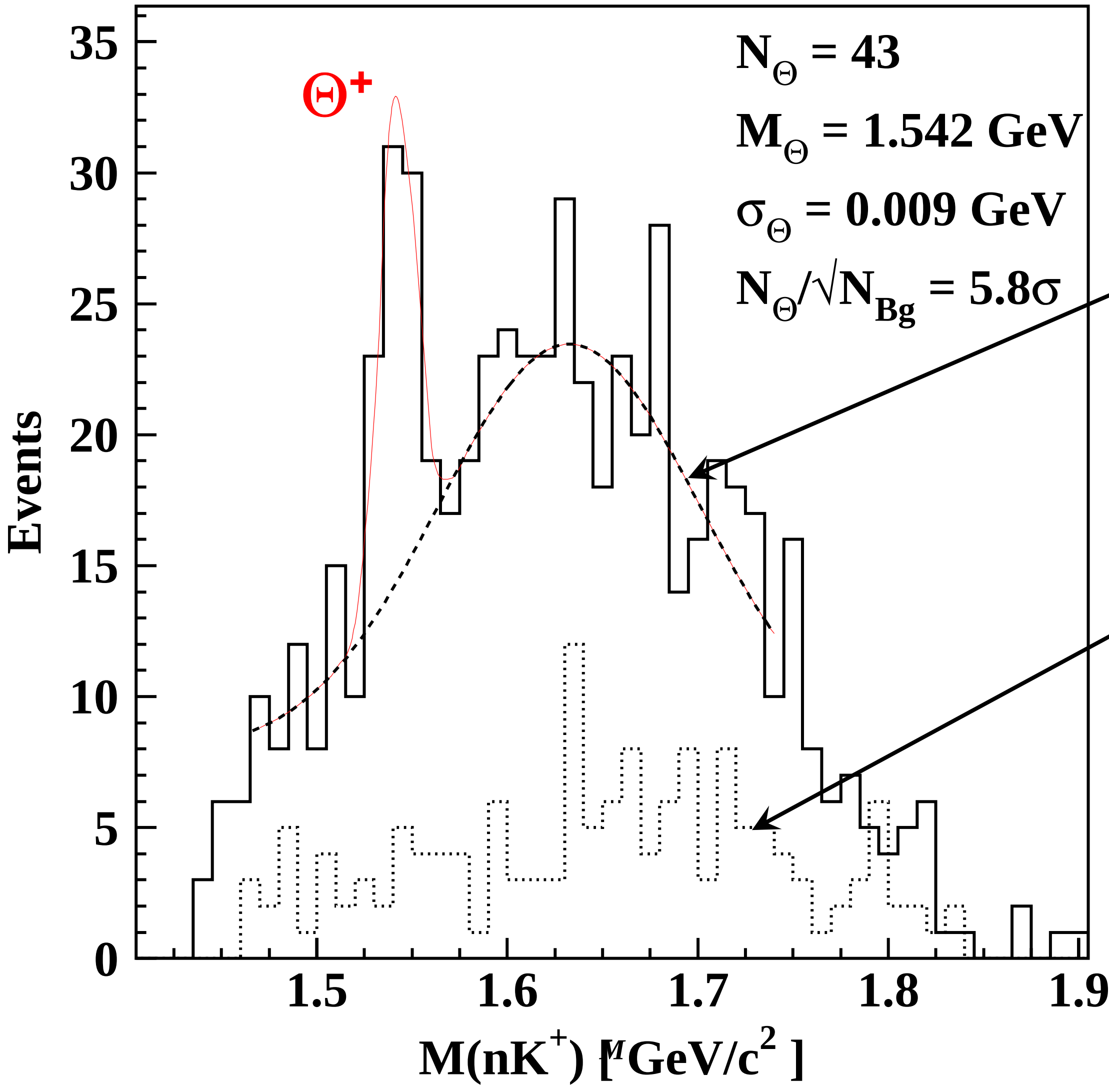


Identification of known resonances



- Remove events with IM(K^+K^-)→ φ(1020) by IM > 1.07 GeV
- Remove events with IM(pK^-)→ Λ(1520)
- Limit K^+ momentum due to $\gamma\, d \to p\, K^-\, \Theta^+$ phase space **p_{K^+} < 1.0GeV/c**
- C. Meyer (CLAS note 03-009): checked narrow structure impossible in $\gamma d \Rightarrow K^+ Y^* N \Rightarrow K^+ (K^- N) N$,+ KN rescattering

nK^+ invariant mass distribution



$$F(M) = G_{\Theta+} + G_{Bg} + P_0$$

Distribution of $\Lambda(1520)$ events

Θ^+: experimental status

- Experimental evidence for Θ^+ have been reported at four laboratories.
  - LEPS collaboration at Spring-8 (Japan), January 2003 - peak in the invariant mass of the nK^+ at 1.54 GeV with statistical significance of 4.6σ.
  - DIANA collaboration at ITEP (Moscow), April 2003 – peak in the invariant mass of pK^0 at 1.538 GeV, statistical significance 4.4σ.
  - CLAS collaboration at JLAB, July 2003 – peak in the invariant mass of the nK^+ at 1.542 GeV, statistical significance 5.3σ.
  - SAPHIR collaboration at ELSA (Bonn), August 2003 – peak in the invariant mass of the nK^+ at 1.54 GeV, statistical significance 4.8σ.
- All experiments observe a narrow width.
- Spin, isospin and parity not yet established.
- Subject of intense interest and research.
  - Penta-Quark 2003 Workshop at JLab in November.

Summary

- We have presented two examples which highlight the physics program at Jefferson Lab.
- The electromagnetic interaction can be used to probe deep into the structure of nucleons.
  - From measurements of G_{Ep} up to a $Q^2 = 5.6$ GeV^2 we have gained new insights into the shape of the proton.
  - Orbital angular momentum of quarks is a key ingredient in our understanding of proton structure.
- A key question in non-perturbative QCD is the structure of hadrons
  - We have presented evidence for an exotic baryon with $S = +1$, which would have a minimal quark content of five quarks ($uudd\bar{s}$).
  - This baryon represents a new class of colorless hadrons.

Scaled F_2/F_1 ratio