Strangeness Production Experiments at Jefferson Lab

Reinhard Schumacher

Carnegie Mellon University

Jefferson Lab Users Meeting, June 2003

Physics Topics

- Elementary production from the proton
  - CLAS Λ and Σ^0 photoproduction
    - Cross sections & polarizations: resonance structure
    - Beam asymmetry
  - CLAS electroproduction
    - Separated interference response functions for Λ and Σ^0
    - Polarization transfer from γ_v to Λ : quark-spin physics
    - $\Lambda(1520)$ formation and decay
  - Hall C electroproduction
    - Separation of L/T structure functions for Λ and Σ^0

Physics Topics (continued)

- Hypernuclear production: Halls C and A
  - YN interaction
  - Light hypernuclei
  - High resolution spectroscopy: $^{12}_{\Lambda}B$
- An exotic S = +1 baryonic state: the Θ^+
  - CLAS exclusive data (g2 data set)
  - CLAS exclusive data (g6 data set)
- Other work in progress
- Summary... (if possible!)

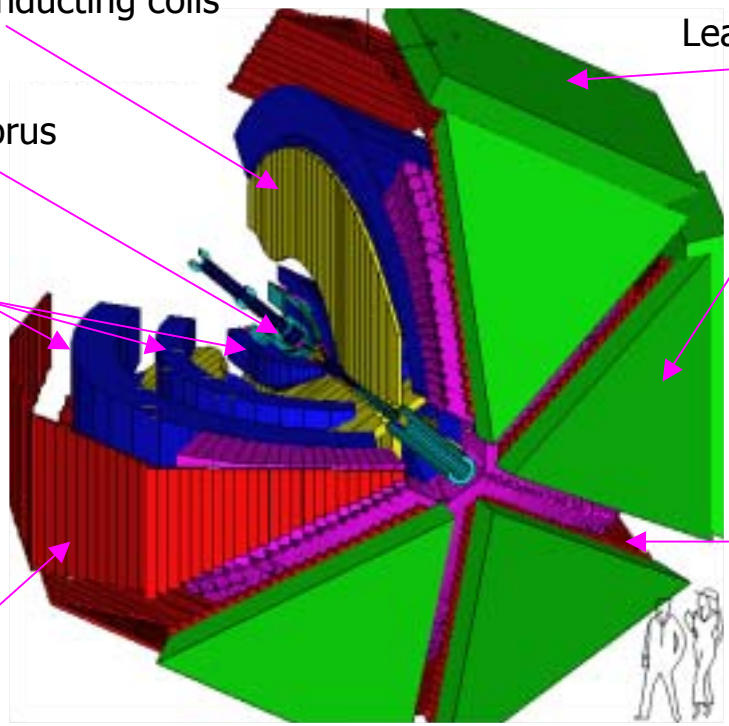
The CLAS System in Hall B

CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid H_2 target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells

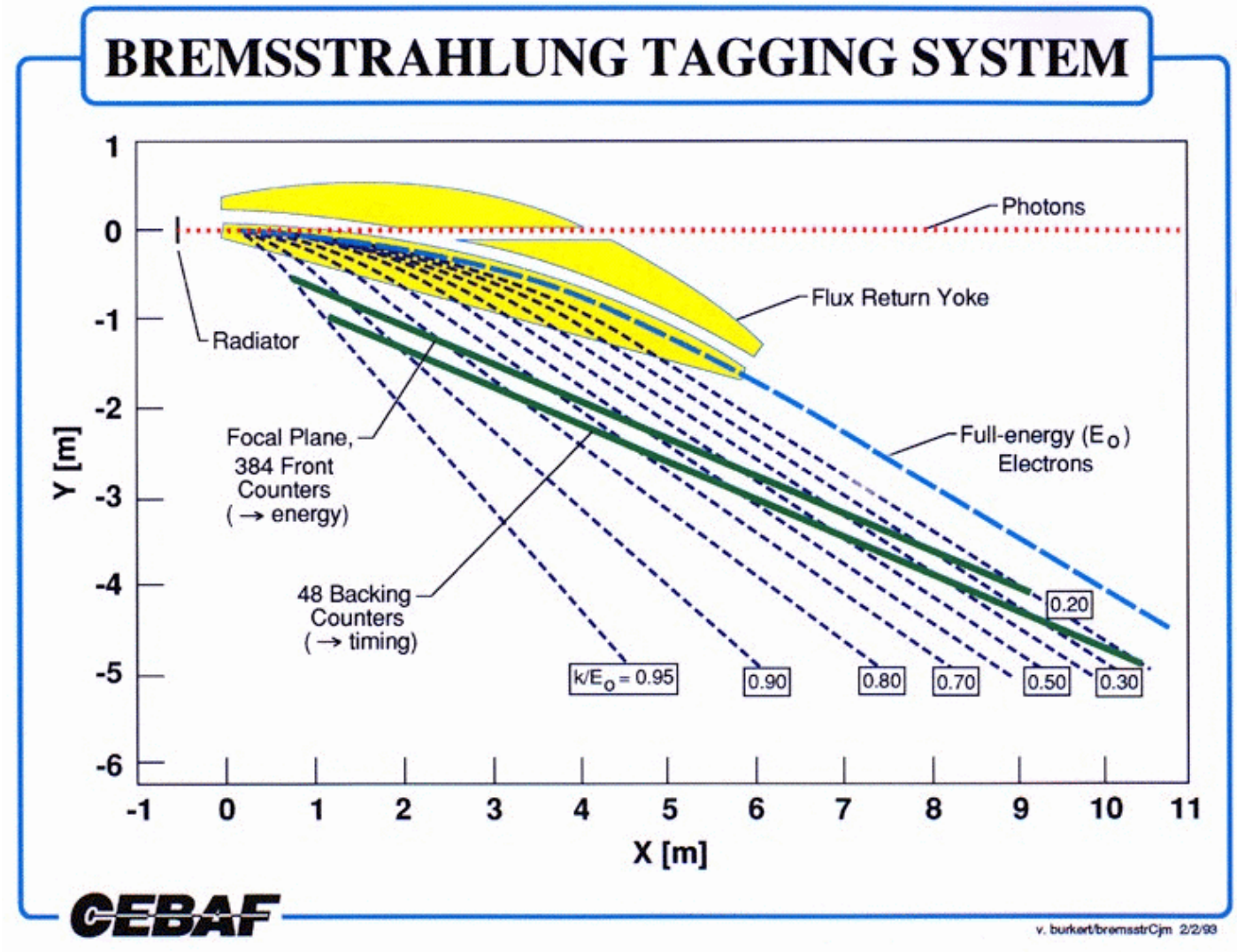


Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

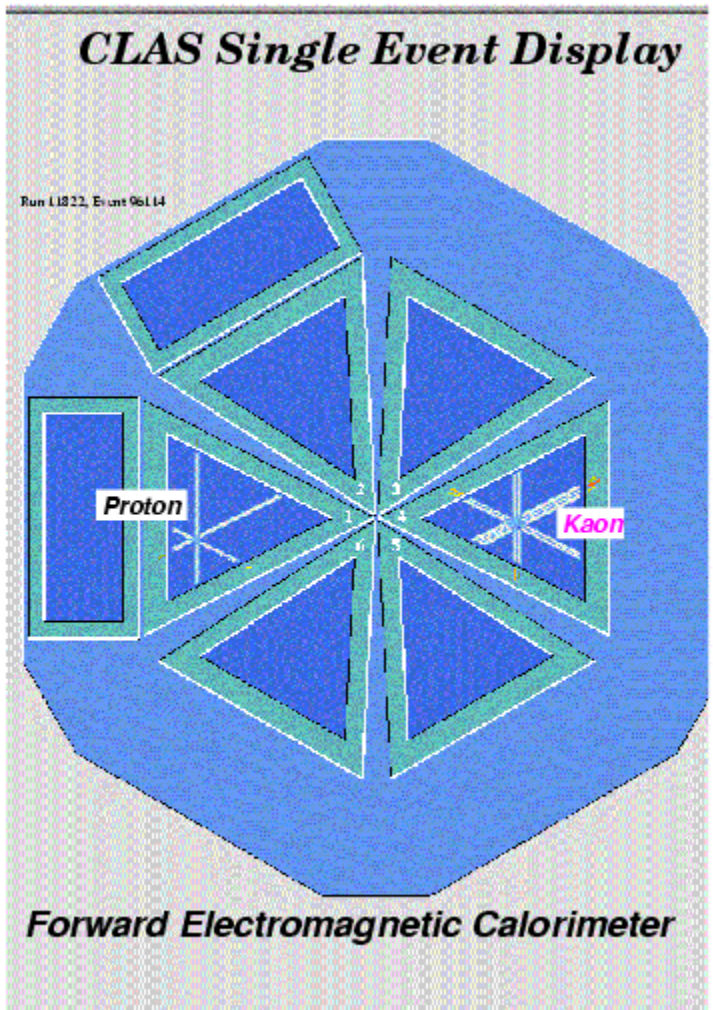
Gas Cherenkov counters
e/π separation, 256 PMTs

Time-of-flight counters
plastic scintillators, 516 photomultipliers

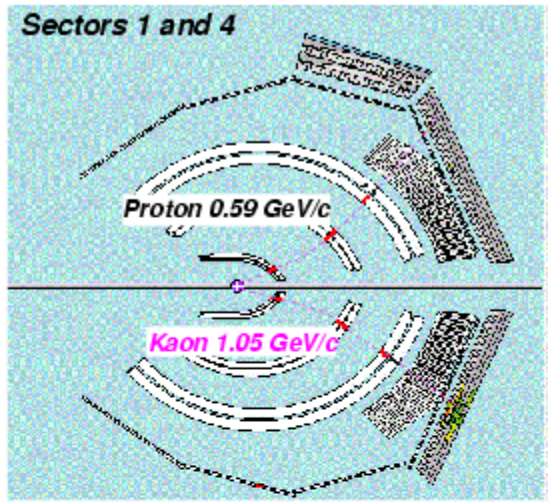
The CLAS Photon Tagger

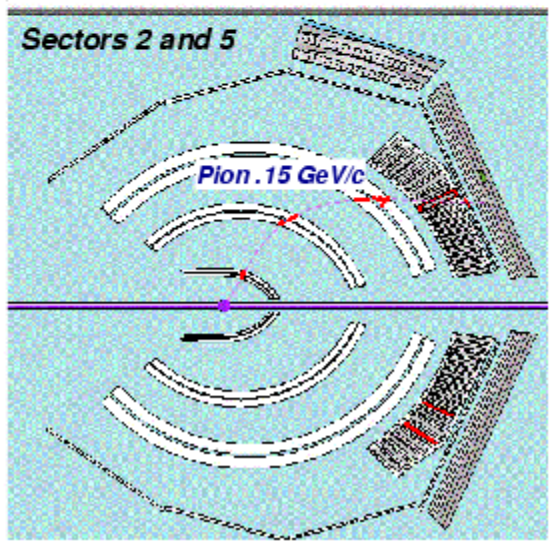


CLAS Single Event

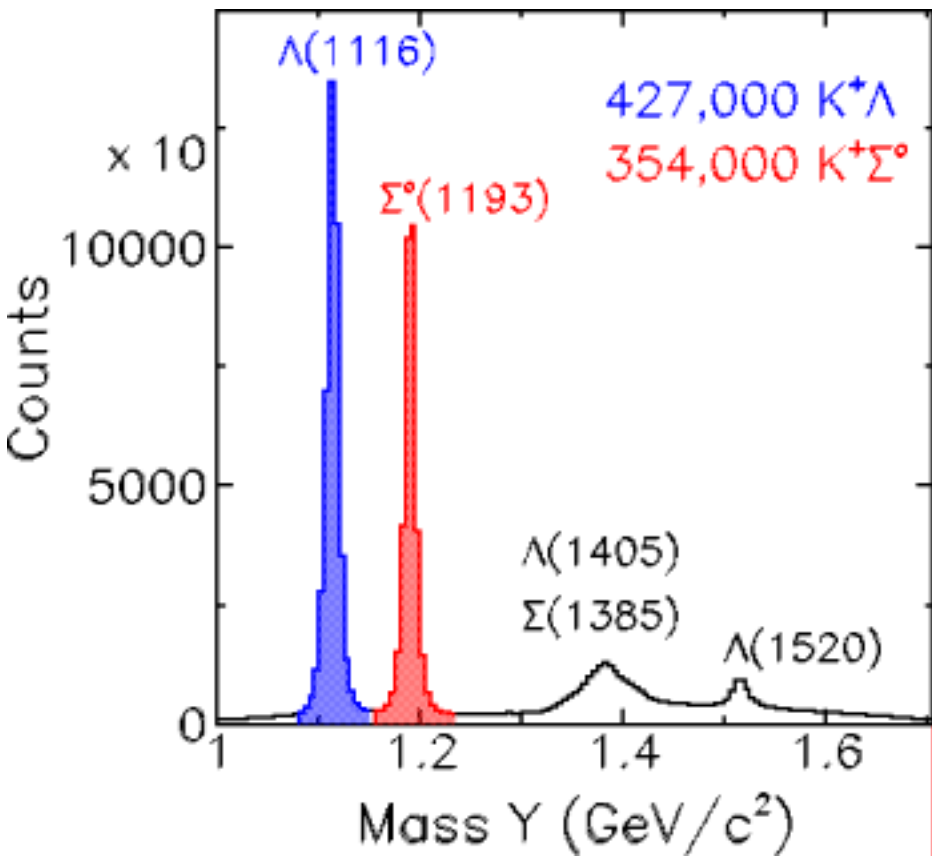


Beam Photon: 1.58 GeV



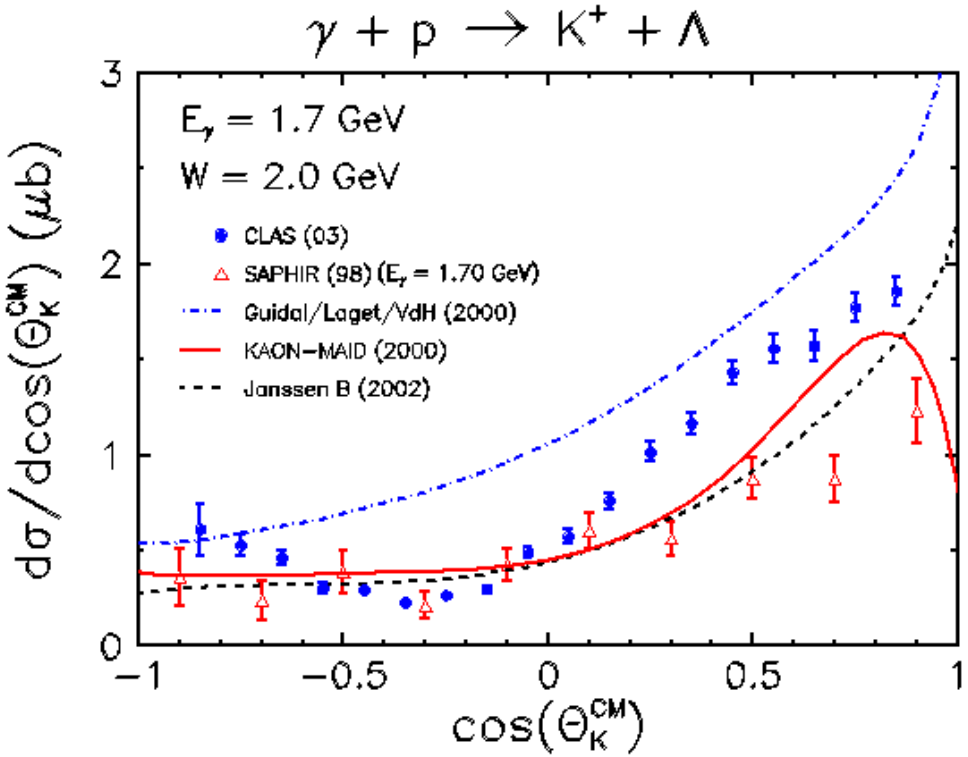


CLAS Λ and Σ^0 Photoproduction



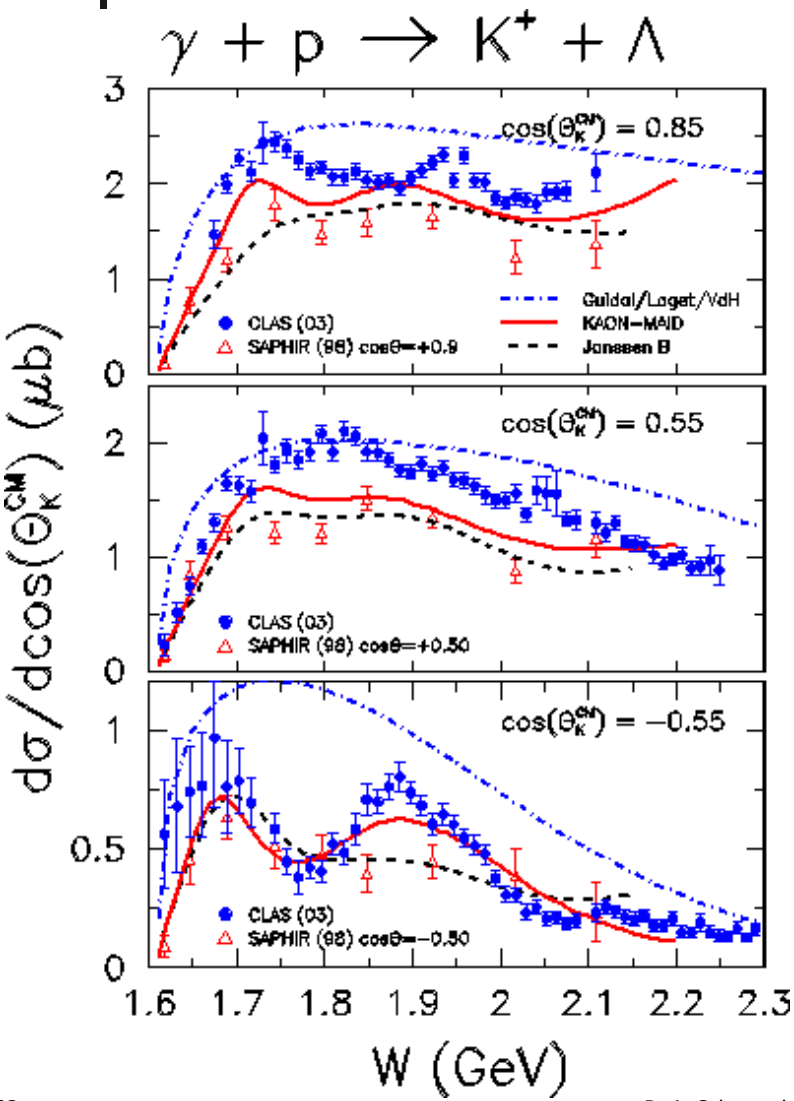
- Missing mass for $\gamma + p \rightarrow K^+ + Y$ summed over full CLAS acceptance
- 2.4 GeV endpoint energy
- Resolution σ = 6.1 MeV
- Polarized photon beams: circular and linear

Differential Cross Sections I



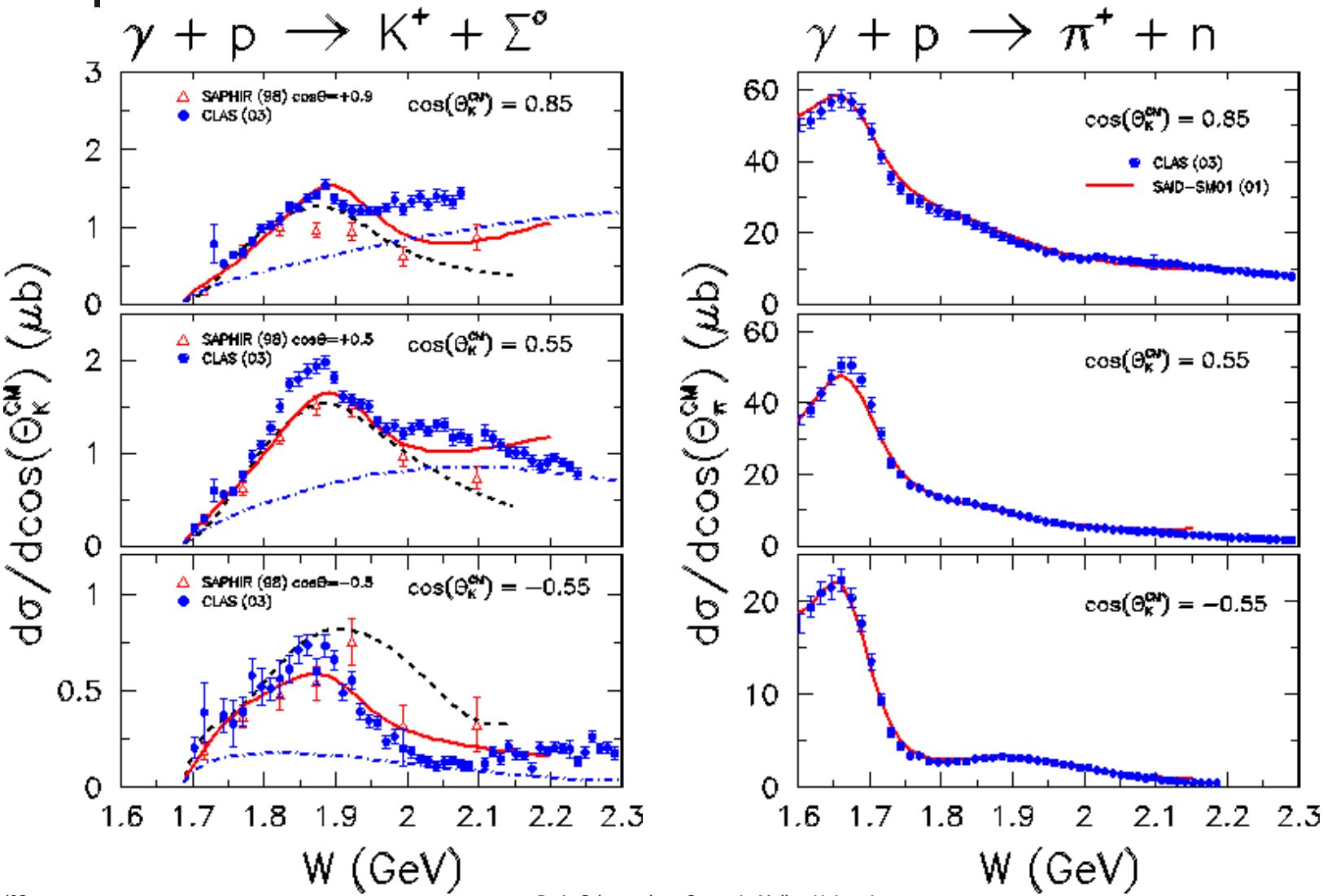
- J. McNabb *et al.* (CLAS)
  - submitted to PRL
  - arXiv:nucl-ex:0305028
  - Sample angle dependence from 921 KΛ data points
- Forward peaking
  - K* exchange in t-channel
- Backward rise
  - Y*'s in the u-channel
  - S-P interference in the s-channel
- Models: {Laget, Mart, Janssen} *et al.*

Differential Cross Sections II

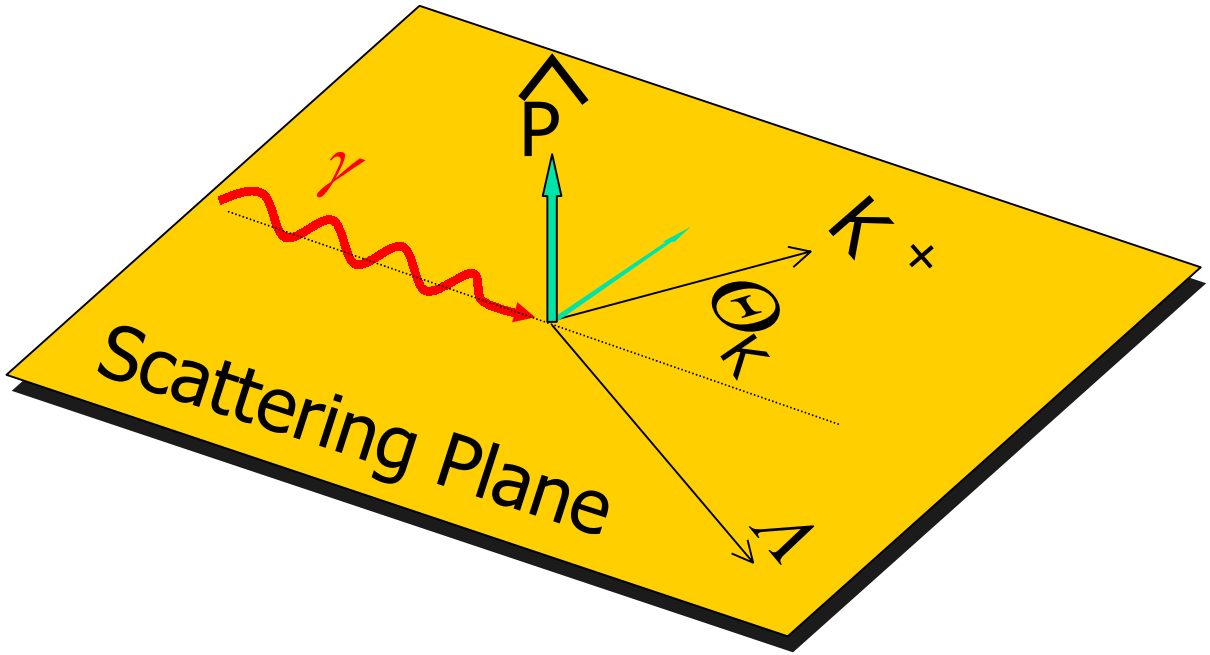


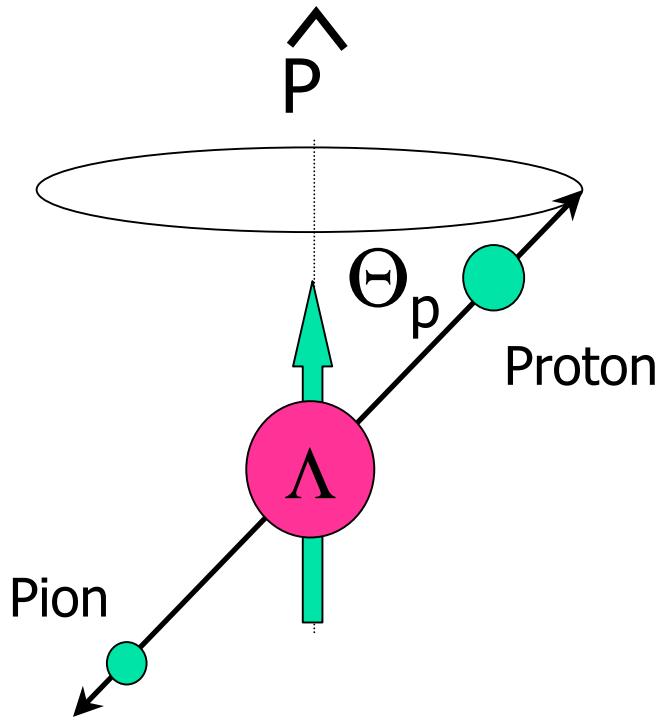
- Double-peaked in W
  - Low W: Known resonances $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$
  - High W: More structures seen near 1.9 GeV
    - Confirms SAPHIR'98
    - Mart *et al*'s D_{13} (1895) ?
- High W peak shifts in position and shape:
  - A sign of interference phenomena
  - Multiple resonances possible

Differential Cross Sections III



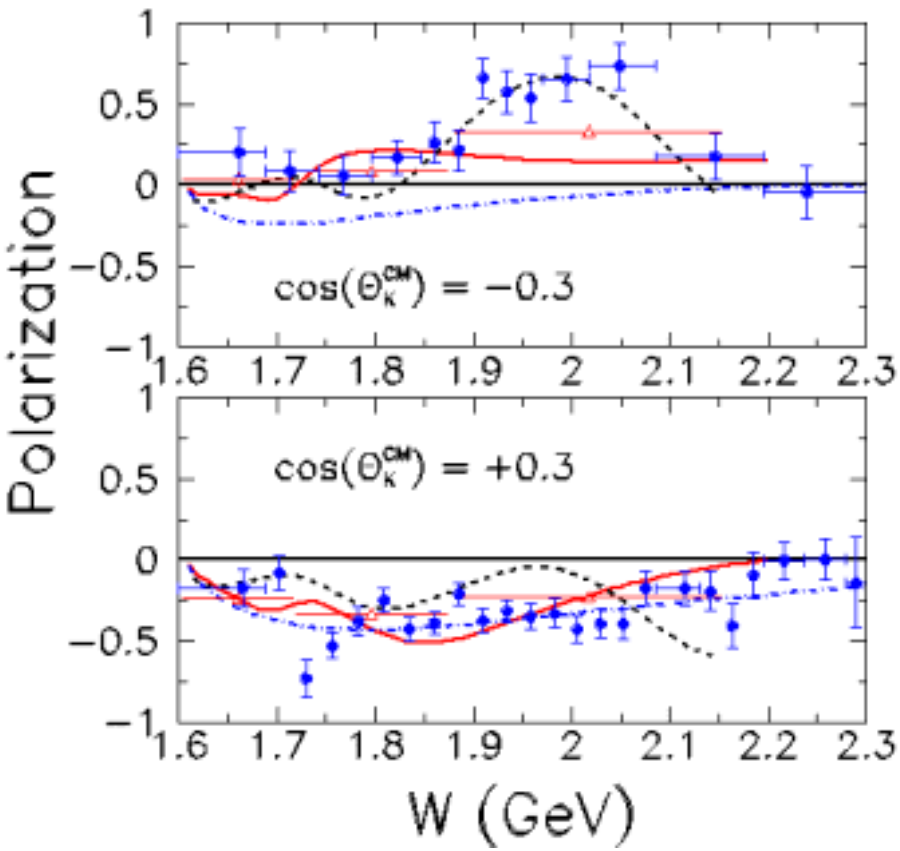
Induced Polarization of the Λ





$$N_p = N_0\{1 + P_\Lambda \, \alpha \cos(\Theta_p)\}$$

Λ Induced (Recoil) Polarization

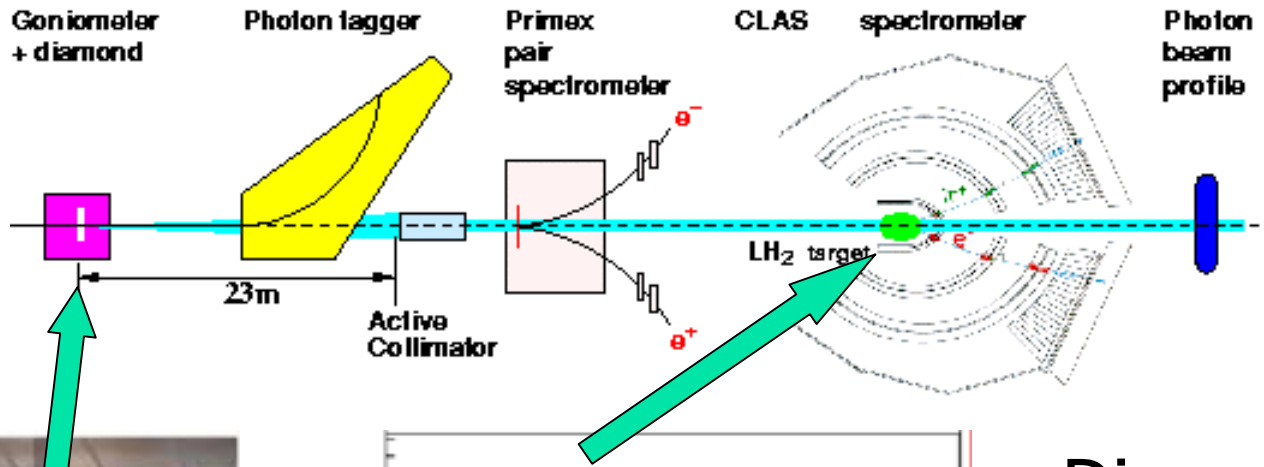


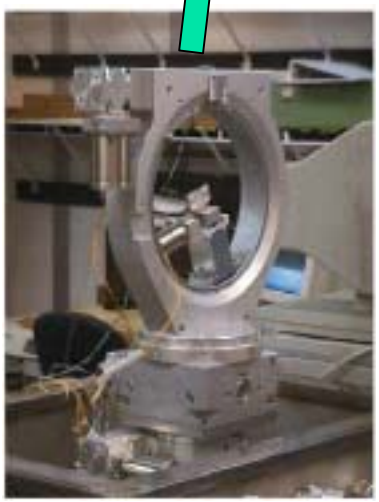
- $\Lambda \rightarrow p\ \pi^-$ P.V. weak decay measures P_Λ
  - $N_p = N_0\{1 + P_\Lambda\ \alpha \cos(\Theta_p)\}$ with respect to ($\gamma\ x\ K^+$) axis
- Forward/Backward sign change of P_Λ
- Possible u-channel contributions at backward angles
- Models: {Laget, Mart, Janssen} *et al.*

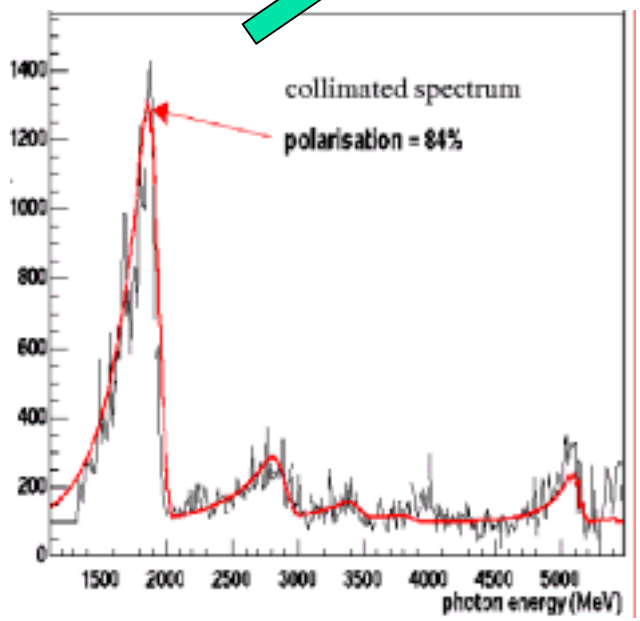
Beam Asymmetry

- J. Melone, K. Livingston, F. Klein *et al.*, (CLAS) very preliminary results
- Linearly polarized photons, E_γ=2.2 GeV
- $d\sigma/d\Omega = \sigma_0\{1 - P_b \Sigma \cos(2\phi)\}$
  - P_b beam polarization
  - Σ beam asymmetry observable
  - ϕ angle between ($\gamma x K^+$) reaction plane and γ polarization axis
- Sensitivity to resonance contributions believed to be large (c.f. Mart & Bennhold)

Linearly Polarized Photons

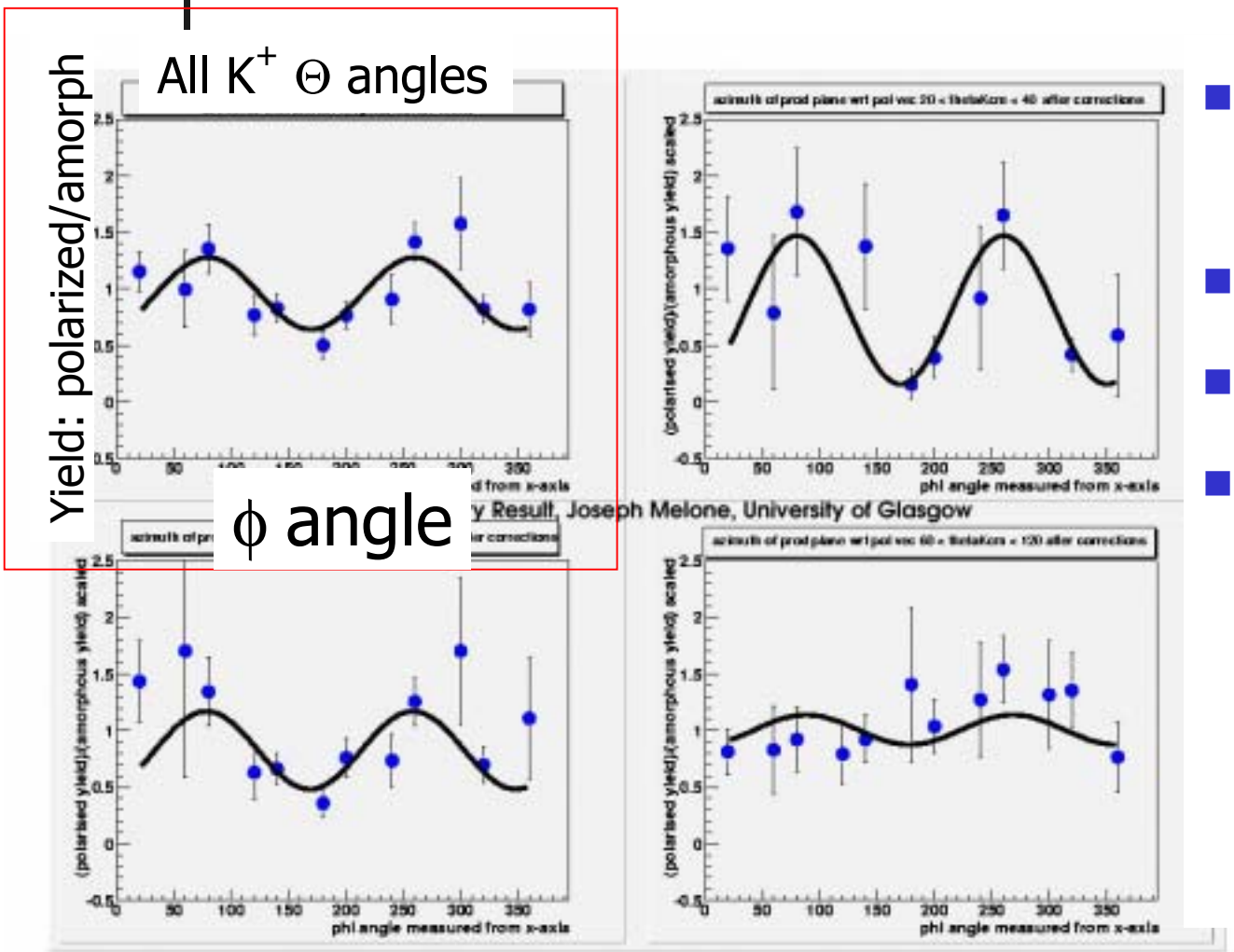






- Diamond radiator
- Coherent bremsstrahlung
- Strong collimation

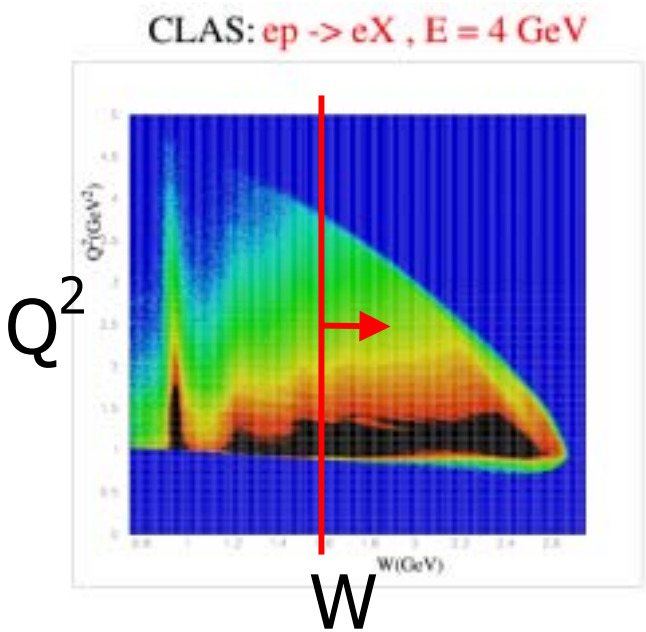
Linearly Polarized Photons



- ϕ asymmetry seen
- E_γ=2.2 GeV
- $|\Sigma| \sim 0.41$
- Magnitude decreases with increasing Θ_K

CLAS Electroproduction

- Optimized for nucleon resonance experiments
- Hyperon production starts at W=1.6 GeV



- First Measurements of σ_{LT} and σ_{TT}
- First Polarization Transfer: $\vec{e} \rightarrow \vec{\Lambda}$
- $\Lambda(1520)$ $J^{\pi}=3/2^{+}$ Decay Angular Distribution

Electroproduction Formalism

With unpolarized beam, target, recoil, we have five kinematic variables:

$$Q^2,\ W,\ \cos(\theta_K),\ \phi,\ \varepsilon.$$

Given Q^2 and W, for any pseudo–scalar meson, the (virtual) one–photon exchange cross section is:

$$\frac{d\sigma}{d\Omega_K} = \sigma_T + \epsilon_L \sigma_L + \epsilon \sigma_{TT} \cos(2\phi) + \sqrt{2\epsilon(\epsilon+1)}\, \sigma_{TL} \cos(\phi)$$

where

$$\sigma_i \equiv \frac{d\sigma}{d\Omega_K}(W, \Theta_K)$$

are the Transverse, Longitudinal, LT–interference, and TT–interference virtual photon structure functions.

Kinematic factors:

$$\epsilon = \left(1 + 2\,\frac{\vec{q}^{\,2}}{Q^2}\,\tan^2\frac{\Theta_e}{2}\right)^{-1}$$

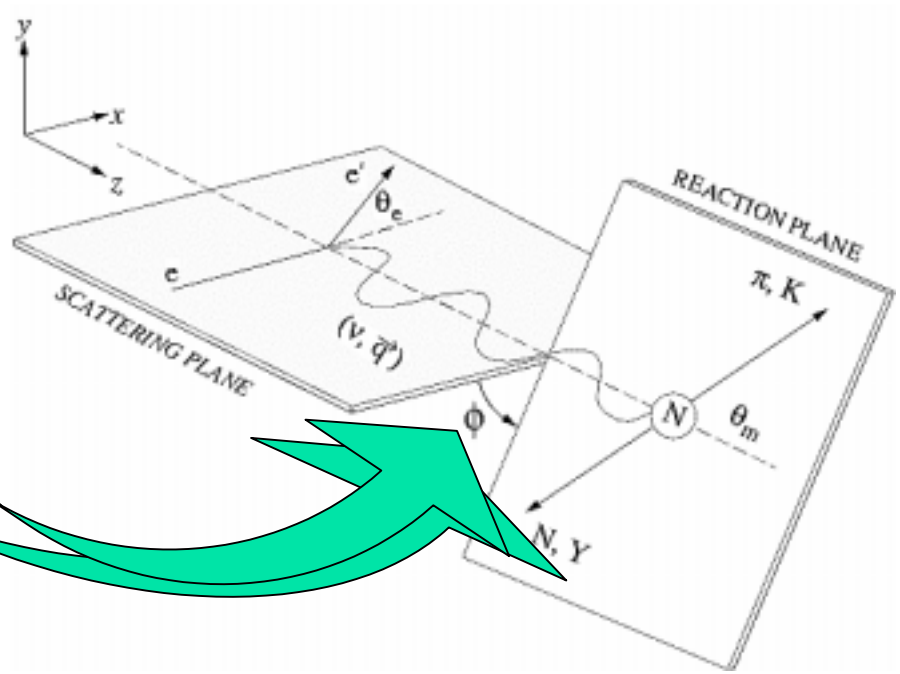
$$\epsilon_L = \frac{Q^2}{\nu^2}\epsilon \ ; \ \nu = (E_e - E_{e'})_{lab} \ ; \ \vec{q} = (\vec{p}_e - \vec{p}_{e'})_{lab}$$

With CLAS one detects:

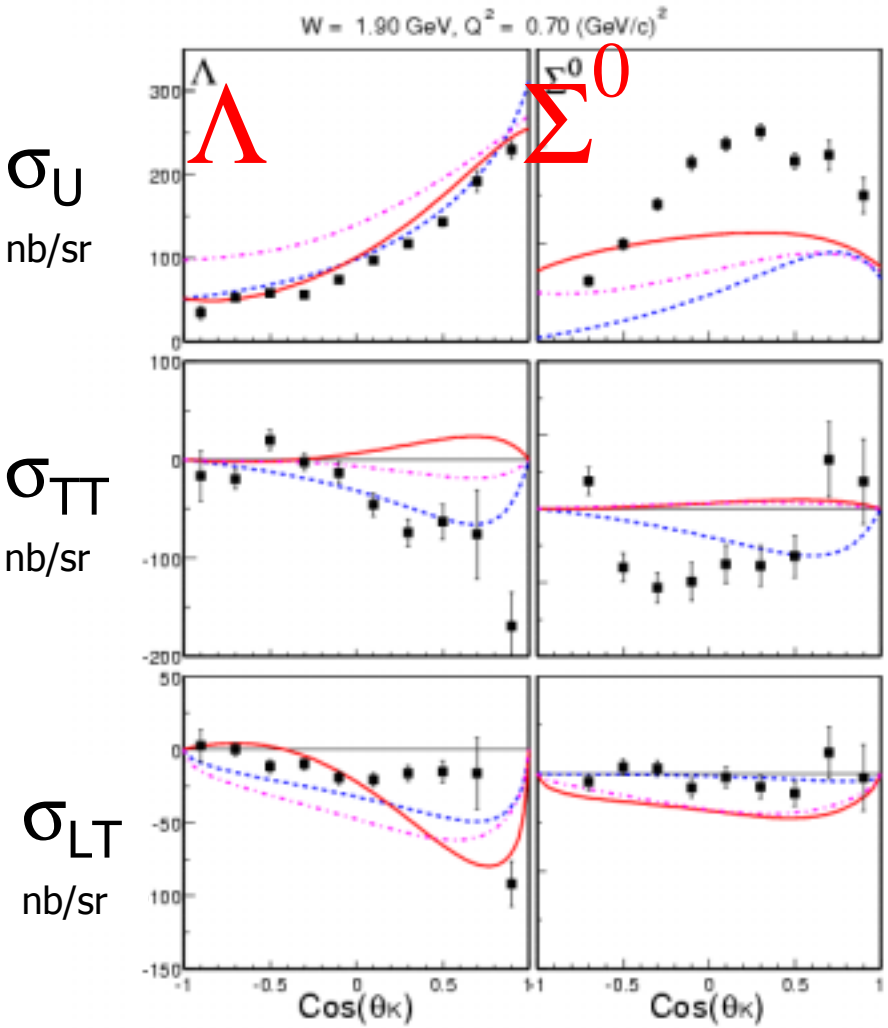
$$\frac{d^4\sigma}{dQ^2\, dW\, d\Omega_K} = \Gamma(Q^2, W)\, \frac{d\sigma}{d\Omega_K}(Q^2, W, \Theta_K, \phi)$$

where the virtual photon flux, Γ, is

$$\Gamma(Q^2, W) = \frac{\alpha}{4\pi}\, \frac{W}{E_e^2 m_N^2}\, (W^2 - m_N^2)\, \frac{1}{Q^2}\, \frac{1}{1-\epsilon}$$

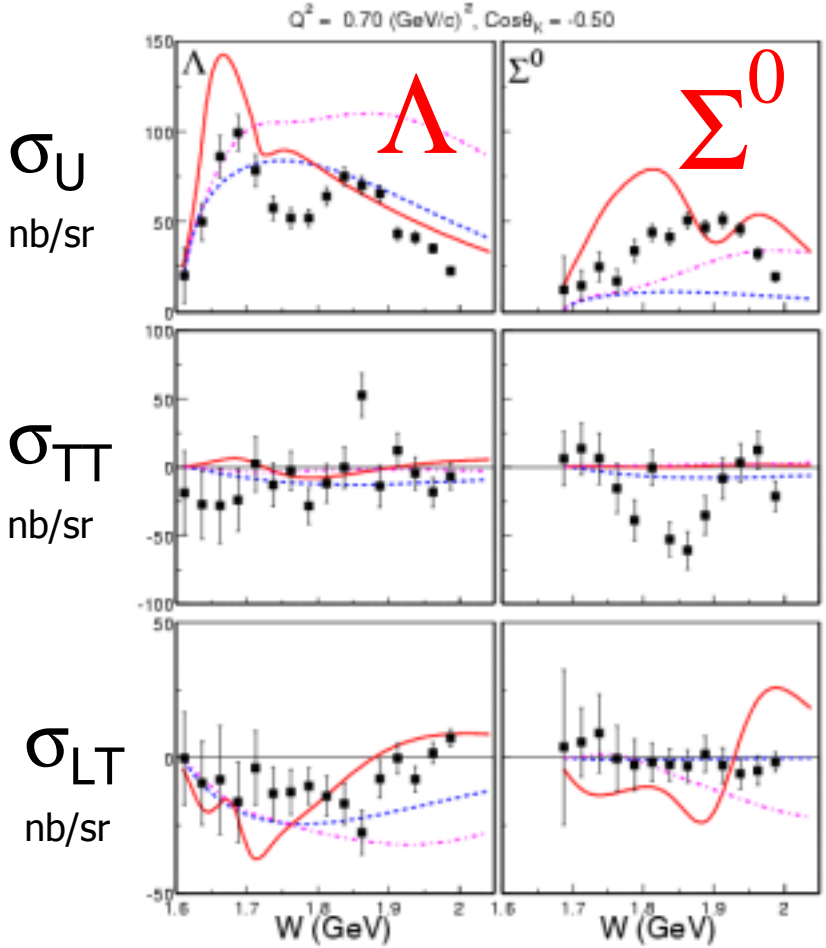


First Measurements of σ_{LT} and σ_{TT}



- R. Feuerbach, K. Hicks, M. Mestayer *et al.* (CLAS, to be published)
  - Sample result, for W=1.90 GeV, $\langle Q^2 \rangle$=0.70 (GeV/c)^2
- Variation with Kaon Θ:
  - Λ forward (t-channel),
  - Σ^0 more central
- Models: {Laget, Mart, Janssen} *et al.*

W-Dependence at Backward K^+ Angles



- $-.67 < \cos\Theta_K < -.33$
- σ_U for Λ shows two 'peaks'
  - Confirms CLAS photo-production results
- σ_{TT} for Σ^0 shows unexplained structure
- Models are all quite poor: need better form factors!

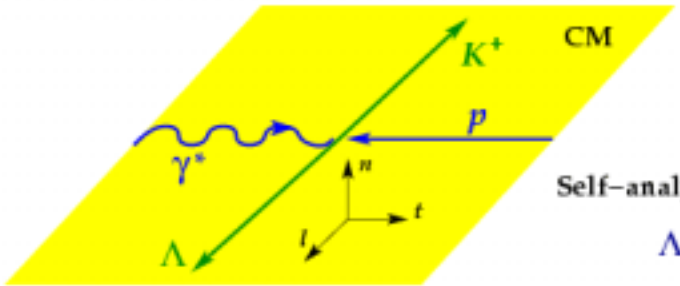
Polarization Transfer: e → Λ

- D. S. Carman *et al.* (CLAS Collaboration), Phys Rev Lett., **90**, 131804 (2003)
- Polarized electron beam probed exclusive

$$\vec{e}\, p \rightarrow e' K^+ \vec{\Lambda}$$

  - $0.3<Q^2<1.5$ $(GeV/c)^2$, $1.6<W<2.15$ GeV
  - Detected e′, K^+, and proton from $\Lambda \rightarrow \pi^- p$
- Result suggests $s\bar{s}$ quark pair produced with spins anti-aligned

Polarization Transfer: Concept



Self–analyzing weak decay

$\Lambda \rightarrow p\pi^-$

$\sigma_p^{RF} \sim 1 + \alpha P_\Lambda \cos\theta_p^{RF}$ $\quad \alpha = 0.642 \quad P_b = 0.67$

$P_\Lambda = P^0 + hP'$

induced transferred

- Extract induced polarization from unpolarized beam sort of acceptance–corrected $\cos\theta_p^{RF}$ yields.

$P_l^0 = P_t^0 = 0$ Only P_n^0 survives.

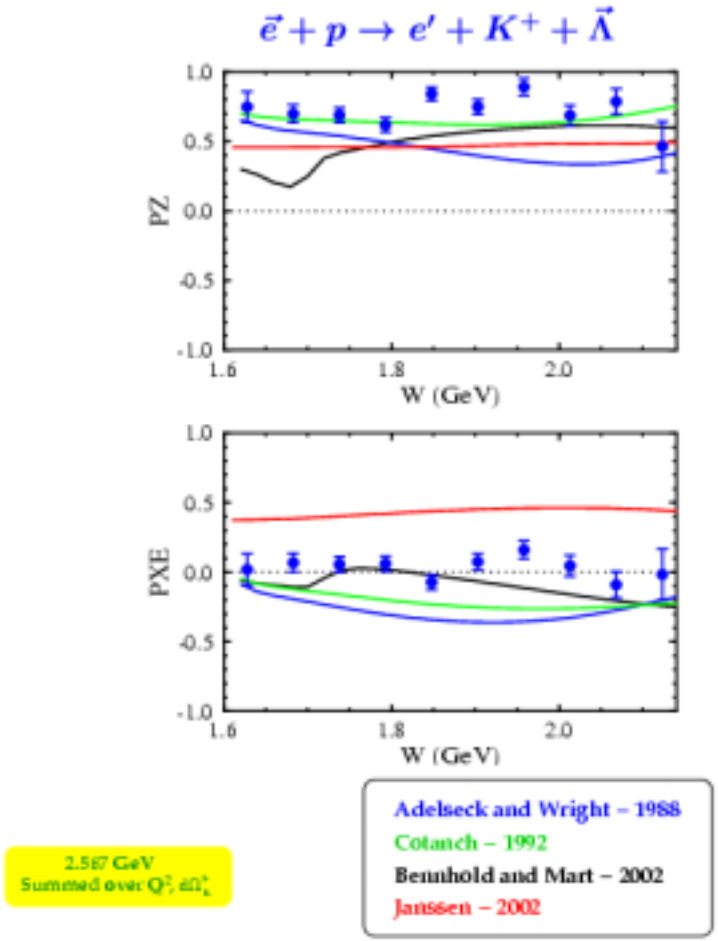
- Extract transferred polarization from yield asymmetry :

$$A = \frac{N^+ - N^-}{N^+ + N^-} = \frac{\alpha P_b \cos\theta_p^{RF} P'_\Lambda}{1 + \alpha \cos\theta_p^{RF} P_\Lambda^0}$$

Much reduced sensitivity to detector acceptance.

$A_n = 0$ but both A_l and A_t can be non-zero.

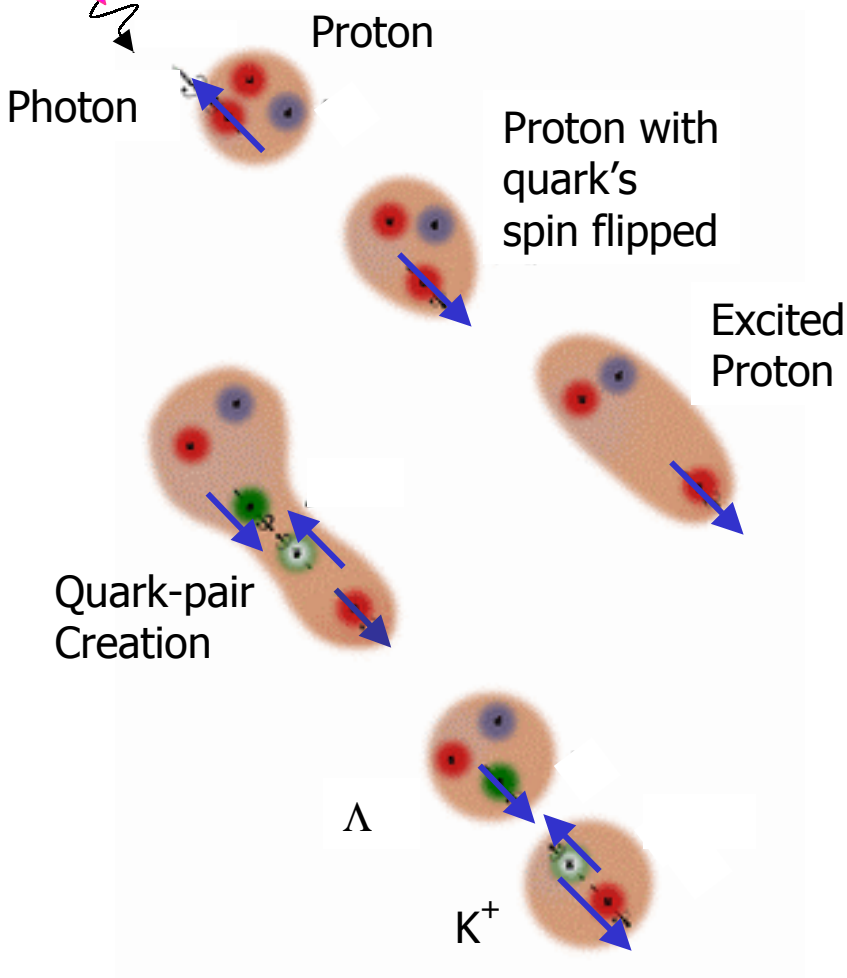
Polarization Transfer: Result



- Lambda is polarized along the direction of the virtual photon helicity: "z"
- Transverse polarization is consistent with 0: "x"
- Large P_z, independent of W, suggests quark-model interpretation:

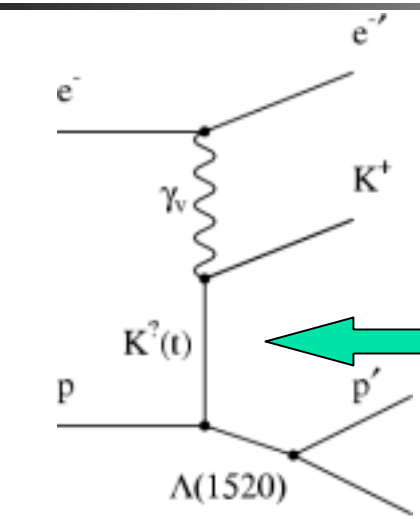
D.S. Carman Ohio University, Dept. of Physics

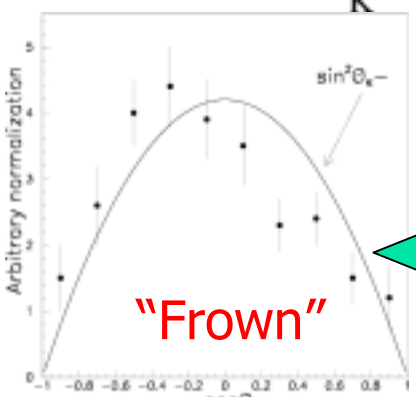
Test of $^3P_0$ Quark-Pair Creation



- In the Breit frame: have helicity conservation in photon-quark interaction
- K is pseudo-scalar, this selects spin-direction of anti-s quark
- Need s quark anti-aligned to get $P_\Lambda \sim +1$
- $^3P_0$ mechanism doubtful in this case
  - 2:1 aligned vs. anti-aligned

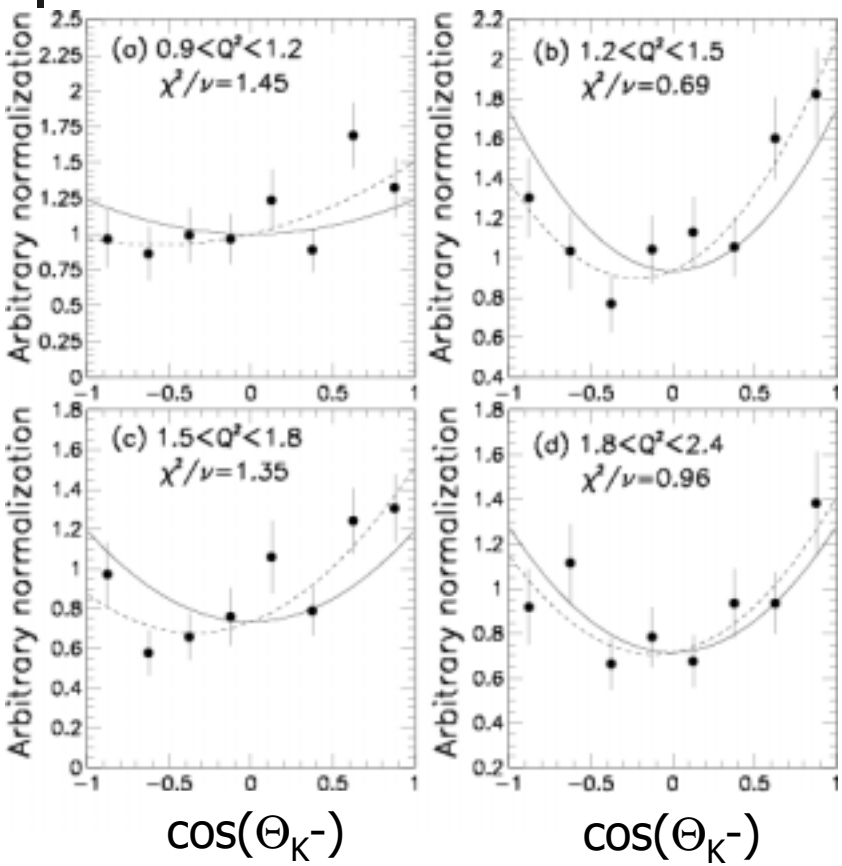
$\Lambda(1520)$ $J^{\pi}=3/2^{+}$ Decay Angular Distribution





- S.P. Barrow *et al.* (CLAS) Phys. Rev. **C64** 044601 (2001)
- Is the exchange of K^{+} $J^{\pi}=0^{-}$ or the exchange of K* J>0 dominant?
- Examine $\Lambda(1520)$ decays in the t-channel helicity frame
- 0^{-} exchange leads to $|m_z|=1/2$
- J>0 exchange leads to $|m_z|=3/2$
  - Dominant at $Q^2=0$: photoproduction
  - D.Barber *et al.* Z. Physik **C7**, 17(1980)

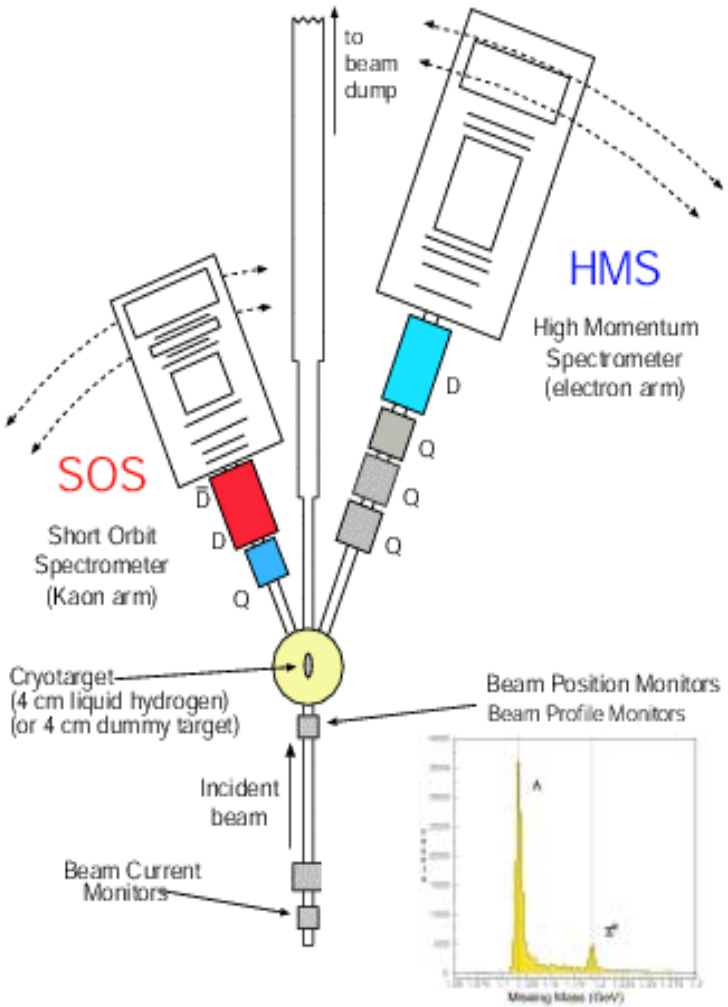
$\Lambda(1520)$ Decay Result



"Smiles"

- For $Q^2>0.9$ $(GeV/c)^2$ contributions from $|m_z|=1/2$ become big
  - ~60% $|m_z|=1/2$ parentage seen
  - More K (J=0) exchange than in photoproduction
  - A caveat: W and t ranges differ from photoproduction result

Hall C Electroproduction: E93-018

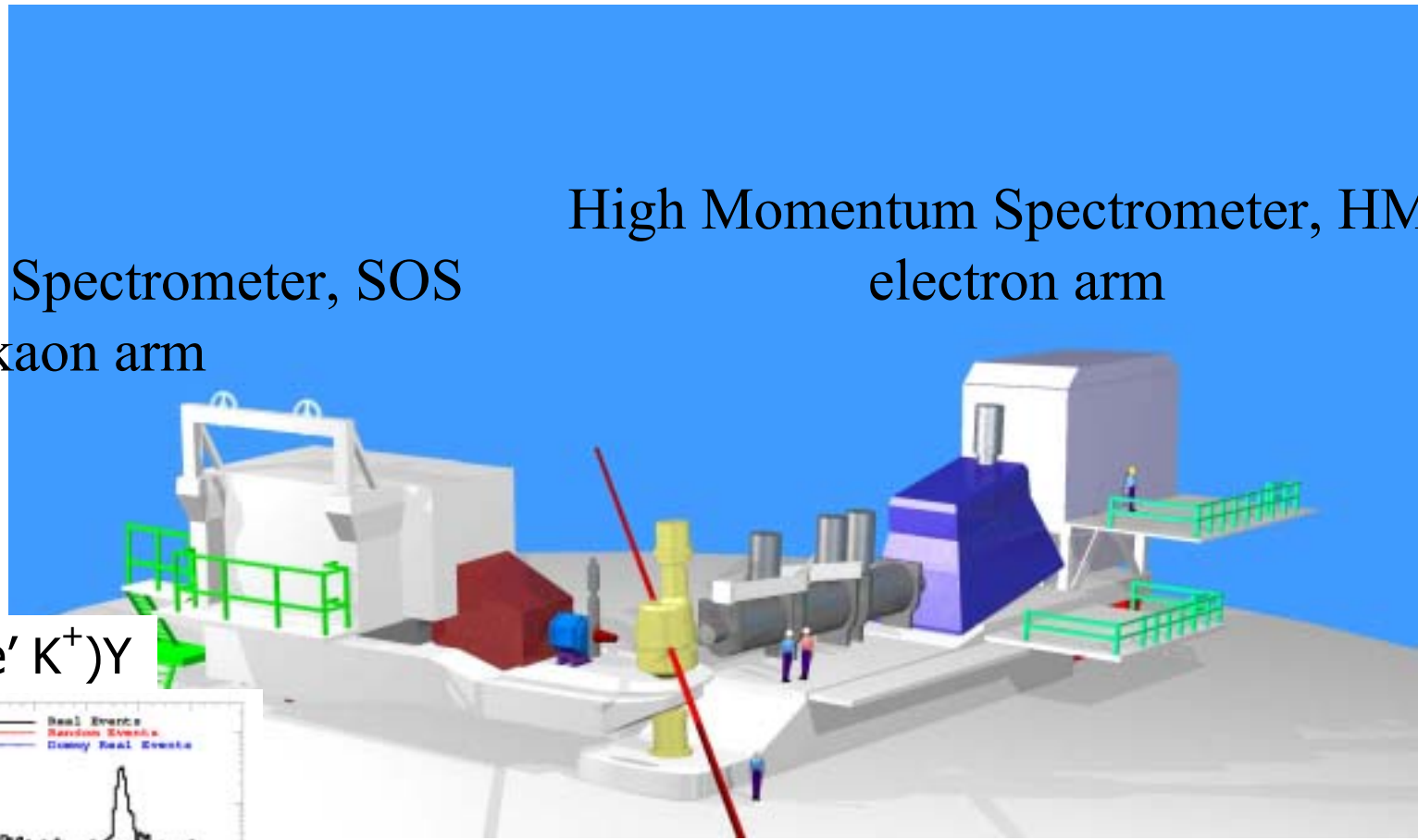


- R.M.Mohring *et al.* Phys. Rev. **C67**, 055205 (2003)
  (supercedes G. Niculescu *et al.*, Phys. Rev. Lett. 81, 1805 (1998))
- Separation of Longitudinal and Transverse Cross Sections in $p(e,e'K^+)Y$
  - W = 1.84 GeV
  - $\Theta_{\gamma K} = 0^o$
  - $0.5<Q^2<2$ (GeV/c)^2

Hall C Spectrometers

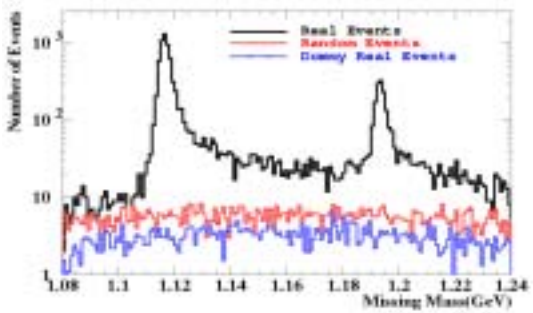
Short Orbit Spectrometer, SOS
kaon arm

High Momentum Spectrometer, HMS
electron arm

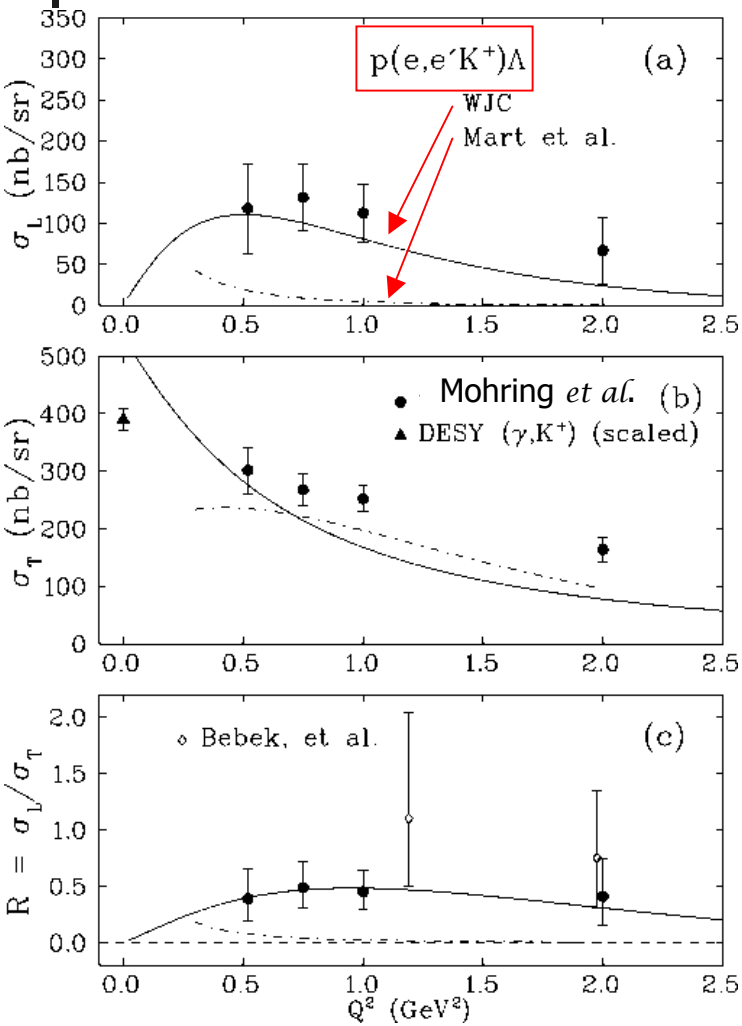


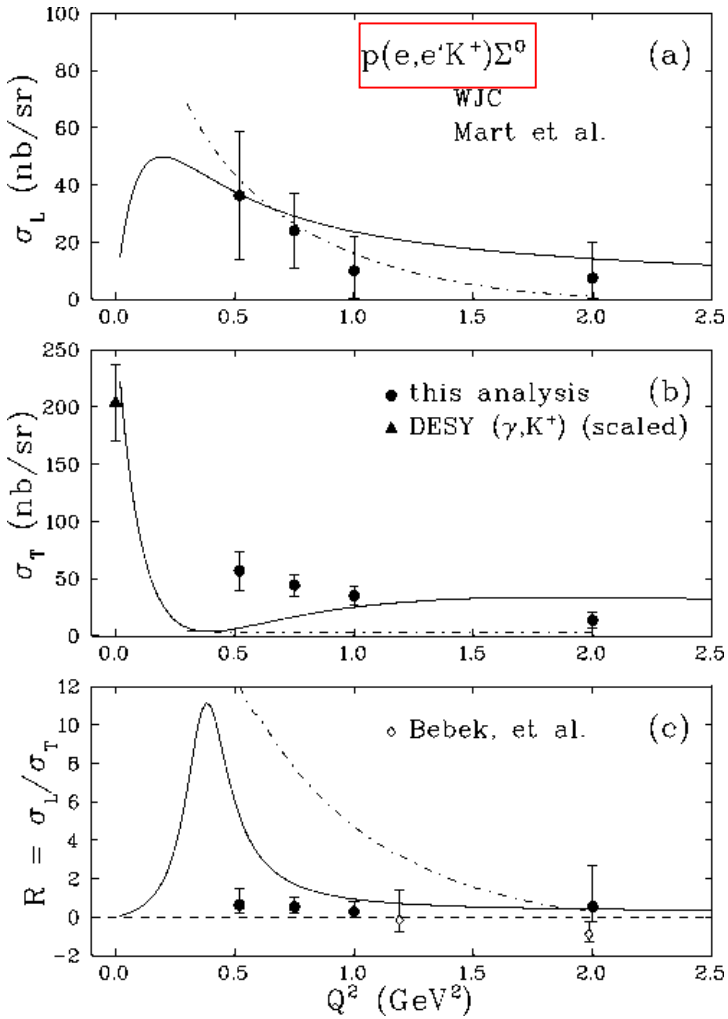
Electron beam

p(e,e′ K^+)Y

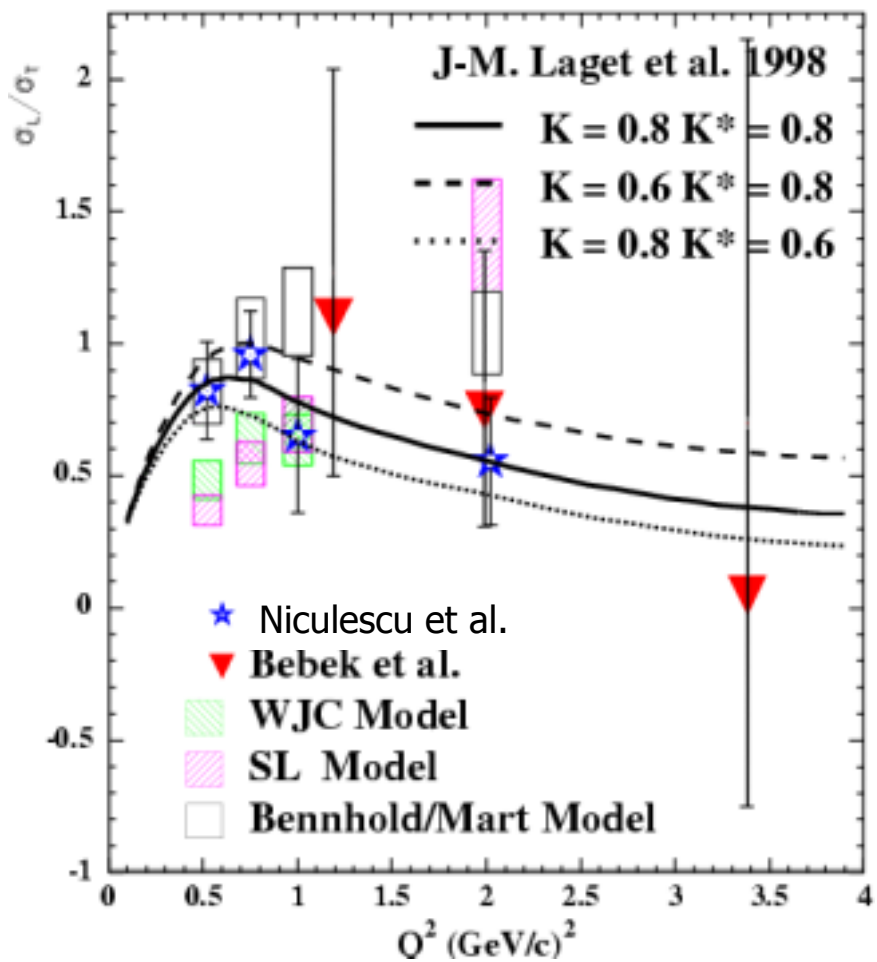


σ_L, σ_T, & Ratio, vs. Q^2



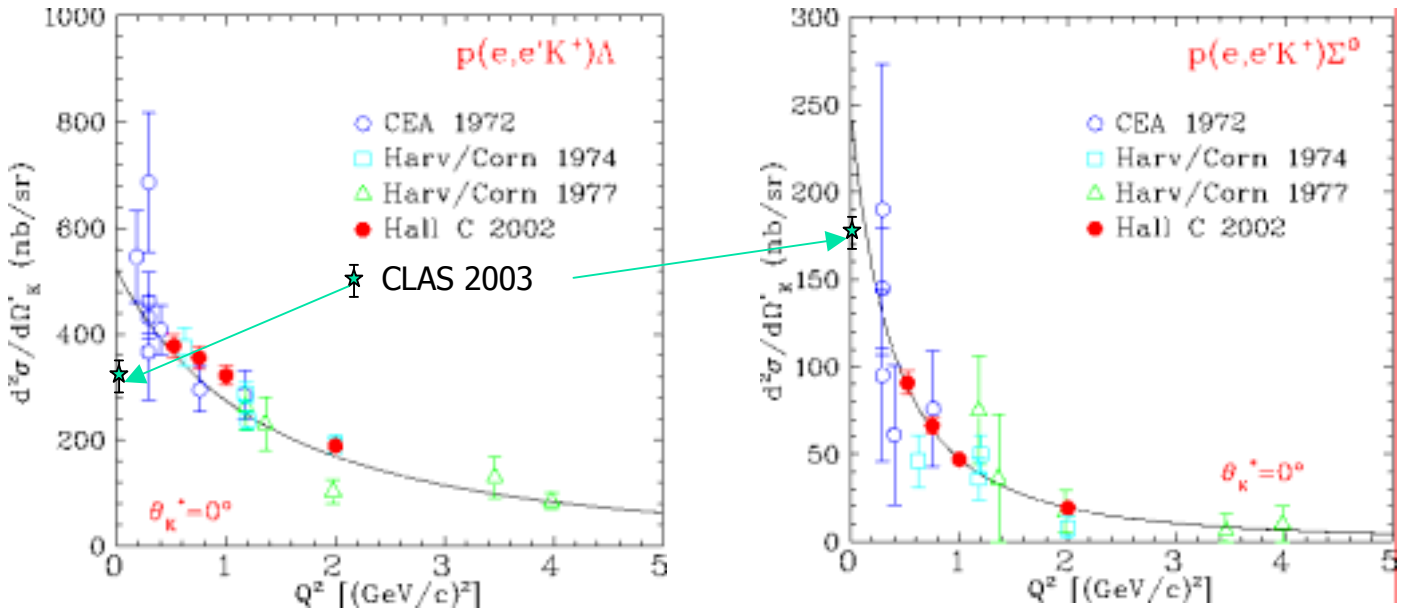


Another View of σ_L/σ_T Models



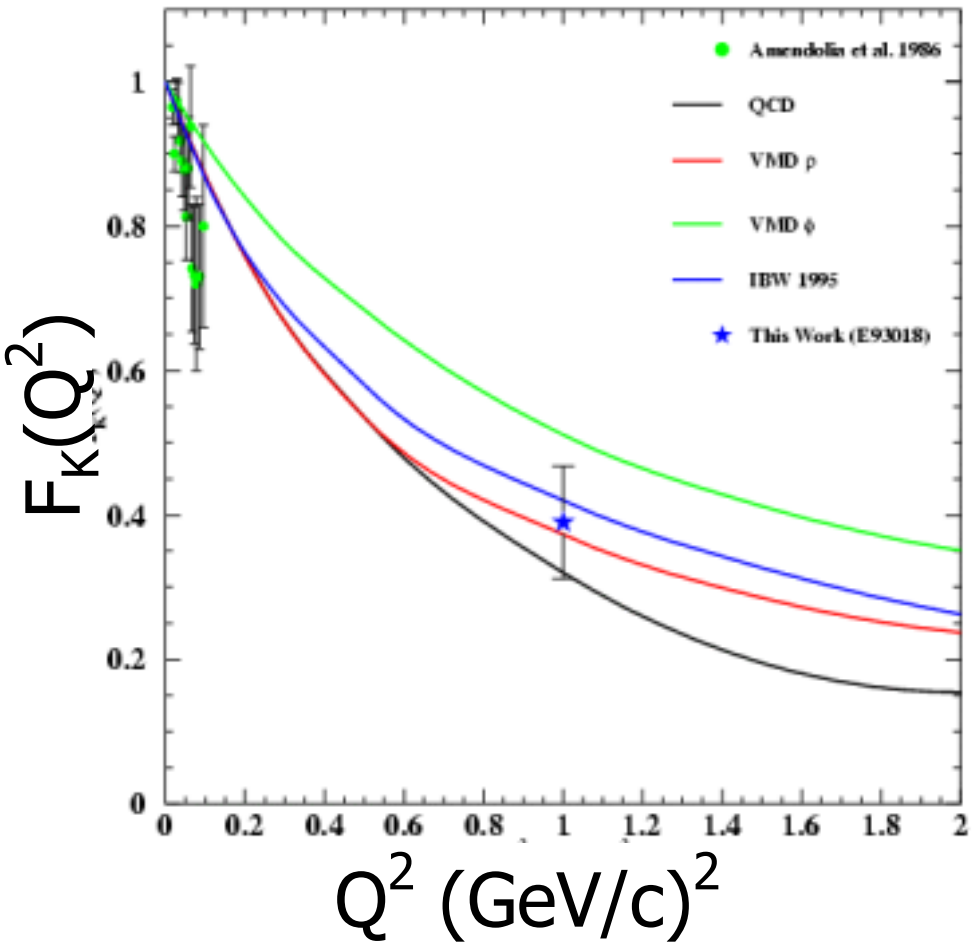
- G. Niculescu *et al.*, Phys. Rev. Lett. **81**, 1805 (1998)
  - Data superceded by R.M.Mohring *et al.* Phys. Rev. **C67**, 055205 (2003)
- Illustrates dependence on choice of Kaon form factor, in model of J-M Laget

Unseparated Q^2 Dependence



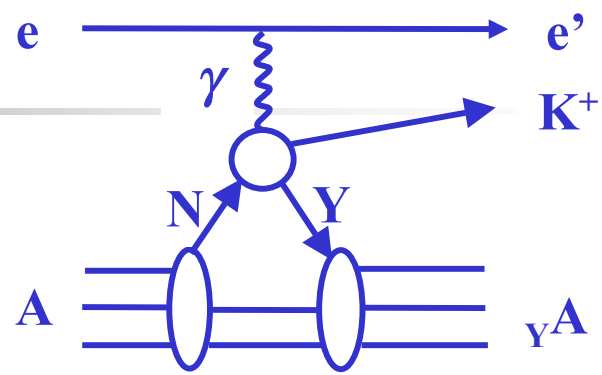
- World's data, with E93-018, at W=2.15 GeV
- Add CLAS data at $Q^2 = 0$
  - Steep Q^2 fall for Σ^0; much flatter for Λ

The K^+ Charge Form Factor



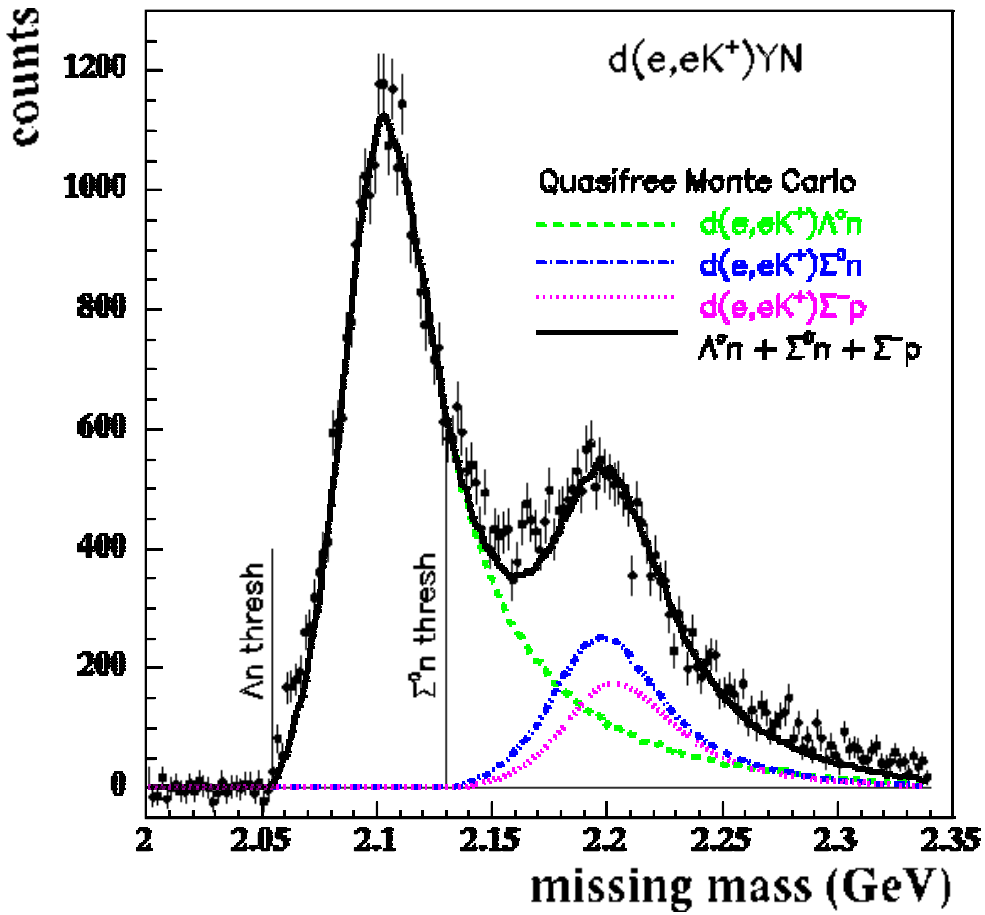
- Keith Baker (private comm.) E93-018
- Extrapolation of t-dependence of σ_L to K^+ pole (Chew-Low method)
- Result at $Q^2 = 1.0$
- Analysis in progress of Hall A data for $Q^2 = 0.5$ & 2.0 $(GeV/c)^2$

YN Interaction and Hypernuclear Structure



- E91-016 Collaboration, Hall C
  - J. Reinhold, F. Dohrmann, J. Cha, B. Zeidman, *et al.*
  - HMS and SOS used in standard setup
  - Deuteron, ^{3}He and ^{4}He target results (J. Reinhold, private comm.)
- First demonstration of the feasibility of light hypernuclear electroproduction

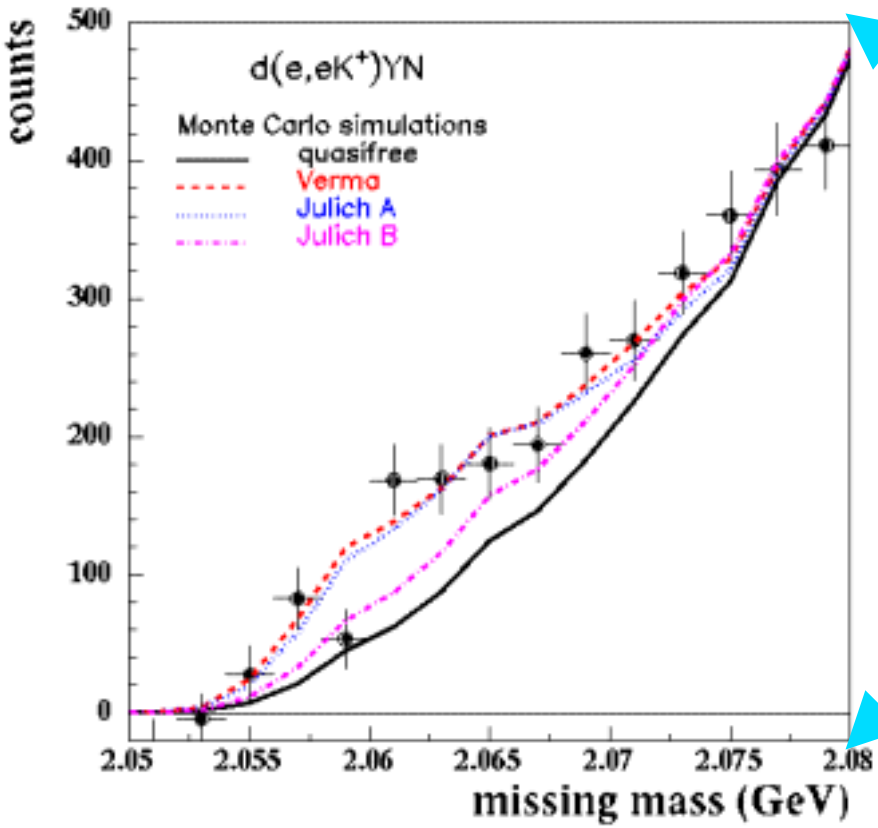
Electroproduction on the Deuteron



- Quasi-free production
  - E = 3.245 GeV
  - Q^2 = 0.38 GeV^2
- Access to Λ, Σ^0, and Σ^- cross section
- Access to YN final state interaction → scattering lengths and effective ranges
- No "cusps" or "dibaryons" seen

YN Interaction and Hypernuclear Structure

Λn FSI from $^2H(e,e'K^+)$



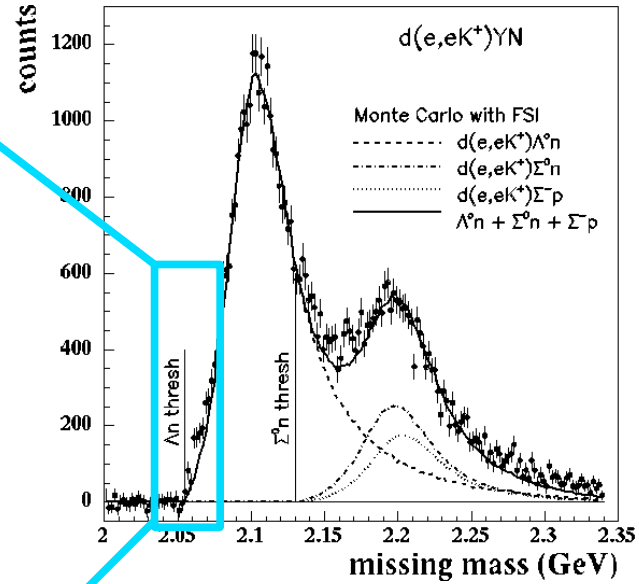
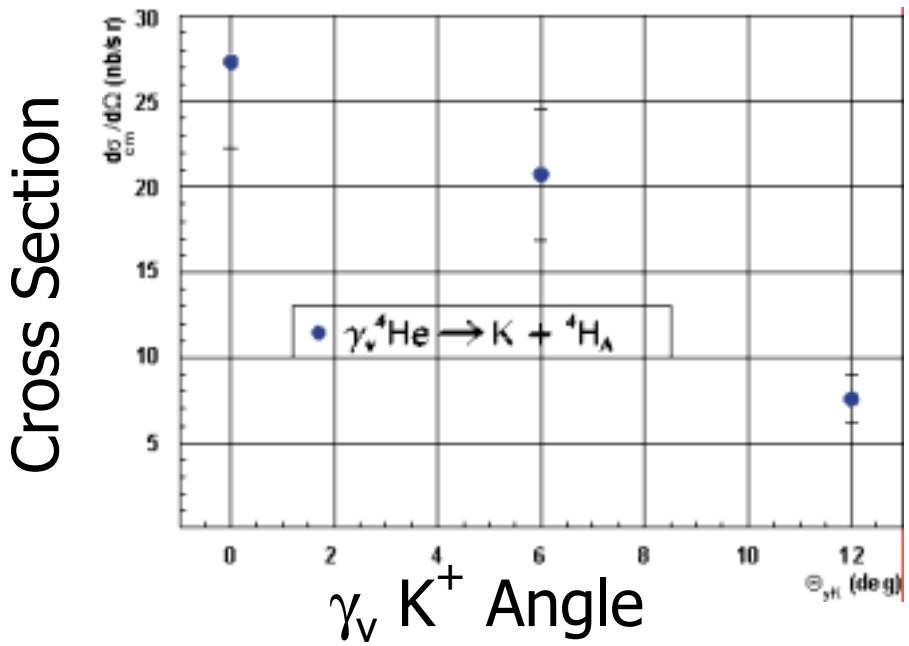


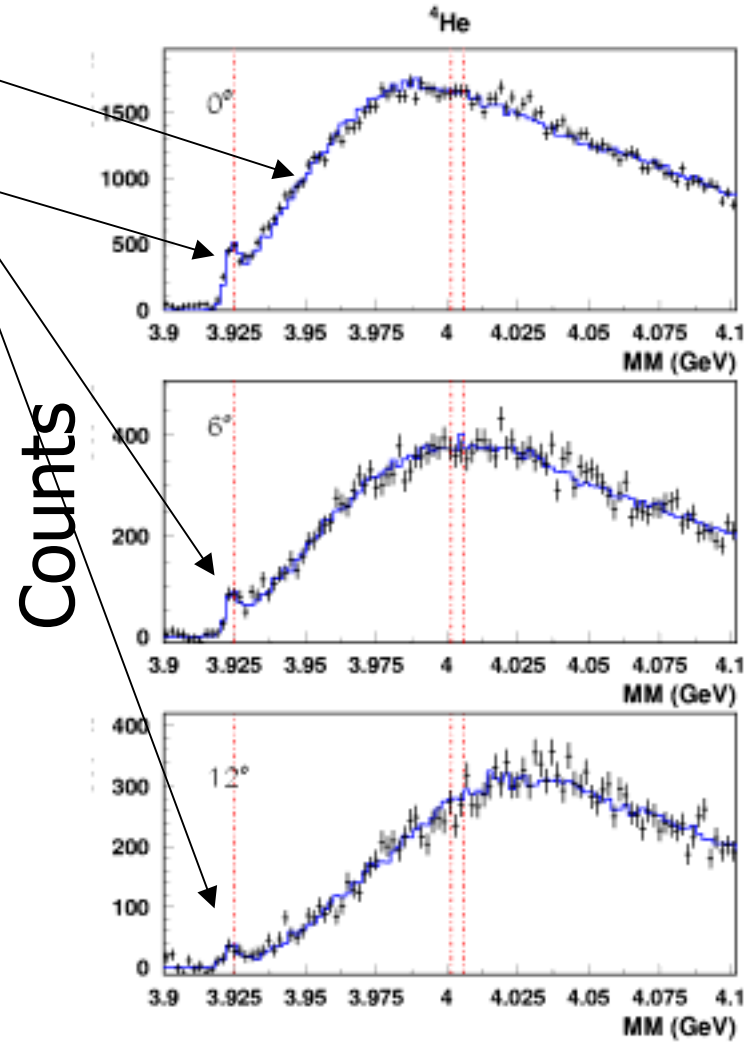
Table 1: Scattering length and effective range for the three hyperon-nucleon potentials used in the simulations.

Model	State	a (fm)	r (fm)
Verma	$^1S_0$	-2.29	3.15
	$^3S_1$	-1.77	3.25
Jülich A	$^1S_0$	-1.60	1.33
	$^3S_1$	-1.60	3.15
Jülich B	$^1S_0$	-0.57	7.65
	$^3S_1$	-1.94	2.42

^{4}He(e,e′ K$^+$) $^4_\Lambda$H Hypernuclear State Measured

- Quasi-free production
- Angle-independent peaks
- Λ bound by 2.0 MeV

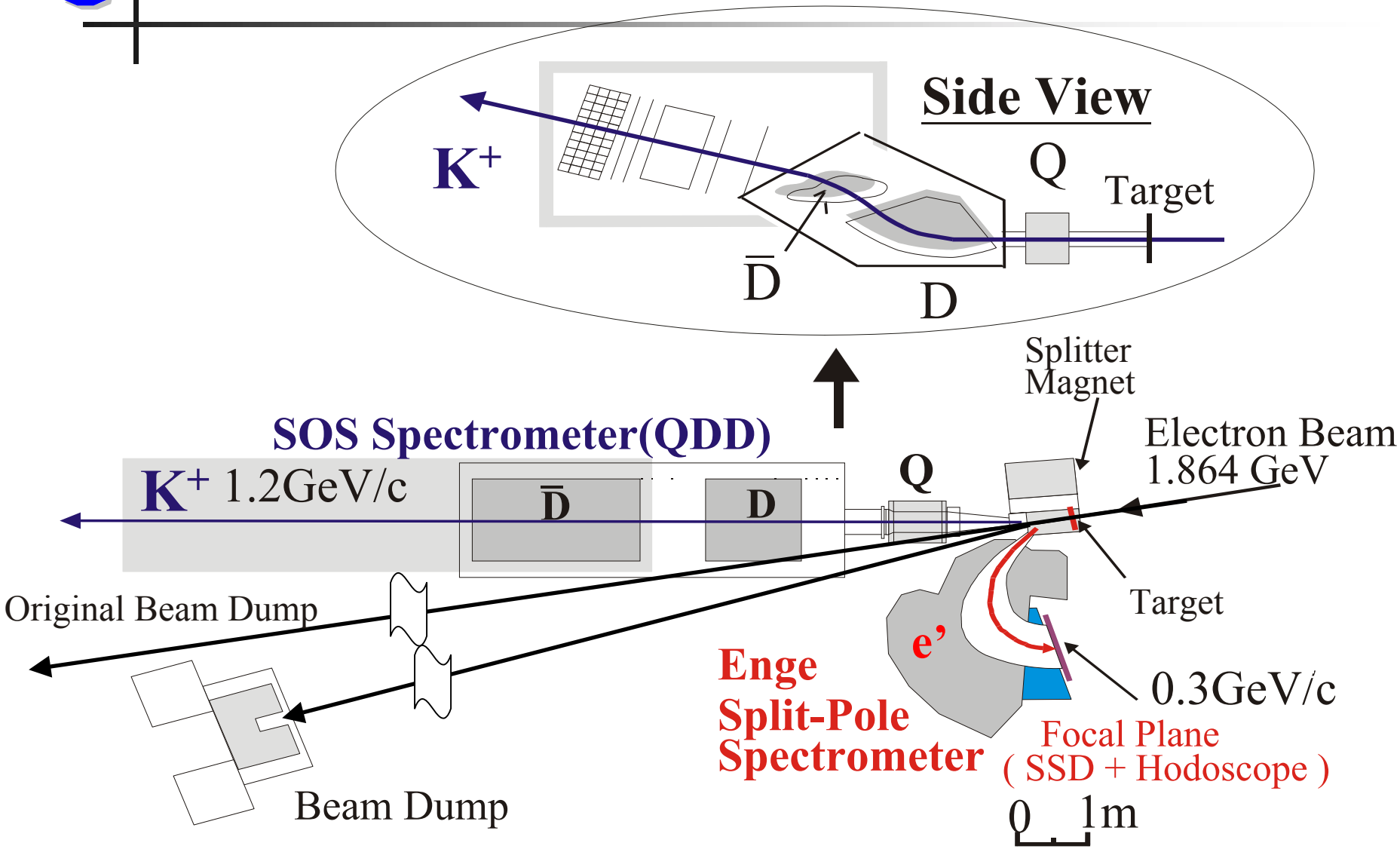




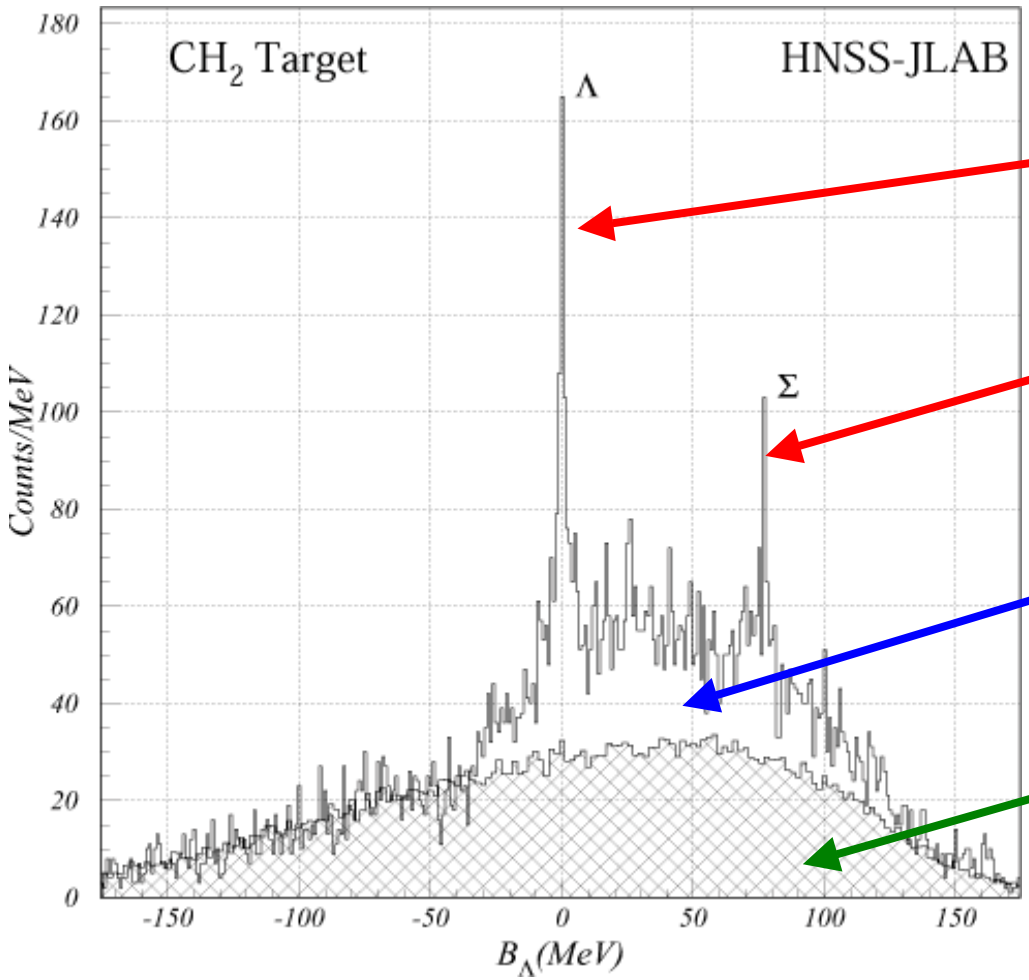
High Resolution Hypernuclear Spectroscopy

- Physics goals:
  - Measure p-shell ΛN spin-orbit splitting
  - (γ,K^+) spectra favor high J, unnatural parity states
- E89-009 L. Tang, E. Hungerford, R.Chrien *et al.*
  - Showed $A(e,e'K^+)_\Lambda A$ with $\delta E \sim 900$ keV is possible
  - Used Hall C SOS for K^+, Enge Splitpole for e'
  - Tour-de-Force demonstration of $^{12}C(e, e' K^+)^{12}_\Lambda B$
- E01-011 O.Hashimoto, J.Reinhold, L.Tang *et al.*
  - Strive for x250 in event rate, $\delta E < 400$ keV
  - Replace SOS with "HKS" built by Japanese team
  - Improve Enge spectrometer to evade bremsstrahlung electrons; "tilt method"

E89-009 Setup



Calibration on Hydrogen



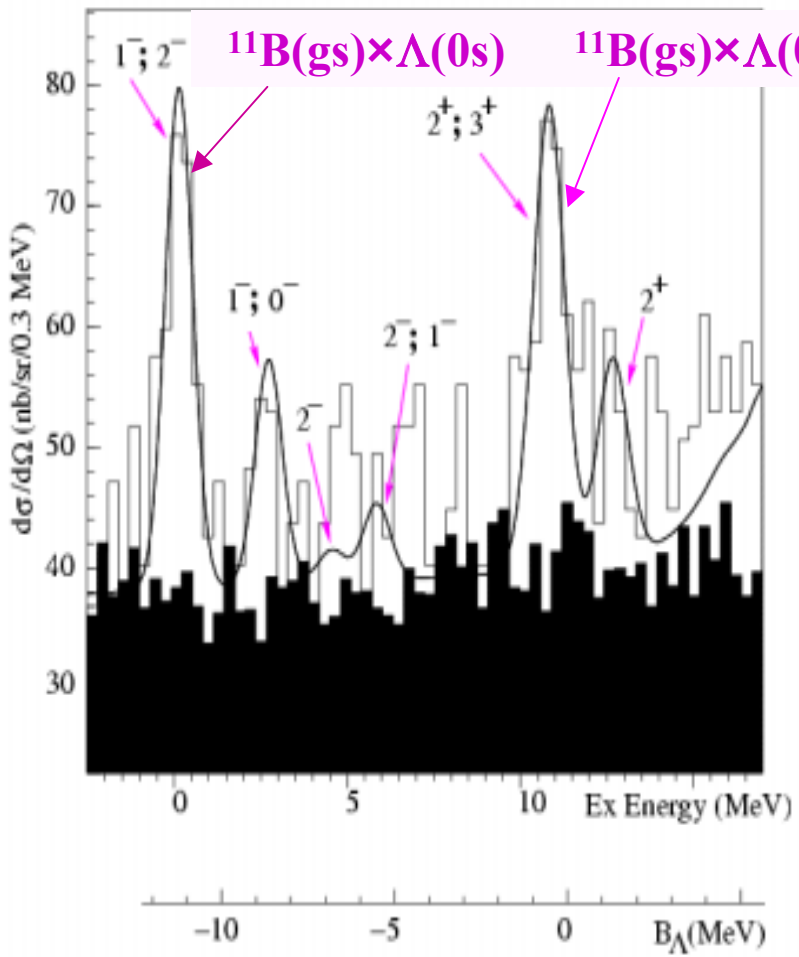
$p(e,e'K^+)\Lambda$

$p(e,e'K^+)\Sigma^0$

$^{12}C(e,e'K^+)(Q.F.)$

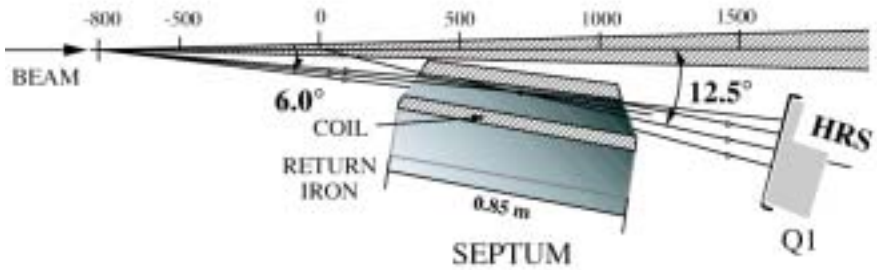
Accidentals

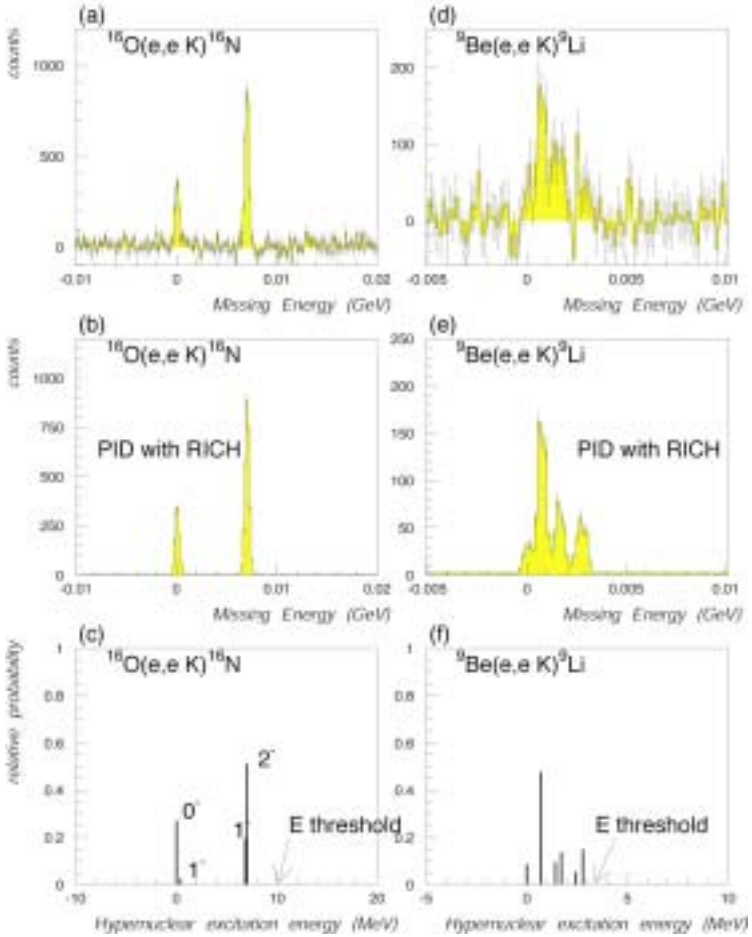
$^{12}C(e, e' K^+)^{12}{}_{\Lambda}B$ (E89-009)



- Bound states resolved
  - $\delta E \sim 0.9$ MeV FWHM
  - Compare to 1.5 MeV using (π^+,K^+) reaction
  - 1 month data taking
  - Calculation by Motoba & Milliner
- Ground state doublet
  - $3/2^- + 1/2^+ = 1^-, 2^-$
- Λ in P-shell states
  - $3/2^- + \{1/2^-, 3/2^-\} = 2^+, 3^+$
- Core excited states

Hypernuclear Spectroscopy - E94-107



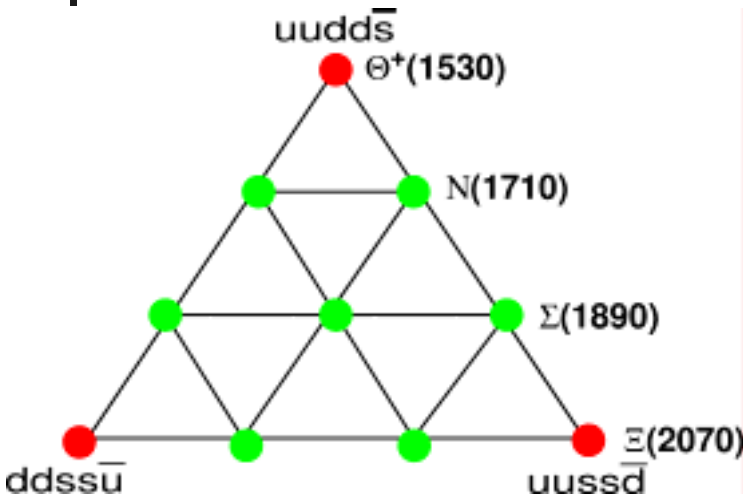


- Next experiment in Hall A
- Symmetric set-up of HRS at 6° with two septum magnets
- Energy resolution ~ 350 keV
- Improved particle ID with RICH
- Targets ^{7}Li, ^{9}Be, ^{12}C, ^{16}O, ^{52}Cr
- Scheduled to run December 4, 2003

Outlook for Hypernuclear Spectroscopy

- Technical challenges manageable for (e,e' K^+)
  - High resolution of ~400 keV is goal
  - High rates of > few 100/day for $^{12}_{\Lambda}$B ground state (comparable to (π^+,K^+) work)
  - Installation of HKS planned in mid-2004
- Program Elements:
  - Core excited states & splitting of the p_Λ-state of $^{12}_{\Lambda}$B…
  - Prove that medium-heavy targets, e.g. ^{28}Si(e,e'K^+)$^{28}_{\Lambda}$Al, are possible

An Exotic S=+1 Baryon: Θ^+

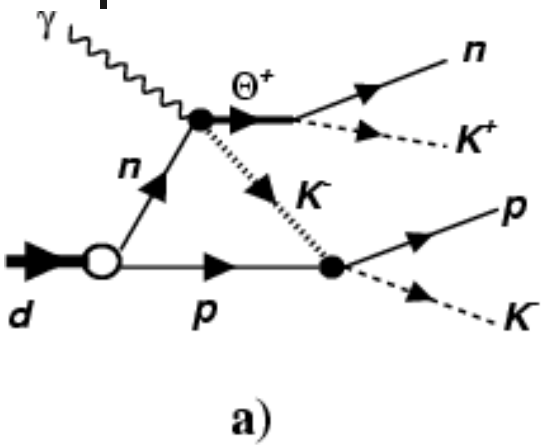


Anti-decuplet in a chiral soliton model

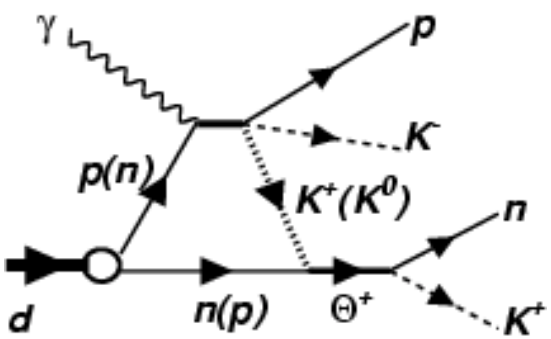
D. Diakonov , V. Petrov, M. Polyakov,
Z. Phys. **A359**, 305 (1997).

- 5-quark I=0 resonance
- "Exotic" since it contains an s-bar quark → S=+1
- Predicted at mass 1.53 GeV & width of 15 MeV
- Not excluded by KN phase shift data
- Evidence reported by:
  - LEPS/Spring-8 $\gamma + {}^{12}C$
    - PRL, to be published
  - DIANA/ITEP $K^+ + Xe$
    - arXiv:hep-ex/0304040

Θ^+: Photoproduction in CLAS



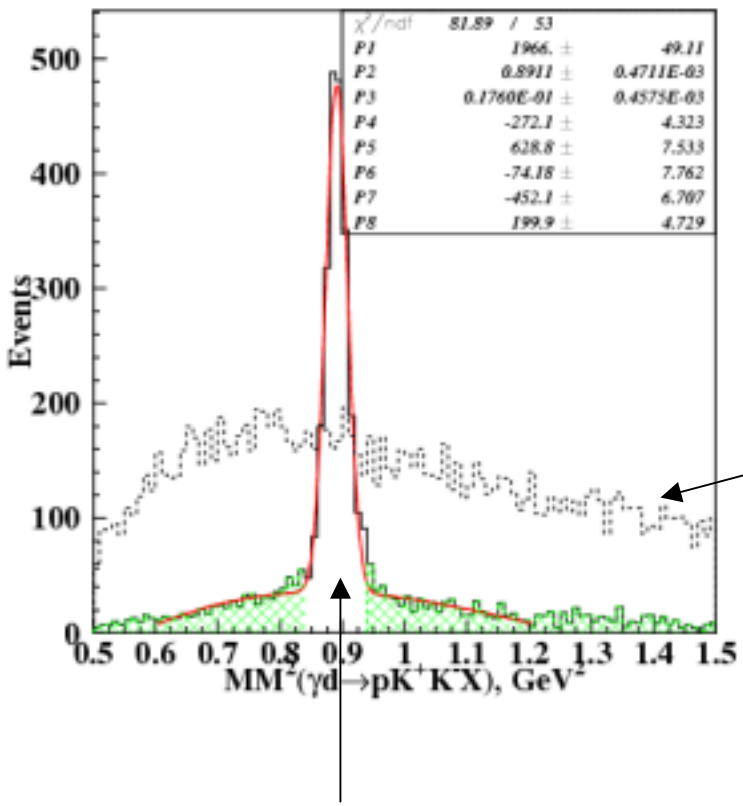
a)



b)

- "g2 data" group: D. Carman, K. Hicks, V. Koubarovski, E. Pasyuk, R. Schumacher, E. Smith, S. Stepanyan , D. Tedeschi, L. Todor
- γ **d** $\rightarrow$ **p** K^+ K^- **(n)** exclusive channel
  - No Fermi motion correction to make (as was done at LEPS)
  - FSI puts K^- at larger lab angles: better CLAS acceptance
  - FSI not rare: in ~50% of $\Lambda(1520)$ events both nucleons detected with p>0.2 GeV/c
- No statistically significant result seen in the LEPS "spectator" channel
  - γ n (p) $\rightarrow$ n K^+ K^-(p) with Fermi motion correction

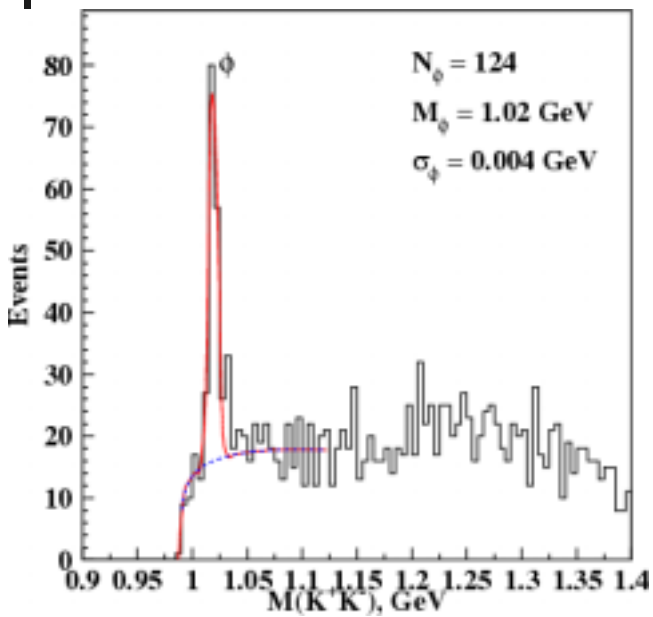
Θ^+: Channel Identification

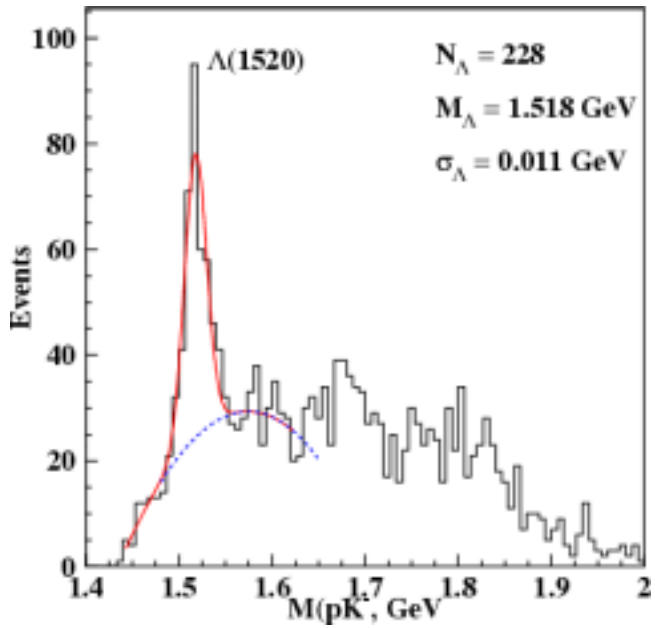


Reconstructed Neutrons

- Detected K^+ K^- p
  - Reconstruct neutron via missing mass
  - $1.5 < E_\gamma < 3.1$ GeV
- No K^+K^-pn events rejected by cuts (dashed histogram)
- ~15% non-K^+K^-pn events within 3σ range

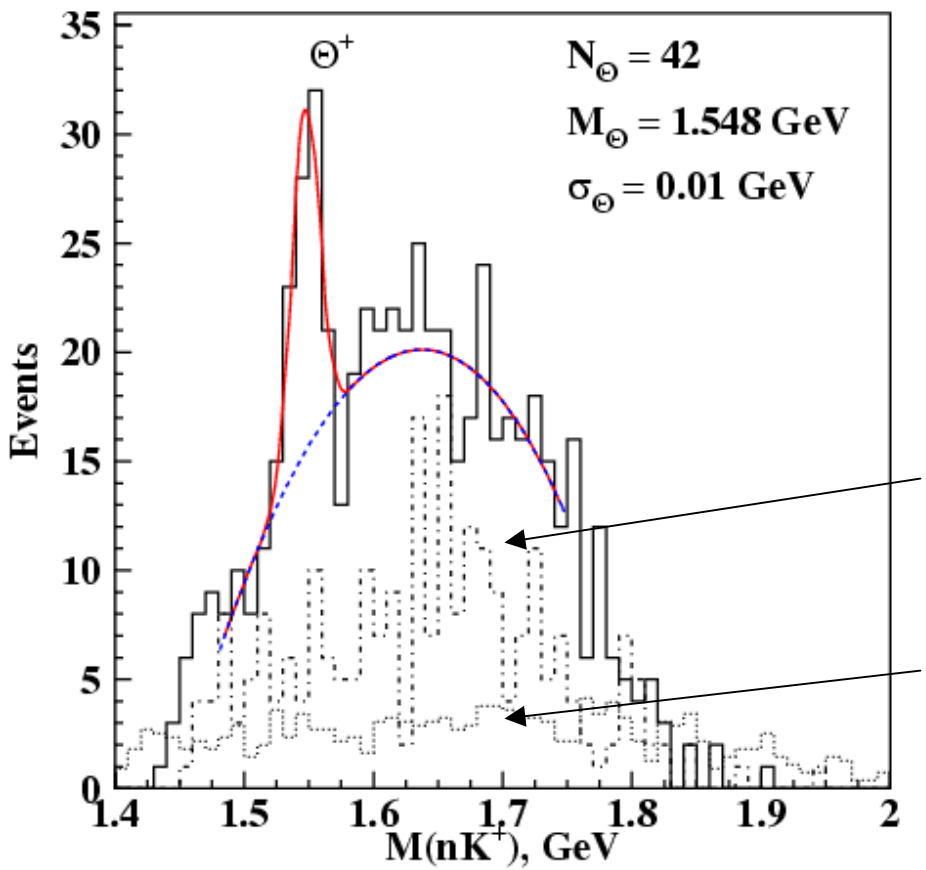
Θ^+: Background Rejection





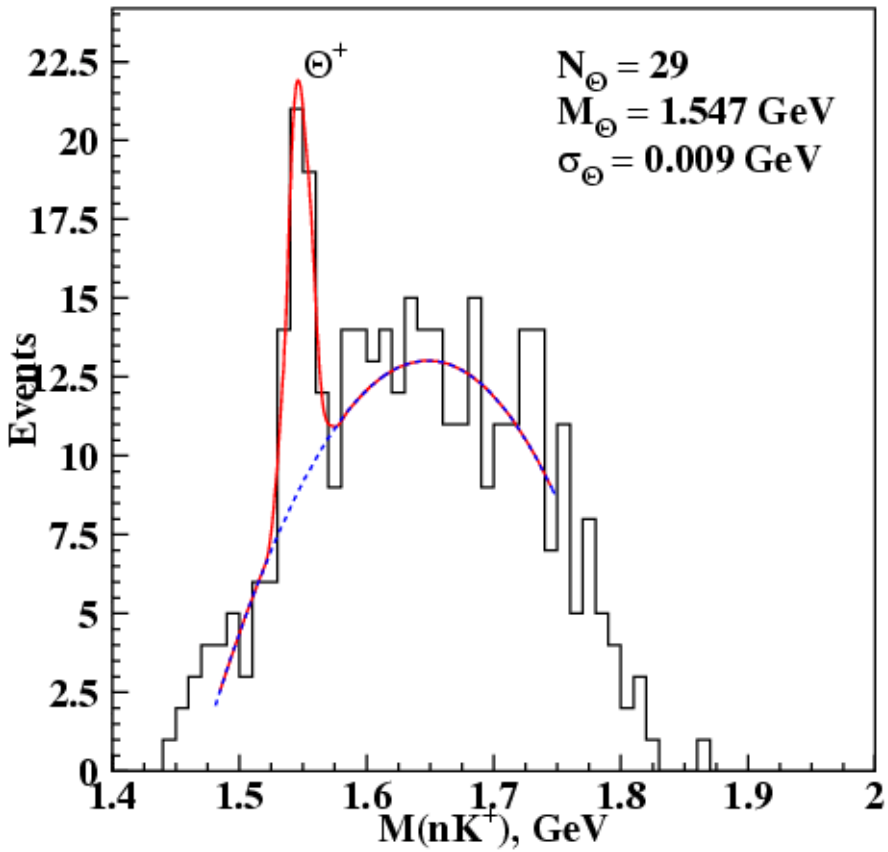
- Remove events with IM(K^+K^-)→ ϕ(1020)
  - IM < 1.07 GeV
- Remove events with IM(pK^-)→ Λ(1520)
- Limit K^+ momentum due to γ d→p K^- Θ^+ phase space
  - p_{K^+} < 1.0 GeV/c

Θ^+: Exclusive Result I



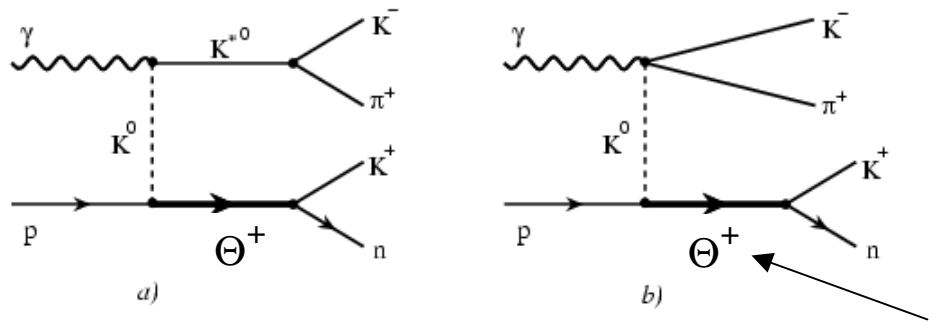
- Result of "g2" analysis of channel $\gamma\, d \rightarrow p\, K^-\, K^+\, (n)$
- $M(nK^+) = MM(\gamma d \rightarrow pK^-X)$
- Narrow peak at 1.548 GeV
- Estimate $N_\Theta/\sqrt{N_B} \sim 5\ \sigma$ significance
- Background from $p\, K^-$ resonances
- Background from non-pKK events (scaled)

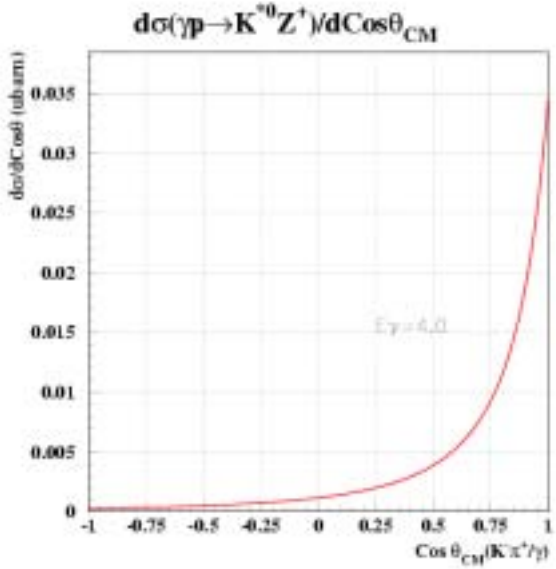
Θ^+: Exclusive Result I



- Tighter timing cut on kaon-proton vertex: $\Delta t(pK)<0.75$ nsec
- Mass and width consistent with observations at other labs

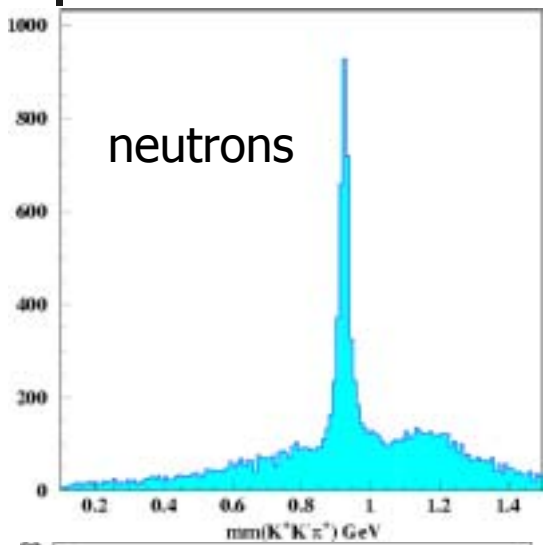
Θ^+: Another Channel in CLAS

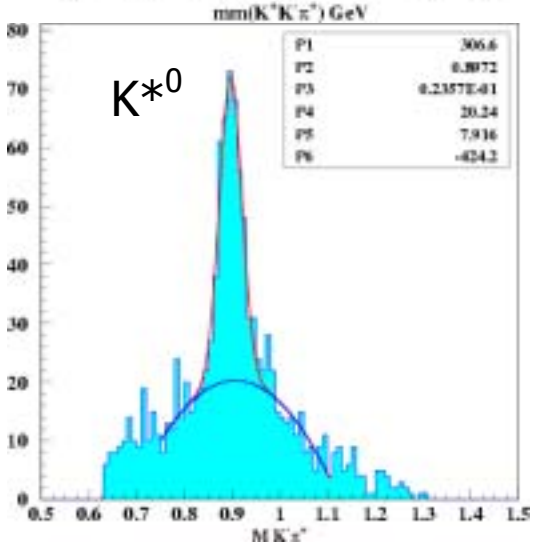




- "g6 data" group:
  V. Koubarovski *et al.*
- $\gamma p \rightarrow \pi^+ K^- K^+ (n)$ exclusive channel
- Production via t-channel K^0 exchange
  - Largest cross section at smallest t (M. Polyakov)
- At CLAS:
  - 2-charged particle trigger
  - $E_\gamma < 5.2$ GeV

Θ^+: Channel Identification



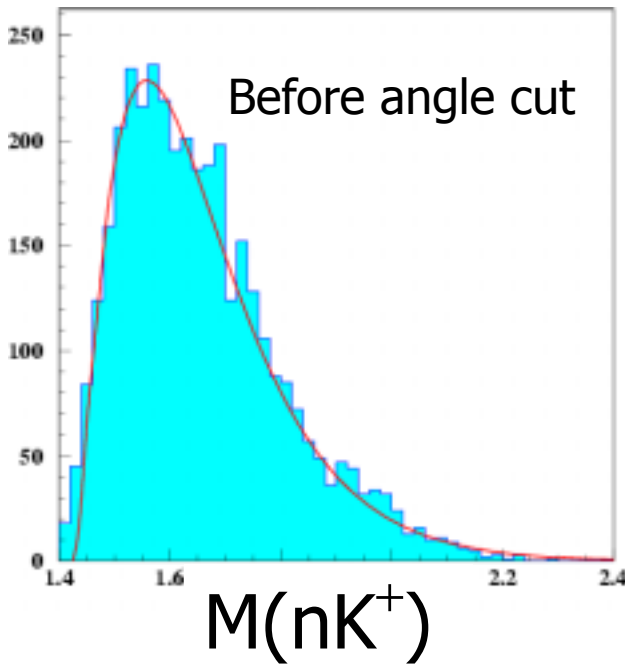


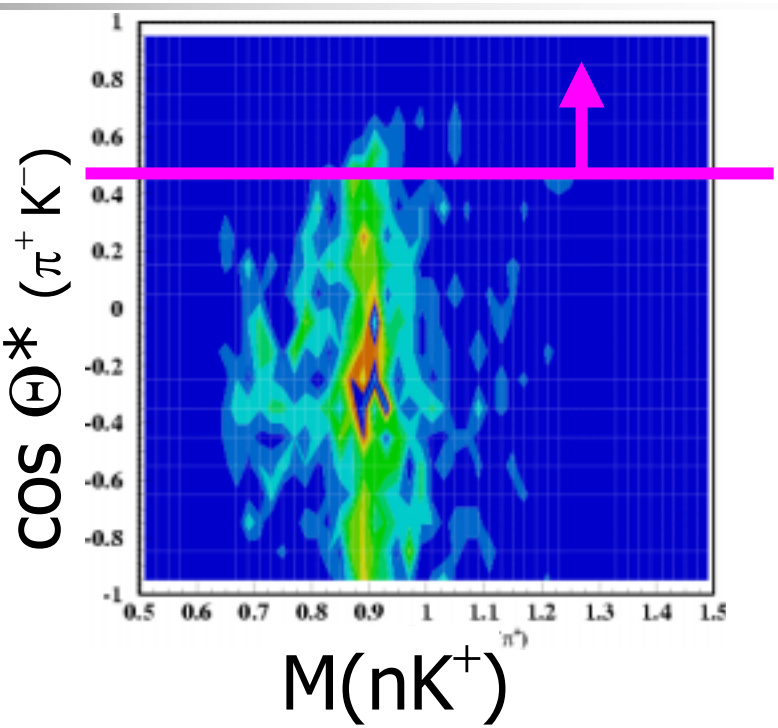
- Missing mass selects neutrons:

  $\gamma p \rightarrow \pi^+ K^+ K^- X$

- Invariant mass of $\{\pi^+ K^-\}$ selects K^{*0}

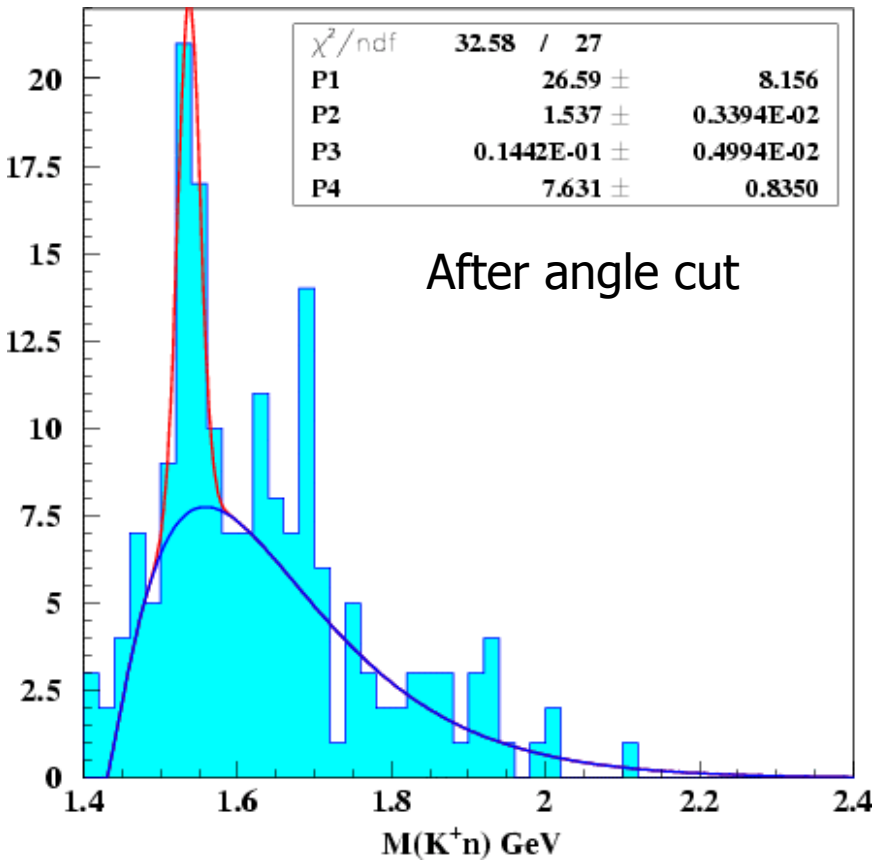
Θ^+: Select Small t





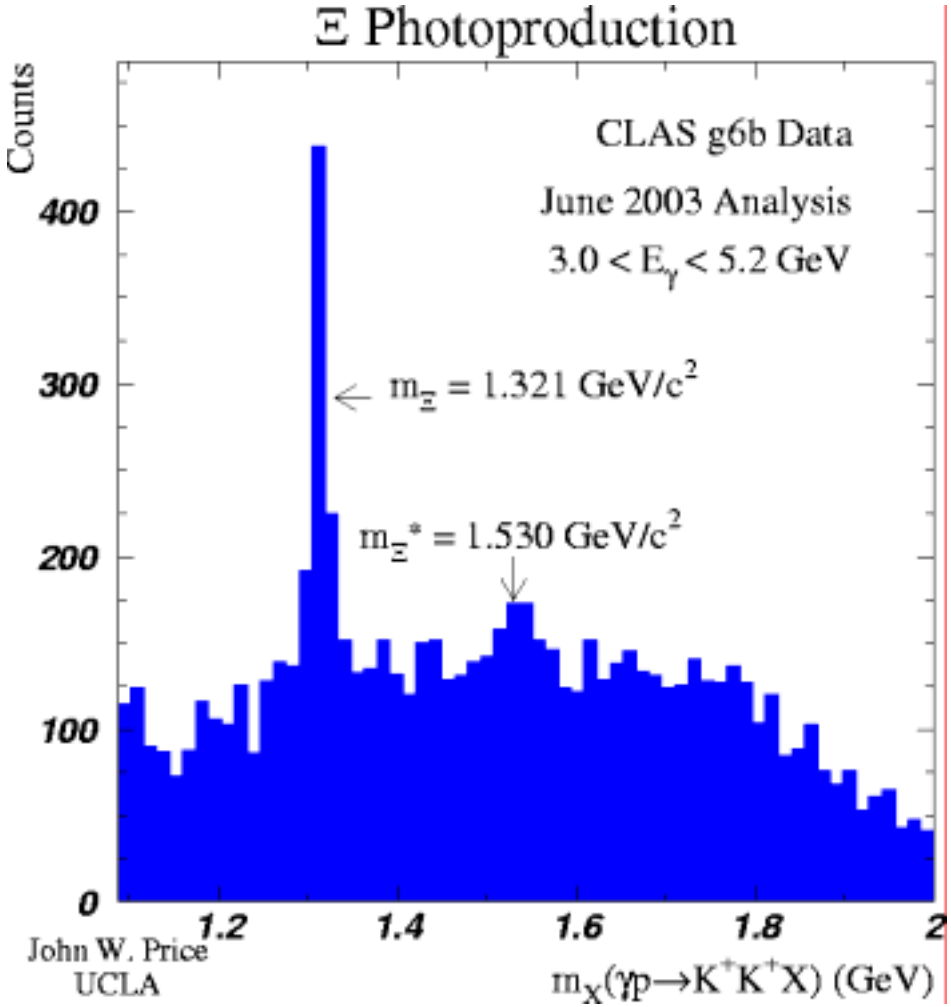
- $M(nK^+) = MM(\gamma p \rightarrow \pi^+ K^- X)$
- Select small angle (t) to enhance signal-to-noise

Θ^+: Exclusive Result II



- Result of "g6" analysis of channel $\gamma p \rightarrow \pi^+ K^- K^+ (n)$
- Invariant mass of $\{K^+ n\}$ after selecting $\cos \Theta^*_{(\pi^+ K^-)} > 0.5$
- Background shape taken from spectrum without small-t cut
- Estimate 4.8 σ significance

Other Hyperon Analysis Work



- Photoproduction of the Ξ^- (J. Price *et al.*)
  - $\gamma + p \rightarrow K^+ K^+ \Xi^-$ seen in CLAS
  - Proof-of-principle for a new S = –2 Ξ spectroscopy tool
  - $SU(3)_F$ predicts 44 Ξ states, only 11 seen

Other Hyperon Analysis Work

- Radiative decay of the $\Sigma(1385)$
  - G.Mutchler, S. Taylor *et al.*
  - Test of quark-model wavefunctions
- Observables $C_{x'}$ and $C_{z'}$ in $p(\vec{\gamma}, K^+)\vec{\Lambda}$
  - R. Bradford
  - With circularly polarized photon beam
  - Beam-recoil double polarization using CLAS
- Photoproduction off deuteron
  - I. Niculescu, A. Lima *et al.*
  - Isolate $\gamma + n \rightarrow K^+ + \Sigma^-$
- (e,e' K^+) 5th structure function
  - B. Raue, *et al.*

Summary

- Elementary photo-production experiments have both confirmed and shown new resonance-like structure near W = 1.9 GeV
- Electroproduction of hypernuclei is now an experimental reality, ready for exploitation
- An exotic S = +1 baryon, the Θ^+, has been seen in two CLAS data sets
- Several more strangeness-production experiments are in the JLab analysis pipeline