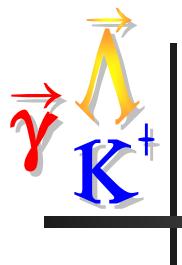
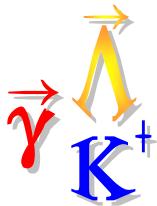


# Polarization in Hyperon Photo- and Electro- Production



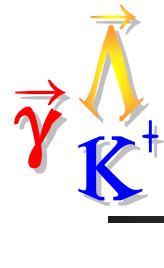
Reinhard Schumacher

Carnegie Mellon

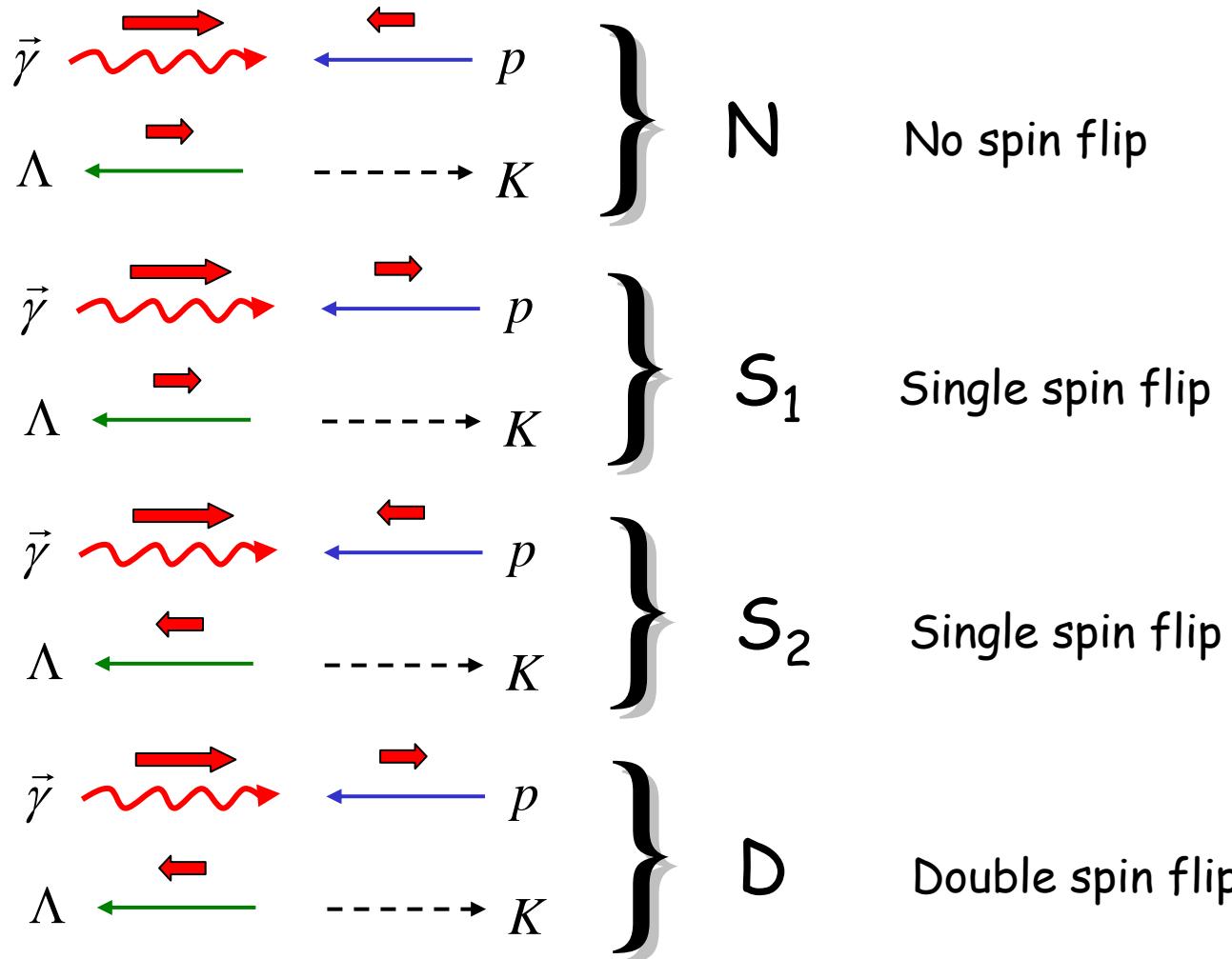


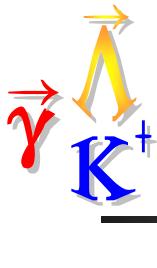
# Overview:

- What are the polarization observables?
  - Explain what  $C_x$  and  $C_z$  and  $P$  represent
  - Brief survey of recent data and models:
    - $P$ : J. McNabb *et al.*, Phys. Rev. C **69**, 042201 (2004).
    - $C_x, C_z$ : R. Bradford *et al.*, Phys. Rev. C **75**, 035205 (2007).
    - GRAAL ( $P$ ), LEPS ( $\Sigma$ ), CLAS electroproduction.
- CLAS finds:  $P^2 + C_x^2 + C_z^2 \approx 1$  for  $K^+\Lambda$ 
  - The  $\Lambda$  is produced fully polarized off a circularly polarized beam . Why!?
  - A quantum mechanical interpretation
    - R.S., to be published Eur. Phys. Jour. A, arXiv:nucl-ex/0611035
  - A semi-classical interpretation



# Helicity Amplitudes





# 16 Pseudoscalar Meson Photoproduction Observables

Table 1  
Observables

Single Polarization {

Beam & Target {

Beam & Recoil {

Target & Recoil {

Usual symbol	Helicity representation	Experiment required a)	Type
$d\sigma/dt$	$ N ^2 +  S_1 ^2 +  S_2 ^2 +  D ^2$	{-; -; -}	S
$\Sigma d\sigma/dt$	$2\text{Re}(S_1^* S_2 - ND^*)$	{ $L(\frac{1}{2}\pi, 0); -; -$ }	
$T d\sigma/dt$	$2\text{Im}(S_1 N^* - S_2 D^*)$	{-; $y; y$ }	
$P d\sigma/dt$	$2\text{Im}(S_2 N^* - S_1 D^*)$	{-; $y; -$ } { $L(\frac{1}{2}\pi, 0); 0; y$ }	
$G d\sigma/dt$	$-2\text{Im}(S_1 S_2^* + ND^*)$	{ $L(\pm\frac{1}{4}\pi); z; -$ }	BT
$H d\sigma/dt$	$-2\text{Im}(S_1 D^* + S_2 N^*)$	{ $L(\pm\frac{1}{4}\pi); x; -$ }	
$E d\sigma/dt$	$ S_2 ^2 -  S_1 ^2 -  D ^2 +  N ^2$	{c; z; -}	
$F d\sigma/dt$	$2\text{Re}(S_2 D^* + S_1 N^*)$	{c; x; -}	
$O_x d\sigma/dt$	$-2\text{Im}(S_2 D^* + S_1 N^*)$	{ $L(\pm\frac{1}{4}\pi); -; x'$ }	BR
$O_z d\sigma/dt$	$-2\text{Im}(S_2 S_1^* + ND^*)$	{ $L(\pm\frac{1}{4}\pi); -; z'$ }	
$C_x d\sigma/dt$	$-2\text{Re}(S_2 N^* + S_1 D^*)$	{c; -; x'}	
$C_z d\sigma/dt$	$ S_2 ^2 -  S_1 ^2 -  N ^2 +  D ^2$	{c; -; z'}	
$T_x d\sigma/dt$	$2\text{Re}(S_1 S_2^* + ND^*)$	{-; x; x'}	TR
$T_z d\sigma/dt$	$2\text{Re}(S_1 N^* - S_2 D^*)$	{-; x; z'}	
$L_x d\sigma/dt$	$2\text{Re}(S_2 N^* - S_1 D^*)$	{-; z; x'}	
$L_z d\sigma/dt$	$ S_1 ^2 +  S_2 ^2 -  N ^2 -  D ^2$	{-; z; z'}	

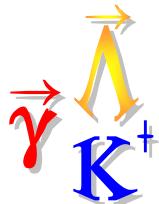
a) Notation is  $\{P_\gamma; P_T; P_R\}$  where:

$P_\gamma$  = polarisation of beam,  $L(\theta)$  = beam linearly polarised at angle  $\theta$  to scattering plane,  
 $C$  = circularly polarised beam;

$P_T$  = direction of target polarisation;

$P_R$  = component of recoil polarisation measured.

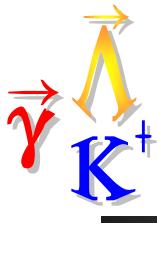
In the case of the single polarisation measurements we also give the equivalent double polarisation measurement.



# Polarization Observables

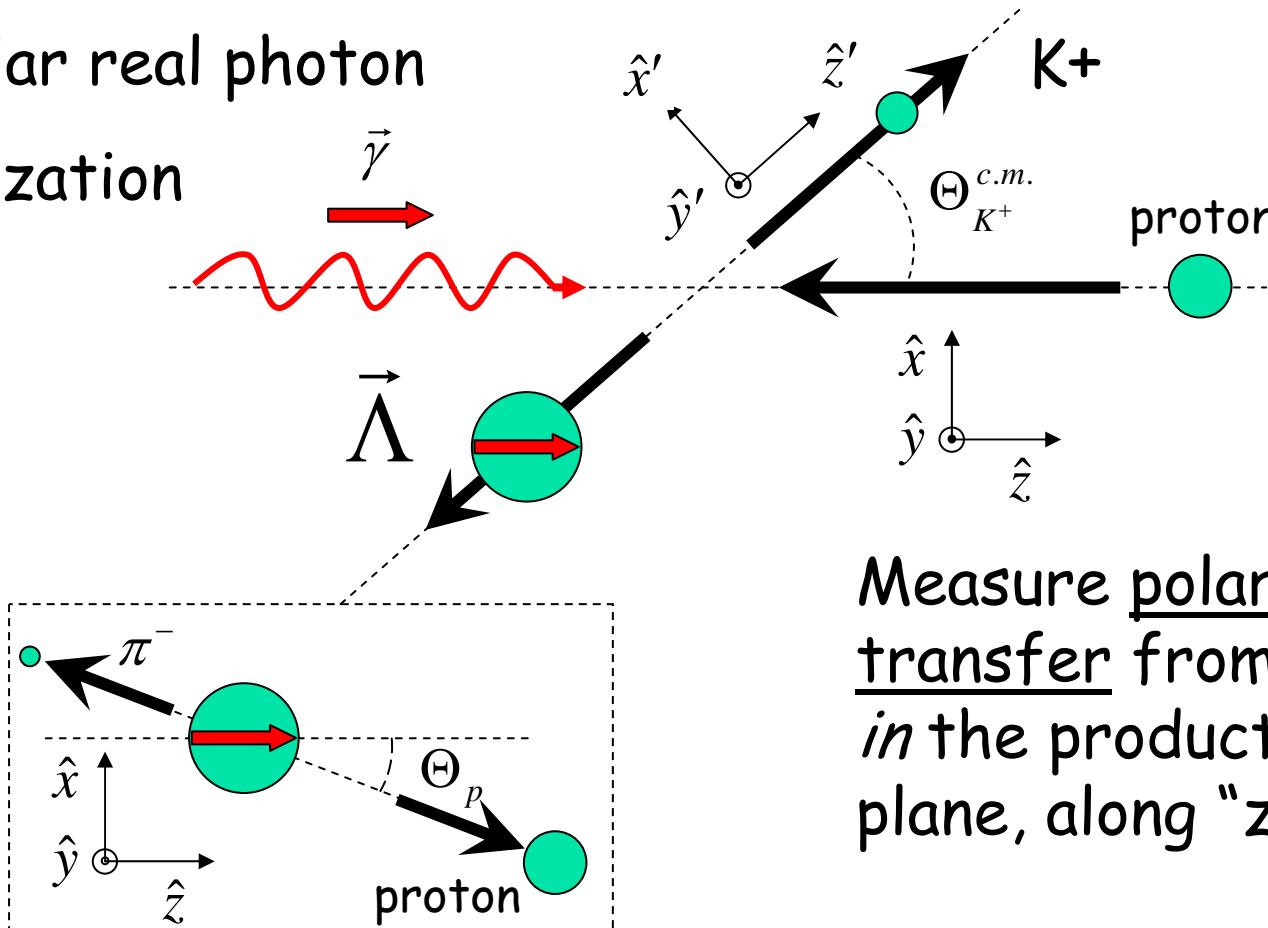
- Photoproduction described by 4 complex amplitudes
- Bilinear combinations define 16 observables
- 8 measurements needed to separate amplitudes at any given  $W$ 
  - differential cross section:  $d\sigma/d\Omega$
  - 3 single polarization observables:  $P, T, \Sigma$
  - 4 double polarization observables...

CLAS FROST program aims to create a "complete" set

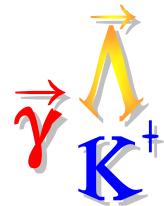


# Defining $C_x$ and $C_z$ and P

Circular real photon polarization



Measure polarization transfer from  $\gamma$  to  $\gamma$  in the production plane, along "z" or "x"



# Defining $C_x$ and $C_z$ and P

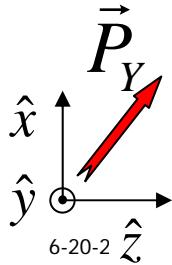
$$\rho_Y \frac{d\sigma}{d\Omega_{K^+}} = \frac{d\sigma}{d\Omega_{K^+}} \Big|_{unpol.} \left\{ 1 + \sigma_y P + P_\square (C_x \sigma_x + C_z \sigma_z) \right\}$$

$\rho_Y = (1 + \vec{\sigma} \cdot \vec{P}_Y)$  ← density matrix;  $\vec{\sigma}$ : Pauli spin matrix

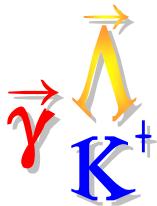
$P_{Yx} = P_\square C_x$  ← transferred polarization along x

$P_{Yy} = P$  ← induced polarization along y

$P_{Yz} = P_\square C_z$  ← transferred polarization along z



Notation: I.S. Barker, A. Donnachie, J.K. Storrow, Nucl. Phys. B95 347 (1975).



# Measuring $C_x$ and $C_z$ and $P$

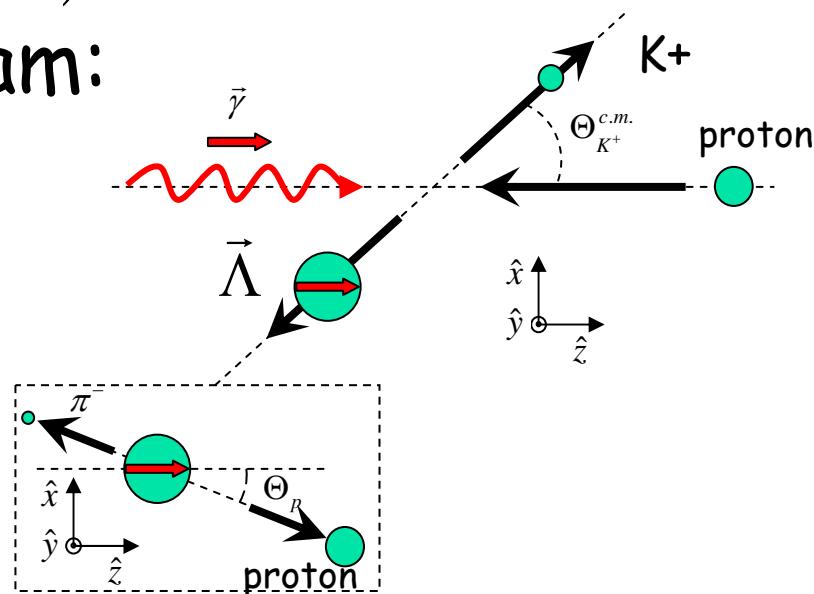
## ■ Unpolarized beam:

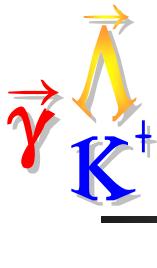
- Sensitive to  $P$  only: e.m. parity conservation
- Use  $\Lambda$  weak decay asymmetry w.r.t.  $y$  axis

$$I(\cos \Theta_p) = \frac{1}{2} (1 + \alpha P \cos \Theta_p)$$

## ■ Circularly polarized beam:

- Sensitive to  $C_x$  and  $C_z$  via helicity asymmetry

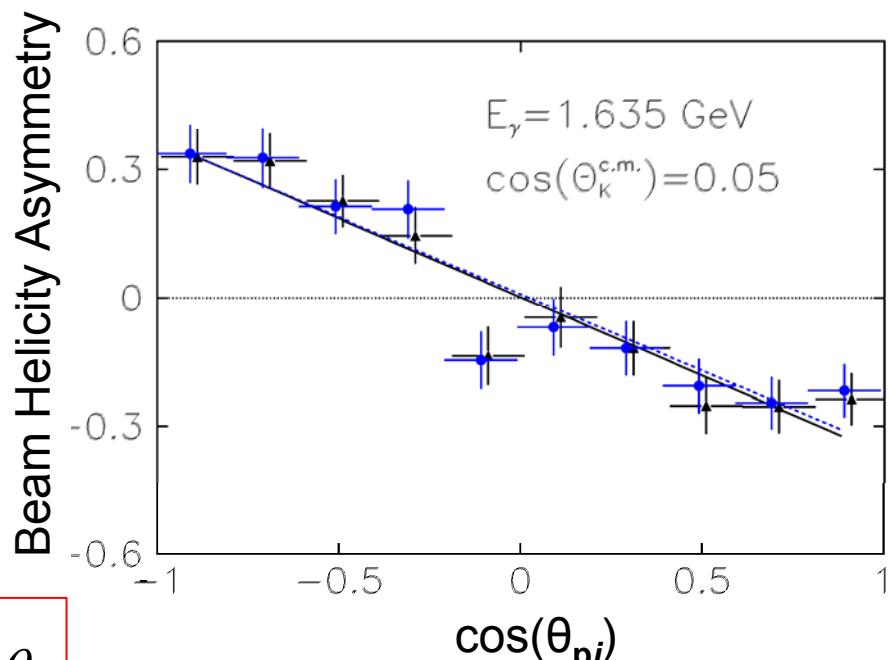




# Experimental Method

- Construct beam helicity asymmetries from extracted yields.
- Slope of asymmetry distribution is proportional to  $C_x$  and  $C_z$  observables:

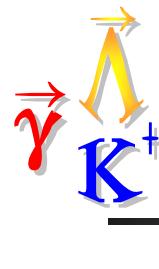
$$A(\cos \theta_{pi}) = \frac{N_+ - N_-}{N_+ + N_-} = \alpha P_{\square} C_i \cos \theta_{pi}$$



$N_{\pm}$  = helicity-dependent yields

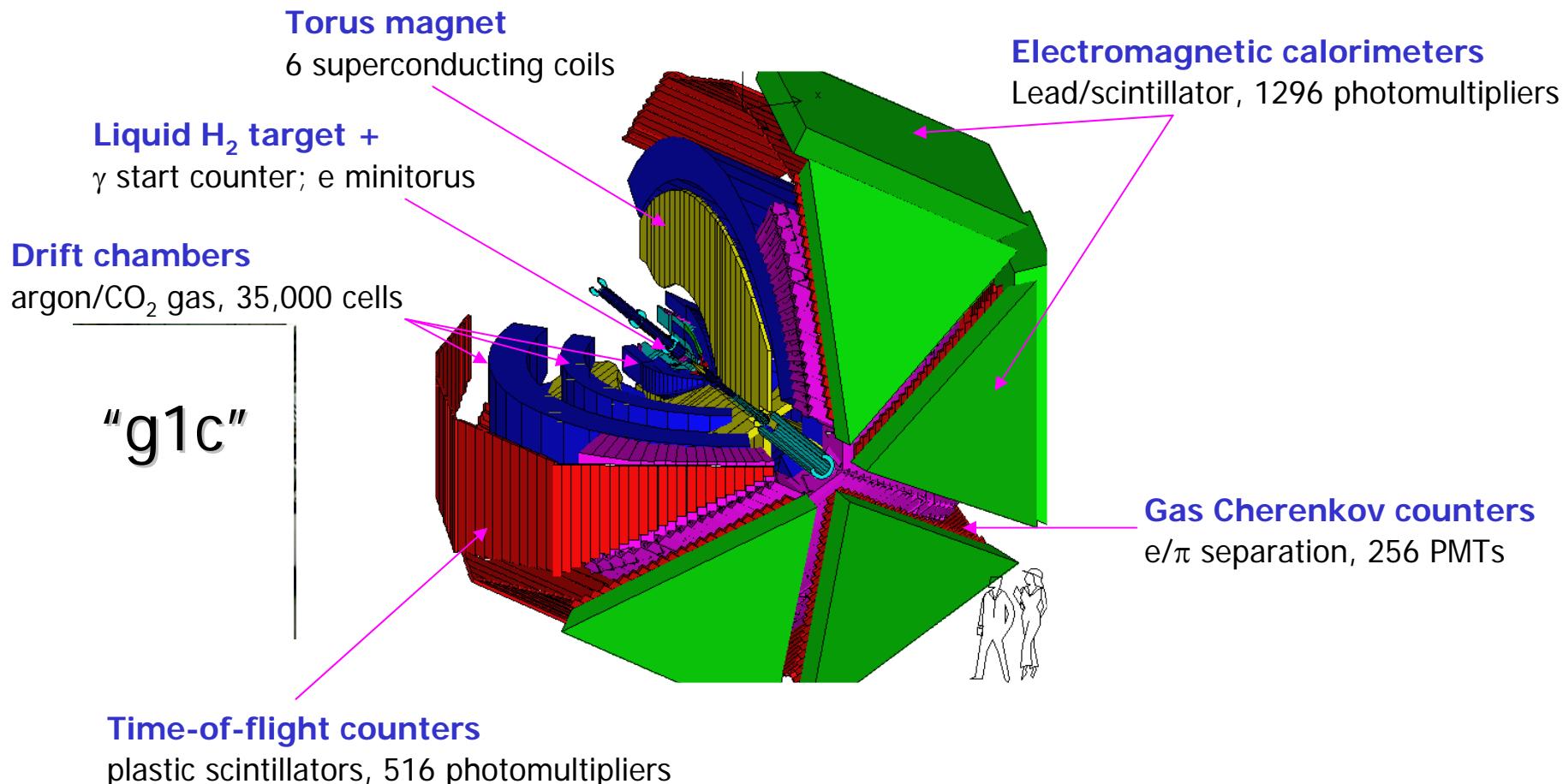
$\alpha$  =  $\Lambda$  weak decay asymmetry = 0.642

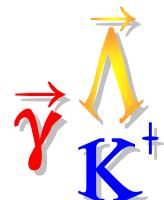
$P_{\square}$  = photon beam polarization (via Moller polarimeter)



# The CLAS System in Hall B

## CEBAF Large Acceptance Spectrometer

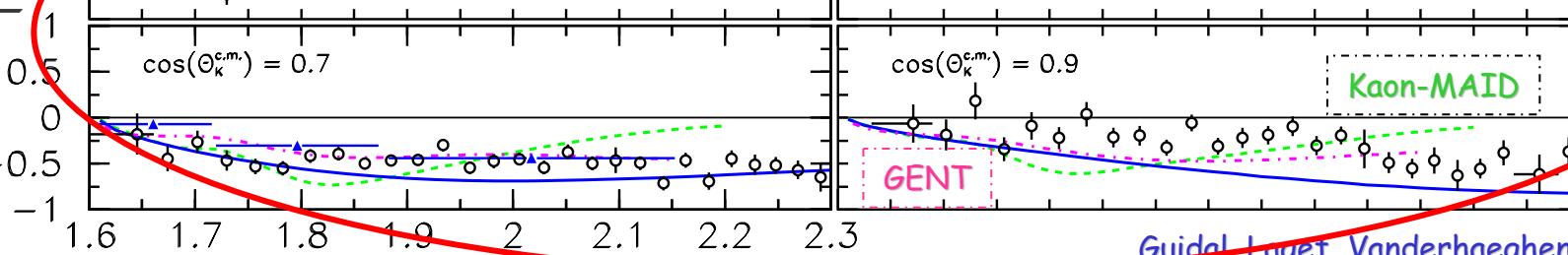




# P vs. W Results for $\Lambda$

Positive at backward K angles

Induced Polarization,  $P_\Lambda$



W (GeV)

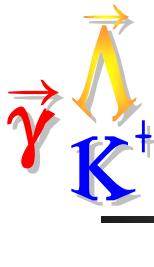
Negative at forward K angles

ty

Kaon-MAID

GENT

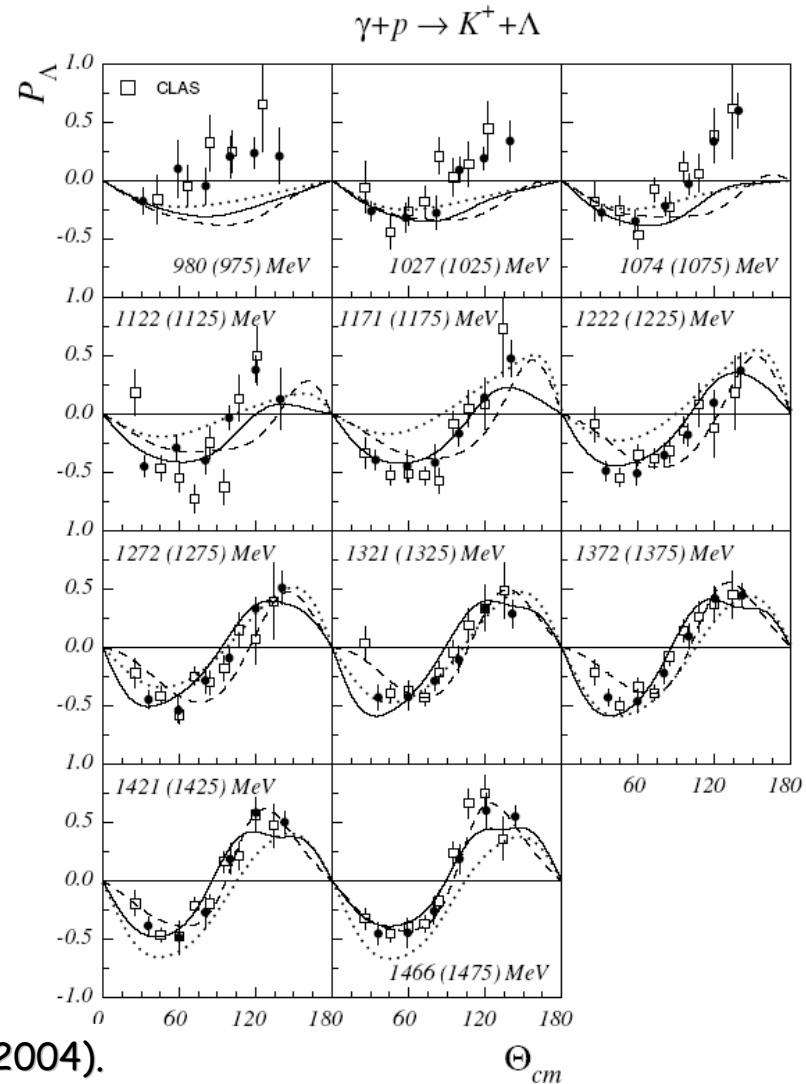
Guidal, Laget, Vanderhaeghen



# Recoil (Induced) Polarization, P

Excellent agreement between CLAS and new GRAAL results up to 1500 MeV.

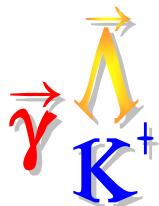
Confirms that  $\Lambda$  is negatively polarized at forward kaon angles, and positively polarized at backward kaon angles.



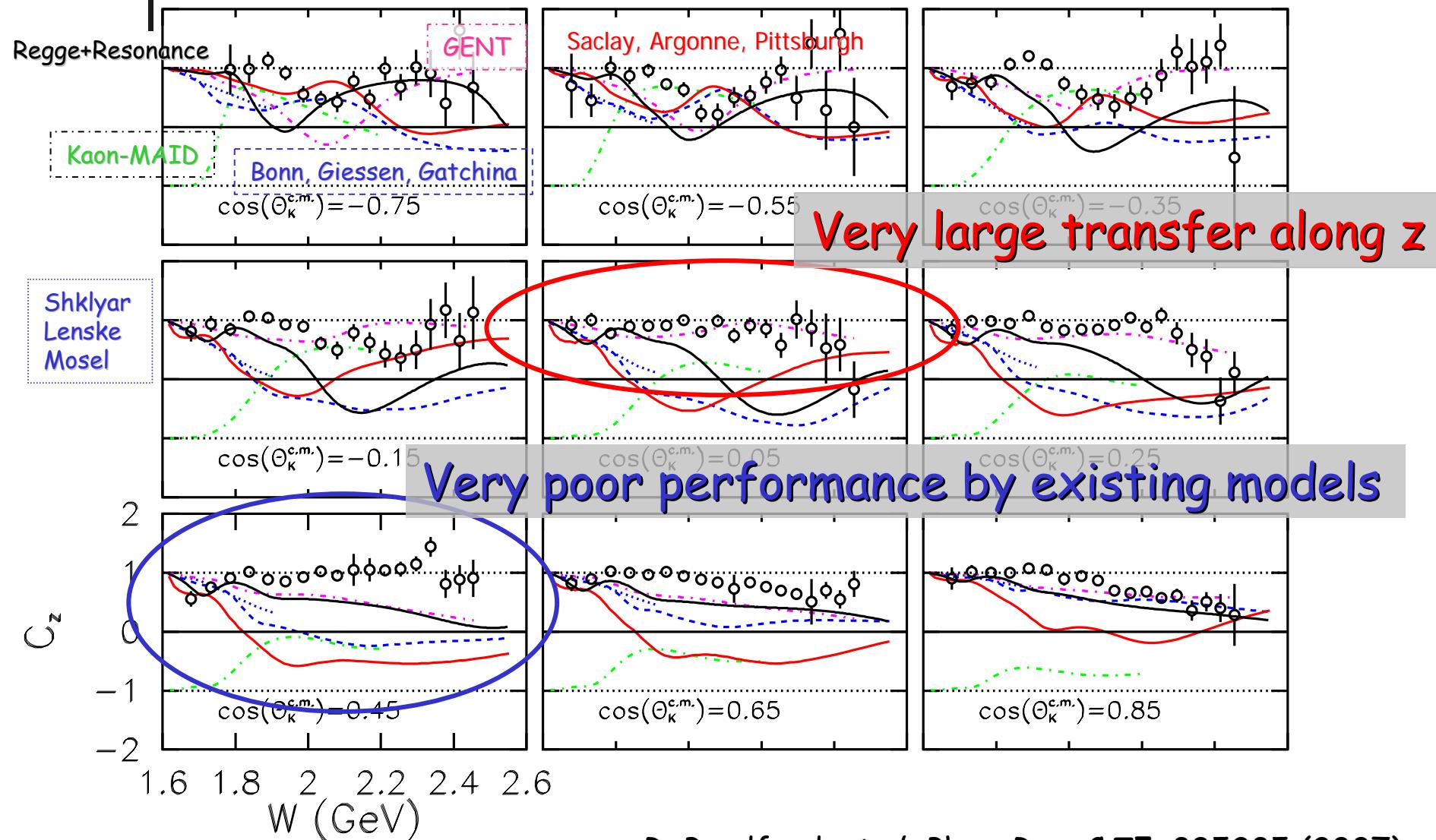
J. McNabb *et al.* (CLAS) Phys. Rev. C 69, 042201 (2004).

A. Lleres *et al.* (GRAAL) Eur. Phys. J. A 31, 79 (2007).

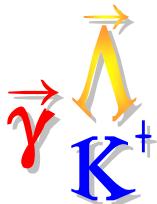
lar distributions of the  $\Lambda$  recoil polarizations for  $\gamma p \rightarrow K^+ \Lambda$  and  $\gamma$ -ray energies ranging from threshold up to comparison between GRAAL (closed circles) and CLAS (open squares—energies in parenthesis) results. Data are the predictions of the BCC (solid line), SAPCC (dashed line) and GI (dotted line) models.



# $C_z$ vs. $W$ Results for $\Lambda$



R. Bradford *et al.*, Phys. Rev. C 75, 035205 (2007).



# Model Comparisons

## ■ Effective Lagrangian Models

- Kaon-MAID; Mart, Bennhold, Haberzettl, Tiator
  - $S_{11}(1650)$ ,  $P_{11}(1710)$ ,  $P_{13}(1720)$ ,  $D_{13}(1895)$ ,  $K^*(892)$ ,  $K_1(1270)$
- GENT: Janssen, Ryckebusch *et al.*; Phys Rev C 65, 015201 (2001)
  - $S_{11}(1650)$ ,  $P_{11}(1710)$ ,  $P_{13}(1720)$ ,  $D_{13}(1895)$ ,  $K^*(892)$ ,  $\Lambda^*(1800)$ ,  $\Lambda^*(1810)$
- RPR (Regge plus Resonance) Corthals, Ryckebusch, Van Cauteren, Phys Rev C 73, 045207 (2006).

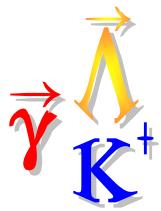
## ■ Coupled Channels or Multi-channel fits

- SAP (Saclay, Argonne, Pittsburgh) Julia-Diaz, Saghai, Lee, Tabakin; Phys Rev C 73, 055204 (2006).
  - rescattering of KN and  $\pi N$
  - $S_{11}(1650)$ ,  $P_{13}(1900)$ ,  $D_{13}(1520)$ ,  $D_{13}(1954)$ ,  $S_{11}(1806)$ ,  $P_{13}(1893)$

- ★ ■ BGG (Bonn, Giessen, Gachina): Sarantsev, Nikonov, Anisovich, Klempt, Thoma; Eur. Phys. J. A 25, 441 (2005)
  - multichannel (pion, eta, Kaon) PWA
  - $P_{11}(1840)$ ,  $D_{13}(1875)$ ,  $D_{13}(2170)$
- SLM: Shklyar, Lenske, Mosel; Phys Rev C 72 015210 (2005)
  - coupled channels
  - $S_{11}(1650)$ ,  $P_{13}(1720)$ ,  $P_{13}(1895)$ , but NOT  $P_{11}(1710)$ ,  $D_{13}(1895)$

## ■ Regge Exchange Model

- M. Guidal, J.M. Laget, and M. Vanderhaeghen; Phys Rev C 61, 025204 (2000)
  - $K$  and  $K^*(892)$  trajectories exchanged

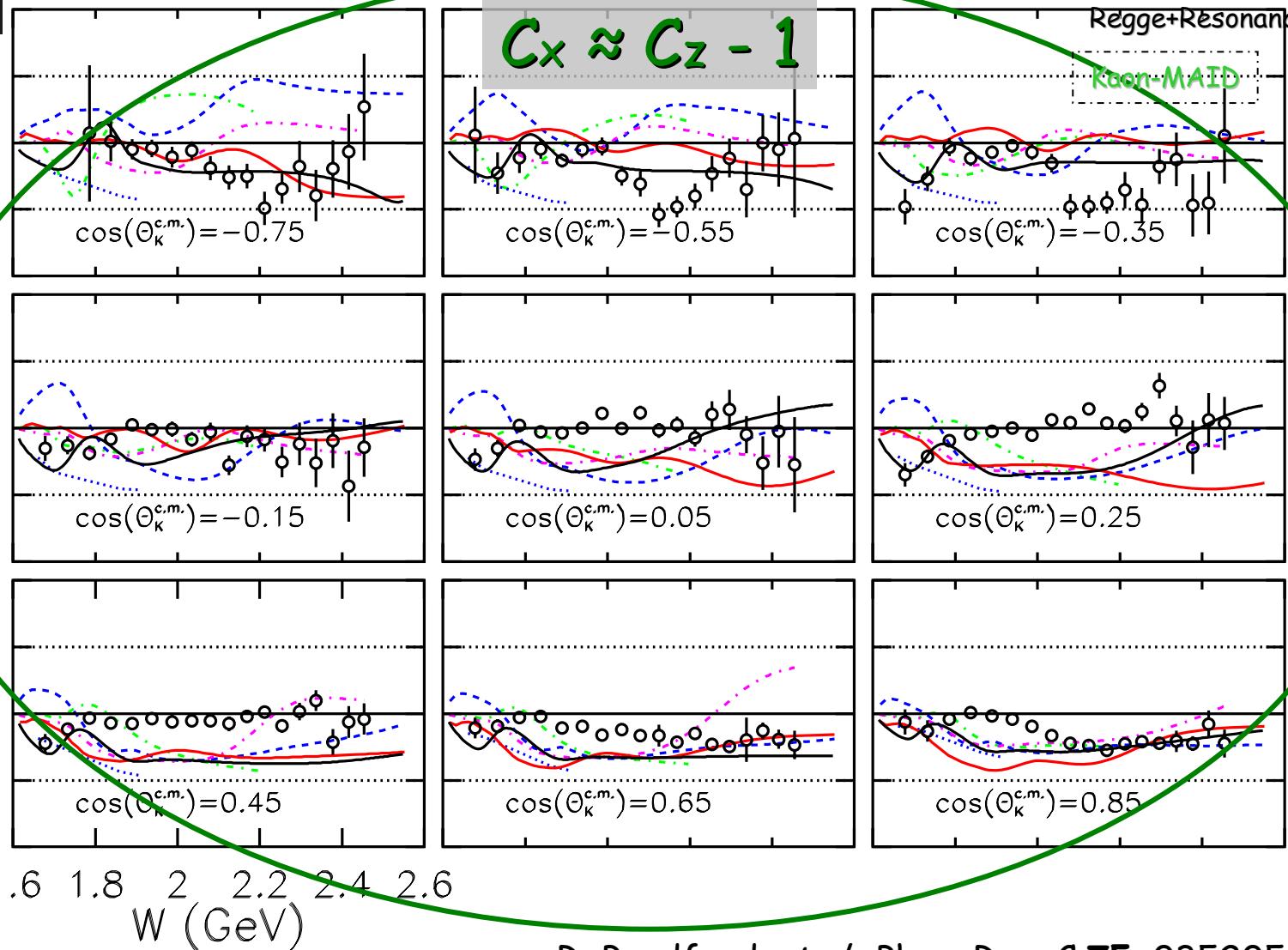


Saclay, Argonne, Pittsburgh

# $C_x$ vs. $W$ Results for

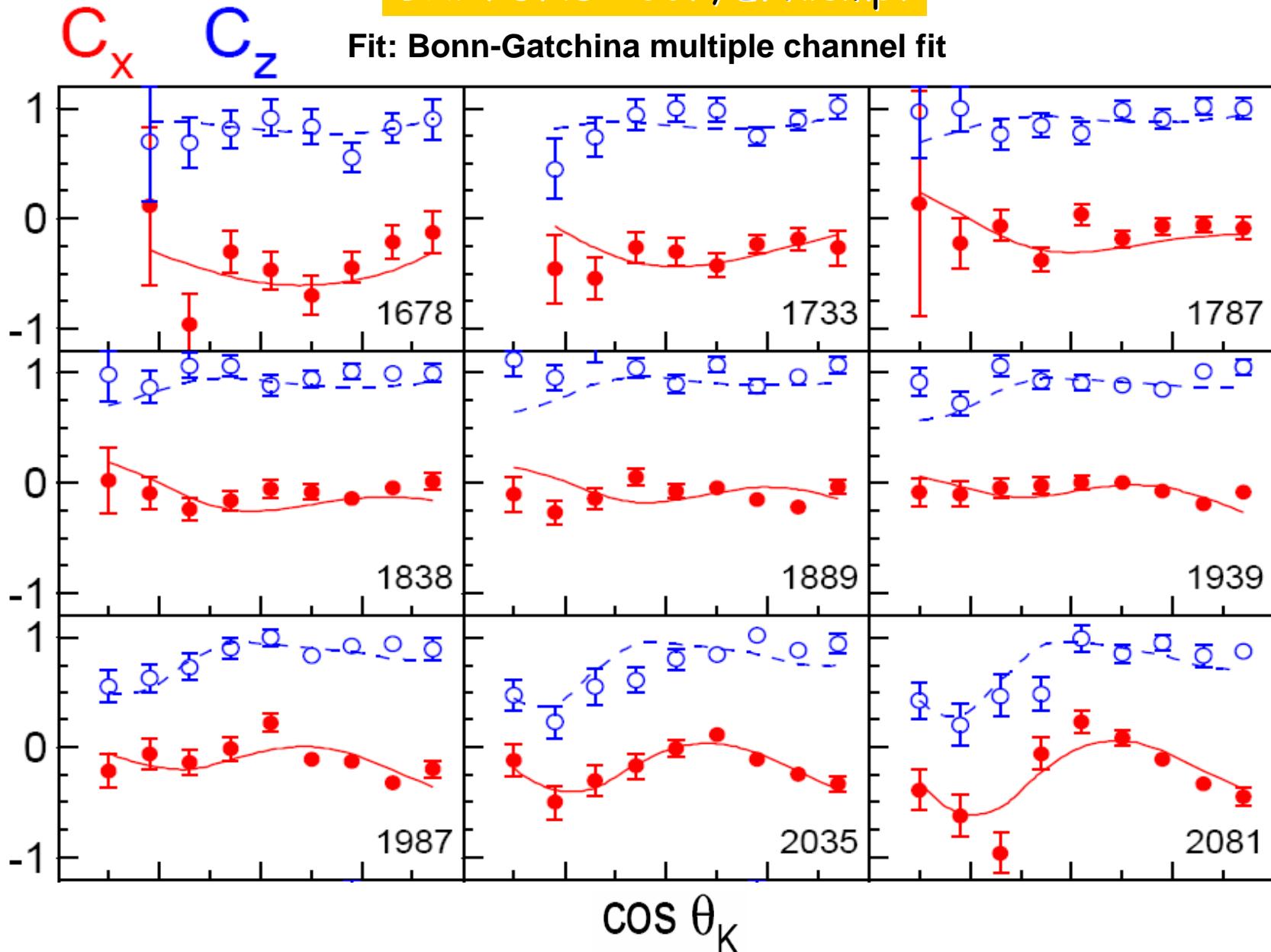
Bonn, Giessen, Gatchina  
Shklyar, Lenske, Mosel

GENT



R. Bradford *et al.*, Phys. Rev. C 75, 035205 (2007).

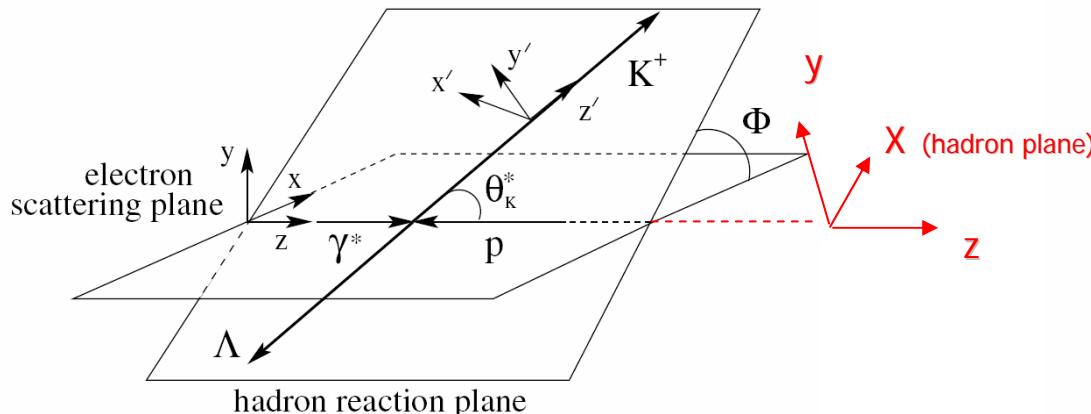
# BARYONS 2007, E. Klempt



“one additional resonance needed :  $P_{13}(1860)$ ”



# $K^+\Lambda$ Electroproduction



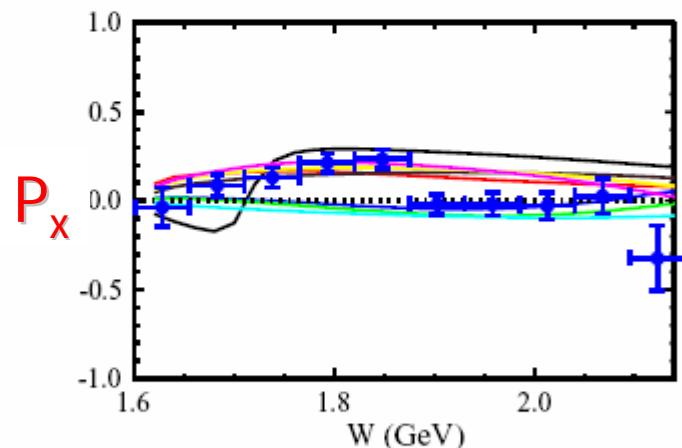
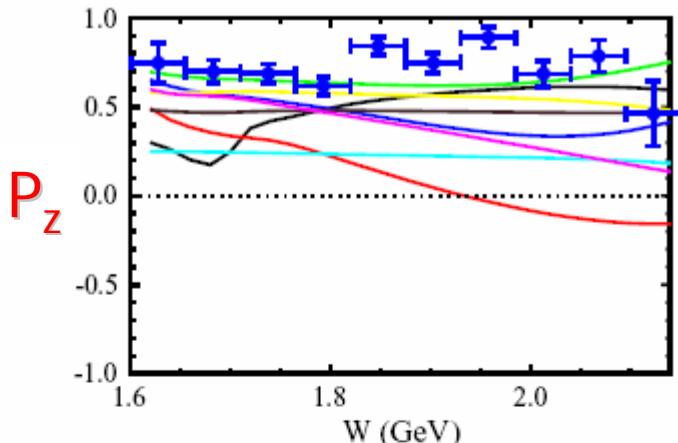
The same large polarization transfer *along photon direction* (not the  $z'$  helicity axis) is seen in **CLAS electro-production**.

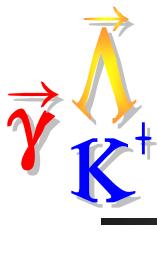
D. S. Carman et al. (CLAS)  
Phys. Rev. Lett. 90, 131804 (2003).

$0.3 < Q^2 < 1.5 \text{ (GeV/c)}^2$   
Integrated over all K angles

AW88	AS90	TMSU
WJC90	TMFF	
WJC92	TMST	

(Dipole  $\Lambda$ ,  $K$  F.F.s)





# Beam Asymmetry, $\Sigma$

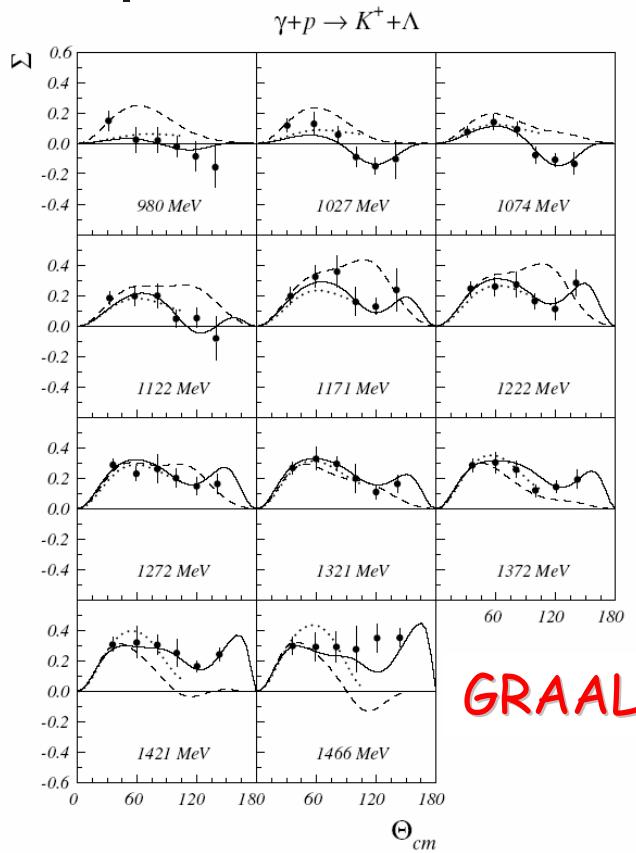


Fig. 14. Angular distributions of the beam asymmetries  $\Sigma$  for  $\gamma p \rightarrow K^+ \Lambda$  and  $\gamma$ -ray energies ranging from 1500 MeV. Data are compared with the new solutions of the BCC (solid line), SAPCC (dashed line) and GRPI models.

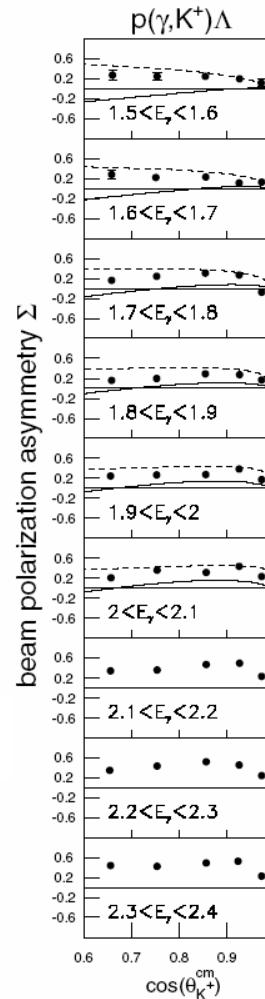


FIG. 3. Beam polarization asymmetries for the  $p(\gamma, K^+) \Lambda$  reaction. The data points (black circles with error bars) are taken by LEPS (solid lines) and by Janssen et al. (dashed lines) and compared with the theoretical predictions (solid and dashed lines).

$$\left. \frac{d\sigma}{d\Omega_{K^+}} = \frac{d\sigma}{d\Omega_{K^+}} \right|_{unpol.} \quad \{1 + \sum P_\gamma \cos 2\phi\}$$

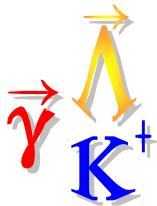
GRAAL threshold range,  
 $E_g < 1.5$  GeV

LEPS  $1.5 < E_g < 2.4$  GeV

The trends are consistent:  
 $\Sigma$  is smooth and featureless  
at all energies and angles.

LEPS

R. G. T. Zegers *et al.* (LEPS) Phys. Rev. Lett. 91, 092001 (2003).  
A. Lleres *et al.* (GRAAL) Eur. Phys. J. A 31, 79 (2007).



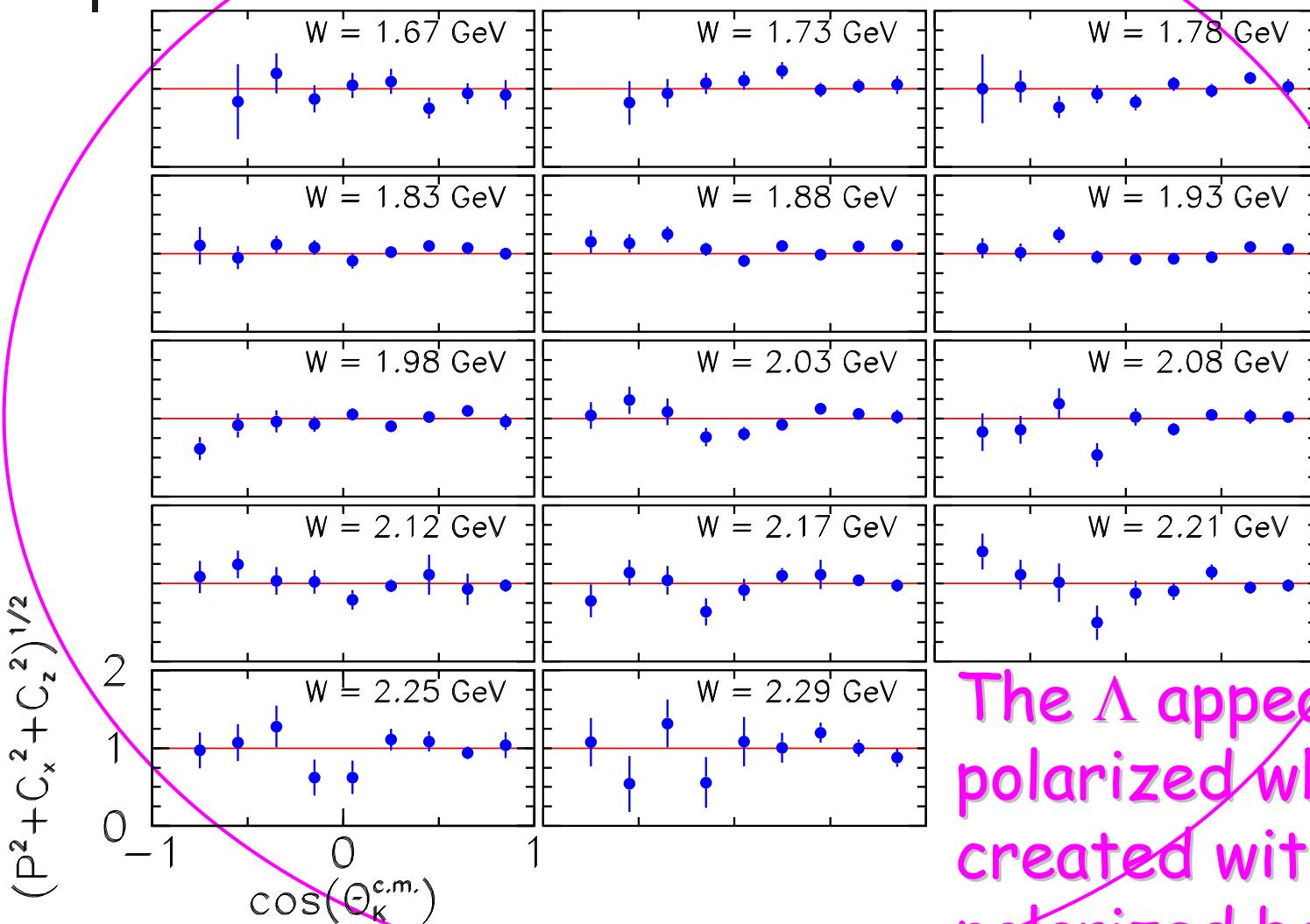
# Unexpected Result / Puzzle

- What is the magnitude of the  $\Lambda$  hyperon's polarization vector given circular beam polarization?
- Expect:  $R^2 \equiv P^2 + C_x^2 + C_z^2 \leq 1$
- R is not required to be close to 1, BUT angle & energy average turns out to be:  
$$\bar{R} = 1.01 \pm 0.01$$
- How does  $\Lambda$  come to be 100% spin polarized?
  - Not required to be polarized in hadrodynamic models

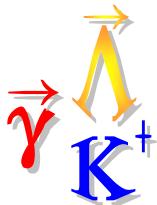


# R Values for the $\Lambda$

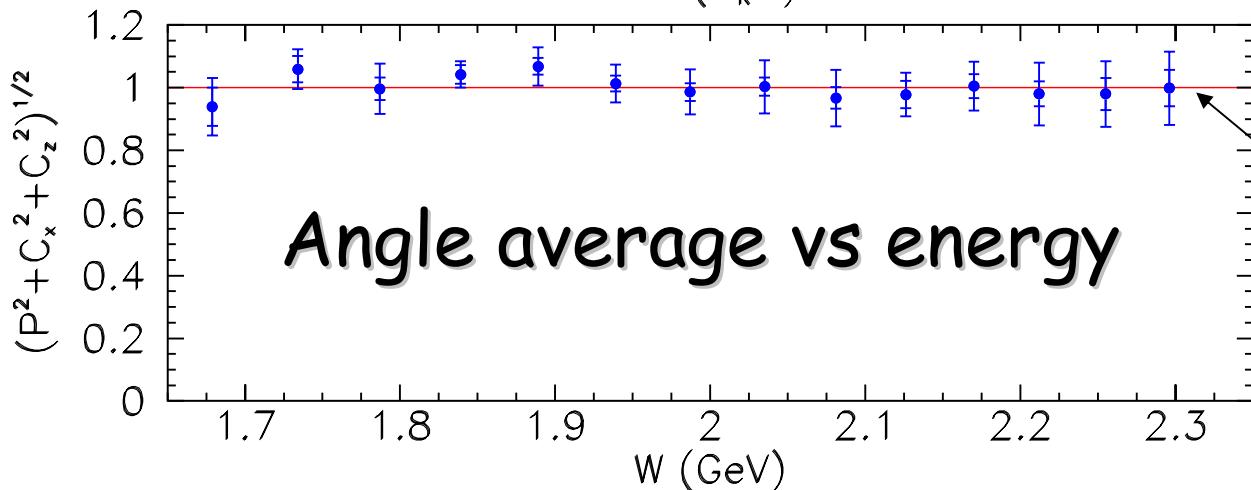
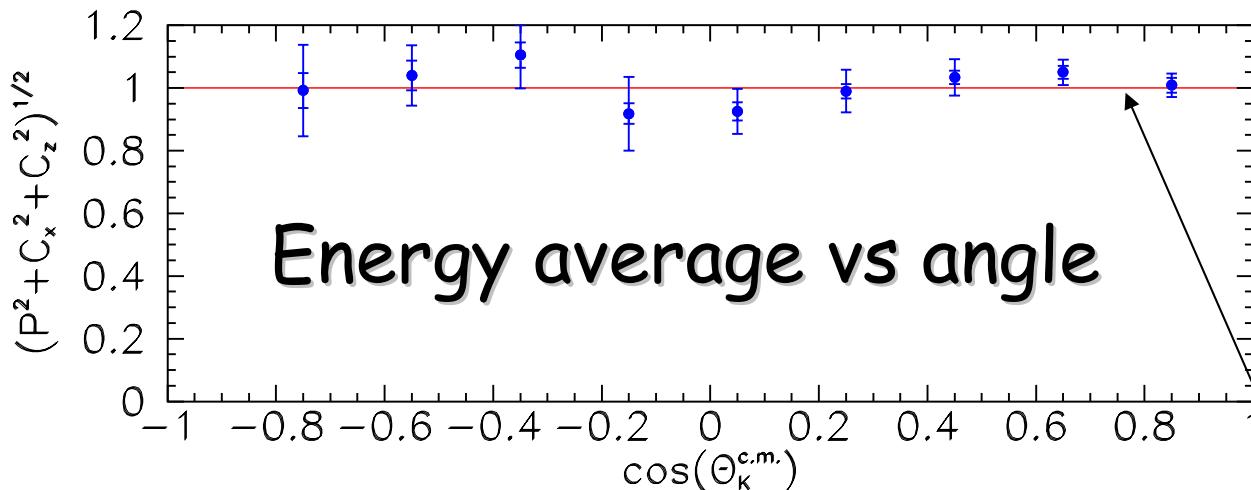
$$R \equiv \sqrt{P^2 + C_x^2 + C_z^2}$$



The  $\Lambda$  appears 100% polarized when created with a fully polarized beam.



# Average R Values for the $\Lambda$



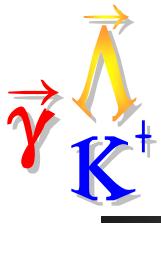
$$R \equiv \sqrt{P^2 + C_x^2 + C_z^2}$$

$$\bar{R} = 1.01 \pm 0.01$$

$$\chi^2_v = 1.18 \text{ (good)}$$

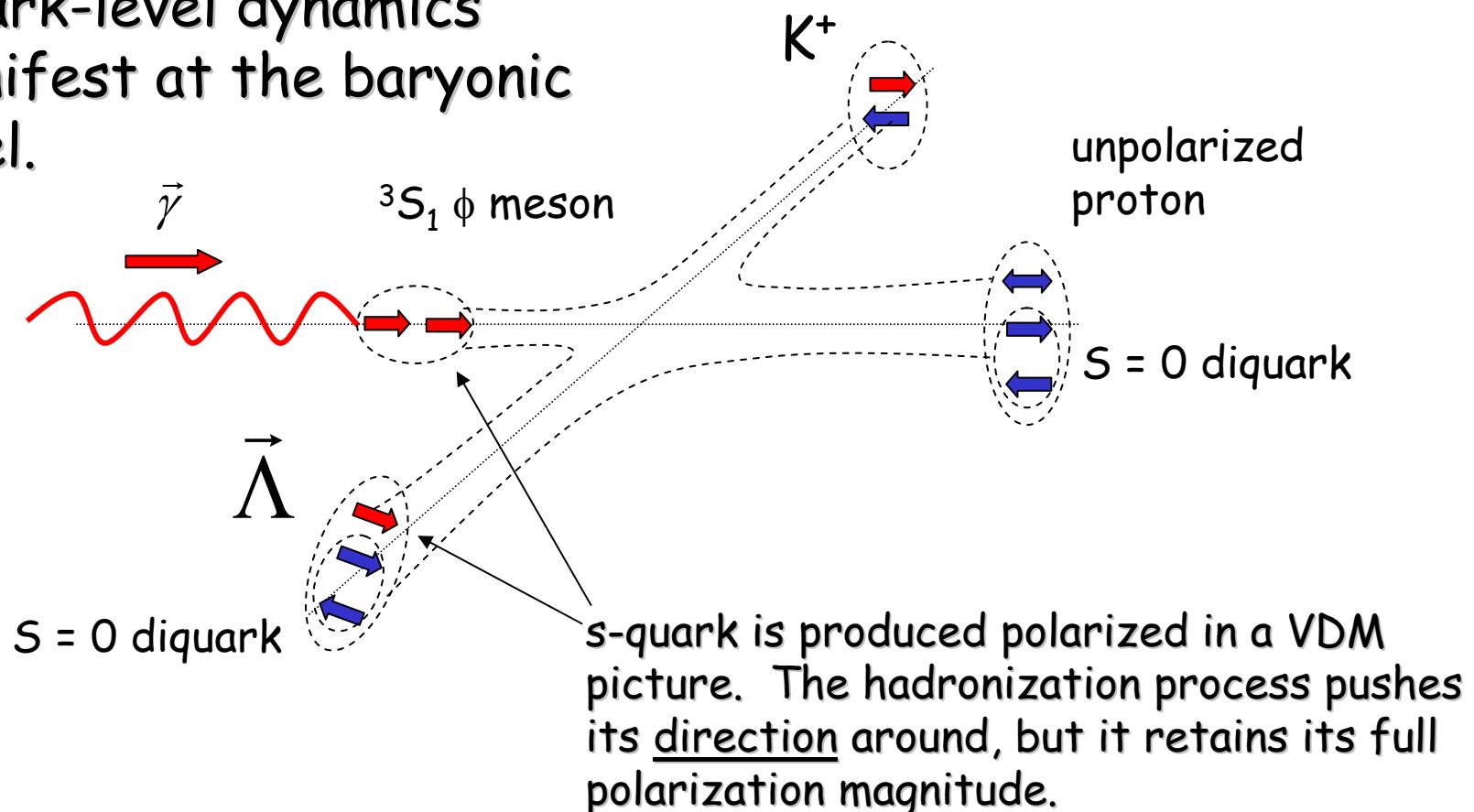
Energy and angle averages are consistent with unity.

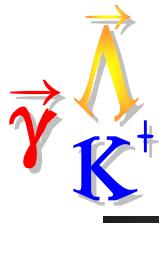
No model predicted this CLAS result.



# Ansatz for the Explanation

Quark-level dynamics manifest at the baryonic level.





# Quantum Mechanical Model

Fact: a spin-orbit or spin-spin type of Hamiltonian leaves the magnitude of an angular momentum vector invariant. I.e. the spin polarization direction,  $\hat{P}_Y$ , is not a constant of the motion, but its magnitude is.

$$\vec{P}_Y = \langle \vec{\sigma} \rangle = \frac{\chi_Y^\dagger \vec{\sigma} \chi_Y}{\chi_Y^\dagger \chi_Y} = \frac{\chi_0^\dagger S^\dagger \vec{\sigma} S \chi_0}{\chi_0^\dagger S^\dagger S \chi_0}$$

Scattering matrix:

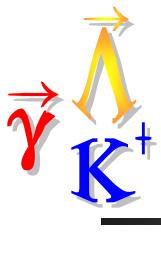
$$S = \begin{pmatrix} g(\theta) & h(\theta)e^{-i\phi} \\ -h(\theta)e^{i\phi} & g(\theta) \end{pmatrix} = g(\theta) + i h(\theta) \hat{n} \cdot \vec{\sigma}$$

$\hat{n}$ : normal to reaction plane

$g(\theta)$ : spin non-flip amplitude }

$h(\theta)$ : spin flip amplitude }

Key ingredients



# $C_x$ , $C_z$ , and $P$ in terms of amplitudes $g(\theta)$ (non-flip) and $h(\theta)$ (spin-flip)

Measured components of  $\Lambda$  hyperon polarization

$$\frac{d\sigma}{d\Omega} = g^* g + h^* h$$

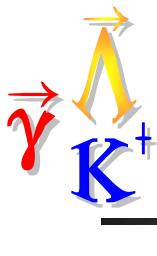
$$P_{Yx} = \frac{g^* h + h^* g}{g^* g + h^* h} P_\square \equiv -C_x P_\square$$

$$P_{Yy} = i \frac{g^* h - h^* g}{g^* g + h^* h} \equiv P$$

$$P_{Yz} = \frac{g^* g - h^* h}{g^* g + h^* h} P_\square \equiv C_z P_\square$$

"Observables"

Can solve for  $g(\theta)$  and  $h(\theta)$  magnitudes and phase difference using the measured values of  $C_x$ ,  $C_z$ ,  $P$  and  $d\sigma/d\Omega$ .



# $C_x$ , $C_z$ , and $P$ in terms of helicity amplitudes

Measured components of  $\Lambda$  hyperon polarization

$$\frac{d\sigma}{d\Omega} = |N|^2 + |S_1|^2 + |S_2|^2 + |D|^2$$

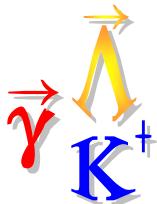
$$P_{Yx'} = \frac{-2 \operatorname{Re}(F_2 N^* + F_1 D^*)}{|N|^2 + |S_1|^2 + |S_2|^2 + |D|^2} P_\square \equiv C_x' P_\square$$

$$P_{Yy} = \frac{-|N|^2 - |S_1|^2 + |S_2|^2 + |D|^2}{|N|^2 + |S_1|^2 + |S_2|^2 + |D|^2} \equiv P$$

$$P_{Yz'} = \frac{+2 \operatorname{Im}(F_2 N^* - F_1 D^*)}{|N|^2 + |S_1|^2 + |S_2|^2 + |D|^2} P_\square \equiv C_z' P_\square$$

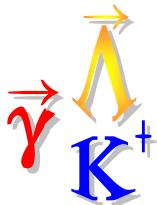
"Observables"

Work in progress: relate  $g$  and  $h$  to  $N$ ,  $S_1$ ,  $S_2$ , and  $D$ . Make predictions for other observables such as  $\Sigma$ ,  $O_x$  and  $O_z$ .



# Quantum Mechanical Results

- Thus, the polarization observables  $C_x$ ,  $C_z$ , and  $P$  are "explained" in terms of two complex amplitudes
  - $g(\theta)$  - spin non-flip transition amplitude for a spin  $\frac{1}{2}$  quark described in a z-axis basis.
  - $h(\theta)$  - spin flip transition amplitude for...(etc).
- $g(\theta)$  and  $h(\theta)$  arise from a "deeper" theory of the hadronization process that we do not have.
  - By construction, any  $g$  and  $h$  leaves  $|\vec{P}_y|$  unchanged.
- BUT, we can do better, using a physical picture based on a semi-classical model (see next).

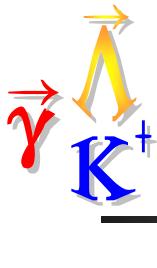


# Semi-Classical Model

- Fact: the expectation value of a quantum mechanical spin operator evolves in time the same way as the classical angular momentum "spin" vector does.
  - (cf. Cohen-Tannoudji p450, or Merzbacher p281).
  - For any interaction of the form  $H_{\text{int.}} = \vec{Q} \cdot \vec{\sigma}$  one gets

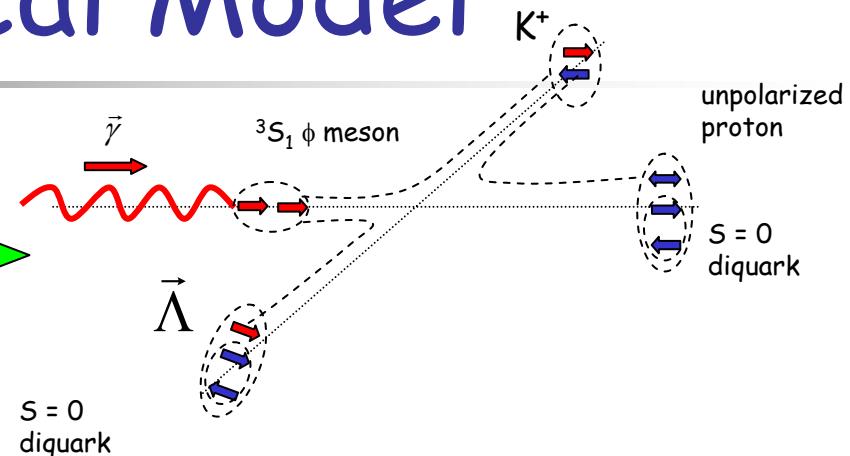
$$\hbar \frac{d\langle \vec{\sigma} \rangle}{dt} \equiv \hbar \frac{d\vec{P}(t)}{dt} = \vec{Q}(t) \times \vec{P}(t) = \vec{Q}(t) \times \langle \vec{\sigma} \rangle$$

- For this discussion  $\vec{Q} \rightarrow \vec{B}$ , where  $B$  is the external field of proton and/or magnetic moment of another quark.
- Use a spin-spin and spin-orbit type of interaction to model polarization evolution during hadronization.
  - use classical electromagnetic field interaction
  - scale up strength to model strong color-magnetic interaction

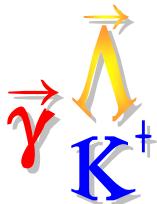


# Semi-Classical Model

Treat the picture literally



- The virtual  $\bar{s}s$  pair in a spin “triplet” state is subject to a spin-spin dipole interaction
- The approaching charged proton serves to precess both spins via spin-orbit interaction:
$$\vec{\tau}_{quark} = \vec{\mu}_{quark} \times \vec{B}_{proton}$$
- Spins interact with moving proton and each other during hadronization length/time:  $R_{rms} \sim 1\text{fm}$
- $\Lambda$  carries spin polarization of  $s$  at freeze-out time

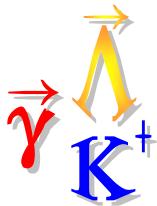


# Contents of the Model:

- Quark  $\bar{s} s$  triplet spaced according to photon  $\pm \lambda / 4$  in  $\{\gamma, p\}$  c.m. frame,  $\lambda = hc / p_{cm}$
- Field of quarks: classical dipole form:

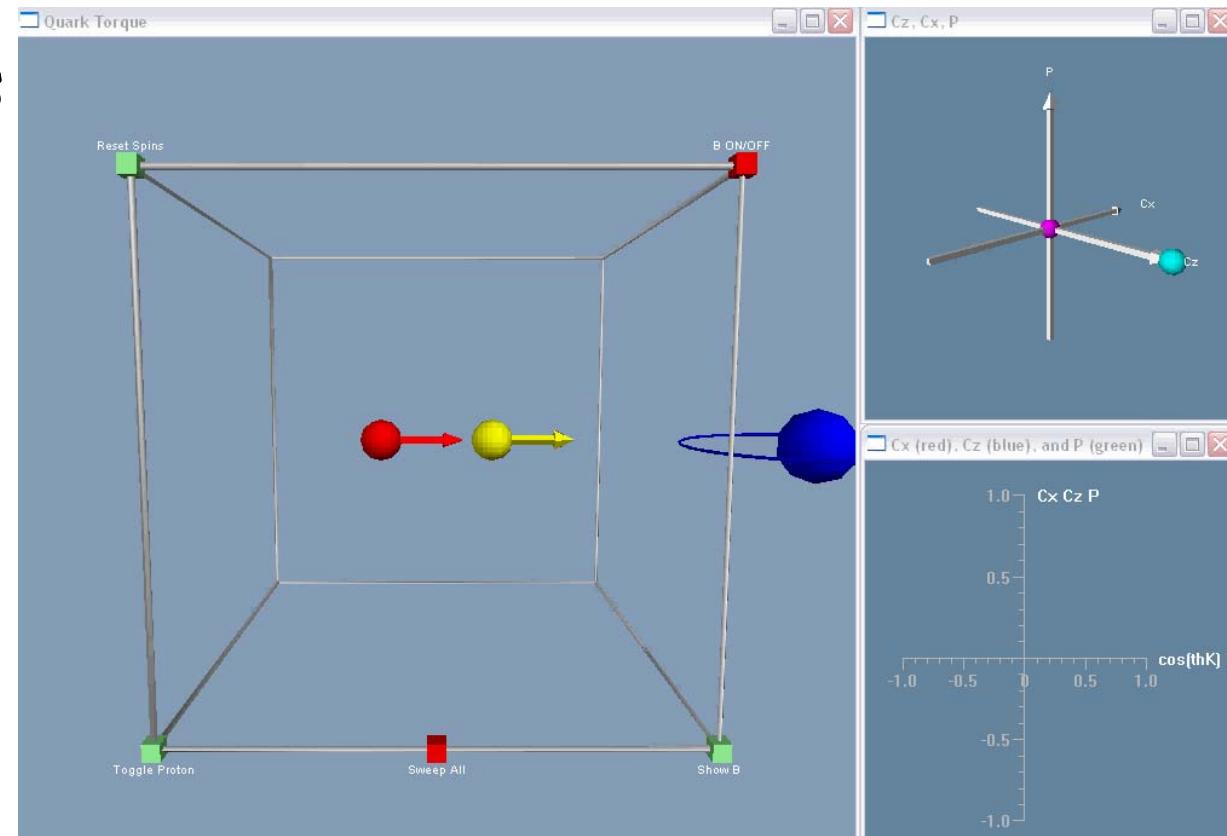
$$\vec{B} = \frac{1}{r^3} [3(\vec{\mu} \square \hat{r}) \hat{r} - \vec{\mu}] \quad \text{where} \quad |\vec{\mu}| = g \mu_0 \frac{|\vec{s}|}{\hbar} = \left( \alpha \frac{2}{3} \frac{m_p}{m_s} \right) \left( \frac{e \hbar}{2 m_p} \right) \sqrt{\frac{1}{2} \left( \frac{1}{2} + 1 \right)}$$

- Proton charge distribution:  $\rho(r) = \rho_0 e^{-r/r_0}$ , and  $r_0 = R_{rms} / \sqrt{12}$  where proton  $R_{rms} = 0.86 \text{ fm}$
- Proton motional B field in c.m. frame:  $\vec{B}(\vec{r}) = -\frac{1}{c^2} (\vec{v}_{c.m.} \times \vec{E}(\vec{r}))$
- Impact parameter,  $b$ , maps onto scattering angle  $\theta$ , via the Rutherford-like form  $\theta = 2 \tan^{-1}(2b/r_0)$

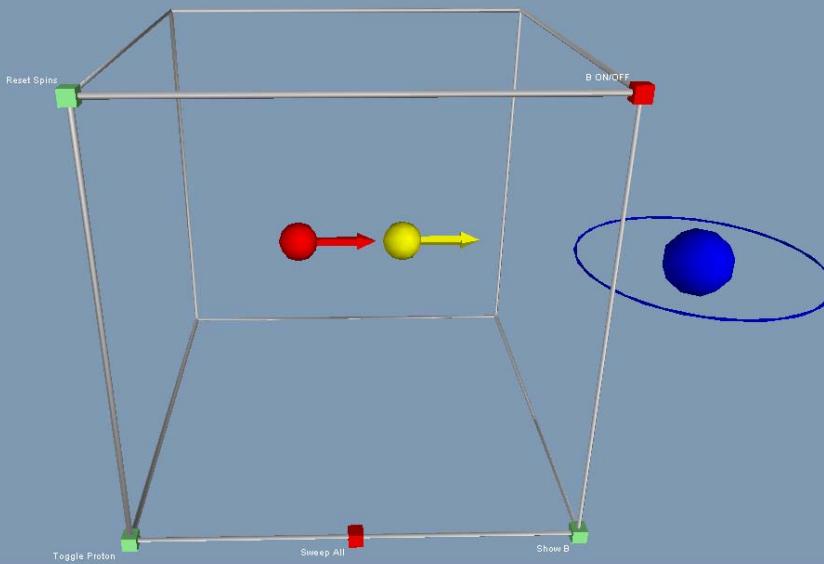


# Demonstration animation...

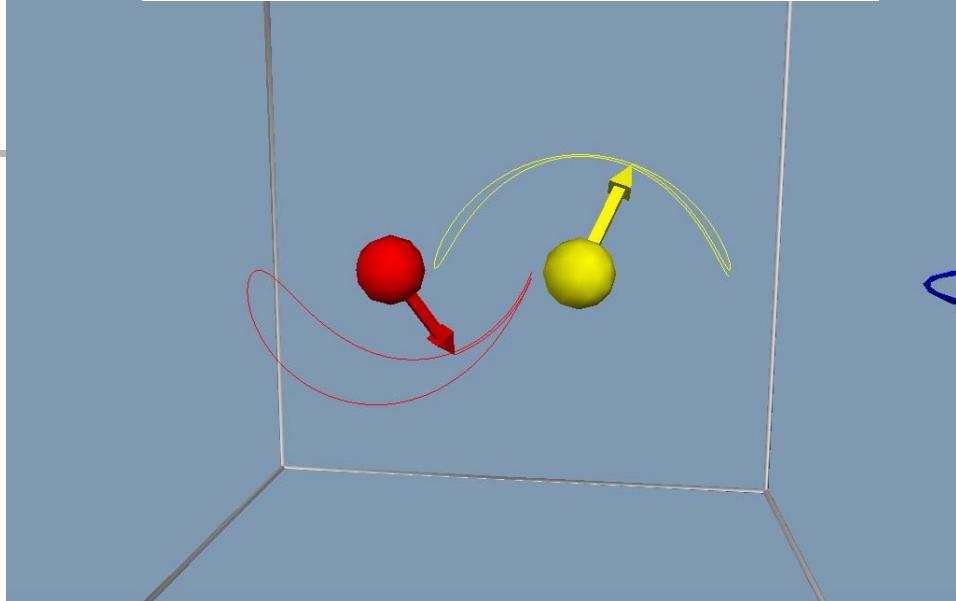
- (Hope this works...)
- Proton knocks spins off axis initially...
- ...then spin-spin interaction rotates spins out of reaction plane.
- Impact parameter maps to scattering angle
- Spin direction is frozen after one hadronization time/length elapses



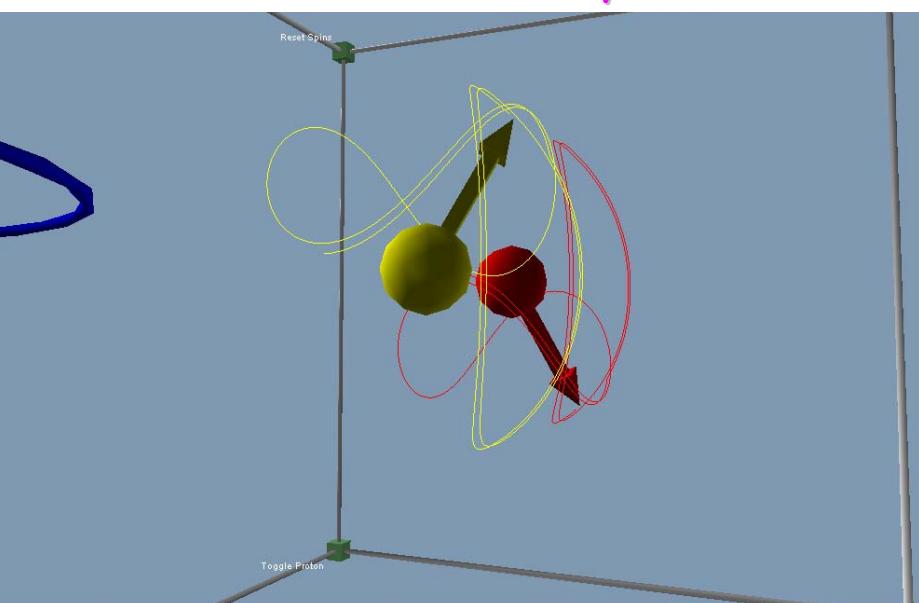
## Initial Configuration



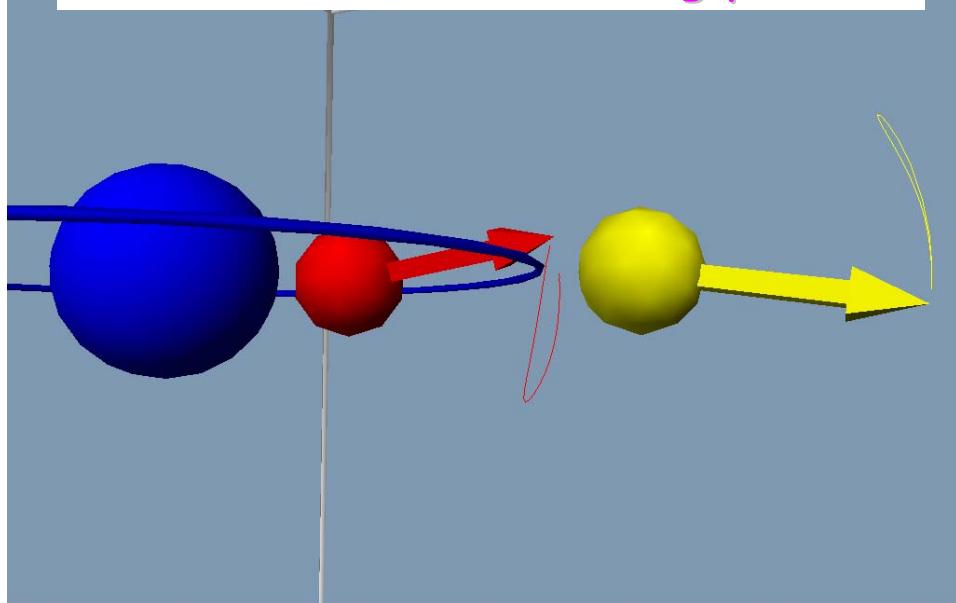
## Constant external field in y

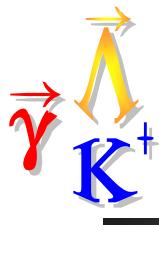


## After external field in y turned off

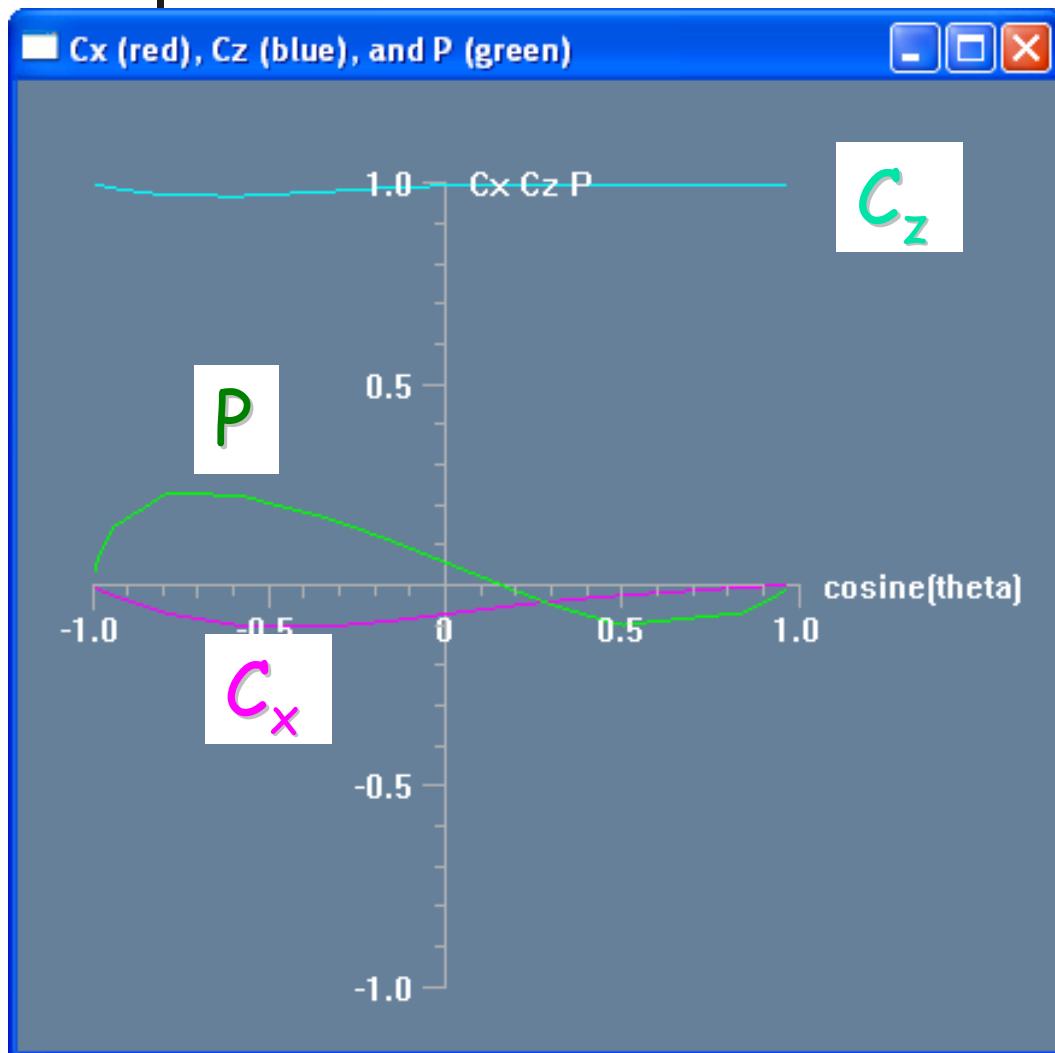


## Precessed due to arriving proton

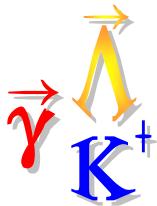




# Preliminary Result, W=2 GeV



- Observed phenomenology is reproduced:
  - $C_z$  is large and positive
  - $C_x$  is small and negative
  - $P$  is negative at forward angles, positive at backward angles
- The electromagnetic interaction not strong enough to account for observed magnitude: scale up strength by  $\times 30$ 
  - Suggests that color-magnetic effects are what we are actually modeling

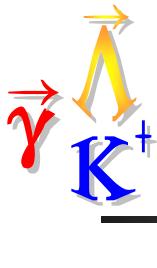


# Conclusions

- The 100% polarization of the  $\Lambda$  in  $K^+\Lambda$  photoproduction is a remarkable new fact.
- Ansatz: Photon couples to an  $s\bar{s}$  spin triplet, followed by spin precession in hadronizing system.
- Spin flip/non-flip amplitudes can model this phenomenon quantum mechanically.
- Dipole-dipole & spin-orbit interactions (e.m. or color-magnetic) offer a physical picture of spin precession during hadronization.
- Continuing program at CLAS (FROST, HD-ice) will pin down more hyperon polarization observables.

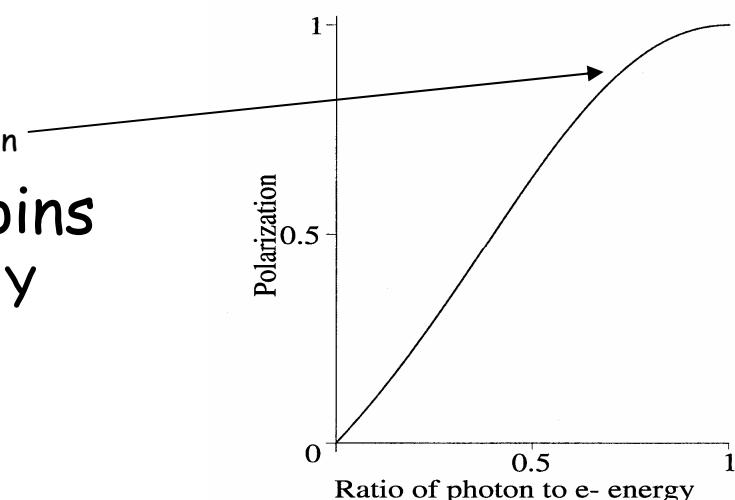
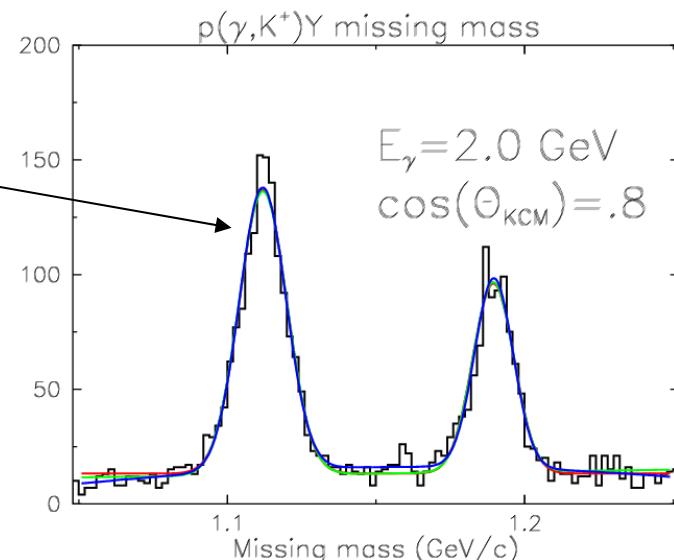


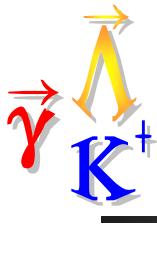
# Supplemental Slides



# Analysis Ingredients

1. Require  $K^+$  and p detection
2. Hyperon yields from  $(\gamma, K^+) Y$   
m.m. by 2 methods:
  - Gaussian + polynomial fits
  - sideband subtractions
3. Beam polarization
  - Moeller scattering for electron beam:  $65 \pm 3\%$
  - Pol. Transfer to photon in Bremsstrahlung: Olsen & Maximon
4. No Wigner rotation of spins
  - Polarization is the same in Y rest frame and c.m. frame





# Quantum Mechanical Model

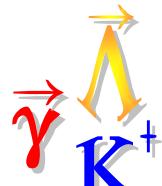
Fact: a spin-orbit or spin-spin type of Hamiltonian leaves the magnitude of an angular momentum vector invariant. I.e. the spin polarization direction,  $\hat{P}_f$ , is not a constant of the motion, but its magnitude is.

$$\vec{P}_f = \langle \vec{\sigma} \rangle = \frac{\chi_f^\dagger \vec{\sigma} \chi_f}{\chi_f^\dagger \chi_f} = \frac{\chi_0^\dagger S^\dagger \vec{\sigma} S \chi_0}{\chi_0^\dagger S^\dagger S \chi_0}$$

where  $\chi_{f,0}$  are spin 1/2 states w.r.t. the z-axis basis, i.e.

$$\chi_0 = \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad \chi_f = S \chi_0$$

The scattering matrix,  $S$ , has the form:



## Scattering matrix:

$$S = \begin{pmatrix} g(\theta) & h(\theta)e^{-i\phi} \\ -h(\theta)e^{i\phi} & g(\theta) \end{pmatrix} = g(\theta) + ih(\theta) \hat{n} \cdot \vec{\sigma}$$

$\hat{n}$ : normal to reaction plane

$g(\theta)$ : spin non-flip amplitude

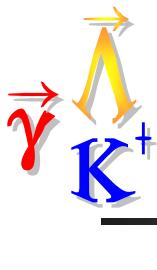
$h(\theta)$ : spin flip amplitude

} Key ingredients

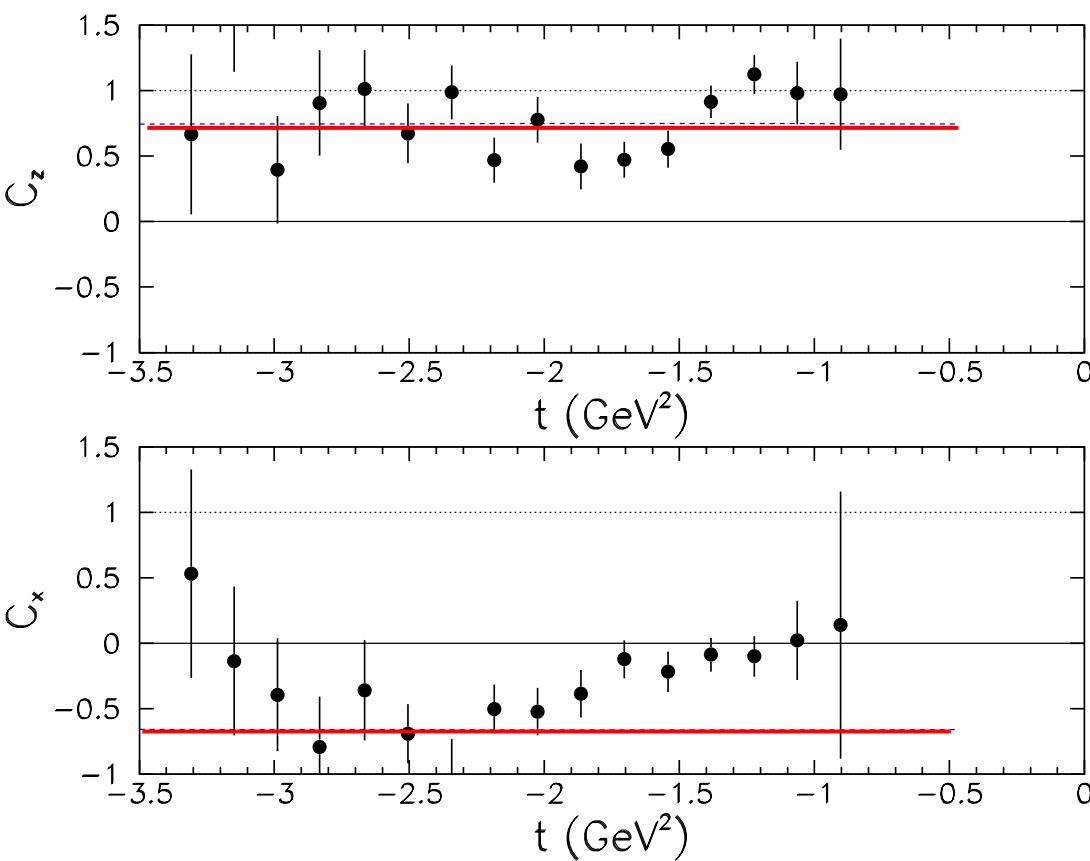
Use a density matrix formalism and trace algebra to find:

$$\begin{aligned} & \vec{P}_f \left( g^* g + h^* h + i(g^* h - h^* g)(\vec{P}_0 \cdot \hat{n}) \right) \\ &= \underbrace{(i(g^* h - h^* g) + 2h^* h \vec{P}_0 \cdot \hat{n})}_{\textcolor{red}{\hat{n}}} \hat{n} + \underbrace{(g^* g - h^* h) \vec{P}_0}_{\textcolor{red}{\vec{P}_0}} + \underbrace{(g^* h + h^* g)(\vec{P}_0 \times \hat{n})}_{\textcolor{red}{\vec{P}_0 \times \hat{n}}} \end{aligned}$$

For the CLAS experiment  $\vec{P}_0 = (0, 0, P_\perp)$ , so we have expressions for three orthogonal components of the final state polarization  $\vec{P}_f$ .

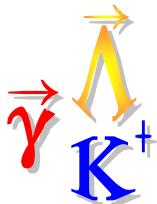


# Comparison to pQCD limits

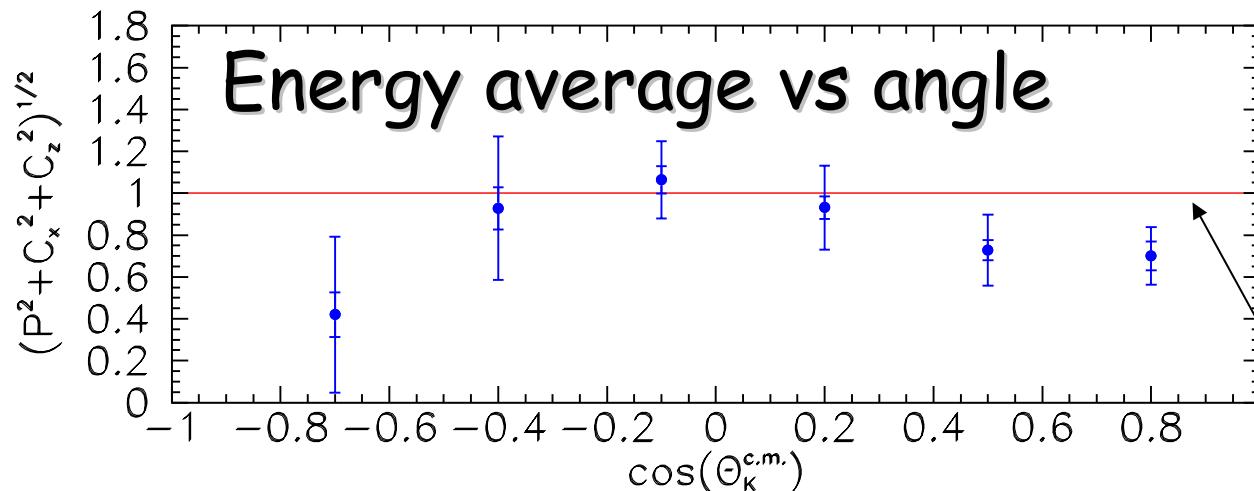


- A. Afanasev, C. Carlson, & C.Wahlquist predicted [Phys Lett B 398, 393 (1997)]:
  - For large  $t, s, u$   
 $P = C_x' = 0$   
 $C_z' = (s^2-u^2)/(s^2+u^2) \rightarrow 1$  at large  $t$  and small  $u$
  - Based on  $s$ -channel quark helicity conservation
- CLAS data shows clear helicity NON-conservation
  - Spin of  $\Lambda$  points mostly along  $z$  for all production angles
- CLAS largest  $t$  / smallest  $u$  results are in "fair to good" agreement with prediction
  - ...but so what?

data from  $\cos \theta_K^{\text{c.m.}} = -0.75$

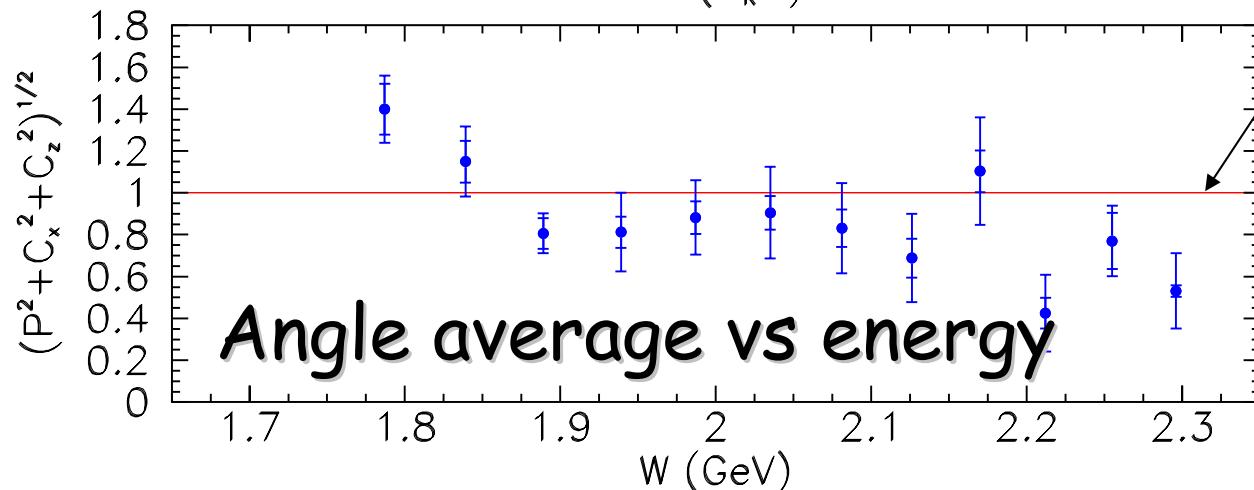


# Average R Values for $\Sigma^0$



$$R \equiv \sqrt{P^2 + C_x^2 + C_z^2}$$

$$\bar{R} = 0.82 \pm 0.03$$



Poorer statistics for  $\Sigma^0$ , but R is not unity everywhere.