Angular Dependence of Recoil Proton Polarization in High-Energy Deuteron Photo-Disintegration

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for JLab Hall A E00-007 collaboration

- Introduction. Deuteron photo-disintegration
- Hall A experiment E00-007
- Results nucl-ex/0702002

Nuclear Physics or Quark-Gluon Physics ?

- Nuclear structure for its own sake
  - What are the limits of understanding nuclei, using hadronic degrees of freedom, starting from the NN force?
  - When should we use a quark model / QCD for nuclei?
- Nuclei as neutron targets
- Nuclei provide a source of external fields that modify individual nucleon properties
  - Are there pions, or even nucleons, in nuclei?

Deuteron Photo-disintegration

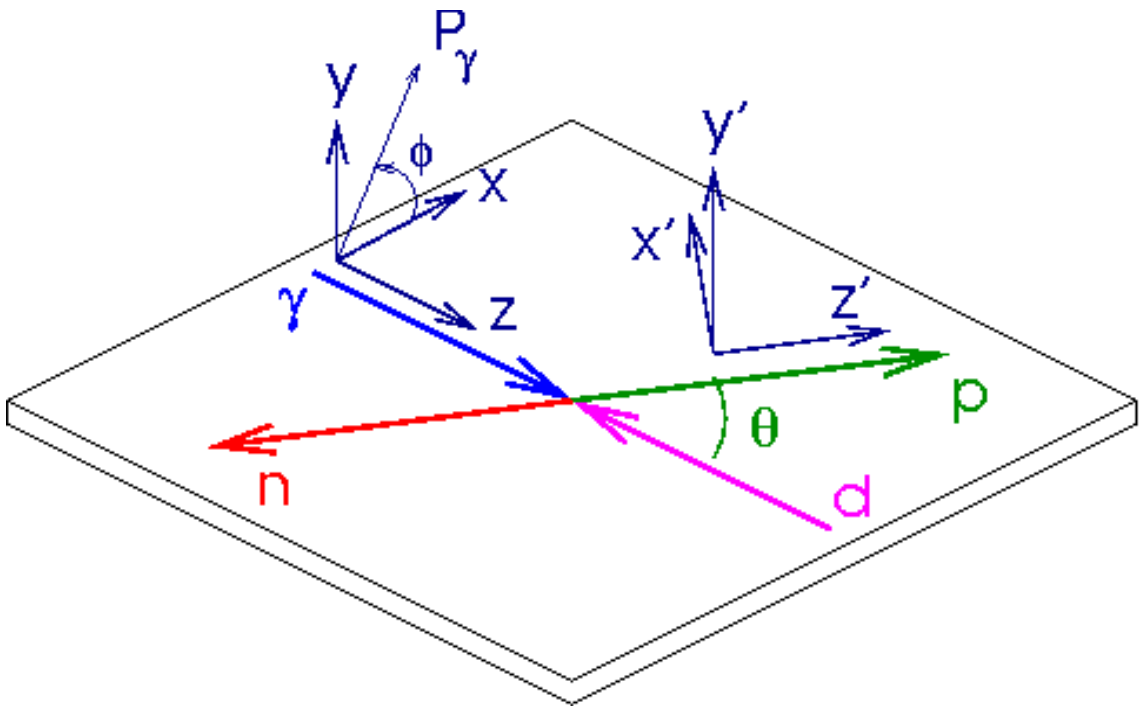
- When one probes the nucleus (nucleon) in elastic scattering, the transferred energy and momentum match to boost the nucleus (nucleon); internal degrees of freedom are not "explicitly" excited
  - With high q, but small W, perhaps we should not be surprised to not see quarks in the deuteron
- Photodisintegration provides high q AND high W: 286 channels (combinations of different allowed intermediate states of 24 baryon resonances) are explicitly excited for E_γ = 0 – 4 GeV

Data Overview

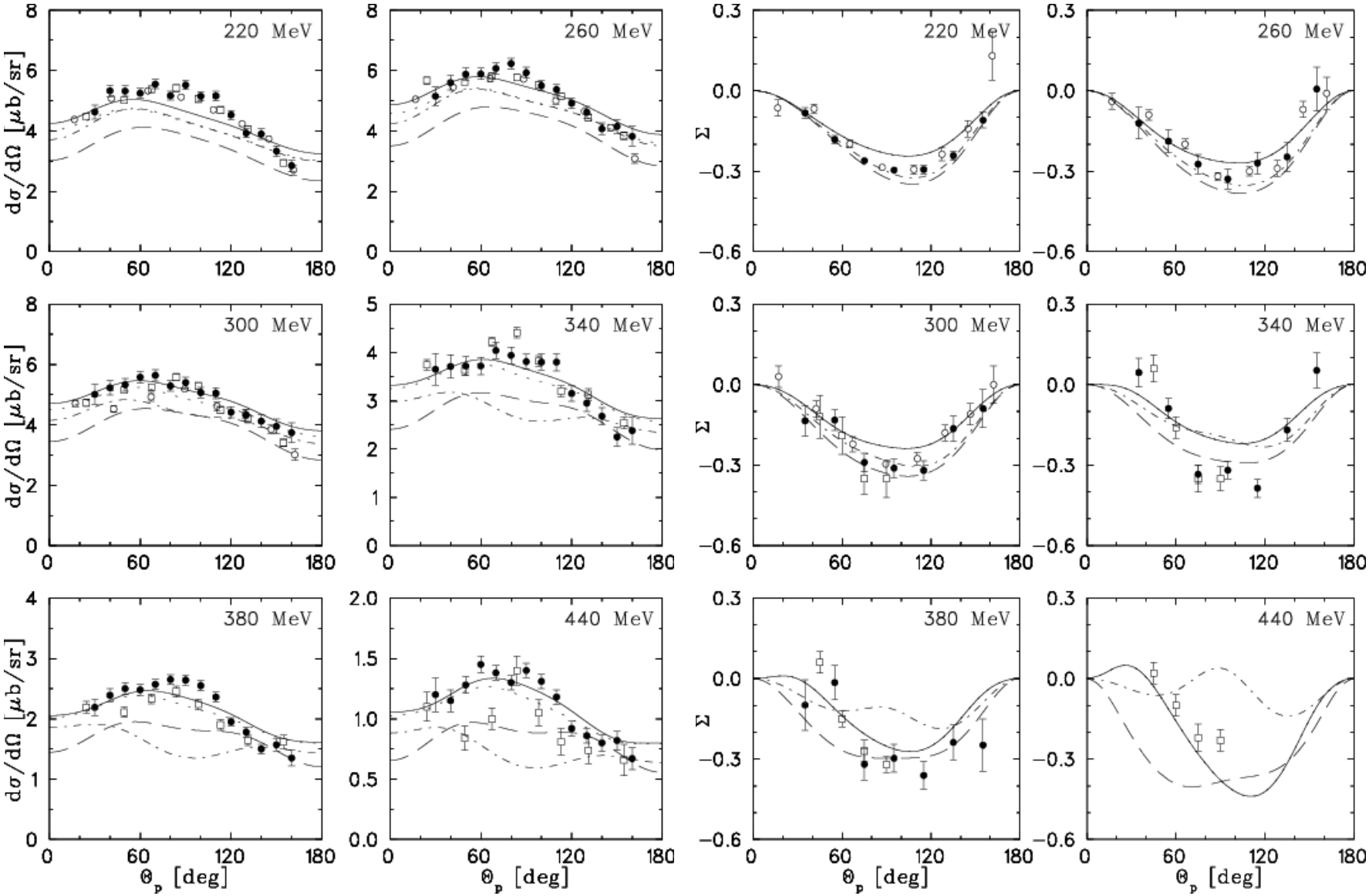
- Extensive low E_γ studies, for $d\sigma/d\Omega$ and polarizations, (~1100 data points, mostly p_y and Σ)
  - Recent measurements from LEGS, Mainz, and TUNL
  - Generally good agreement between theory (Schwamb and Arenhövel) and data
- High energy studies from SLAC and JLab, mostly $d\sigma/d\Omega$ plus some recoil polarimetry ($C_{x'}$, p_y $C_{z'}$)
  - Conventional theory fails above 1 GeV; some non-perturbative quark models not ruled out

Observables in d(γ,p)n

- $d\sigma/d\Omega$, Σ, T, $C_{x'}$, $p_{y'}$, $C_{z'}$

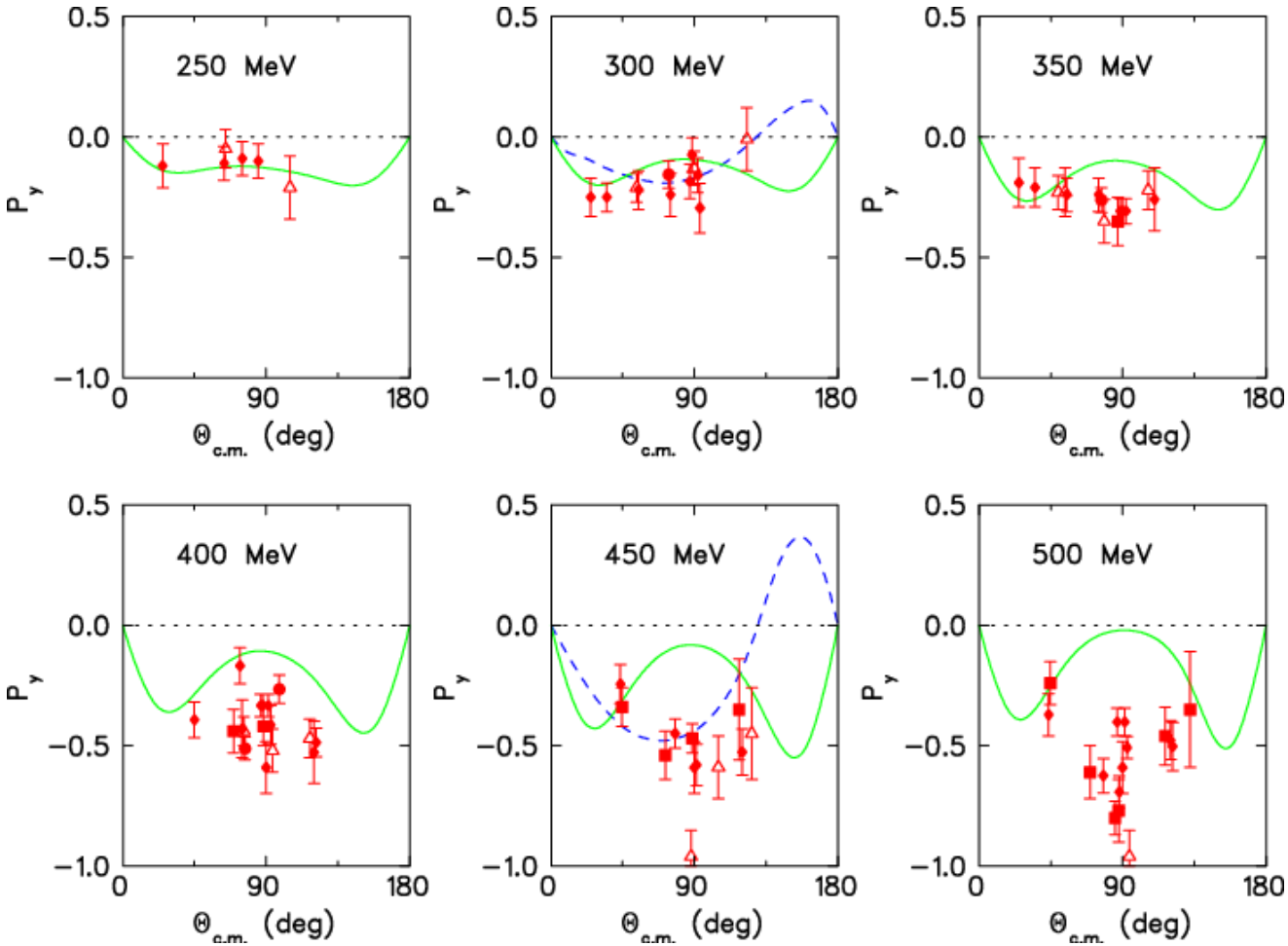


Agreement at low energy in dσ/dΩ, Σ

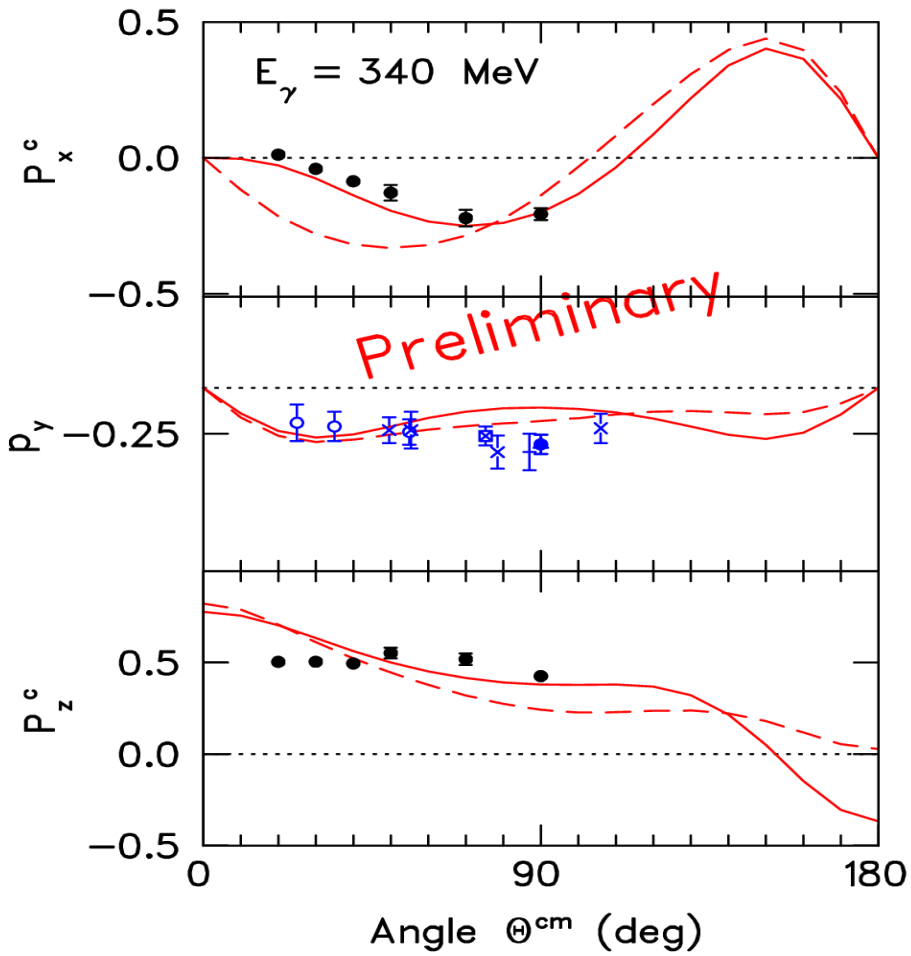


Disagreement in induced polarization p_y

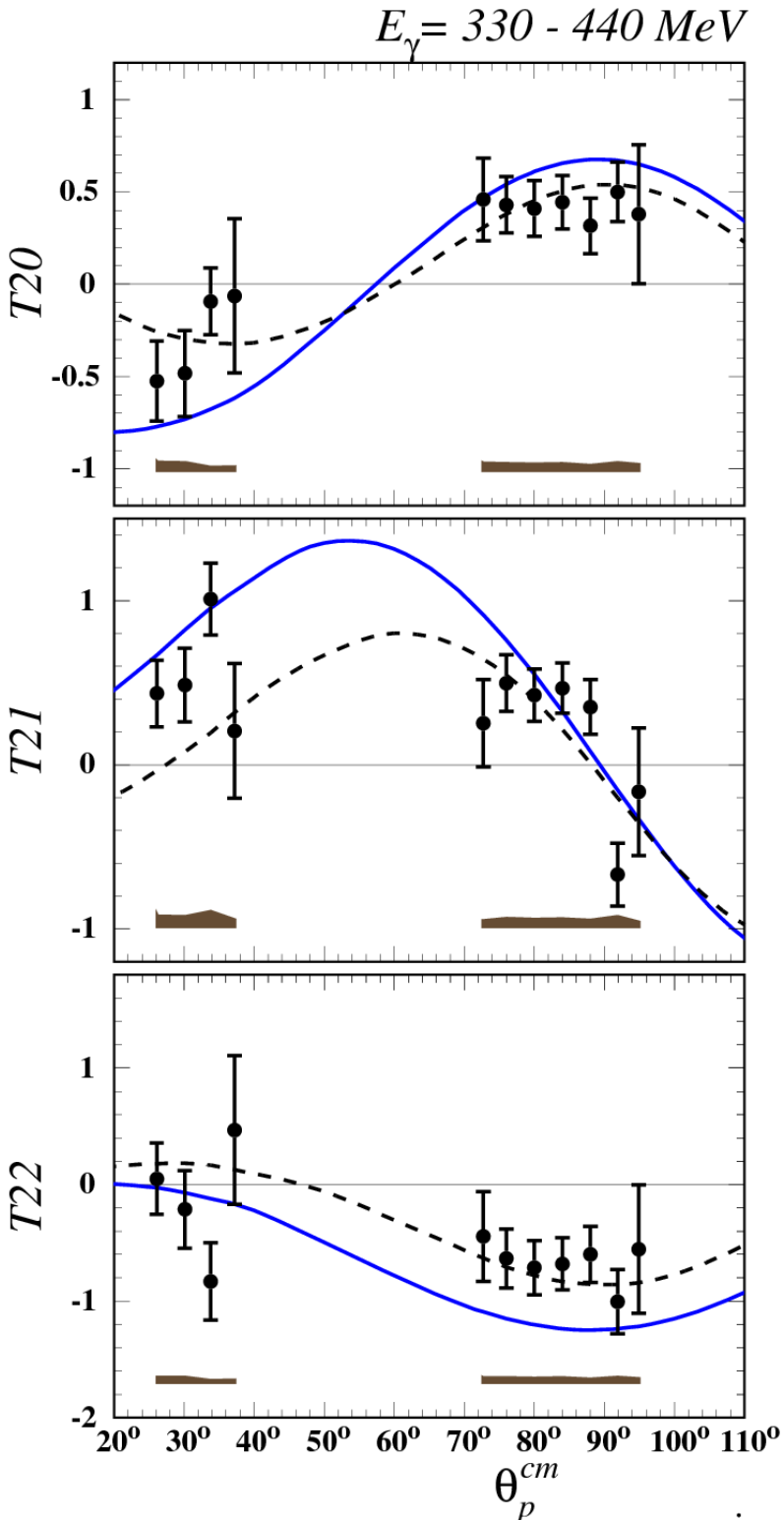
- The p_y problem led to dibaryon excitement in the 1970s/80s
- It remains unresolved



- Hall A experiment E05-103 (Sarty, Strauch, Gilman) has collected data in 2006.
- $C_{x'}$ and P_y are Re and Im parts of the same amplitudes



- Arenhovel +Schwamb (solid).
- Recent Schwamb, improved FSI (dashed).



- Rachek et al, nucl-ex/0611030
- Arenhovel (solid).
- Recent Schwamb (dashed).

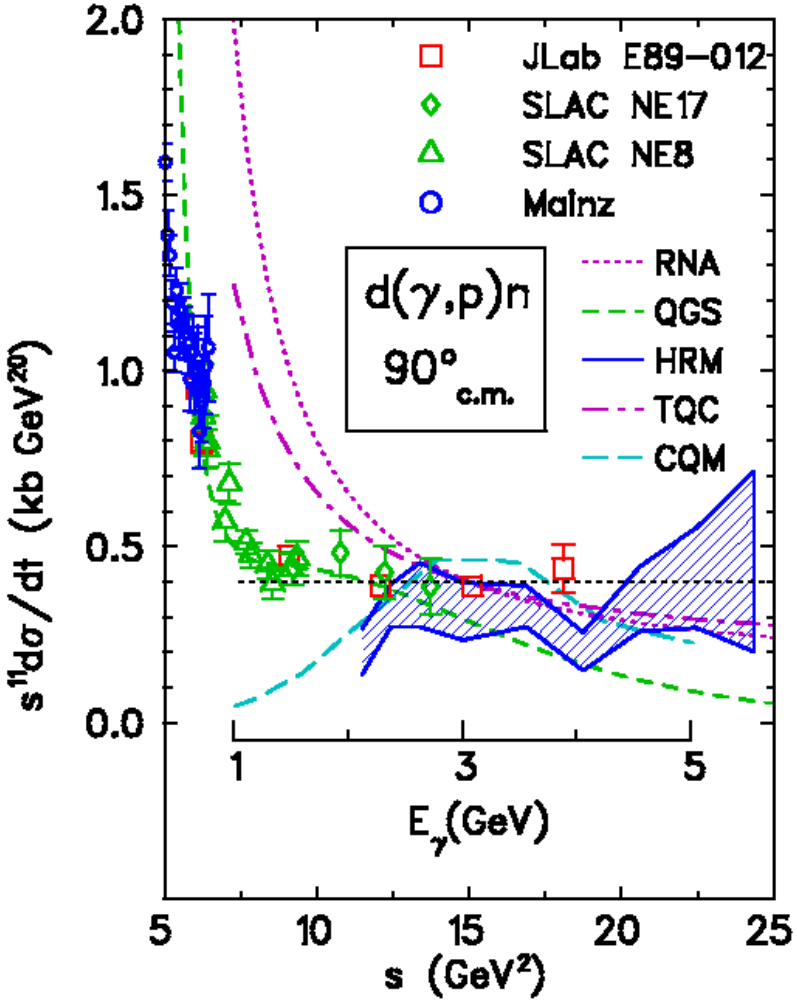
The Hard Scattering Regime

- SLAC NE8, NE17
- JLab Hall C E89-012, E96-003
- Yerevan (Σ)
- JLab Hall A E89-019 ($C_{x'}$, p_y, $C_{z'}$), E99-008
- JLab Hall B E93-017
- JLab Hall A E00-007 ($C_{x'}$, p_y, $C_{z'}$), this work.

- Does pQCD apply? -> Is there a good quark model? Is there a phase transition?

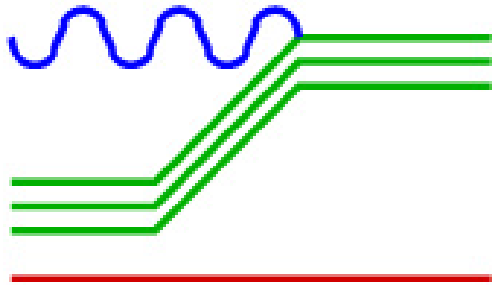
90° Excitation Functions

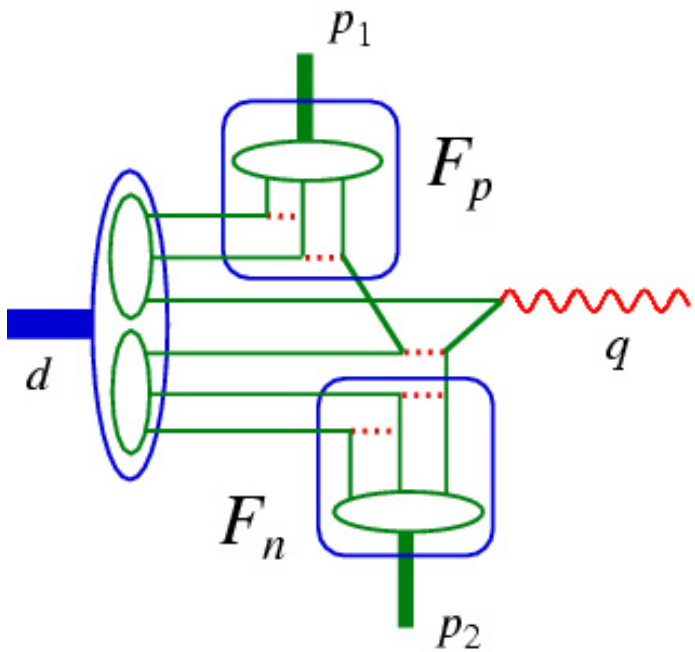
- Cross sections fall by a factor of 30,000 from 1 – 4 GeV, ~following ``expected'' quark scaling, $d\sigma/dt \sim s^{-11}$
- Hadronic theories not satisfactory and not shown
- Most quark models normalized



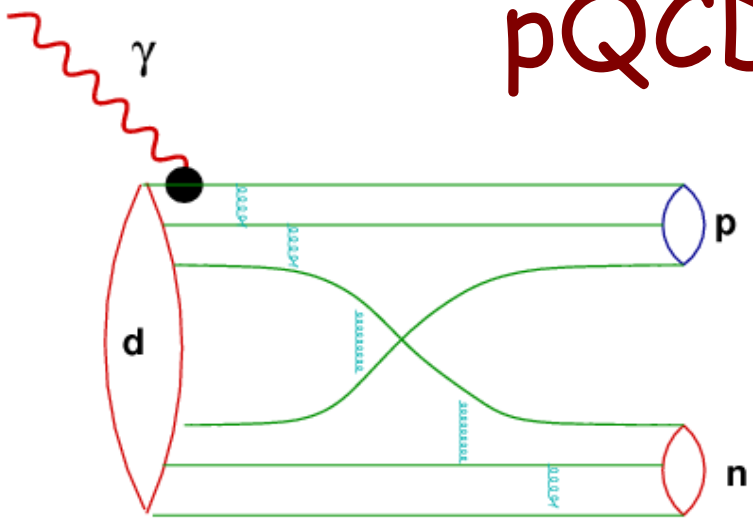
The Quark Models

- Quark-Gluon String model (QGS): Regge phenomenology to evaluate 3-quark exchange, justified by dominance of planar diagrams
- Hard Rescattering model (HR): Photon absorbed and quarks exchanged; might be related to *NN* elastic scattering – all use hard scattering approximations





pQCD Picture



n=1+6+6=13

- Cross section follow the constituent counting rules ?

(S. J. Brodsky and G. F. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).)

$$\frac{d\sigma}{dt} \propto s^{2-n} f(\theta_{cm}).$$

- Hadron helicity conservation satisfied ?

(S. J. Brodsky and G. P. LePage, Phys. Rev. D. **22**, 2157 (1980).)

$$\lambda_d = \lambda_p + \lambda_n$$

Hadron Helicity Conservation in $\vec{\gamma} + d \to \vec{p} + n$

- 12 independent helicity amplitudes: $\langle \lambda_\gamma \lambda_d | T | \lambda_p \lambda_n \rangle$.
- Hadron Helicity Conservation $\Rightarrow$ only 4 non-zero helicity amplitudes:

$$F_{1+} = \langle 11|T|+1/2+1/2\rangle \qquad F_{5+} = \langle 10|T|+1/2-1/2\rangle$$
$$F_{3-} = \langle 1-1|T|-1/2-1/2\rangle \qquad F_{5-} = \langle 10|T|-1/2+1/2\rangle$$

- $p_y \propto Im$ (interference amplitudes):

$$p_y = \frac{2}{f(\theta)} Im(F_{1+}^* F_{4-} + F_{2+}^* F_{5-} + F_{3+}^* F_{6-} + F_{4+}^* F_{1-} + F_{5+}^* F_{2-} + F_{6+}^* F_{3-}) \Longrightarrow 0$$

- $C_x \propto Re$ (interference amplitudes):

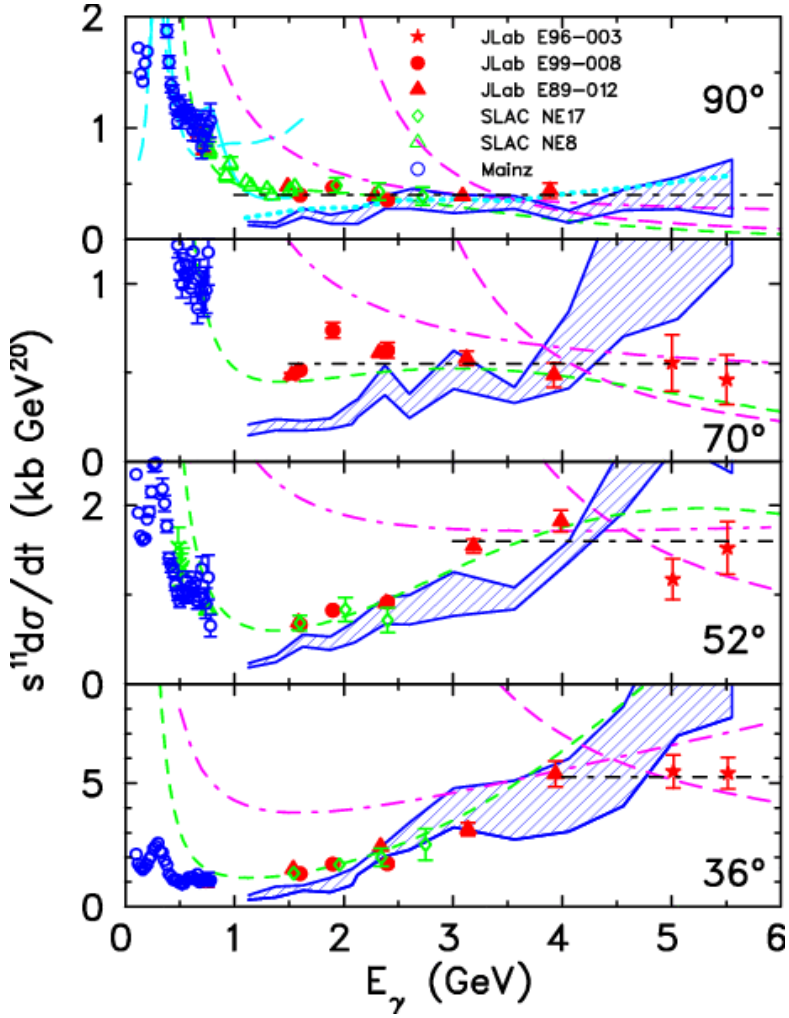
$$C_x = \frac{2}{f(\theta)} Re(F_{1+}^* F_{4-} + F_{2+}^* F_{5-} + F_{3+}^* F_{6-} + F_{4+}^* F_{1-} + F_{5+}^* F_{2-} + F_{6+}^* F_{3-}) \Longrightarrow 0$$

- C_z at $\theta_{cm} = 90°$:

$$C_z = \frac{1}{f(\theta)} \sum_{i=1}^{6} (|F_{i+}|^2 + |F_{i-}|^2) \Longrightarrow 0.$$

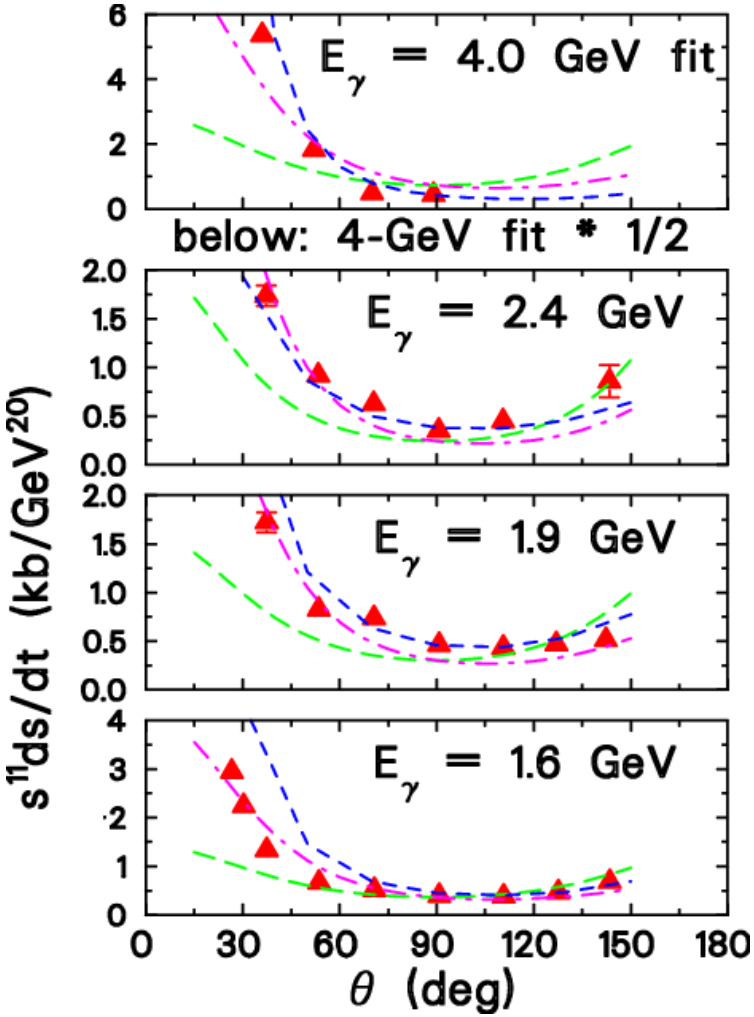
90° Excitation Functions

- Cross sections fall by factor of 1.2×10^6 from 1 – 6 GeV
- The onset of ~quark scaling, $d\sigma/dt \sim s^{-11}$, at each angle corresponds to $p_T \sim 1.1$ GeV: P Rossi et al, PRL 04, 012301 (2005)



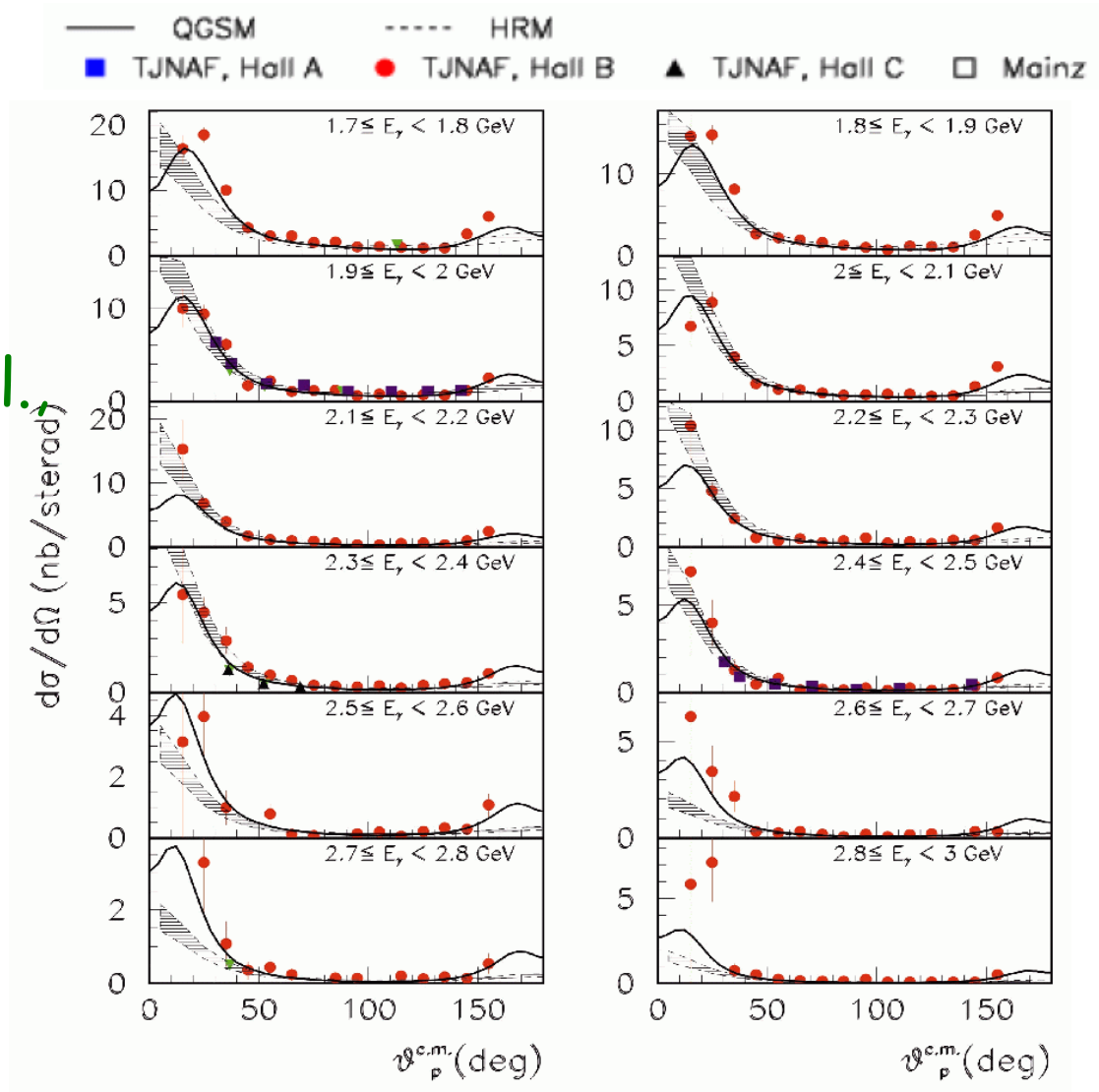
JLab Hall A Angular Distributions

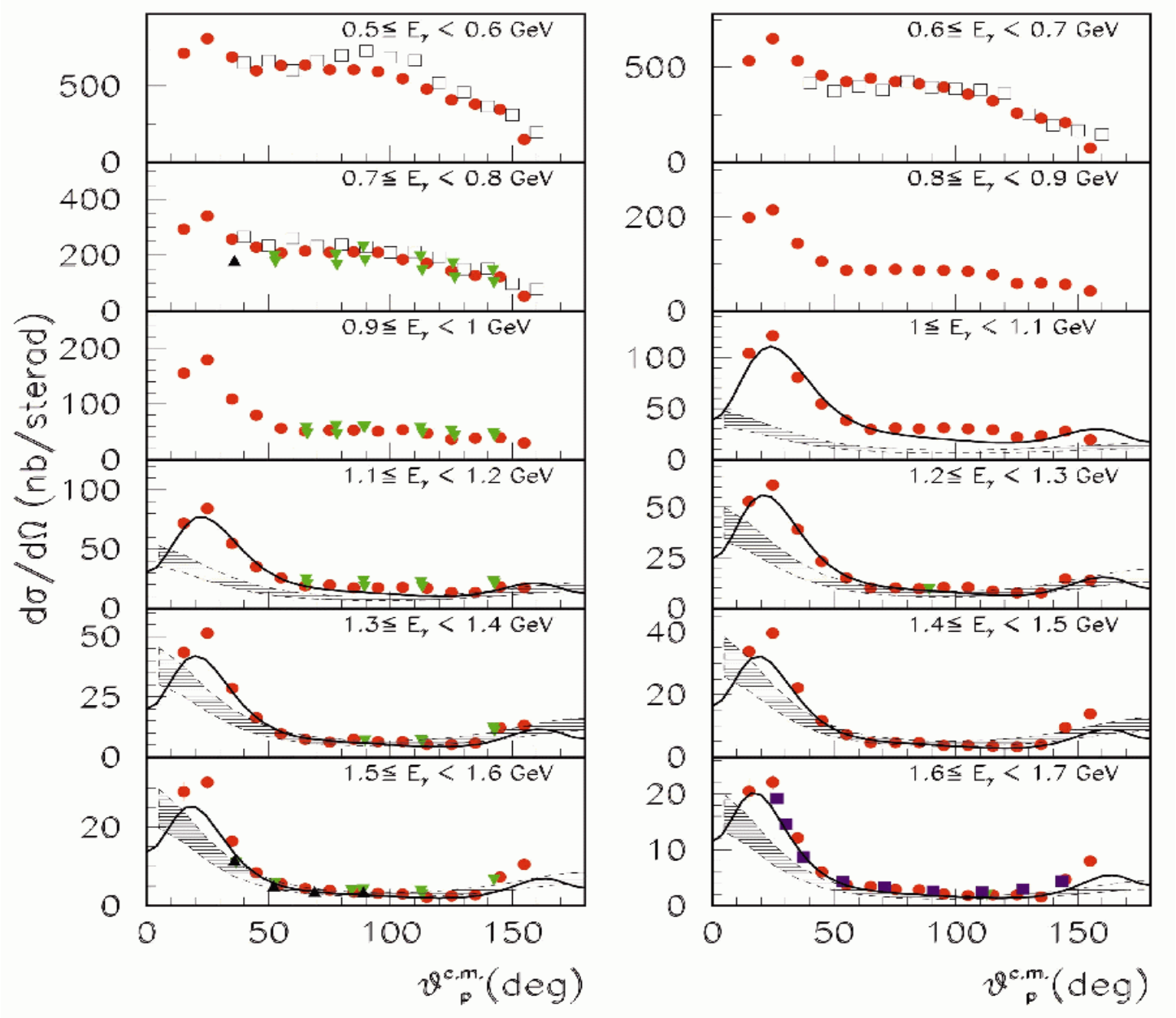
- Blue dash: HRM
- TQC (Radyushkin):
- $d\sigma/d\Omega_{sym} = NF_p^2F_n^2/\{[s-\Lambda^2]\sqrt{[s(s-m_d^2)]}\}$
- $d\sigma/d\Omega_{asym} = d\sigma/d\Omega_{sym}/\{1-A\cos\theta/\sqrt{[1+m_p/E]}\}^2$
- Similar AD shapes -- insensitive to dynamics?



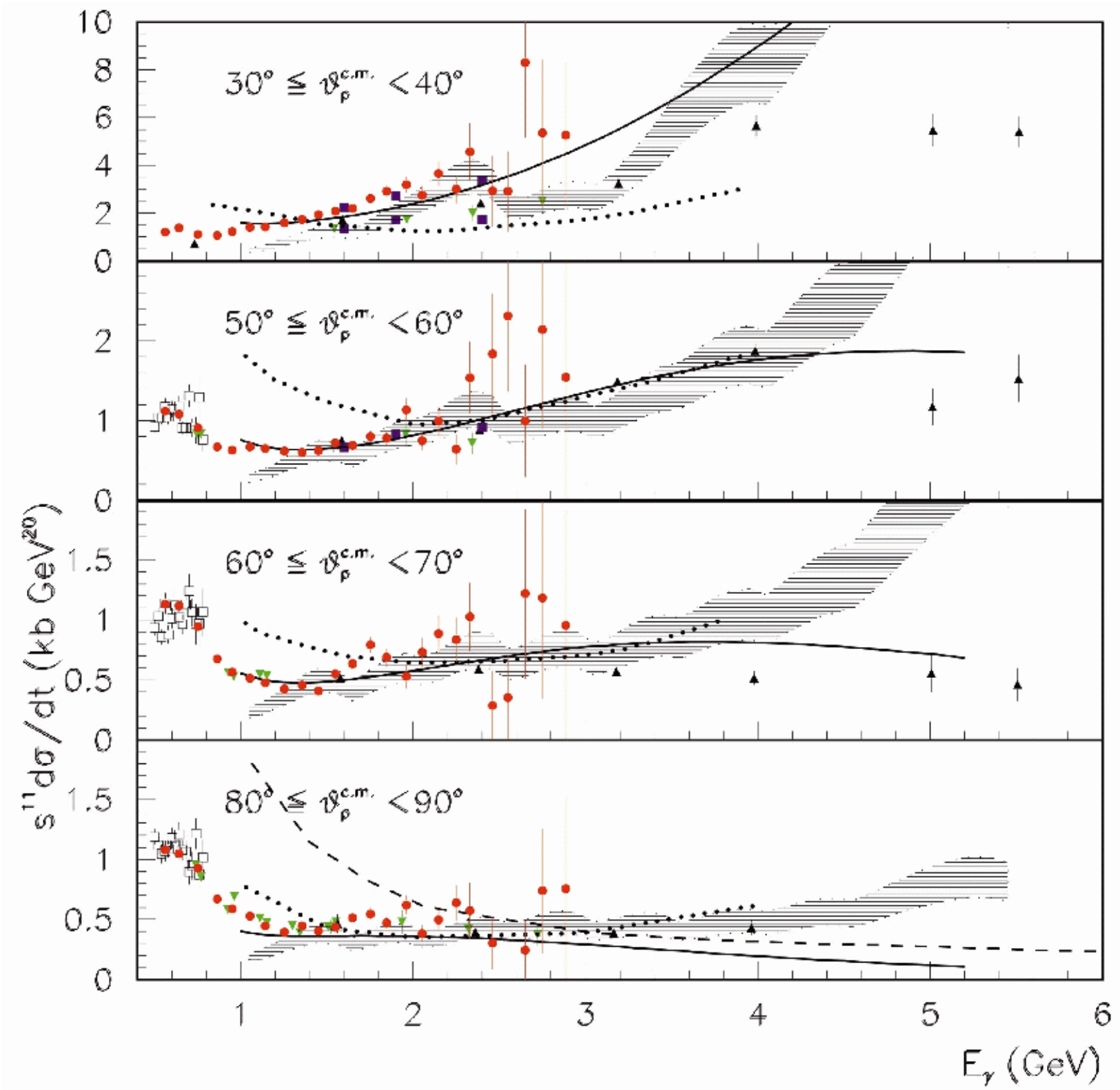
JLab Hall B Angular Distributions

- Angular distributions vs. photon energy
- M. Miraztia et al., PRC 70, 014005 (2004).





- Perhaps the hard physics is already there by ~1 GeV, over much of the angle range.


30° ≤ ϑ_p^c.m. < 40°
50° ≤ ϑ_p^c.m. < 60°
60° ≤ ϑ_p^c.m. < 70°
80° ≤ ϑ_p^c.m. < 90°
s^11 dσ/dt (kb GeV^20)
E_γ (GeV)

s^{-11} scaling

PRL 94, 012301 (2005) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2005

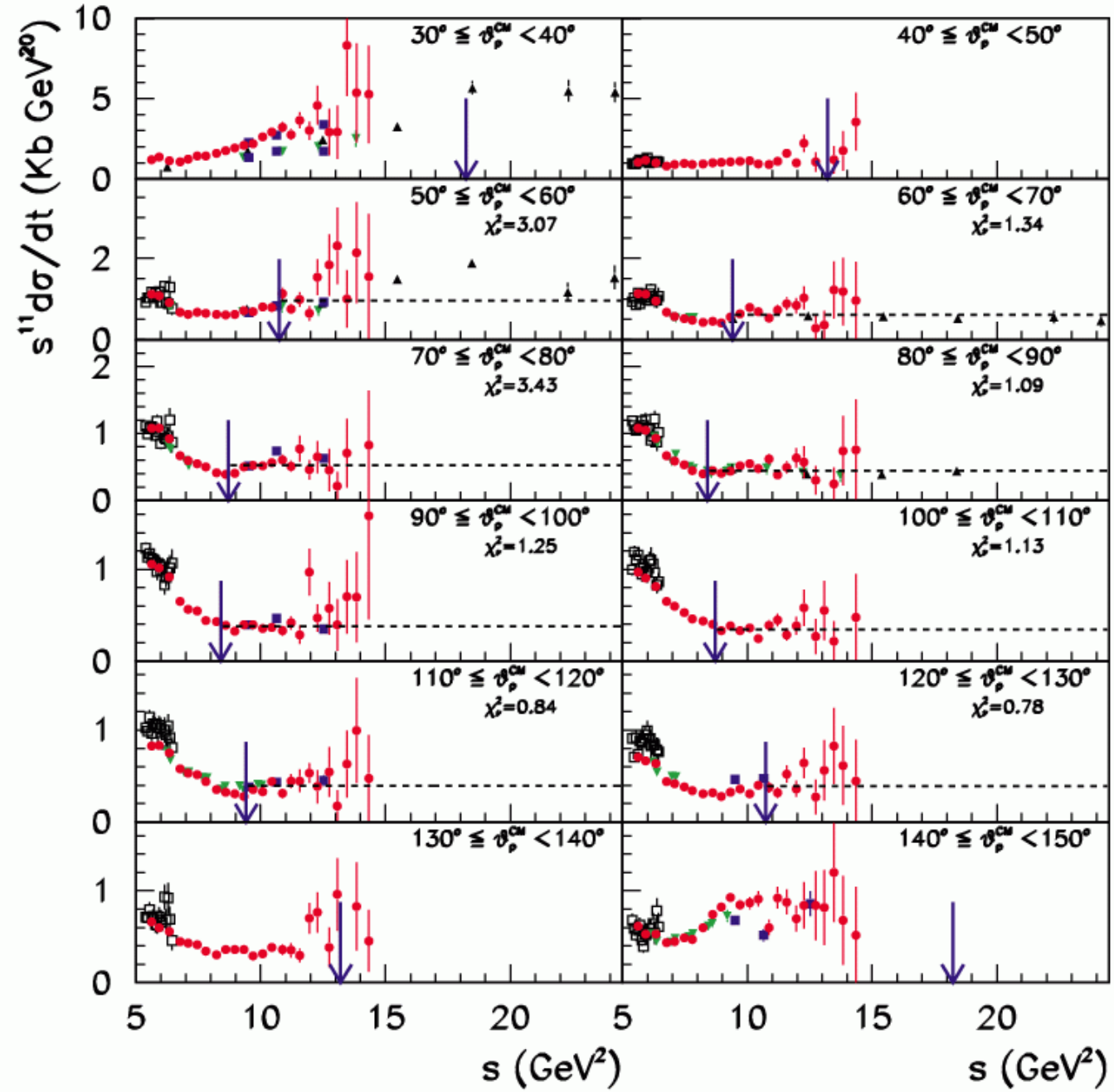
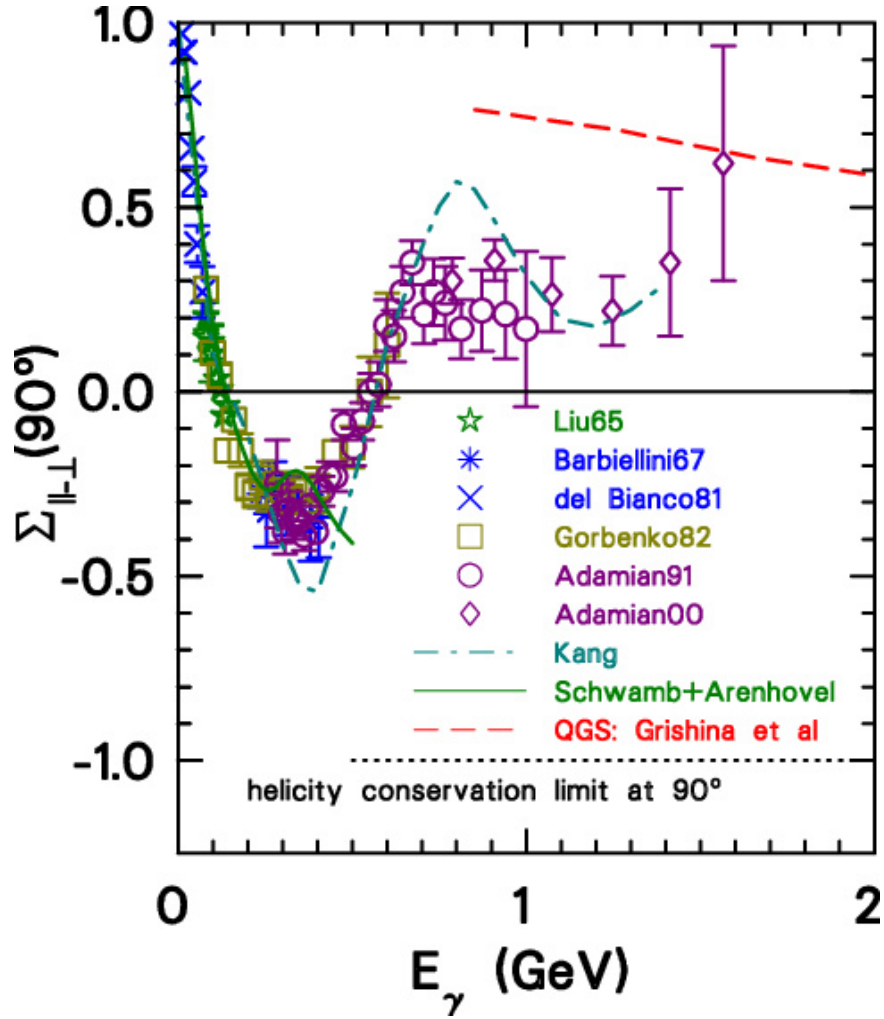


FIG. 2 (color). Deuteron photodisintegration cross section, $s^{11}d\sigma/dt$, as a function of s for the given proton scattering angles. Dashed lines are the fits of the data to s^{-11} for $P_T \geq 1.1$ GeV/c. The vertical arrows indicate the s value corresponding to $P_T = 1.1$ GeV/c. Fits are not shown for $\vartheta_p^{\text{c.m.}} = 35°, 45°, 135°$, and $145°$ where there are not enough data above 1.1 GeV/c. Also shown in each panel is the χ^2_ν value of the fit. Data are from CLAS [12] (solid red circles), Mainz [15] (open black squares), SLAC [5–7] (solid down-pointing green triangles), JLab Hall A [11] (solid blue squares) and Hall C [8,9] (solid up-pointing black triangles).

s^{-11} scaling for $p_T > 1.1$ GeV/c

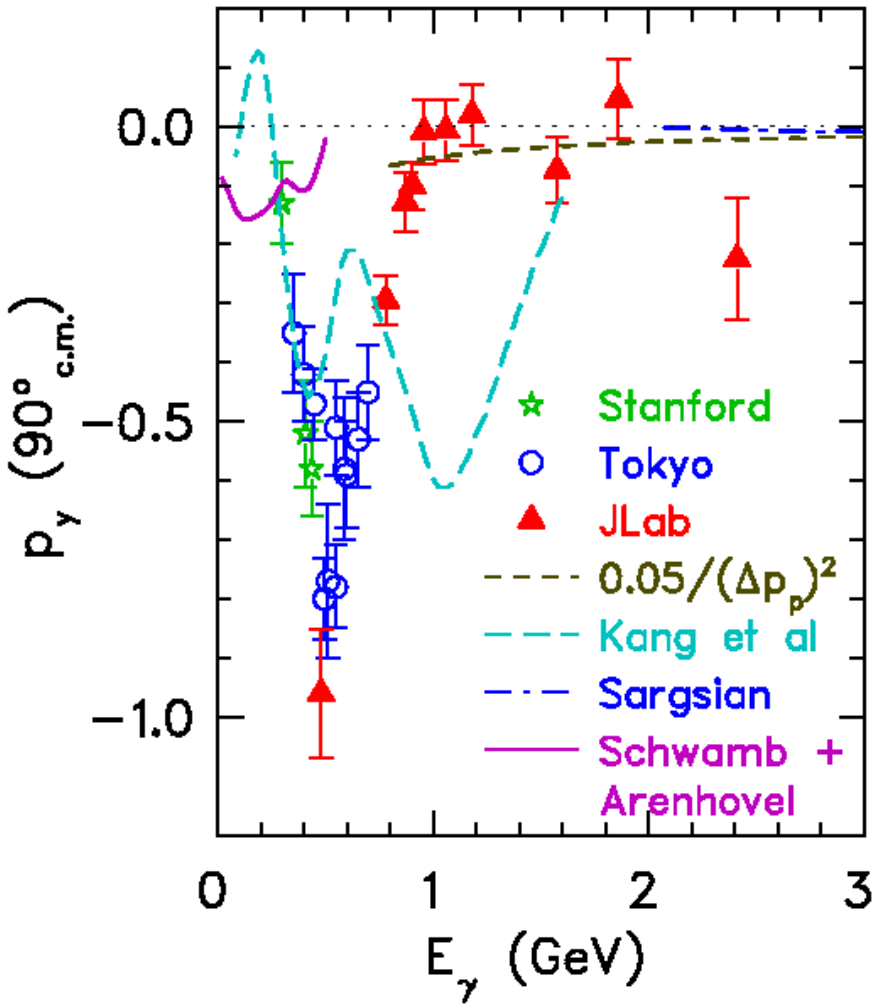
Σ Asymmetry

- HHC - Hadron Helicty Conservation – leads to Σ = -1
- Adamian *et al.* showed Σ heads away from HHC, with increasing energy
- Grishina et al. pointed out iso-vector (scalar) limit is Σ = 1 (-1)



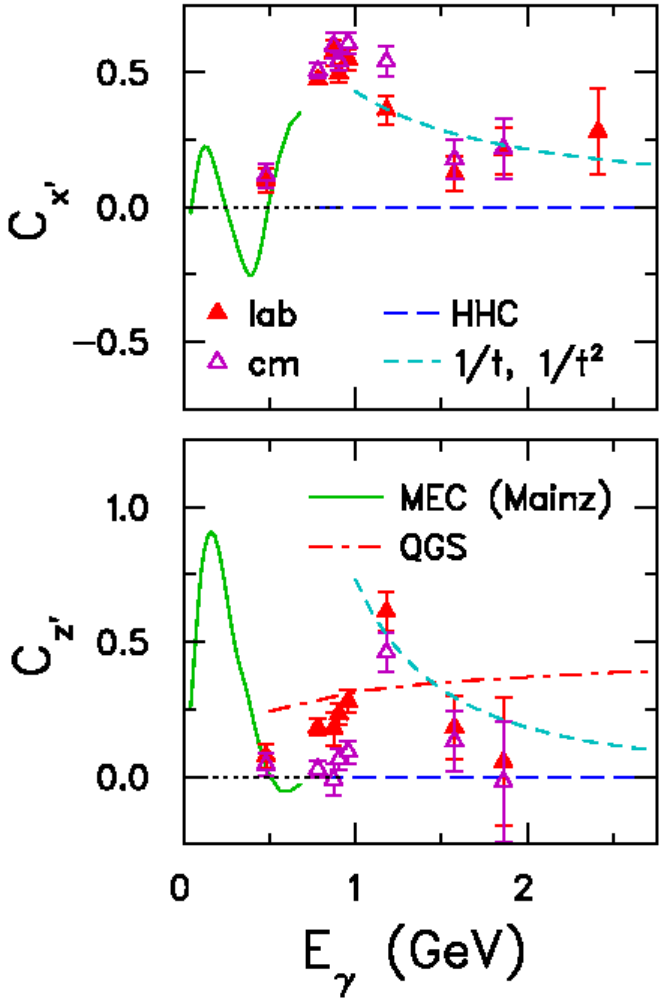
Induced Polarization p_y

- HHC leads to $p_y = 0$, and p_y vanishes above 1 GeV
- HRM predicts p_y small, <0
- Hadronic prediction, that $D_{13} + D_{15}$ leads to large resonance peak, not true.



Polarization Transfer

- Schwamb & Arenhövel prediction good at low energies
- $C_{x'}$ small, but not vanishing, so no HHC
- Cannot rule out or strongly support HRM / QGS / approach to HHC



JLab Hall A Experiment E00-007

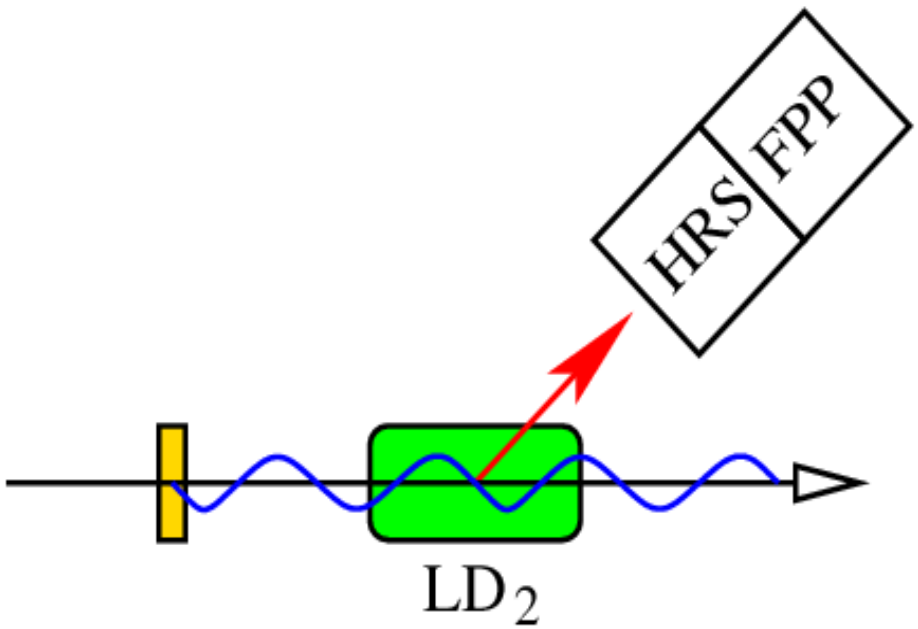
Spokespersons:
R. Gilman, Rutgers University
R. J. Holt, University of Illinois
Z.-E. Meziani, Temple University

$$\vec{\gamma} + d \rightarrow \vec{p} + n$$

Induced polarization: p_y

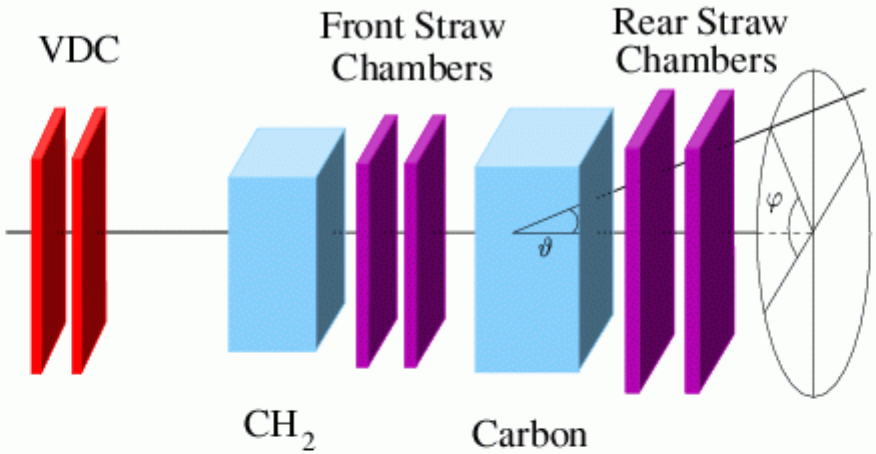
Polarization transfer: C_x and C_z

Experiment E00-007 at Jefferson Lab Hall A



- Polarized electron beam ($E_0 = 2.045$ GeV, $P_e = 0.79$) on a 6% r.l. radiator to generate polarized photons.
- A 15 cm long LD$_2$ target.
- Spectrometer HRS$_L$ to detect recoil protons (p_p and $\theta_p \Rightarrow E_\gamma$ and θ^p_{cm}).
- Two sets of focal plane polarimeters (FPP: CH$_2$ and Carbon analyzer) to measure recoil proton polarizations.

Two Sets of Focal Plane Polarimeters



- Polarized protons rescatter on nuclei (CH_2 or Carbon) generate azimuthal angle (ϕ_{FPP}) distribution asymmetries through spin-orbit interactions.
- Only sideway polarization components can be measured. Spectrometer dipole magnet rotates the proton spin direction.
- Analyzing power of the two analyzers were caliberated using elastic ep scattering (with the same p_p as in γd)
- Independent meaasurements from two analyzers provide consistency crosschecks.

Kinematics: 5 proton angular settings

TABLE I: Kinematics of the data and FPP parameters. A 2 GeV photon energy corresponds to a center of mass energy of $W = 3.3$ GeV.

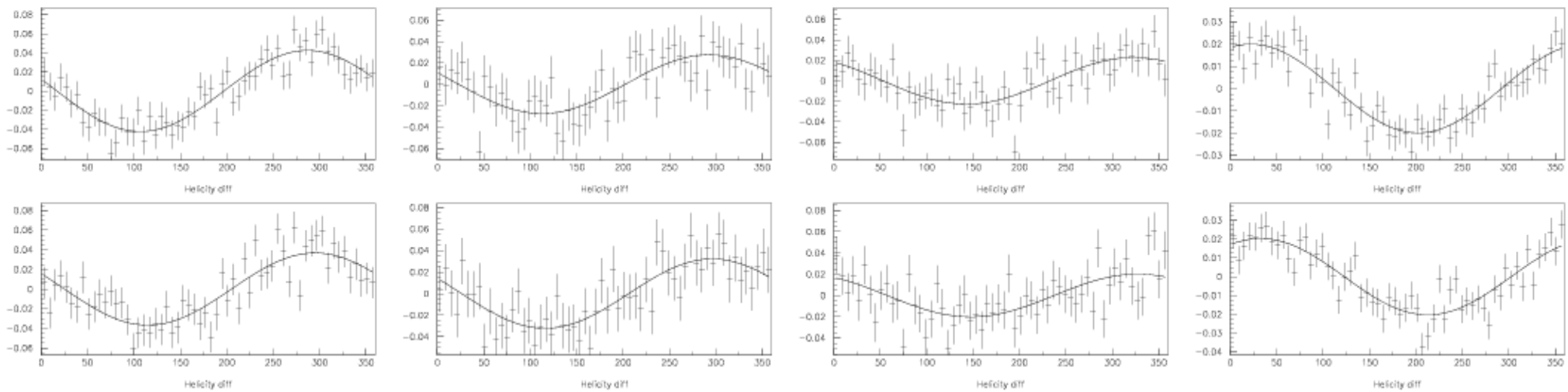
$\langle E_\gamma \rangle$ GeV	$\langle \theta^p_{cm} \rangle$	$\langle p_p \rangle$ GeV/c	$\langle \theta^p_{lab} \rangle$	spin precession	FPP analyzer	elastic $\vec{e}p$ calibration
2.01	36.9°	2.41	19.8°	226.5°	dual	yes
2.00	52.9°	2.24	29.1°	209.6°	dual	yes
1.99	69.8°	2.01	39.7°	191.9°	dual	yes
1.97	89.8°	1.68	53.9°	167.1°	dual	yes
1.94	109.5°	1.35	70.6°	144.2°	carbon	no

Elastic $\vec{e} + p \rightarrow e + \vec{p}$ to Calibrate FPP

At the same momentum as in the γd data, we took calibration runs using protons from elastic reaction ...

- While G_E^p/G_M^p is sensitive to the phase shift of ϕ_{FPP} asymmetry ...
- The P_l component comes mostly from kinematic factors and can be used to calibrate the analyzing power of FPP.
- The induced polarization $P_y \approx 0$ in elastic ep (to $1 \sim 2\%$), can be used for false asymmetry corrections in P_y analysis of γd data.

Elastic ep Calibration: ϕ_{FPP} Helicity Asymmetries.



Top: CH_2. Bottom: Carbon.

- Good agreements in focal plane asymmetries.

Focal plane:

$$N(\vartheta,\varphi) = N_0(\vartheta)\{1 + [A_y(\vartheta)P_t^{fpp} + a_{in}]\sin\varphi - [A_y(\vartheta)P_n^{fpp} + b_{in}]\cos\varphi\}$$

Translate to the reaction plane, consider spin processions in magnets:

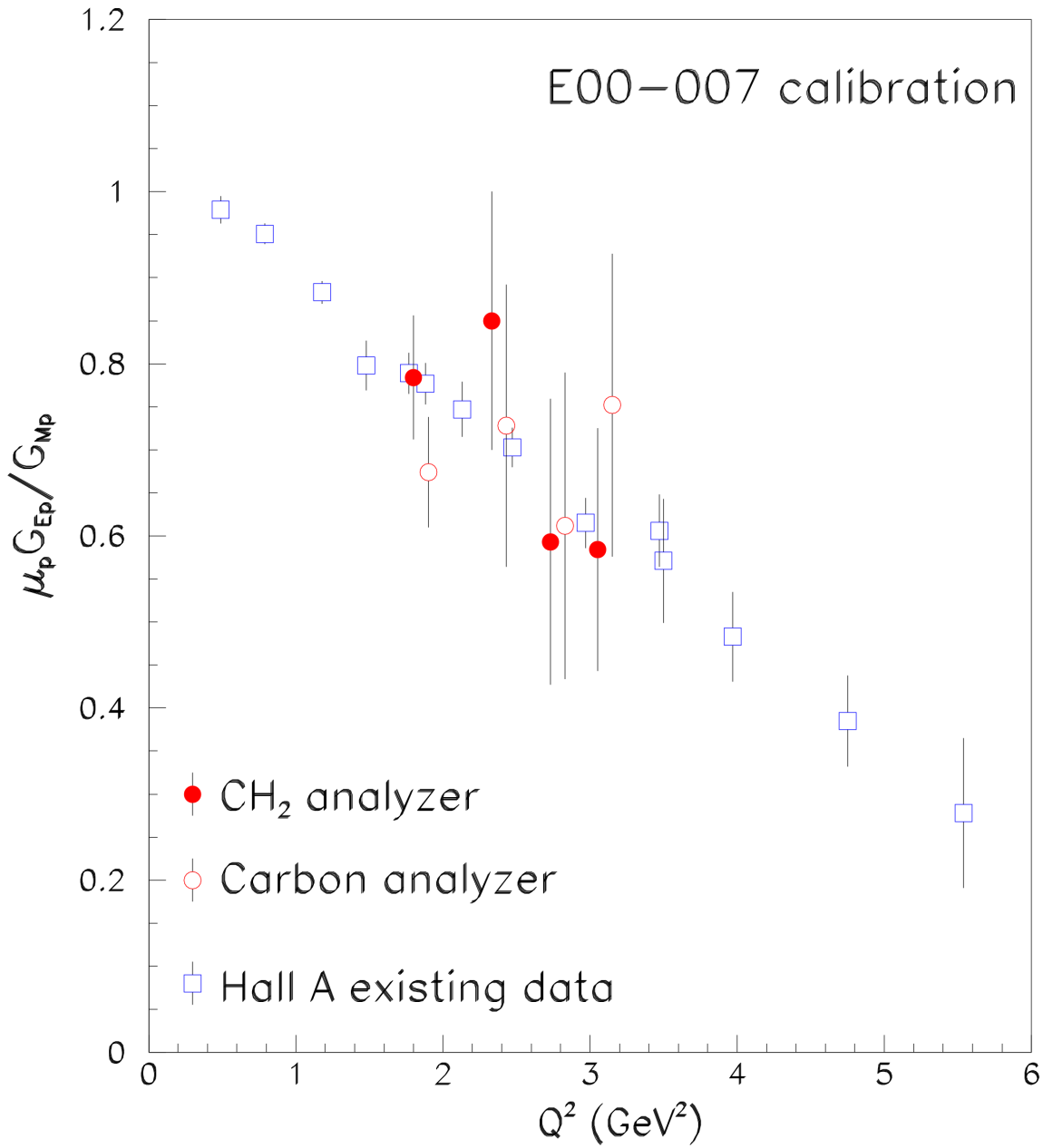
$$L(P_t,P_\ell) = \prod_{i=1}^{N_p}\{1 \pm A_y(\vartheta_i)(S_{tt,i}hP_t + S_{t\ell,i}hP_\ell)\sin\varphi_i \mp A_y(\vartheta_i)(S_{nt,i}hP_t + S_{n\ell,i}hP_\ell)\cos\varphi_i\},$$

Calibration of analyzing power

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P_t}{P_\ell}\frac{(E_{beam}+E_e)}{2M_p}\tan\frac{\theta_e}{2}$$

Table 1: The extracted form factor ratio $\mu_p G_{Ep}/G_{Mp}$ and the averaged analyzing power $\langle A_c \rangle$ are listed for both the CH_2 analyzer and the Carbon analyzer, the expected value of $\mu_p G_{Ep}/G_{Mp}$ from a fit to the Hall A G_{Ep}-II data are also listed.

			CH_2		Carbon	
Q^2	P_p	G_{Ep}-II	$\mu_p G_{Ep}/G_{Mp}$	$\langle A_c \rangle$	$\mu_p G_{Ep}/G_{Mp}$	$\langle A_c \rangle$
1.85	1.68	0.782	0.784 ± 0.072	0.178 ± 0.010	0.674 ± 0.064	0.199 ± 0.012
2.38	2.00	0.708	0.850 ± 0.150	0.146 ± 0.015	0.728 ± 0.164	0.140 ± 0.018
2.78	2.23	0.652	0.593 ± 0.166	0.121 ± 0.012	0.612 ± 0.178	0.125 ± 0.013
3.10	2.41	0.607	0.584 ± 0.141	0.113 ± 0.007	0.752 ± 0.176	0.103 ± 0.008



As a cross-check: proton form factor ratios agree with earlier measurements.

We obtained ep elastic data only to calibrate the analyzing power, to 10% level, not to measure form factor ratios.

Proton momentum: same as in γd settings.

Figure-Of-Merit of an analyzer is defined as:

$$F.O.M = \int_{\theta_{min}}^{\theta_{max}} \epsilon(\theta) A_c^2(\theta) d\theta$$

Table 2: The value of FOM obtained from the ep-calibration run. The relative statistical uncertainties are $\sim 15\%$. We also listed $T_{p_{analy}}$ in GeV, the proton kinetic energy at the mid-point of each analyzer. In comparison, the FOM values from the Gep long paper are alos listed.

		44 cm CH_2		Carbon 49.5 cm		Gep-III Carbon 49.5 cm	
P_p^{init}	T_p^{init}	$T_{p_{analy}}$	FOM	$T_{p_{analy}}$	FOM	$T_{p_{analy}}$	FOM
1.68	0.99	0.94	0.99×10^{-2}	0.78	1.53×10^{-2}	0.88	0.98×10^{-2}
2.00	1.28	1.24	0.70×10^{-2}	1.08	0.92×10^{-2}	1.05	0.83×10^{-2}
2.23	1.49	1.45	0.48×10^{-2}	1.29	0.69×10^{-2}	1.26	0.65×10^{-2}
2.41	1.65	1.60	0.41×10^{-2}	1.45	0.52×10^{-2}	1.53	0.50×10^{-2}

Polarization components in ep calibration data

both longitudinal and transverse polarizations agree with the expected values

$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_{Ep} G_{Mp} \tan\frac{\theta_e}{2}$$

$$I_0 P_\ell = \frac{1}{M_p}(E_{beam} + E_e)\sqrt{\tau(1+\tau)} G_{Mp}^2 \tan^2\frac{\theta_e}{2}$$

$$I_0 = G_{Ep}^2 + \frac{\tau}{\epsilon} G_{Mp}^2$$

Table 3: Polarization transfer components in the reaction plane P_t and P_l. The expected values (e.-val.) at bin-center are calculated based on a fit to the Hall A G_{Ep}-II data, the extracted values from both the CH_2 analyzer and the Carbon analyzer are listed.

	P_t			P_l		
Q^2	e.-val.	CH_2	Carbon	e.-val.	CH_2	Carbon
1.85	-0.148	-0.148 ± 0.010	-0.131 ± 0.010	0.394	0.392 ± 0.007	0.405 ± 0.007
2.38	-0.148	-0.171 ± 0.024	-0.150 ± 0.029	0.497	0.480 ± 0.018	0.494 ± 0.018
2.78	-0.143	-0.130 ± 0.033	-0.134 ± 0.035	0.572	0.577 ± 0.014	0.575 ± 0.016
3.10	-0.137	-0.131 ± 0.029	-0.164 ± 0.034	0.629	0.631 ± 0.011	0.616 ± 0.017

γd Data Analysis: Event Selections

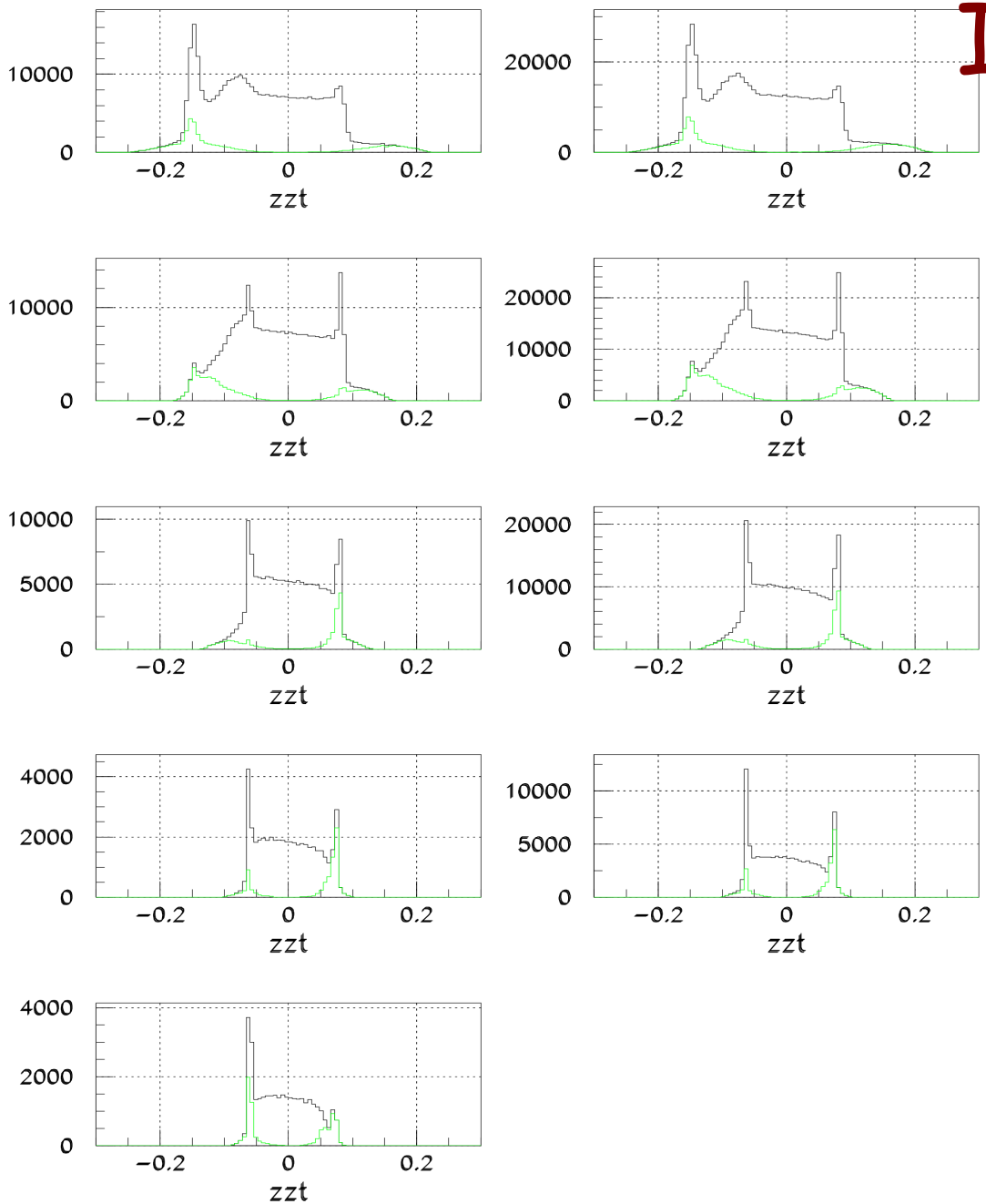
Protons from γd:

- Spectrometer acceptance cuts, focal plane $x-y$ profile cuts, reconstructed target position cut to eliminate target window contributions.
- Reconstructed E_γ cut, pion threshold cut to eliminate $\gamma + d \rightarrow p + n + \pi^0$ events.

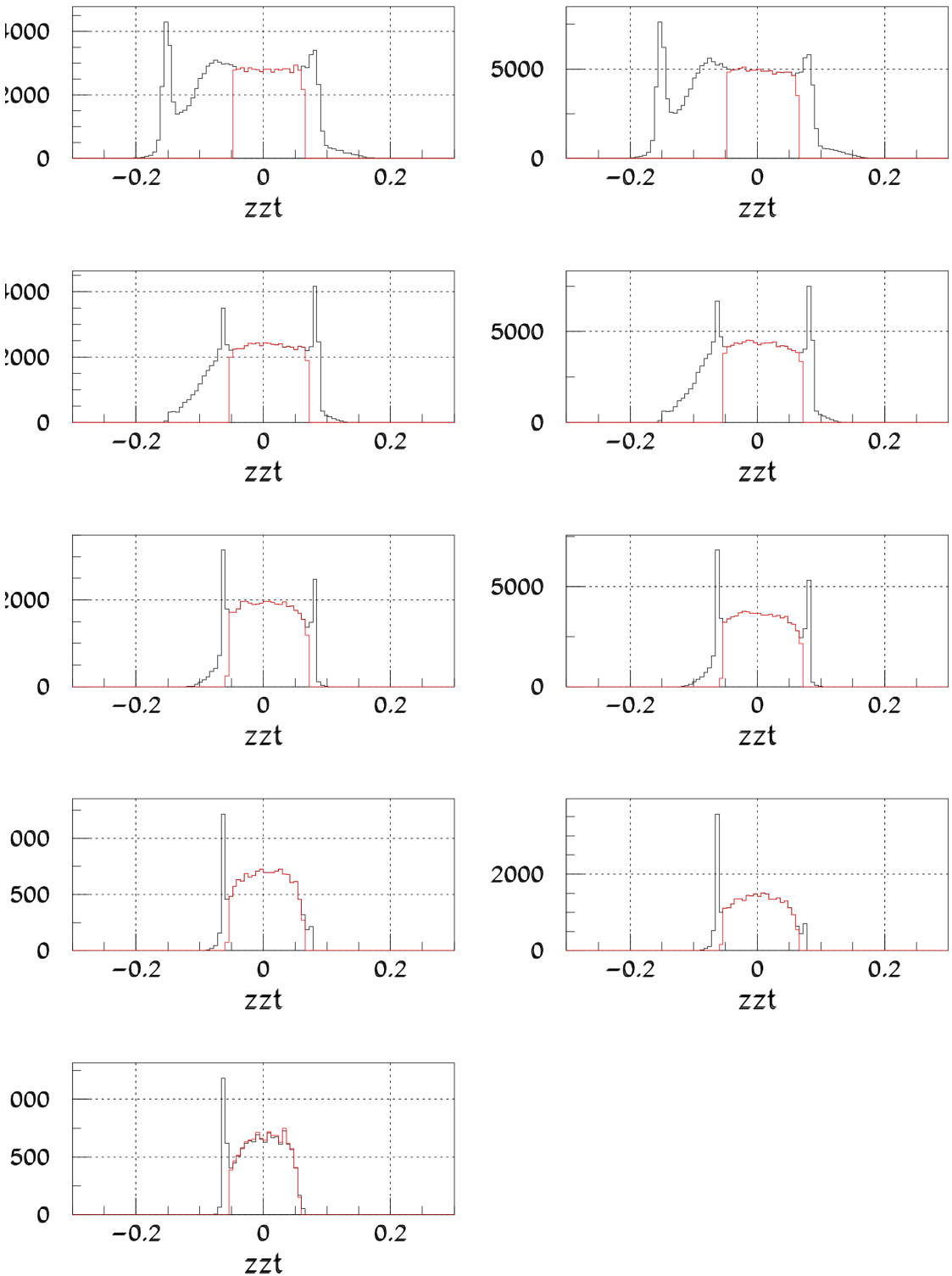
Protons at the FPP:

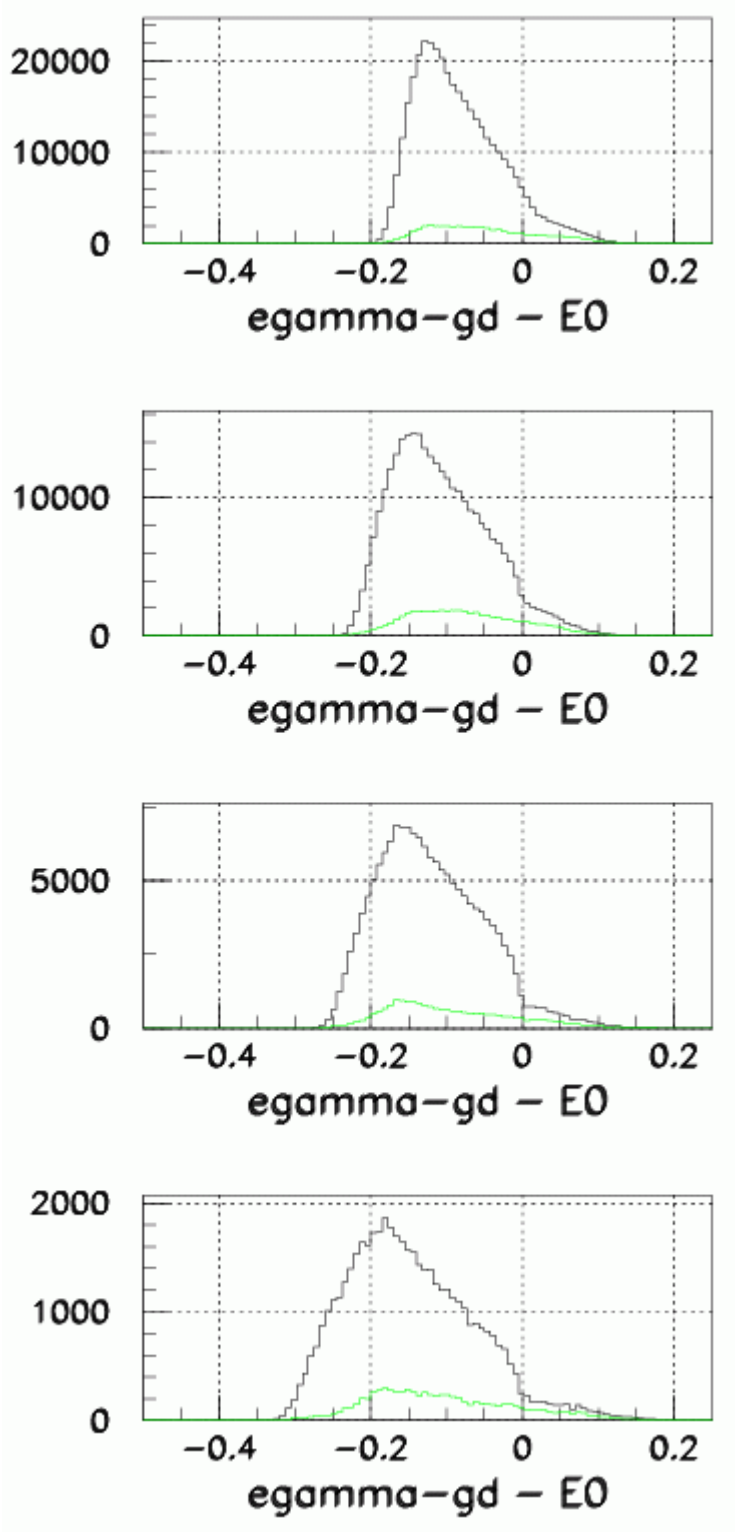
- Cut on scattering location. Cuts on FPP tracking quality, etc.
- $\theta_{FPP} > 3^\circ$, FPP cone test (full re-scattering cone fall into the FPP acceptance).
- For events in Carbon analyzer, require that in CH_2 $\theta_{FPP} < 2^\circ$.

Interaction Points



Cuts

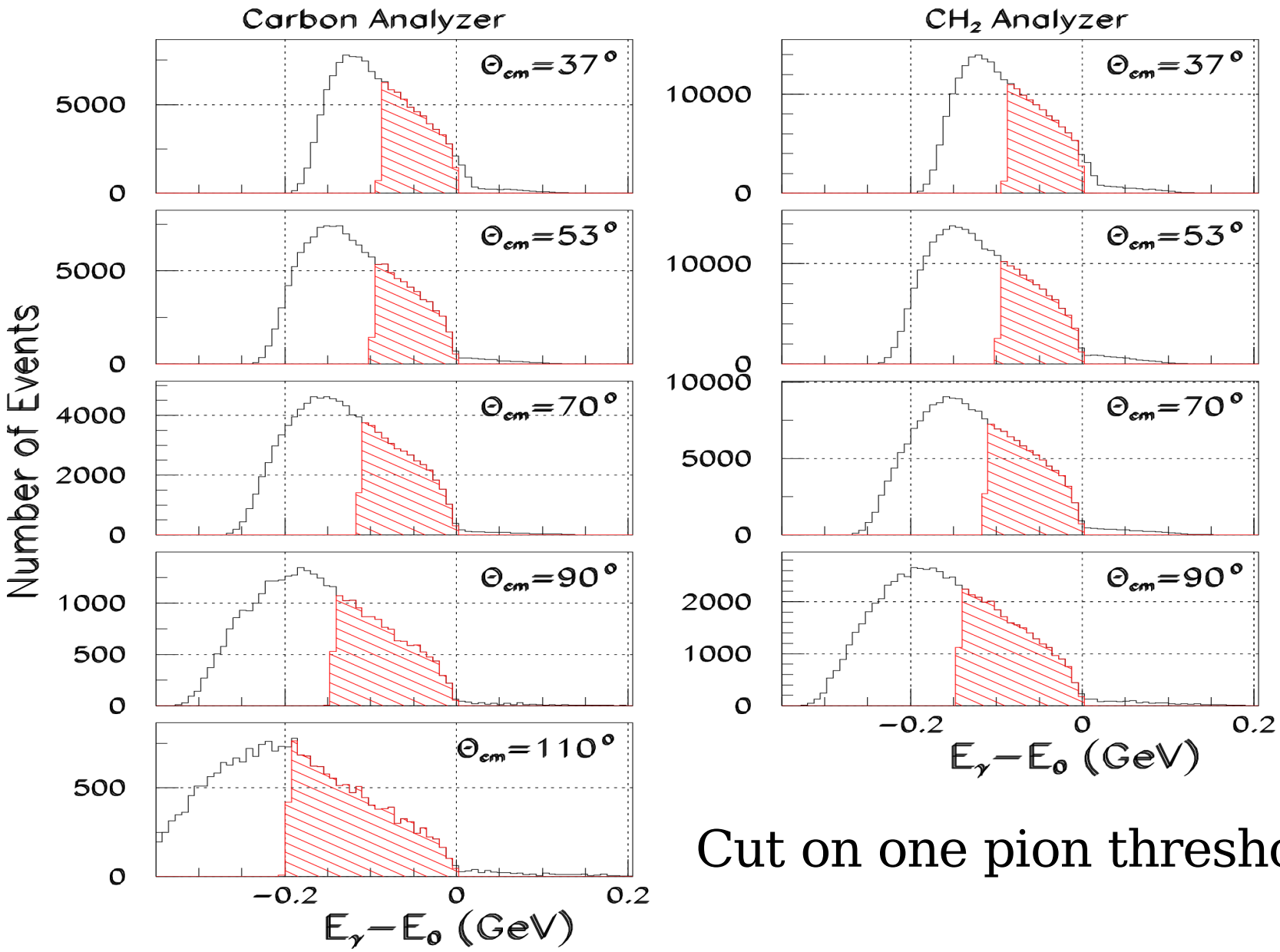




Focal plane profile cuts help to eliminate background.

Use 2-D correlation profiles of x_f, θ_f, y_f and φ_f obtained from a "white" momentum spectrum run without the radiator.

Reconstructed Eγ



Cut on one pion threshold

γd Data Analysis Induced polarization P_y:

- From ϕ_{FPP} distribution of beam helicity sum, FPP instrumentation asymmetries dominate the systematics.

However, we know that P_y in elastic ep reaction is very small ($1 \sim 2\%, T - odd$ vanishes in 1γ exchange.)

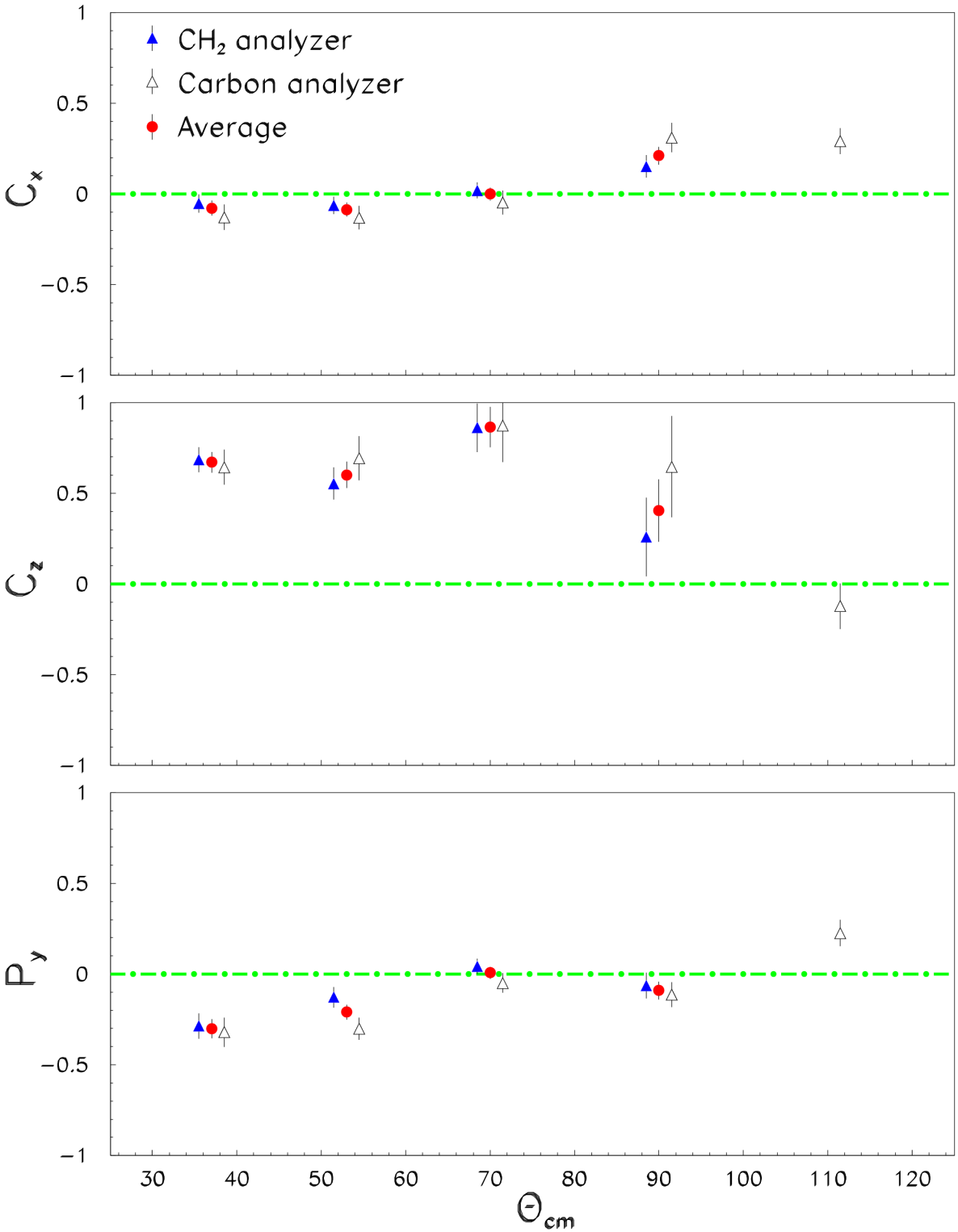
- Use exactly the same FPP phase space for ep and γd analysis of P_y.

The induced polarization P_y in ep data

The induced polarization P_y in ep elastic data with statistical uncertainties

Q^2	P_p	CH_2 Analyzer	Carbon analyzer
1.85	1.68	0.038 ± 0.015	-0.006 ± 0.011
2.38	2.00	0.016 ± 0.027	0.086 ± 0.027
2.78	2.23	0.063 ± 0.043	0.020 ± 0.038
3.10	2.41	0.102 ± 0.043	0.015 ± 0.043

Set the systematic uncertainties in P_y.
In one-photon exchange $P_y=0$ for elastic ep scattering.
With two-photon exchange $P_y<0.01$.



Recoil proton polarization in the Lab Frame

Comparison between CH2 and carbon analyzer.

Systematic Uncertainties in C_x

		C_x systematics CH_2 analyzer		
θ_{cm}	C_x	rel. sys.	δC_x^{offset}	total systematic
37°	-0.053	0.004	0.008	0.009
53°	-0.063	0.007	0.007	0.010
70°	0.020	0.002	0.011	0.011
90°	0.152	0.012	0.005	0.013

		C_x systematics carbon analyzer		
θ_{cm}	C_x	rel. sys.	δC_x^{offset}	total systematic
37°	-0.128	0.009	0.017	0.019
53°	-0.131	0.017	0.018	0.025
70°	-0.047	0.005	0.009	0.010
90°	0.311	0.022	0.015	0.027
110°	0.292	0.032	0.010	0.034

Systematic Uncertainties in C_z

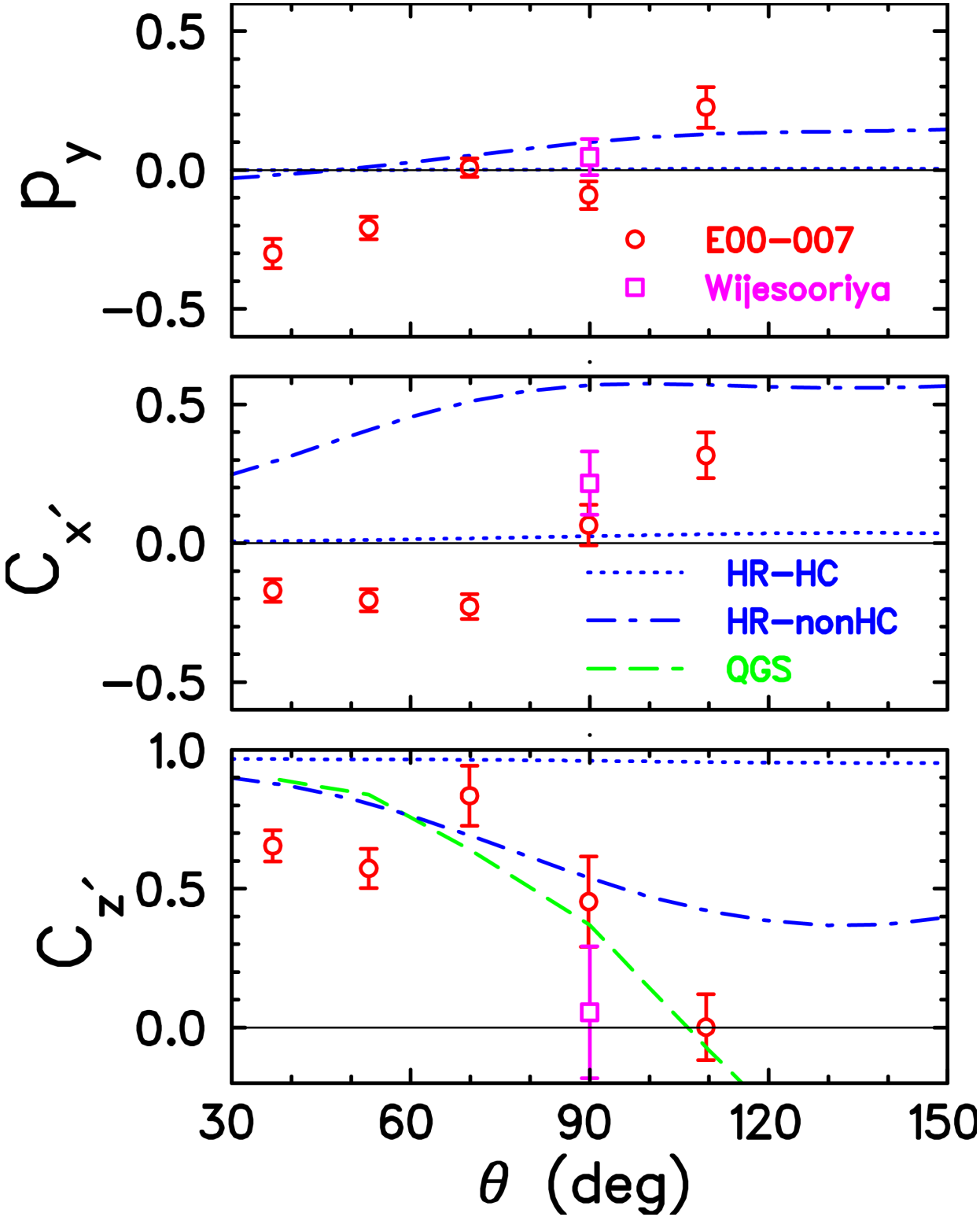
		C_z systematics CH_2 analyzer		
θ_{cm}	C_z	rel. sys.	δC_z^{offset}	total systematic
37°	0.685	0.048	0.030	0.057
53°	0.554	0.061	0.048	0.077
70°	0.862	0.086	0.024	0.089
90°	0.260	0.021	0.061	0.065

		C_z systematics carbon analyzer		
θ_{cm}	C_z	rel. sys.	δC_z^{offset}	total systematic
37°	0.644	0.045	0.024	0.051
53°	0.693	0.090	0.028	0.094
70°	0.872	0.096	0.072	0.120
90°	0.647	0.045	0.051	0.068
110°	-0.122	0.013	0.036	0.038

Systematic Uncertainties in P_y

	P_y systematic, CH_2 analyzer.				
θ_{cm}	P_y	$p_y \cdot \frac{\delta A_c}{A_c}$	P_y^{false}	P_y^{offset}	total systematic
37°	-0.286	0.017	0.015	0.028	0.036
53°	-0.128	0.013	0.027	0.016	0.034
70°	0.043	0.004	0.043	0.004	0.043
90°	-0.064	0.004	0.043	0.015	0.046

	P_y systematic, carbon analyzer.				
θ_{cm}	P_y	$p_y \cdot \frac{\delta A_c}{A_c}$	P_y^{false}	P_y^{offset}	total systematic
37°	-0.321	0.019	0.011	0.019	0.029
53°	-0.301	0.036	0.027	0.027	0.052
70°	-0.049	0.005	0.038	0.007	0.039
90°	-0.114	0.007	0.043	0.013	0.045
110°	0.226	0.023	0.043	0.021	0.053



In CM frame

Compare with theory predictions

- $\theta_{cm}=90^o$ points agree with our earlier measurements.
- Smooth variation with angle, crossing zero near $\theta_{cm}=90^o$
- $C_{x'}$ and p_y generally small, but not zero. HHC does not hold.
- $C_{z'}$ large at forward angles, like QGS

Comments on theory predictions:

$C_{z'}$ is not sensitive to phases of amplitudes, can be predicted more reliably as: $$f(\theta)C_{z'} = \sum_{i=1}^{6}\sum_{\pm} \pm|F_{i,\pm}|^2$$

$C_{x'}$ and P_y are the real and imaginary parts of interference amplitudes, sensitive to phases, difficult to predict.

QGS model makes no prediction for $C_{x'}$ and P_y. Predicts cross sections agree with data in the few GeV region.

For the Hard Rescattering Model

Calculations are at the lower end of the validity range.

p-n spin amplitudes with large uncertainties, based on p-p amplitudes.

$C_{x'}$ of HR-nonHC is off.

M. Sargsian pointed out: in the iso-vector channel at $\theta_{cm}=90^o$ $C_{x'}=0$ (p-n amplitude proportional to φ_5).

Thus the new data might indicate iso-vector channel dominates over iso-scaler channel.

Statistical uncertainties dominate, except in $C_{z'}$

TABLE III: Center-of-mass frame proton recoil polarization components, with statistical and systematical uncertainties.

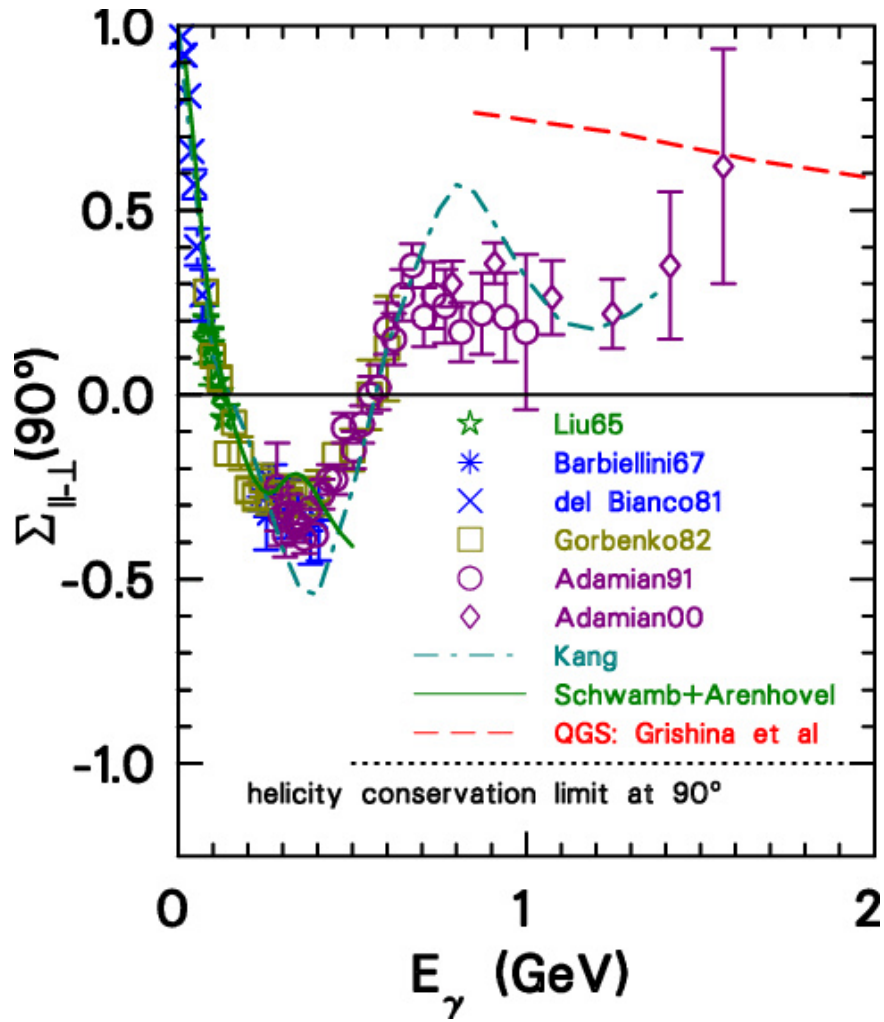
θ^p_{cm}	p_y	C'_x	C'_z
36.9°	-0.301 ± 0.053 ± 0.029	-0.170 ± 0.041 ± 0.020	0.654 ± 0.056 ± 0.051
52.9°	-0.209 ± 0.041 ± 0.052	-0.205 ± 0.040 ± 0.031	0.573 ± 0.071 ± 0.092
69.8°	0.008 ± 0.033 ± 0.039	-0.228 ± 0.045 ± 0.033	0.835 ± 0.108 ± 0.116
89.8°	-0.090 ± 0.049 ± 0.045	0.065 ± 0.074 ± 0.034	0.453 ± 0.162 ± 0.065
109.5°	0.226 ± 0.073 ± 0.053	0.316 ± 0.082 ± 0.035	0.001 ± 0.119 ± 0.037

Summary

- In γd -> pn, at low energy meson-nucleon picture works well. At high energy, cross section scales as s^{-11}, consistent with quark counting rule.
- We've measured the angular dependence of $C_{x'}$, $C_{z'}$ and P_y at Eγ=2.0 GeV. Spin observables do not agree with HHC.
- Data suggests iso-vector channel dominate over iso-scaler channel.
- The next step would be ...

To extend the Σ Asymmetry Measurement in Hall B to Higher Eγ

- HHC - Hadron Helicty Conservation – leads to Σ = -1
- Adamian *et al.* showed Σ heads away from HHC, with increasing energy
- Grishina et al. pointed out iso-vector (scalar) limit is Σ = 1 (-1)



Thanks

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