Structure of the Roper Resonance from Measurements of $p(\vec{e},e'\vec{p})\pi^0$ using Recoil Polarization Observables

Spokespeople:

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Plus support of many Hall A Collaboration members.

Executive Summary

- **"Roper Resonance": P_{11}(1440)**
  - Lowest + parity N* ; wide (~ 350 MeV)
  - Very little known about internal structure

- **This proposal:**
  - Measure **double-polarization** observables in $p(\vec{e},e'\vec{p})\pi^0$ that are very sensitive to Roper excitation/structure.
  - "Map" structure over extended range in W and Q^2
  - Experimental method and analysis/interpretation of this approach benefit from last 10+ years of studies focused on Δ(1232) resonance

The Driving Physics: Many Views of the Roper

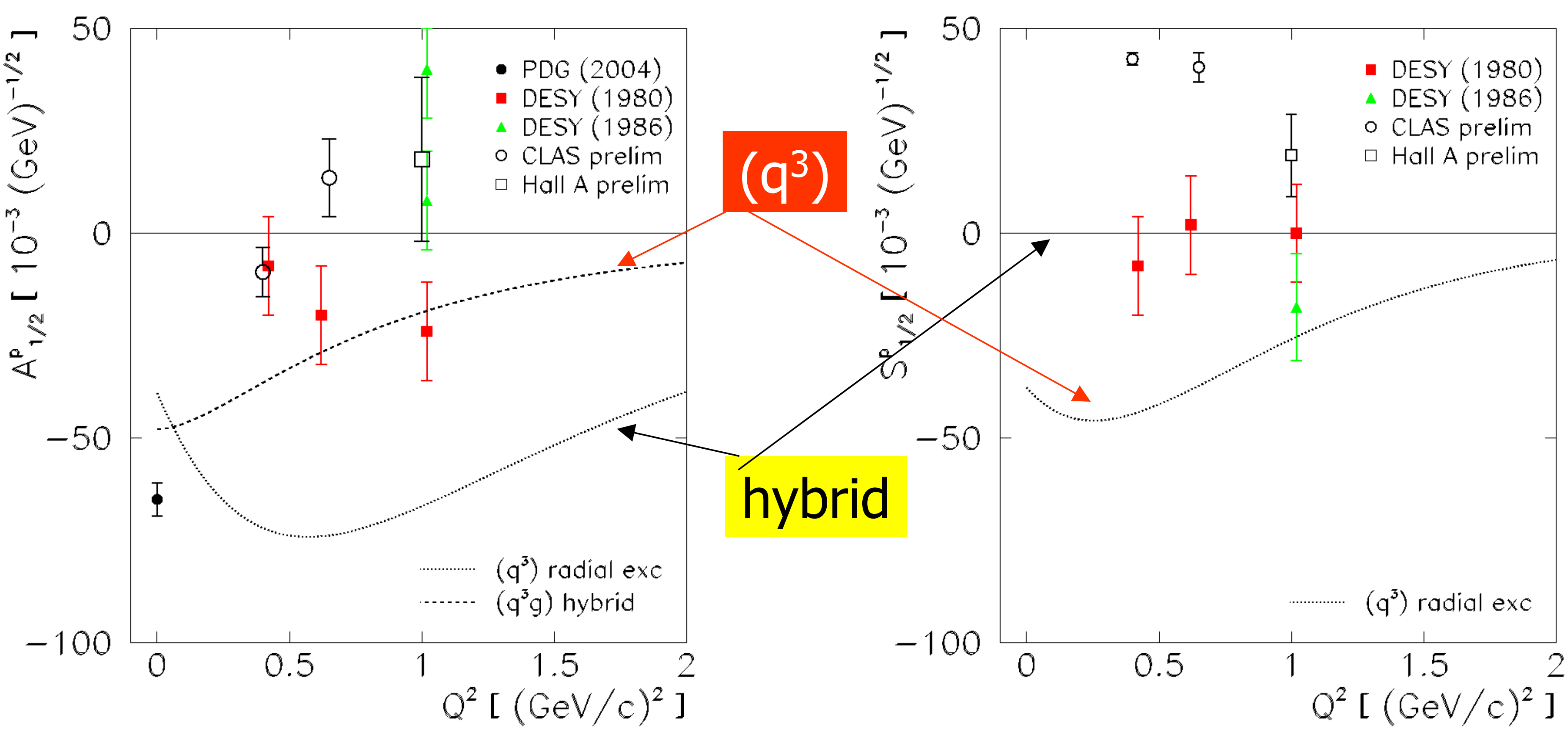
1. **Simplest:** spherically sym quark model
   - Radial excitation: $(1s)^2\ (2s)^1$
   - "Breathing Mode": sizable C0 excitation (S_{1-}) relative to M1 excitation (M_{1-})

2. **Hybrid Baryon:** gluonic partner of proton
   - Gluonic field excitation: (q^3g)
   - Can't identify such hybrid by spectroscopy alone (same q.n.'s as standard quark config)…
   - BUT: same spatial wf as proton, so C0 transition highly suppressed: no "breathing"!

Views of the Roper (cont'd): (Radial q excitation) vs. (Hybrid)

Transverse Excitation (~M1)

Scalar Excitation (~C0)



Views of the Roper (cont'd)

3. **Other Hybrid Models:**
   - e.g. via QCD sum-rules; pQCD domain …
   - Roper mass from vibrating flux-tubes
   - Current inability to predict dynamical properties
4. **Lattice QCD:**
   - Very recent ID by Kentucky group (quenched calc., pion mass = 180 MeV) of Roper at correct mass! (1 Dec 2004 update of hep-ph/0306199)
   - Supports Roper as (q^3)
   - "unraveling the nature of the Roper resonance has direct bearing on our understanding of the quark structure and chiral dynamics of baryons, which is one of the primary missions at experimental facilities like Jefferson Lab"

Views of the Roper (cont'd)

5. **Constituent Quark Models:** extensive studies with different specific approaches – varying degrees of success to date
   - Semi-relativ., linear confinement V (Stancu, Stassart)
   - Potential q model w/ relativ. EM int (Li, Close)
   - NR q model w/ mixed wf's, rel corrections to transition operator (Capstick)
   - Light front q model (Capstick, Keister, Weber, Cardarelli…)
   - NR q model w/ vector meson exch (Cano, Gonzalez)
   - Many using meson dof…MEC, chiral mesons, Cloudy Bag Model … pentaquark??

Where do we stand?
Existing Data & Other Experiments

Single-pion electro-production experiments have been conducted in all 3 Halls at JLab

- Most cases: cross sections (angular distributions) only
- Handful of single- and double-polarization measurements so far

JEFFERSON LAB: HALL B (CLAS)

- *Joo et al.:* Published angular dist and W-dependence, including e-beam asymmetry (σ_{LT}'), for π^+ and π^0 channels in $\Delta(1232)$ region at $Q^2 = 0.4$ and $0.65\ (GeV/c)^2$
  - Legendre analysis showed about 15-20% of D_1' moment coming from Im($\mathbf{M_{1-}}^*$ S_{1+}) term … points to influence of **Roper**

Existing Data & Other Experiments
Jefferson Lab Hall B (CLAS)

- **More recent analysis of this CLAS data into the 2nd-resonance region** (Aznauryan et al., nucl-th/0407021)
  - Used JLAB unitary isobar model ("JANR") to extract transition multipoles up to higher resonances: Roper, D_{13}(1520) and S_{11}(1535)
  - Within this model fitting, able to extract Transverse and Scalar Roper-resonance transition amplitudes (this is what was shown on the earlier figure!)

  - In these fits:
    - σ_{LT} (cross section) is sensitive to real parts of the P_{11} multipoles
    - σ_{LT}' (beam asym) is sensitive to Imag parts of P_{11} multipoles

Existing Data & Other Experiments

Jefferson Lab Hall B (CLAS)

Final Note: CLAS PhotoProduction plans

- E01-105 will measure double-polarization observables in the photoproduction of π^+ and π^0
  - long. polarized Beam and both long. and trans. polarized Target
  - Almost full angular coverage in W range across Roper
- These polarization observables will greatly reduce model-dependent uncertainties in resonance properties extracted at Photon Point

- **This current proposal:** aimed at achieving similar goal, but in electroproduction, to complement CLAS measurements and thus achieve accurate isolations of the Roper transitions at finite Q^2

Existing Data & Other Experiments

Jefferson Lab Hall A (using “FPP”)

- Recoil polarimetry in Hall A allows access to **several different** bi-linear combinations of transition multipoles (**both real and imaginary pieces**) in $p(\vec{e},e'\vec{p})\pi^0$
  - Such bi-linear combinations allow for amplification of small multipoles when interfering with larger multipoles
  - As has been demonstrated in the $\Delta(1232)$ region, such measurements complement the wider kinematic range CLAS angular distributions, and provide stringent constraints on dynamical models describing the transitions (particularly where multipoles vary quickly with energy, and precise kinematic definition is needed)

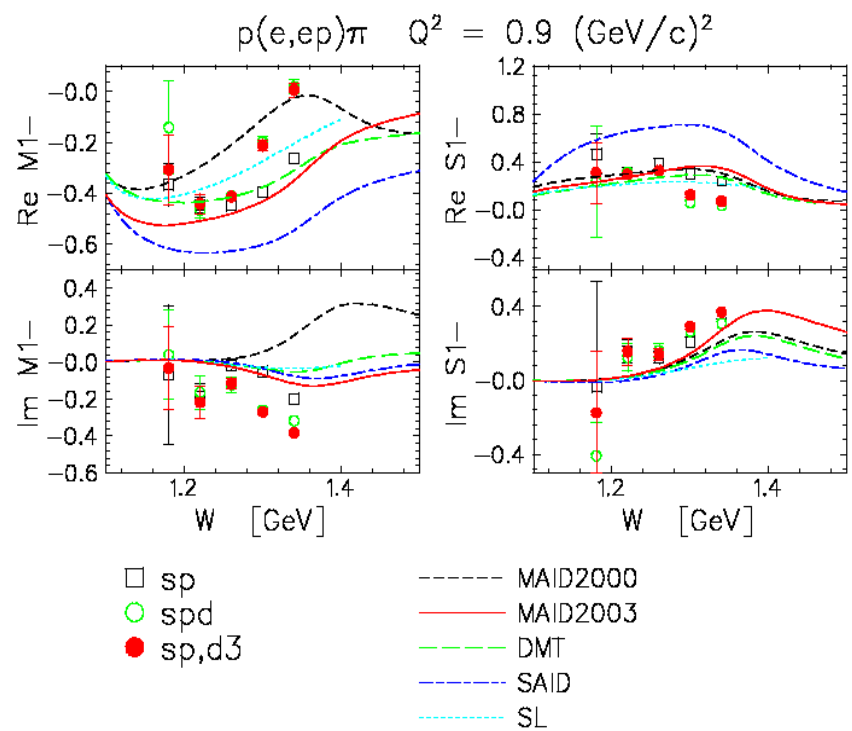
To Demonstrate: E91-011 – centered on $\Delta(1232)$

Existing Data & Other Experiments

Jefferson Lab Hall A (using "FPP"): E91011

- **Data collected in 2000**: full angular distribution of recoil polarization components (6) measured
  - Centered at W=1232 MeV and $Q^2 = 1\ (\mathrm{GeV}/c)^2$
  - High $Q^2 \Rightarrow$ large out-of-plane coverage attained
  - 14 independent responses (+ 2 Rosenbluth combinations) extracted $\Rightarrow$ multipole analysis with full freedom in all $\ell = 0,1$ contributions
  - The "1-" multipoles associated with Roper visible

Preliminary E91011 Results



Existing Data & Other Experiments
Mainz Microtron (MAMI)

- **Electroproduction (A1 Collab.):**
  - Used FPP in same technique as Hall A at W=1232 MeV and $Q^2 = 0.12\ (GeV/c)^2$ .. but only at one angle (yet still an influential result on constraining models!)
  - Facility constraints don't allow similar measurement for Roper region
- **Photoproduction (A2 Collab.):**
  - Planned double-polarization measurement very similar in nature to the CLAS E01-105

Pion ElectroProduction Models:
The Bridge
between Experiments and Baryon Structure

- **Currently:** 3 available state-of-the-art models to deal with both resonant and non-resonant dynamical contributions to pion electroproduction:

1. **MAID:** Mainz unitary isobar model
2. **DMT:** Dubna-Mainz-Taipei dynamical model
3. **SL:** dynamical model of Sato and Lee

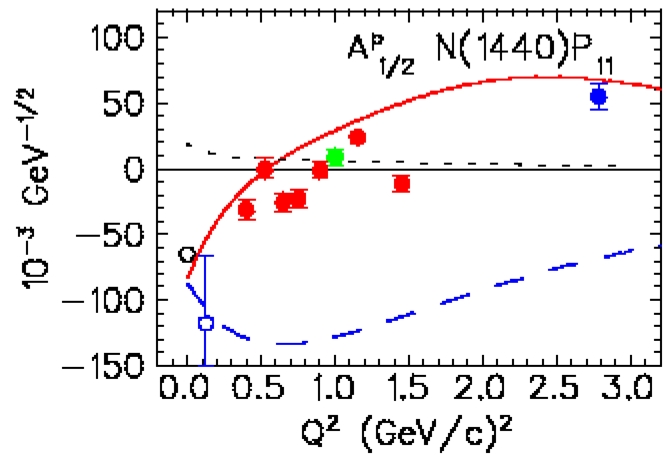
- All have been exercised thoroughly in the past couple of years when faced with the new double-polarization data in the Δ region (just discussed)

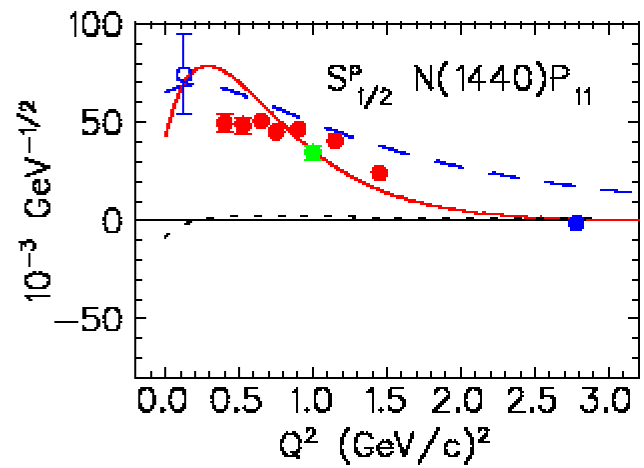
- MAID, DMT are appropriate into Roper region to allow comparison to new data for extraction of Roper transition amplitudes.

Pion ElectroProduction Models: MAID

- To incorporate all new electroproduction data from various experiments, MAID is pursuing “super-global fits” – to simultaneously reproduce as much data as possible
- Figure shows pre-2003 (no CLAS data) Roper result of fit. (NOTE: transverse excitation goes thru zero somewhere around 0.5)
- Need pol (and double-pol) observables (at W’s across resonance) to stabilize physics extractions… these observables provide strict constraints for any partial-wave analysis.

Transverse Excitation





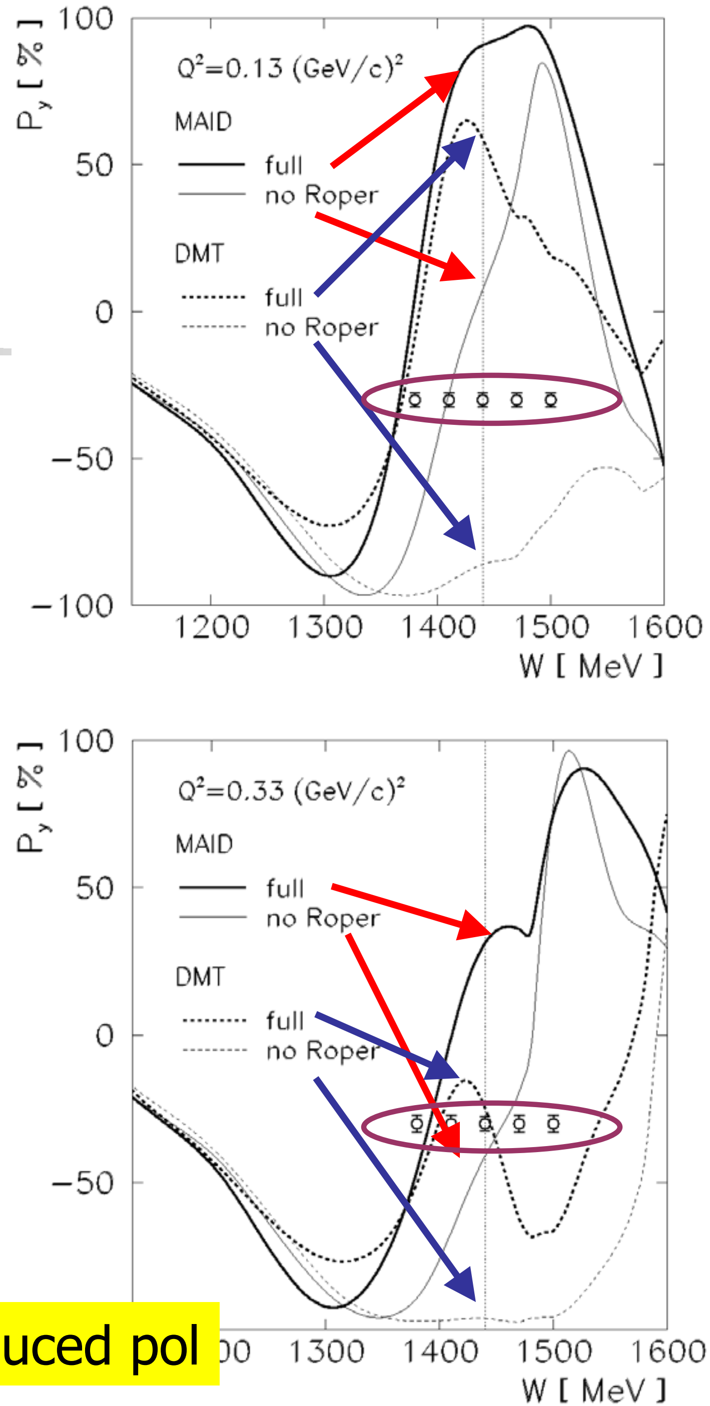
Scalar Excitation

Pion ElectroProduction Models:

DMT Dynamical Model

- Include πN FSI to dynamically preserve unitarity (coupling the $\gamma^*N \rightarrow \pi N$ transition potential to πN t-matrix)…resonance part thus computed dynamically, background same as in MAID.

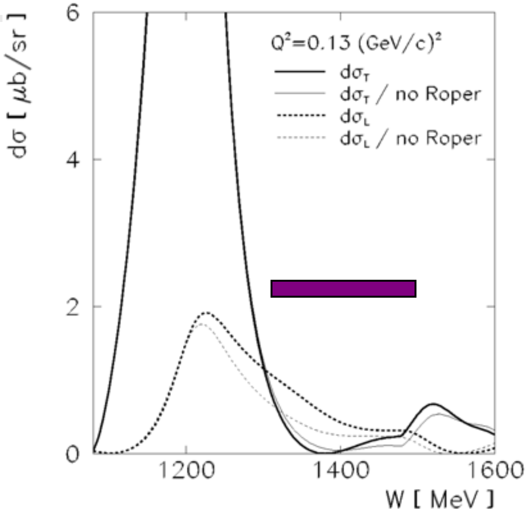
- Current versions – MAID2003 and DMT2001 – give same cross sections, but quite different recoil polarization predictions (thus measurement of these provide an important step towards understanding the “bare” vs. “dressed” approach for resonance couplings)

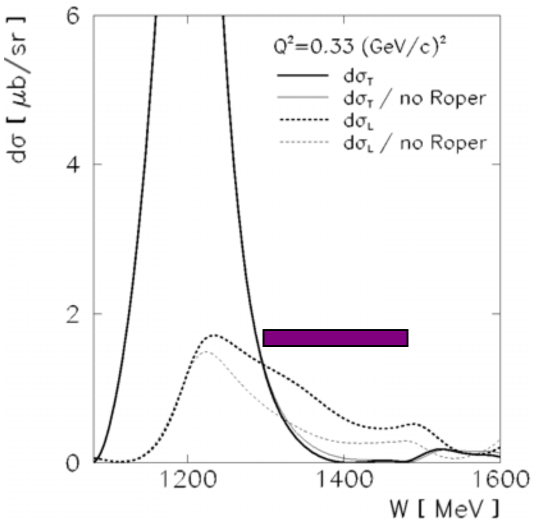


Normal component of induced pol

STRATEGY OF CURRENT PROPOSAL
to provide critical insight into Roper excitation

- Focus on **specific** recoil-polarization components that exhibit **strong sensitivity** to Roper resonance multipoles.
- Because of: low rates (~10 times lower than in Δ) and theoretical uncertainty where (Q^2) transverse excitation crosses zero:
  - measure at one-angle (**anti-parallel kinematics**) per (W, Q^2)
  - Span Q^2 (resolve above uncertainty)
  - Span W across resonance (to understand off-pole W behaviour – proved important in Δ studies)



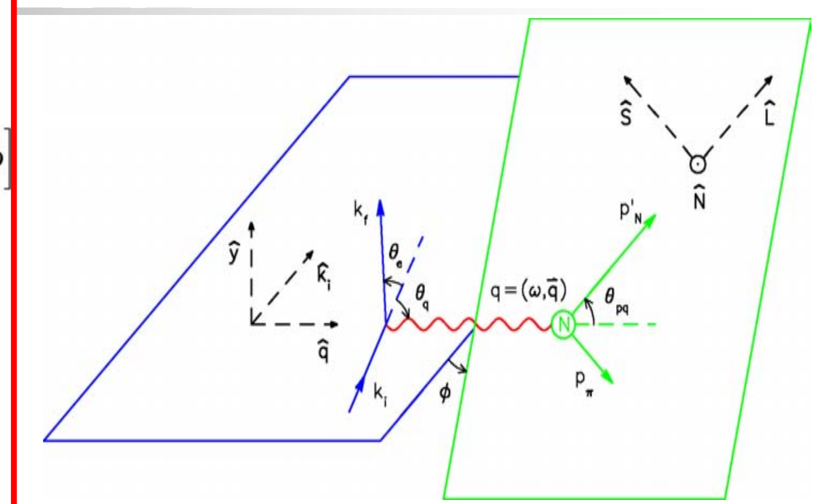


Formalism for p($\vec{e}$,e′ $\vec{p}$)π^0 Reaction

$$\frac{d^5\sigma}{d\varepsilon_f d\Omega_e d\Omega_{cm}} = \frac{p_{cm}}{k_{\gamma cm}}\Gamma_\gamma\, \bar{\sigma}_0 \left[1 + hA + \boldsymbol{S}\cdot(\boldsymbol{P} + h\boldsymbol{P}')\right]$$

$$\begin{aligned}
\bar{\sigma}_0 &= \nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT} \cos\phi + \nu_{TT} R_{TT} \cos 2\phi \\
A\bar{\sigma}_0 &= \nu'_{LT} R'_{LT} \sin\phi \\
P_N\bar{\sigma}_0 &= \left[\nu_L R_L^N + \nu_T R_T^N + \nu_{LT} R_{LT}^N \cos\phi + \nu_{TT} R_{TT}^N \cos 2\phi\right] \\
P_m\bar{\sigma}_0 &= \left[\nu_{LT} R_{LT}^m \sin\phi + \nu_{TT} R_{TT}^m \sin 2\phi\right] \qquad (m \in \{L,S\}) \\
P'_N\bar{\sigma}_0 &= \nu'_{LT} R'^N_{LT} \sin\phi \\
P'_m\bar{\sigma}_0 &= \left[\nu'_{LT} R'^m_{LT} \cos\phi + \nu'_{TT} R'^m_{TT}\right] \qquad (m \in \{L,S\})
\end{aligned}$$

handle	real type	imaginary type
left/right	R_{LT}, $R'^{L,S}_{LT}$, $R'^{L,S}_{TT}$	R^N_{LT}
OOP	R_{TT}, R'^N_{LT}, R^N_{TT}	R'_{LT}, $R^{L,S}_{LT}$, $R^{L,S}_{TT}$
Rosenbluth	R_L, R_T	R^N_L, R^N_T



- left/right asymmetry (in plane) offers 1 unpolarized and 5 polarized response functions
- OOP acceptance would give additional 7 polarized, 1 unpolarized response functions

Formalism for $p(\vec{e},e'\,\vec{p})\pi^0$ Reaction:

Polarizations in Anti-Parallel Kinematics ($\theta_{\pi q}^{cms} = 180°$)

Large simplification in this configuration

- Only 3 pol. Components survive:
  - 2 comp's of helicity-dependent (transferred) pol **[t', l']**
  - 1 comp of helicity-independent (induced) pol **[n]**
- Notation note…here, 2 transverse directions (t,n) arbitrary, so choose:
  - "x" transverse direction // to spectrometer B-field
  - "z" direction // p-momentum ("y" = other transverse "normal")

$$\sigma_0 (P'_x / P_e) = -\sqrt{2\varepsilon_L^*(1-\varepsilon)}\, R_{LT'}^{t} ,$$

$$\sigma_0 P_y = -\sqrt{2\varepsilon_L^*(1+\varepsilon)}\, R_{LT}^{n} ,$$

$$\sigma_0 (P'_z / P_e) = \sqrt{1-\varepsilon^2}\, R_{TT'}^{l} .$$

Polarizations in Anti-Parallel Kinematics:
Multipole Decomposition → Sensitivity to Roper

- The **2 transverse components** measure the Real and Imaginary parts of the same multipole combinations:

Large, dominant term

$$
\begin{aligned}
P'_x \sim R^{t}_{LT'} &= \mathrm{Re}\{ L^*_{0+} E_{0+} \\
&\quad + (L^*_{0+} - 4L^*_{1+} - L^*_{1-}) M_{1-} \\
&\quad + L^*_{1-} (M_{1+} - E_{0+} + 3E_{1+}) \\
&\quad - L^*_{0+} (3E_{1+} + M_{1+}) + L^*_{1+} (4M_{1+} - E_{0+}) + 12 L^*_{1+} E_{1+} \,, \\
P_y \sim R^{n}_{LT} &= -\mathrm{Im}\{ \cdots \} \,.
\end{aligned}
$$

Large, sensitive to Roper excitation (show plots later) – strong W,Q^2 dep

(MAID2003: other terms small or cancel)

- No simplification from "M_{1+} dominance" (or similar) like in Δ(1232) region
- Another Notation note…Scalar (S) and Longitudinal (L) multipoles are simply related through: $L \equiv (\omega/q)S$

Polarizations in Anti-Parallel Kinematics: Multipole Decomposition → Sensitivity to Roper

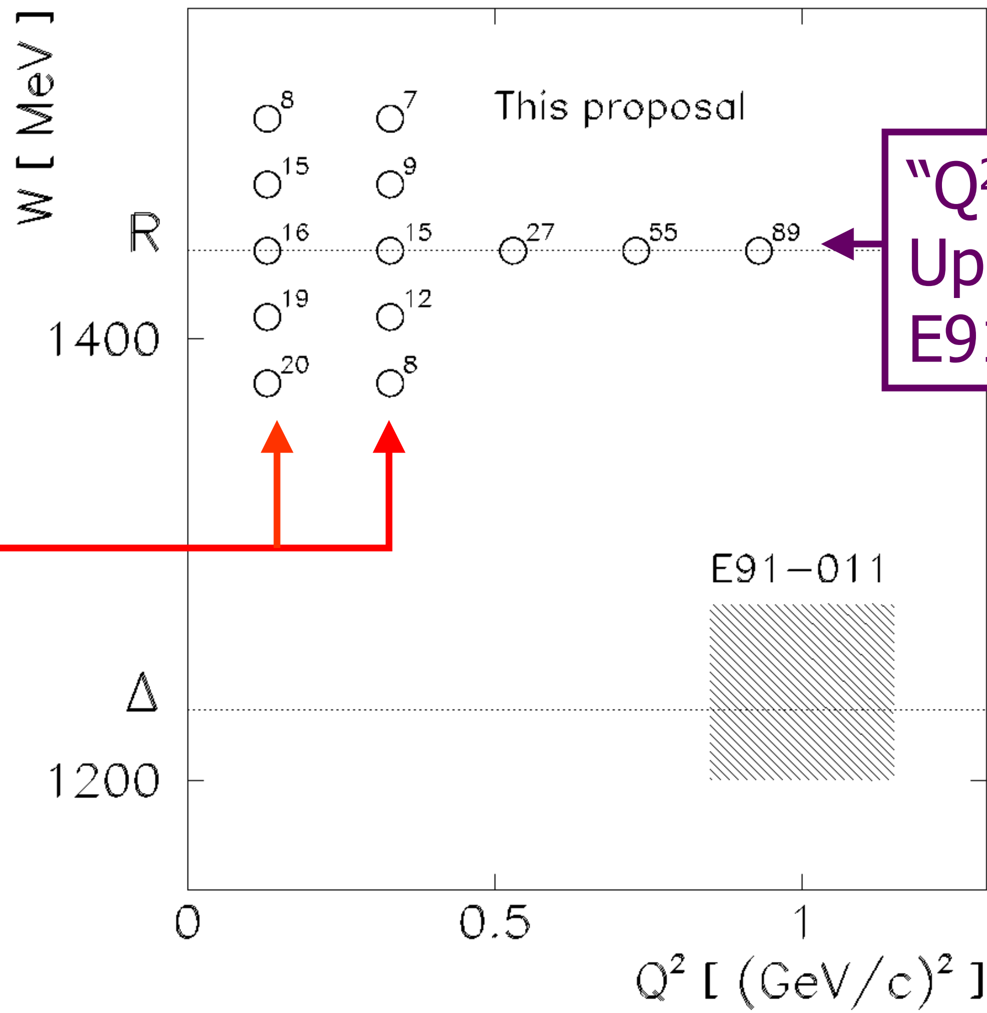
- The **longitudinal component** is less sensitive to the Roper-excitation multipoles:

$$
\begin{aligned}
P'_z \sim R^{l}_{\mathrm{TT}'} \quad = \quad & \mathrm{Re}\{ E^*_{0+}(3E_{1+} + M_{1+} + 2M_{1-}) \} \\
& + |E_{0+}|^2 + 9\,|E_{1+}|^2 + |M_{1+}|^2 + |M_{1-}|^2 \\
& - 6\,\mathrm{Re}E^*_{1+}M_{1+} - 2\,\mathrm{Re}M^*_{1+}M_{1-} - 3\,\mathrm{Re}E^*_{0+}(3E_{1+} + M_{1+})
\end{aligned}
$$

- Dominated by M_{1+} and E_{0+} multipoles
- Serves as benchmark/calibration for any model comparison: all 3 components must be reproduced

Proposed Measurements:

3 comp's of recoil-pol in anti-// kinematics

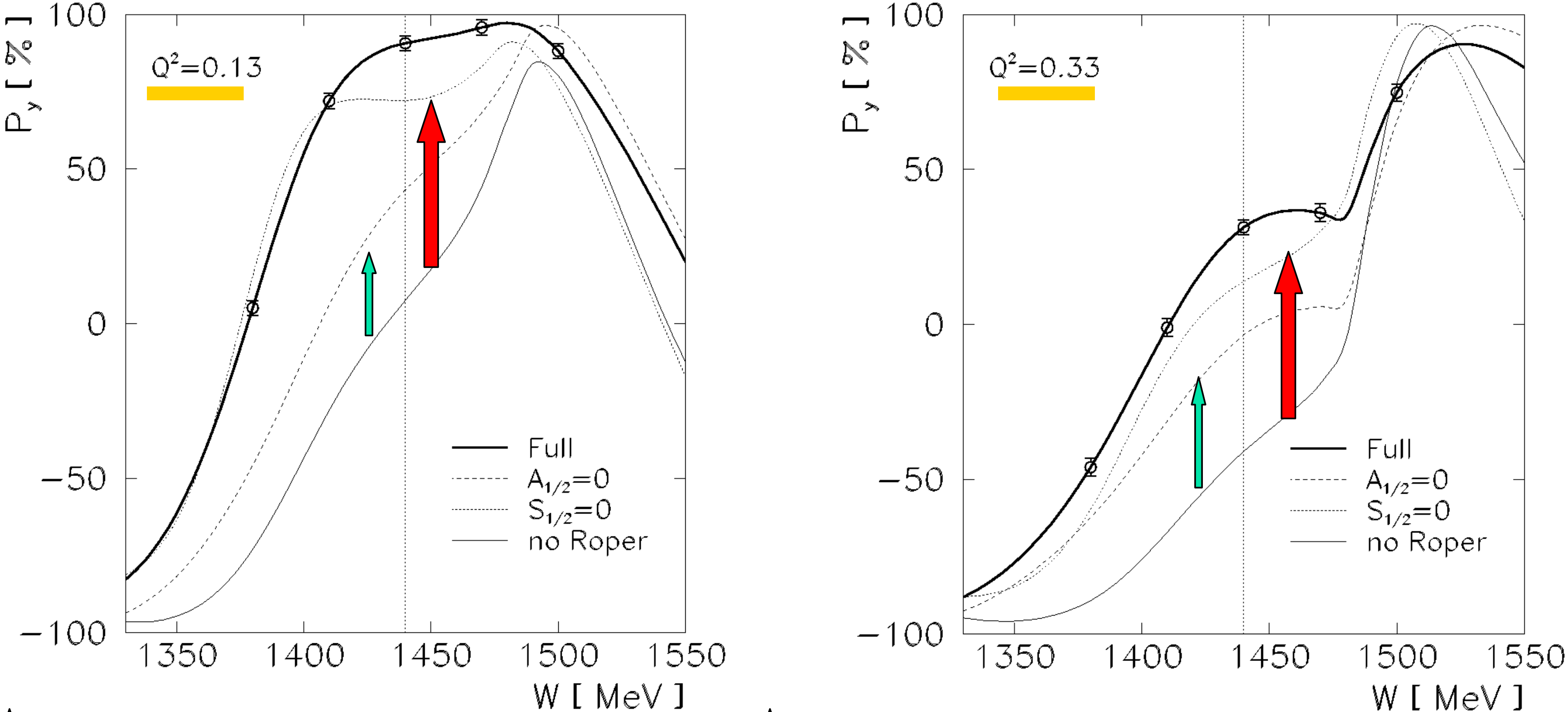


"Q²-scan": Up to overlap E91011

"W-scans" at low Q²: large predicted pol & sensitivity to Roper

Sensitivity to Roper Excitation: "W-scan" kinematics (P_y)

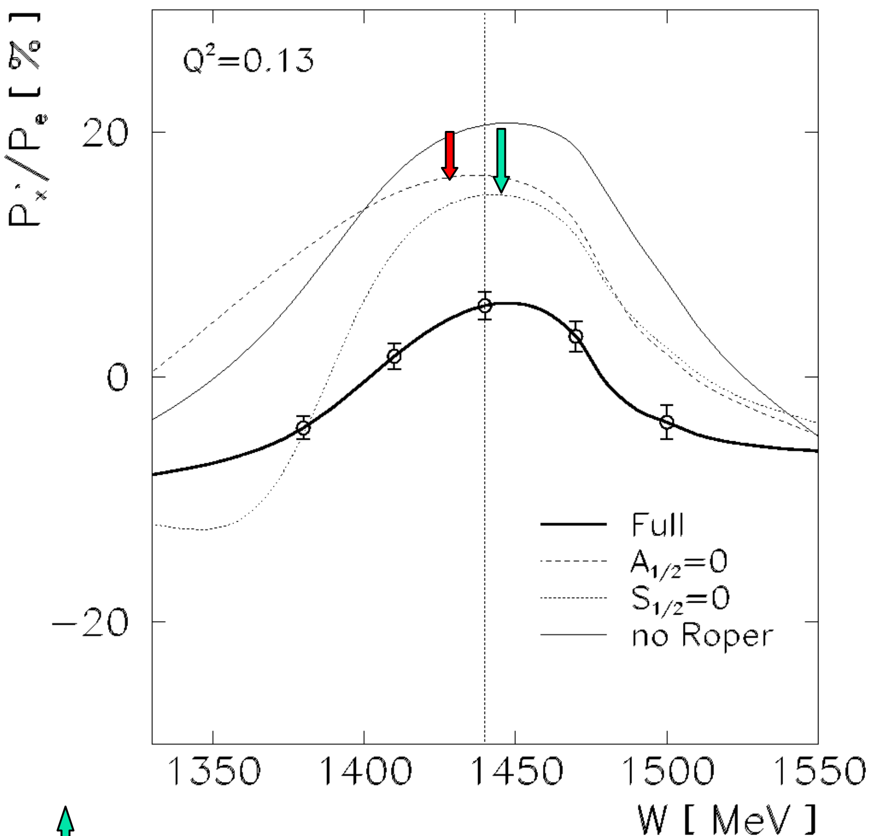
Theory = MAID2003 **"Data" = our projected uncertainties**

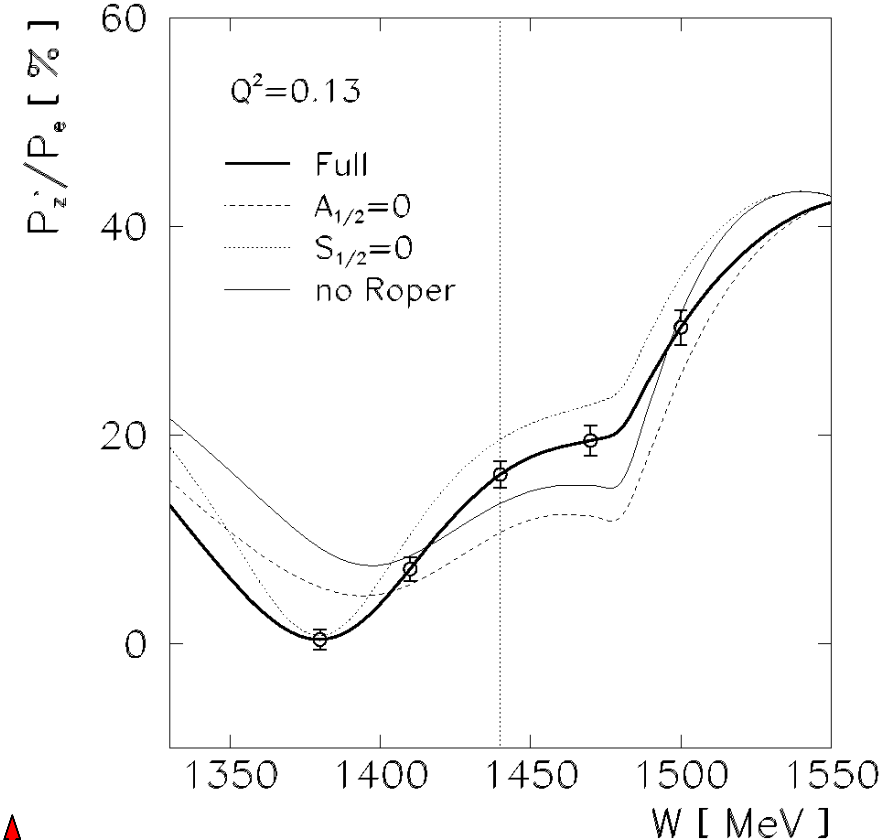


Scalar Roper Excitation only **Transverse Roper Excitation only**

Sensitivity to Roper Excitation: "W-scan" kinematics (P'_x , P'_z)

Theory = MAID2003 **"Data" = our projected uncertainties**

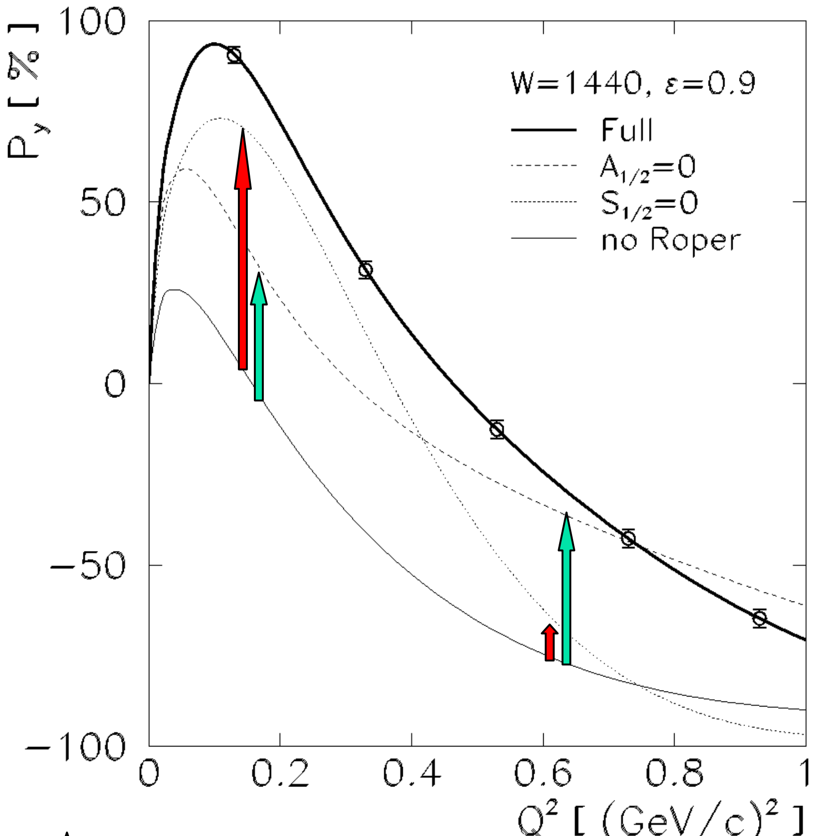


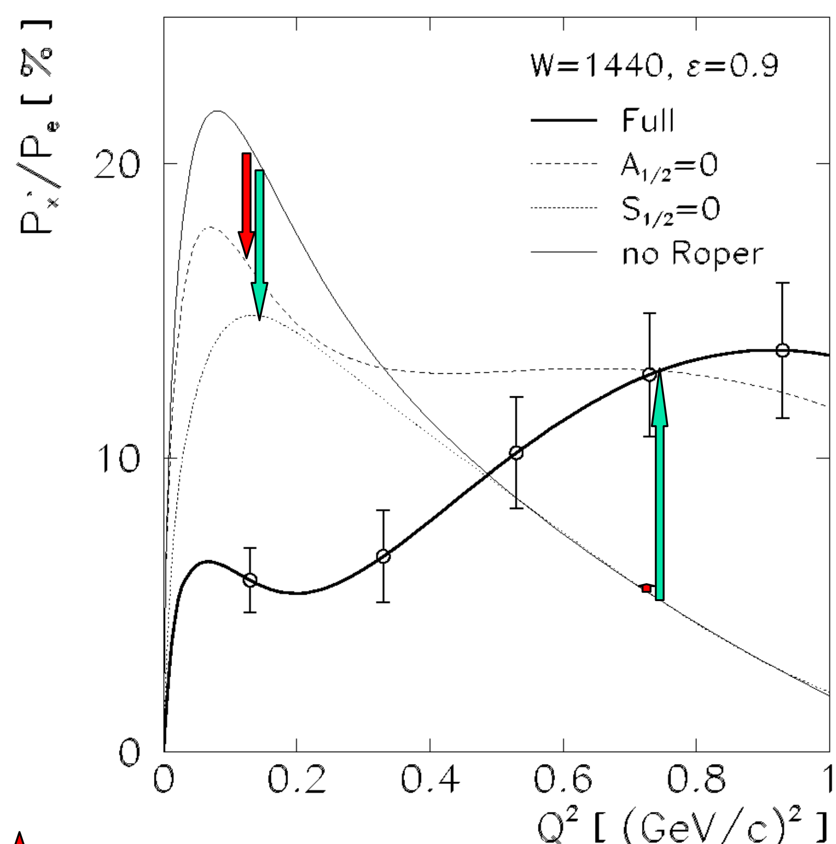


Scalar Roper Excitation only **Transverse Roper Excitation only**

Sensitivity to Roper Excitation: "Q^2-scan" kinematics (P_y , P'_x)

Theory = MAID2003 **"Data" = our projected uncertainties**





Scalar Roper Excitation only

Transverse Roper Excitation only

Equipment Requirements in Hall A … all standard currently

- 2 HRS spectrometers
- Focal Plane Polarimeter (FPP) on 1 HRS
- 15 cm LH2 target
- 75 μA beam, 75% polarization (monitored by Compton Polarimeter)
- E_{beam} = 2 GeV, 3 GeV
- All exactly as was used in 2000 for E91011

Kinematics & Rate Table (Rates using MAID2003)

E_e [MeV]	Q^2 [(GeV/c)^2]	W [MeV]	θ_e [°]	θ_p [°]	—— Singles —— (e) [kHz]	(p) [kHz]	(π^+) [kHz]	Accid. (ep) [Hz]	Trues (ep) [Hz]
2000	0.13	1440	12.9	21.3	398	117	223	10	17
3000	0.33	1440	12.9	29.4	380	79	86	2.3	12
3000	0.53	1440	16.8	30.8	115	41	34	0.37	5
3000	0.73	1440	20.2	30.8	46	23	16	0.09	2
3000	0.93	1440	23.5	30.1	21	14	9	0.03	1
2000	0.13	1380	12.4	24.7	411	119	221	11	20
2000	0.13	1410	12.6	23.0	382	118	221	10	17
2000	0.13	1440	12.9	21.3	398	117	223	10	17
2000	0.13	1470	13.1	19.8	457	115	223	12	16
2000	0.13	1500	13.4	18.5	451	111	219	12	25
3000	0.33	1380	12.6	32.7	335	79	82	2	18
3000	0.33	1410	12.7	31.0	348	79	84	2	13
3000	0.33	1440	12.9	29.4	380	79	86	2	12
3000	0.33	1470	13.0	27.8	423	80	90	3	13
3000	0.33	1500	13.2	26.4	411	79	92	3	16

30 MeV bins in W

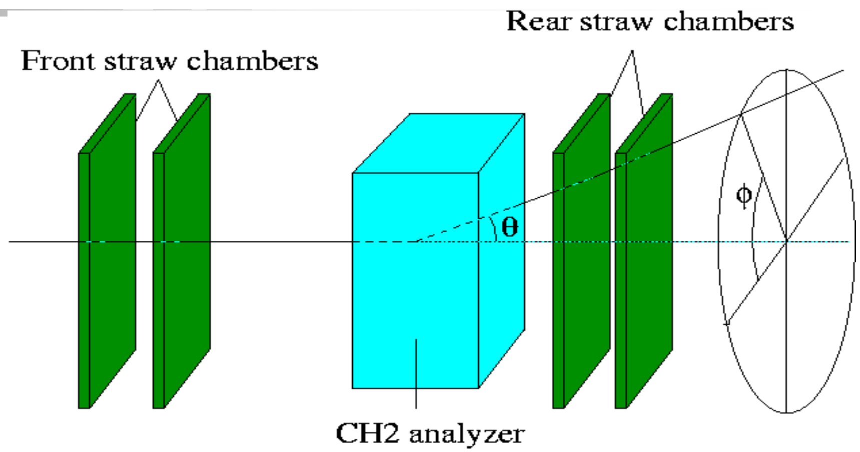
Within 10° of anti-parallel

Required beam time dictated by FPP analysis…

Focal-Plane Polarimeter

$$\mathrm{Prob}(\varphi) = \frac{1}{2\pi}(1 + \varepsilon_x \sin\varphi_{fpp} + \varepsilon_y \cos\varphi_{fpp})$$

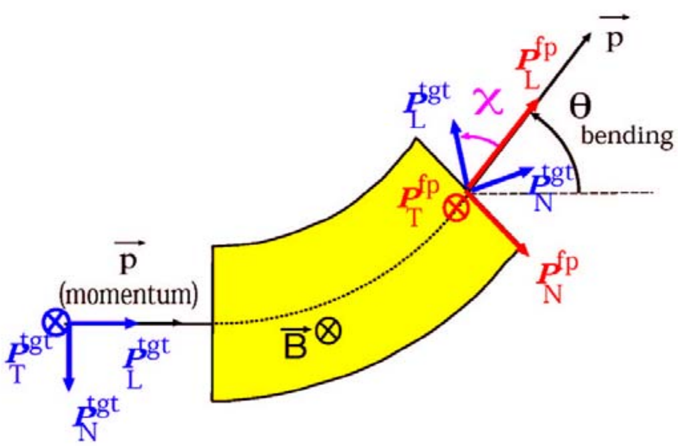
$$\varepsilon_\alpha = \xi_\alpha + A(\theta_{fpp}) \sum_\beta S_{\alpha\beta}(P_\beta + hP'_\beta)$$



- Helicity-dependent polarization from helicity difference, cancels false asymmetry
- Helicity-independent polarization must be corrected for instrumental asymmetry
- Measure 2+2 components at FPP, but obtain 3+3 components at target from variation of spin transport

Spin Precession

$$\begin{pmatrix} P_n \\ P_t \\ P_l \end{pmatrix}_{\text{fp}} = \begin{pmatrix} S_{nn} & S_{nt} & S_{nl} \\ S_{tn} & S_{tt} & S_{tl} \\ S_{ln} & S_{lt} & S_{ll} \end{pmatrix} \begin{pmatrix} P_n \\ P_t \\ P_l \end{pmatrix}_{\text{tgt}}$$



Simple dipole: Precession angle $\chi = \gamma \kappa_p \theta_{bending}$

$S_{tt} = 1 \quad S_{tn} = S_{tl} = S_{nt} = 0$

$S_{nl} = -\sin\chi \qquad S_{nn} = \cos\chi$

$P_t^{fp} = P_t^{tgt}$ and $P_n^{fp} = -P_l^{tgt}\sin(\chi) + P_n^{tgt}\cos(\chi)$

FPP Parameters & Projecting Polarization Uncertainties

$$f = \int_{\vartheta_{min}}^{\vartheta_{max}} \epsilon(\vartheta) A_y^2(\vartheta) d\vartheta$$

$$\Delta P_x^{fp} = \Delta P_y^{fp} = \sqrt{\frac{2}{N_0 f}}$$

$$\Delta P_x' = \frac{1}{P_e}\sqrt{\frac{2}{N_0 f}}$$

$$\Delta P_y = \frac{1}{\cos\chi}\sqrt{\frac{2}{N_0 f}}$$

$$\Delta P_z' = \frac{1}{P_e}\frac{1}{\sin\chi}\sqrt{\frac{2}{N_0 f}}$$

E_e [MeV]	Q^2 [(GeV/c)^2]	W [MeV]	χ [°]	f
2000	0.13	1440	118.7	0.0166
3000	0.33	1440	130.0	0.0125
3000	0.53	1440	140.7	0.0112
3000	0.73	1440	151.0	0.0102
3000	0.93	1440	161.1	0.0100
2000	0.13	1380	112.5	0.0166
2000	0.13	1410	115.5	0.0166
2000	0.13	1440	118.7	0.0166
2000	0.13	1470	121.9	0.0150
2000	0.13	1500	125.3	0.0150
3000	0.33	1380	123.7	0.0150
3000	0.33	1410	126.8	0.0125
3000	0.33	1440	130.0	0.0125
3000	0.33	1470	133.2	0.0125
3000	0.33	1500	136.6	0.0120

Time Request Summary

E_e	Q^2	W	(e, e′p)	$\Delta(P'_x/P_e)$	ΔP_y	$\Delta(P'_z/P_e)$	Beam time [h]
2000	0.13	1440	17	0.0110	0.0229	0.0126	16
3000	0.33	1440	12	0.0156	0.0243	0.0204	15
3000	0.53	1440	5	0.0189	0.0245	0.0298	27
3000	0.73	1440	2	0.0210	0.0240	0.0432	55
3000	0.93	1440	1	0.0230	0.0243	0.0710	89
2000	0.13	1380	20	0.0091	0.0237	0.0098	20
2000	0.13	1410	17	0.0103	0.0239	0.0114	19
2000	0.13	1440	17	0.0110	0.0229	0.0126	–
2000	0.13	1470	16	0.0125	0.0236	0.0147	15
2000	0.13	1500	25	0.0137	0.0237	0.0168	8
3000	0.33	1380	18	0.0161	0.0291	0.0194	8
3000	0.33	1410	13	0.0171	0.0286	0.0214	12
3000	0.33	1440	12	0.0156	0.0243	0.0204	–
3000	0.33	1470	13	0.0198	0.0289	0.0271	9
3000	0.33	1500	16	0.0206	0.0284	0.0301	7
		FPP calibration					24
		2×Møller					16
		2×Beam energy					8
		Total					348

14.5 days

Few last comments:

- Systematic Uncertainties on Extracted Polarizations:
  - **~ 3%**
  - dominated by COSY spectrometer model of spin-transport

- "Double-FPP" option:
  - Recent RCS experiment E99-114 inserted extra CH_2 material between HRS VDC's and the first FPP straw chambers
  - This option may serve to improve our FPP figure-of-merit

Summary:

- **14.5 days is requested**
- Using standard Hall A equipment and 2 GeV & 3 GeV polarized beam.
- Recoil Polarization will be measured in anti-parallel kinematics in $p(\vec{e},e' \vec{p})\pi^0$
- Focus on Roper Resonance excitation, spanning range in (W, Q^2)
- **Will provide unparalleled sensitivity to Roper resonance transition amplitudes, providing critical insight into this (still) intriguing state.**