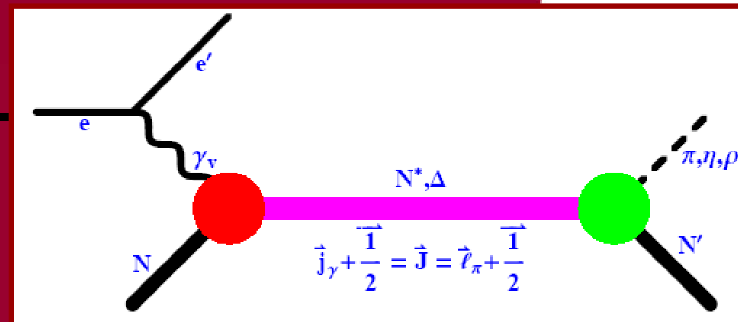
Measurement of the Coulomb quadrupole amplitude in the $\gamma^{*}p \rightarrow \Delta(1232)$ reaction in the low momentum transfer region (E08-010)



Adam J. Sarty

Saint Mary's University

representing

David Anez (SMU & Dalhousie U., PhD student)

Doug Higinbotham (Jefferson Lab)

Shalev Gilad (MIT)

Nikos Sparveris (spokesperson Emeritus!)

Experiment proposal spear-headed by Nikos 2 years ago … he has handed it over for us to complete!

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E08-010:
A short/little few-day "N $\rightarrow \Delta$" Experiment!

- Currently Scheduled to Run for 6 days:
  - April 3-8, 2011
  - "squeezed" in between and "SRC" (E07-006) and "x>2" (E08-014) experiments.
- The focus on low Q^2 allows the high rates / short run
- Personnel from this experiment will clearly be linked into the other two experiments.
- Let me now overview the physics goals of the experiment, and give a few of the particulars. (Start with a general review …)

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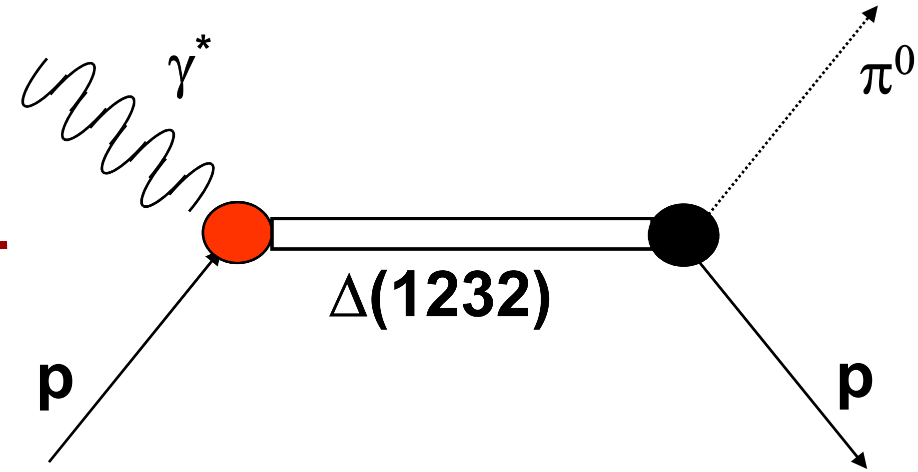
Where/How the Physics comes in:



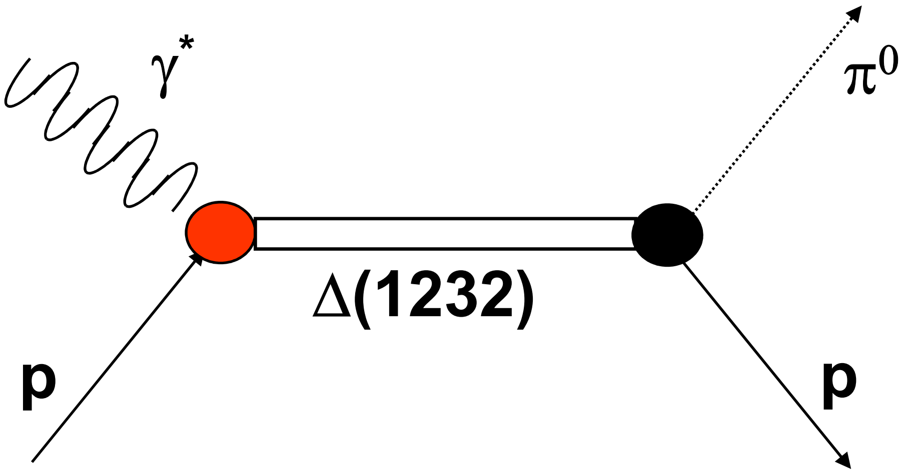
γ^* : **EM Multipolarity of transition**
(Electric, Magnetic, Scalar)
(Dipole, Quadrupole, etc.)

Vertex #1 : Nucleon Structure <u>model</u> enters here: $\gamma^* + p \rightarrow \Delta$
(CQM or "pion cloud" Bag Model, etc.)

Vertex #2 : $\Delta(1232)$ <u>Model</u> for decay
PLUS $\pi^0 p$ reaction Dynamics

$L_{\pi p}$ value for nomenclature of transition amplitude determined here.

Where/How the Physics comes in:



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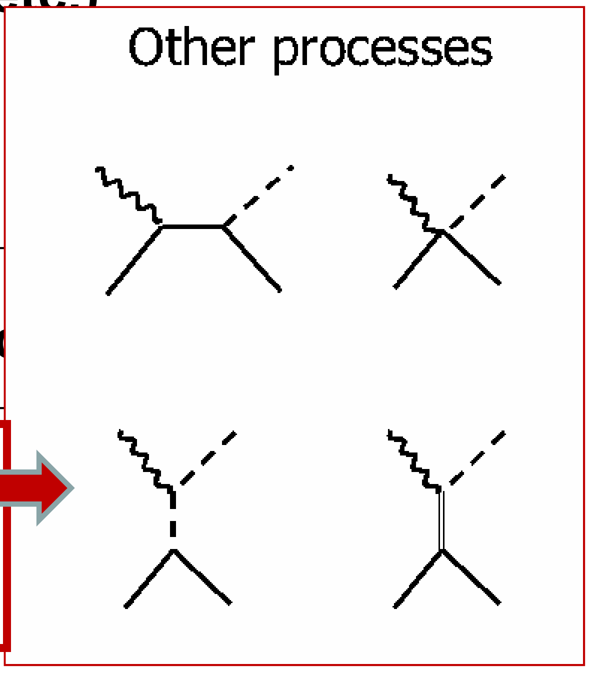
$L_{\pi p}$ value for nomenclature of transition amplitude determined

NOTE: any full model for the reaction has to deal with separating the desired Resonant excitation from "Other Processes")



Understanding the Nomenclature: #1 – the incident photon

What "kind" (MULTIPOLE) of Photon can Excite $p \rightarrow \Delta$?

$$\gamma^* + p \rightarrow \Delta(1232)$$

$$(L_\gamma^\pi \otimes \tfrac{1}{2}^+ = 3/2^+)$$

- Conserve Parity: Final π is +, so …

  $\pi_{initial} = (\pi_\gamma)(\pi_{proton}) = (\pi_\gamma)(+) = +$

- So photon's parity is Even.

- Recalling Parity of EM Multipoles:
  - Electric: $EL = (-1)^L$
  - Magnetic: $ML = (-1)^{L+1}$
  - Scalar (or Coulomb): $CL = (-1)^L$

- So…

  $L_\gamma^\pi = 1^+ \Leftrightarrow$ M1 (magnetic dipole)

  OR

  $L_\gamma^\pi = 2^+ \Leftrightarrow$ E2, C2 (quadrupole)

Understanding the Nomenclature: #2 – the Nπ final state

Ensuring the intermediate state was (or could be!) resonance of interest - we're interested here in the Δ(1232)

$$\Delta(1232) \rightarrow p + \pi^0$$

$$J^\pi = 3/2^+ \rightarrow [\ (\tfrac{1}{2}^+ \otimes 0^-)_S \otimes \ell\ ]$$

$$S^\pi = \tfrac{1}{2}^+$$

So, Constraints on ℓ :

(the relative angular momentum of the $p\pi^0$ pair in Final State)

1. Can have: $\ell + \tfrac{1}{2} = 3/2$ (i.e. $\ell = 1$)
   or $\ell - \tfrac{1}{2} = 3/2$ (i.e. $\ell = 2$)
2. MUST conserve Parity: final $\pi = +$

$$\pi_{final} = (\pi_\pi)(\pi_{proton})\,(-1)^\ell = (+)(-)\,(-1)^\ell$$

$$+ = (-1)^{\ell+1} \quad \ldots \text{ so: } \ell = \text{ODD}$$

$$\therefore \ell = 1$$

Understanding the Nomenclature: #3 – The final labeling

Joining the Photon and Nπ angular momentum constraints

(focusing still on Δ(1232) resonance)

- The full Multipole label for a specific γ^***N** $\rightarrow$ π**N** transition amplitude carries information about the constraints on the initial virtual-photon & final pion-nucleon angular momentum …

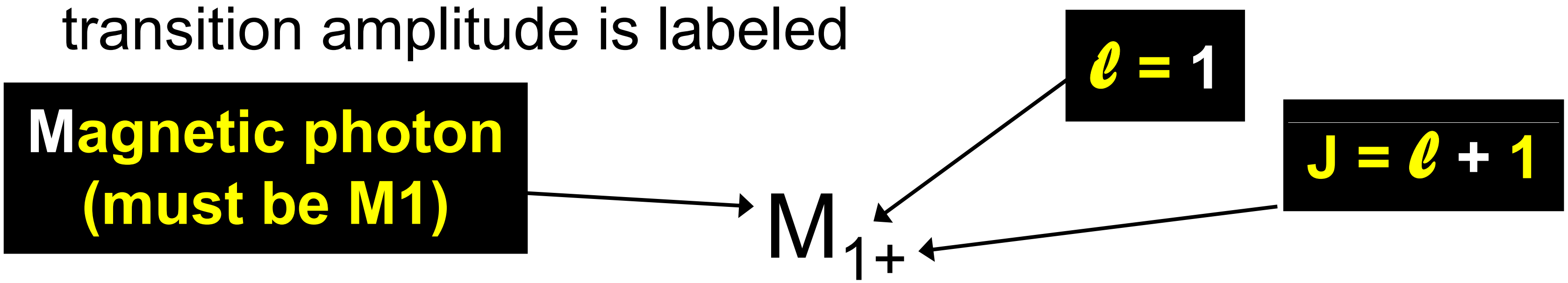
Understanding the Nomenclature: #3 – The final labeling

Joining the Photon and Nπ angular momentum constraints (focusing still on Δ(1232) resonance)

- The full Multipole label for a specific γ^***N** $\rightarrow$ π**N** transition amplitude carries information about the constraints on the initial virtual-photon & final pion-nucleon angular momentum

  …

  Example: The dominant "Spherical" (single-quark spin-flip) transition amplitude is labeled



Understanding the Nomenclature: #3 – The final labeling

Joining the Photon and Nπ angular momentum constraints (focusing still on Δ(1232) resonance)

- The full Multipole label for a specific $\gamma^* \mathbf{N} \to \pi \mathbf{N}$ transition amplitude carries information about the constraints on the initial virtual-photon & final pion-nucleon angular momentum …

Example: The dominant "Spherical" (single-quark spin-flip) transition amplitude is labeled

Magnetic photon (must be M1)

ℓ = 1

J = ℓ + 1

$$M_{1+}$$

and the smaller "Deformed" (quadrupole) transitions;

$$E_{1+} \text{ and } S_{1+}$$

(with E meaning "electric" and S "scalar" photon)

The "S" can also be written "L" ("longitudinal") – related by a kinematic factor to amplitudes written with "S"

Goal of these kind of "N $\rightarrow \Delta$" Experiments:
Quantify "non-spherical" Components of Nucleon wf

Talking with a CQM view of a nucleon wave-function:

- Dominant M_{1+} is a "spin-flip" transition;
  N and Δ both "spherical"…L=0 between 3 quarks
- BUT, the Quadrupole transitions (E_{1+} , S_{1+}) "sample" the "not L=0" parts of the wavefunctions.
- Consider writing wavefunctions like so:

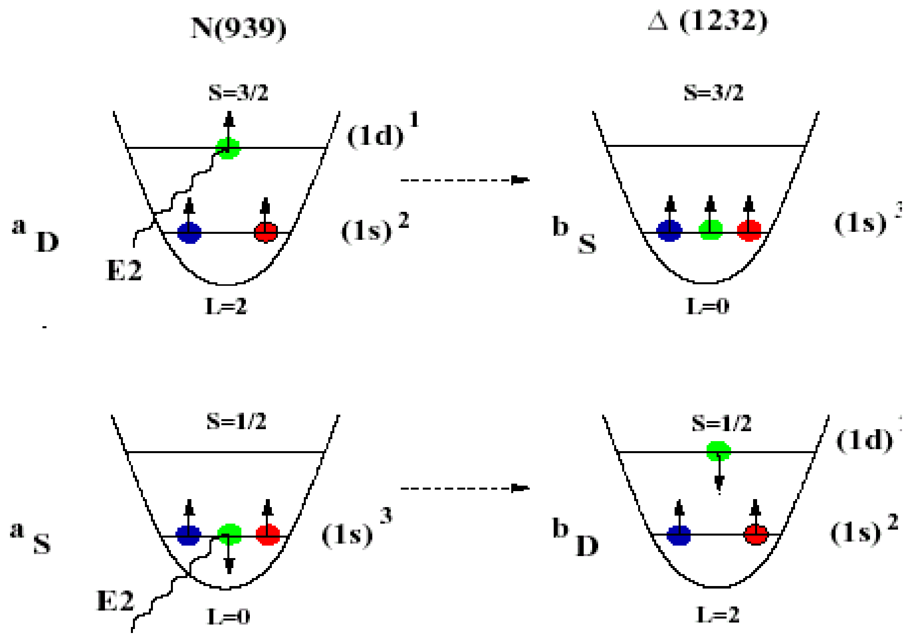
$$\left|N(939)\right\rangle = a_S\left|\left(S=\tfrac{1}{2}, L=0\right)J^\pi = \tfrac{1}{2}^+\right\rangle + a_D\left|\left(S=\tfrac{3}{2}, L=2\right)J^\pi = \tfrac{1}{2}^+\right\rangle$$
$$\left|\Delta(1232)\right\rangle = b_S\left|\left(S=\tfrac{3}{2}, L=0\right)J^\pi = \tfrac{3}{2}^+\right\rangle + b_D\left|\left(S=\tfrac{1}{2}, L=2\right)J^\pi = \tfrac{3}{2}^+\right\rangle$$

then,

we can view the quadrupole tx as…

Goal of these kind of "N $\rightarrow \Delta$" Experiments:
Quantify "non-spherical" Components of Nucleon wf

- These Quadrupole transitions thus give insight into small L=2 part of wf.



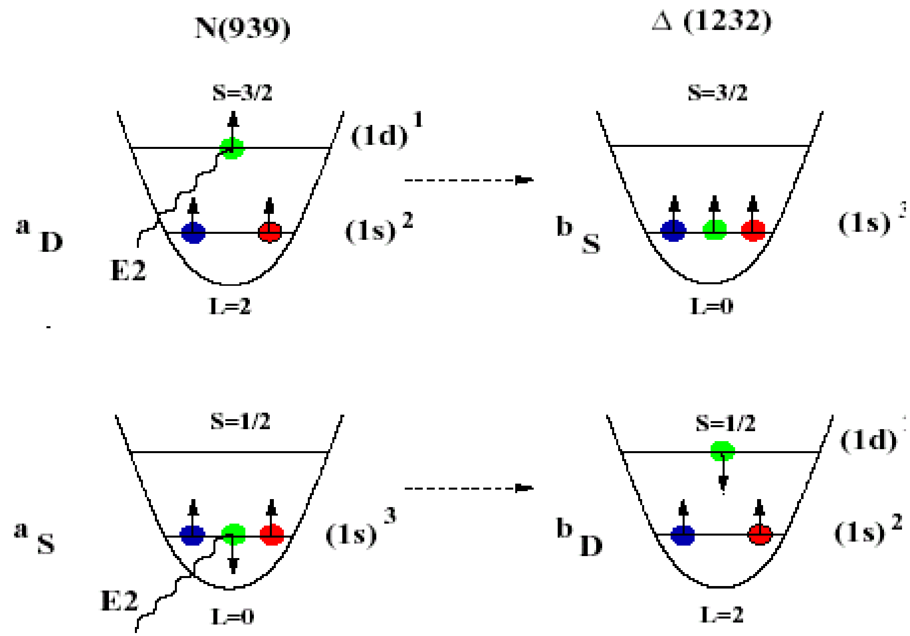
Phys. Rev. **C63**, 63 (2000)

Goal of these kind of "N → Δ" Experiments:
Quantify "non-spherical" Components of Nucleon wf

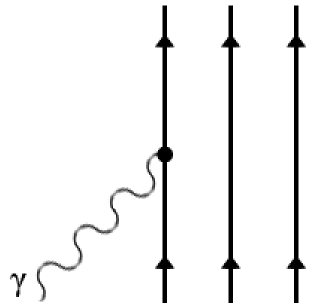
- These Quadrupole transitions thus give insight into small L=2 part of wf.
- Such L=2 parts arise from "colour hyperfine interactions" between quarks

  IF

  the assumption is a "one-body interaction":



Phys. Rev. **C63**, 63 (2000)

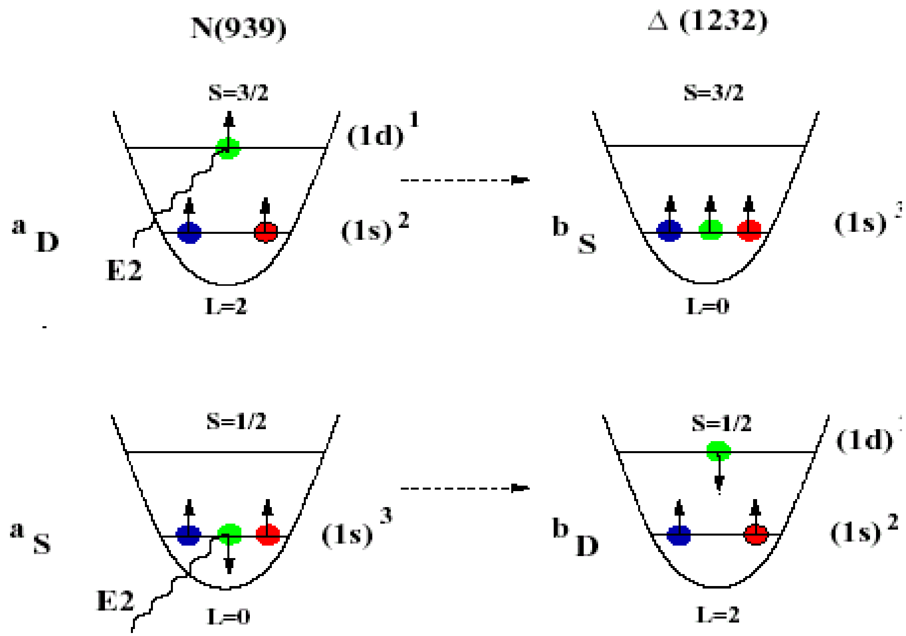


$$\hat{Q}_{[1]} = \sqrt{\frac{16\pi}{5}\sum_{i=1}^{3} e_i r_i^2 Y_0^2(\vec{r}_i)} = \sum_i e_i\left(3z_i^2 - r_i^2\right)$$

Goal of these kind of "N → Δ" Experiments:
Quantify "non-spherical" Components of Nucleon wf

- These Quadrupole transitions thus give insight into small L=2 part of wf.
- **BUT** L=2 transitions can also arise via interactions with virtual exchanged pions (the "pion cloud"):

$$\hat{Q}_{[2]} = B \sum_{i \neq j = 1}^{3} e_i \left(3\sigma_{iz}\sigma_{jz} - \vec{\sigma}_i \cdot \vec{\sigma}_j \right)$$



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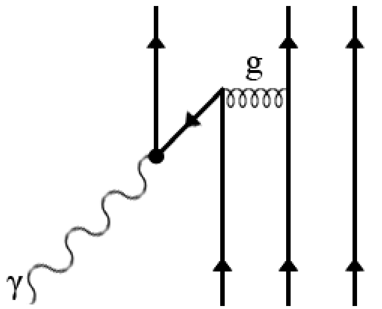

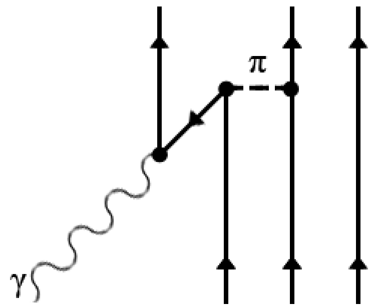

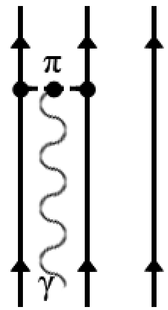

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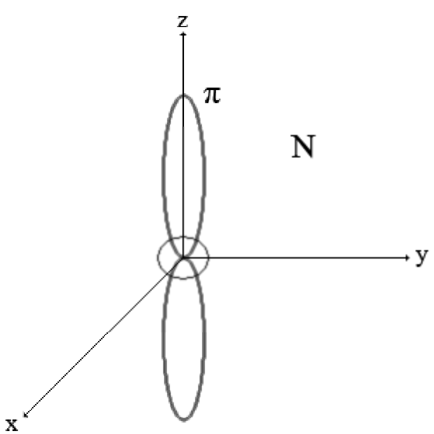
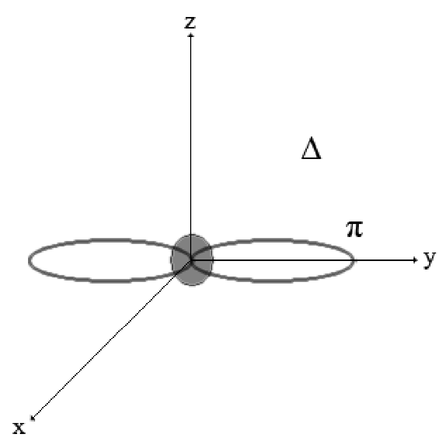
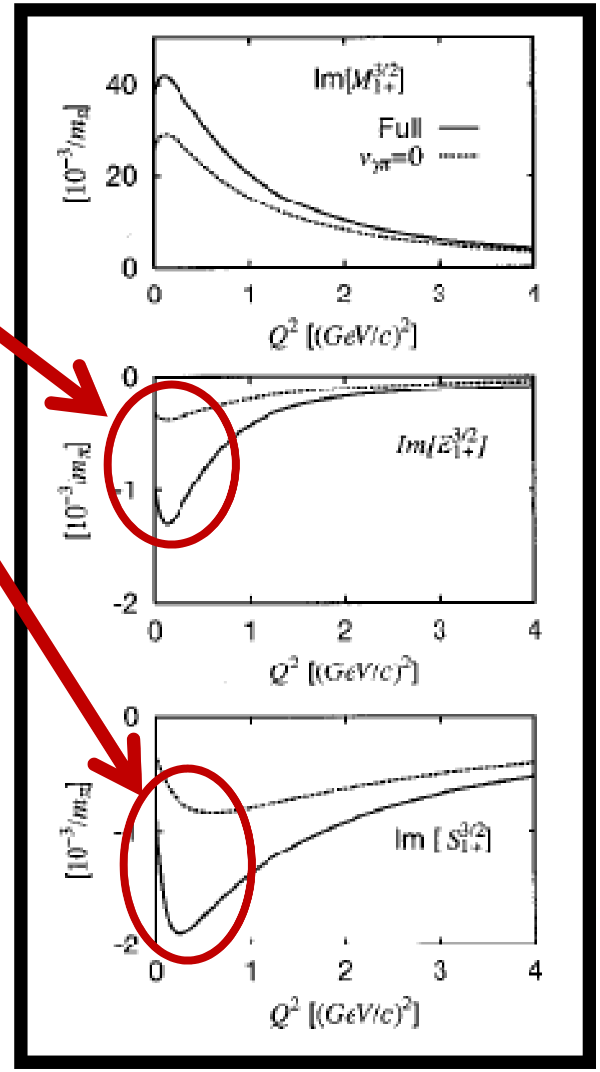
Goal of THIS "N $\rightarrow \Delta$" Experiment:
FOCUS ON LOW Q^2 WHERE PION CLOUD DOMINATES

- At low momentum transfer: the Pion Cloud dominates the "structure" of wavefunctions
- These pion dynamics dictate the long-range non-spherical structure of the nucleon … and that is where we focus.

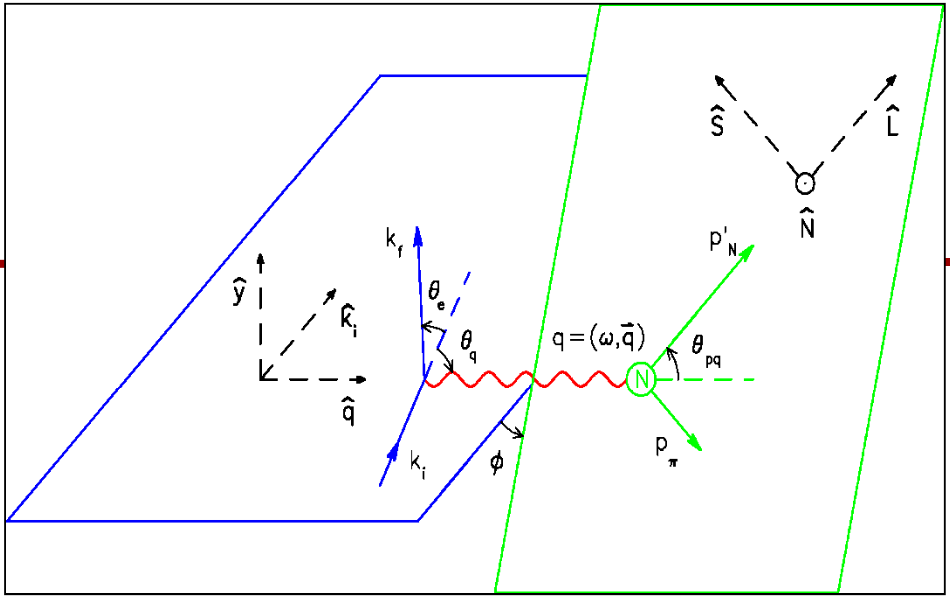






NOW: to p($\vec{e}$, e' $\vec{p}$)π^0 Measurements

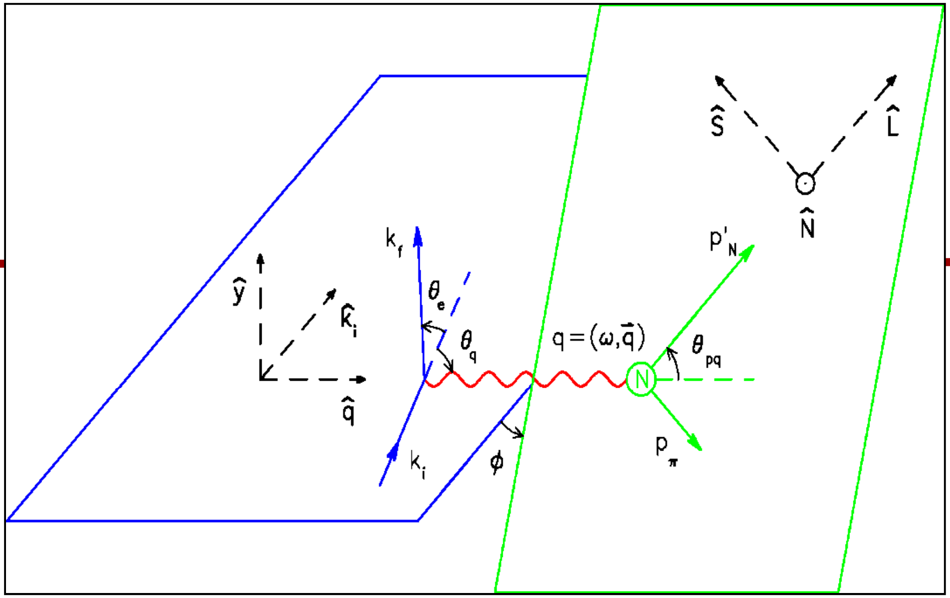
18 Response Functions:
Each with their own Unique/Independent combination of contributing Multipole transition amplitudes



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

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

NOW: to $p(\vec{e}, e'\vec{p})\pi^0$ Measurements



18 Response Functions:
Each with their own Unique/Independent combination of contributing Multipole transition amplitudes

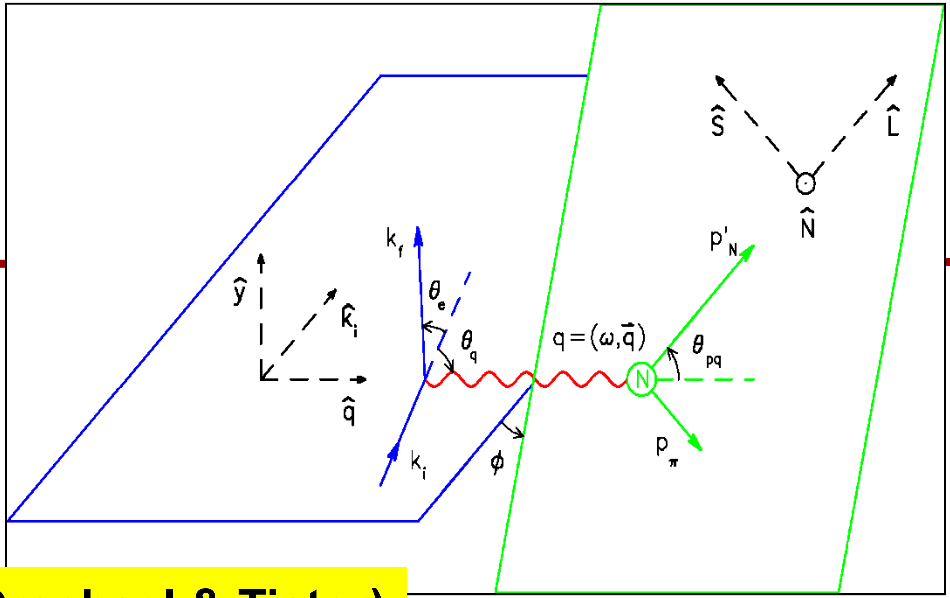
$$\frac{d^5\sigma}{d\varepsilon_f d\Omega_e d\Omega_{cm}} = \frac{p_{cm}}{k_{\gamma cm}}\Gamma_\gamma\, \bar{\sigma}_0 \left[1 + hA + \boldsymbol{S}\cdot(\boldsymbol{P} + h\boldsymbol{P}')\right]$$

$$\bar{\sigma}_0 = \nu_L R_L + \nu_T R_T + \nu_{LT} R_{LT}\cos\phi + \nu_{TT} R_{TT}\cos 2\phi$$

- No polarization required for these Responses (R's)
- L and T via cross-sections at fixed (W,Q^2) but different ν's ("Rosenbluth")
- LT and TT via cross-sections at different Out-Of-Plane angles ϕ

- **We will extract just R_{LT} (by left/right measurements) – and σ_0 – since LT term is very sensitive to size of L_{1+} (see next slide…)**

NOW: to p($\vec{e}$, e’ $\vec{p}$)π^0 Measurements



18 Response Functions:
Each with their own Unique/Independent combination of contributing Multipole transition amplitudes

For Example: decomp of 5 R’s (Drechsel & Tiator)

$$R_L = |L_{0+}|^2 + 4|L_{1+}|^2 + |L_{1-}|^2 - 4\,\mathrm{Re}\{L_{1+}^* L_{1-}\} + 2\cos\theta\,\mathrm{Re}\{L_{0+}^*(4L_{1+} + L_{1-})\} + 12\cos^2\theta\left(|L_{1+}|^2 + \mathrm{Re}\{L_{1+}^* L_{1-}\}\right)$$

$$R_T = |E_{0+}|^2 + \tfrac{1}{2}|2M_{1+} + M_{1-}|^2 + \tfrac{1}{2}|3E_{1+} - M_{1+} + M_{1-}|^2 + 2\cos\theta\,\mathrm{Re}\{E_{0+}^*(3E_{1+} + M_{1+} - M_{1-})\}$$
$$+\cos^2\theta\left(|3E_{1+} + M_{1+} - M_{1-}|^2 - \tfrac{1}{2}|2M_{1+} + M_{1-}|^2 - \tfrac{1}{2}|3E_{1+} - M_{1+} - M_{1-}|^2\right)$$

$$R_{TL} = -\sin\theta\,\mathrm{Re}\{L_{0+}^*(3E_{1+} - M_{1+} + M_{1-}) - (2L_{1+}^* - L_{1-}^*)E_{0+} + 6\cos\theta\left(L_{1+}^*(E_{1+} - M_{1+} + M_{1-}) + L_{1-}^* E_{1+}\right)\}$$

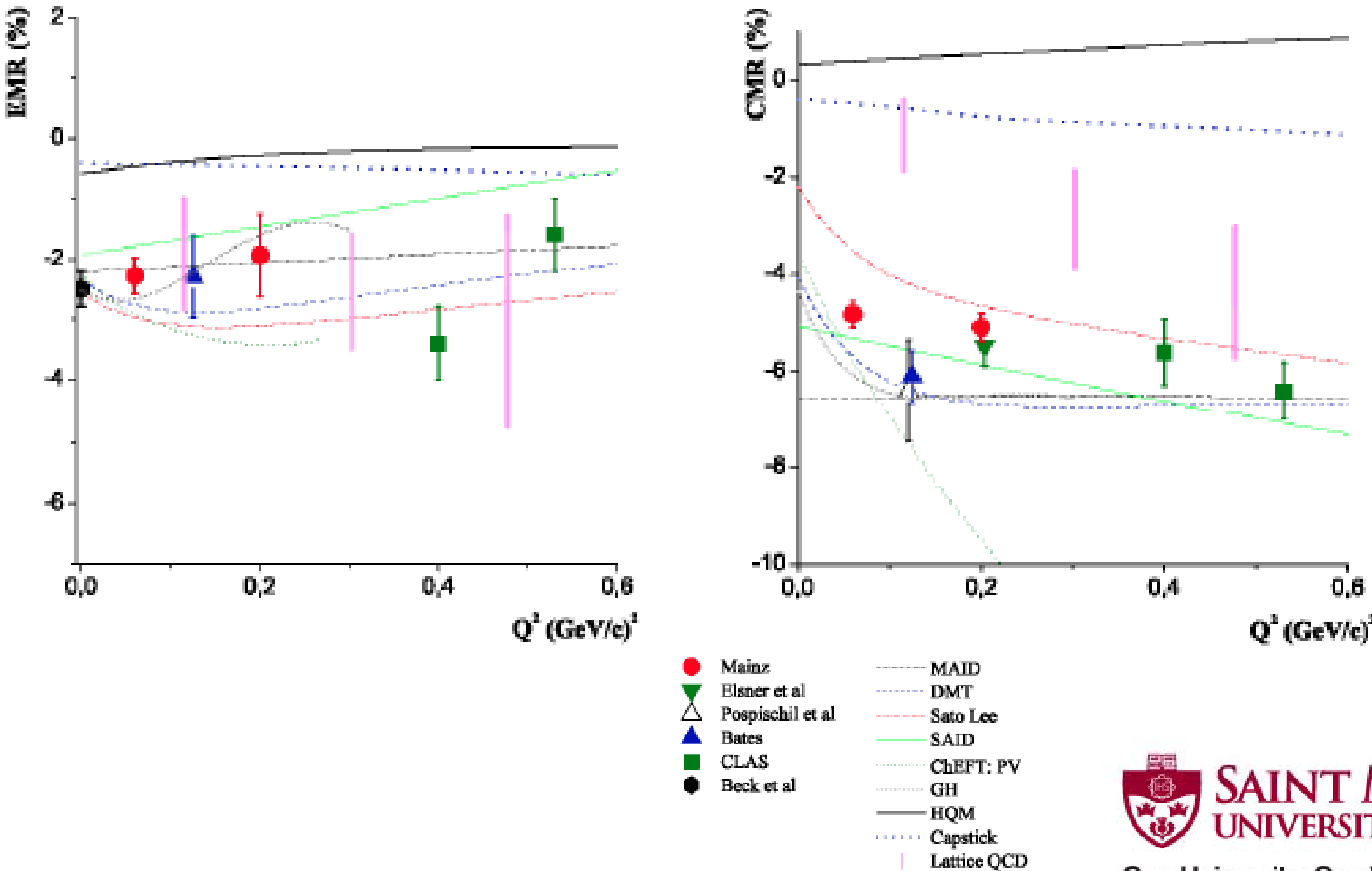
$$R_{TT} = 3\sin^2\theta\left(\tfrac{3}{2}|E_{1+}|^2 - \tfrac{1}{2}|M_{1+}|^2 - \mathrm{Re}\left(E_{1+}^*(M_{1+} - M_{1-}) + M_{1+}^* M_{1-}\right)\right)$$

$$R_{TL'} = \sin\theta\,\mathrm{Im}\{L_{0+}^*(3E_{1+} - M_{1+} + M_{1-}) - (2L_{1+}^* - L_{1-}^*)E_{0+} + 6\cos\theta\left(L_{1+}^*(E_{1+} - M_{1+} + M_{1-}) + L_{1-}^* E_{1+}\right)\}$$

Status of World Data at Low Q^2

(2 years old…from proposal)

EMR ~ E2/M1 ratio **CMR ~ C2/M1 ratio**



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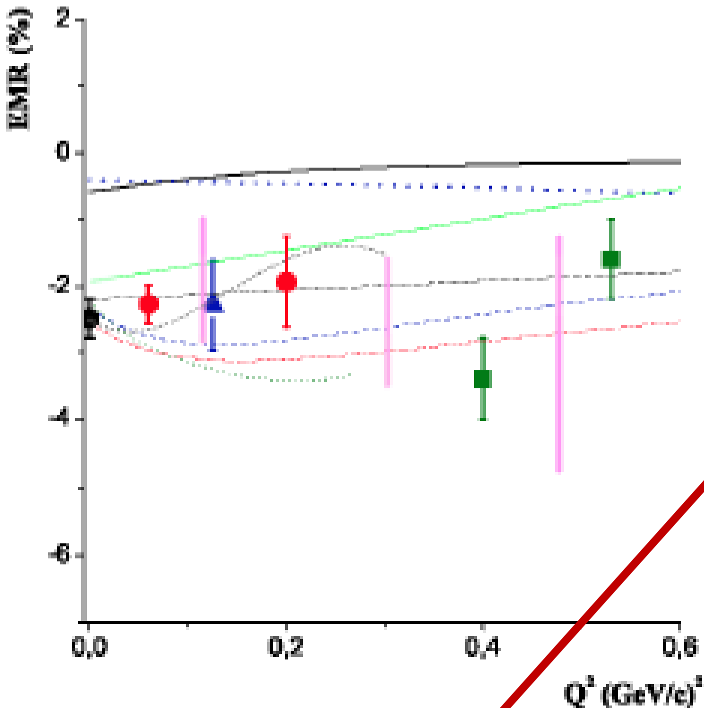

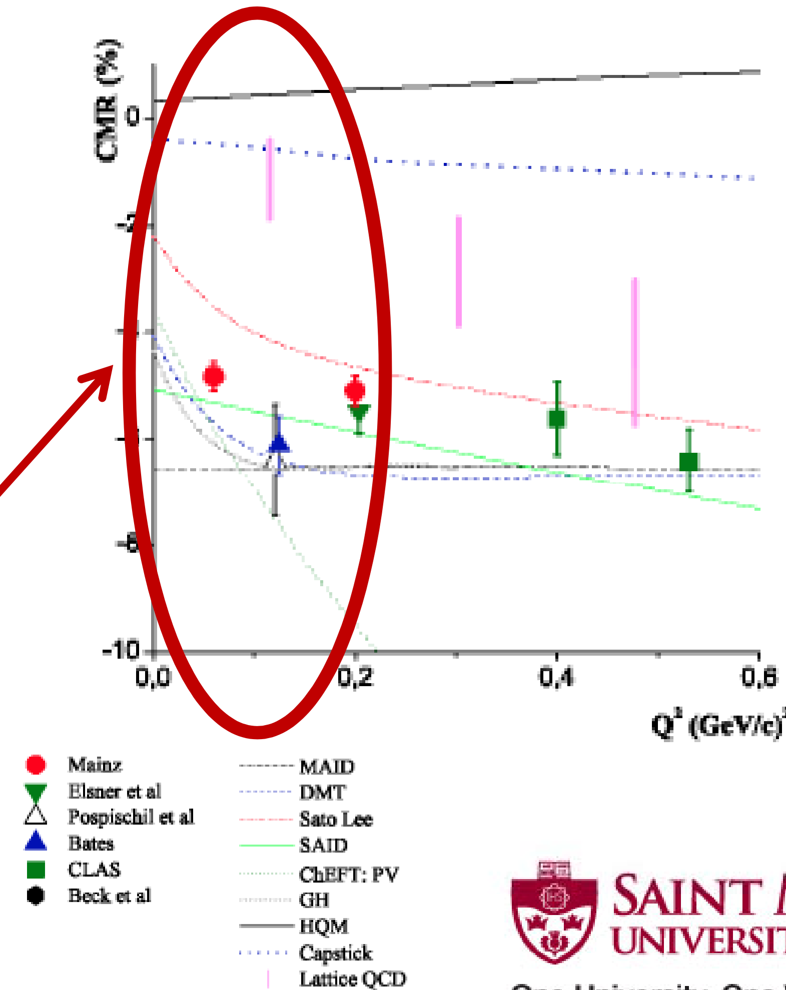

We focus on getting CMR values in this region

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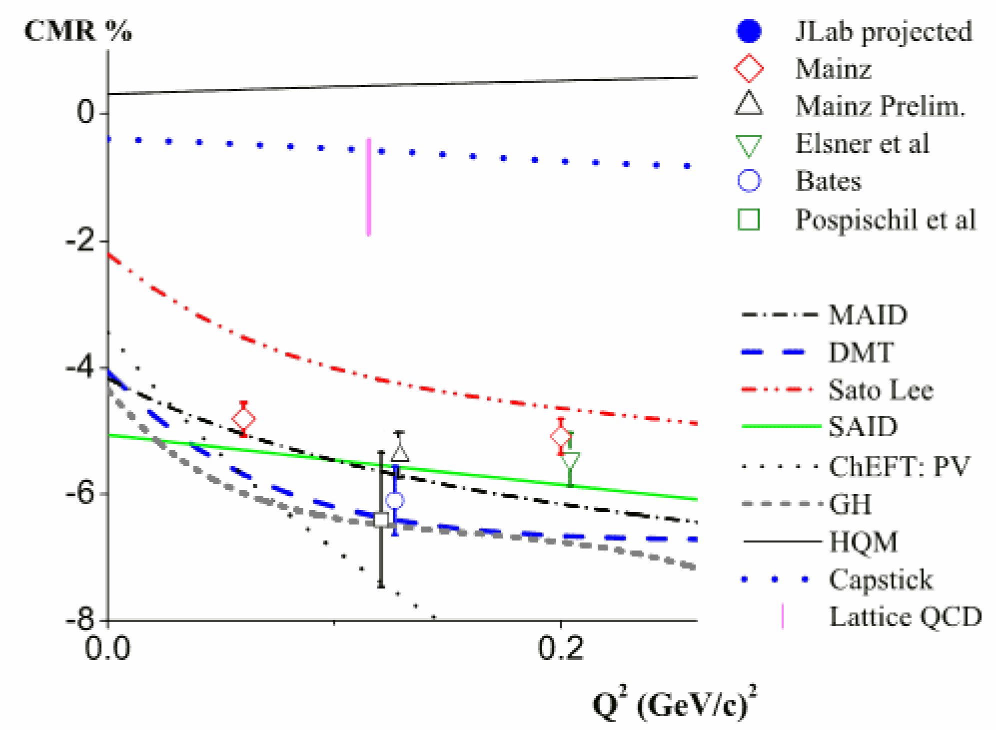
Where our Planned Results Fit
(2 years old…from proposal)
focus on: CMR ~ C2/M1 ratio at lowest Q^2



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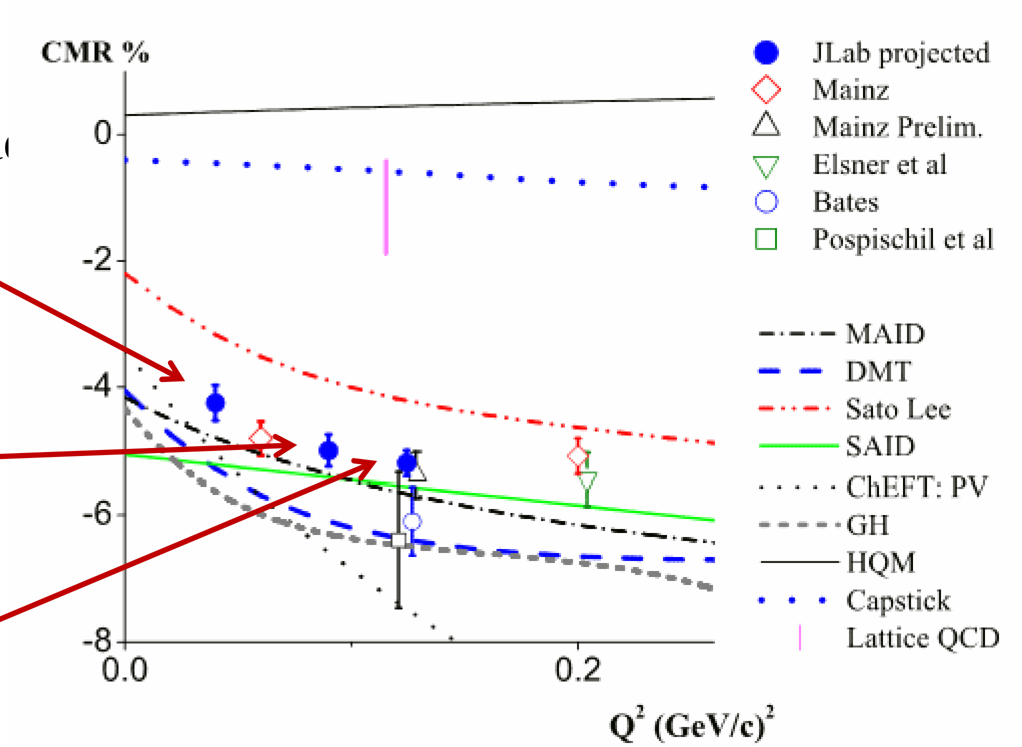
Where our Planned Results Fit

(2 years old…from proposal)

focus on: CMR ~ C2/M1 ratio at lowest Q^2

- $Q^2 = 0.040\ (\mathrm{GeV}/c)^2$
  - New lowest CMR valu
  - $\theta_e = 12.5°$
- $Q^2 = 0.125\ (\mathrm{GeV}/c)^2$
  - Validate previous measurements
- $Q^2 = 0.090\ (\mathrm{GeV}/c)^2$
  - Bridge previous measurements



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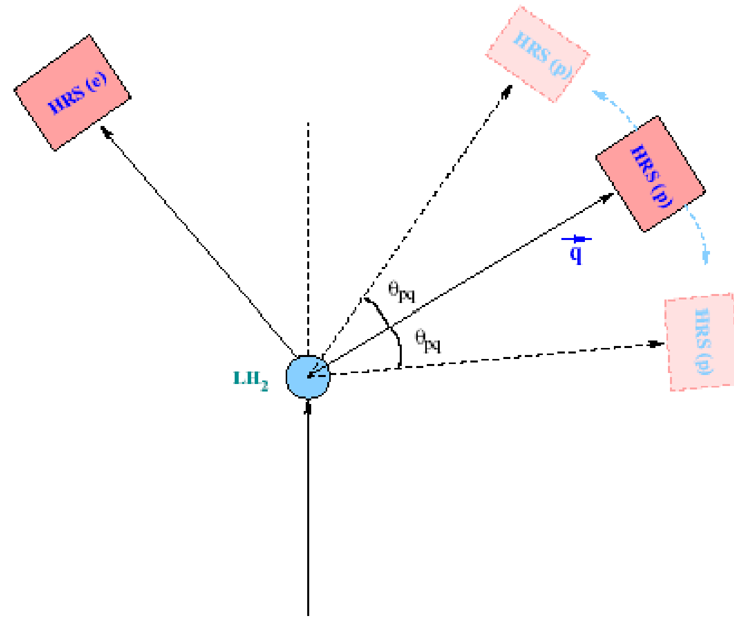
Step back to look at what we actually will measure:

Q^2 (GeV/ c)^2	W (MeV)			(MeV/ c)		(MeV/ c)	Time (hrs)
0.040	1221	0	12.52	767.99	24.50	547.54	1.5
0.040	1221	30	12.52	767.99	12.52	528.12	2
0.040	1221	30	12.52	767.99	36.48	528.12	3.5
0.040	1260	0	12.96	716.42	21.08	614.44	1.5
0.090	1230	0	19.14	729.96	29.37	627.91	1.5
0.090	1230	40	19.14	729.96	14.99	589.08	3
0.090	1230	40	19.14	729.96	43.74	589.08	4.5
0.125	1232	0	22.94	708.69	30.86	672.56	3.5
0.125	1232	30	22.94	708.69	20.68	649.23	7
0.125	1232	30	22.94	708.69	41.03	649.23	7
0.125	1232	55	22.94	708.69	12.52	596.43	3.5
0.125	1232	55	22.94	708.69	49.19	596.43	3.5
0.125	1170	0	21.74	788.05	37.31	575.57	3
0.125	1200	0	22.29	750.16	34.06	622.63	2
Configuration changes							17
Calibrations							8
				Total:			72



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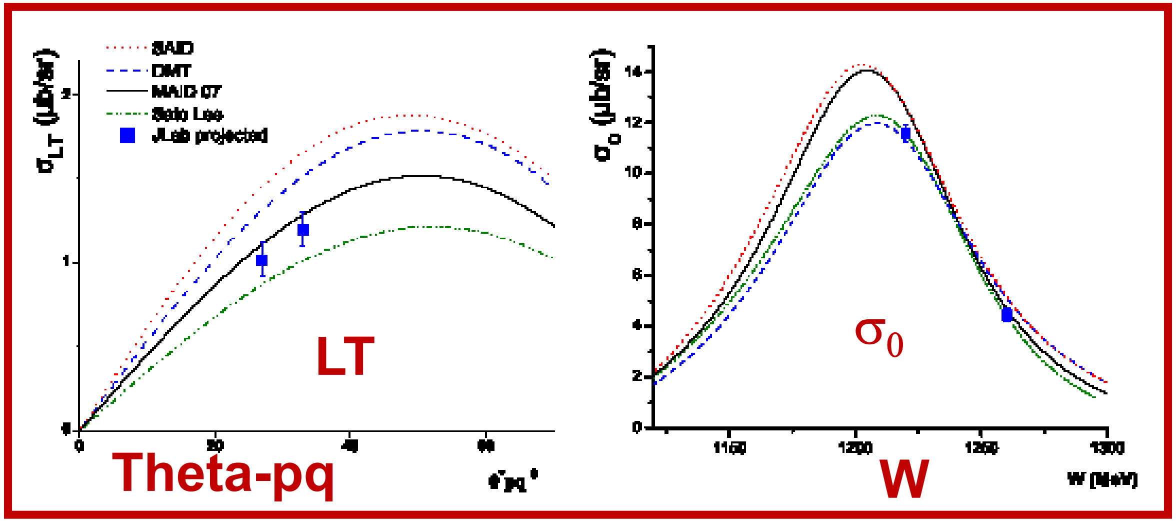
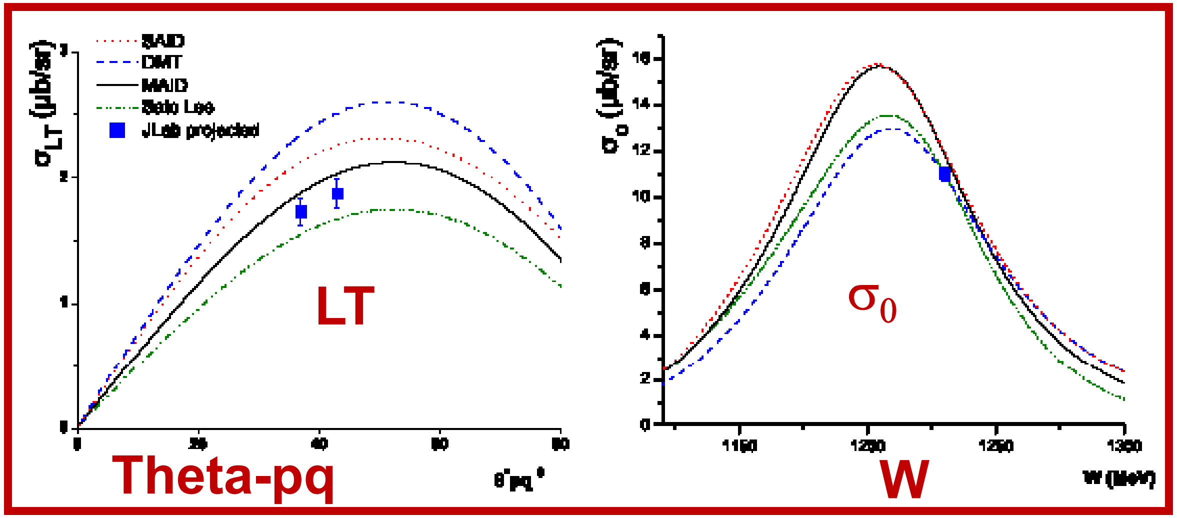
Finish
with a Step back to look at what we actually will measure:

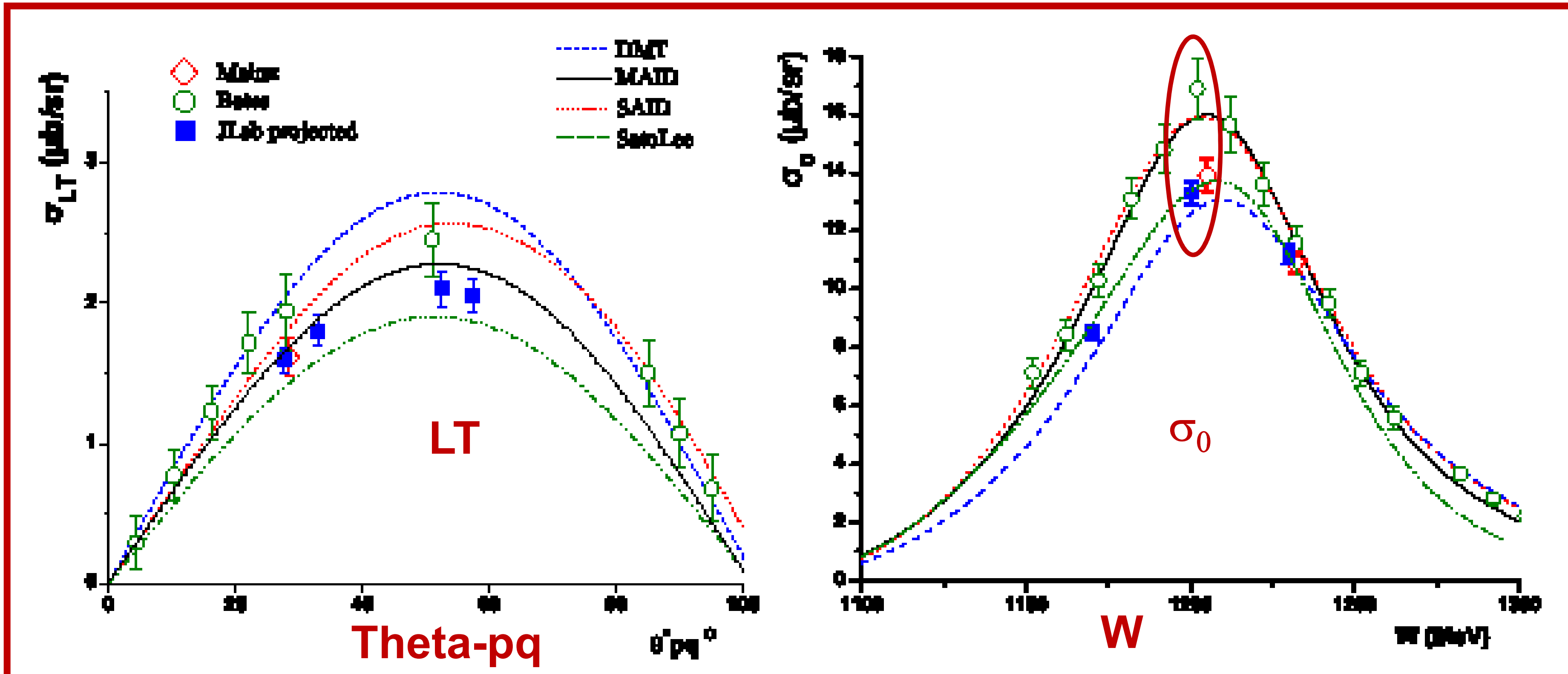


Q^2 = 0.040 GeV^2



Q^2 = 0.090 GeV^2

Finish with a Step back to look at what we actually will measure:



$Q^2 = 0.125\ GeV^2$

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