The $N \Rightarrow \Delta$ transition at low momentum transfers

- The issue
- The MIT/Bates and the Mainz Programs
- Future Prospects

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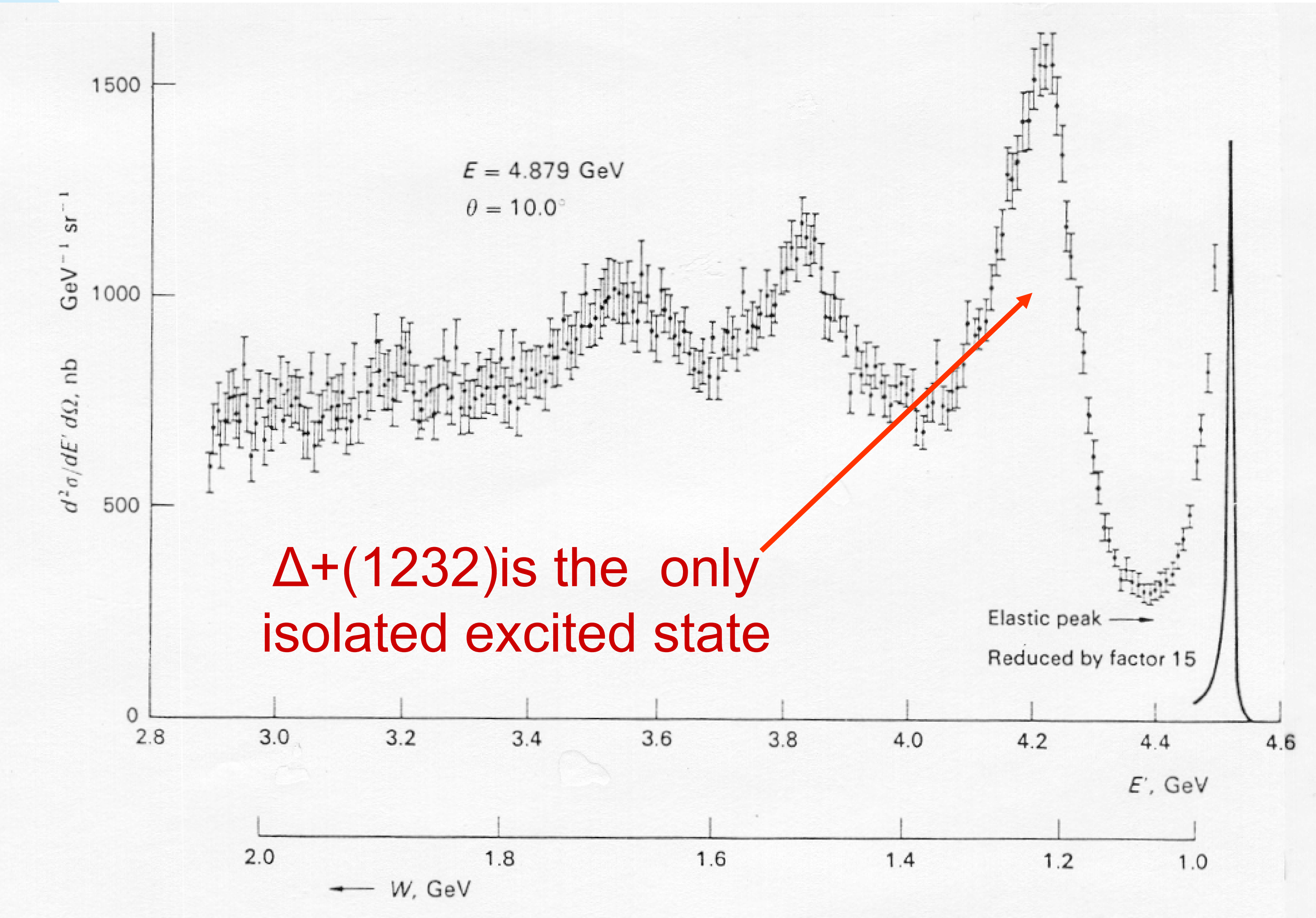
ANL Workshop, August 30, 2005

How do we measure the deformation of the proton?

Proton: a J= ½ system, with a very complicated excitation spectrum.



The signal for deformation in the N $\Rightarrow$ Δ transition

SIMPLISITIC: spherically symmetric

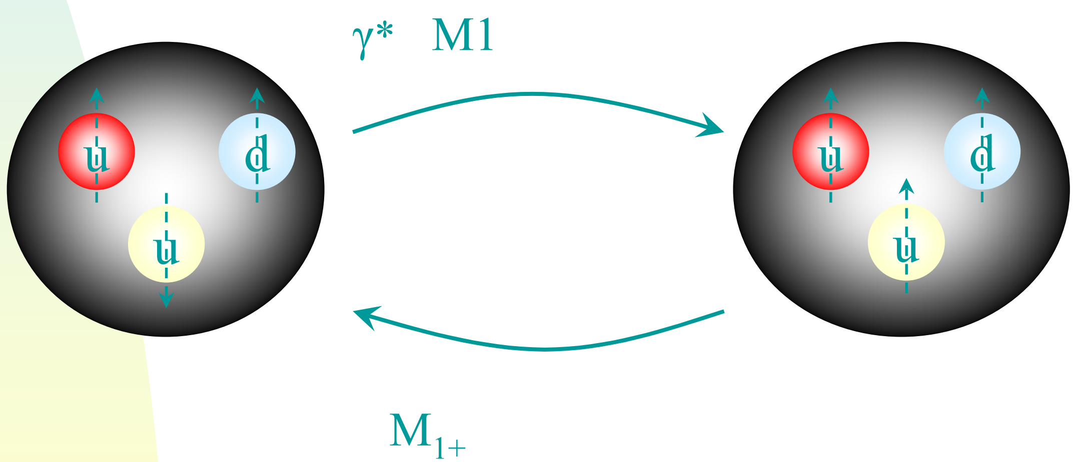
In SU(6) quark model, N and Δ have their quarks in s-state (L=0)

N→Δ transition is a pure spin-flip (Mag. Dipole, M1) transition

p(qqq)

$I = \frac{1}{2} \quad J = \frac{1}{2}$

938 MeV



Δ(qqq)

$I = \frac{3}{2} \quad J = \frac{3}{2}$

1232 MeV

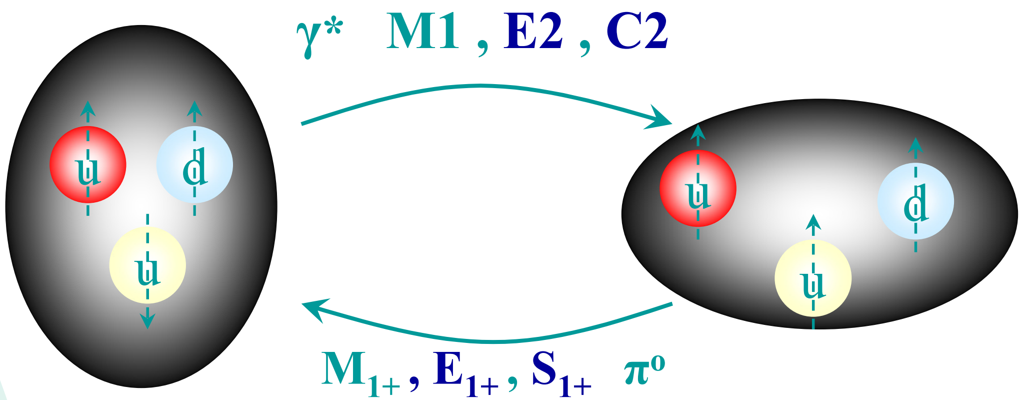
Spherical $\Rightarrow$ M1

The signal for deformation in the $N \Rightarrow \Delta$ transition

p(qqq)

$I = \frac{1}{2} \quad J = \frac{1}{2}$

938 MeV



Δ(qqq)

$I = \frac{3}{2} \quad J = \frac{3}{2}$

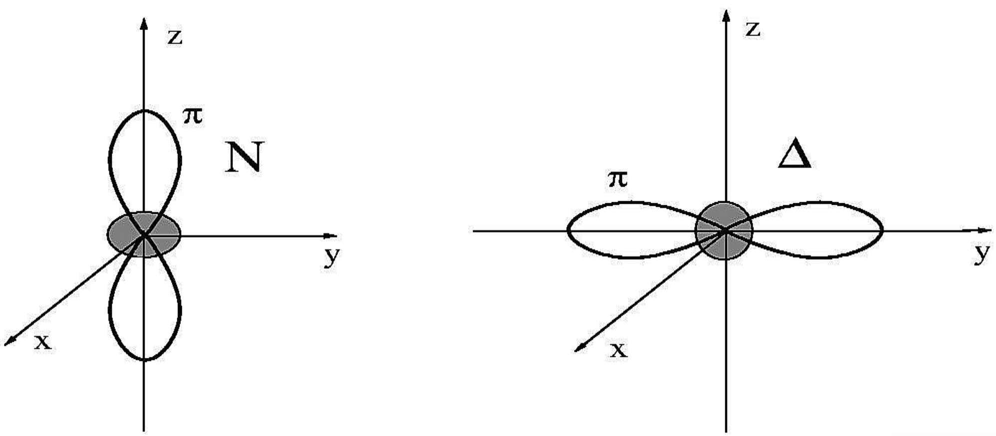
1232 MeV

Spherical $\Rightarrow$ M1

Deformed $\Rightarrow$ M1 , E2 , C2

Deformation signal
$$\begin{cases} \text{CMR} = \text{Re}\left(\dfrac{S_{1+}^{3/2}}{M_{1+}^{3/2}}\right) \\ \text{EMR} = \text{Re}\left(\dfrac{E_{1+}^{3/2}}{M_{1+}^{3/2}}\right) \end{cases}$$

Origins of N→Δ Quadrupole Amplitude

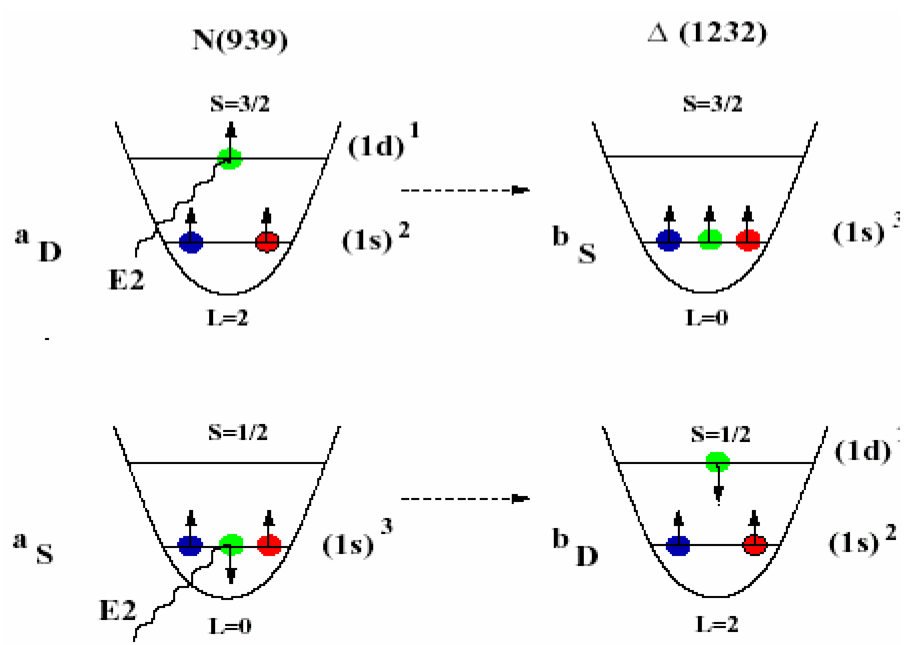


deformed pion cloud

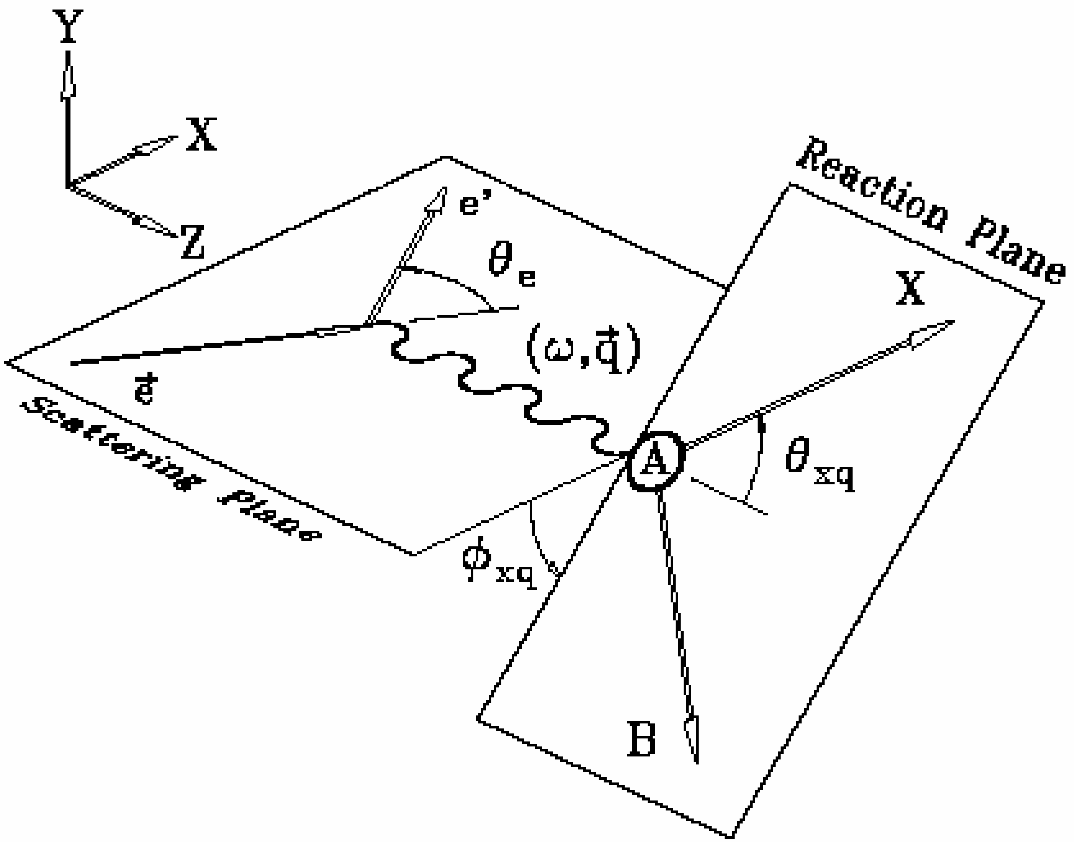
(large distances)

color hyperfine interaction gives d state admixtures

(short distances)



Using the precison of the electromagnetic probe



$$\sigma = J_\Omega \, \Gamma_v \, \frac{p_{cm}}{k_{cm}} \left(R_T + \epsilon_L R_L + \epsilon \, R_{TT} \cos 2\phi_{X\gamma} - v_{LT} R_{LT} \cos\phi_{X\gamma} - h \, v'_{LT} R'_{LT} \sin\phi_{X\gamma} \right)$$

Confronting Theory with Experiment

- Comparing EMR & CMR is necessary but not sufficient

- Need detailed study and comparison of isolated Responses

Extract the Information from the Interference Responses

$$R_{LT} = -\sin\theta^*_{pq}\mathrm{Re}\left\{S^*_{0+}\left[M_{1-} - M_{1+} + 3E_{1+}\right] - \left[2S^*_{1+} - S^*_{1-}\right]E_{0+}\right.$$
$$\left. -6\cos\theta^*_{pq}\left[S^*_{1+}\left(M_{1-} - M_{1+} + E_{1+}\right) + S^*_{1-}E_{1+}\right]\right\}$$

$$R'_{LT} = -\sin\theta^*_{pq}\mathrm{Im}\left\{S^*_{0+}\left[M_{1-} - M_{1+} + 3E_{1+}\right] - \left[2S^*_{1+} - S^*_{1-}\right]E_{0+}\right.$$
$$\left. -6\cos\theta^*_{pq}\left[S^*_{1+}\left(M_{1-} - M_{1+} + E_{1+}\right) + S^*_{1-}E_{1+}\right]\right\}$$

Primarily: Sensitive to C2

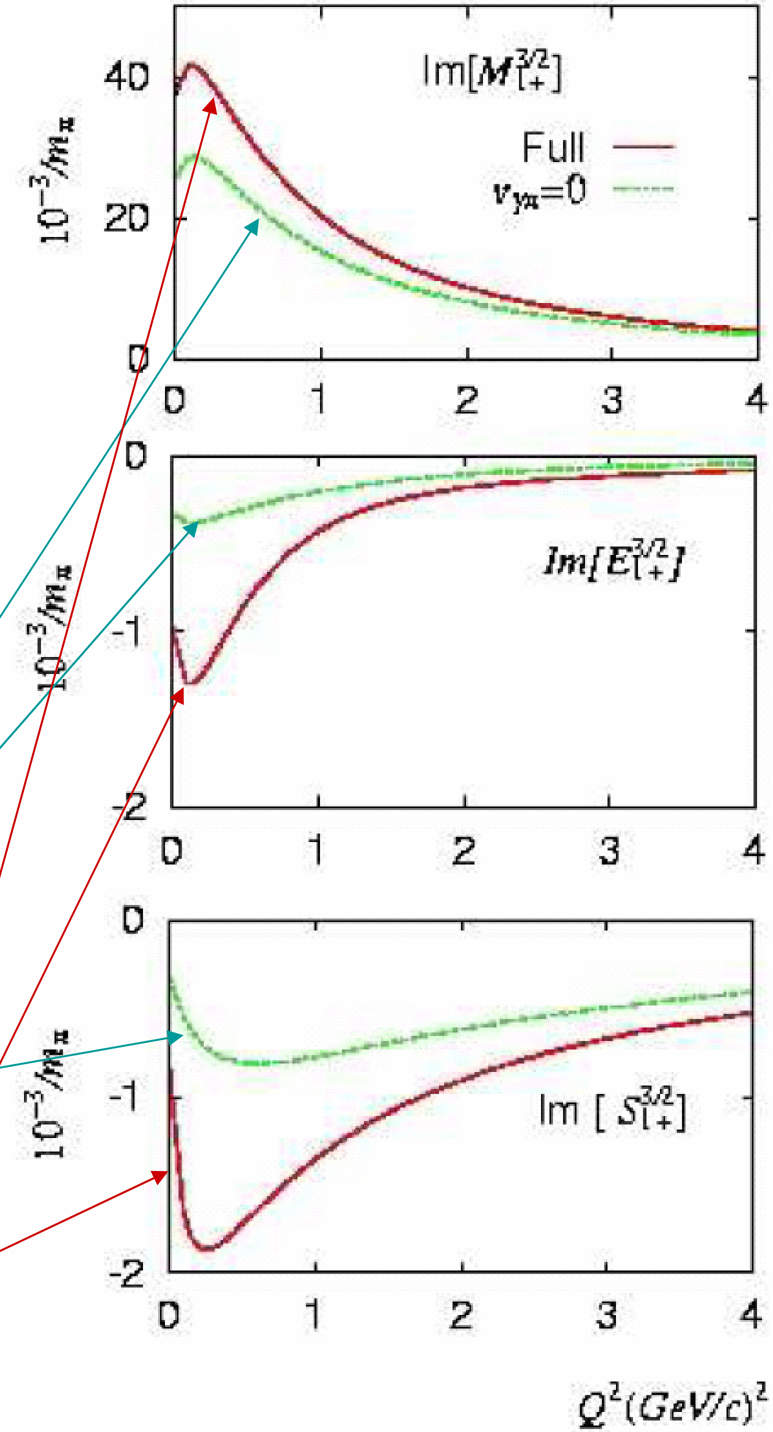
$$R_{TT} = 3\sin^2\theta^*_{pq}\left[\frac{3}{2}\left|E_{1+}\right|^2 - \frac{1}{2}\left|M_{1+}\right|^2\right.$$
$$\left. -\mathrm{Re}\left\{E^*_{1+}\left[M_{1+} - M_{1-}\right] + M^*_{1+}M_{1-}\right\}\right]$$

Primarily: Sensitive to E2

Dynamical Model of Sato-Lee

e.g. PRC 63, 055201 (2001)

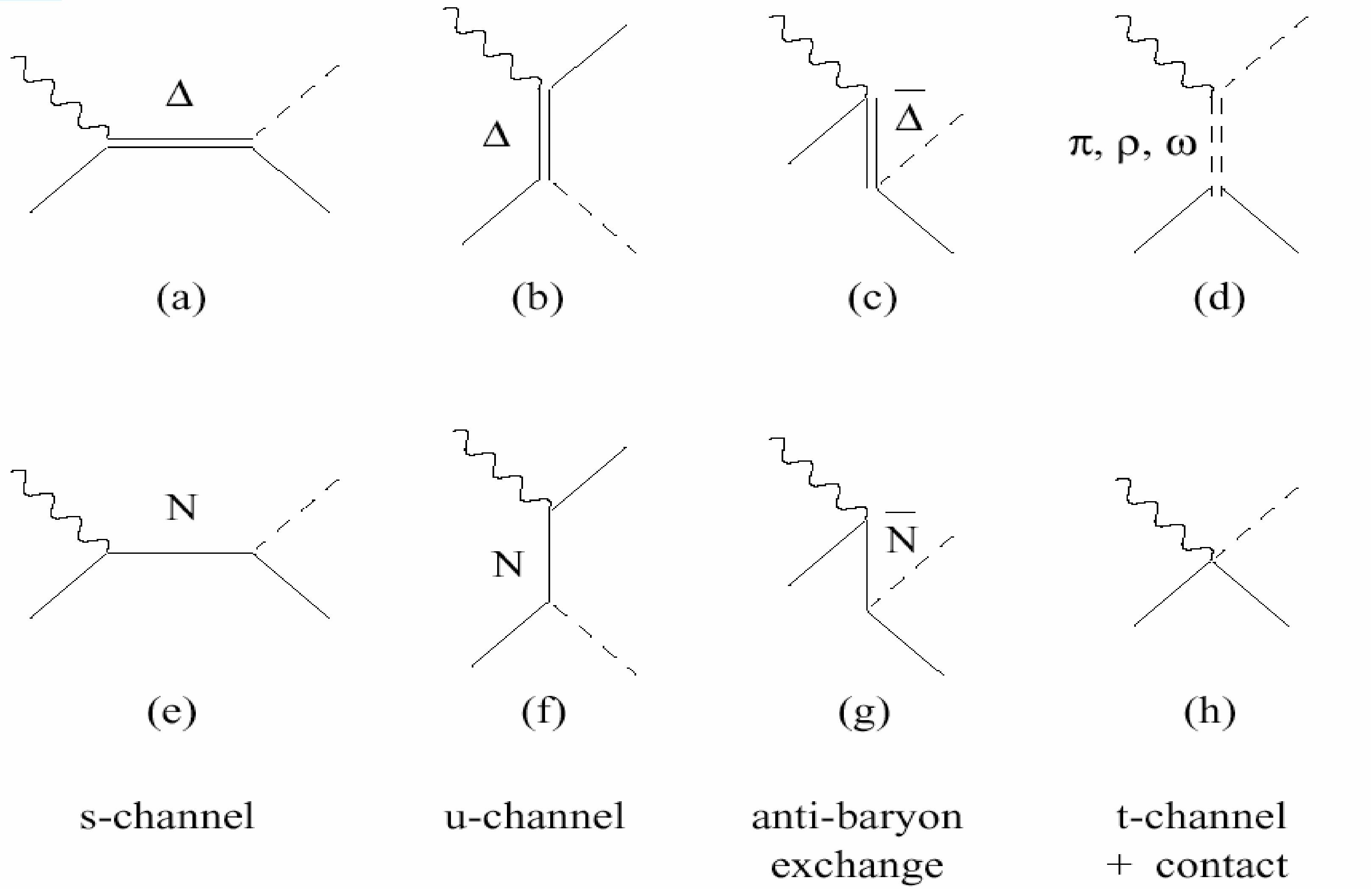
- Quark core and pion-cloud contributions
- Dynamical scattering equation using effective Lagrangian; accounts for off-shell pion interactions effects



Effect of quark core

Effect of quark core + meson cloud

Background !


Δ
(a)
Δ
(b)
$\bar{\Delta}$
(c)
π, ρ, ω
(d)
N
(e)
N
(f)
$\bar{N}$
(g)
(h)
s-channel
u-channel
anti-baryon exchange
t-channel + contact

EMR at the photon point

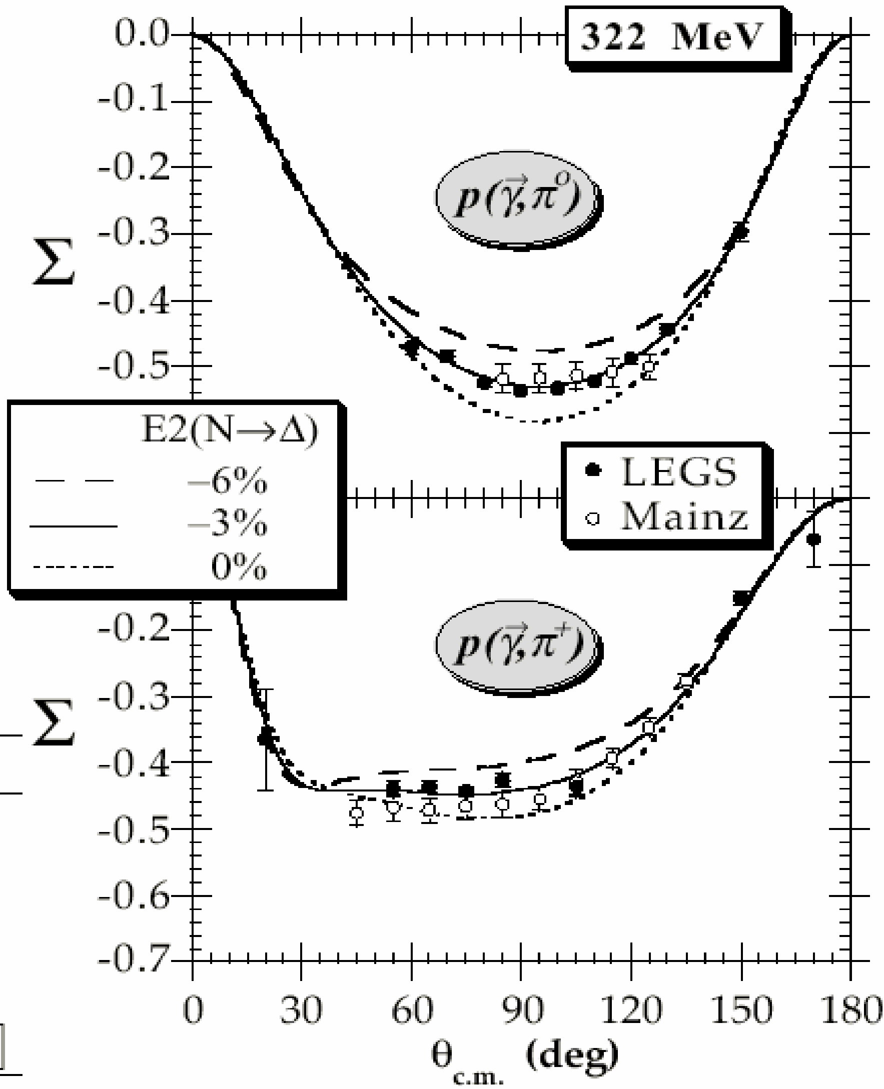
- Agreement in asymmetry measurements
- Disagreement at the cross section level

L.Tiator et al

Nucl. -Th/0012046

E2/M1 ratios for Q^2=0 from different analyses.

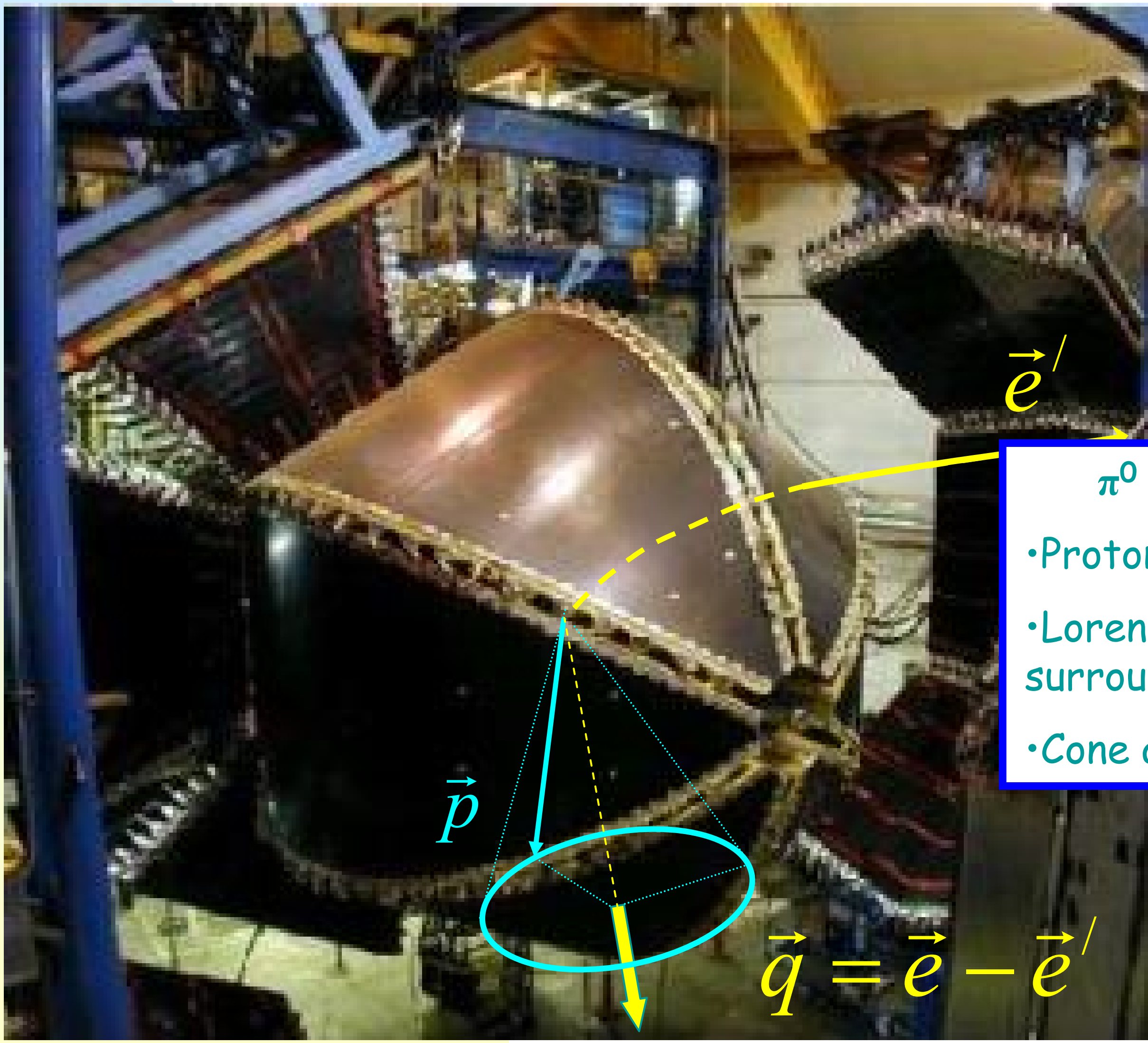
$R_{EM}[\%]$	Reference
-2.54 ± 0.10	Hanstein et al. [17]
$-2.5 \pm 0.1_{stat.} \pm 0.2_{syst.}$	Beck et al. [18]
$-3.0 \pm 0.3_{stat.+syst.} \pm 0.2_{mod.}$	Blanpied et al. [12]
-1.5 ± 0.5	Arndt et al. [19]
-3.19 ± 0.24	Davidson et al. [20]
-2.5 ± 0.5	PDG 2000 estimate



Electroproduction

- **Results from second generation experiments are now being released**
- **All possible reaction channels are being explored. Two general trends:**
  - Measure with high precision (high luminosity, high resolution) crititically important points to isolate the important amplitude (Bates/OOPS, Mainz, FPP@Hall-A….)
  - Measure «everything» (maximum angular and invariant mass coverage). Get a global picture of the picture. (Bonn, Hall B, Hall C..)
- ***Consistent picture begining to emerge***

CEBAF Large Acceptance Spectrometer (CLAS)



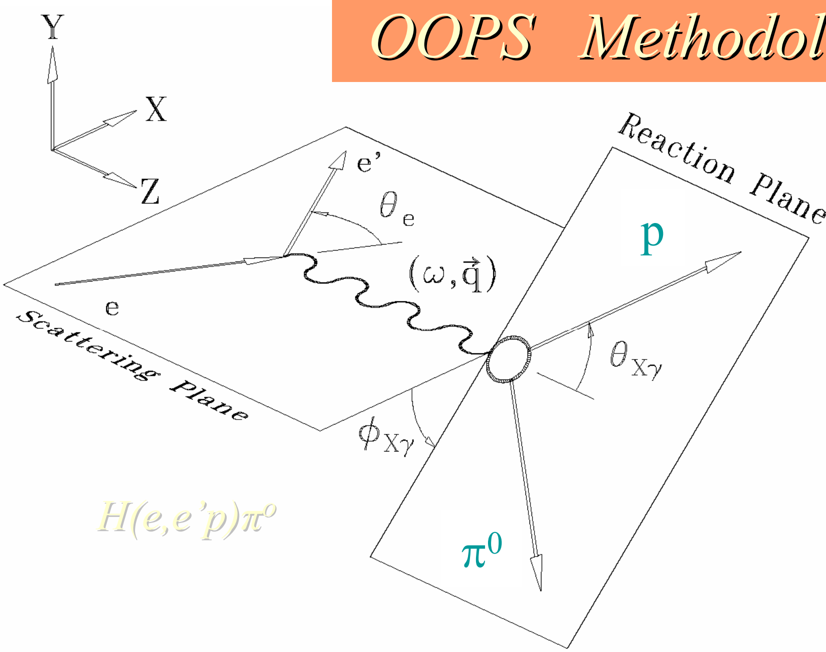
- Six identical sectors
- 5 T toroidal B-field
- $\Delta\theta$=15-140 degrees
- $\Delta\varphi$ = 0-50 degrees
- $\Delta p/p = 10^{-2}$-10^{-3}

π^0 electroproduction

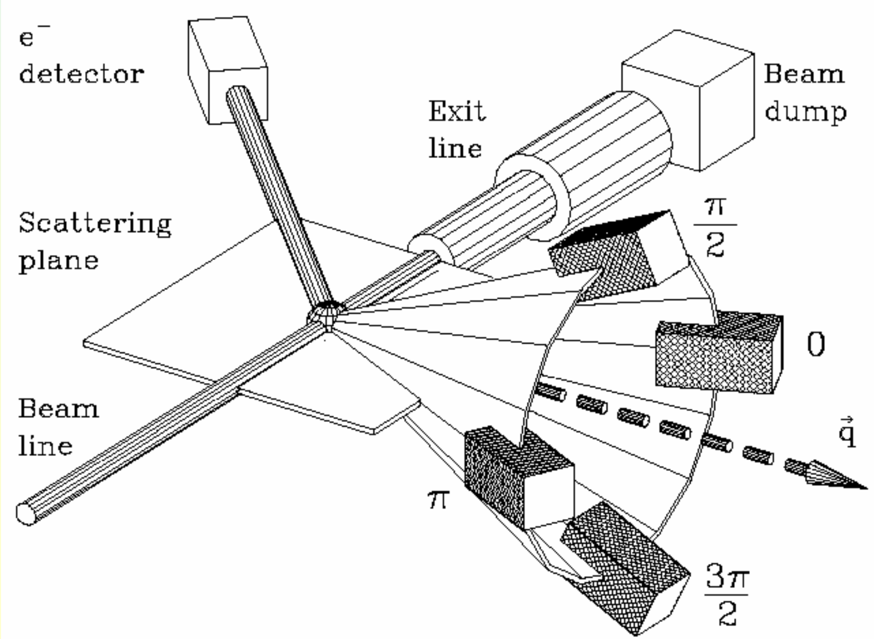
- Proton detected
- Lorentz boost forms cone surrounding q vector.
- Cone angle Q^2,W dependent

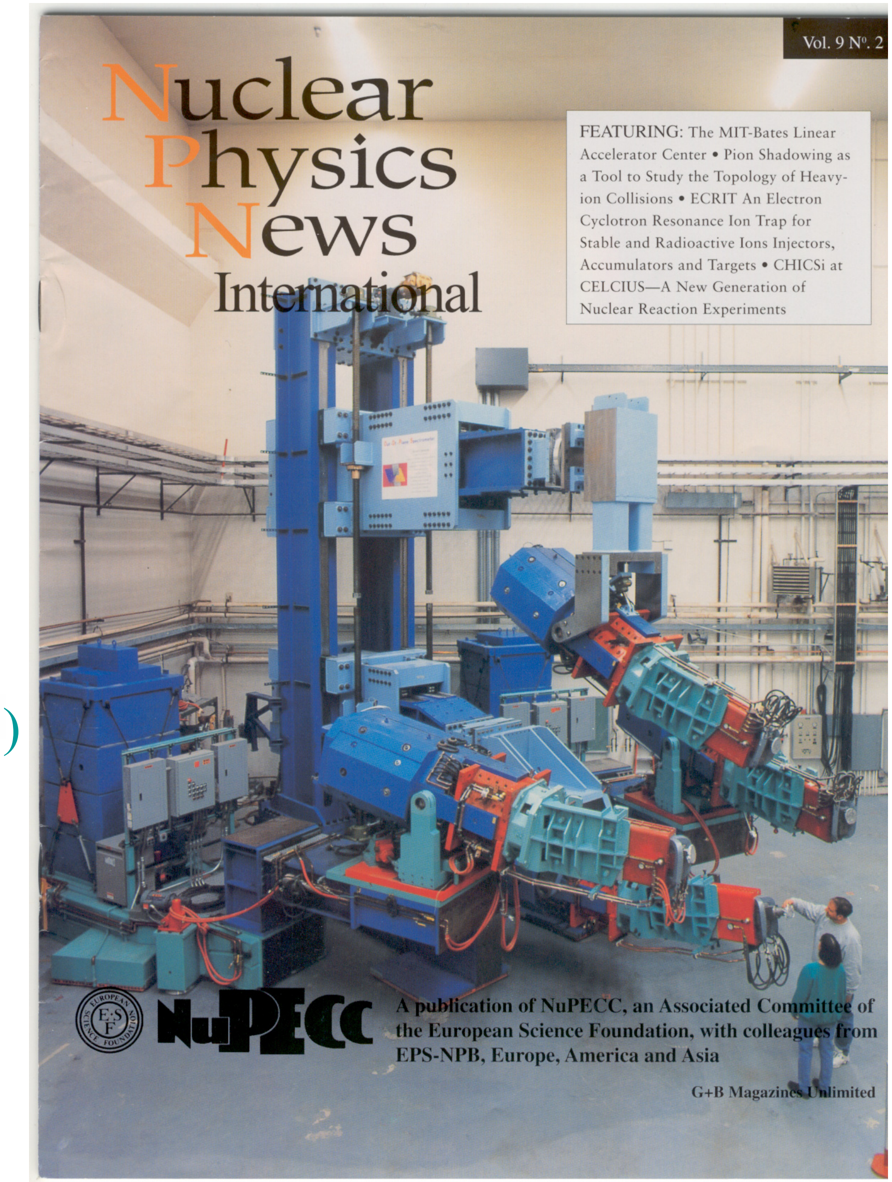
C. Smith, Osaka 05

OOPS Methodology



$$\sigma = J_{\Omega}\, \Gamma_v \frac{p_{cm}}{k_{cm}} \left(R_T + \epsilon_L R_L + \epsilon\, R_{TT} \cos 2\phi_{X\gamma} - v_{LT} R_{LT} \cos \phi_{X\gamma} \right)$$

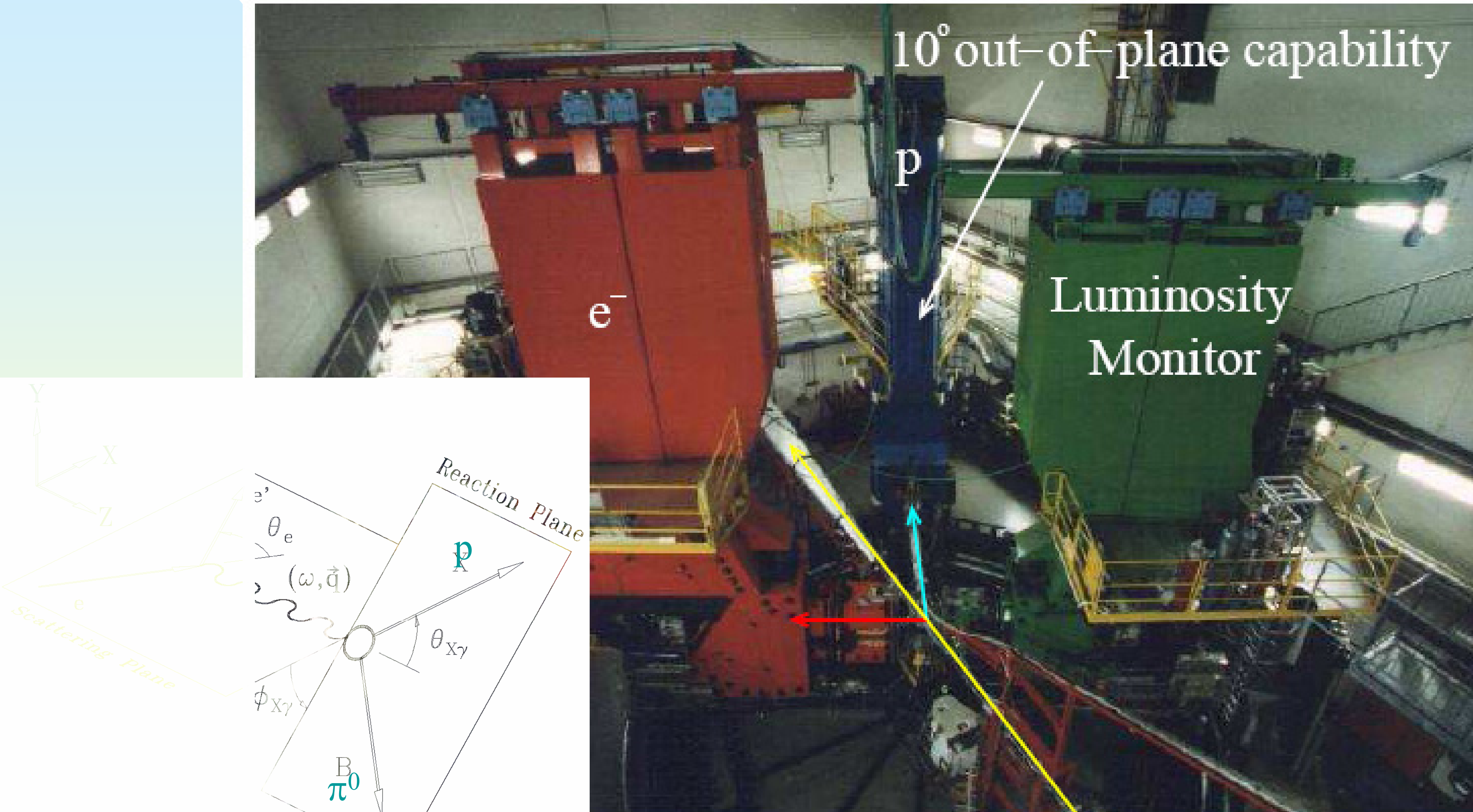




alignment precision: 1 mm , 1 mrad

Out of plane capability: ~ 65°

MAMI e scattering facility
(University of Mainz, Germany)

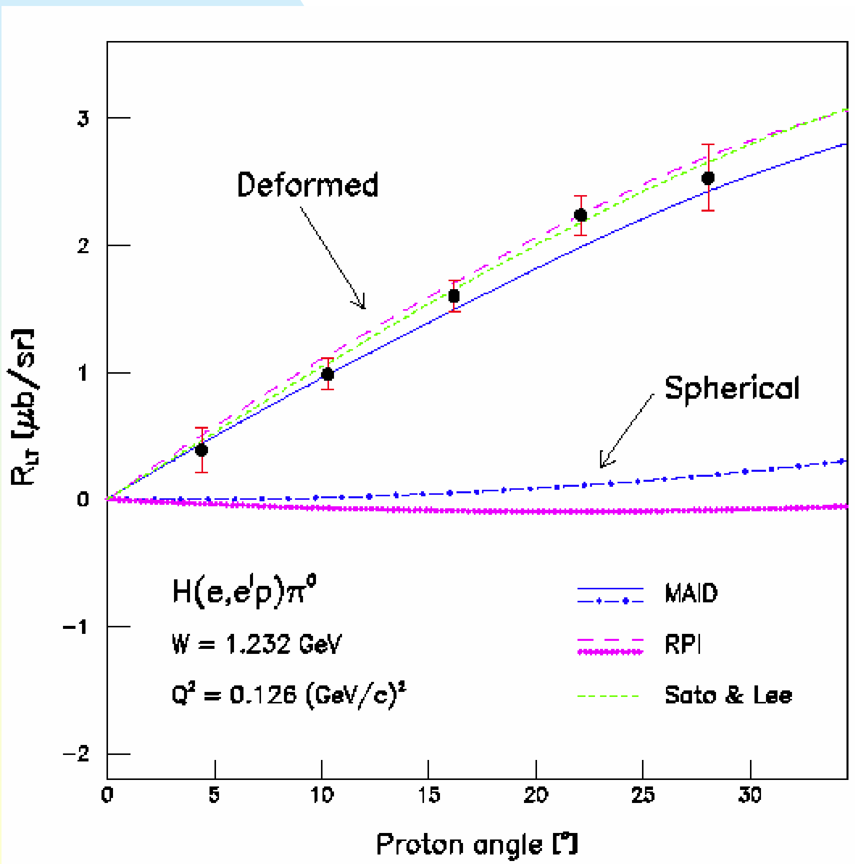


Bates and Mainz Strategy

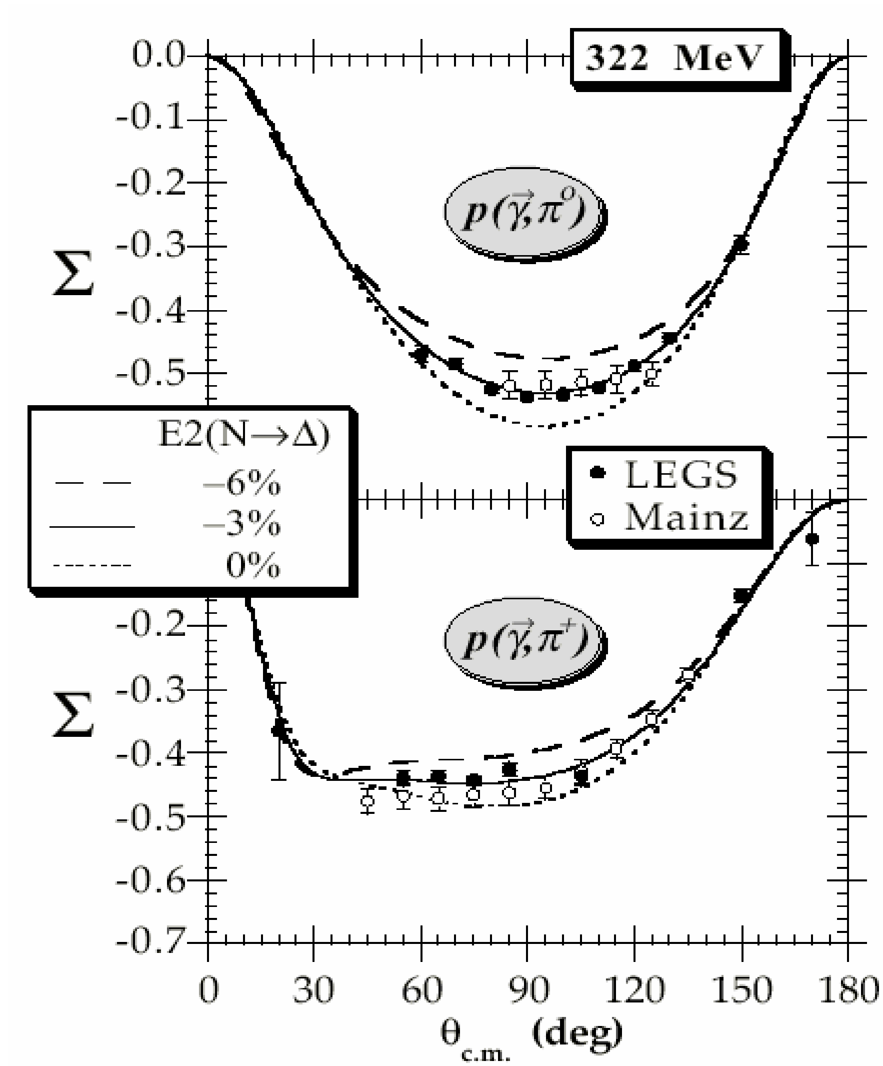
- A detailed measurement at one Q_2 to calibrate reaction and Models
  - **Measure precisely E2/C2 sensitive terms [R_{LT}, R_{oo}]**
  - **Control background terms [R_T, R_{TT}, R_{LT}']**
  - **Make isospin separation, measure γ-channel, FPP**
  - **Key Dynamical Variables: W, θ_{pq} dependence**
- Critical measurements at other small momentum transfers

Sensitivity to Quadrupole Amplitudes

Virtual photons



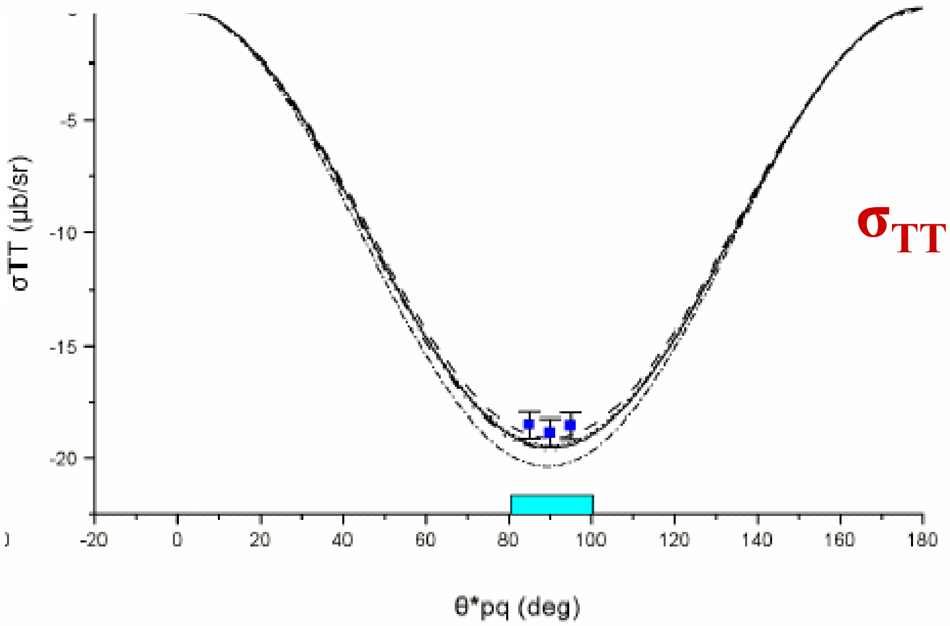
Real photons



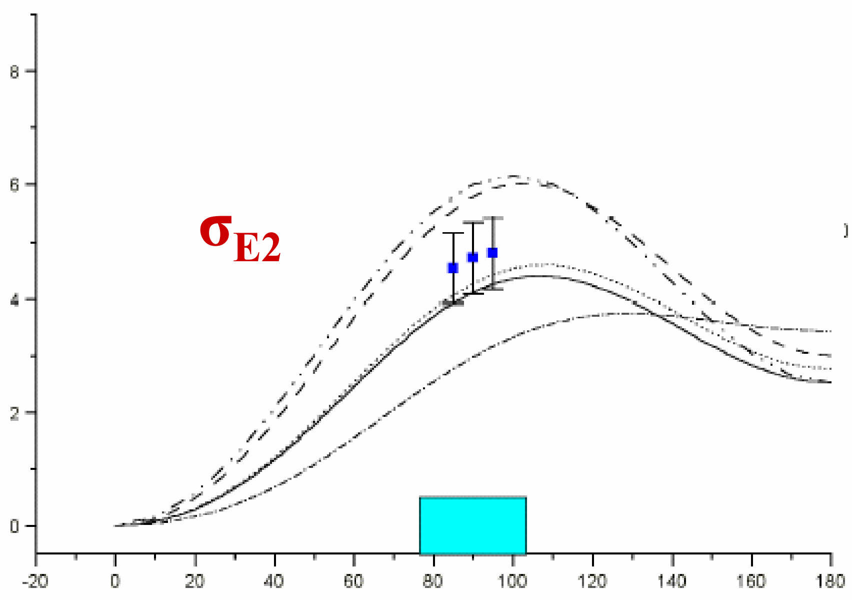
Sensitivity to E2

→ **Measure σ_{E2}**

$$\sigma_{E2}(\theta_\pi) = \sigma_0(\theta_\pi) + \sigma_{TT}(\theta_\pi) - \sigma_0(\pi)$$
$$\approx 2(\cos\theta_\pi + 1)\mathrm{Re}\{E^*_{0+}M_{1+}\} - 12\sin^2\theta_\pi \mathrm{Re}\{E^*_{1+}M_{1+}\}$$
$$\sigma_0(\theta_\pi) \equiv \sigma_T(\theta_\pi) + \epsilon\sigma_L(\theta_\pi)$$



σ_{TT}



σ_{E2}

N. Sparveris et al

PRL **94**, 022003 (2005)

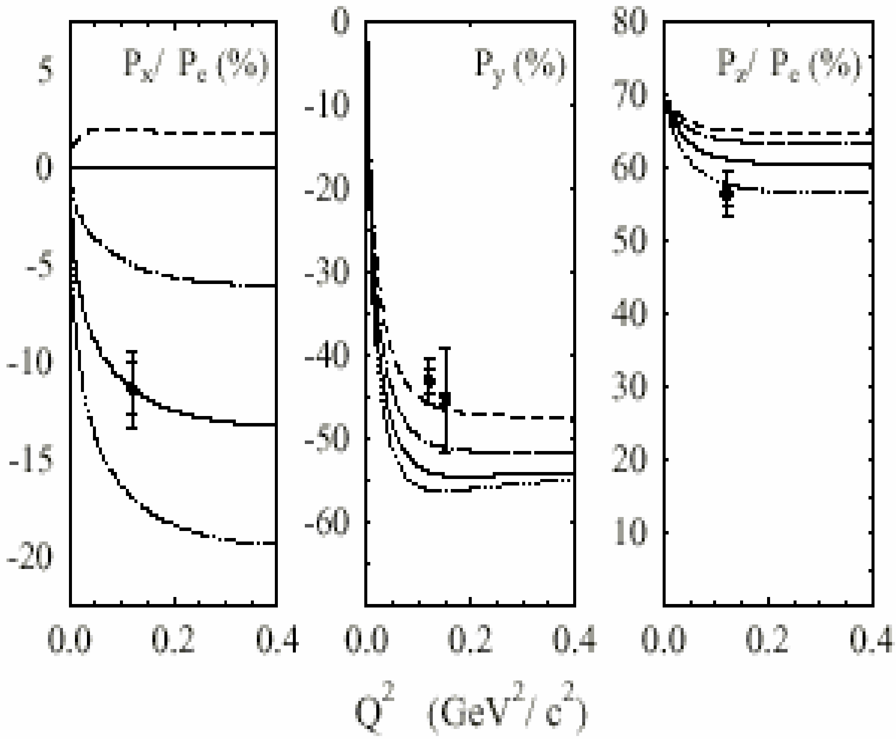
Sparveris Ph.D. Thesis (2003)

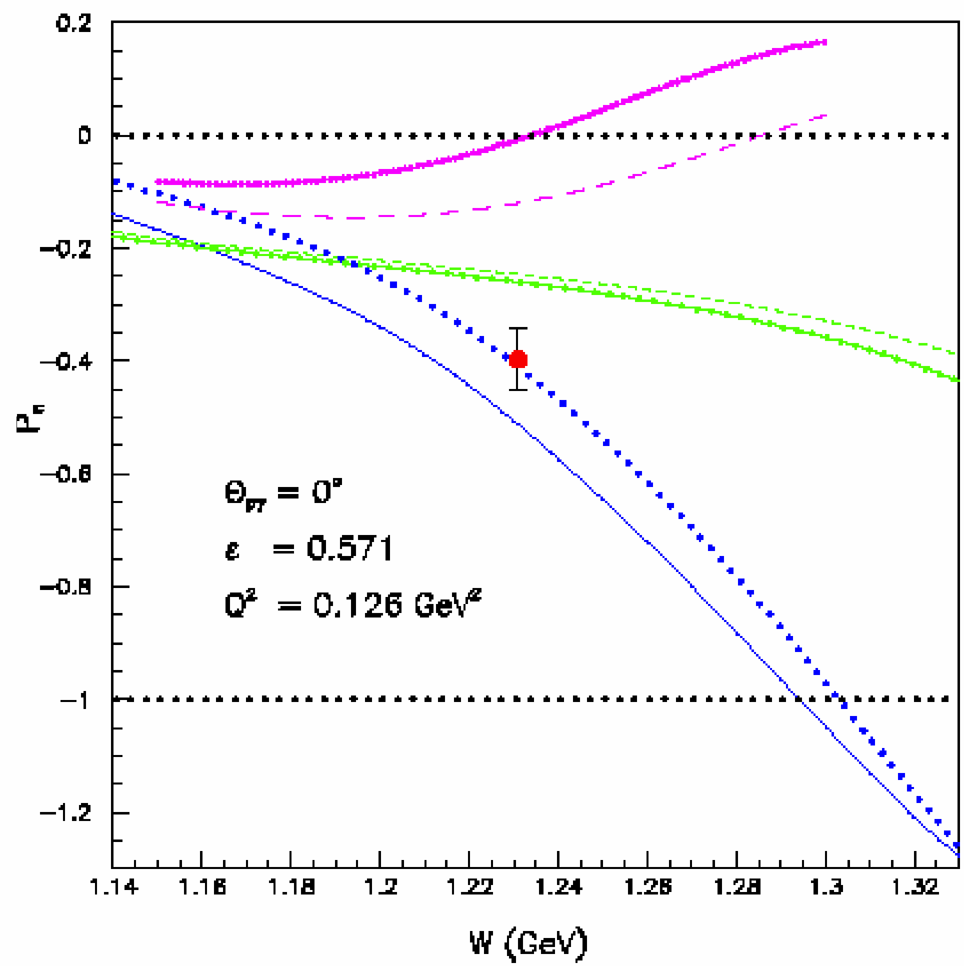
Proton Recoil Polarization

FPP at Bates

G. Warren et al

Th. Pospischil et al PRL 86, 2959 (2001)

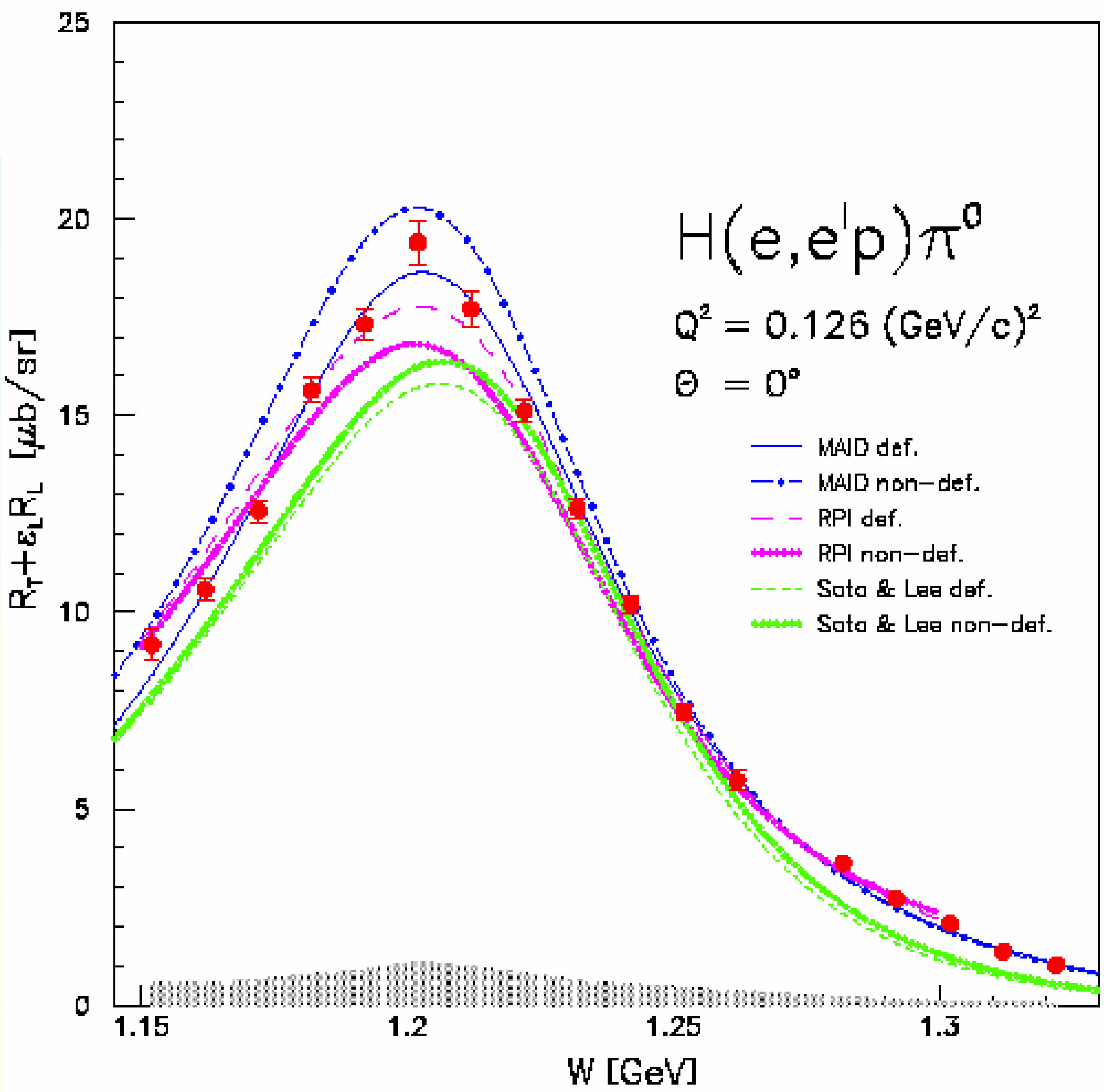




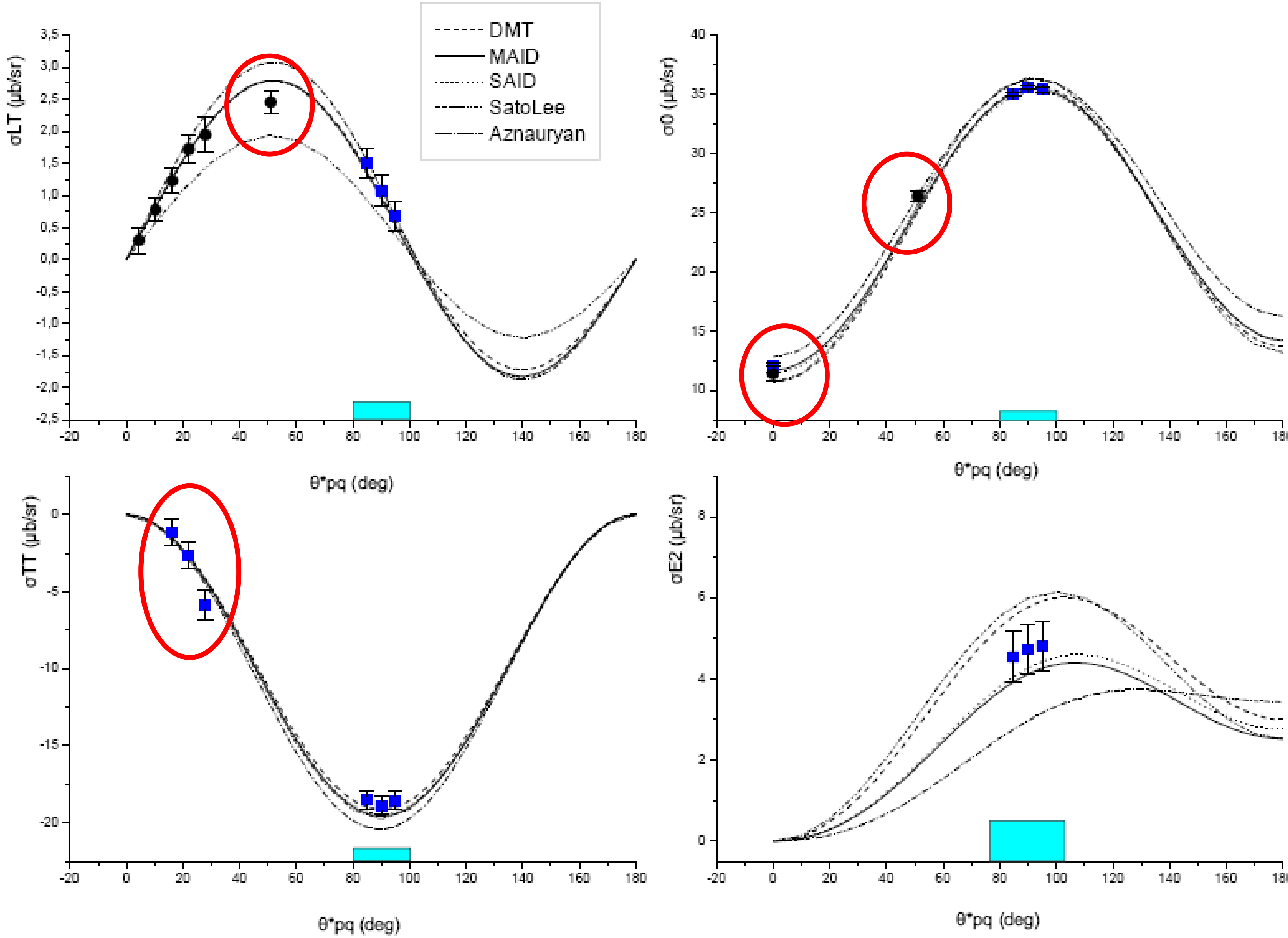
$$R_{SM} = (-5.8 \pm 1.0)\%$$

Bates Results

Parallel Coincident Cross section
(Mertz, Vellidis et al PRL86,2963 (2001))

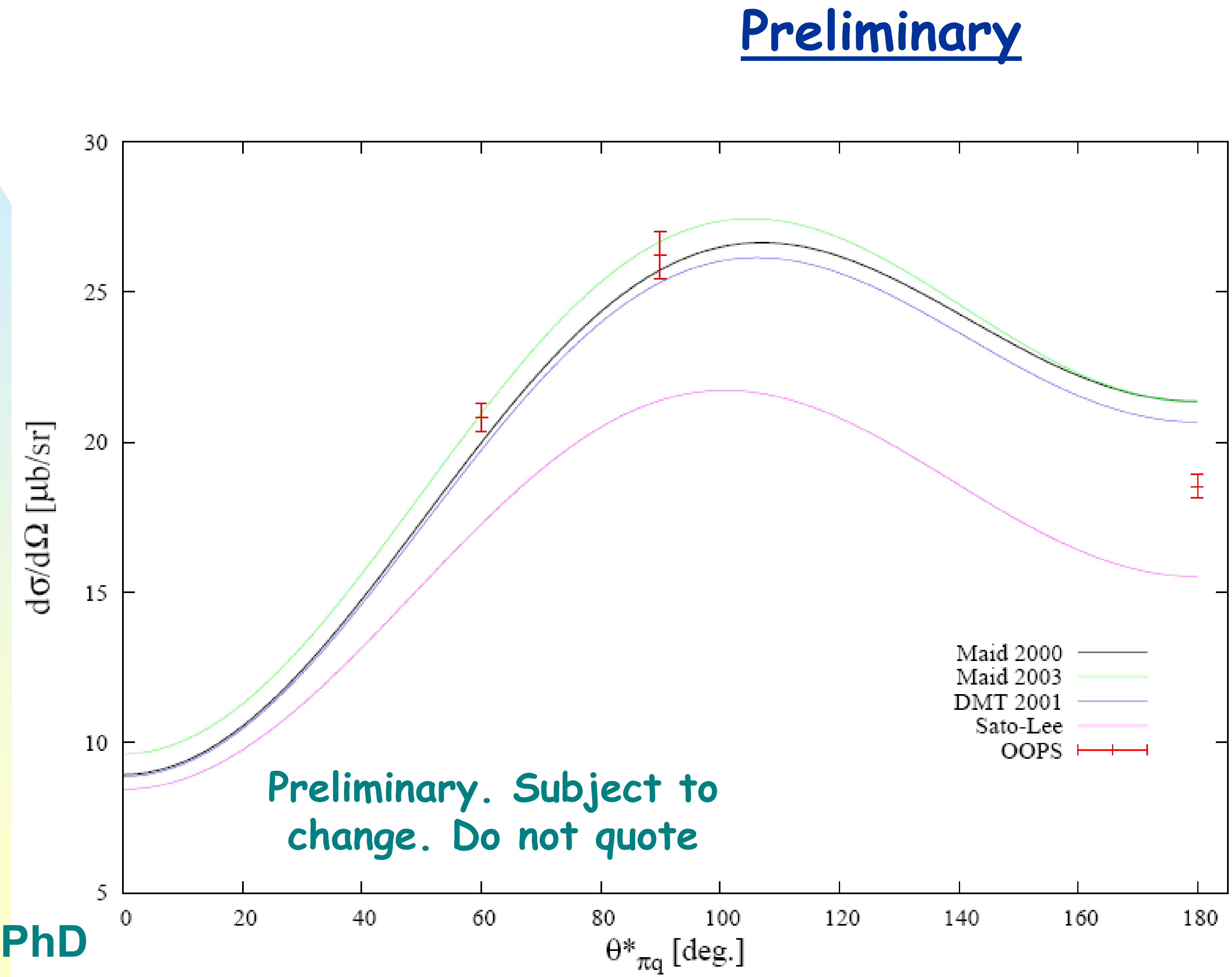


OOPS data on N→Δ



N. Sparveris et al PRL **94**, 022003 (2005) + new

(e,e'π+) OOPS data



J. Kirkpatrick PhD

Sparveris Ph.D. Thesis (2003)

Fitting $|M_{1+}|$, $\mathrm{Re}(E_{1+}/M_{1+})$, $\mathrm{Re}(S_{1+}/M_{1+})$
other multipoles $\longrightarrow$ 0

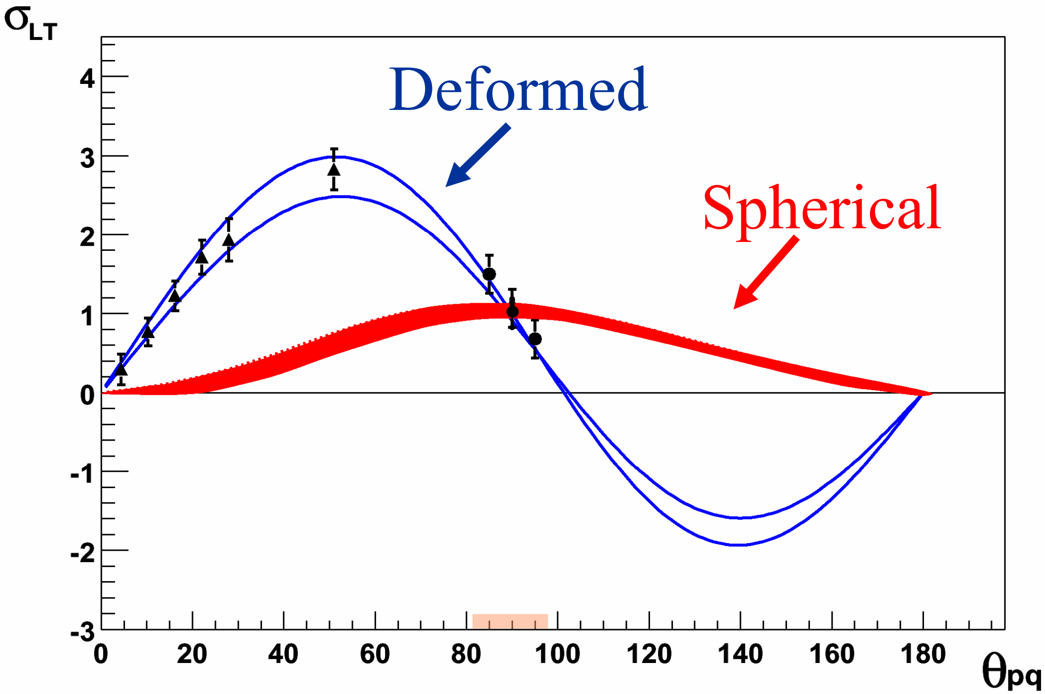
Truncated fit with other multipoles evaluated from model calculations

	CMR (%)	EMR (%)
$(\mathrm{TME})_a$	$-6.84 \pm 0.32_{stat+sys}$	$-3.05 \pm 0.40_{stat+sys}$
$(\mathrm{TME})_{MAID}$	$-6.31 \pm 0.33_{stat+sys}$	$-2.27 \pm 0.42_{stat+sys}$
$(\mathrm{TME})_{DMT}$	$-6.23 \pm 0.33_{stat+sys}$	$-1.73 \pm 0.42_{stat+sys}$
$(\mathrm{TME})_b$	$-6.27 \pm 0.32_{stat+sys} \pm 0.10_{mod}$	$-2.00 \pm 0.40_{stat+sys} \pm 0.27_{mod}$

Theoretical models adjusted to data:

	CMR (%)	EMR (%)
MAID	$-6.10 \pm 0.10_{stat+sys}$	$-2.30 \pm 0.20_{stat+sys}$
DMT	$-6.10 \pm 0.20_{stat+sys}$	$-1.90 \pm 0.20_{stat+sys}$
SAID	-4.8	-1.4
Aznauryan	$-8.00 \pm 0.90_{stat+sys}$	$-0.90 \pm 0.50_{stat+sys}$
Sato Lee	-4.3	-3.2

- ✓ *SAID ... fails recoil polarization measurements*
- ✓ *Aznauryan ... fail in LT below resonance*
- ✓ *Sato-Lee ... fail in LT both on and below resonance as well as in recoil polarization*

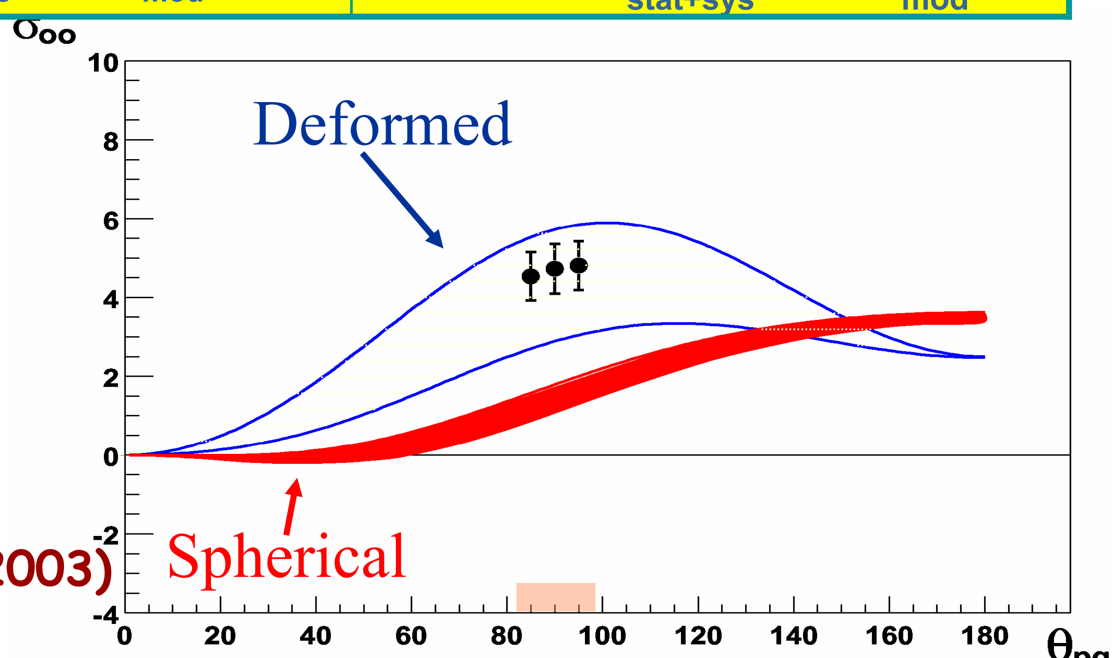


Precise data strongly "suggesting" that the Nucleon is *not spherical*

CMR & EMR	$-6.27 \pm 0.32_{stat+sys} \pm 0.10_{mod}$	$-2.00 \pm 0.40_{stat+sys} \pm 0.27_{mod}$

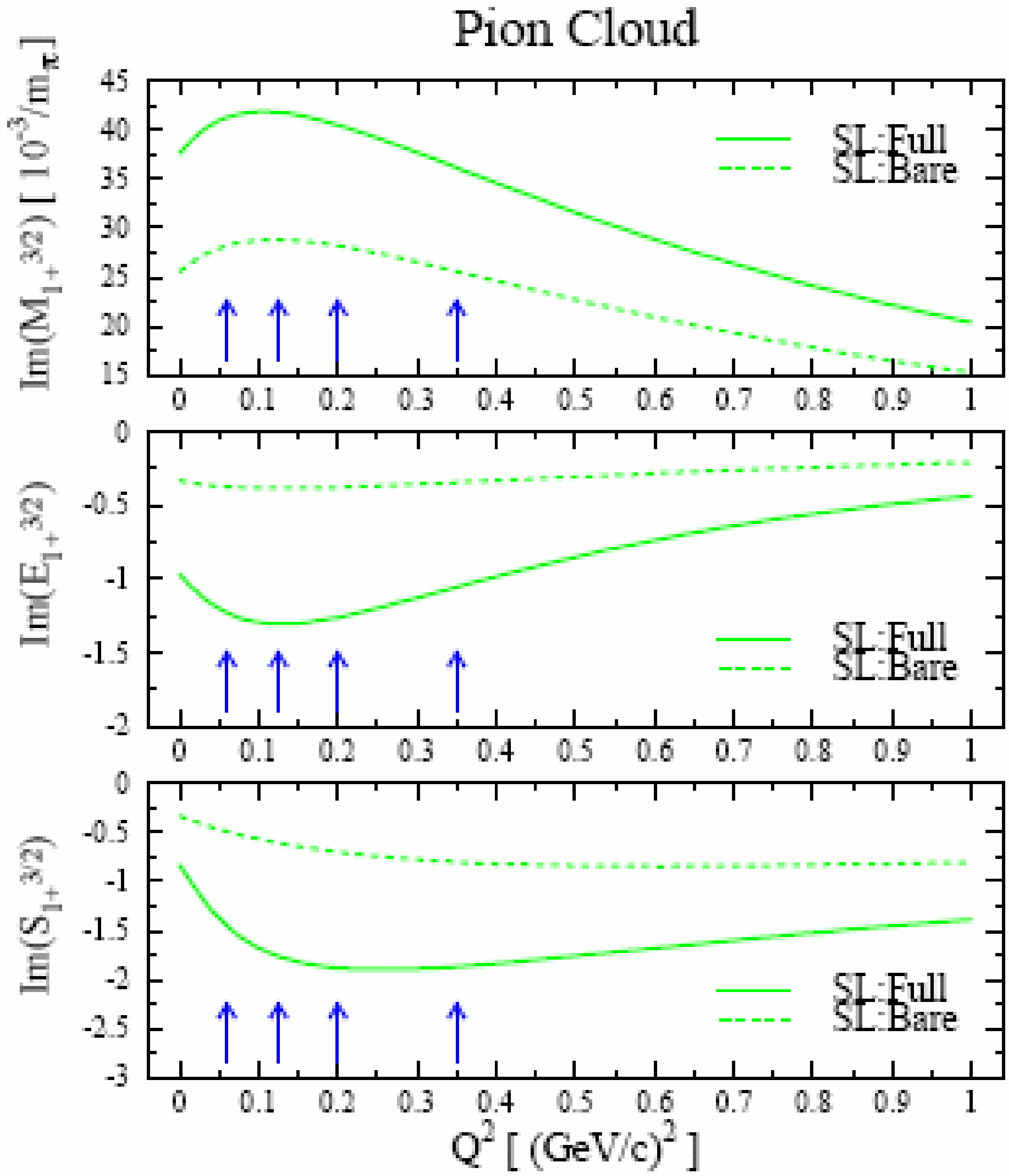
N. Sparveris et al

PRL **94**, 022003 (2005)



CNP Eur. Phys. J. A18, 141 (2003)

The role of the pion cloud

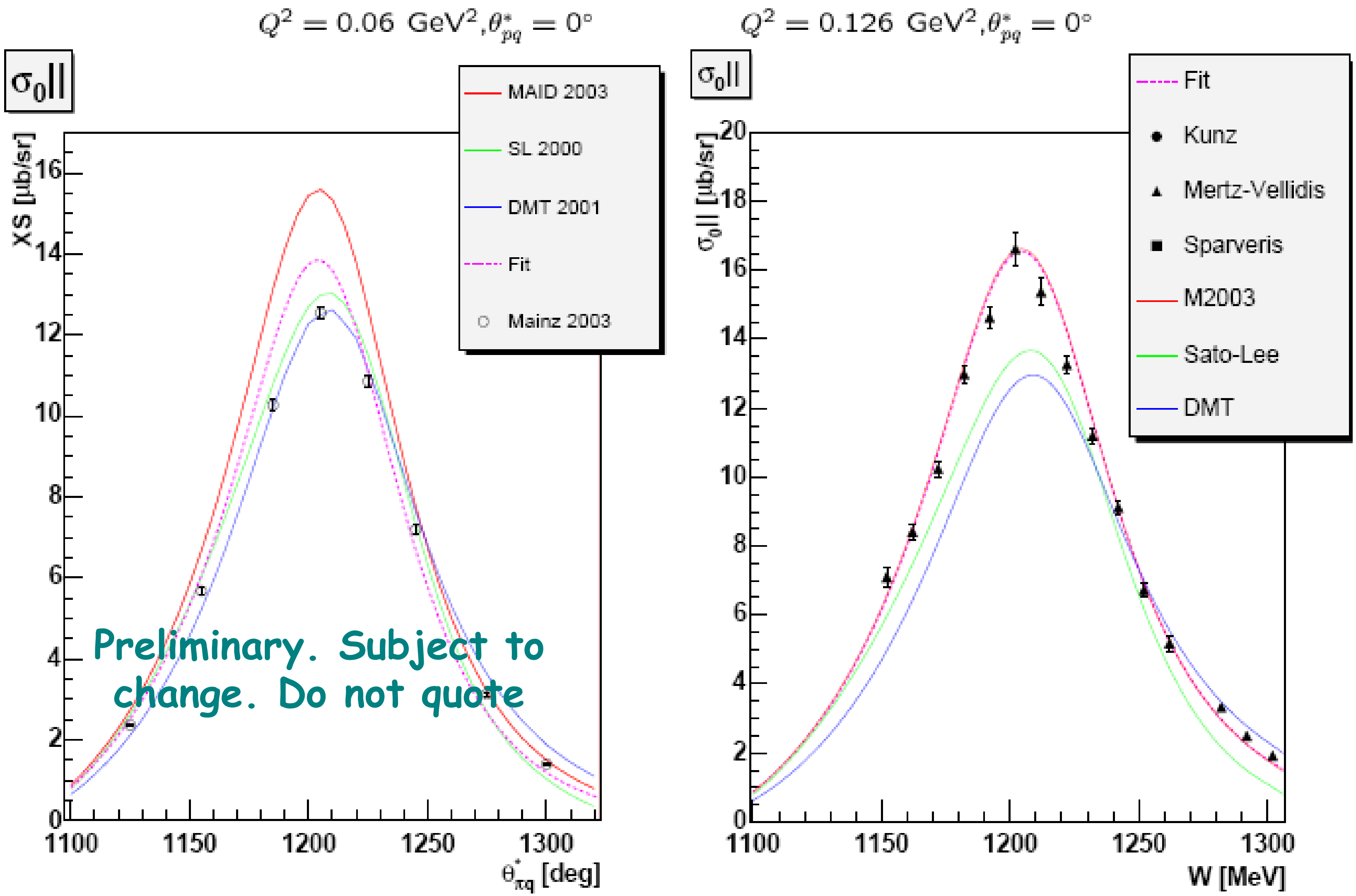


N → Δ program @ Mainz

CW beam

Parallel Cross section

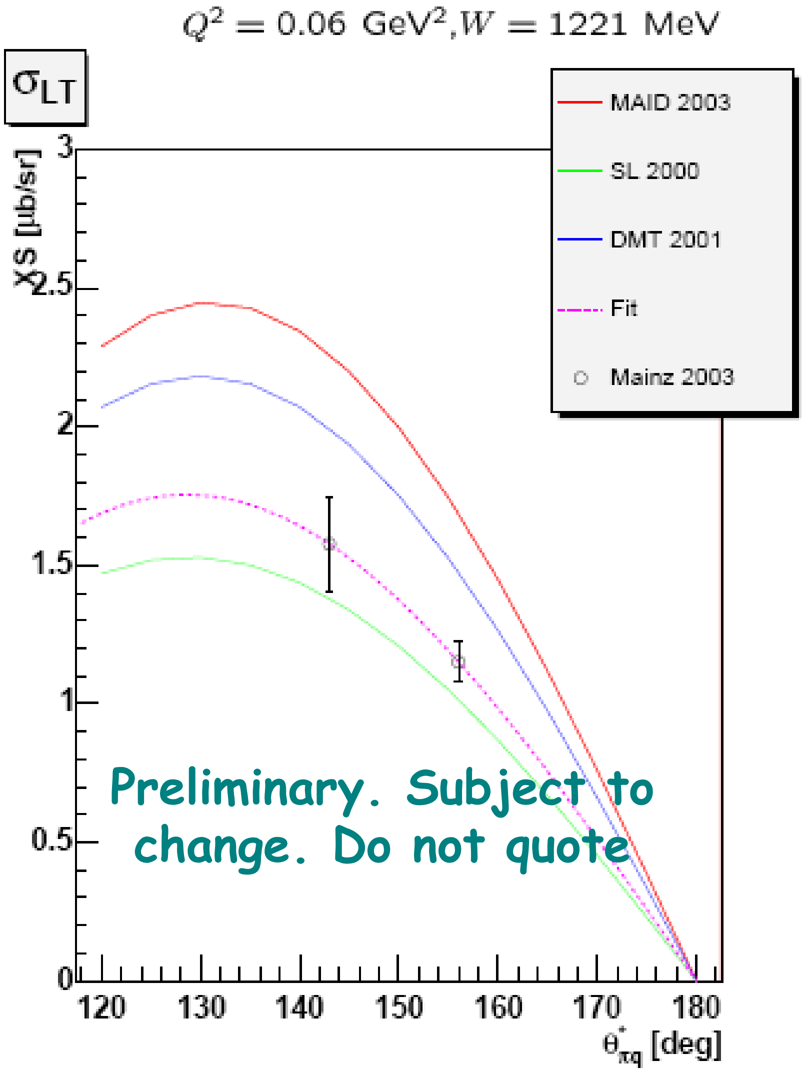
S. Stave PhD

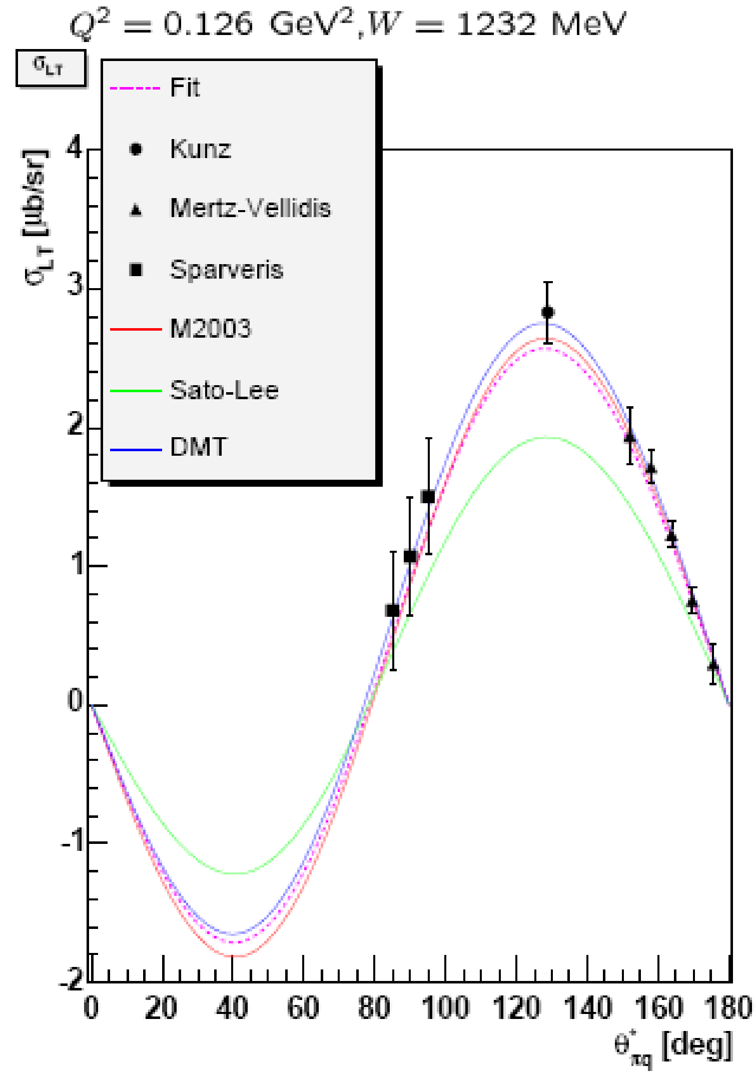


PRELIMINARY

Mainz Preliminary Results

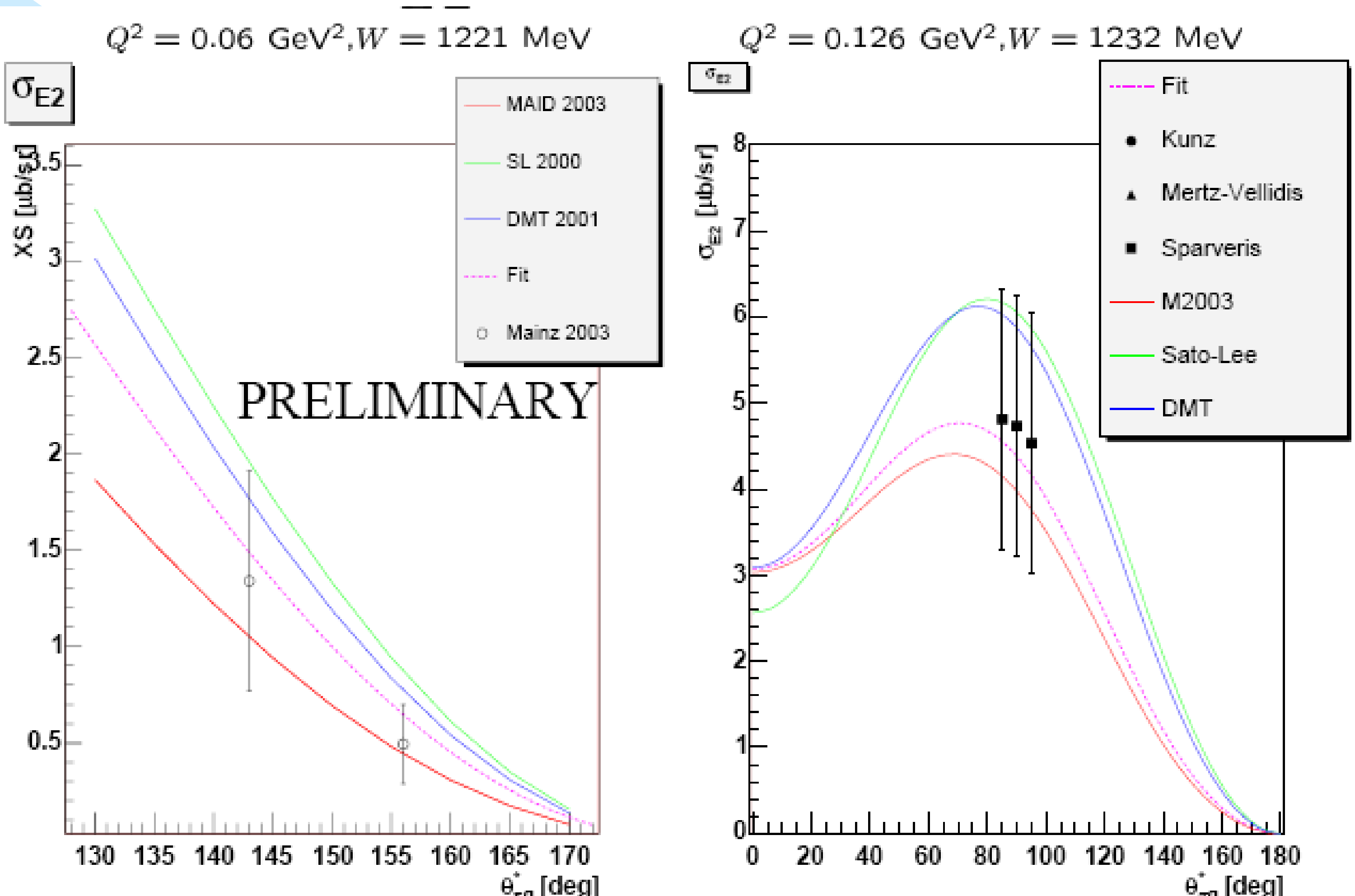
S. Stave PhD





PRELIMINARY

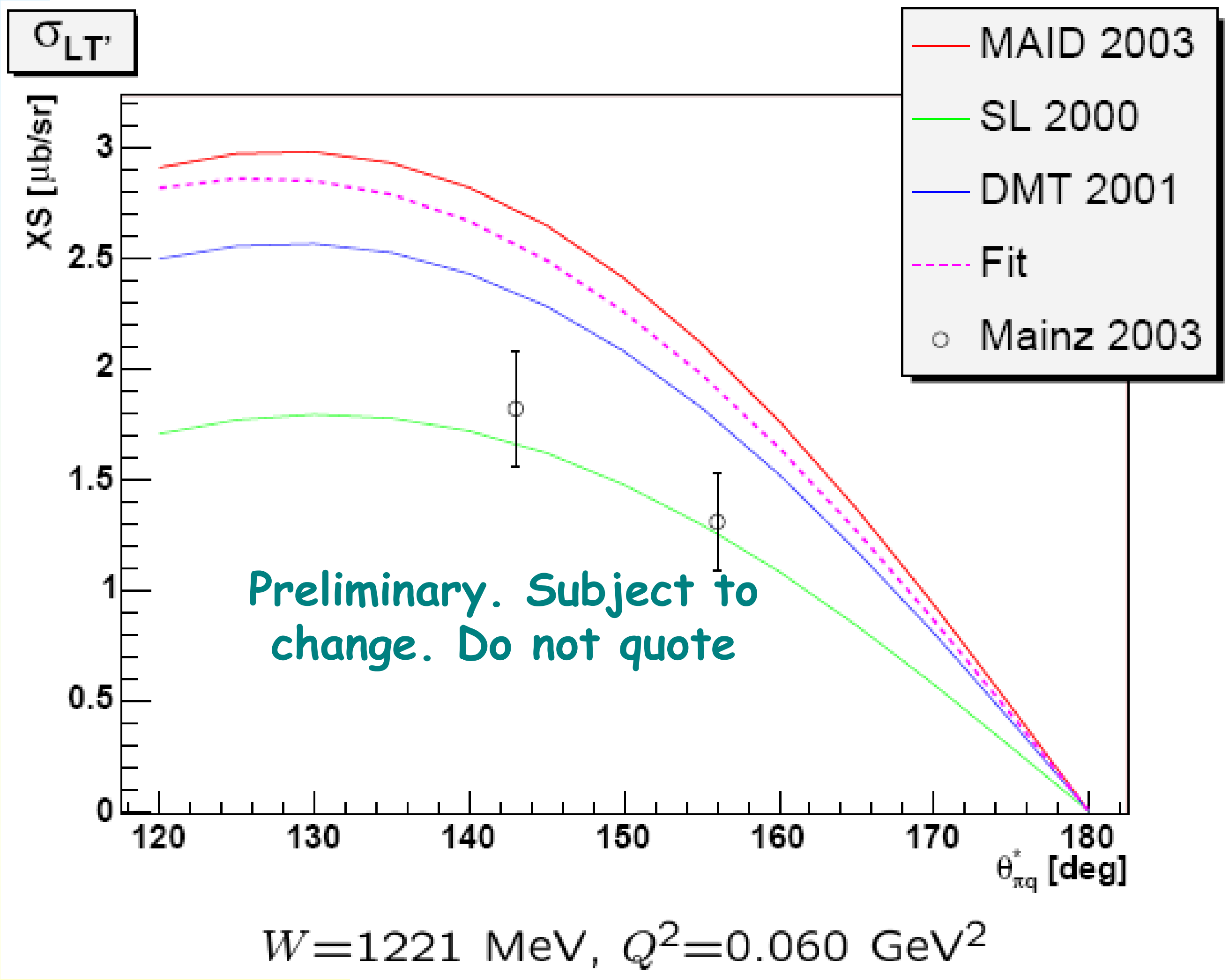
Mainz Preliminary Results



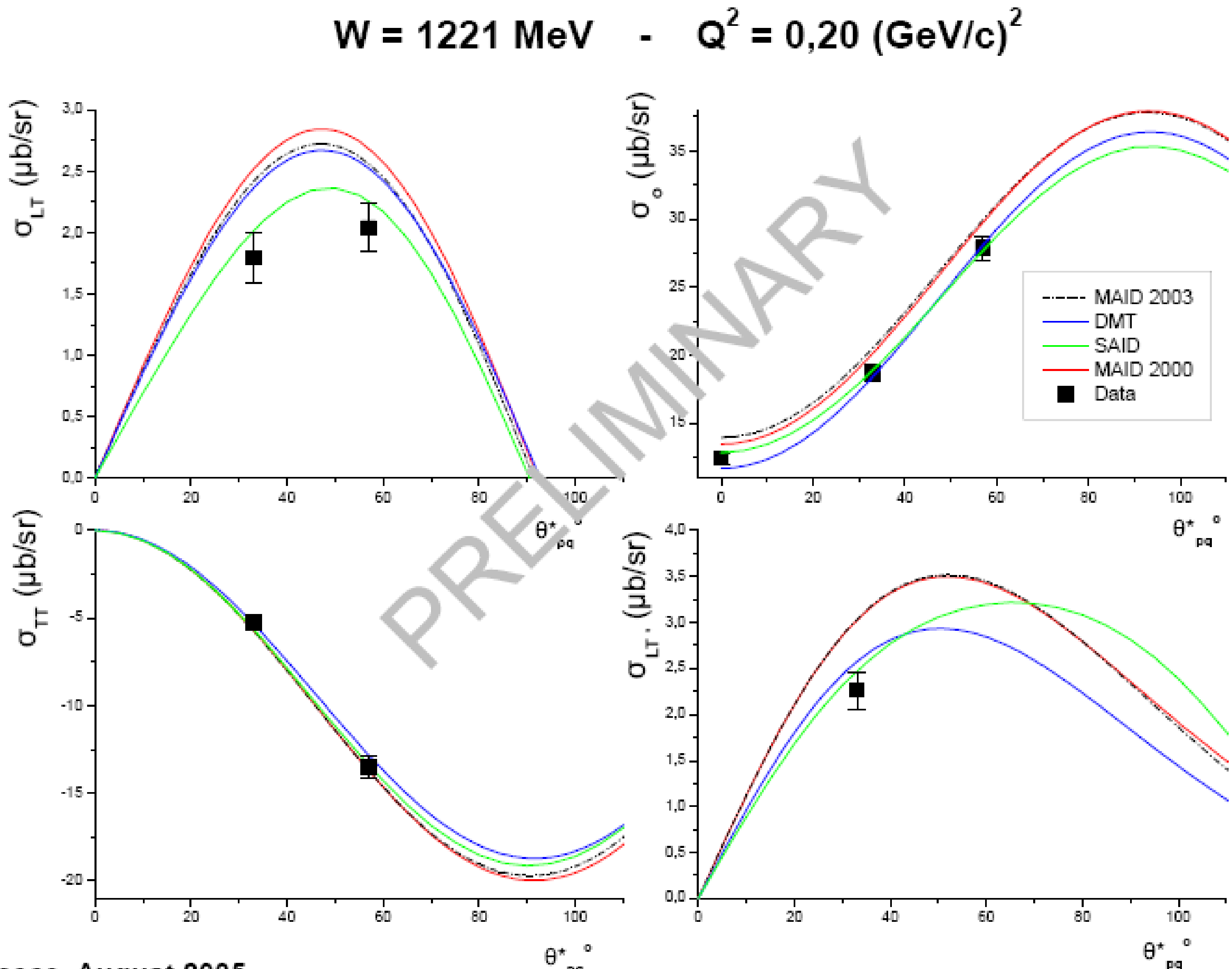
$$\begin{aligned}\sigma_{E2}(\theta^*_\pi) &= \sigma_0(\theta^*_\pi) + \sigma_{TT}(\theta^*_\pi) - \sigma_0(\pi) \\ &\approx 2(\cos\theta^*_\pi + 1)\mathrm{Re}\{E^*_{0+}M_{1+}\} \\ &- 12\sin^2\theta^*_\pi \mathrm{Re}\{E^*_{1+}M_{1+}\}\end{aligned}$$

S. Stave PhD

Mainz Preliminary Results



Mainz Preliminary Results



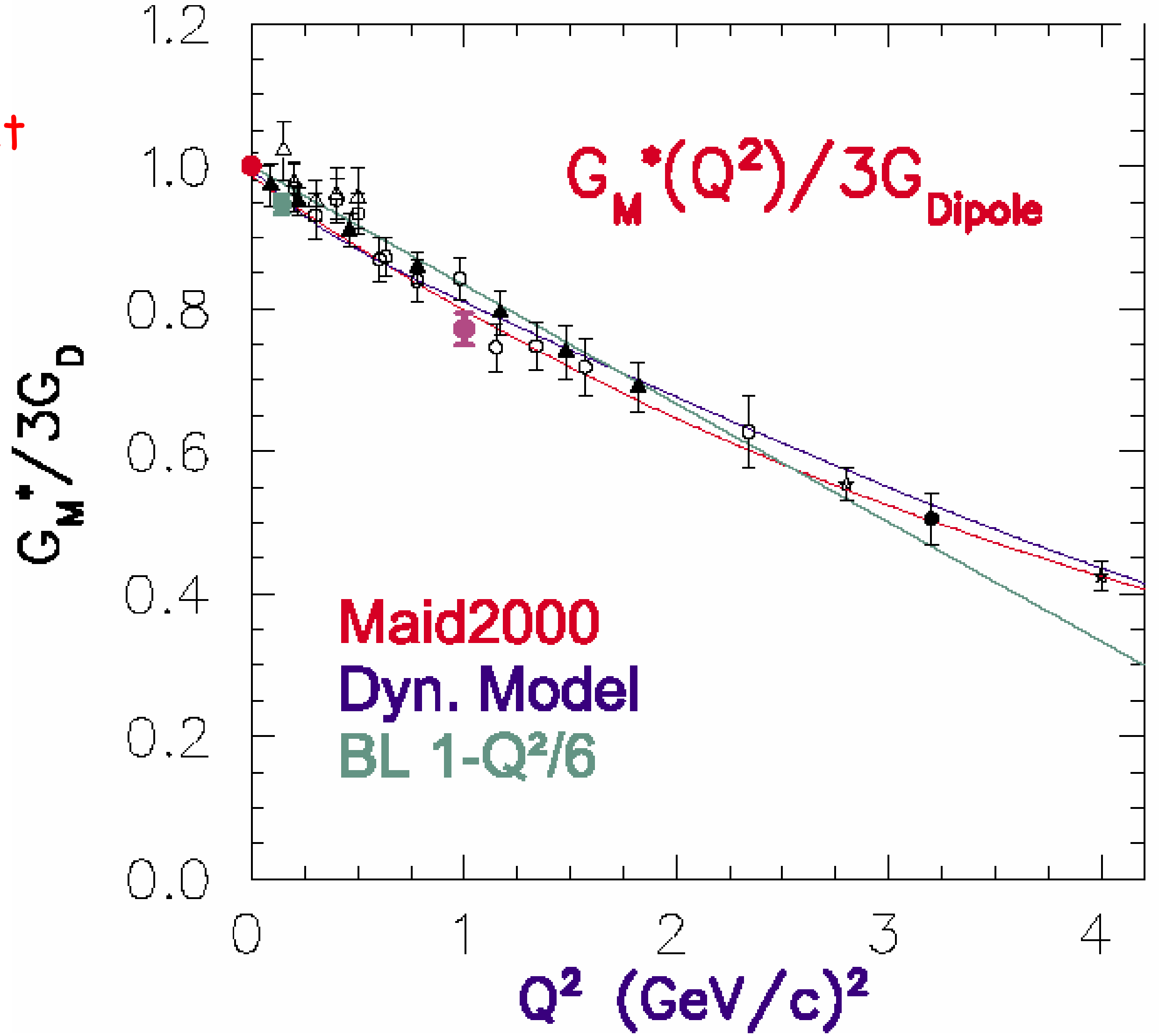
Greece, August 2005

M1 Transition Form Factor

$$G_M^*(0) = \sqrt{\frac{m_N}{m_\Delta}}\,\mu_{N\Delta} = 1.006 \pm 0.010$$

$$\mu_{N\Delta} = 3.46 \pm 0.03$$

Quark models predict
M1+ 30% too small



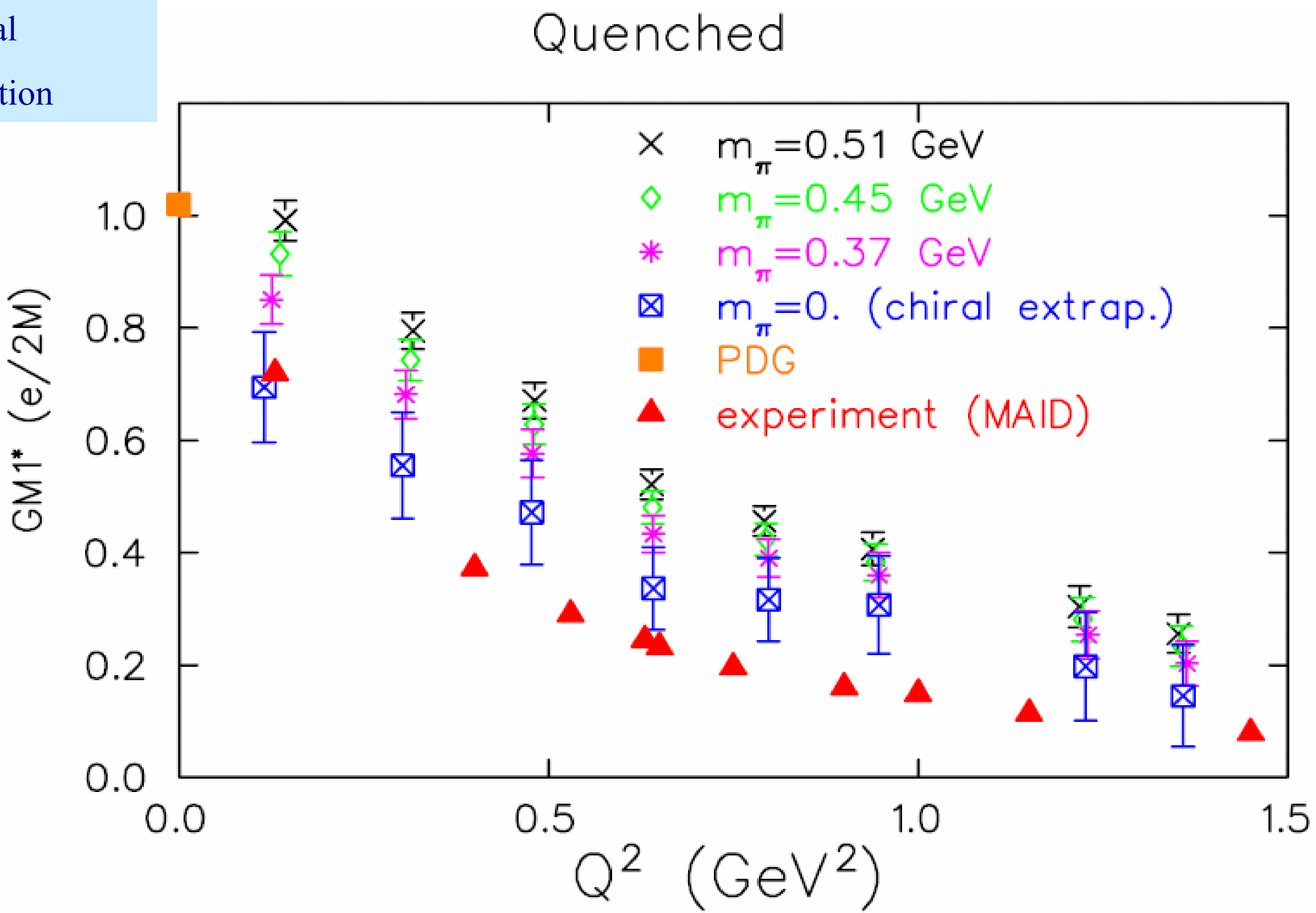
L.Tiator et al

Nucl. -Th/0012046

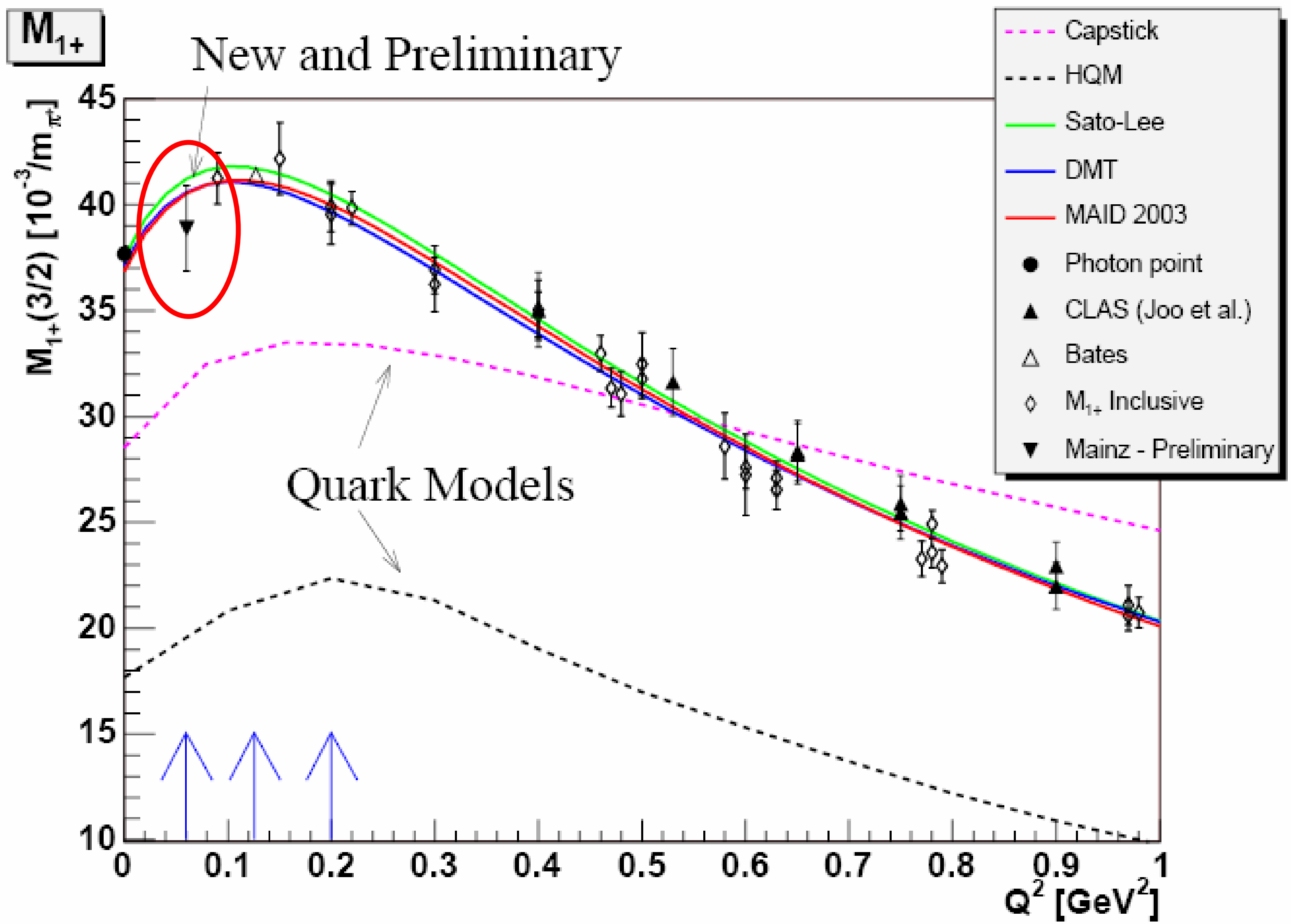
M1 Transition Form Factor

Alexandrou C. et al

Priv. Communication

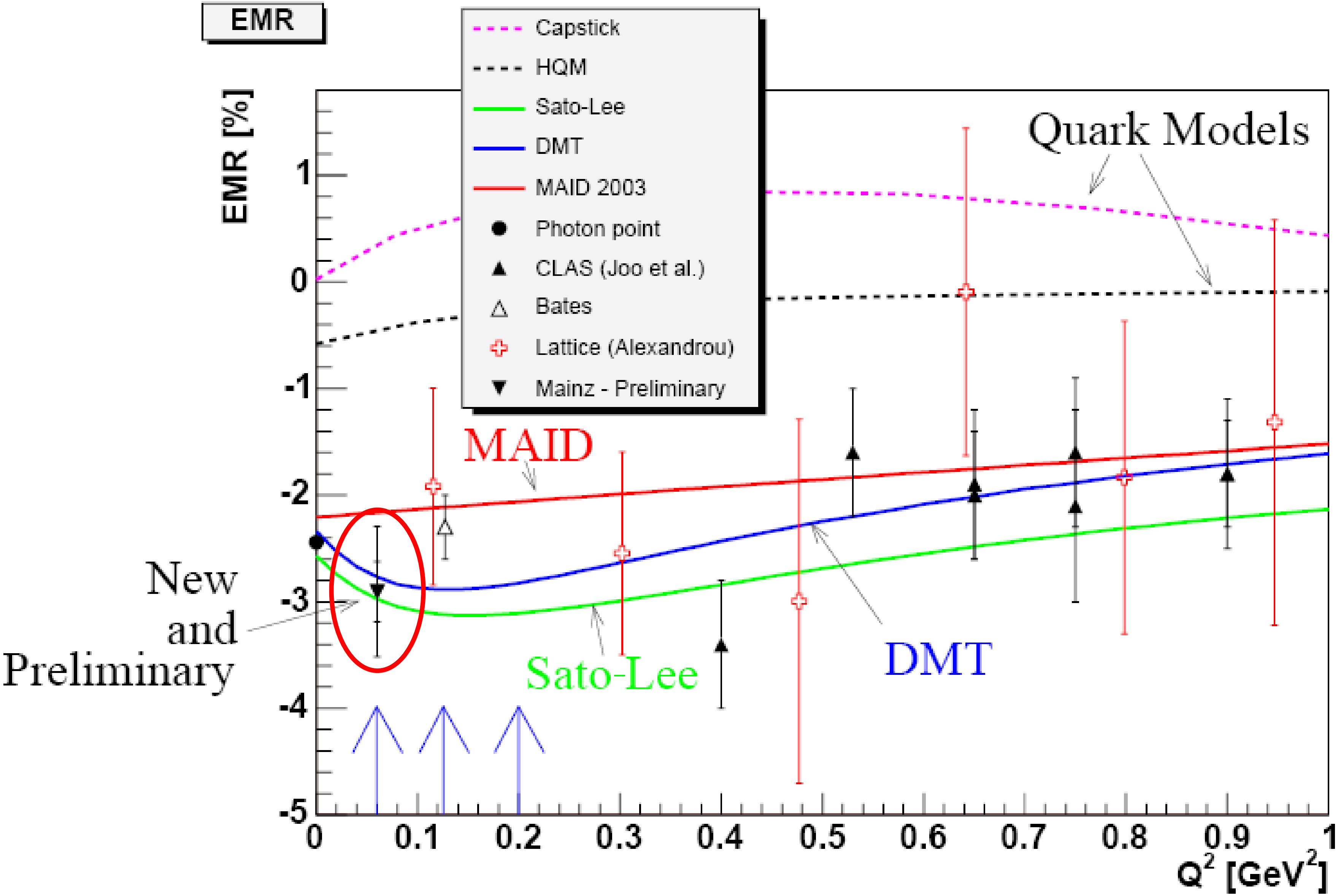


M1 Transition Form Factor



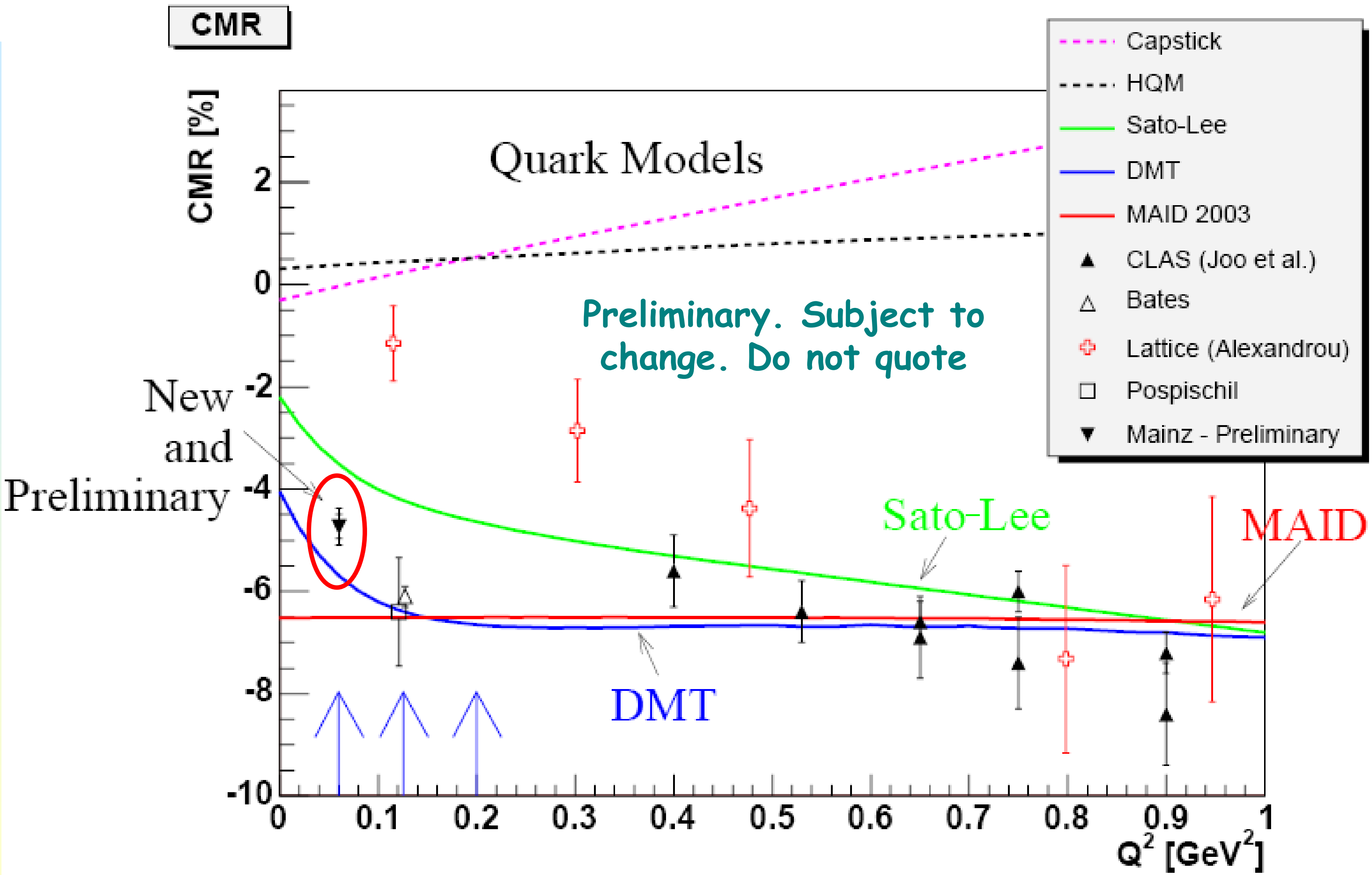
$W = 1232$ MeV

EMR



$W = 1232$ MeV

CMR

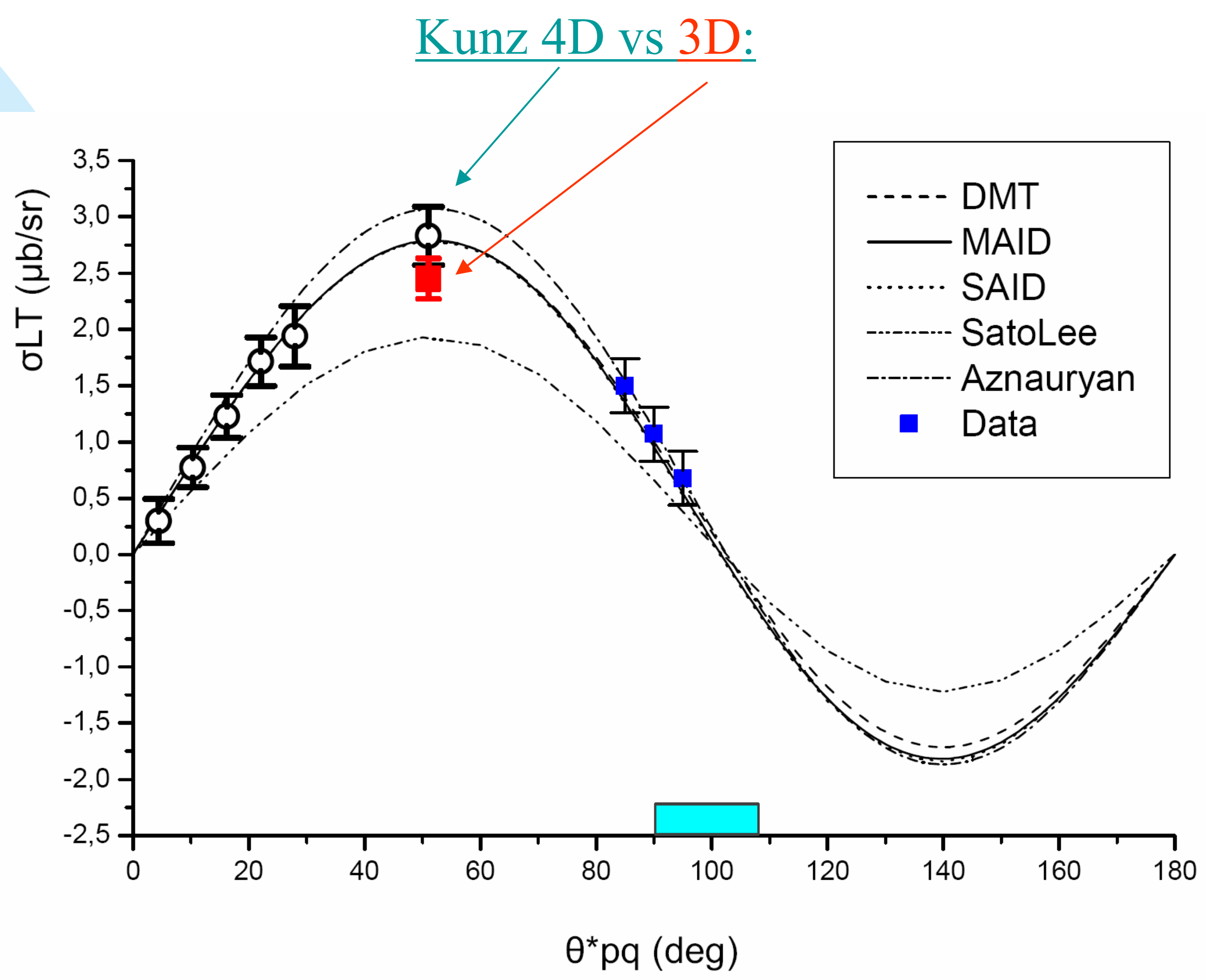


$W = 1232$ MeV

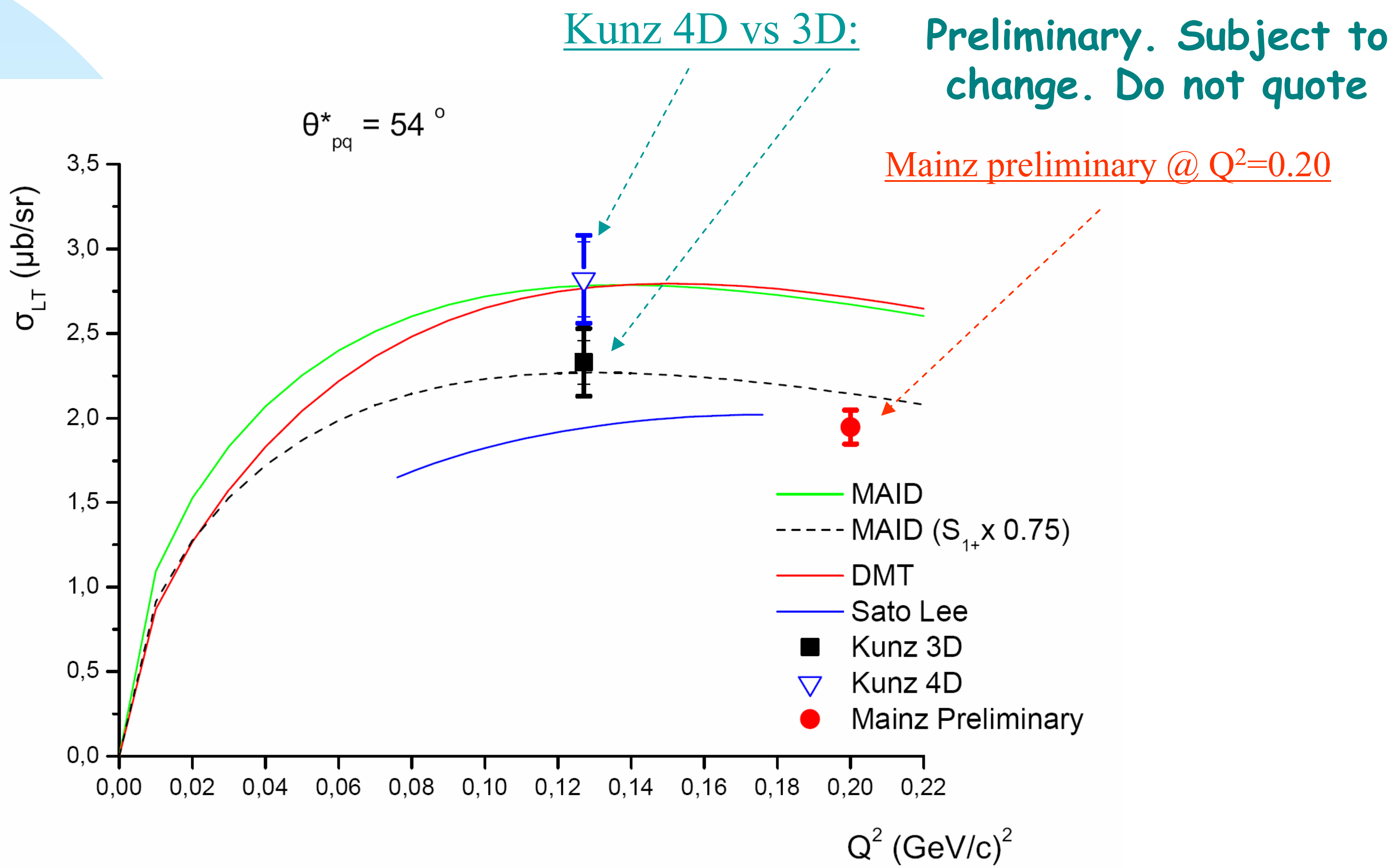
ISSUE #1 Comparison with CLAS and the Kunz point

- Is there a problem with the Kunz point?
- Can the disagreement between the CLAS and Bates be cured ?

Comparison of Kunz 3D and 4D LT results.



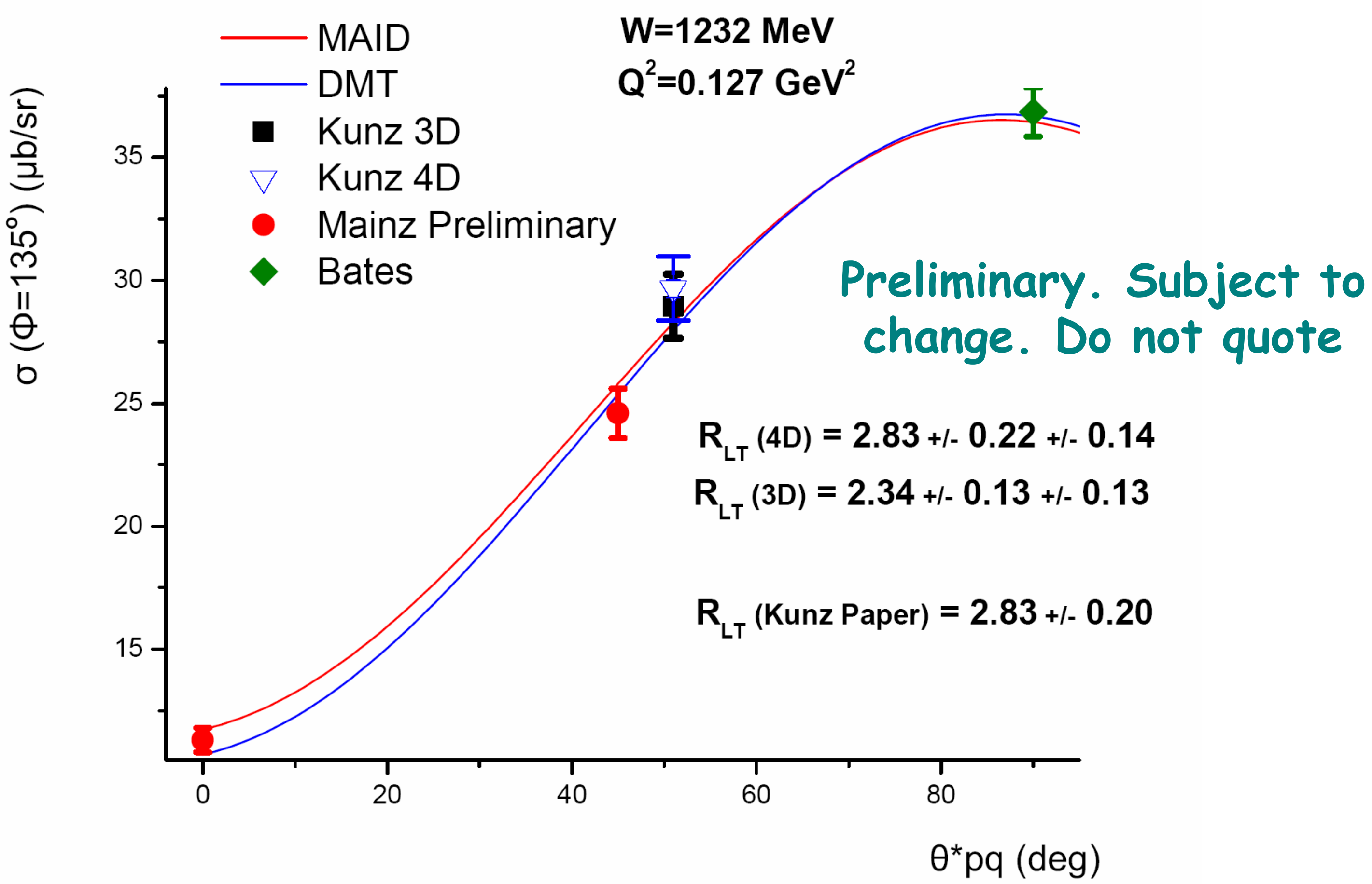
σ_{LT} as a function of Q^2 versus models



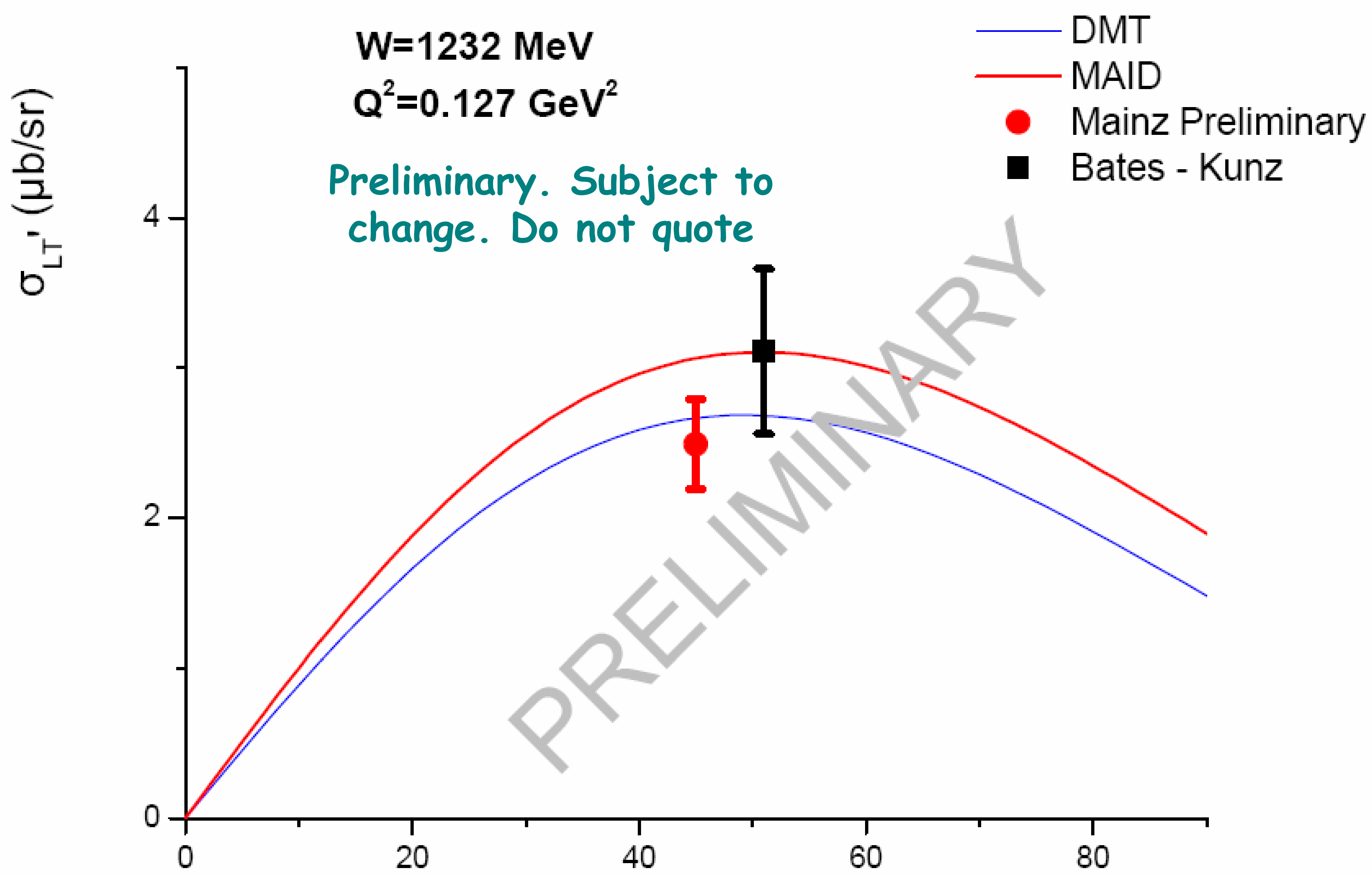
(Kunz results from 51° extrapolated to 54°)

(Mainz result from 57° extrapolated to 54°)

$\sigma(\Phi_{pq}=135^o)$ Bates & Mainz preliminary results

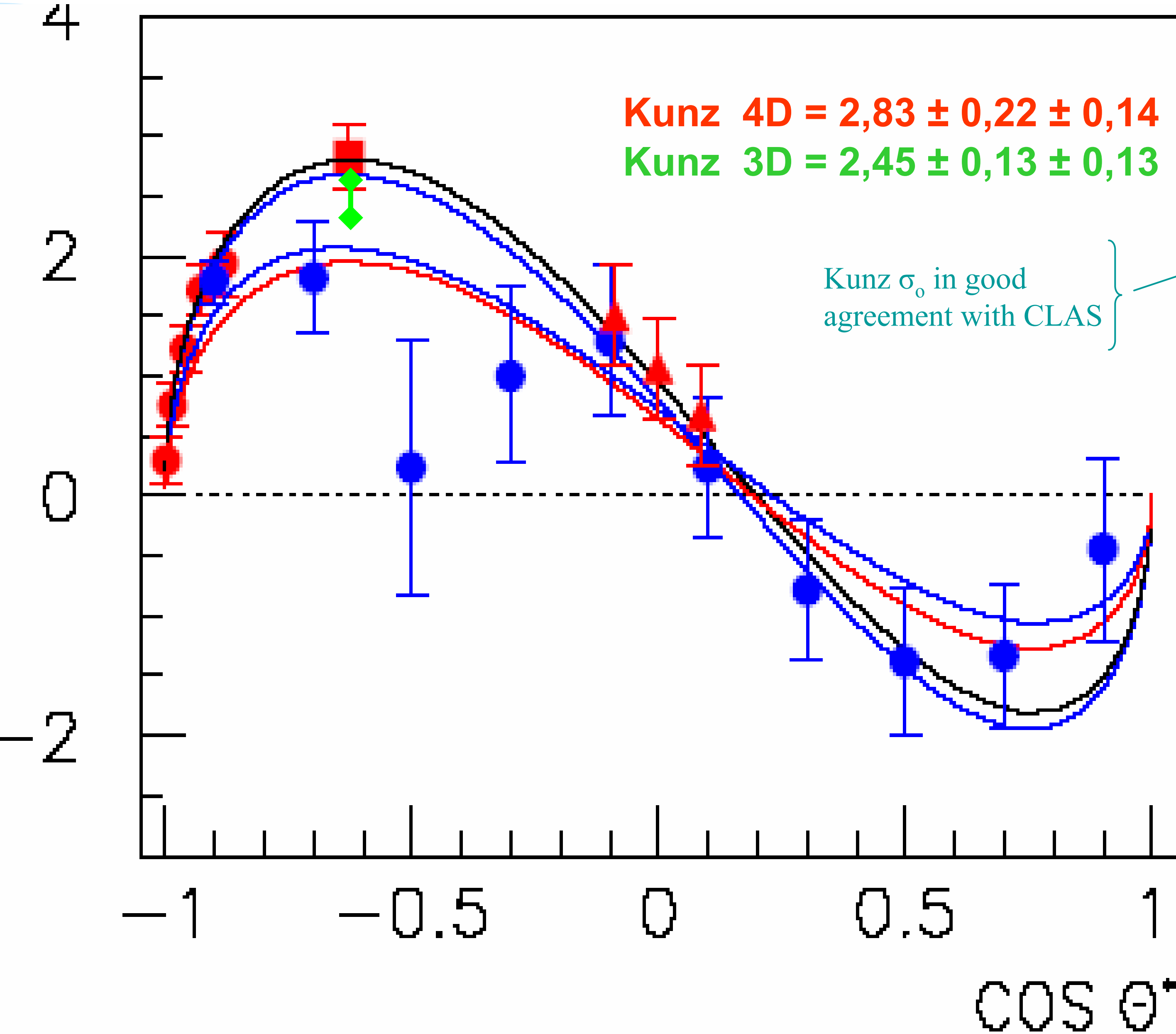


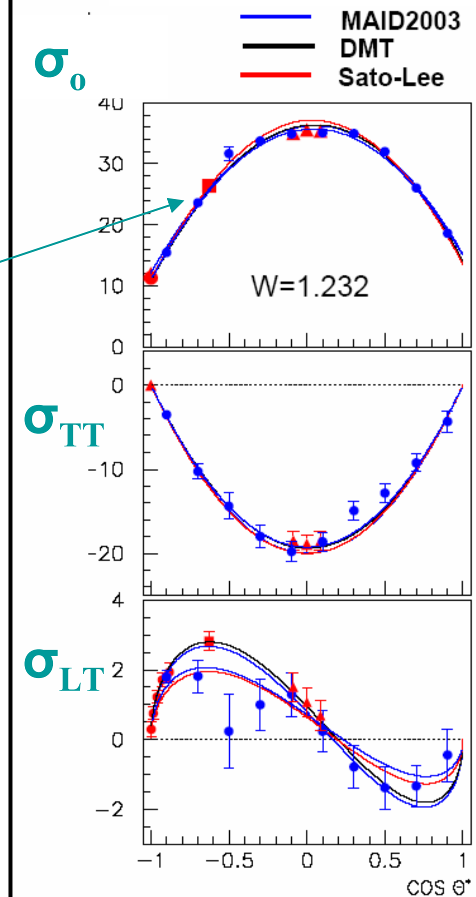
$\sigma_{LT'}$ kunz and Mainz preliminary



Comparison of kunz and CLAS

JLab
Bates





Mainz: Elsner et al (nucl ex/0507014)

	$\frac{\Re\{S^*_{1+}M_{1+}\}}{\lvert M_{1+}\rvert^2}$ (%)	$\frac{\Re\{S^*_{0+}M_{1+}\}}{\lvert M_{1+}\rvert^2}$ (%)
from eqs. (7,8)	-4.78±0.69	0.56±3.89
Maid2003 re-fit	$-6.15\pm1.40_{fit}$	$6.27\pm2.15_{fit}$
Maid2003	-6.65	7.98
Sato/Lee	-4.74	5.14

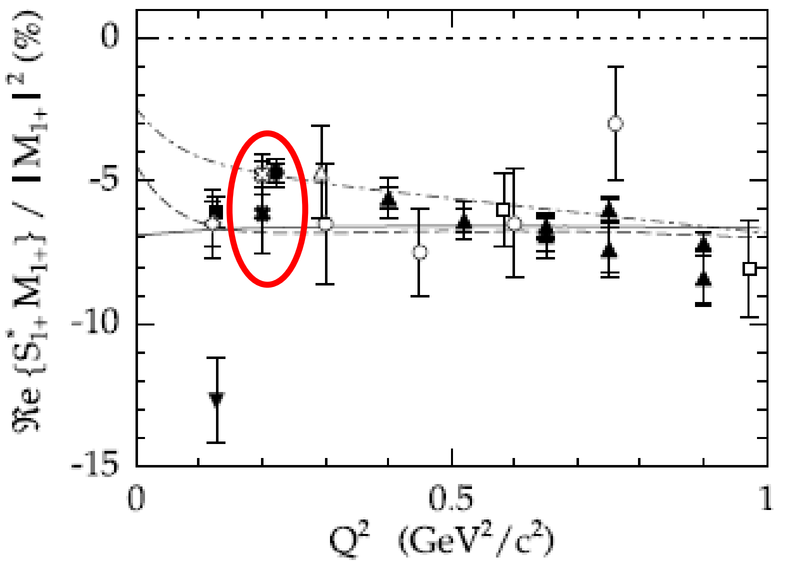


Fig. 4. Results for $\Re\{S^*_{1+}M_{1+}\}/|M_{1+}|^2$ with statistical and systematical errors as extracted from this experiment using both the approximation of eq. (7) (open cross) and the full MAID2003 analysis (full cross), compared to measurements. Data where only statistical errors are given: DESY [31] (open square), NINA [32] (open circles), Bonn synchrotron [40] (open triangle tip up) and ELSA [27] (full triangle tip down). Data, where statistical and systematical errors are given: ELSA [28] (full circle, to improve the presentation shiftet from Q^2=0.201 $(GeV/c)^2$ to Q^2=0.221 $(GeV/c)^2$), MAMI [24] (open diamond), CLAS [21] (full triangles) and BATES [29,30] (full square). The curves show model calculations MAID2003 [18] (solid), DMT2001 [12] (dashed) and Sato/Lee [13] (dashed dotted).

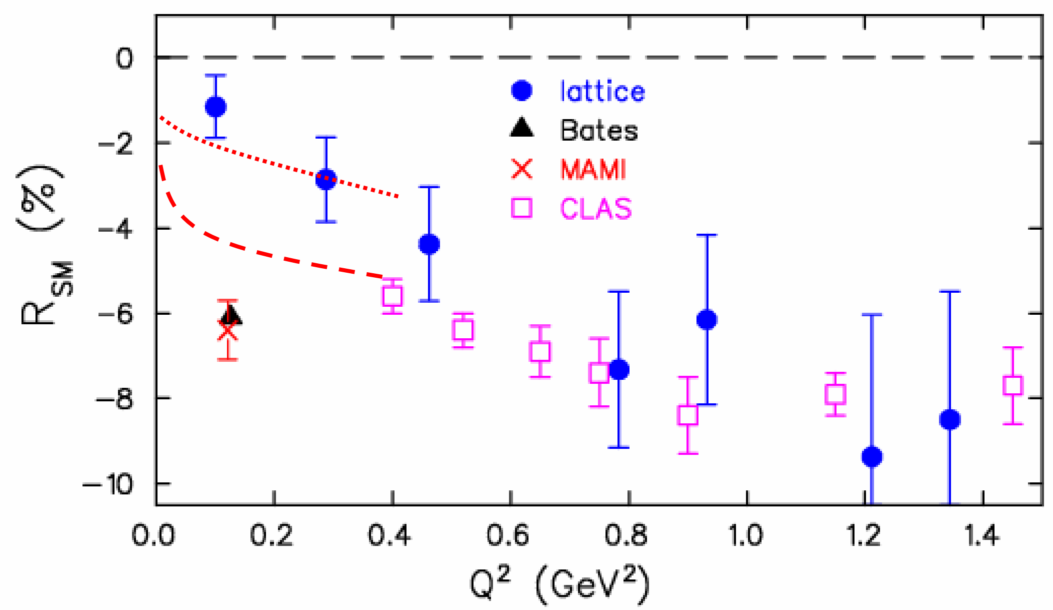
Lattice Results: CMR

Lattice Results **Alexandrou et al**
PRD **66**, (2002) 094503
PRL **94**, (2005) 021601

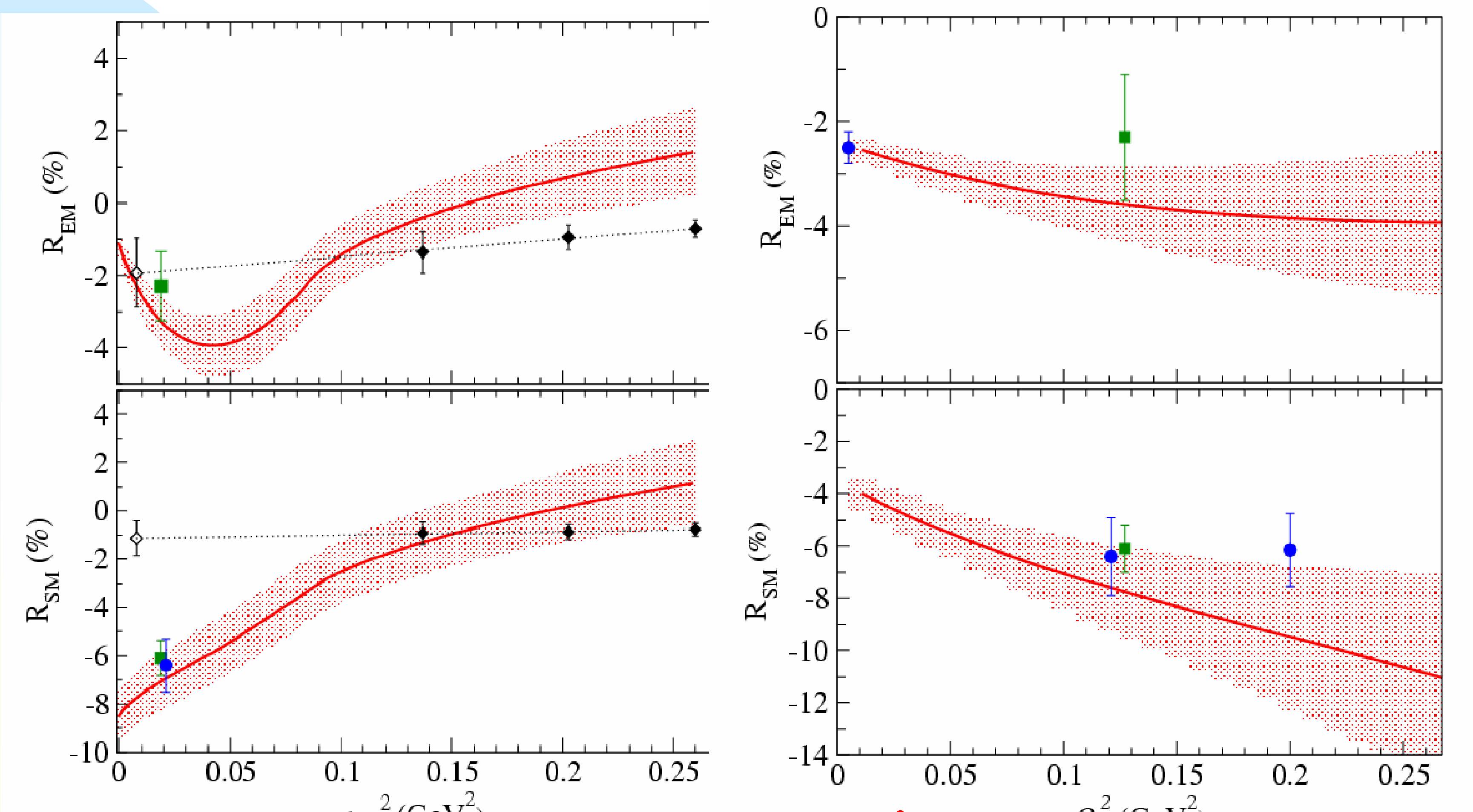
pQCD: **CMR** $\xrightarrow{Q^2\to\infty}$ **constant**

Linear extrapolation in m_π^2 to obtain results at the chiral limit

Discrepancy at low Q^2 where pion cloud contributions are expected to be important



Chiral extrapolation



NLO chiral extrapolation on the ratios using $m_\pi/M \sim \delta^2$, $\Delta/M \sim \delta$. G_{M1} itself not given.

V. Pascalutsa and M. Vanderhaeghen, hep-ph/0508060

Chiral perturbation expansion calculation (Pascalutcha & Vanderhaegen)

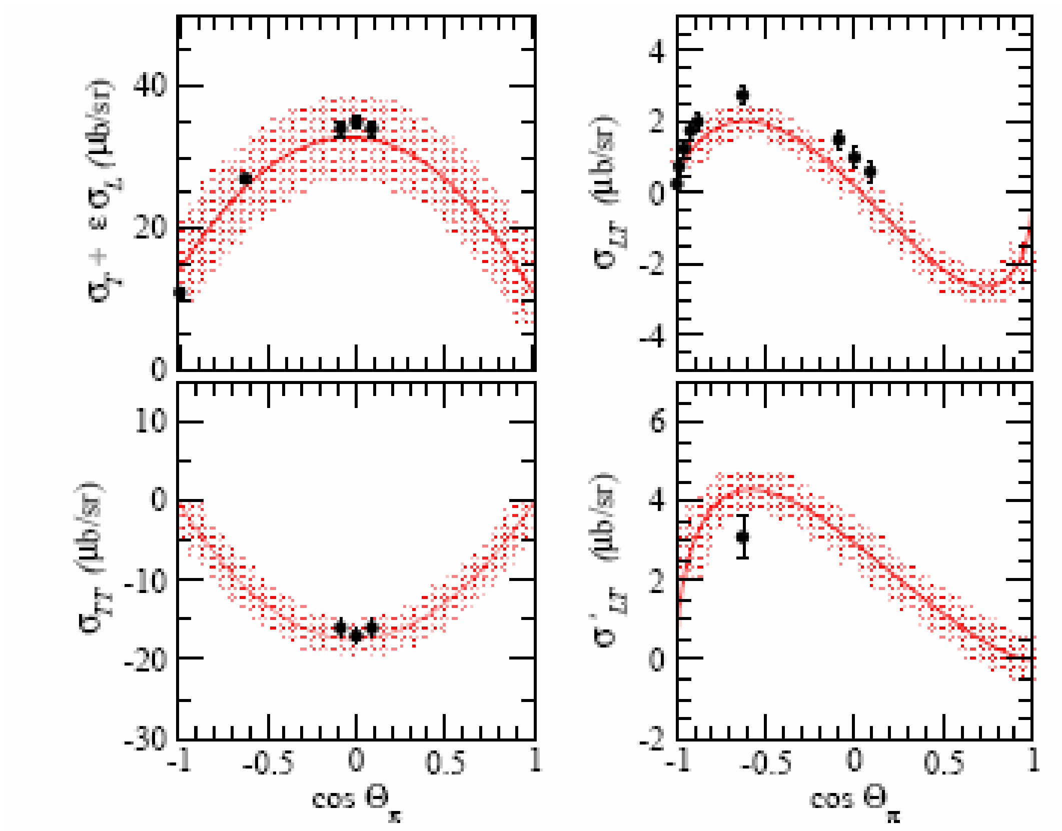
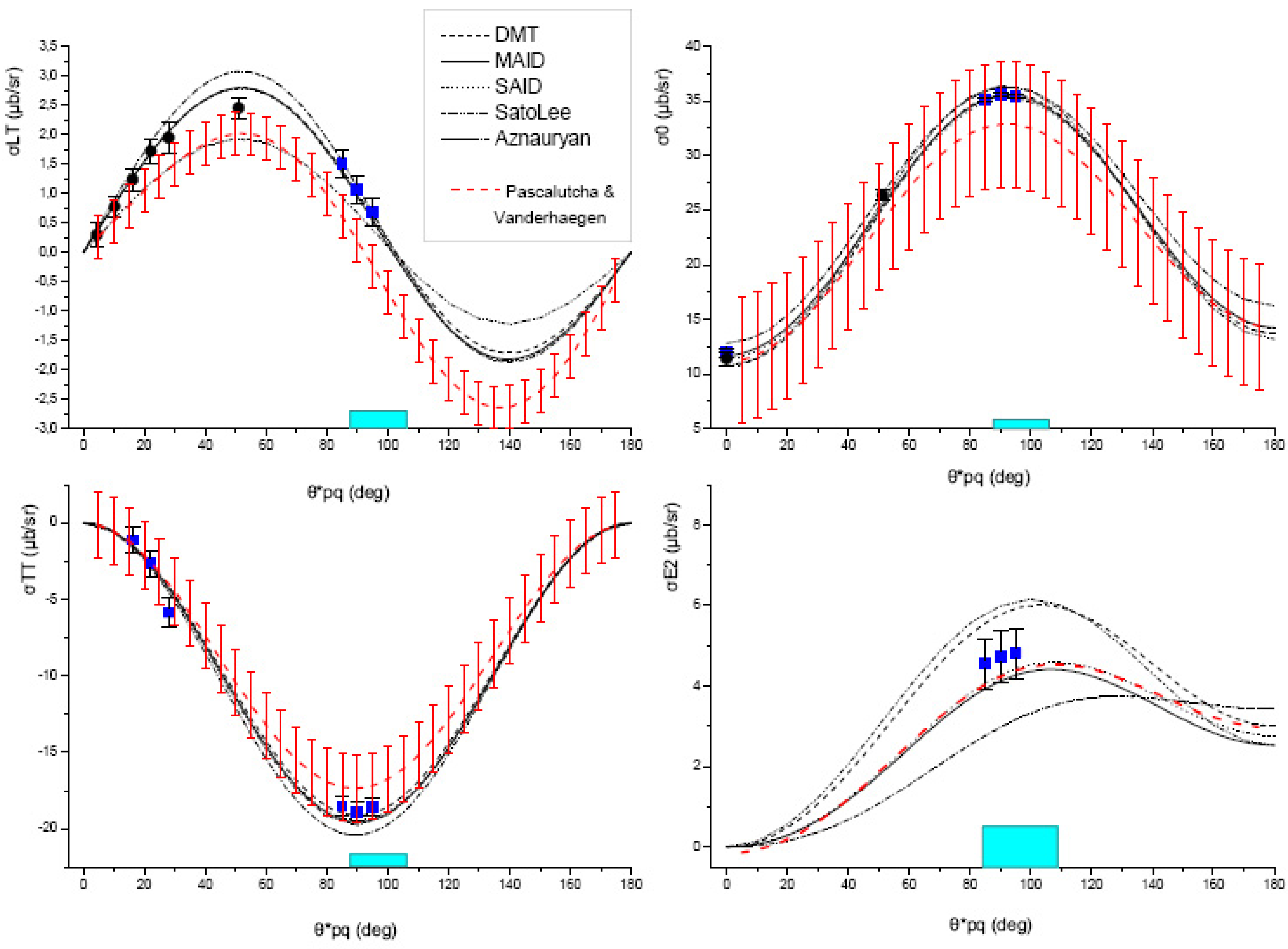


FIG. 2: (Color online) χEFT NLO results for the Θ_π dependence of the $\gamma^* p \to \pi^0 p$ cross sections at $\sqrt{s} = 1.232$ GeV and $Q^2 = 0.127$ GeV^2. The theoretical error bands are described in the text. Data points are from BATES experiments [3, 21].

Latest Compilation of Bates Data



Concluding Remarks on the N- Delta Program

Reduce Model Uncertainty

- Richer and of higher precision data basis
- Understand the Reaction Mechanism

Get the signature of the pion cloud

Q^2 dependence

Need improved phenomenology and theoretical calculations

Impressive progress in both theory & experiment
Precise results are emerging and access to the physics of interest for the first time is undisputed.

"The Shape of Hadrons"

Athens, Greece April 27-30 2006

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