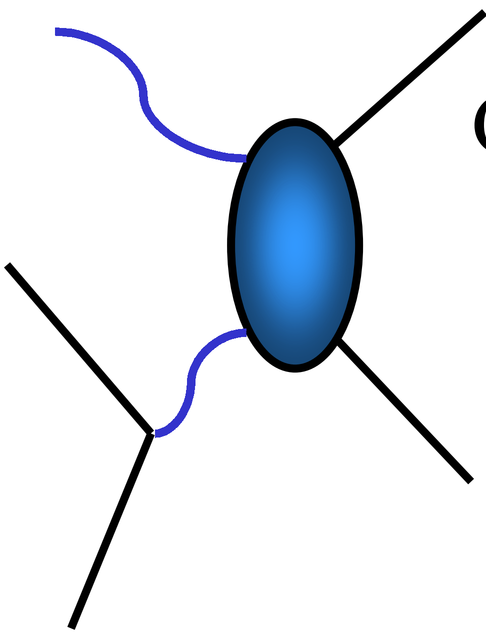
Workshop on Nucleon Form Factors
INFN-Frascati, Italy
12-14 October 2005

Recent Results in Real and Virtual Compton Scattering at Jefferson Lab



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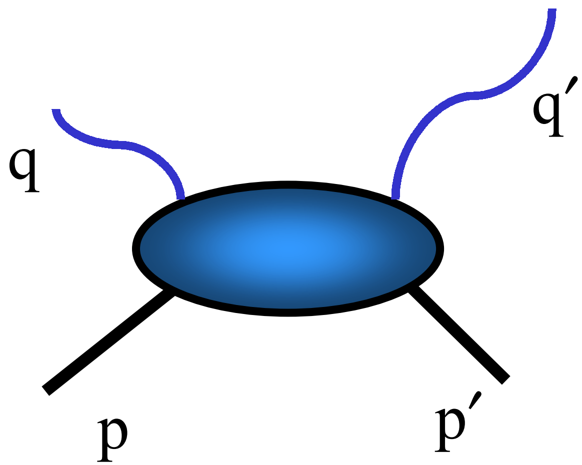
Compton Scattering

Different physics highlighted in different kinematic domains.



$s = (q+p)^2$,
$u = (p-q')^2$
$t = (q-q')^2$

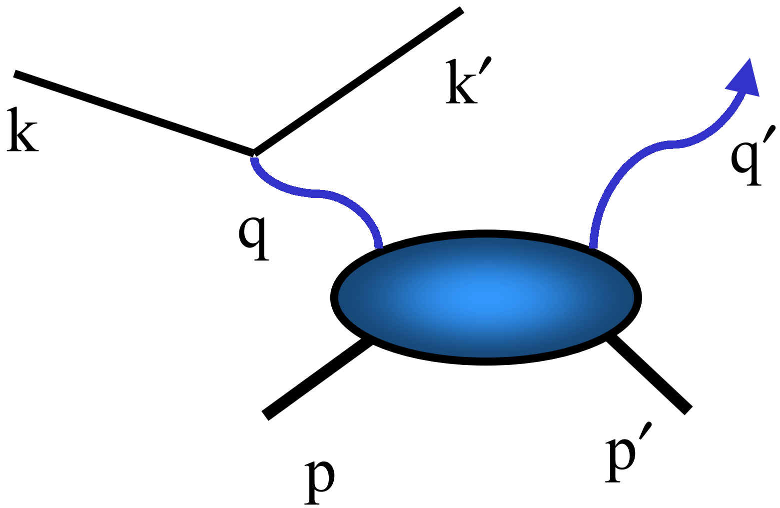
Real Compton Scattering

Forward limit
Dispersion Relations,

Low Energy Theorem:
GDH Sum Rule
Electric, Magnetic, & Spin Polarizabilities

High Energy,
Wide Angle Compton Scattering
$s-M^2,\ M^2-u,\ -t \gg \Lambda_{QCD}^2$

Virtual Compton Scattering



$s = (q+p)^2$,
$Q^2 = -q^2$,
$u = (p-q')^2$
$t = (q-q')^2$

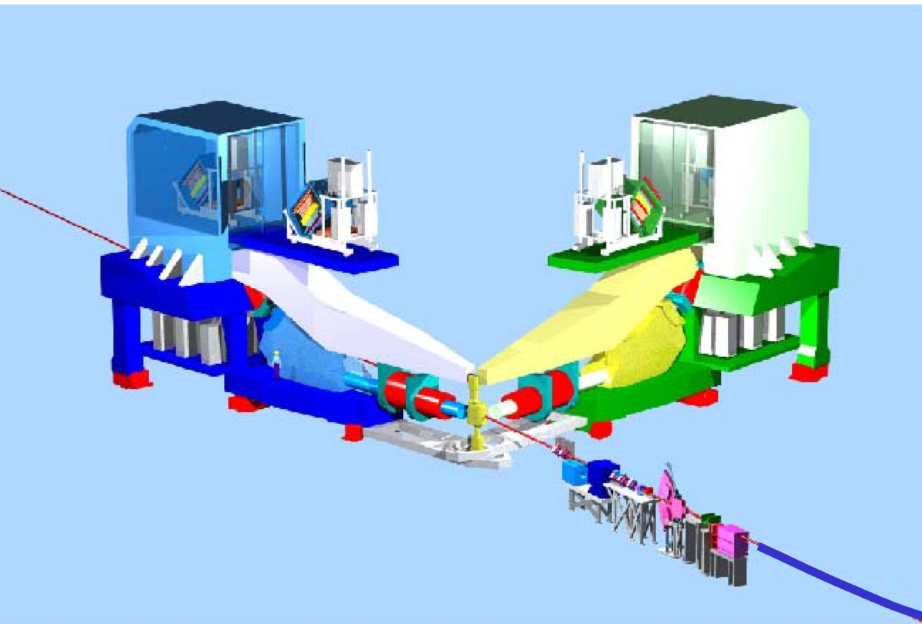
Low Energy Theorem:
(P. Guichon et al)
Generalized Polarizabilities
Dispersion Relations,
(B. Pasquini et al)

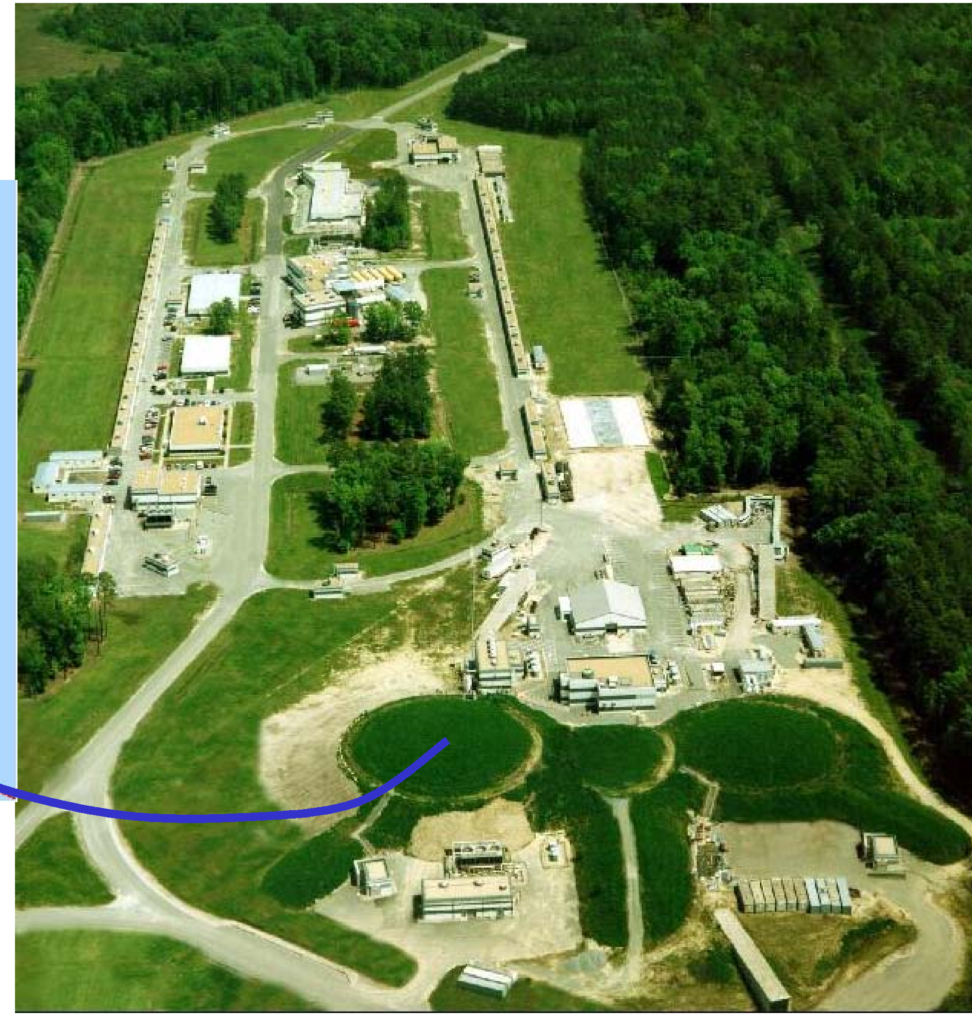
Deeply Virtual Compton Scattering
$s\text{-}M^2,\ Q^2 >> \Lambda_{QCD}{}^2$
$-t << Q^2$
Generalized Parton Distributions
Spatial imaging of quarks & gluons

Wide angle Compton Scattering
$s, Q^2, -t$ large, no constraint on u.

Jefferson Lab
Continuous Electron Beam Accelerator Facility

Hall A
High Resolution Spectrometers (HRS^2)



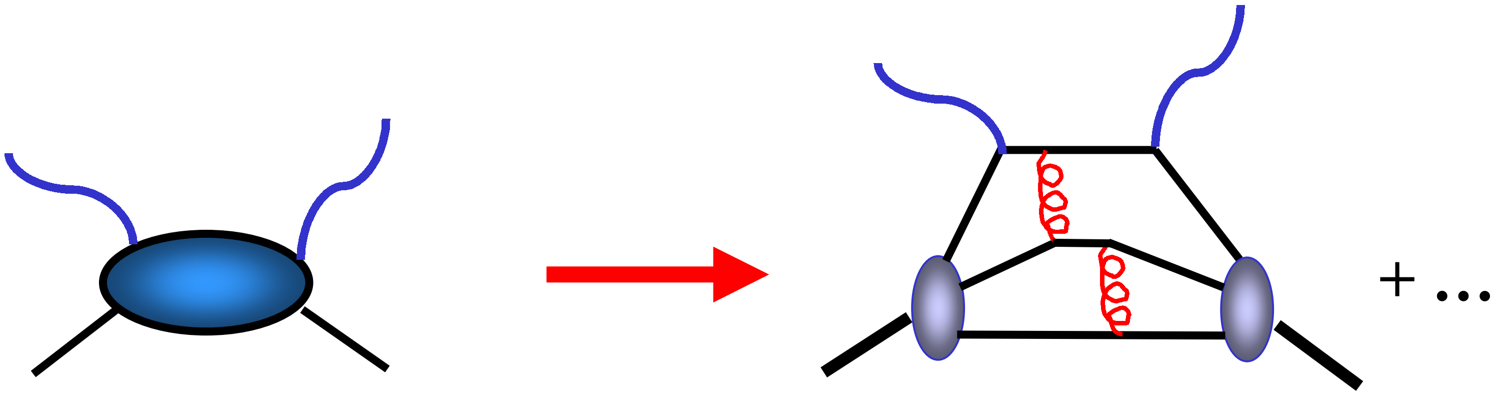


VCS: H(e,e'p)X
100μA e^- on 15 cm liquid H_2 target

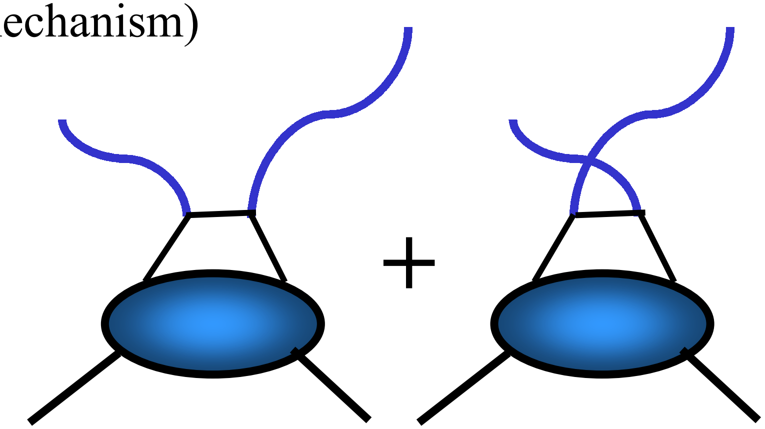
RCS: H(γ,γ'p)
≤ 40μA e^- on Cu radiator + 15 cm liquid H_2 target

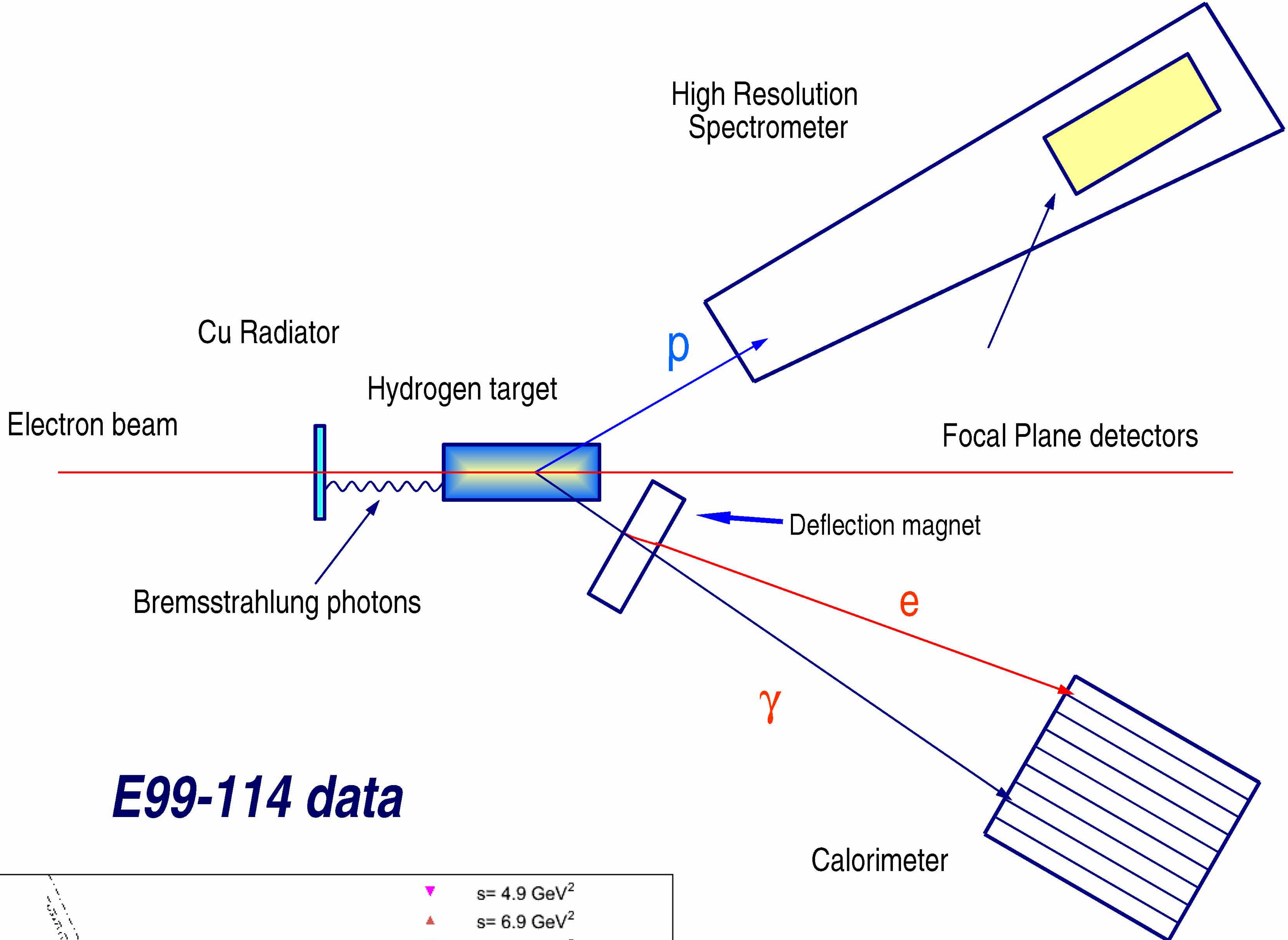
Wide Angle Compton Scattering

- Asymptotic limit: $s\text{-}M^2,\ -t,\ M^2\text{-}u \rightarrow \infty$ …
  - "pure" Perturbative QCD (G.Farrar & S.J.Brodsky…)



- Sub-asymptotic: $s\text{-}M^2,\ -t,\ M^2\text{-}u \leq 10\ \text{GeV}^2$
  - Conjecture: Handbag dominance (Feynman mechanism)
  - Radyushkin, Kroll: Factorized ansatz (GPD).
    - Quark propagator $(xP+k_\perp+q)^2 \rightarrow xP\cdot q$
  - G.Miller, unfactorized
    - Exact Klein-Nishina amplitude
      - Constituent Quarks
    - Wave function ansatz

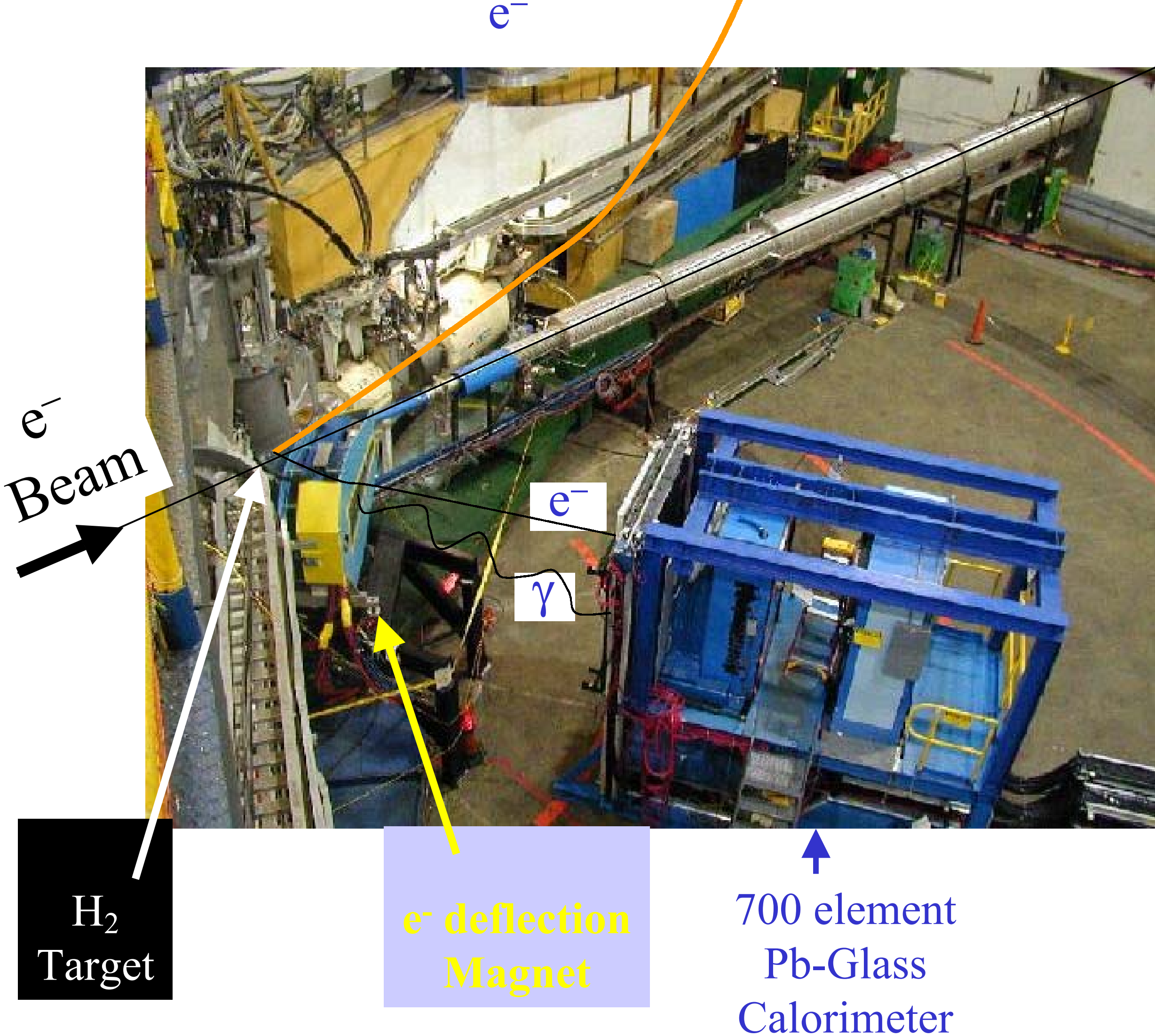



High Resolution
Spectrometer
Cu Radiator
p
Hydrogen target
Electron beam
Focal Plane detectors
Deflection magnet
Bremsstrahlung photons
e
γ
Calorimeter

E99-114 data


s= 4.9 GeV^2
s= 6.9 GeV^2
s= 8.9 GeV^2

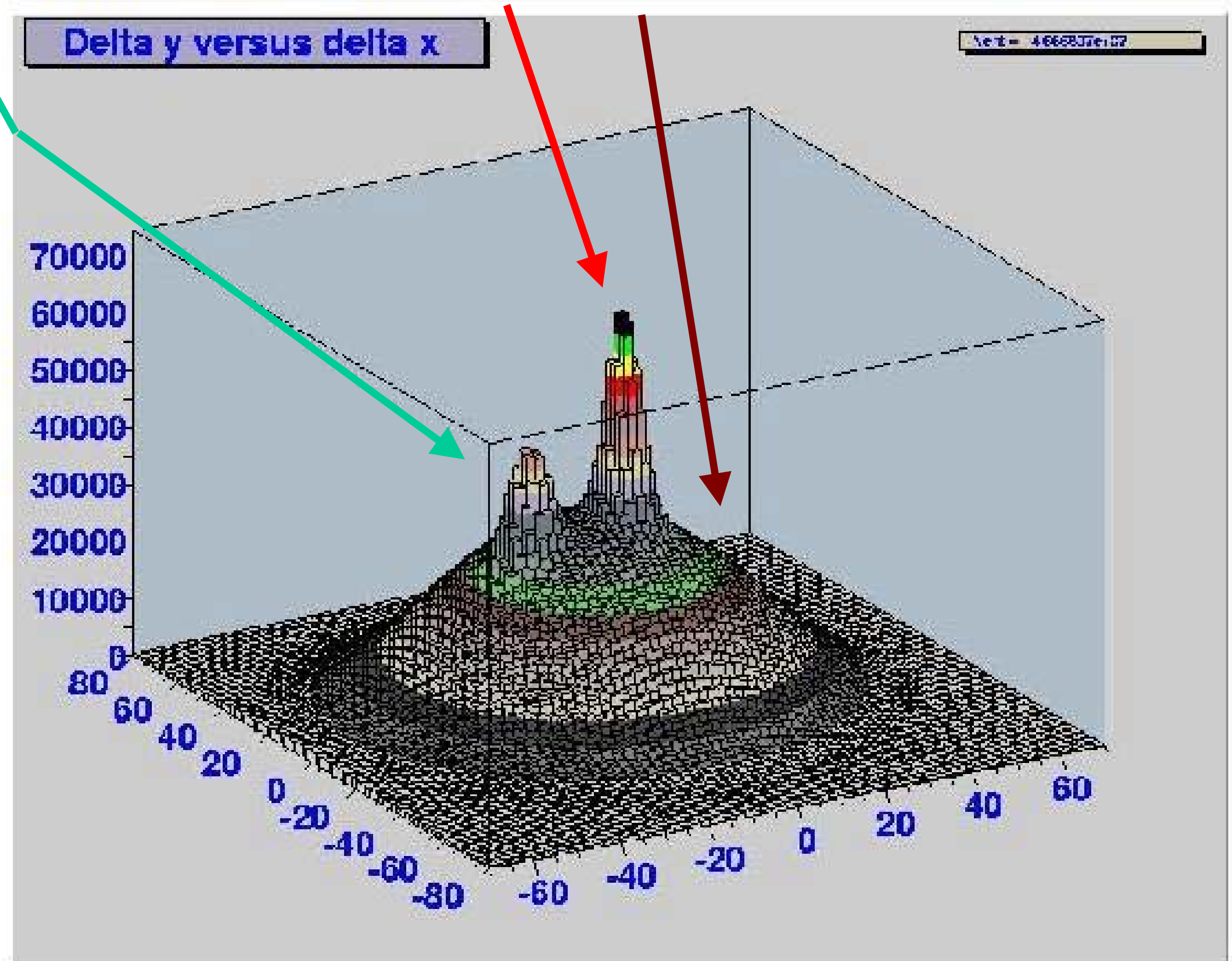
Jefferson Lab E99-114
H(γ,γ)p



- 10-40μA beam on 6% radiator and 1g/cm² H_2 (mixed γ+e beam)
- Recoil Proton detected in HRS
  - Focal Plane Polarimeter
- Scattered photon detected in 700 element Pb-Glass array
- Scattered electron deflected by magnet and detected in Pb-Glass.

Electron, Compton, π^0 events

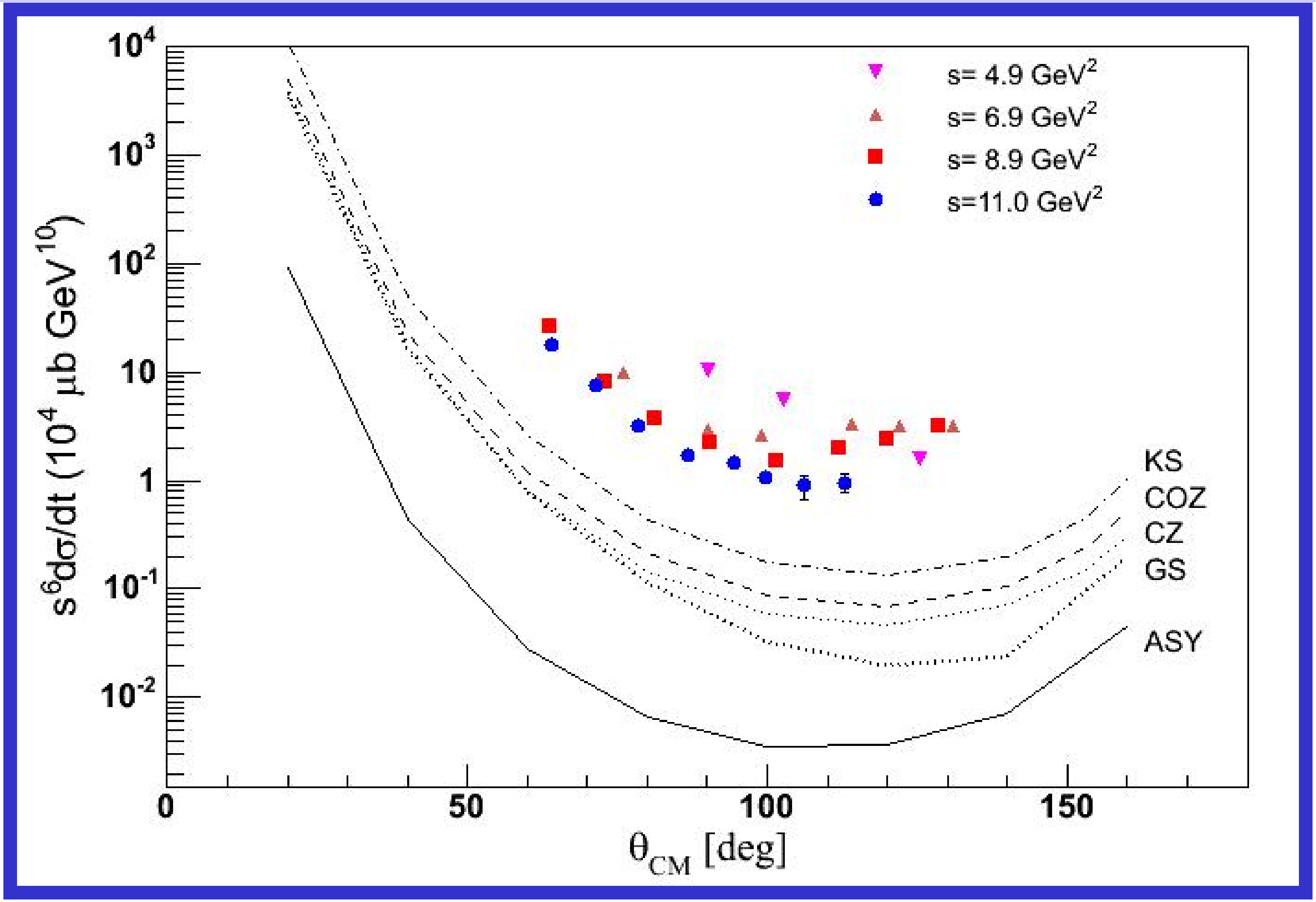
- 2-D plot of position of EM shower, relative to elastic prediction from recoil proton kinematics



RCS Differential Cross Sections

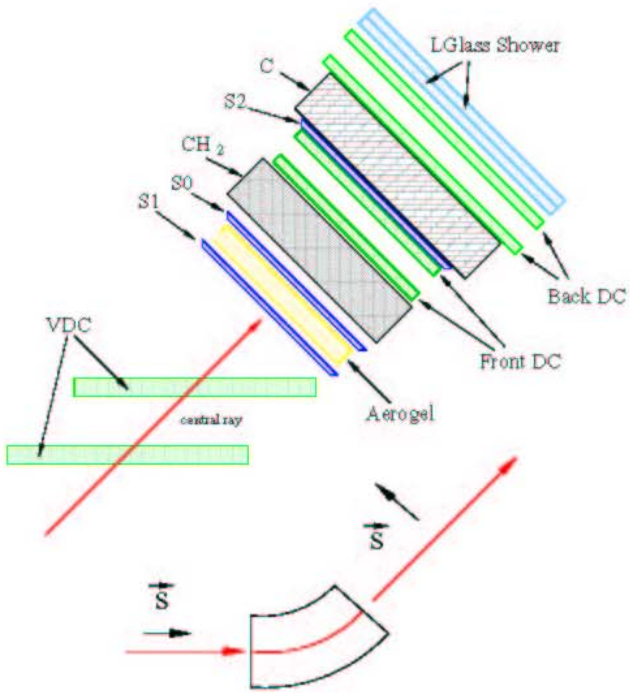
JLab E99-114, 25 kinematic points w/ statistical errors.

2 gluon exchange pQCD calculations only generate a small piece of the scattering amplitude, even with highly asymmetric Distribution Amplitudes



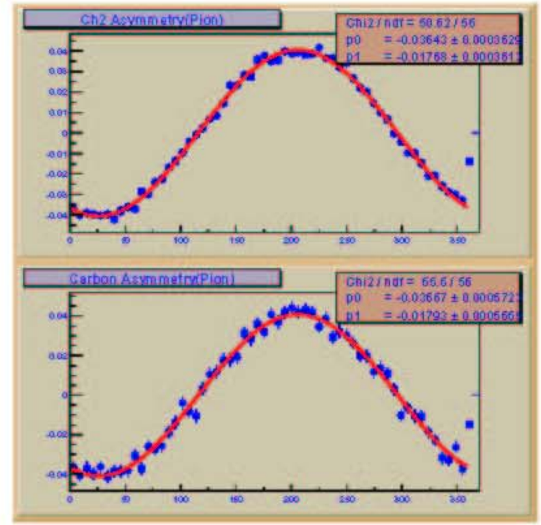
Asymmetries for Pion and Compton processes

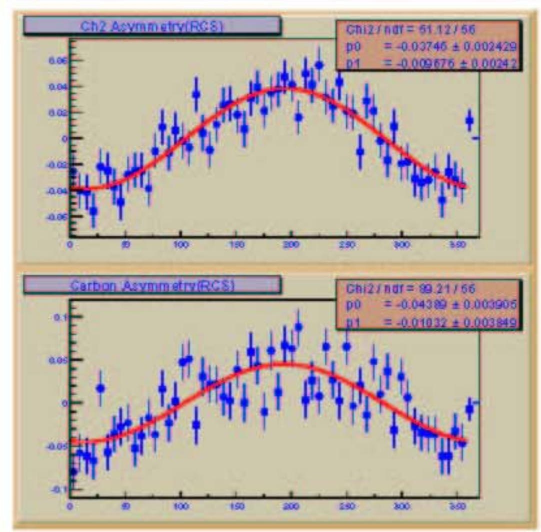
Proton Spectrometer and Focal Plane Polarimeter



$$\Theta_{\vec{sp}} = 86° \cdot E_p(GeV) \cdot \frac{\theta_{bend}}{45°}$$

in E99-114 $\Theta_{\vec{sp}}$ at focal plane is 270 degree. Asymmetries are proportional to p_L and p_S of the proton polarization.

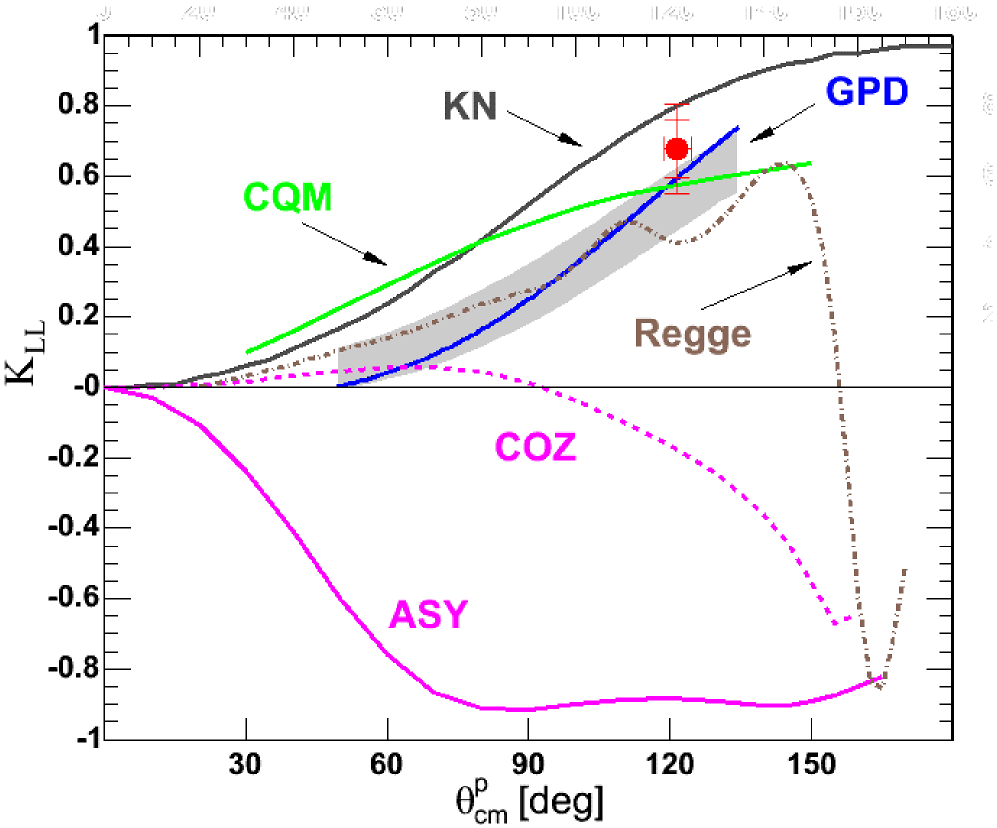




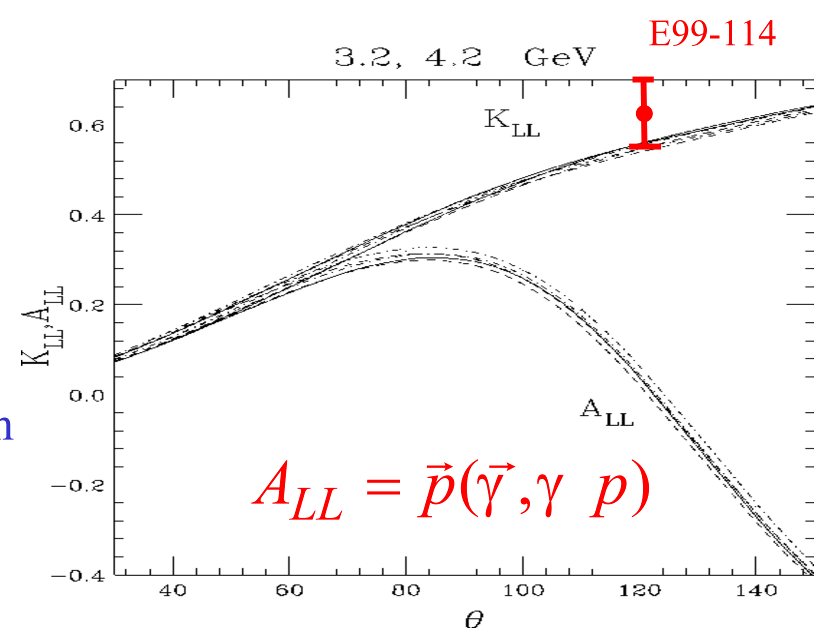
Longitudinal Polarization Transfer in RCS

$K_{LL} = p(\vec{\gamma},\gamma\ \vec{p})$

E_{γ}=3GeV

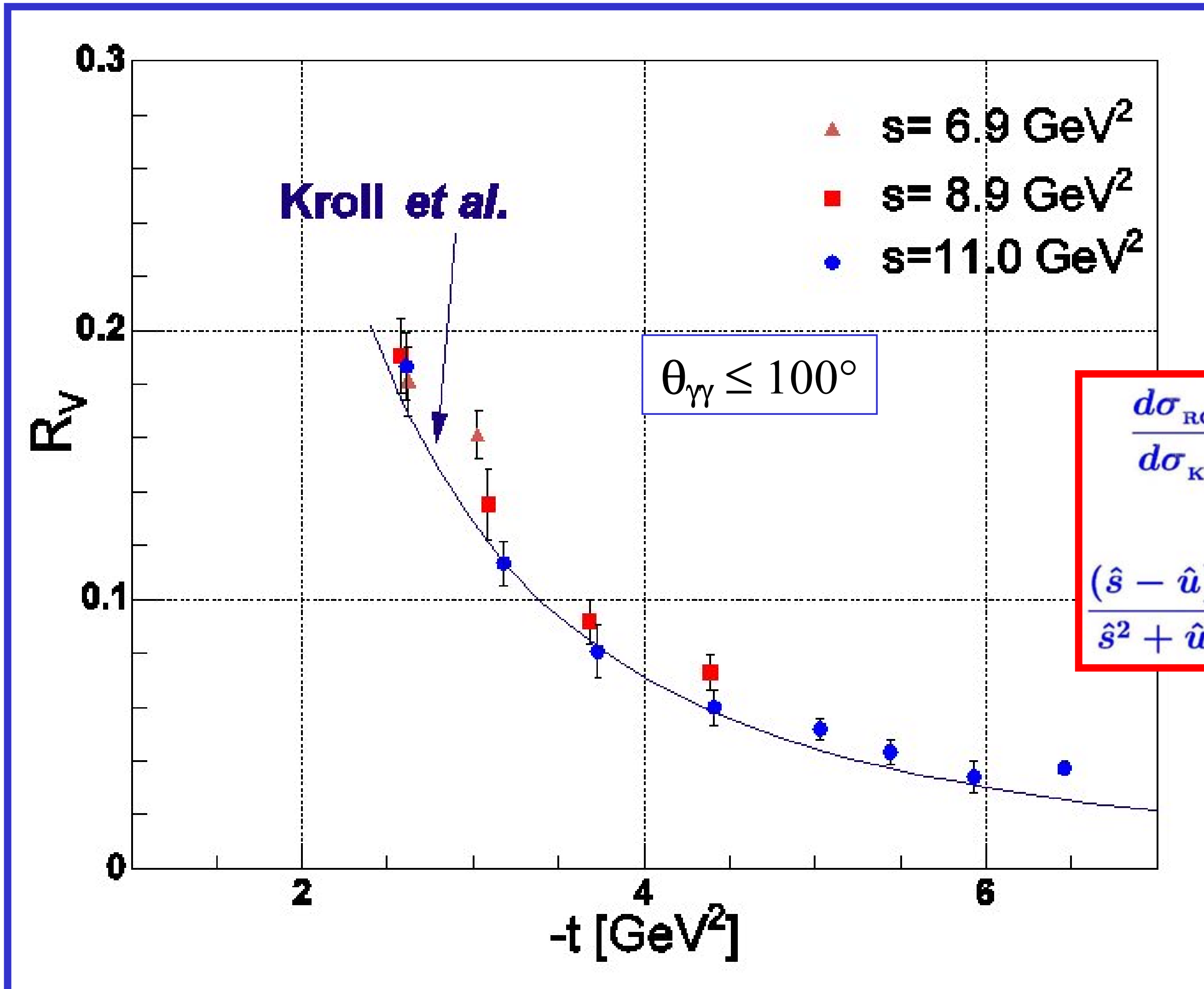


CQM=G.A.Miller PRC **69**(2004)



- Experimental evidence for Handbag mechanism
  - **CQM** & GPD Calculations
- pQCD (2Gluon exchange) strongly ruled out

Handbag Amplitude: Klein-Nishina Scaling at fixed -t?



$$\frac{d\sigma_{\rm RCS}}{d\sigma_{\rm KN}} = \frac{2\hat{s}\hat{u}}{\hat{s}^2+\hat{u}^2}R_A^2(t) + \frac{(\hat{s}-\hat{u})^2}{\hat{s}^2+\hat{u}^2}\left[R_V^2(t) + \frac{-t}{4m^2}R_T^2(t)\right]$$

$\gamma p \rightarrow \gamma p$

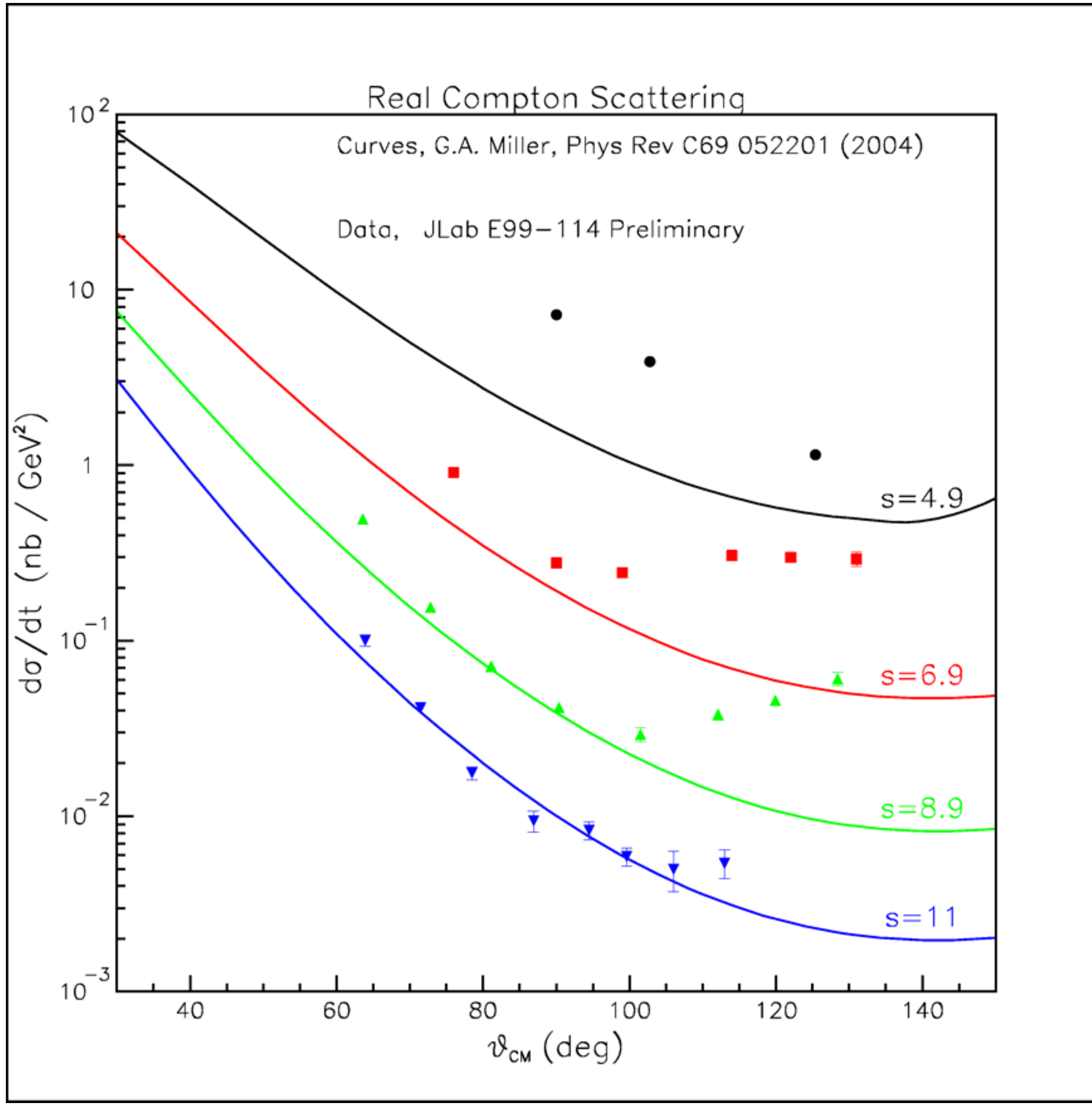
E99-114 Statistical errors only

Light Front Cloudy Bag Model
(only 3-quark content included
at large x for RCS

Handbag amplitude &
Wavefunction ansatz

$$\Phi(k_1, k_2, k_3) = \frac{(spin)N}{\left[M_{123}{}^2 + \beta^2\right]^\gamma}$$

Parameters β, γ, m_q
fitted to H(e,e')p

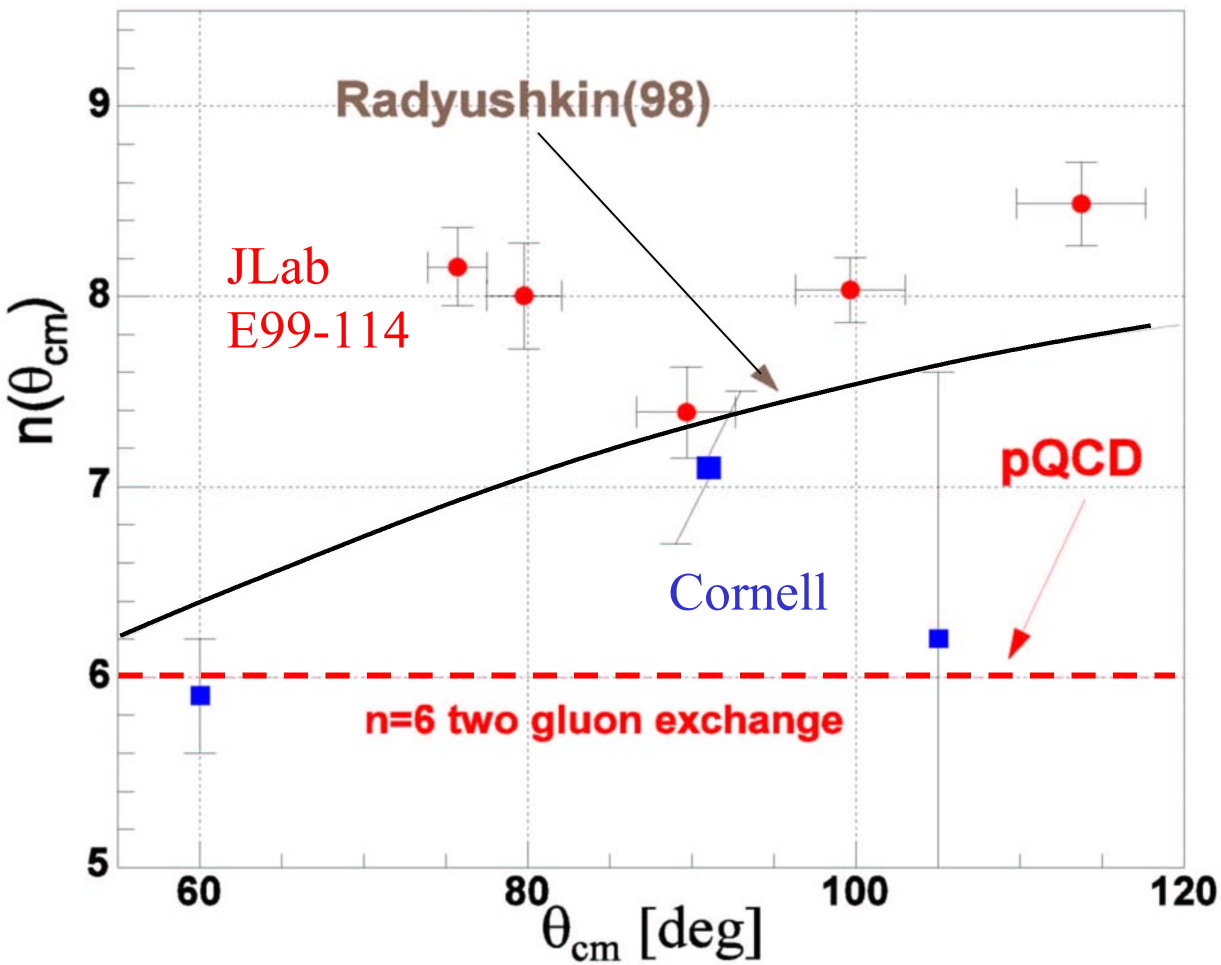


Cross section scaling at fixed $\theta_{\gamma\gamma}^{CM}$

$$\frac{d\sigma}{dt} \rightarrow \frac{f(\theta)}{s^n}$$

n+2 = Sum of # of elementary fields in initial & final state

$p_\perp$ largest at θ^{CM}=90°

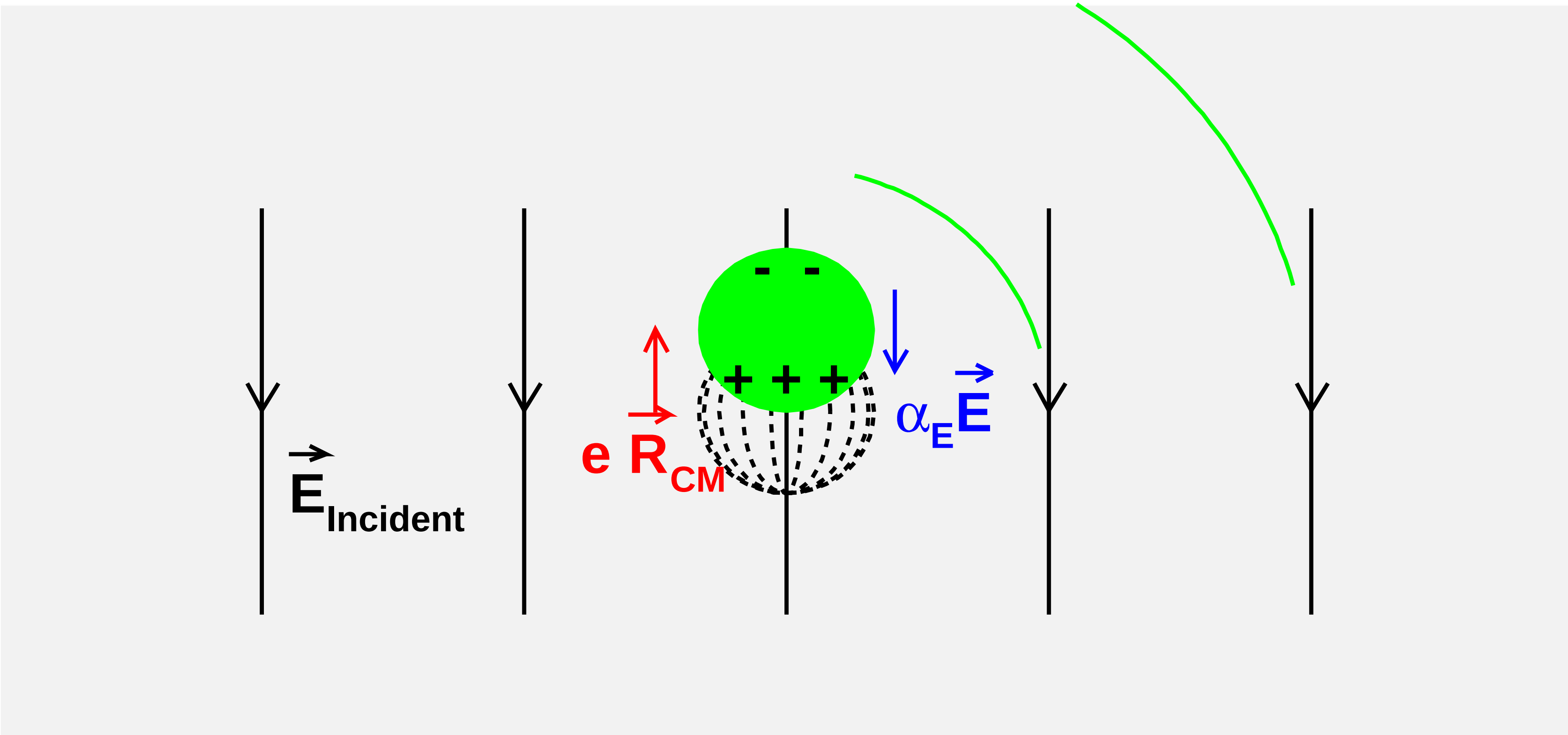


Future Prospects for RCS

- Ales Psaker, A. Radyushkin (ODU):
  - Improved treatment of $k_\perp$ in handbag amplitude
- C. Weiss: Massless quarks in constituent quark wavefunction of proton.

- Measurement of A_{LL} at 4 GeV and 120° (Hall C)
- Double kinematic range in *s* and *t* with JLab @ 12 GeV

Low Energy Compton Scattering



Power radiated: $P = \dfrac{2}{3c^3} \left| \dfrac{\partial^2 \vec{\mathbf{d}}}{\partial t^2} \right|^2$

Center of Mass motion and induced dipole: $\dfrac{\partial^2 \vec{\mathbf{d}}}{\partial t^2} = \dfrac{e^2}{m}\mathbf{E} - \alpha_E \omega^2 \mathbf{E}$

Forward and Backward Low Energy Scattering Amplitudes

D. Babusci, *et al.*, *Phys. Rev.* **C58**, 1013 (1998):

$$
\begin{aligned}
\frac{1}{8\pi M} T_{fi}(0^\circ) &= \vec{\epsilon}_f^{\,*} \cdot \vec{\epsilon}_i \left[-\frac{e^2}{4\pi M} + \omega^2 (\alpha_E + \beta_M) + \mathcal{O}(\omega^4) \right] \\
&+ i\sigma \cdot \vec{\epsilon}_f^{\,*} \times \vec{\epsilon}_i \left[-\omega \frac{e^2}{4\pi} \frac{\kappa^2}{2M^2} + \omega^3 \gamma_0 + \mathcal{O}(\omega^5) \right] \\
-\gamma_0 &= \gamma_{E1} + \gamma_{M1} + \gamma_{E2} + \gamma_{M2} \\
\frac{1}{8\pi M} T_{fi}(\pi) &= \vec{\epsilon}_f^{\,*} \cdot \vec{\epsilon}_i \left[-\frac{e^2}{4\pi M} + \omega\omega' (\alpha_E - \beta_M) + \mathcal{O}(\omega^4) \right] \\
&+ i\sqrt{\omega\omega'}\sigma \cdot \vec{\epsilon}_f^{\,*} \times \vec{\epsilon}_i \left[-\omega \frac{e^2}{4\pi} \frac{\kappa^2 + 4\kappa + 2}{2M^2} + \omega\omega' \gamma_0 + \mathcal{O}(\omega^4) \right] \\
\gamma_\pi &= -\gamma_{E1} + \gamma_{M1} + \gamma_{E2} - \gamma_{M2}
\end{aligned}
$$

Compton Scattering Cross Section

$$
\frac{d\sigma}{d\Omega_{\gamma\gamma}^{\mathrm{Lab}}} = \left| \frac{1}{8\pi M} \frac{\omega_f}{\omega_i} T_{fi} \right|^2
$$

Real Compton Scattering & Proton Polarizabilities

World Data: (1960 - 2001, Moscow, Saskatoon, Illinois, Mainz)

RCS Experiment: V. Olmos de Leon *et al.*, *Eur. Phys. J* **A10**, 207 (2001):

$\mathcal{O}(p^3)\chi$PT: V. Bernard, *et al.*, *Phys. Lett. B* **319** 269 (1993).

$\mathcal{O}(p^4)\chi$PT: V. Bernard, *et al.*, *Z. Phys.* **348** 317 (1993):

	Experiment	$\mathcal{O}(p^3)\chi$PT	
α_E	$(12.1 \pm 0.3_{\text{stat}} \mp 0.4_{\text{syst}})$	12.5	$10^{-4}\,\text{fm}^3$
β_M	$(1.6 \pm 0.4_{\text{stat}} \pm 0.4_{\text{syst}})$	1.25	$10^{-4}\,\text{fm}^3$
γ_π	$-(36.1 \pm 2.1_{\text{stat}} \pm 0.9_{\text{syst}})$	-38.3	$10^{-4}\,\text{fm}^4$
γ_0	$(1.02 \pm 0.08_{\text{stat}} \pm 0.10_{\text{syst}})$	4.5	$10^{-4}\,\text{fm}^4$

$\mathcal{O}(p^4)\chi$PT introduces uncertainties $\approx \pm 3$ in each quoted value from phenomenological constants, esp. Δ and N^* terms.

Harmonic Oscillator model: $\alpha_E \approx \alpha_{\text{QED}} \cdot \text{Volume} \cdot (b/\lambda_C)$

$\alpha_E <<$ Volume: proton is very stiff, intrinsically relativistic ($\lambda_C \approx$ size)

$\beta_M << \alpha_E$: Strong cancellation of para- and dia-magnetism.

$N \to \Delta$ transition over saturates β_M.

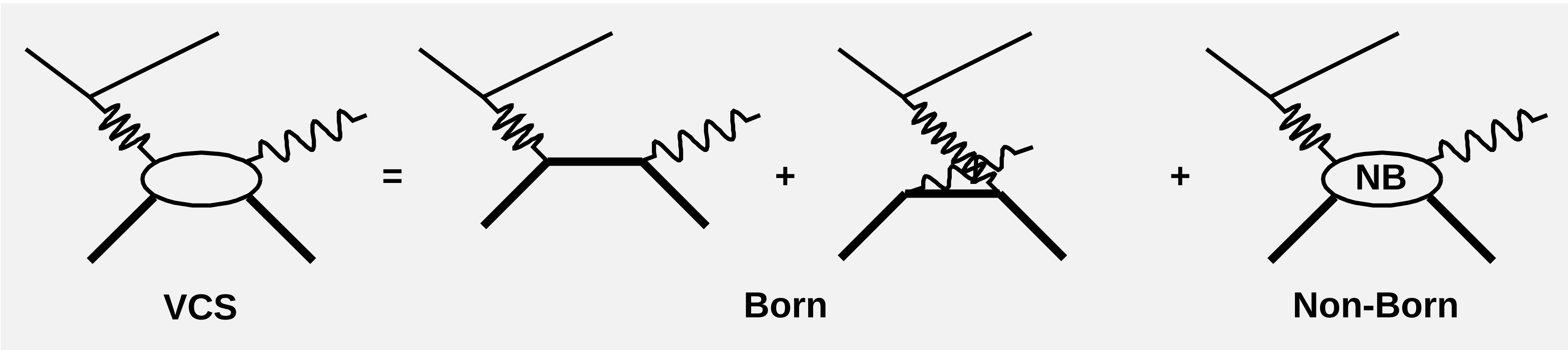
Idea of Virtual Compton Scattering for Polarizabilities:

$\gamma + p$ invariant mass $\leq M + m_\pi$.

$2\pi/q =$ virtual-photon wavelength, controlled by experiment.

Measure spatial variation of polarization inside proton:

$q =$ fourier transform variable.



P.A.M. Guichon, G.Q. Liu, A.W. Thomas, *Nucl. Phys. A,* **591** 606 (1995).

P.A.M. Guichon, M. Vanderhaeghen, *Prog. Part. Nucl. Phys.* **41** 125 (1998).

Lvov...

Low Energy Expansion (LEX) of VCS

q' = final photon energy in γp CM frame.

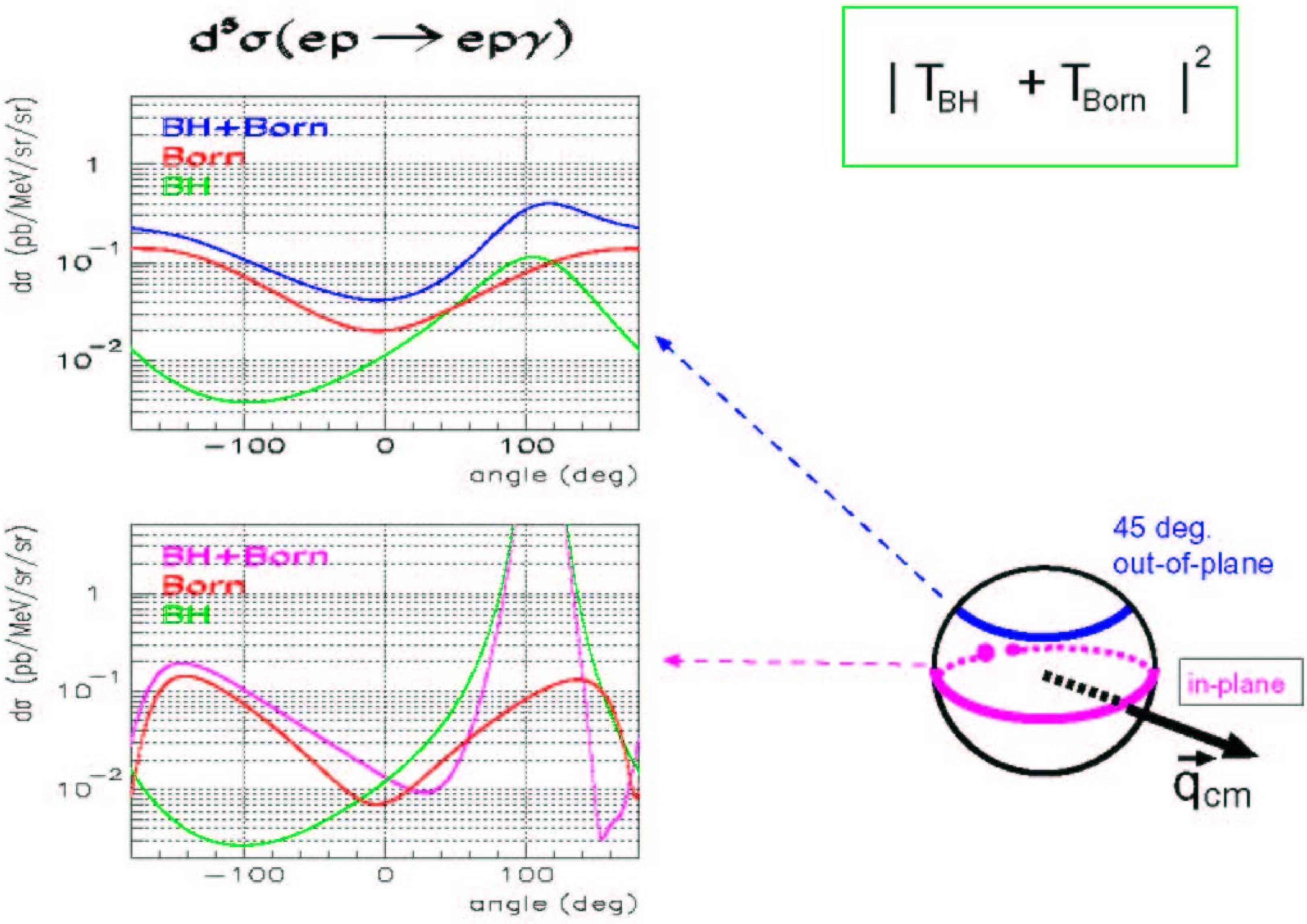
$$\begin{aligned}
d\sigma &= d\sigma^{\text{BH+Born}} + v_{LL}\left[P_{LL} - P_{TT}/\epsilon\right] + v_{LT} P_{LT} + \mathcal{O}(q'), \\
P_{LL} &= -\sqrt{24} M\, G_{E,p}(\tilde{Q}^2)\, P^{(C1,C1)0}(\tilde{Q}^2) = \frac{4M}{\alpha_{QED}} G_{E,p}(\tilde{Q}^2) \alpha_E(\tilde{Q}^2) \\
P_{TT} &= 6M(1+\tilde{\tau}) G_{M,p}(\tilde{Q}^2)\left[P^{(M1,M1)1}(\tilde{Q}^2) + \sqrt{8}\tilde{\tau} P^{(C1,M2)1}(\tilde{Q}^2)\right] \\
P_{LT} &= \sqrt{\frac{3}{2}} M \sqrt{1+\tilde{\tau}}\left[G_{E,p}(\tilde{Q}^2) P^{(M1,M1)0}(\tilde{Q}^2) - \sqrt{6} G_{M,p}(\tilde{Q}^2) P^{(C1,C1)1}(\tilde{Q}^2)\right] \\
&= -\frac{2M}{\alpha_{QED}}\sqrt{1+\tilde{\tau}} G_{M,p}(\tilde{Q}^2) \beta_M(\tilde{Q}^2) - \text{spin G.P.}
\end{aligned}$$

where v_{LL}, v_{TT}, and ϵ are kinematic factors and
$\tilde{Q}^2 = Q^2$ in $q' \to 0$ limit.

Generalized Polarizabilities (GP) $P^{(\Lambda_f,\Lambda_i)\Delta S}(\tilde{Q}^2)$,
(Λ_f, Λ_i) = (final, initial) Multipolarity; $\Delta S = 0, 1$: Proton spin flip.
In $\tilde{Q}^2 \to 0$ limit:

$$\begin{aligned}
P^{(C1,C1)0} &\longrightarrow -\sqrt{2/3}\ \overline{\alpha}_E/\alpha_{\text{QED}} \\
P^{(M1,M1)0} &\longrightarrow -\sqrt{8/3}\ \overline{\beta}_M/\alpha_{\text{QED}} \\
P_{TT} &\longrightarrow 0 \\
P^{(C1,C1)1} &\longrightarrow 0
\end{aligned}$$

Components of BETHE-HEITLER + BORN cross section



Virtual Compton Scattering Experiments:

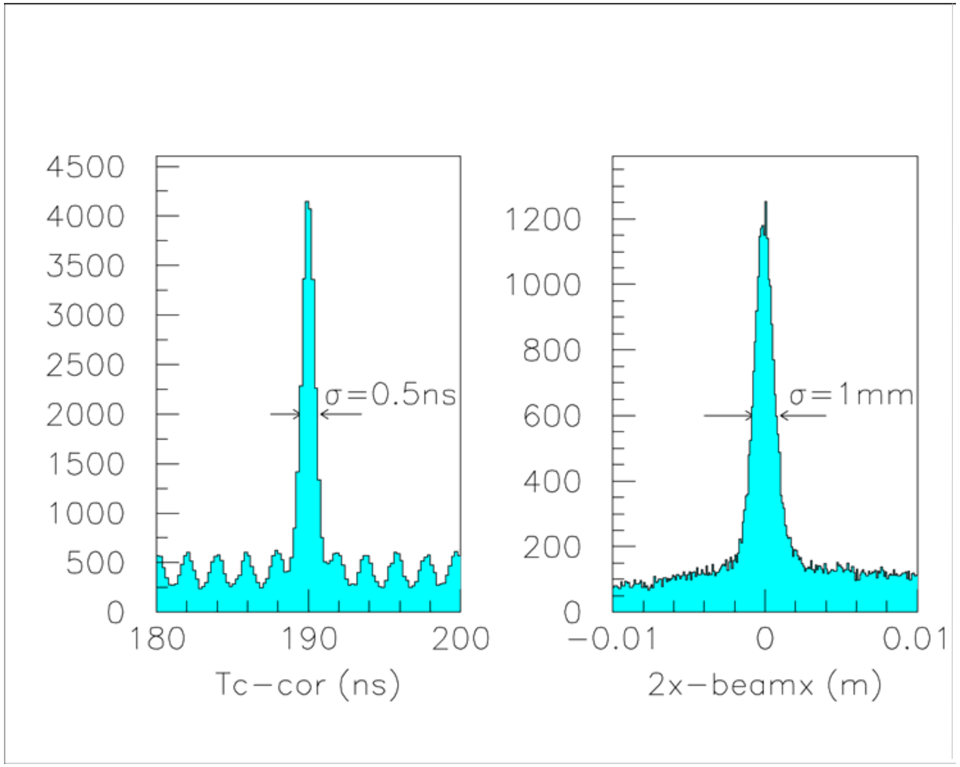
- MAMI: $k \leq 0.8$ GeV $\qquad q_{cm} = 0.6$ GeV/c
  J. Roche *et al.*, *Phys. Rev. Lett.*, **85**, 708 (2000)

- Jefferson Lab: $k = 4$ GeV $\qquad Q^2 = 1.0$, 1.9 GeV^2.
  hallaweb.jlab.org/physics/experiments/E93-050
  G. Laveissiere *et al.*, *Phys. Rev. Lett.*, **93**, 122001 (2004).

- Bates-Linac: $k = 0.6$ GeV $\qquad Q^2 = 0.05$ GeV^2.
  R. Miskimen, UMass-Amherst, spokesperson

Reconstruct H(e,e'p)X coincidence at target

500 MHz Beam Structure



Time Coincidence

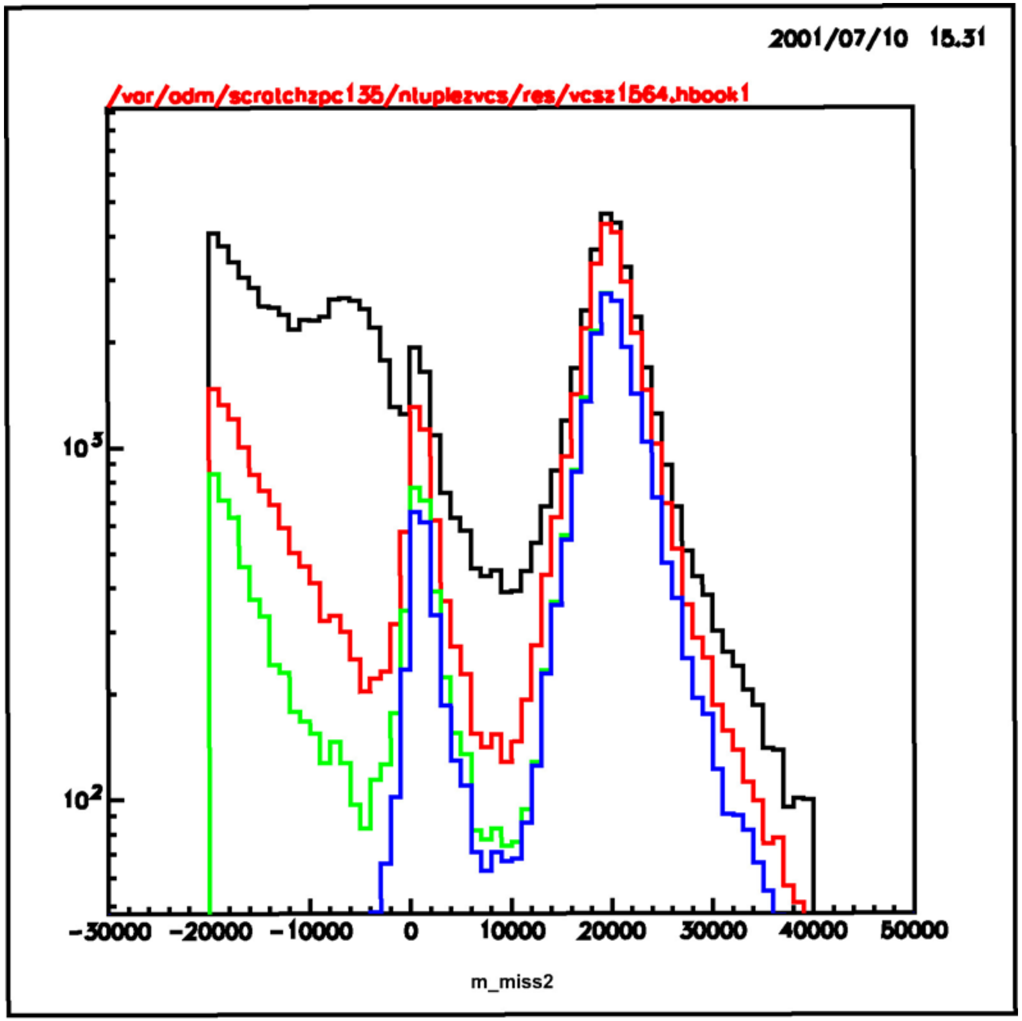
Spatial Coincidence

Reconstruct 1mm precision from 4mm⊗20KHz raster, with 30 KHz bandwidth Beam Position Monitor

Raw H(e,e'p)X Missing Mass squared (M_X^2) Spectrum

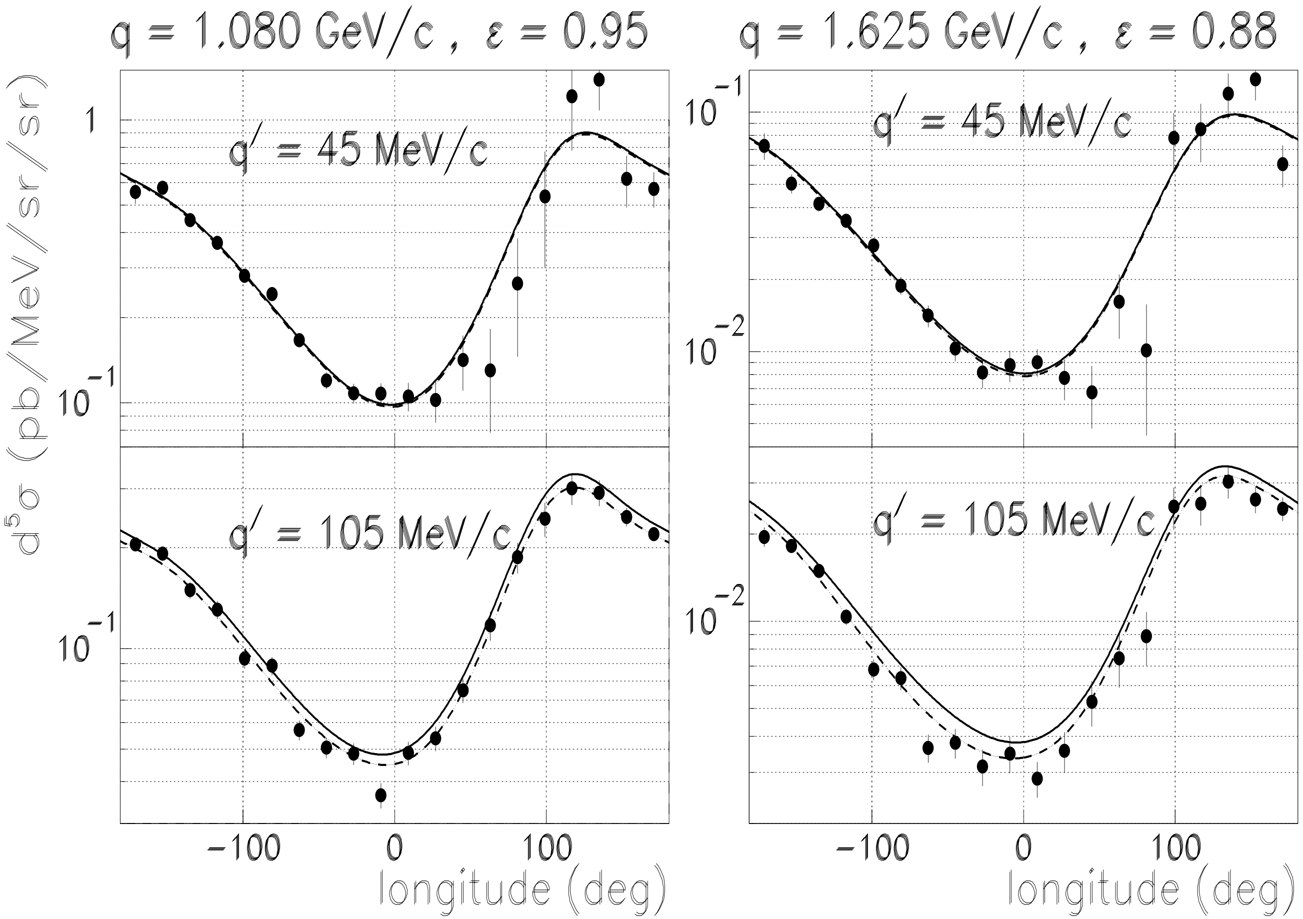
Prominent H(e,e'p)π^0 peak at $M_X^2 = m_\pi^2 = 20{,}000$ MeV^2

Large unphysical background obscures for $M_X^2 =$ 0 VCS events

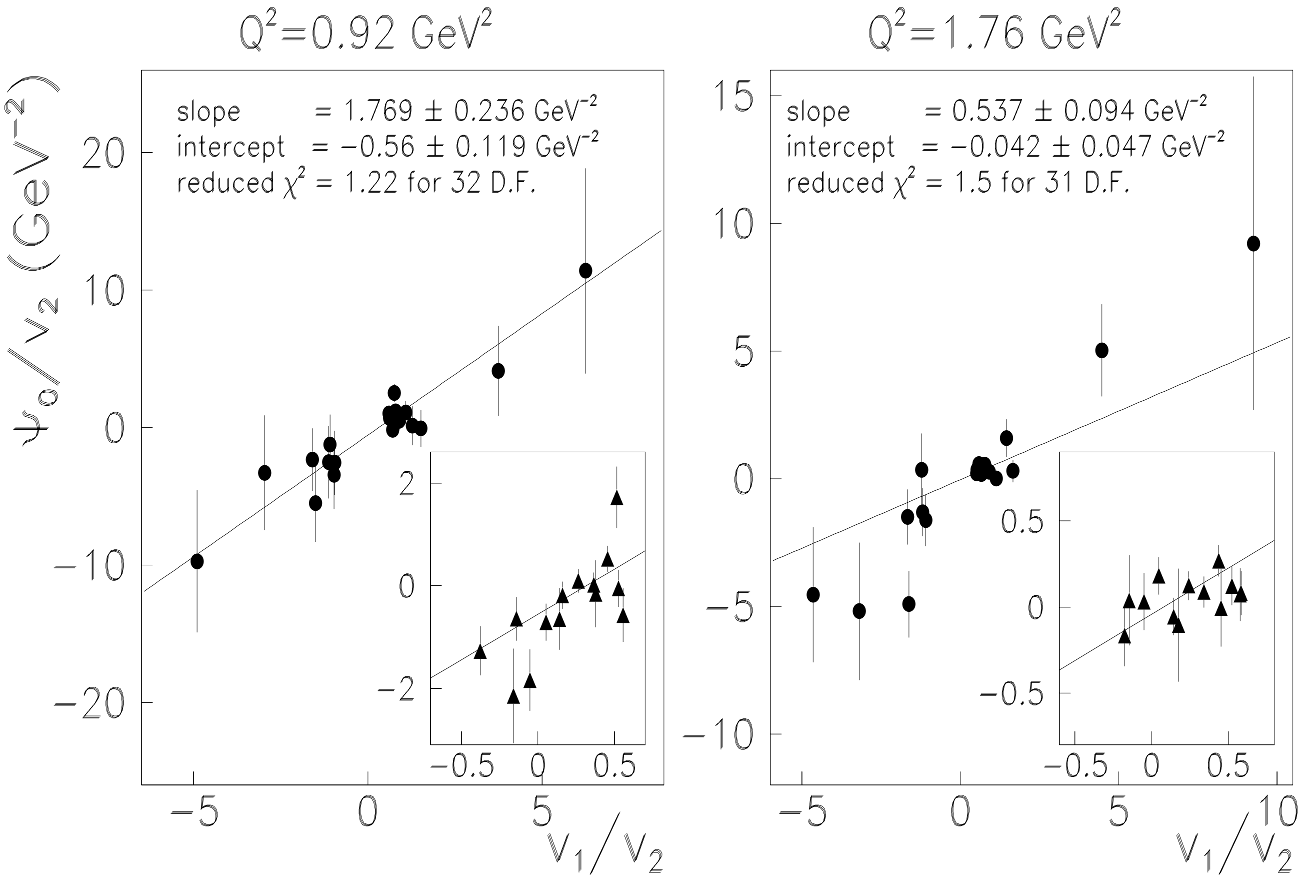


Cuts to remove:

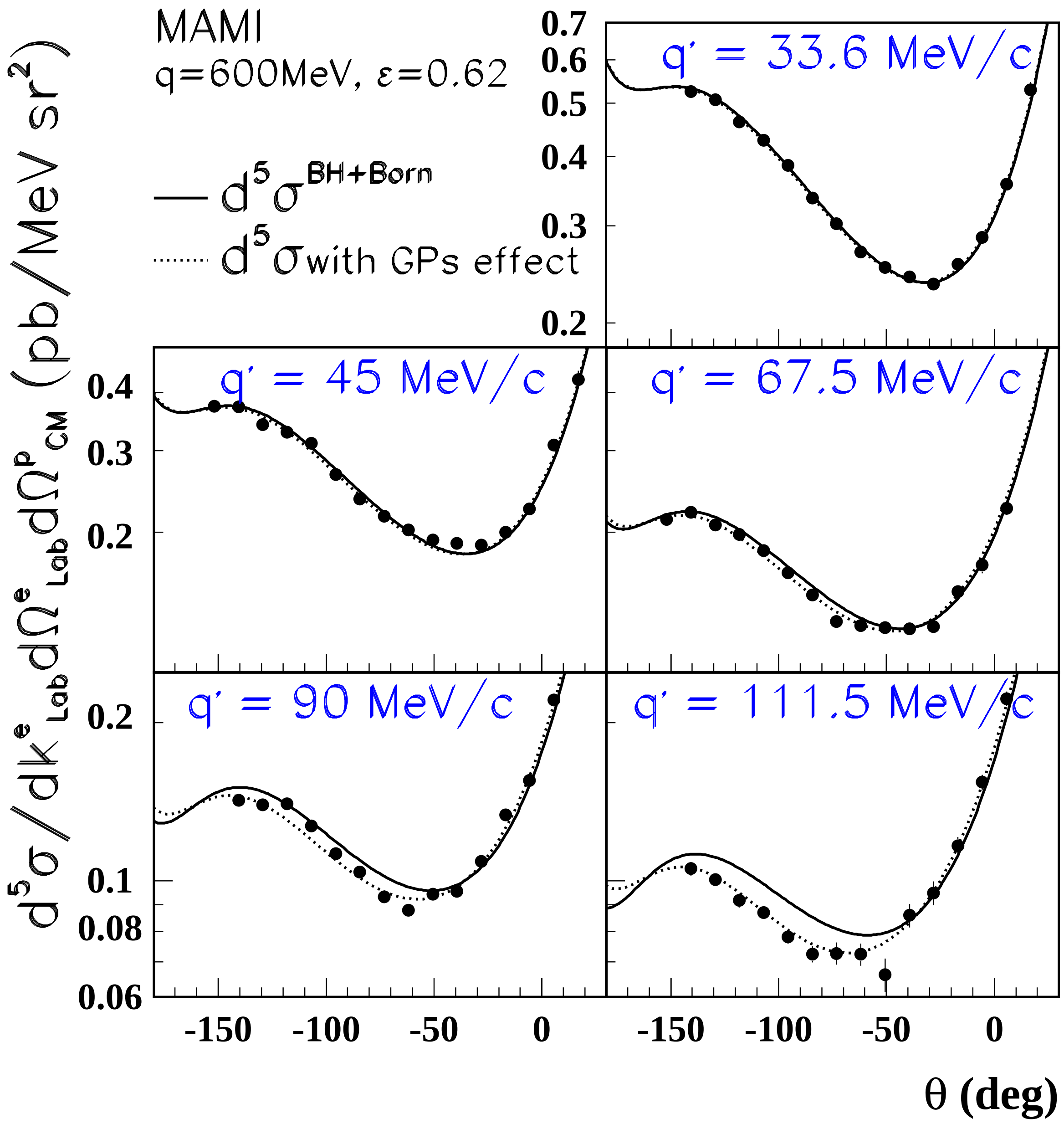
- Elastic ep→ep events. Cut on electron removes mis-identified elastic events with proton punching through collimator
- H(e,e'p)X events with proton reconstructed to punch through collimator
- H(e,e'p)γ events, if assumption that γ||beam puts proton in collimator



JLab ($ep \to ep\gamma$) cross section for the lowest and highest q' bin, at 40° out-of-plane (lattitude) Only statistical errors are shown. The abscissa is the azimuthal angle (or longitude). The full curve is the (BH+Born) cross section, the dashed curve includes the first-order GP effect fitted in this analysis.



LEX fit to VCS data below threshold (straight line) for each data set of JLab data. Black circles correspond to out-of-plane data, and the inner plot is a zoom on the lepton plane data (triangles).



J. Roche *et al.*

Phys. Rev. Lett.

85, 708 (2000)

Dispersion Relations

B. Pasquini, *et al.*, Eur. Phys. J. A **11**, 185 (2001)

I. Complete formalism for VCS cross section up to $N\pi\pi$ threshold.
Input from

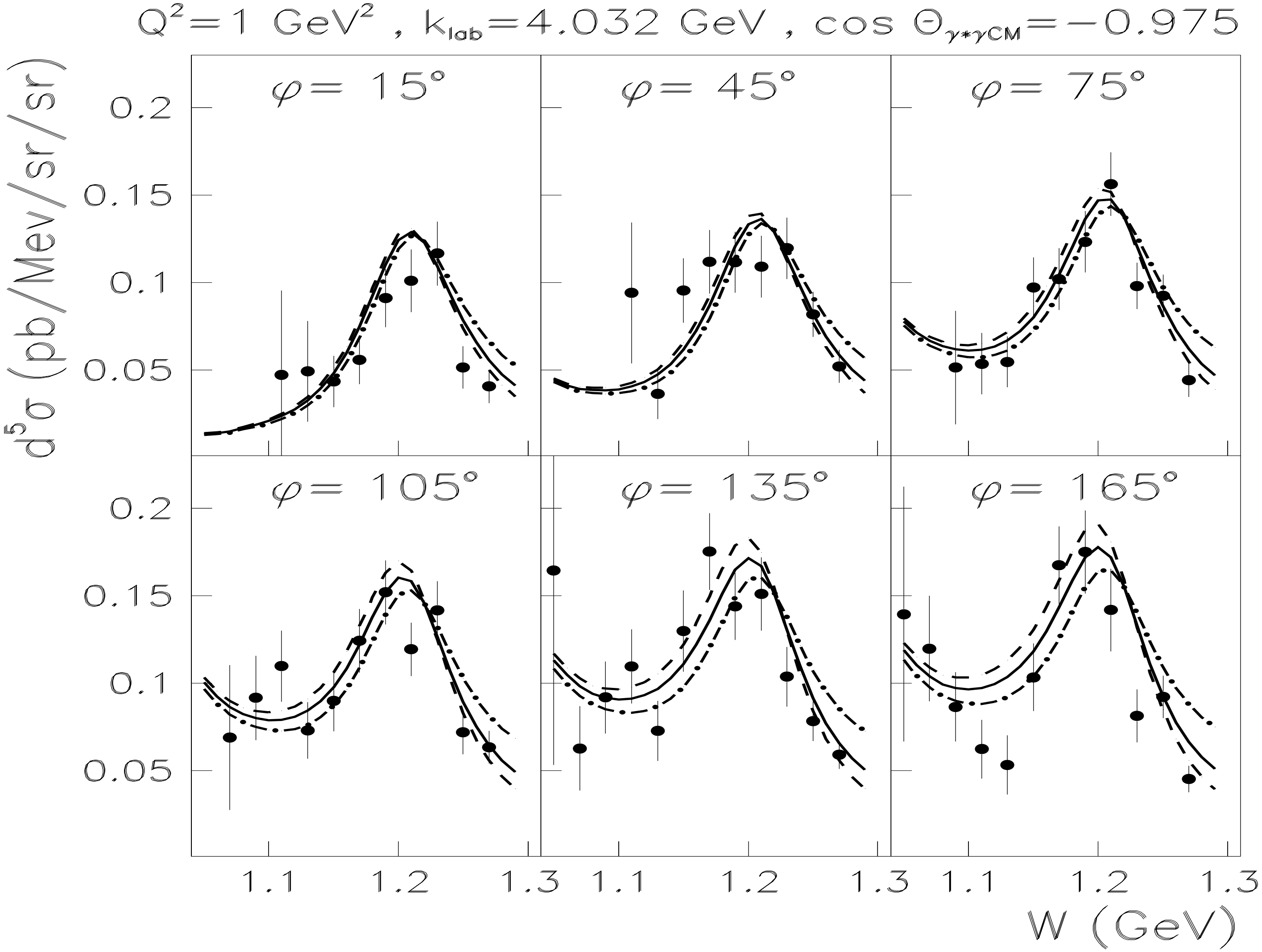
- $\gamma N \to N\pi$ multipoles (MAID)
- t-channel π^0 exchange
- Two low-energy subtraction "constants" (functions of Q^2):
  - $\Delta\beta(Q^2)$: t-channel σ-meson exchange
  - $\Delta[\alpha+\beta](Q^2)$ s-channel $N\pi\pi$ and $N\eta$ resonances not included in MAID.
- $\Delta\beta$ and $\Delta\alpha$ fitted independently to data at $Q^2 = 1$ and $Q^2 = 1.9$ GeV^2 with dipole ansatz:

$$\Delta\beta = \frac{\Delta\beta(0)}{\left[1 + Q^2/\Lambda_\beta^2\right]^2} \qquad \Delta\alpha = \frac{\Delta\alpha(0)}{[1 + Q^2/\Lambda_\alpha^2]^2}$$

II. Predictions of spin polarizabilities.

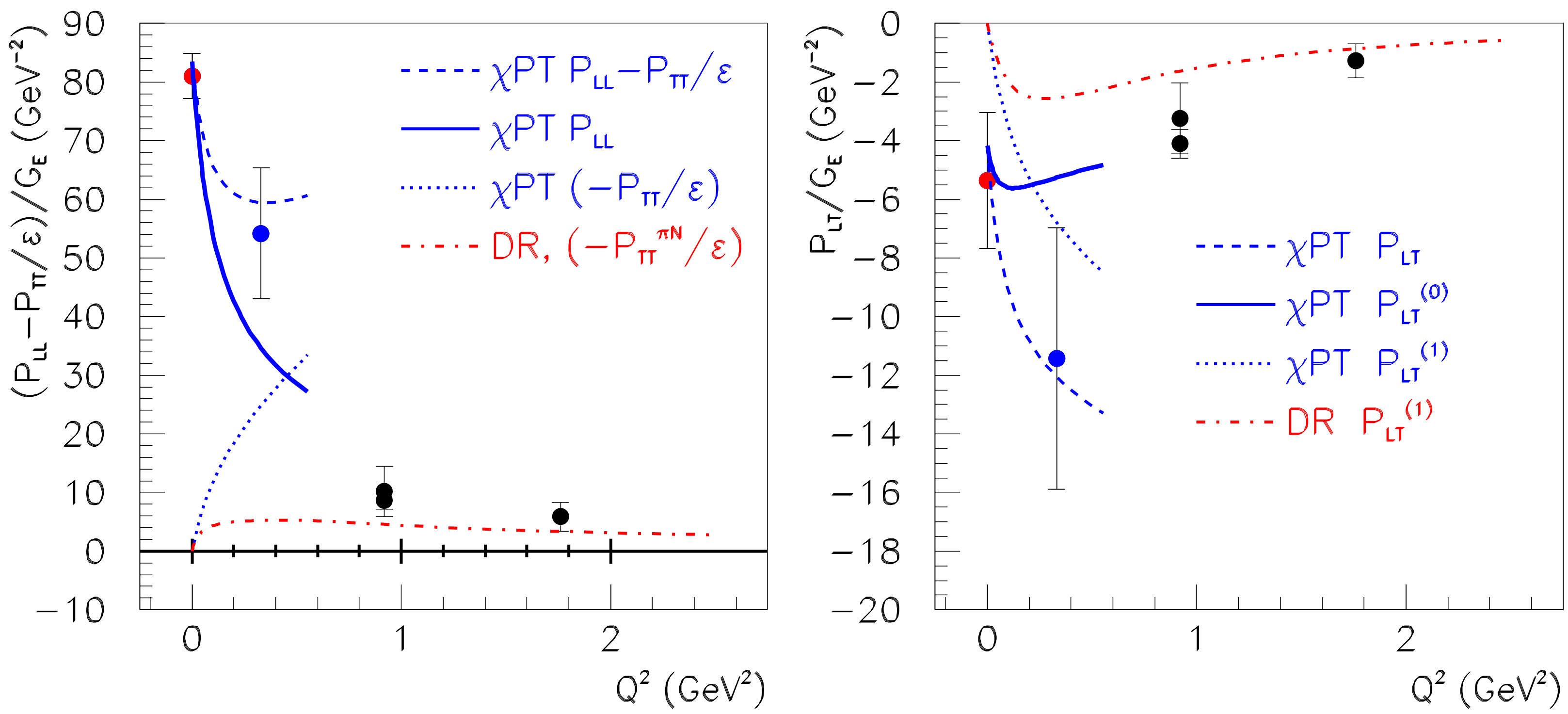
- Separation of α_E from $[P_{LL} - P_{TT}/\epsilon]$ and β_M from P_{LT}

III. Interpretation of generalized polarizabilities.



($ep \to ep\gamma$) cross section for JLab data set I-b in six intervals of the azimuthal angle φ (angle between lepton and hadron planes) as a function of W.

The curves are 1-σ DR fits to total of 700 data points.



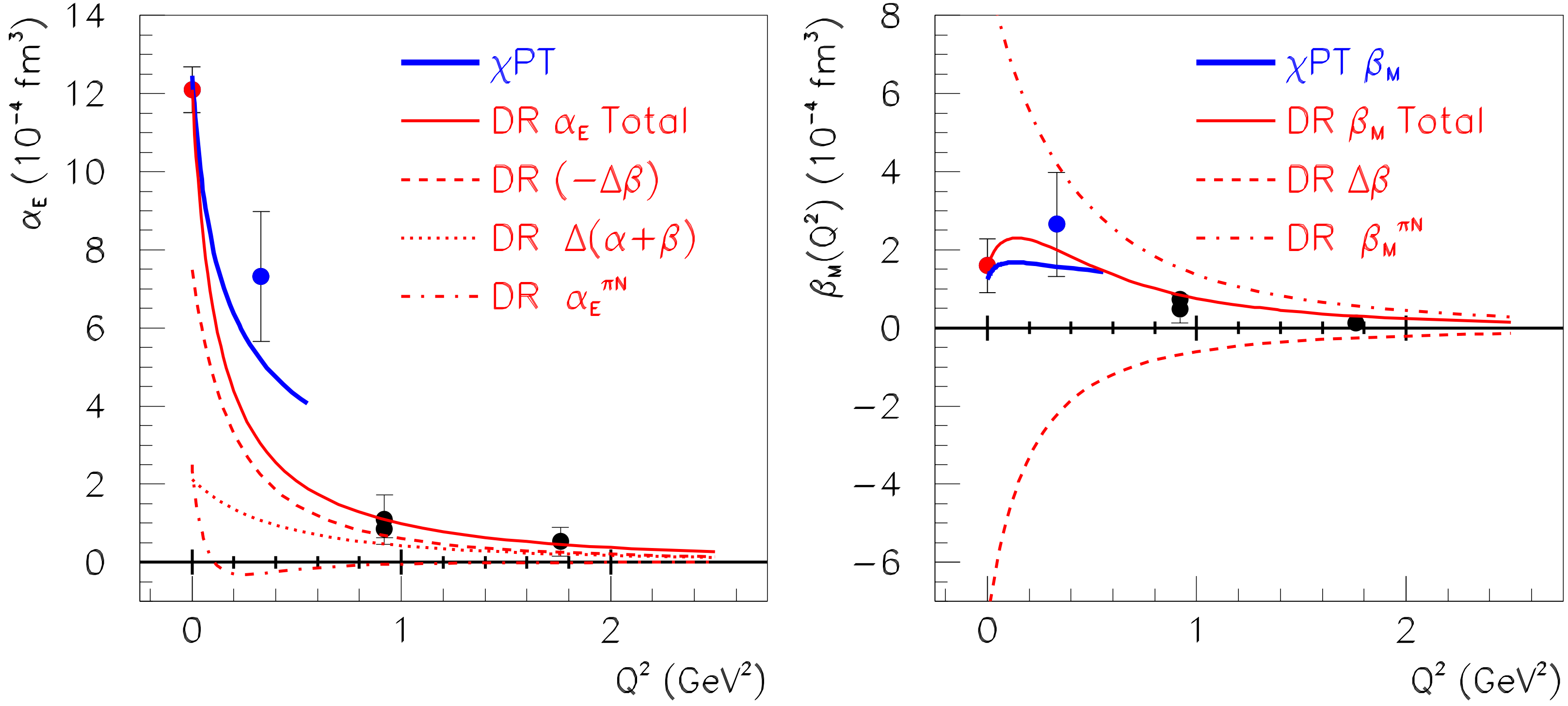
RCS: Olmos de Leon et al [MAMI],,

VCS: J. Roche et al [MAMI-A1], G. Laveissiere et al [JLab E93050].

Dashed Curves are total χPT, Solid curves are χPT for P_{LL} and scalar part of P_{LT} only.

Dotted curves are χPT for P_{TT} and spin-flip part of P_{LT}.

DotDashed Curves are Dispersion Relation πN predictions for P_{TT} and spin-flip part of P_{LT}.



Generalized Polarizabilities:

Obtained by subtracting DR predictions for spin-flip polarizabilities from data.

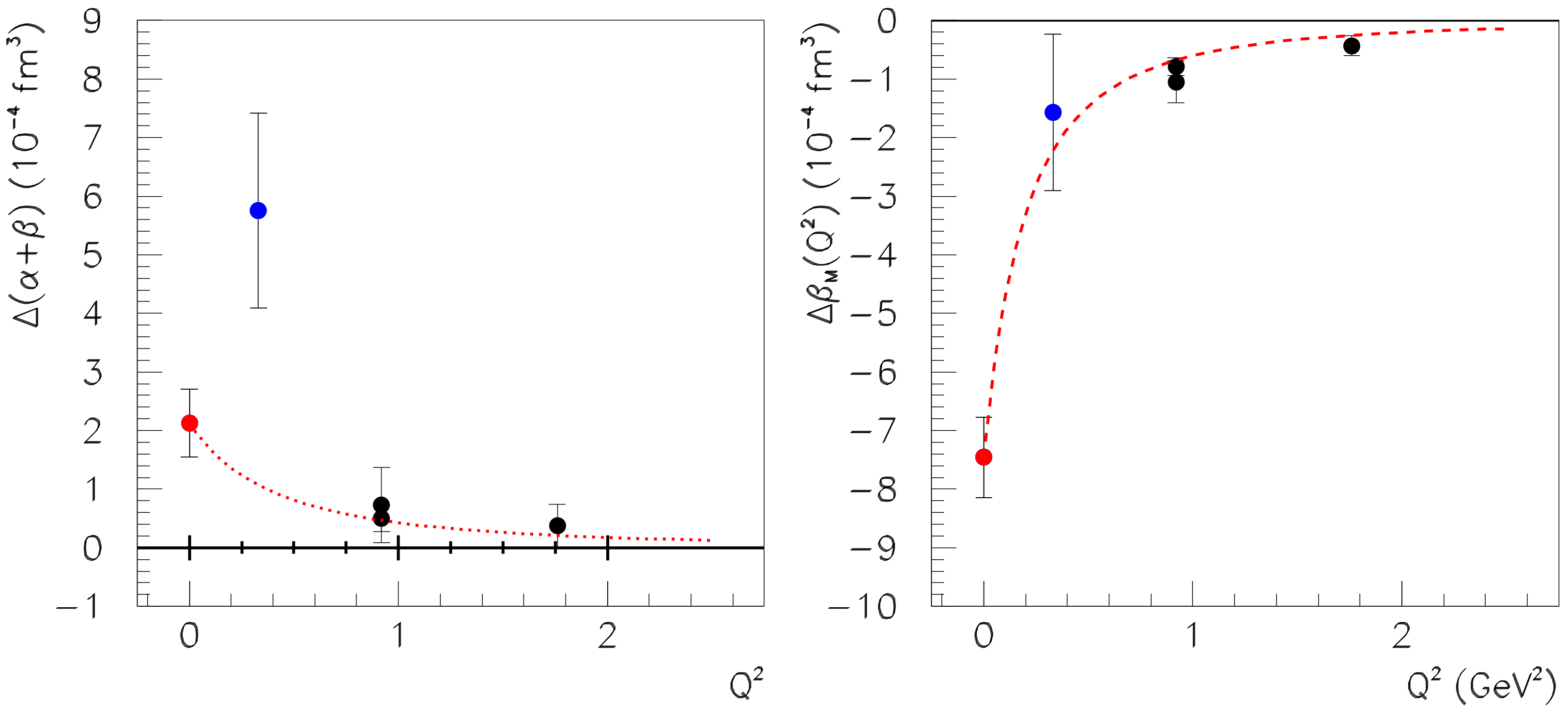
Solid curves are χPT for α_E and β_M.

DotDashed curves are πN contributions to α_E and β_M.

Dashed curves are σ-meson (pion-cloud) exchange term $\Delta\beta$ (fitted)

Dipole parameter $\Lambda_\beta < \Lambda$(elastic): Indicative of large size of pion cloud.

Dotted curve is $\Delta[\alpha + \beta]$ term, fitted with dipole ansatz to $Q^2 = 0$&1 GeV^2 data.



$\Delta[\alpha+\beta] = \alpha_E - \alpha_E^{\pi N} + \Delta\beta$

$\Delta[\alpha+\beta] = F_2^{asy}$ amplitude in DR.

Spatial distribution not the same as G_E.

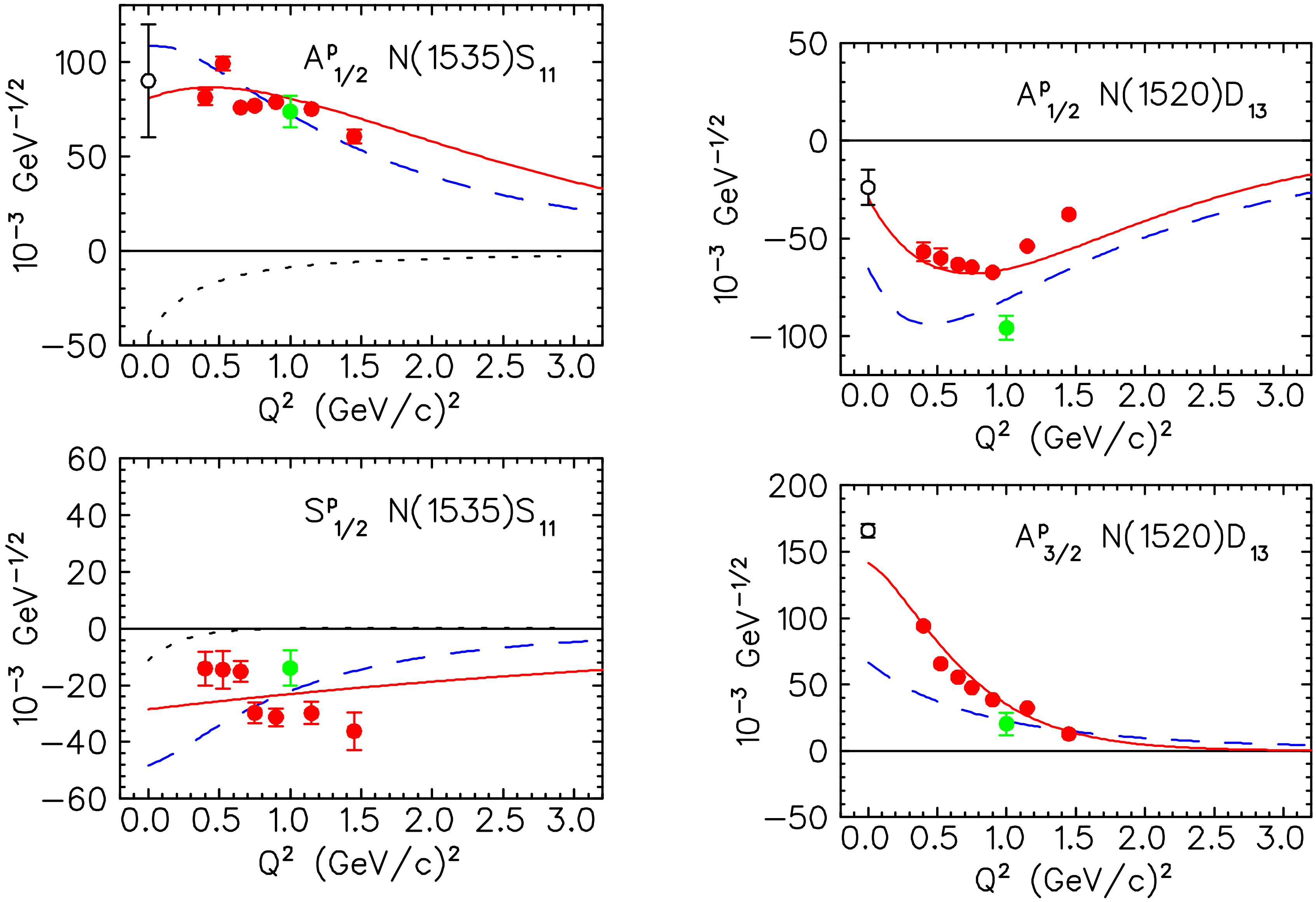
Dashed Curve is σ-exchange term $\Delta\beta$,

Dipole paramater $\Lambda_\beta < \Lambda$(elastic) .

Indicative of large size of pion cloud.

Contributions to $\Delta[\alpha + \beta](Q^2)$

$\gamma^* p \to N^*$ Amplitudes: L. Tiator, *et al.*, nucl-th 0310041

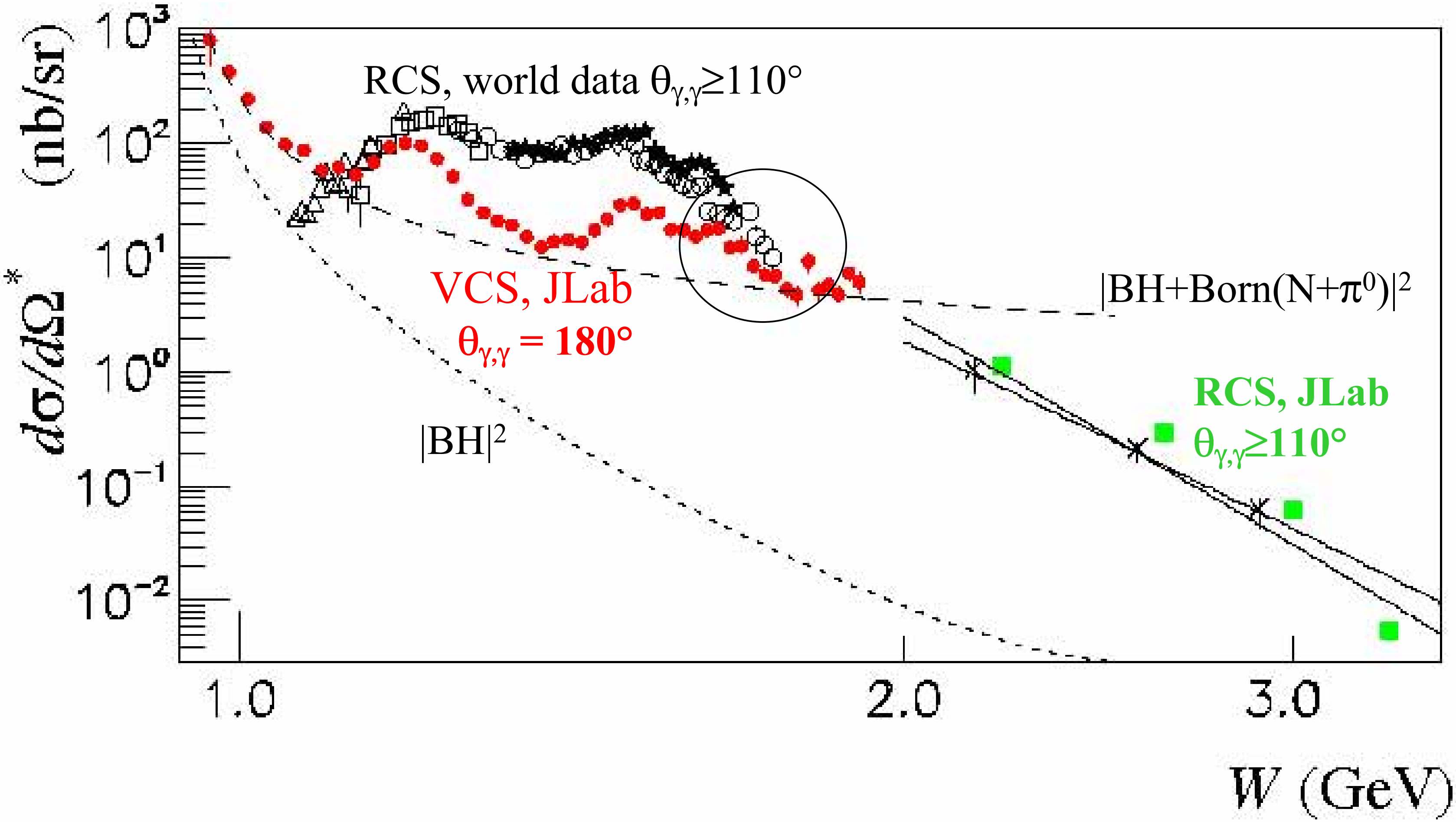


Conclusions and Prospects for VCS/Generalized-Polarizabilities

- Low Energy Expansion analysis of data up to $N\pi$ threshold and Dispersion Relation Analysis of data up through $N\pi\pi$ threshold give consistent results.
- DR interpretation of Generalized Polarizabilities:
  - Diamagnetism shows large spatial size, as expected from pion cloud.
  - Large contribution to Electric Polarizability from excitations beyond $N\pi$, with non-trivail Q^2 dependence.
  - Two photon amplitude is not dominated by low energy excitations.
- New Results soon from
  - Low Q^2 Bates experiment;
  - Single and Double Spin asymmetries at MAMI
- Future experiments with MAMI upgrade.

VCS(Q^2=1GeV^2) $d\sigma(\gamma^*,\gamma)$ at large $-t$:

(for $\theta_{\gamma\gamma}\approx 180°$, $-t \approx W^2 = s$)



- Resonance form-factors at Δ and S11, D13
- Evidence for compton scattering from point-like objects for W ≈ 2 GeV?; or
- Evidence for Nucleon pole dominance of u-channel Regge: $\mathcal{T} \propto s^{a(u)}$?

Normal Beam Asymmetry from 2γ-exchange

- Preliminary data from HAPPEX on the proton and He-4 targets
- Measures absorptive part of Compton scattering amplitude, integrated over photon virtualities and W
- Calculations by Afanasev&Merenkov