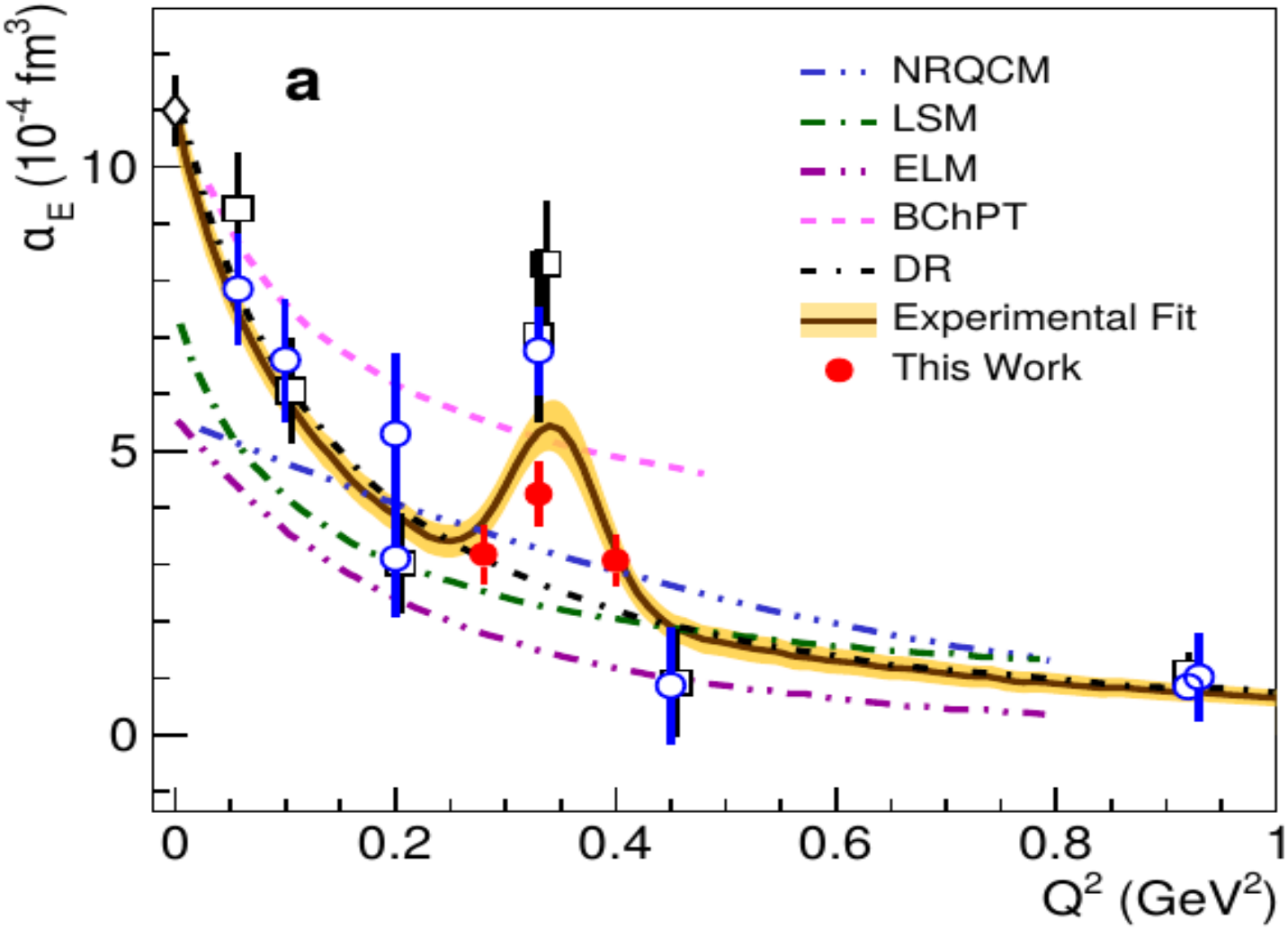
Measured proton electromagnetic structure deviates from theoretical predictions

2210.11461



Generalized Polarizability

JLab confirms the peak at $Q^2 = 0.33$ GeV^2

(2210.11461)

1. Definitions and Kinematics

2. Experiment

3. Theor. description

4. Discussion.

Polarizability —

In electric(magnetic) field the system get an additional electric(magnetic) dipole moment

$$d = \alpha_E E \qquad (\beta_M H)$$

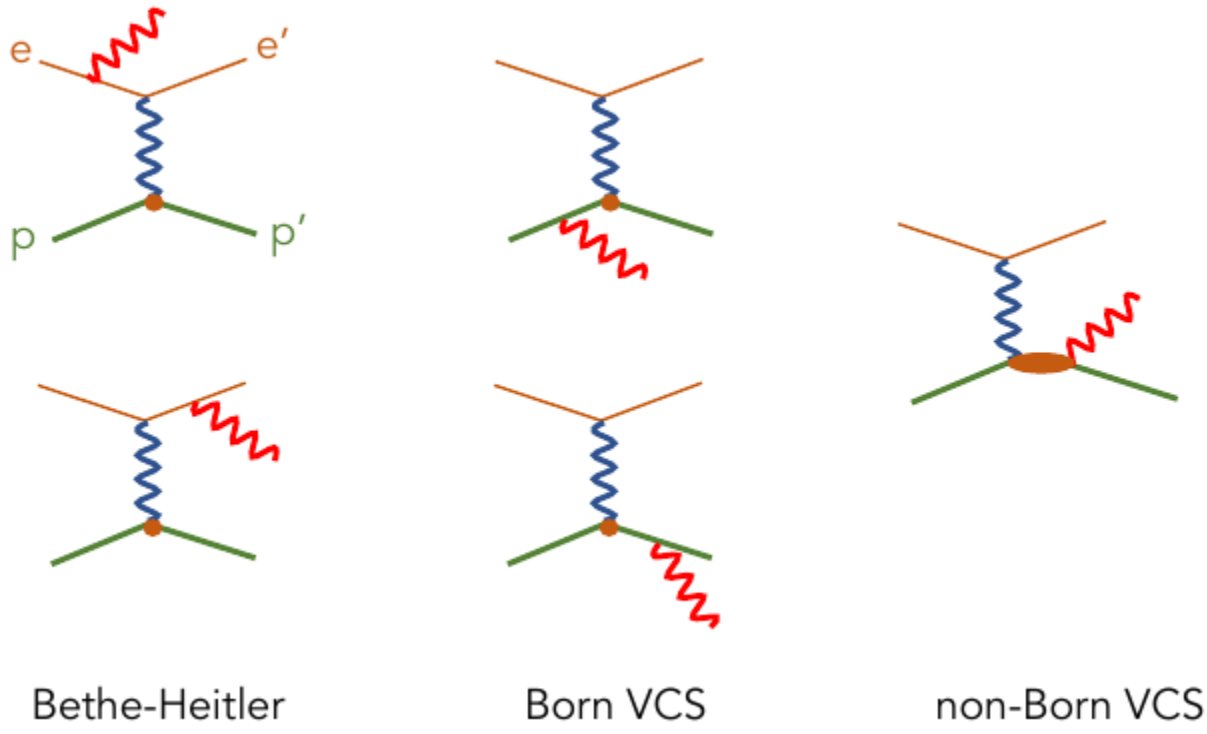
Energy of interaction with this dipole is

$$H^{(2)}_{eff} = -4\pi(\frac{1}{2}\alpha_E \vec{E}^2 + \frac{1}{2}\beta_M \vec{H}^2).$$

since $E \sim qA$ $\qquad H^{(2)}_{eff} \propto q^2$

Since $H^{(2)}_{eff} \propto A^2 \quad \rightarrow$ search in Compton

$\gamma p \rightarrow \gamma p$ or $ep \rightarrow e'p'\gamma$



Bethe-Heitler Born VCS non-Born VCS

Notations:

Incoming		Outgoing
k	electron	k'
$q = k - k'$	photon	q'
p	proton	p'

$$T^{\mathrm{BH}} + T^{\mathrm{Born}} = \frac{b_{-1}(q_{\mathrm{cm}}, \epsilon, \theta_{\mathrm{cm}}, \varphi)}{q'_{\mathrm{cm}}} + \mathcal{O}(q'^{\,0}_{\mathrm{cm}}) \,,$$

$$T^{\mathrm{NB}} = b_1(q_{\mathrm{cm}}, \epsilon, \theta_{\mathrm{cm}}, \varphi) \cdot q'_{\mathrm{cm}} + \mathcal{O}(q'^{\,2}_{\mathrm{cm}})$$

$$d\sigma = d\sigma_{\mathrm{BH+Born}} + \Phi \cdot q'_{\mathrm{cm}} \cdot \Psi_0 + \mathcal{O}(q'^{\,2}_{\mathrm{cm}})$$

$$\Psi_0 = V_{LL} \cdot (P_{LL} - P_{TT}/\epsilon) + V_{LT} \cdot P_{LT} \,,$$

$$d\sigma \;=\; d\sigma_{\rm BH+Born} \;+\; \Phi\cdot q'_{\rm cm}\cdot\Psi_0 \;+\; \mathcal{O}(q'^2_{\rm cm}) \qquad q'\to 0$$

The next term of the formula, $(\Phi\cdot q'_{\rm cm}\cdot\Psi_0)$, is where the GPs first appear in the expansion. Ψ_0 is the first-order polarizability term, obtained from the interference between the BH+Born and non-Born amplitudes at the lowest order; it is therefore of order $q'^0_{\rm cm}$, i.e., independent of $q'_{\rm cm}$. The term $(\Phi\cdot q'_{\rm cm})$ is a phase-space factor (see the Appendix for details), in which an explicit factor $q'_{\rm cm}$ has been factored

$$\Psi_0 \;=\; V_{LL}\cdot(P_{LL}-P_{TT}/\epsilon)+V_{LT}\cdot P_{LT}$$

$$V_{LL} \;=\; 2K_2\cdot v_1\cdot\epsilon$$

$$V_{LT} \;=\; 2K_2\cdot\left(v_2-\frac{\tilde{q}_{0\rm cm}}{q_{\rm cm}}\cdot v_3\right)\cdot\sqrt{2\epsilon(1+\epsilon)}$$

$$P_{LL}(0) \;=\; \frac{4M_N}{\alpha_{QED}}\cdot\alpha_{\rm E1}(0)$$

$$P_{TT}(0) \;=\; 0$$

$$P_{LT}(0) \;=\; \frac{-2M_N}{\alpha_{QED}}\cdot\beta_{\rm M1}(0)$$

$$\epsilon \;=\; 1/\left[1+2\frac{q^2_{\rm lab}}{Q^2}\tan^2(\theta'_{e\,\rm lab}/2)\right]$$

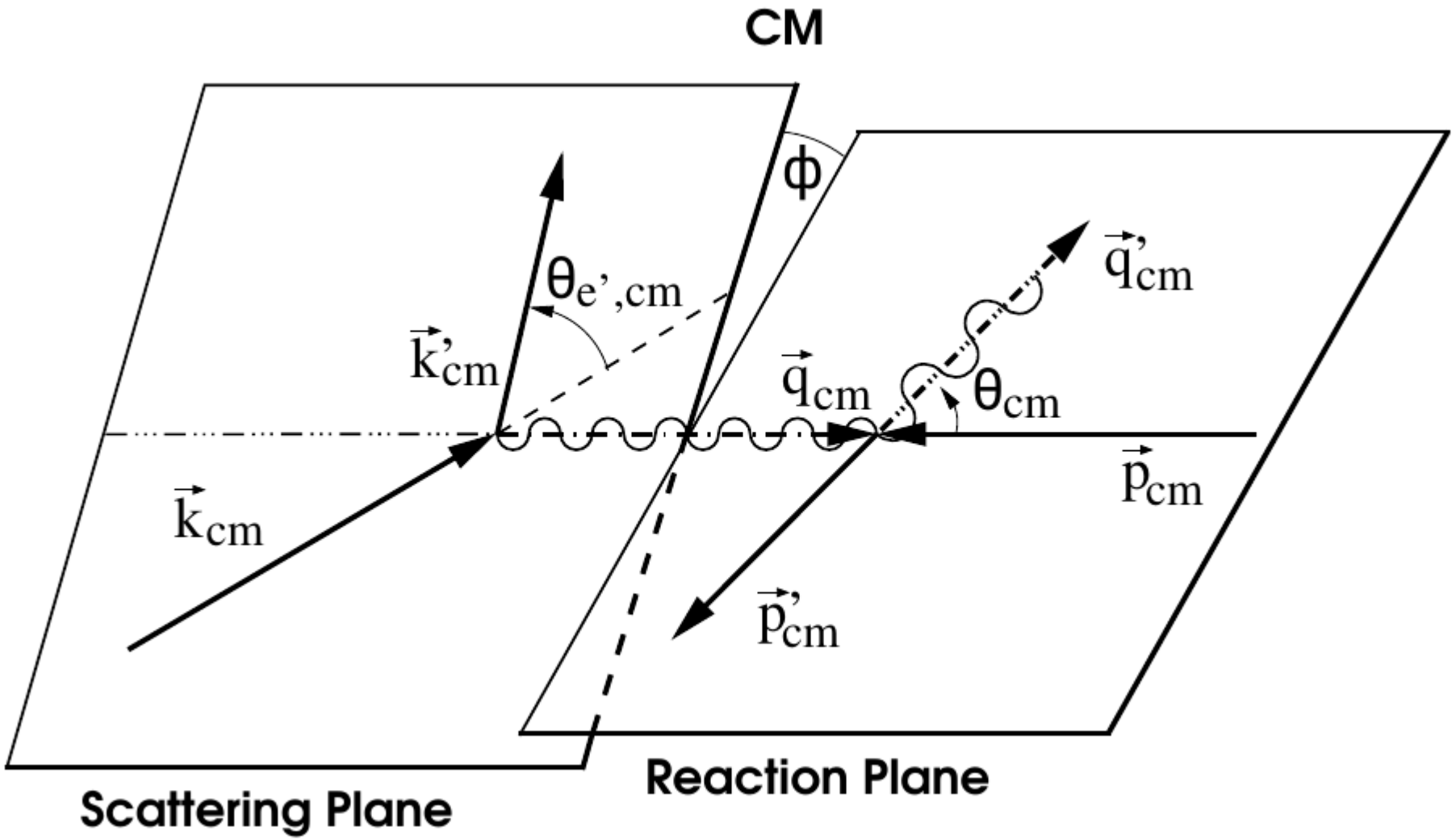
$$K_2 = e^6 \frac{\mathrm{q}}{\tilde{Q}^2} \frac{2m}{1-\varepsilon} \sqrt{\frac{2E_q}{E_q + m}}, \quad E_q = \sqrt{m^2 + \mathrm{q}^2}.$$

The angular dependent functions $(v_1, v_2, \ldots)$ are given by

$$v_1 = \sin\theta \left(\omega^{''} \sin\theta - \mathrm{k}_T \omega^{'} \cos\theta \cos\phi \right),$$

$$v_2 = - \left(\omega^{''} \sin\theta \cos\phi - \mathrm{k}_T \omega^{'} \cos\theta \right),$$

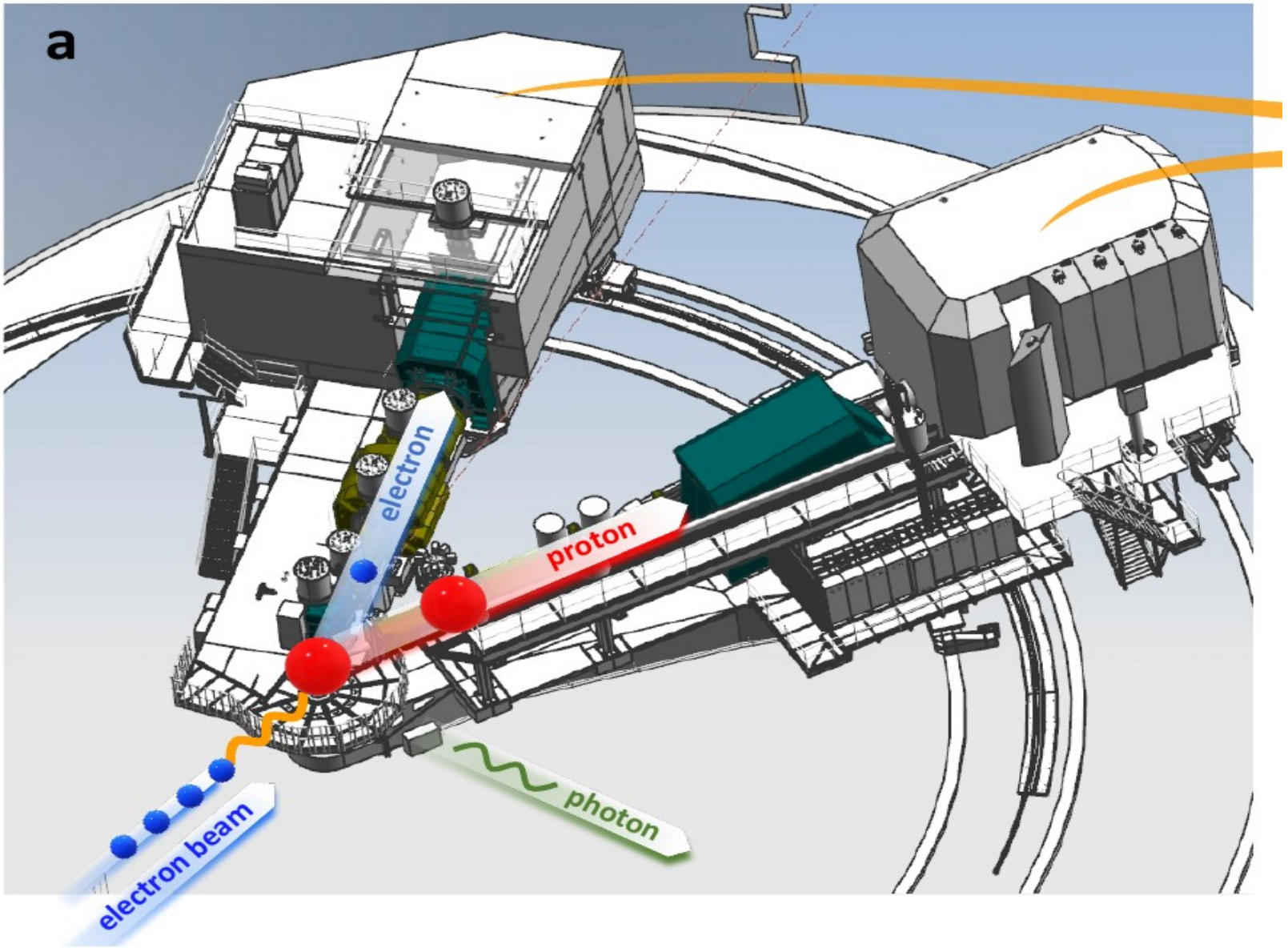
$$v_3 = - \left(\omega^{''} \sin\theta \cos\theta \cos\phi - \mathrm{k}_T \omega^{'} \left(1 - \sin^2\theta \cos^2\phi \right) \right),$$


CM
ϕ
$\theta_{e',cm}$
$\vec{k}'_{cm}$
$\vec{q}_{cm}$
θ_{cm}
$\vec{q}'_{cm}$
$\vec{p}_{cm}$
$\vec{k}_{cm}$
$\vec{p}'_{cm}$
Reaction Plane
Scattering Plane

$P^{(\rho' L', \rho L) S}(q_{\rm cm})$	$P^{(f,i)S}(q_{\rm cm})$	RCS limit $(Q^2 \to 0)$
$P^{(01,01)0}$	$P^{(L1,L1)0}$	$-\frac{4\pi}{e^2}\sqrt{\frac{2}{3}}\ \alpha_{\rm E1}$
$P^{(11,11)0}$	$P^{(M1,M1)0}$	$-\frac{4\pi}{e^2}\sqrt{\frac{8}{3}}\ \beta_{\rm M1}$
$P^{(01,01)1}$	$P^{(L1,L1)1}$	0
$P^{(11,11)1}$	$P^{(M1,M1)1}$	0
$P^{(01,12)1}$	$P^{(L1,M2)1}$	$-\frac{4\pi}{e^2}\frac{\sqrt{2}}{3}\ \gamma_{E1M2}$
$P^{(11,02)1}$	$P^{(M1,L2)1}$	$-\frac{4\pi}{e^2}\frac{2\sqrt{2}}{3\sqrt{3}}\gamma_{M1E2}$

Experiment

JLab



4.56 GeV at a beam current up to 20 μA

10 cm long liquid-hydrogen target at a temperature of 19 K

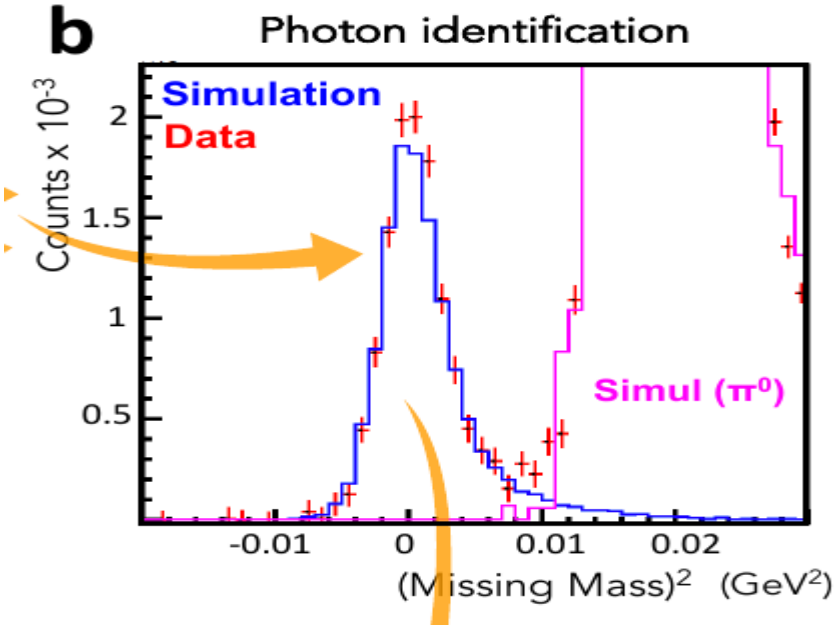
$\mathbf{q} = \mathbf{k} - \mathbf{k}'$, with $Q^2 \equiv -\mathbf{q}^2$.

Time coincidence 1 nsec

time-of-flight proton identification (scintillators)

drift chambers to provide the tracking

$ep \rightarrow e'p'\pi^0$ to control normalization.



Drawback – $q' \sim 250$ MeV (not small)

Δ-isobar region

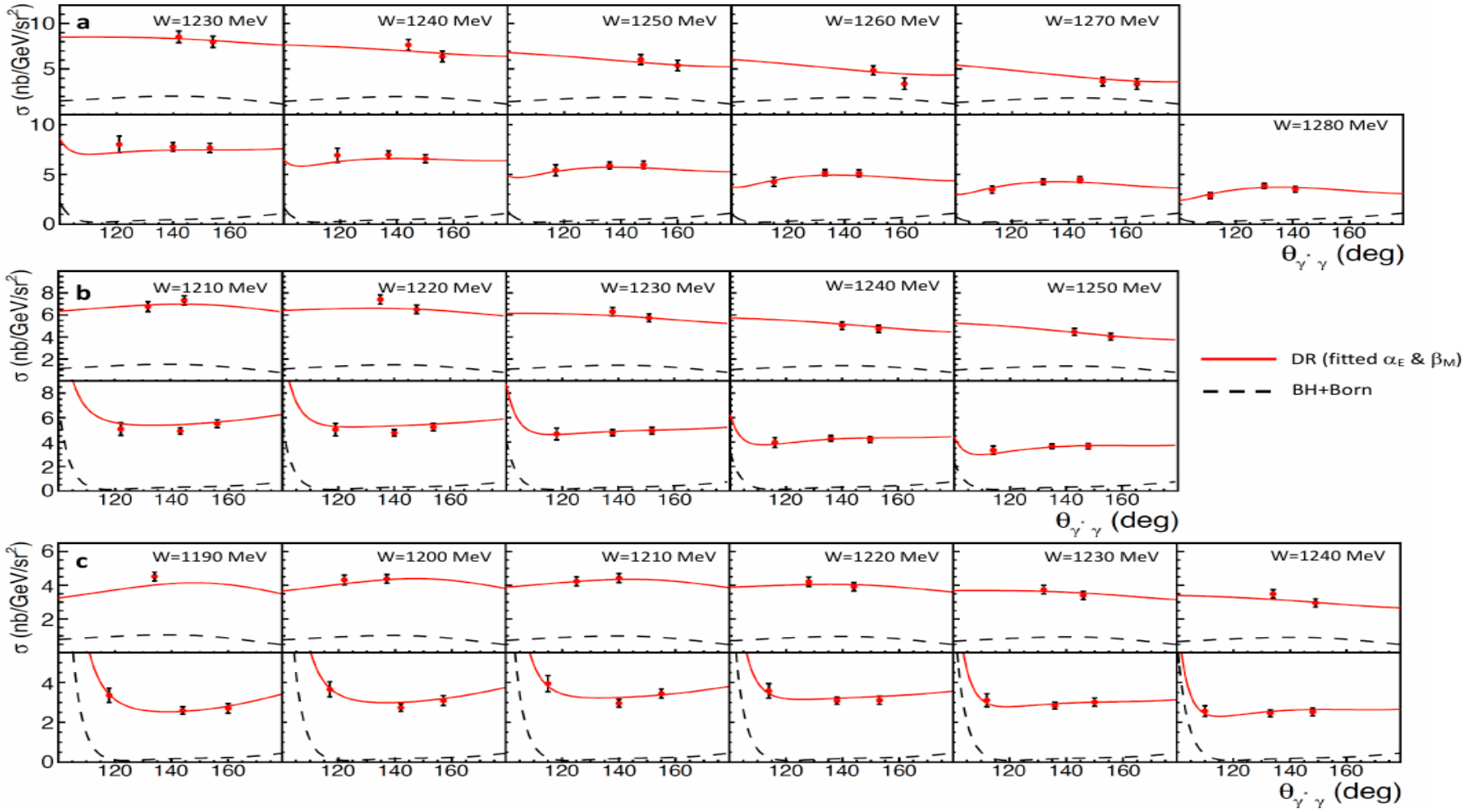
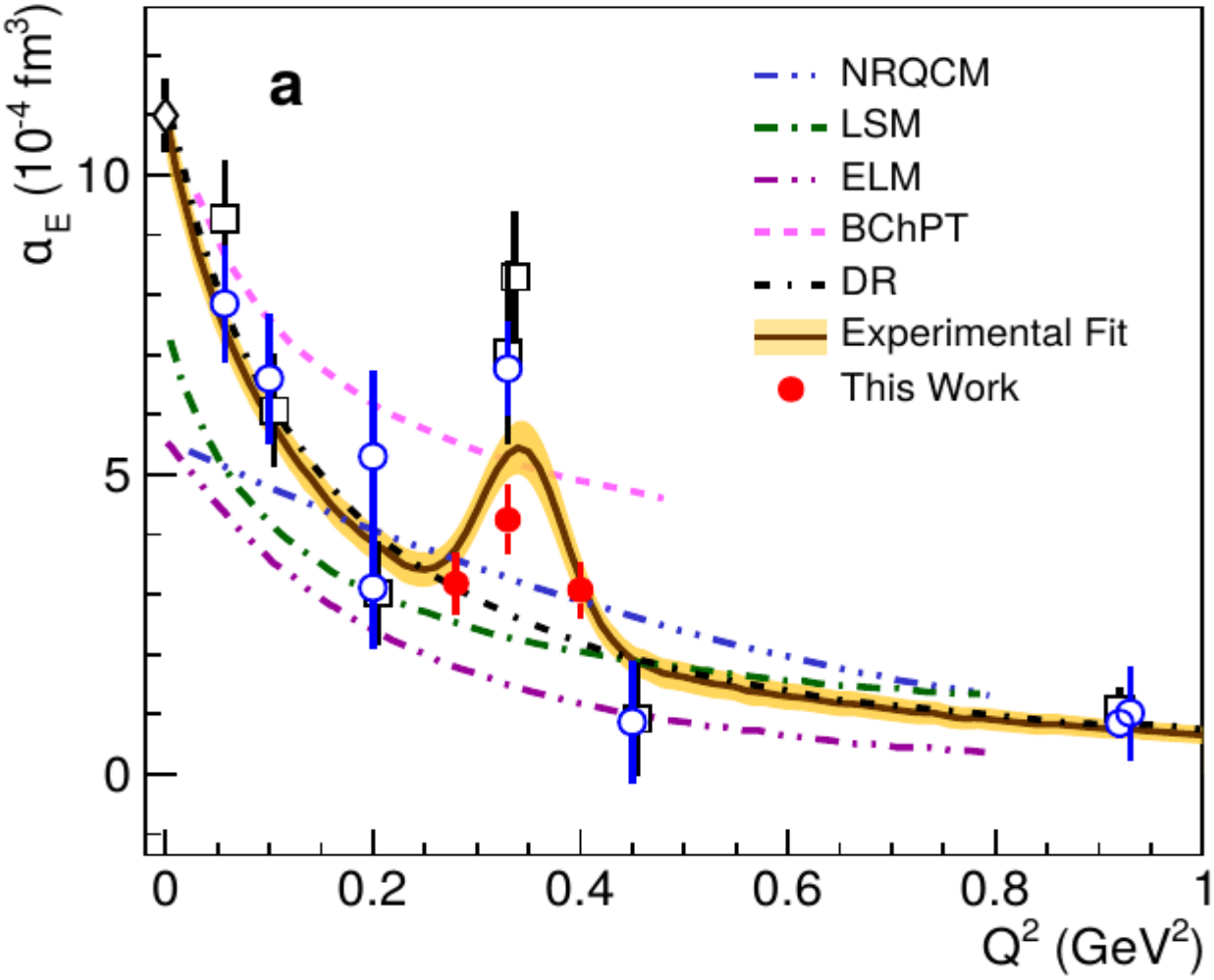
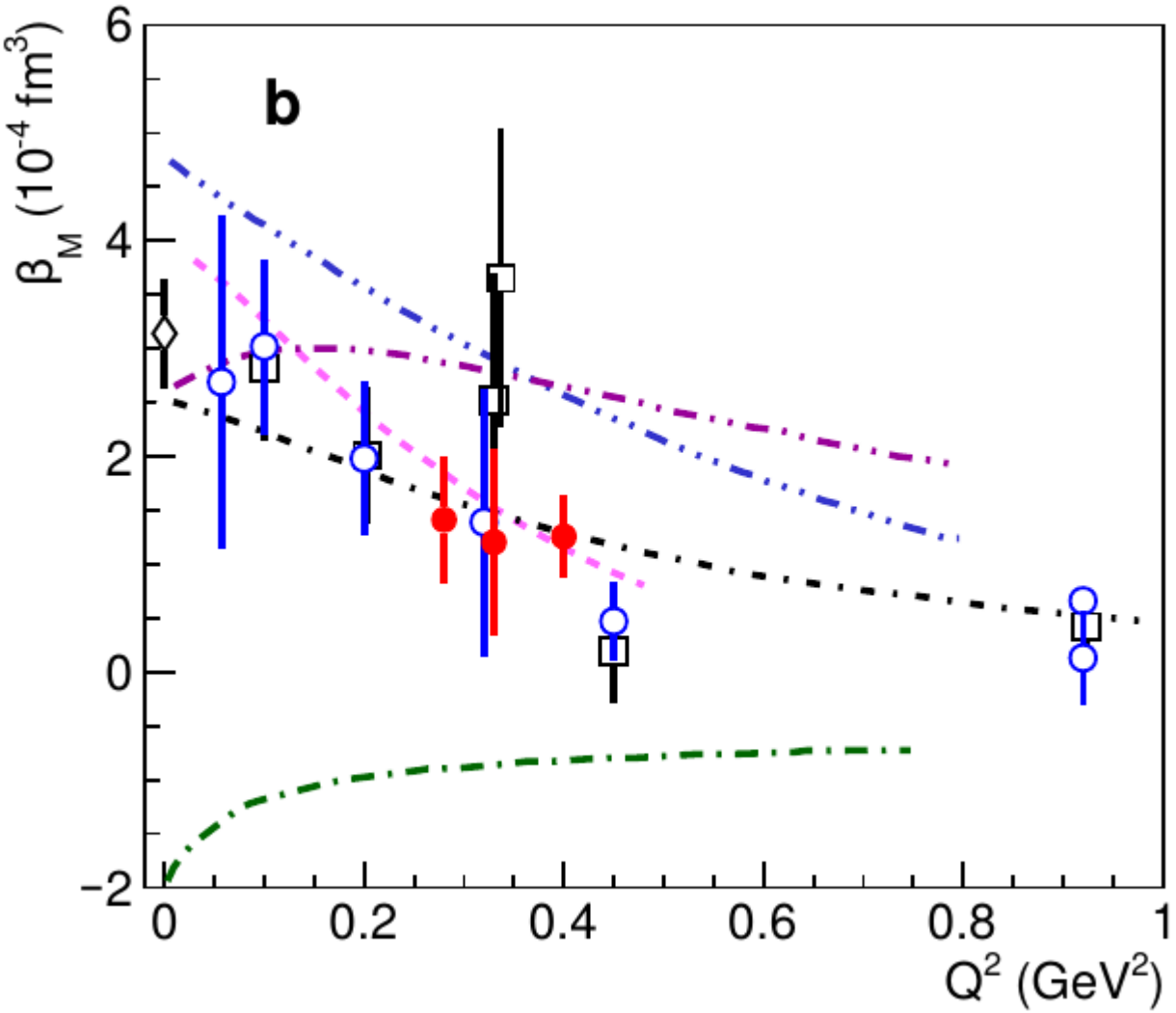


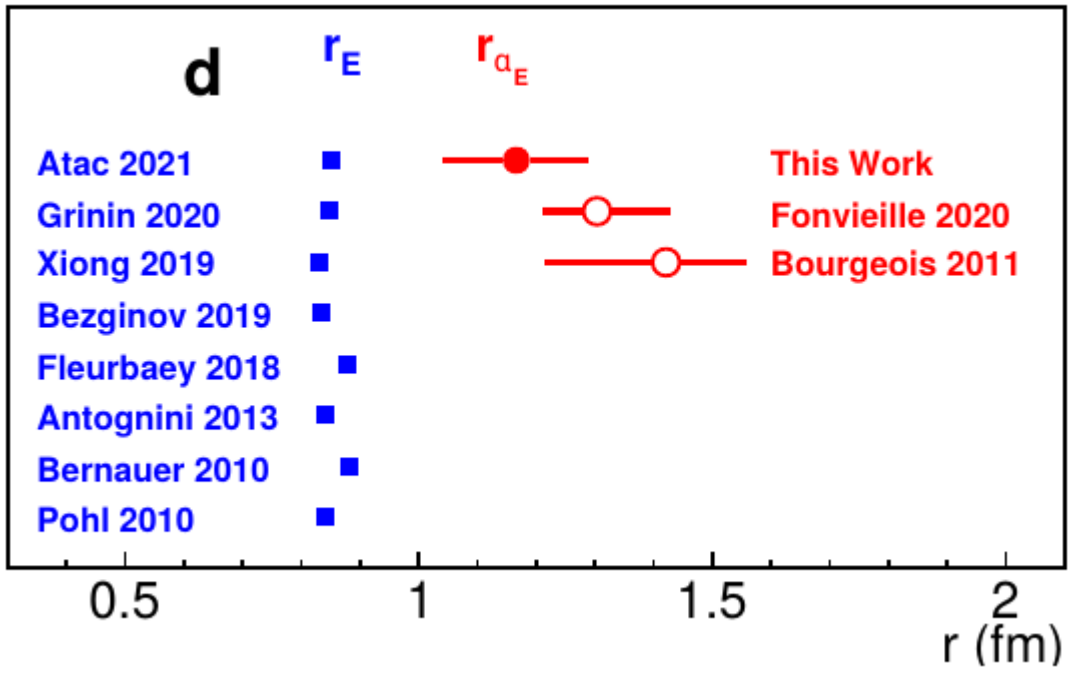
Figure 3. Cross section measurements of the VCS reaction

a) Cross section measurements for in-plane kinematics at Q^2=0.28 GeV^2. Results are shown for different bins in the total c.m. energy, W, of the (γp) system. **b)** Measurements for in-plane kinematics at Q^2=0.33 GeV^2. **c)** Measurements for in-plane kinematics at Q^2=0.40 GeV^2. Top and bottom panels correspond to $\phi_{\gamma^*\gamma} = 180^\circ$ and $\phi_{\gamma^*\gamma} = 0$, respectively. The solid curve shows the Dispersion Relation (DR) fit for the two scalar generalized polarizabilities. The dashed curve shows the Bethe-Heitler plus Born-VCS (BH+Born) cross section. The error bars correspond to the total uncertainty, at the 1σ or 68% confidence level.



NRQCM – constituent quark model
LSM – linear sigma model
ELM — effective Lagrangian
BChPT – chiral perturbative
DR – dispersion relations


b
β_M (10^{-4} fm^3)
6
4
2
0
−2
0
0.2
0.4
0.6
0.8
1
Q^2 (GeV^2)

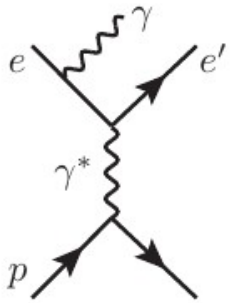


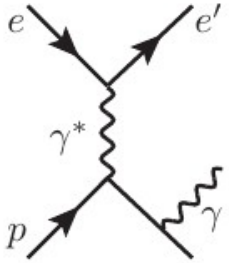
$$r_{\alpha_E} \equiv \sqrt{\langle r^2_{\alpha_E} \rangle}$$

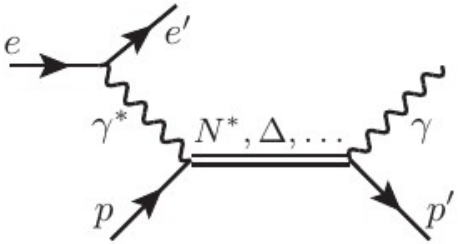
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

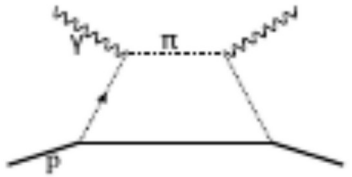
$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \ fm^2 \qquad \langle r^2_{\beta_M} \rangle = 0.63 \pm 0.31 \ fm^2$$

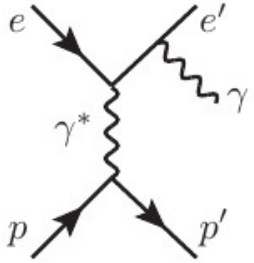
$$\langle r^2_E \rangle \sim 0.7 \ fm^2$$

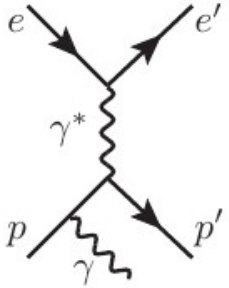


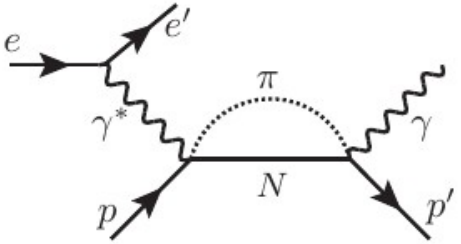


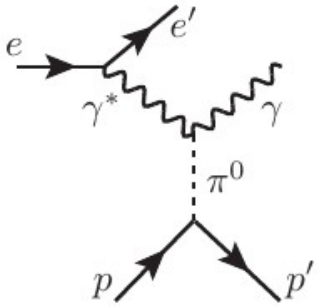












Bethe-Heitler

VCS Born

VCS non-Born

π^0 pole

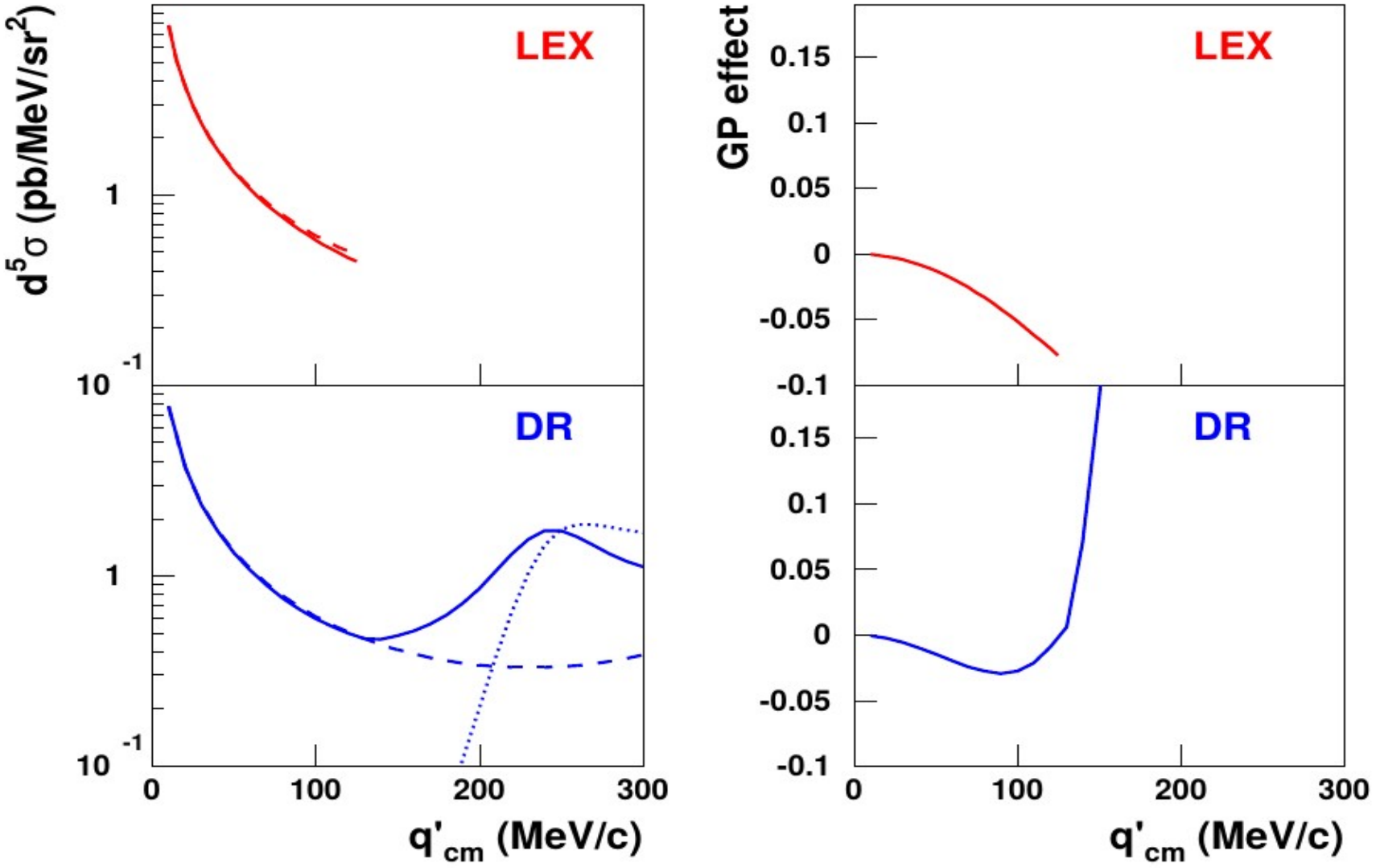
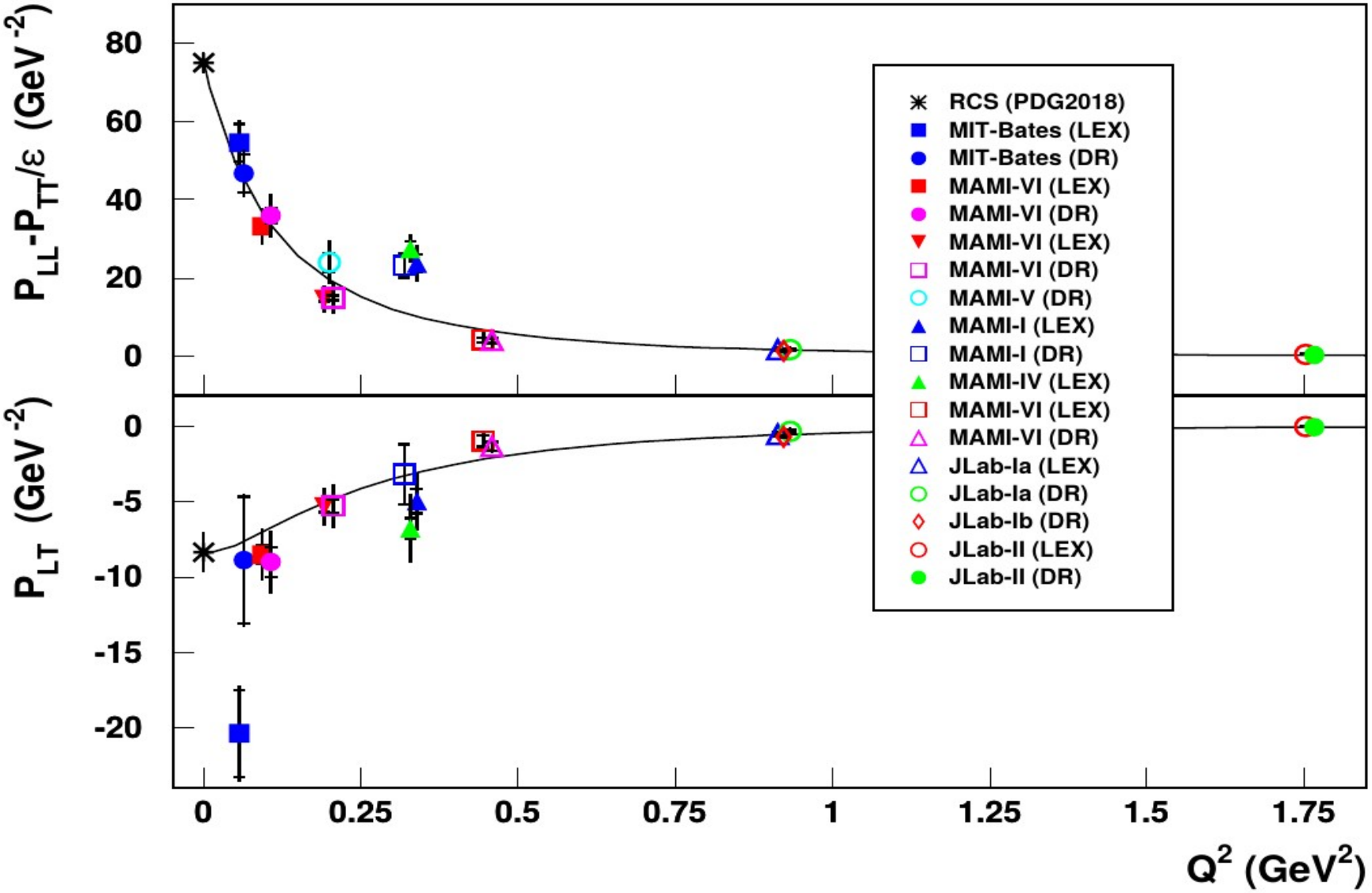
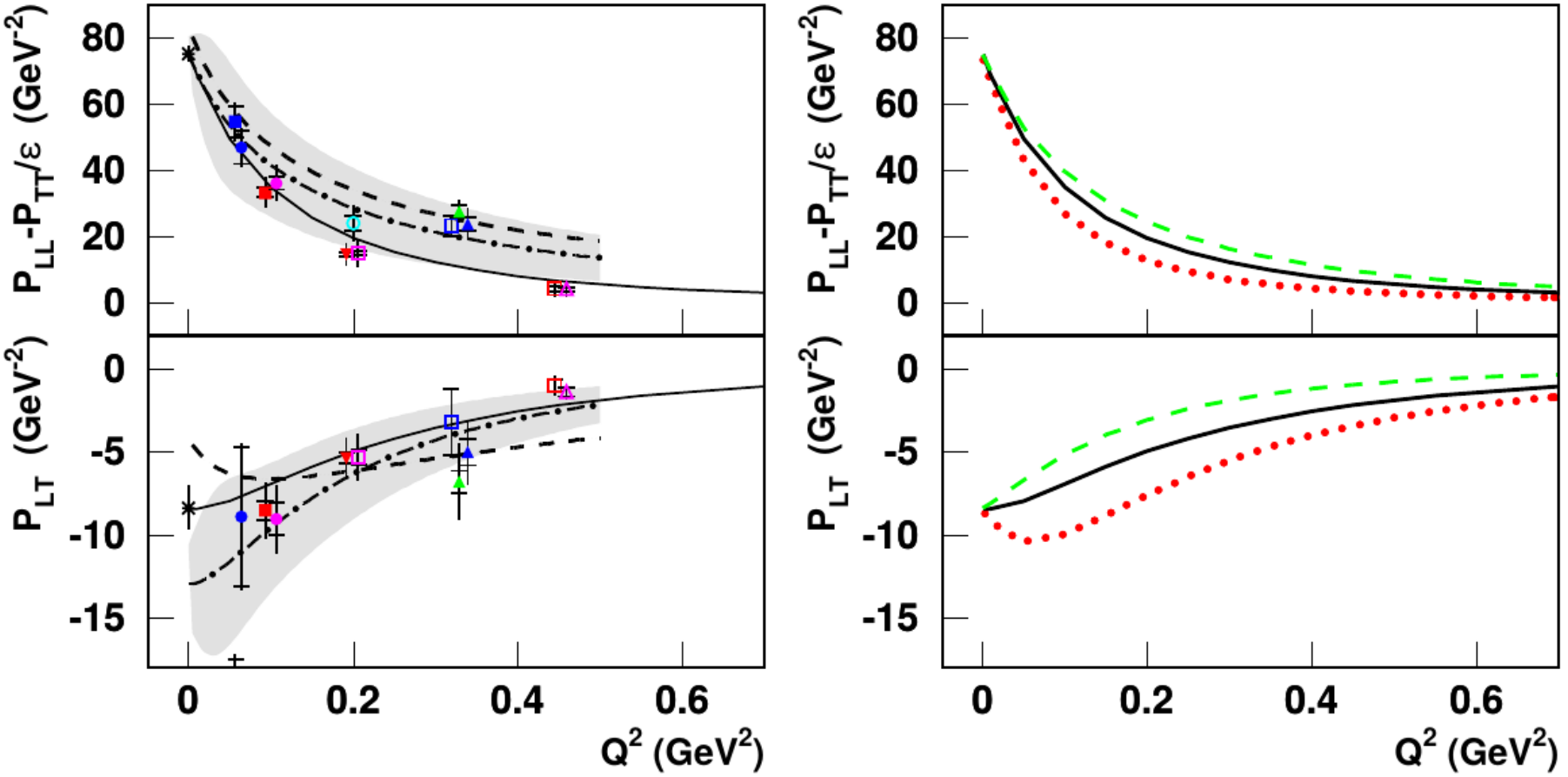


Figure 6: (color online) $q'_{\rm cm}$-dependence of the cross section and the GP effect at fixed $Q^2 = 0.2$ GeV^2, $\epsilon = 0.9$, $\theta_{\rm cm} = 100^\circ$ and $\varphi = 180^\circ$. Top-left plot: the LEX cross section (solid) and BH+Born cross section (dashed). Top-right plot: the GP effect from the LEX,



The solid curve is the DR model calculation for ($\Lambda_\alpha = \Lambda_\beta = 0.7$ GeV)

$$\text{const in DR} = f(0)/(1+Q^2/\Lambda^2)^2$$

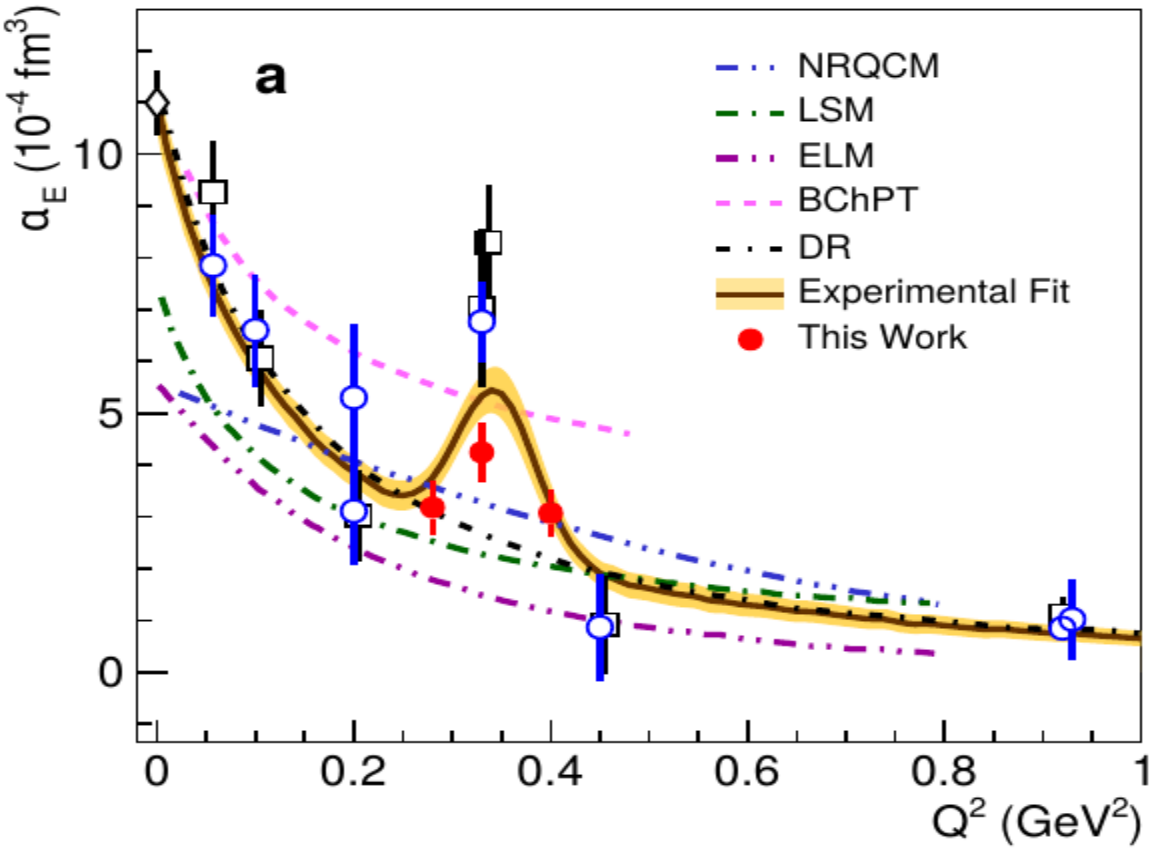


the nomenclature of Fig. 14. The solid curve is the DR model calculation for ($\Lambda_\alpha = \Lambda_\beta = 0.7$ GeV). The dashed curve is the HBChPT $\mathcal{O}(p^3)$ calculation of Ref. [34]. The dashed-dotted curve with its error band (shaded area) is from covariant BChPT at $\mathcal{O}(p^3) + \mathcal{O}(p^4/\bar{\Delta})$ [36]. Right plots: the DR model calculation [39] for three different choices of the dipole mass parameter: $(\Lambda_\alpha = \Lambda_\beta) = 0.5$ GeV (dotted curve), 0.7 GeV (solid curve), 0.9 GeV (dashed curve). Model calculations use $\epsilon = 0.65$.

$$\alpha_{\rm E1} \;=\; 2\sum_{N^*\neq N}\frac{|<N^*|D_z|N>|^2}{E_{N^*}-E_N},$$

D_z is the electric dipole moment operator and N^* indicates a nucleon resonance.

$$\Delta(1700)\;\; J^P=\tfrac{3}{2}^- \qquad Br(N\gamma)=0.2-0.6\%$$
$$N(1680)\;\; J^P=\tfrac{5}{2}^+ \qquad Br(N\gamma)=0.2-0.3\%$$



THANK YOU