Exploring the Nucleon Polarizabilities with Positrons

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Overview

(1) A brief introduction to the GPs

(2) Discuss the potential of what we can do with positrons about it, and

(3) Give a quick update of where we are at the moment (codes up and running, debugged and checked, … currently at the stage of working out simulation studies, etc)

Polarizabilities

Polarizability:

- Polarizability of an object is the response of its internal structure to an EM field.
- A fundamental characteristic of the proton (Such as mass, size, shape, …)
- Sensitive to the full excitation of the nucleon
- Accessed experimentally through Compton scattering processes

PDG

N BARYONS
($S = 0$, $I = 1/2$)
$p, N^+ = uud$; $n, N^0 = udd$

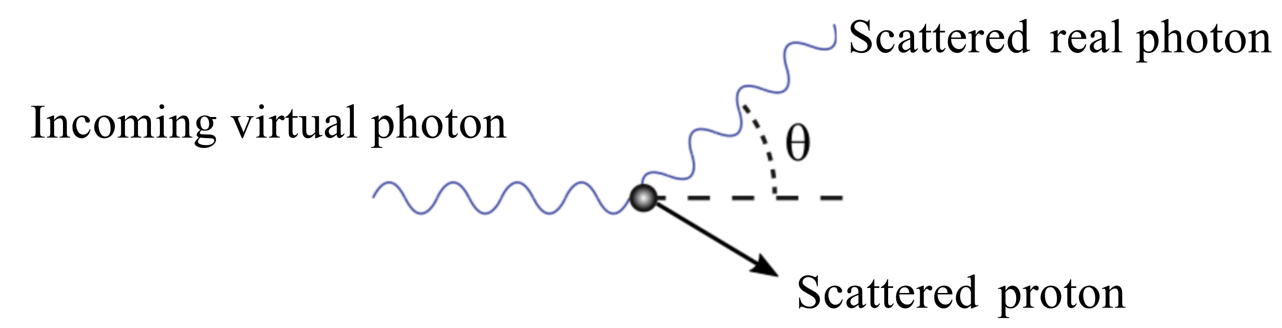
p $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.00727646688 \pm 0.00000000009$ u
Mass $m = 938.272081 \pm 0.000006$ MeV [a]
$|m_p - m_{\overline{p}}|/m_p < 7 \times 10^{-10}$, CL = 90% [b]
$|\frac{q_{\overline{p}}}{m_{\overline{p}}}|/(\frac{q_p}{m_p}) = 1.00000000000 \pm 0.00000000007$
$|q_p + q_{\overline{p}}|/e < 7 \times 10^{-10}$, CL = 90% [b]
$|q_p + q_e|/e < 1 \times 10^{-21}$ [c]
Magnetic moment $\mu = 2.7928473446 \pm 0.0000000008\ \mu_N$
$(\mu_p + \mu_{\overline{p}}) / \mu_p = (0.3 \pm 0.8) \times 10^{-6}$
Electric dipole moment $d < 0.021 \times 10^{-23}$ $e$cm
Electric polarizability $\alpha = (11.2 \pm 0.4) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius, μp Lamb shift = 0.84087 ± 0.00039 fm [d]
Charge radius, ep CODATA value = 0.8751 ± 0.0061 fm [d]
Magnetic radius = 0.78 ± 0.04 fm [e]
Mean life $\tau > 2.1 \times 10^{29}$ years, CL = 90% [f] ($p \to$ invisible mode)
Mean life $\tau > 10^{31}$ to 10^{33} years [f] (mode dependent)

Scaler GP at the four-momentum transferred squared Q^2=0 (RCS limit)

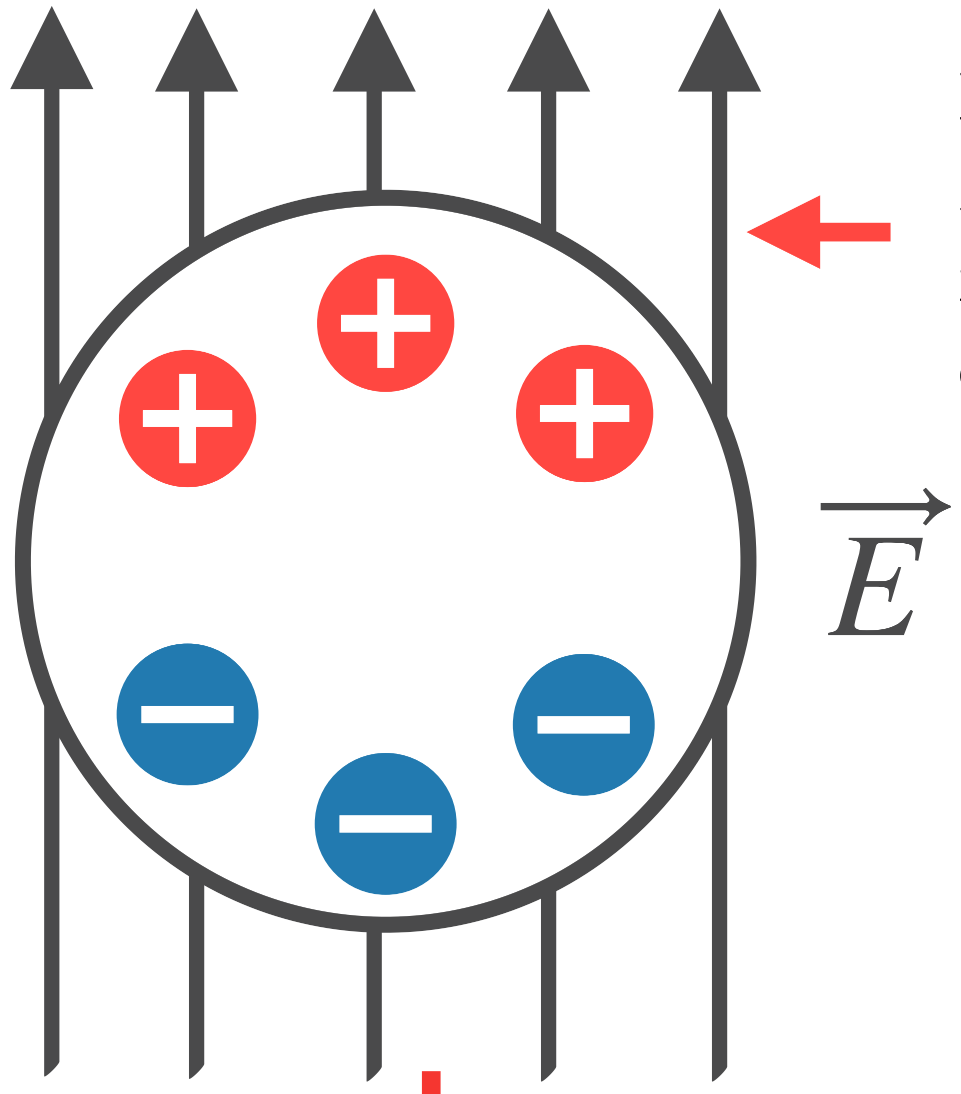
Generalized Polarizabilites (GPs):

- Access by Virtual Compton Scattering (VCS)

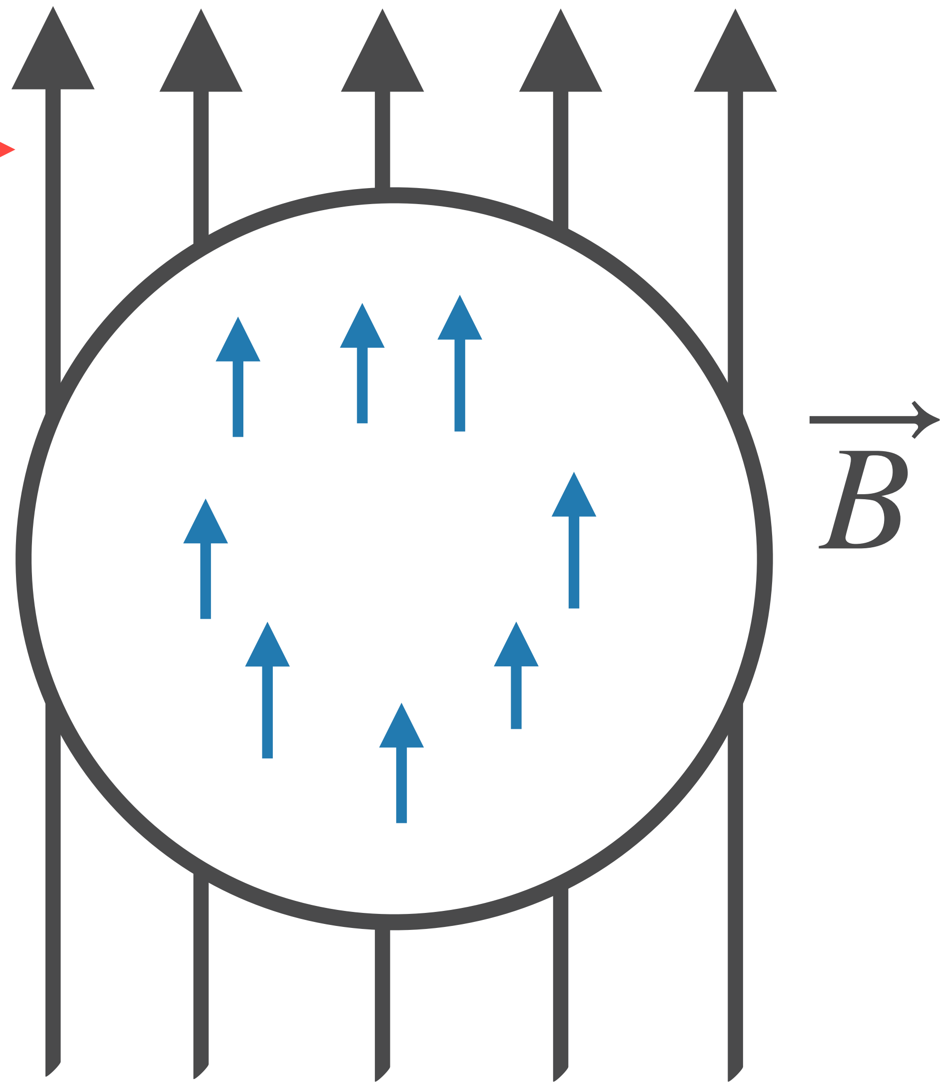


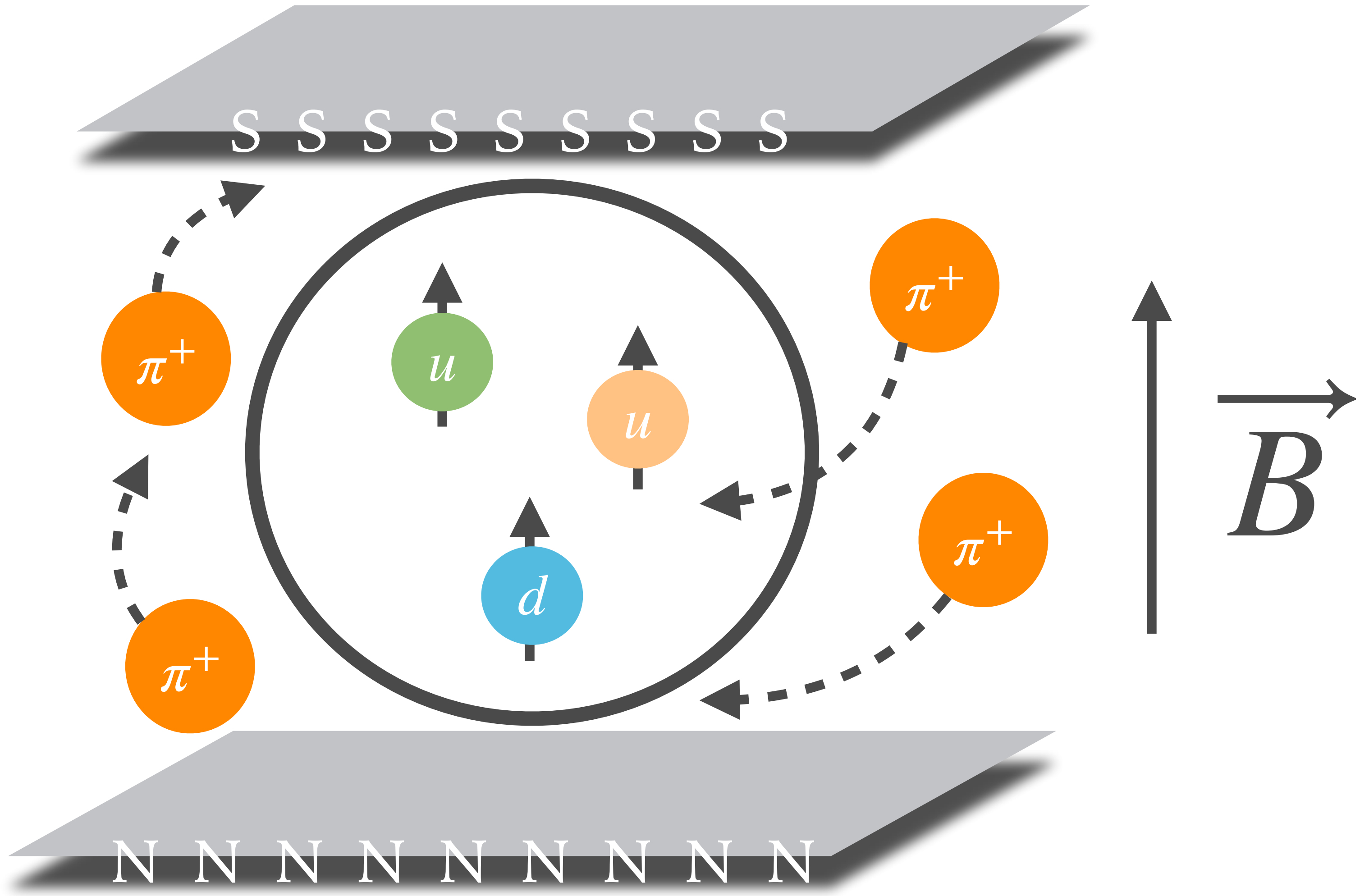
- Two scalar and four vector GPs ($\alpha_E(Q^2)$ & $\beta_M(Q^2)$ and 4 spin GPs)
- Fourier transform can map out the spatial distribution density of the polarization induced by an EM field

Scalar Polarizabilities



Interaction of the EM field with the internal structure of the nucleon





Electric Polarizability

$$\vec{p} = \alpha_E \vec{E}$$

- External field deforms the charge distribution
- Electric polarizability α_E reflects the rigidity of proton

Magnetic Polarizability

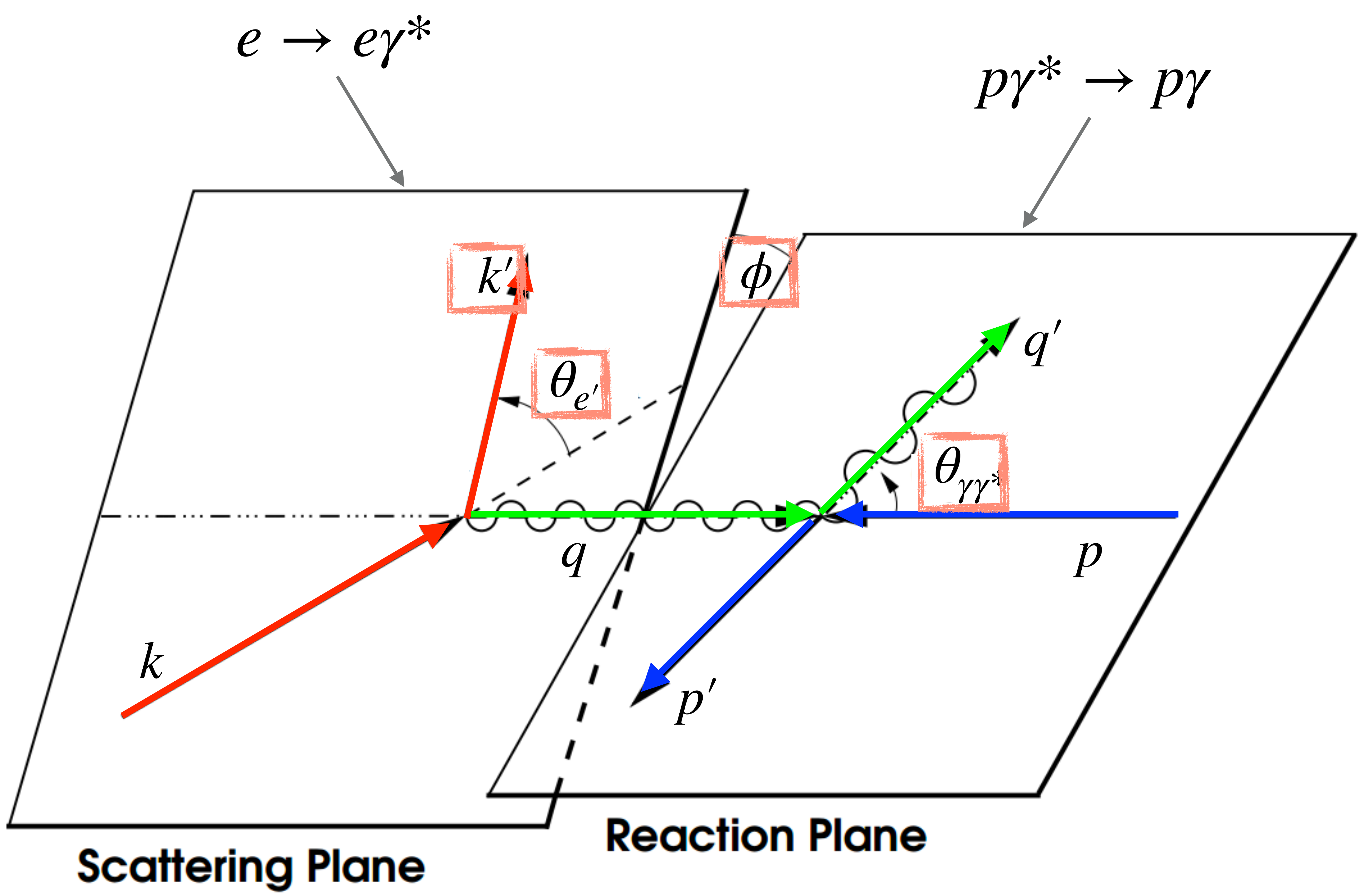
$$\vec{m} = \beta_M \vec{B}$$

- **Paramagnetic**: >0, quarks align along magnetic field;
- **Diamagnetic**: <0, pion cloud induced magnetic field in opposite direction
- Partially cancels each other, makes β_M value small

Virtual Compton scattering

k-incoming electron q-virtual photon p-initial proton

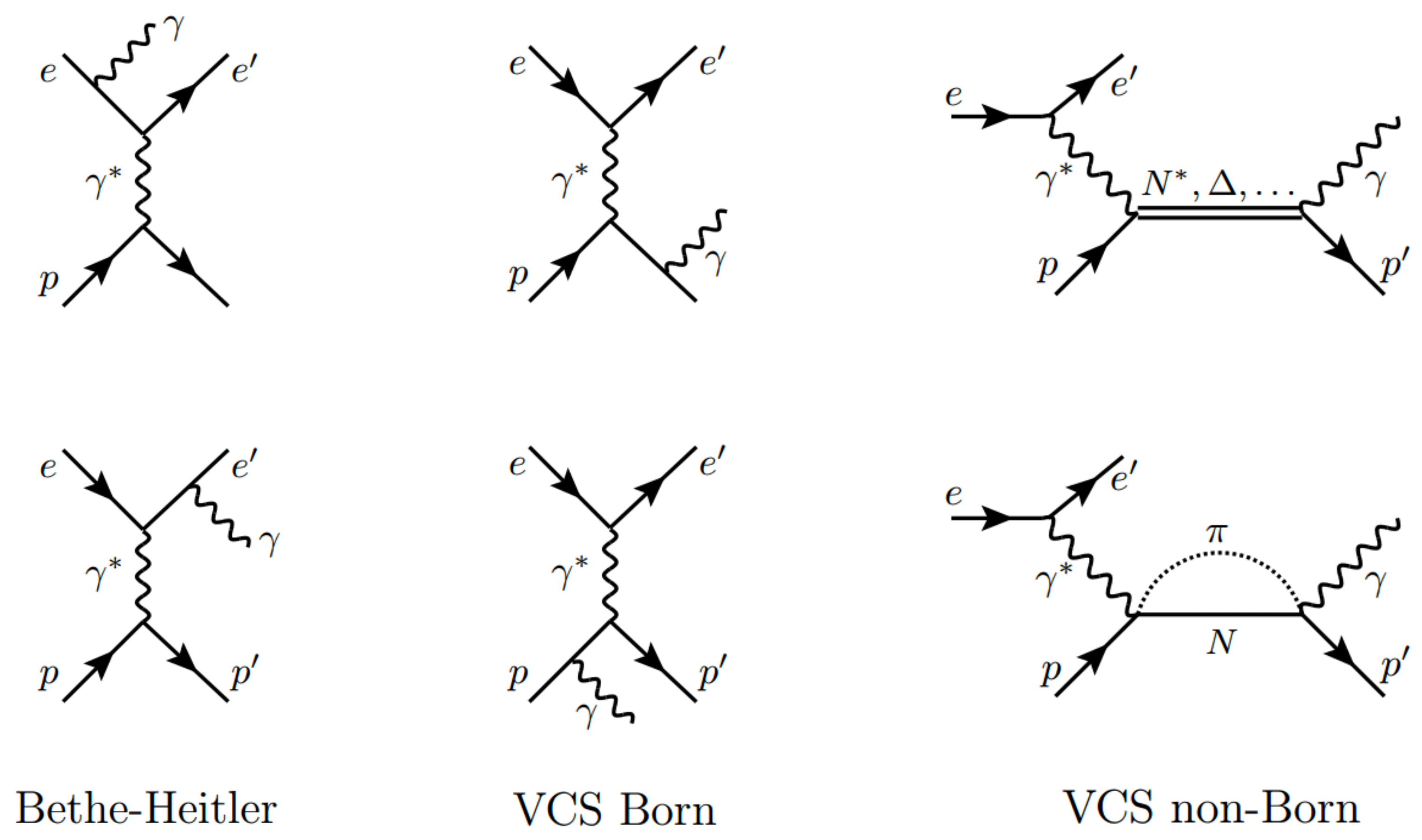
k'-scattered electron q'-real photon p'-final proton



Kinematics of $ep \rightarrow ep\gamma$ reaction

VCS cross-section = $d^5\sigma/(dk'_{lab}d\Omega'_{elab}d\Omega_{p_{cm}})$

VCS process → photon electro-production reaction



Bethe-Heitler + VCS Born → Elastic FFs

VCS non-Born → GPs

$$\alpha_{E1}(Q^2) = -\frac{e^2}{4\pi}\cdot\sqrt{\frac{3}{2}}\cdot P^{(L1,L1)0}(Q^2) \qquad \beta_{M1}(Q^2) = -\frac{e^2}{4\pi}\cdot\sqrt{\frac{3}{8}}\cdot P^{(M1,M1)0}(Q^2)$$

$P^{(L1,L1)0}(Q^2)$ → Electric Scalar GP

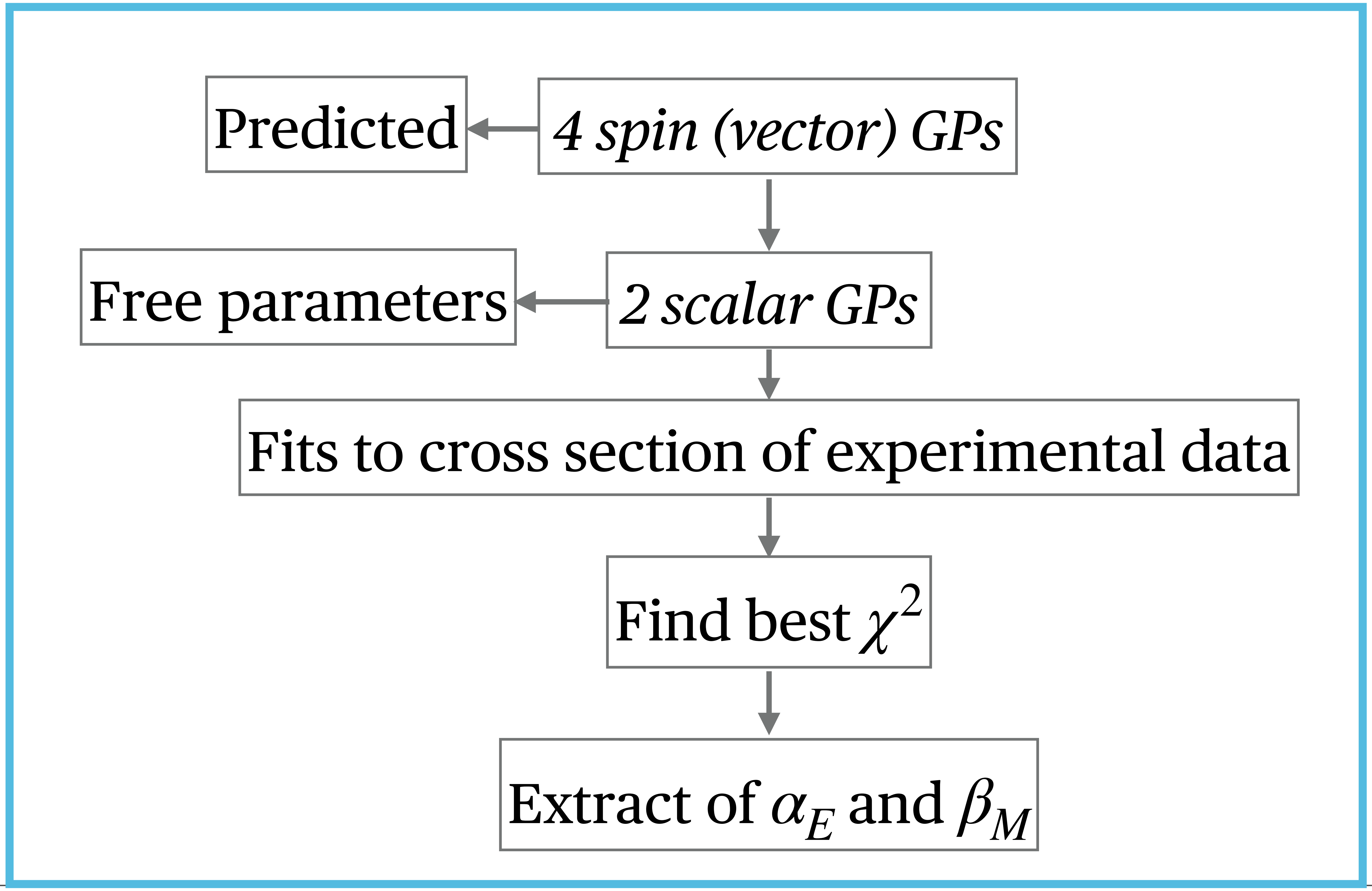
$P^{(M1,M1)0}(Q^2)$ → Magnetic Scalar GP

$P^{(\rho' L', \rho L)S}(Q^2)$

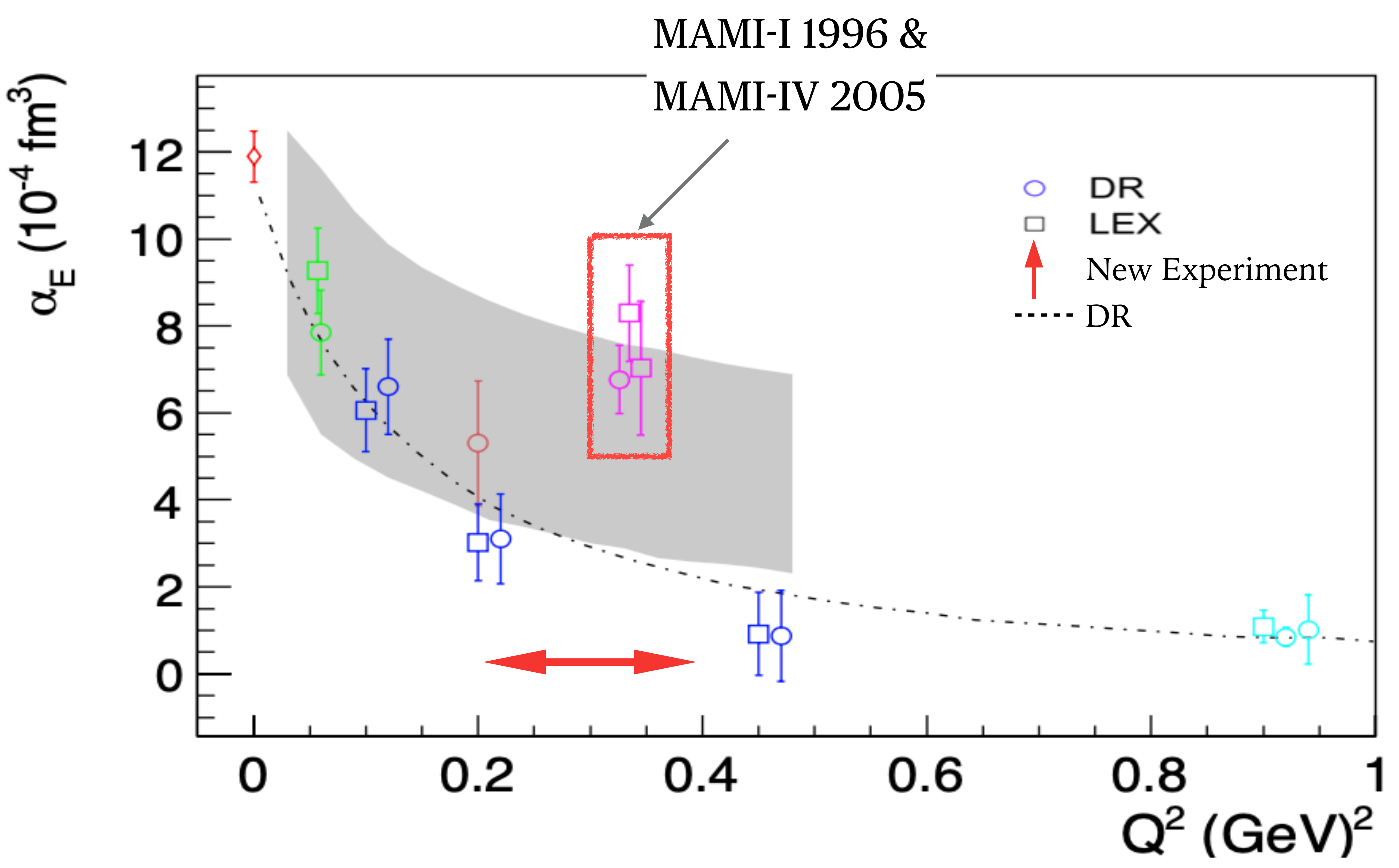
- $\rho(\rho')$ photon longitudinal or EM nature
- $L(L')$ angular momentum
- $[S = 1,0]$ spin flip or non spin flip

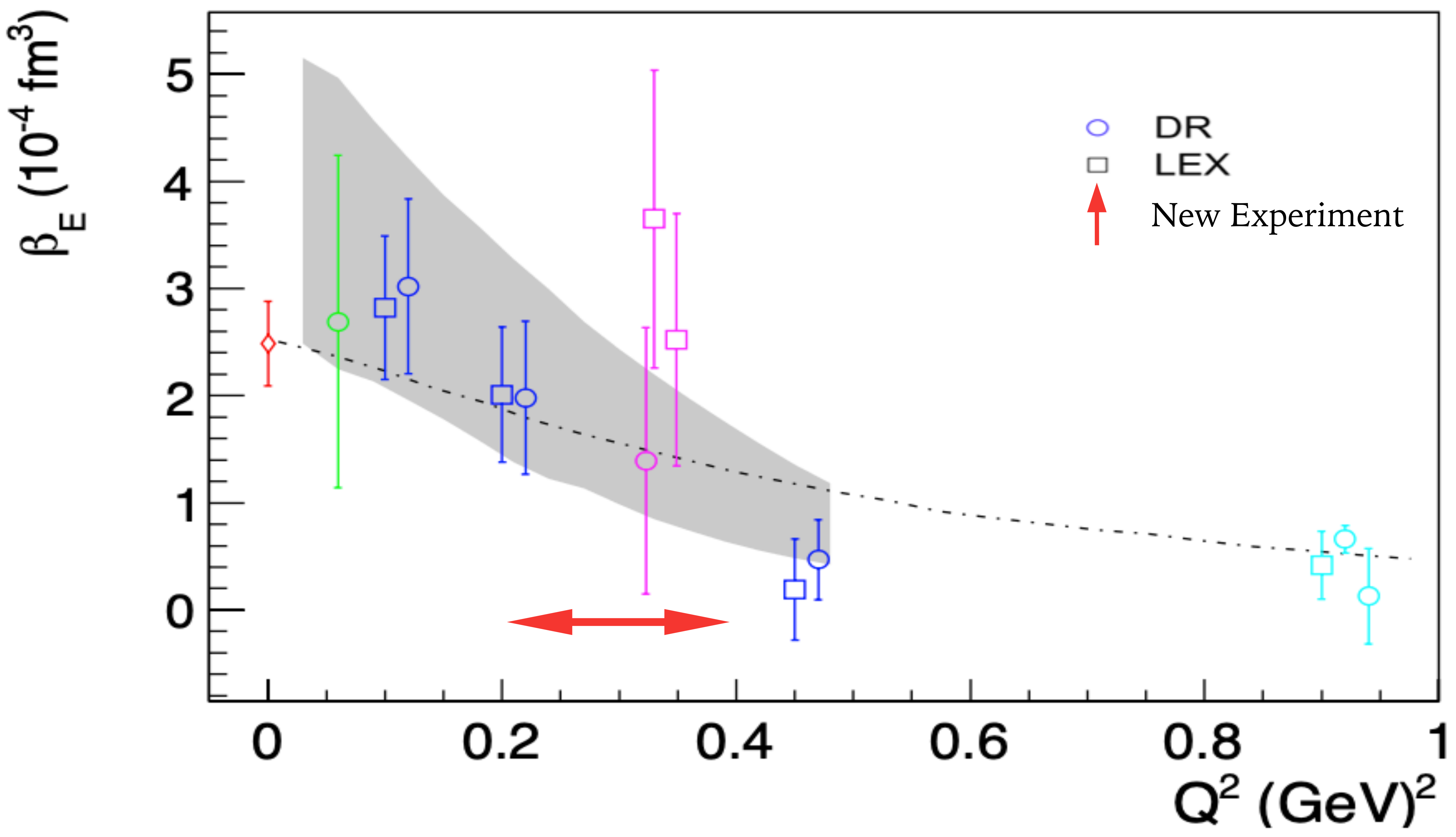
Generalized Polarizabilities

- **LEX - Low Energy Expansion** *Below pion threshold*
- **DR - Dispersion Relation Formalism** *Below & Above pion threshold*



World Data & Motivation



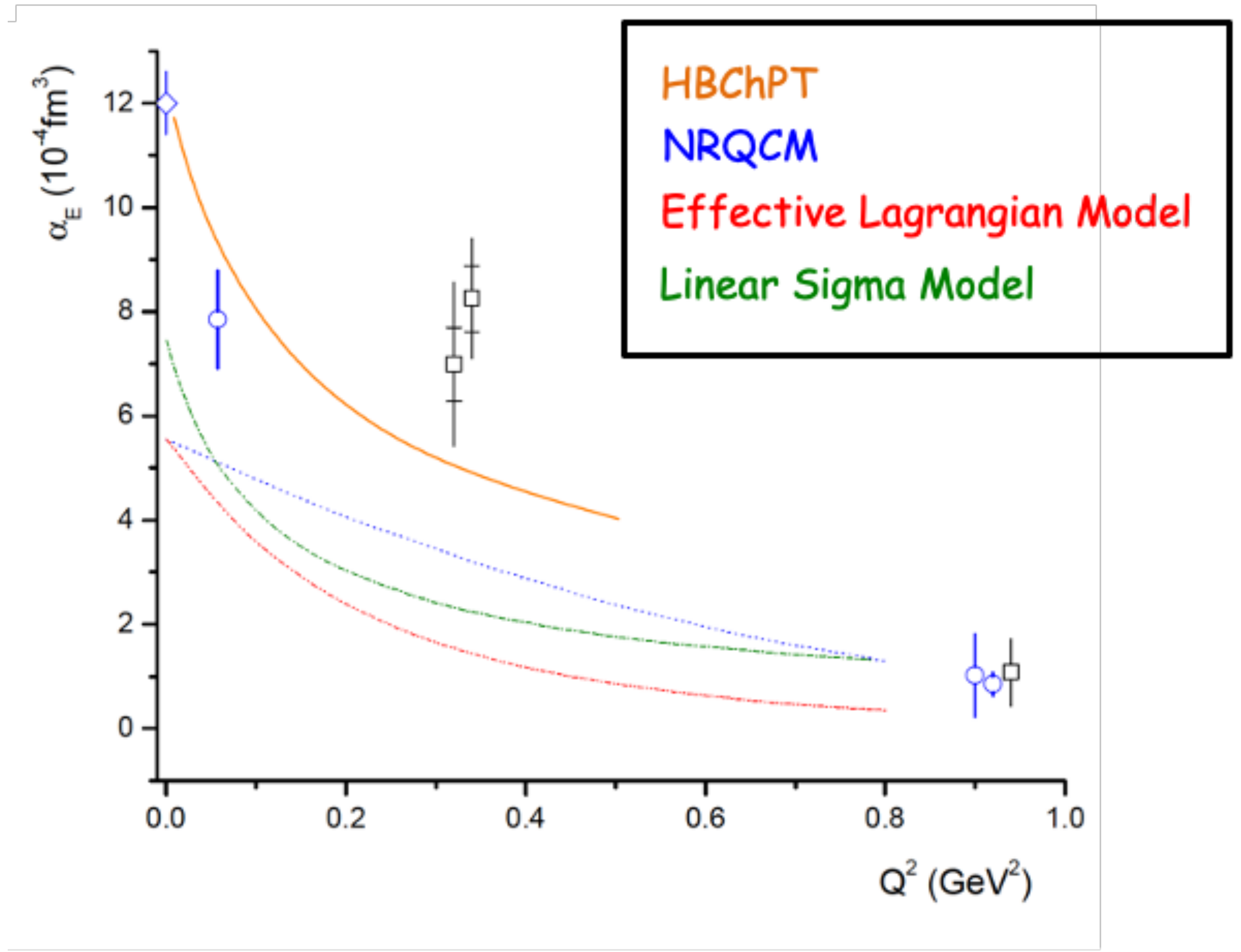


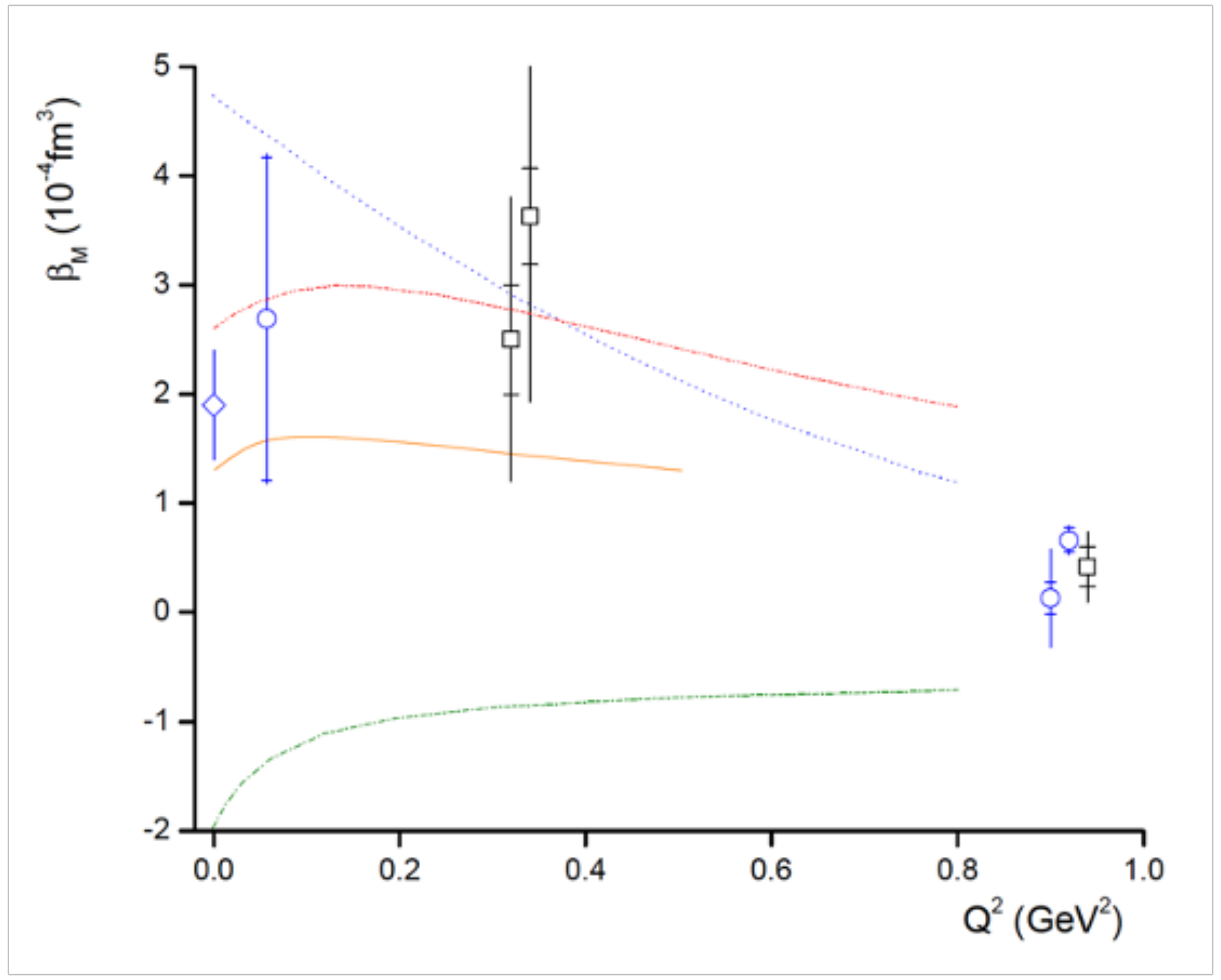
- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Improve precision

- Small values, 1/3 ~ 1/4 of α_E
- Large uncertainties
- New experiment can:
  - Improve precision
  - Explore para-& dia-magnetic mechanism inside nucleon

J. Roche, et al., Phys. Rev. Lett. 85 (2000) 708-711; P. Janssens, et al., Eur. Phys. J. A37 (2008) 1-8; G. Laveissiere, et al., Phys. Rev. Lett. 93 (2004) 122001; H. Fonvieille, et al., Phys. Rev. C86 (2012) 015210;P. Bourgeois, et al., Phys. Rev. Lett. 97 (2006) 212001; Eur.Phys.J.A55(2019)no. 10,182; Phy.Rev.Lett. 123(2019)no.19,192302;Phys.Rev.C 103, 025205(2021)

Theory



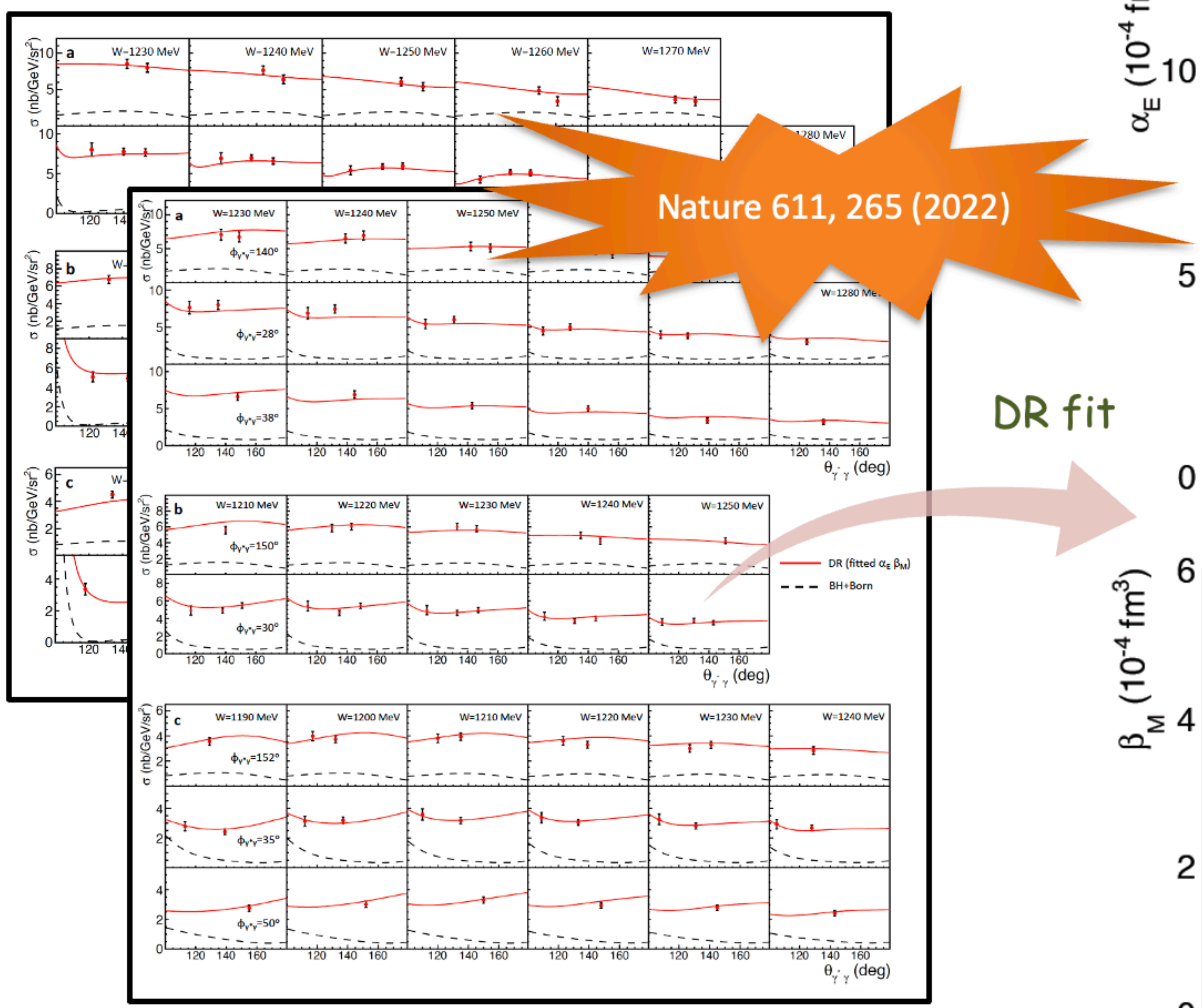


T.R. Hemmert et al	Phys. Rev. D 62, 014013 (2000)
B. Pasquini et al	Phys. Rev. C 63, 025205 (2001)
A. Yu. Korchin and O. Scholten	Phys. Rev. C 58, 1098 (1998)
A. Metz and D. Drechsel	Z. Phys. A 356, 351 (1996)

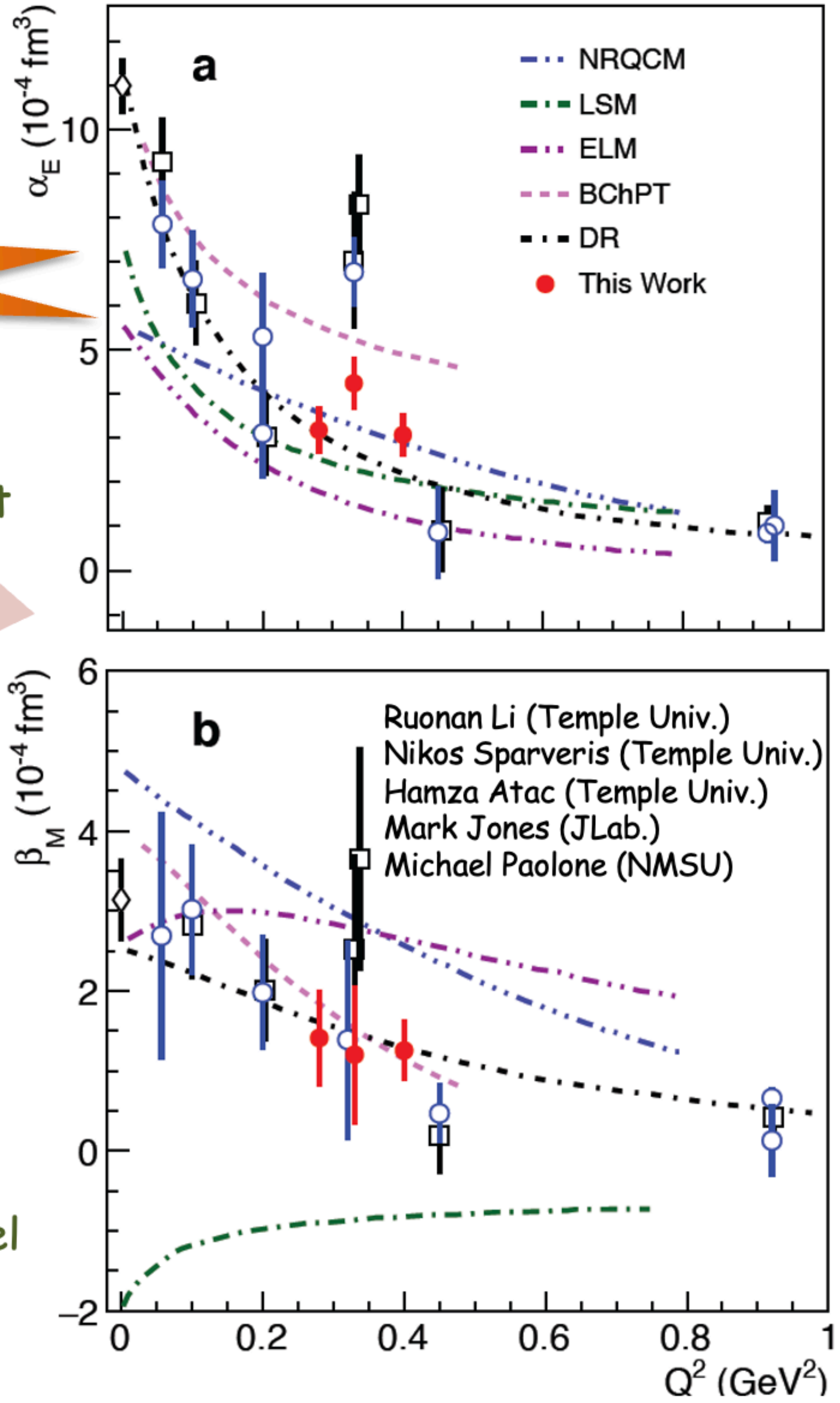
Theory: smooth fall off for α_E

Can not account for a non-trivial structure of α_E as suggested by the data

New results: GPs



DR fit

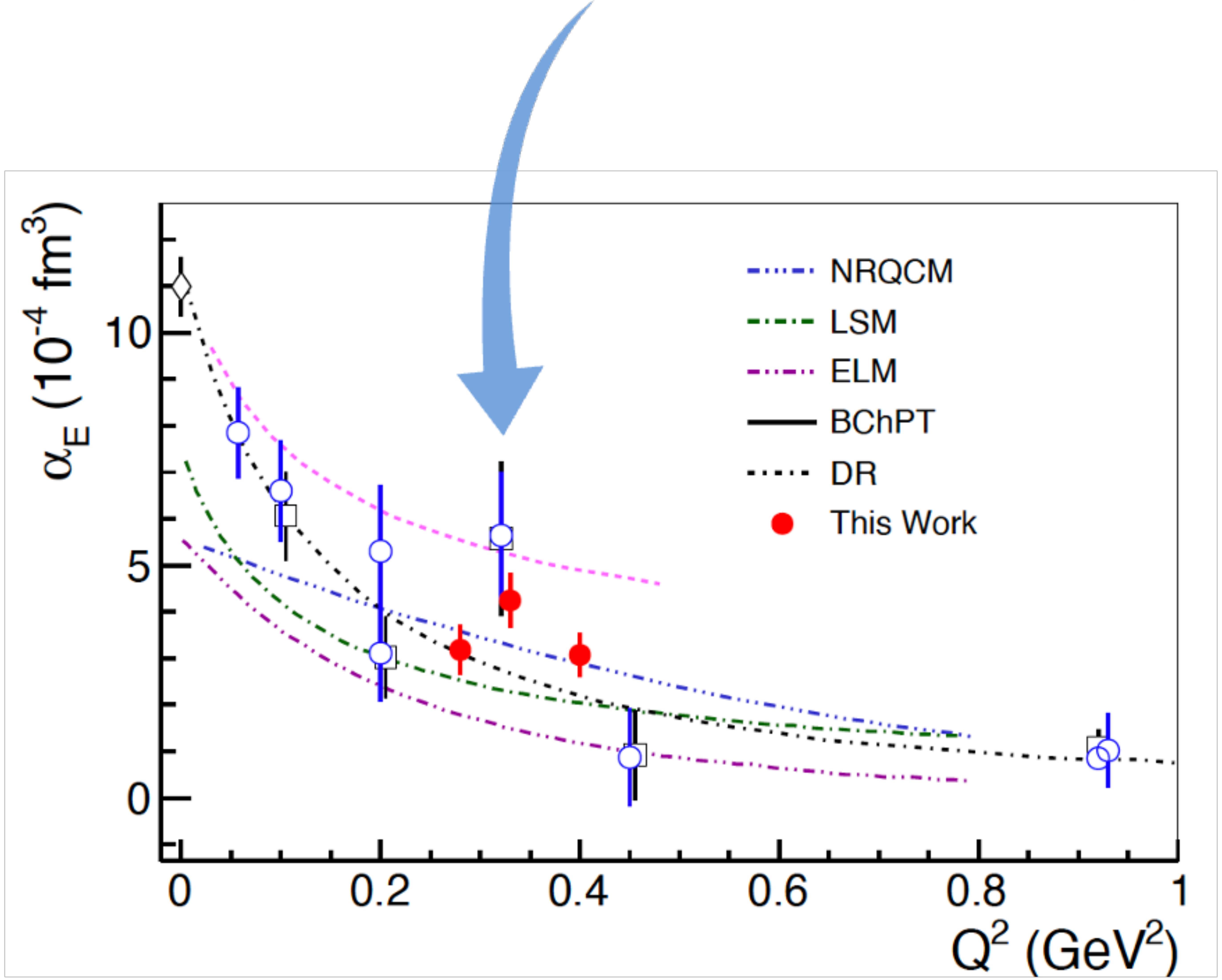


Experimental cross sections are compared to the DR model predictions for all possible values for the GPs

→ $\alpha_E(Q^2)$ and $\beta_M(Q^2)$ are fitted by a χ^2 minimization

Is there a non-trivial structure?

MAMI-I re-analysis (unpublished)

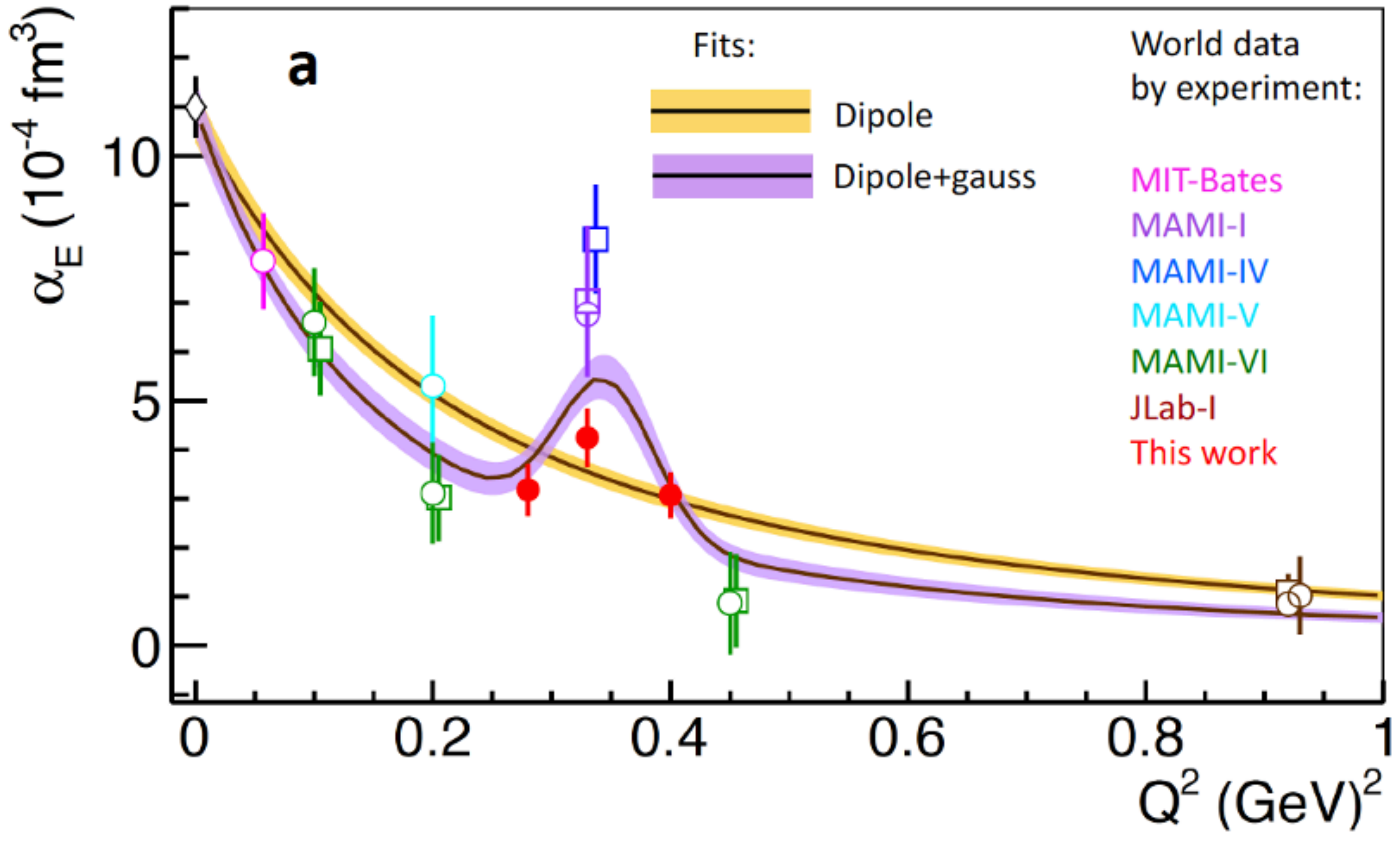


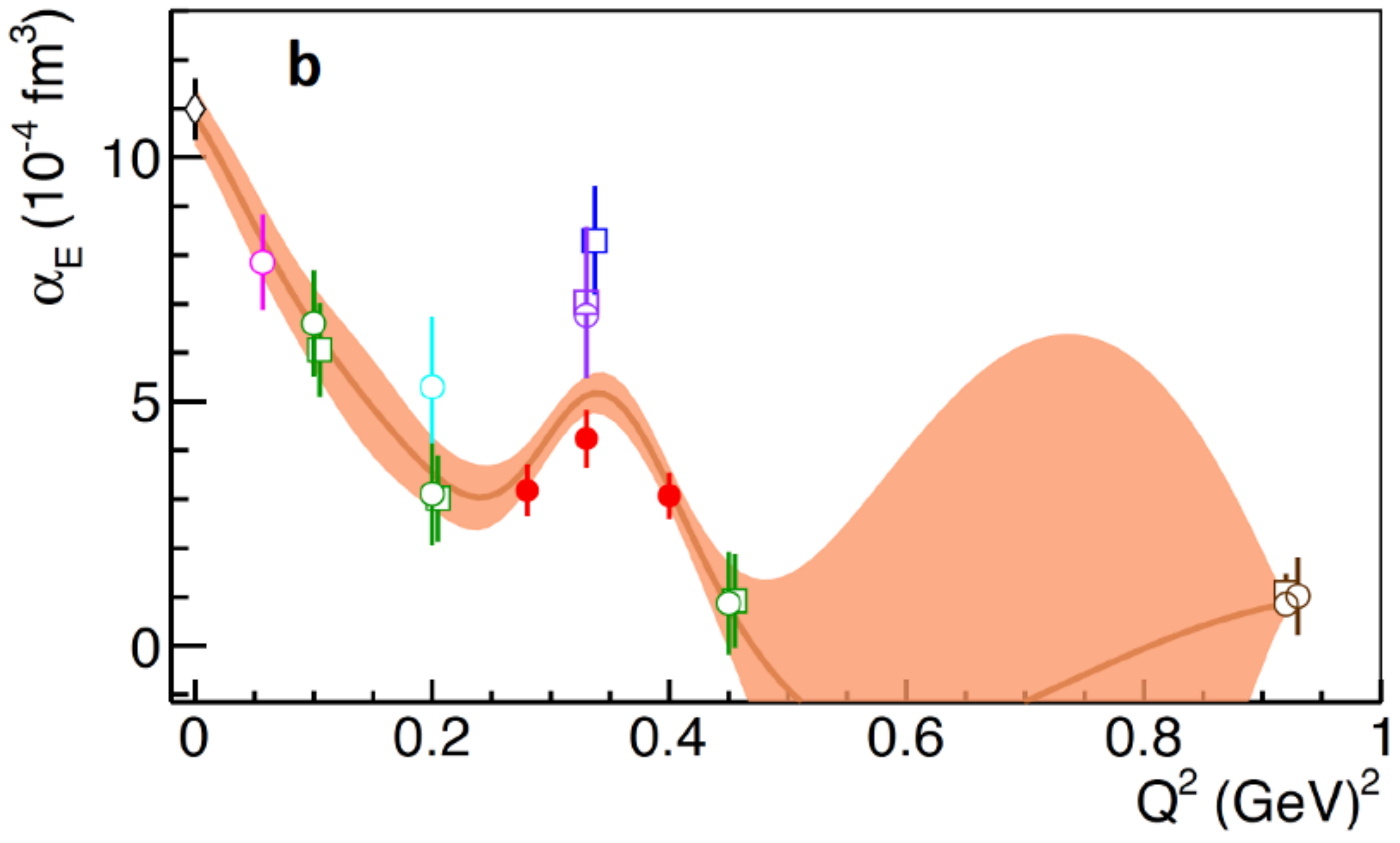
Q2 dependence of the electric GPs

Traditional fits using predefined functional forms

Data-driven techniques

no direct underlying functional form is assumed





Dipole (?) $(\chi^2_\nu = 3.7)$

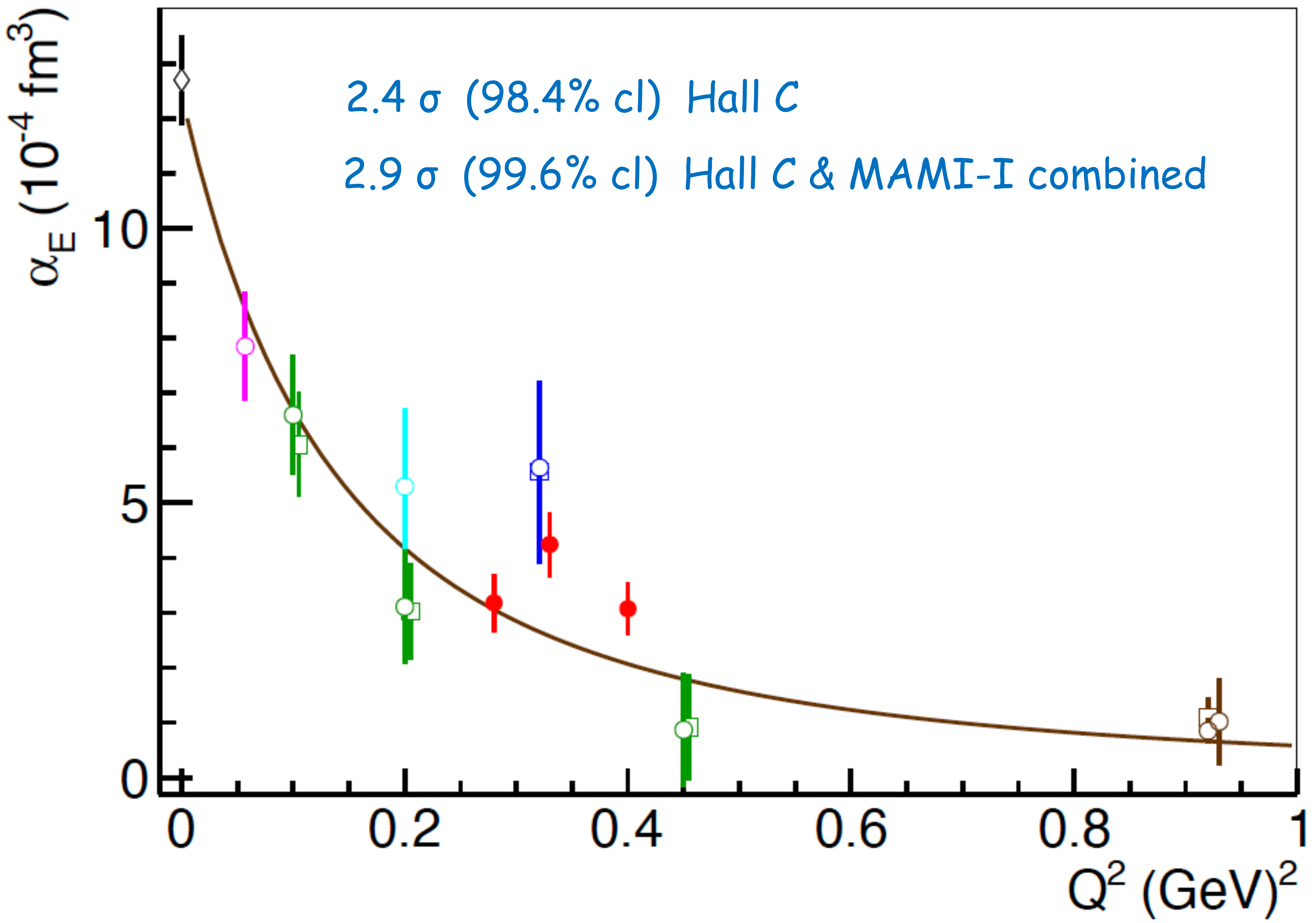
Systematically overestimates MAMI-VI

Systematically underestimates MAMI-I & IV

Cuts grossly through the new measurements

Rasmussen, C. E., and Williams, C. K. I. *Gaussian Processes for Machine Learning* the MIT Press, Cambridge Massachusetts, 2006, ISBN 026218253X, ©2006 Massachusetts Institute of Technology.

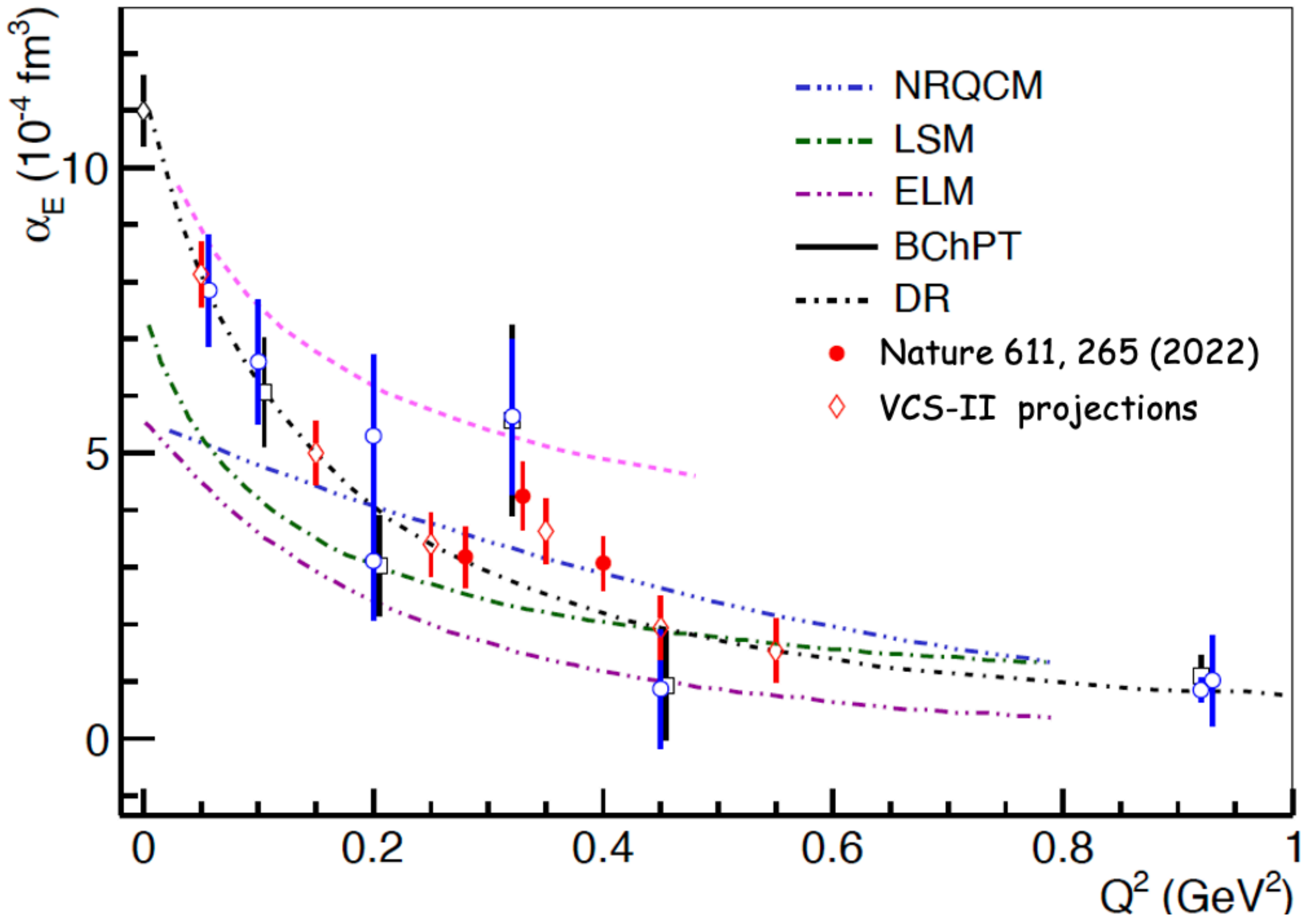
Deviation from a dipole fit at $Q^2 = 0.33\ GeV^2$



New Proposal

VCS-II : new JLab proposal for PAC51 (summer 2023):

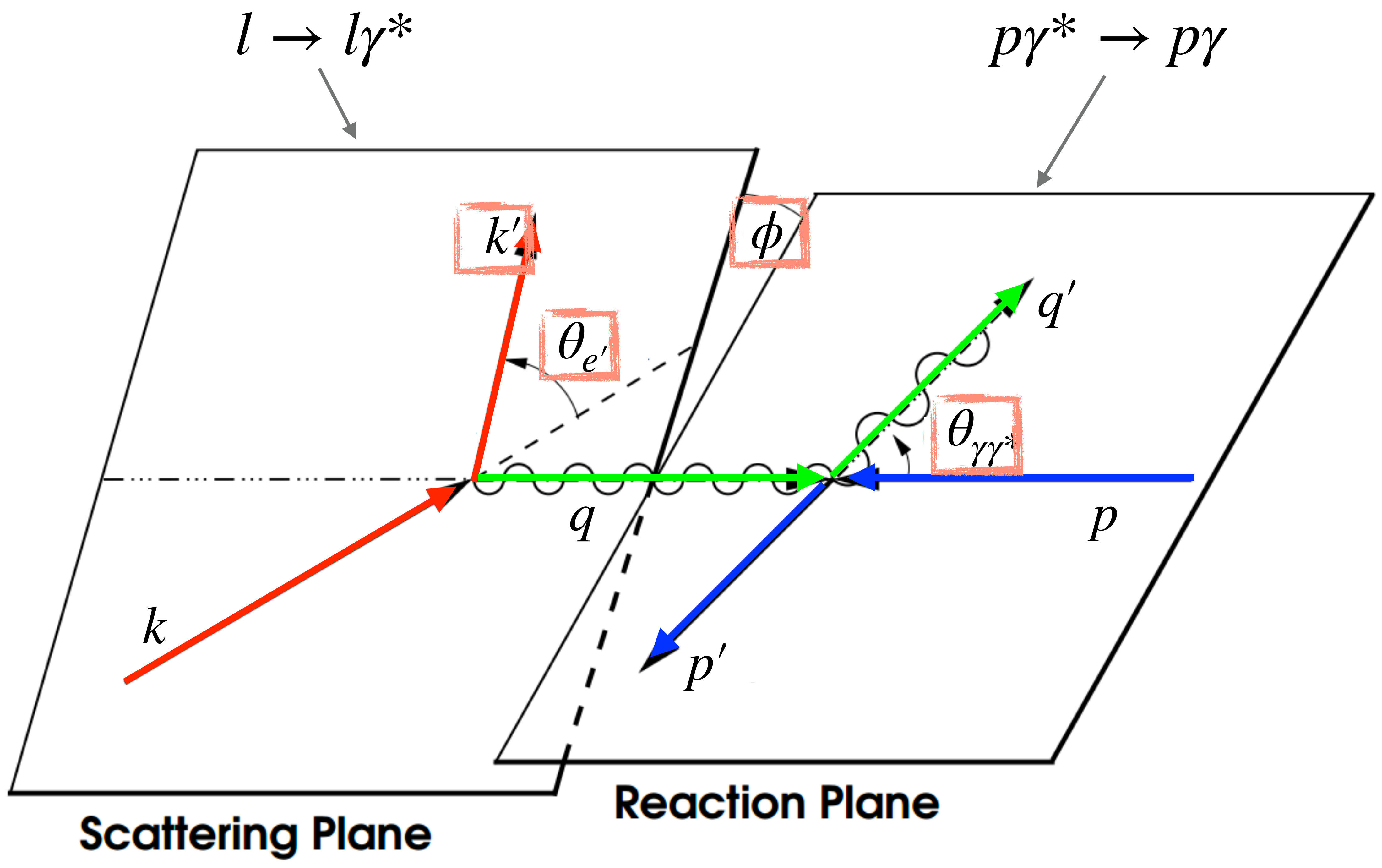
High precision measurements throughout an extended Q^2 range



Electron Beam of 1.1, 2.2 and 3.3 GeV and ~40 days of beam time

Nucleon Polarizabilities with Positrons

Using electron and positron beams



Kinematics of $lp \to lp\gamma$ reaction

$$d\sigma^e_\lambda = d\sigma_{\rm BH} + d\sigma_{\rm VCS} + \lambda\, d\tilde{\sigma}_{\rm VCS} + e\,(d\sigma_{\rm INT} + \lambda\, d\tilde{\sigma}_{\rm INT})$$

e = lepton beam charge, λ= polarization

Beam-Charge Asymmetry

$$A^C_{UU} = \frac{(d\sigma^+_+ + d\sigma^+_-) - (d\sigma^-_+ + d\sigma^-_-)}{d\sigma^+_+ + d\sigma^+_- + d\sigma^-_+ + d\sigma^-_-} = \frac{d\sigma_{\rm INT}}{d\sigma_{\rm BH} + d\sigma_{\rm VCS}}.$$

Beam-Spin Asymmetry

$$A^e_{LU} = \frac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-} = \frac{d\tilde{\sigma}_{\rm VCS} + e\,d\tilde{\sigma}_{\rm INT}}{d\sigma_{\rm BH} + d\sigma_{\rm VCS} + e\, d\sigma_{\rm INT}}.$$

$d\tilde{\sigma}_{INT}$ = Imaginary part of the interference between VCS amplitudes

$d\sigma_{INT}$ = Real part of the interference between VCS amplitudes

Nucleon Polarizabilities with Positrons

Virtual Compton scattering at low energies with a positron beam

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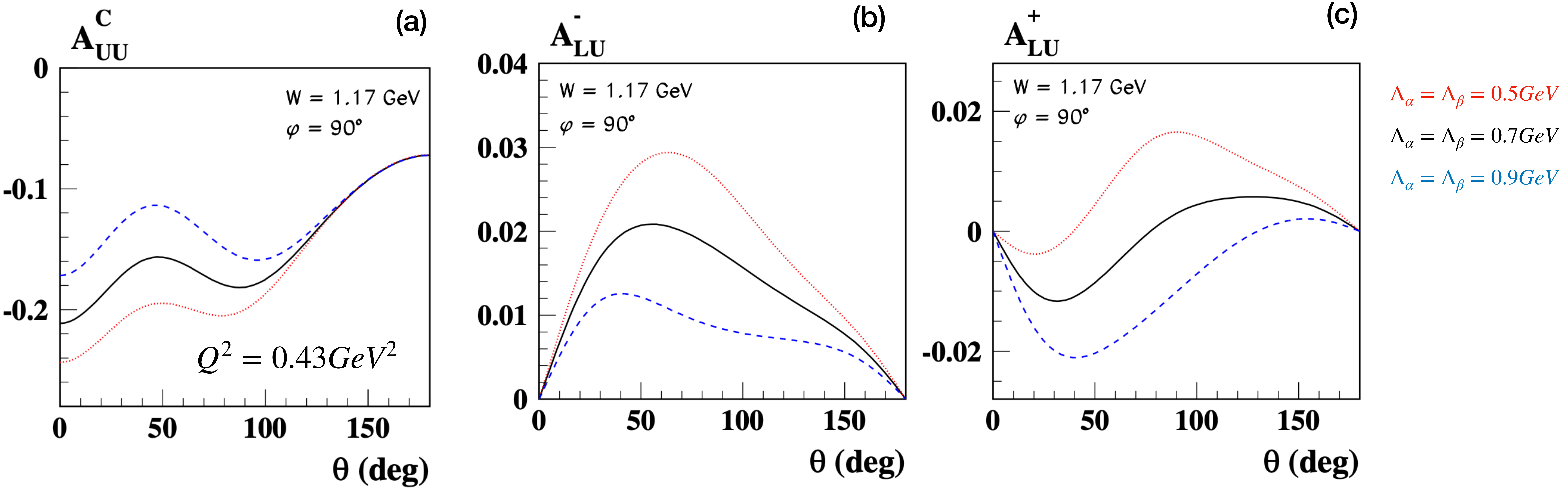

(a) Beam-charge asymmetry as a function of the photon scattering angle at Q^2 =0.43 GeV^2

(b) & (c) The electron and positron beam-spin asymmetry as a function of the photon scattering angle for out-of-plane kinematics

Summary

- Future measurements can pin down precisely the shape of the structure (if it exists) and results will be an important input for the theory.
- On going efforts for a new proposal.
- Measure GPs with positrons:
  - ✦ Independent method of measurement of these important quantities.
  - ✦ Software tools to extract theoretical cross sections and asymmetries are ready.
  - ✦ Simulation work is in progress.
  - ✦ Studies to identify the feasibility and the optimal Hall and experimental setup at JLab for this experiment. Current studies focus on Hall C (SHMS & HMS).
  - ✦ Once a setup is identified, proceed with optimizing kinematics and measurements.
  - ✦ Aiming for a LOI at the PAC.