First Measurement of the Proton Generalized Polarizabilities with a polarized electron beam in Virtual Compton Scattering (VCS-IIIp)

A Proposal to Jefferson Lab PAC-53

Speaker: Michael Paolone (New Mexico State University)

On behalf of the VCS-IIIp collaboration and its spokespeople:

N. Sparveris*, H. Atac, S. Lee, M.K. Jones and M. Paolone

*contact person

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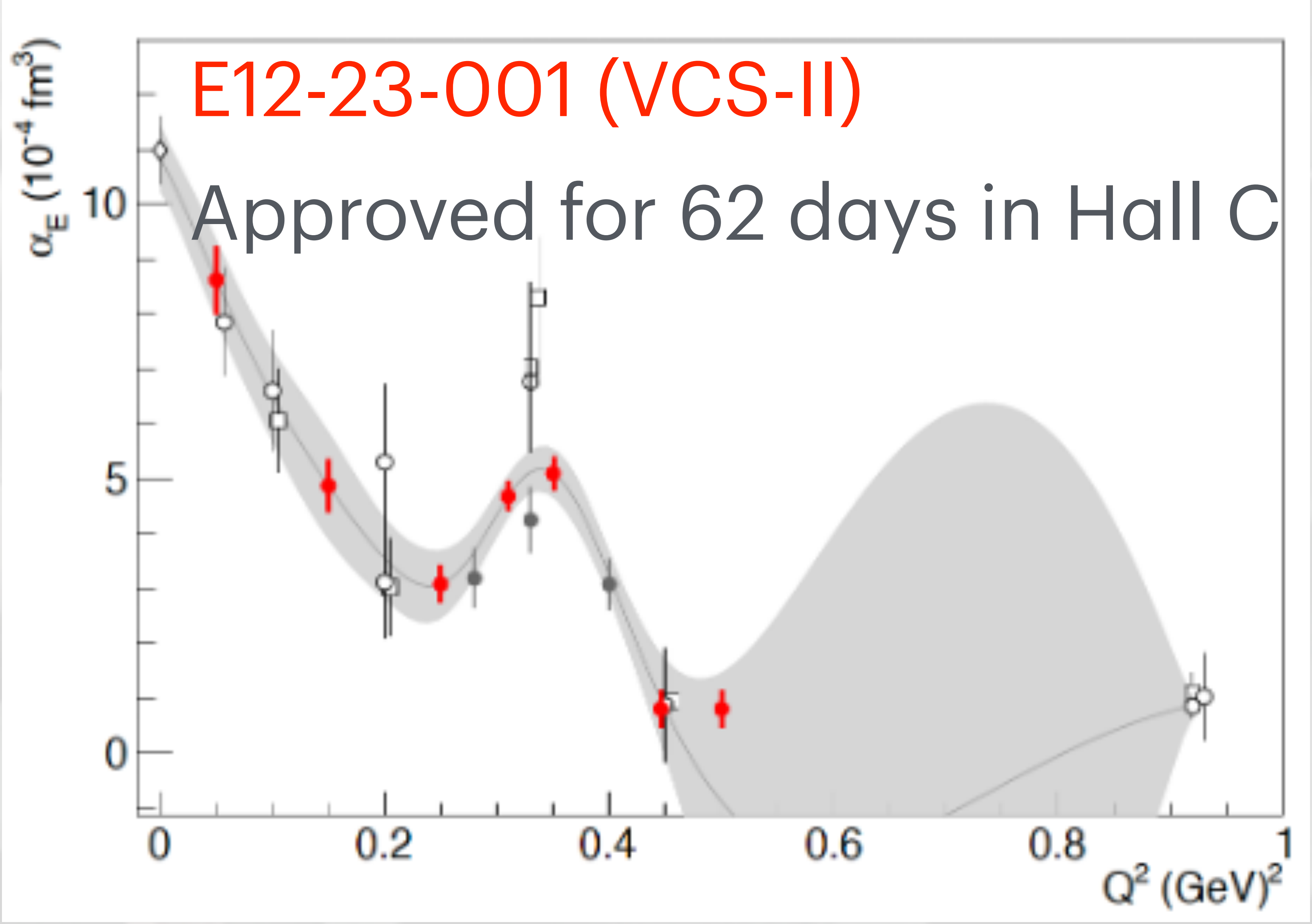
The proposal follows the Letter-of-Intent LOI12-23-001

PAC51 Recommendation:

"The physics case presented in the proposal is robust, and the document is very well-written. Feasibility concerns have not been identified, and the PAC encourages the proponents to proceed and submit a full proposal ..."

The proposal adds a unique component to an ongoing experimental program at JLab



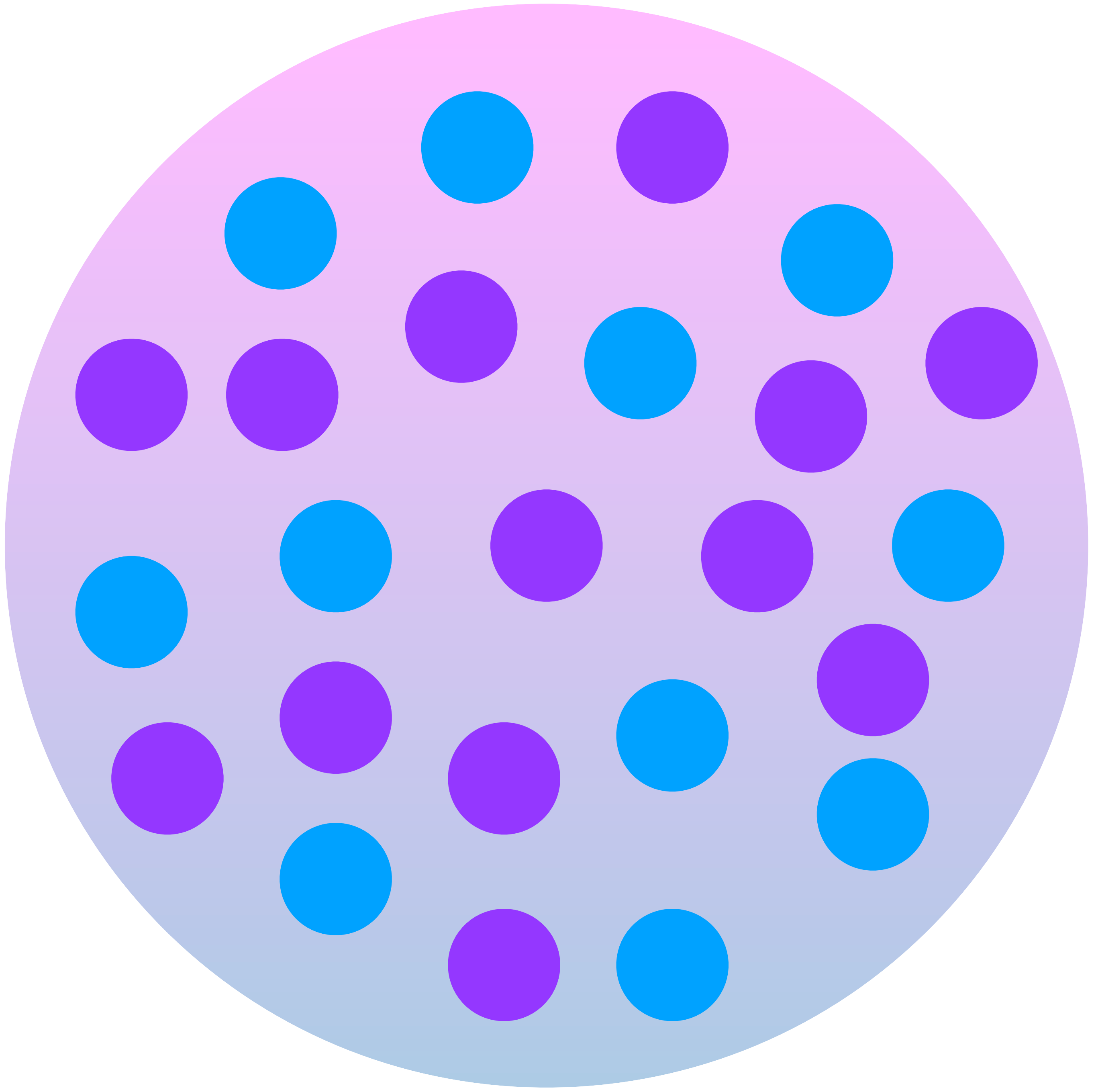
First measurement of the proton GPs utilizing polarization measurements (BSAs) as an alternative to the unpolarized VCS cross section measurements

Motivation: Explore the fundamental properties of the nucleon

If we **want** to understand the characteristics of the proton as a building block of the universe… we **need** to understand the dynamics of the proton's constituents and how they contribute to those emergent characteristics.

- **Polarizability** is in an important characteristic of the proton:
  - How rigid is the proton in the presence of an EM field?
    - A fundamental property of the proton!
  - Sensitive to the excitation of the proton.
  - Can be accessed by Compton scattering (the photon acting as an induced EM field)
- **Generalized Polarizabilities** (GPs)
  - Accessed via virtual photon interaction.
  - Probe length (Q2) provides information on proton constituents in relation to structure of the proton

The proton is the only known stable composite particle!



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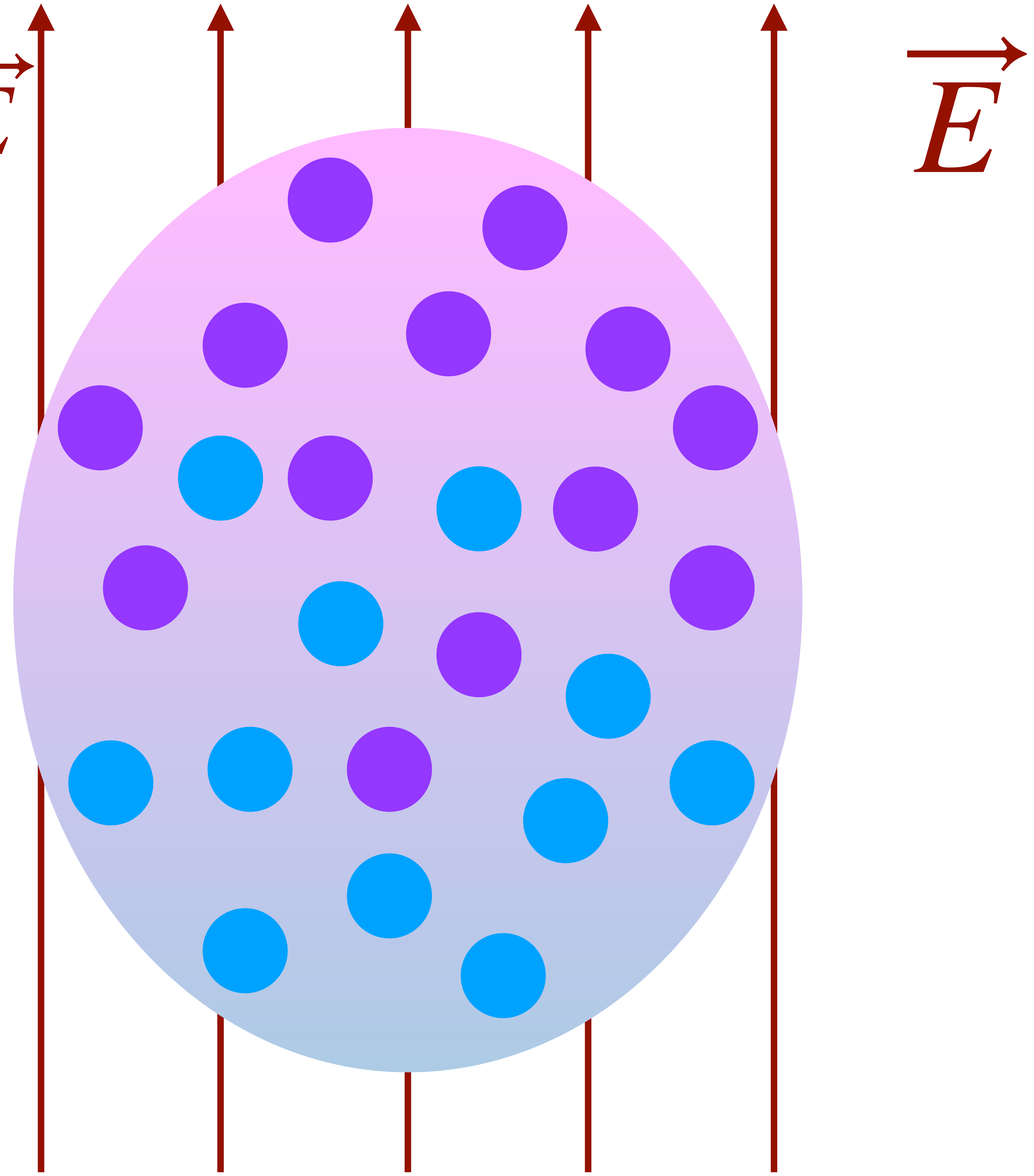
$$\vec{p} = \alpha_E \vec{E}$$

Electric Polarizability



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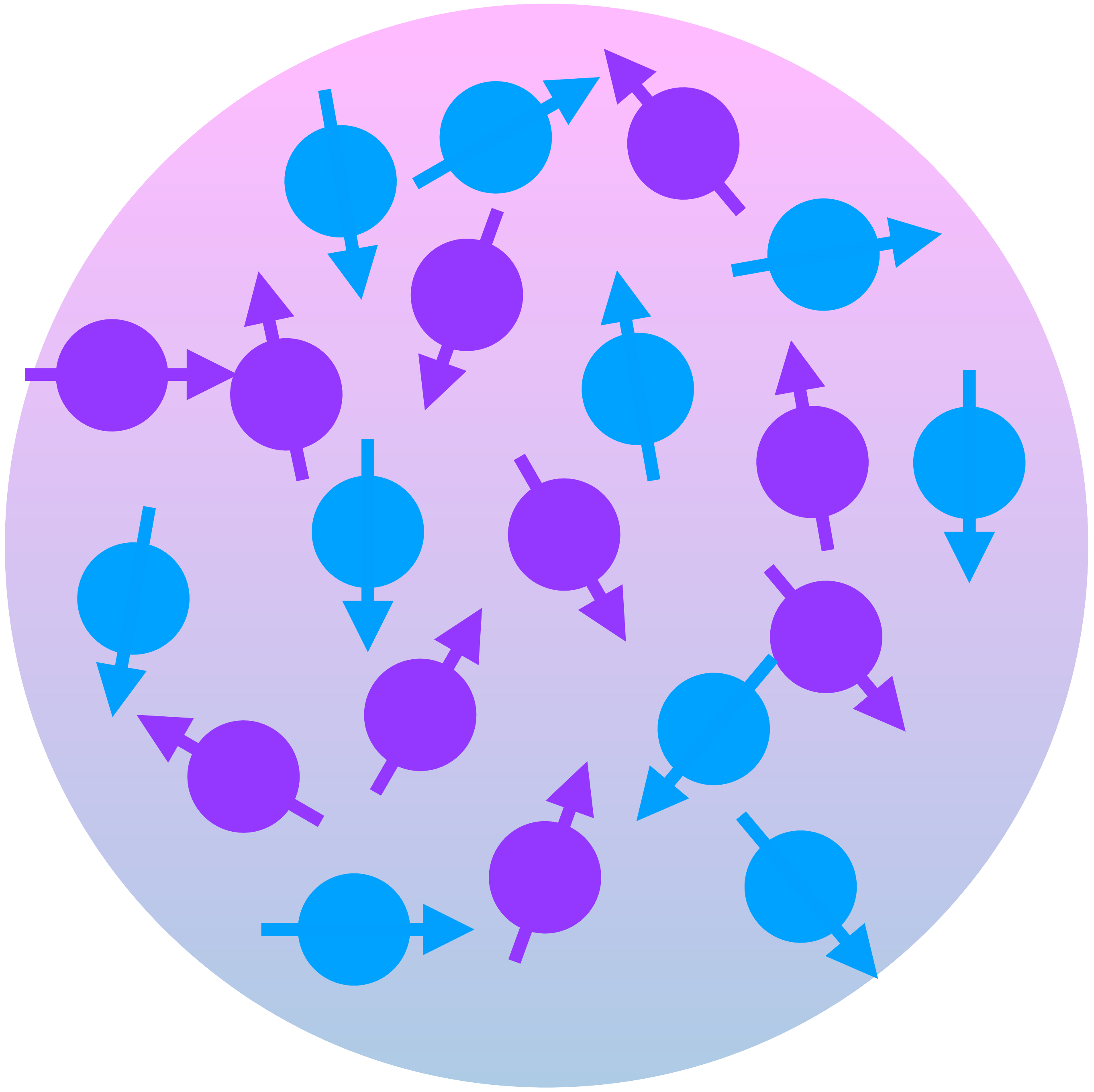

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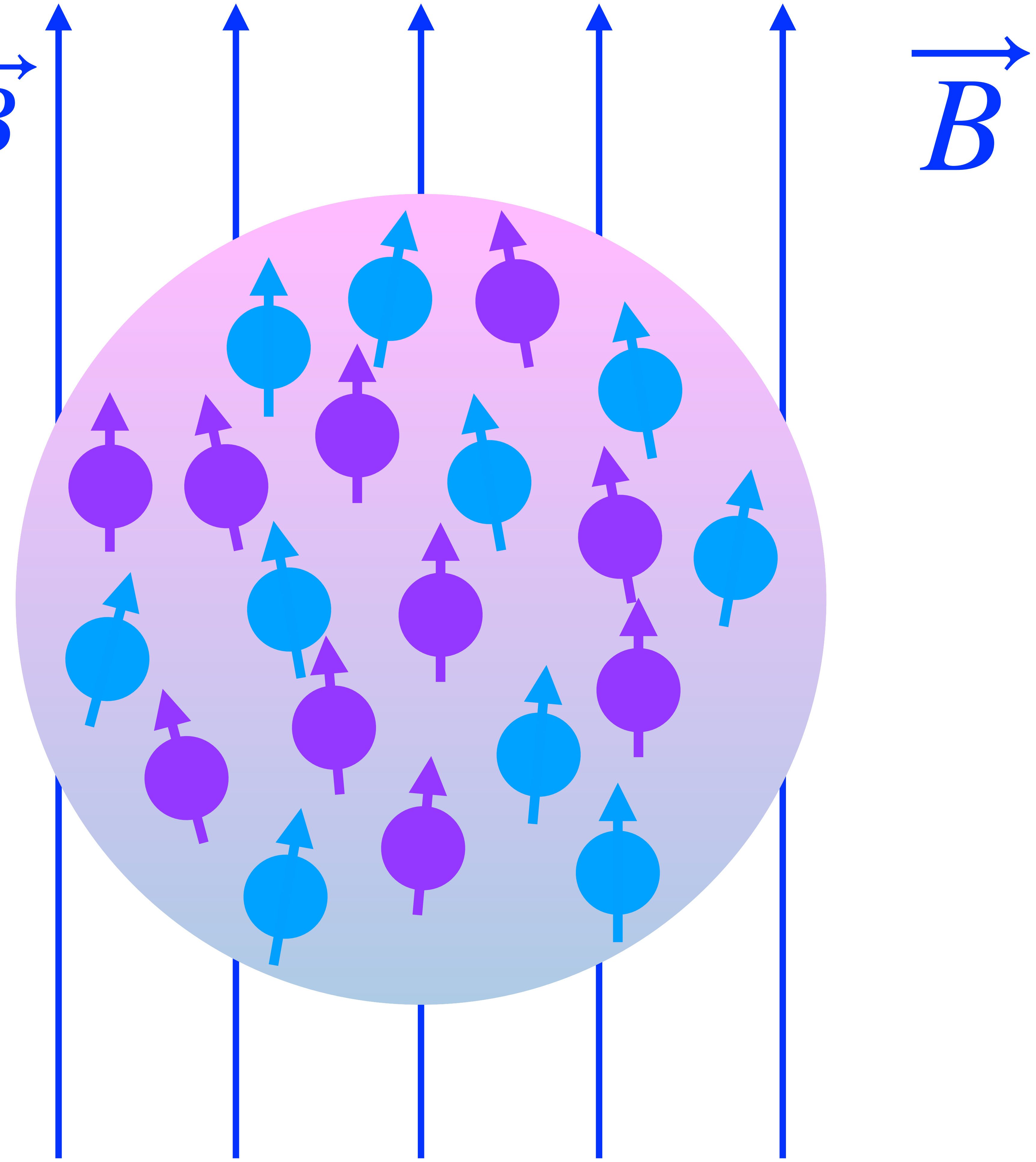
$$\vec{m} = \beta_M \vec{B}$$

Magnetic Polarizability

Paramagnetic Contribution from direct alignment



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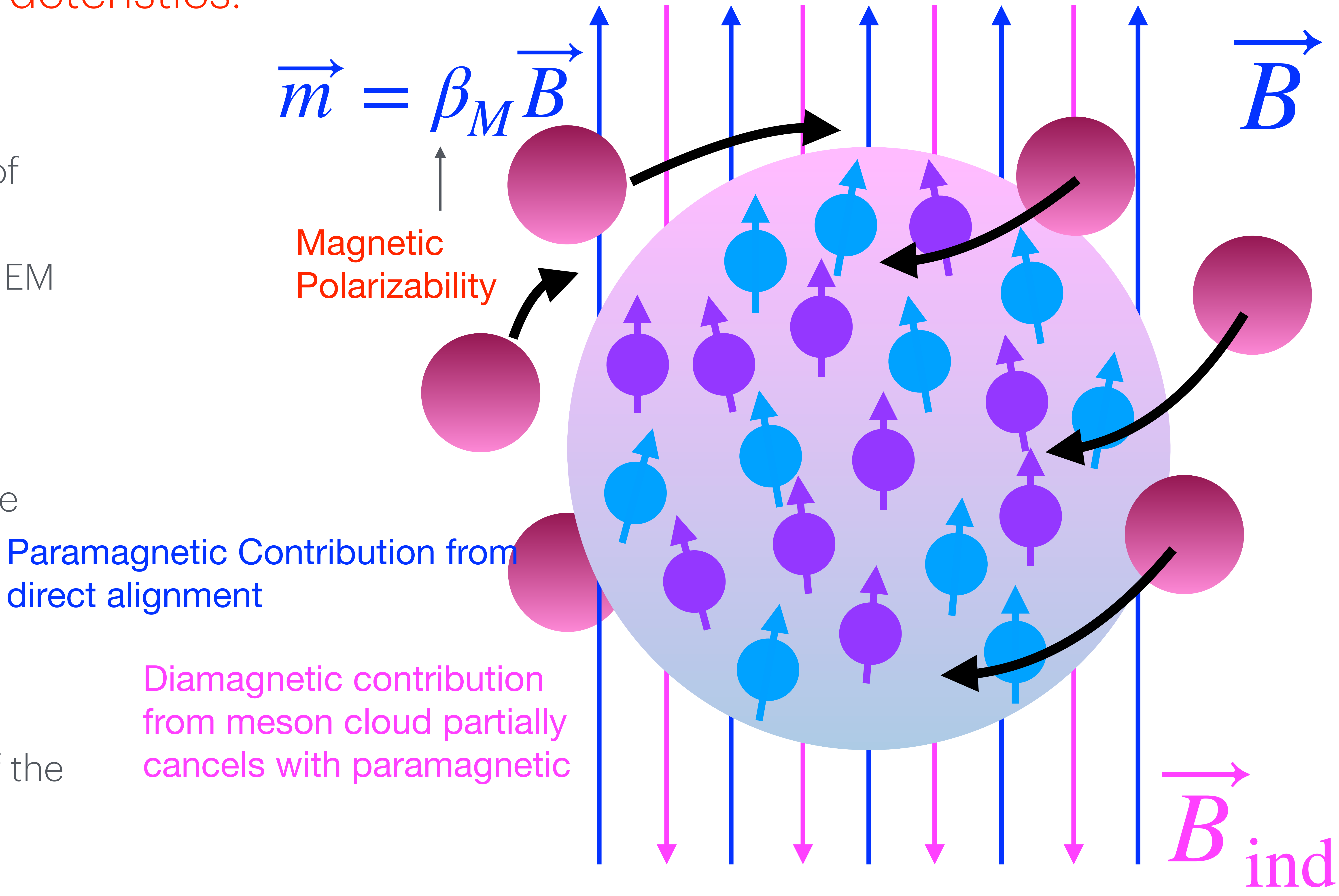


Static Polarizabilities

Listed in the PDG as a fundamental property:

$$\alpha = (11.2 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$$

$$\beta = (2.5 \pm 0.4) \times 10^{-4}\ \mathrm{fm}^3$$

Integrated effect on the nucleon

PDG Live particle data group

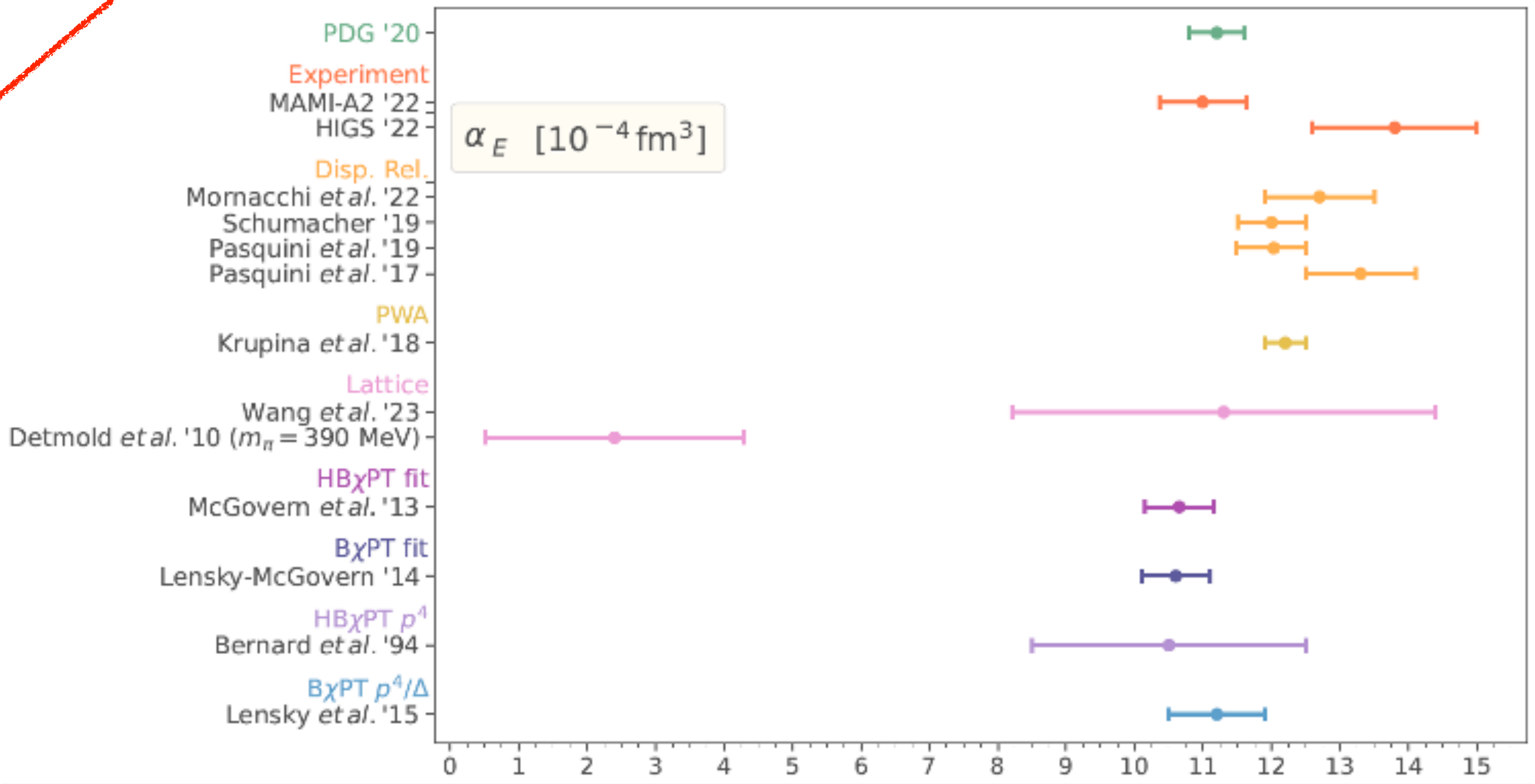
N BARYONS
($S = 0$, $I = 1/2$)
$p, N^+ = u\,u\,d;\ n, N^0 = u\,d\,d$

PDGID:S016 JSON (beta) INSPIRE

p $\quad I(J^P) = 1/2(1/2^+)$

p MASS (atomic mass units u)	$1.007276466621 \pm 0.000000000053$ u
p MASS (MeV)	$938.27208816 \pm 0.00000029$ MeV
$\lvert m_p - m_{\bar p}\rvert / m_p$	$< 7 \times 10^{-10}$ CL=90.0%
$\lvert \frac{q_{\bar p}}{m_{\bar p}} \rvert / (\frac{q_p}{m_p})$	$1.000000000003 \pm 0.000000000016$
$(\lvert \frac{q_{\bar p}}{m_{\bar p}} \rvert - \frac{q_p}{m_p}) / \frac{q_p}{m_p}$	$(0.1 \pm 6.9) \times 10^{-11}$
$\lvert q_p + q_{\bar p} \rvert / e$	$< 7 \times 10^{-10}$ CL=90.0%
$\lvert q_p + q_e \rvert / e$	$< 1 \times 10^{-21}$
p MAGNETIC MOMENT	$2.7928473446 \pm 0.0000000008\ \mu_N$
$\bar p$ MAGNETIC MOMENT	$-2.792847344 \pm 0.000000004\ \mu_N$
$(\mu_p + \mu_{\bar p}) / \mu_p$	$(2 \pm 4) \times 10^{-9}$
p ELECTRIC DIPOLE MOMENT	$< 2.1 \times 10^{-25}$ e cm
Electric polarizability α	0.00112 ± 0.00004 fm^3
Magnetic polarizability β	$(2.5 \pm 0.4) \times 10^{-4}$ fm^3 (S = 1.2)
Charge radius	0.8409 ± 0.0004 fm
Magnetic radius	0.851 ± 0.026 fm
Mean life τ	$> 9 \times 10^{29}$ years CL=90.0%
$\bar p$ MEAN LIFE	

Decay Modes ‣ Expand all decays



Generalized Polarizabilities

Accessed via virtual Compton scattering (VCS) as a function of Q2

(As $Q^2 \to 0$, the RCS static polarizabilities are found)

Can provide:

- spatial distribution of the polarization densities
- electric & magnetic polarizability radii
- manifestation of dynamical mechanisms for the EM polarizability effects

PDG Live

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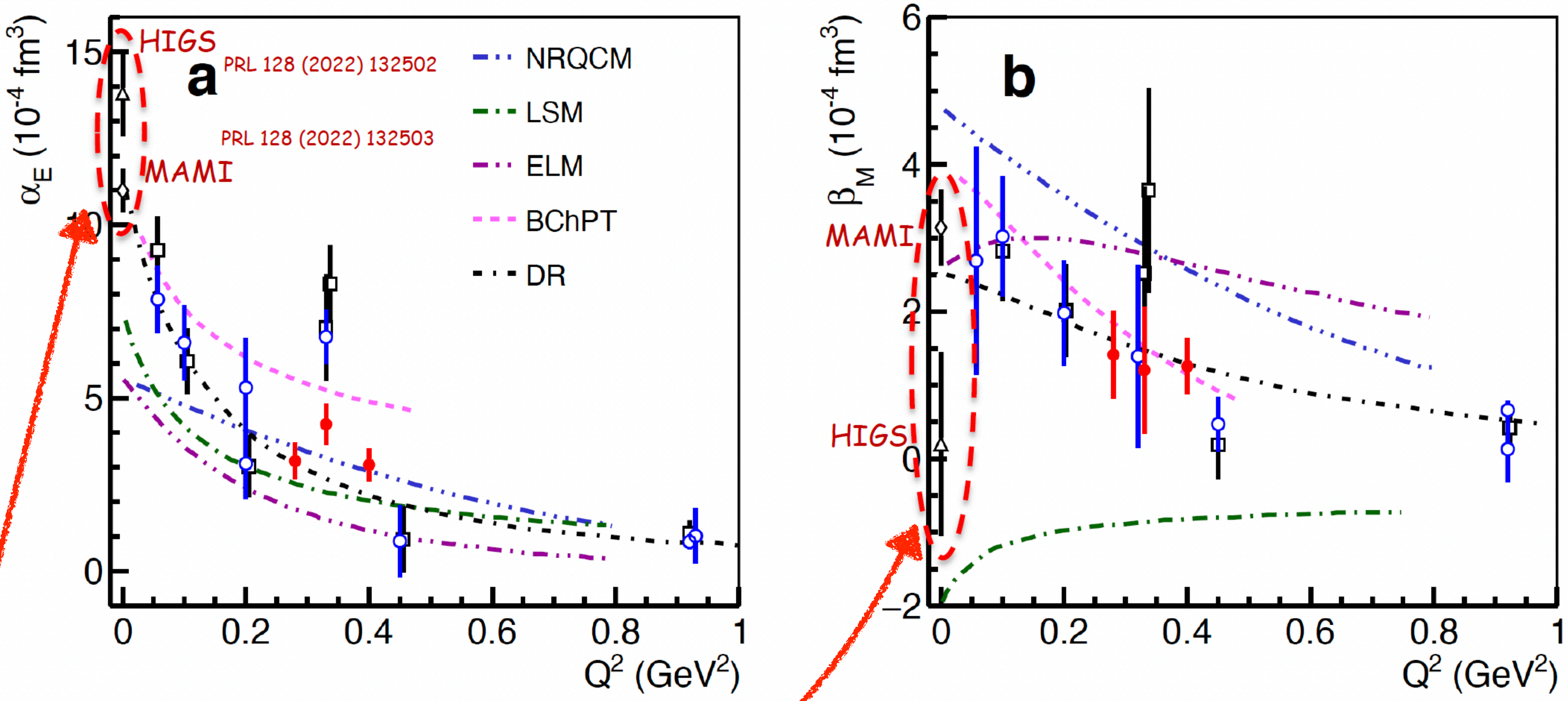
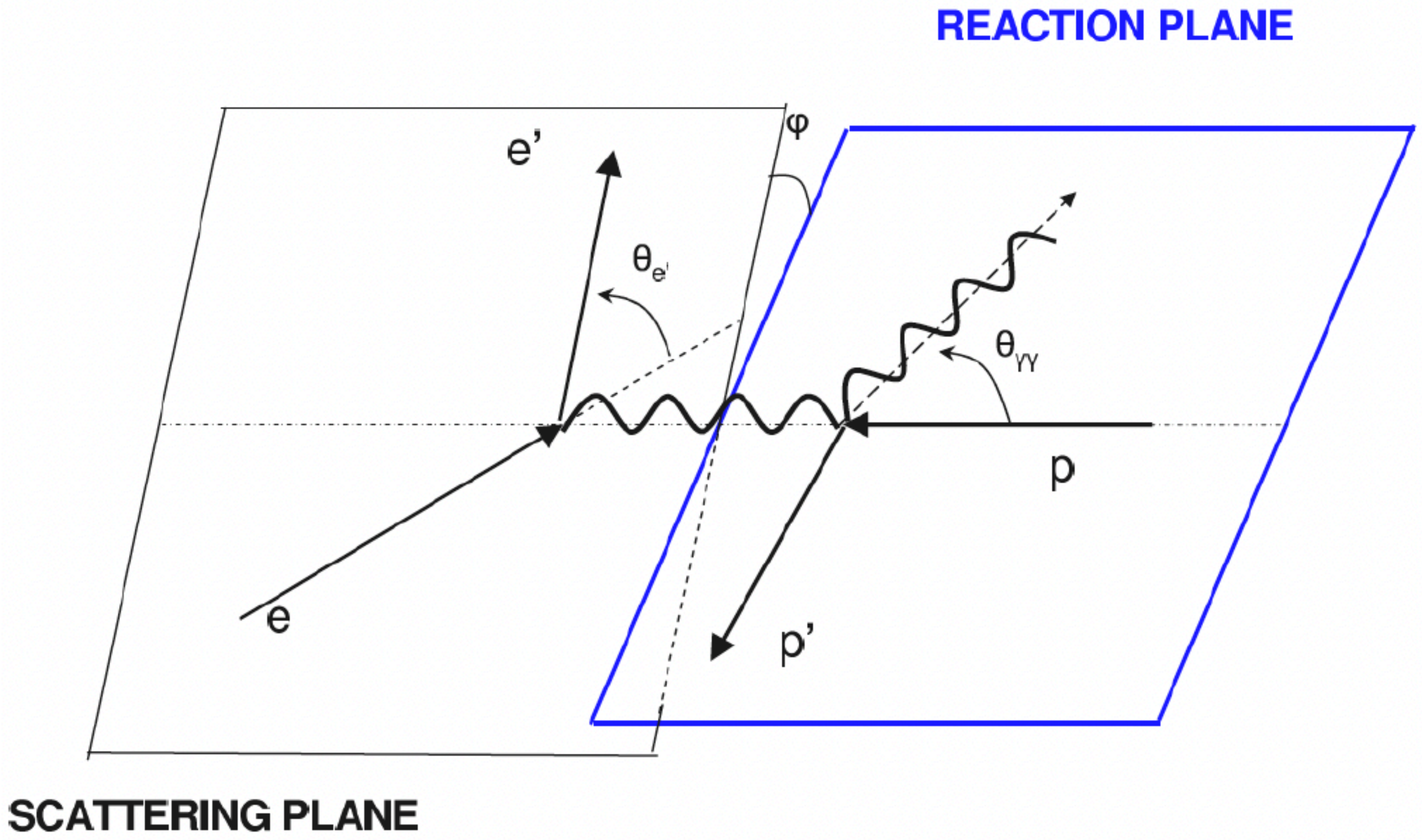
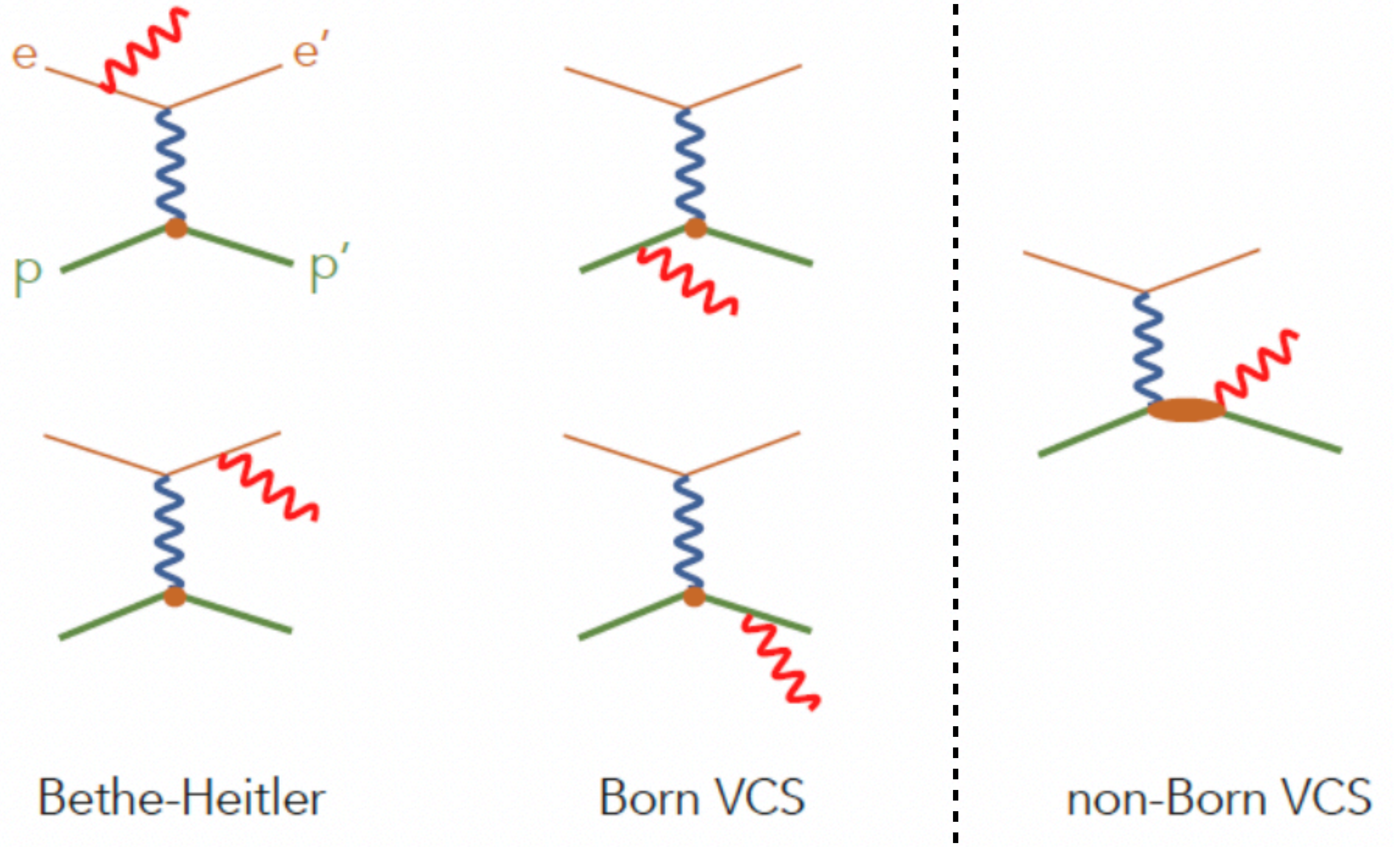


Virtual Compton Scattering





Elastic FFs

GPs

Unpolarized

Cross section is five-fold differential: $\dfrac{d^5\sigma}{d\Omega_{e'}dE_{e'}d\theta_{\gamma^*\gamma}d\phi}$

- Traditionally, there are two methods to extract the polarizabilities:
  - The **DR** (dispersion relations) method:
    - Available above and below the pion threshold
    - The scalar polarizabilities enter as free parameters to be fit.
  - The **LEX** (Low energy expansion) method
    - Valid only below the pion threshold

DR

valid below & above
Pion threshold

Dispersive integrals
for Non Born amplitudes

Spin GPs are fixed

Scalar GPs have
an unconstrained part

Fit to the experimental
cross sections at each Q^2

LEX

valid only below
Pion threshold

$$d^5\sigma = d^5\sigma^{BH+Born} + q'_{cm}\cdot\phi\cdot\Psi_0 + \mathcal{O}(q'^2_{cm})$$

$$\Psi_0 = v_1\cdot\left(P_{LL} - \frac{1}{\epsilon}P_{TT}\right) + v_2\cdot P_{LT}$$

Subtract the spin part

$$P_{TT} = [P_{TT\ spin}]$$

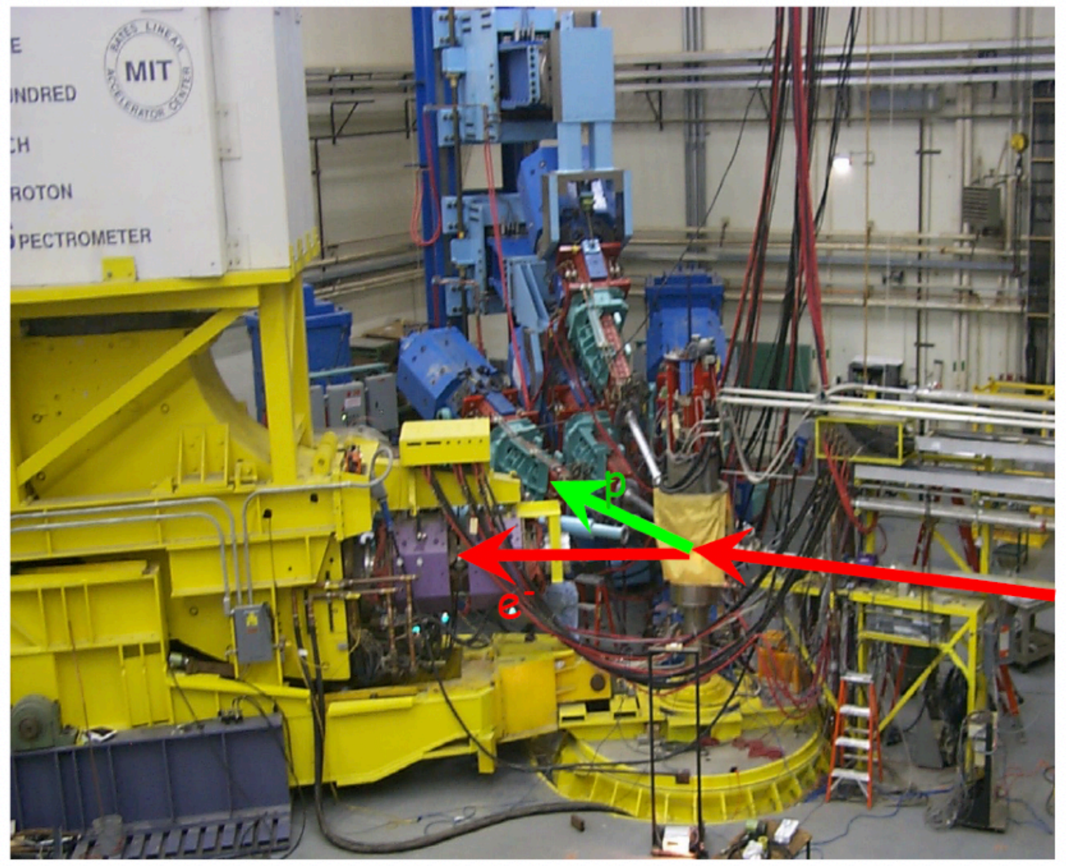
$$P_{LT} = -\frac{2M}{\alpha_{em}}\sqrt{\frac{q^2_{cm}}{Q^2}}\cdot G_E^p(Q^2)\cdot\beta_M(Q^2) + [P_{LT\ spin}]$$

utilize DR

scalar GPs α_E and β_M

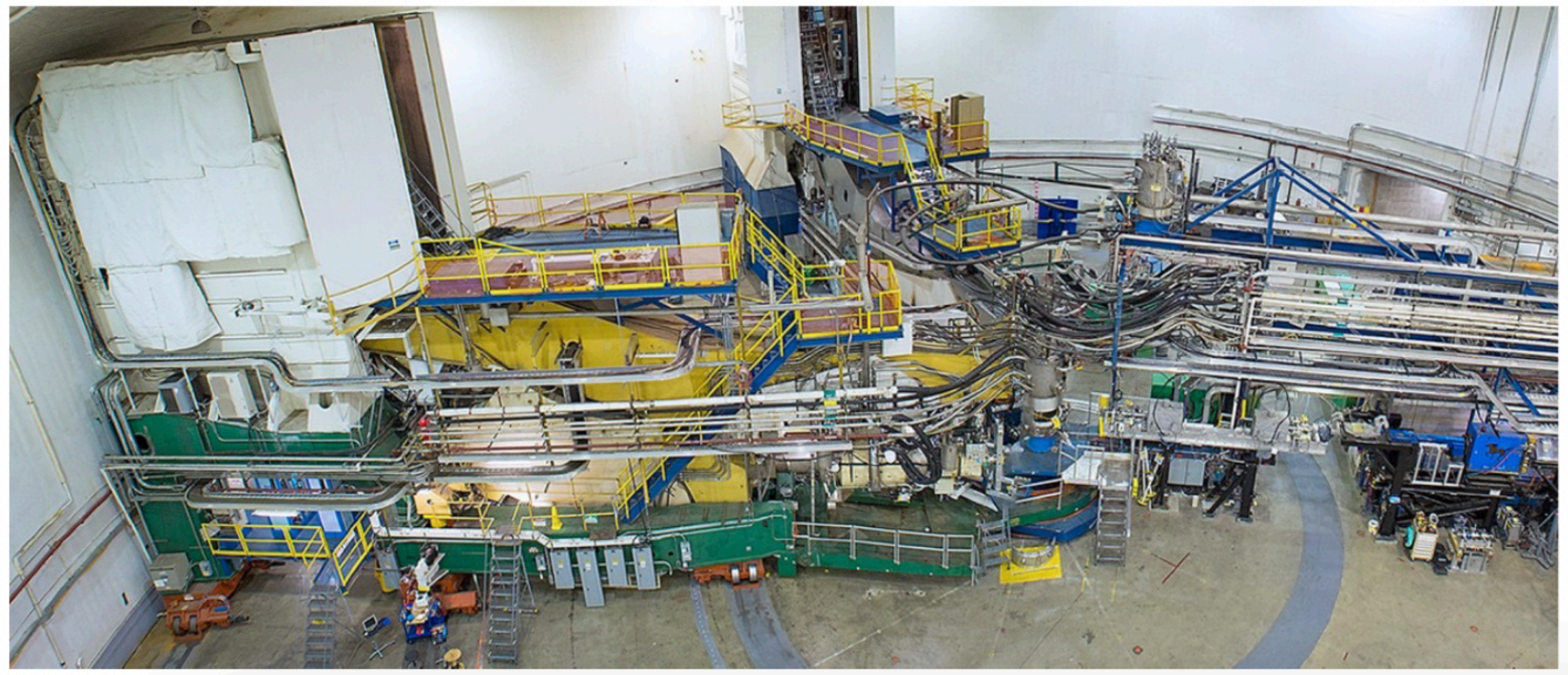
Early Experiments

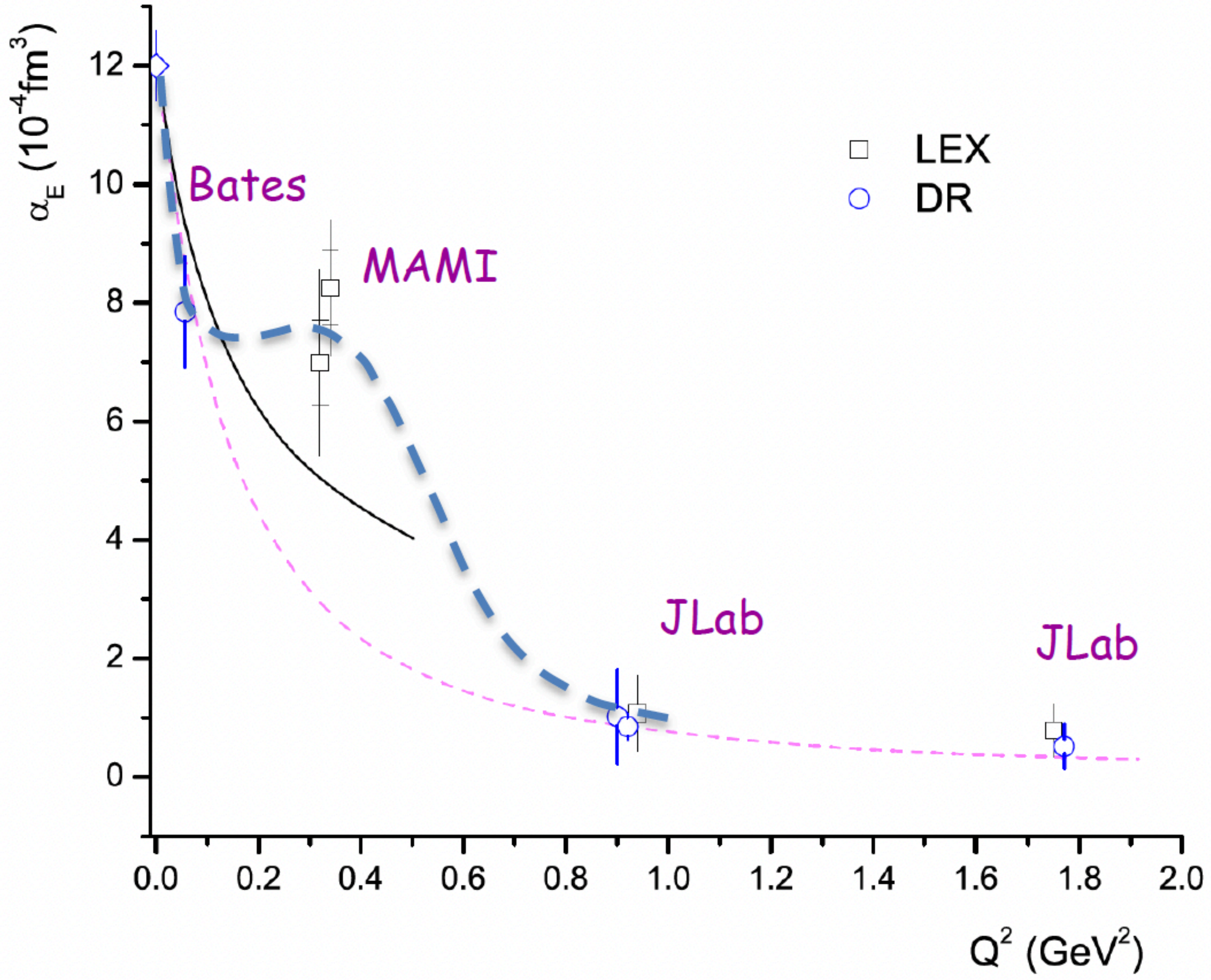
MIT-Bates @ Q^2=0.06 GeV^2

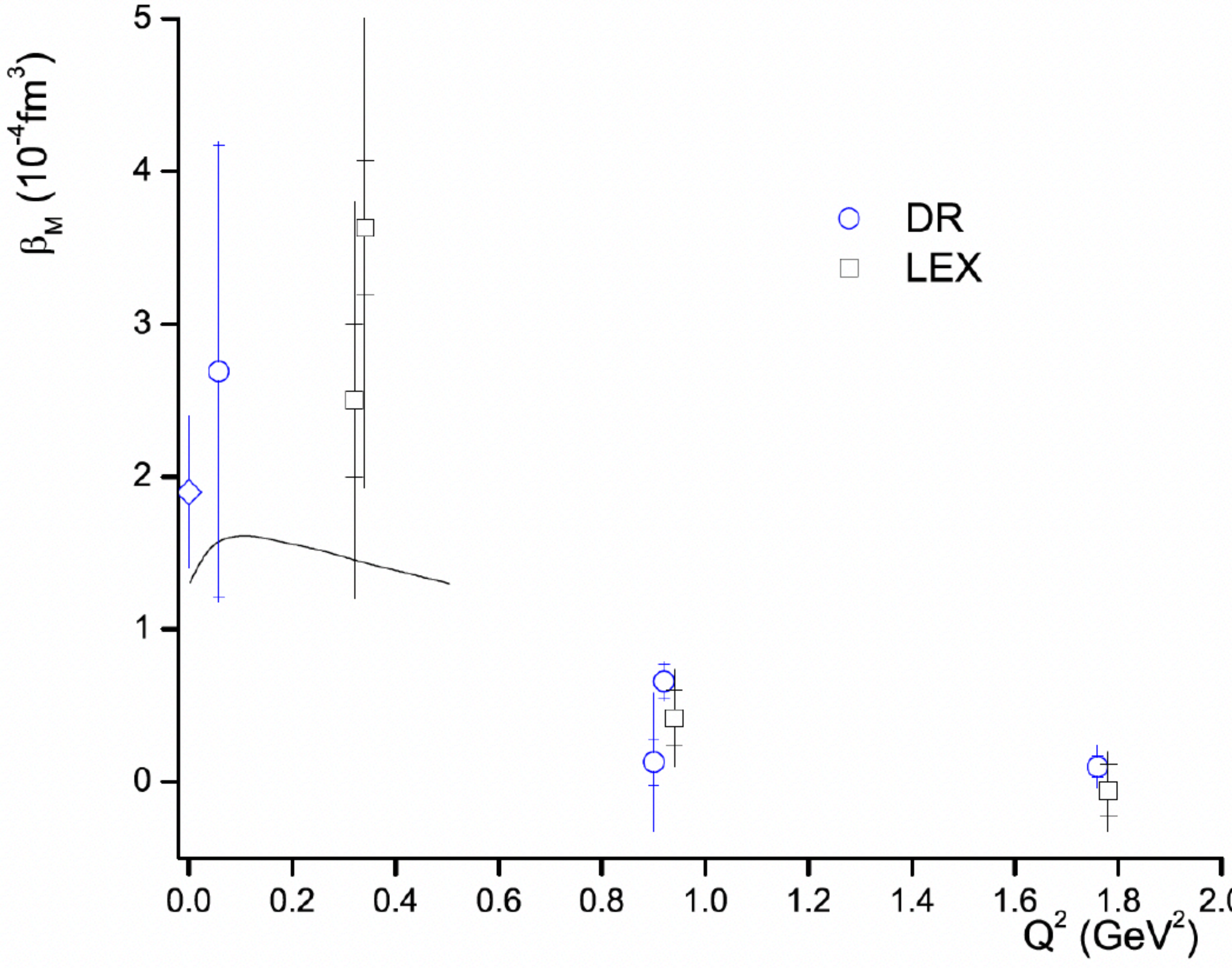


MAMI-A1 @ Q^2=0.33 GeV^2

Jlab-Hall A @ Q^2=0.9 & 1.8 GeV^2







Initial investigations showed that the proton generally increases in stiffness as Q2 increases.

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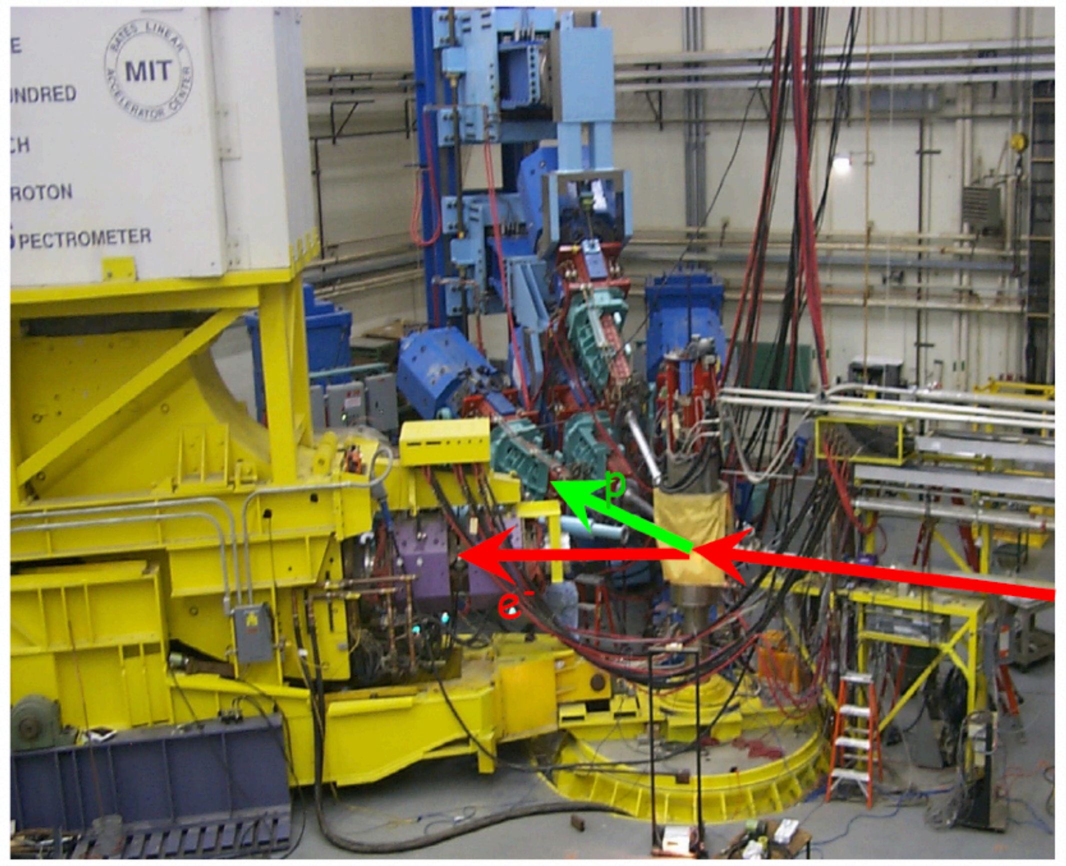

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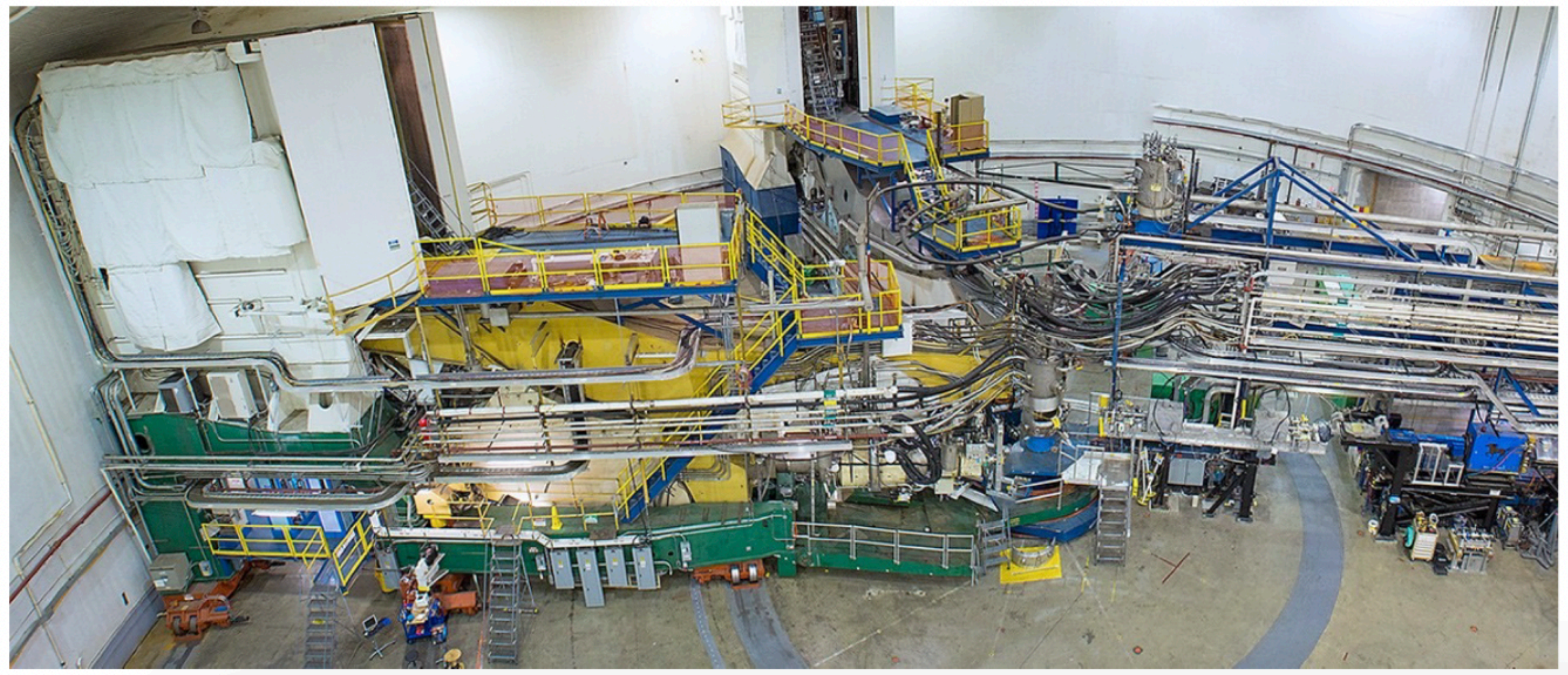
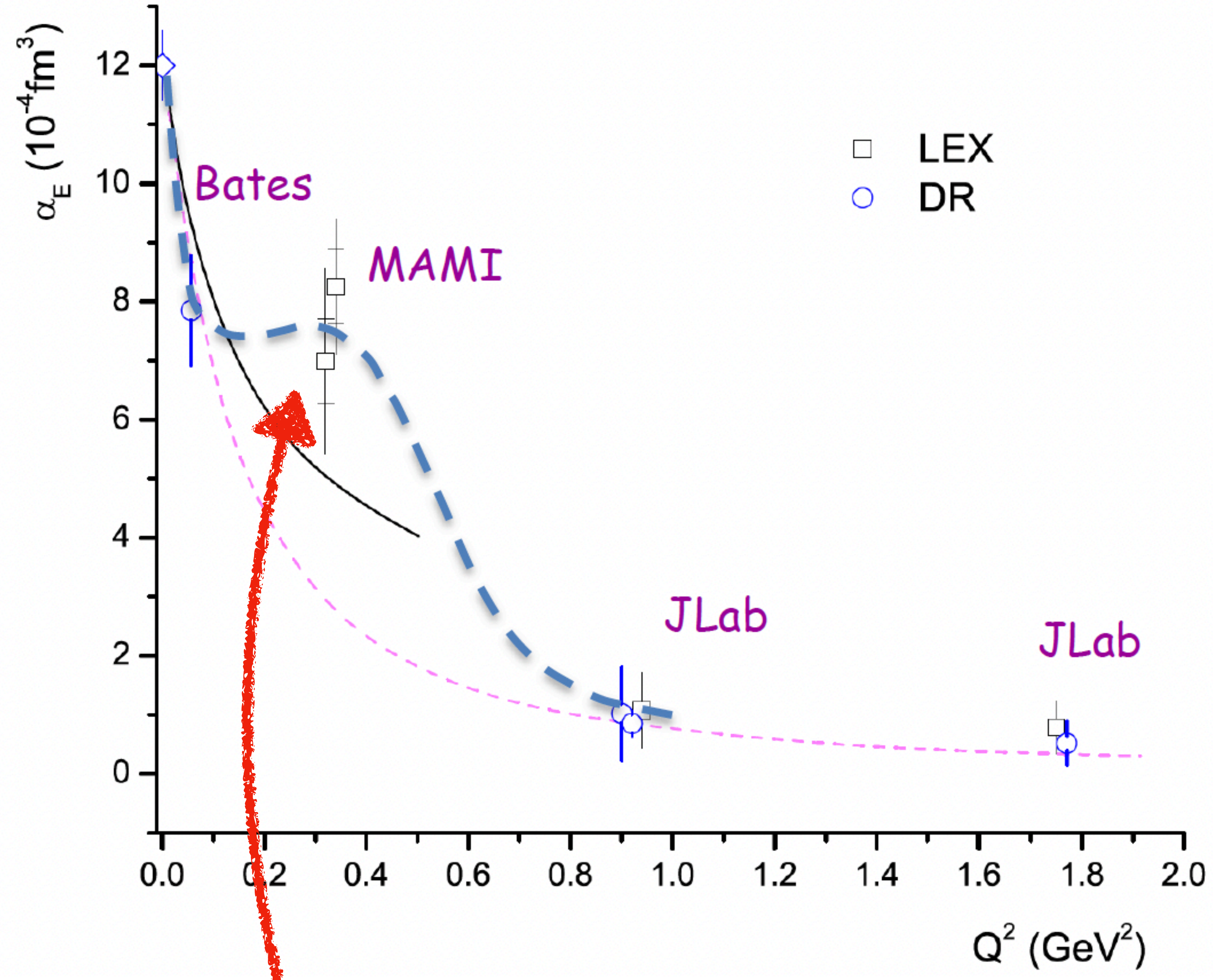
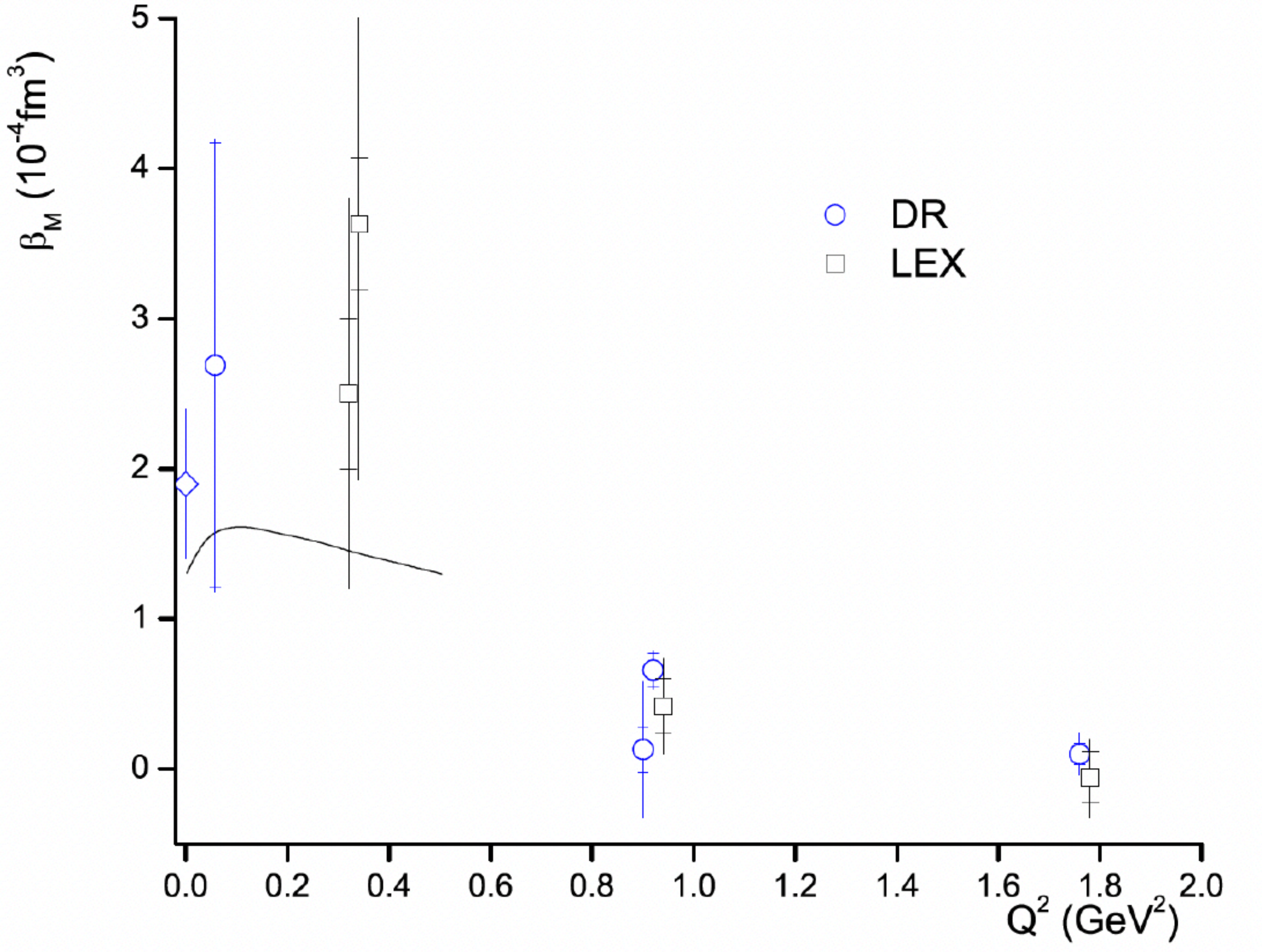






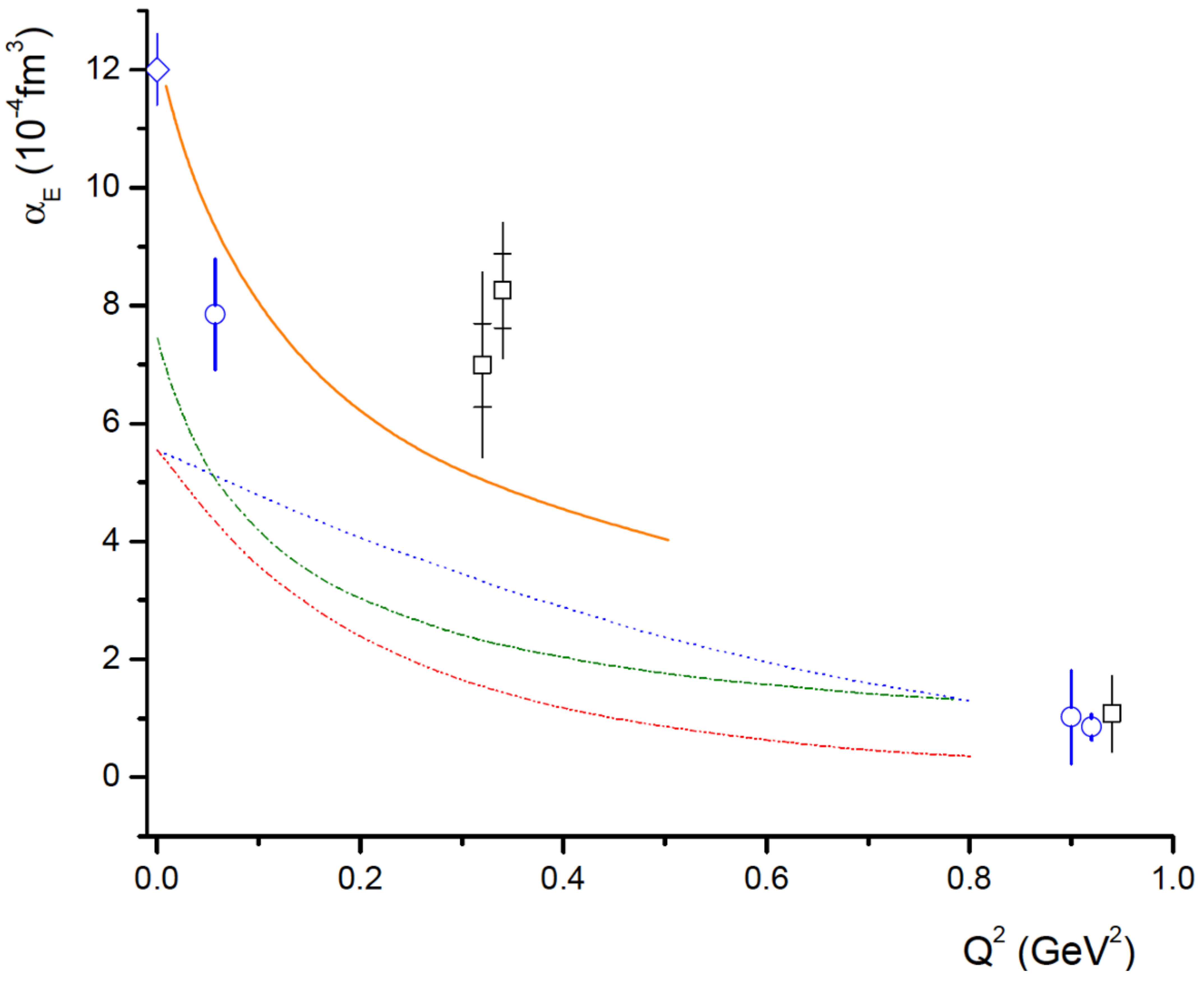
Initial investigations showed that the proton generally increases in stiffness as Q2 increases.

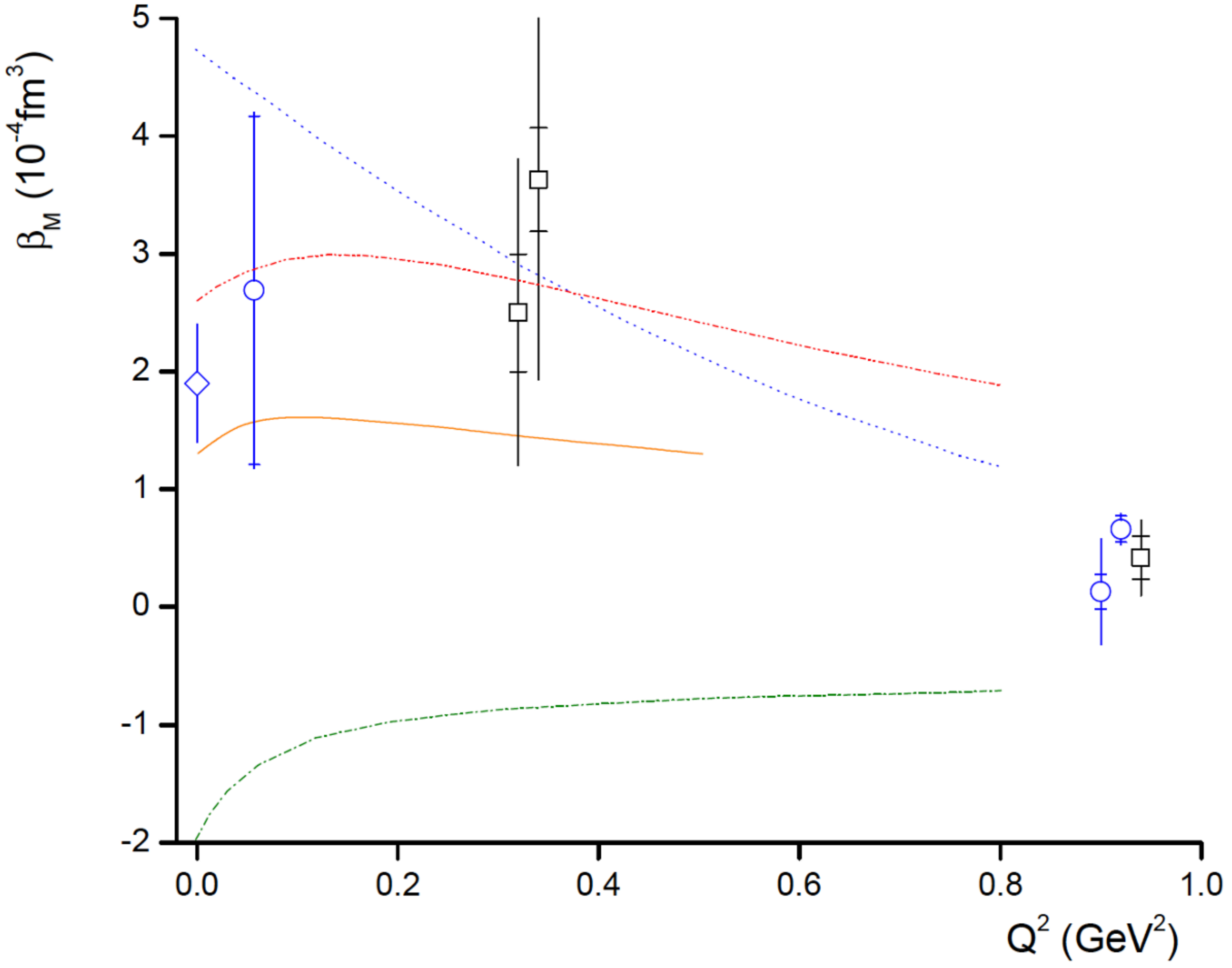
Early Q2 = 0.33 GeV2 measurement at MAMI seemed to buck the trend of a monatomic decrease. A second measurement at MAMI had similar results.

Phys. Rev. Lett 85, 708 (2000)

Eur. Phys. J. A37, 1-8 (2008)

Theoretical Predictions





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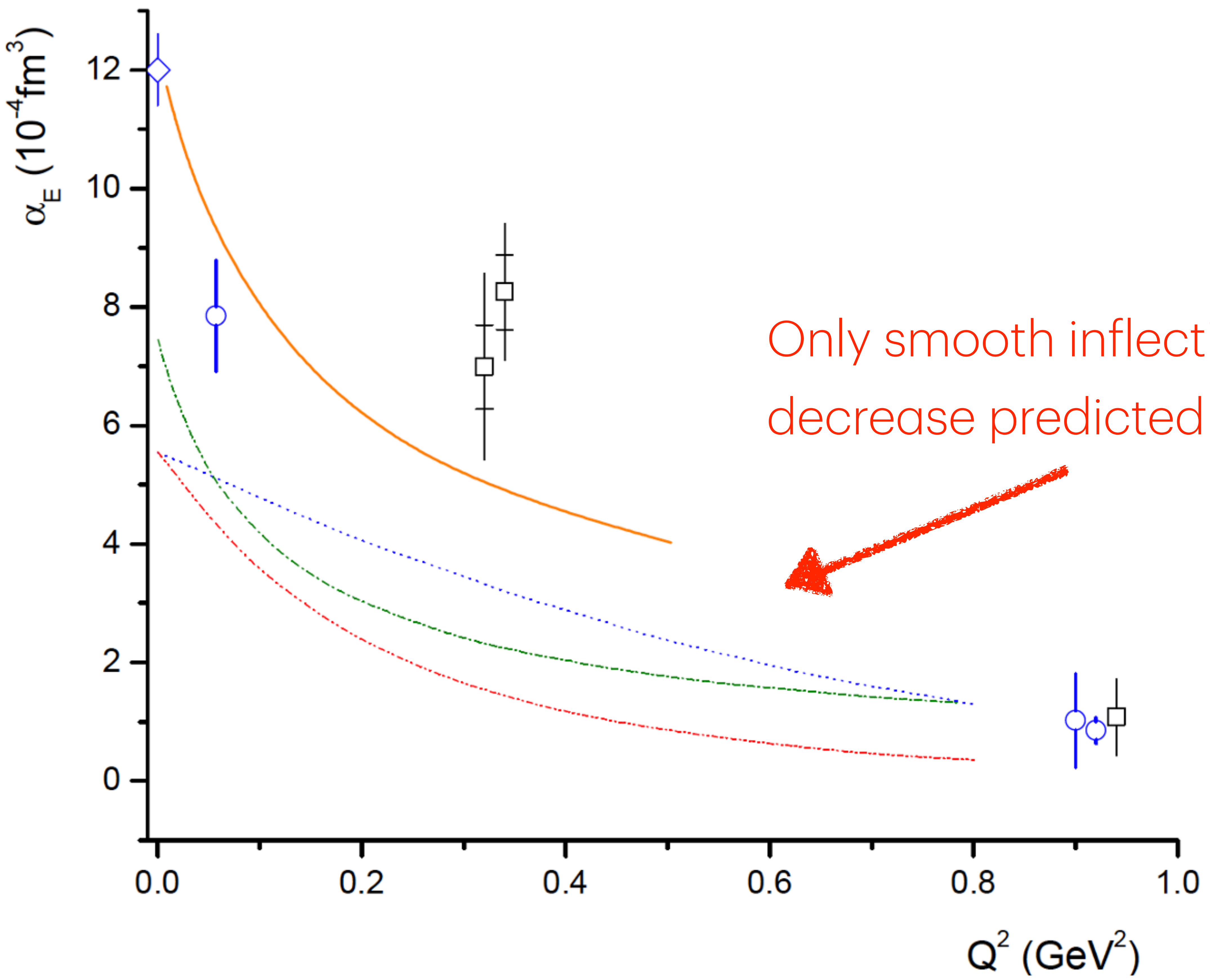
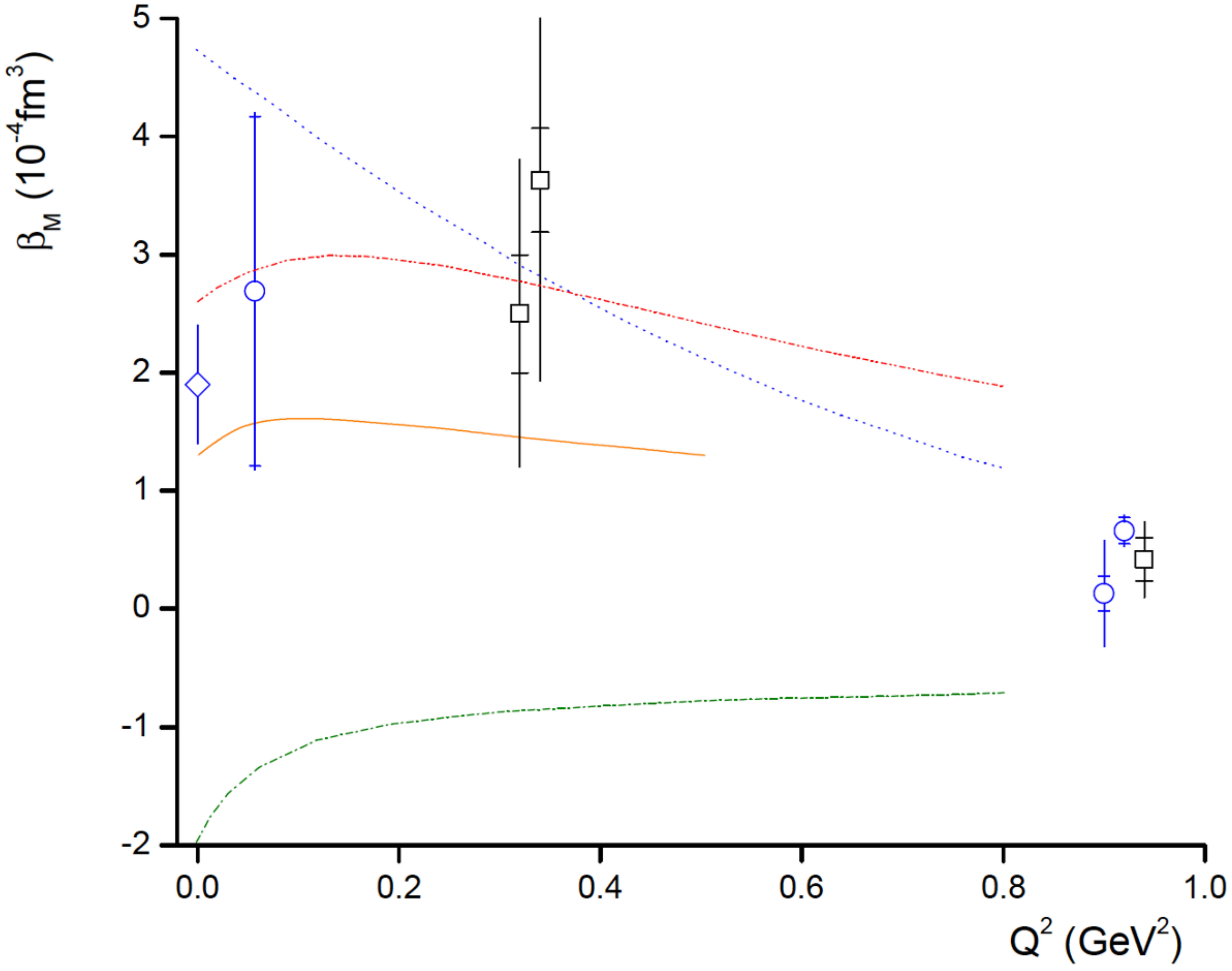


Only smooth inflectionless decrease predicted in α_E



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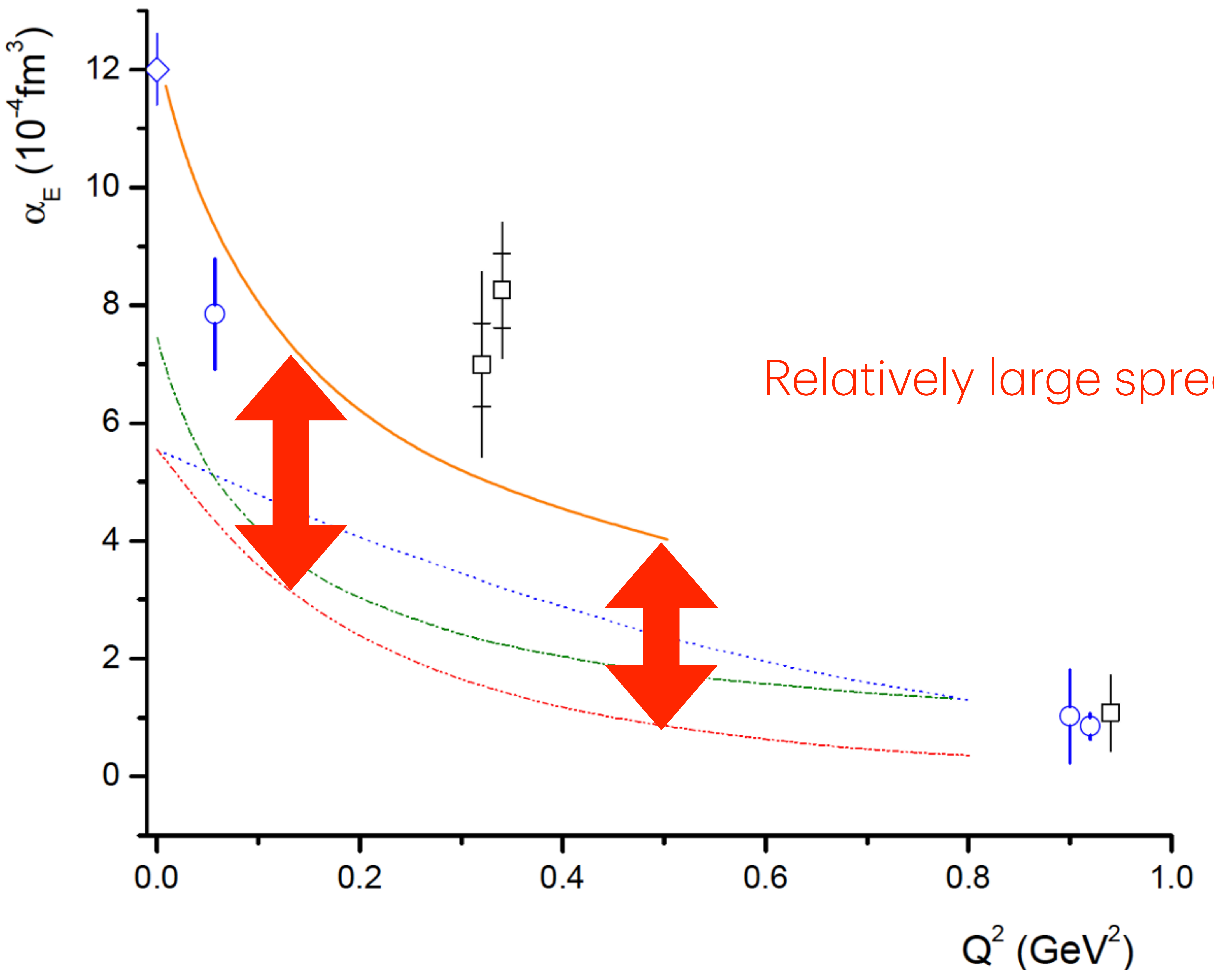
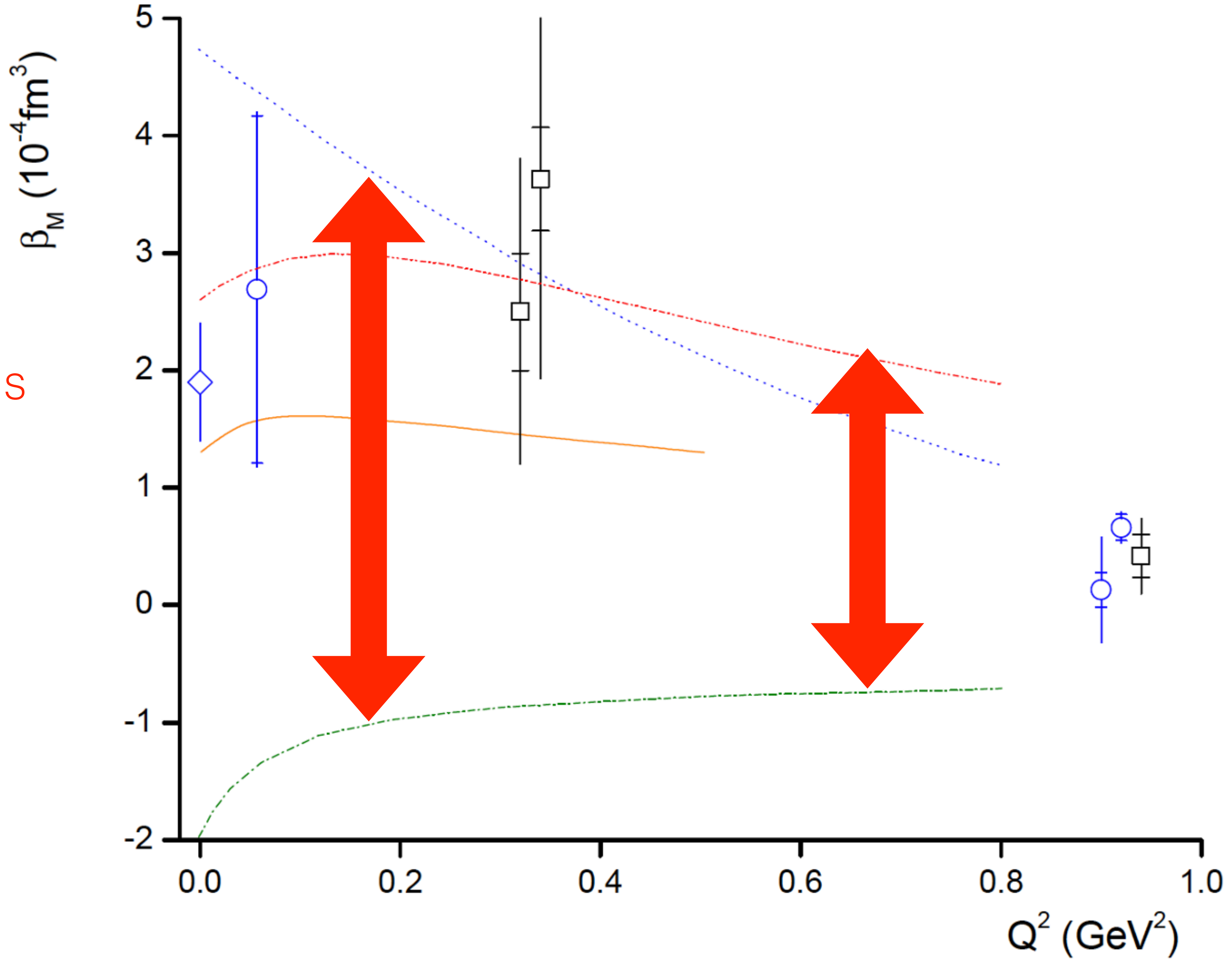


Relatively large spread in predictions



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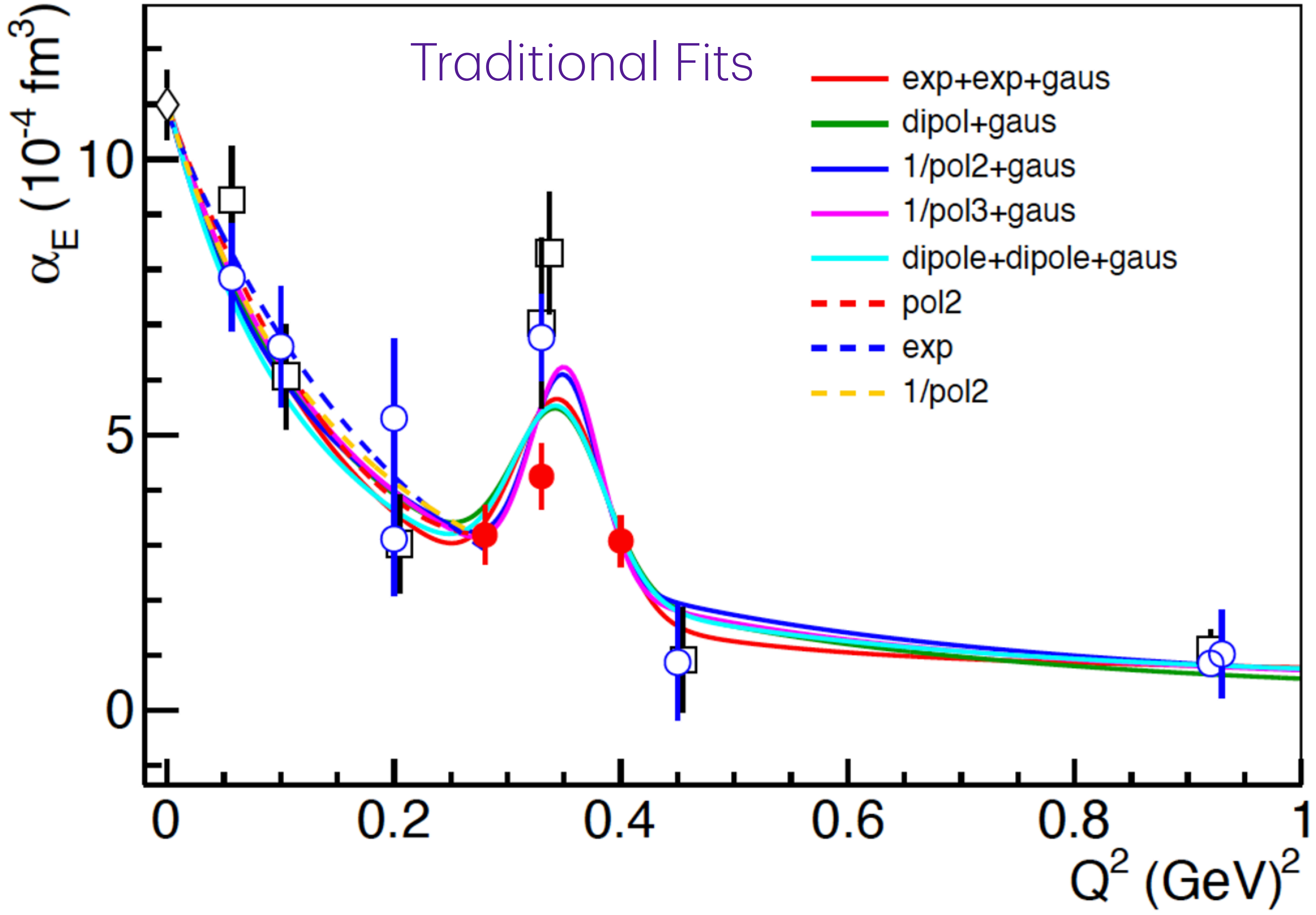
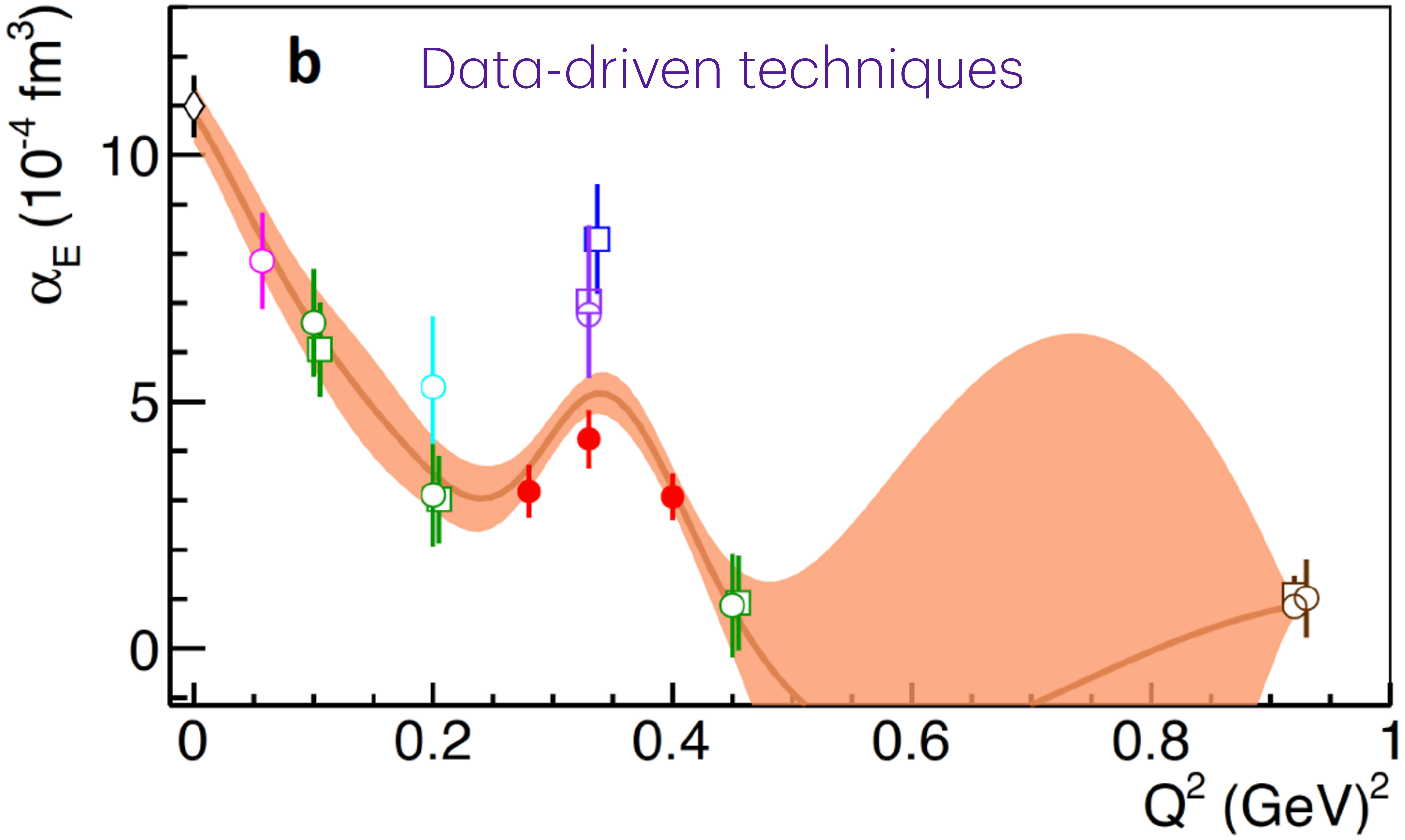
Recent Experiments





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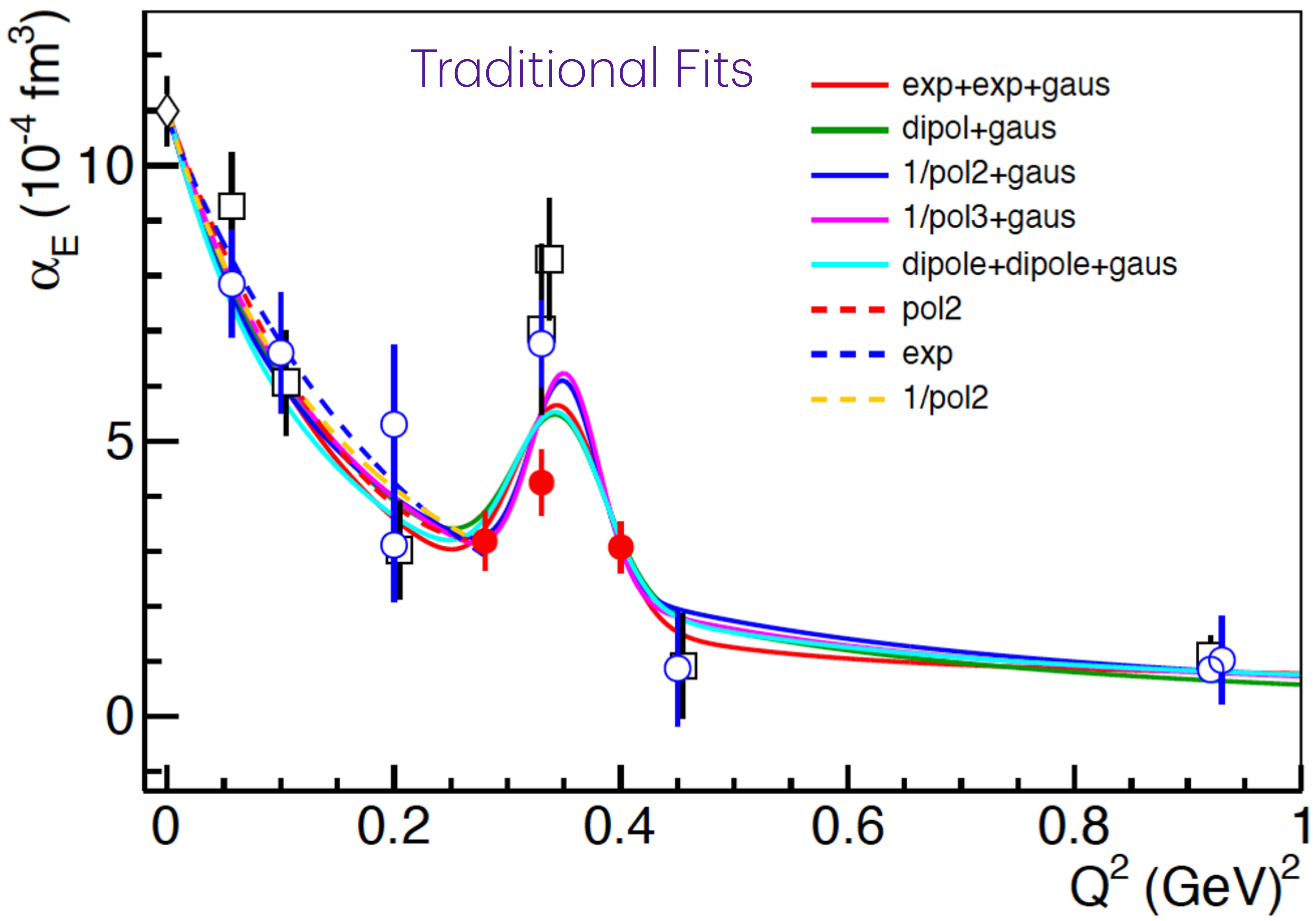

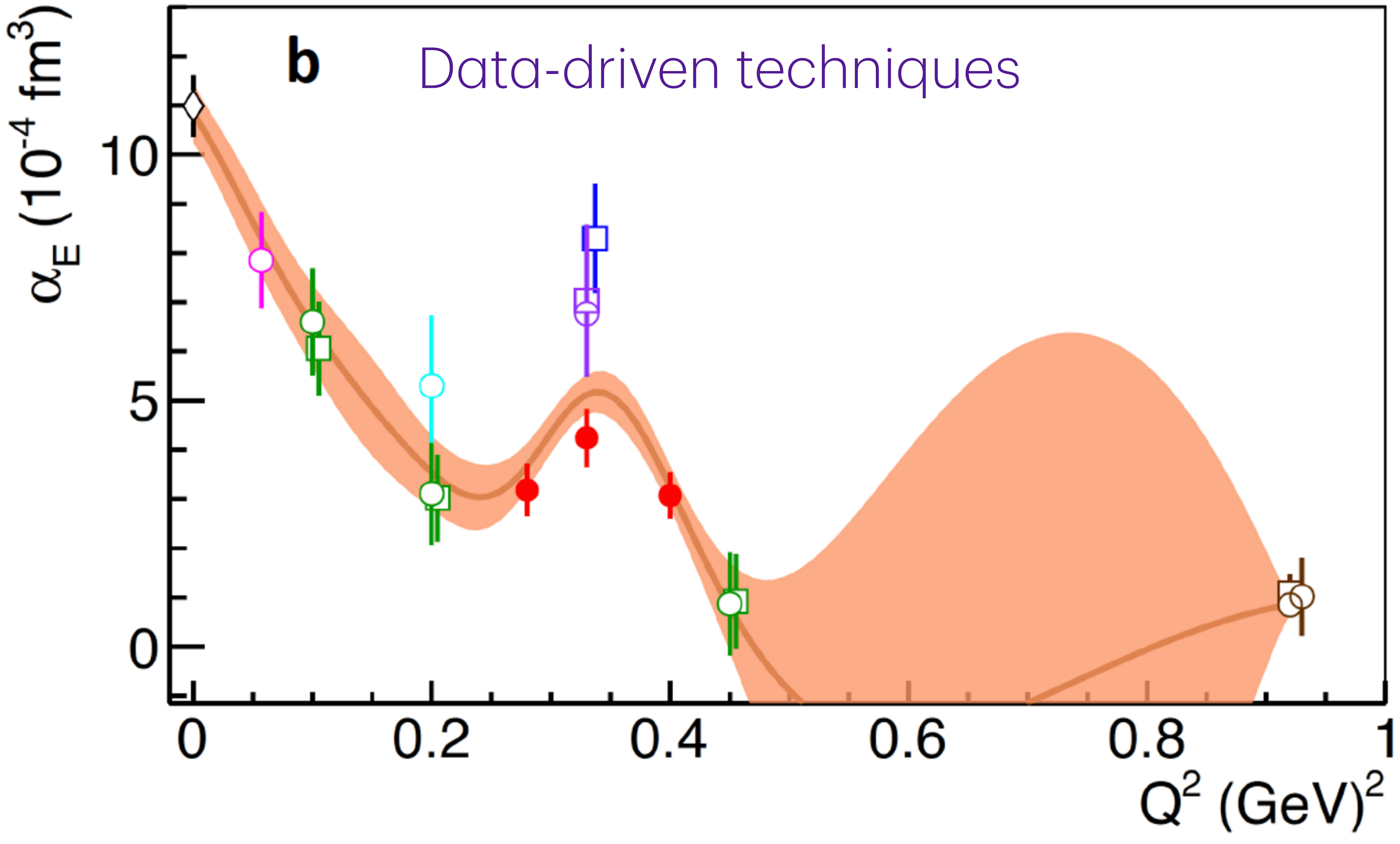

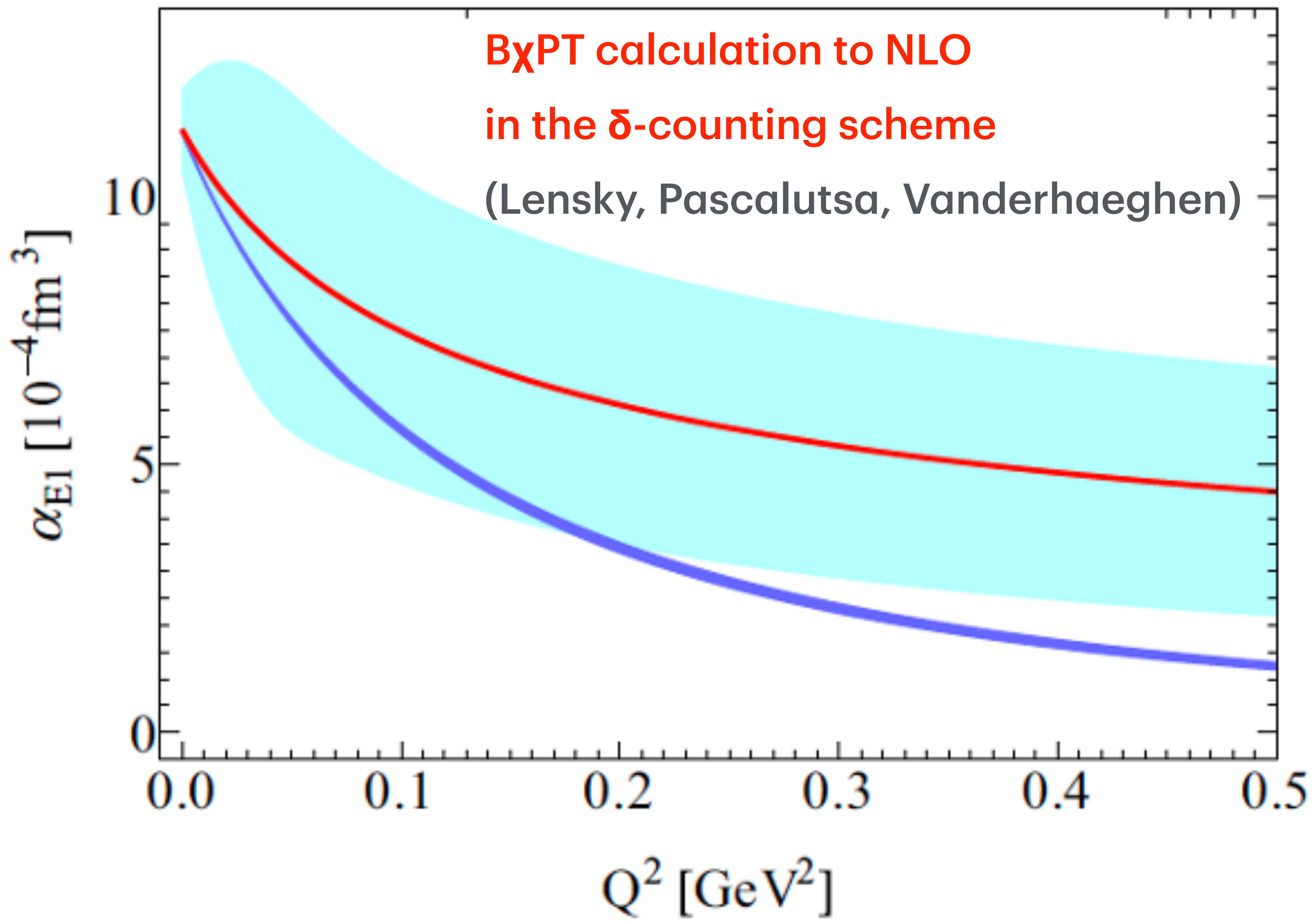

Theory predicts monatomic fall-off

Current Landscape and Questions

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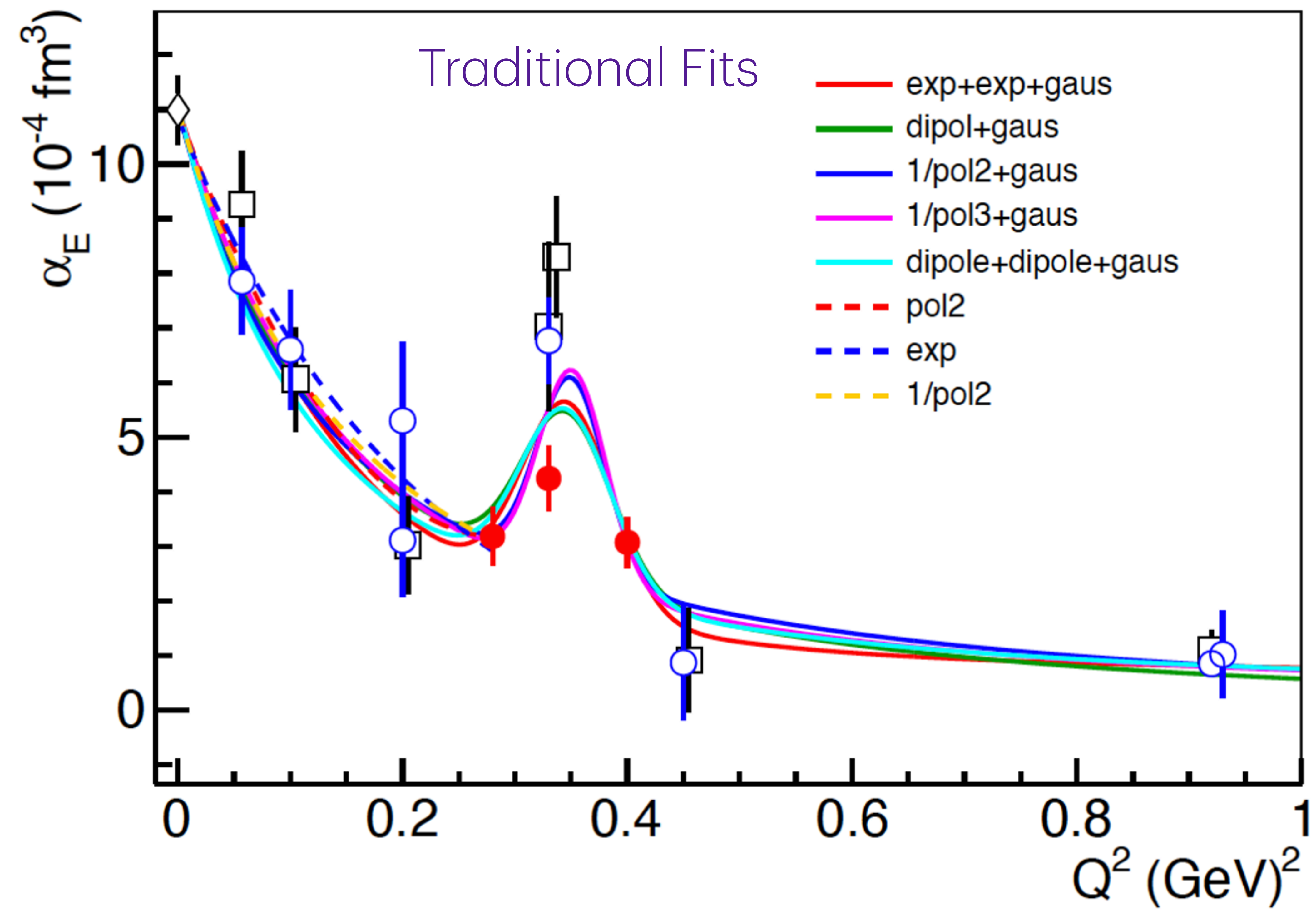
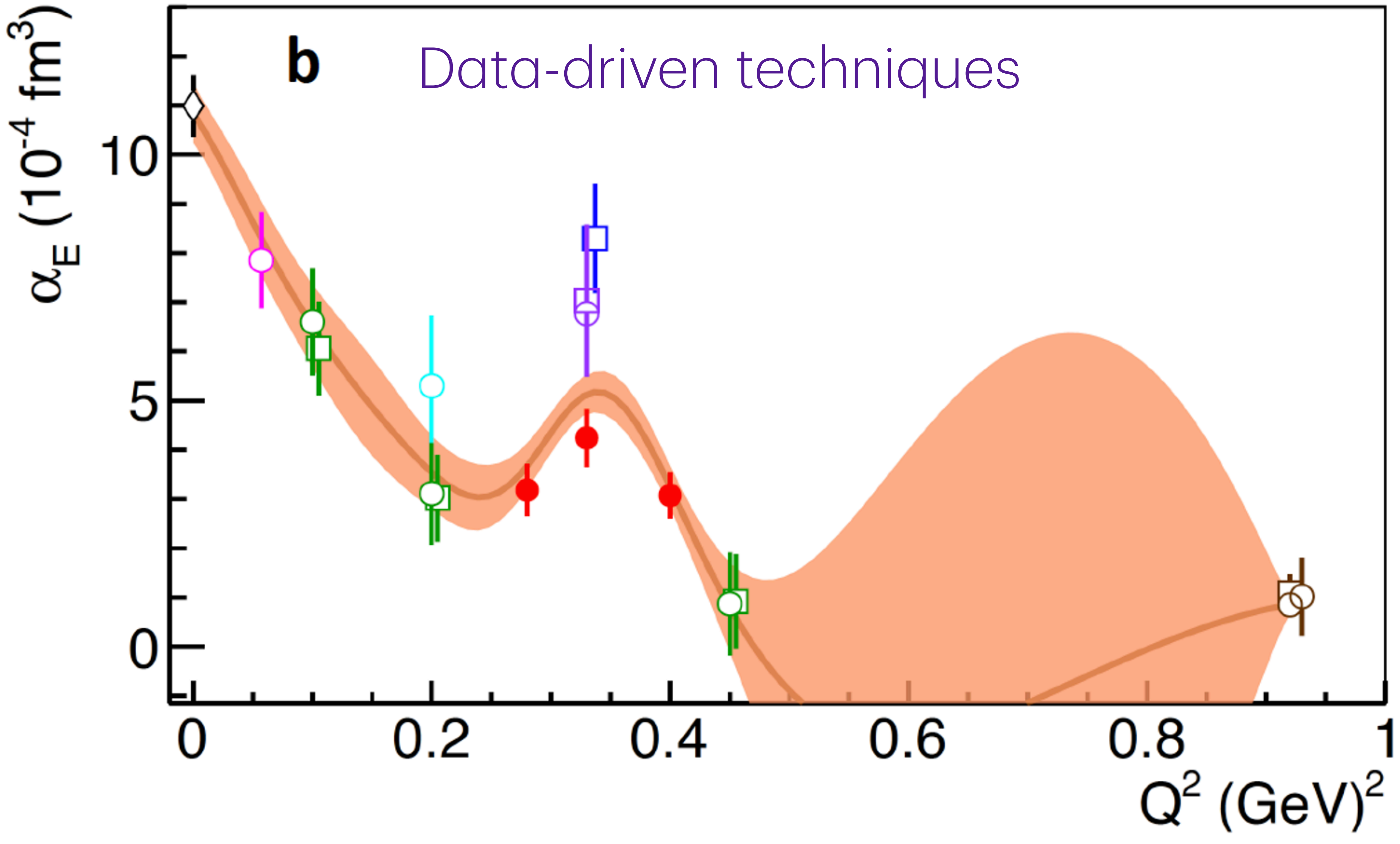
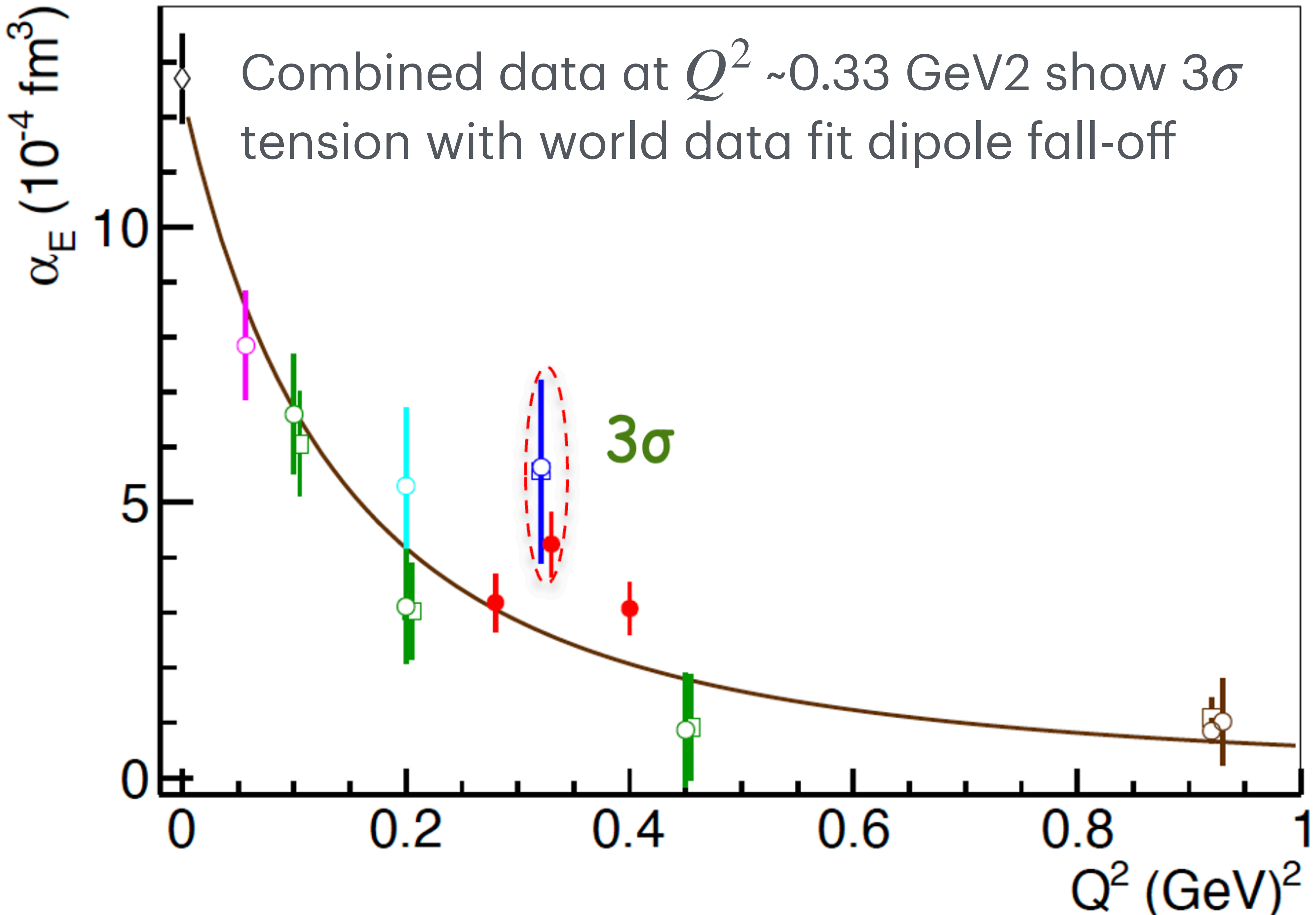
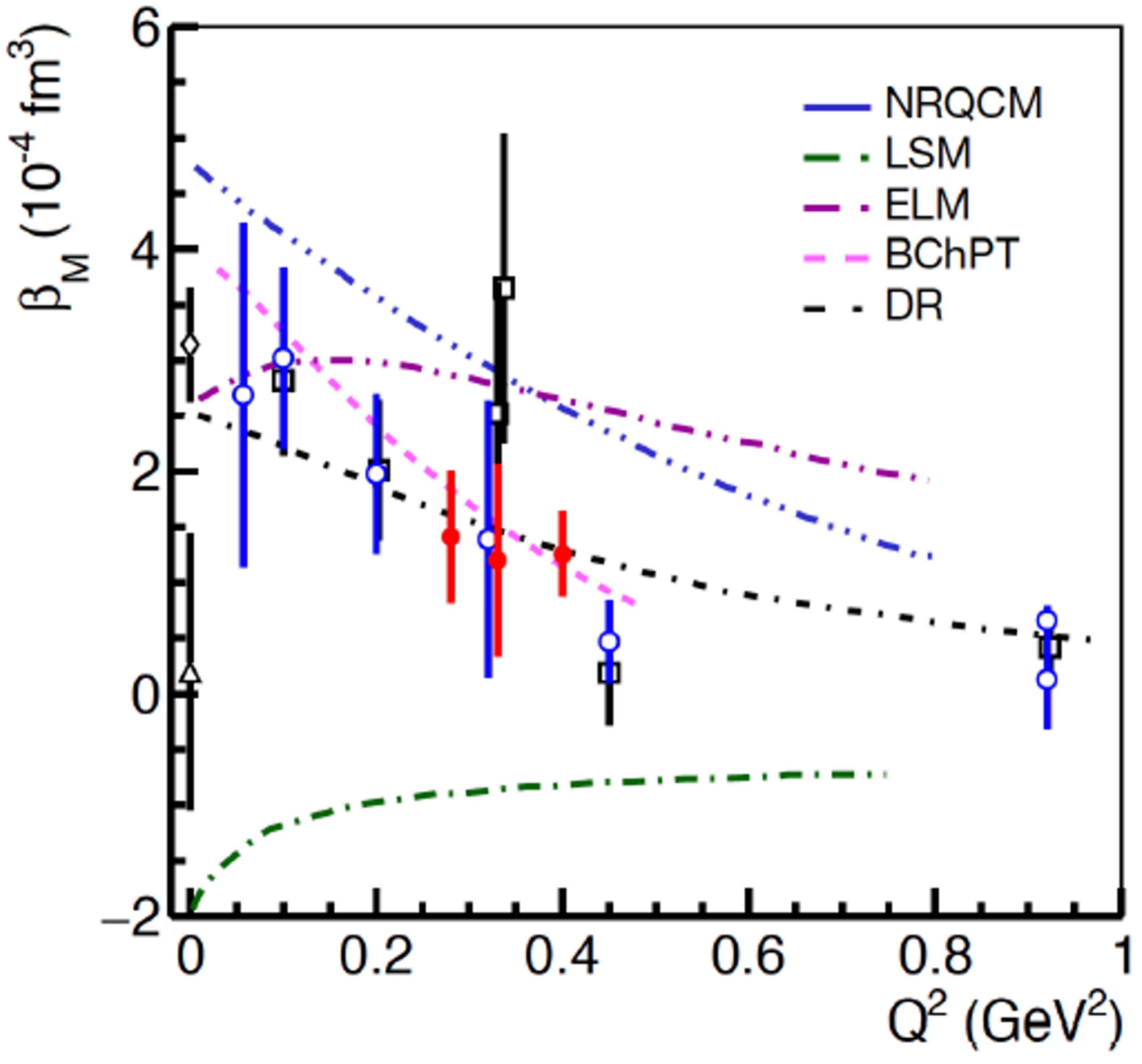
    - **If not:** Strong tension exists in the world data. Additional measurements can help pinpoint possible sources of tension









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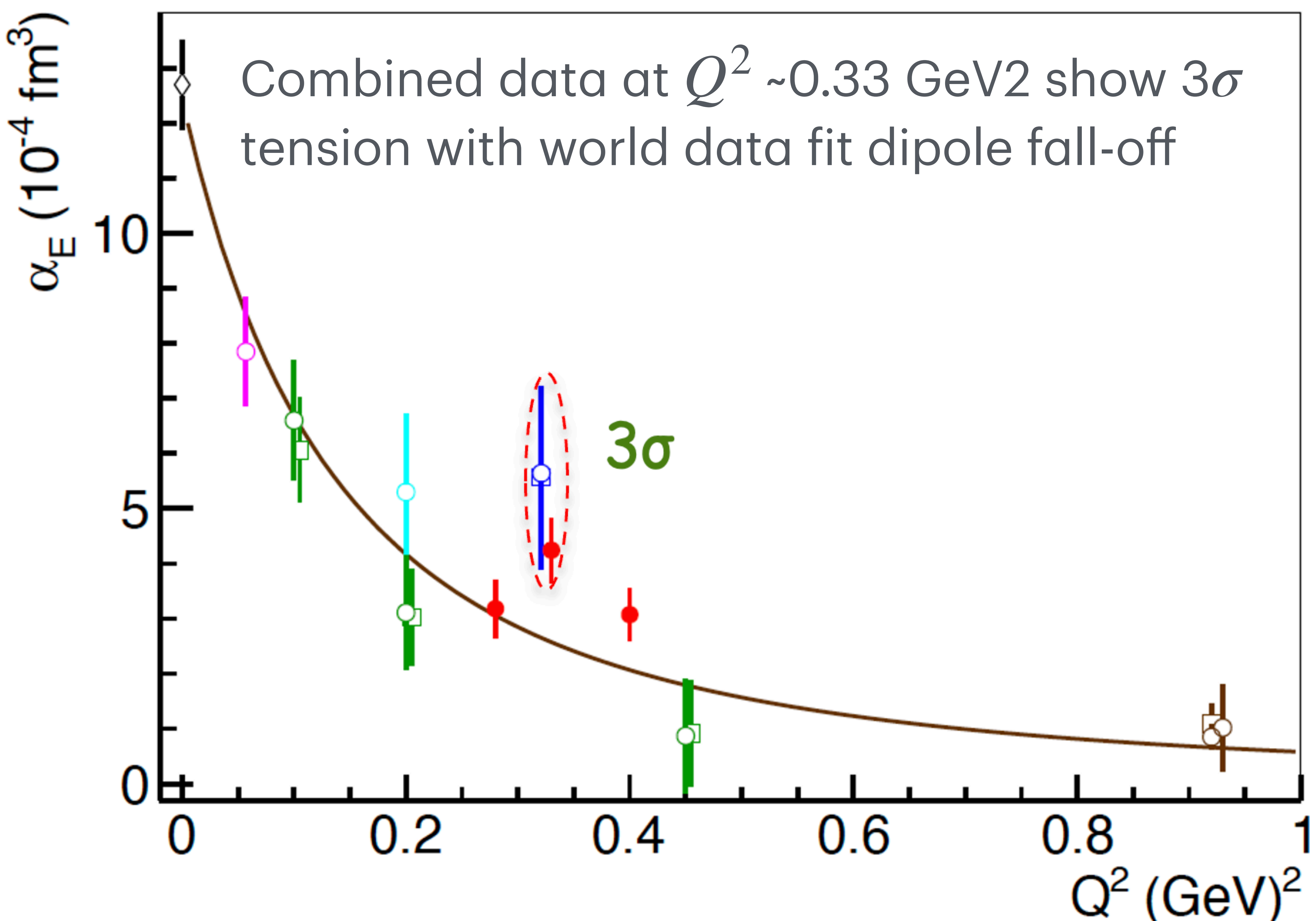
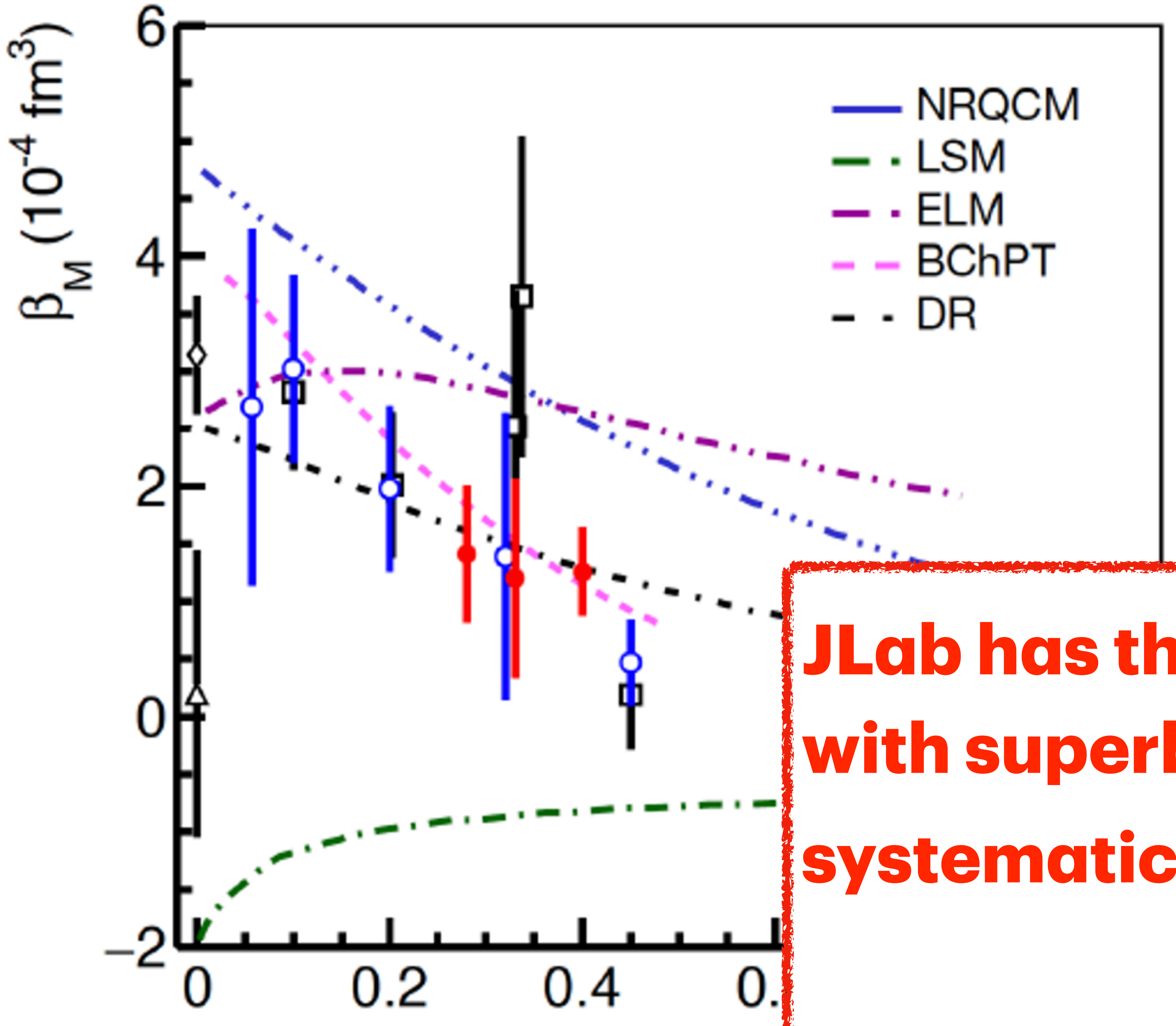


- Magnetic Polarizability
  - Large uncertainties and discrepancies exist in the world data.
  - High precision data is needed to disentangle diamagnetic and paramagnetic contributions in the nucleon.

Current Landscape and Questions



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JLab has the unique capability to measure α_E and β_M with superb precision and with consistent systematics across Q^2

Precision can be increased with additional measurements (VCS-II and this proposal)

Methodology can be cross-checked with alternative extractions (this proposal)

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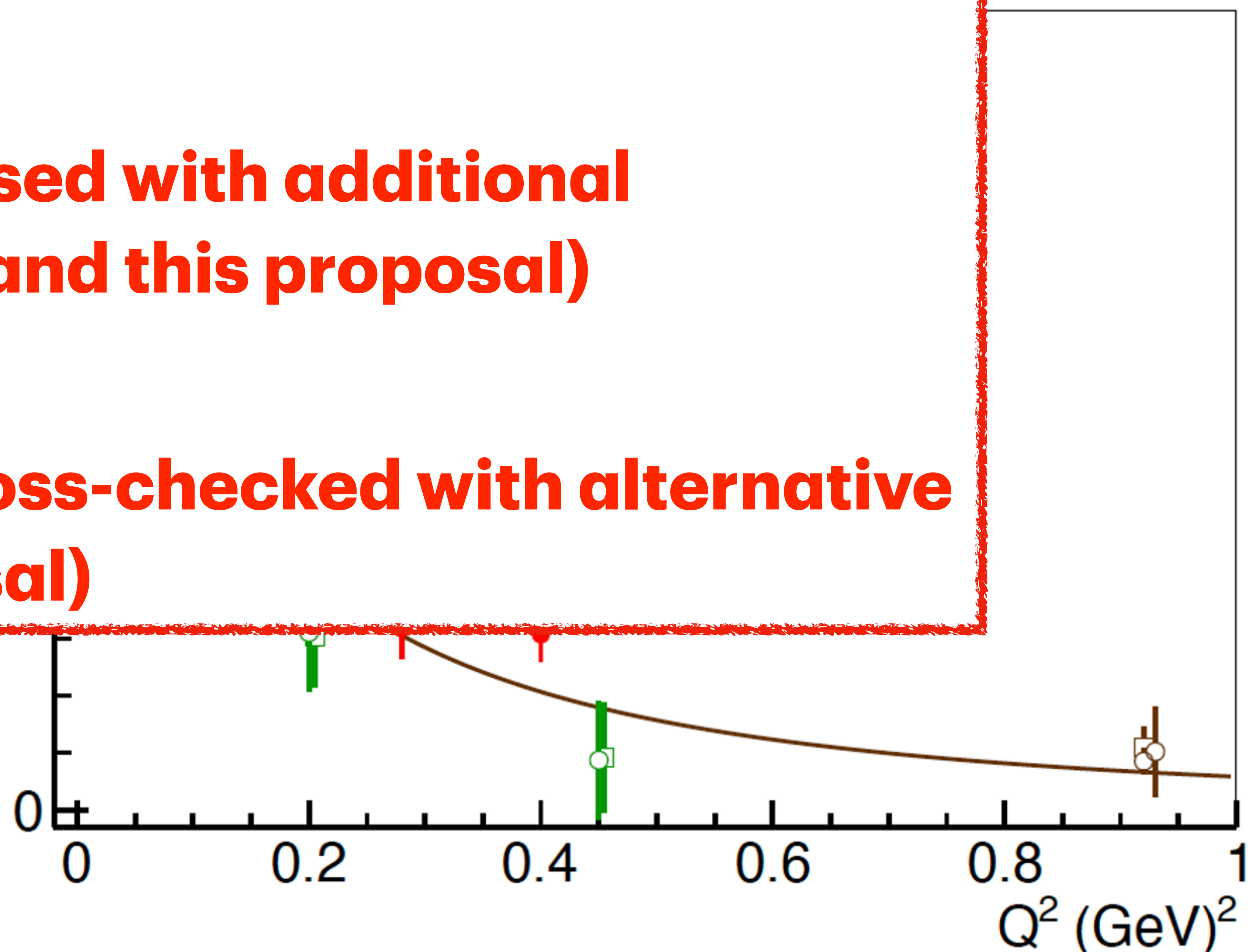

A new path to measure GPs: Induced asymmetries

One can set-up and measure beam-charge or beam-spin asymmetries as an independent path to extracting the generalized polarizabilities.

Virtual Compton scattering at low energies with a positron beam

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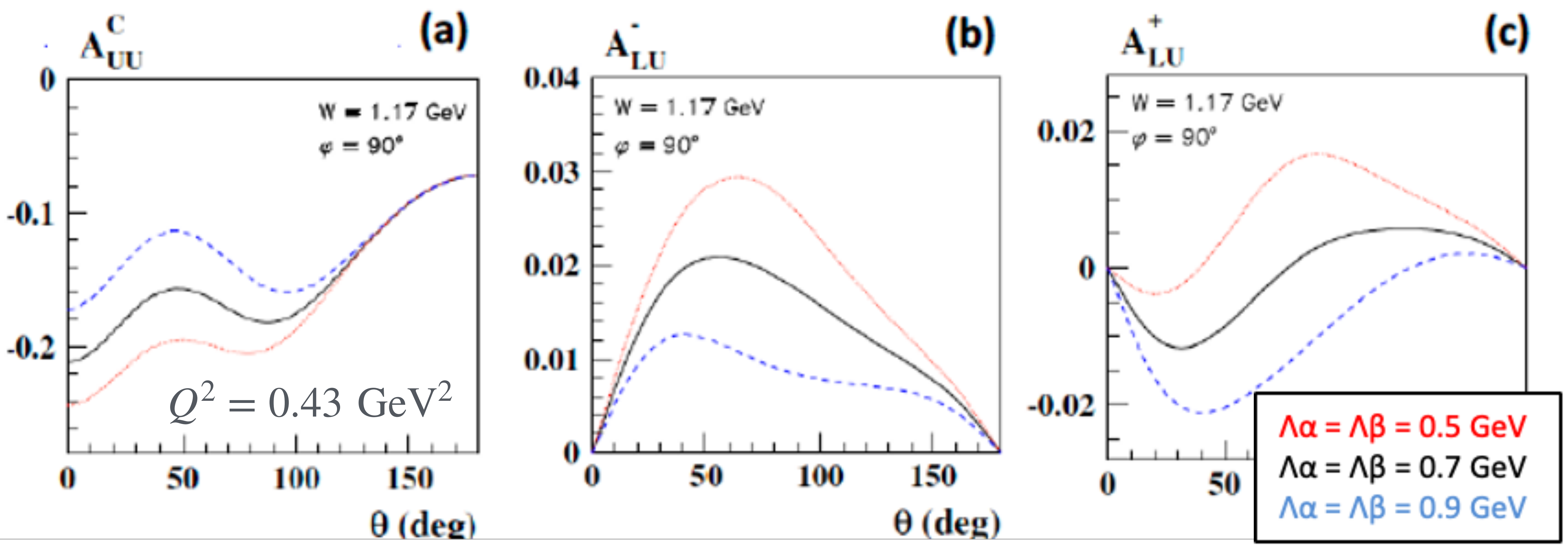
[3]Institut für Kernphysik and PRISMA+ Cluster of Excellence, Johannes Gutenberg Universität, D-55099 Mainz, Germany

Eur. Phys. J. A 57 (2021) 11, 316



(a): The beam-charge asymmetry as a function of the photon scattering angle at Q2 = 0.43 GeV2.

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

This proposal:

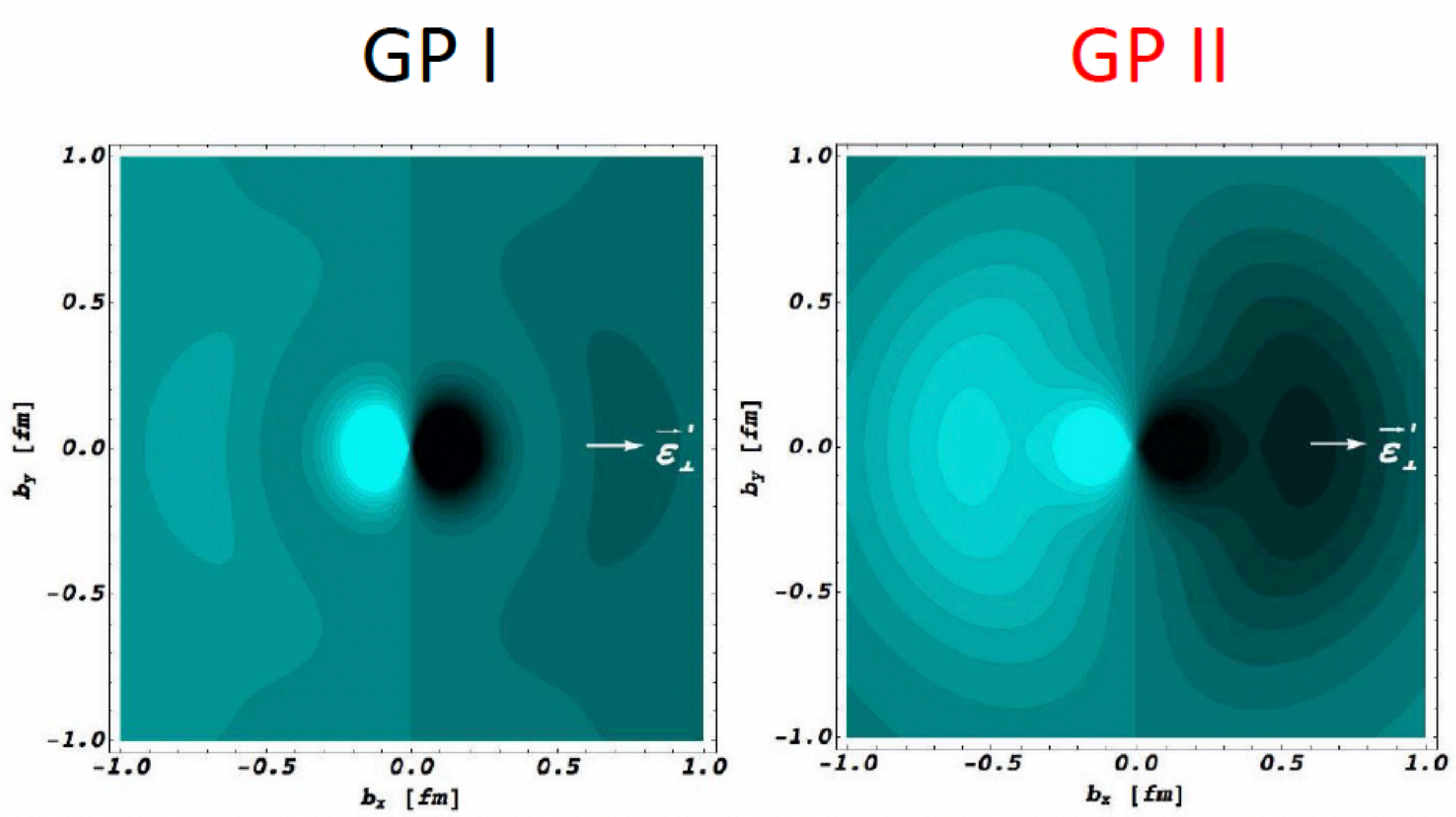
Beam-Spin Asymmetry (BSA): $A^e_{LU} = \dfrac{d\sigma^e_+ - d\sigma^e_-}{d\sigma^e_+ + d\sigma^e_-}$

Future proposal (positron-beam):

Beam-Charge Asymmetry (BCA): $A^C_{UU} = \dfrac{(d\sigma^+_+ + d\sigma^+_-) - (d\sigma^-_+ + d\sigma^-_-)}{d\sigma^+_+ + d\sigma^+_- + d\sigma^-_+ + d\sigma^-_-}$

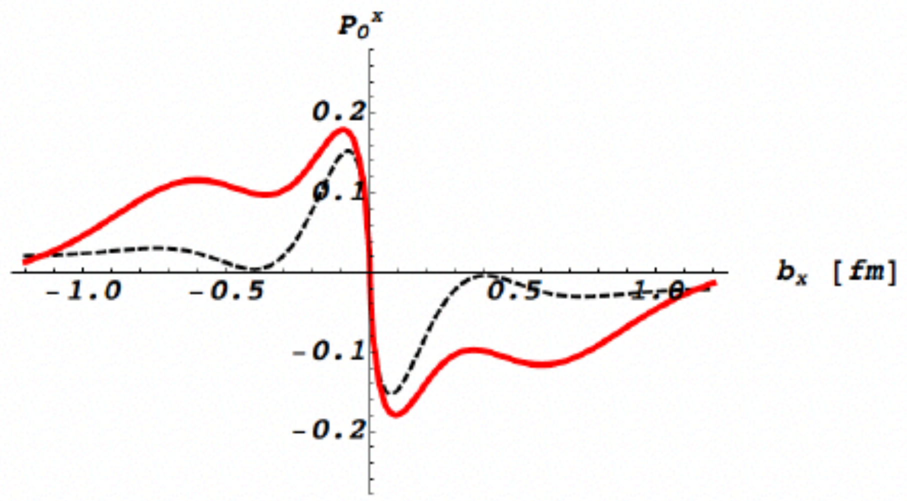
Extensions: Spatial Dependence of induced polarizations

Light-front quark charge densities → Deformation under EM field



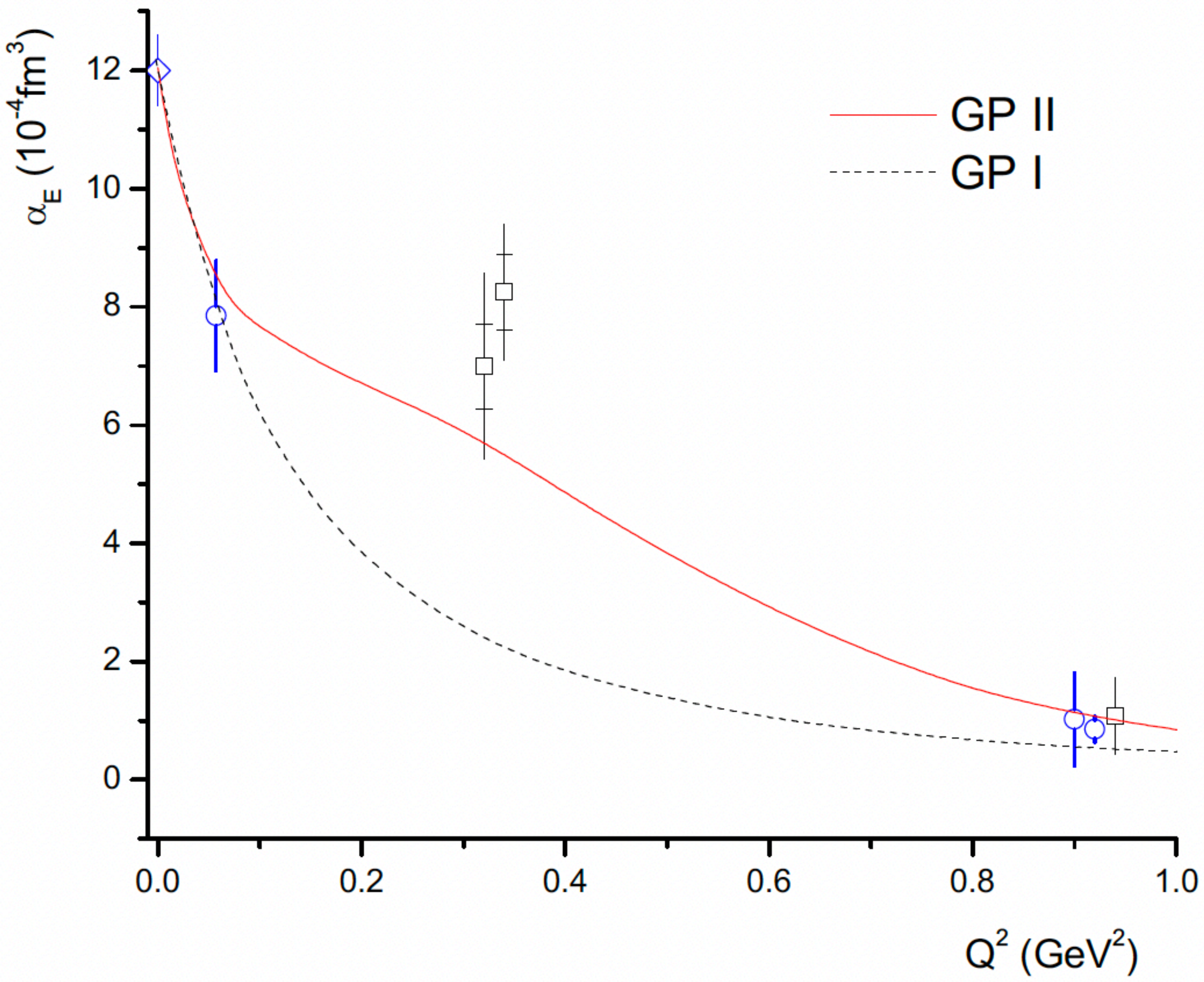
-

Light (**dark**) regions ➔ **largest** (**smaller**) values
(photon polarization along x-axis, as indicated)



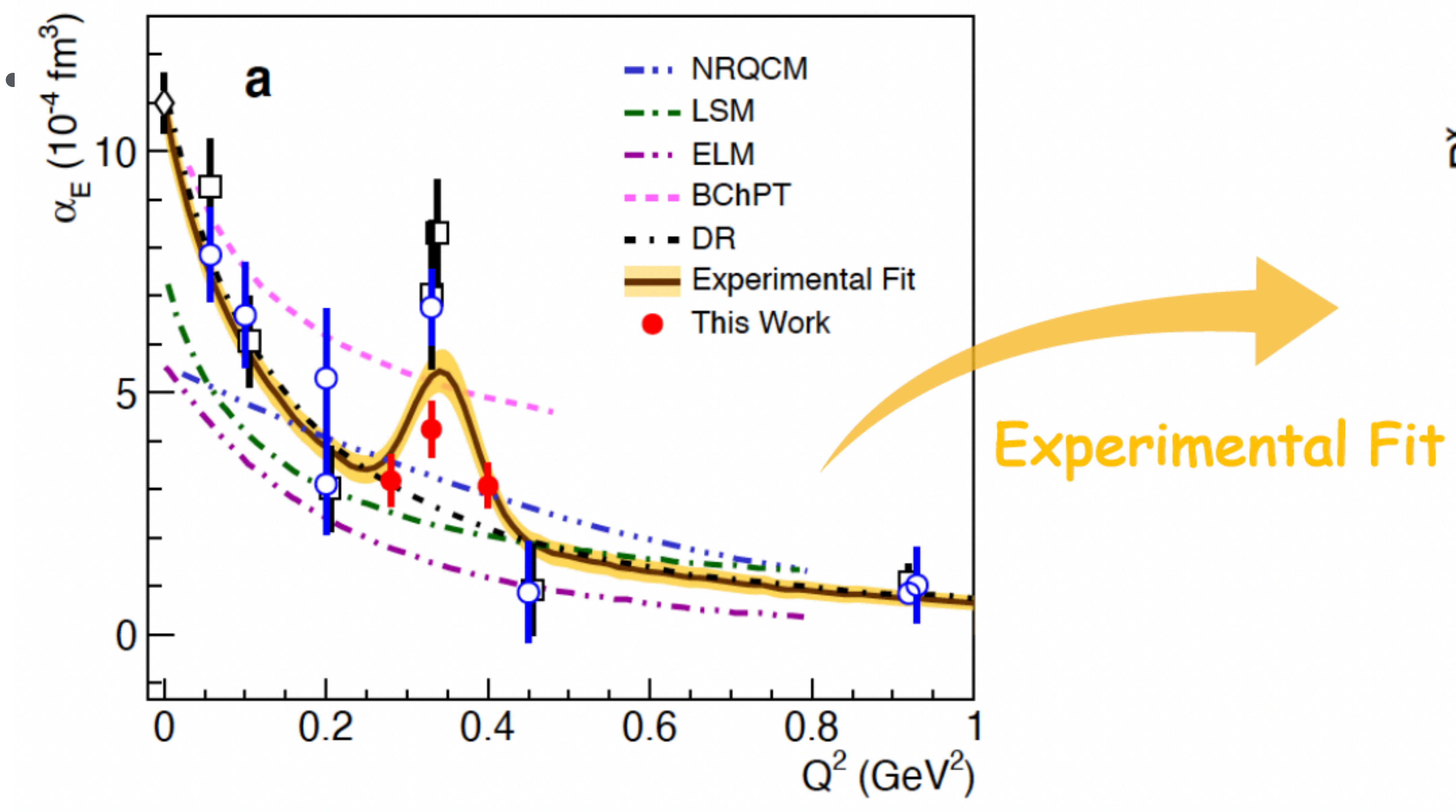
Induced polarization along b_y=0

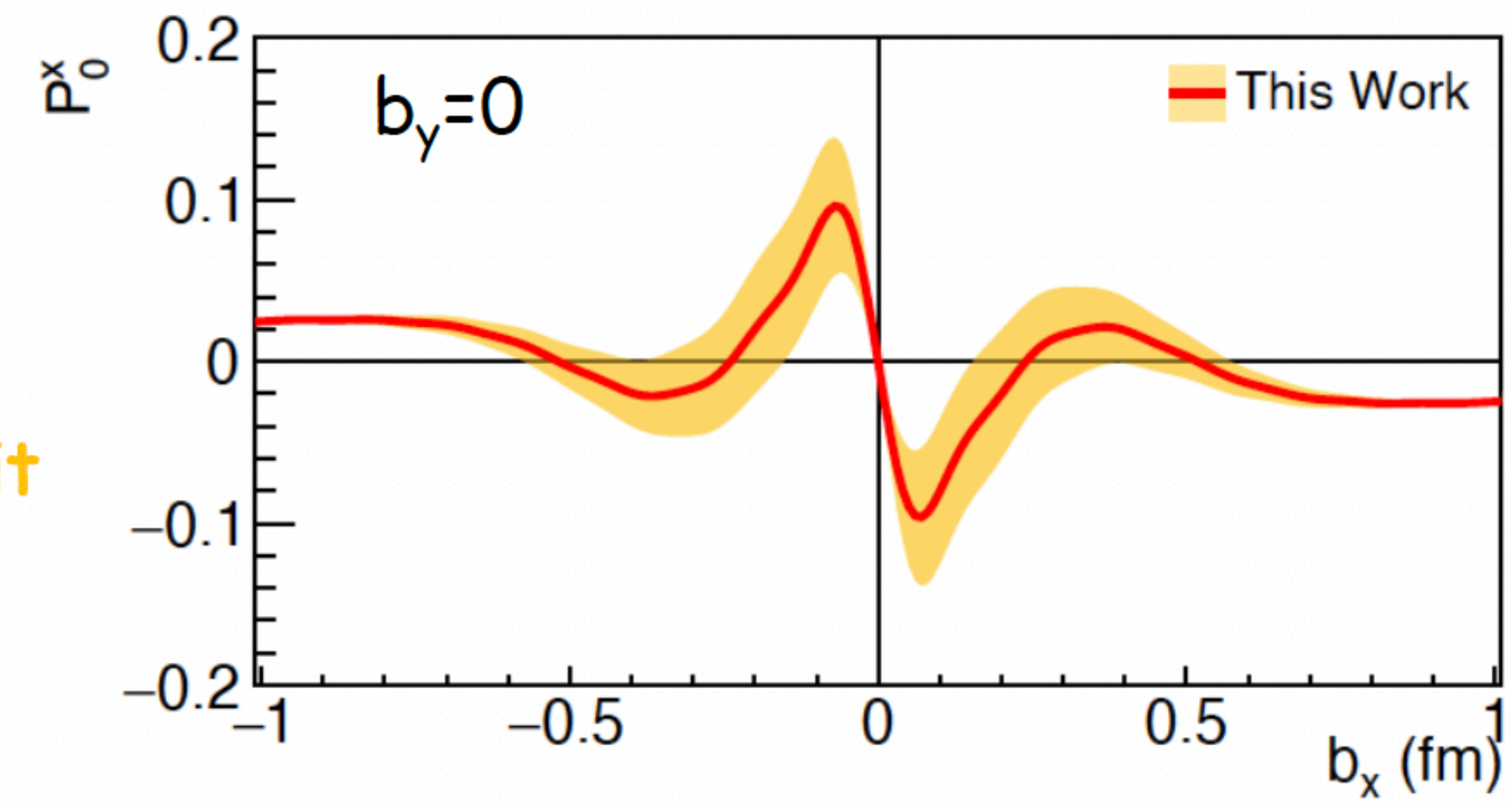
Phys. Rev. Lett. 104, 112001 (2010)
M. Gorchtein, C. Lorce, B. Pasquini, M. Vanderhaeghen



Extensions: Spatial Dependence of induced polarizations

Light-front quark charge densities ⟶ Deformation under EM field



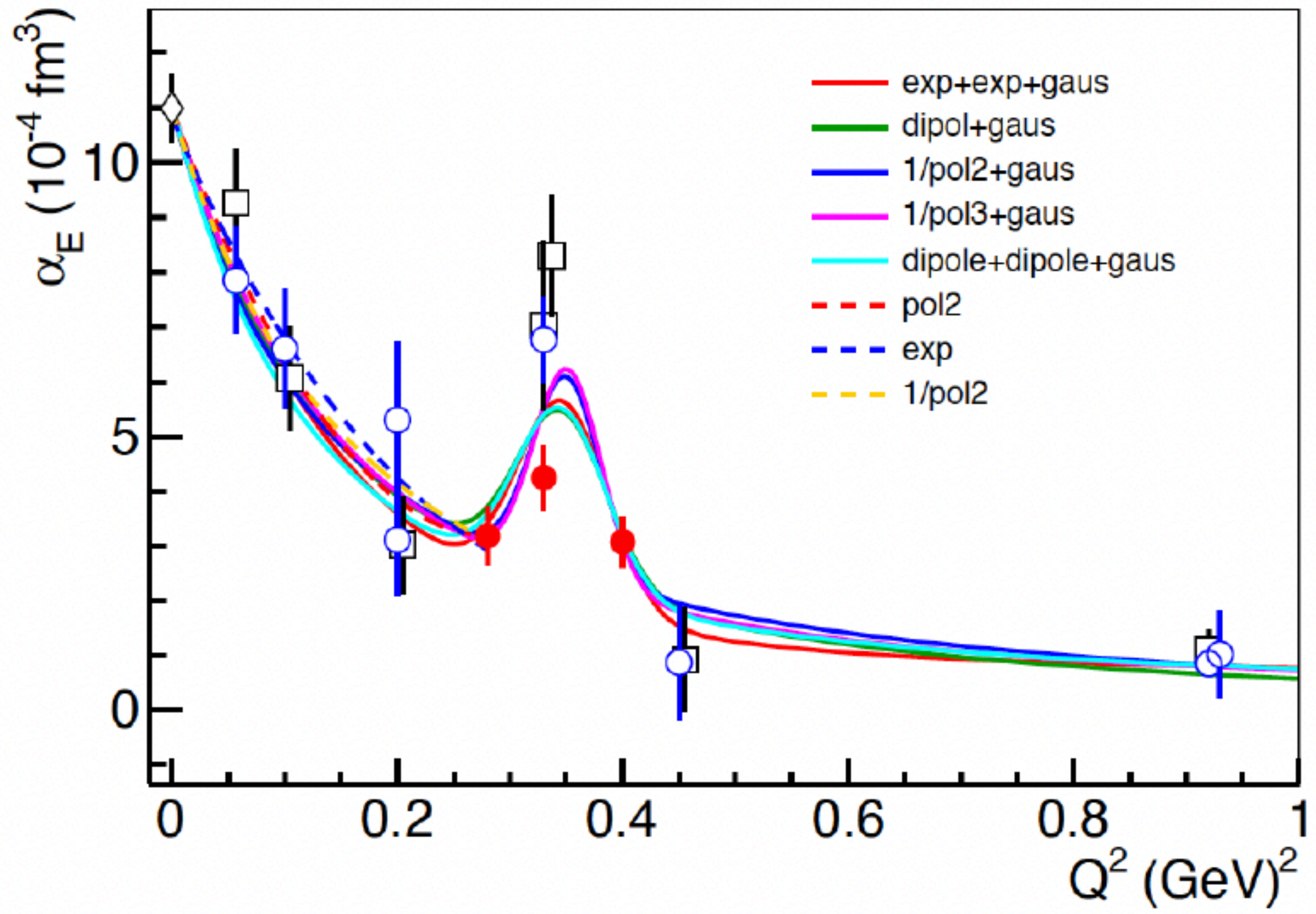


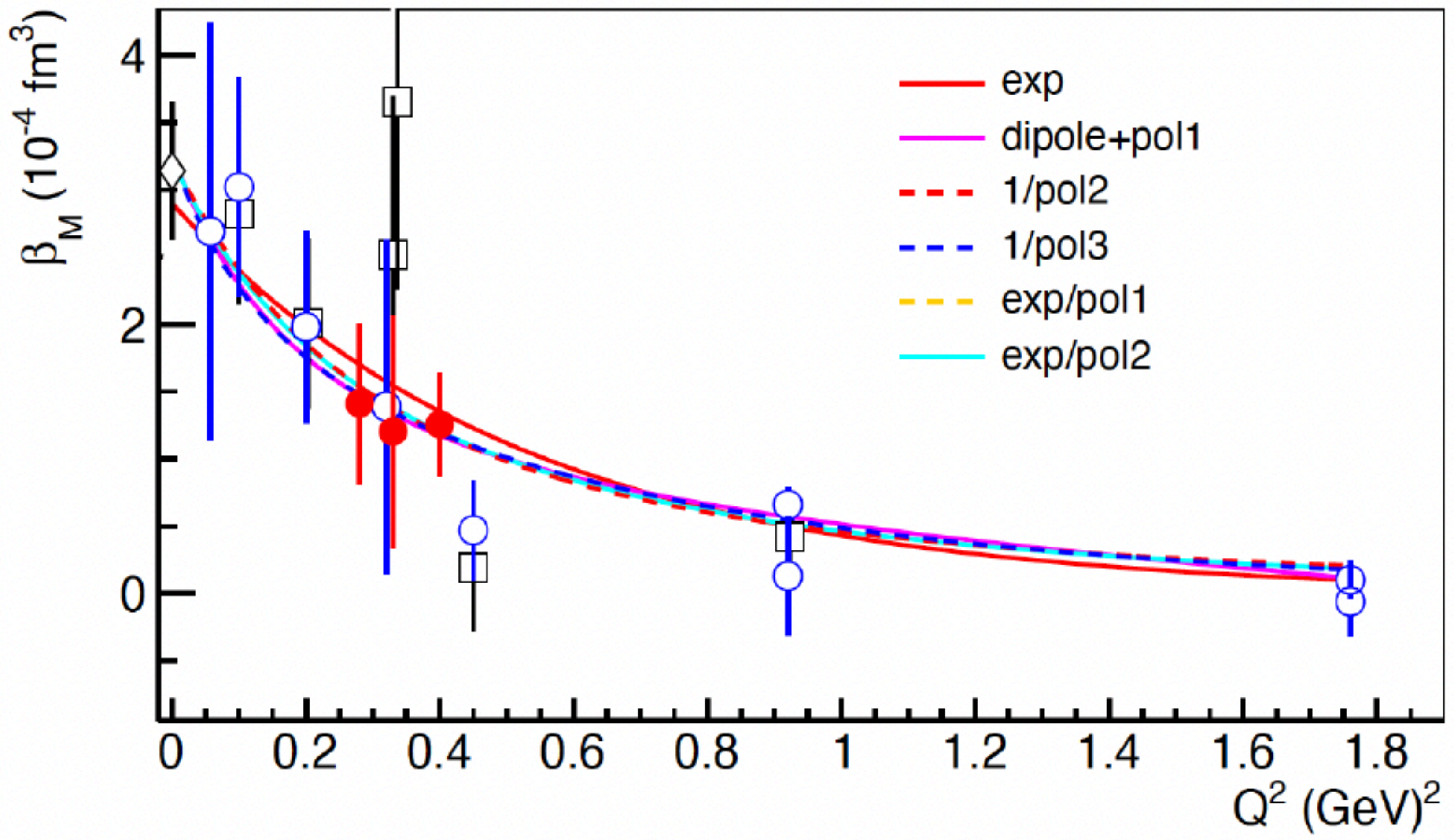
x-y defines the transverse plane with the z-axis being the direction of the fast-moving proton

Extensions: Polarizability Radii

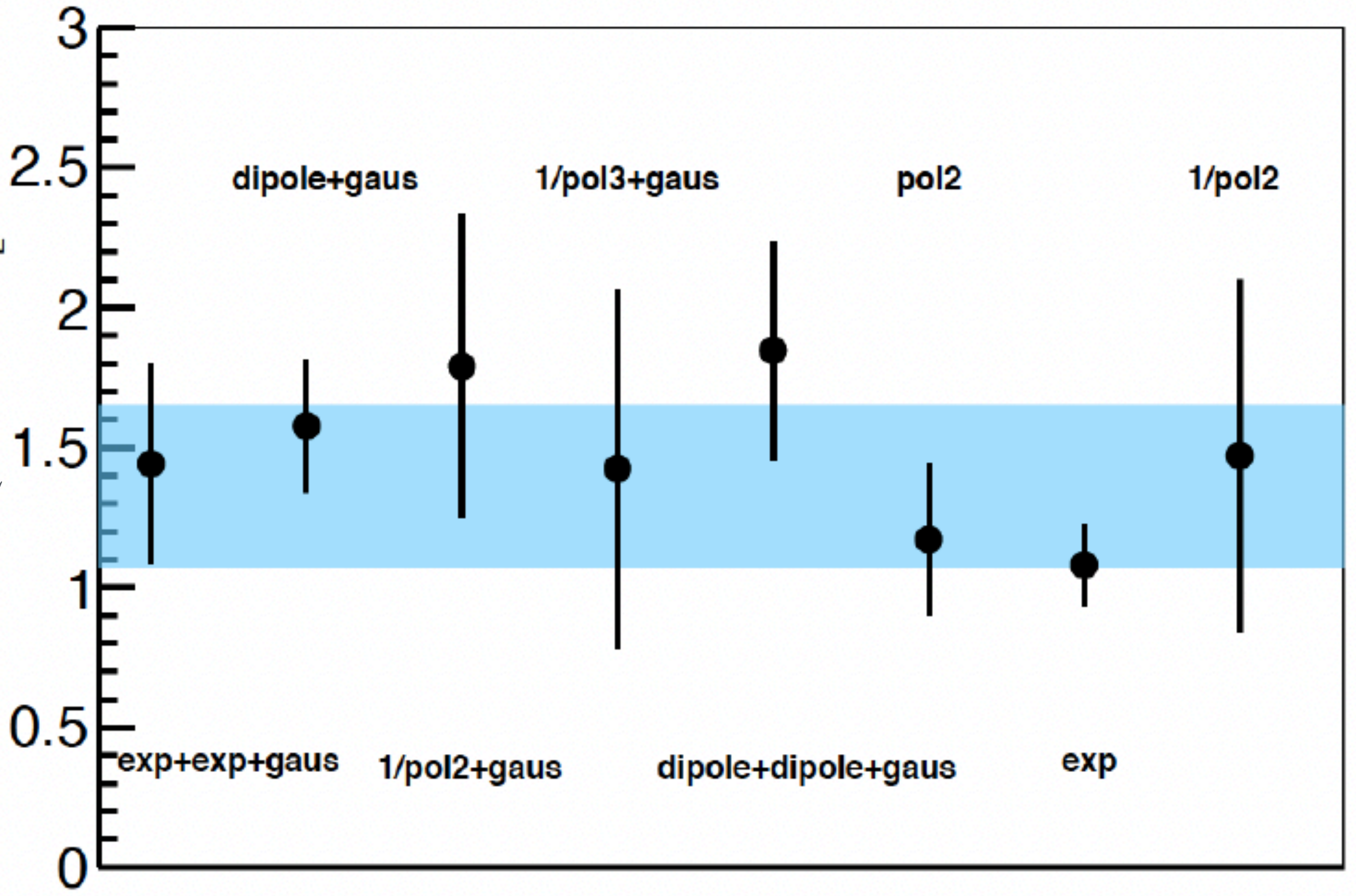
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2}\alpha_E(Q^2)\Big|_{Q^2=0}$$

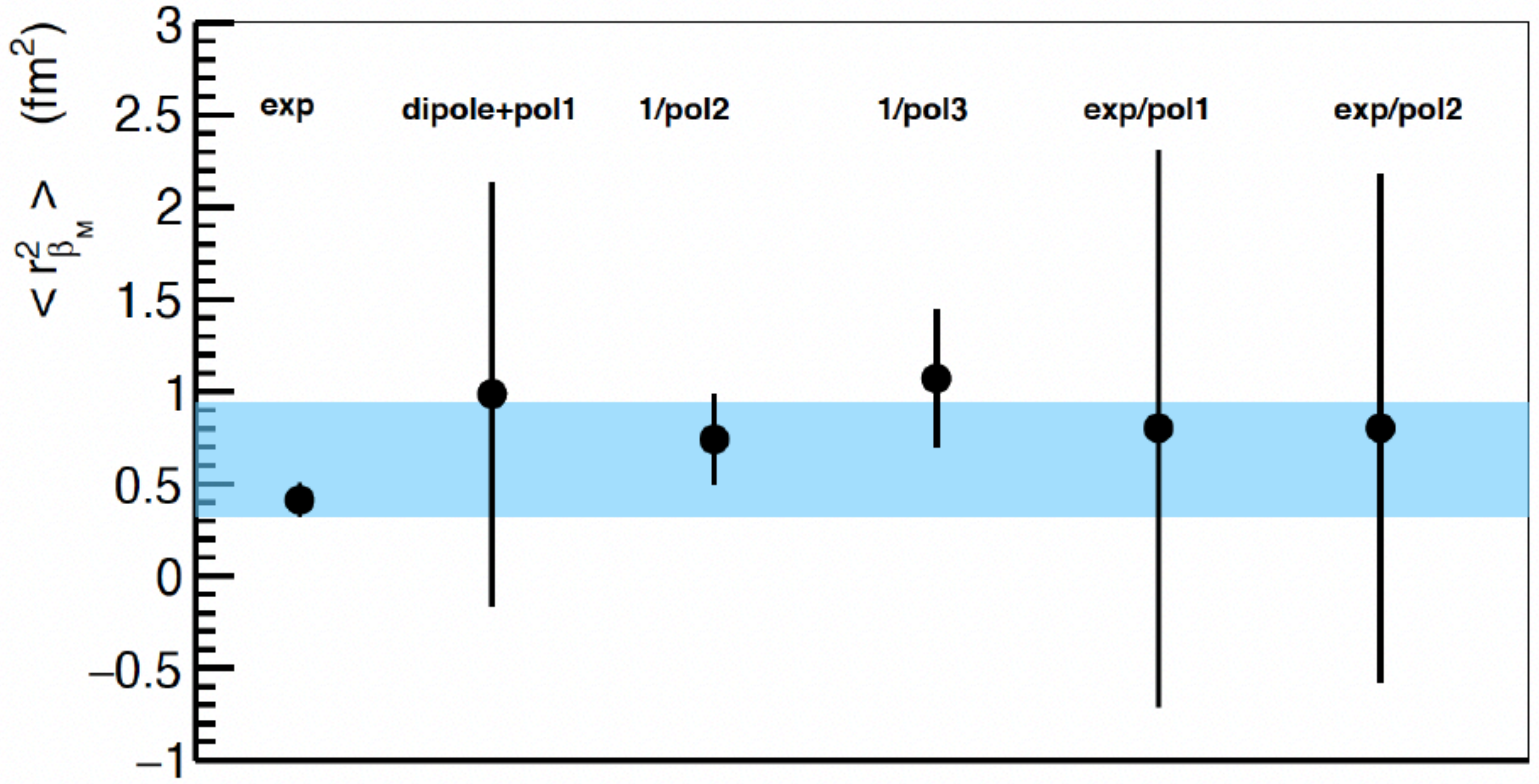
$$\langle r^2_{\beta_M} \rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2}\beta_M(Q^2)\Big|_{Q^2=0}$$





$$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29 \text{ fm}^2$$



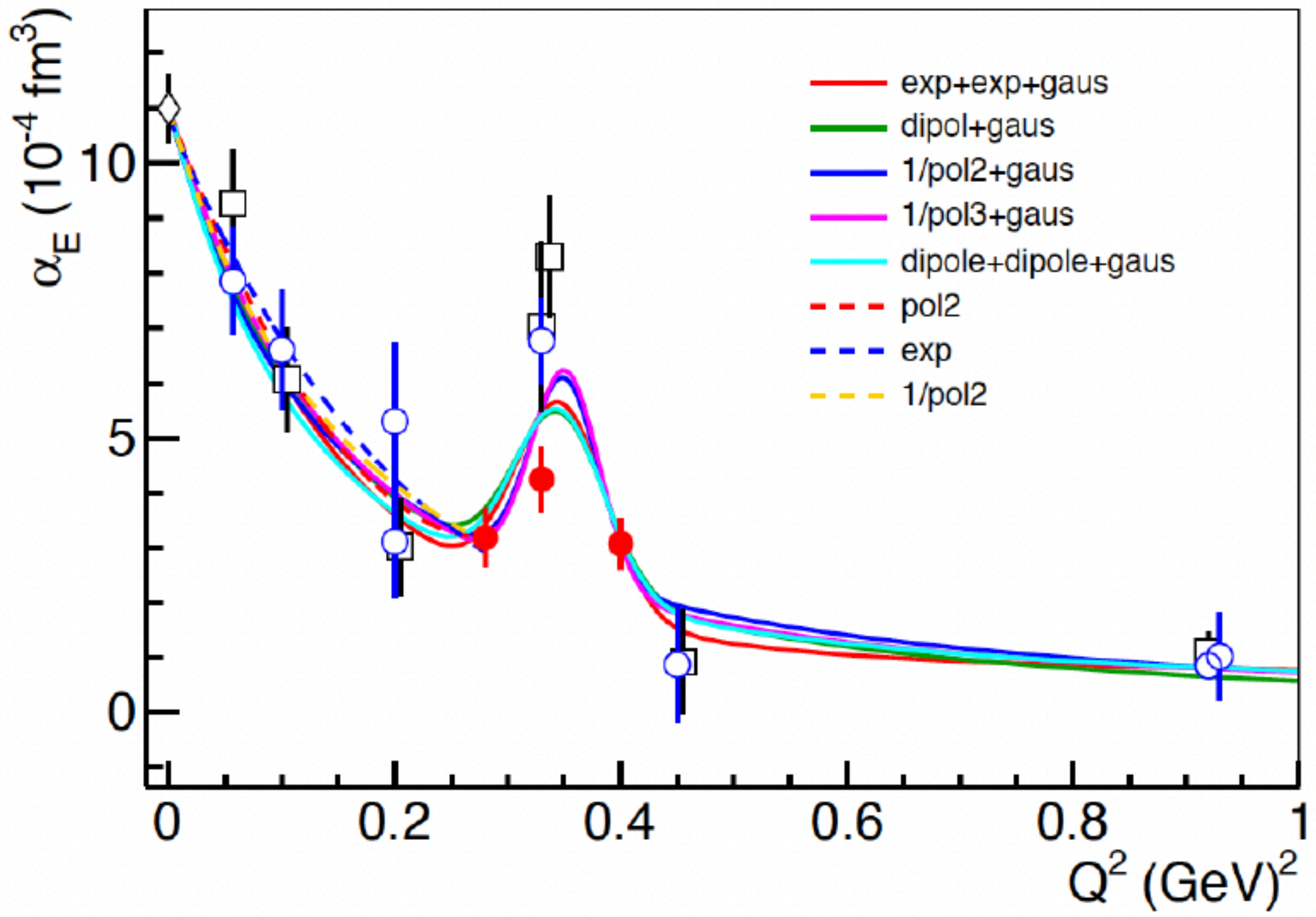


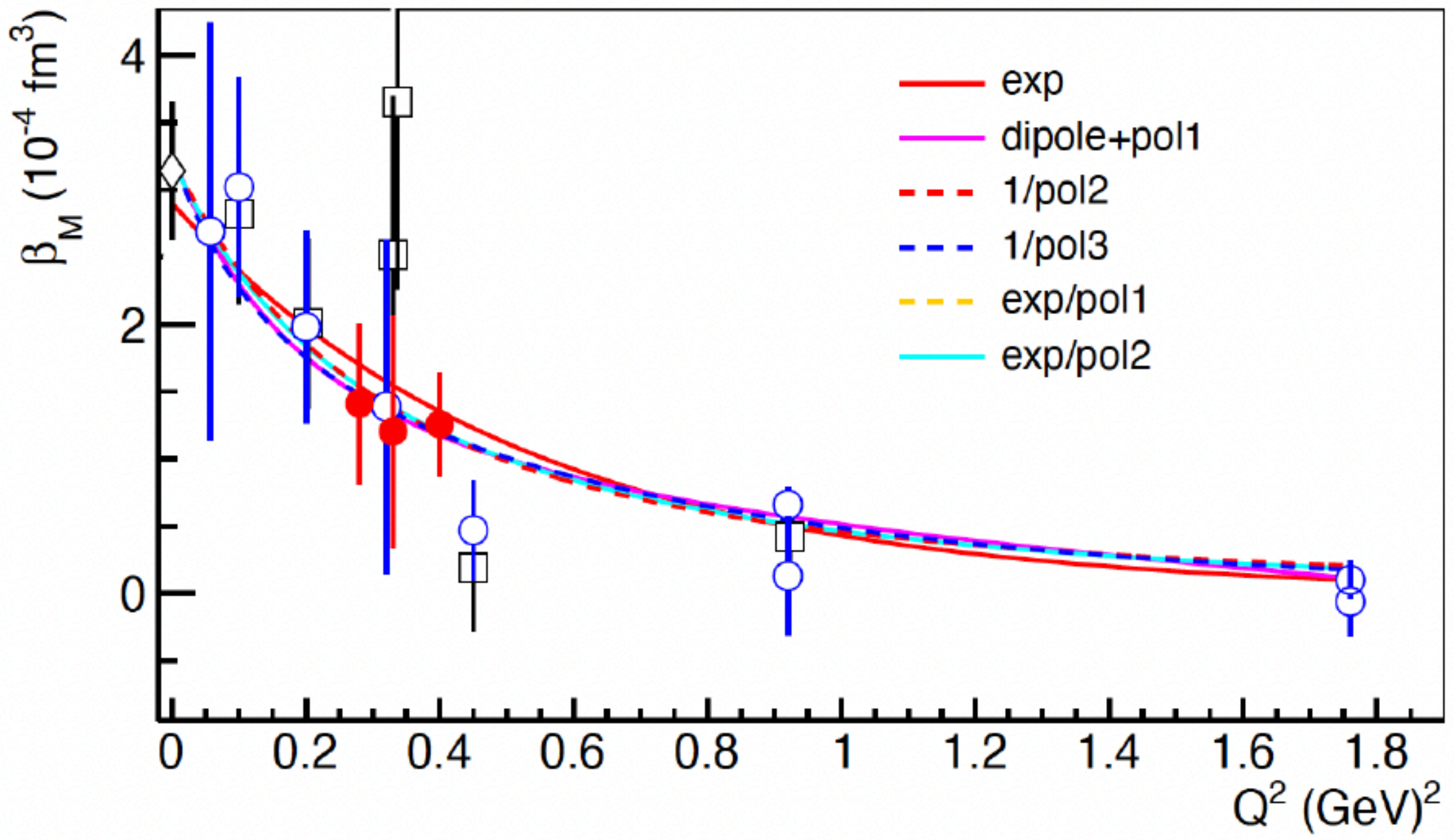
$$\langle r^2_{\beta_M} \rangle = 0.63 \pm 0.31 \text{ fm}^2$$

Extensions: Polarizability Radii

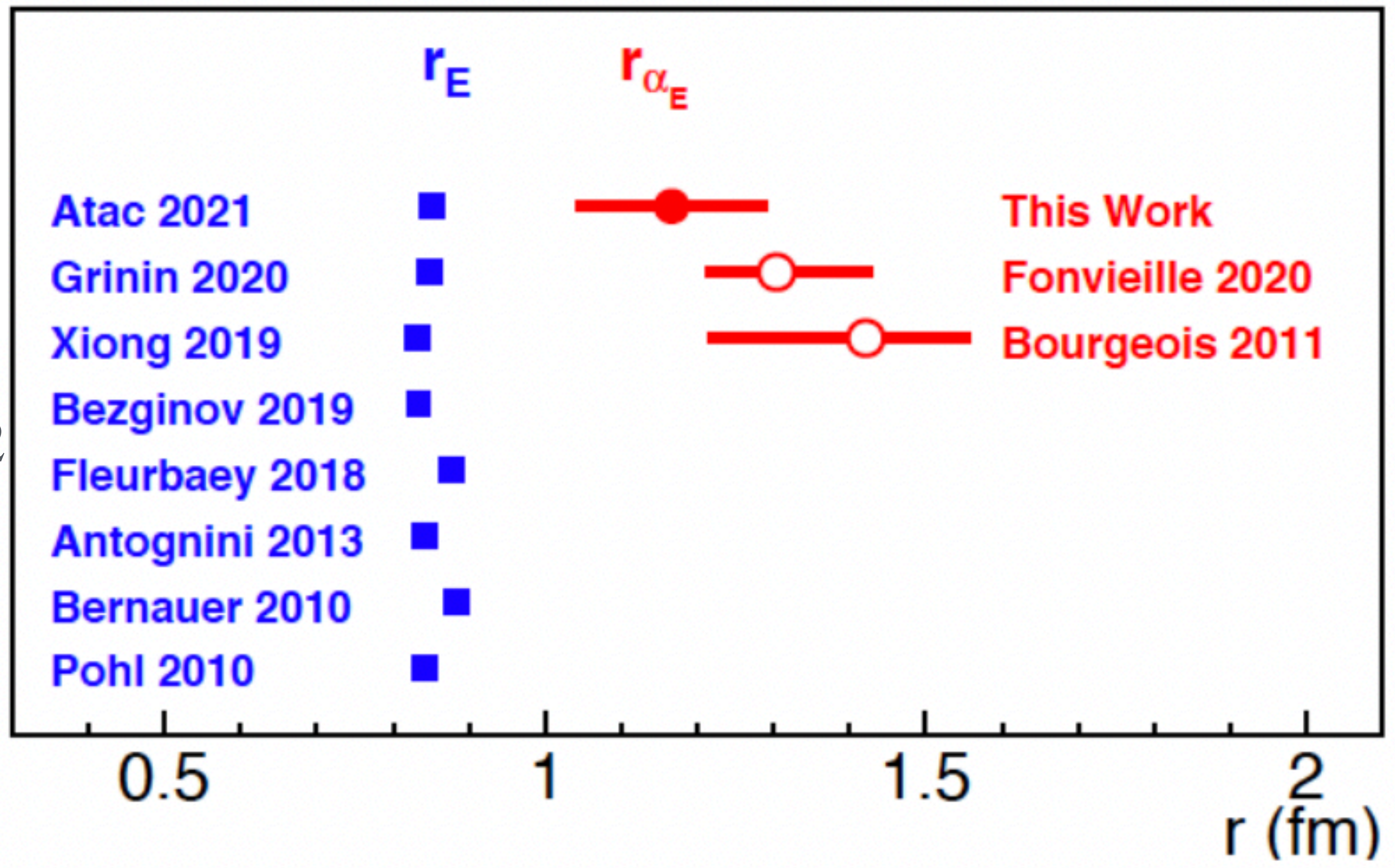
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

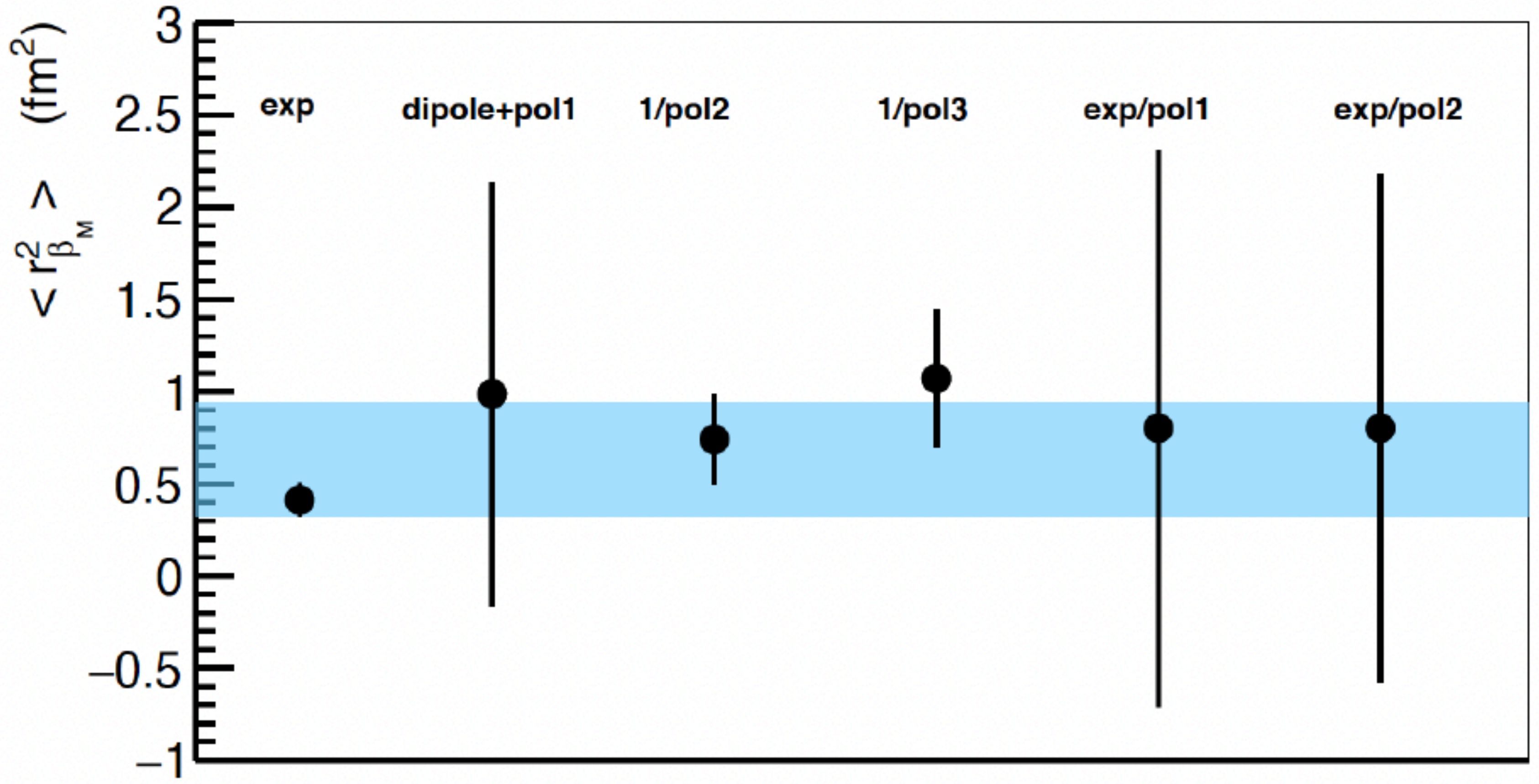
$$\langle r^2_{\beta_M} \rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2} \beta_M(Q^2) \Big|_{Q^2=0}$$





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

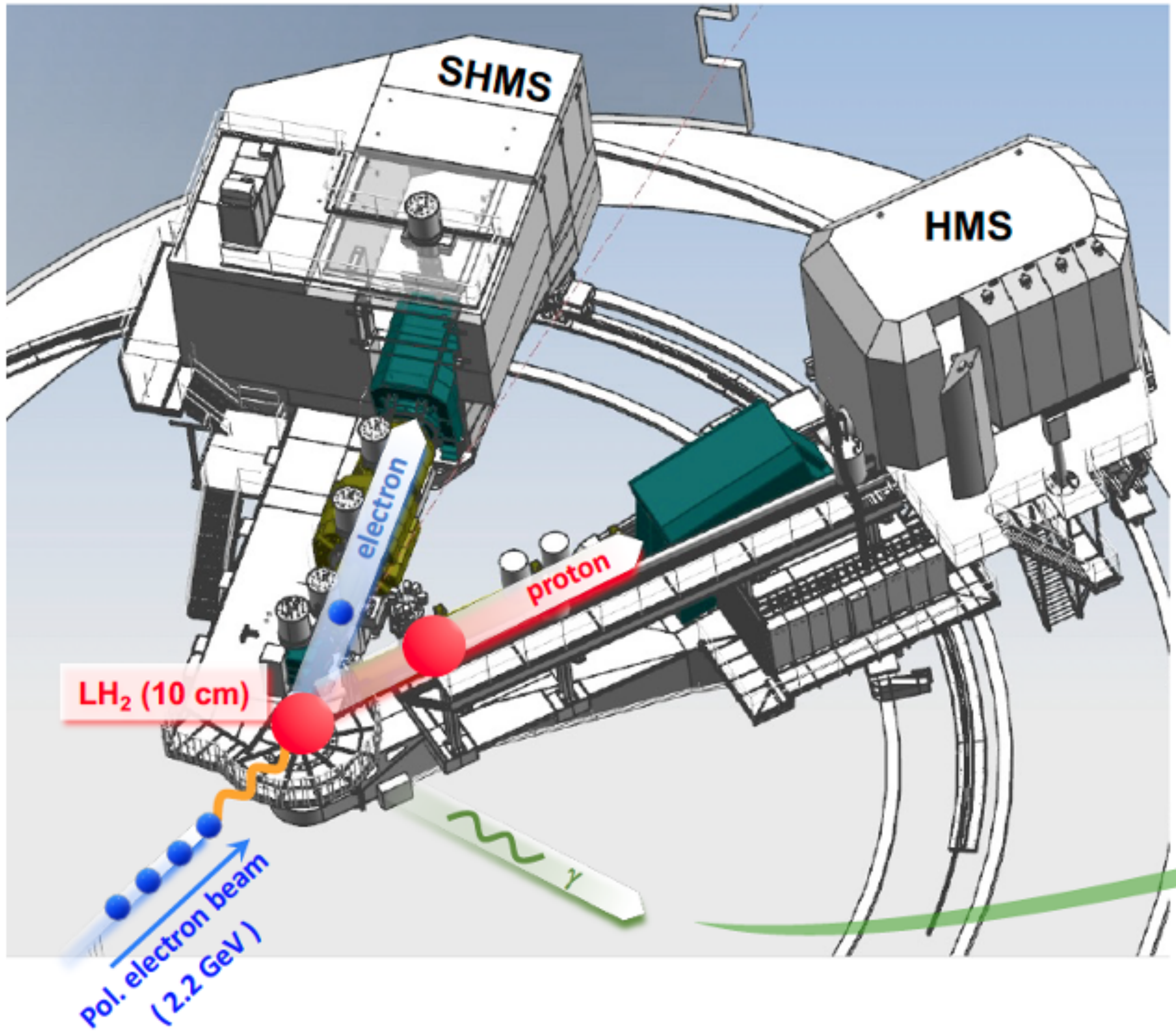


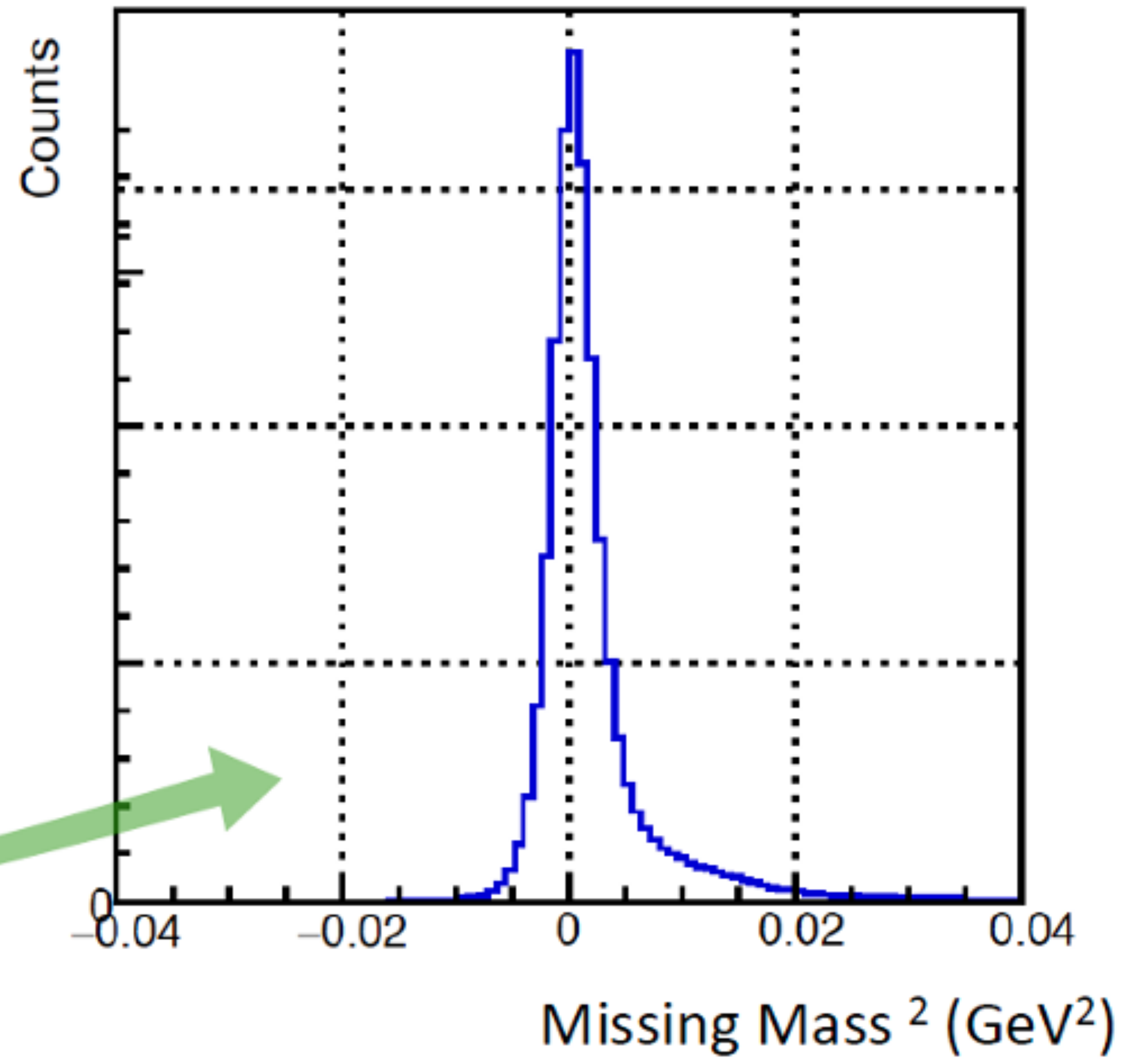


$\langle r^2_{\beta_M} \rangle = 0.63 \pm 0.31$ fm^2

Experimental Setup

Effectively, the experiment uses the same experimental setup as in the VCS-II with the addition of a polarized electron beam





$$A_{LU}^{e} = \frac{d\sigma_{+}^{e} - d\sigma_{-}^{e}}{d\sigma_{+}^{e} + d\sigma_{-}^{e}}$$

Hall C: SHMS, HMS (in standard configuration)

E=2.2 GeV I=70μA 85% polarization

LH2 10 cm

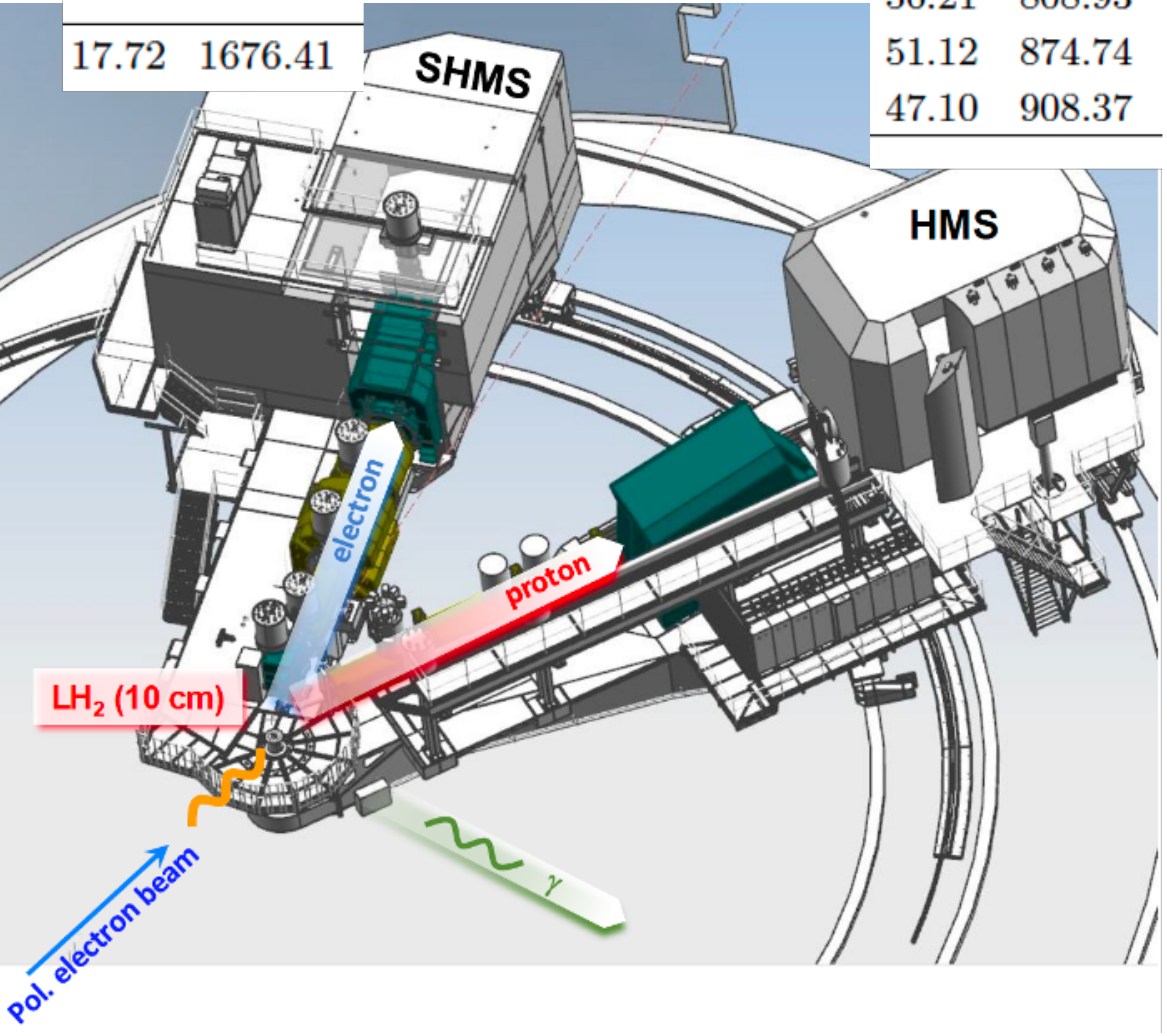
Kinematic settings:

θ_e°	P_e' (MeV/c)
17.72	1676.41

SHMS singles: 250 kHz

HMS singles: 50-80 kHz

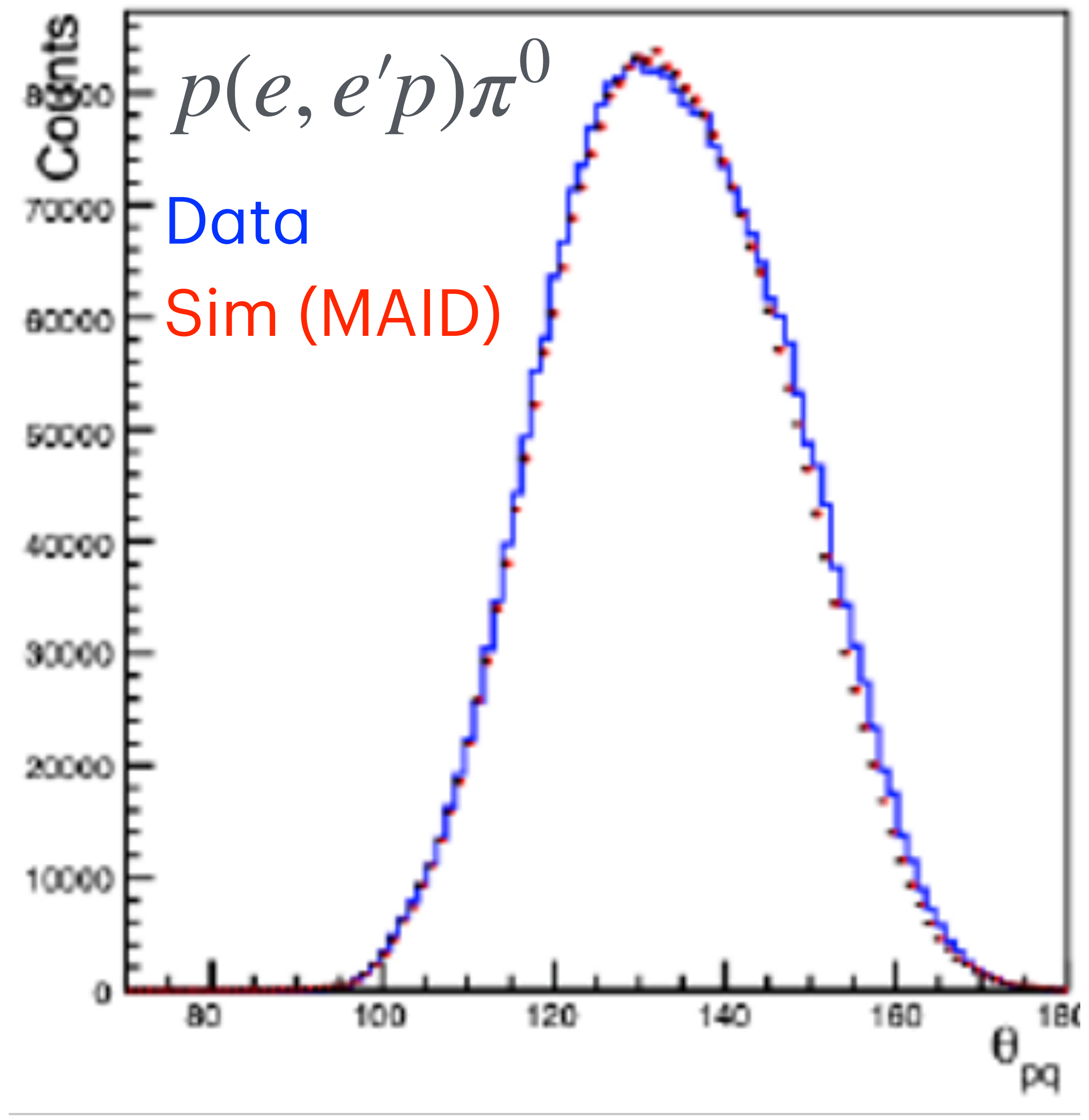
θ_p°	P_p' (MeV/c)
60.71	723.69
56.21	808.93
51.12	874.74
47.10	908.37

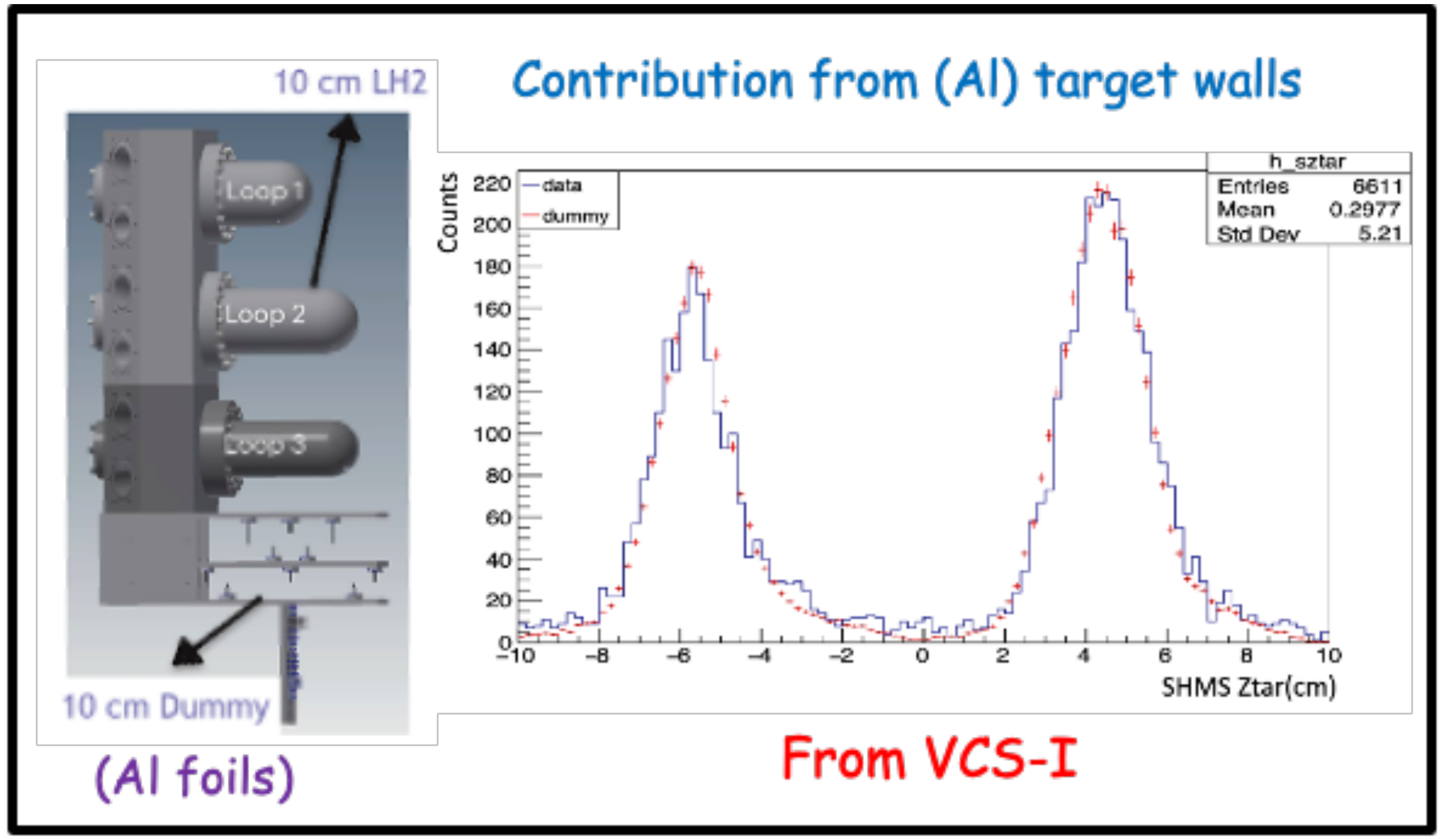


Experience running, extracting, and publishing with similar setups in Hall-C

Settings are within normal operating conditions

Singles rates are low

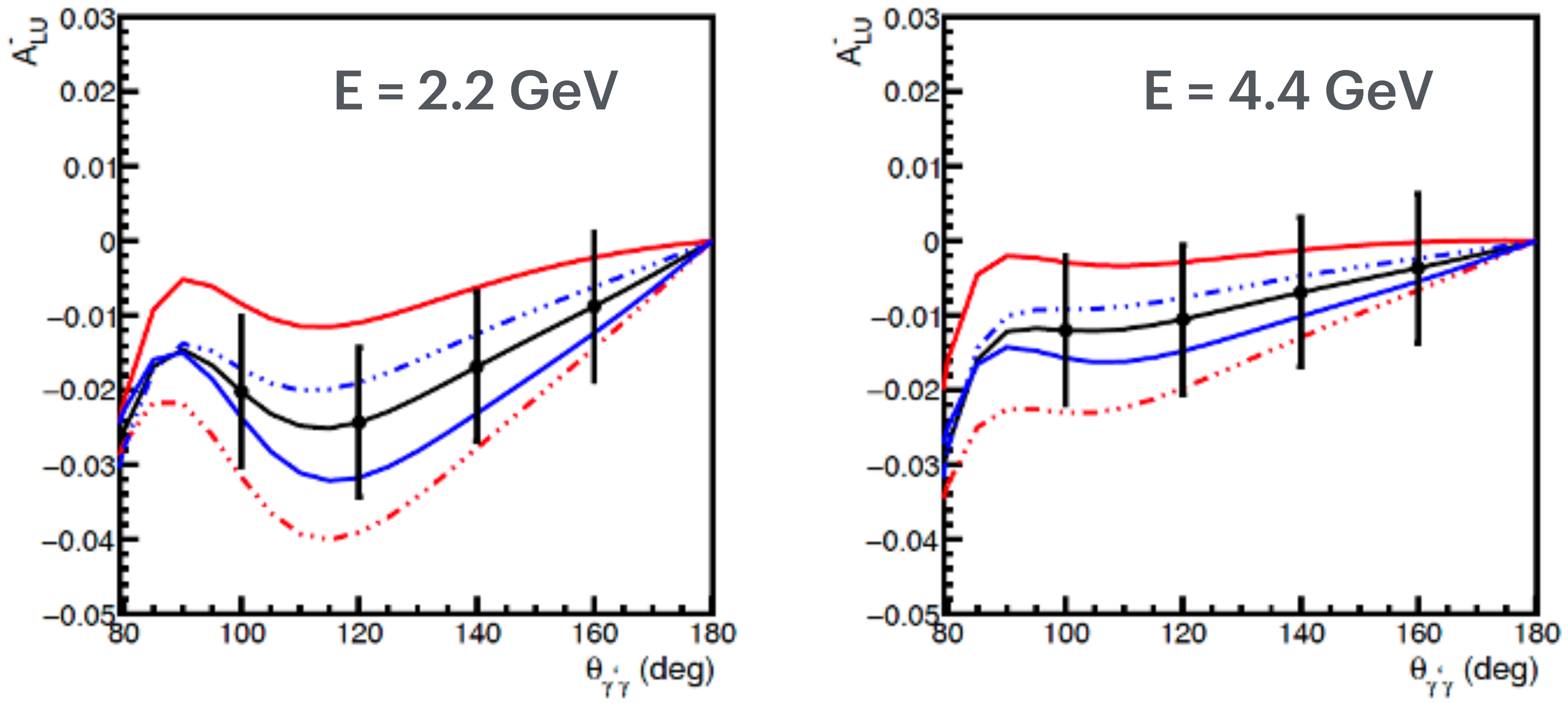




Studies to optimize the experiment kinematics

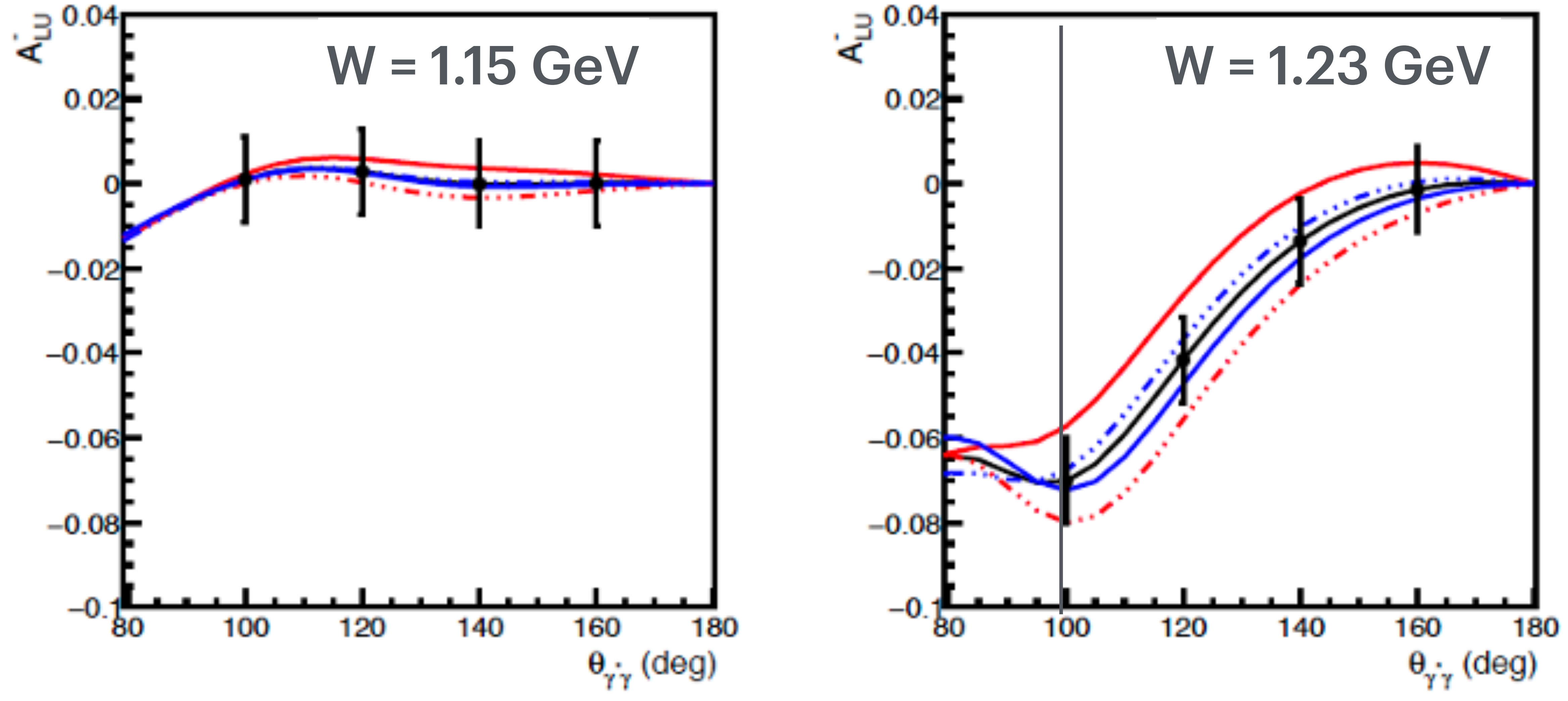
This proposal focuses on extracting one Q2 point with high precision → $Q^2 = 0.35\,\mathrm{GeV}^2$

BSA Beam Energy Study



Better sensitivity at 2.2 GeV

BSA center-of-mass Study

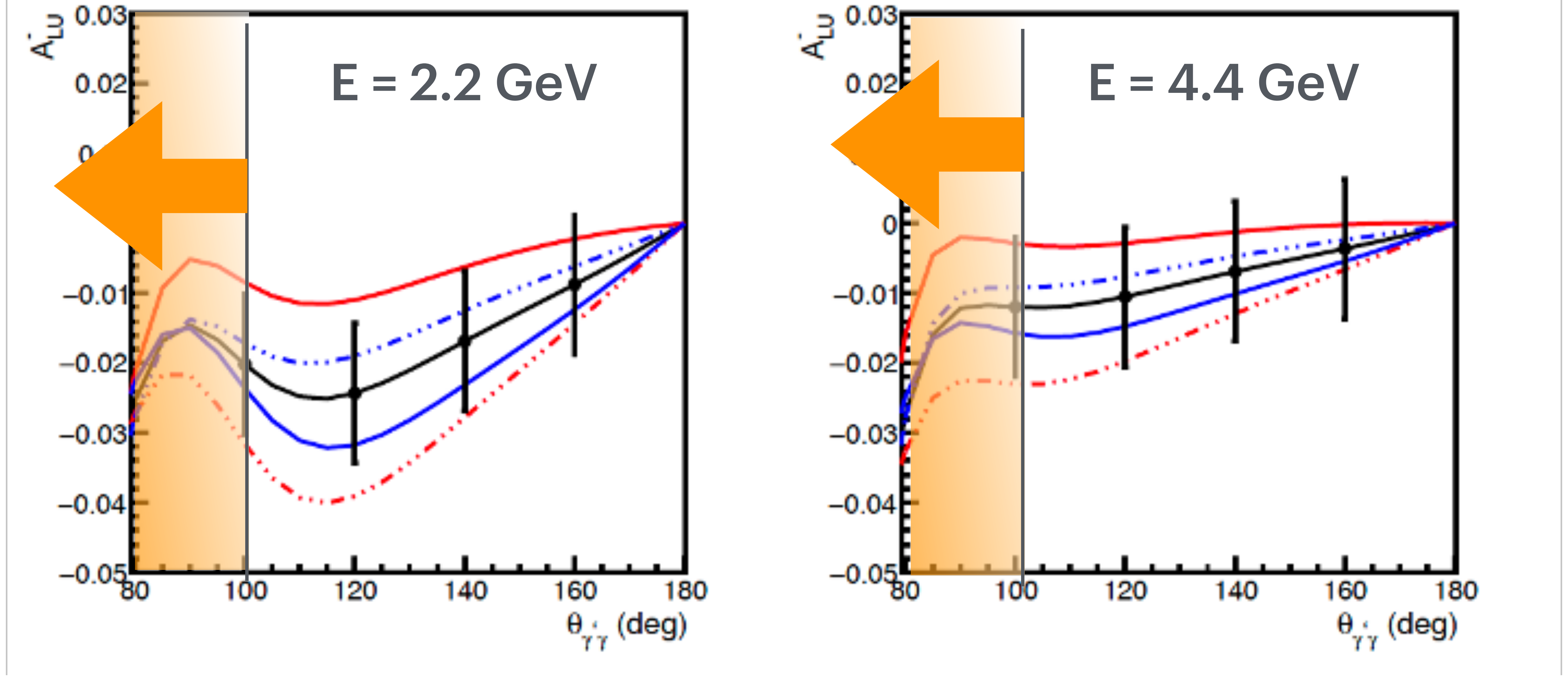


Sensitivity grows near pole-mass of Δ(1230) resonance

Studies to optimize the experiment kinematics

This proposal focuses on extracting one Q2 point with high precision → $Q^2 = 0.35\,\mathrm{GeV}^2$

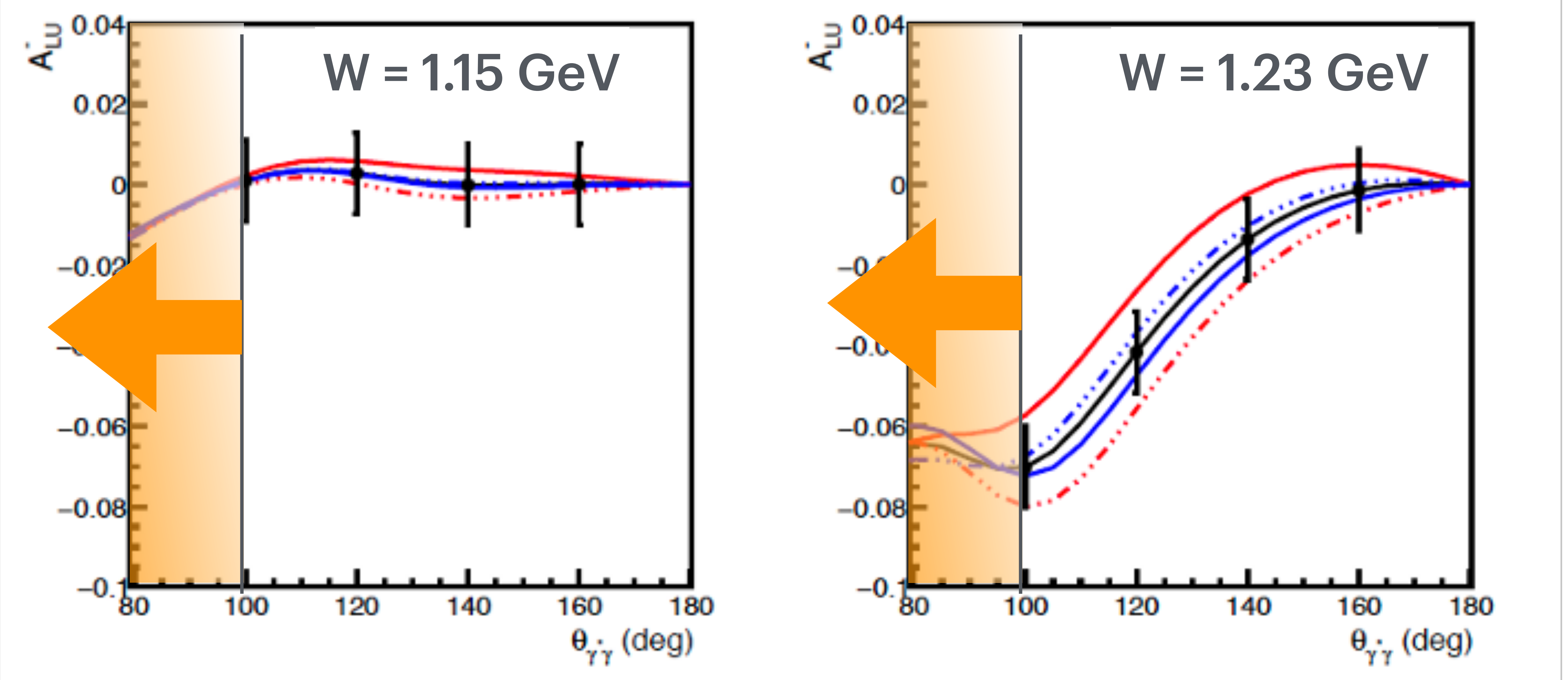
BSA Beam Energy Study



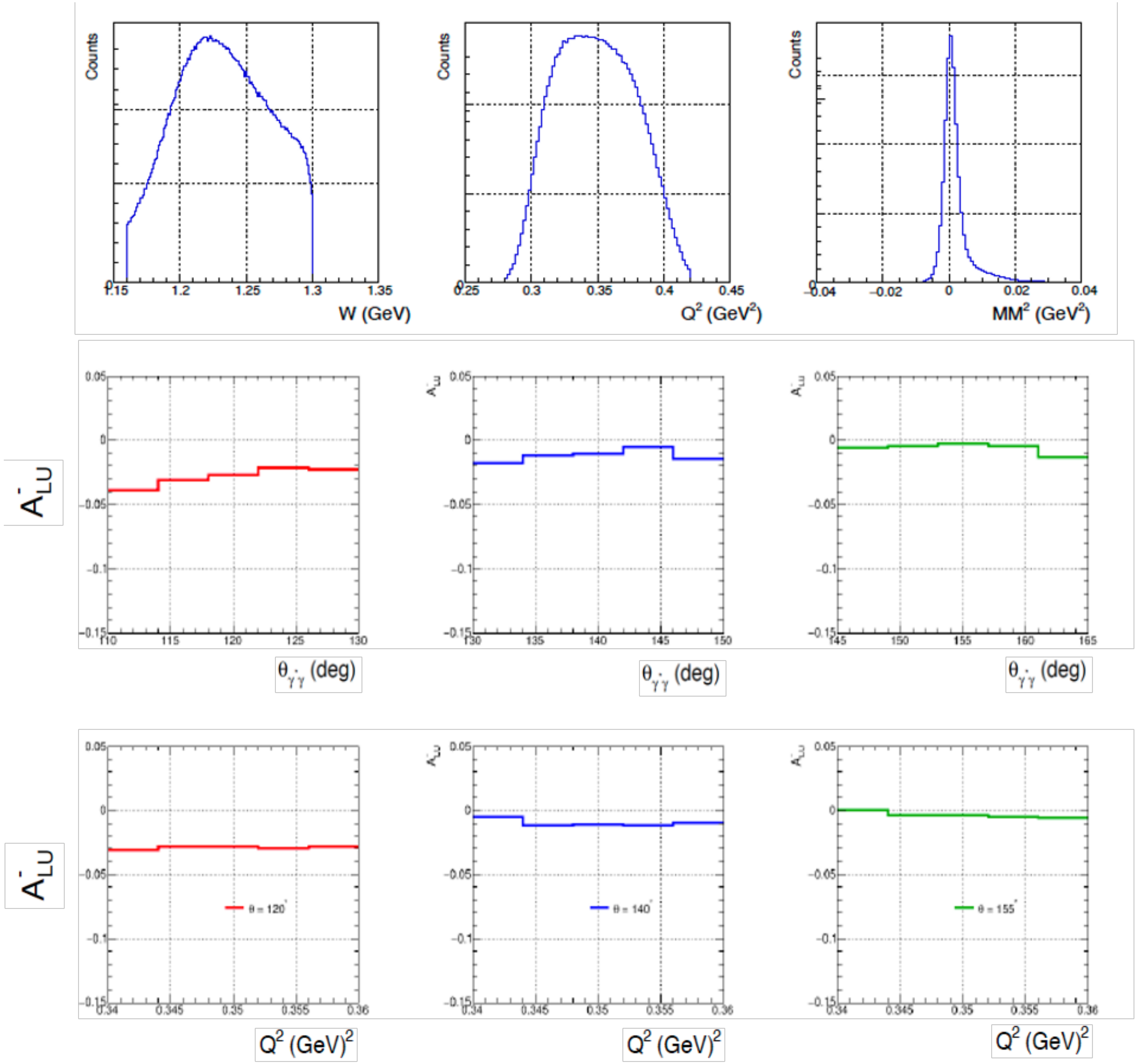
Better sensitivity at 2.2 GeV

Decreased sensitivity: $\theta_{\gamma^*\gamma} < 100$ deg

BSA center-of-mass Study



Sensitivity grows near pole-mass of Δ(1230) resonance



Simulation Studies

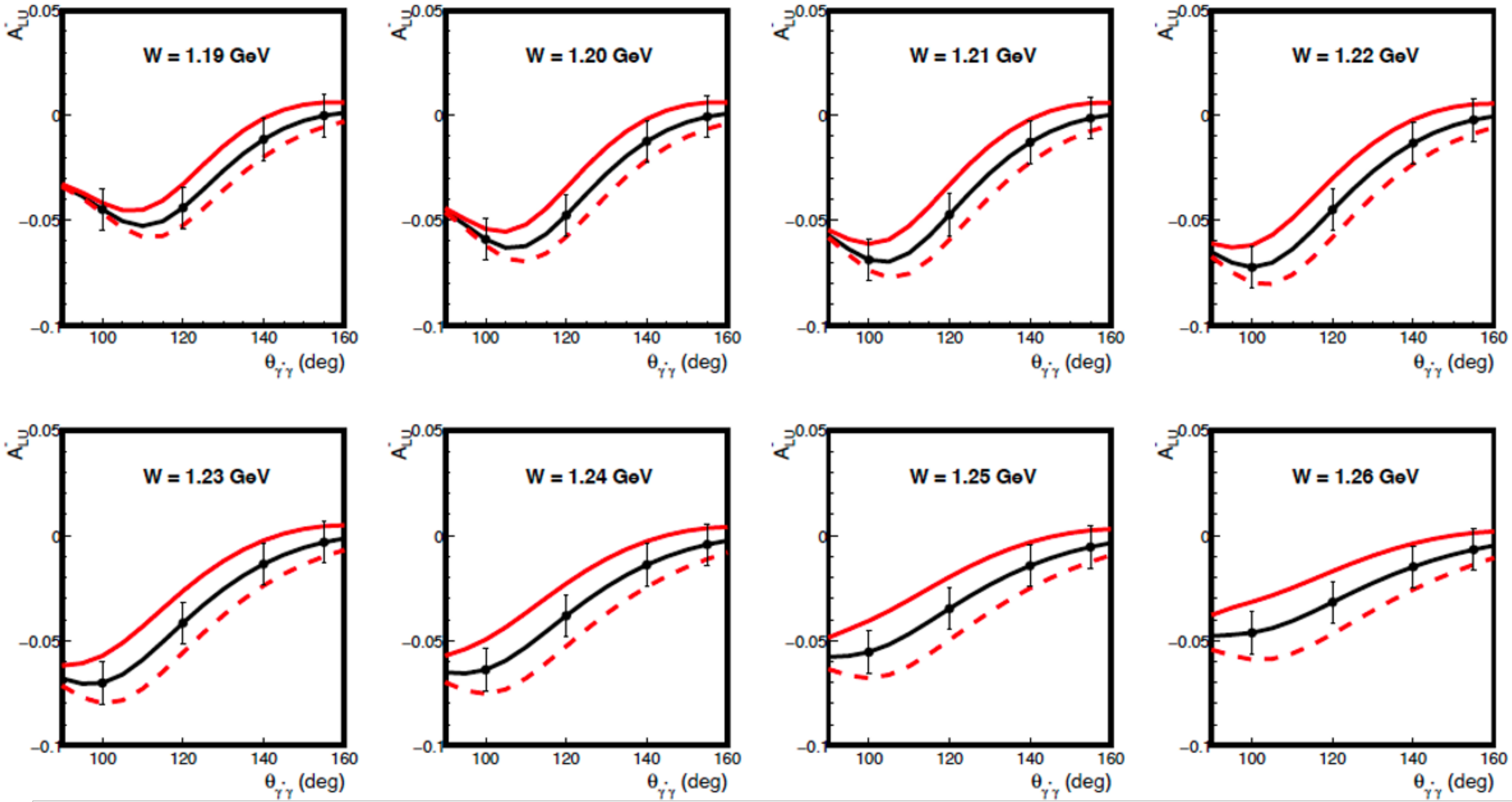
Simulation weighted with the DR model for VCS (Pasquini et al)

Systematics:

Acceptance / bin migration	5%
Bin centering	6% - 8%
Radiative effects	2% - 3%
Beam polarization	3%
Background subtraction	1%
Target wall	1%
Pion contamination	1%

System. uncertainties ~ 50% compared to the statistical

Projected BSA measurements



Projected beam spin asymmetry measurements. The sensitivity to the electric GP is shown for Λ_α from 0.5 to 0.9.

GPs extracted through a DR fit to the BSA measurements.

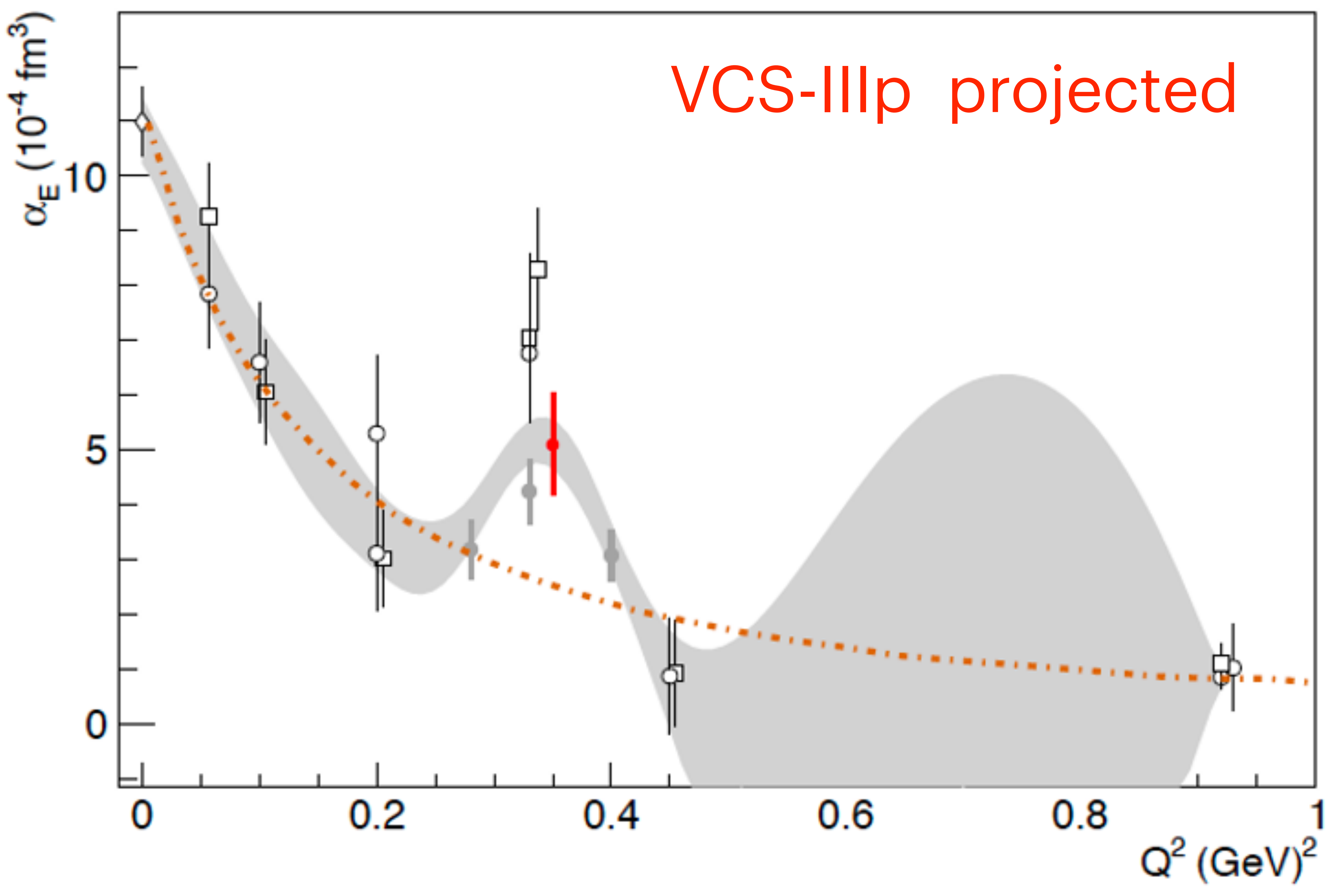
Λ_α & Λ_β fitted by an $\chi 2$ minimization which compares the DR asymmetries to the measured ones and the GPs are determined

Experiment Kinematics & Projected Measurement

Beam Energy (GeV)	Beam Current (uA)	Beam Requirements	Target	θ_e°	P_e' (MeV/c)	θ_p°	P_p' (MeV/c)	Beamtime (days)
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	60.71	723.69	2
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	56.21	808.93	6
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	51.12	874.74	6
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	47.10	908.37	6
Total Time								20

+ 0.5 (dummy & check outs)

Total beam time : 20.5 days



Experiment Kinematics & Projected Measurement

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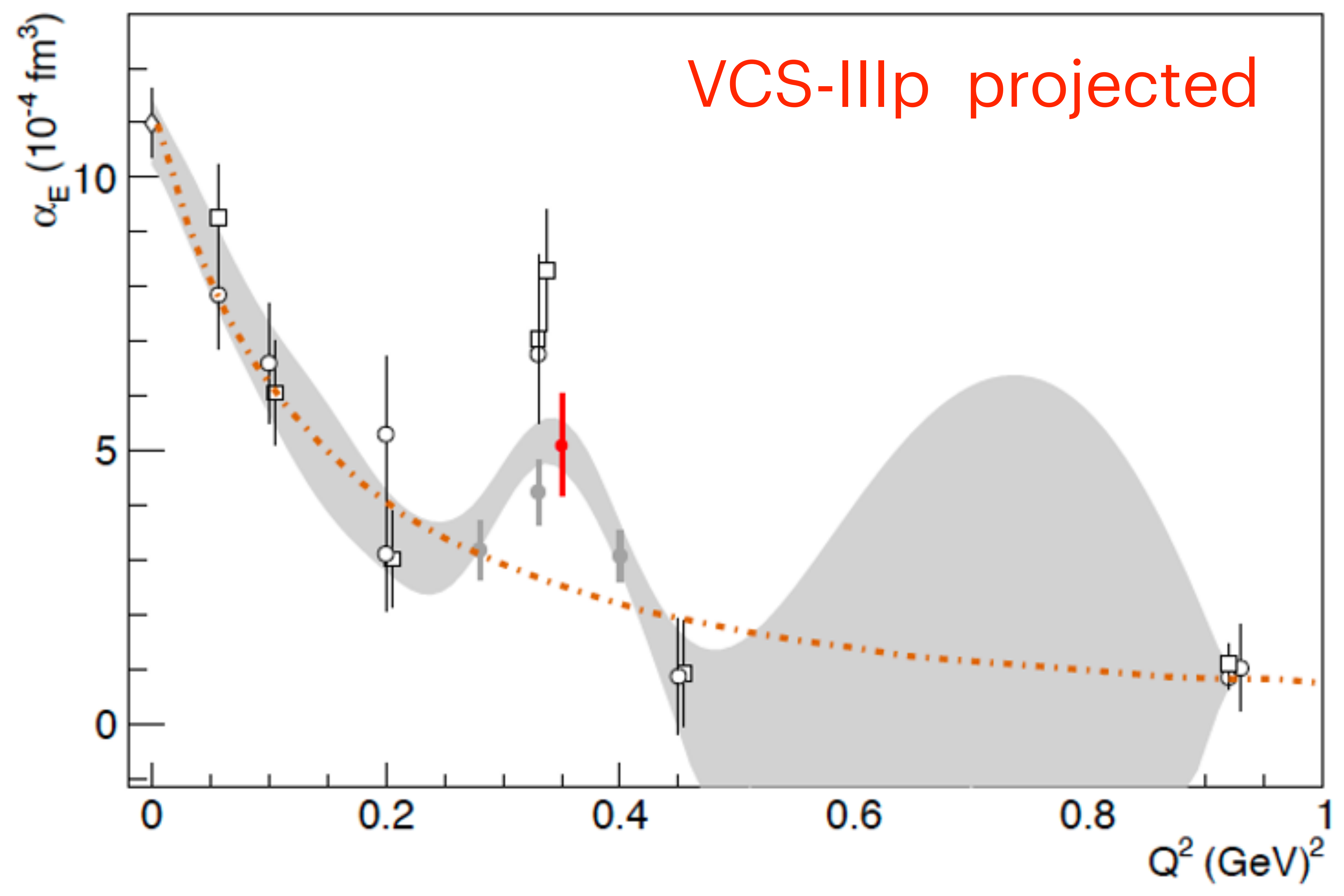
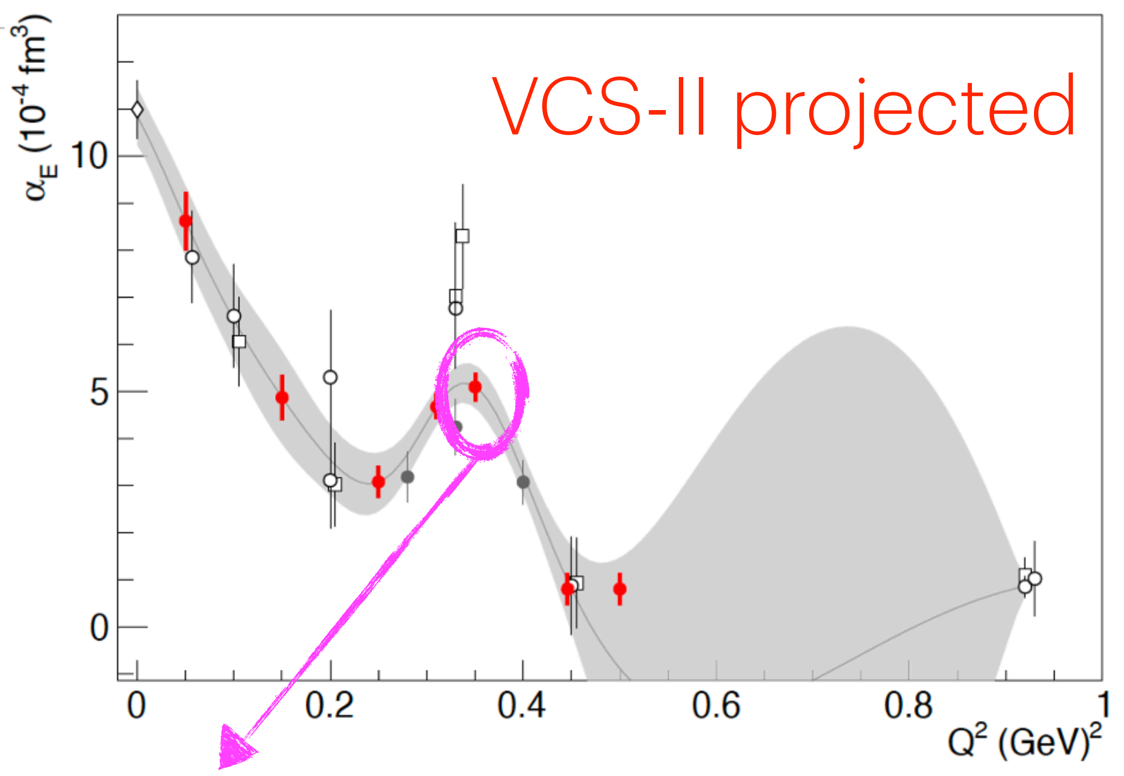
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	47.10	908.37	6
Total Time								20

+ 0.5 (dummy & check outs)

(With-out VCS-II)

Total beam time : 20.5 days





If combined with E12-23-001 (VCS-II)

4 days can be commonly shared

Total beam time (with VCS-II) : 16.5 days

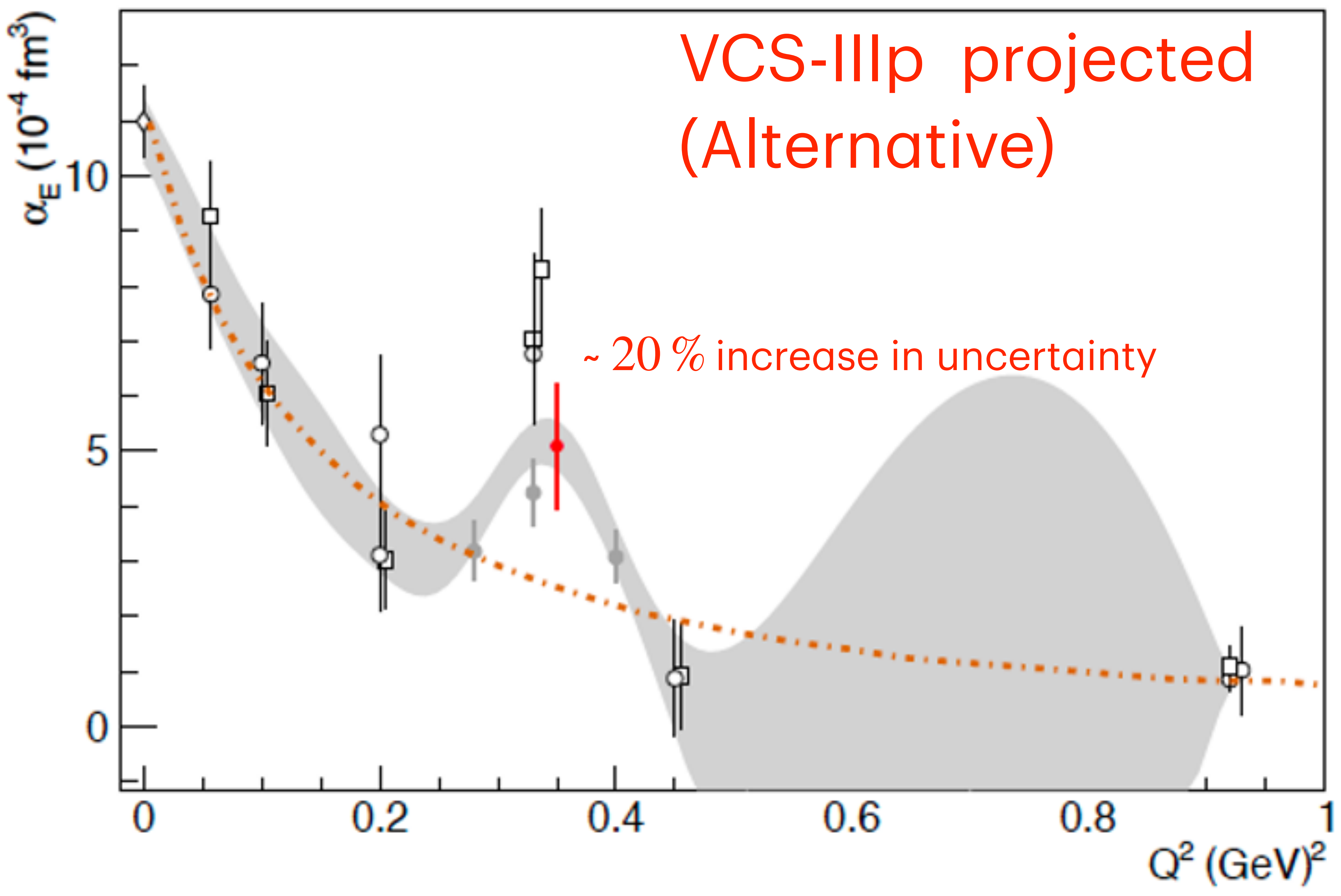
Experiment Kinematics & Projected Measurement

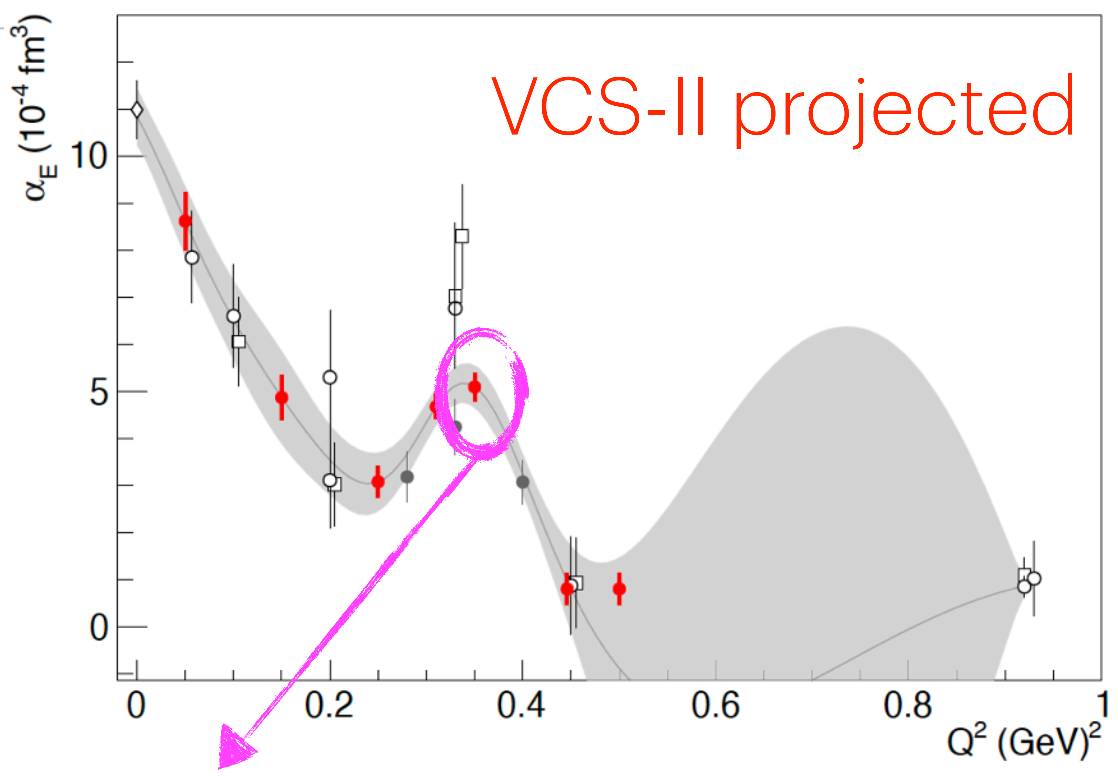
Beam Energy (GeV)	Beam Current (uA)	Beam Requirements	Target	θ_e°	P'_e (MeV/c)	θ_p°	P'_p (MeV/c)	Beamtime (days)
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	60.71	723.69	(1.5)
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	56.21	808.93	(3.5)
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	51.12	874.74	(3.5)
2.2	70	Polarized	LH2 (10cm)	17.72	1676.41	47.10	908.37	(4)
Total Time								(12.5)

+ 0.5 (dummy & check outs)

(With-out VCS-II)

Total beam time : ~~20.5~~ 13 days



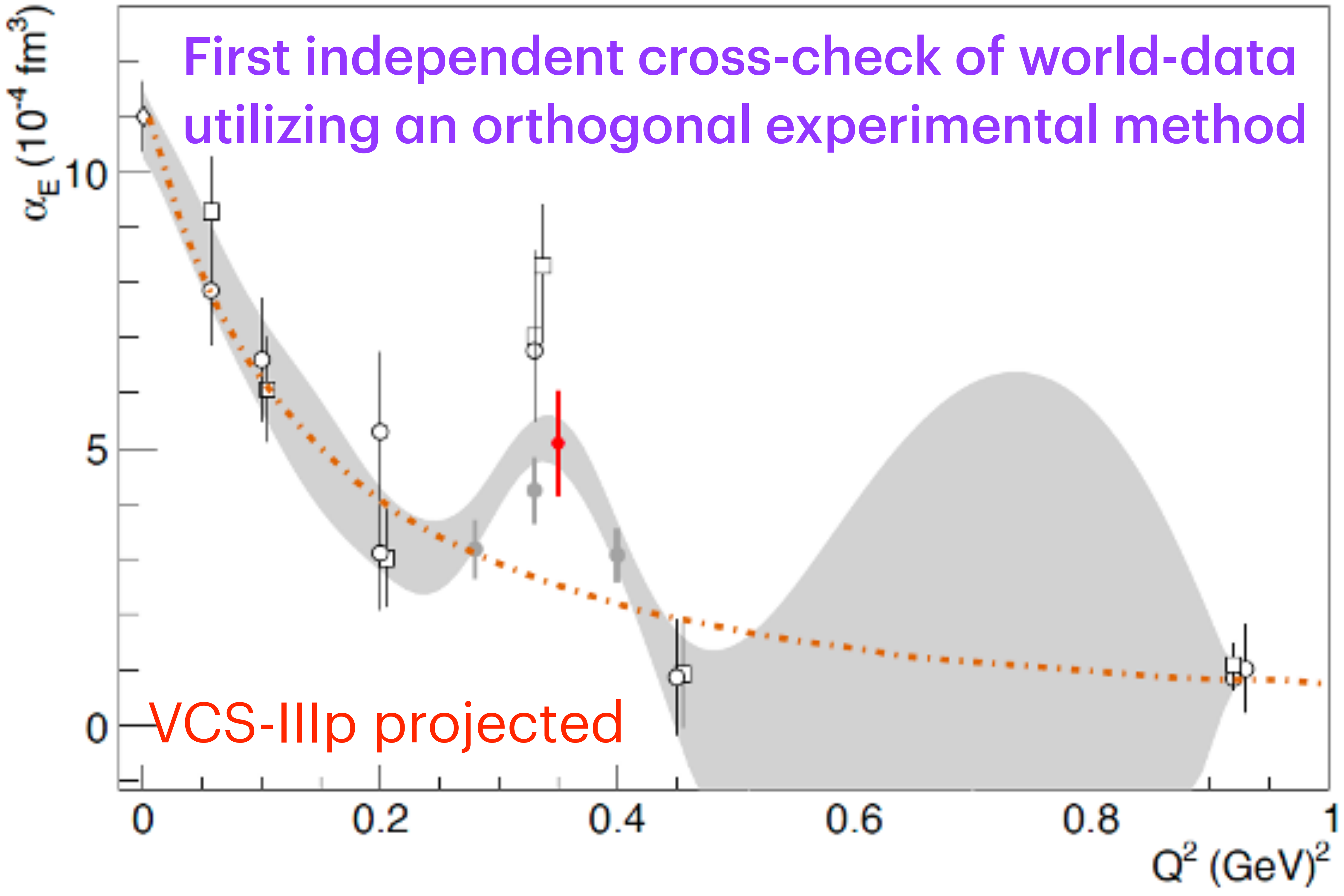


If combined with E12-23-001 (VCS-II)

4 days can be commonly shared

Total beam time (Alt. w/ VCS-II) : 9 days

VCS-IIIp Primary Experiment Goals

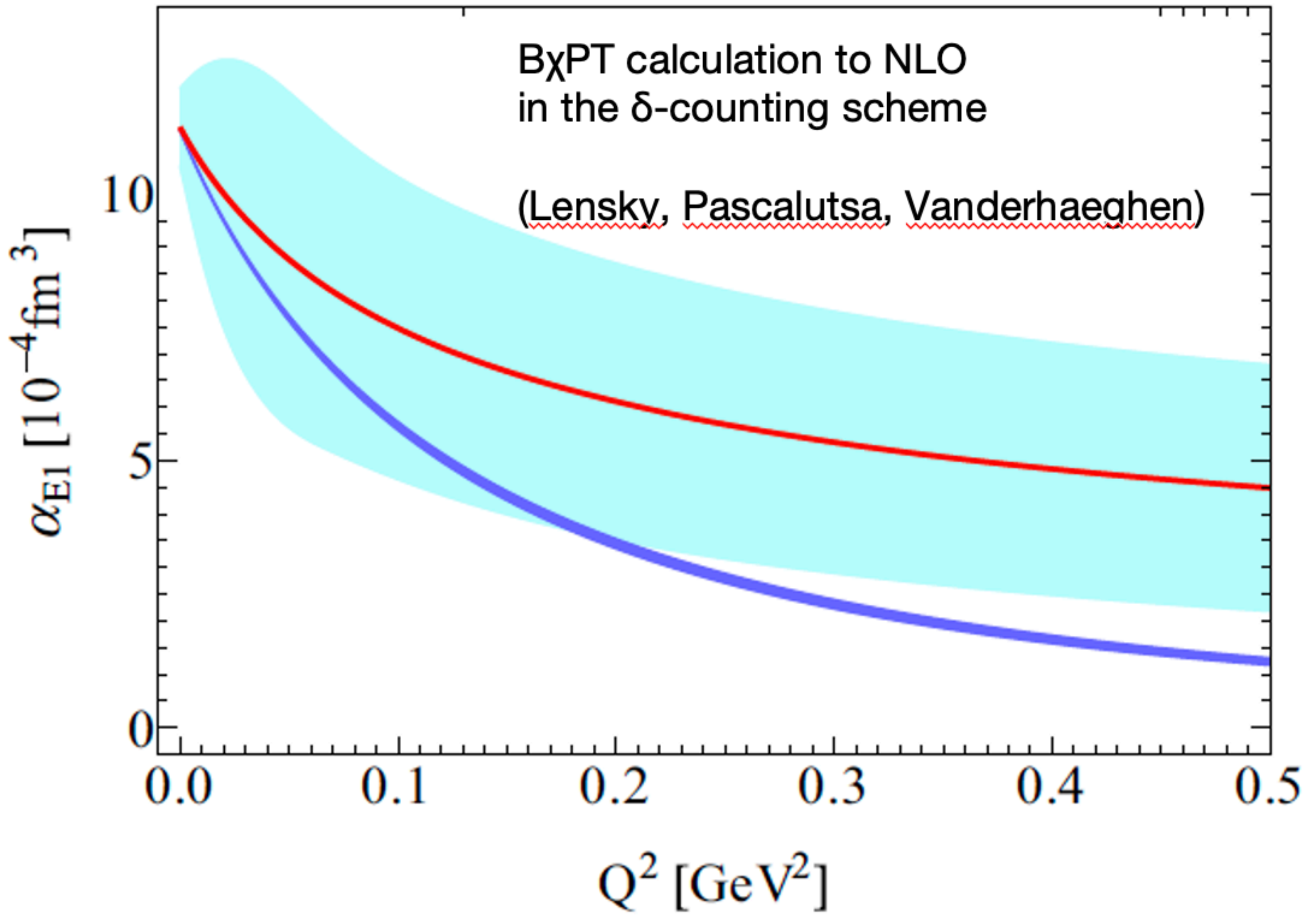


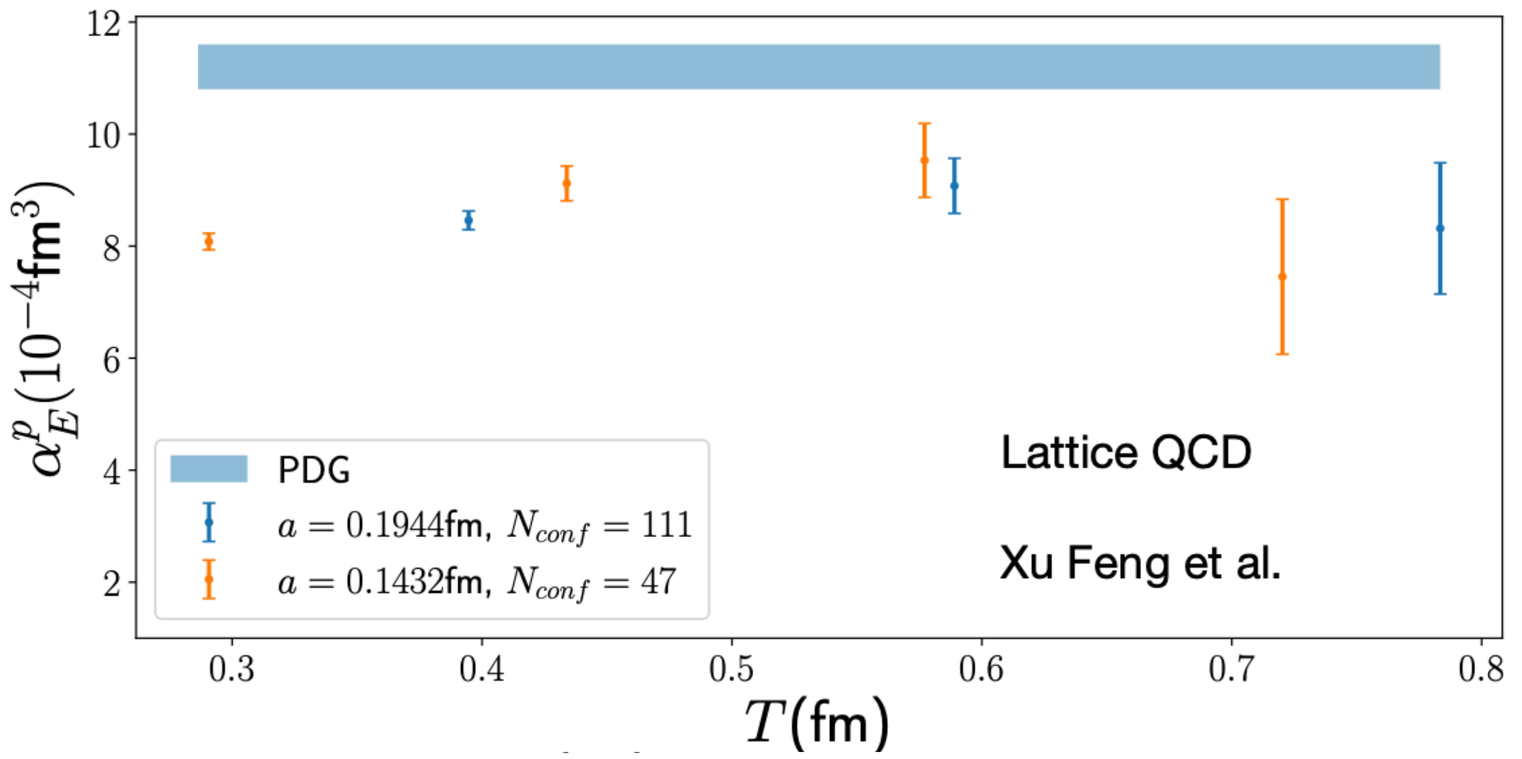
High precision benchmark data

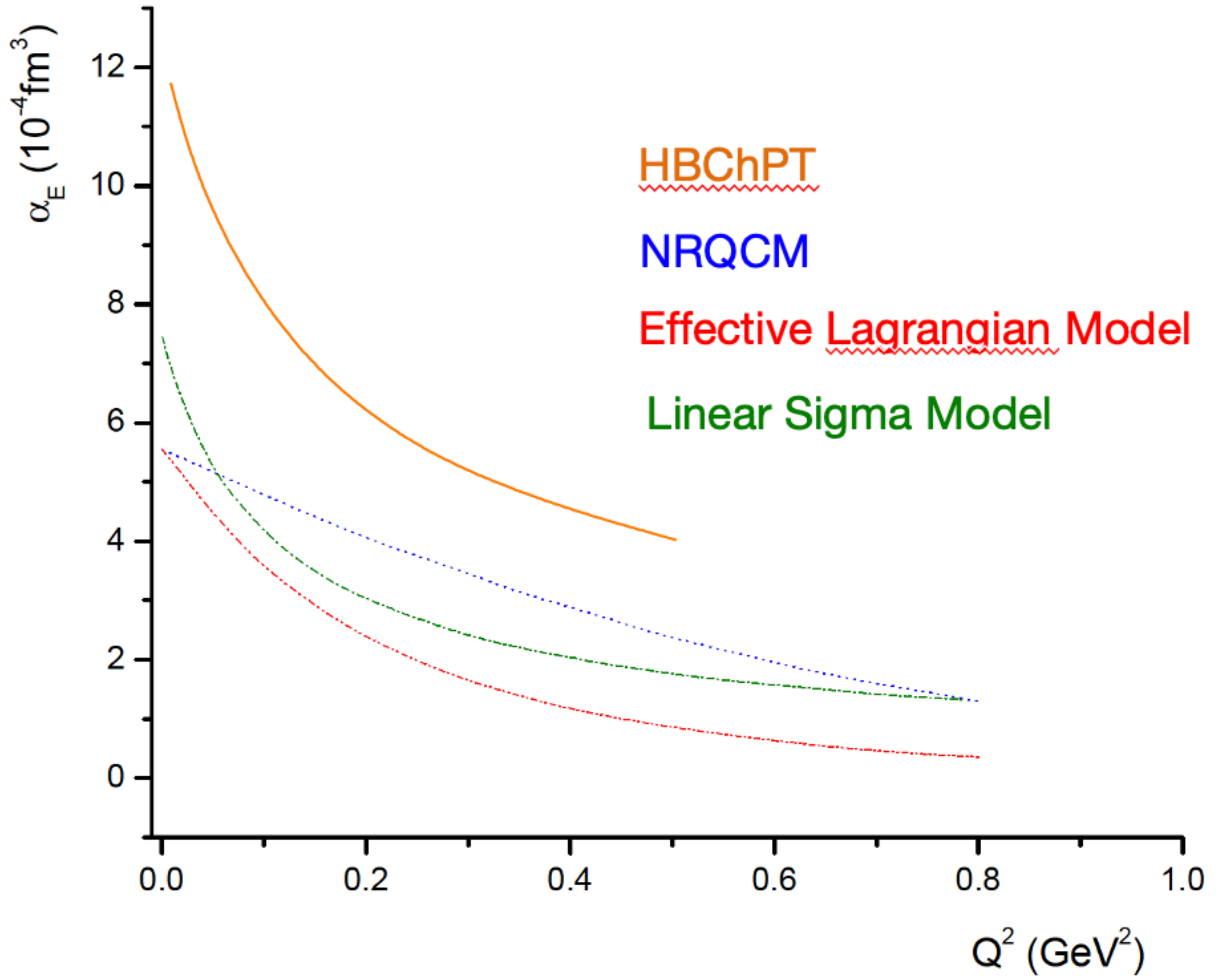
χPT

LQCD

theoretical models

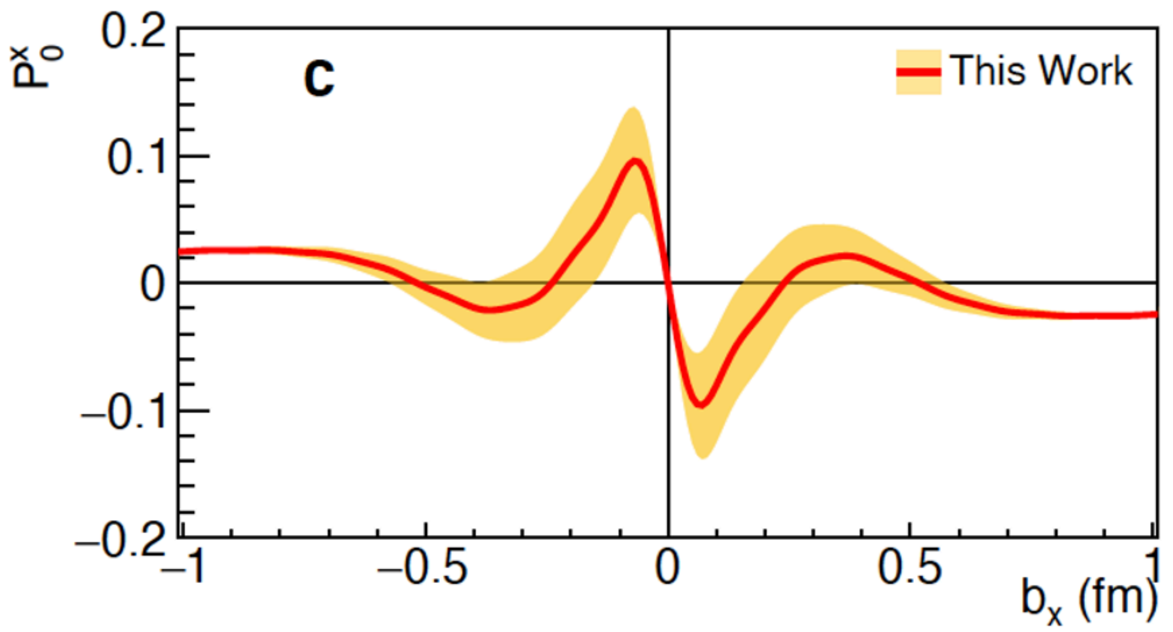


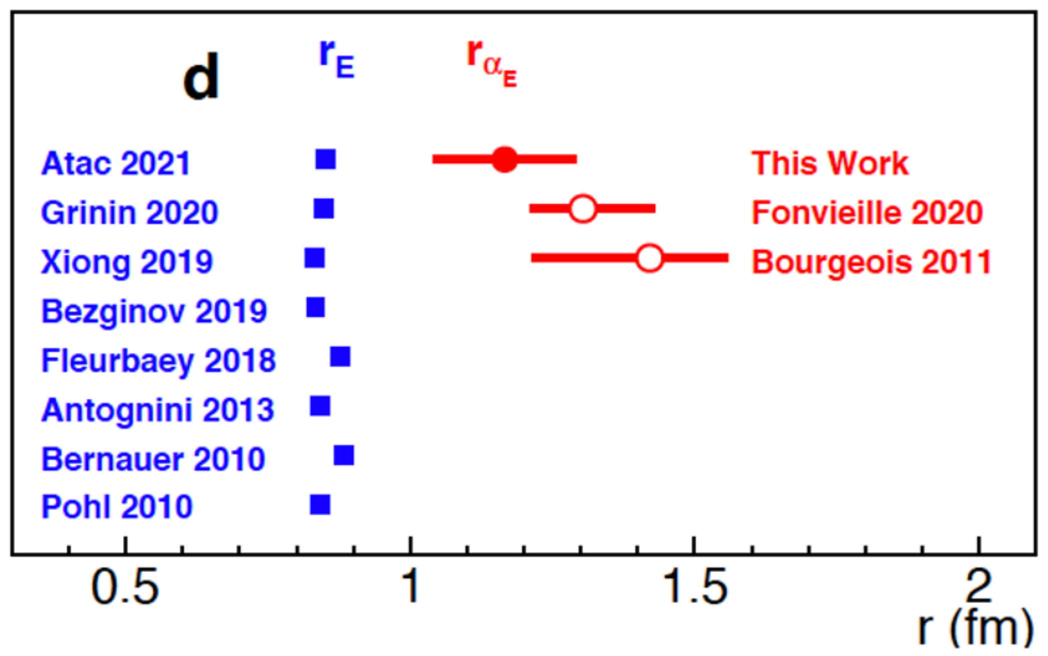




Tomography: Induced polarization in the proton

Polarizability radii $\langle r_{\alpha E}\rangle$, $\langle r_{\beta M}\rangle$





Summary

- **Focus on the study of fundamental proton properties**
  - Gain insight to the response of the proton constituents to an external EM field, to the interplay of the polarizability mechanisms & to the tomography of the polarizability effects in the proton
- **First measurement of the polarizabilities using a new experimental method**
  - Unique independent cross check to the world data
  - Employing alternative experimental methods is instrumental in the scientific process, frequently revealing surprises and new knowledge (e.g. proton EM form factors, proton charge radius)
  - Particularly valuable in addressing the theoretical challenges with the electric GP
- **The proposal complements an ongoing experimental program at Jlab with a unique & novel approach**
- **The experiment uses a standard experimental setup in Hall C that is already employed for the unpolarized VCS measurements and is well tested and understood**
  - E=2.2 GeV, I=70μA, 85% polarization, LH2 10 cm
  - θ_{SHMS} ~ 18 deg, p_{SHMS} ~ 1.7 GeV, θ_{HMS} ~ 47 to 60 deg, p_{HMS} ~ 0.7 to 0.9 GeV
- **The collaboration is well prepared & ready, considering the upcoming VCS-II experiment**
  - Matching the kinematics of the two experiments reduces the beam-time request by 4 days