Measurement of the Generalized Polarizabilities of the Proton in Virtual Compton Scattering (VCS-II)

A Proposal to Jefferson Lab PAC-51

On behalf of the VCS-II collaboration and its spokespeople:
N. Sparveris*, H. Atac, A. Camsonne, M.K. Jones and M. Paolone

Michael Paolone, New Mexico State University, July 26th 2023

*contact person

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M. Demirci
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D. Androic
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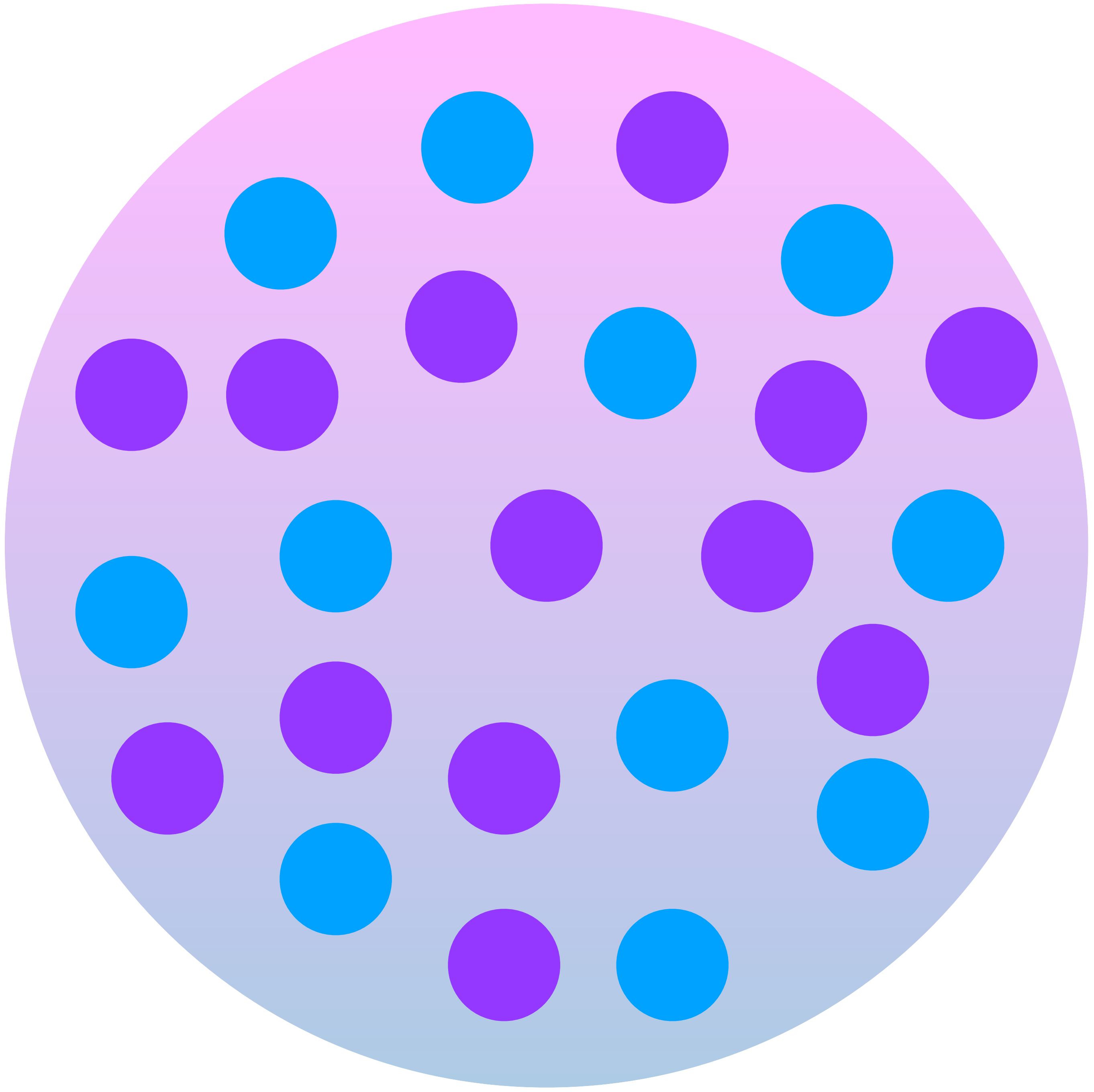
Motivation: Explore the fundamental properties of the nucleon

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.

The proton is the only known stable composite particle!



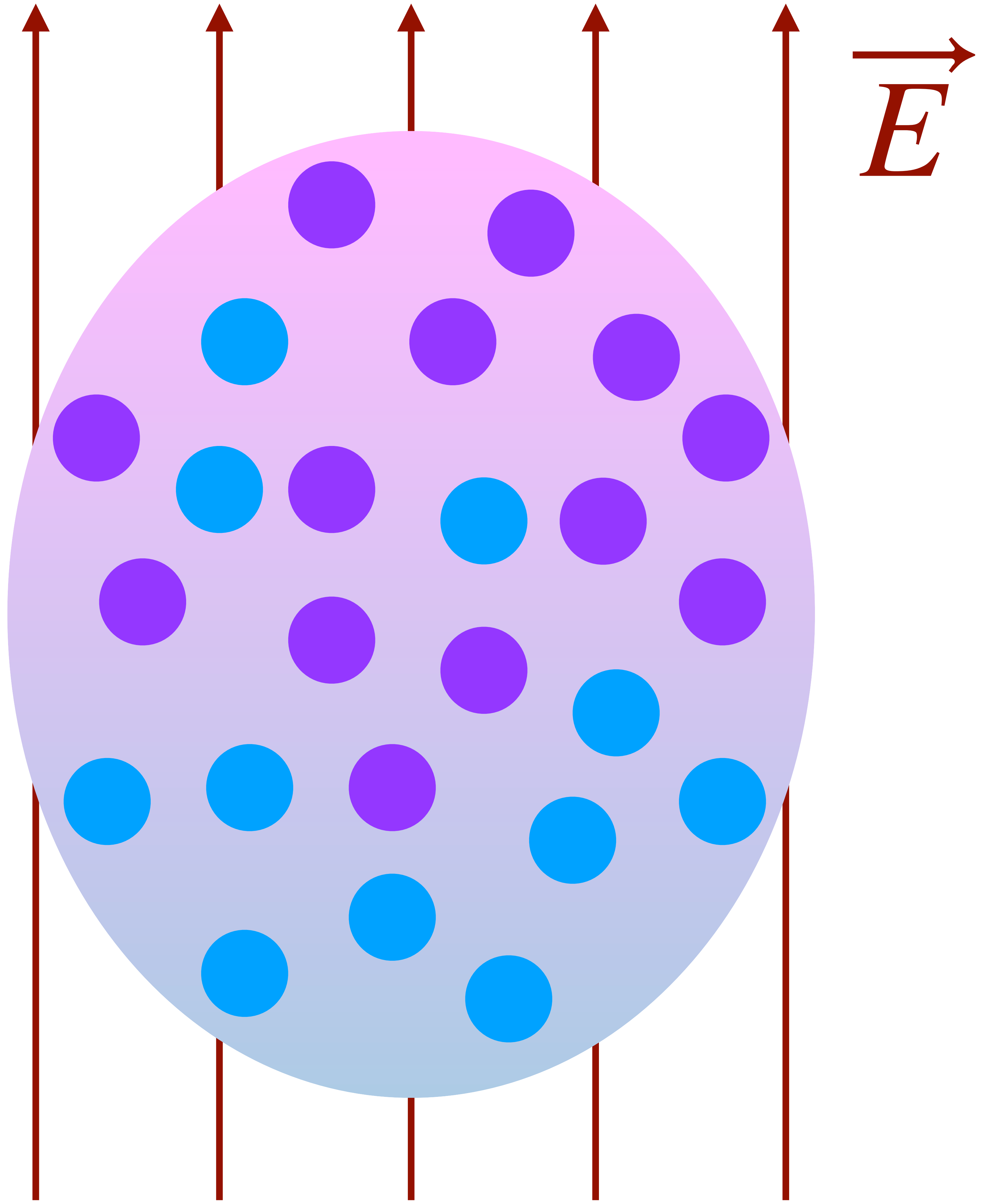
- **Polarizability** is in an important characteristic of the proton:
  - How rigid is the proton in the presence of an EM field?
    - A fundamental property of the proton!
  - Sensitive to the excitation of the proton.
  - Can be accessed by Compton scattering (the photon acting as an induced EM field)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

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.

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

Electric Polarizability



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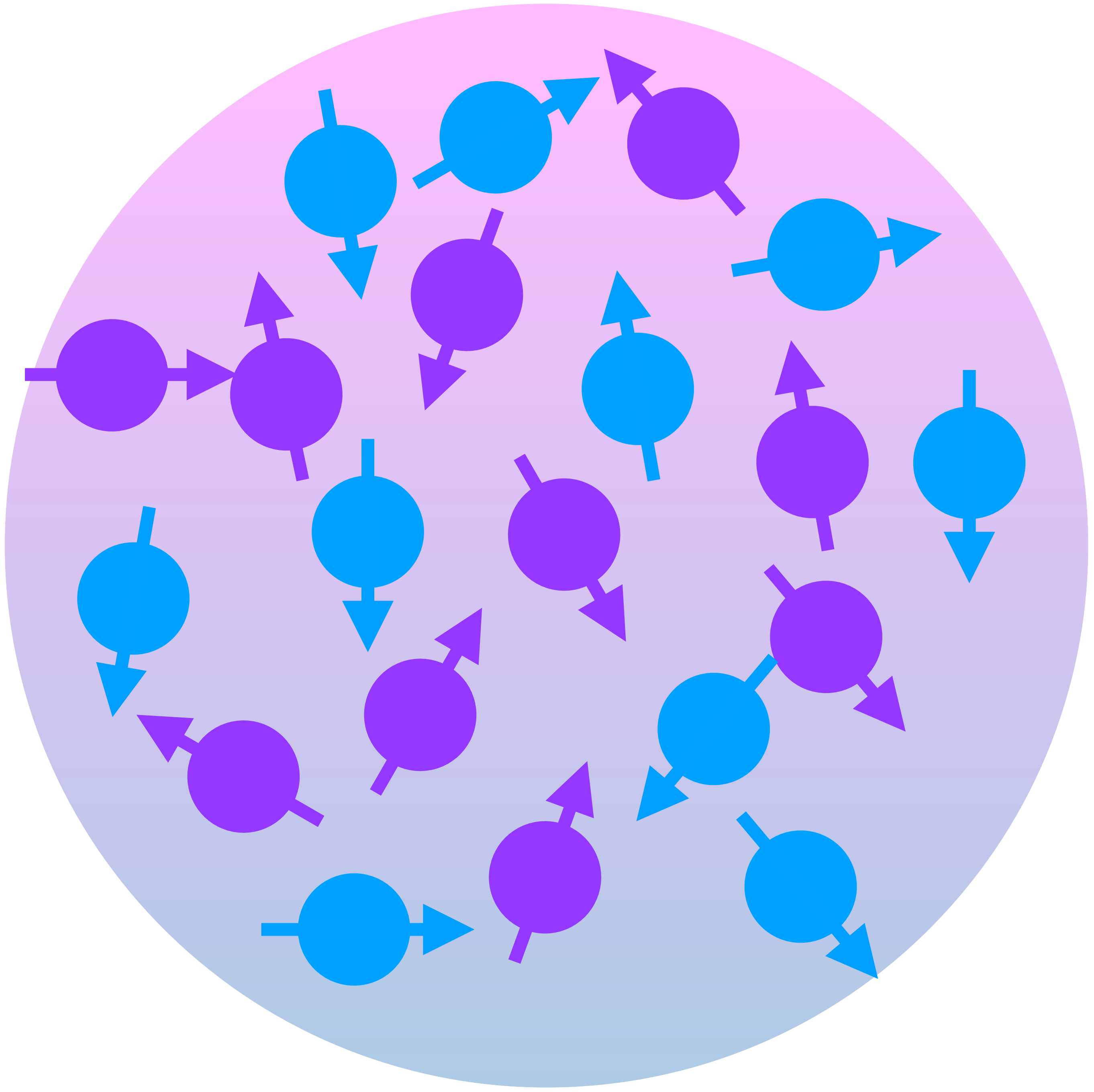
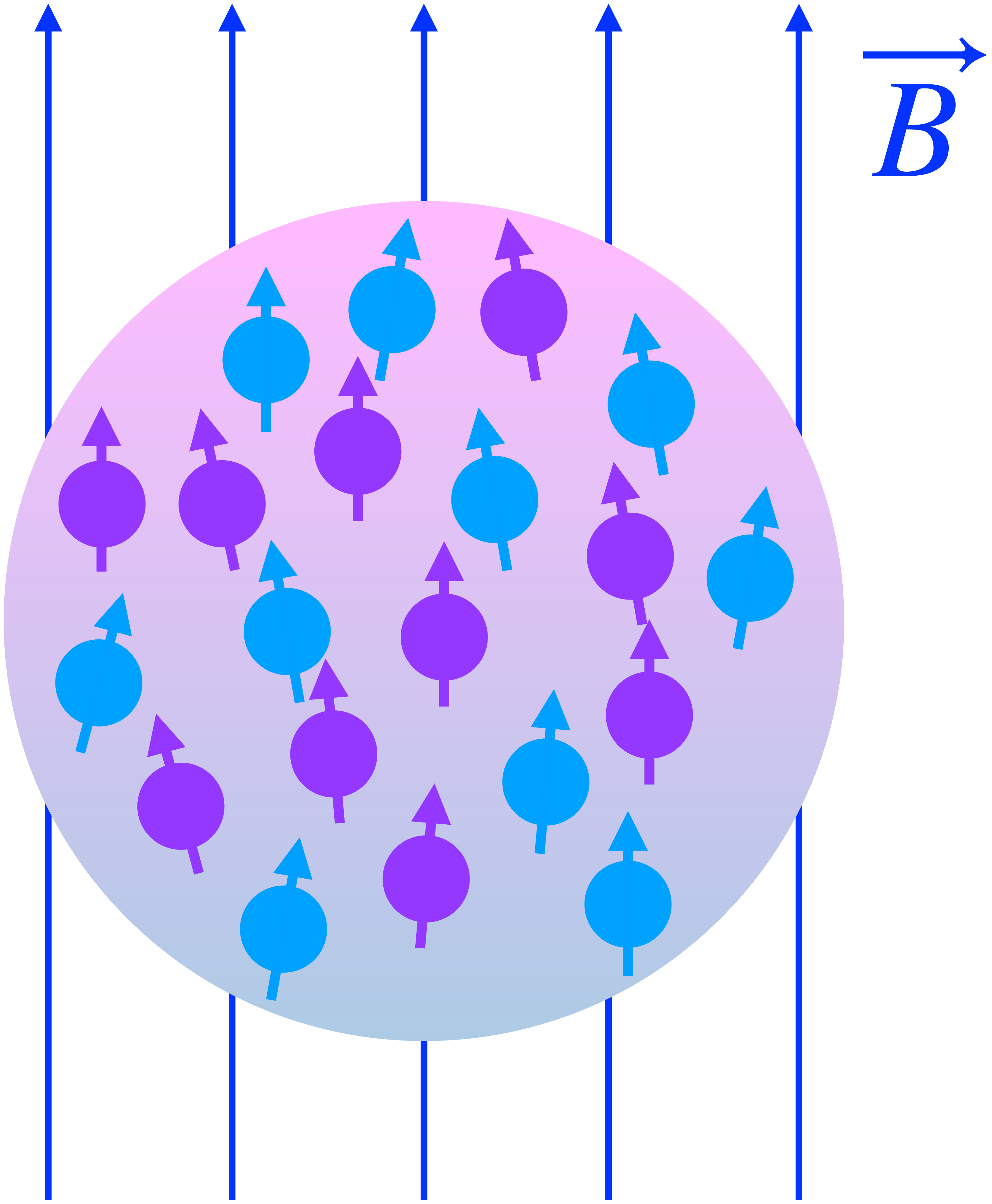


Motivation: Explore the fundamental properties of the nucleon

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.

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

Magnetic Polarizability



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Paramagnetic Contribution from direct alignment

Motivation: Explore the fundamental properties of the nucleon

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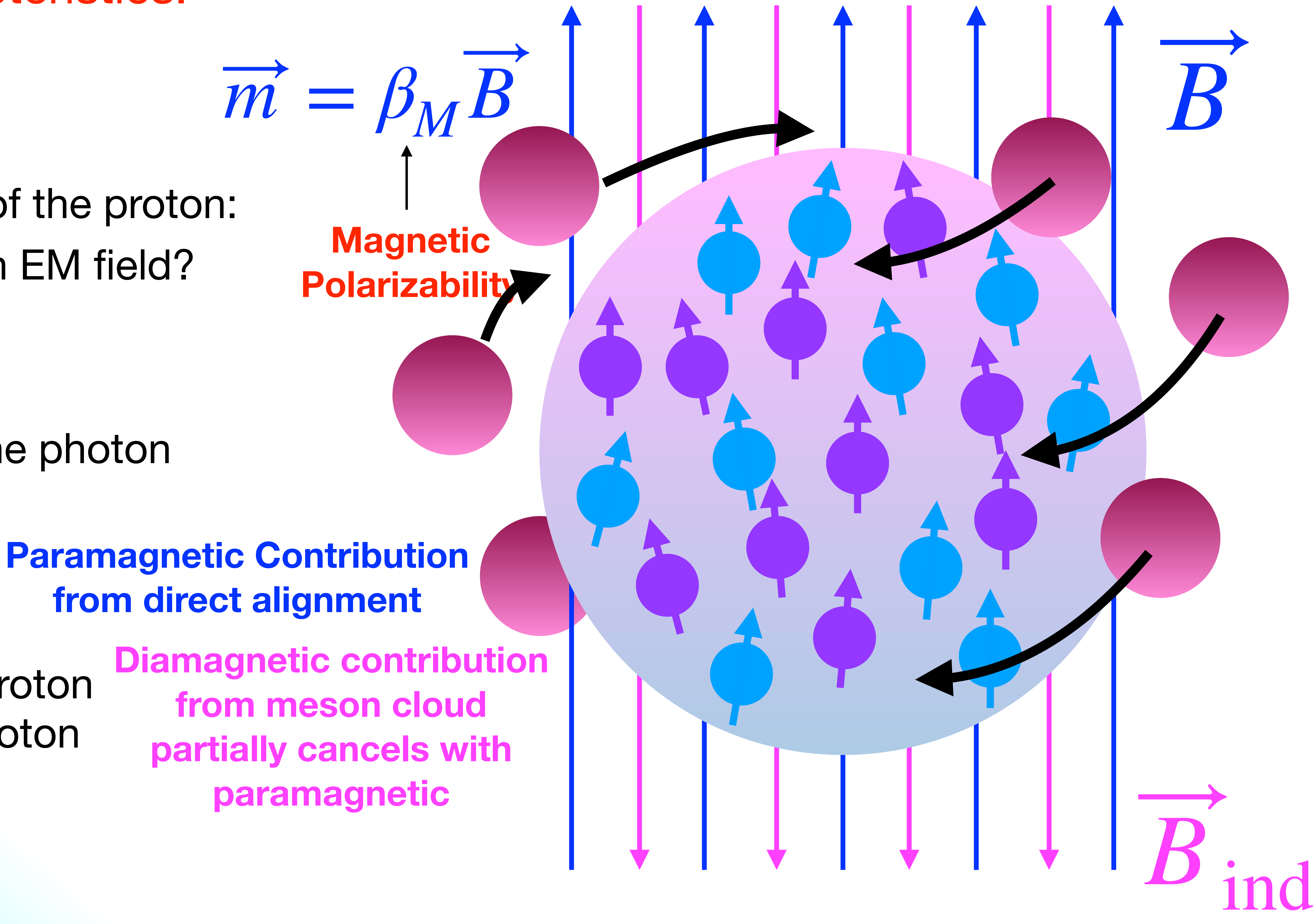

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Static Polarizabilities

Listed in the PDG as a fundamental property:

$$\alpha = (11.2 \pm 0.4) \times 10^{-4}\ \text{fm}^3$$
$$\beta = (2.5 \pm 0.4) \times 10^{-4}\ \text{fm}^3$$

PDG particle data group Live

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

PDGID:S016 JSON (beta) INSPIRE

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

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

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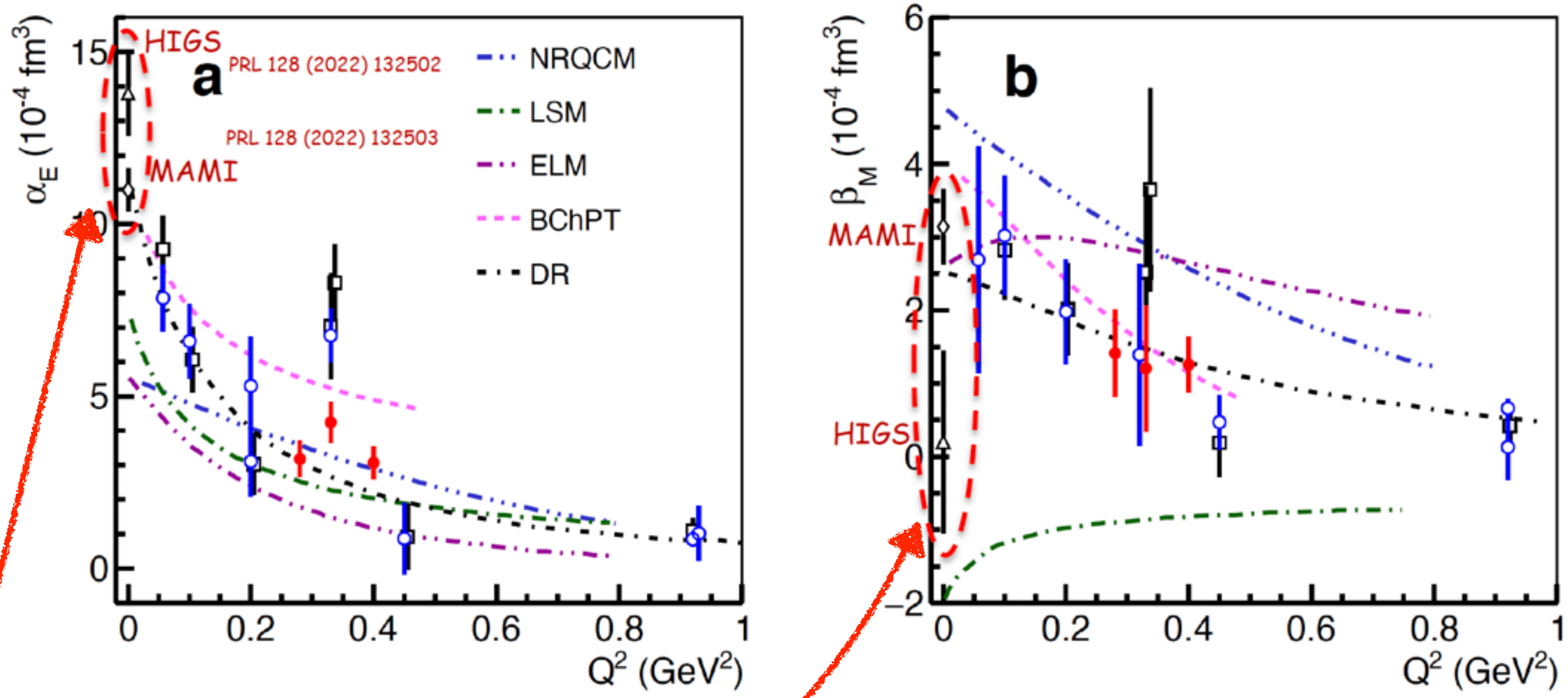
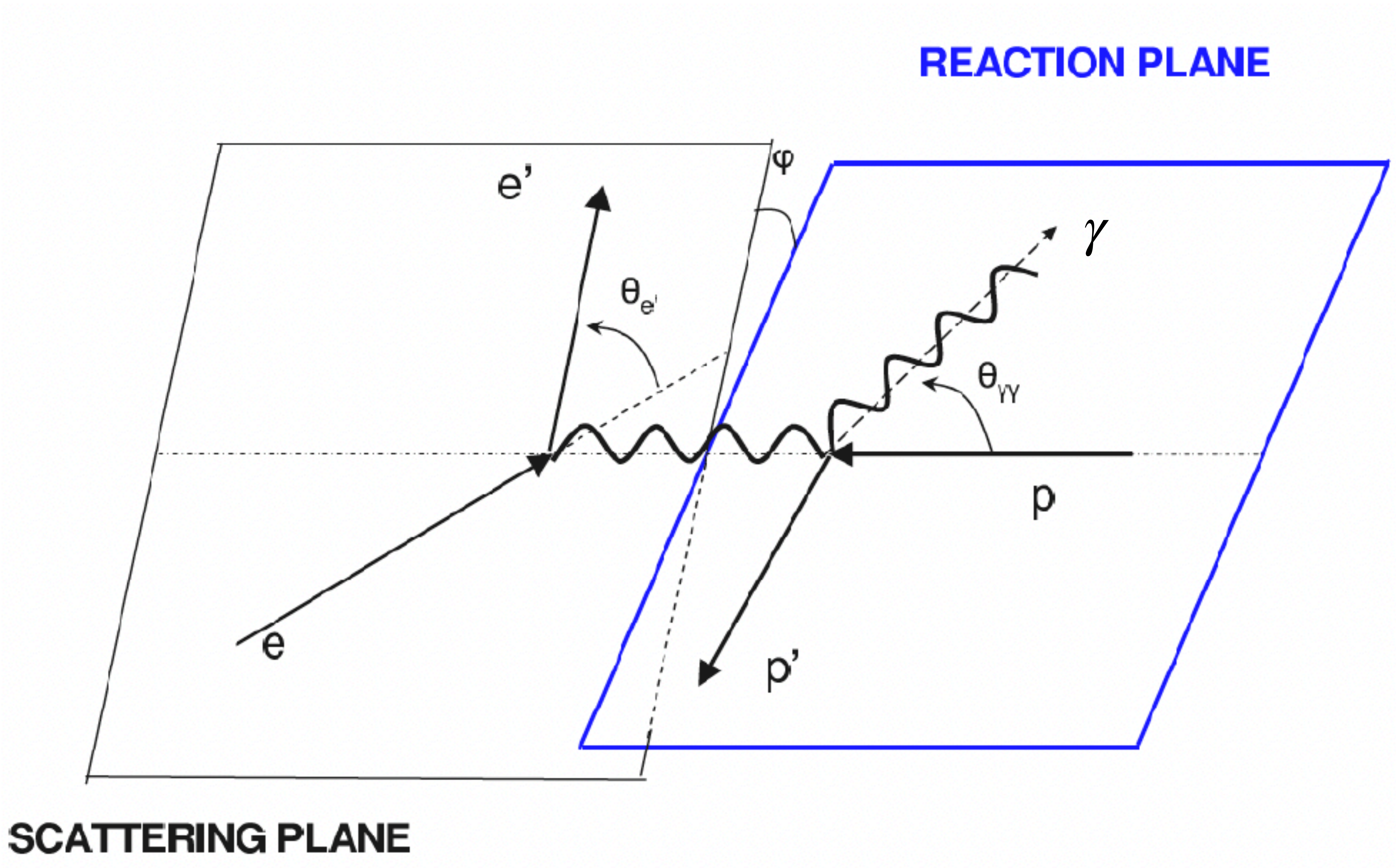
Generalized Polarizabilities

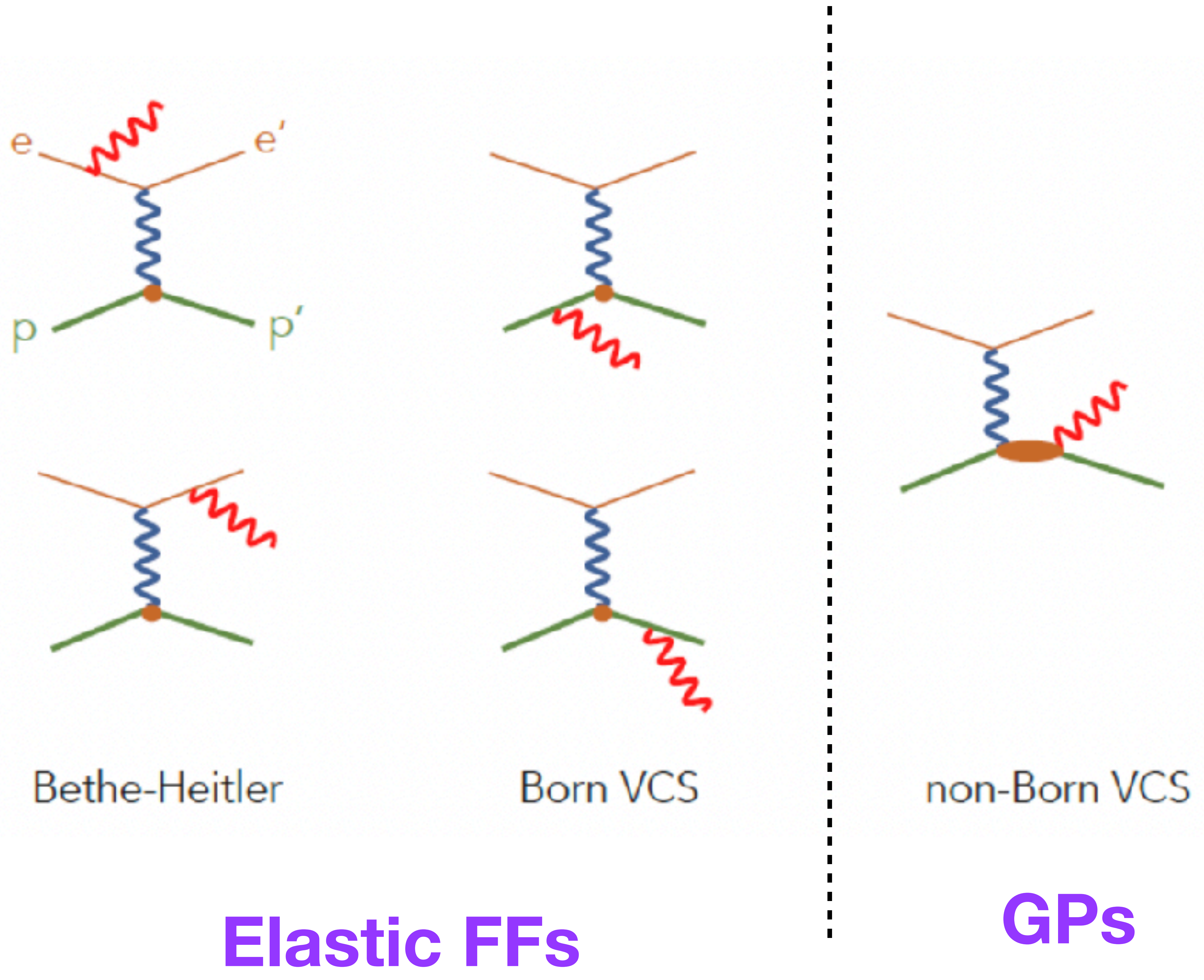
Accessed via virtual Compton scattering (VCS)
Dependent on Q2



Virtual Compton Scattering

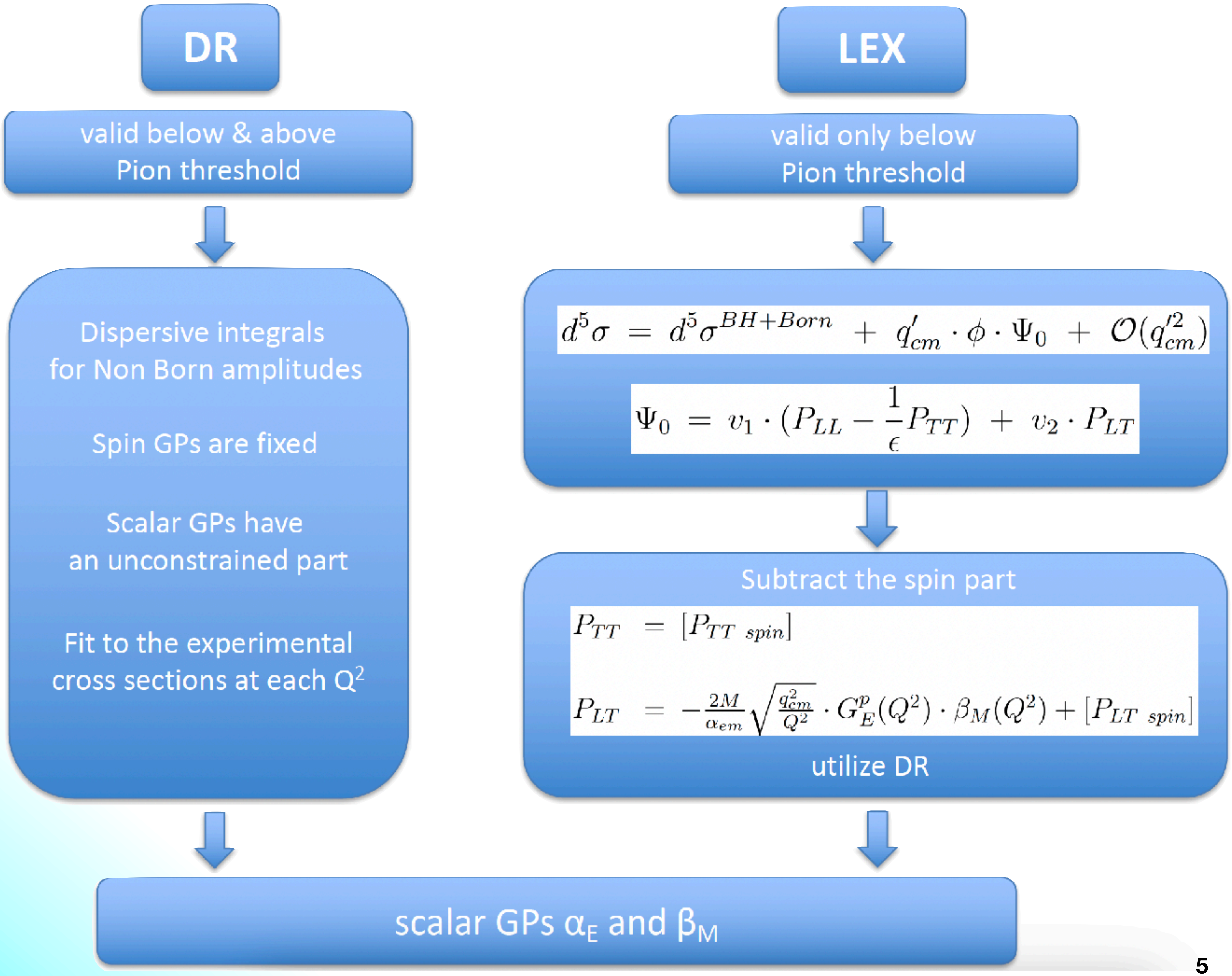
$$e + p \rightarrow e' + p' + \gamma$$





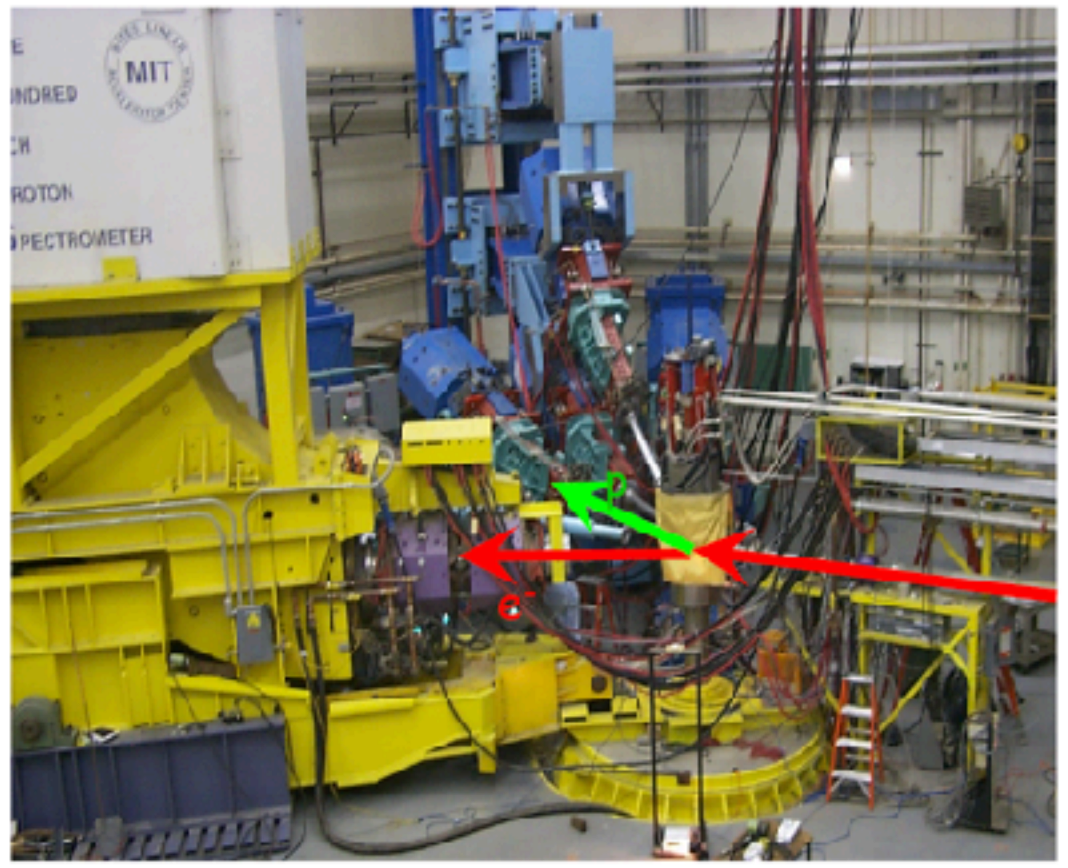
Cross section is five-fold differential: $\dfrac{d^5\sigma}{d\Omega_{e'} dE_{e'} d\theta_{\gamma^*\gamma} d\phi}$

- 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



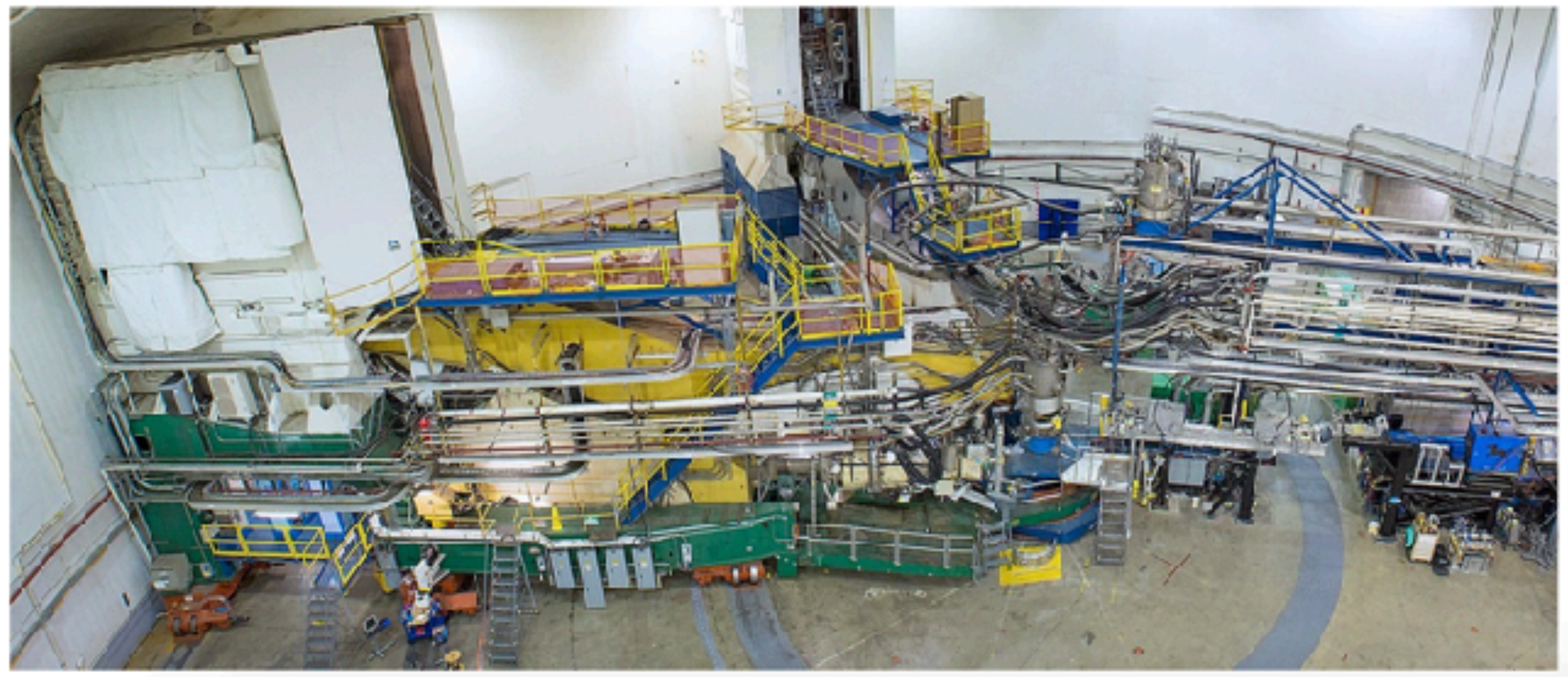
Early Experiments

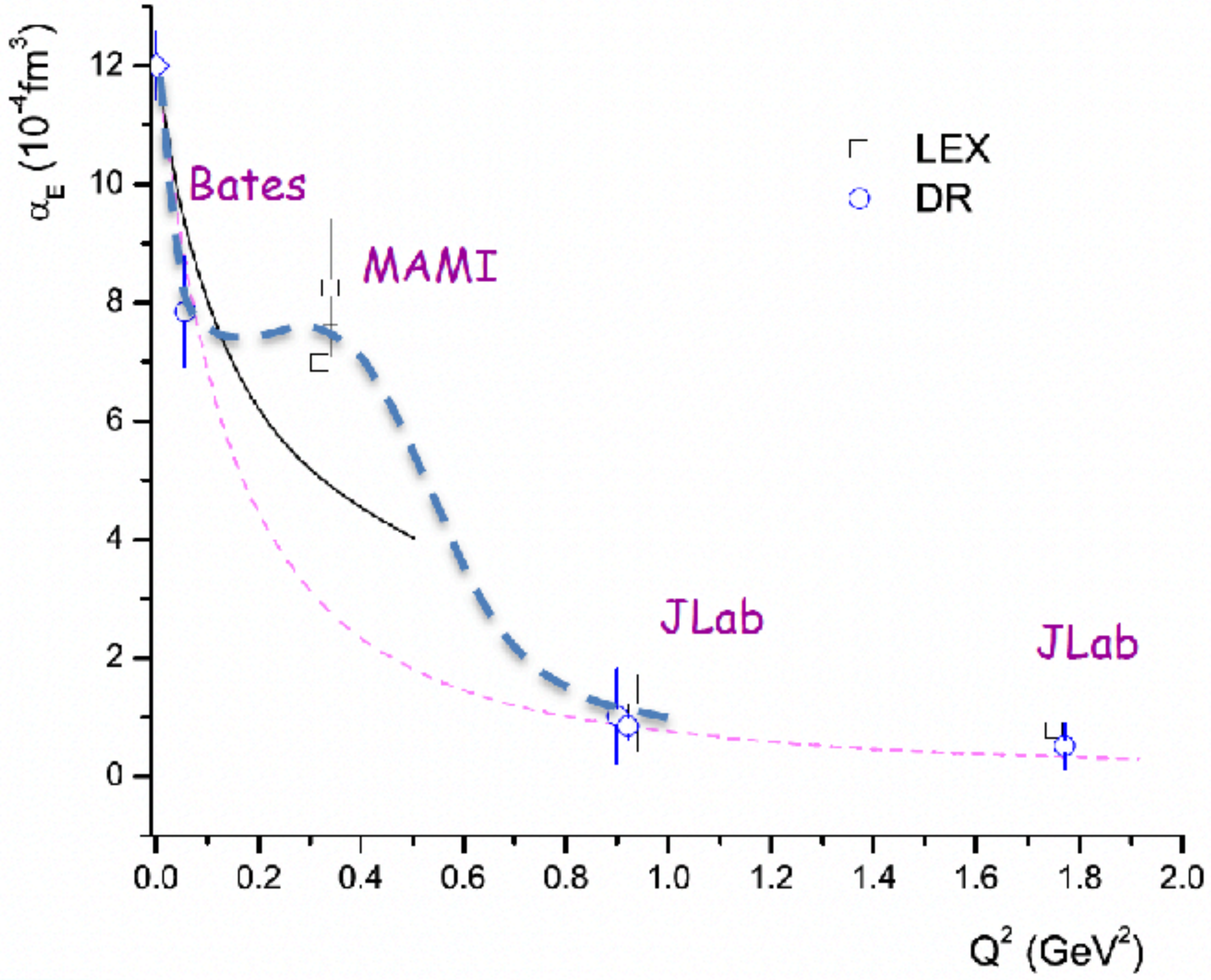
MIT-Bates @ Q^2=0.06 GeV^2

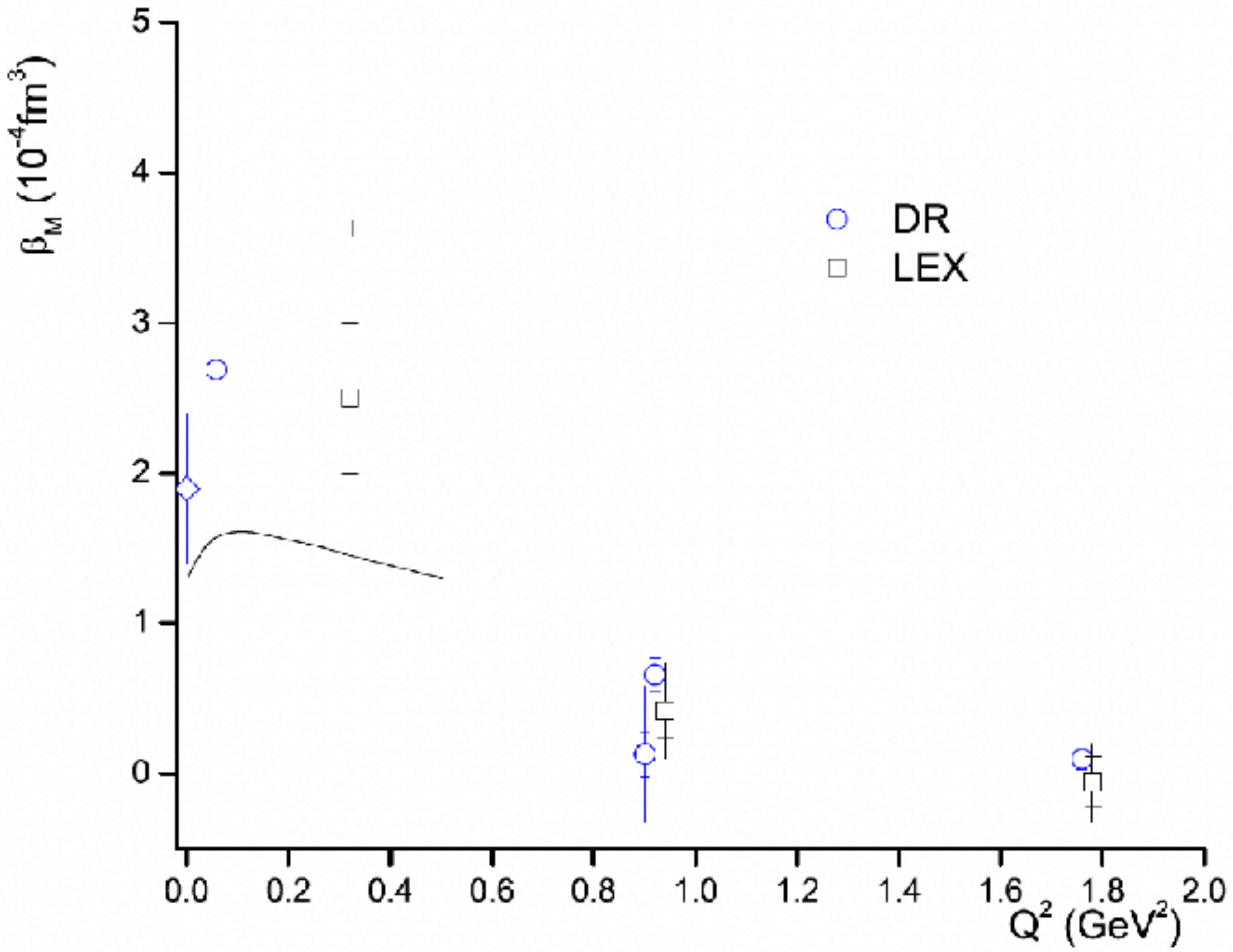


MAMI-A1 @ Q^2=0.33 GeV^2

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







Initial investigations showed that the proton generally increases in stiffness as Q^2 increases.

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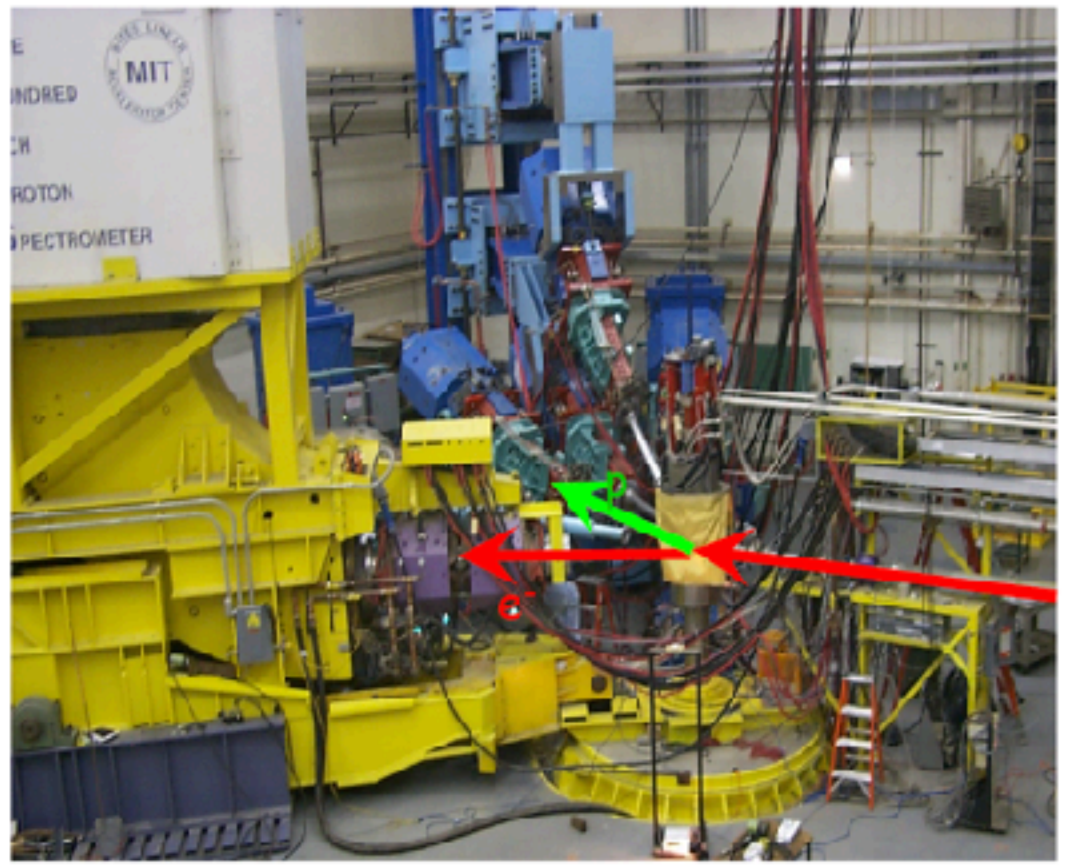

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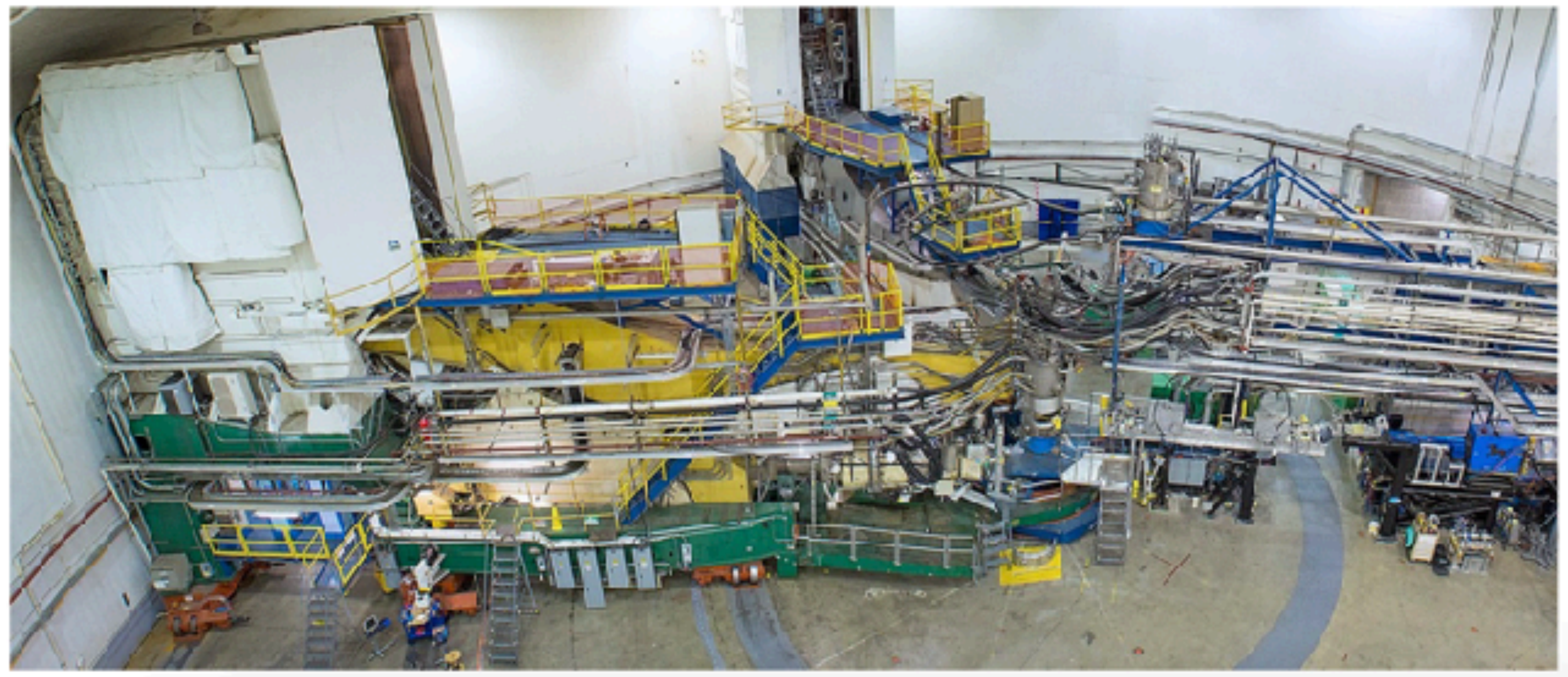
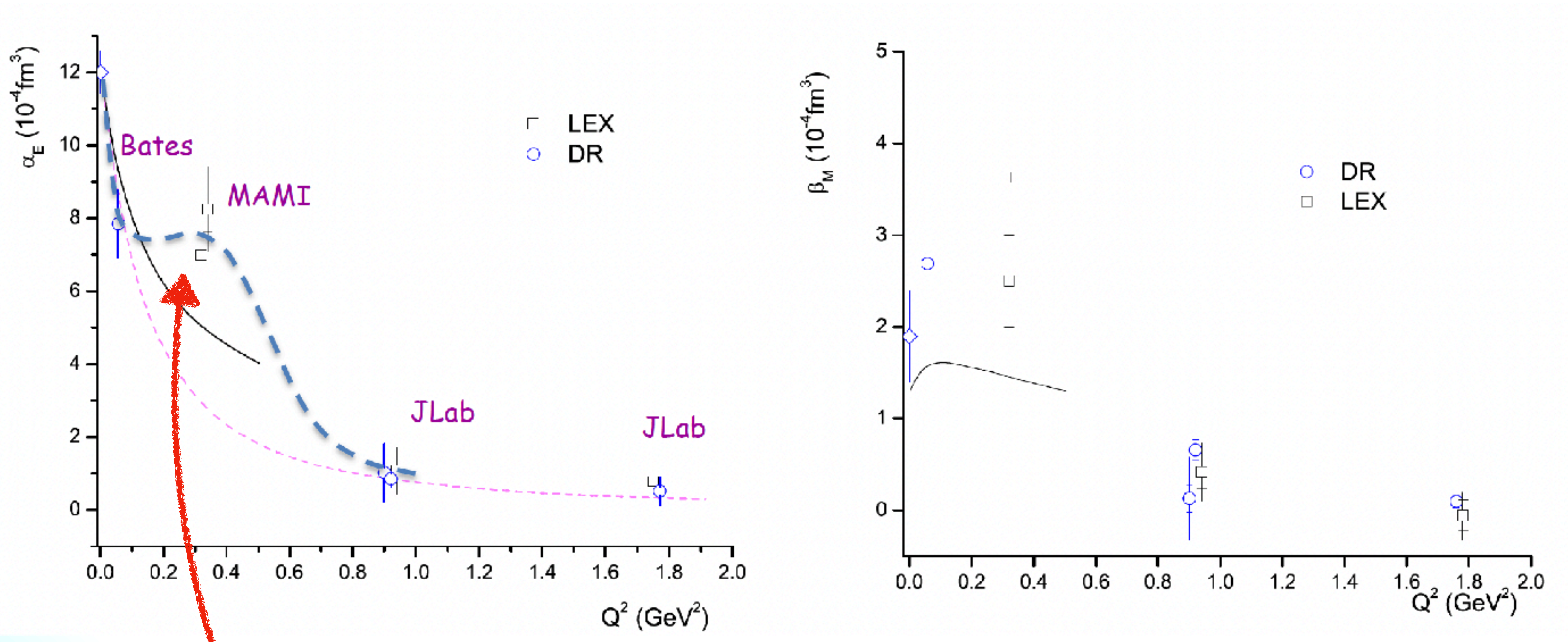




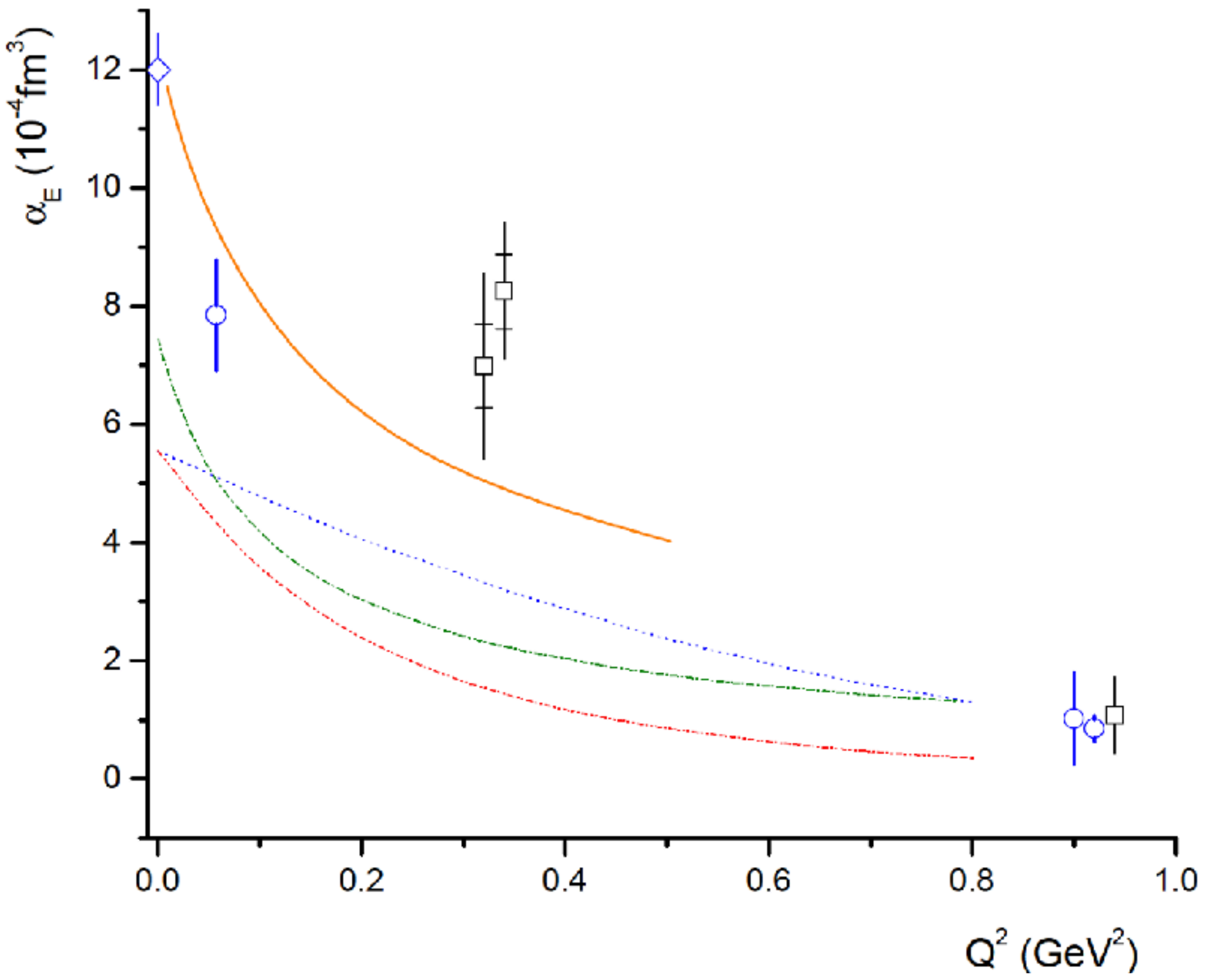
Initial investigations showed that the proton generally increases in stiffness as Q^2 increases.

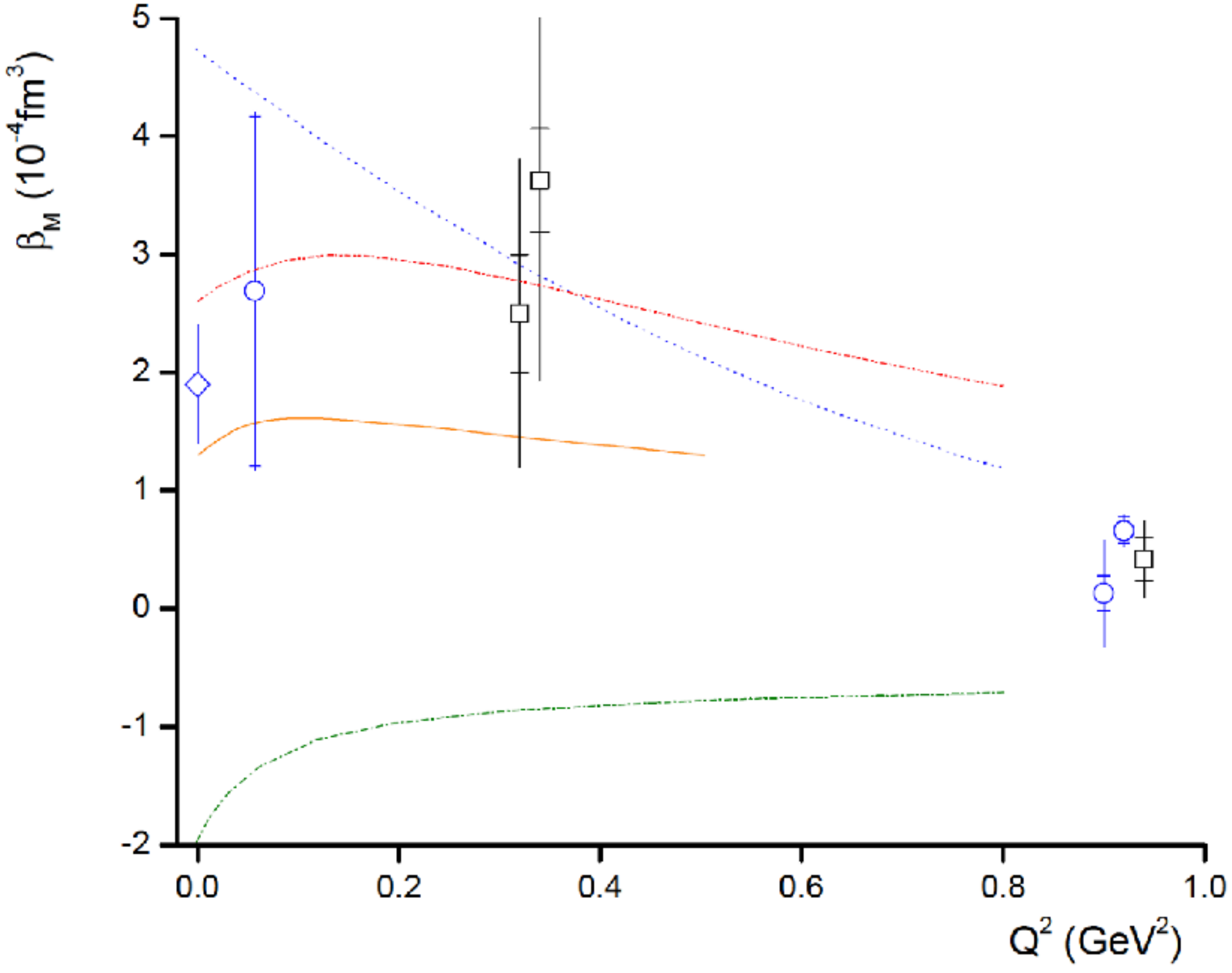
Early $Q^2 = 0.33\ \mathrm{GeV}^2$ measurement at MAMI seemed to buck the trend of a monatomic decrease. A second measurement at MAMI had similar results.

Phys. Rev. Lett 85, 708 (2000)

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

Theoretical Predictions





HBChPT	T.R. Hemmert et al	Phys. Rev. D 62, 014013 (2000)
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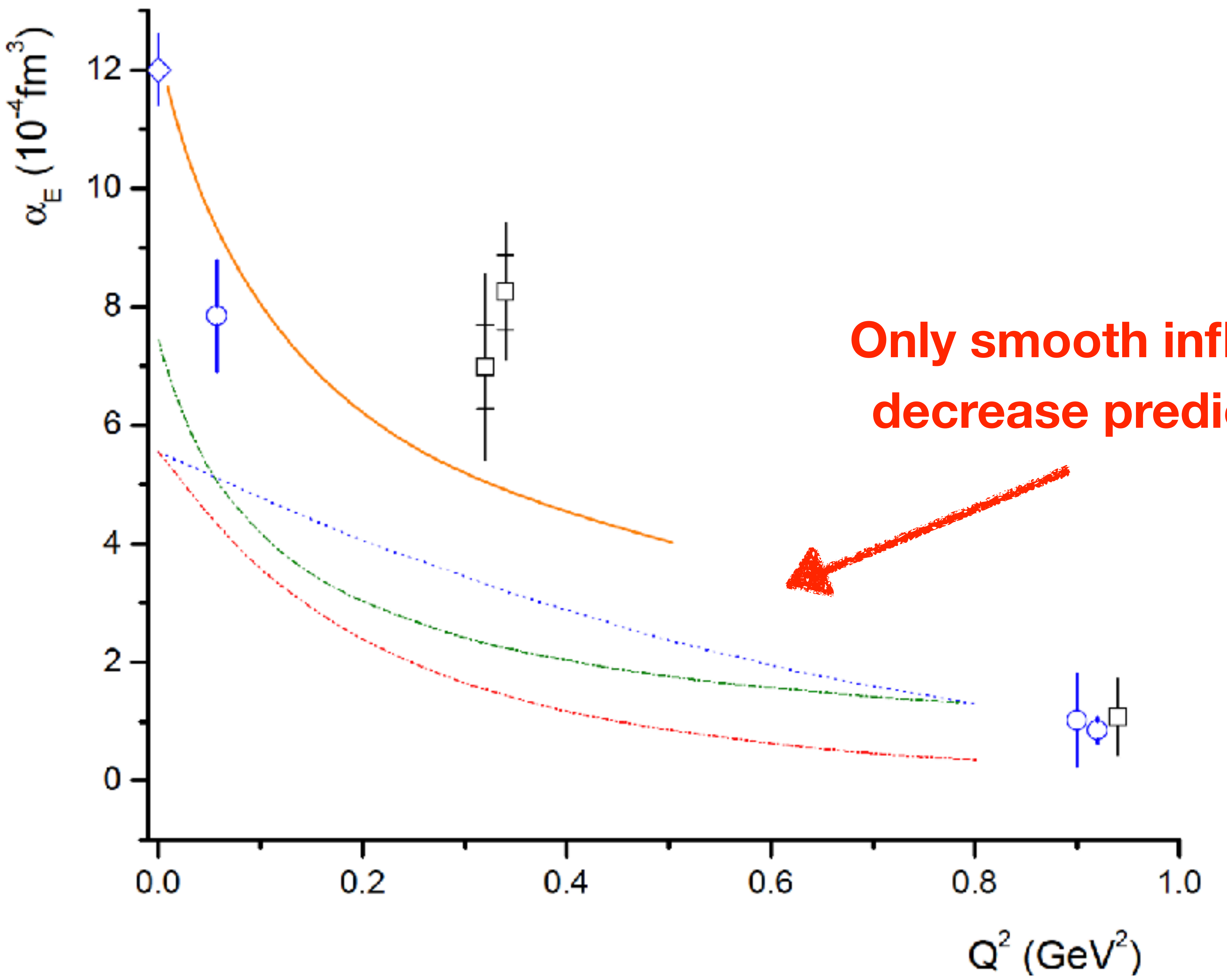

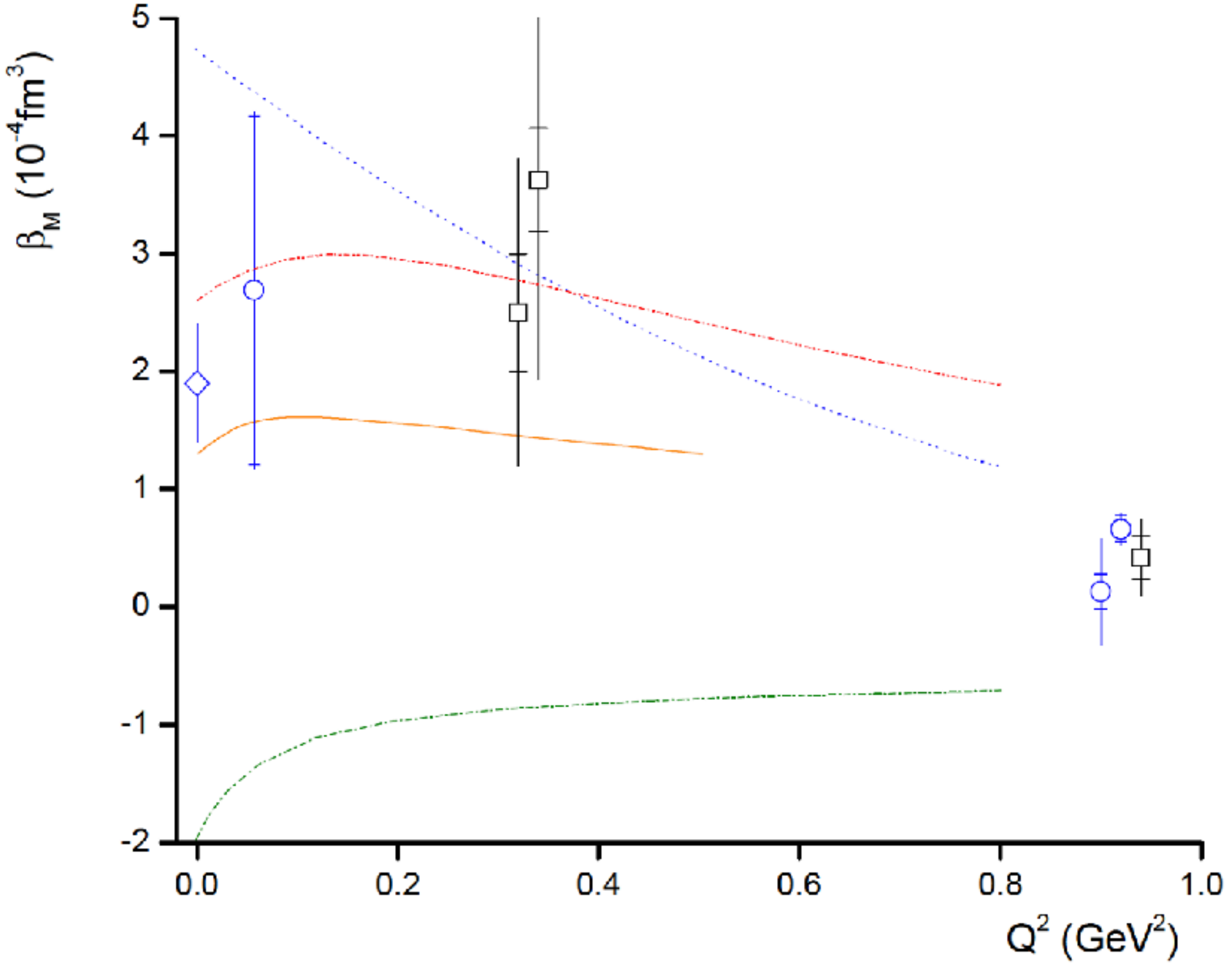

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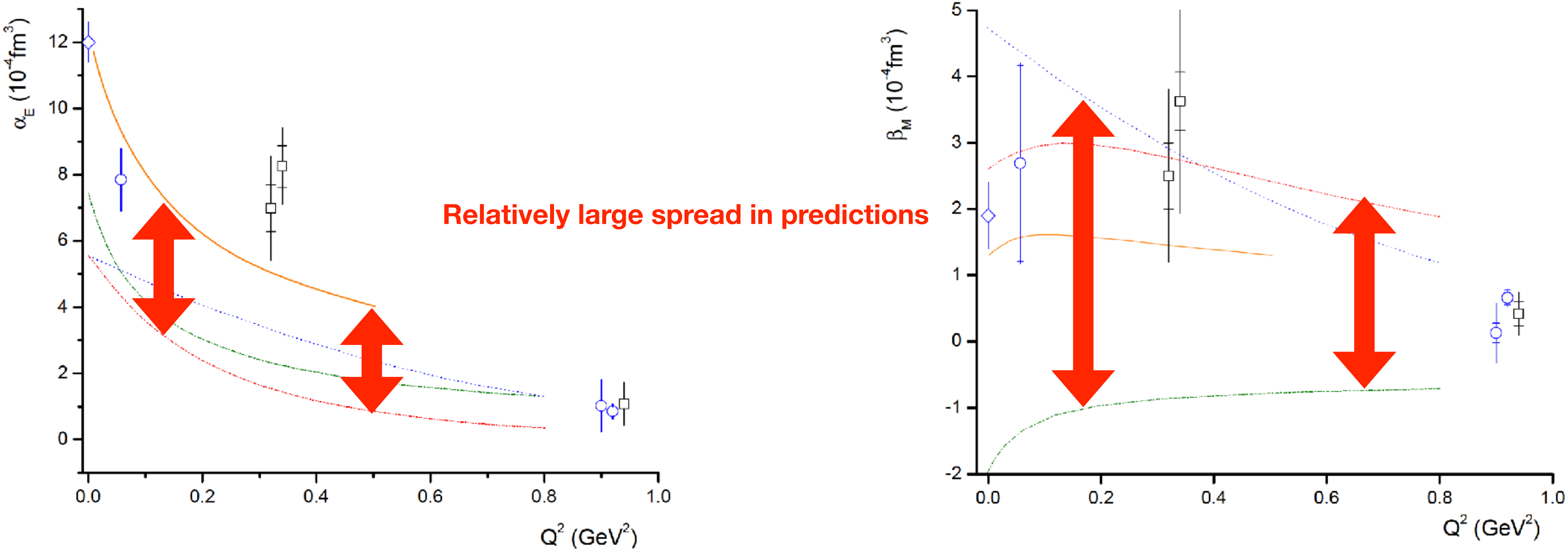

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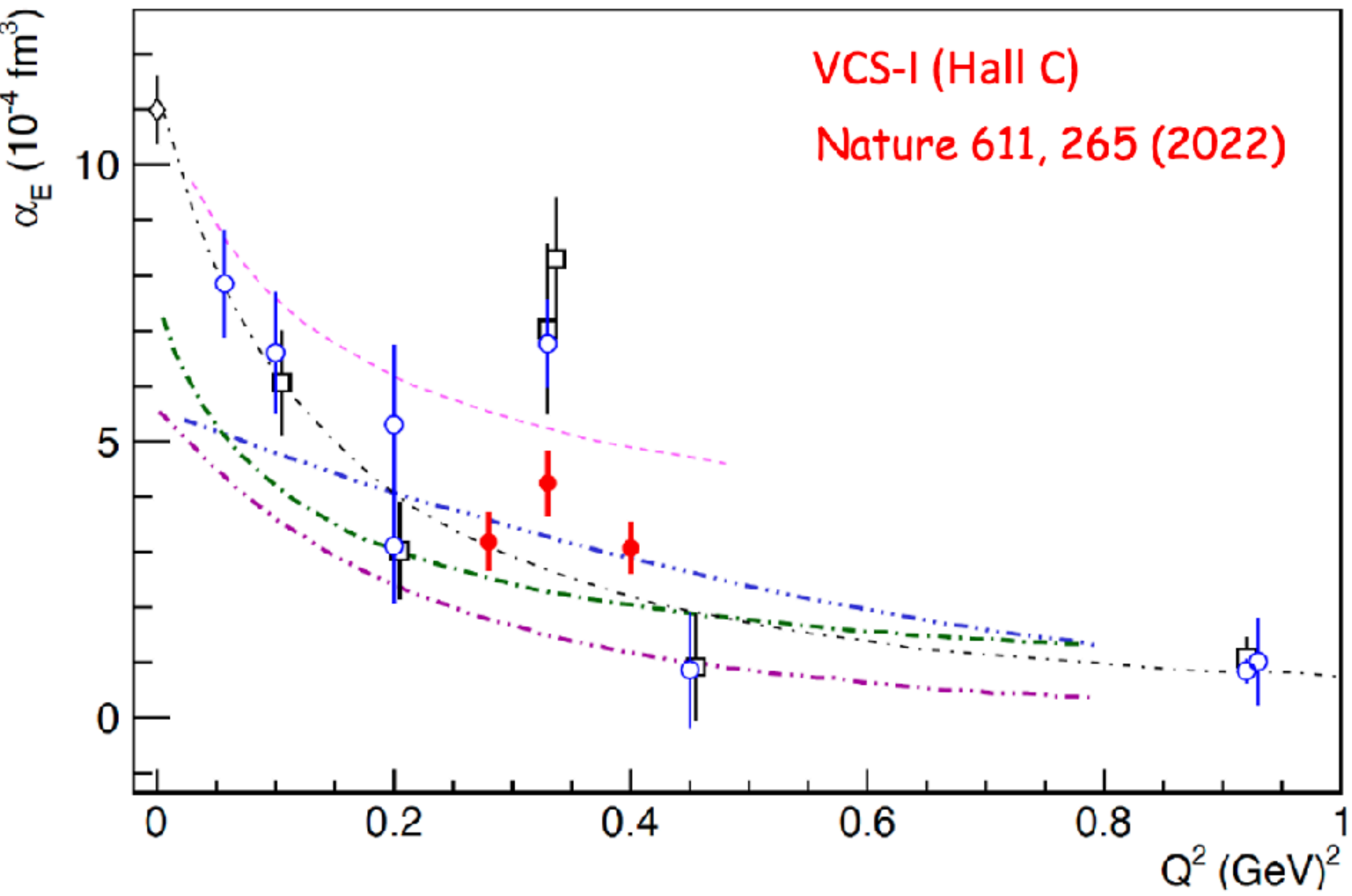
Recent Experiments/Efforts



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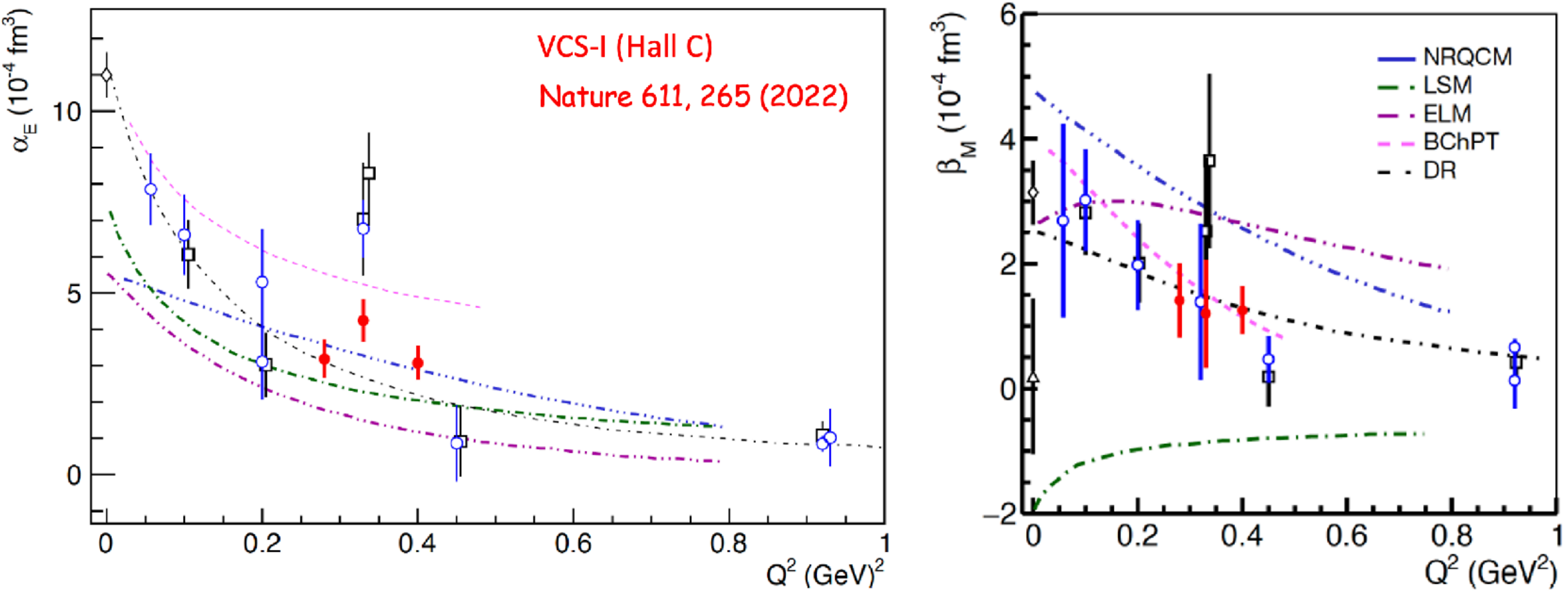
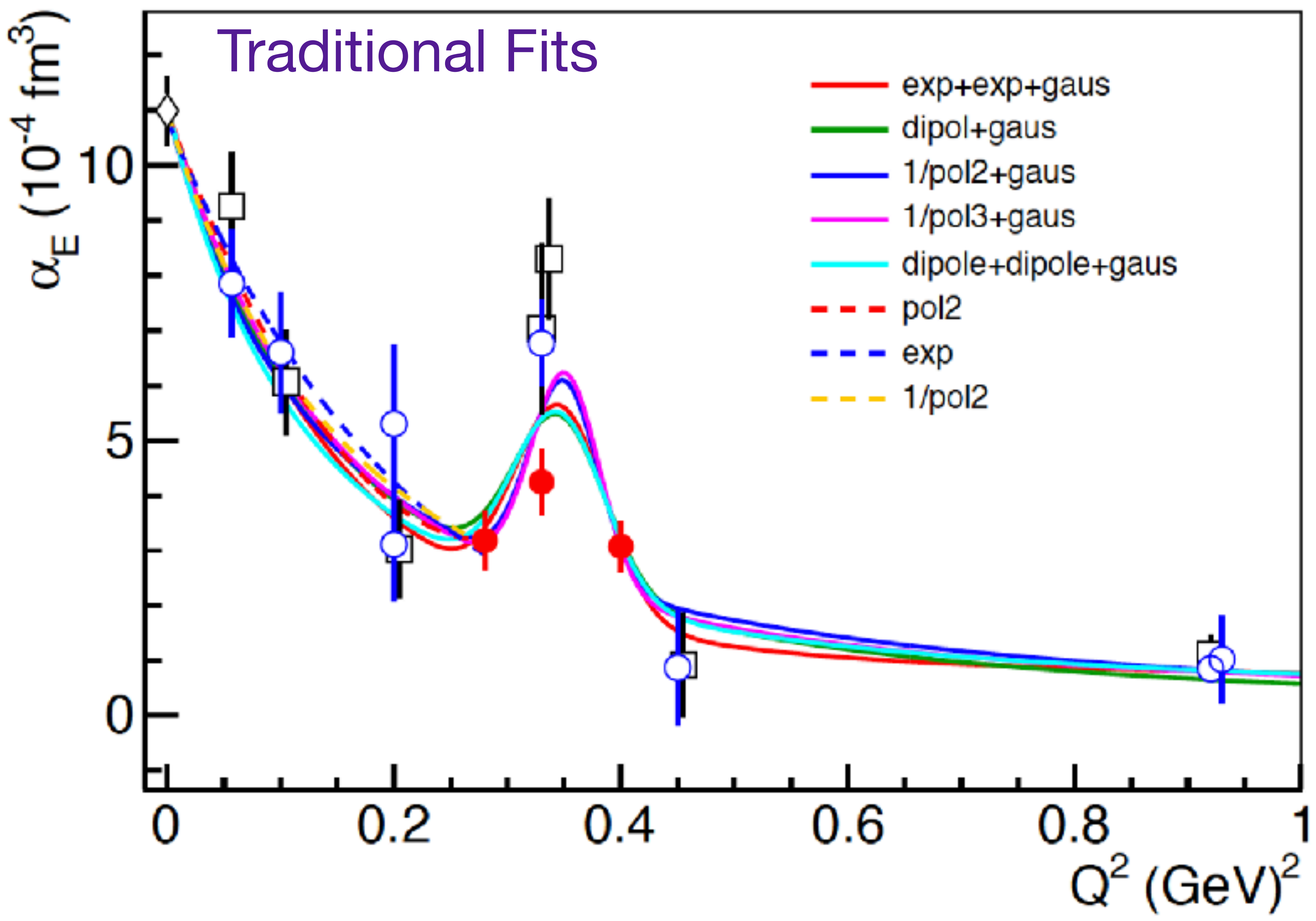
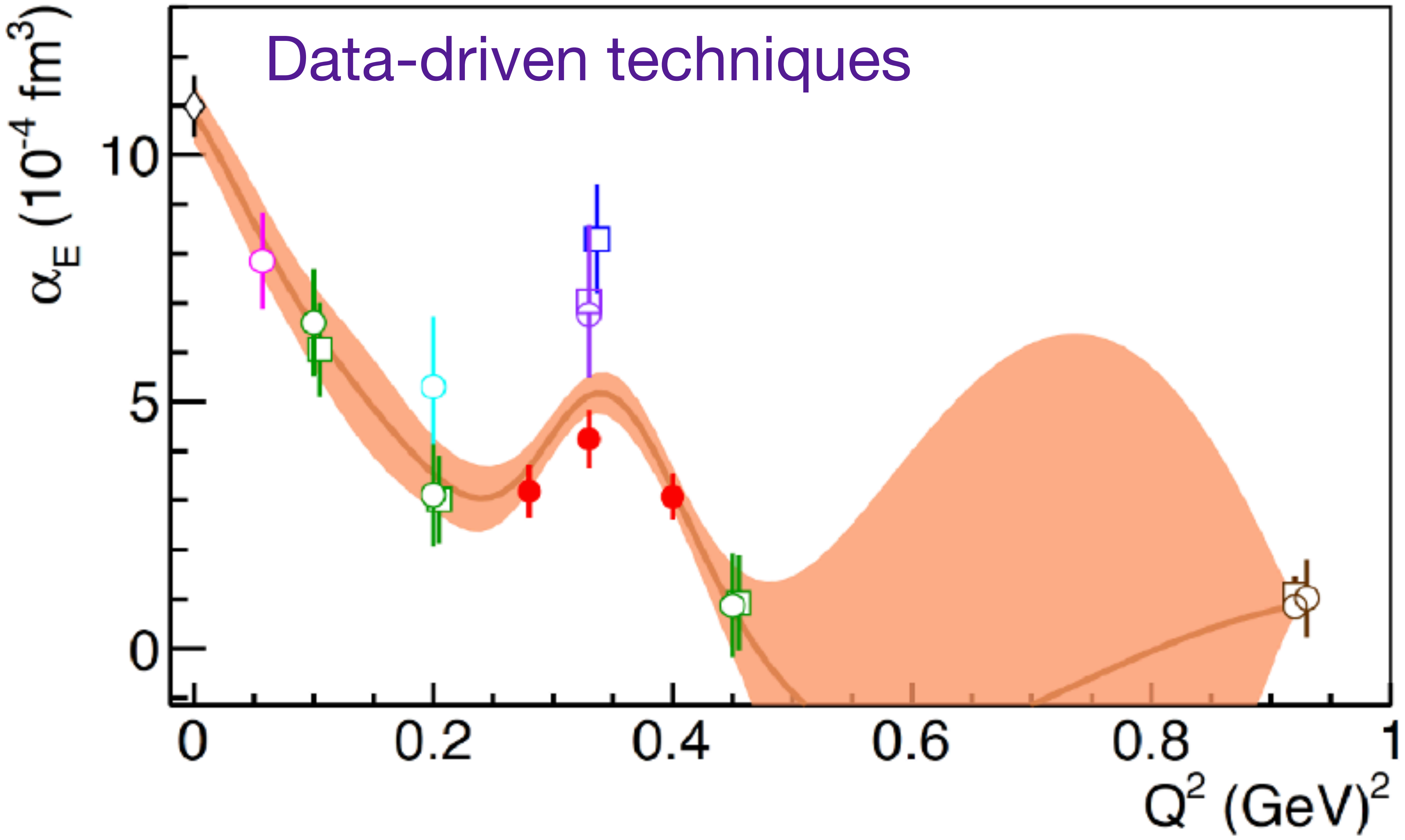


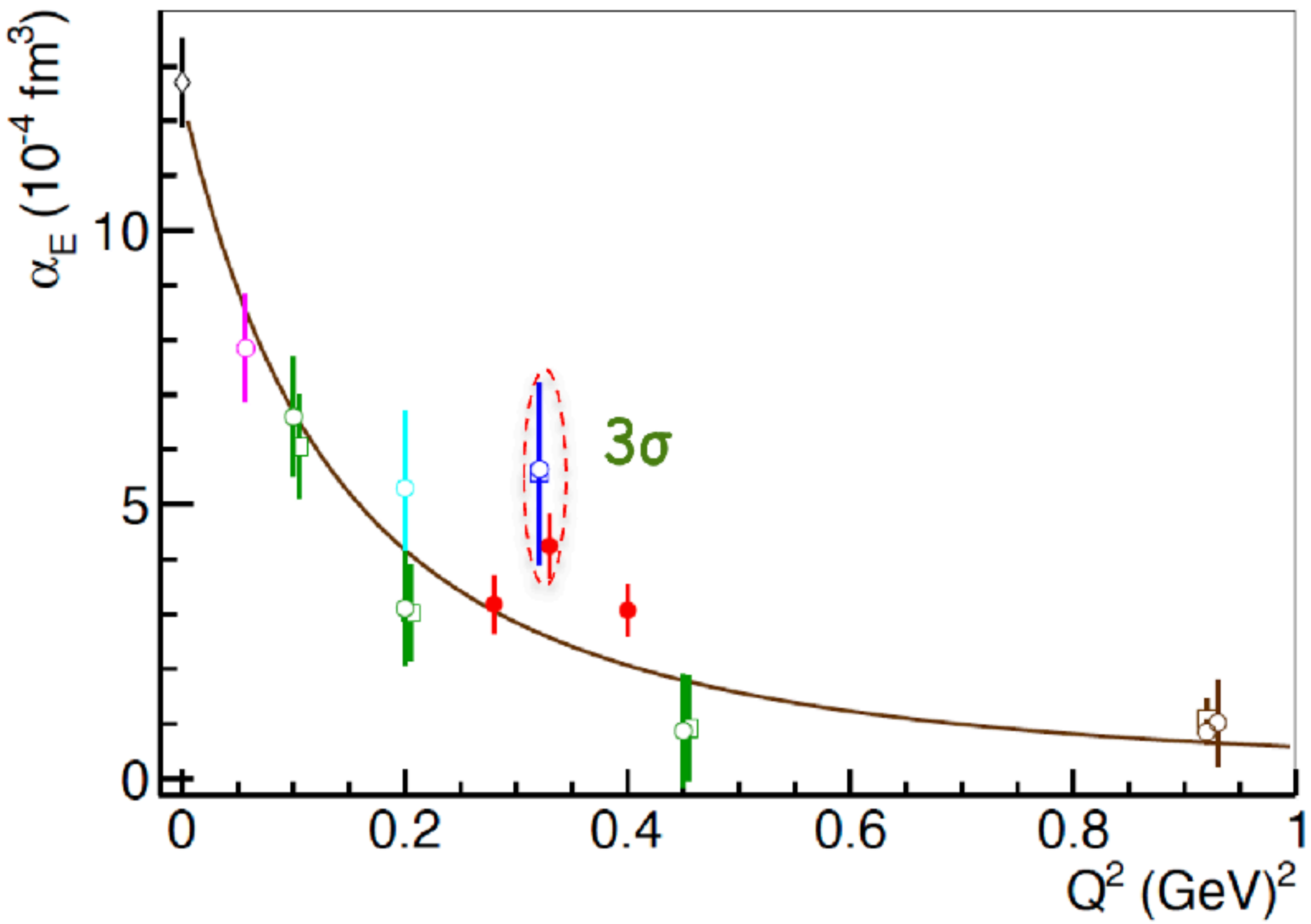
VCS-I : Illustrated the ability to perform measurements of superb precision at Jlab (Hall C)

Current Landscape and Questions





- **Electric Polarizability:**
  - Is the observed structure coincidental?
    - **If so:** More precise measurements will help inform theory.
    - **If not:** Strong tension exists in the world data. Additional measurements can help pinpoint possible sources of tension



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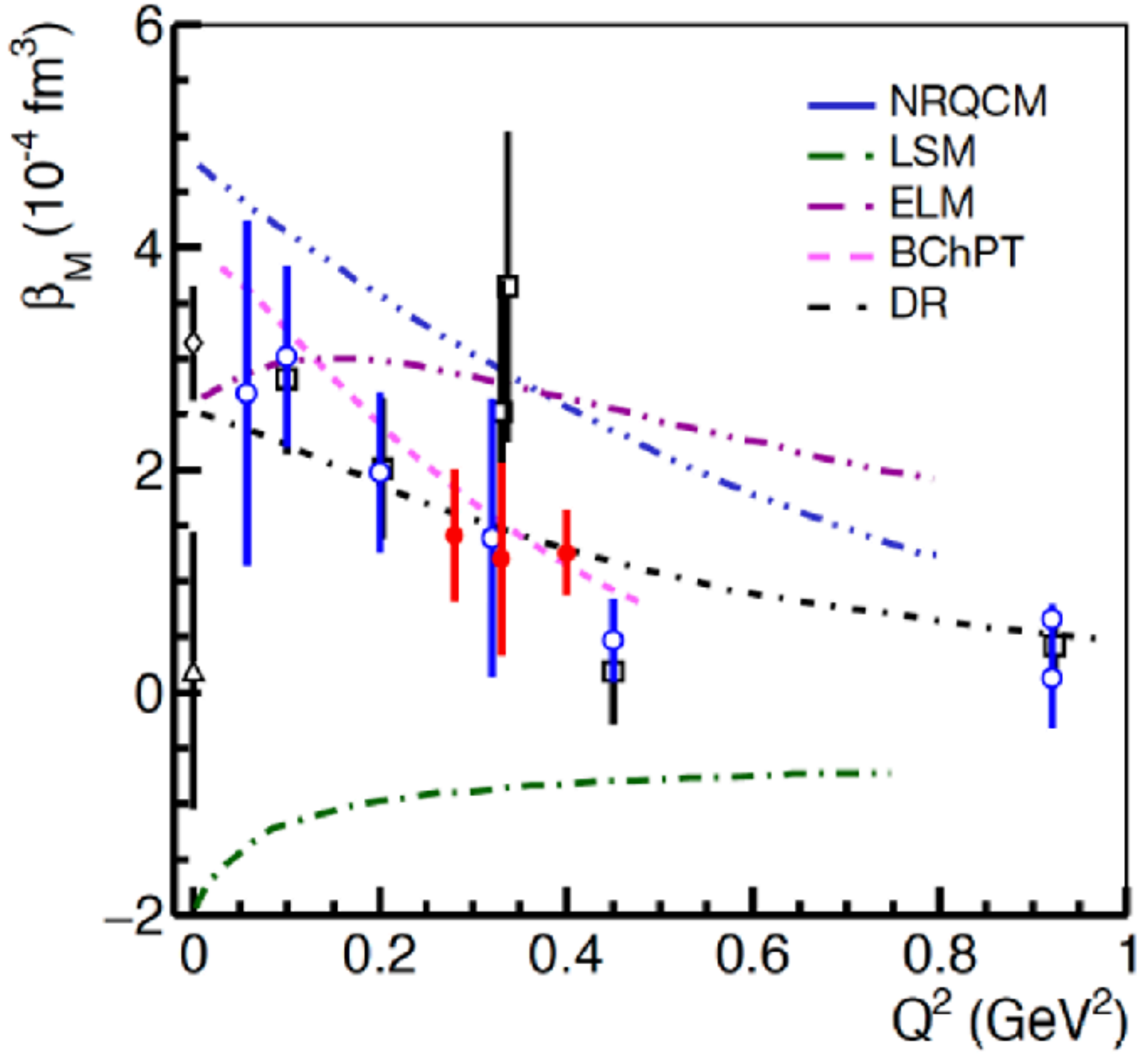

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  - Large uncertainties and discrepancies exist in the world data.
  - High precision data is needed to disentangle diamagnetic and paramagnetic contributions in the nucleon.

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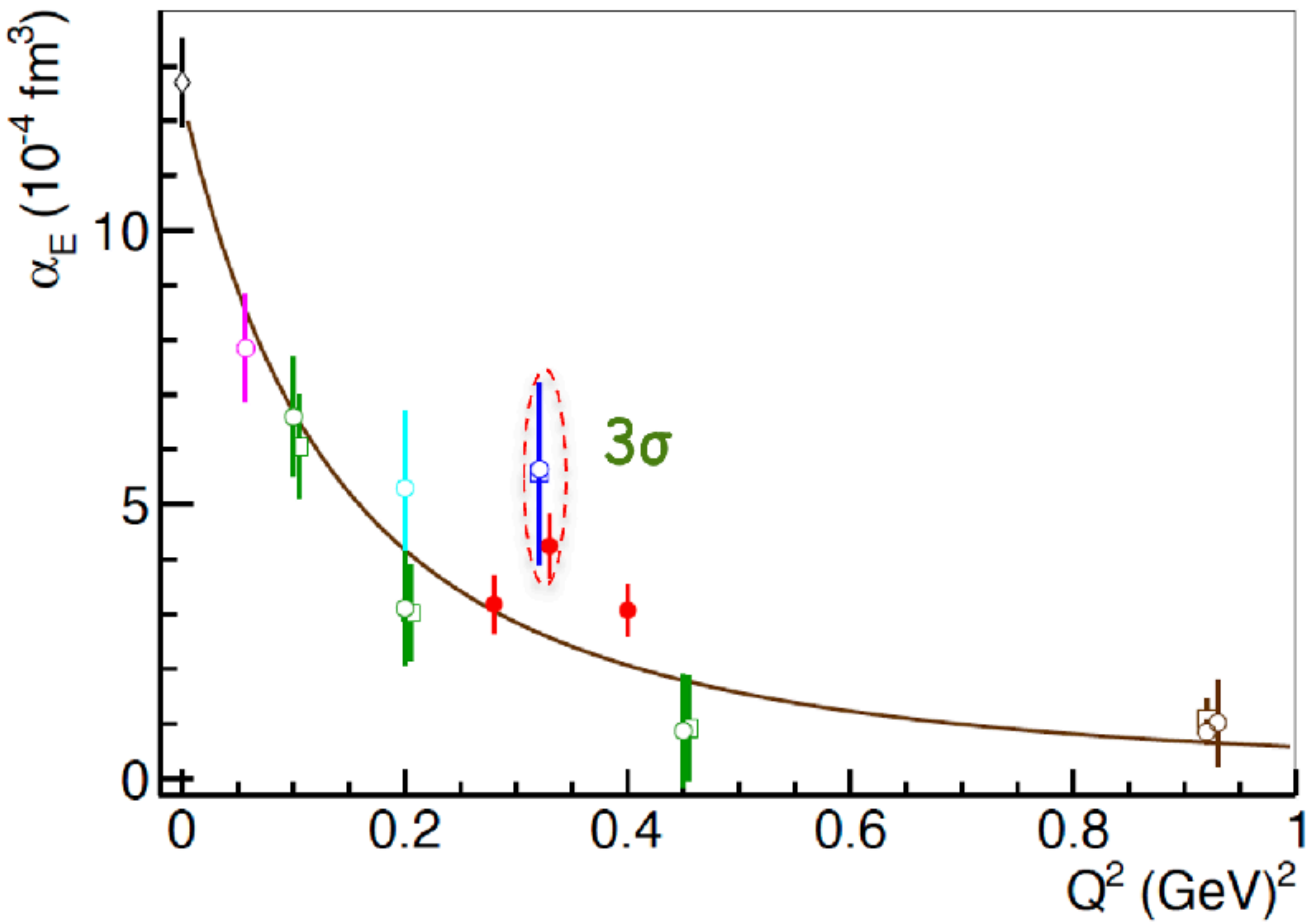

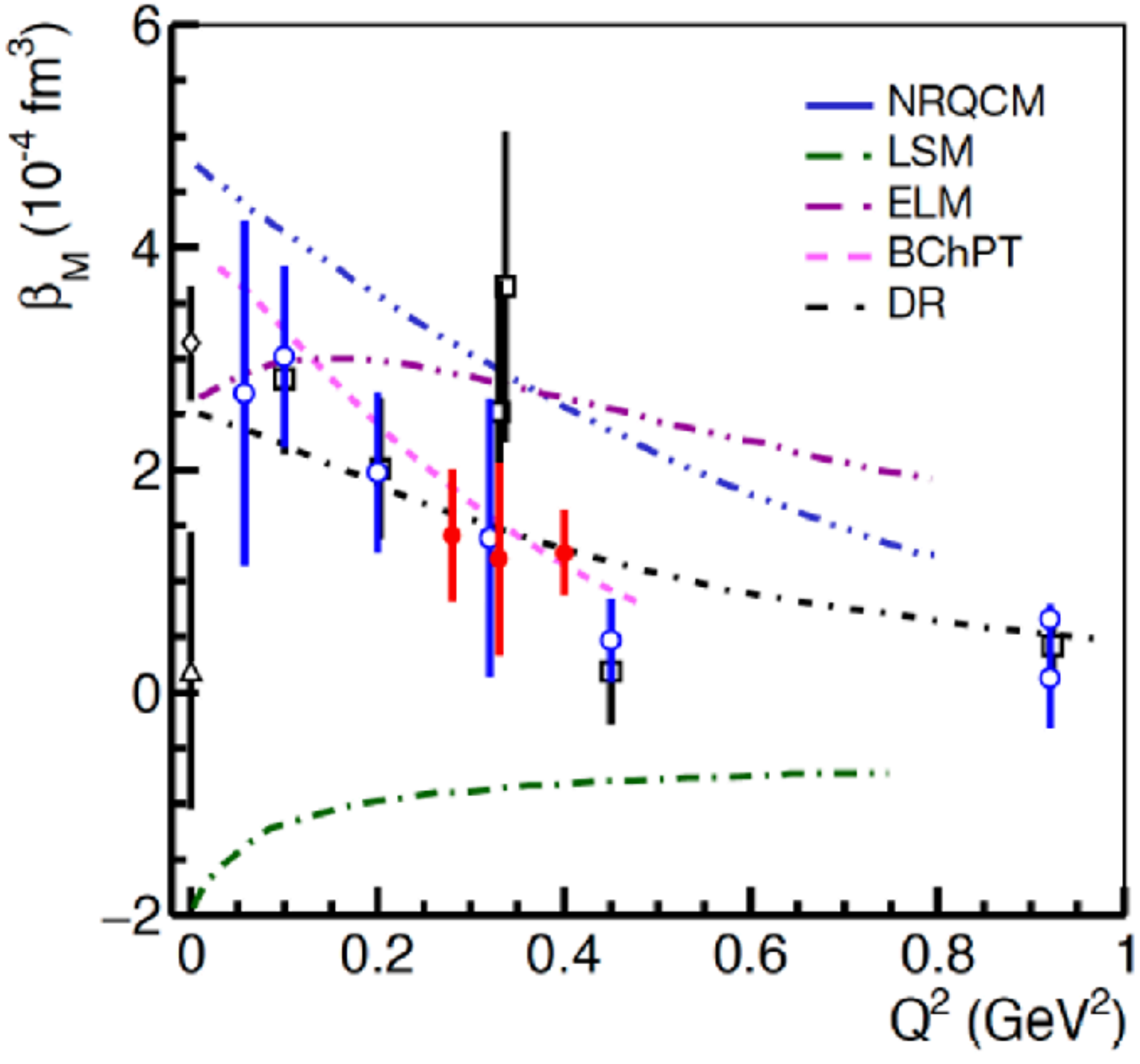

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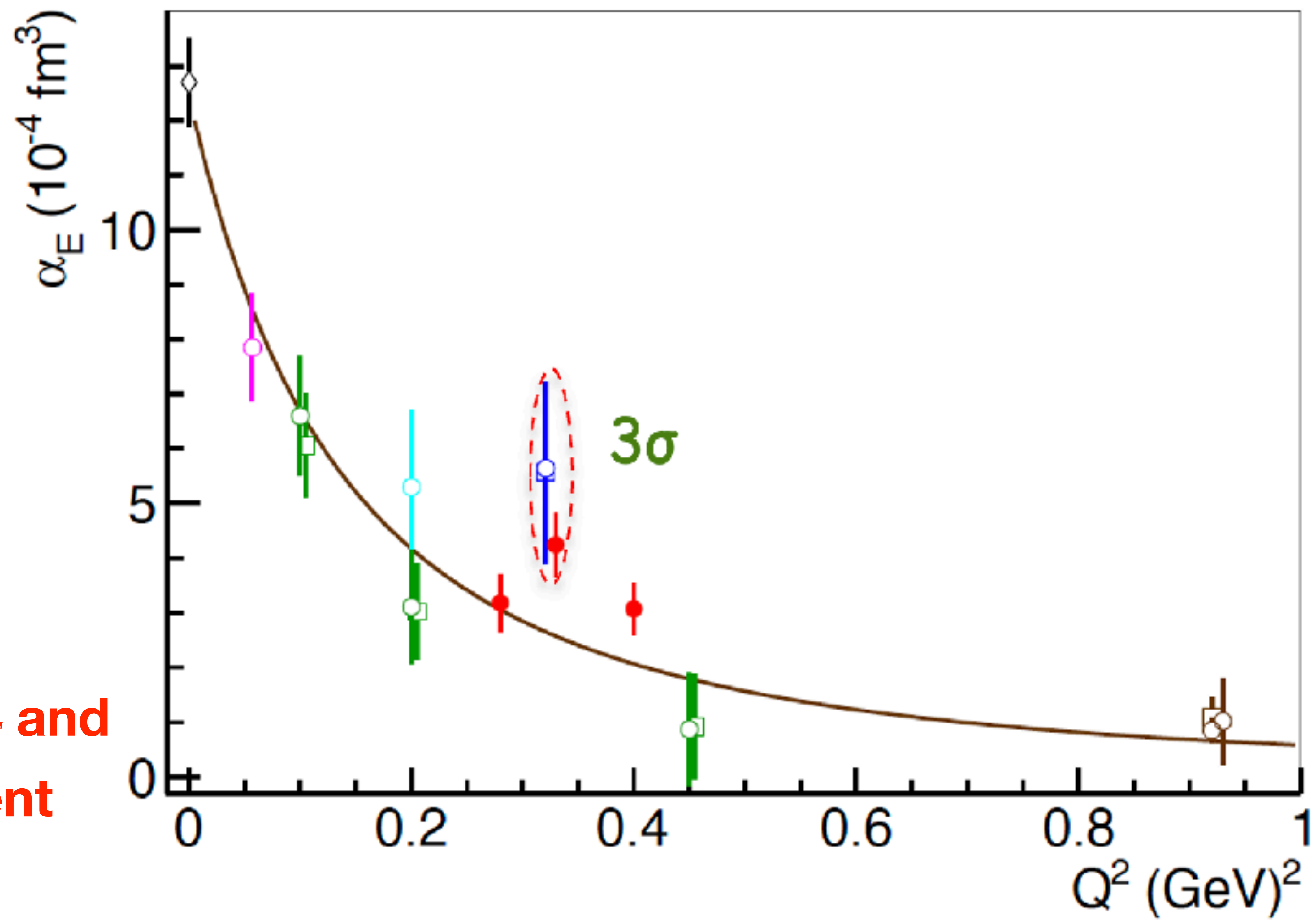

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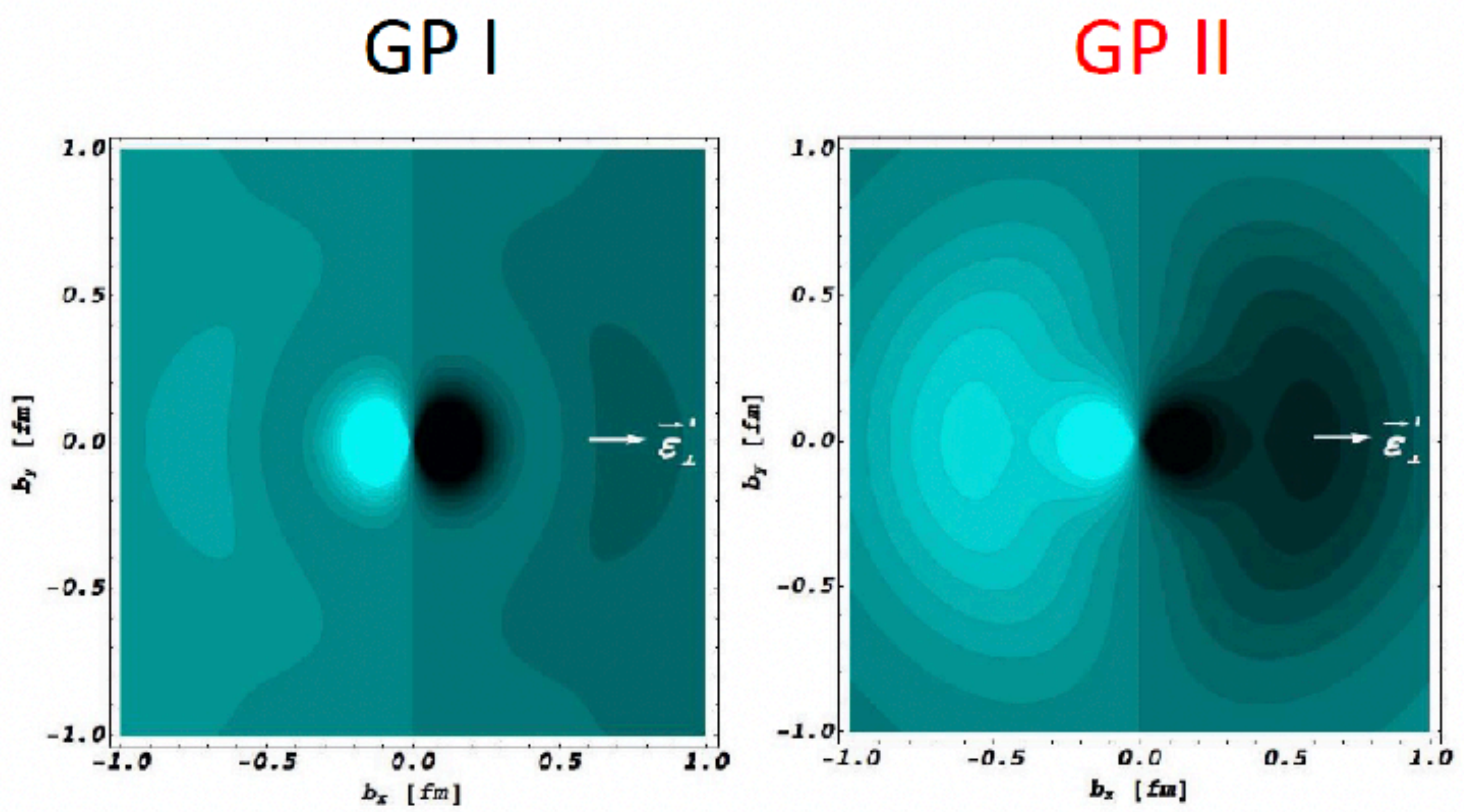
JLab has the unique capability to measure α_E and β_M with superb precision and with consistent systematics across Q^2

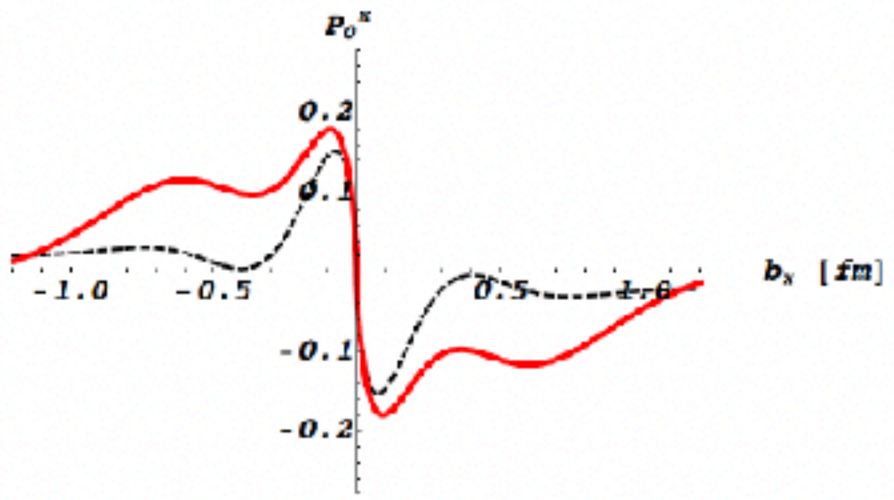
Spatial Dependence of Induced Polarizations

- In the same vein of transforming nucleon form-factor data to quark charge density on the light-cone:
  - Generalized polarizabilities can be transformed to density deformation with respect to the direction of induced polarization.



Light (dark) regions ➔ largest (smaller) values

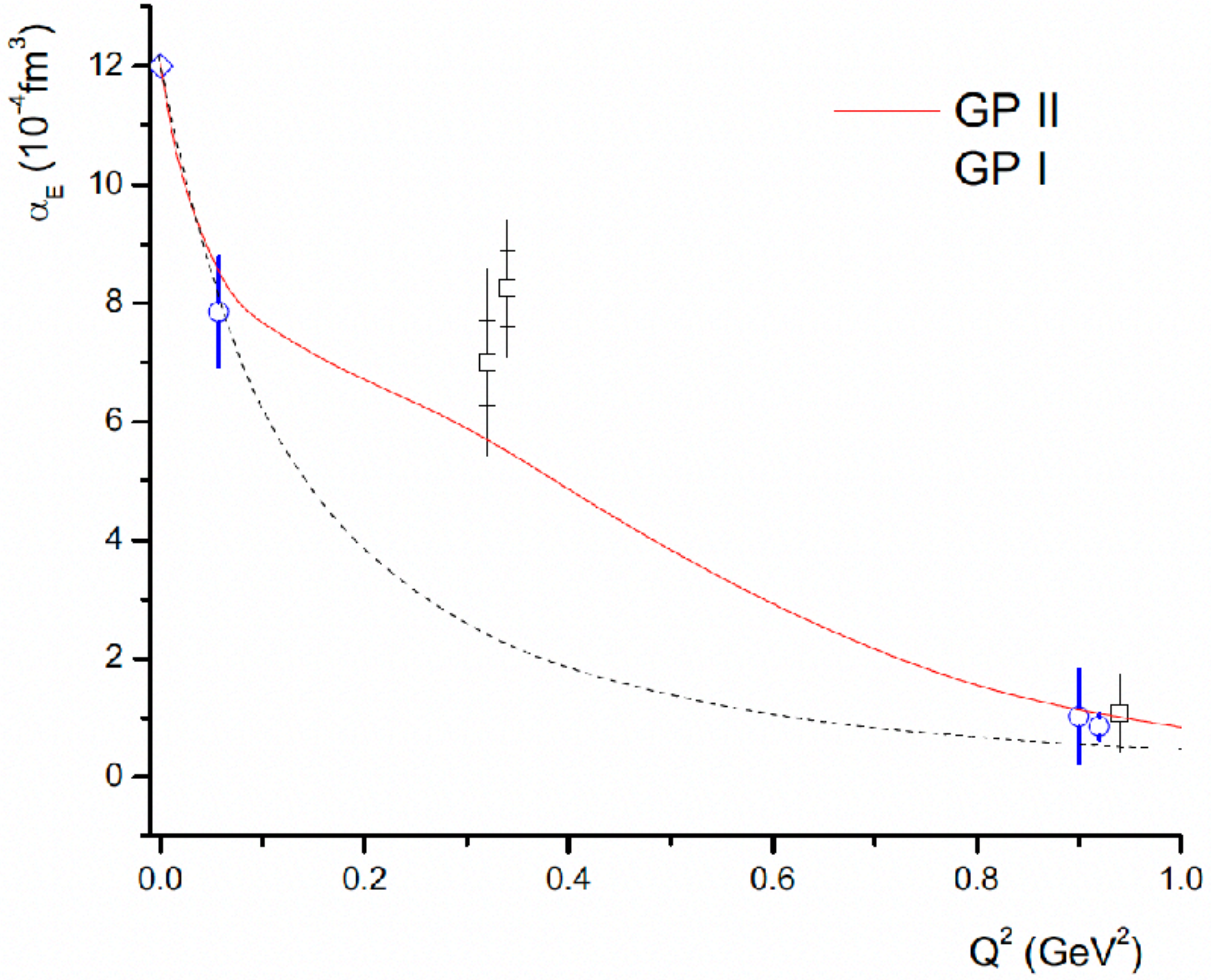
(photon polarization along x-axis, as indicated)



Induced polarization along b_y=0

Phys. Rev. Lett. 104, 112001 (2010)

M. Gorchtein, C. Lorce, B. Pasquini, M. Vanderhaeghen



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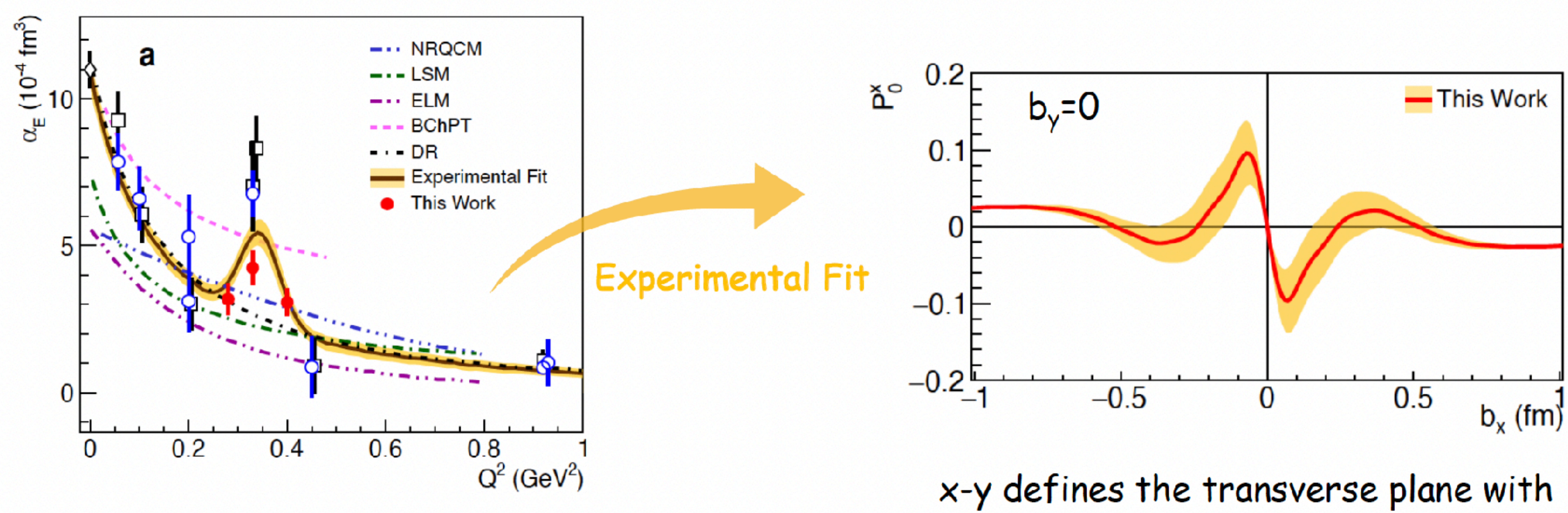
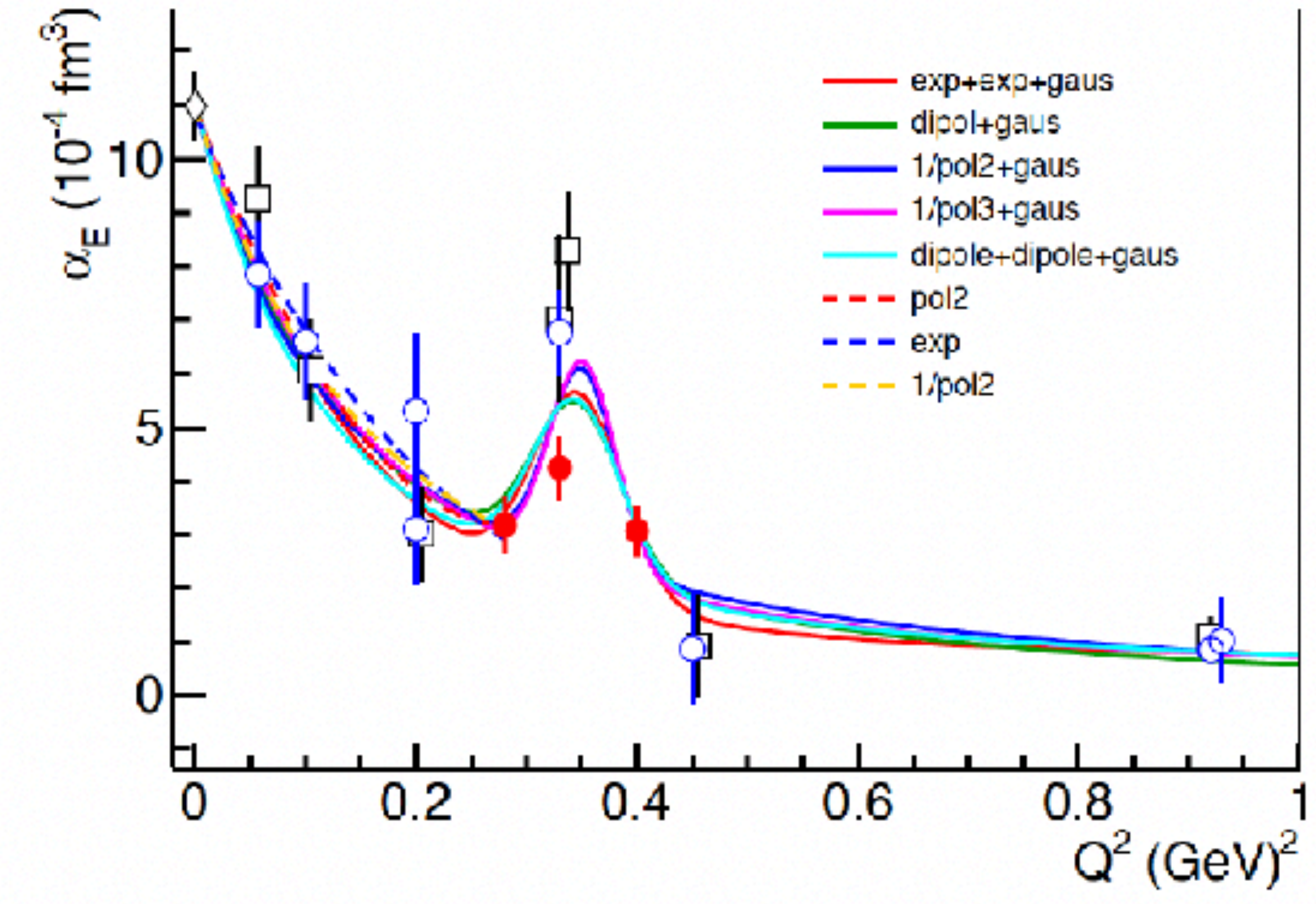


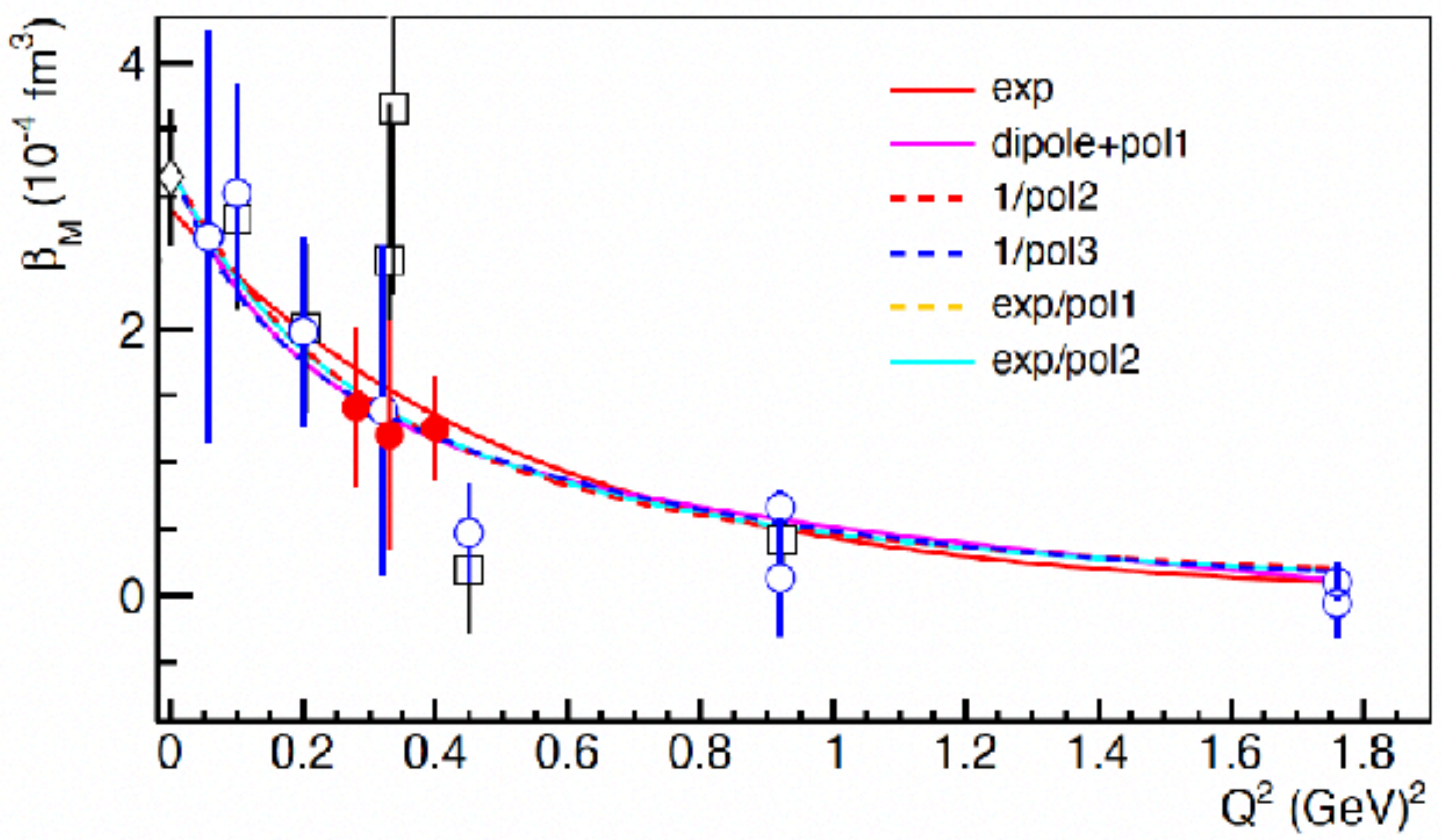
x-y defines the transverse plane with the z-axis being the direction of the fast-moving proton

Polarizability Radii

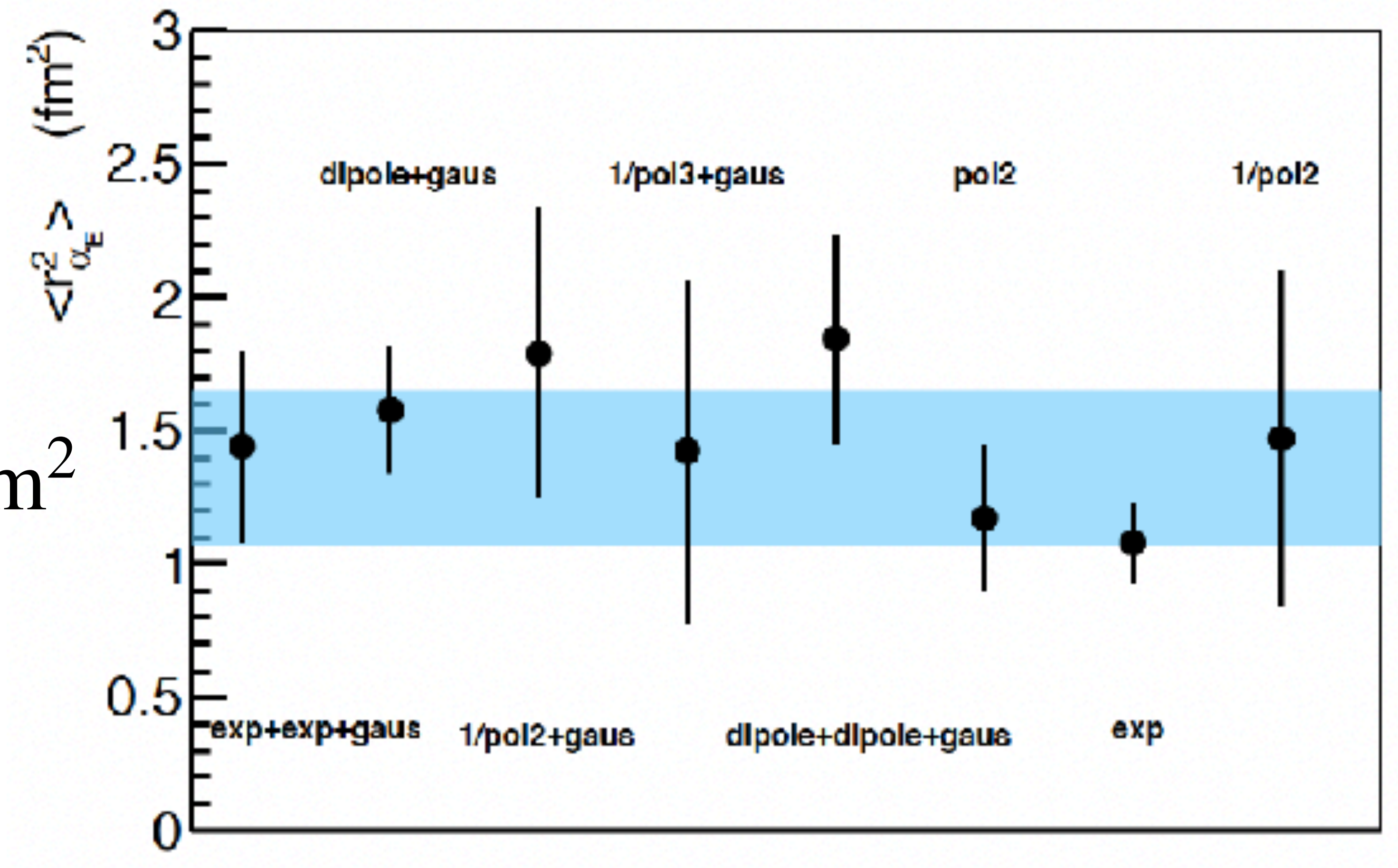
$$\langle r^2_{\alpha_E} \rangle = \frac{-6}{\alpha_E(0)} \cdot \frac{d}{dQ^2} \alpha_E(Q^2) \Big|_{Q^2=0}$$

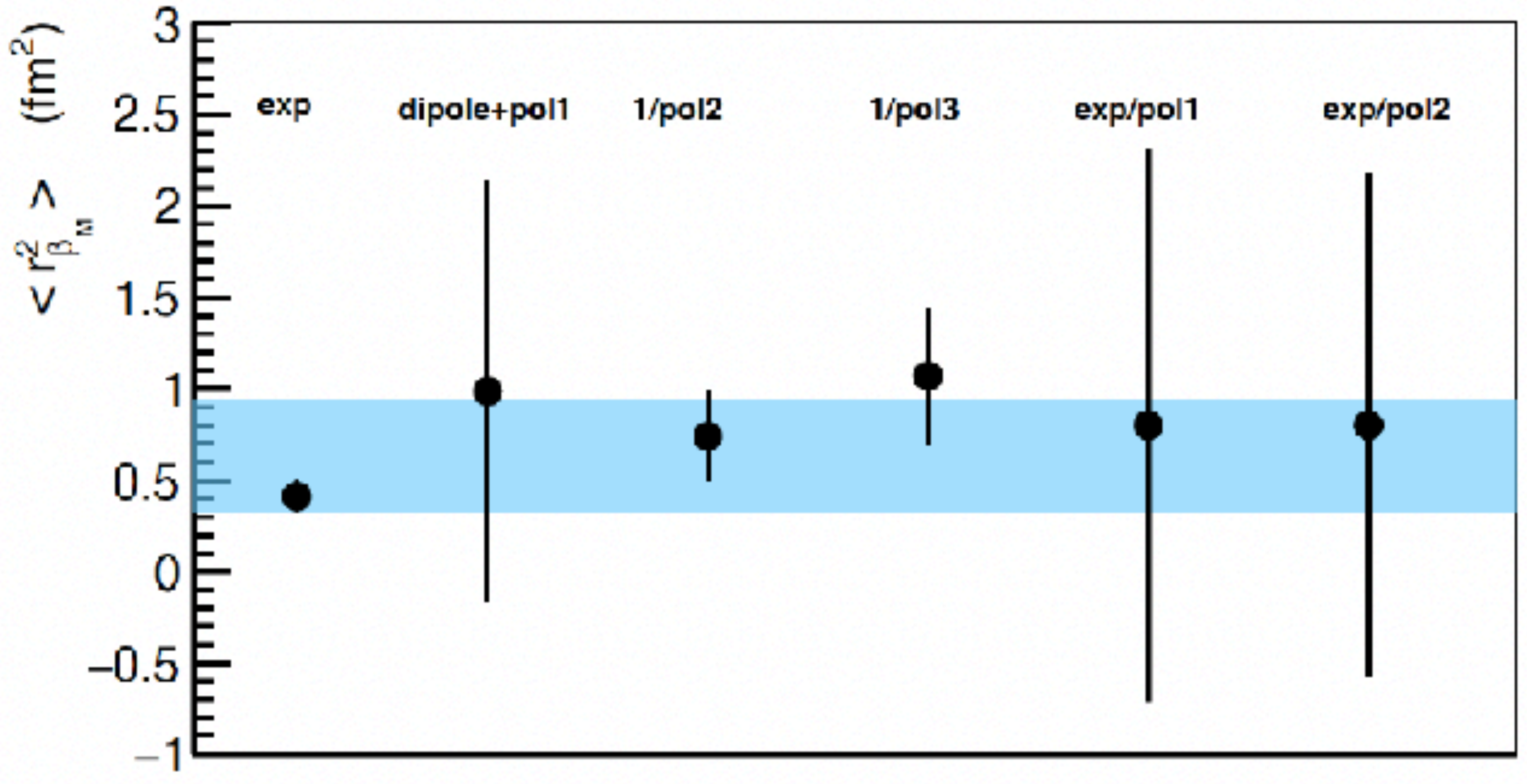
$$\langle r^2_{\beta_M} \rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2} \beta_M(Q^2) \Big|_{Q^2=0}$$





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



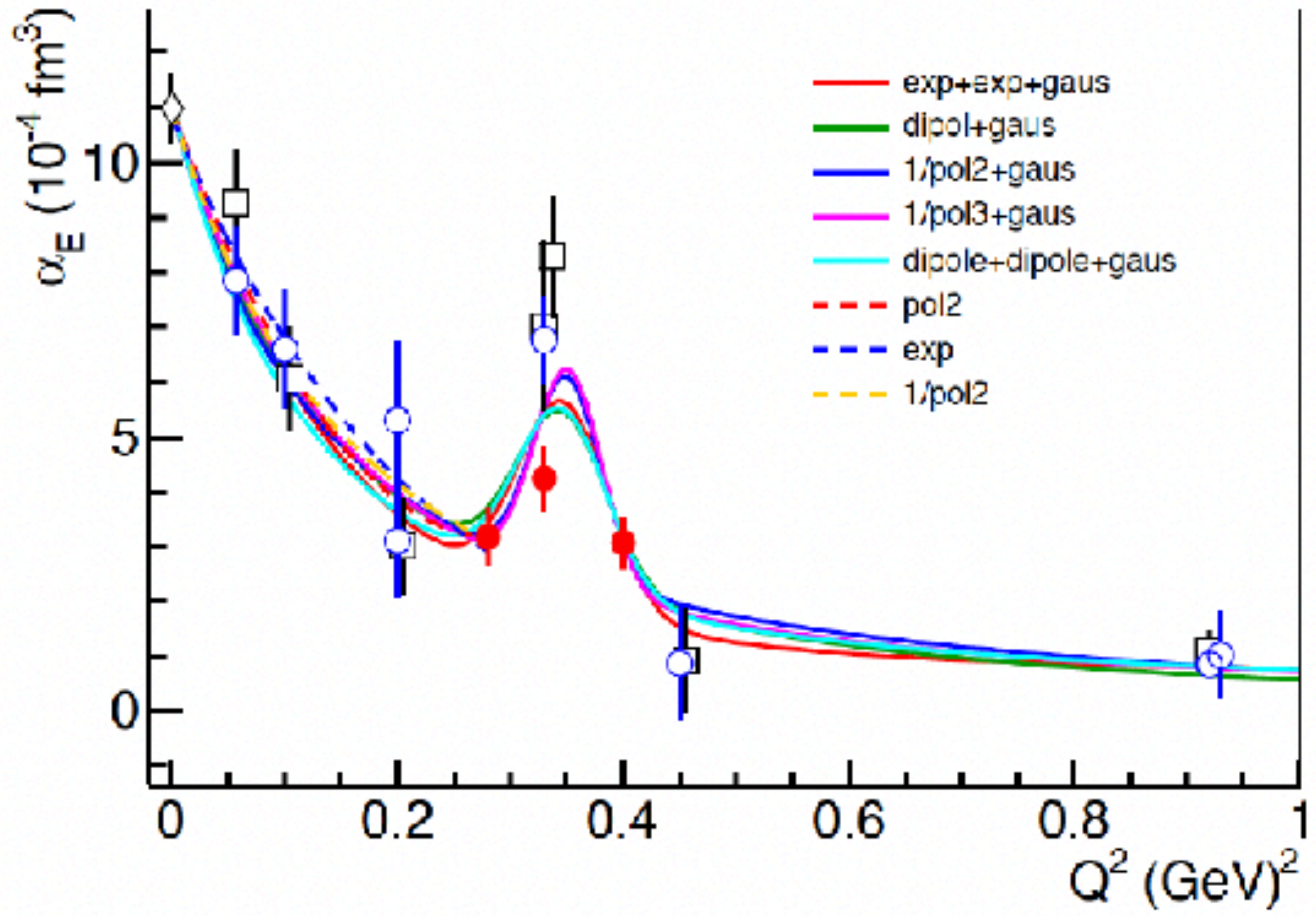


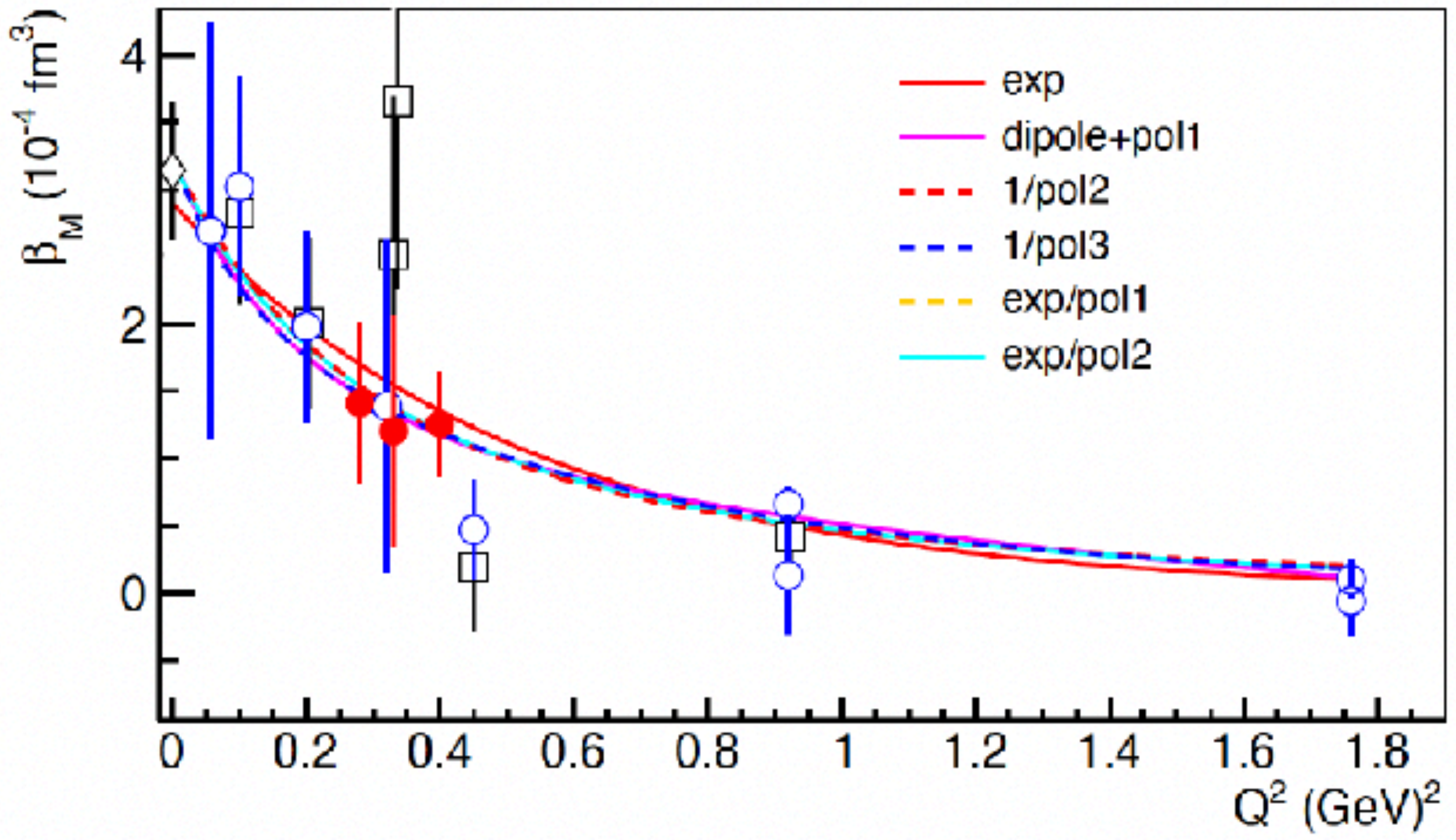
$$\langle r^2_{\beta_M} \rangle = 0.63 \pm 0.31 \ \mathrm{fm}^2$$

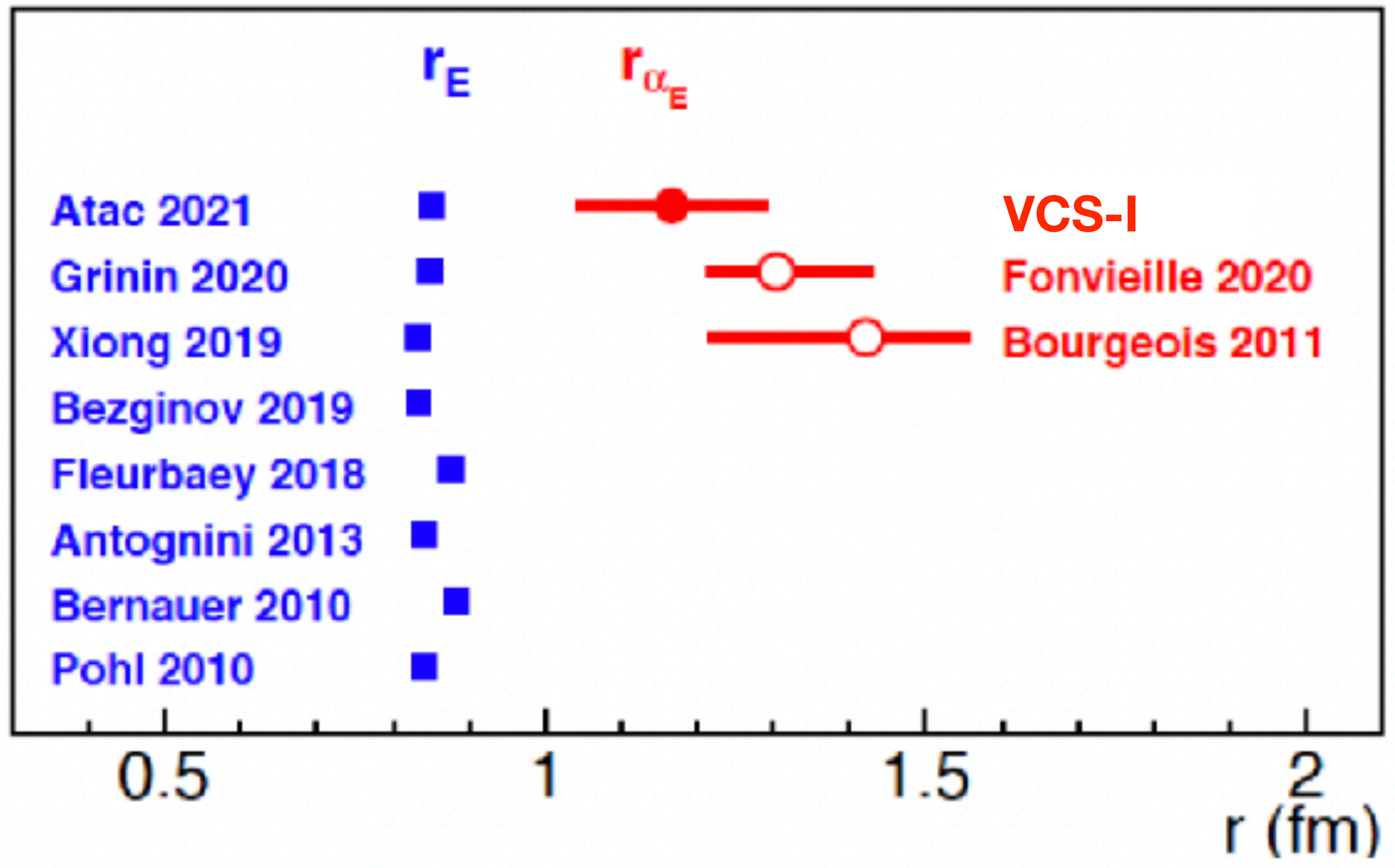
Polarizability Radii

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

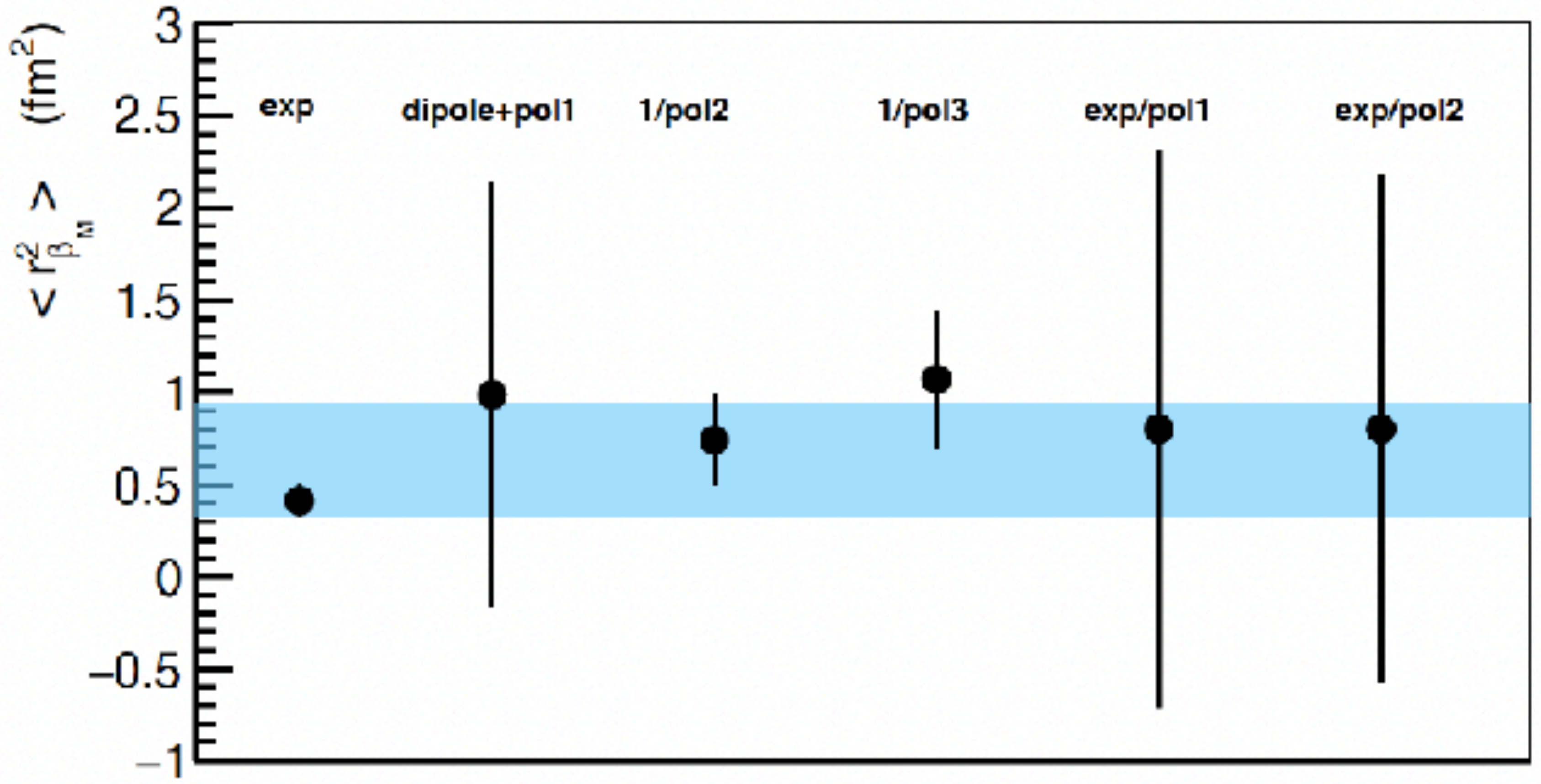
$$\langle r^2_{\beta_M} \rangle = \frac{-6}{\beta_M(0)} \cdot \frac{d}{dQ^2}\beta_M(Q^2)\Big|_{Q^2=0}$$







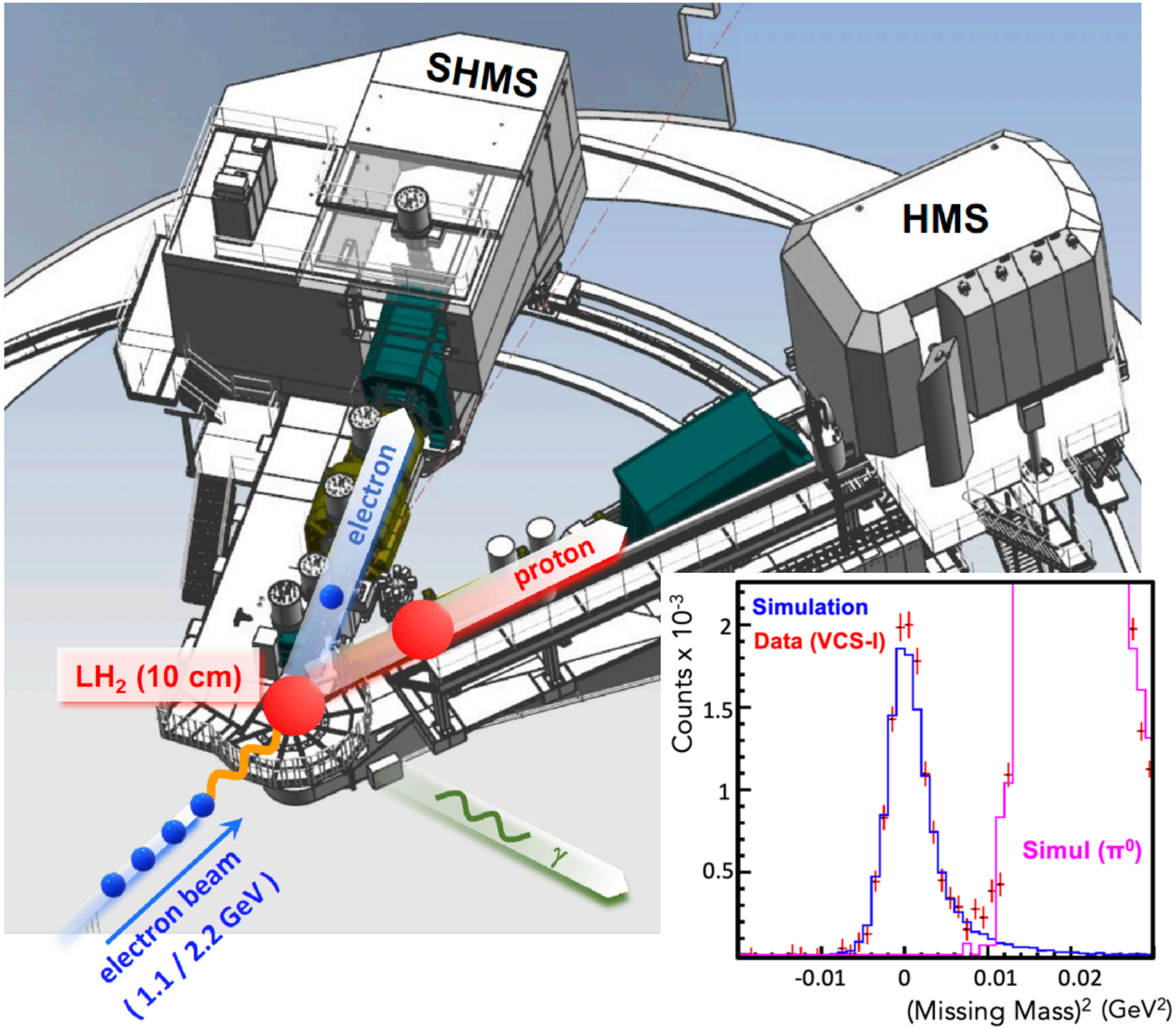
$\langle r^2_{\alpha_E} \rangle = 1.36 \pm 0.29\ \text{fm}^2$



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

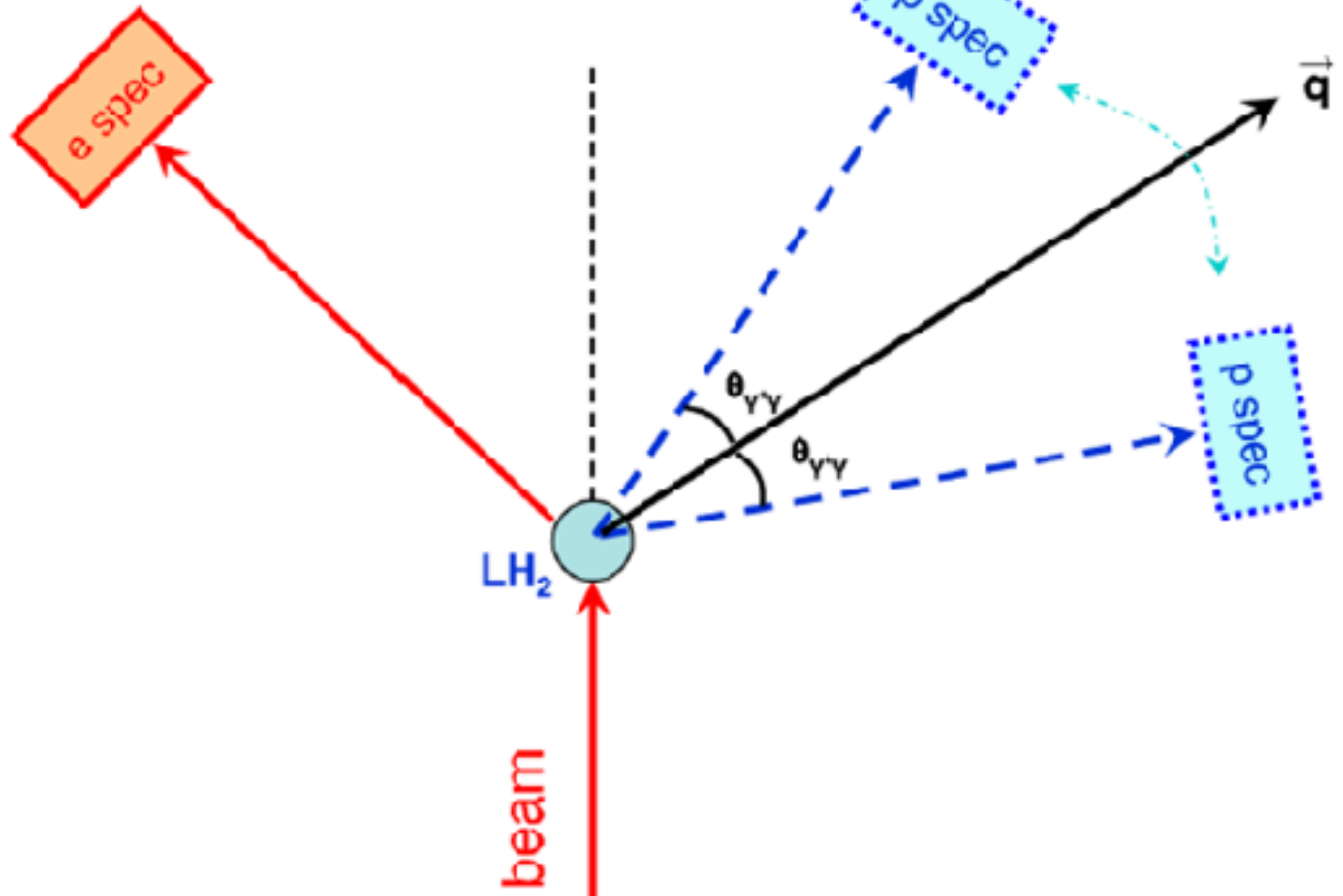
Proposed Experiment: VCS-II

Experimental Setup

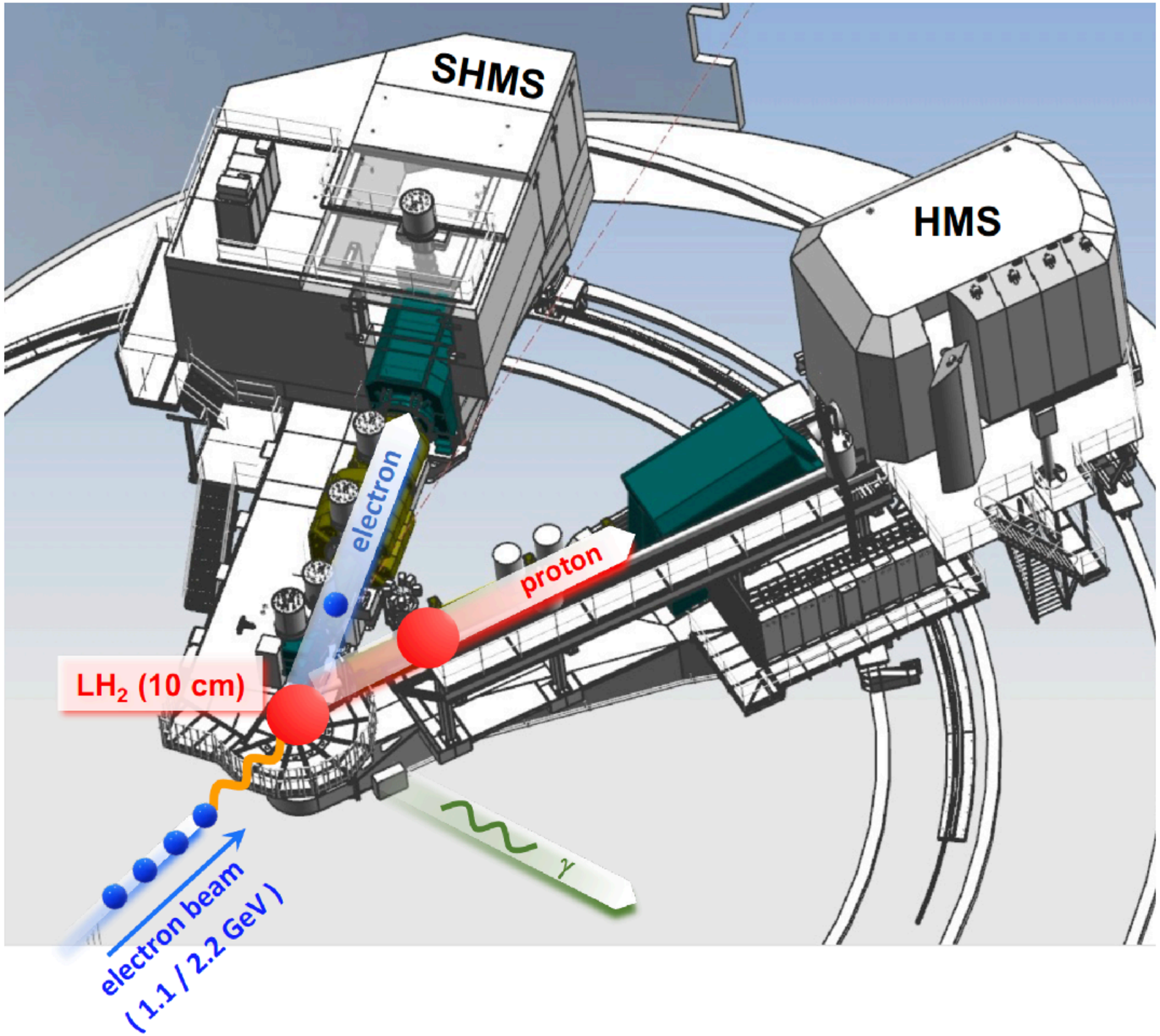


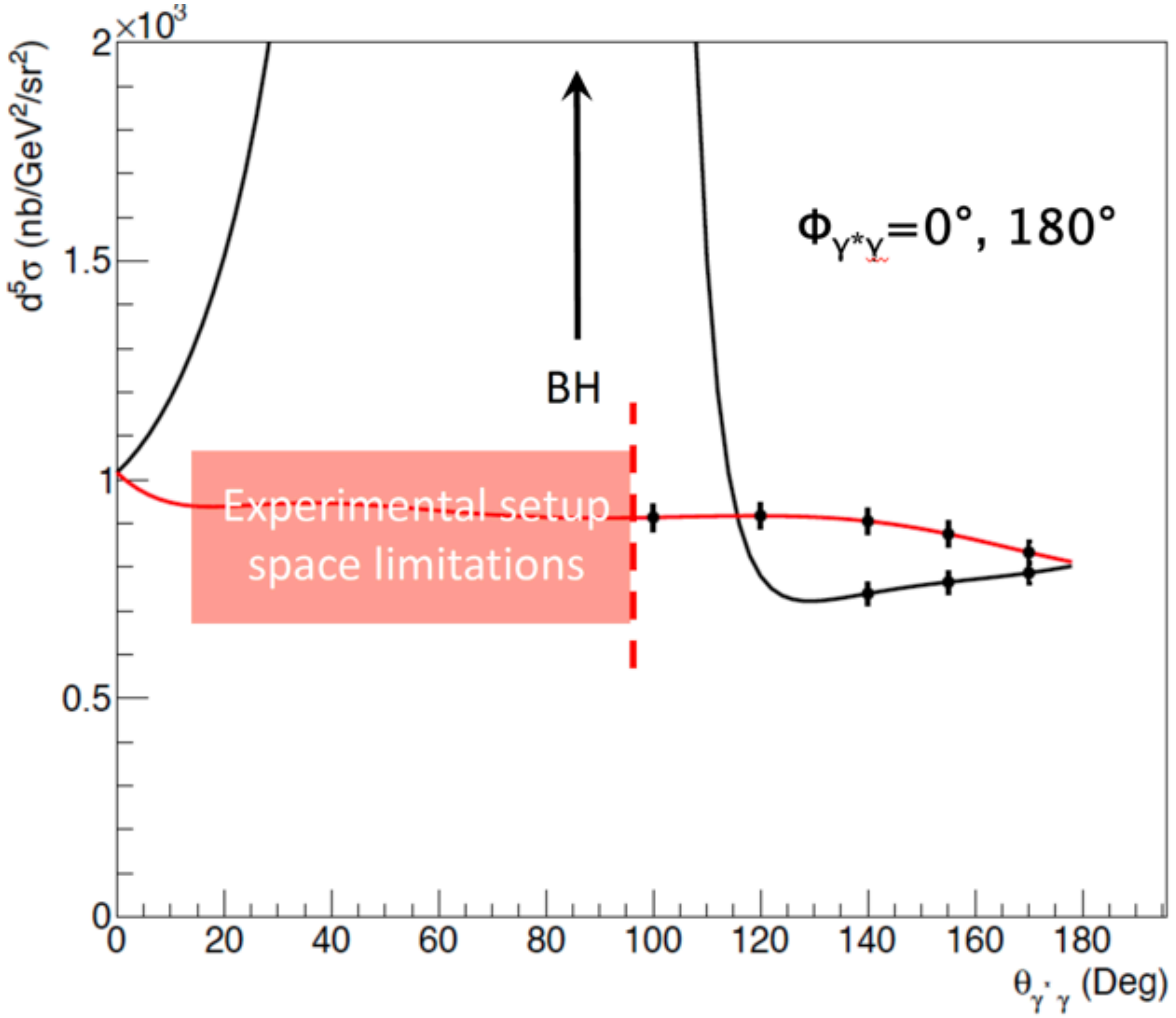
- **Standard Hall-C setup:**
  - SHMS detects electron
  - HMS detects proton
  - Final state photon identified via missing mass.
  - 10cm LH2 target
  - Beam energies of 1.1 and 2.2 GeV
- **Exploit azimuthal asymmetric configurations**
  - Suppression of systematic uncertainties
  - Additional handle on spectrometer momentum calibration

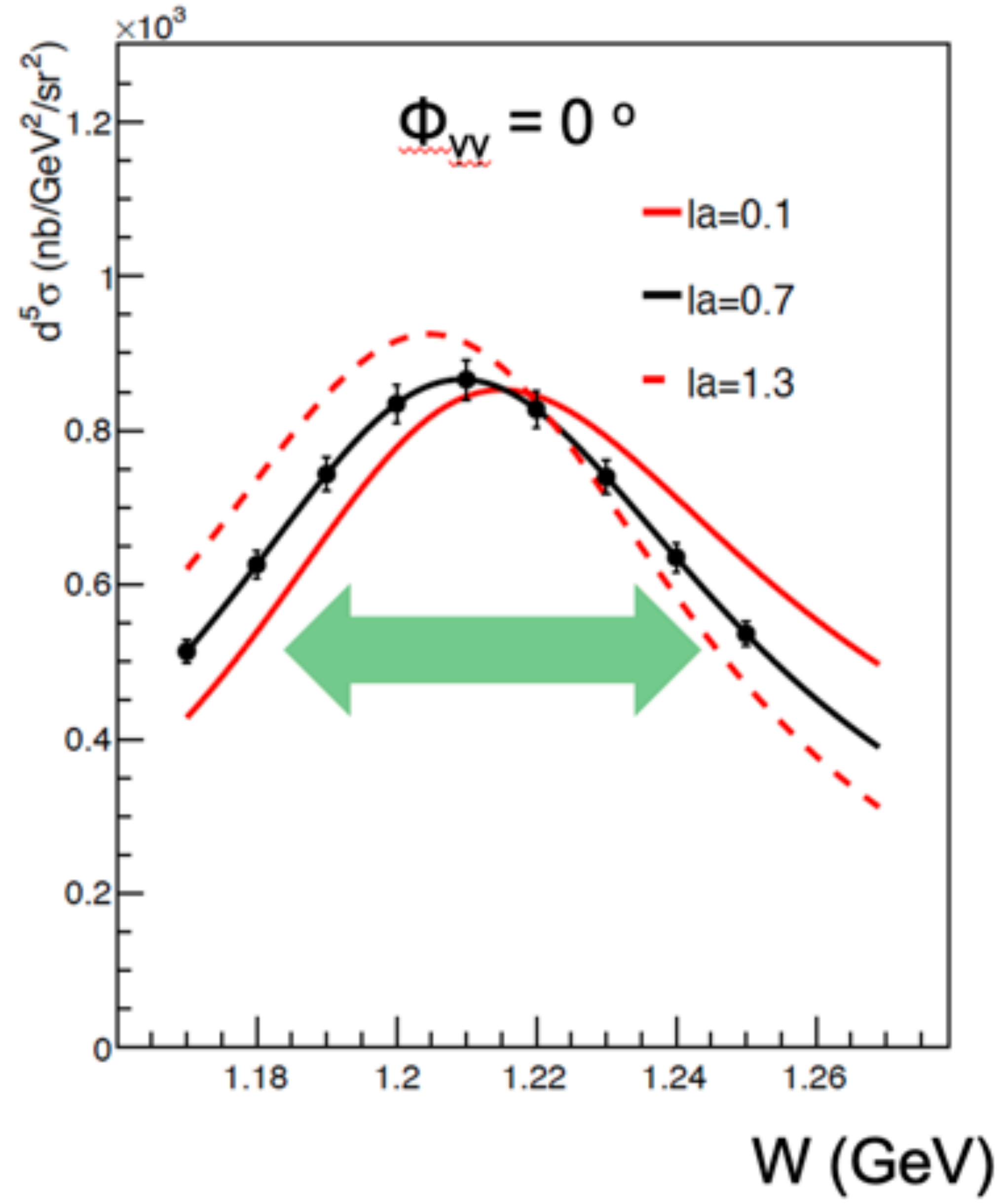
$$A_{(\phi_{\gamma^*\gamma}=0,\pi)} = \frac{\sigma_{\phi_{\gamma^*\gamma}=0} - \sigma_{\phi_{\gamma^*\gamma}=180}}{\sigma_{\phi_{\gamma^*\gamma}=0} + \sigma_{\phi_{\gamma^*\gamma}=180}}$$

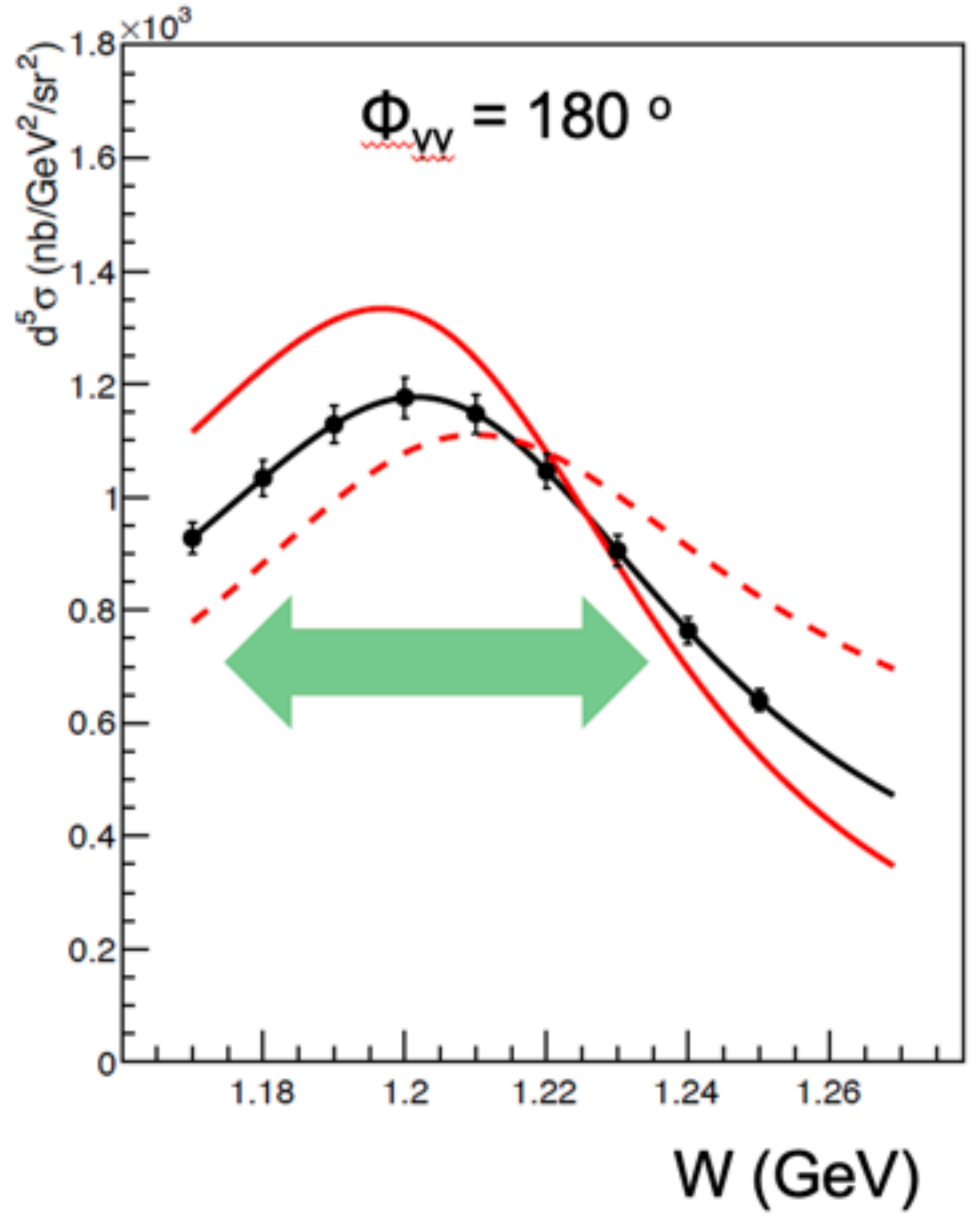


Experimental Setup

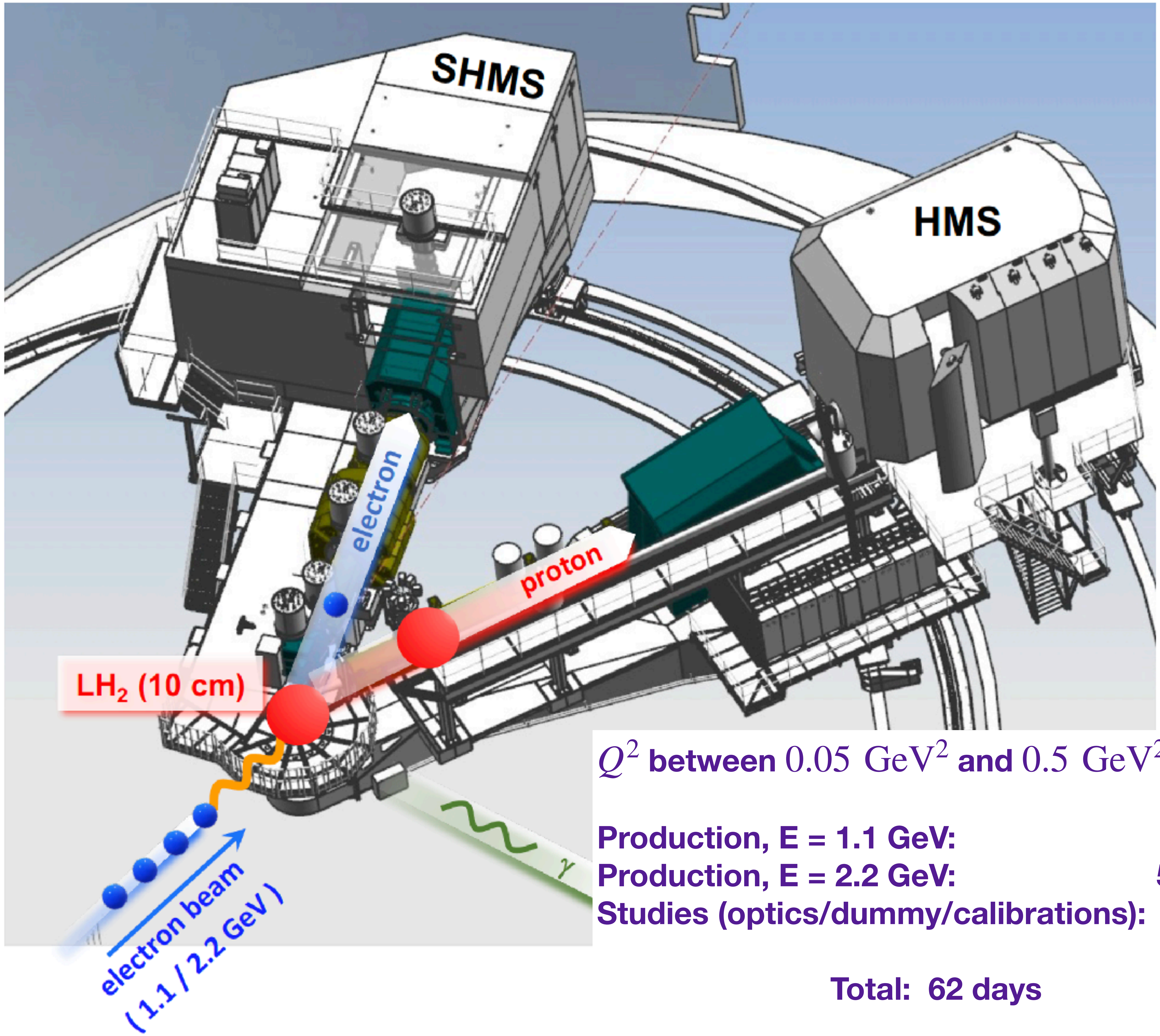








Kinematics

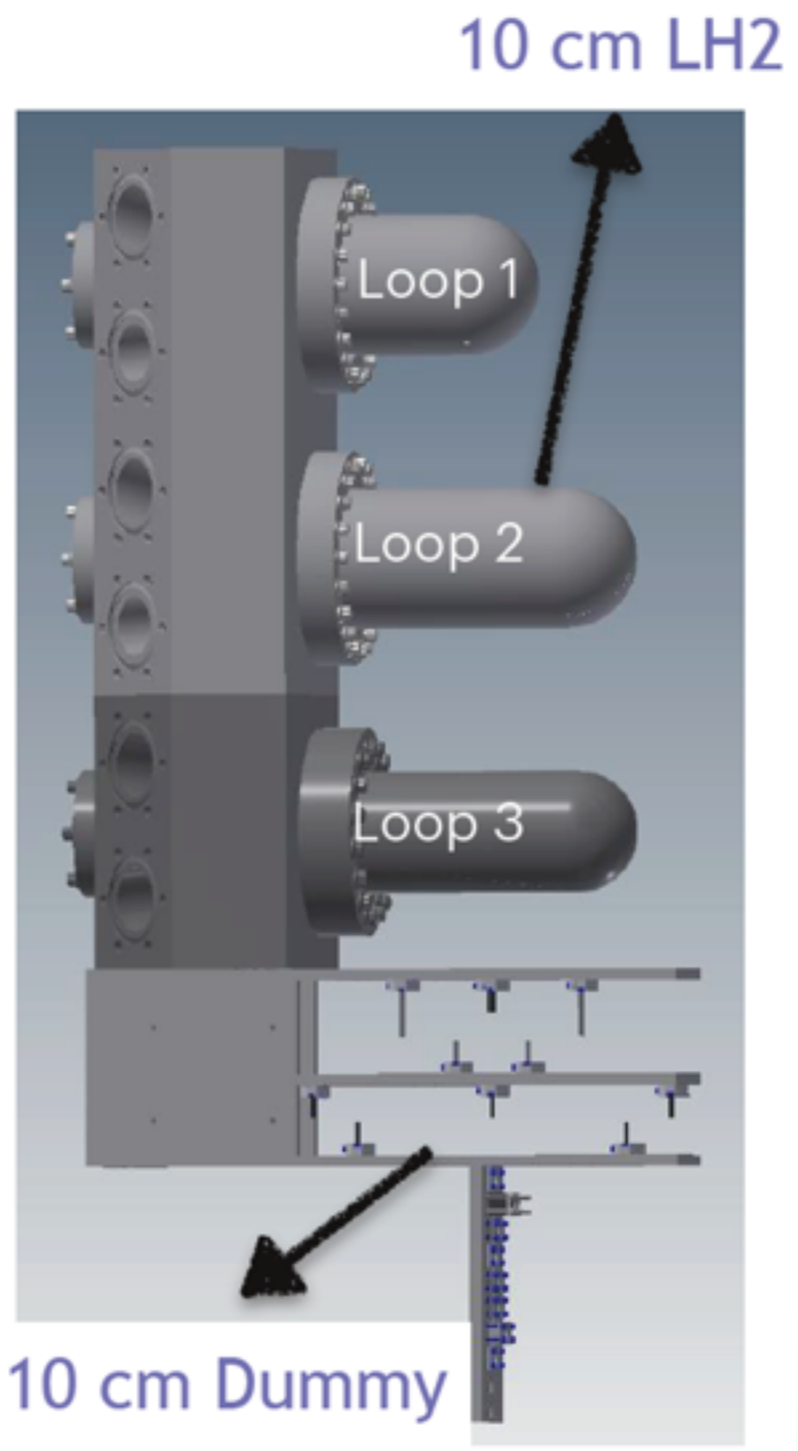


Q^2 **between** $0.05\ \mathrm{GeV}^2$ **and** $0.5\ \mathrm{GeV}^2$

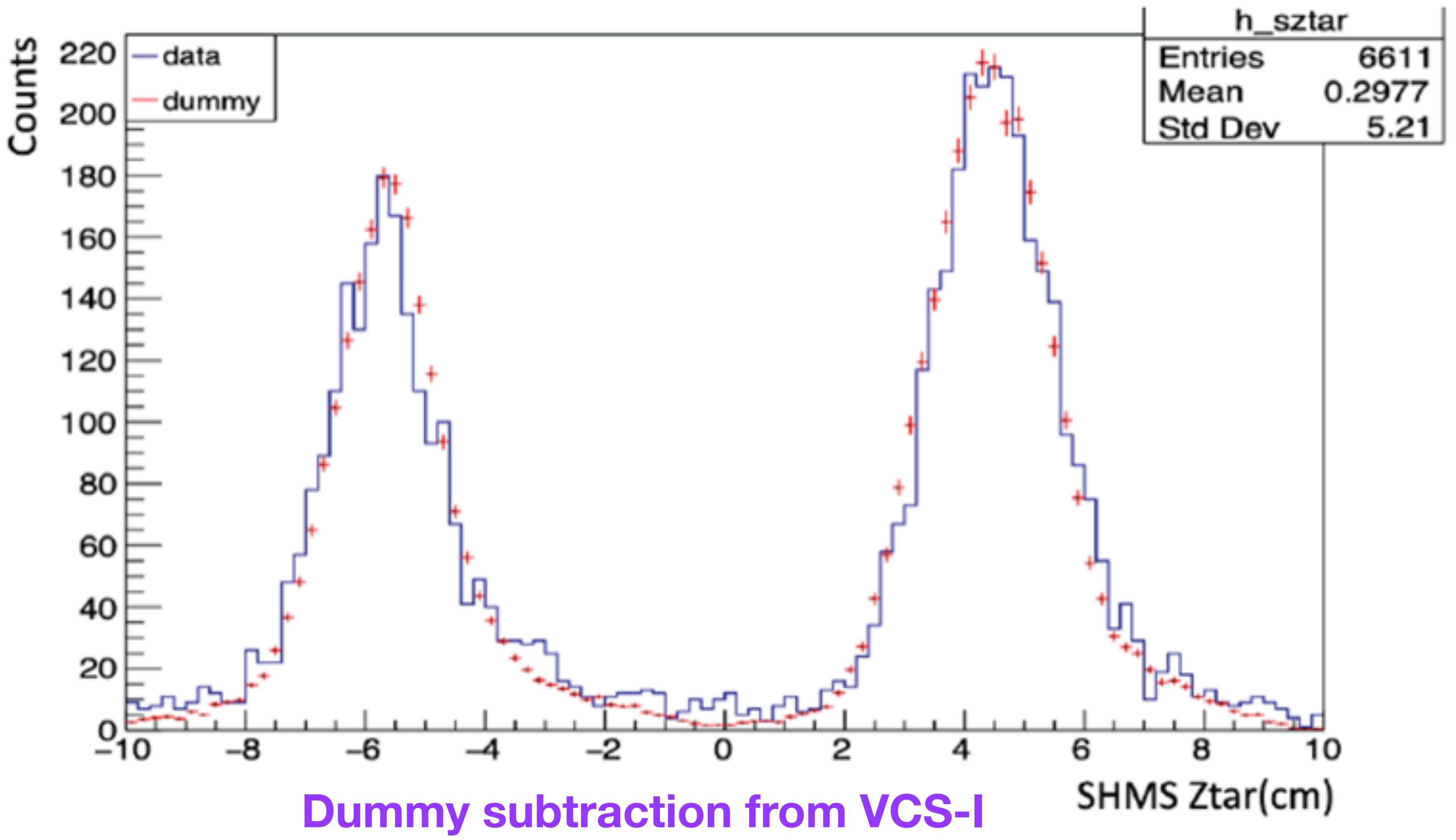
Production, E = 1.1 GeV: 6 days
Production, E = 2.2 GeV: 53 days
Studies (optics/dummy/calibrations): 3 days

Total: 62 days

Kinematic Group	Kinematic Setting	$\theta_{\gamma^*\gamma}$°	θ_e°	$P'_e(MeV/c)$	θ_p°	$P'_p(MeV/c)$	I (μA)	beam time (days)
GI	Kin I	110	14.3	736.3	54.45	493.93	15	1.00
	Kin II	133	14.3	736.3	44.93	556.10	15	1.00
	Kin IIIa	147	14.3	736.3	11.26	583.05	15	1.00
	Kin IIIb	147	14.3	736.3	39.06	583.05	15	1.00
	Kin IVa	160	14.3	736.3	16.73	599.95	15	1.00
	Kin IVb	160	14.3	736.3	33.59	599.95	15	1.00
GII	Kin I	115	11.22	1783.0	15.33	615.69	10	1.50
	Kin IIa	125	11.22	1783.0	56.54	647.85	10	2.50
	Kin IIb	125	11.22	1783.0	18.60	647.85	10	1.50
	Kin IIIa	145	11.22	1783.0	49.77	697.99	10	1.50
	Kin IIIb	145	11.22	1783.0	25.37	697.99	10	1.00
	Kin IVa	165	11.22	1783.0	42.82	726.87	10	1.00
	Kin IVb	165	11.22	1783.0	32.32	726.87	10	1.00
GIII	Kin I	115	14.73	1729.7	20.58	706.89	30	1.75
	Kin IIa	130	14.73	1729.7	54.89	758.24	30	2.00
	Kin IIb	130	14.73	1729.7	24.78	758.24	30	1.75
	Kin IIIa	150	14.73	1729.7	48.99	808.24	30	1.75
	Kin IIIb	150	14.73	1729.7	30.68	808.24	30	1.75
	Kin IVa	170	14.73	1729.7	42.90	834.12	30	1.00
	Kin IVb	170	14.73	1729.7	36.76	834.12	30	1.00
GIV	Kin I	100	16.32	1749.3	23.83	664.52	35	1.75
	Kin II	120	16.32	1749.3	28.01	738.39	50	1.25
	Kin IIIa	140	16.32	1749.3	32.84	795.37	70	1.00
	Kin IIIb	140	16.32	1749.3	53.80	795.37	70	2.00
	Kin IVa	155	16.32	1749.3	36.69	824.46	70	1.50
	Kin IVb	155	16.32	1749.3	49.95	824.46	70	2.50
	Kin Va	170	16.32	1749.3	40.66	840.48	70	1.00
	Kin Vb	170	16.32	1749.3	45.99	840.48	70	1.00
GV	Kin I	100	17.72	1676.41	19.75	723.69	35	2.00
	Kin II	120	17.72	1676.41	24.25	808.93	50	1.50
	Kin IIIa	140	17.72	1676.41	29.34	874.74	70	1.50
	Kin IIIb	140	17.72	1676.41	51.12	874.74	70	2.00
	Kin IVa	155	17.72	1676.41	33.36	908.37	70	2.00
	Kin IVb	155	17.72	1676.41	47.10	908.37	70	2.00
	Kin Va	170	17.72	1676.41	37.47	926.91	70	1.00
	Kin Vb	170	17.72	1676.41	42.99	926.91	70	1.00
GVI	Kin I	120	20.45	1623.1	25.31	886.59	75	1.00
	Kin IIa	140	20.45	1623.1	29.91	956.82	75	1.00
	Kin IIb	140	20.45	1623.1	49.81	956.82	75	1.50
	Kin IIIa	155	20.45	1623.1	33.58	992.83	75	1.50
	Kin IIIb	155	20.45	1623.1	46.14	992.83	75	2.00



- **3 days of optics/ dummy/calibrations are requested.**



Dummy subtraction from VCS-I

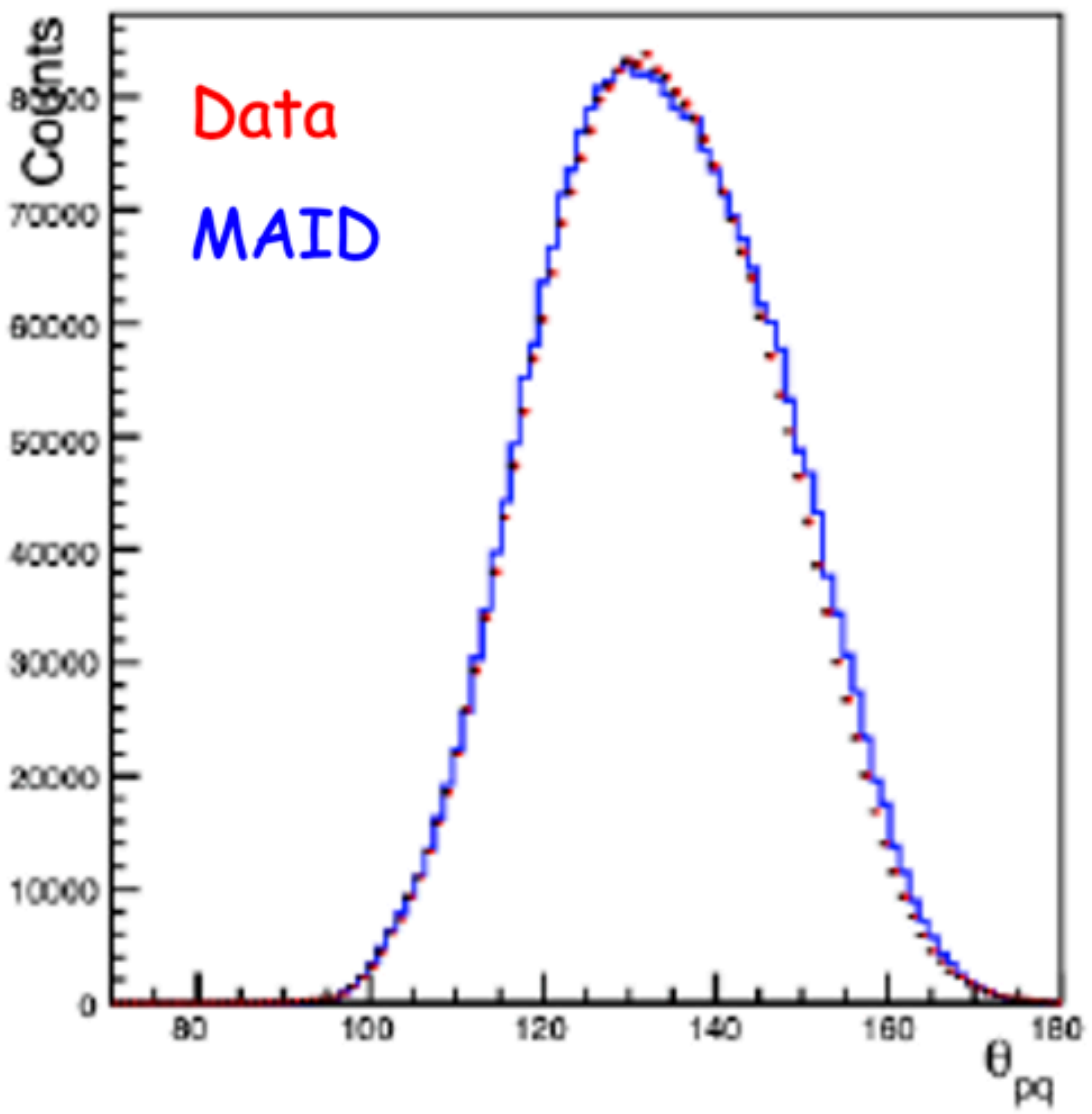
Kinematic Group	Kinematic Setting	HMS singles rates (kHz)
GIV	Kin I	476
	Kin II	497
	Kin IIIa	453
	Kin IIIb	64
	Kin IVa	313
	Kin IVb	89
	Kin Va	212
	Kin Vb	127
GV	Kin I	483
	Kin II	502
	Kin IIIa	444
	Kin IIIb	51
	Kin IVa	295
	Kin IVb	72
	Kin Va	192
	Kin Vb	108
GVI	Kin I	591
	Kin IIa	349
	Kin IIb	33
	Kin IIIa	527
	Kin IIIb	49

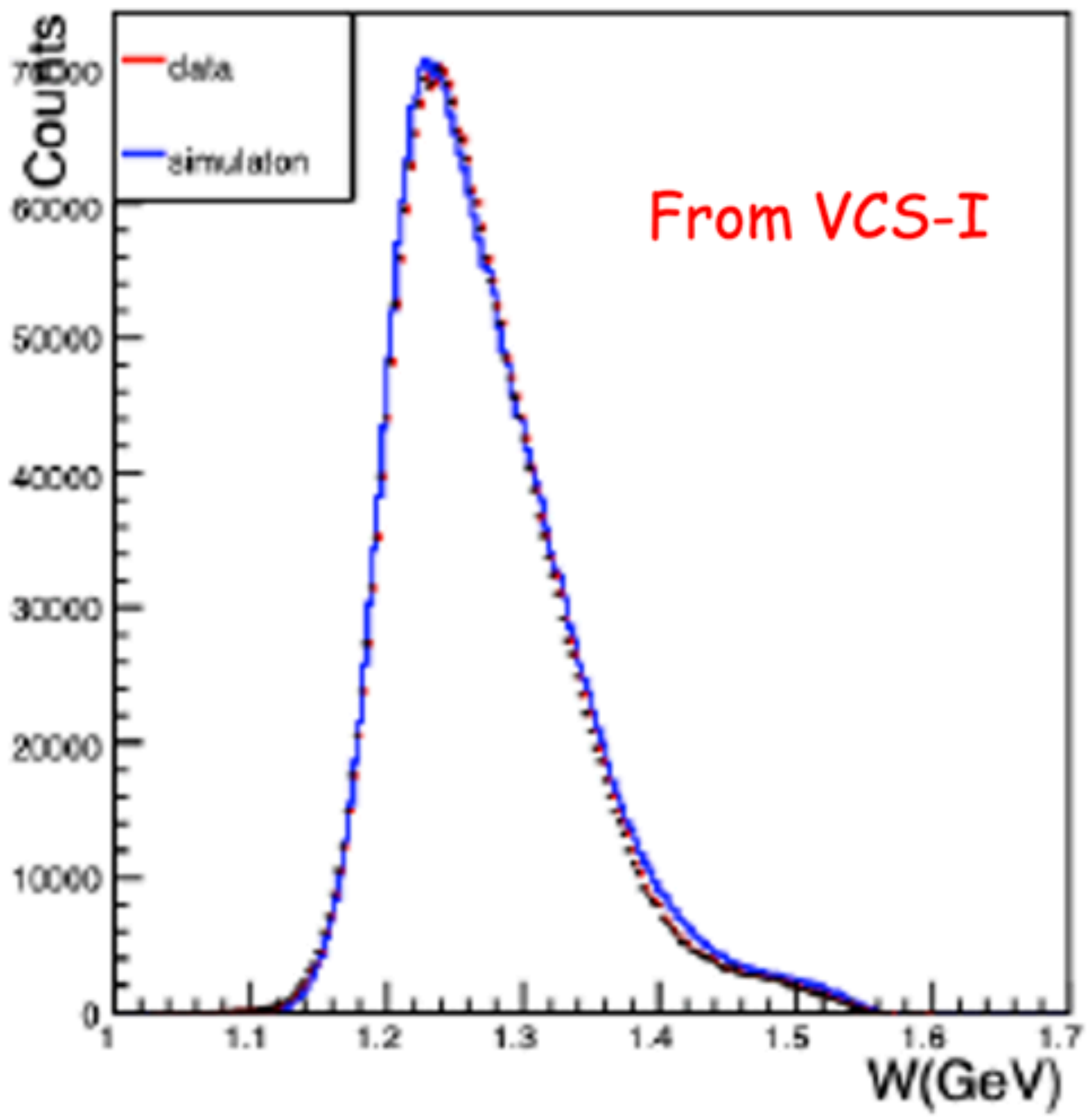
Kinematic Group	Kinematic Setting	HMS singles rates (kHz)
GI	Kin I	43
	Kin II	53
	Kin IIIa	119
	Kin IIIb	65
	Kin IVa	128
	Kin IVb	80
GII	Kin I	159
	Kin IIa	21
	Kin IIb	155
	Kin IIIa	28
	Kin IIIb	122
	Kin IVa	42
	Kin IVb	82
GIII	Kin I	347
	Kin IIa	27
	Kin IIb	330
	Kin IIIa	47
	Kin IIIb	214
	Kin IVa	77
	Kin IVb	129

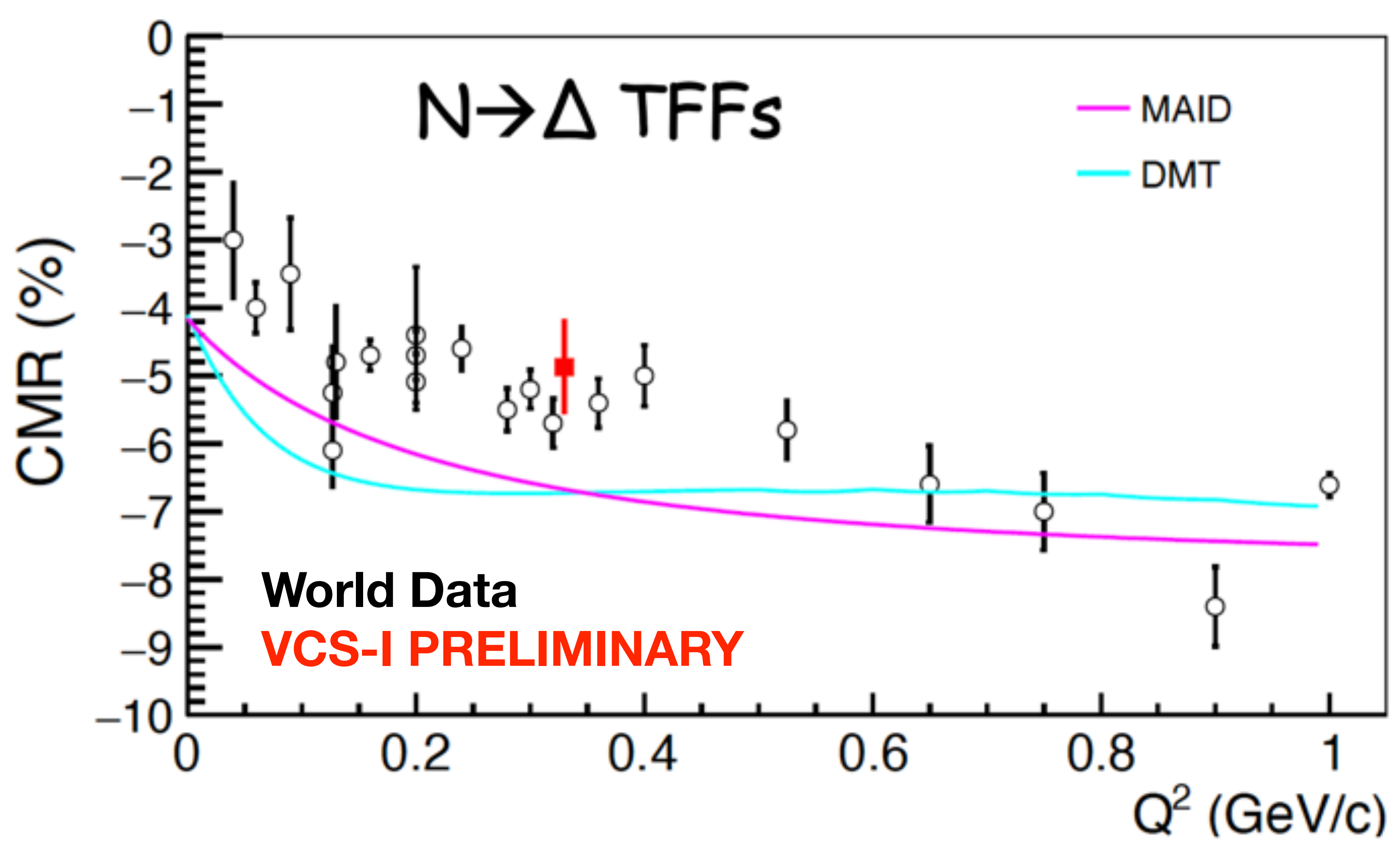
- **Singles rates are well under control (~0.5 MHz or less)**

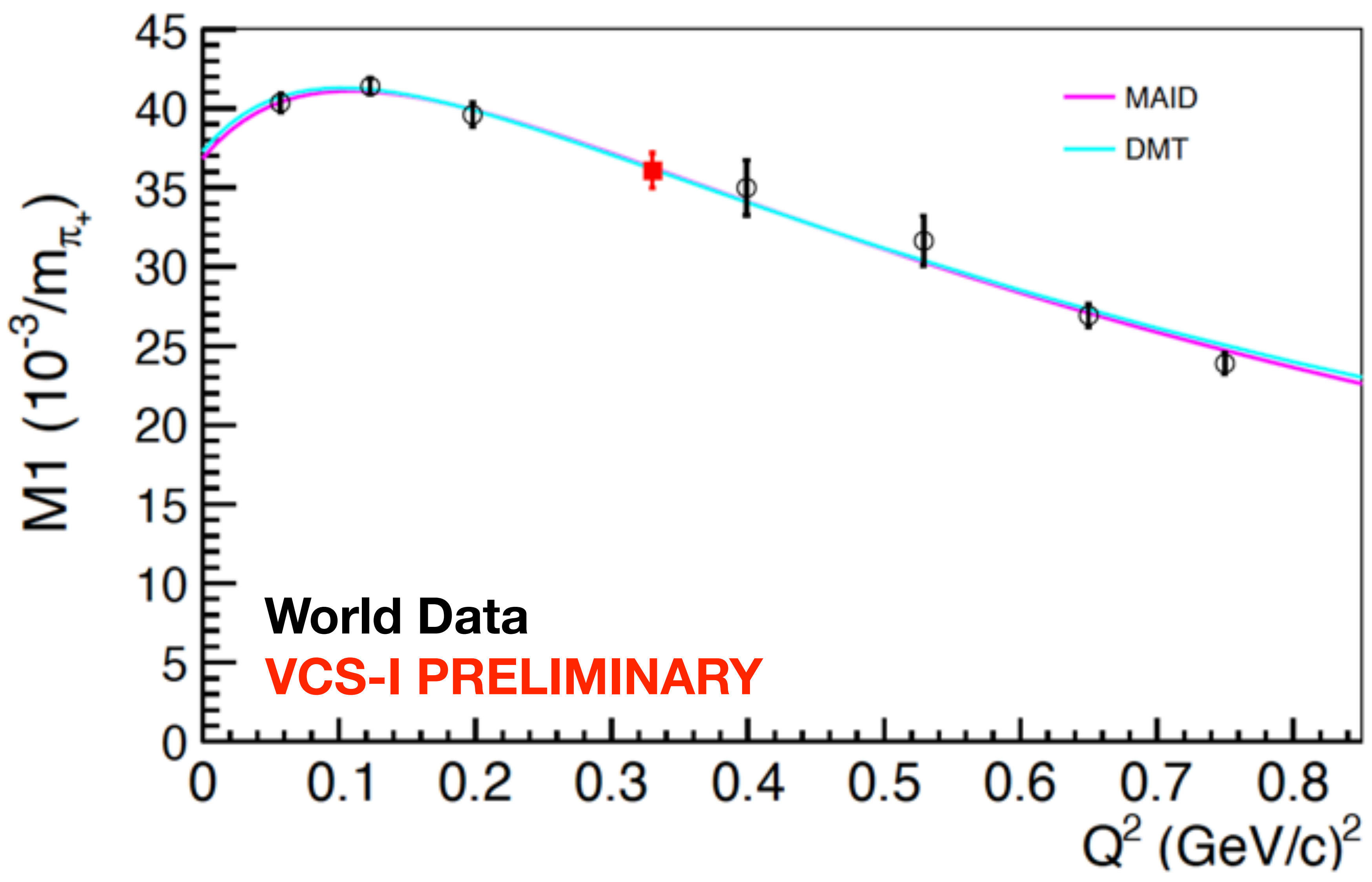
Other Studies

- $p(e, e'p)\pi^0$ **channel:**
  - Measured for free within acceptance
  - Well known cross-section
  - Provides additional handle for normalization and spectrometer acceptance studies

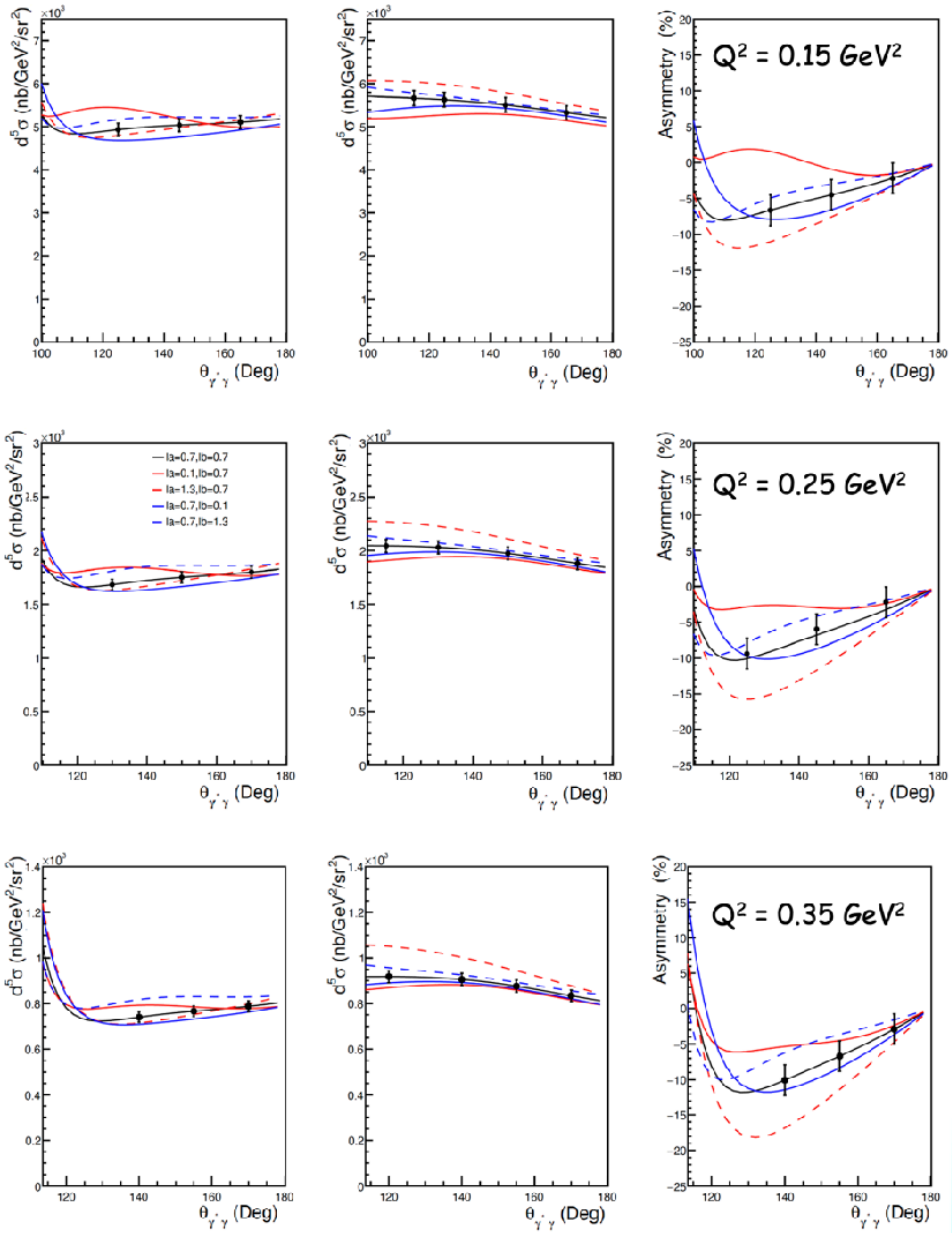


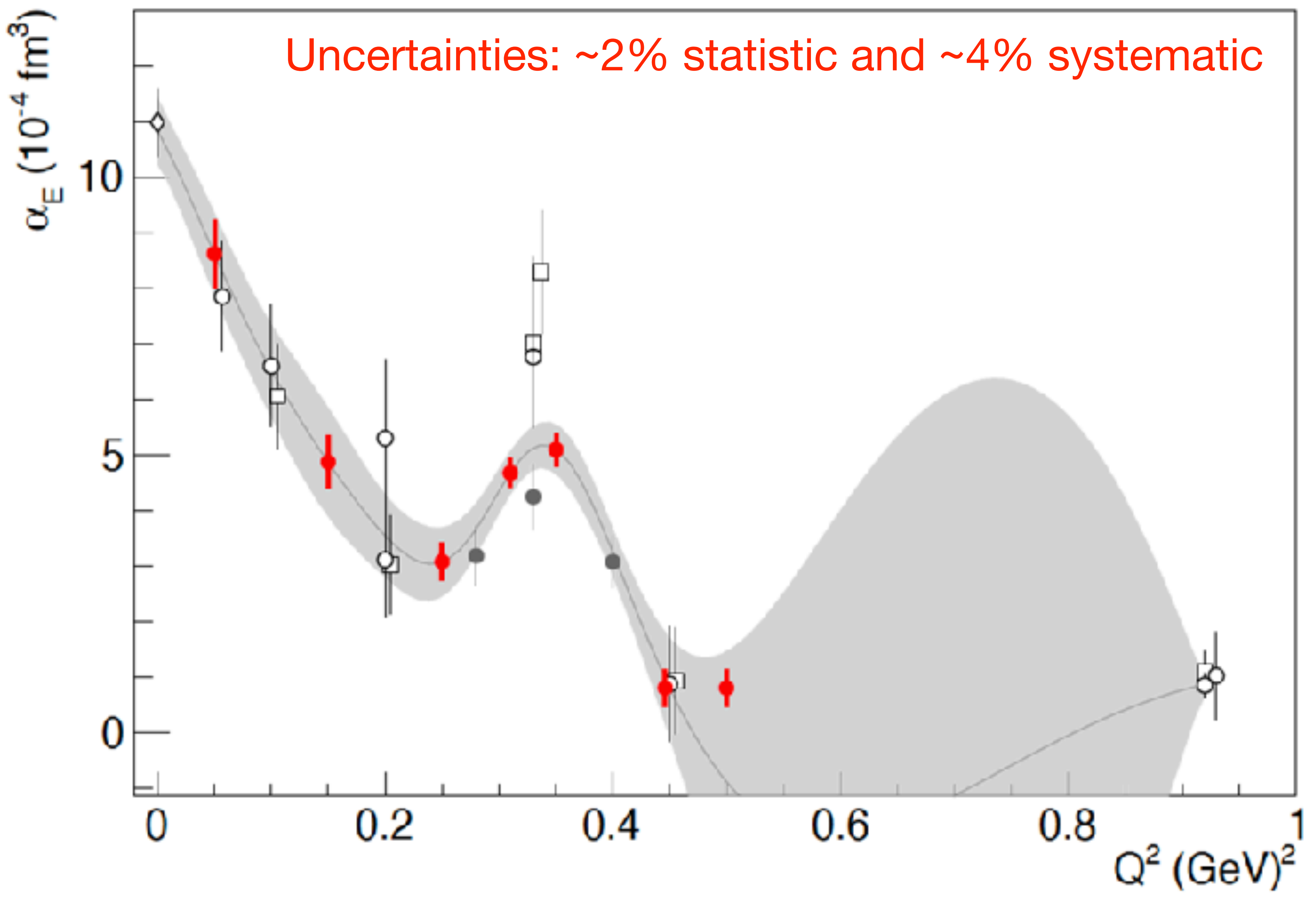


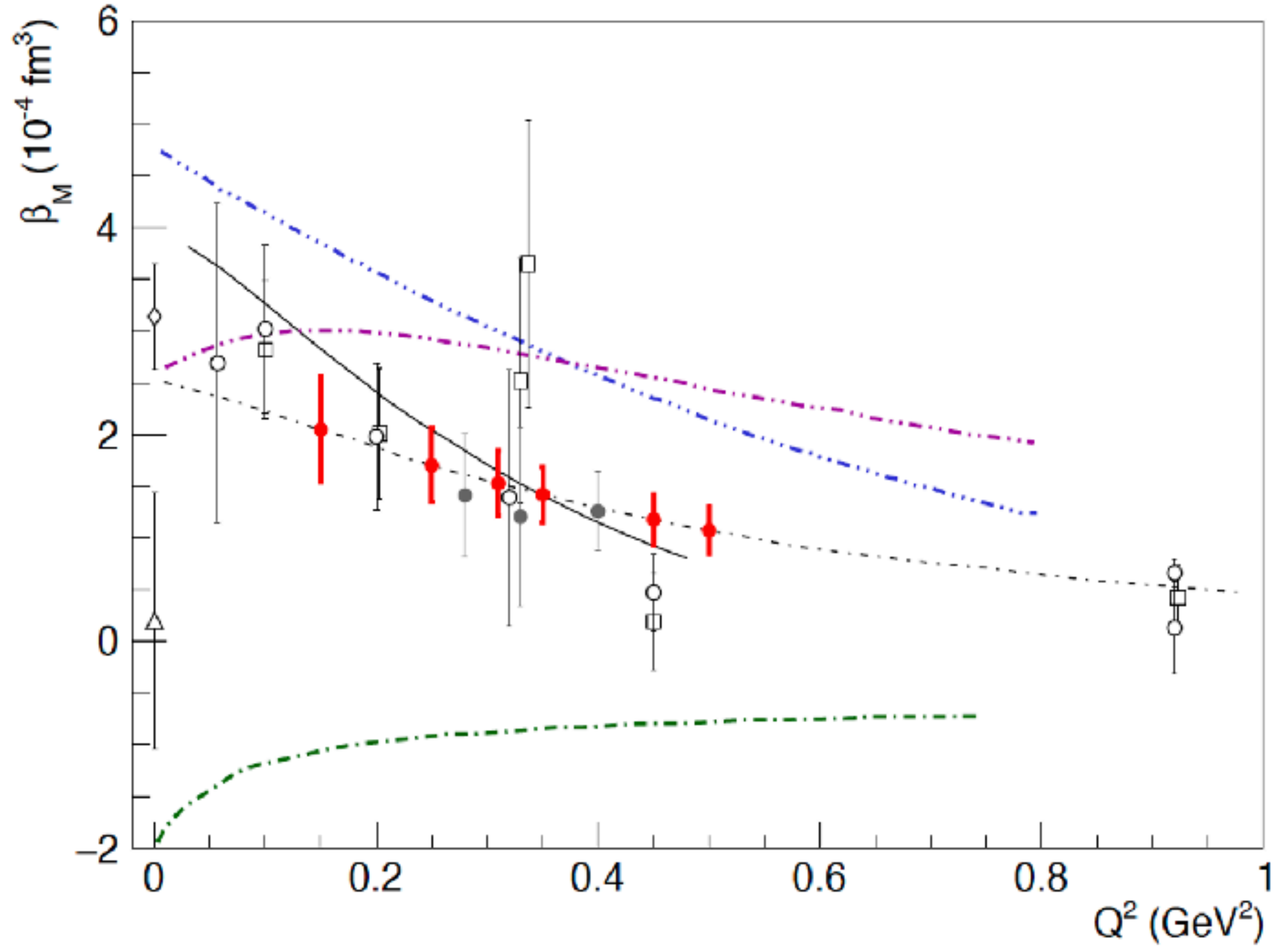




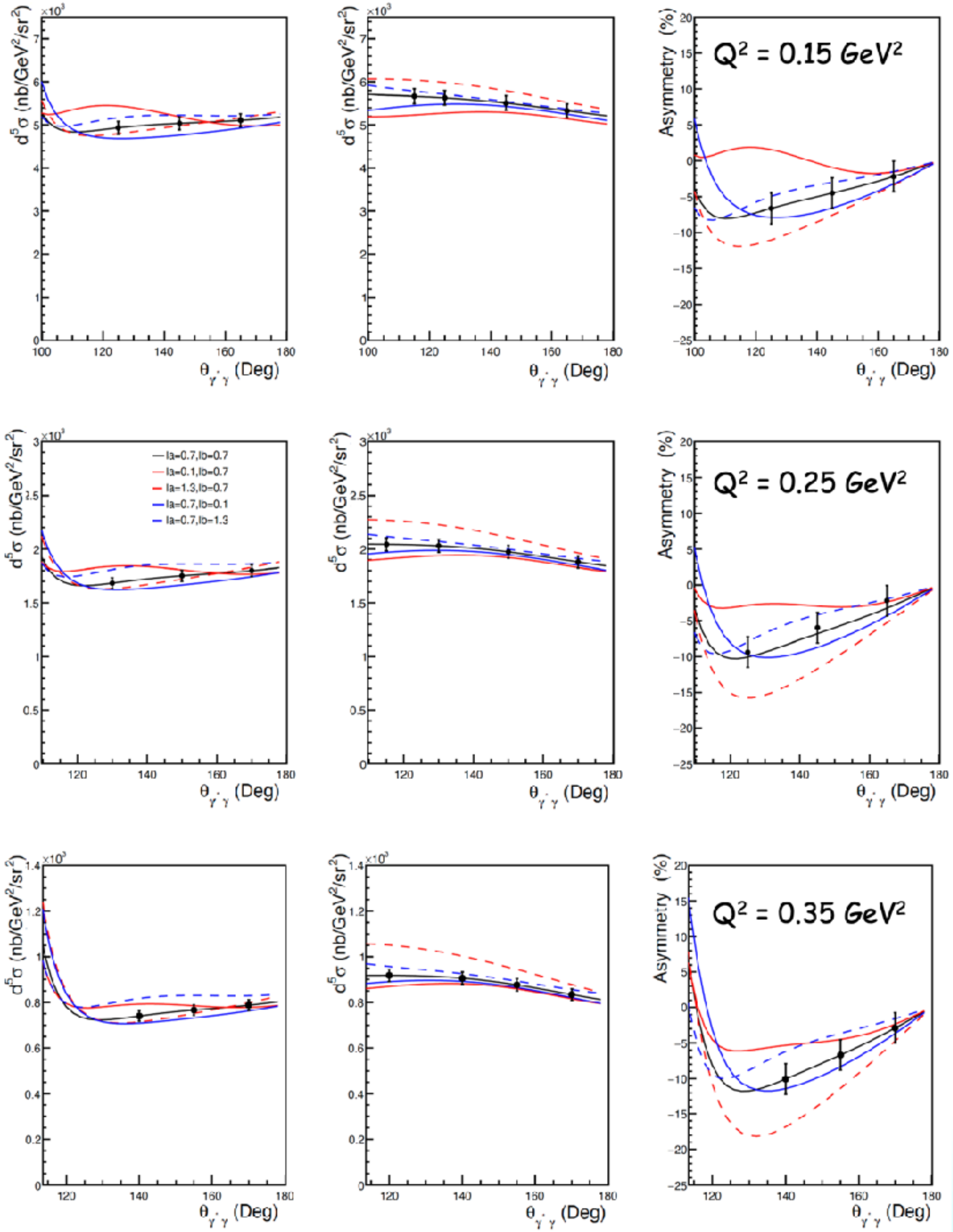
Projections

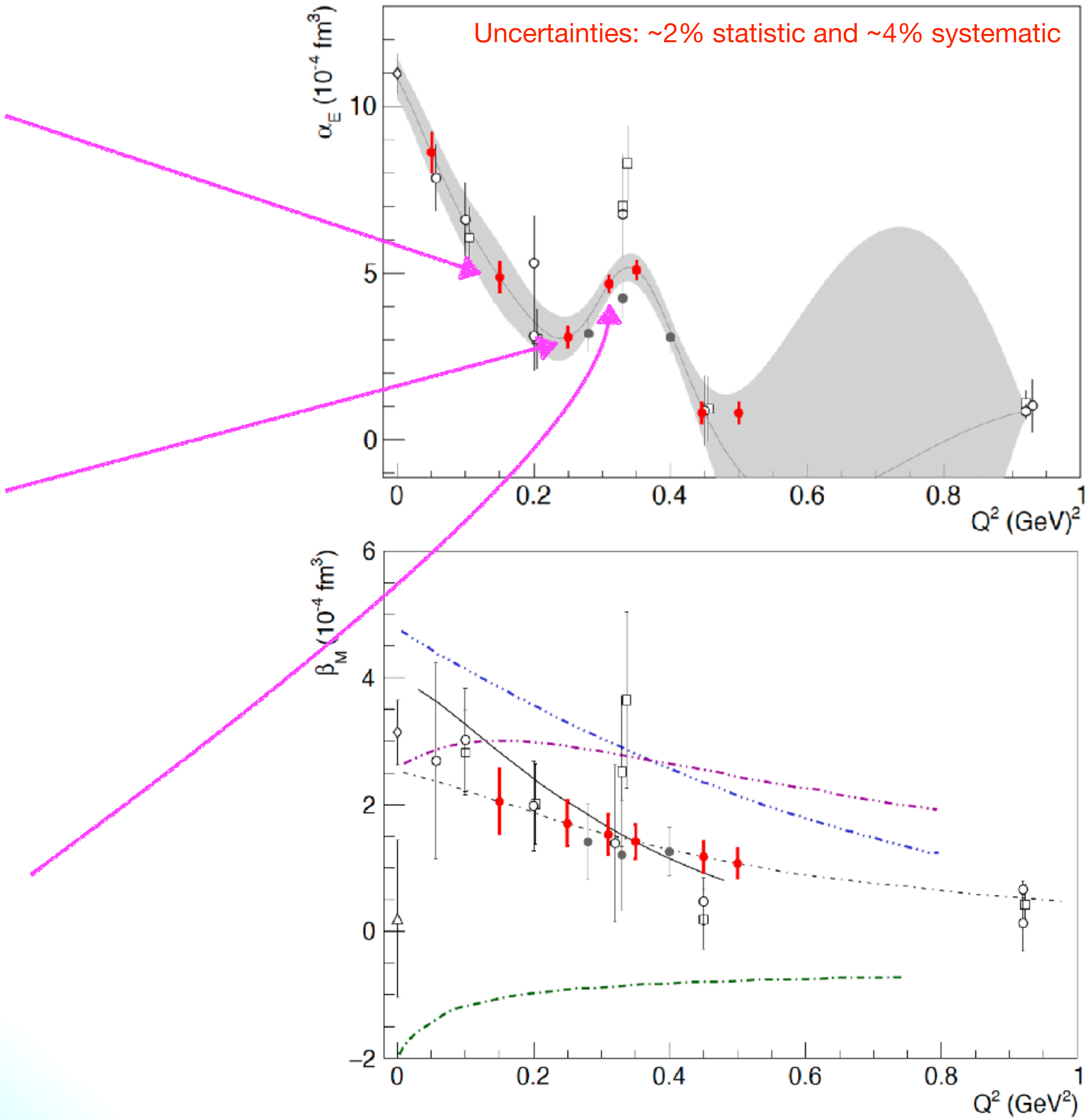






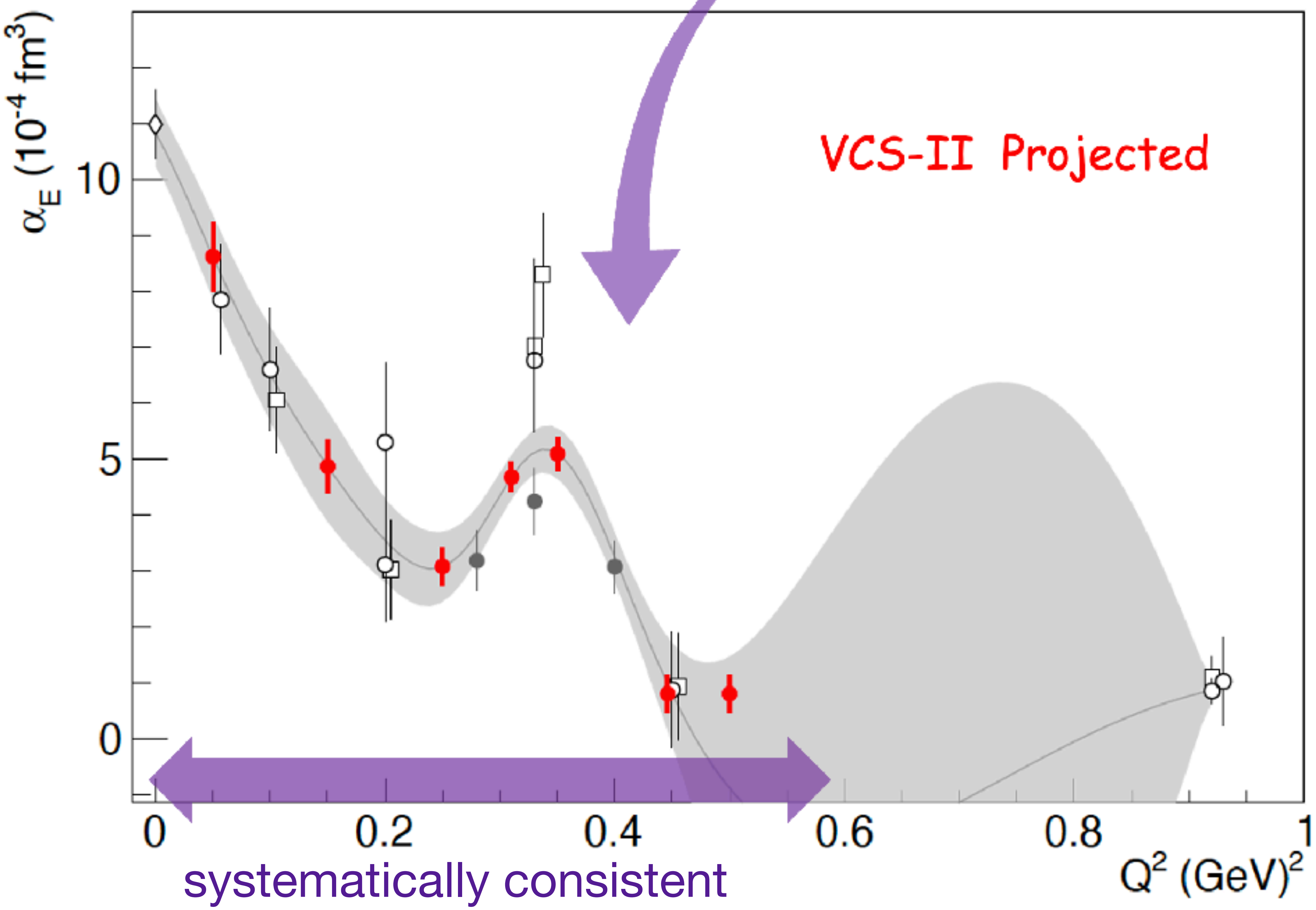
Projections



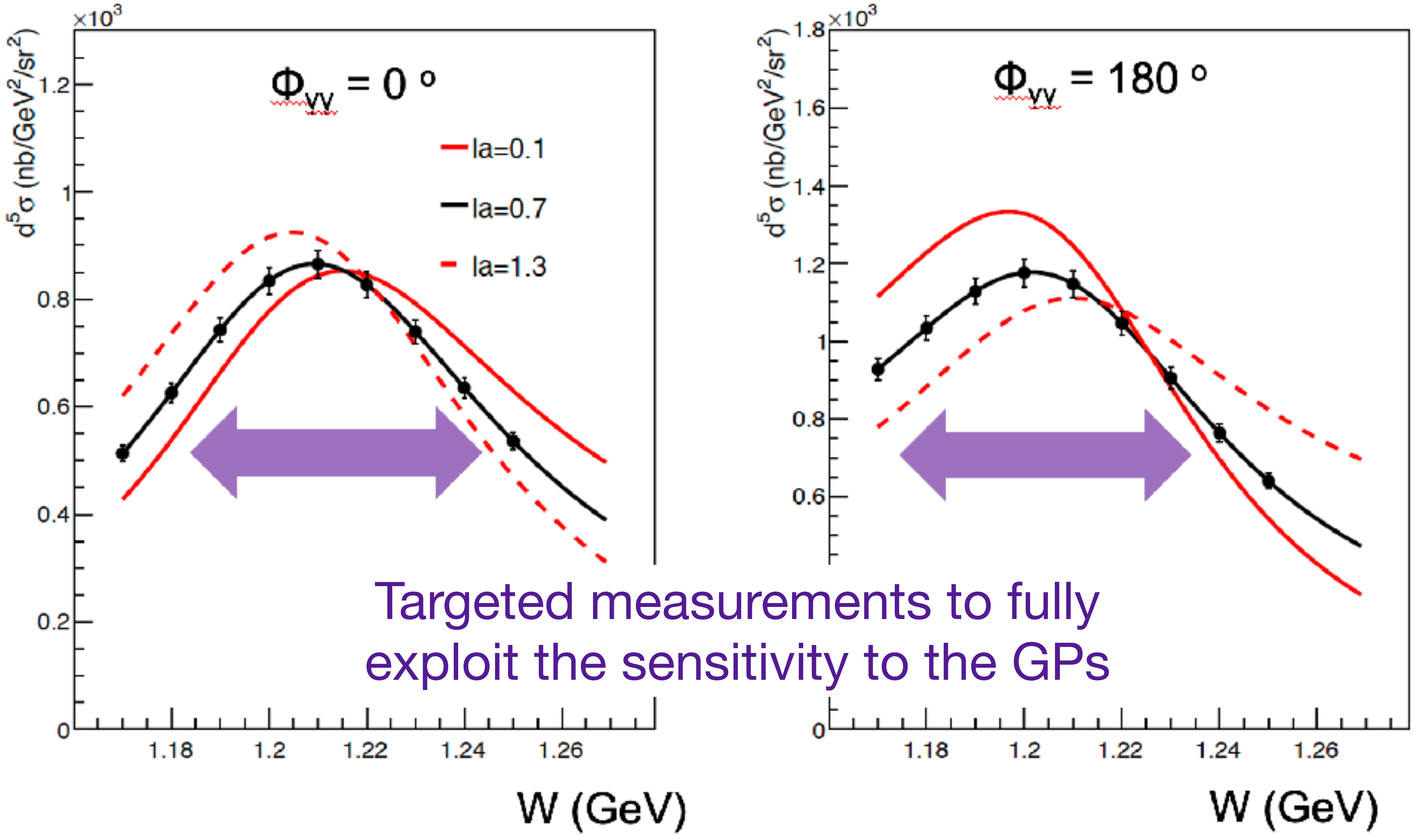


VCS-II Primary Experiment Goals

High precision measurements combined with a fine mapping in Q2



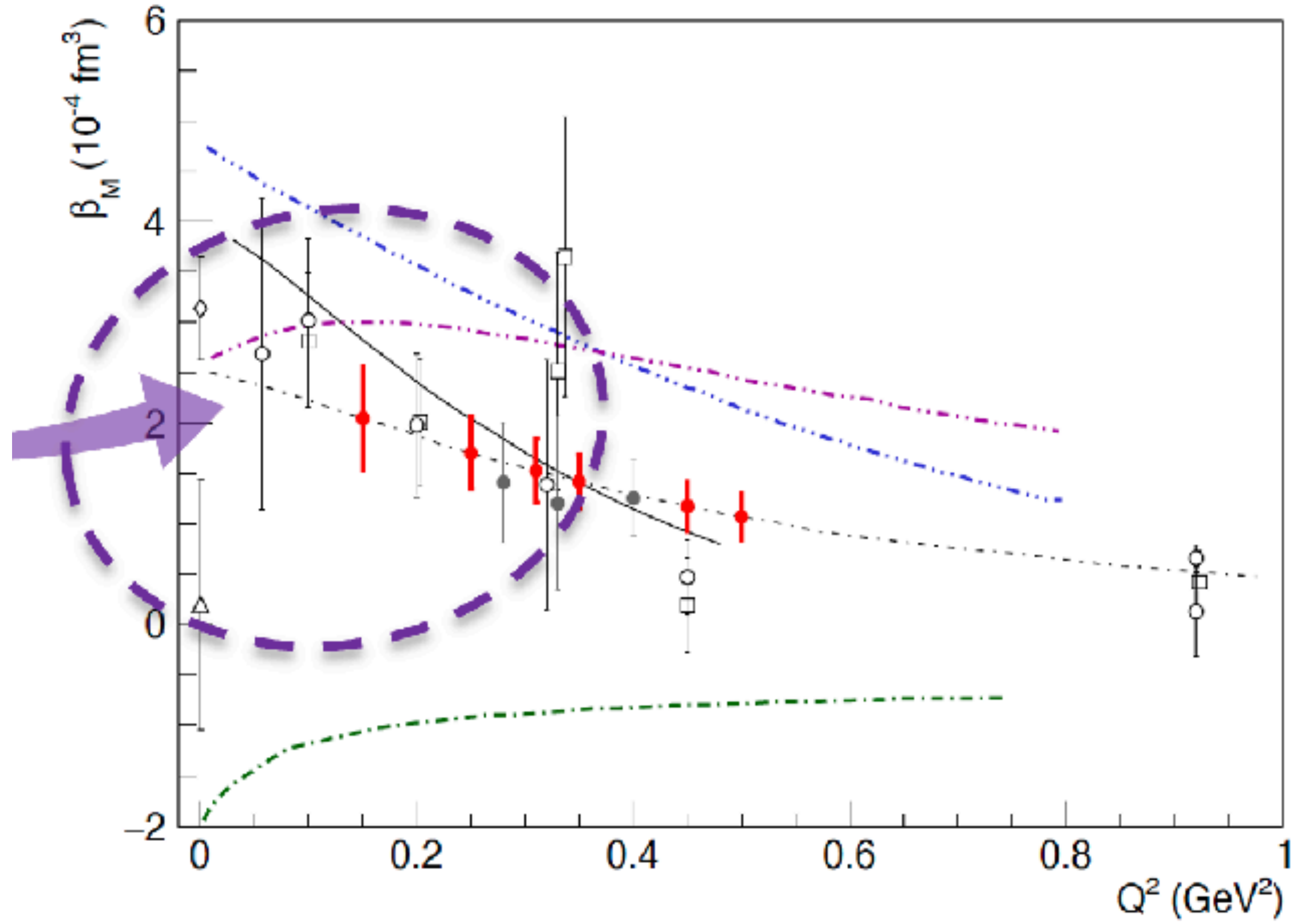
systematically consistent measurements throughout Q2



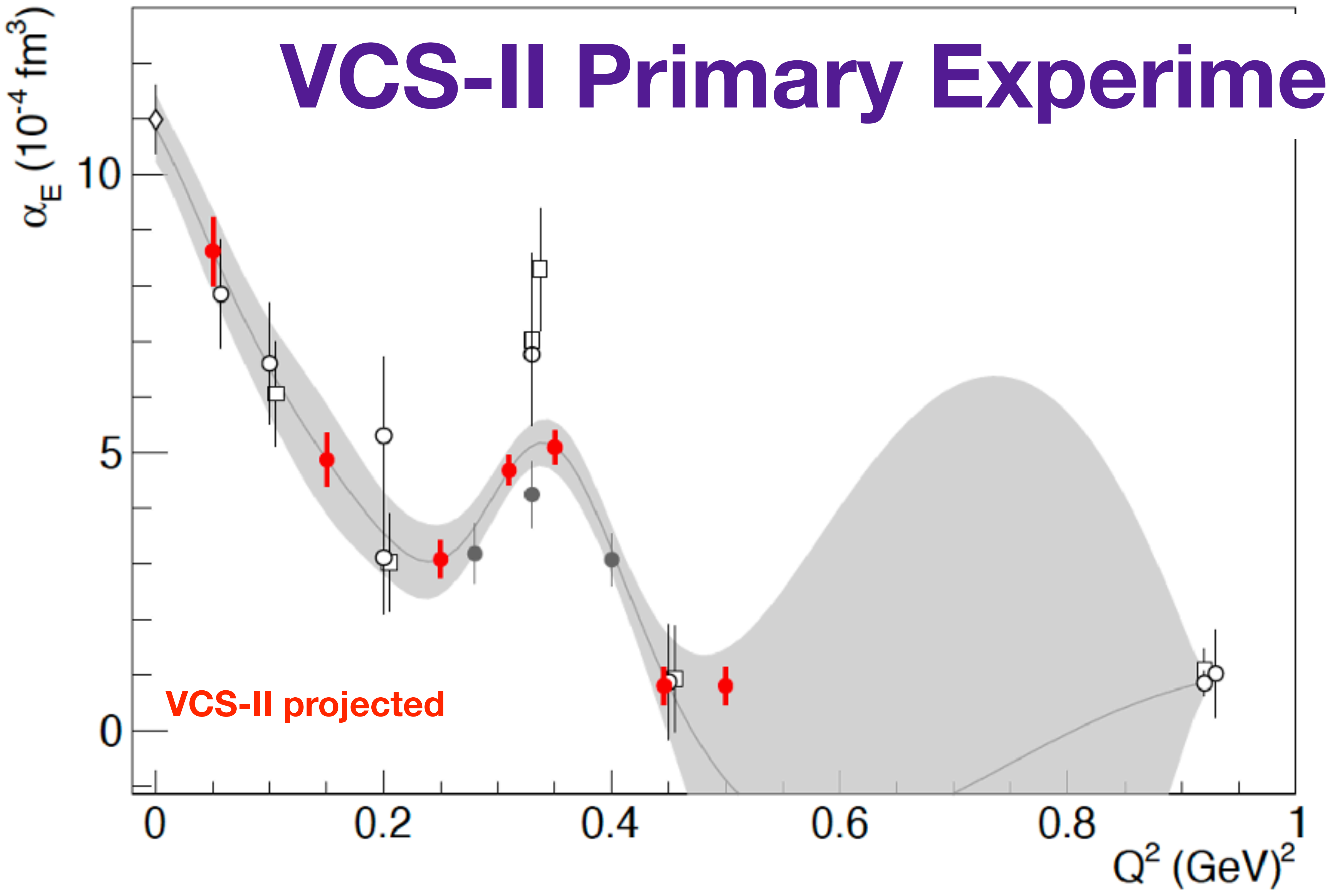
Targeted measurements to fully exploit the sensitivity to the GPs

Improve upon βM :

Pin down the competing para/dia-magnetic contributions in the nucleon

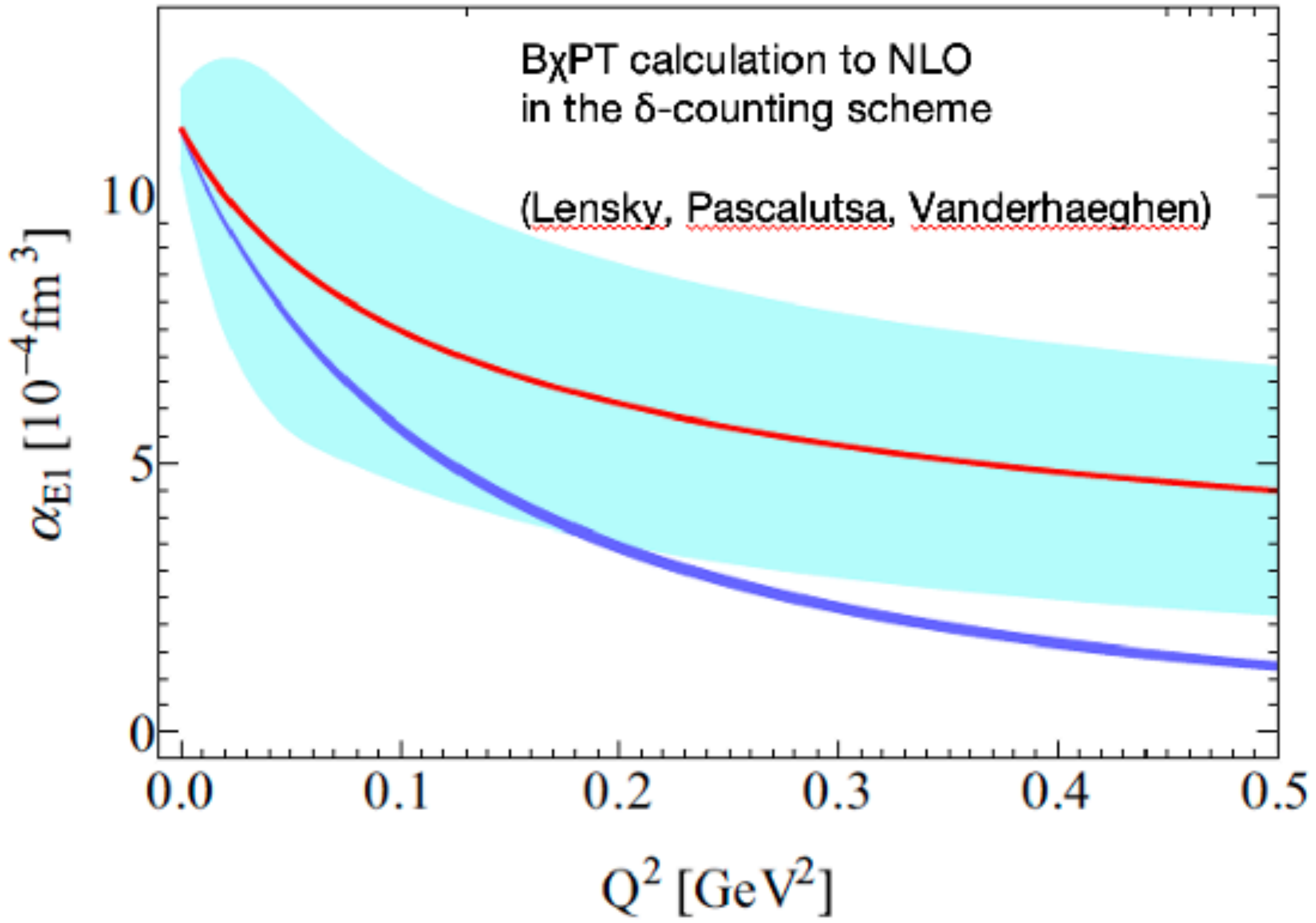


VCS-II Primary Experiment Goals

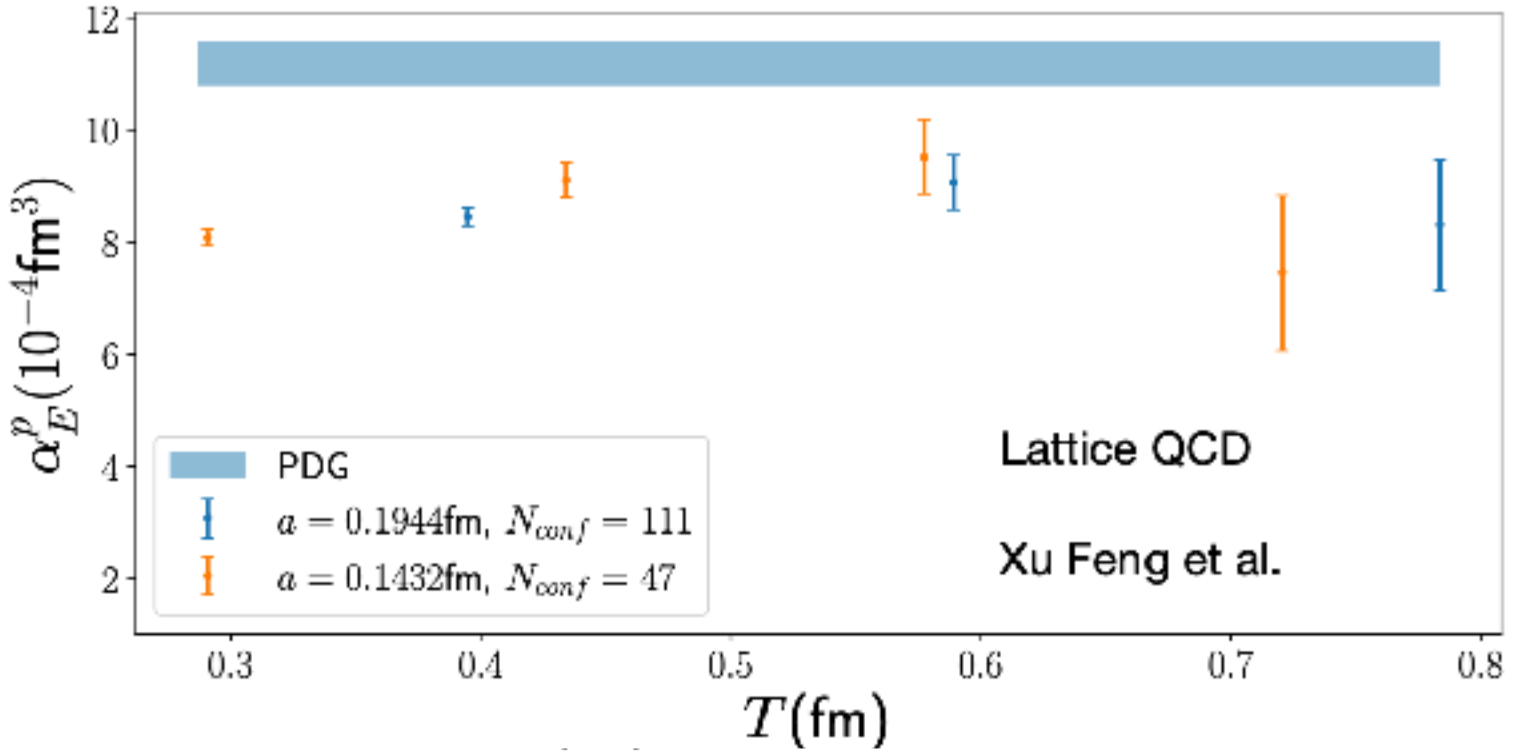


High precision benchmark data

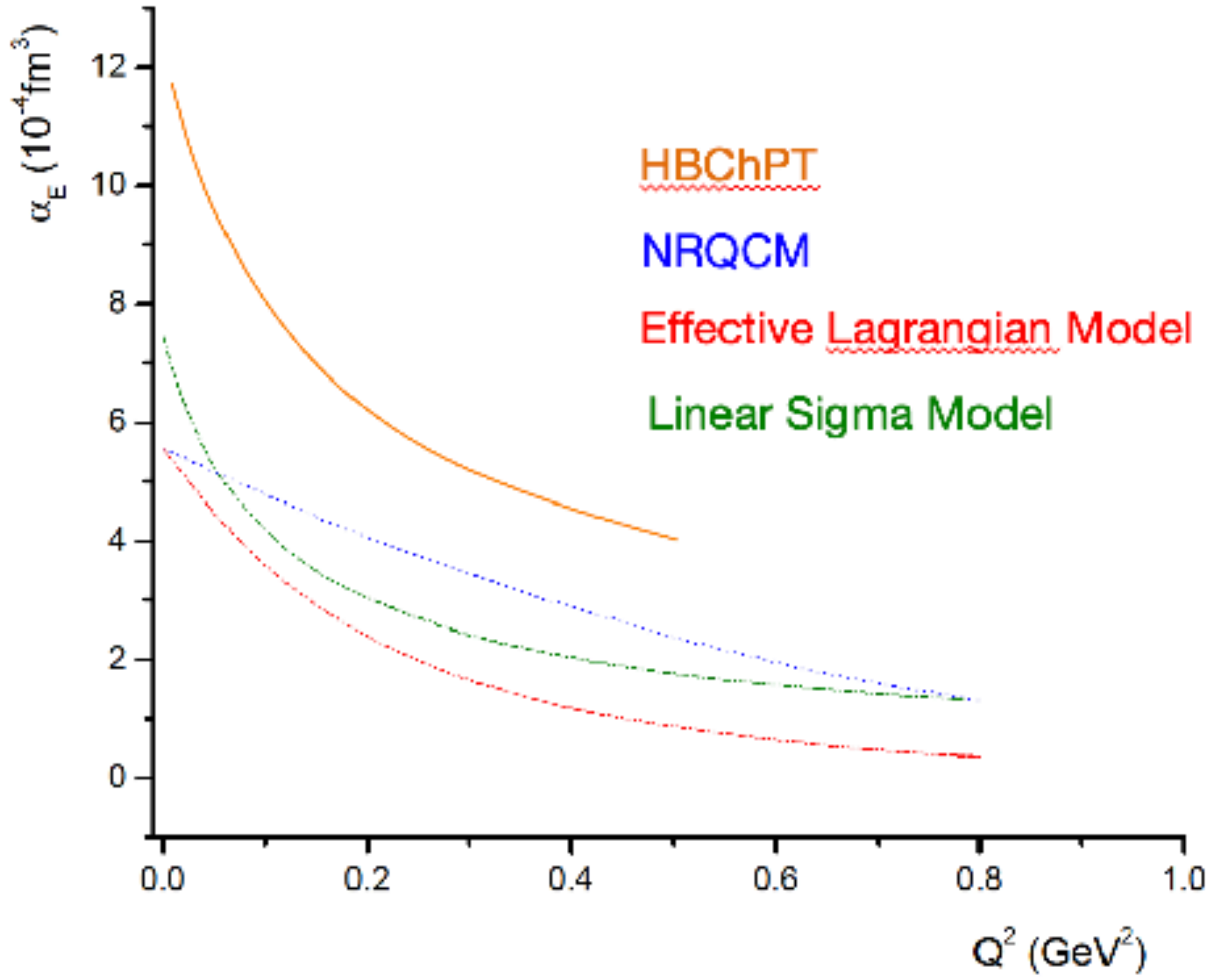
χPT



LQCD

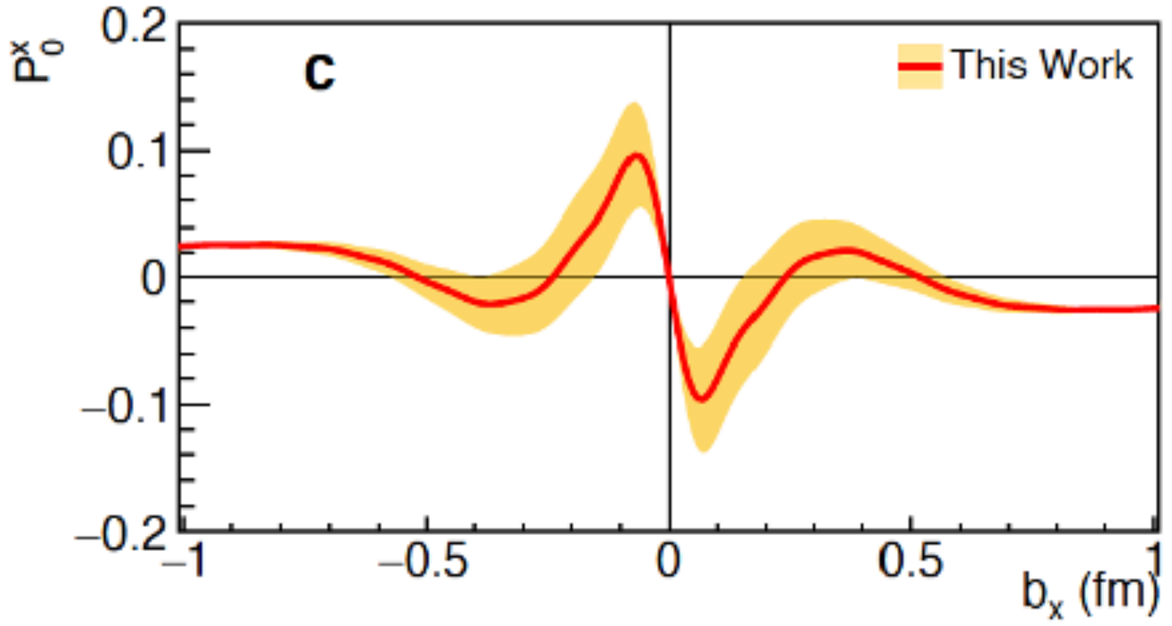


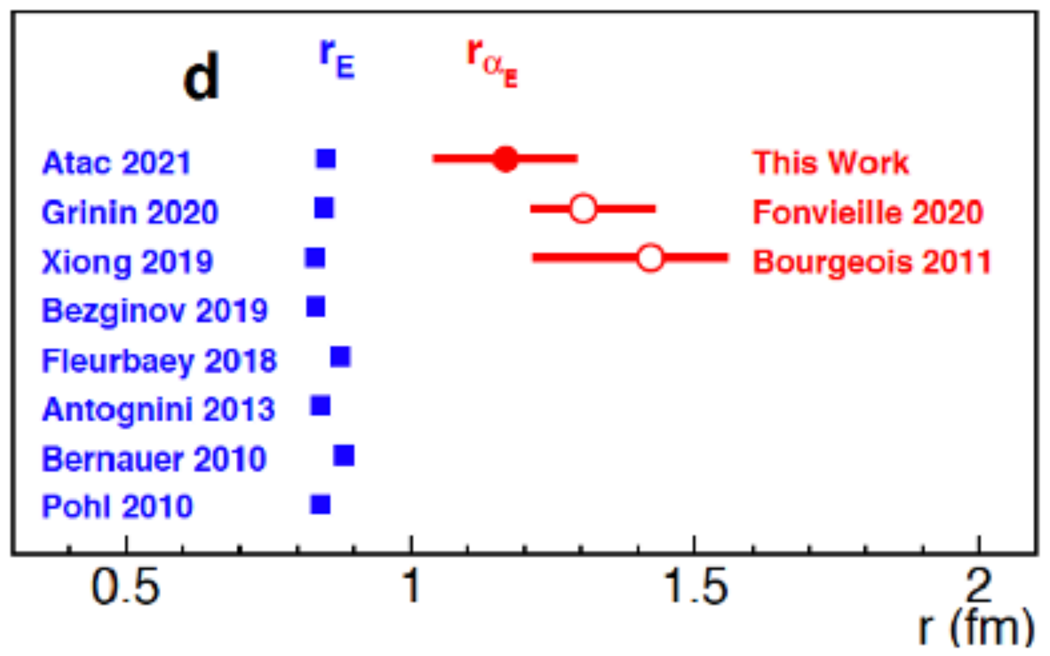
theoretical models



Induced polarization in the proton

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





Theory and TAC Reports

- **Theory Report:**
  - "Summarizing, the proposed experiment is an excellent addition to the ongoing studies of the nucleon structure. Similar experiments have already been performed, with interesting and unexpected results that challenge the current understanding of the nucleon non perturbative QCD dynamics. High precision data is now needed to progress, which may indeed be obtained with the proposed experiment."

- **TAC Report:**
  - Standard setup in Hall C will be used for the experiment. No issues or concerns.

Summary

- **We will measure fundamental properties of the proton:**
  - Improve precision ($\times 2$) of world-data combined with a fine mapping in Q^2 of the scalar GPs
  - Insight to the response of proton constituents to an external EM field, deformation of the proton densities, interplay of para/dia-magnetism in the proton, polarizability radii, …
  - Understand the dynamical signature of α_E (?) or the tension in the world-data (?)
  - Precise benchmark data for χPT & LQCD calculations

- **Facilities Request:**
  - 62 days of beam-on-target:
  - 6 days (1.1 GeV) + 53 days (2.2 GeV) + 3 days (calibrations)
  - Standard setup in Hall C: SHMS & HMS / 10 cm LH2

THANK YOU!