What do we know about the neutron radius

and...

what can we learn about neutron structure from N-Delta transition form factors?

Michael Paolone

New Mexico State University

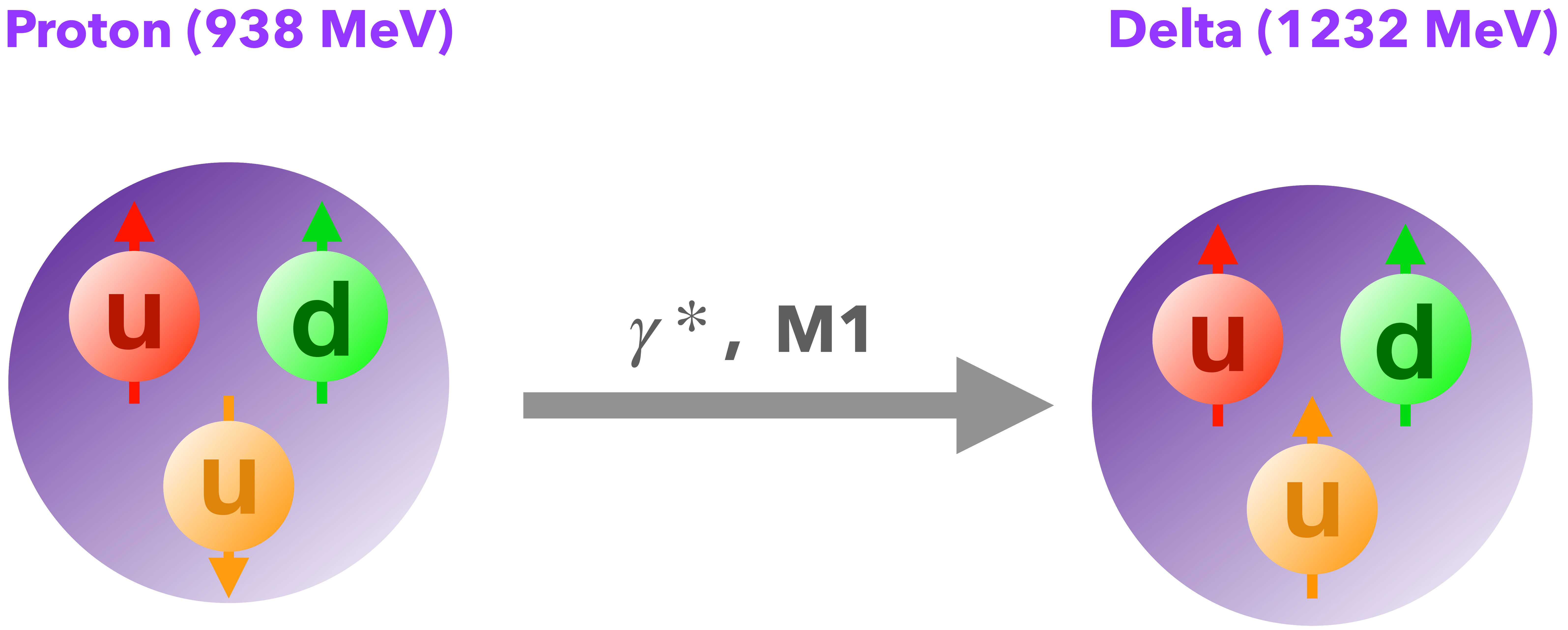
NREC 2026, Stony Brook University, NY

NM STATE

U.S. DEPARTMENT of ENERGY | Office of Science

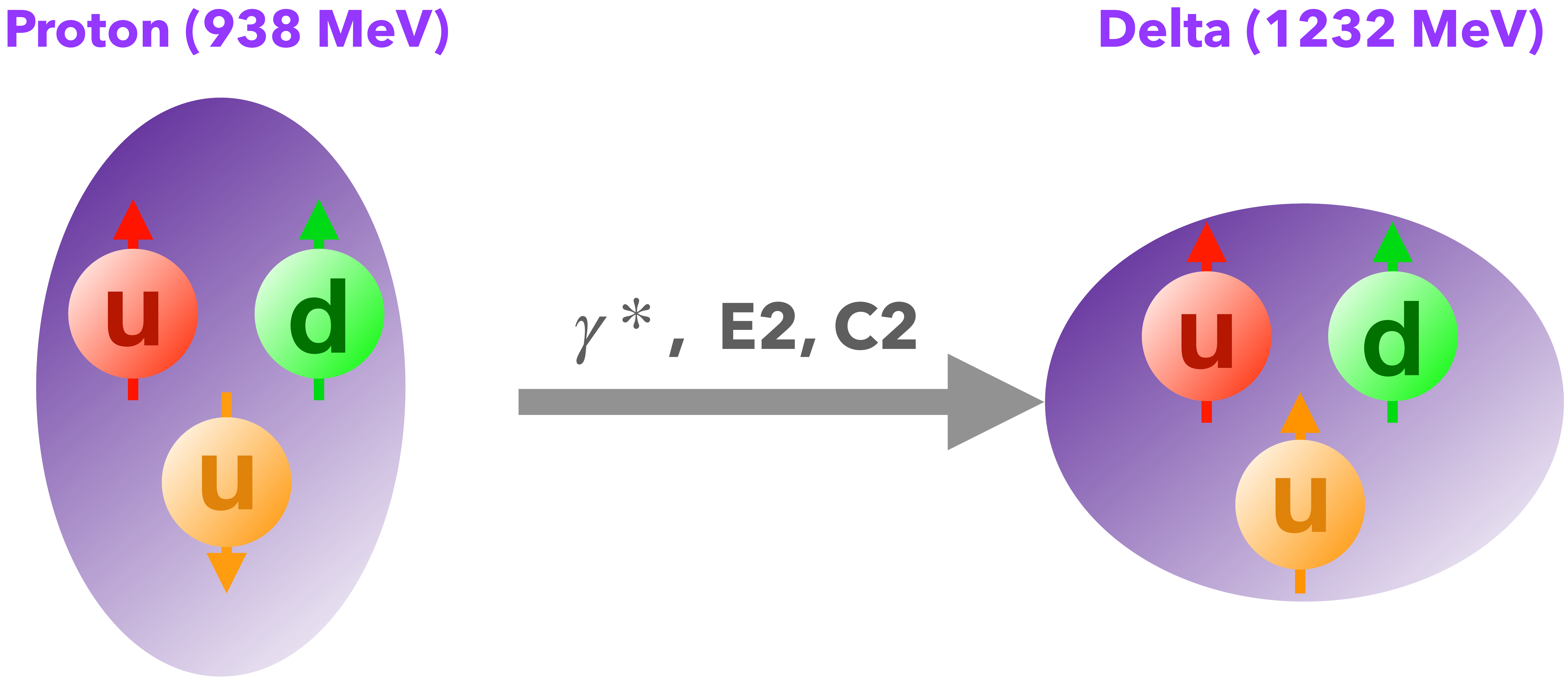
Supported by contract: DE-SC0023199

The N-Δ transition



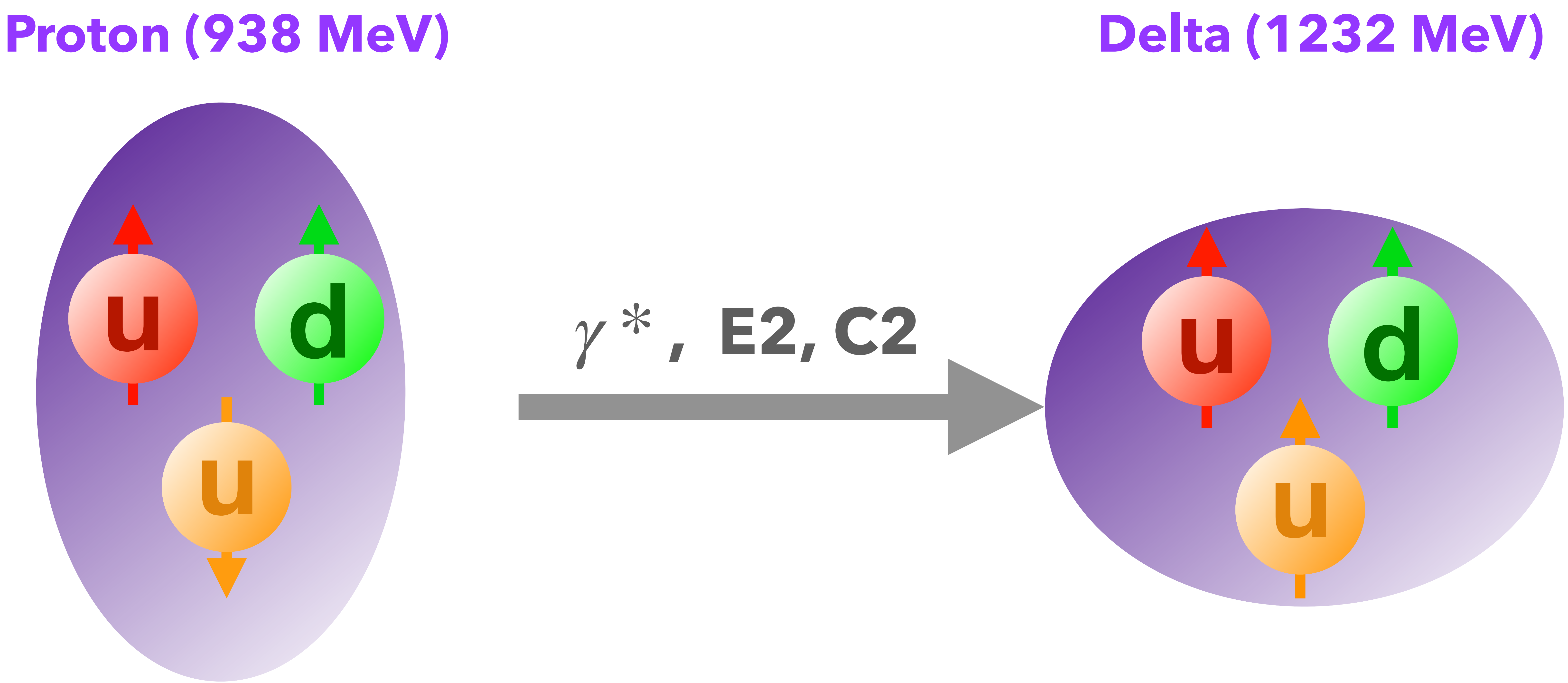
The dominant transition from proton to delta involves a dipole (M1) transition (spherical S-wave proton WF -> spherical S-wave Delta WF)

The N-Δ transition



There also exists a quadrupole (E2 or C2) transition from proton to delta.
(The quadrupole amplitudes are associated with the existence of non-spherical components in the proton and Delta WF)

The N-Δ transition



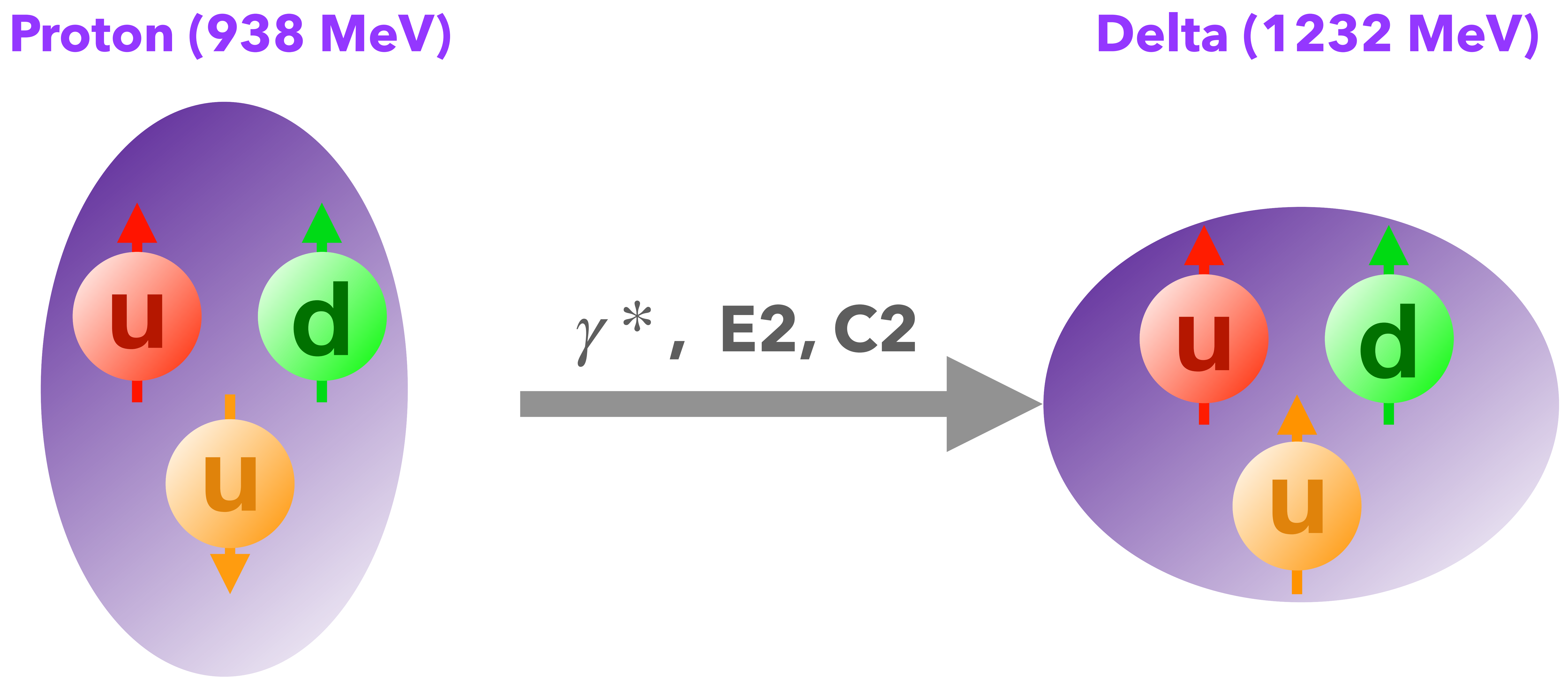
There also exists a quadrupole (E2 or C2) transition from proton to delta. (The quadrupole amplitudes are associated with the existence of non-spherical components in the proton and Delta WF)

The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero... Why?

Electric-Quadrupole to **M**agnetic-Dipole **R**atio = **EMR** = E2/M1

Coulomb-Quadrupole to **M**agnetic-Dipole **R**atio = **CMR** = C2/M1

The N-Δ transition

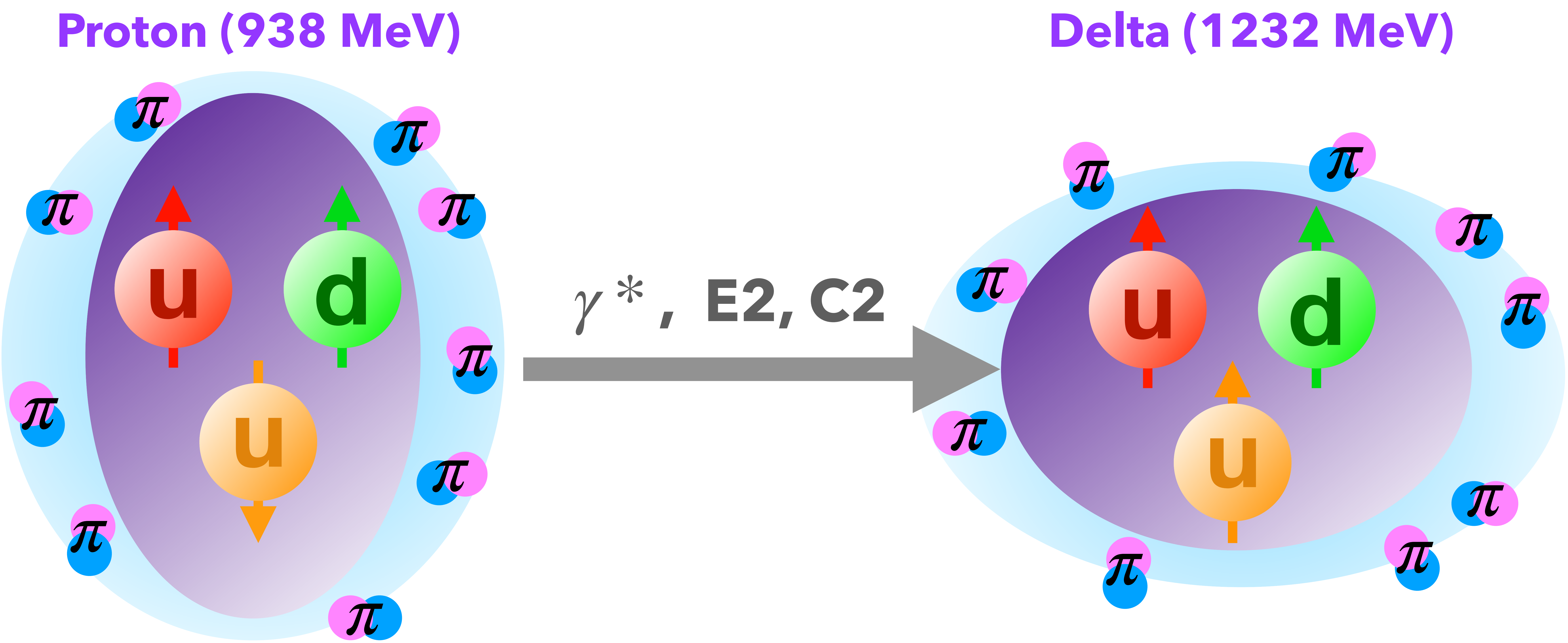


There also exists a quadrupole (E2 or C2) transition from proton to delta. (The quadrupole amplitudes are associated with the existence of non-spherical components in the proton and Delta WF)

The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero... Why?

Non-central (tensor) interactions between quarks can account for some of the spherical deviation, but not all...

The N-Δ transition



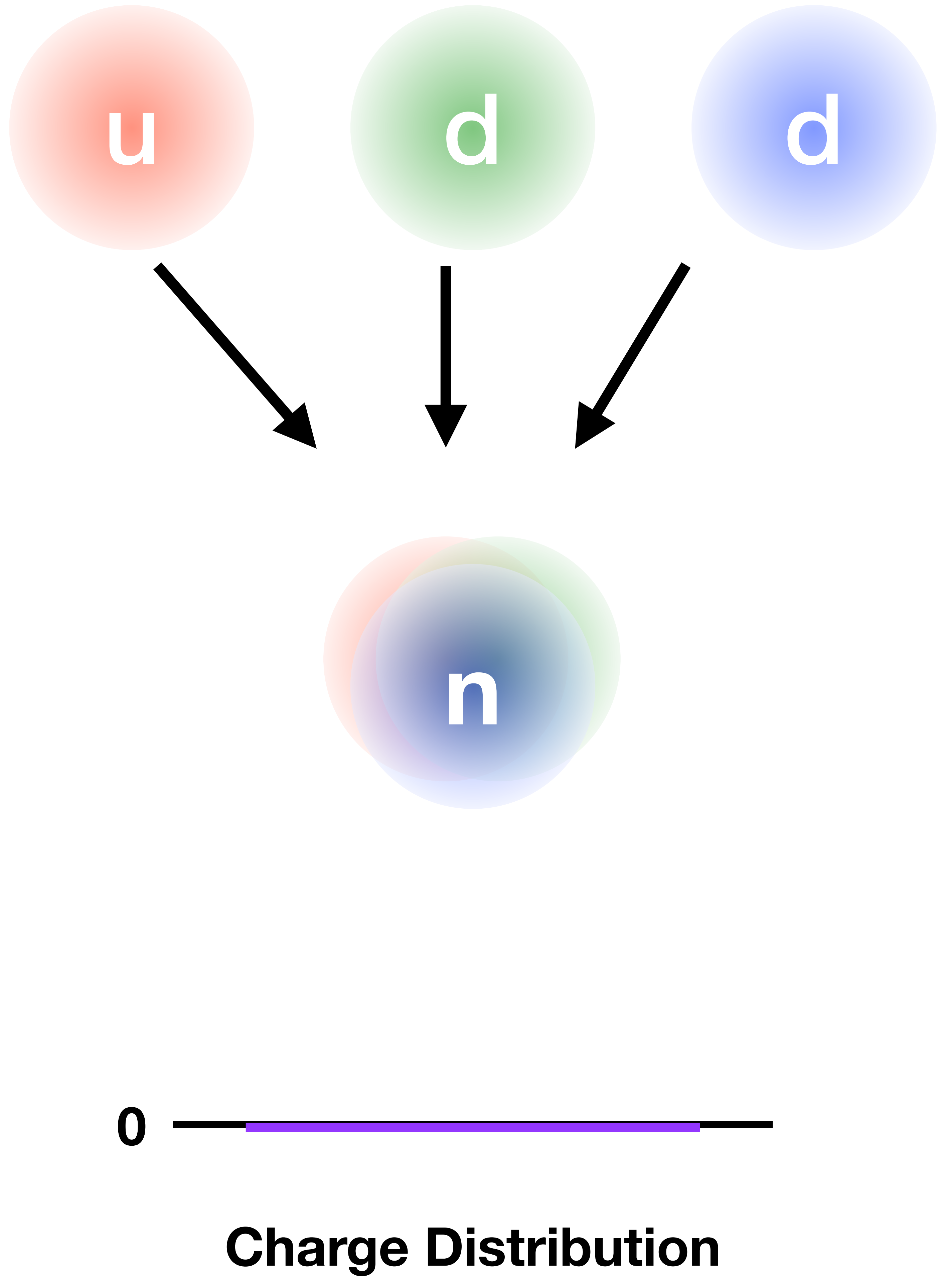
There also exists a quadrupole (E2 or C2) transition from proton to delta.
(The quadrupole amplitudes are associated with the existence of non-spherical components in the proton and Delta WF)

The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero... Why?

The dynamics of a meson cloud are important to describe the structure of the nucleon.

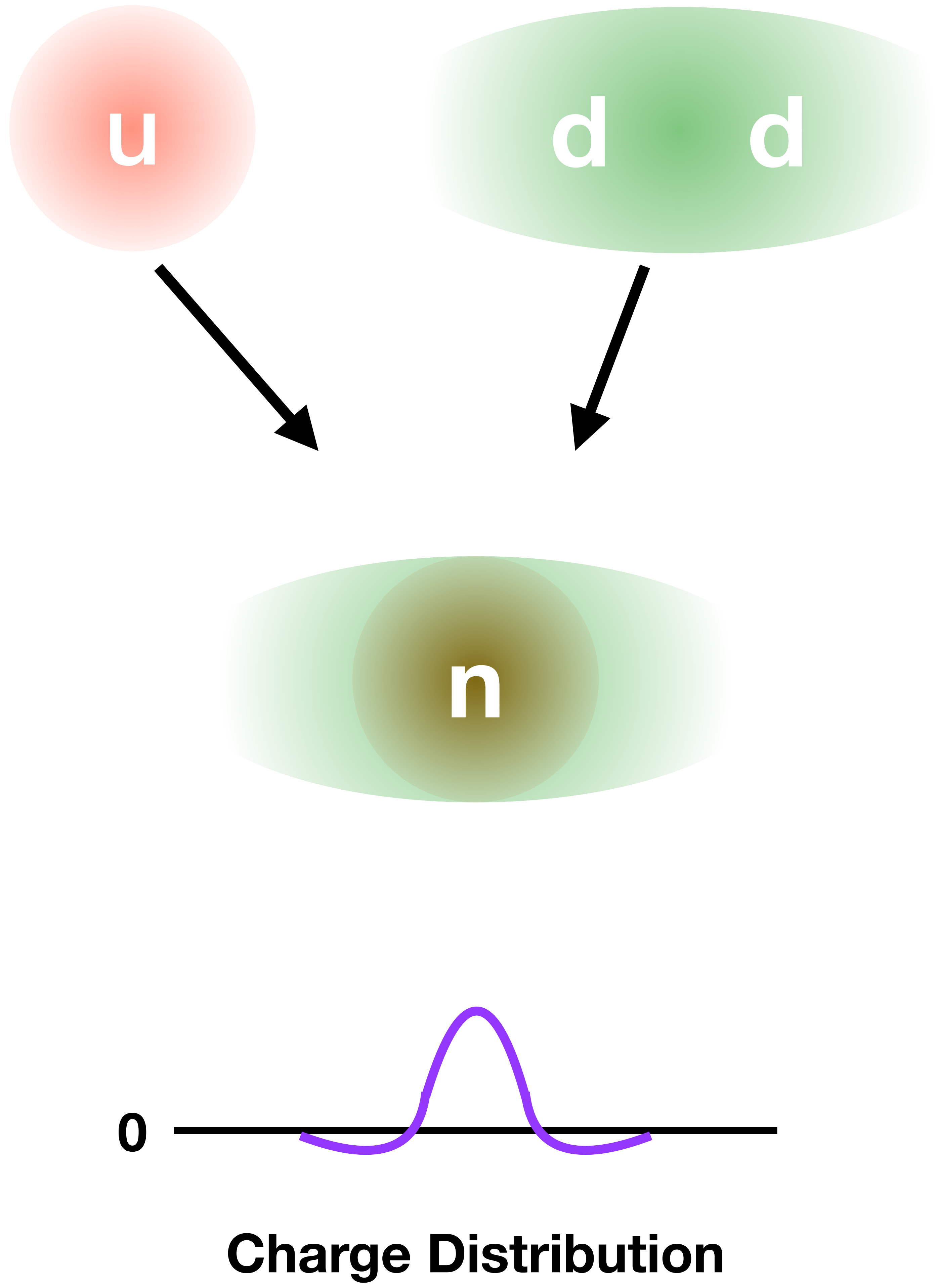
How does the N-Δ transition provide information on the neutron?

- **The neutron has a non-zero charge radius:**
  - Direct measurements of the neutron scattering length show a net negative charge radius for a neutral object: how?



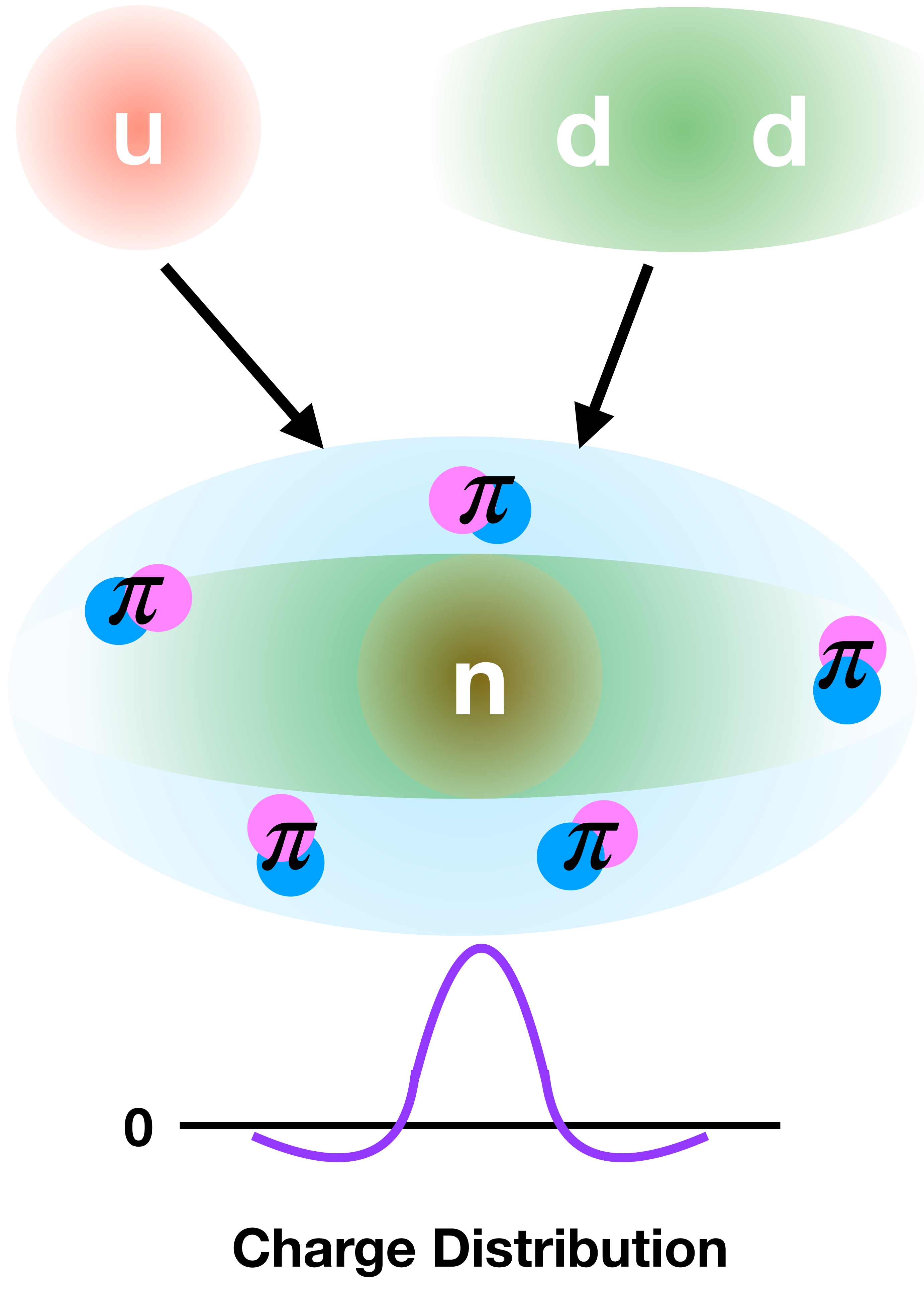
How does the N-Δ transition provide information on the neutron?

- **The neutron has a non-zero charge radius:**
  - Direct measurements of the neutron scattering length show a net negative charge radius for a neutral object: how?
    - One interpretation includes a spin-1 dd diquark configuration:
      - Not adequate to describe the magnitude of the radius



How does the N-Δ transition provide information on the neutron?

- **The neutron has a non-zero charge radius:**
  - Direct measurements of the neutron scattering length show a net negative charge radius for a neutral object: how?
    - One interpretation includes a spin-1 dd diquark configuration:
      - Not adequate to describe the magnitude of the radius
    - Including the two-body pion currents can describe the measurements.
- **How the nucleon excites provides some information on the structure of initial nucleon.**



Why do we care about the neutron charge radius?

The fundamental properties of the neutron play a significant role in our understanding of nature. Compared to the proton, those properties have been notoriously more difficult to measure.

- **The significance of understanding the neutron cannot be overstated:**
  - A cornerstone in the understanding of the hadronic structure.
  - Plays a central role in cosmological theories: it's properties offer valuable constraints in searches for new physics.
- **Precision is key:**
  - It is required in the determination of its properties in order to achieve the required level of understanding – consequence of the system dynamics & the interactions of the constituents
- **What if...**
  - ... the proton-neutron mass difference (~0.1%) were swapped?
    - There would be no hydrogen, water, stable long-lived stars which use hydrogen as a nuclear fuel... The universe would be drastically different.

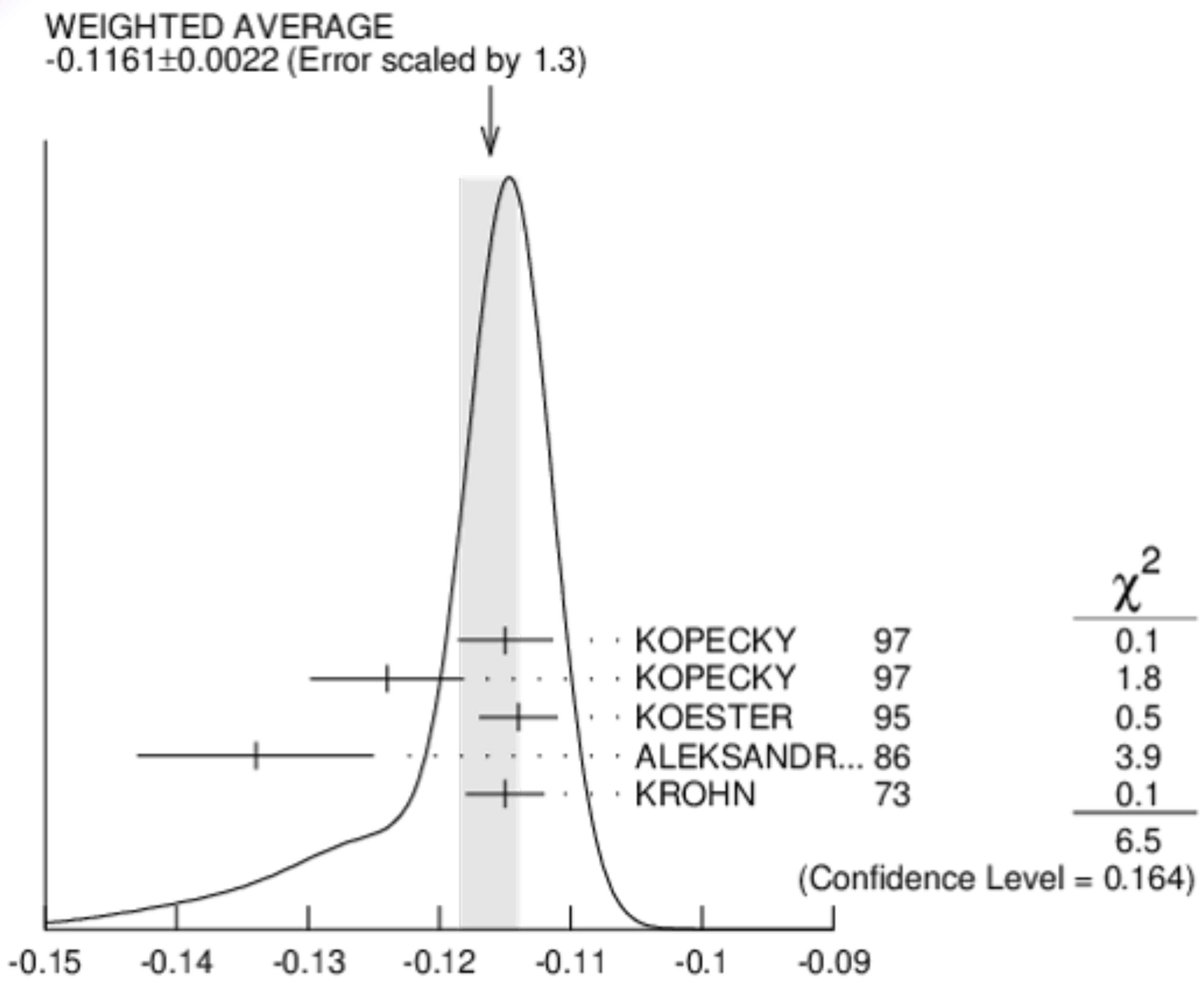
Bottom line: A precise understanding of the neutron's basic properties is critical.
<u>The charge radius is one of those properties.</u>

What do we know about the neutron charge radius?

- Data from atomic physics
- Data from quasi-free neutron scattering
- Lattice calculations
- Flavor decomposition
- Relations to excited nucleon states.

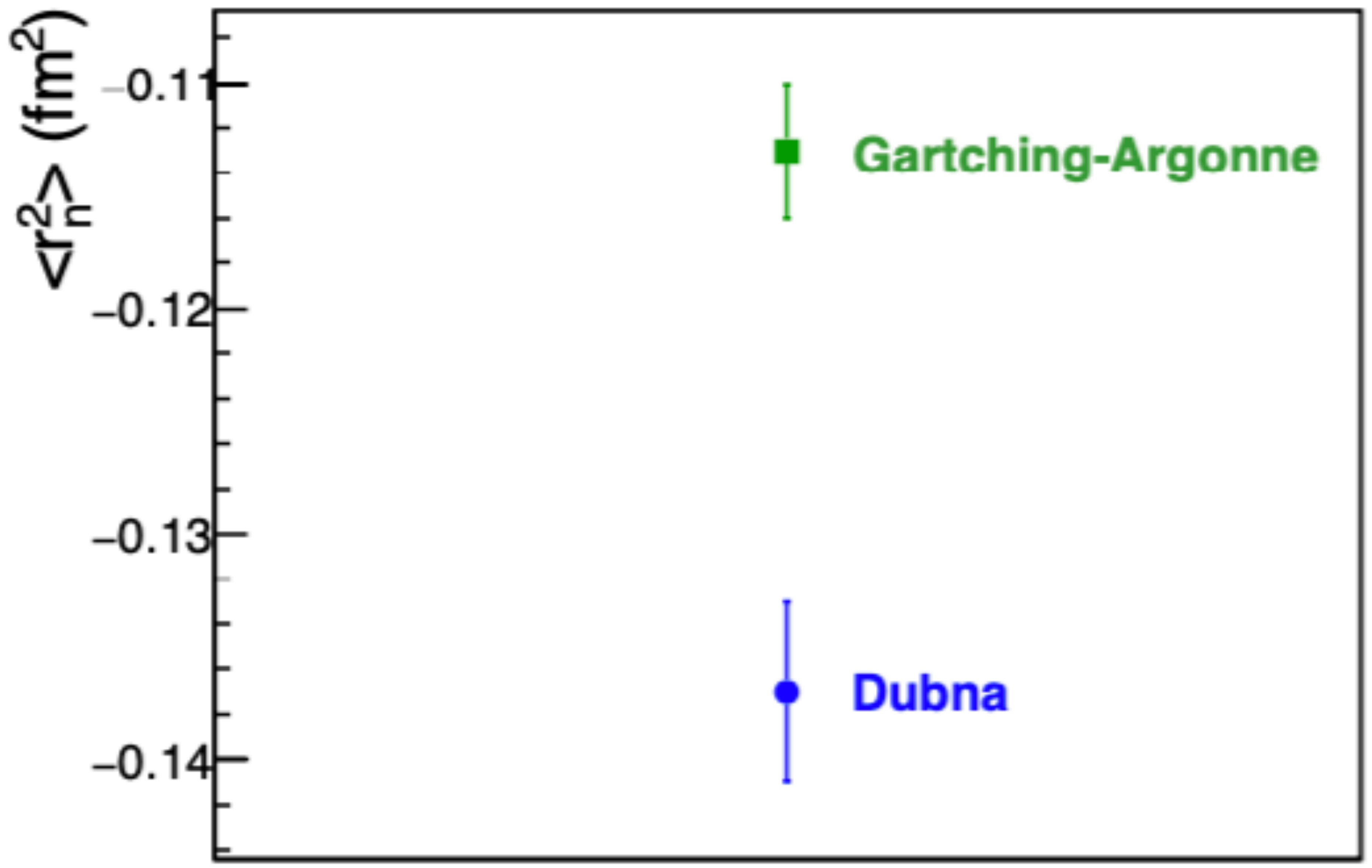
Atomic electron scattering determination of $\langle r_n^2 \rangle$

The value of $< r_n^2 >$ is based on one method of extraction → measurement of b_{ne} using Pb, Bi, …(very indirect method)



- **Some details on the PDG compiled neutron radius:**
  - Most recent measurements are at least 3 decades old.
  - Some world data is omitted.
  - Input data shows significant tension
    - Simply averaging data with significant discrepancies can be misleading.

The world data results essentially come from two research groups:
Gartching-Argonne and Dubna
With a 5σ tension between them!!!



PRC 56, 2229 (1997) ; Annu. Rev. Nucl. Part. Sci. 55, 27 (2005) ; PRD 77 034020 (2008) …

Atomic electron scattering determination of $\langle r_n^2 \rangle$

The value of $< r_n^2 >$ is based on one method of extraction → measurement of b_{ne} using Pb, Bi, …(very indirect method)

The same methodology is used in each group's radius extraction: a measurement of b_{ne}

A 5σ discrepancy most likely implies an underestimation of systematic uncertainty associated with the methodology

This is a long standing discrepancy and there is NO obvious path using neutron scattering alone that can resolve this.

Atomic electron scattering determination of $\langle r_n^2 \rangle$

Transmission rate of neutrons is measured

$$T(E) = \exp[-N\sigma_{tot}(E)]$$

S(E) functions are condensed matter corrections

$$\sigma_{tot}(E) = \sigma_{coh}(E) S_{coh}(E) + \sigma_{inc}(E) S_{inc}(E) + \sigma_{abs}(E)$$

Absorption XS

Inclusive XS requires a sum over isotope states

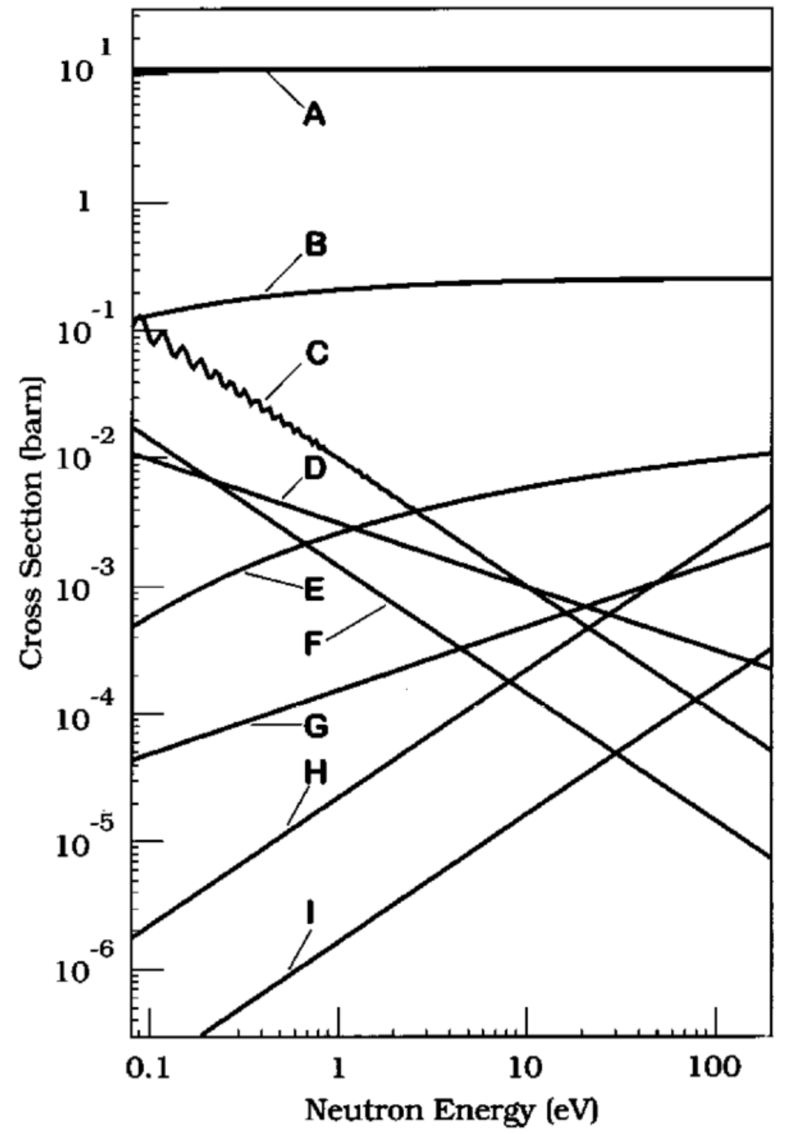
$$\sigma_{inc} = \sum_{j,k} \sum_{s,s'} p_j p_k g_{js} g_{ks'} (a_{js} - a_{ks'})^2$$

Scattering lengths b(E): c = nucleus coherent, R = resonance, p = polarizability

$$\sigma_{coh} = 4\pi\{b_c(E) + b_R(E) - b_{ne}[Z - f(Z,E)] + b_p(E)\}^2 + \sigma_{LS}(E)$$

$$\langle r_n^2 \rangle = \frac{3 m_e a_0}{m_n} b_{ne}$$

Electron cloud contribution calculated by 4π integration of atomic form factor



Some consequences of the current precision

PHYSICAL REVIEW D 77, 034020 (2008)

Neutron scattering and extra-short-range interactions

V. V. Nesvizhevsky*
Institute Laue Langevin, 6 rue Jules Horowitz, F-38042, Grenoble, France

G. Pignol† and K. V. Protasov‡
Laboratoire de Physique Subatomique et de Cosmologie, UJF-CNRS/IN2P3-INPG, 53 Av. des Martyrs, Grenoble, France
(Received 14 November 2007; published 25 February 2008)

The available data on neutron scattering were reviewed to constrain a hypothetical new short-range interaction. We show that these constraints are several orders of magnitude better than those usually cited in the range between 1 pm and 5 nm. This distance range occupies an intermediate space between collider searches for strongly coupled heavy bosons and searches for new weak macroscopic forces. We emphasize the reliability of the neutron constraints insofar as they provide several independent strategies. We have identified a promising way to improve them.

PHYSICAL REVIEW D 77, 034020 (2008)

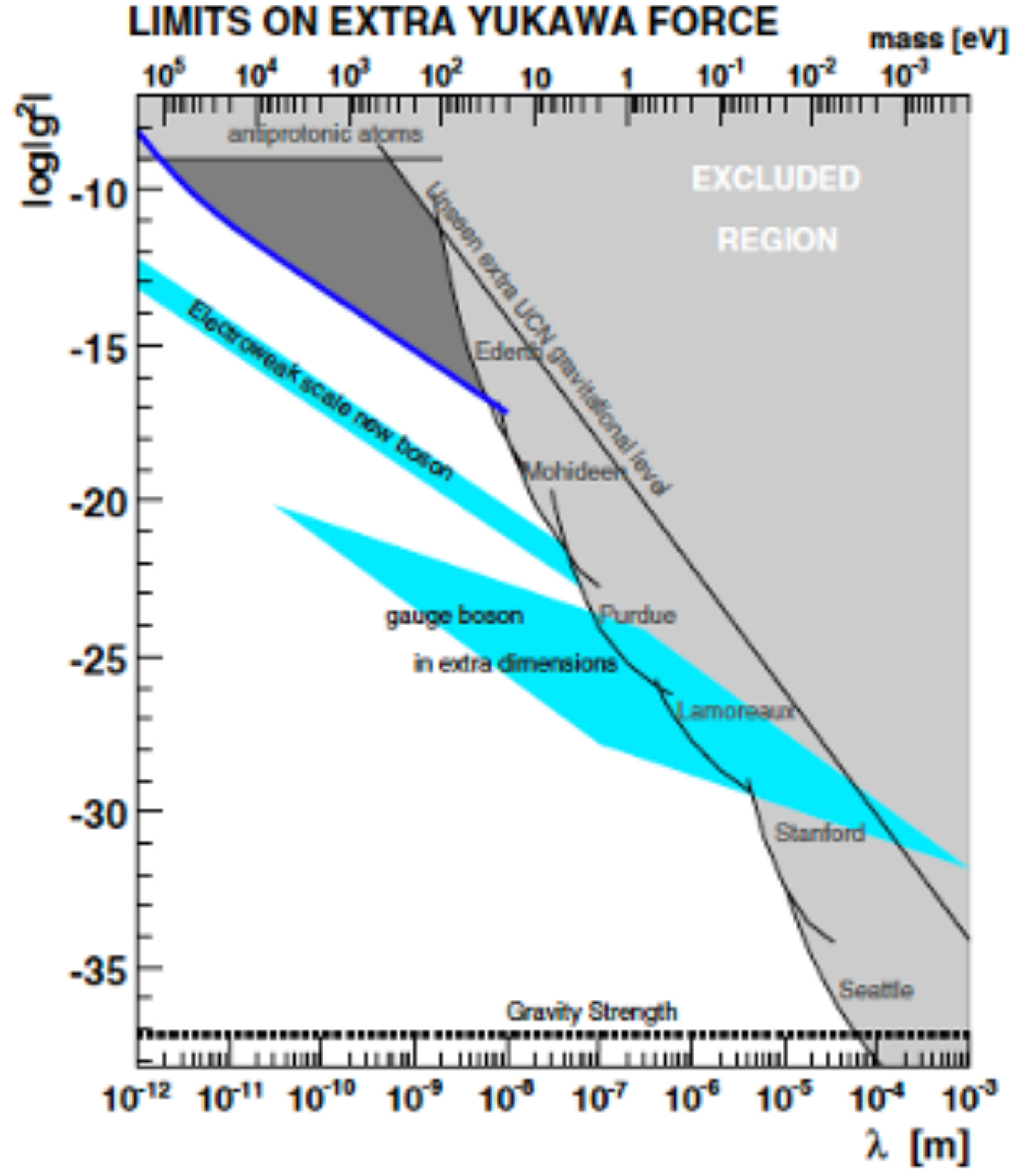


FIG. 8 (color online). Experimental limits on extra interactions including the best neutron constraint obtained in this article (bold line). Two theoretical regions of interest are shown: a new boson with mass induced by electroweak symmetry breaking [10], and a new boson in extra large dimensions [4].

BSM physics: constrains on forces due to new bosons modeled by a Yukawa-type scattering potential: $f(q) = f_{\text{nucl}}(q) + f_{ne}(q) + f_{\text{new}}(q)$

Depends on b_{ne} , limited by precision

Unfortunately, there is very clear disagreement between the two groups of values for $b_{ne}^{\text{exp}} = \frac{b(1\text{ eV}) - b(0)}{Z}$ known as the Garching-Argonne and Dubna values [27]

$$b_{ne}^{\text{exp}} = (-1.31 \pm 0.03) \times 10^{-3} \text{ fm} \quad \text{[Gartching-Argonne]}$$

$$b_{ne}^{\text{exp}} = (-1.59 \pm 0.04) \times 10^{-3} \text{ fm} \quad \text{[Dubna].} \qquad (18)$$

The discrepancy is much greater than the quoted uncertainties of the experiments and there evidently an unaccounted for systematic error in at least one of the experiments.

→

In order to overcome this difficulty we could determine b_{ne} from the experimental data on the neutron form factor (5). The simplest way to do this consists in using a commonly accepted general parametrization of the neutron form factor [28]:

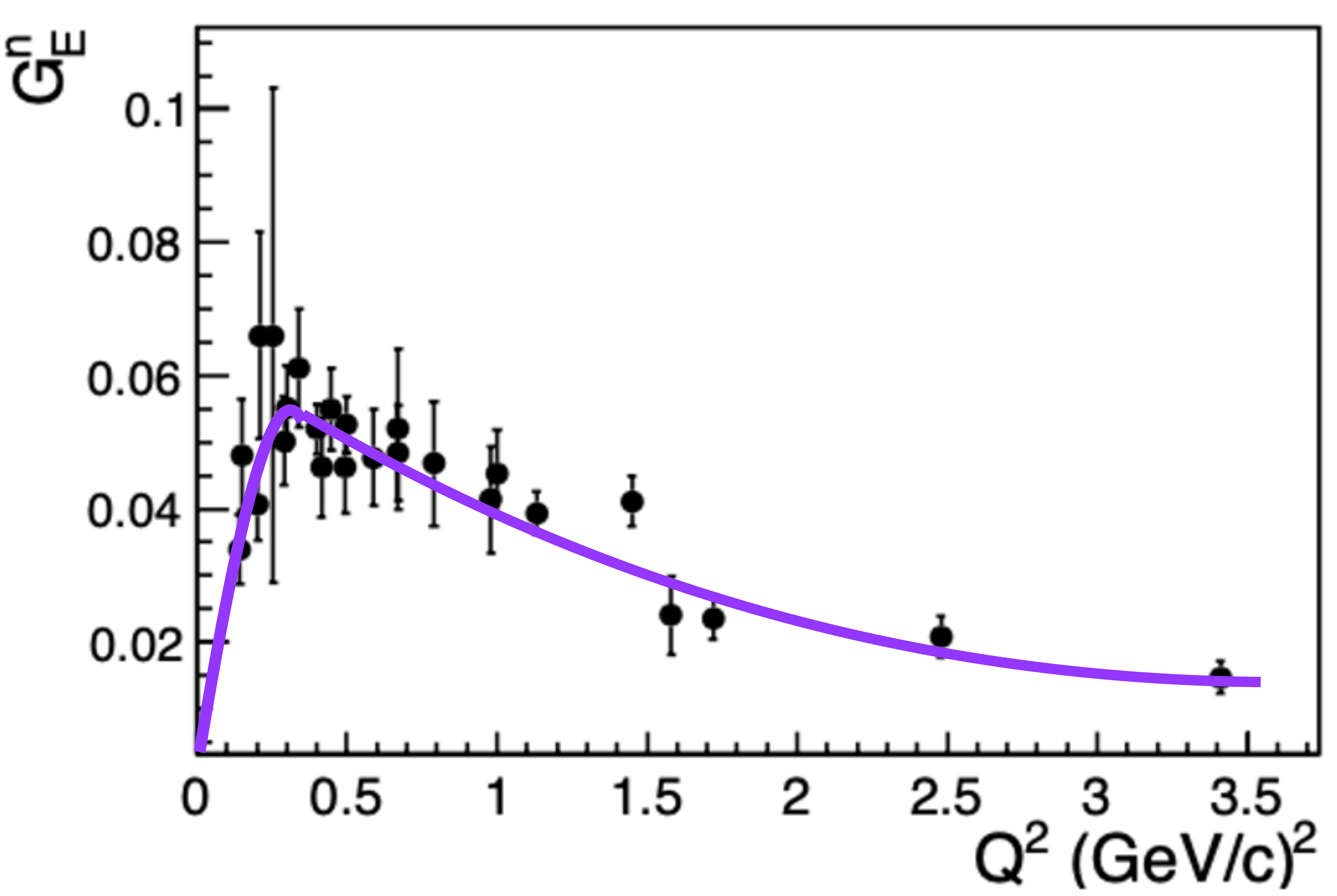
$G^n \to r_n \to b_{ne}$

→

Our principal conclusion consists of the observation of (underestimated) systematical uncertainties in the presented experiments. Therefore a single experiment/method cannot be used for any reliable constraint. A conservative estimate of the precision of the b_{ne} value could be obtained from analyzing the discrepancies in the results obtained by different methods; it is equal to $\Delta b_{ne} \lesssim 6 \times 10^{-4}$ fm. The

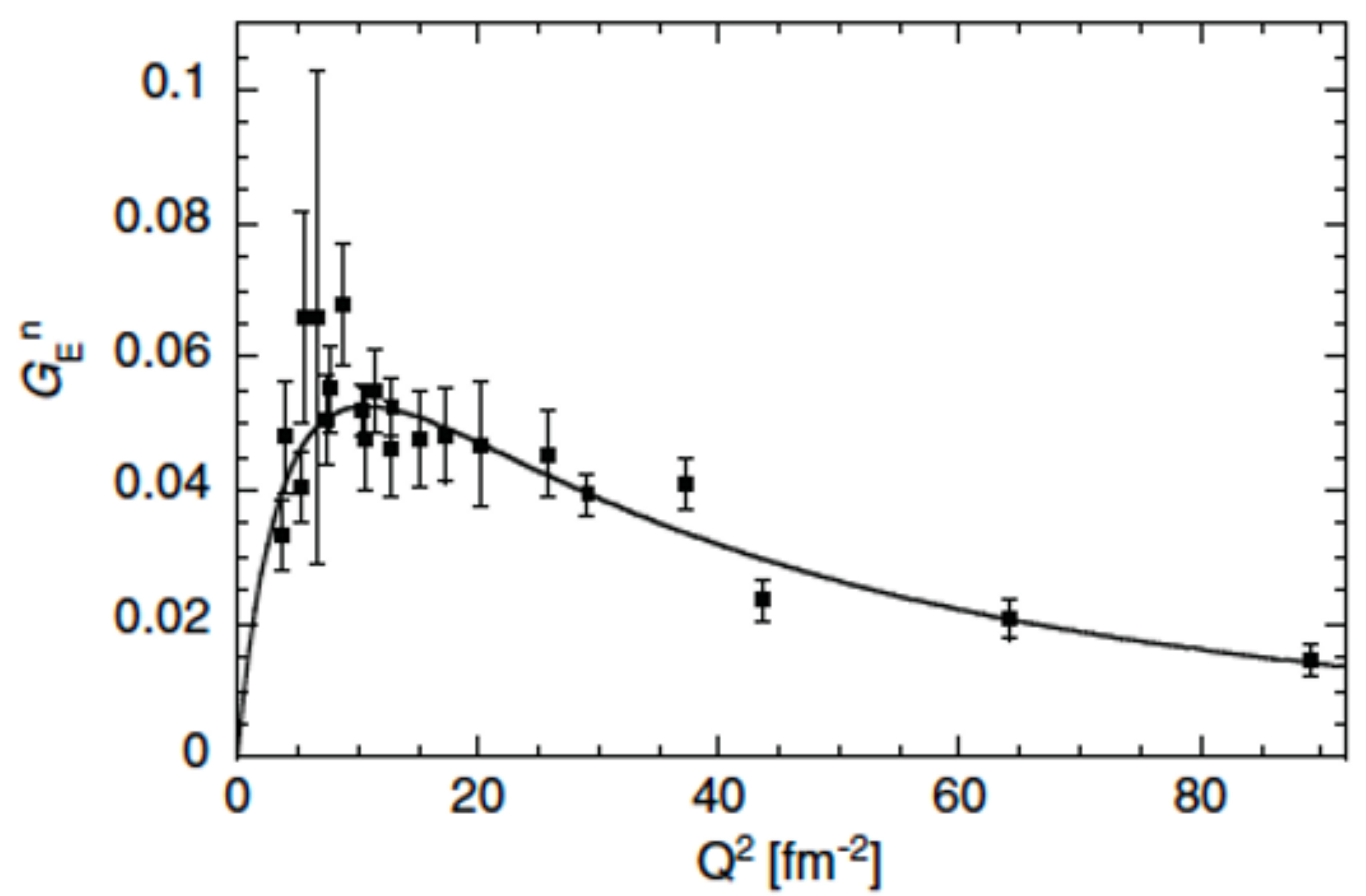
Electron scattering on quasi-free neutrons to measure the neutron charge radius

- **Historical electron quasi-free neutron G_E^n measurements:**
    - No truly "free" neutron target
    - Polarized ^2H, ^3He targets & polarized electron beam
    - Quasi-elastic electron scattering
    - Double polarization observables
- **A fit is needed for $Q^2 \to 0$**
    - Relies on precision of measurements
    - ... and on how close measurements are to $Q^2 = 0$



Electron scattering on quasi-free neutrons to measure the neutron charge radius

T.R. Gentile & C.B. Crawford
PRC 83, 055203 (2011)



- **Parameterizations of the fit forms are not well constrained as $Q^2 \to 0$**
  - Recent attempts using quasi-free neutron target measurements of G_E^n have yielded radii ~33% from pdg values.

TABLE I. Results of fitting G_E^n with the Galster form. For this table and Table II, the column labelled "$\langle r_n^2 \rangle^d$" lists the reference for the $\langle r_n^2 \rangle$ datum included in the fit, χ^2_{red} is the reduced χ^2 for the fit and "dof" refers to the number of degrees of freedom for each fit. The parameters A and B are listed, along with the resulting value for $\langle r_n^2 \rangle$.

Form	Eq.	$\langle r_n^2 \rangle^d$	A	B	$\langle r_n^2 \rangle$ (fm^2)	χ^2_{red}	dof
Galster	(1)	–	1.409(82)	2.09(39)	–0.0935(54)	0.90	20

TABLE II. Results of fitting G_E^n with the Bertozzi and mod-Ber (modified Bertozzi) forms. The parameters $\langle r_n^2 \rangle$, r_{av}, and a are listed (for the Bertozzi form the normalization parameter a is fixed at unity).

Form	Eq.	$\langle r_n^2 \rangle^d$	r_{av} (fm)	a	$\langle r_n^2 \rangle$ (fm^2)	χ^2_{red}	dof
Bertozzi	(3)	–	0.709(19)	1	–0.0906(64)	0.94	20

Connections to the Deuteron Radius

A.A. Filin, V. Baru, E. Epelbaum, H. Krebs, D. Moller, P. Reinert

$$r_{\rm str} = 1.9731^{+0.0013}_{-0.0018}\ \text{fm}$$

Deuteron structure radius from ChEFT

$$r_d^2 - r_p^2 = 3.82070(31)\ \text{fm}^2$$

Deuteron - proton radius difference from atomic data: PRA 97, 062511 (2018)

$$r_{\rm str}^2 = r_d^2 - r_p^2 - r_n^2 - \frac{3}{4m_p^2}$$

$$r_n^2 = -0.106^{+0.007}_{-0.005}\ \text{fm}^2$$

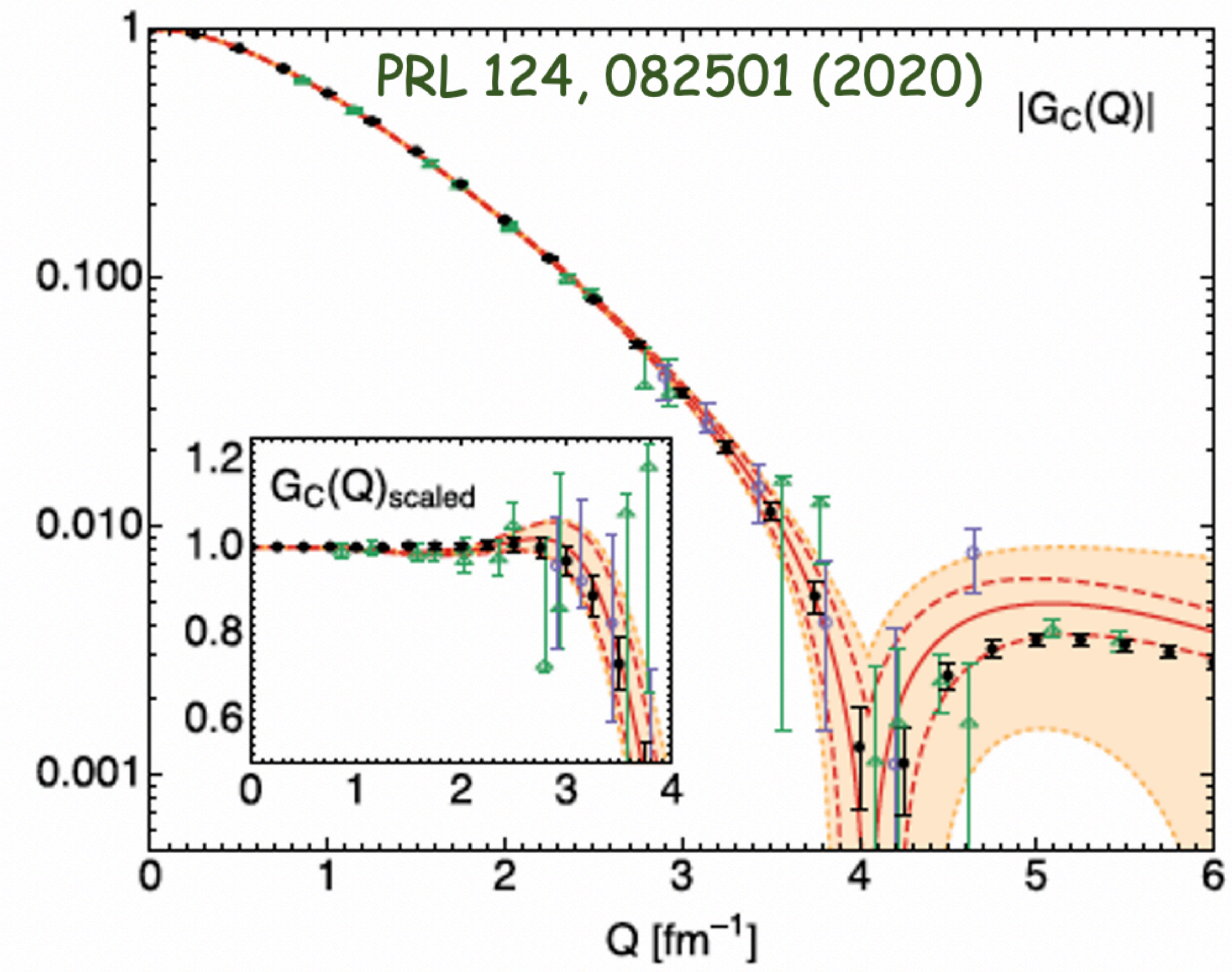


FIG. 1. Deuteron charge FF from the best fit to data up to $Q = 4\ \text{fm}^{-1}$ evaluated for the cutoff $\Lambda = 500$ MeV (solid red lines). Band between dashed (red) lines corresponds to a 1σ error in the determination of the short-range contribution to the charge density operator at N^{4}LO. Light-shaded (orange dotted) band corresponds to the estimated error (68% degree-of-belief) from truncation of the chiral expansion at N^{4}LO. Open violet circles and green triangles are experimental data from Ref. [45] and Refs. [46,47], respectively. Black solid circles correspond to the parametrization of the deuteron FFs from Refs. [16,52] which is not used in the fit and shown just for comparison. The rescaled charge FF of the deuteron, $G_C(Q)_{\rm scaled}$, as defined in Ref. [16], is shown on a linear scale.

Lattice Calculations

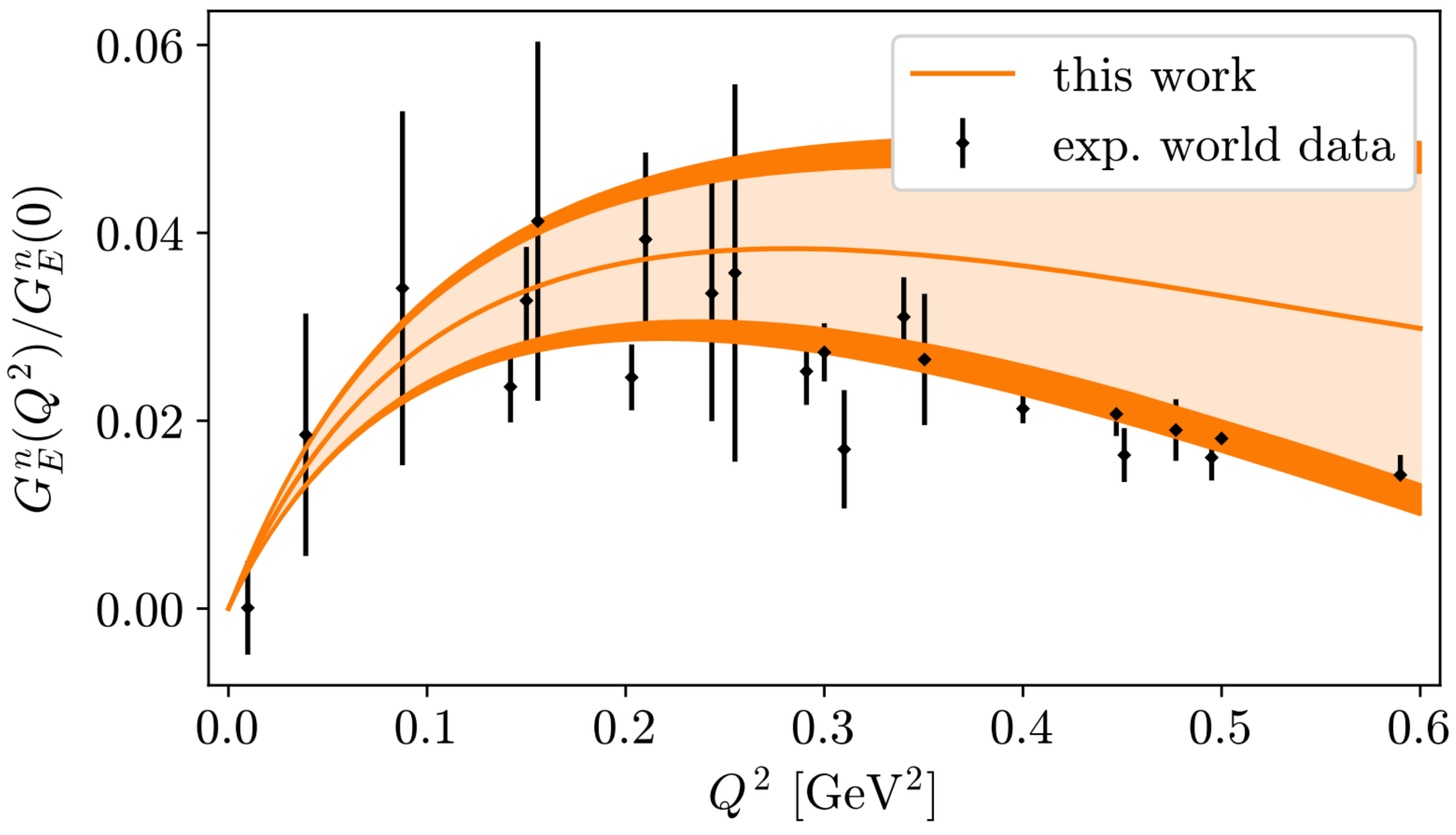
PHYSICAL REVIEW D **109**, 094510 (2024)

Electromagnetic form factors of the nucleon from $N_f = 2+1$ lattice QCD

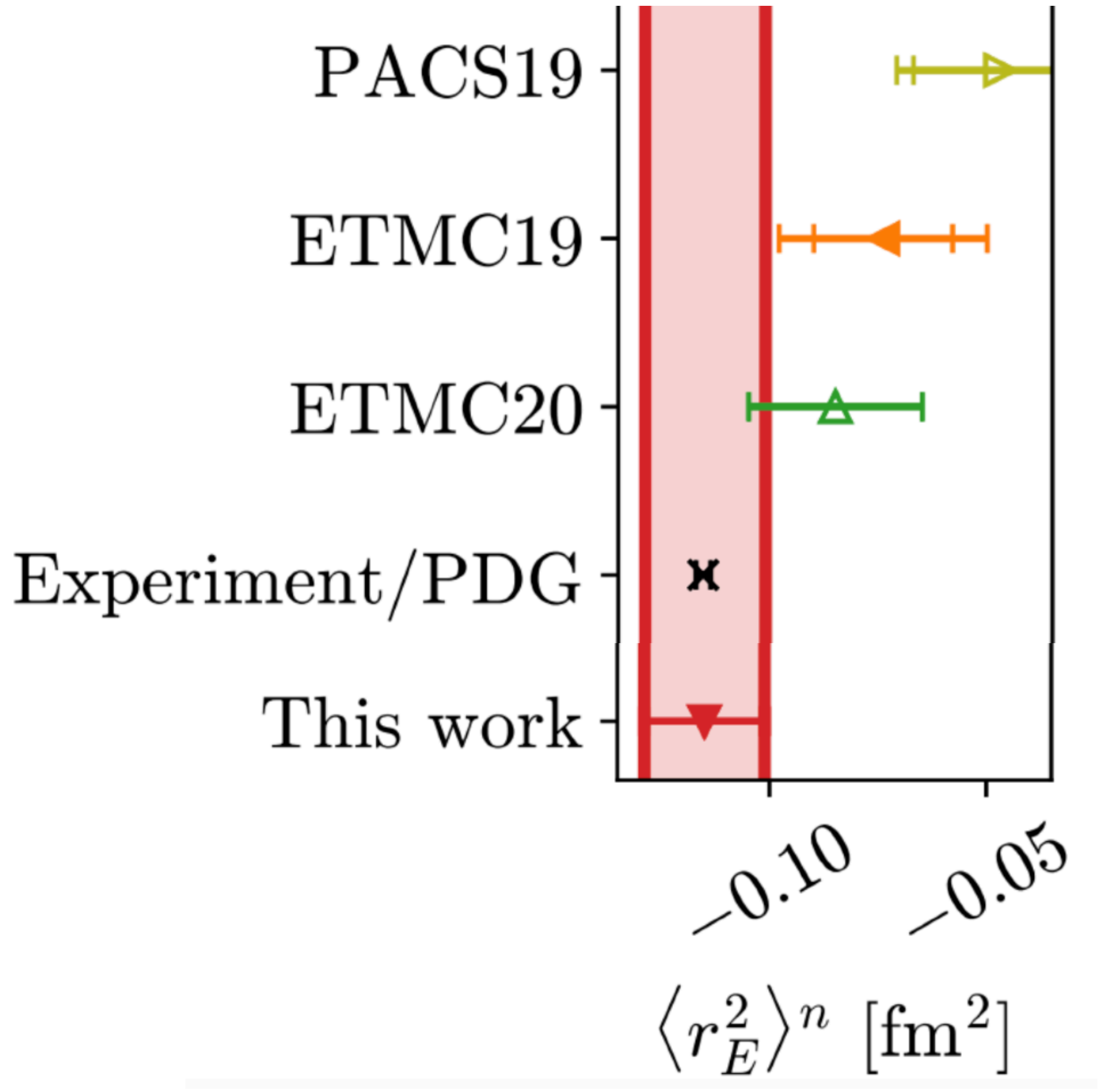
Dalibor Djukanovic,[1,2] Georg von Hippel,[3] Harvey B. Meyer,[1,3] Konstantin Ottnad,[3]
Miguel Salg,[3,*] and Hartmut Wittig[1,3]
[1]*Helmholtz Institute Mainz, Staudingerweg 18, 55128 Mainz, Germany*
[2]*GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[3]*PRISMA+ Cluster of Excellence and Institute for Nuclear Physics, Johannes Gutenberg University Mainz, Johann-Joachim-Becher-Weg 45, 55128 Mainz, Germany*

(Received 20 September 2023; accepted 15 April 2024; published 22 May 2024)

- Latest from Djukanovic et. al.
  - (2 +1) flavor coordinated lattice simulations
    - Allows for quark connected and disconnected contributions
    - Pion mass between 130 and 290 MeV



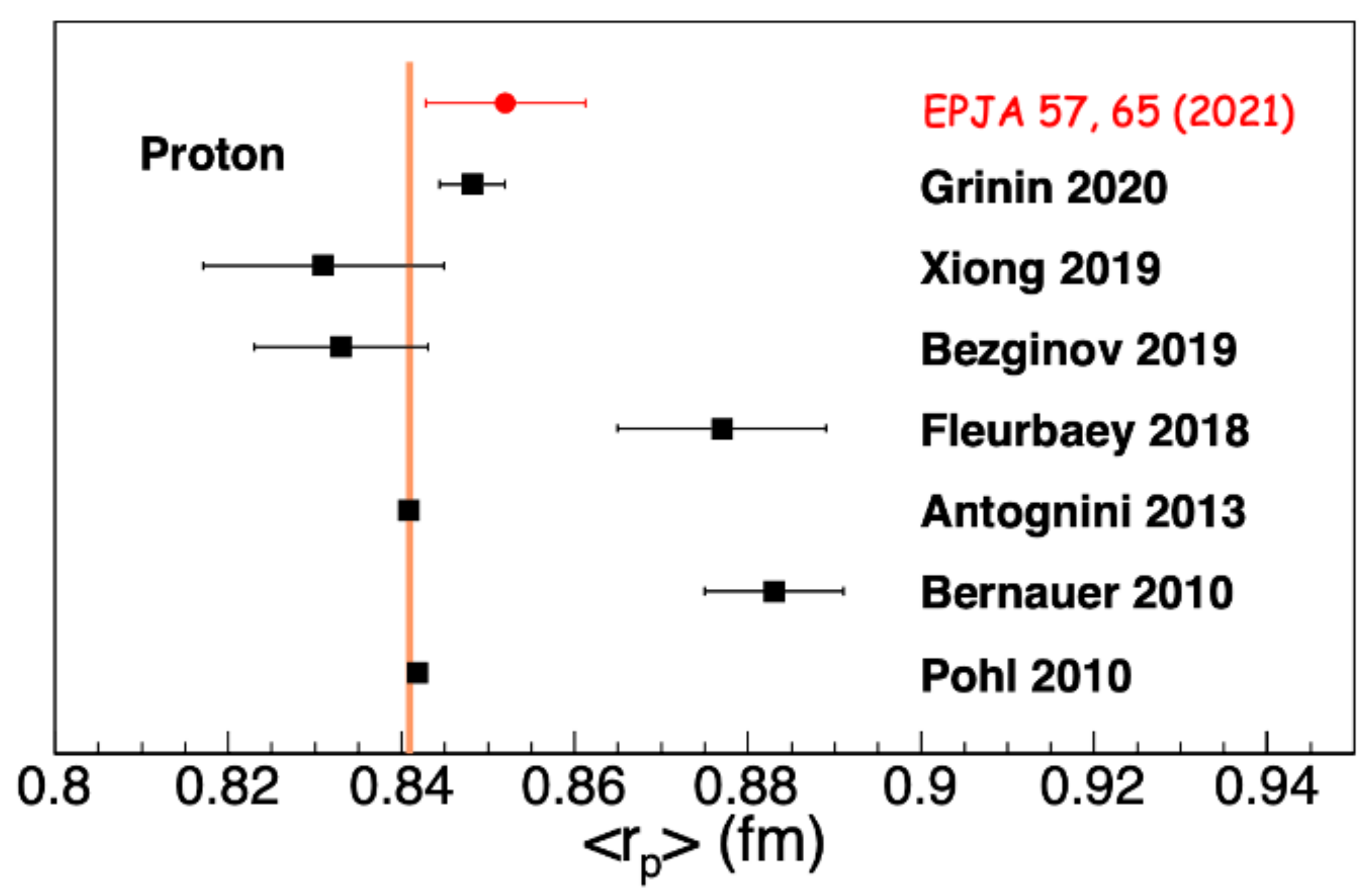
$$\langle r_E^2 \rangle^n = (-0.115 \pm 0.013(\text{stat}) \pm 0.007(\text{syst}))\ \text{fm}^2.$$

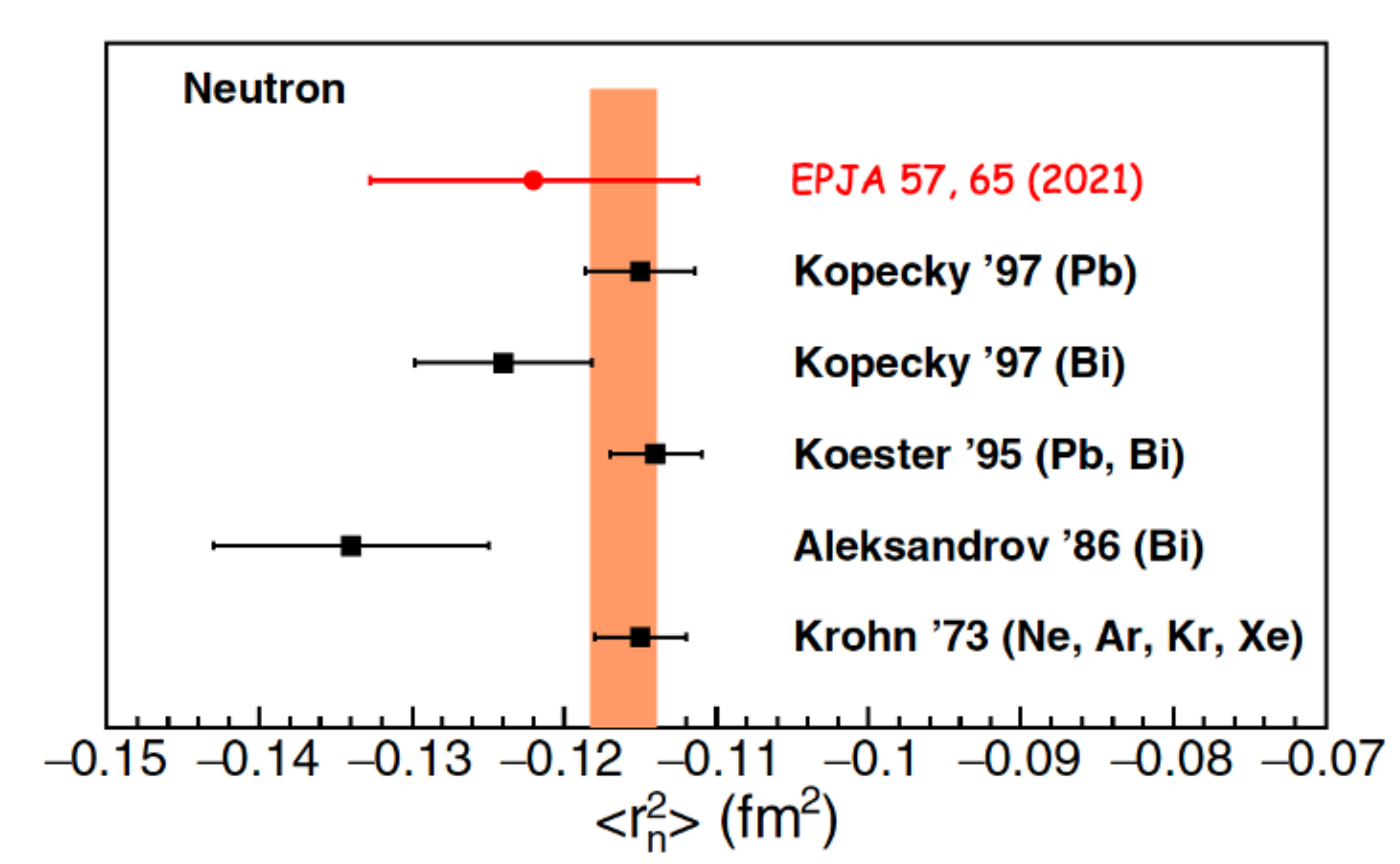


Previous Lattice

Djukanovic et. al. (2024)

Radius extraction through flavor decomposition





$$\langle b^2_{u(d)} \rangle = \frac{-4}{F_1^{u(d)}(0)} \frac{dF_1^{u(d)}(Q^2)}{dQ^2}\Big|_{Q^2 \to 0}$$

$$F_1^u = 2\,F_1^p + F_1^n$$

$$F_1^d = 2\,F_1^n + F_1^p$$

$$\langle r_p^2 \rangle = 2\langle b_u^2 \rangle - \frac{1}{2}\langle b_d^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2}$$

$$\langle r_n^2 \rangle = \langle b_d^2 \rangle - \langle b_u^2 \rangle + \frac{3}{2}\frac{\kappa_N}{M_N^2}$$

G. Miller. Phys. Rev. Lett. 99 (2007) and Phys. Rev. C 99 (2019)

- **By using the neutron and proton FF data together, a flavor decomposition can be performed.**
  - Exploiting isospin symmetry, both proton and neutron radii can be extracted simultaneously.
    - Eur. Phys. J. A 57, 65 (2021), H. Atac, M. Constantinou, Z.E. Meziani, M. Paolone, N. Sparveris:
      - $\langle r_p \rangle = 0.852 \pm 0.002_{(\text{stat.})} \pm 0.009_{(\text{syst.})}$ (fm)
      - $\langle r_n^2 \rangle = -0.122 \pm 0.004_{(\text{stat.})} \pm 0.010_{(\text{syst.})}$ (fm^2)
  - Provides new nucleon radii points:
    - Neutron precision (~9%) remains inadequate to reconcile discrepancies.

A path to extend our low Q^2 reach for G_E^n

PHYSICAL REVIEW D 76, 111501(R) (2007)

Large-N_c relations for the electromagnetic nucleon-to-Δ form factors

Vladimir Pascalutsa*
European Centre for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), Villa Tambosi, Villazzano I-38050 TN, Italy

Marc Vanderhaeghen†
Physics Department, College of William and Mary, Williamsburg, Virginia 23187, USA
and Theory Center, Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA

(Received 3 November 2006; published 6 December 2007)

We examine the large-N_c relations which express the electromagnetic N-to-Δ transition quantities in
terms of the electro
relation between th
derived large-N_c rel
Extending these rel
electromagnetic N
which may be ascri
for the $N \to \Delta$ gen

VOLUME 93, NUMBER 21 PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2004

Electromagnetic $N \to \Delta$ Transition and Neutron Form Factors

A. J. Buchmann*
[1]Institute for Theoretical Physics, University of Tübingen, D-72076 Tübingen, Germany

(Received 10 July 2004; published 17 November 2004)

The $C2/M1$ ratio of the electromagnetic $N \to \Delta(1232)$ transition, which is important for determining the geometric shape of the nucleon, is shown to be related to the neutron elastic form factor ratio G_C^n/G_M^n. The proposed relation holds with good accuracy for the entire range of momentum transfers where data are available.

- **It has been long known that there is a correlation between the N-Δ TFFs and G_E^n**
  - Initially exploited in reverse to infer information for the N-Δ TFFs, while they were not yet very well measured.
  - Almost 20 years later: the N-Δ TFFs can be accessed at lower Q² and with higher precision, compared to the current G_E^n measurements

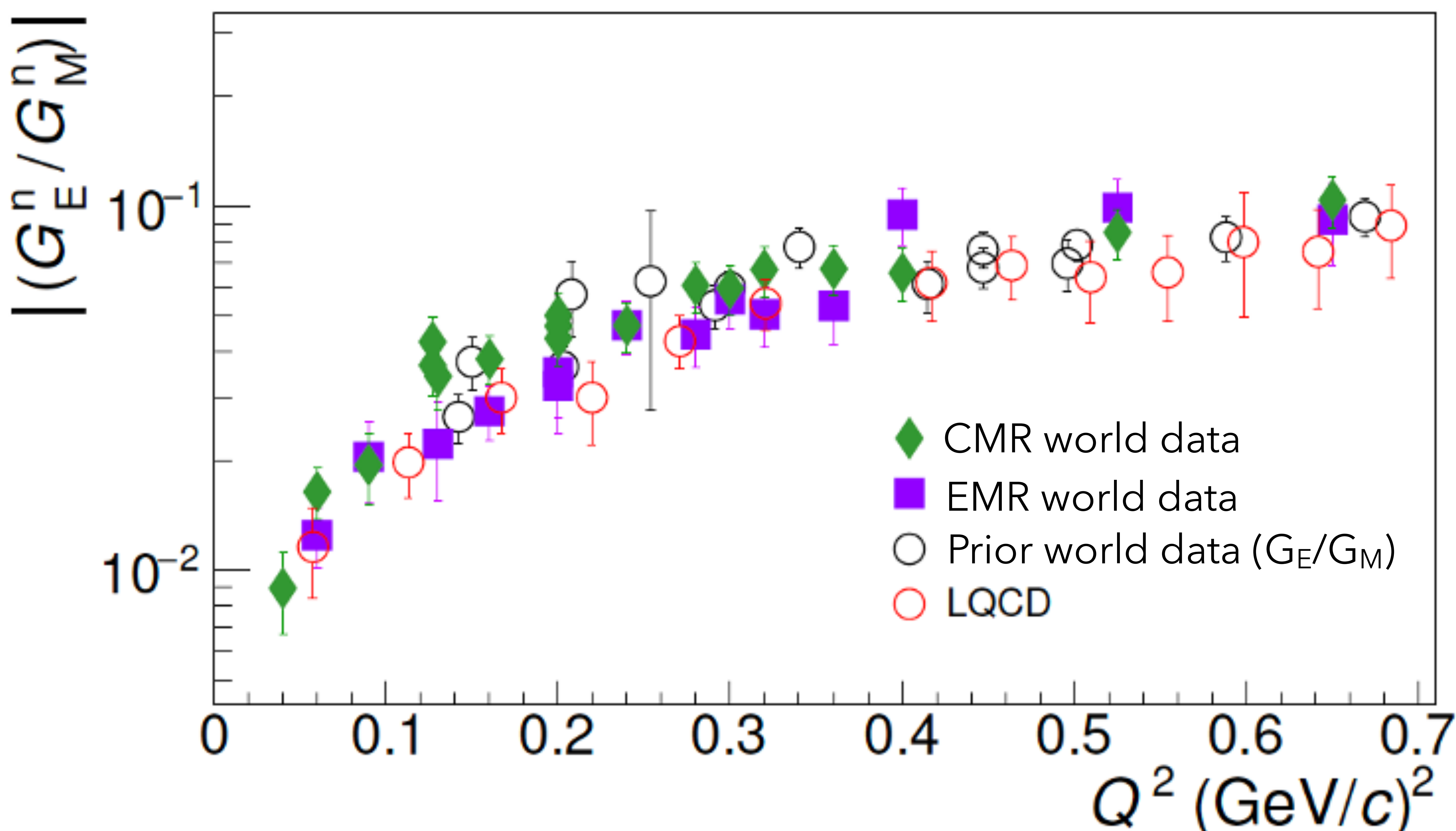
A path to extend our low Q^2 reach for G_E^n

Large-N$_c$ Relations (Pascalutsa & Vanderhaeghen)
Phys. Rev. D76. 93, 111501(R) (2007)

$$\frac{E2}{M1}\left(Q^2\right) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{M_\Delta^2 - M_N^2}{2Q^2} \frac{G_E^n\left(Q^2\right)}{F_2^p\left(Q^2\right) - F_2^n\left(Q^2\right)}$$

$$\frac{C2}{M1}\left(Q^2\right) = \left(\frac{M_N}{M_\Delta}\right)^{3/2} \frac{Q_+Q_-}{2Q^2} \frac{G_E^n\left(Q^2\right)}{F_2^p\left(Q^2\right) - F_2^n\left(Q^2\right)}$$

- **Large-Nc relations:**
  - Carry about 15% theoretical uncertainty.
  - Two relations (CMR and EMR) can be used to cross-check validity.

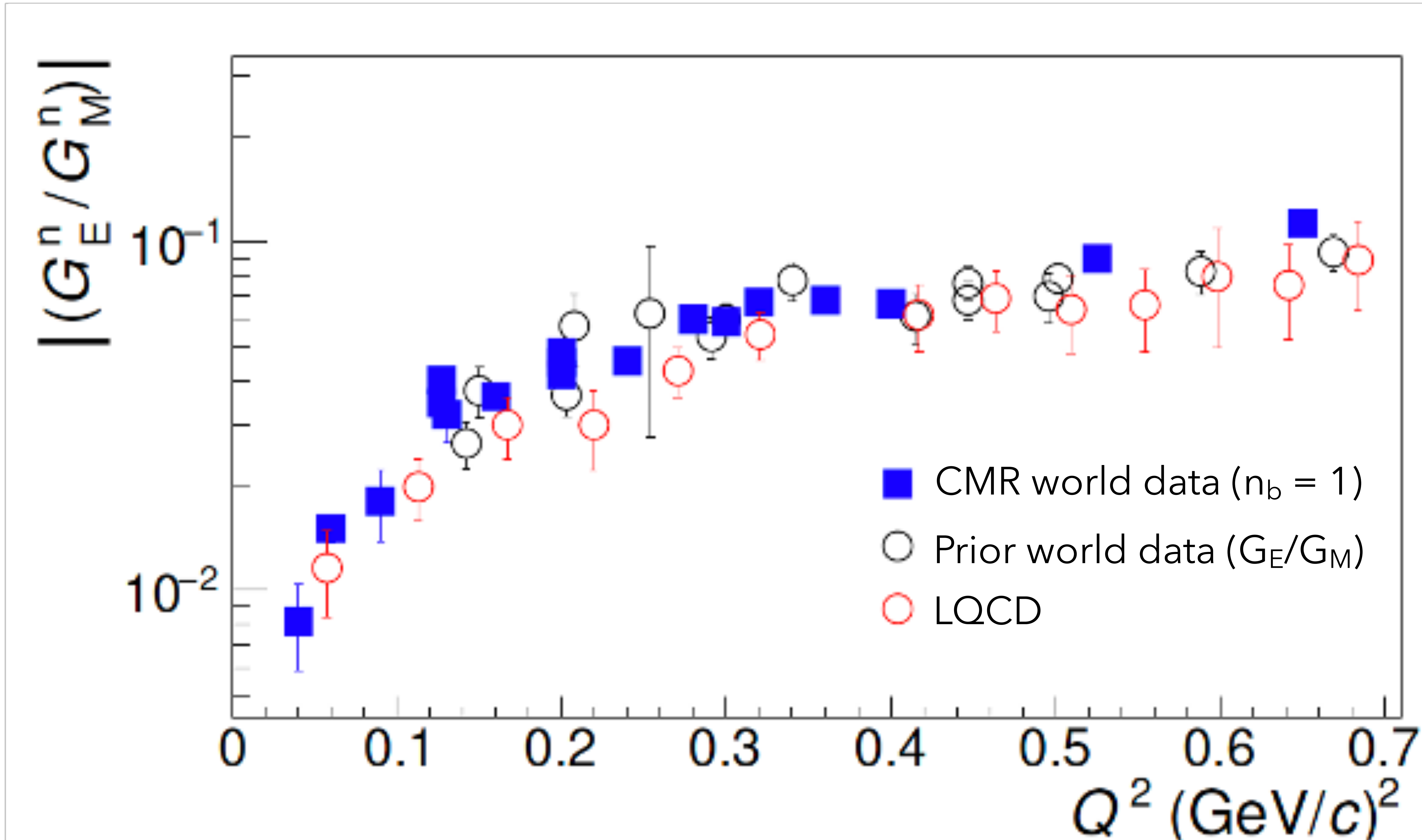


A path to extend our low Q^2 reach for G_E^n

A. J. Buchmann
Phys. Rev. Lett. 93, 212301 (2004)

$$\frac{G_E^n(Q^2)}{G_M^n(Q^2)} = \frac{Q}{|\mathbf{q}|}\frac{2Q}{M_N}\frac{1}{n_b(Q^2)}\frac{C2}{M1}(Q^2)$$

- **Buchmann SU(6) form:**
  - Ratios are related due to the underlying spin-flavor symmetry and its breaking by spin-dependent two- and three-quark currents
  - Theoretical correction (n_b) is ~10% (i.e. it reduces the G_E^n/G_M^n ratio by n_b~1.1) mainly due to third order SU(6) breaking terms (three-quark currents) omitted in the relation between G_M^n and $G_{M1}^{N\rightarrow\Delta}$



NRCQM

- Buchmann NRCQM:
  - Requires quarks to have some charge size
  - To enforce current conservation:
    - Includes spin-independent and spin-dependent two-body currents (to LO and some to NLO)
  - Not included:
    - Relativistic boost corrections
    - Strangeness contributions
    - Magnetic moment of quarks.

One-body quark currents — **Gluon, pion, confinement, and sigma exchange current terms**

$$r_\Delta^2 = b^2 + r_{\gamma q}^2 + \frac{b^2}{6m_q}(5\delta_g - \delta_\pi) + \frac{5}{6m_q^3}V^{conf} + r_\sigma^2$$

$$r_p^2 = b^2 + r_{\gamma q}^2 + \frac{b^2}{2m_q}(\delta_g - \delta_\pi) + \frac{5}{6m_q^3}V^{conf} + r_\sigma^2$$

$$r_n^2 = -\frac{b^2}{3m_q}(\delta_g + \delta_\pi) = -b^2\frac{M_\Delta - M_N}{M_N}$$

$$r_\Delta^2 = r_p^2 - r_n^2 \longrightarrow$$ **the charge radius of the Δ is equal to the isovector charge radius of the nucleon**

This relation has been tested in the form of "general parametrization" of QCD: 3rd order terms and loops contribute to a ~10-20% deviation.

Dillon, Mortugo, PRB 448

Electromagnetic current commutators

Electromagnetic vector currents obey SU(3) Lie algebra

$$\left[J_i^{\alpha}(\vec{r}),\; J_j^{\beta}(\vec{r}\,')\right] = i\, f_{\alpha\beta\gamma}\, \delta_{ij}\, \delta(\vec{r}-\vec{r}\,')\, J_0^{\gamma}(\vec{r}\,')$$

$J_i^{\alpha}(\vec{r})$ ⋯ four−vector current density, i=0, ⋯ , 3

- i, j ⋯ Lorentz 4-vector indices
- α, β, γ ⋯ SU(3) flavor indices
- $f_{\alpha\beta\gamma}$ ⋯ SU(3) structure constants

$$\mu_p^2 = \frac{1}{6}\, r_p^2$$

Gell-Mann Dashen Lee (1965)

Advantage of current algebra method

Gell-Mann (1964)

No matter how badly SU(3) flavor symmetry is broken, the SU(3) commutation relations between group generators are an exact law of nature.

$N \rightarrow \Delta$ form factor relations

$$G_{M1}^{p\rightarrow\Delta^+}(Q^2) = -\sqrt{2}\; G_M^n(Q^2)$$

$$\mu_{p\rightarrow\Delta^+} = -\sqrt{2}\; \mu_n$$

magnetic form factors
Beg, Lee, Pais, 1964

$$G_{C2}^{p\rightarrow\Delta^+}(Q^2) = -\frac{3\sqrt{2}}{Q^2}\; G_C^n(Q^2)$$

$$Q_{p\rightarrow\Delta^+} = \frac{1}{\sqrt{2}}\; r_n^2$$

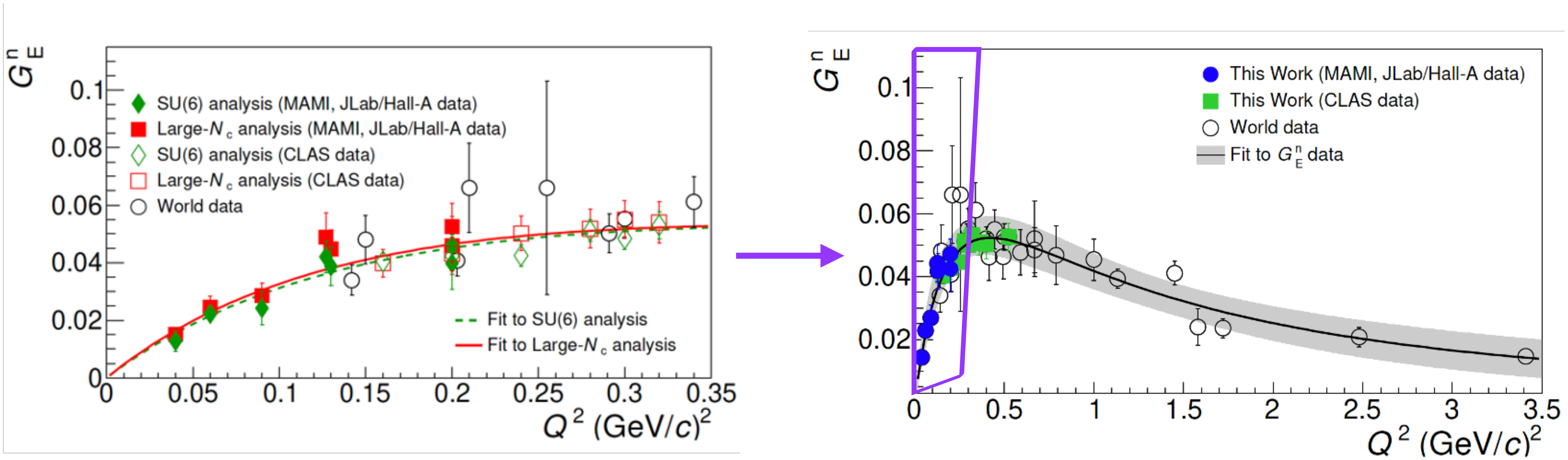
charge form factors
AJB, Phys. Rev. Lett. 93 (2004) 212301

*Slides taken from A.J. Buchmann presentation at N-Star 2017

Model uncertainties

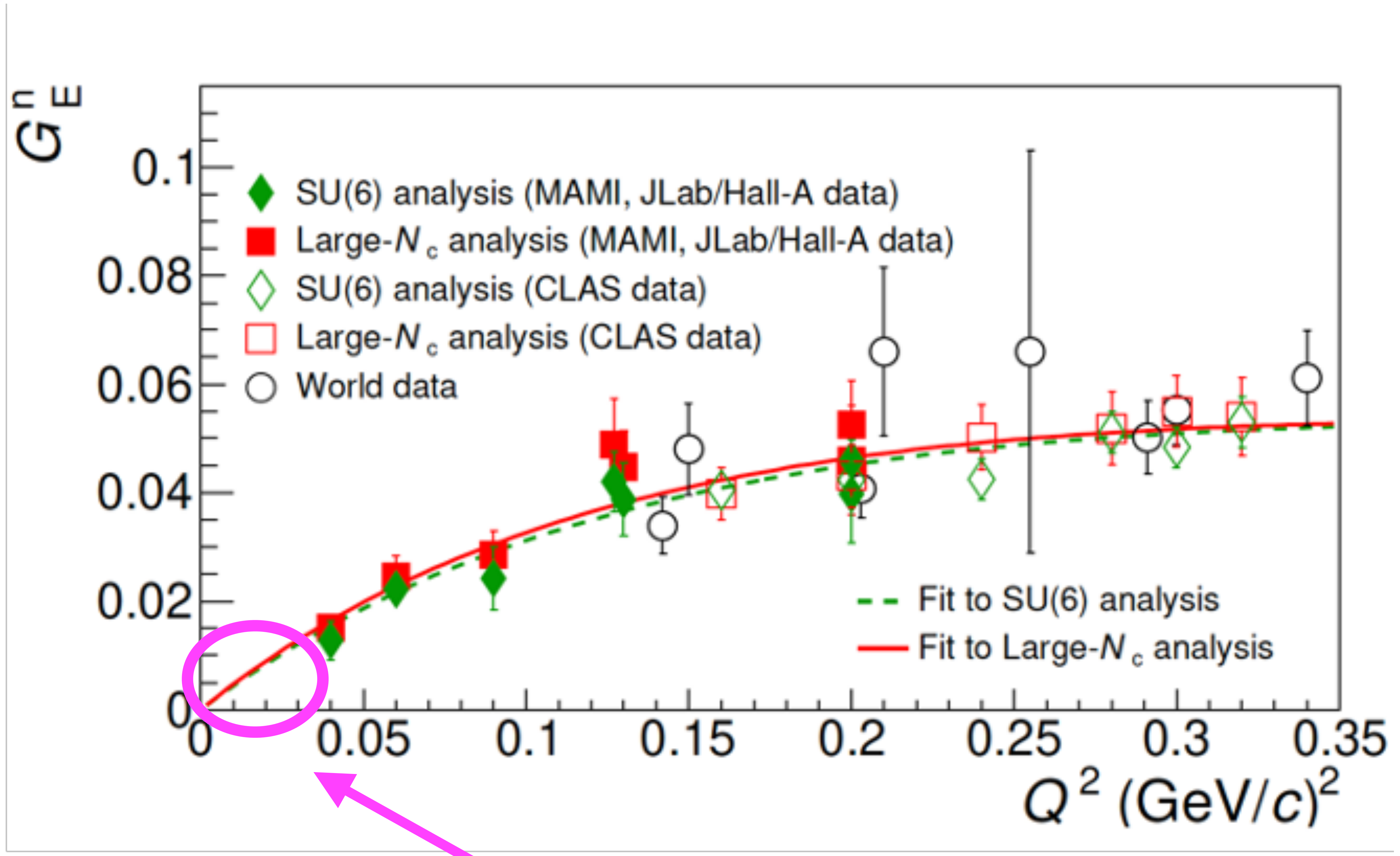
- **Not ChEFT style calculations**
  - No power counting available.
  - Not based on any symmetries of strong interactions that could provide a reference point and enable one to theoretically estimate corrections due to deviations from the idealized symmetric situation.
  - Some concerns about the differences in isoscalar and isovector contributions to the quark model at very low Q2.
  - Uncertainty due to truncation of higher order terms are constrained empirically.

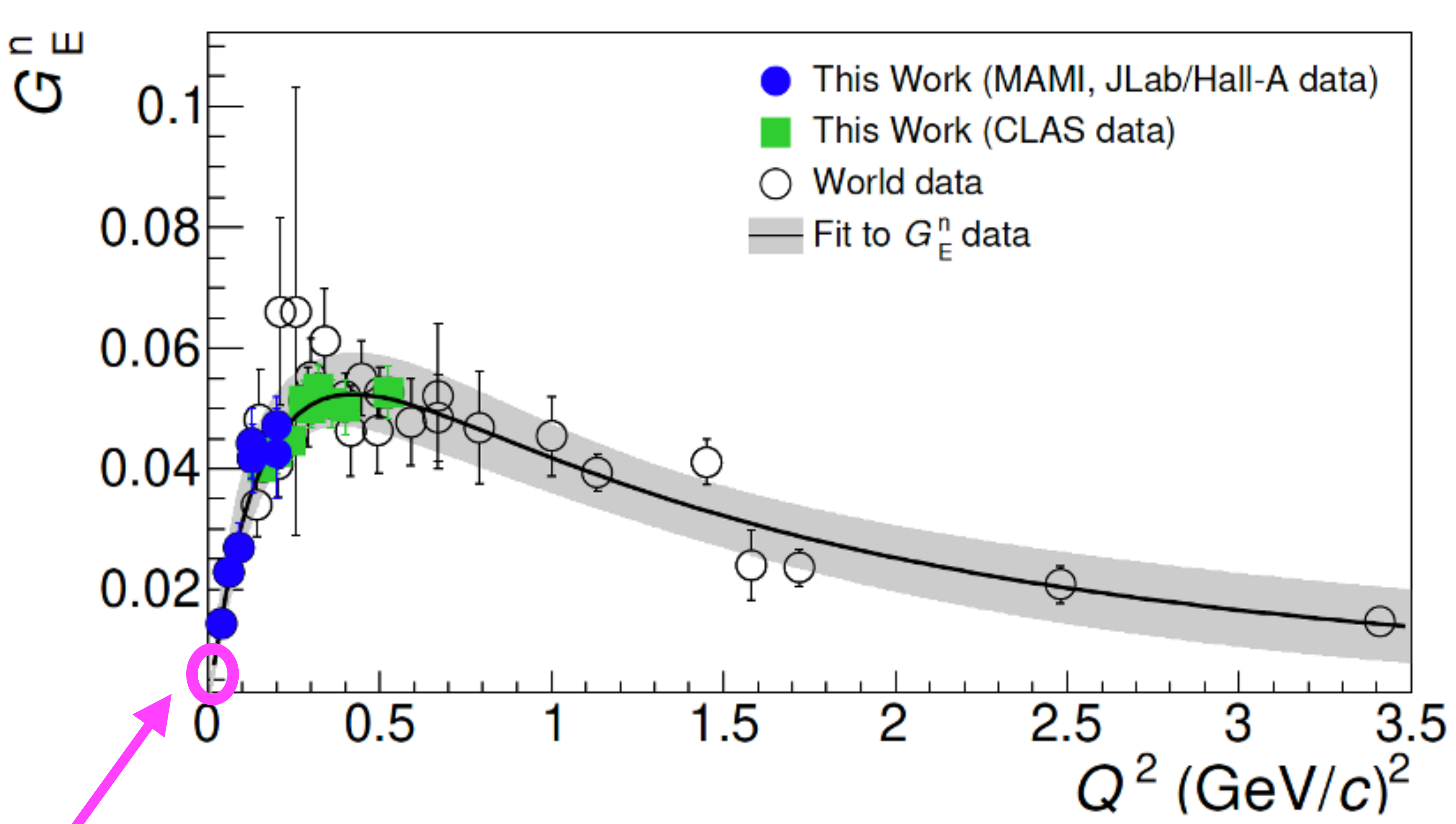
A path to extend our low Q^2 reach for G_E^n

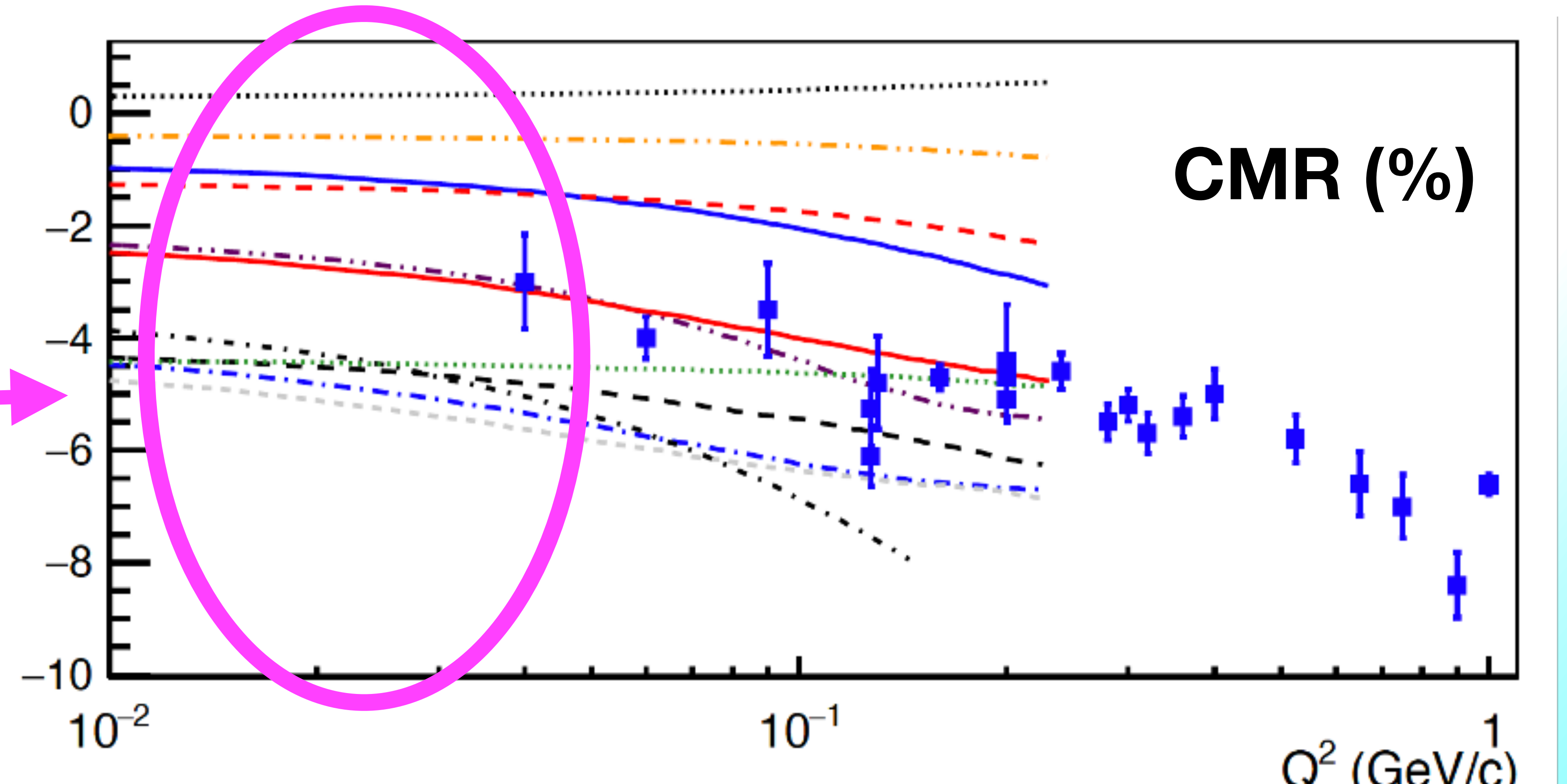


Global analysis using this method has been published in Nature Comm. 12, 1759 (2021)

A path to extend our low Q^2 reach for G_E^n

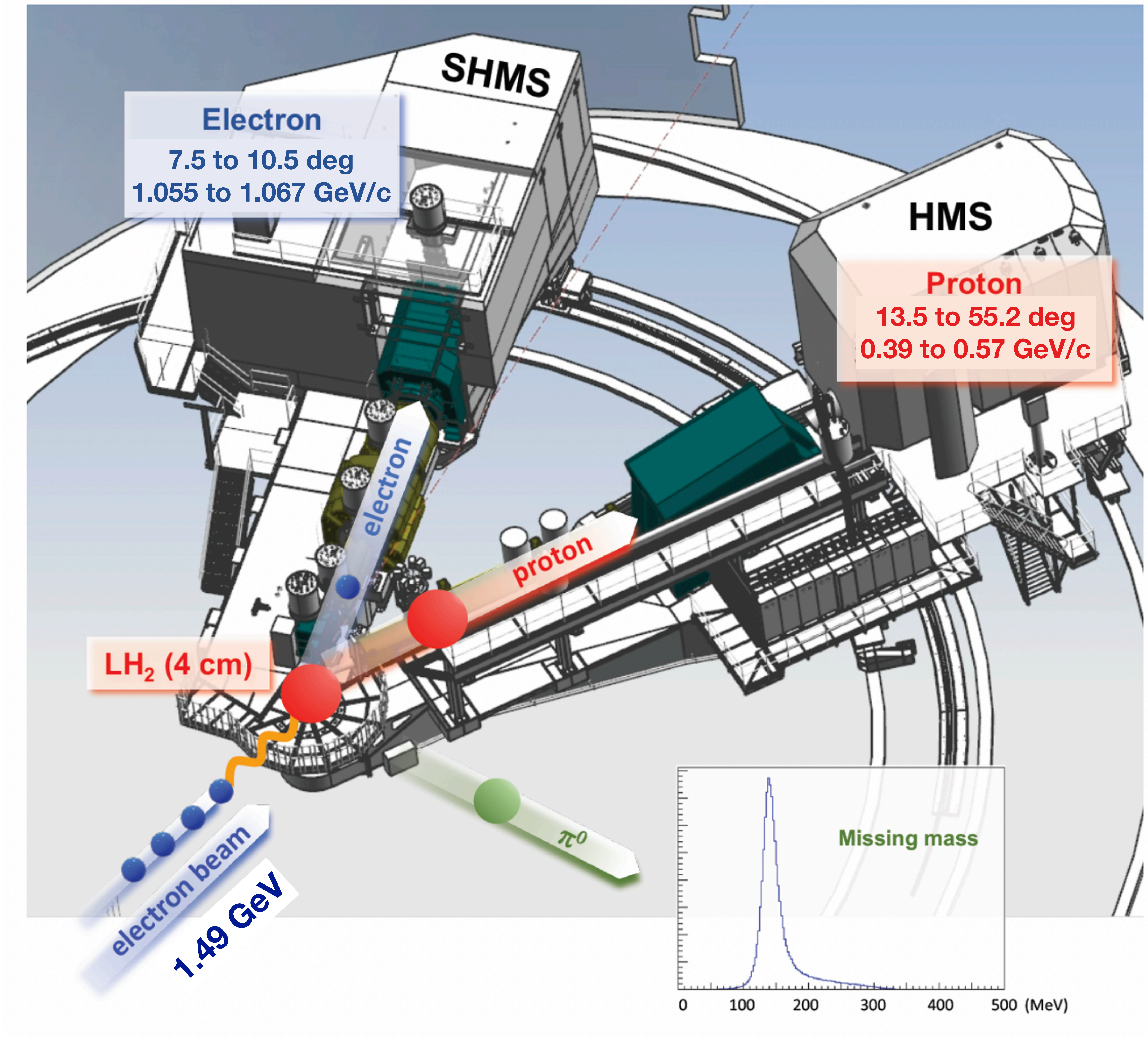






New Experiment Running Now!

JLab NDelta experiment E12-22-001

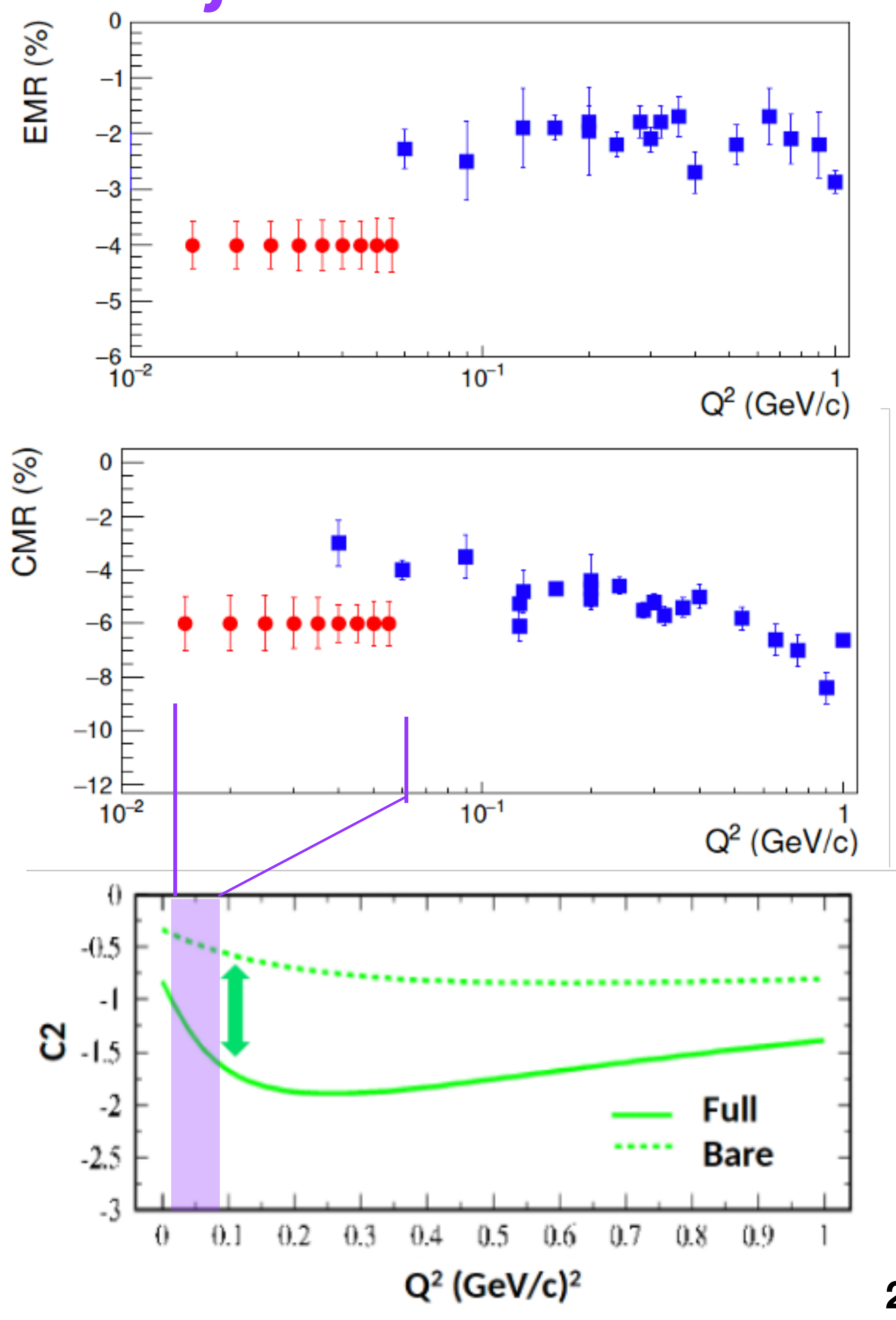


- **Running RIGHT NOW!**
  - from 3/23 until ~4/24
- **Standard Hall-C equipment**
  - 1490 MeV electron beam
  - Detect proton and electron in coincidence
  - Reconstruct pion from missing mass.

Measurement Settings

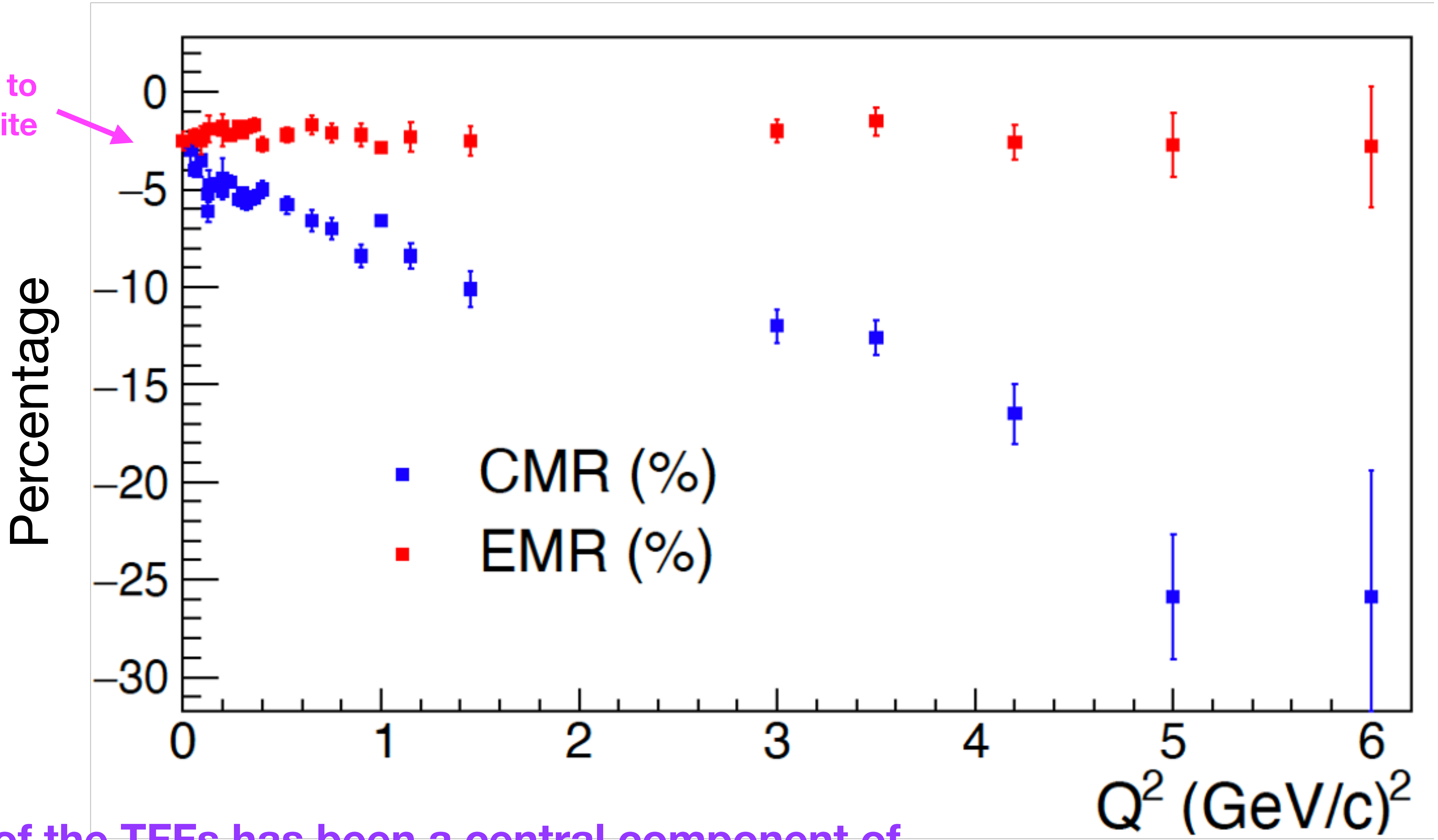
Setting	Central Q2 (GeV2)	SHMS Momentum (GeV)	SHMS Angle (deg)	HMS Momentum (GeV)	HMS Angle (deg)	Progress
1d	0.05	-1.0553	10.48	0.571	26.73	
2d				0.566	32.65	
3d				0.546	13.74	
4d				0.546	39.72	
5d				0.502	48.22	
6d				0.445	55.66	
7d				0.412	59.20	
1a	0.026	-1.0681	7.51	0.536	21.19	
2a				0.531	14.89	
3a				0.531	27.49	
4a				0.509	35.86	
5a				0.470	44.15	
6a				0.416	52.25	
7a				0.384	56.17	As of 4/14
1b	0.03	-1.0659	8.08	0.542	22.01	
2b				0.537	28.61	
3b				0.532	13.66	
4b				0.515	36.89	
5b				0.476	45.07	
6b				0.421	53.06	
7b				0.389	56.90	
1c	0.04	-1.0606	9.35	0.557	24.83	
2c				0.552	30.90	
3c				0.539	13.52	
4c				0.529	38.95	
5c				0.489	46.90	
6c				0.433	54.60	
7c				0.400	58.28	

Projected Measurements



World data and status of TFFs

CMR & EMR predicted to converge at a small finite value as $Q^2 \to 0$



At large Q^2, no direct indication of EMR → 100% and CMR → constant (predicted in pQCD regime)

Extraction of the TFFs has been a central component of Jlab's experimental program:

(Most of these measurements are from JLab Halls A, B, and C)

Exclusive bound n-Δ^0 TFFs in ^{4}He with ALERT and CLAS12 at JLAB

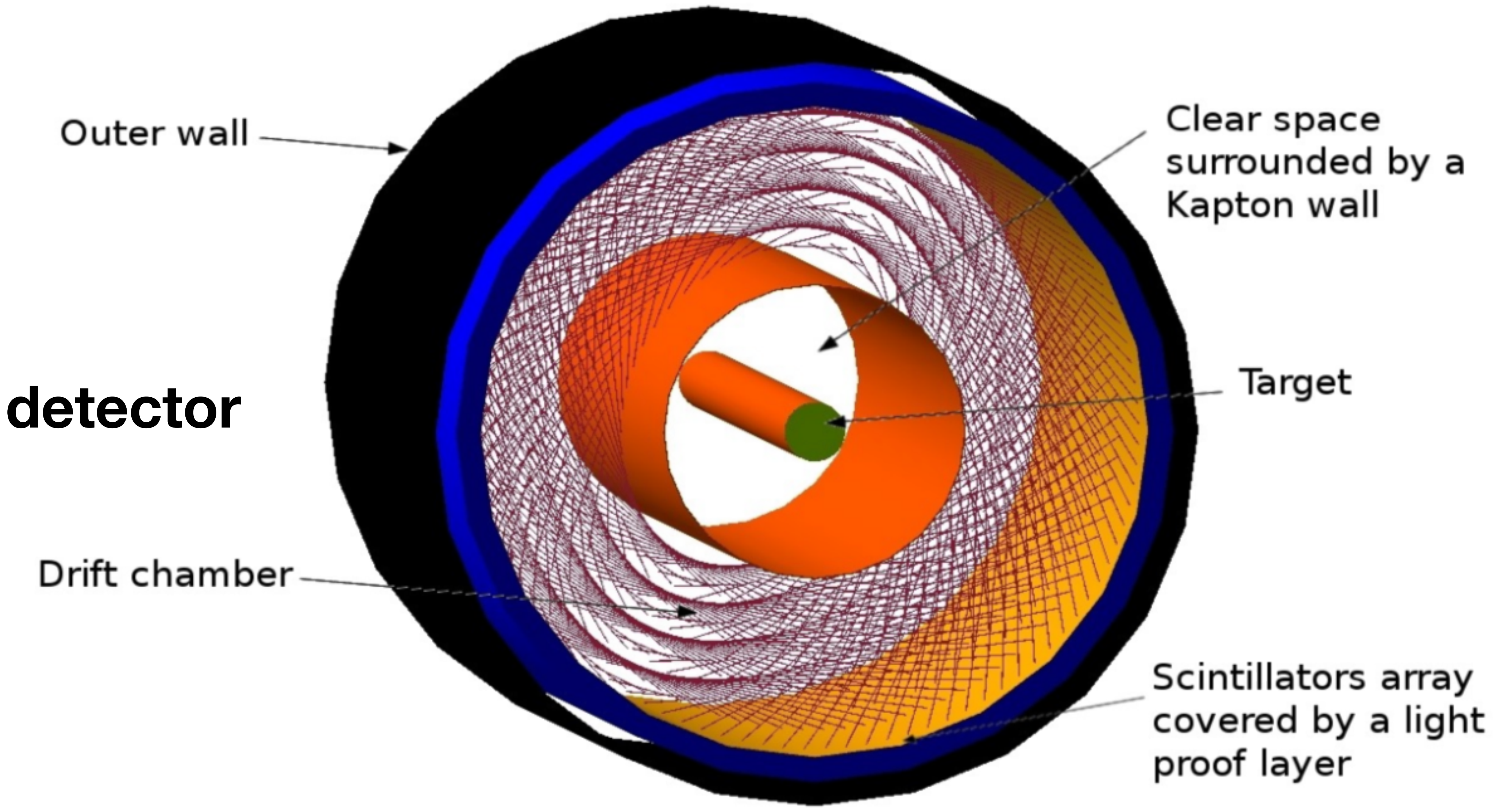
CLAS12 RG-L

11 GeV Beam
40 cm 4He target, d target

CLAS12 Forward detector (standard)
ALERT recoil detector

Running in < 2 weeks (hopefully)

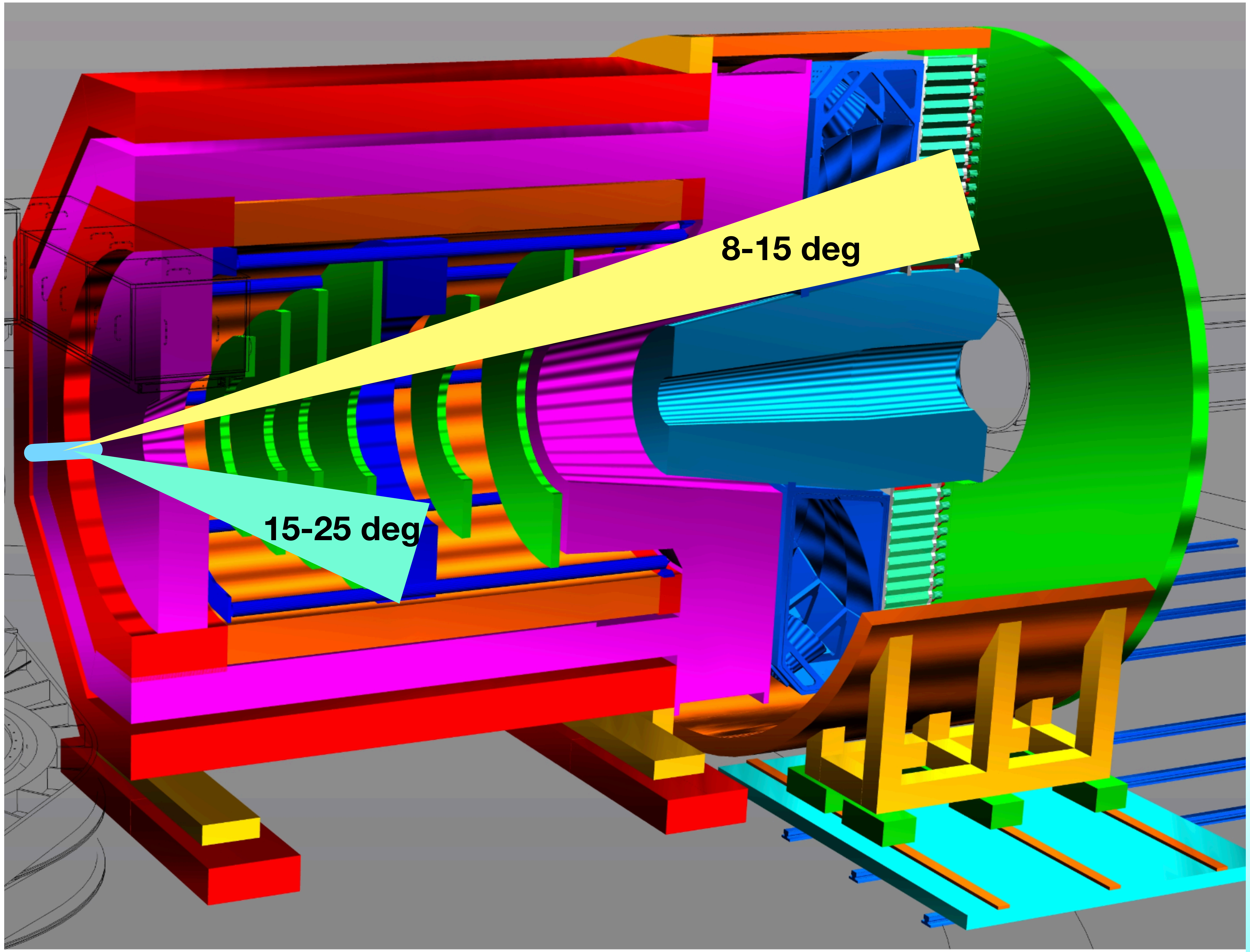
The ALERT detector



High Q2 TFFs with SoLID at JLab (J/psi Set-up)

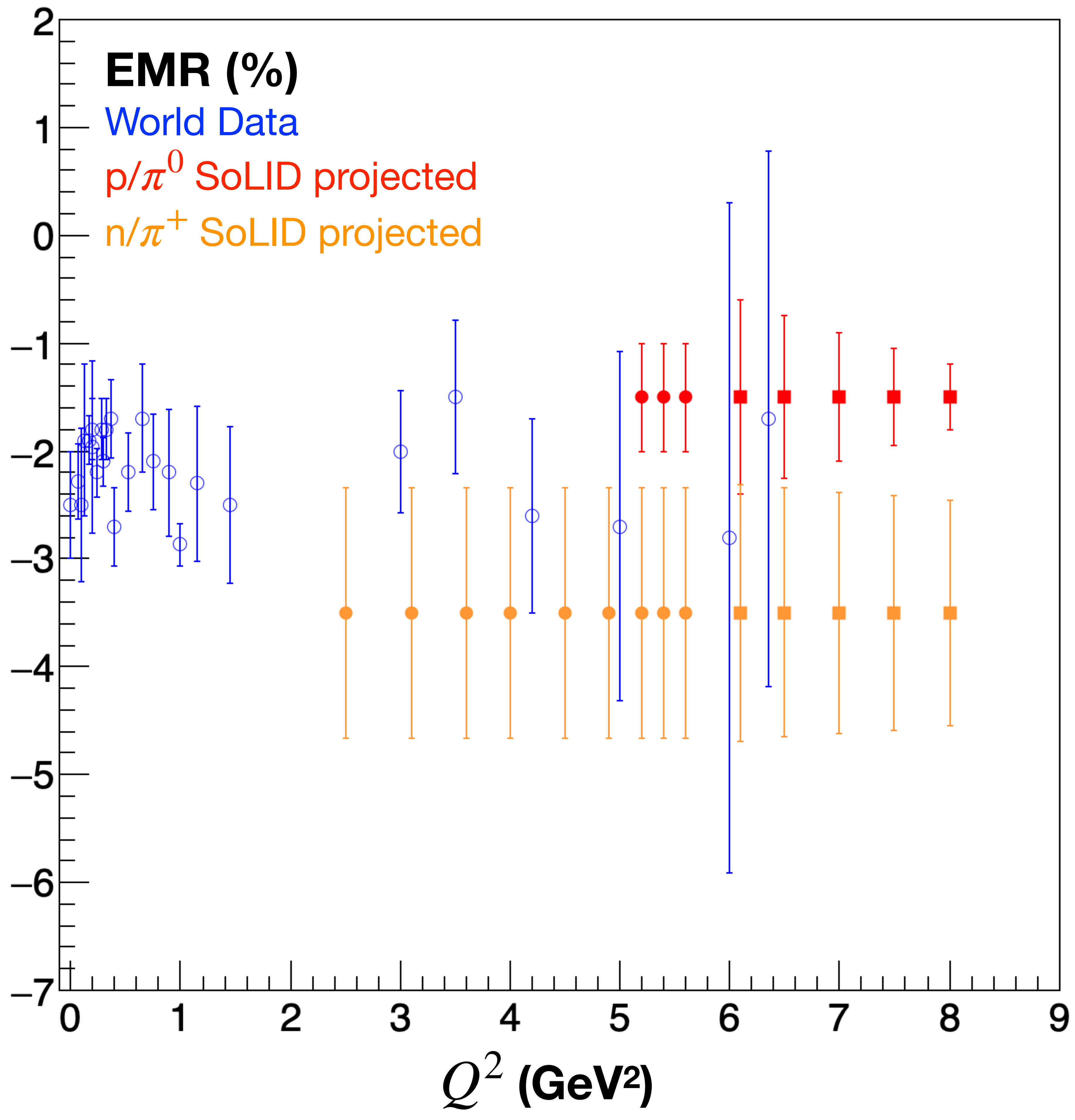
- 15 cm LH2 target
- 11.0 GeV beam Energy
- Luminosity = $10^{37}\,\mathrm{N\,cm^{-2}\,s^{-1}}$

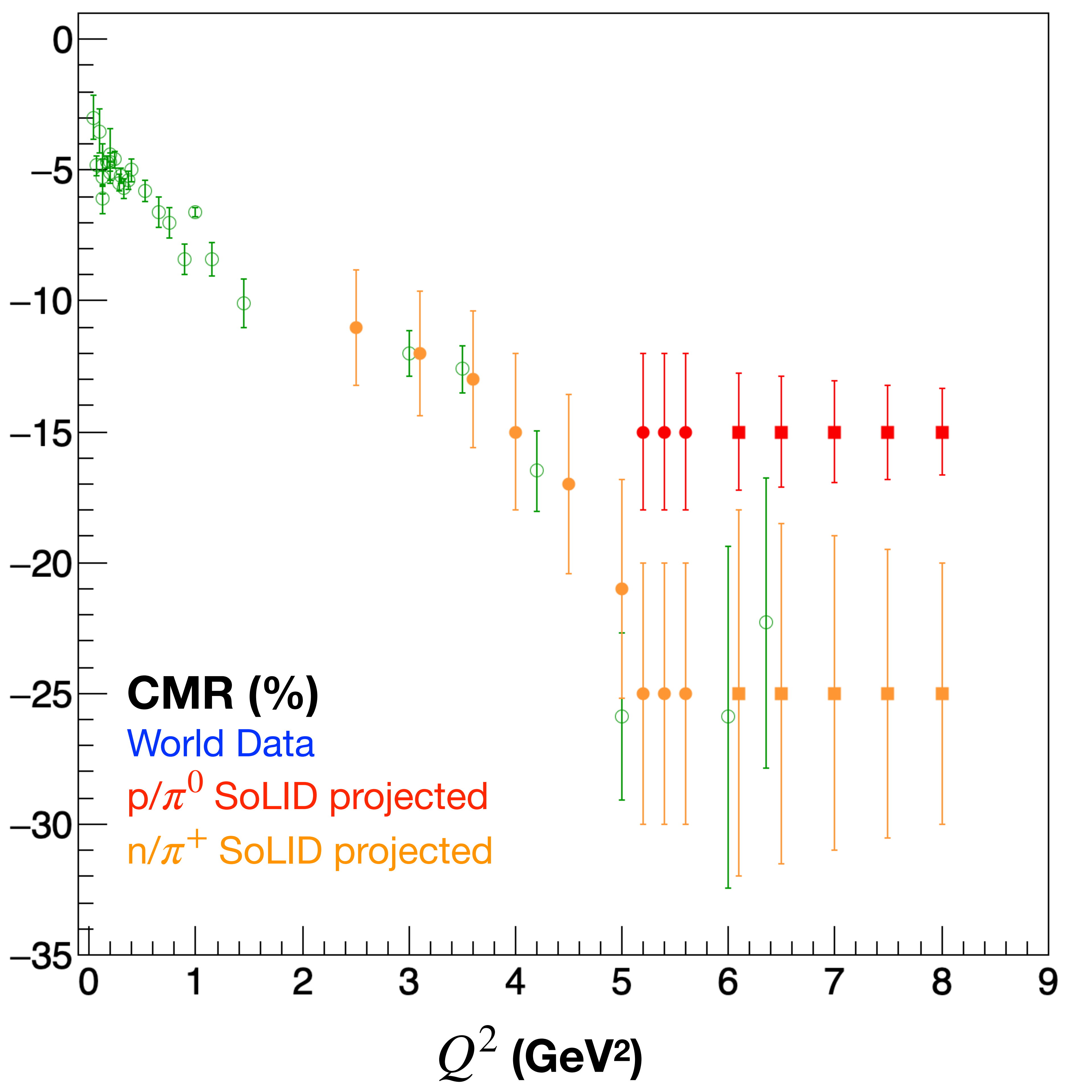
- 4 possible kinematics:
  - $p-\pi^0$
    - Electron detected w small angle
    - Electron detected w large angle
  - $n-\pi^+$
    - Electron detected w small angle
    - Electron detected w large angle



High Q2 TFFs with SoLID at JLab (J/psi Set-up)

- Projections from LOI to JLab





High Q2 TFFs with SoLID at JLab (J/psi Set-up)

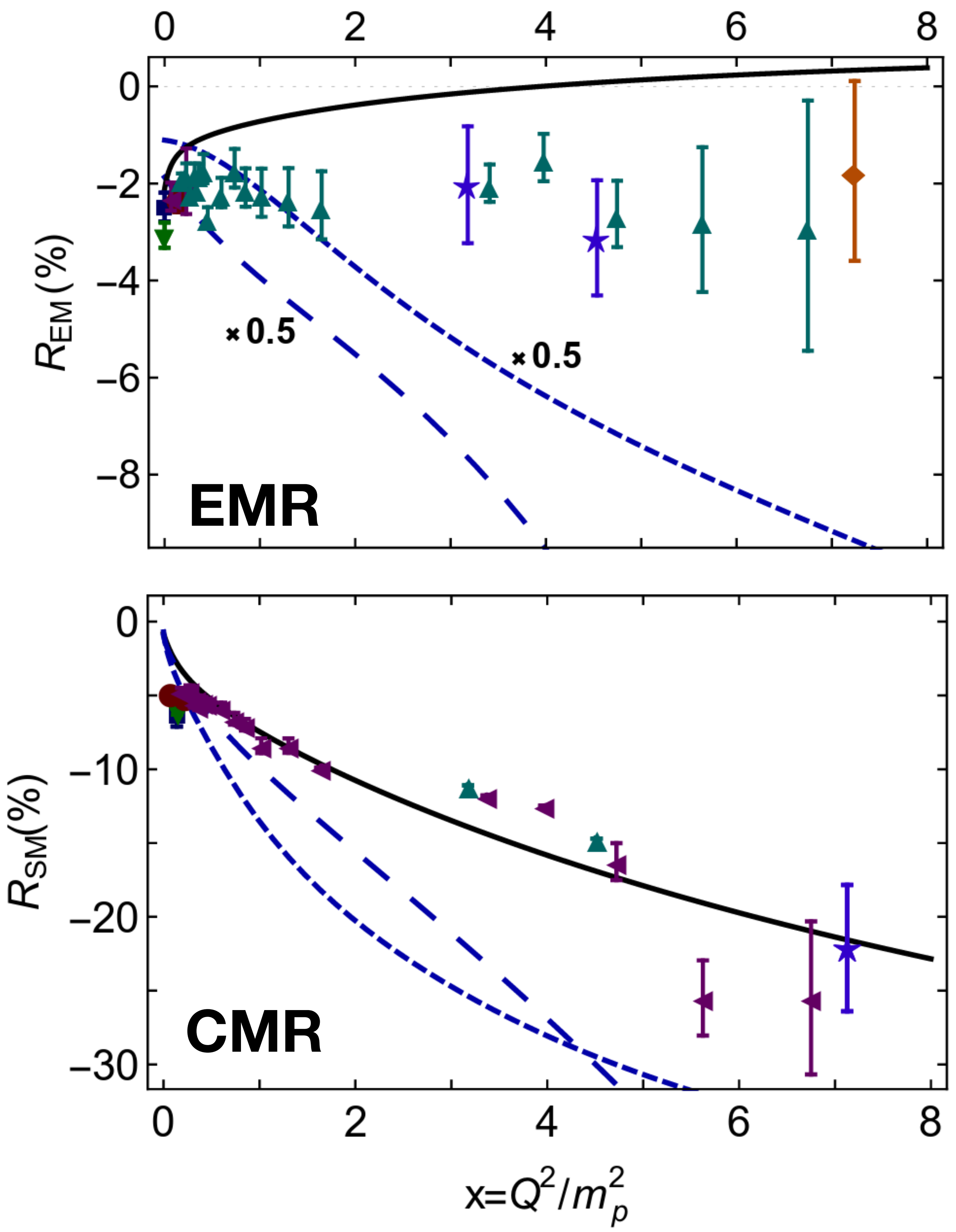
- **Questions from LOI reviewer**
  - "Parasitic" experiment, but requires a more open trigger. Determine what impact new trigger configuration will have:
    - Progress: Mostly done. Latest simulations show that accidentals from additional trigger will not impact rate more than ~10%.
  - Theory motivation at larger Q2 needs to be more robust
    - Some progress:

Transition form factors: $\gamma^* + \mathbf{p} \to \mathbf{\Delta(1232)}, \mathbf{\Delta(1600)}$

Y. Lu,[1,*] C. Chen,[2,†] Z.-F. Cui,[1,‡] C. D. Roberts,[3,§] S. M. Schmidt,[4,¶] J. Segovia,[5,**] and H.-S. Zong[1,6,††]

[1] *Department of Physics, Nanjing University, Nanjing, Jiangsu 210093, China*
[2] *Instituto de Física Teórica, Universidade Estadual Paulista, Rua Dr. Bento Teobaldo Ferraz, 271, 01140-070 São Paulo, SP, Brazil*
[3] *Physics Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
[4] *Institute for Advanced Simulation, Forschungszentrum Jülich and JARA, D-52425 Jülich, Germany*
[5] *Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, E-41013 Sevilla, Spain*
[6] *Joint Center for Particle, Nuclear Physics and Cosmology, Nanjing, Jiangsu 210093, China*

(Dated: 05 April 2019)

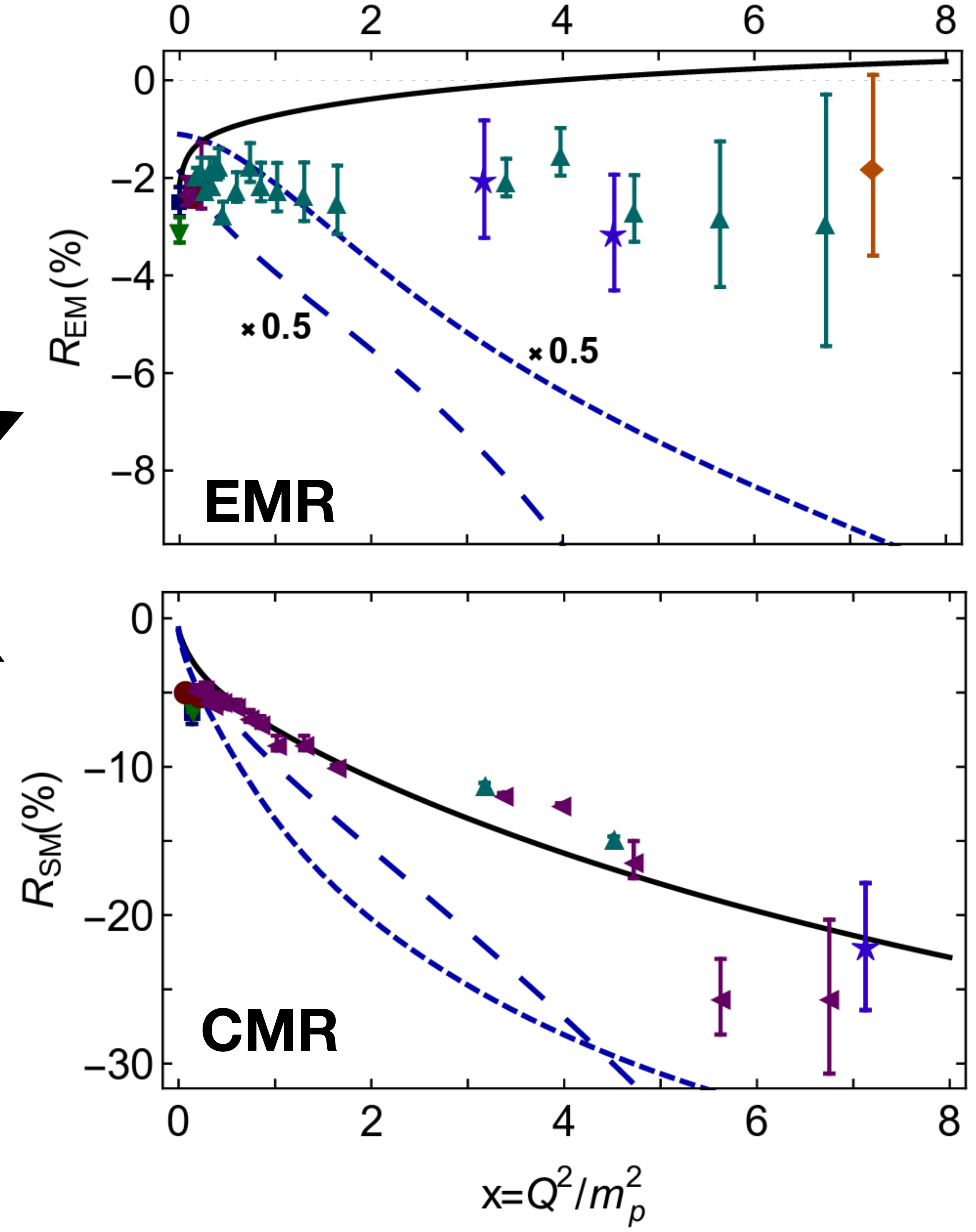


Transitions are computed using a fully-dynamical diquark-quark approximation to the Poincare-covariant three-body bound-state problem in RQFT

High Q2 TFFs with SoLID at JLab (J/psi Set-up)

- Questions from LOI reviewer
  - "Parasitic" experiment, but requires a more open trigger. Determine what impact new trigger configuration will have:
    - Progress: Mostly done. Latest simulations show that accidentals from additional trigger will not impact rate more than ~10%.
  - Theory motivation at larger Q2 needs to be more robust
    - Some progress:

Long Dash: Only keeping s-wave contributions to the Delta in rest frame
Short Dash: Forcing proton and Delta to reduce to S-waves
Black curve: Full treatment



TFFs at large Q2 are VERY sensitive to deformation (higher wave contribution)

Transitions are computed using a fully-dynamical diquark-quark approximation to the Poincare-covariant three-body bound-state problem in RQFT

Summary

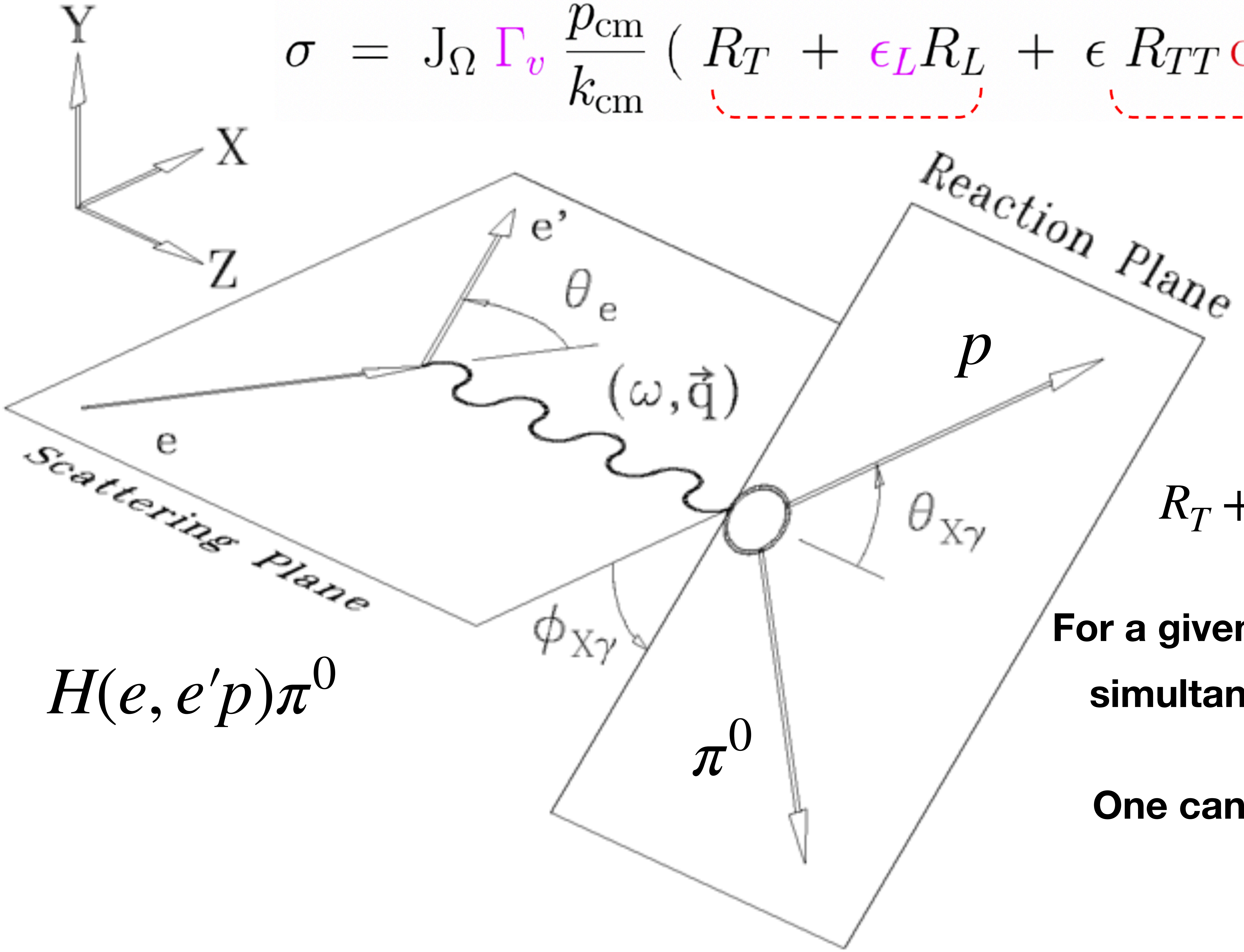
- The neutron radius measured from atomic scattering have significant tension.
- Quasi-free scattering measurements are limited by systematic precision.
- Combined proton/neutron extractions are still lacking in precision.
- Lattice calculations are becoming more precise.
- N-to-Delta transition form factors may offer a path to very low Q^2 G_E^n, but theoretical systematics need to be handled carefully.

Thanks!

Backup Slides

Experimental Methodology

$$\sigma = J_\Omega \, \Gamma_v \frac{p_{cm}}{k_{cm}} \left(R_T + \epsilon_L R_L + \epsilon \, R_{TT} \cos 2\phi_{X\gamma} - v_{LT} R_{LT} \cos \phi_{X\gamma} \right)$$



$H(e, e'p)\pi^0$

$$R_T + R_L, R_{TT}, R_{LT} = f(A(W, Q^2), g(\theta_{X\gamma}))$$

For a given $\theta_{X\gamma}$, one can measure at least 3 $\phi_{X\gamma}$ to simultaneously extract $R_T + R_L, R_{TT}$ and R_{LT}.

One can then scan $\theta_{X\gamma}$ to extract the relevant amplitudes $A(W, Q^2)$.

Experimental Methodology

$$R_{TT} = 3\sin^2\theta\,(E2\,M1 + M1^2 + \ldots\Sigma_{\text{background}})$$

$$R_{LT} = -6\cos\theta\sin\theta\,(C2\,M1 + \ldots\Sigma_{\text{background}})$$

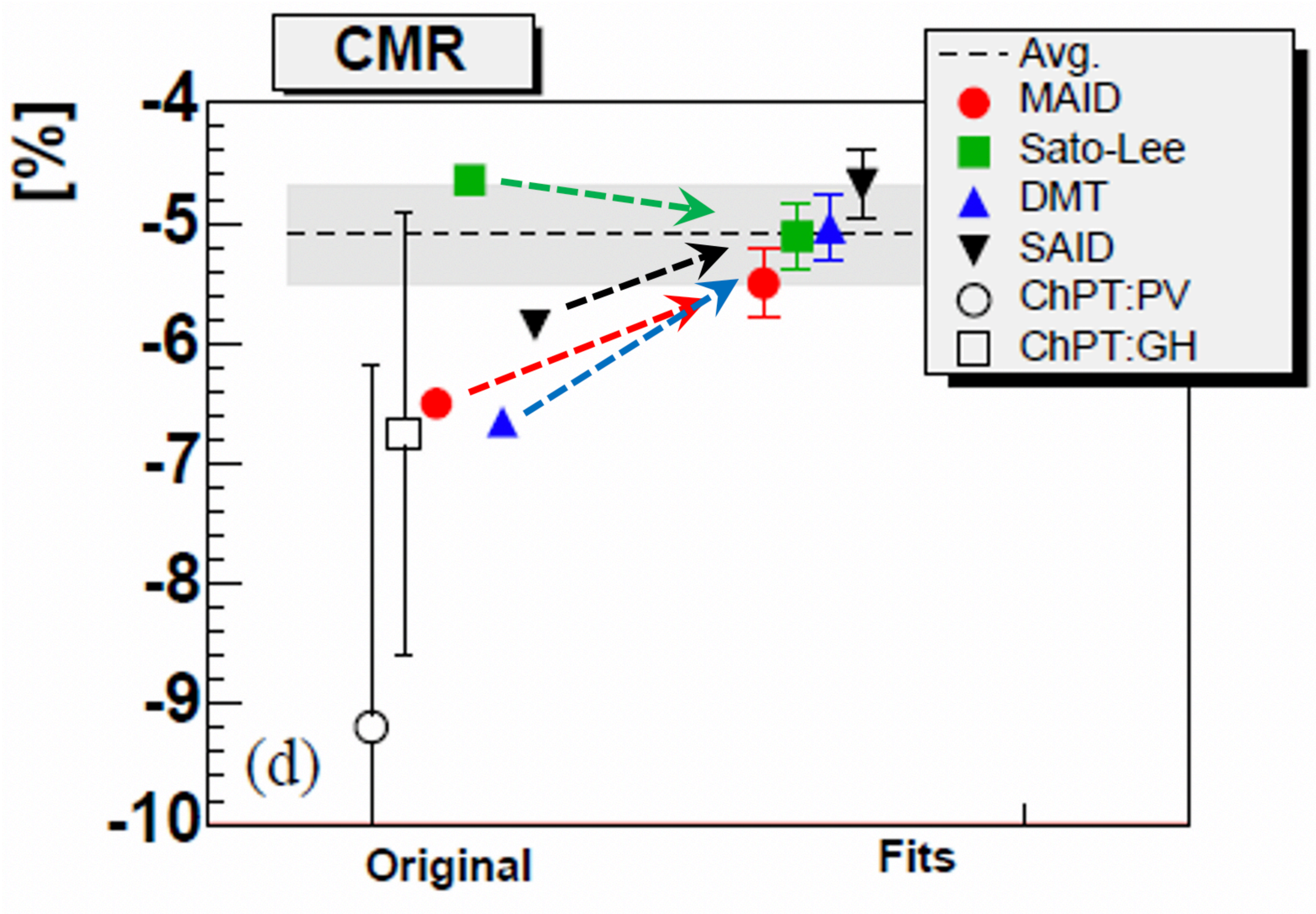
$$R_T + R_L = M1^2 + \ldots\Sigma_{\text{background}}$$

R_{TT} → **sensitive to the EMR**

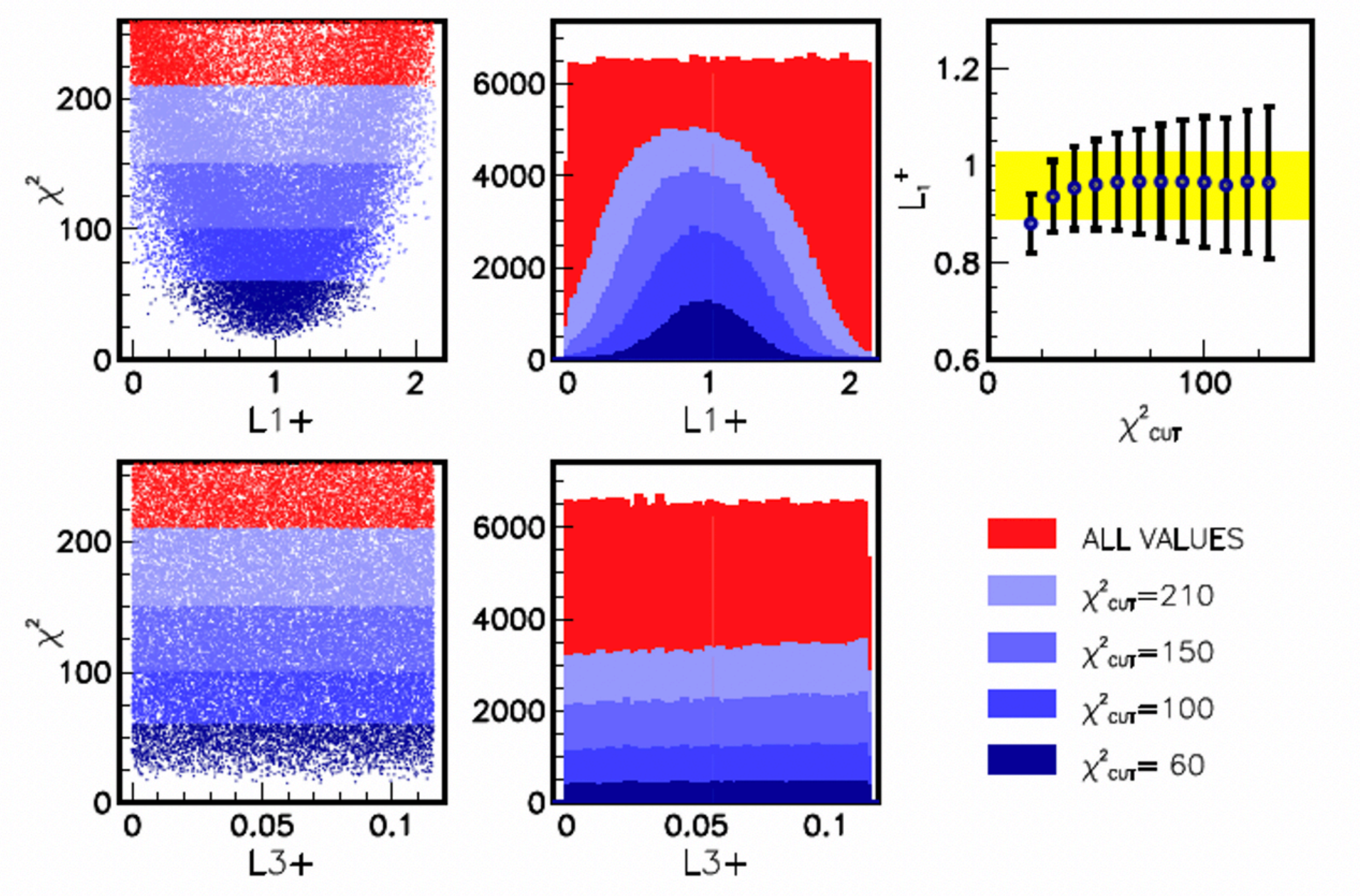
R_{LT} → **sensitive to the CMR**

$R_T + R_L$ → **sensitive to** $M1$

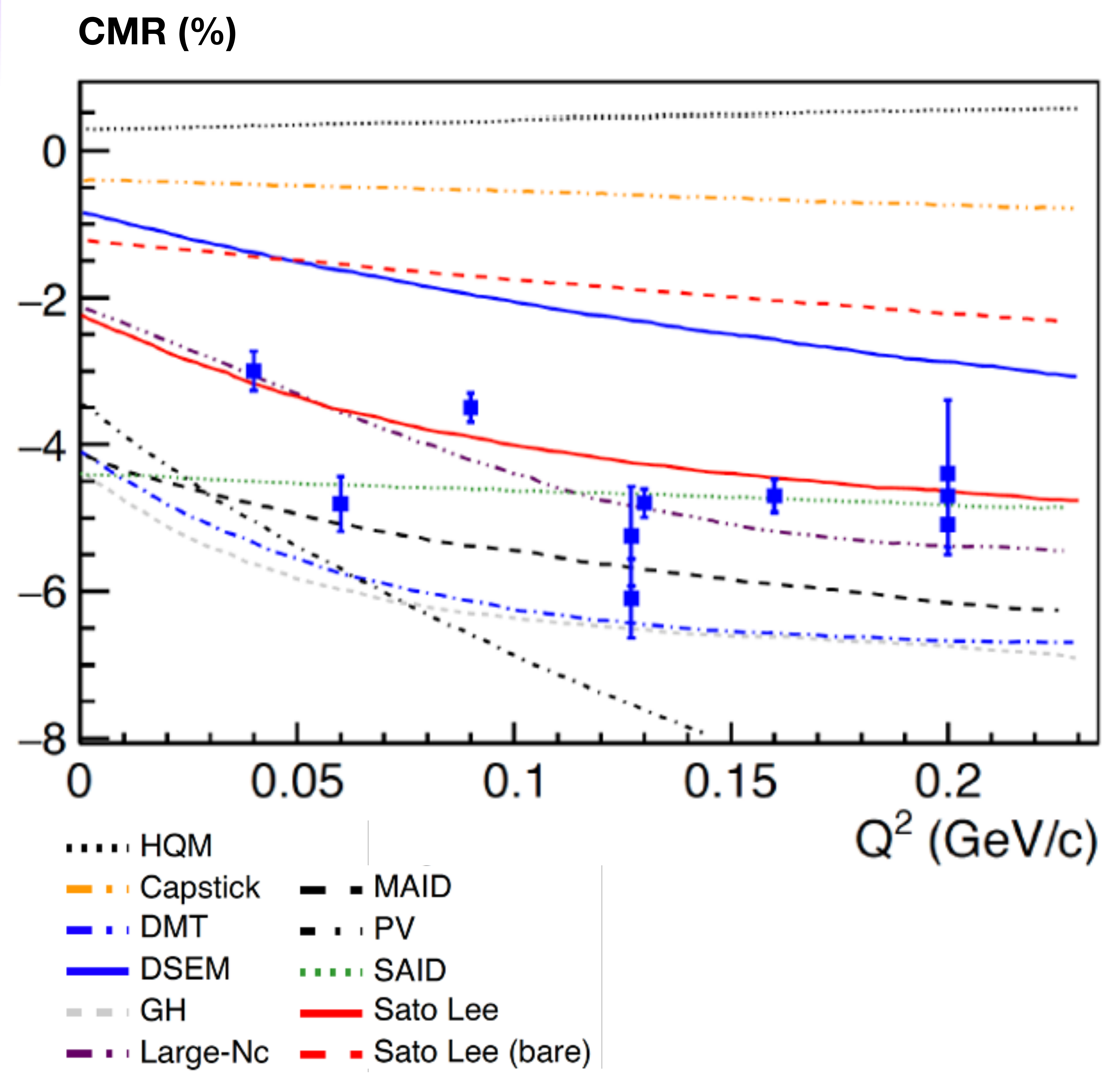
Fit parameterized models to data **and/or**

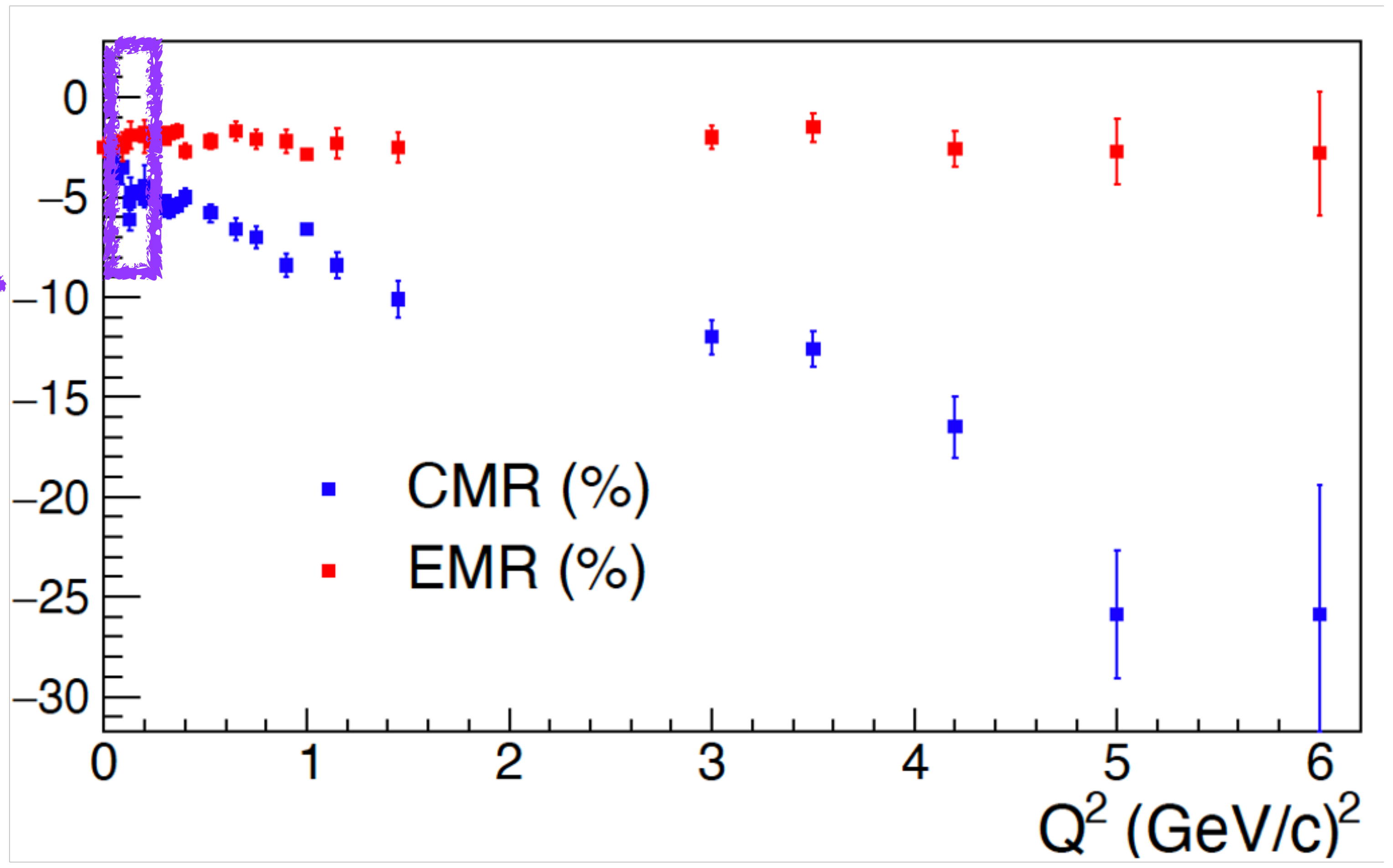


Use model independent statistical methods to identify and determine with maximal precision parameters that are sensitive to the data: AMIAS (Eur. Phys. J. A 56 (2020) 10, 270)



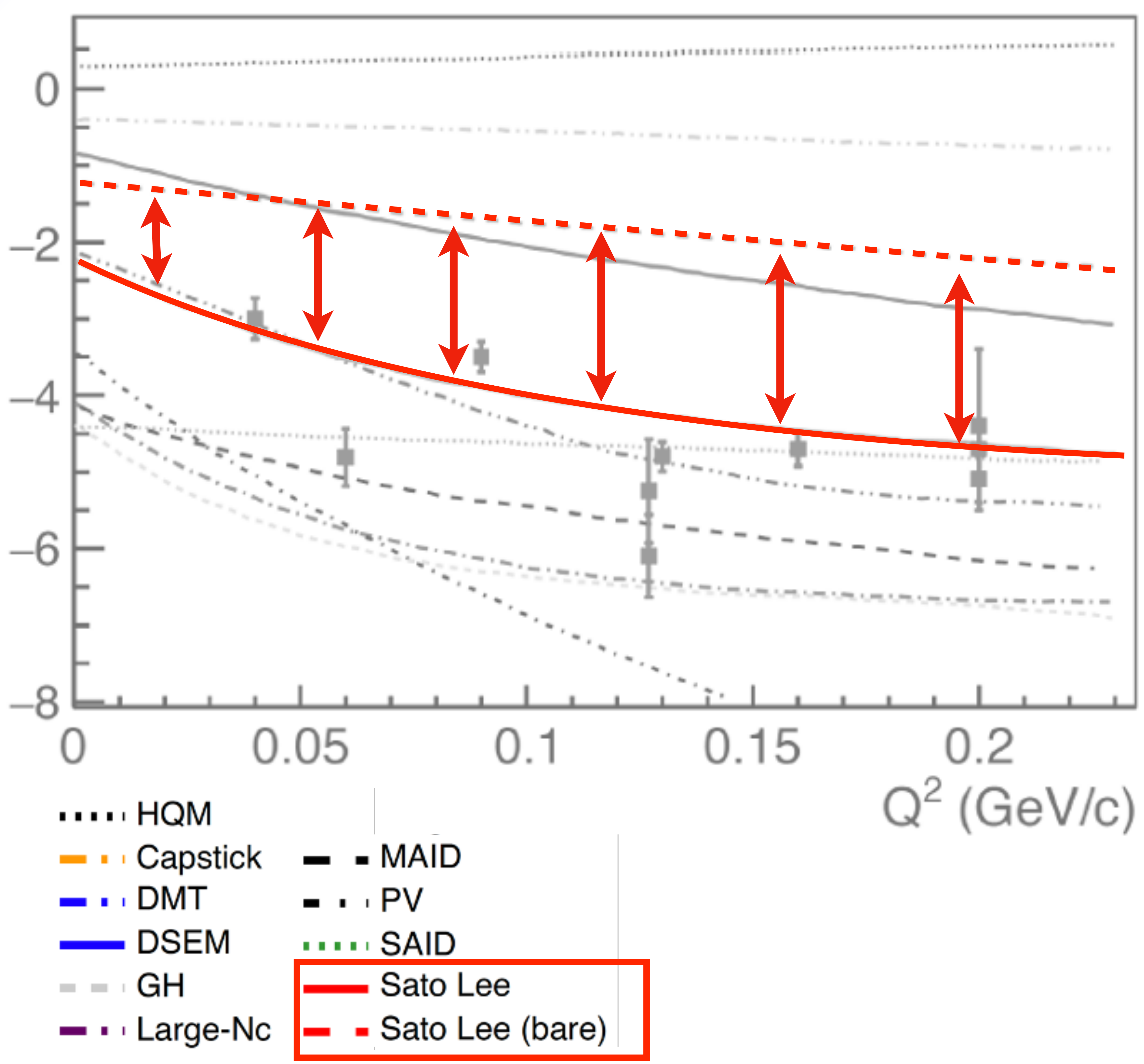
Low Q^2 N-Δ transition form factors

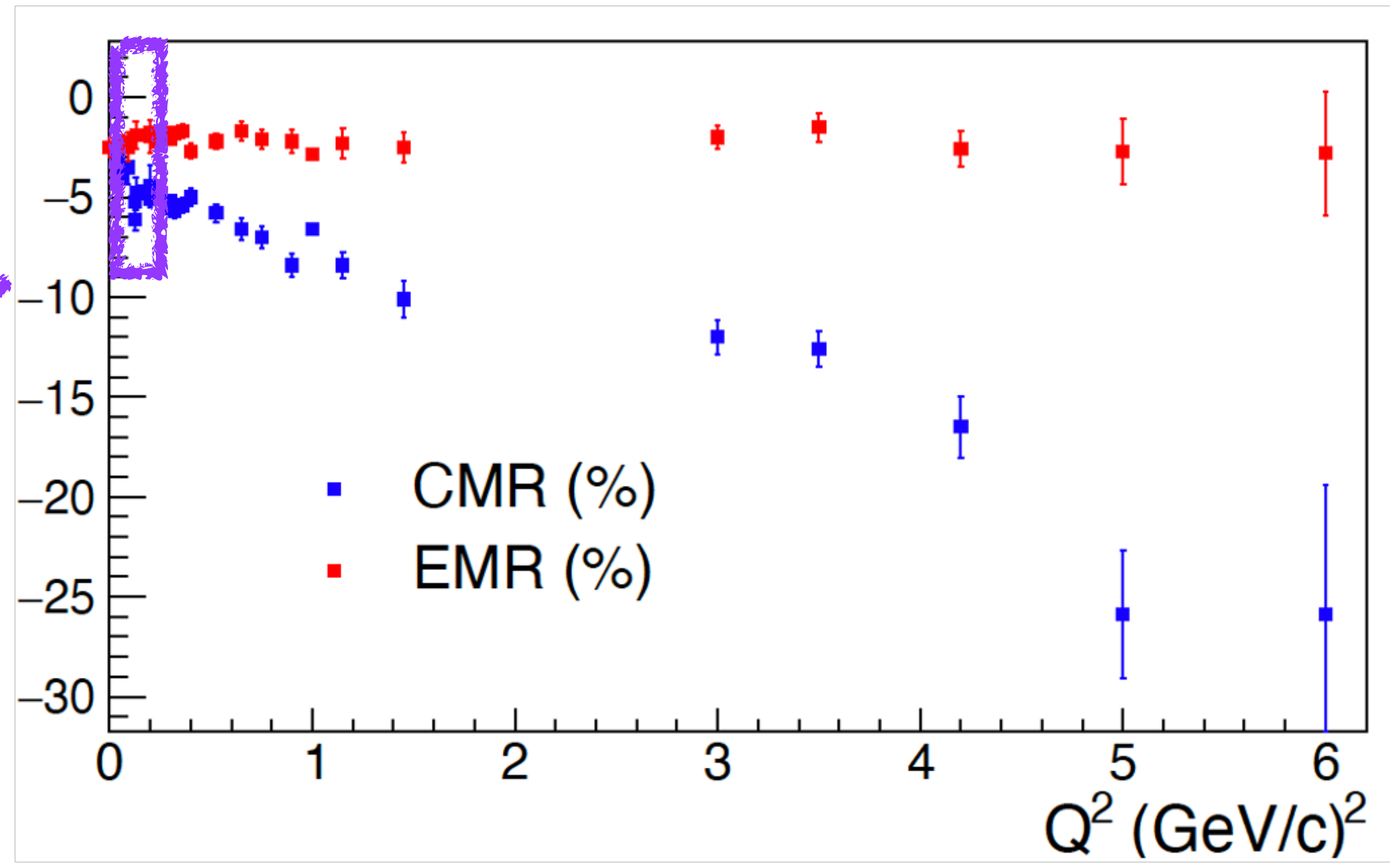




- **Low Q^2 landscape is an important region to measure:**
  - Mesonic cloud effects are predicted to be:
    - dominant in explaining the magnitude of the TFFs
    - changing most rapidly over all Q^2
  - Provides an excellent test bed for ChEFT and LQCD calculations
  - Relates the excitation mechanism to spatial information of the proton and the Delta.
  - Tests the predicted convergence of EMR and CMR as $Q^2 \to 0$.
  - Sparsely measured region.

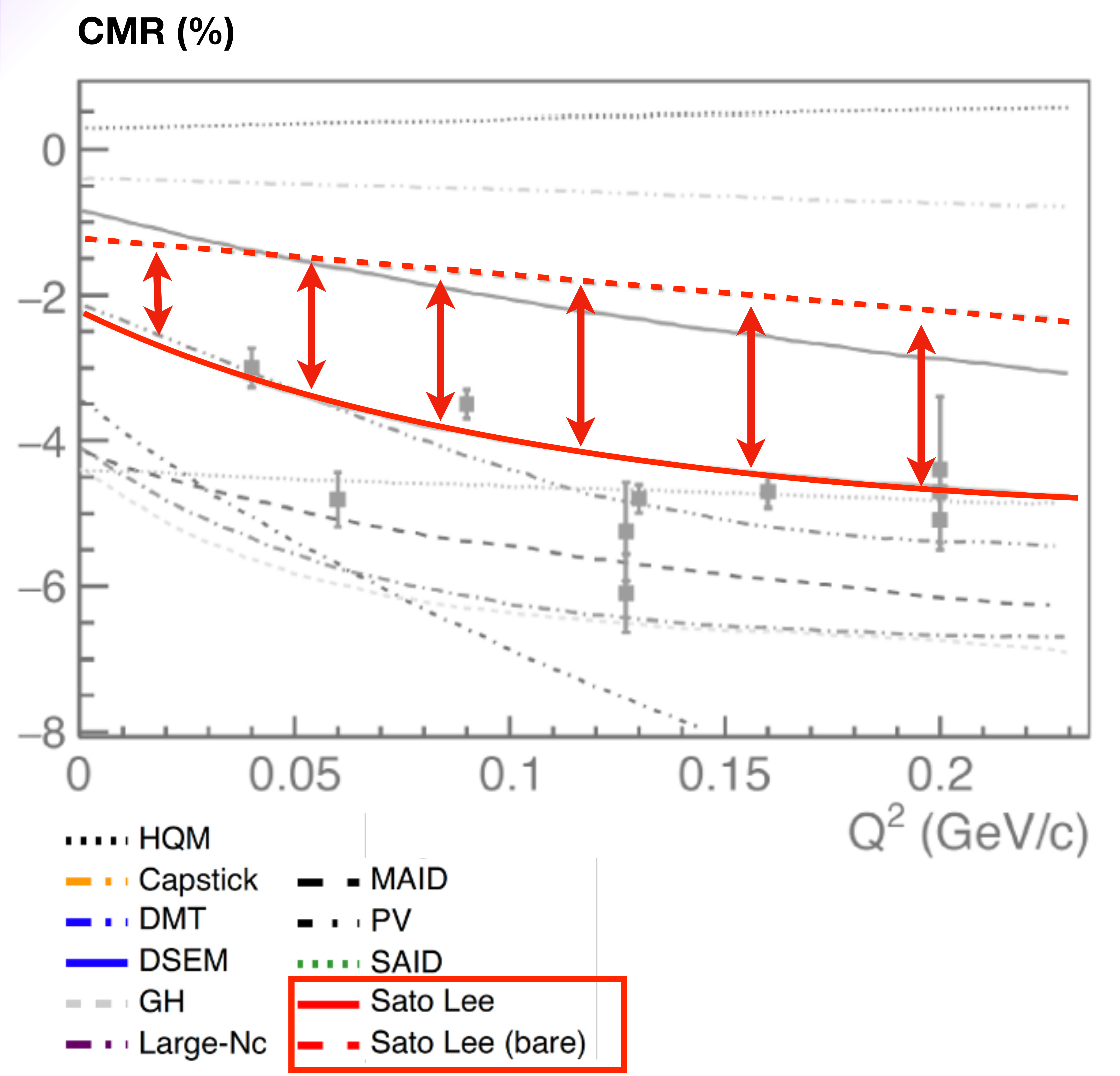
Low Q^2 N-Δ transition form factors

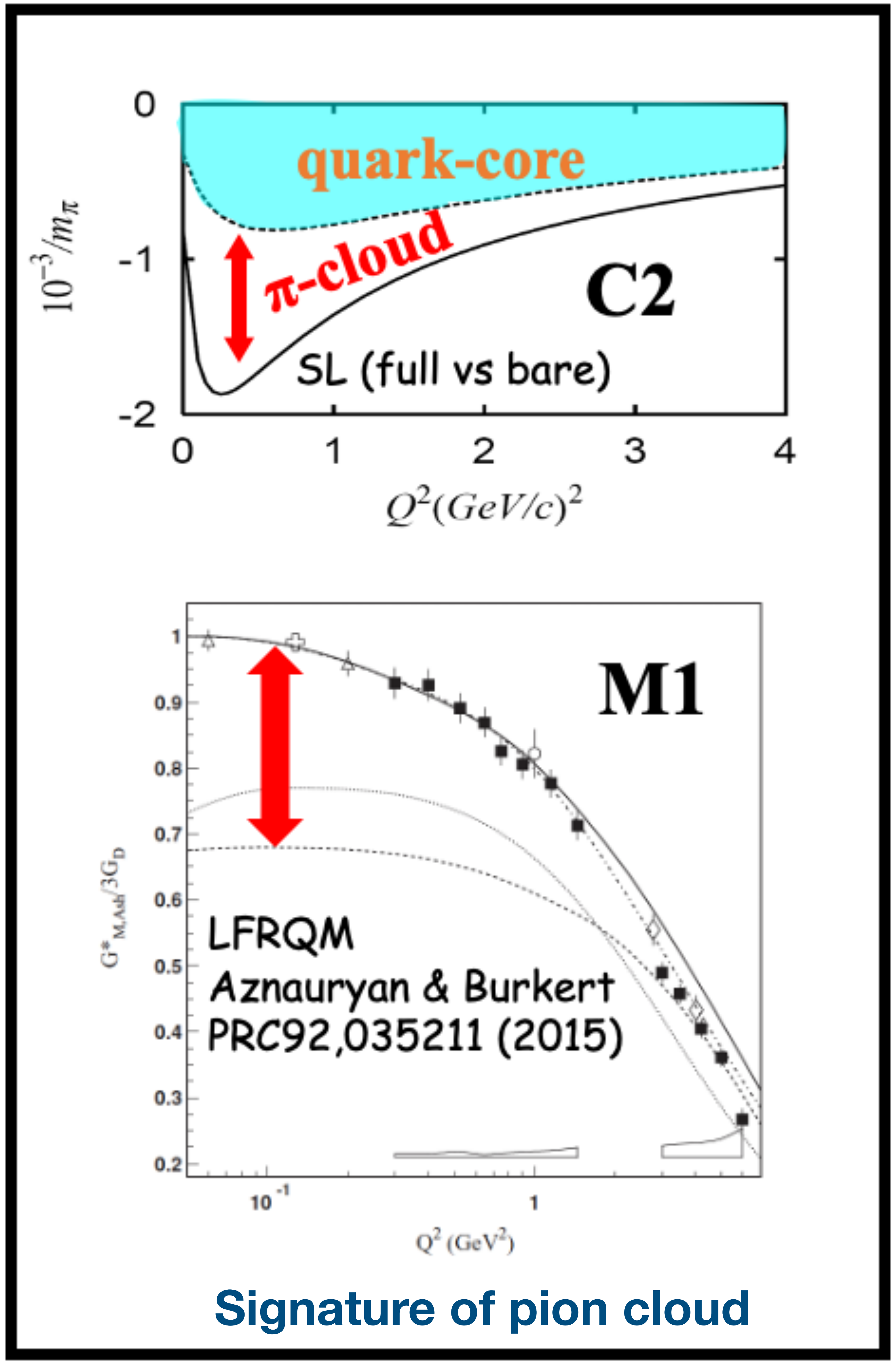




- **Low Q^2 landscape is an important region to measure:**
  - Mesonic cloud effects are predicted to be:
    - dominant in explaining the magnitude of the TFFs
    - changing most rapidly over all Q^2
  - Provides an excellent test bed for ChEFT and LQCD calculations
  - Relates the excitation mechanism to spatial information of the proton and the Delta.
  - Tests the predicted convergence of EMR and CMR as $Q^2 \to 0$.
  - Sparsely measured region.

Low Q² N-Δ transition form factors



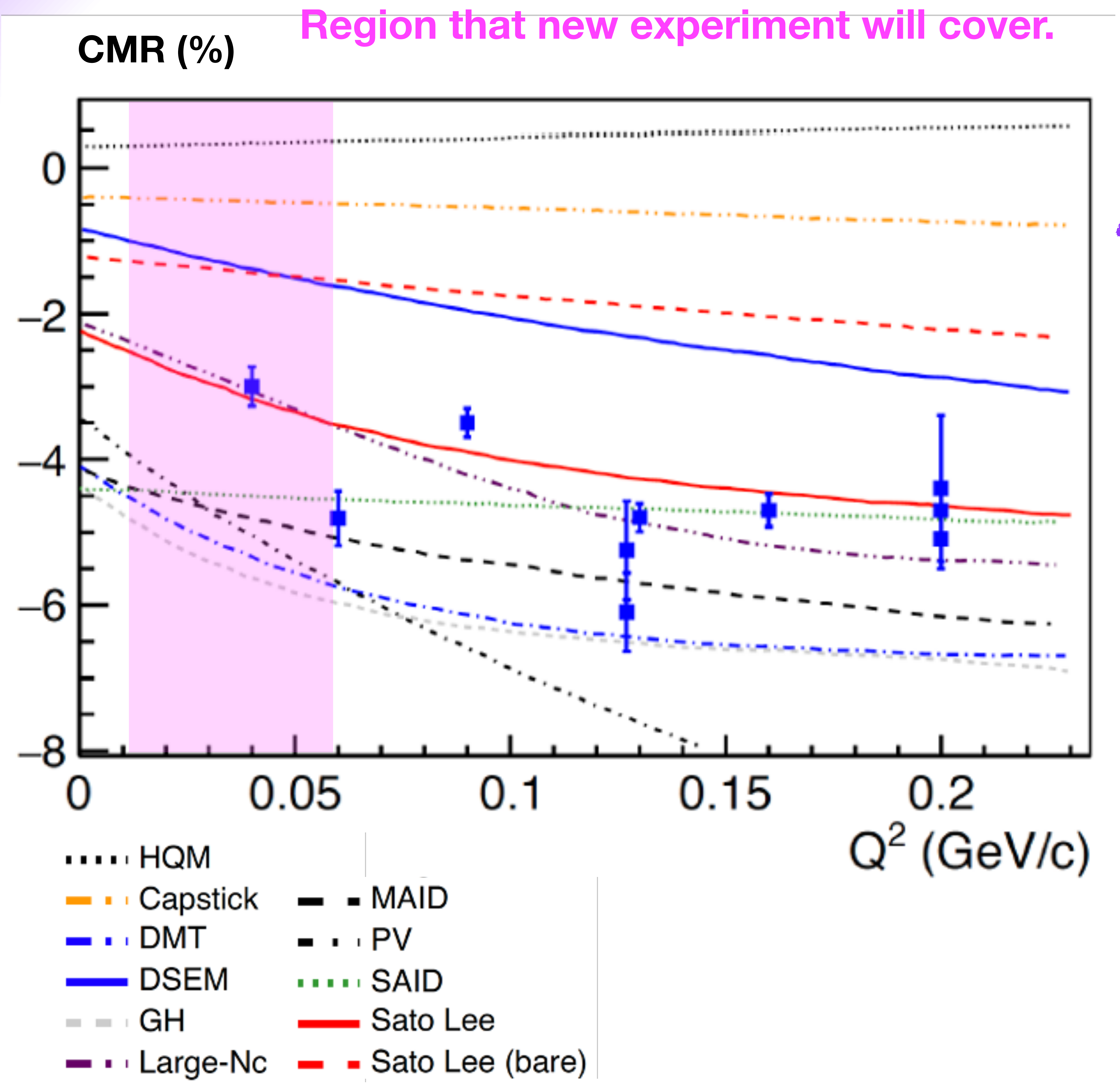


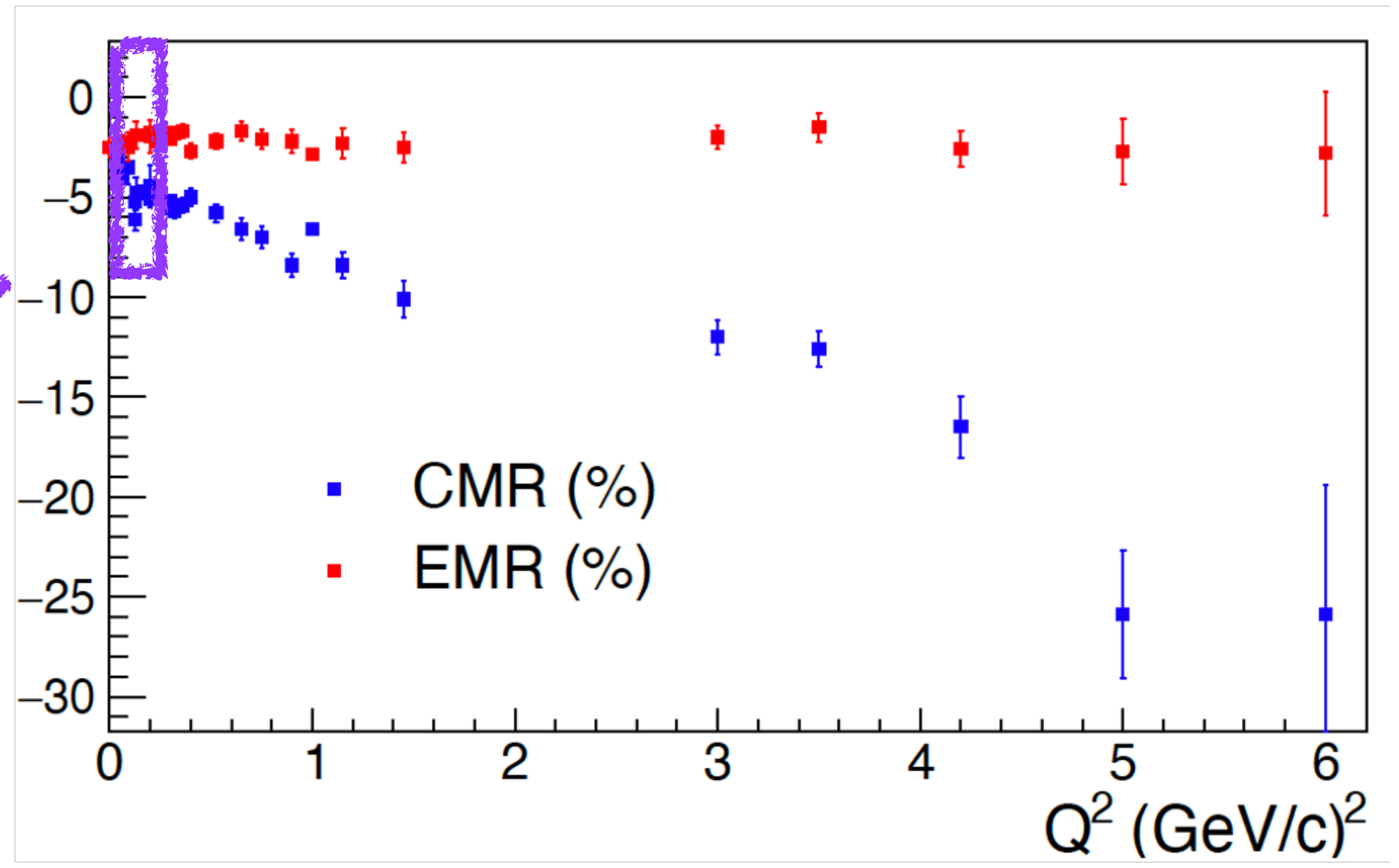
Signature of pion cloud

Dominant role of mesonic d.o.f. at large distance scale:

Mesonic cloud ~ 50% of the quadrupole amplitude magnitude & 1/3 of the magnetic dipole strength

Low Q² N-Δ transition form factors





- **Low Q^2 landscape is an important region to measure:**
  - Mesonic cloud effects are predicted to be:
    - dominant in explaining the magnitude of the TFFs
    - changing most rapidly over all Q^2
  - Provides an excellent test bed for ChEFT and LQCD calculations
  - Relates the excitation mechanism to spatial information of the proton and the Delta.
  - Tests the predicted convergence of EMR and CMR as $Q^2 \rightarrow 0$.
  - Sparsely measured region.

What can we say about the geometry (shape) of the nucleon?

...an issue since the 80's

- What is the "shape" of the nucleon?
  - Is it spherically symmetric or deformed?
    - If deformed, what is the origin of the deformation?
  - Exactly how are shape and structure related?
- How can one explore shape?
  - Quadrupole moment of the ground state is identically 0 for a spin 1/2 system.
    - Pure proton scattering without spin excitation can't give you any information.
  - The only isolated spin-excitation resonance of the proton is the $\Delta^{+}(1232)$.
- A more comprehensive review can be found at:
  - C. Alexandrou, C. Papanicolas, M. Vanderhaeghen,
    - "*The shape of hadrons*", Rev. Mod. Phys. 84, 1231 (2012)
  - A. Bernstein, C. Papanicolas
    - "*Overview: The shape of hadrons*" , AIP Conf. Proc. 904, 1 (2007)

Imaging the Δ and the N-Δ transition

Empirical transverse charge transition densities

Eur. Phys. J. Special Topics 198, 141 (2011)

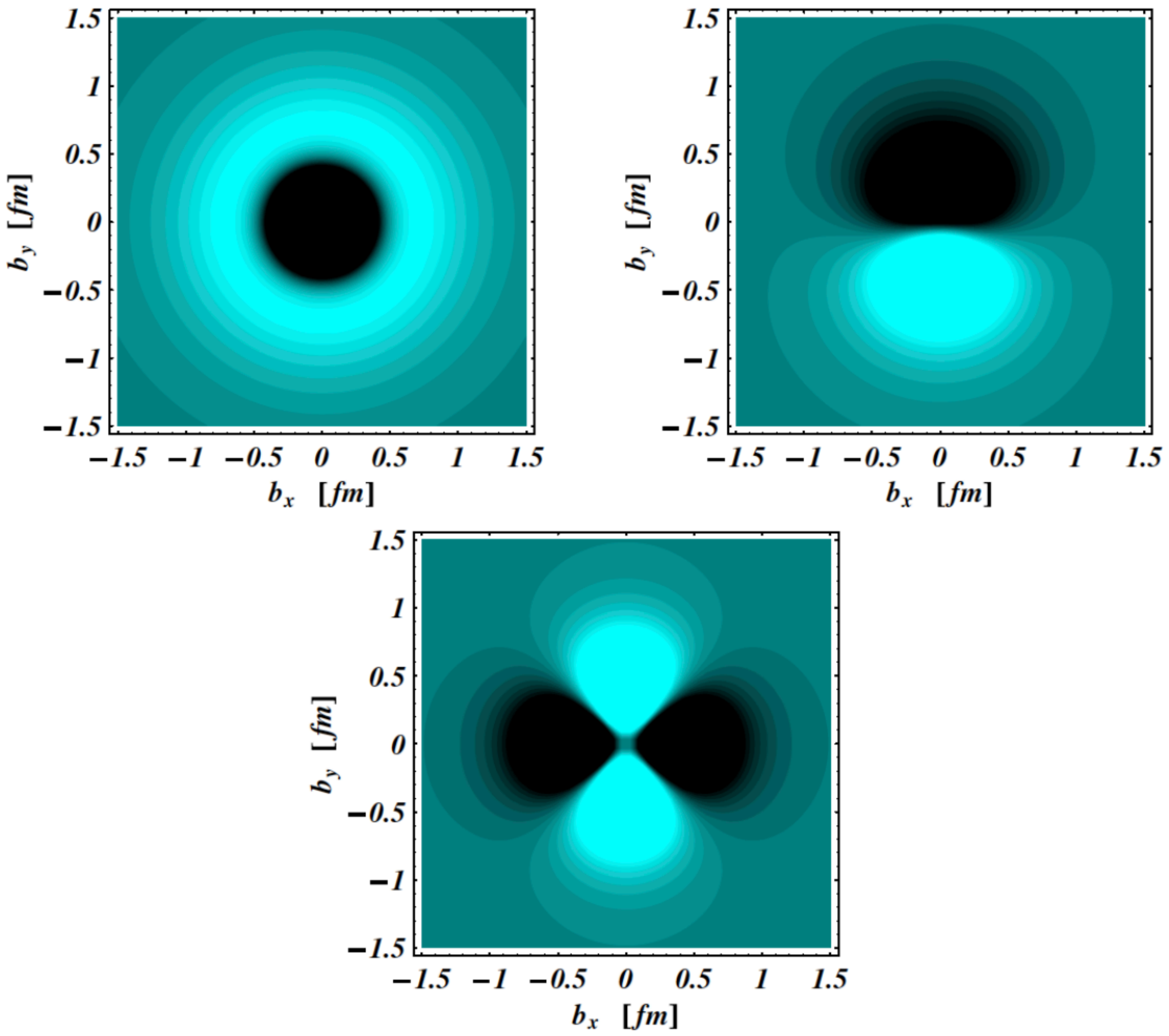


Fig. 18. Quark transverse charge density corresponding to the $p \to \Delta(1232)P_{33}$ e.m. transition. Upper left panel: p and Δ are in a light-front helicity +1/2 state ($\rho_0^{pP_{33}}$). Upper right panel: p and Δ are polarized along the x-axis ($\rho_T^{pP_{33}}$) as in Fig. 14. The lower panel shows the quadrupole pattern, whose contribution to the polarized transition density is very small due to the weak $E2/C2$ admixtures in the $N\Delta$ transition and practically invisible in the upper right panel. The light (dark) regions correspond to positive (negative) densities. For the $p \to P_{33}(1232)$ e.m. transition FFs, we use the MAID2007 parametrization.

Probing hadron wave functions in Lattice QCD

Phys. Rev. D. 66, 094503 (2002)

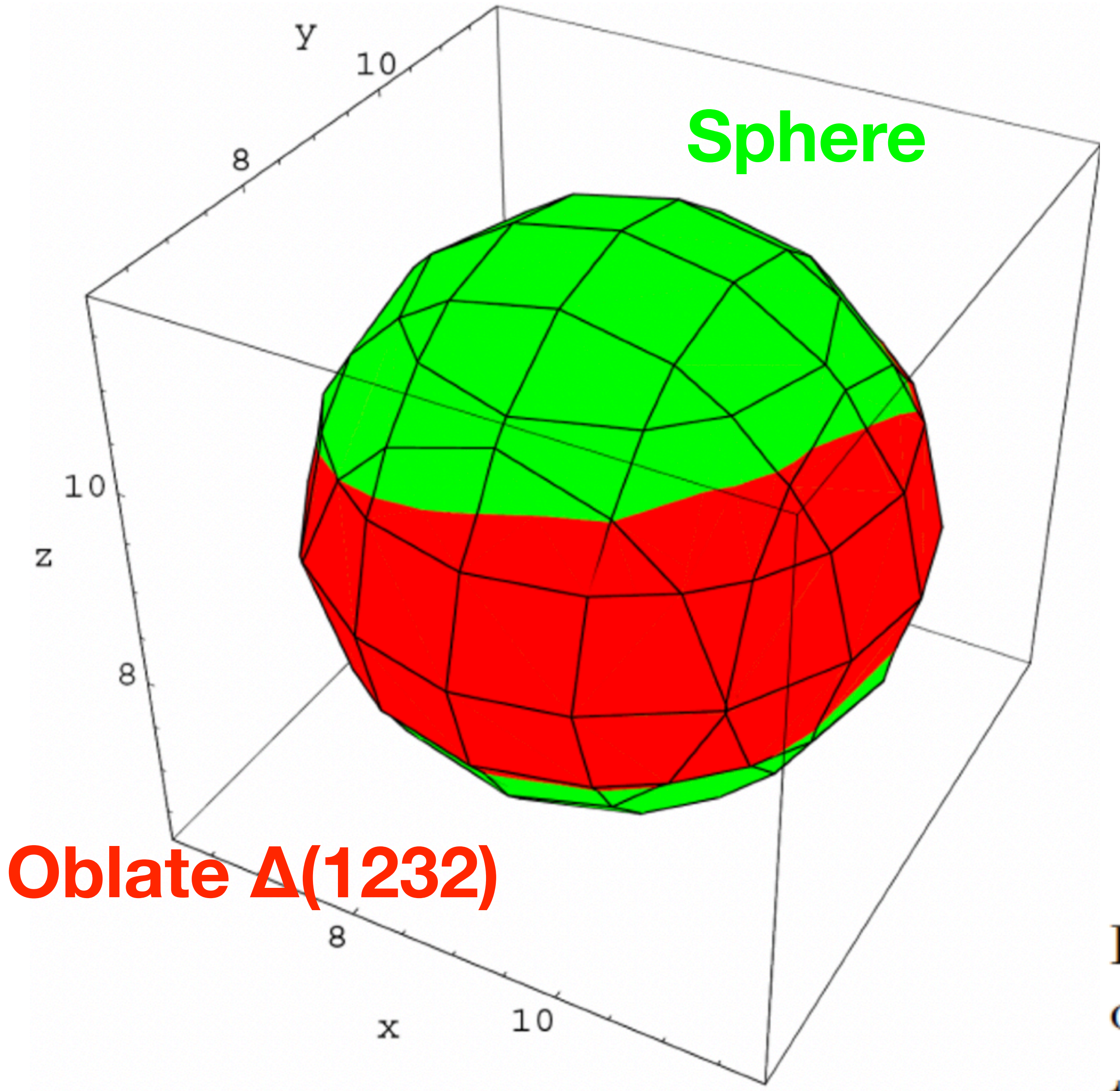


FIG. 18. Three-dimensional contour plot of the correlator (black): upper for the rho state with 0 spin projection (cigar shape) and lower for the Δ^+ state with +3/2 (slightly oblate) spin projection for two dynamical quarks at $\kappa = 0.156$. Values of the correlator (0.5 for the rho, 0.8 for the Δ^+) were chosen to show large distances but avoid finite-size effects. We have included for comparison the contour of a sphere (grey).

Latice QCD: Quark transverse charge density in Δ+(1232)

Phys. Rev. D. 79, 014507 (2009)

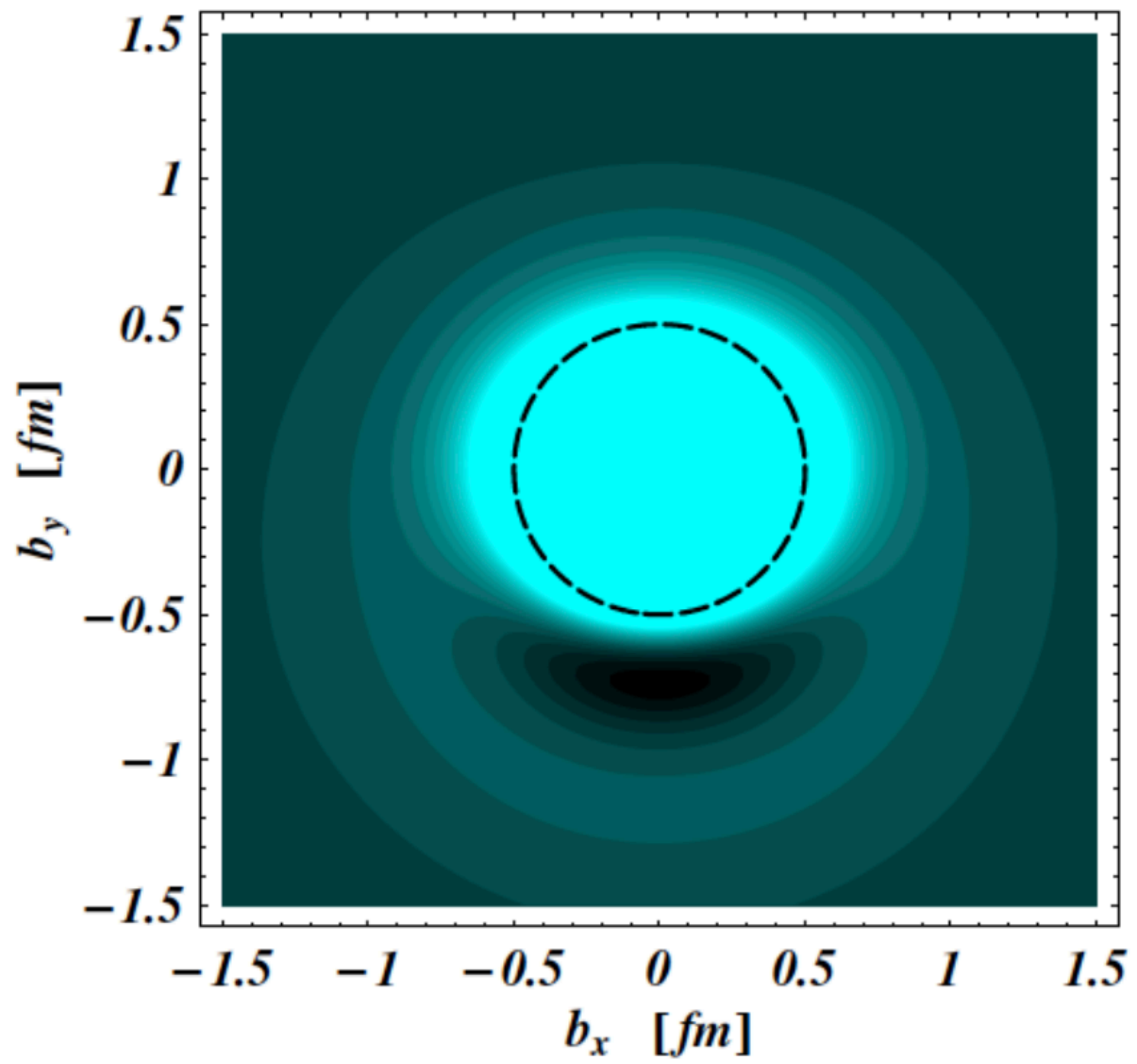


FIG. 10: Lattice QCD results for the quark transverse charge density $\rho^{\Delta}_{T\,\frac{3}{2}}$ in a $\Delta^+(1232)$ which is polarized along the positive x-axis. The light (dark) regions correspond to the largest (smallest) values of the density. In order to see the deformation more clearly, a circle of radius 0.5 fm is drawn for comparison. The density is obtained from quenched lattice QCD results at $m_\pi = 410$ MeV for the Δ e.m. FFs [48].

Impact on other domains of nuclear physics

- Generalized polarizabilities (GPs) of the proton:
  - The TFFs enter as an input in the VCS cross section over the Δ resonance region – their precise knowledge is necessary for the precise extraction of the GPs from the measured cross sections
  - Physics of interest:
    - Electric polarizability puzzle
    - Interplay of paramagnetism & diamagnetism in the proton
    - Extraction of the polarizability radii and imaging of the induced polarization density.
- Neutrino oscillation studies and neutrino-nucleus scattering
  - Dominant source of systematic error: uncertainties in neutrino-nucleus reaction cross sections in the nucleon-resonance region.