Measurement of the neutron charge radius through the study of the nucleon excitation

A proposal for Jlab PAC49

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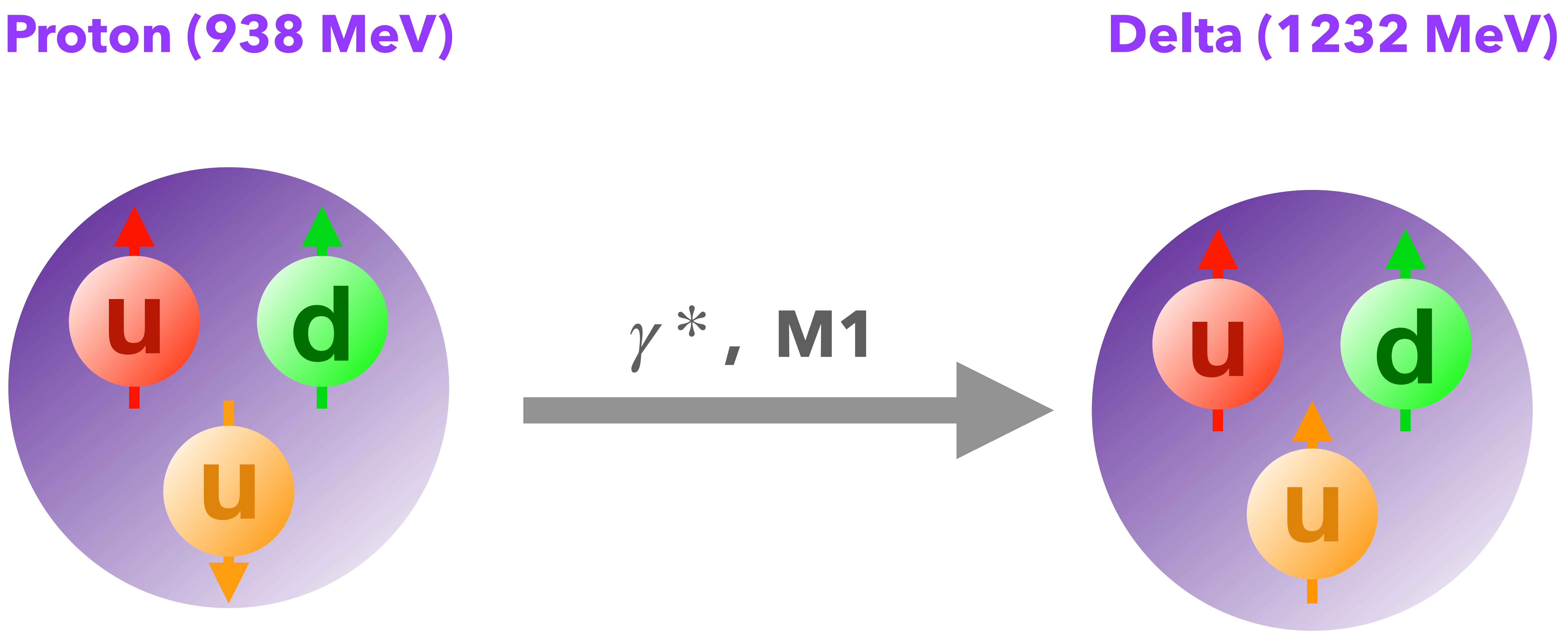
Primary Physics Goals

- **Proton N-Δ Transition Form Factors (TFFs):**
  - JLab has invested significantly to the physics program of the N-Δ TFFs, with multiple experiments (in Halls A, B, and C).
  - TFFs have been measured up to Q^2=6 GeV^2 Here we aim to push the limits of the low Q^2, where the mesonic cloud dynamics is predicted to be dominant and rapidly changing
  - Test bed for ChEFT and LQCD calculations
  - Can constrain systematics from 1/Nc and BChPT calculations

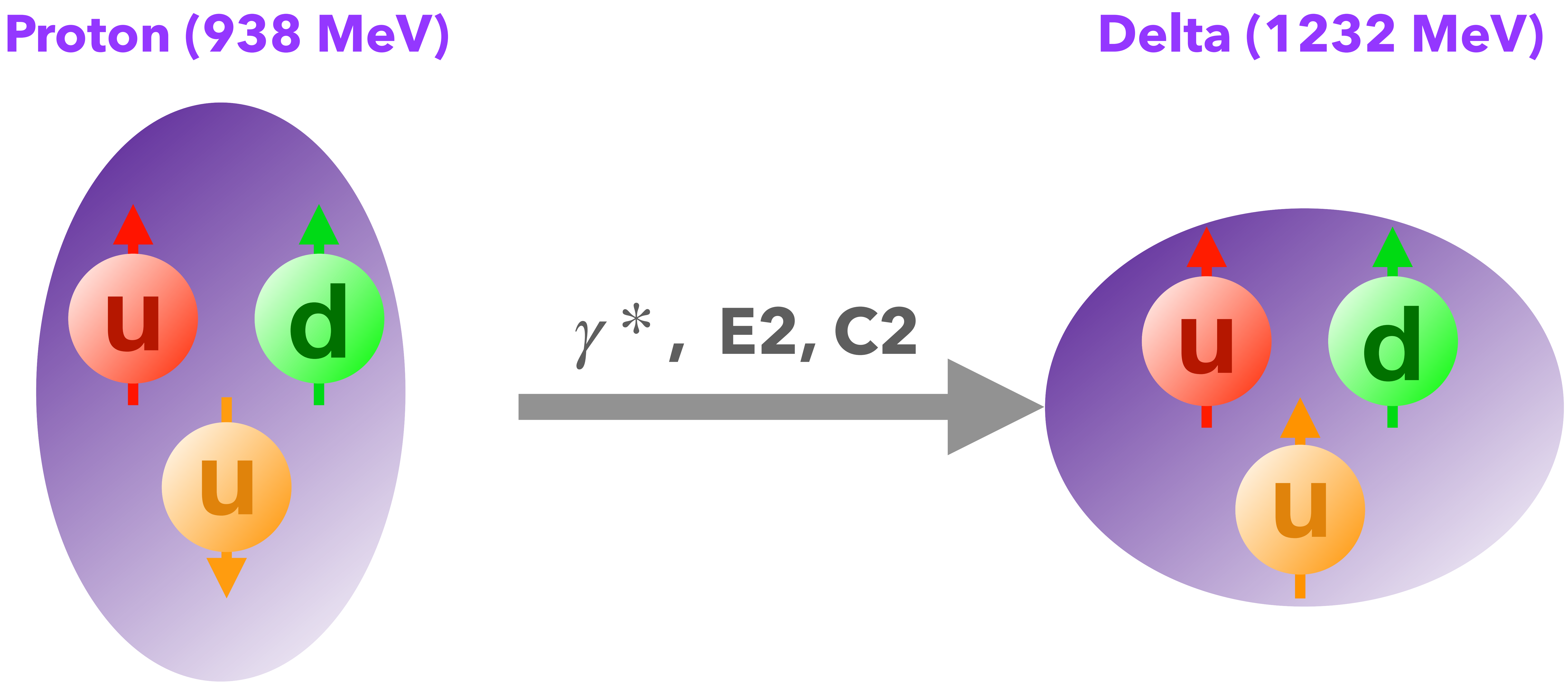
- **Neutron charge radius:**
  - One of the system's most basic properties.
  - Measured with only one (rather indirect) method.
  - World data exhibit tensions. Underestimated systematics.
  - Cross checking with a different method, whenever nature allows a path for it, is a *scientific obligation*.

N-Δ transition as a pathway to nucleon structure



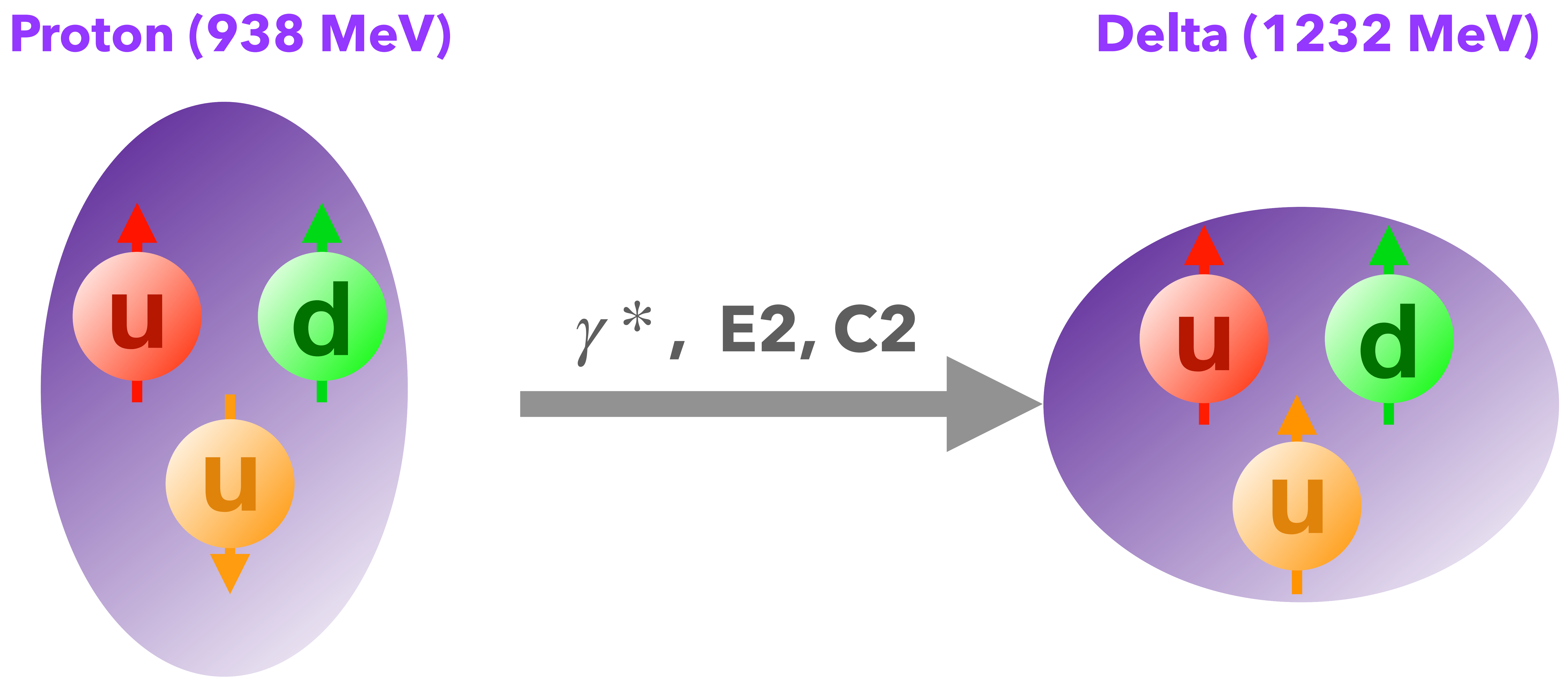
The dominant transition from proton to delta involves a dipole (M1) transition (spherical S-wave proton WF -> spherical S-wave Delta WF)

N-Δ transition as a pathway to nucleon structure



There also exists a quadrupole (E2 or C2) transition from proton to delta.
(non-spherical proton WF -> non-spherical Delta WF)

N-Δ transition as a pathway to nucleon structure



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

EMR CMR

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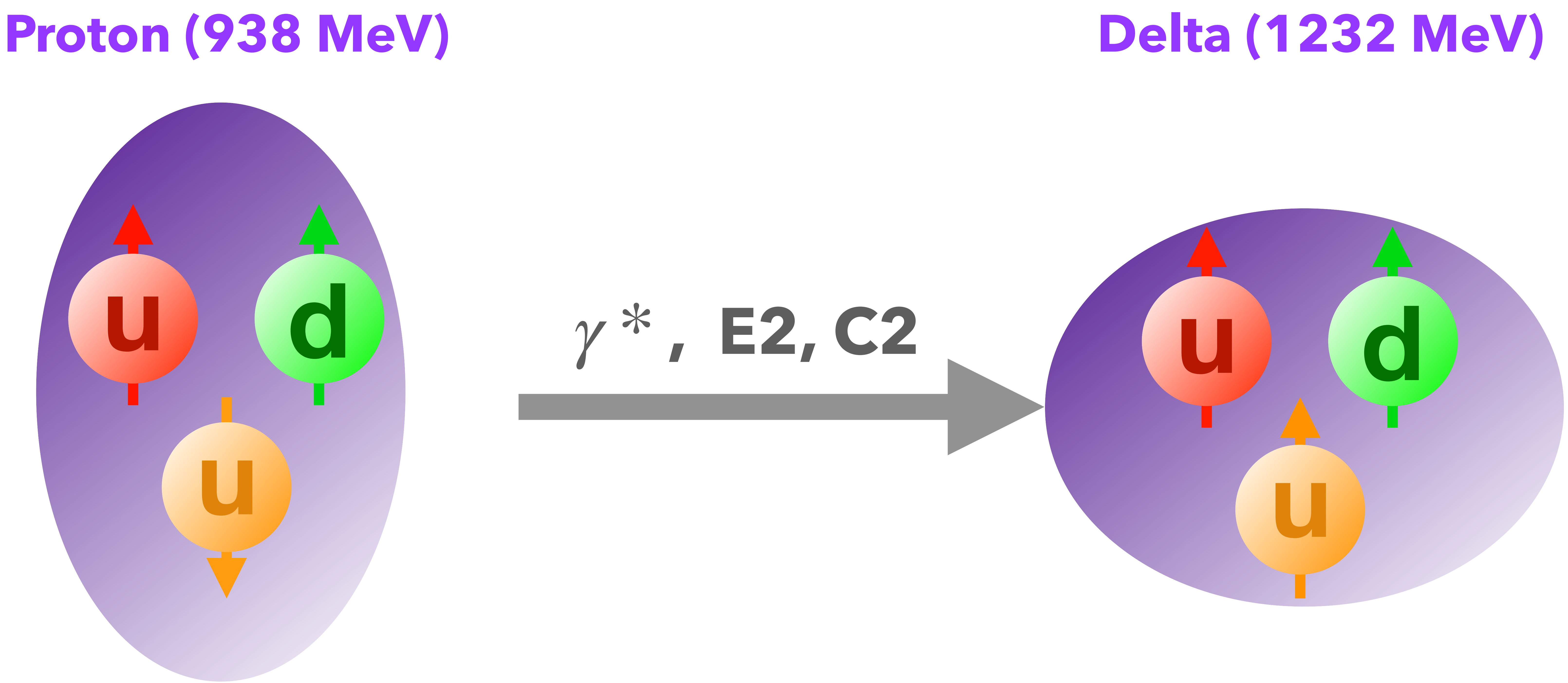

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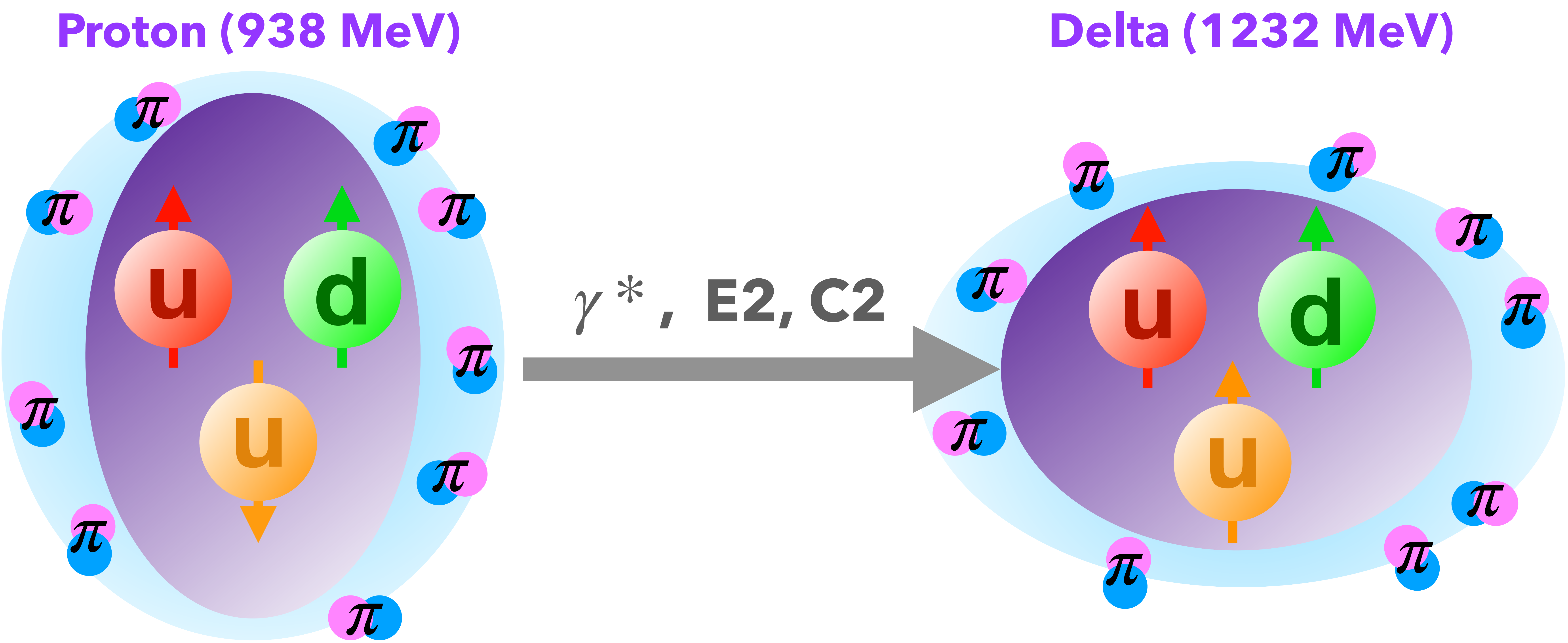
Non-central (tensor) interactions between valence quarks and relativistic corrections can account for some of the spherical deviation, but not all...

N-Δ transition as a pathway to nucleon structure



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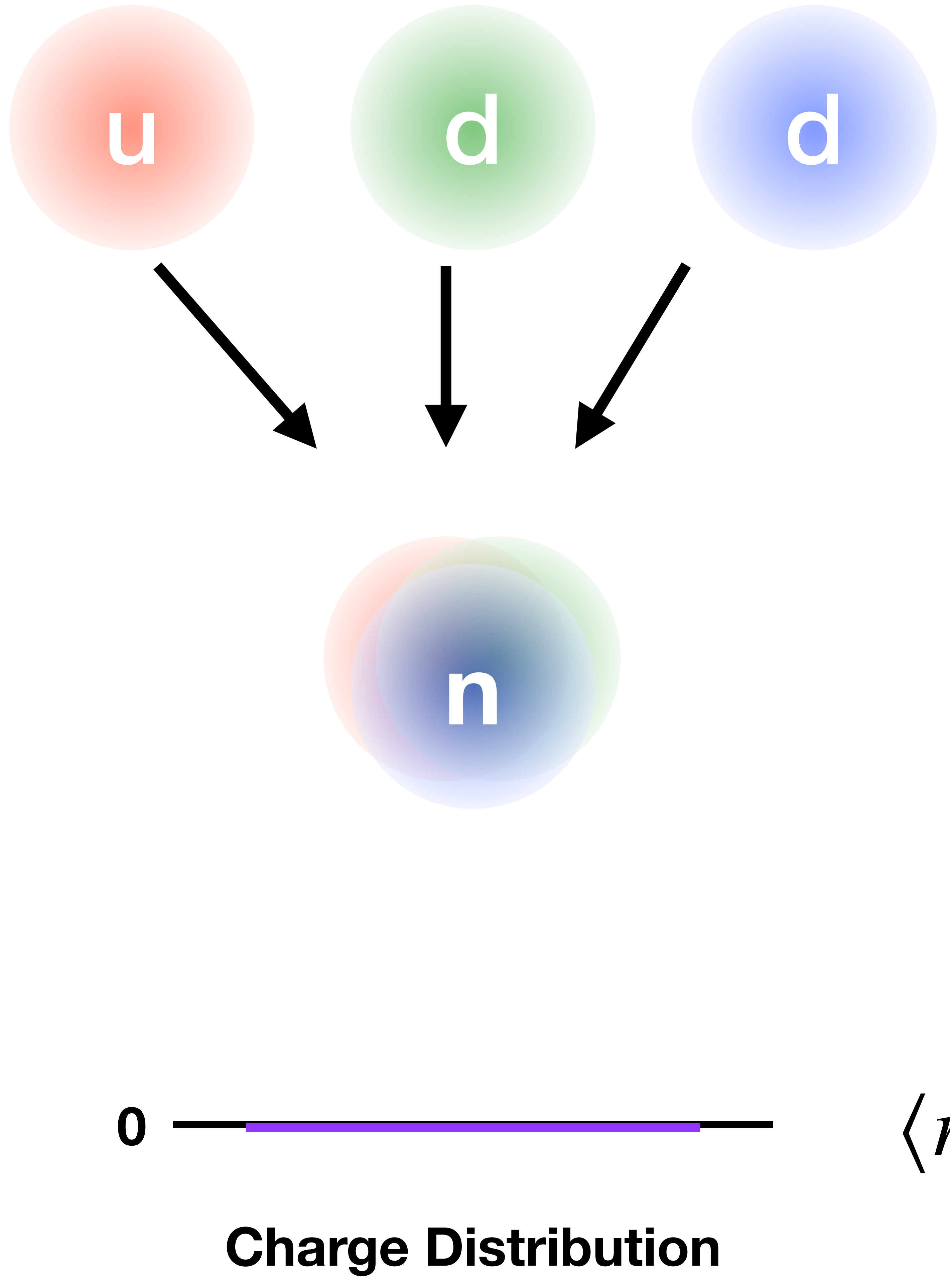
The dynamics of a meson cloud are important to describe the structure of the nucleon:
The nucleon structure directly relates to the nucleon radius.

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

- **The neutron has a non-zero charge radius:**
  - Measurements of the neutron scattering length show a net negative charge radius for a neutral object: how? $\langle r_n^2 \rangle_{\text{PDG}} = -0.1161 \pm 0.0022$



$\langle r_n^2 \rangle = 0$

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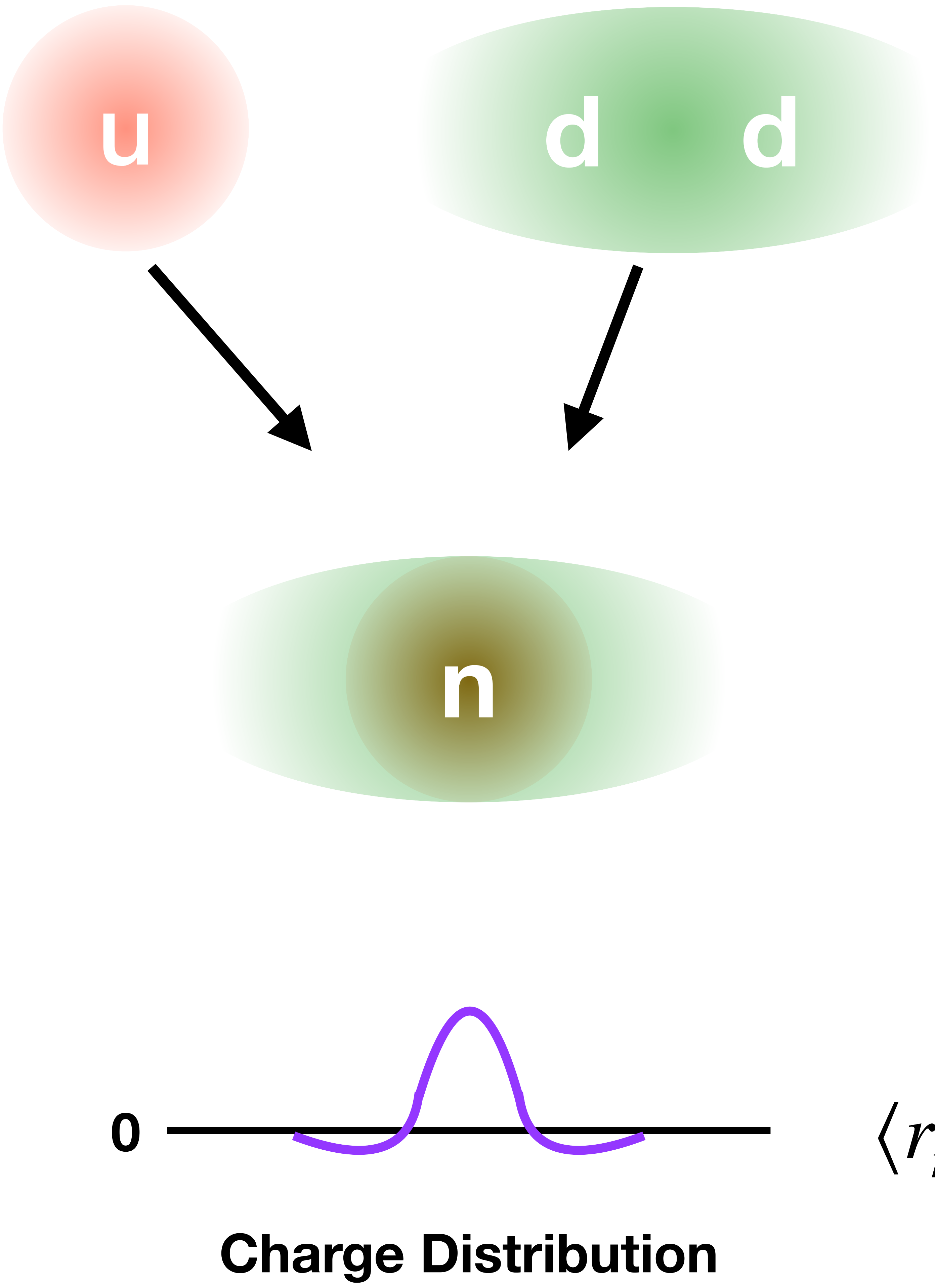
    - One interpretation includes a spin-1 dd diquark configuration:
      - Not adequate to describe the magnitude of the charge radius from measurement!



$\langle r_n^2 \rangle \sim -0.06$

using measured b_{ne}

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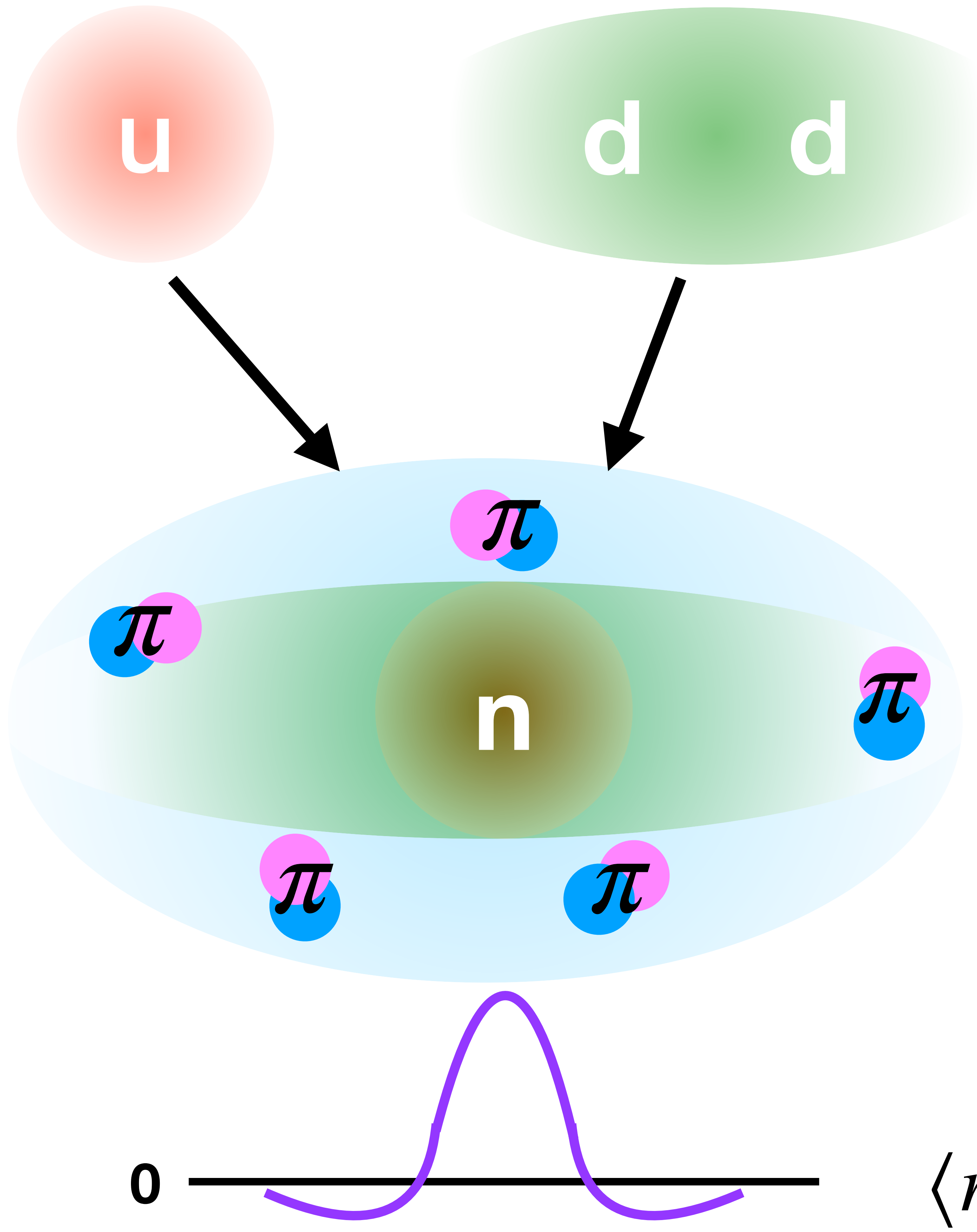
      - Not adequate to describe the magnitude of the charge radius from measurement!
    - Including the two-body exchange currents (valence + pion cloud) **can** describe the measurements. [Buchmann, Phys. Rev. Lett. 93, 212301 (2004)]



Charge Distribution

$\langle r_n^2 \rangle \sim -0.11$

using measured b_{ne}

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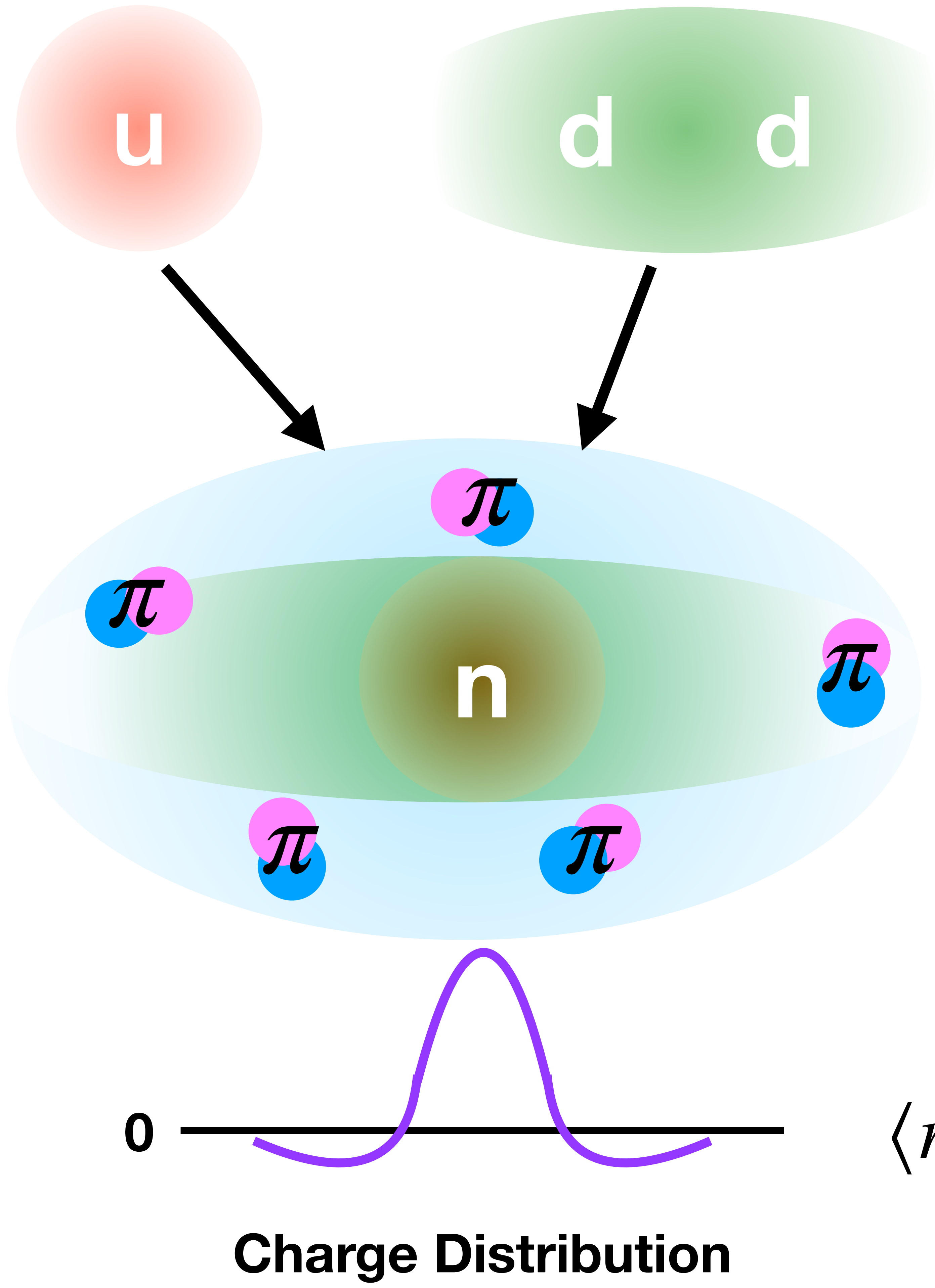
      - Not adequate to describe the magnitude of the charge radius from measurement!
    - Including the two-body exchange currents (valence + pion cloud) **<u>can</u>** describe the measurements. [Buchmann, Phys. Rev. Lett. 93, 212301 (2004)]
      - This same procedure can simultaneously describe the magnitude of the N-Δ TFFs!



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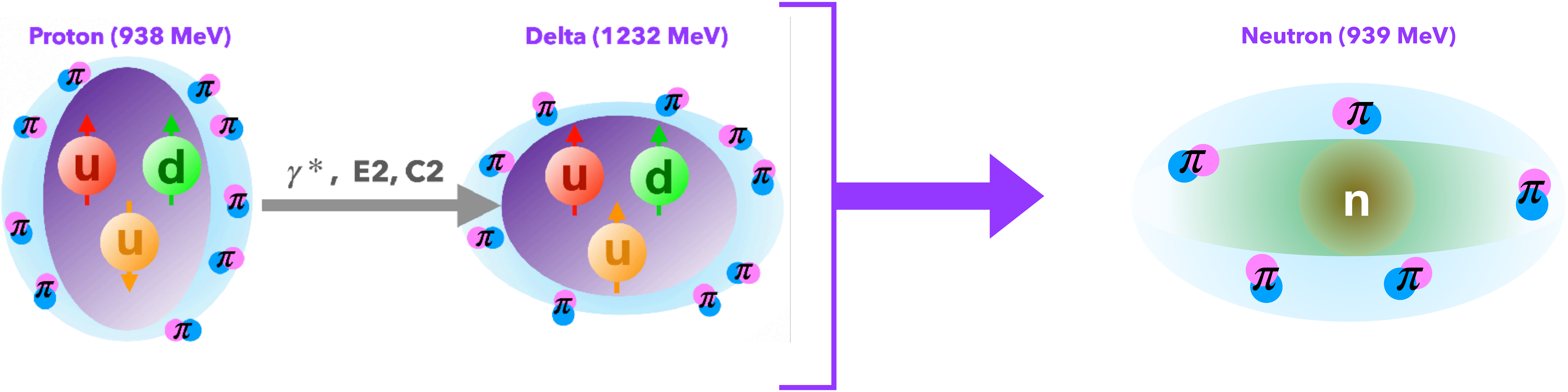
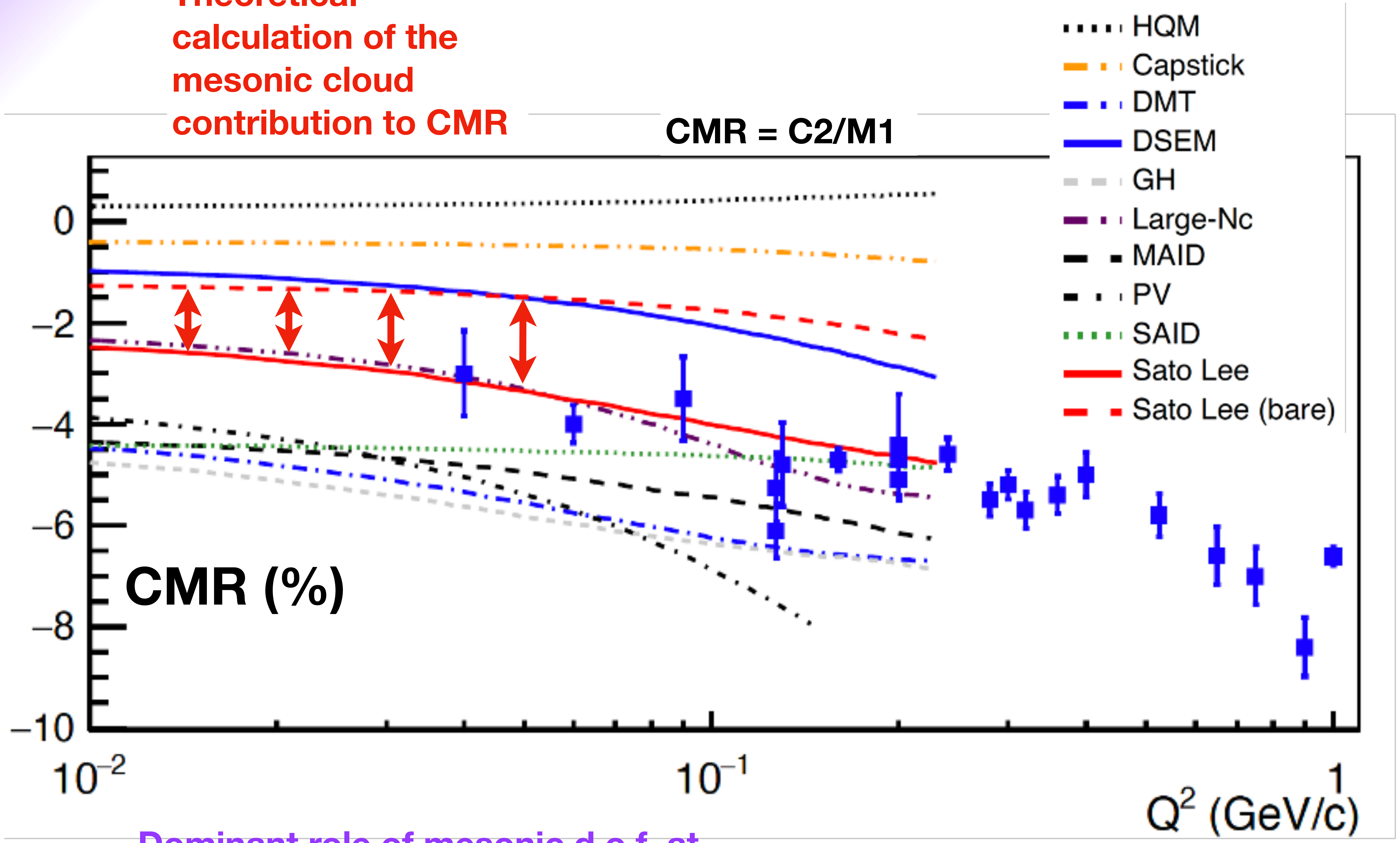
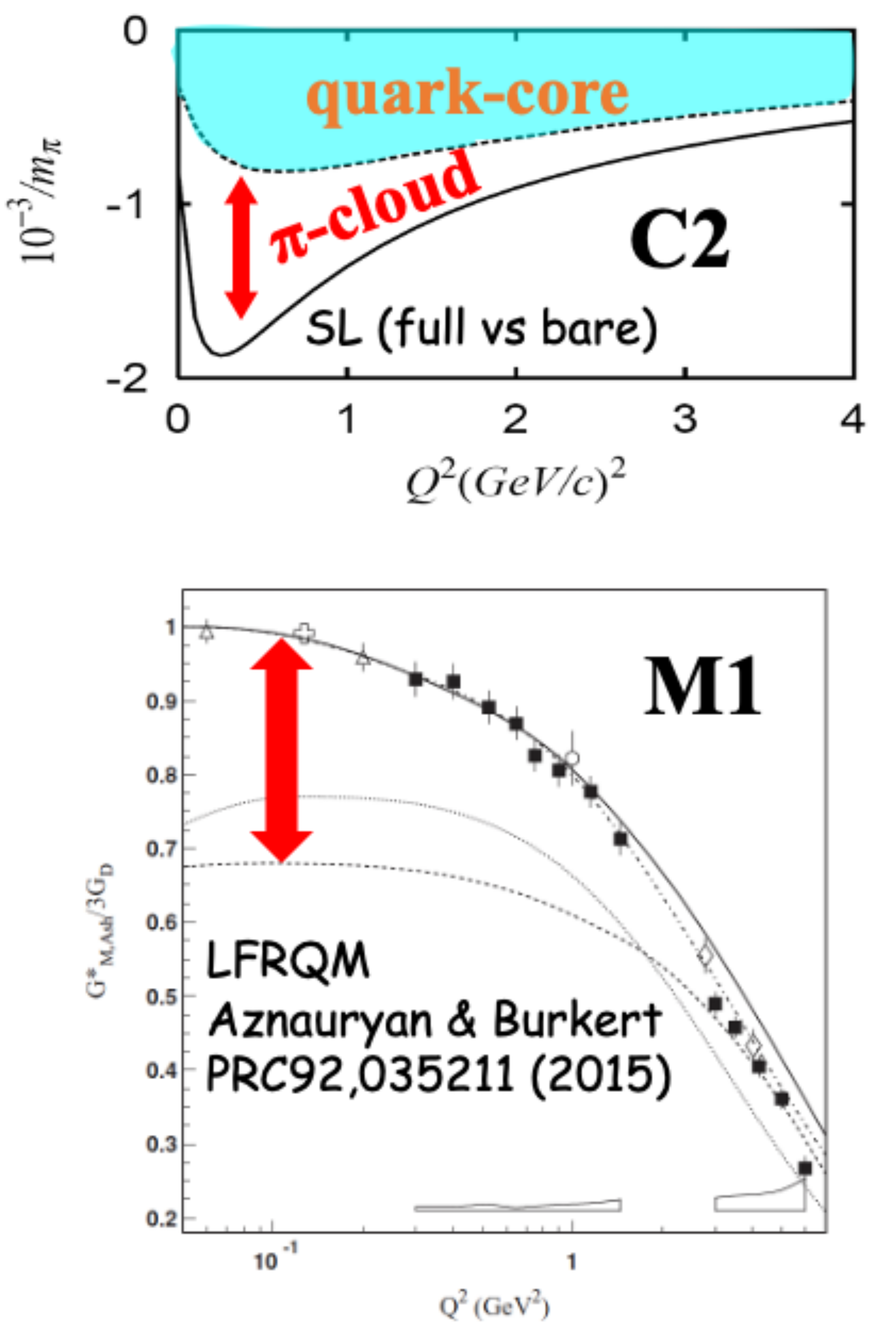


- **Through quadrupole N-Δ transition measurements, we can learn about neutron charge radius!**
  - The connection "*relies only on the spin-flavor structure of the wave functions and operators involved, i.e., only on general algebraic properties of the quark model and* ***not*** *on specific assumptions, such as values for quark masses, coupling constants, etc.*" (Buchmann 2010)
  - Derived initially through the framework of a non-relativistic constituent quark model, but also re-derived via a general SU(6) symmetry-breaking analysis and 1/Nc operator expansion!

N-Δ transition as a pathway to nucleon structure

Theoretical calculation of the mesonic cloud contribution to CMR





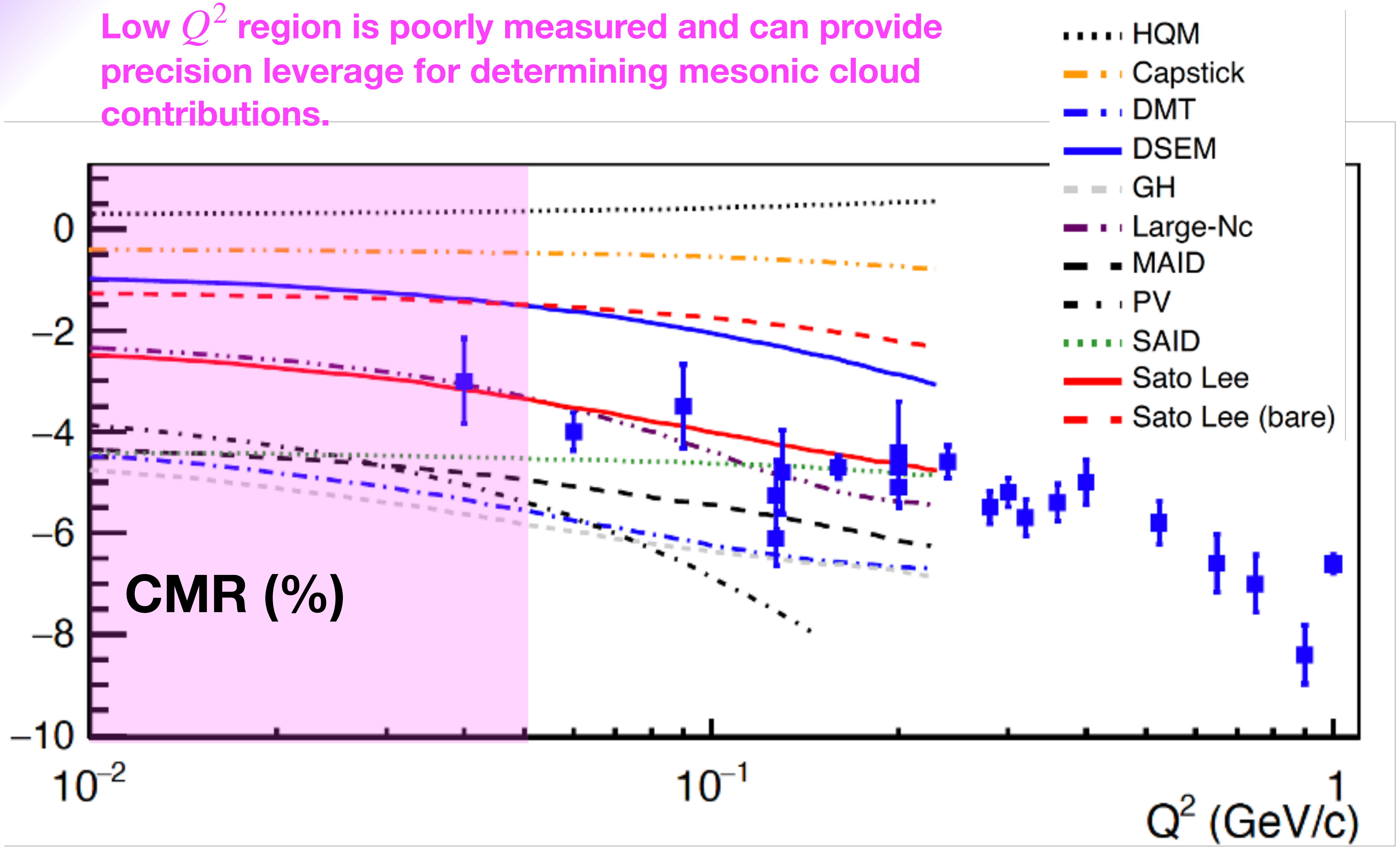
Signature of pion cloud

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

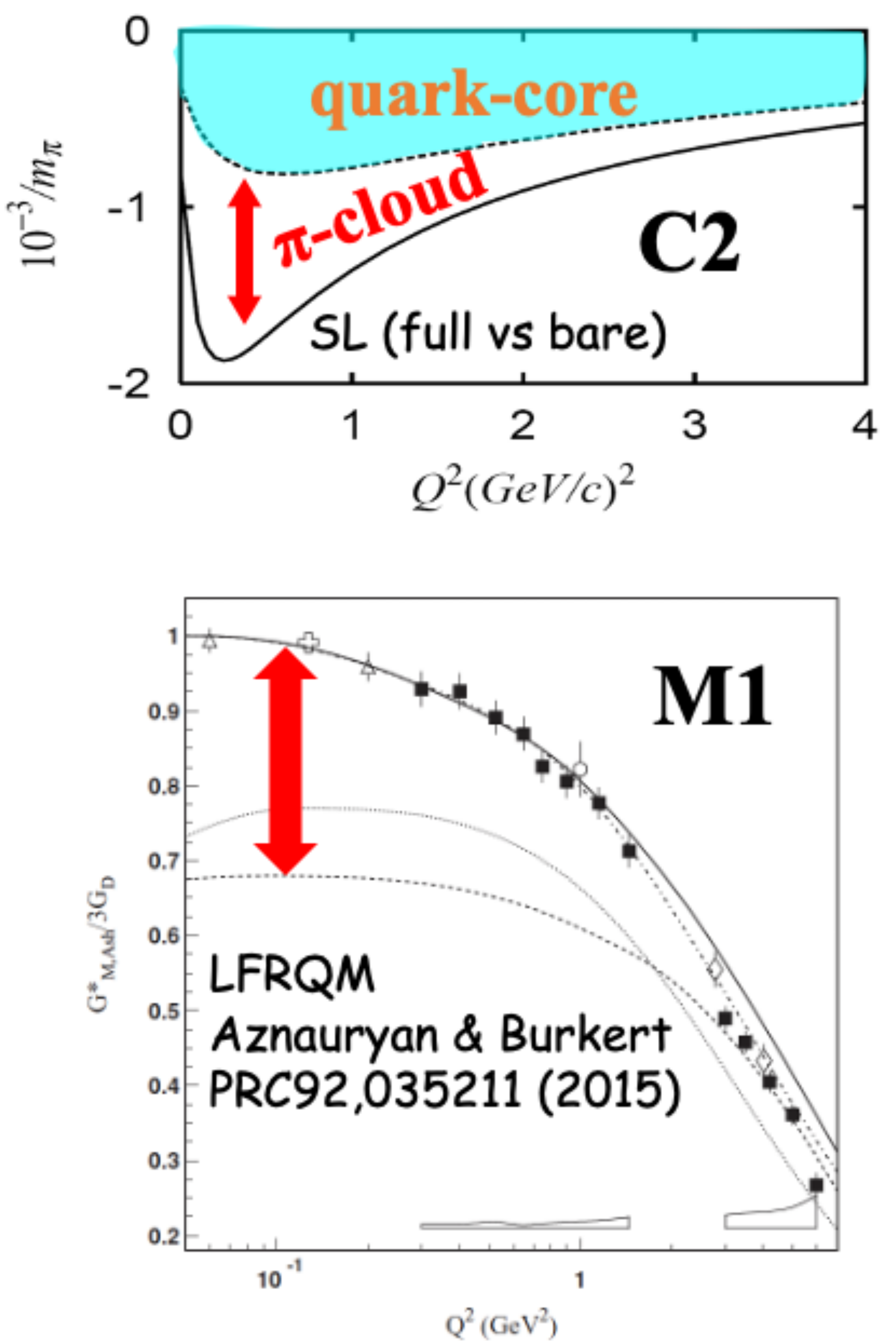
N-Δ transition as a pathway to nucleon structure

Low Q^2 region is poorly measured and can provide precision leverage for determining mesonic cloud contributions.



Can also help constrain uncertainties within a theoretical framework that combines Chiral Perturbation Theory with the 1/Nc expansion [Phys.Rev.D 101 (2020) 5, 054026]

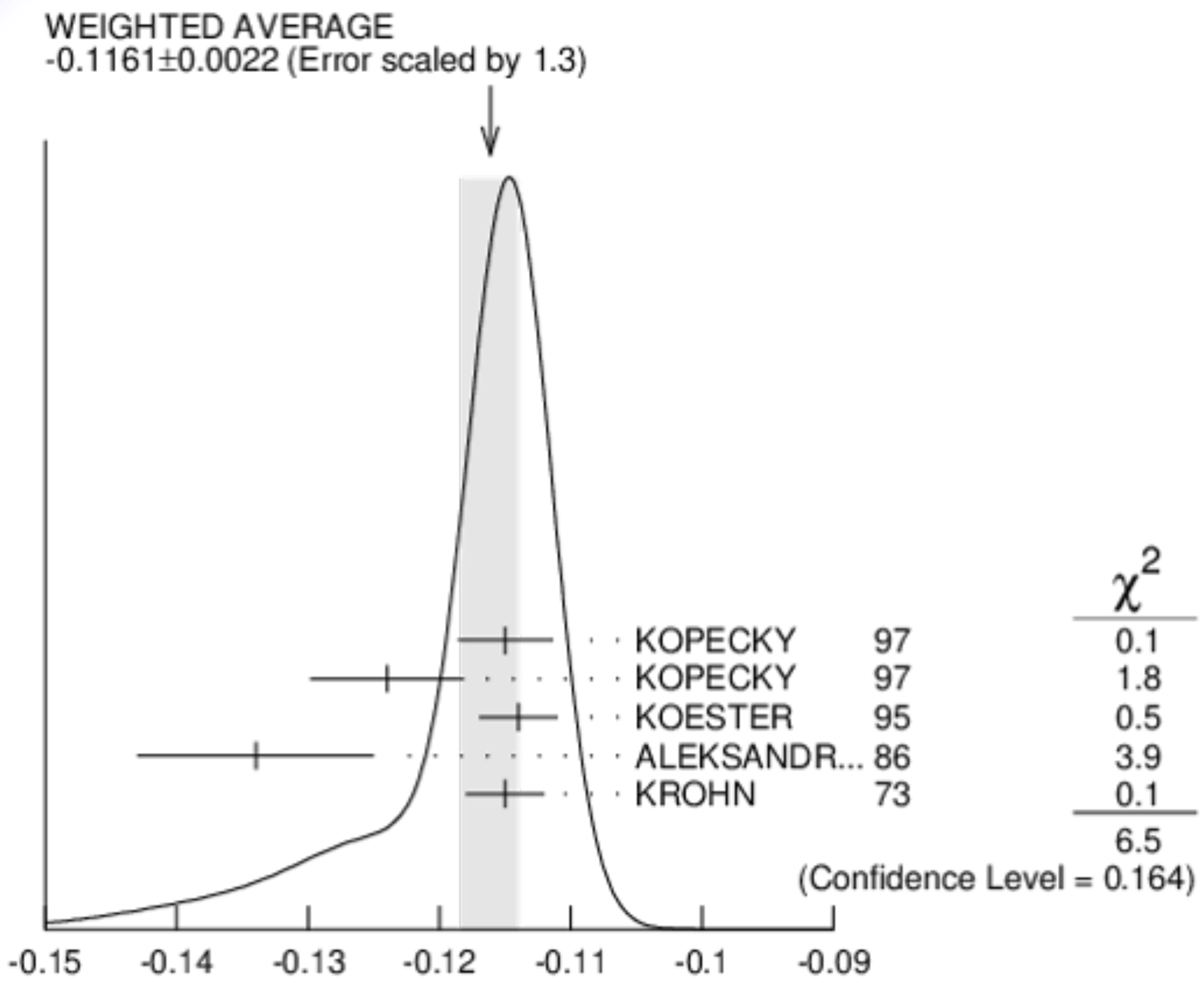
In this region, one can study the interplay of the two dynamical scales in the baryon form factors.



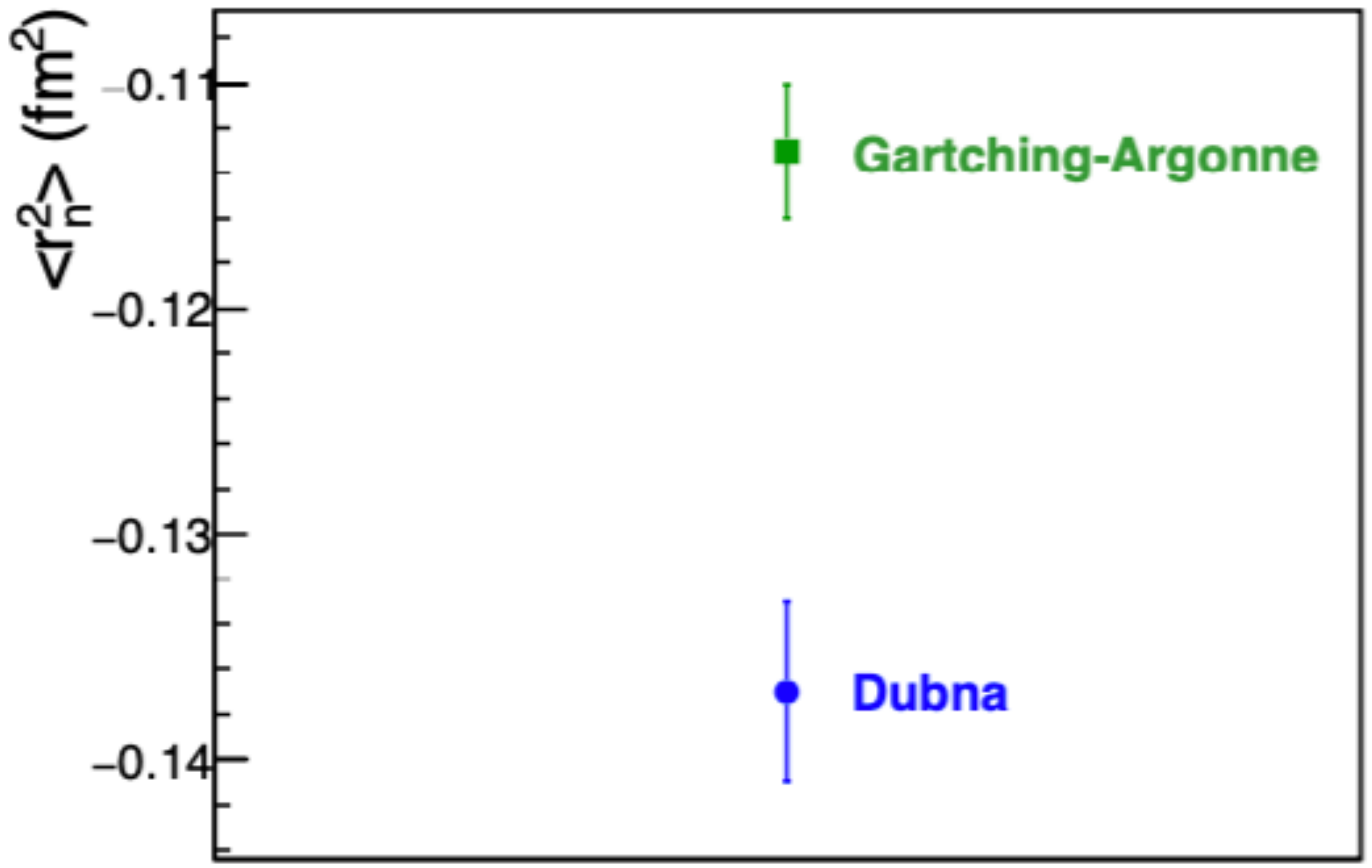
Signature of pion cloud

Our current understanding of the neutron charge radius

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 over 2 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!!!

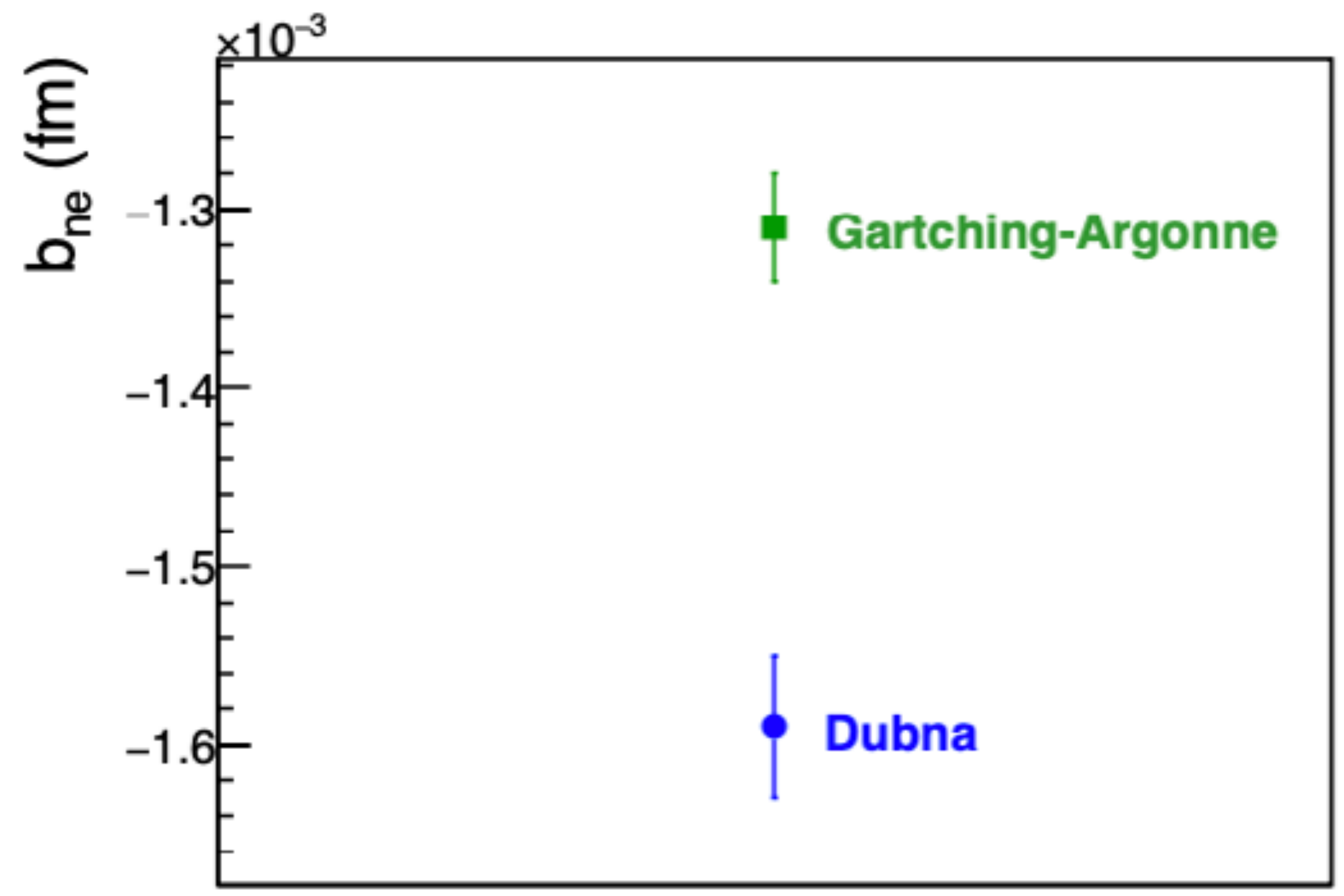
PRC 56, 2229 (1997) ; Annu. Rev. Nucl. Part. Sci. 55, 27 (2005) ; PRD 77 034020 (2008) …

Our current understanding of the neutron charge radius

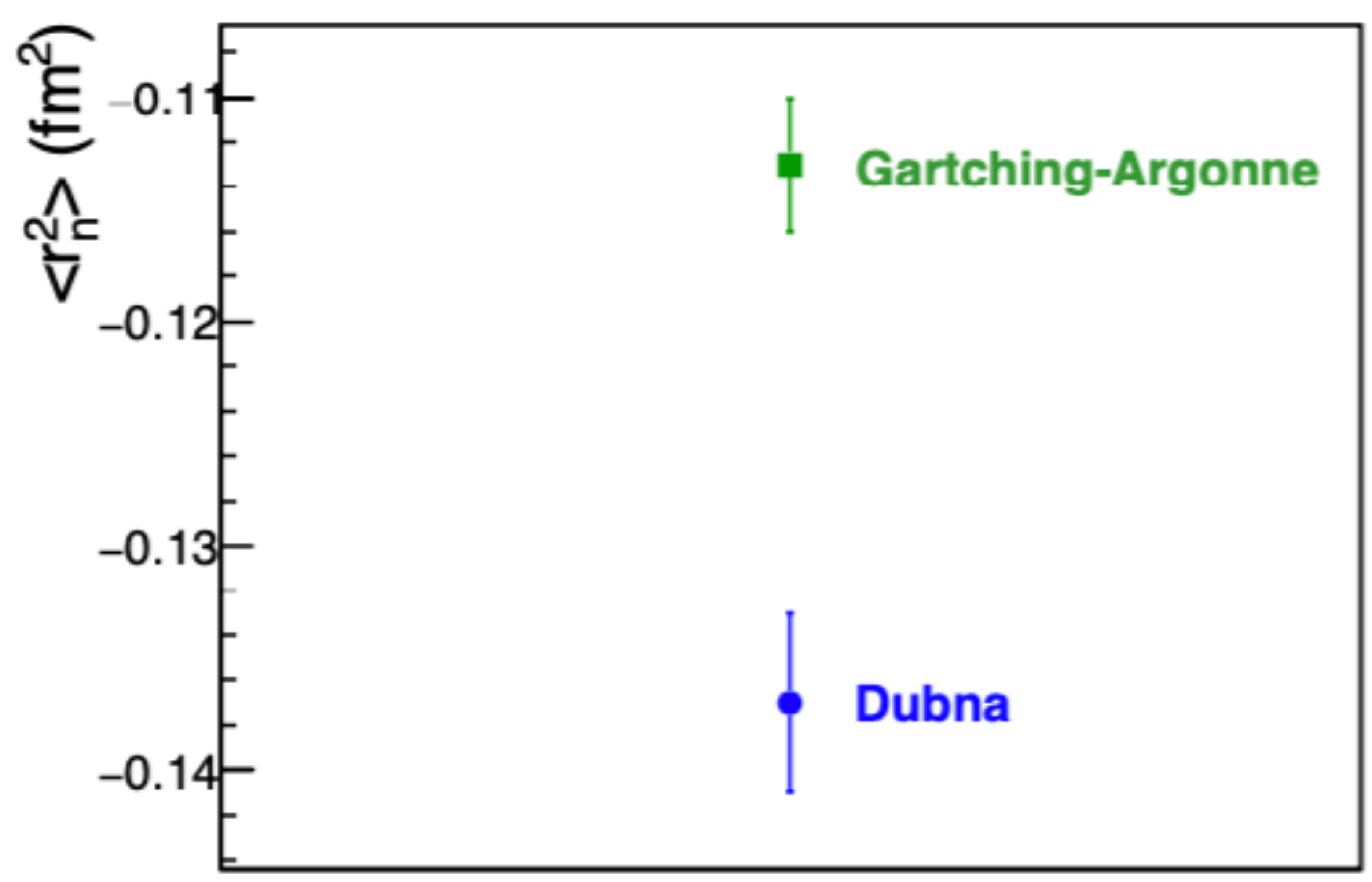
The value of $< r_n^2 >$ is based on one method of extraction → measurement of b_{ne} using Pb, Bi, …(very indirect method)

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



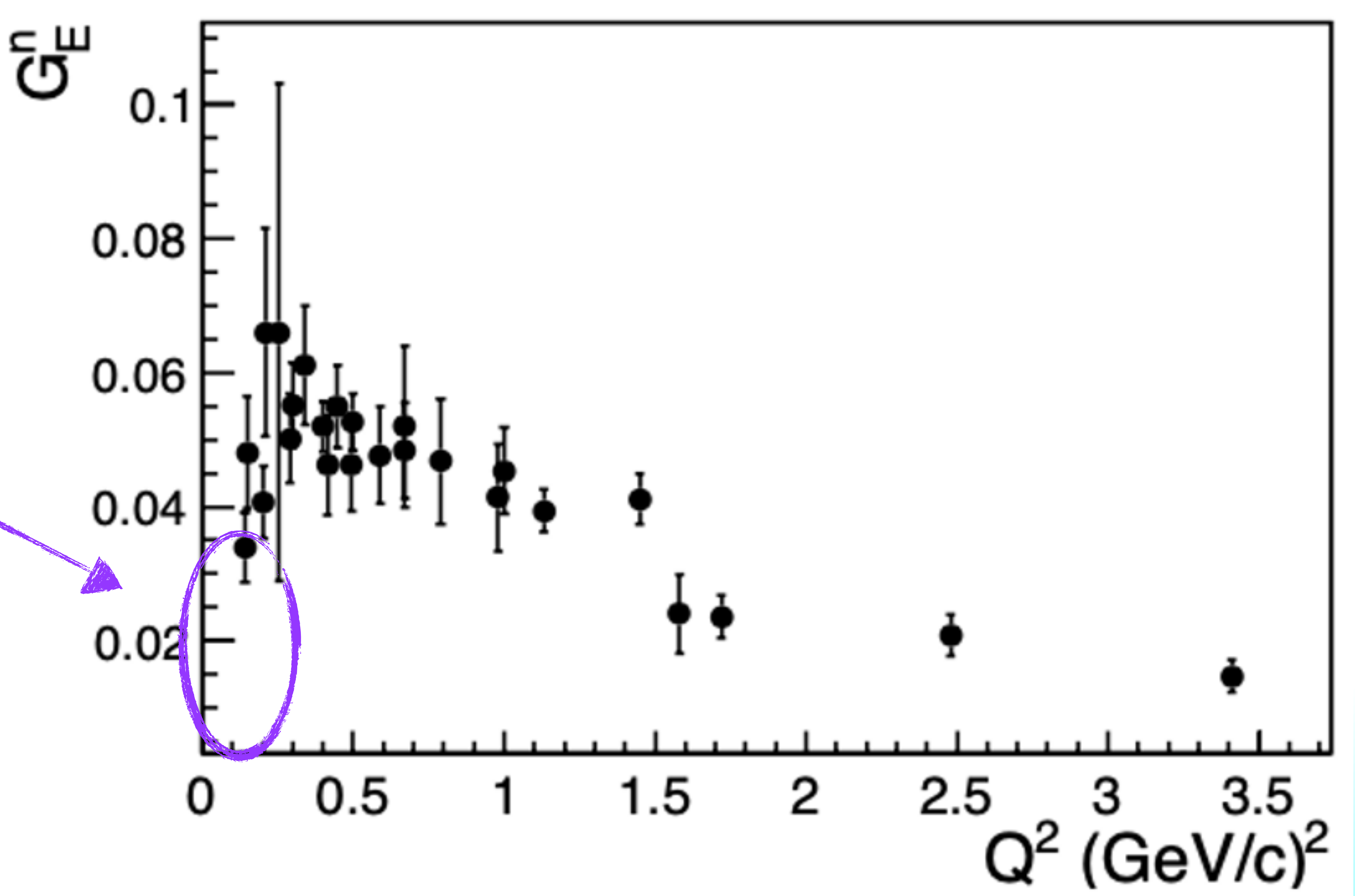
$$< r_n^2 > = 3(m_e a_0 / m_n)\, b_{ne}$$



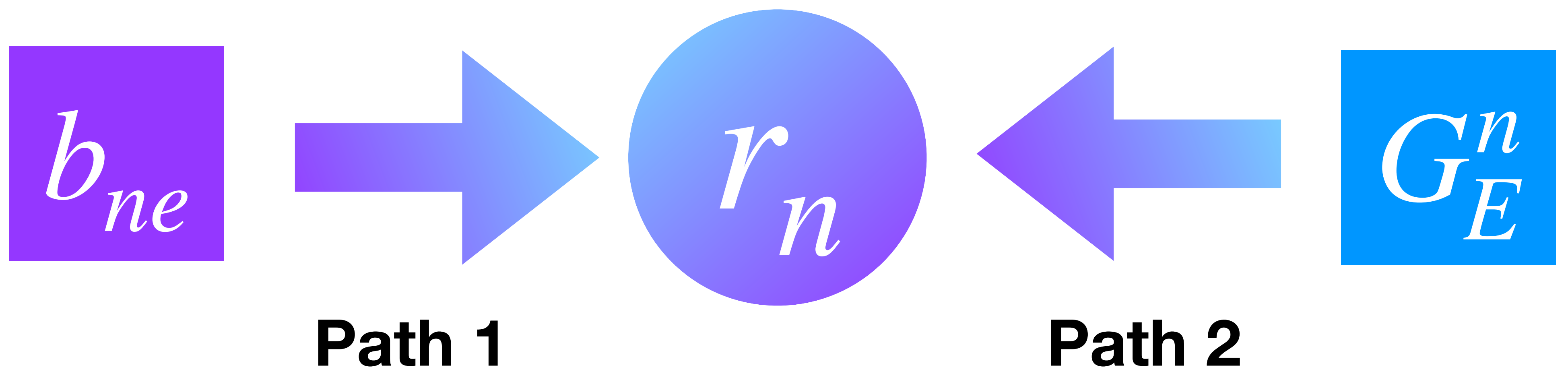
An alternative method to measure the neutron charge radius

$$\langle r_n^2 \rangle = -6 \frac{dG_E^n(Q^2)}{dQ^2} \Big|_{Q^2 \to 0}$$

If one can measure with precision $G_E^n(Q^2 \to 0)$, one can determine the neutron charge radius.

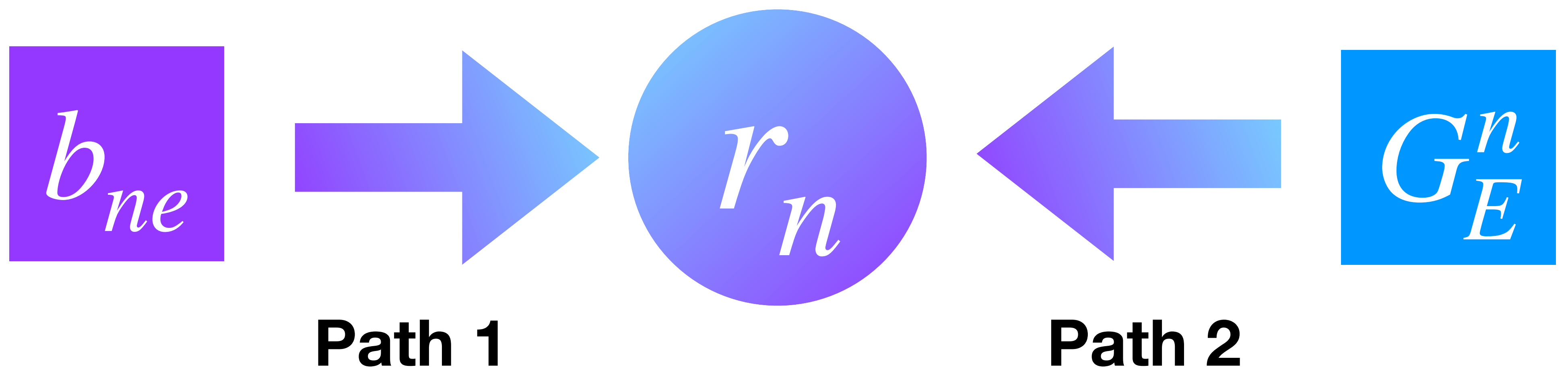


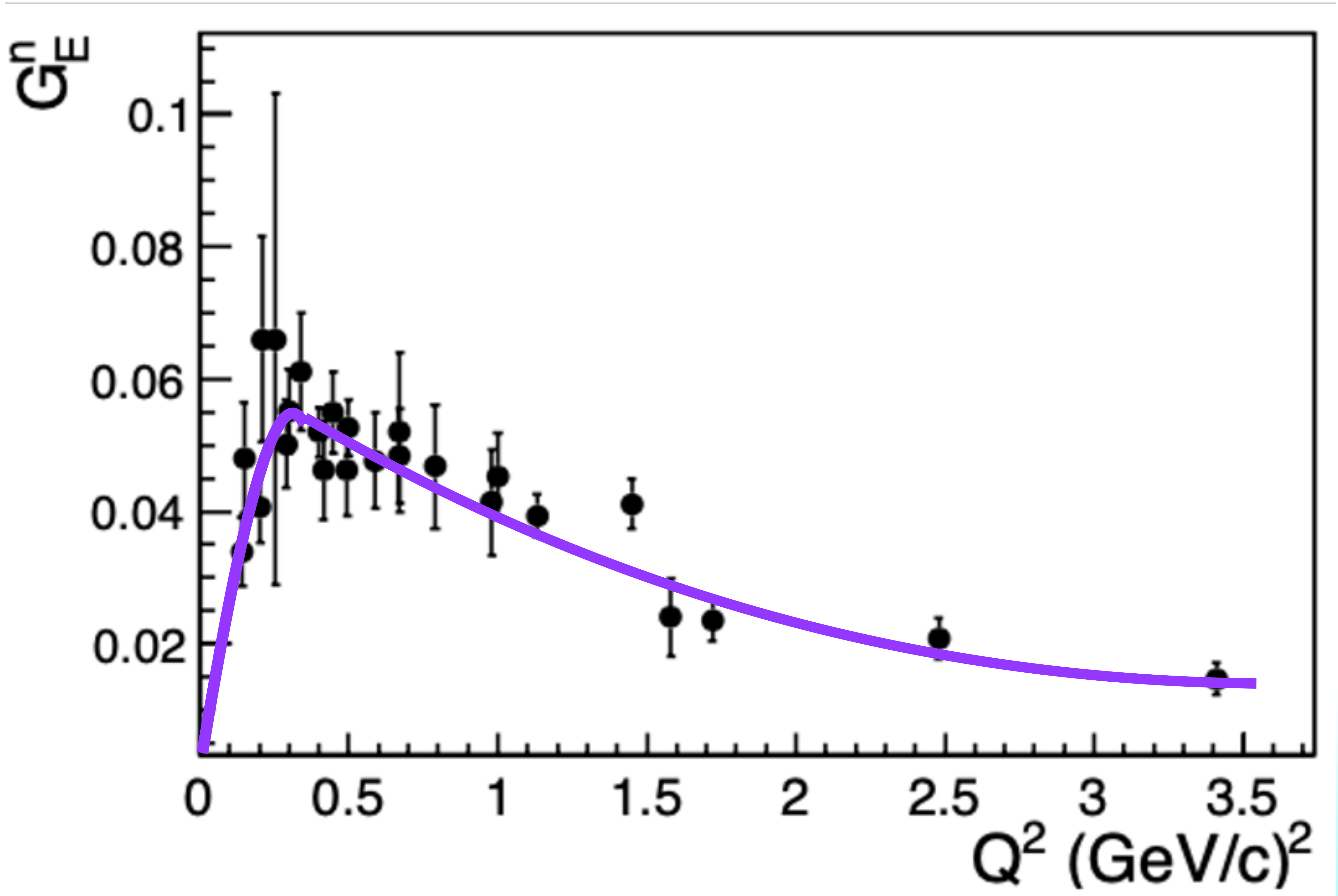
Doing such would provide an alternative path to the charge radius, and provide an important cross-check to the existing measurements. (And could reveal surprises!)



An alternative method to measure the neutron charge radius

- **Historical 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 $Q^2 = 0$





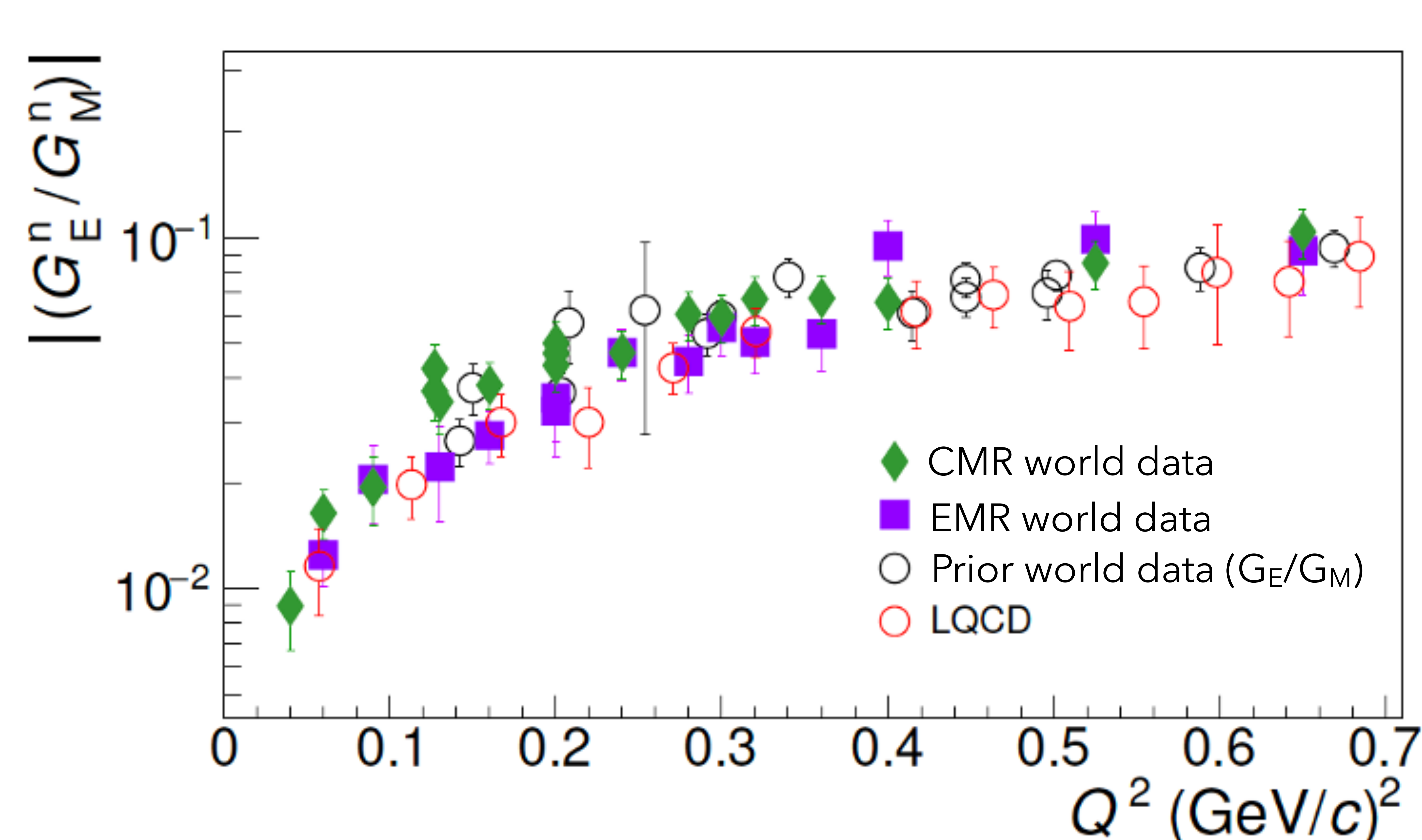
A path to extend our low Q^2 reach for G_E^n

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

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

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

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

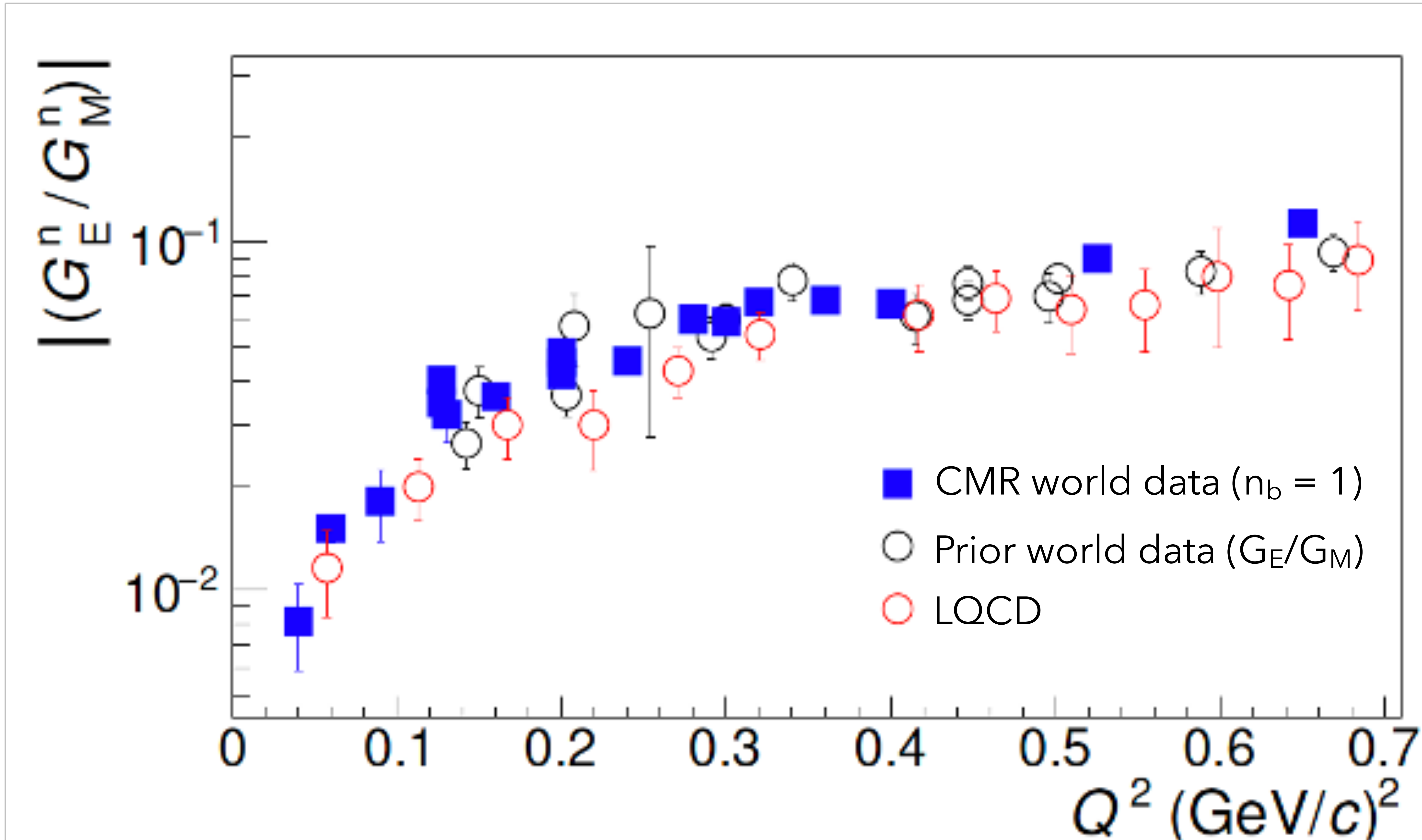


A path to extend our low Q^2 reach for G_E^n

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 $G_{M1}^{N\to\Delta}$



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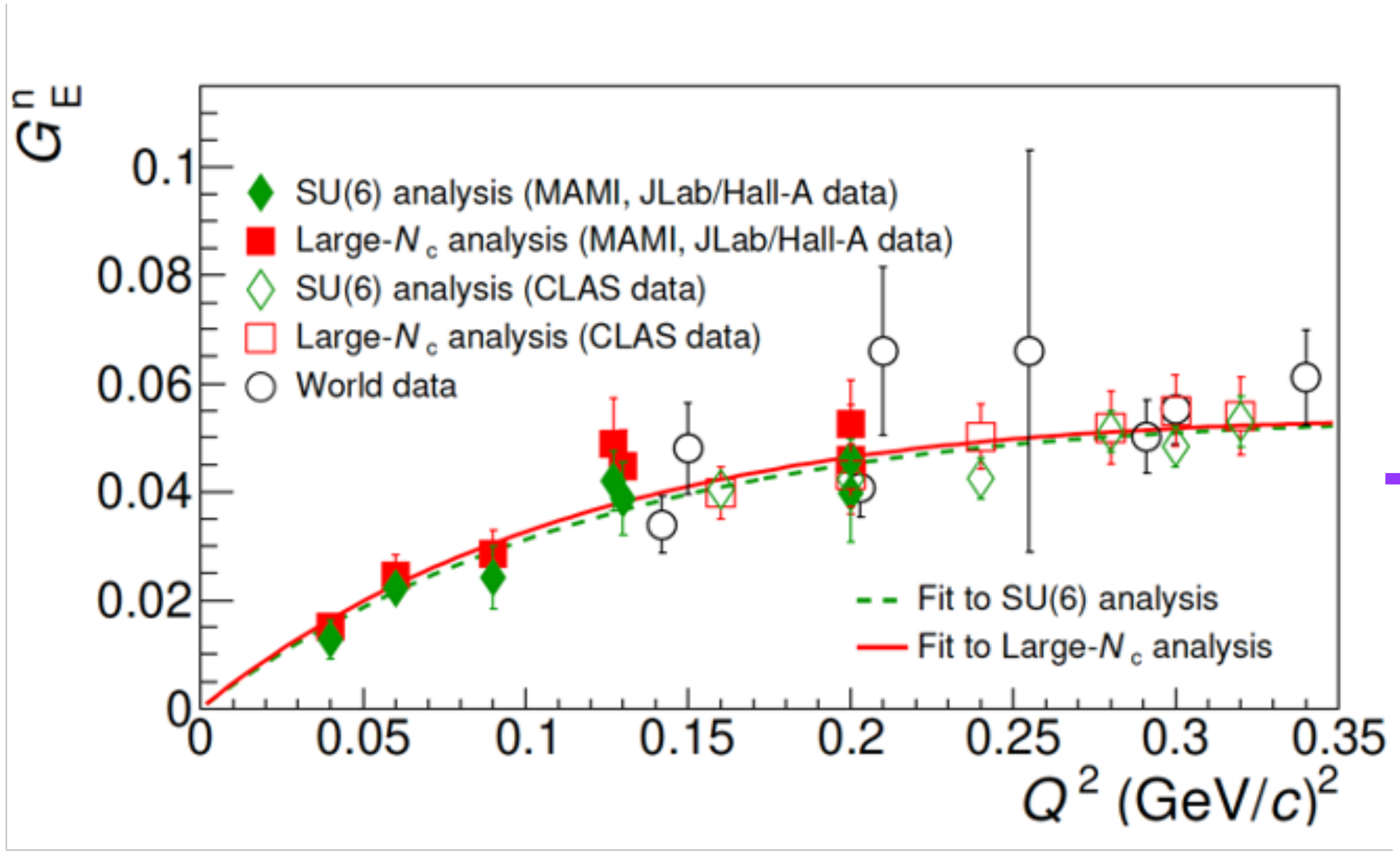
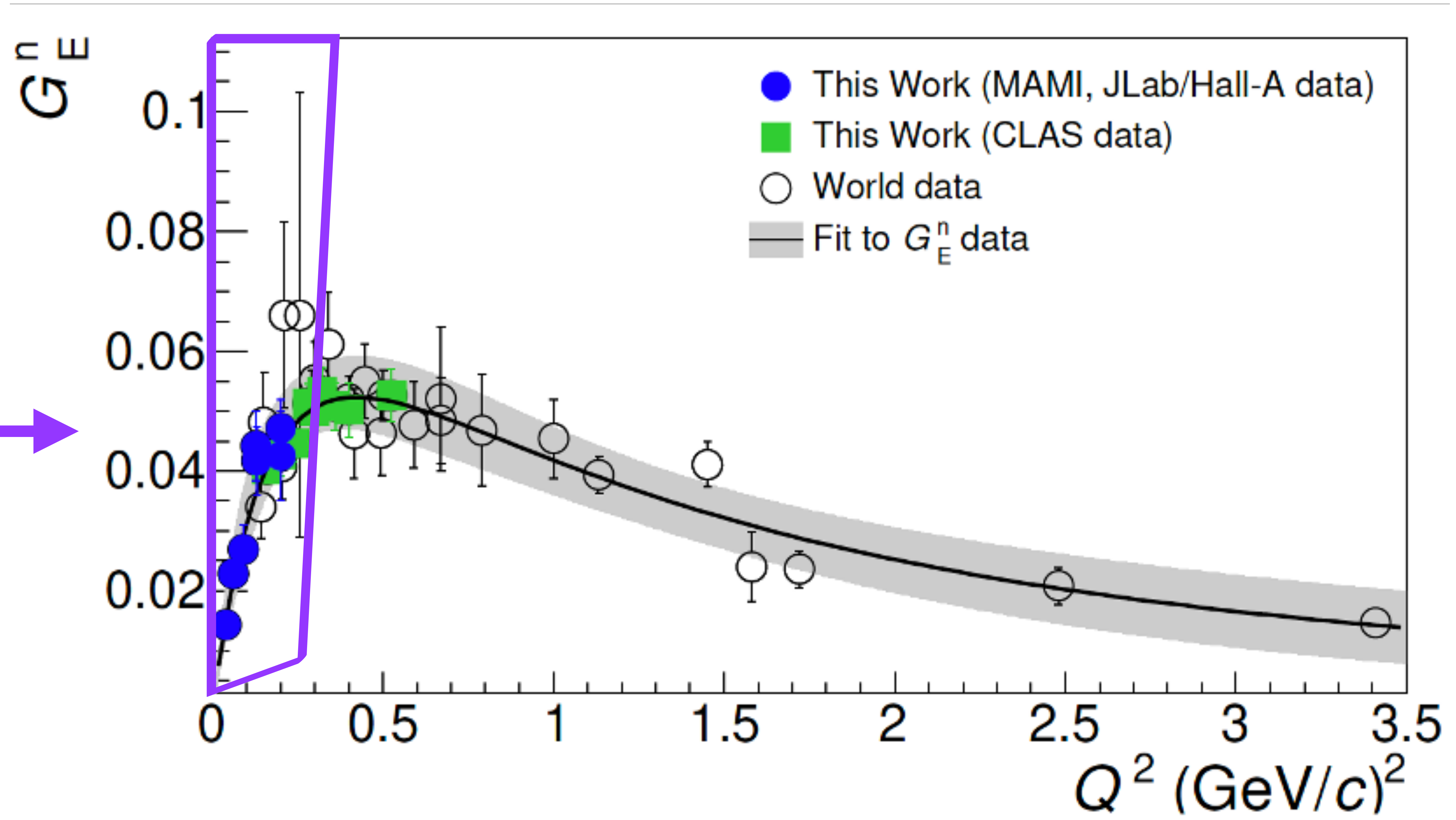
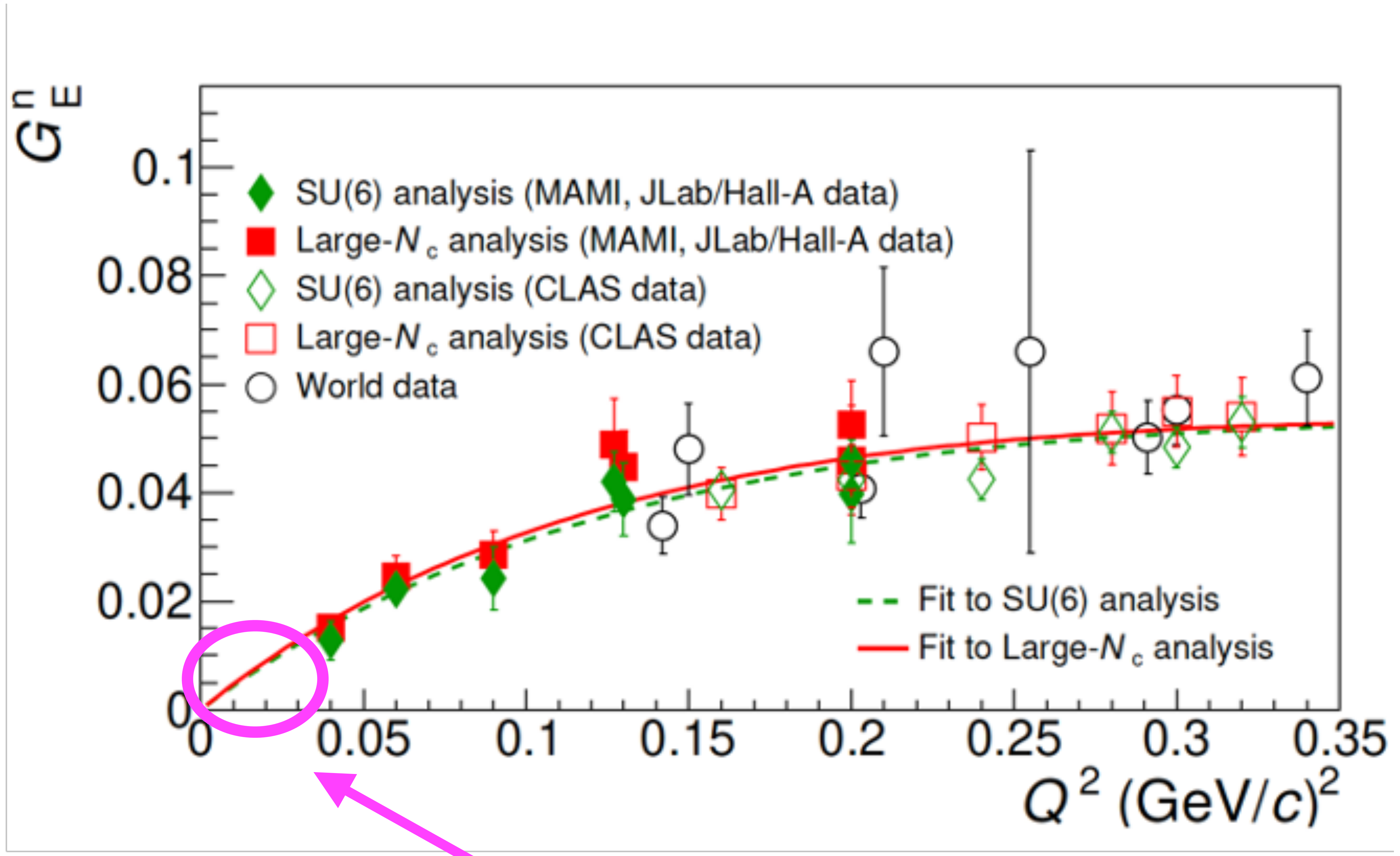
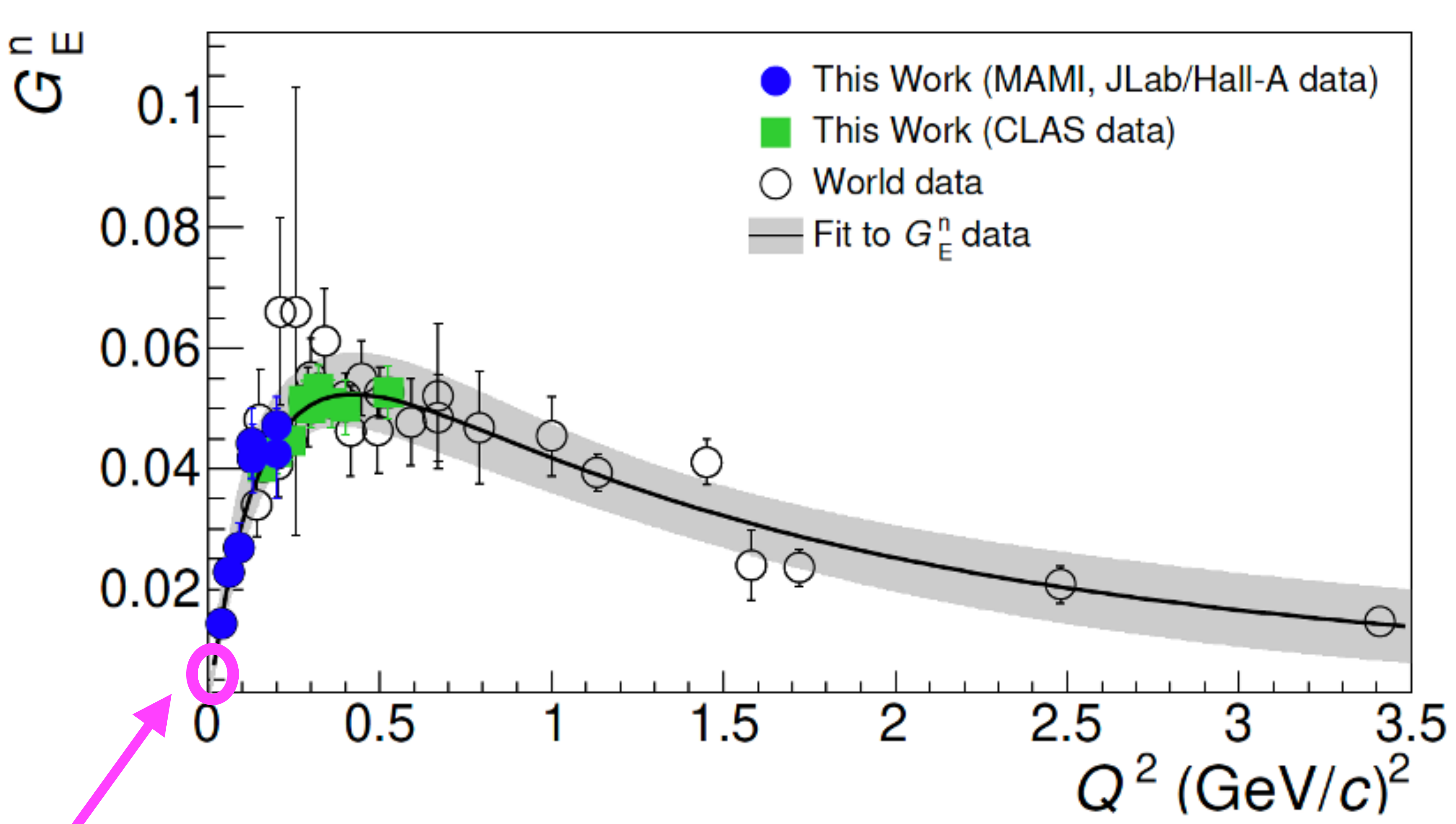




Nature Comm. 12, 1759 (2021)

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





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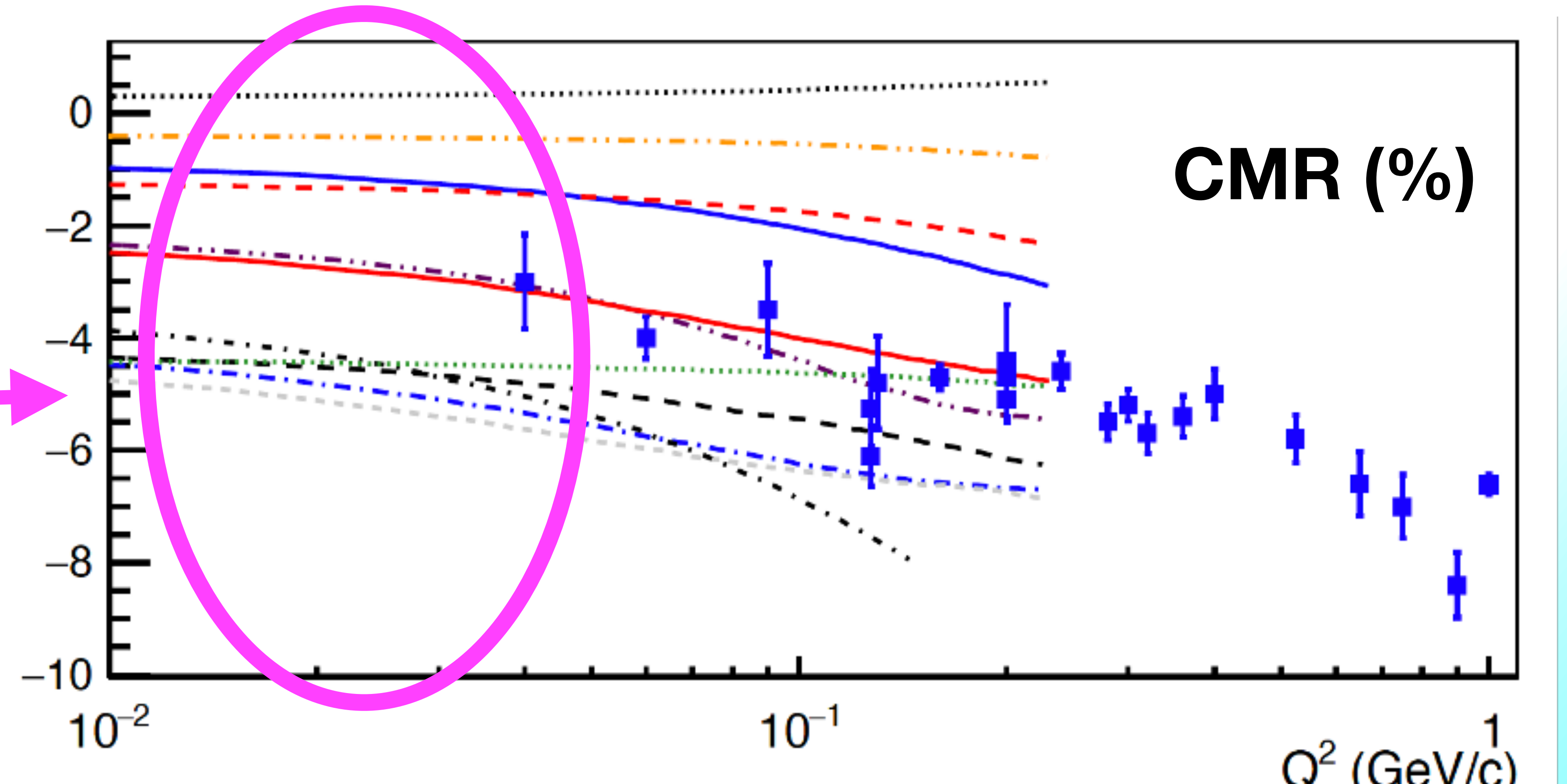
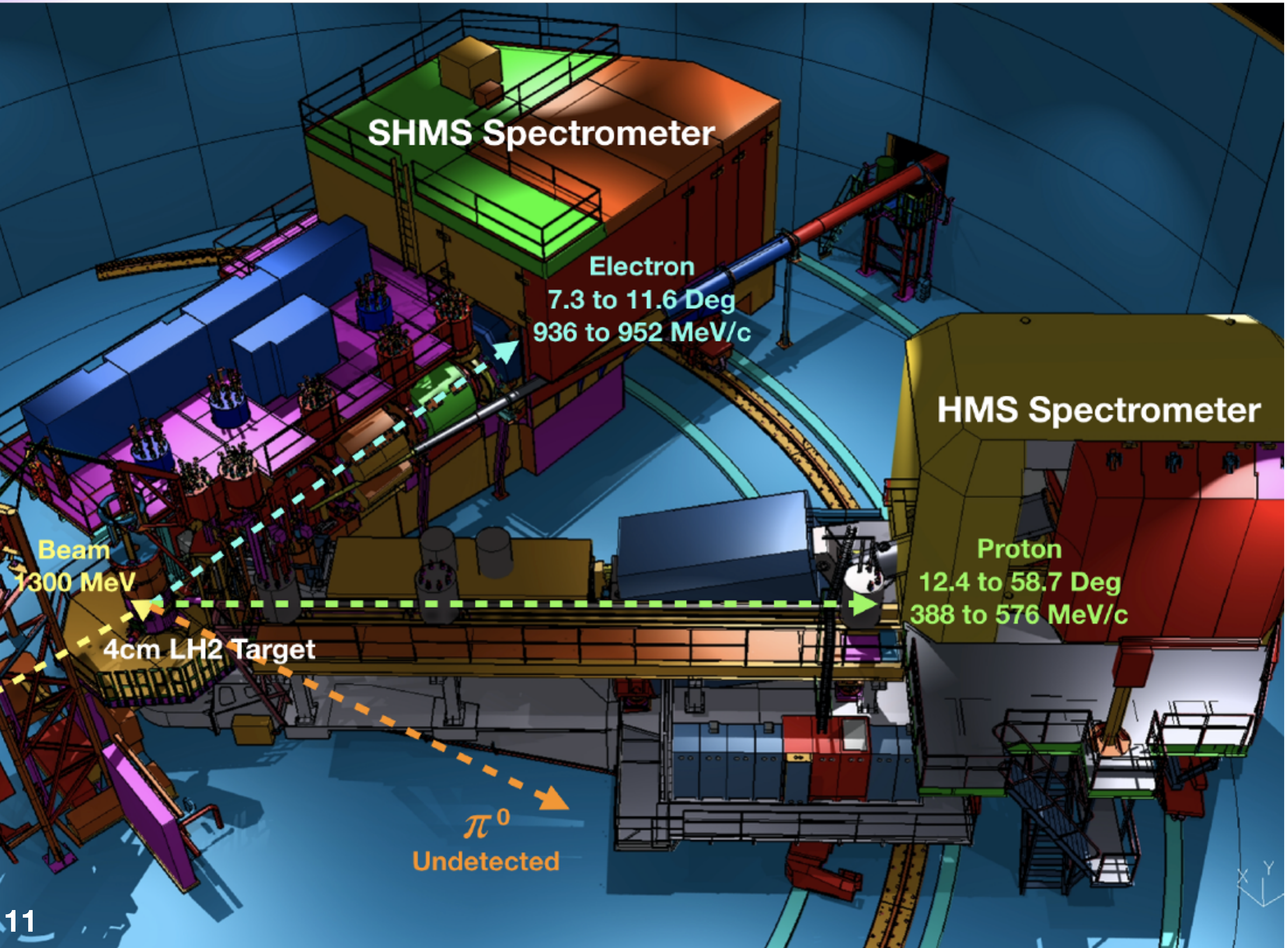
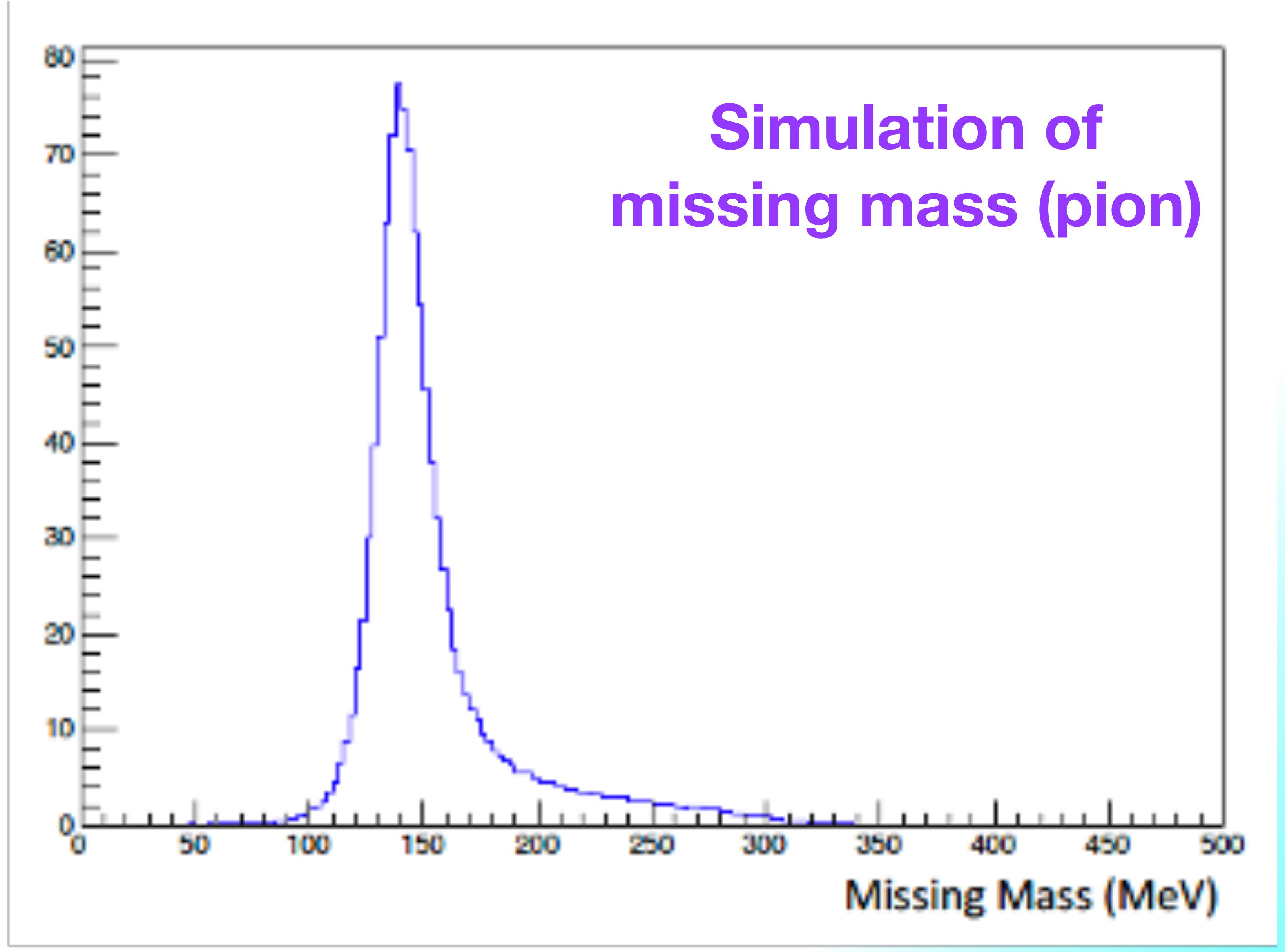


This proposal

Experimental Setup



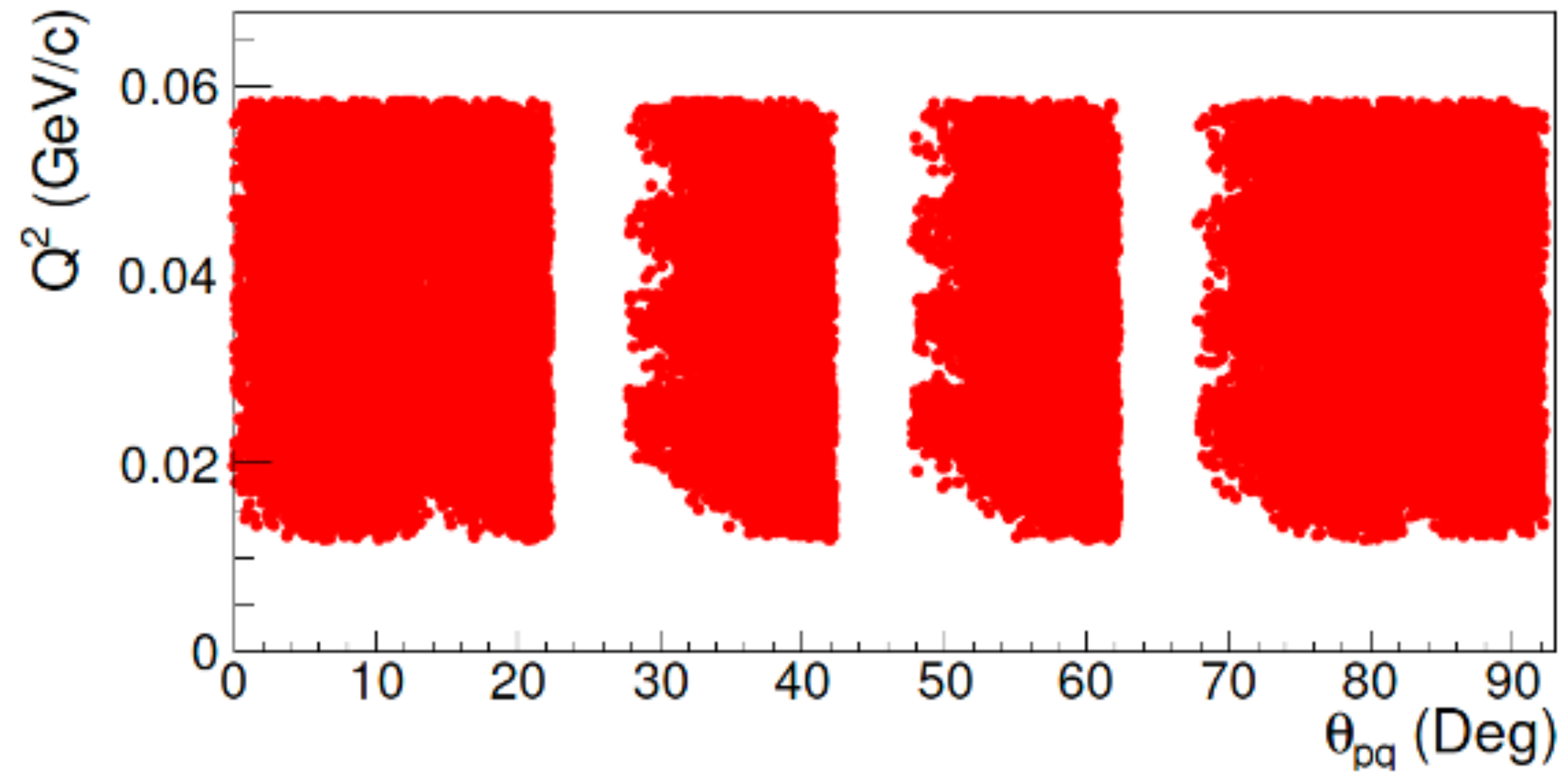
- **Standard Hall-C equipment**
  - 1300 MeV electron beam
  - Detect proton and electron in coincidence
  - Reconstruct pion from missing mass.



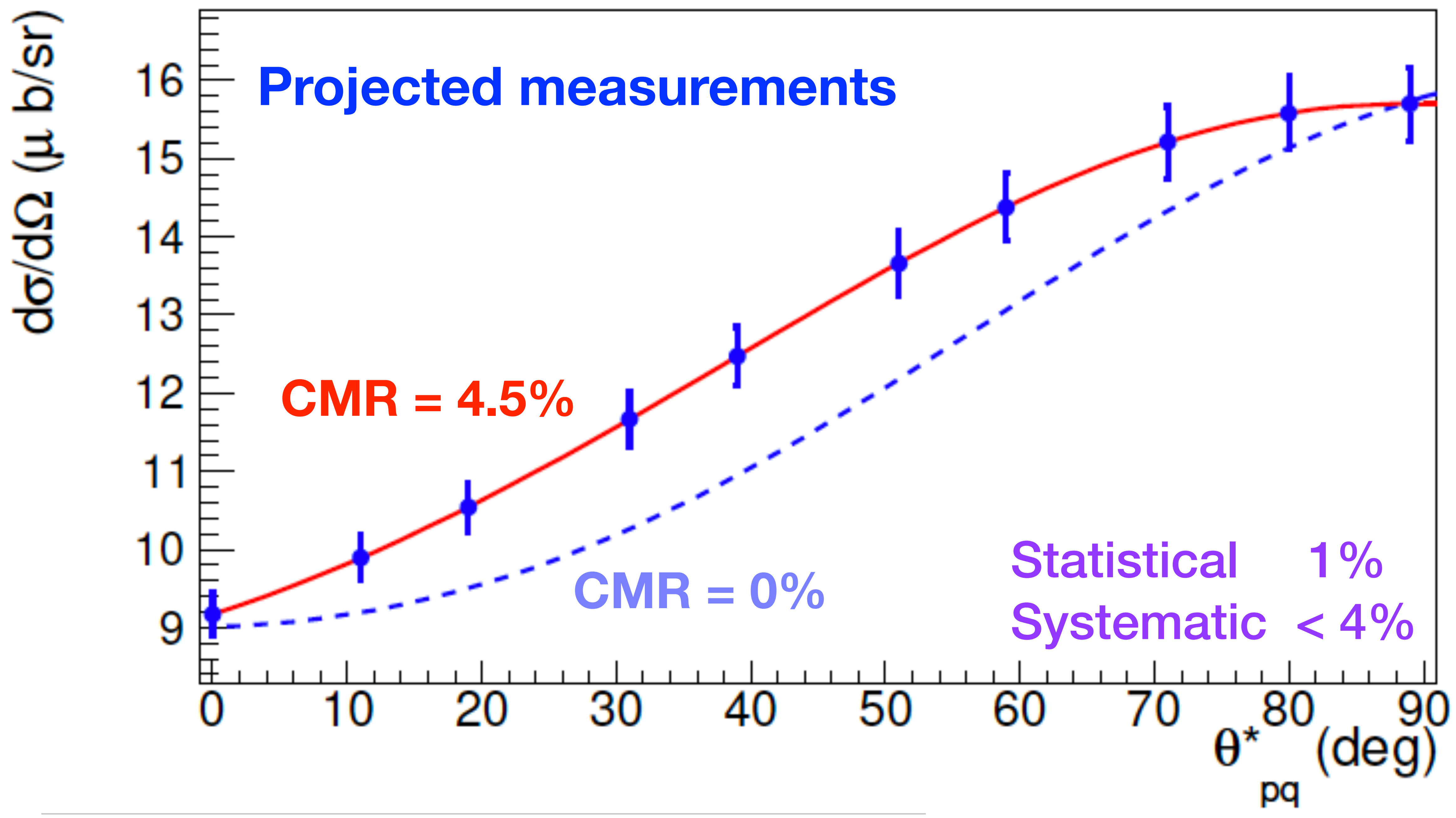
Measurement Settings

Setting	SHMS θ (deg)	SHMS P (MeV/c)	HMS θ (deg)	HMS P (MeV/c)	S/N	Time (hrs)
1a	7.29	952.26	18.77	532.53	2	7
2a			25.17	527.72	2	7
3a			33.7	506.61	3.2	6
4a			42.15	469.66	4.3	5
5a			50.44	418.56	4.9	5
6a			54.47	388.38	4.9	5
7a			12.37	527.72	2.7	6
1b	8.95	946.93	22.01	547.54	1.2	6
2b			28.24	542.61	1.4	6
3b			36.52	520.95	2.5	5
4b			44.64	483.08	3.4	4
5b			52.68	430.78	3.7	4
6b			56.53	399.92	3.5	4
7b			12.46	535.98	1.6	5
1c	10.37	941.61	24.40	562.00	1.5	9
2c			30.47	556.95	1.9	9
3c			38.52	534.79	3.5	6
4c			46.47	496.06	4.4	6
5c			54.17	442.64	4.8	6
6c			57.85	411.16	4.8	6
7c			12.69	543.24	2	6
1d	11.63	936.28	26.24	575.96	1.8	12
2d			32.16	570.80	2.5	11
3d			40.01	548.17	4.5	8
4d			47.73	508.64	5.5	8
5d			55.18	454.17	6.9	7
6d			58.71	422.13	6	8
7d			12.47	548.17	2.1	10

- **Cover a Q^2 range of 0.015 to 0.055 $(GeV/c)^2$**
  - 28 arm configurations
  - Coverage for 9 Q^2 bins.
  - 7.8 days production
  - 1.7 days other (dummy, calibration, etc..)

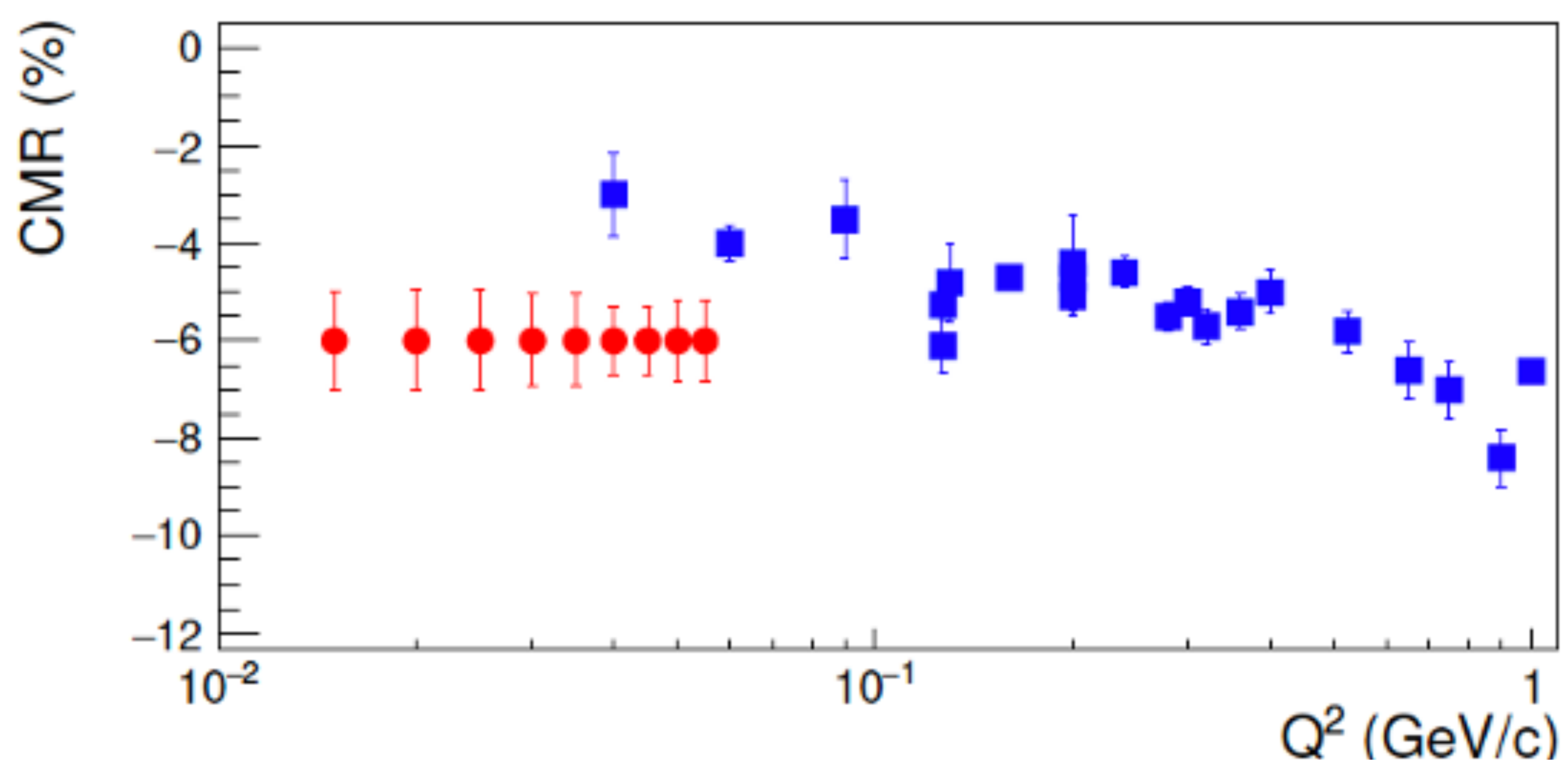


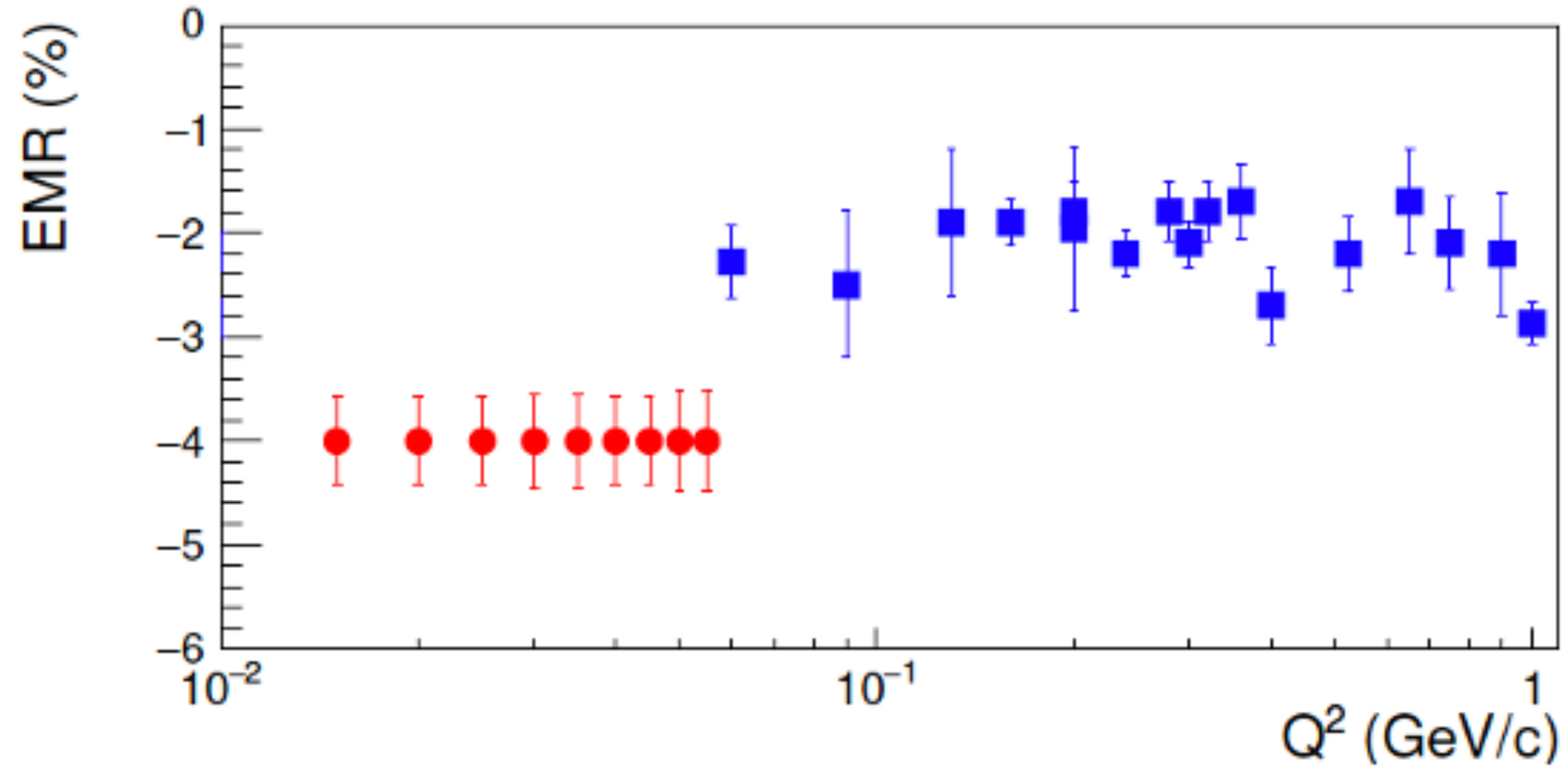
Projected CMR and EMR measurements



Resolution	2% - 3%
Acceptance	1%
Scattering angle	0.4% - 0.6%
Beam energy	0.7% - 1.2%
Beam charge	1%
Target density	0.5%
Detector efficiencies	0.5%
Target cell background	0.5%
Target length	0.5%
Dead-time corrections	0.5%
Total	2.8% - 3.8%

- High precision in very low Q^2 region that is sparsely populated
  - Region where pion-cloud effects are expected to be prominent





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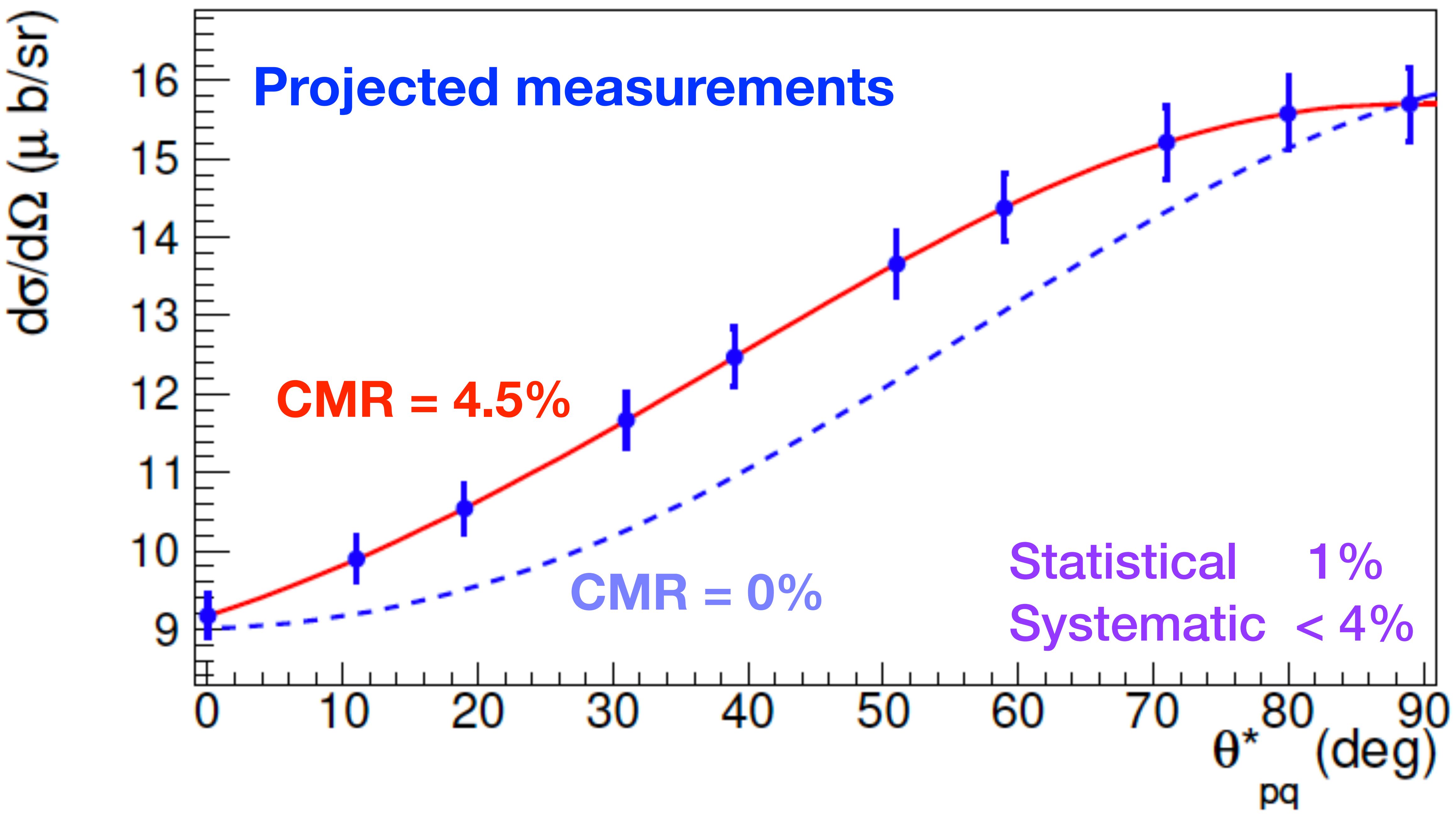
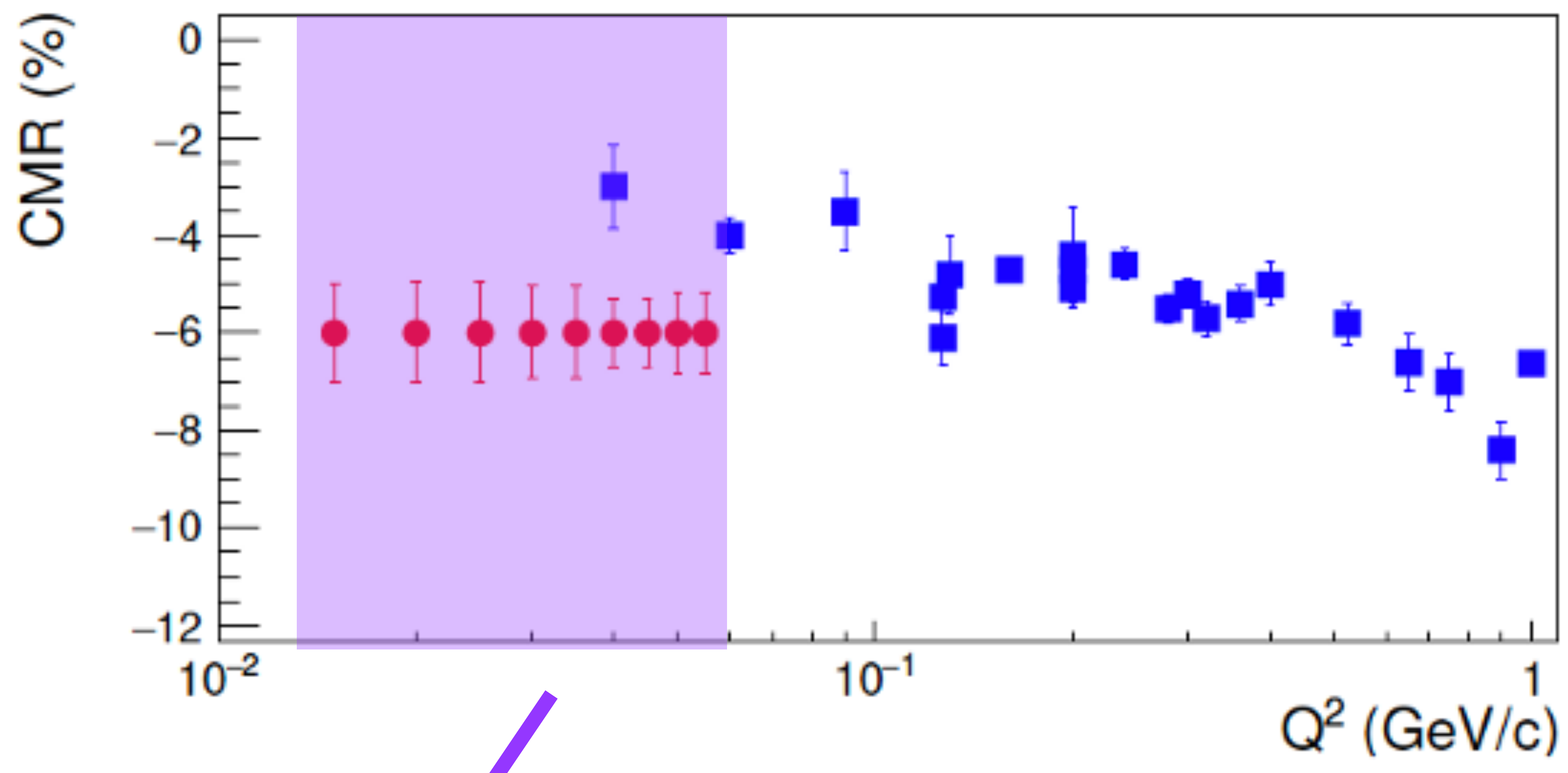
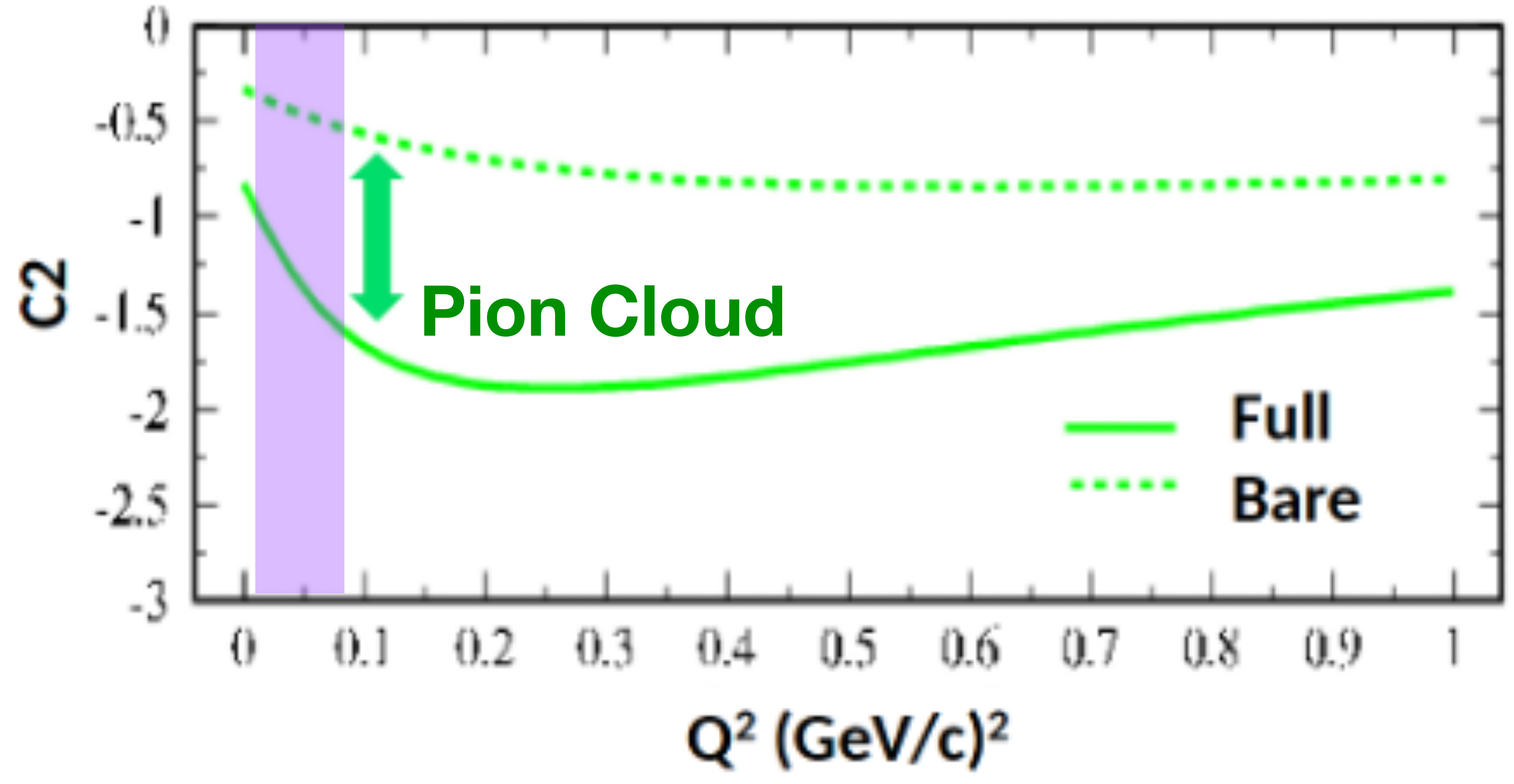


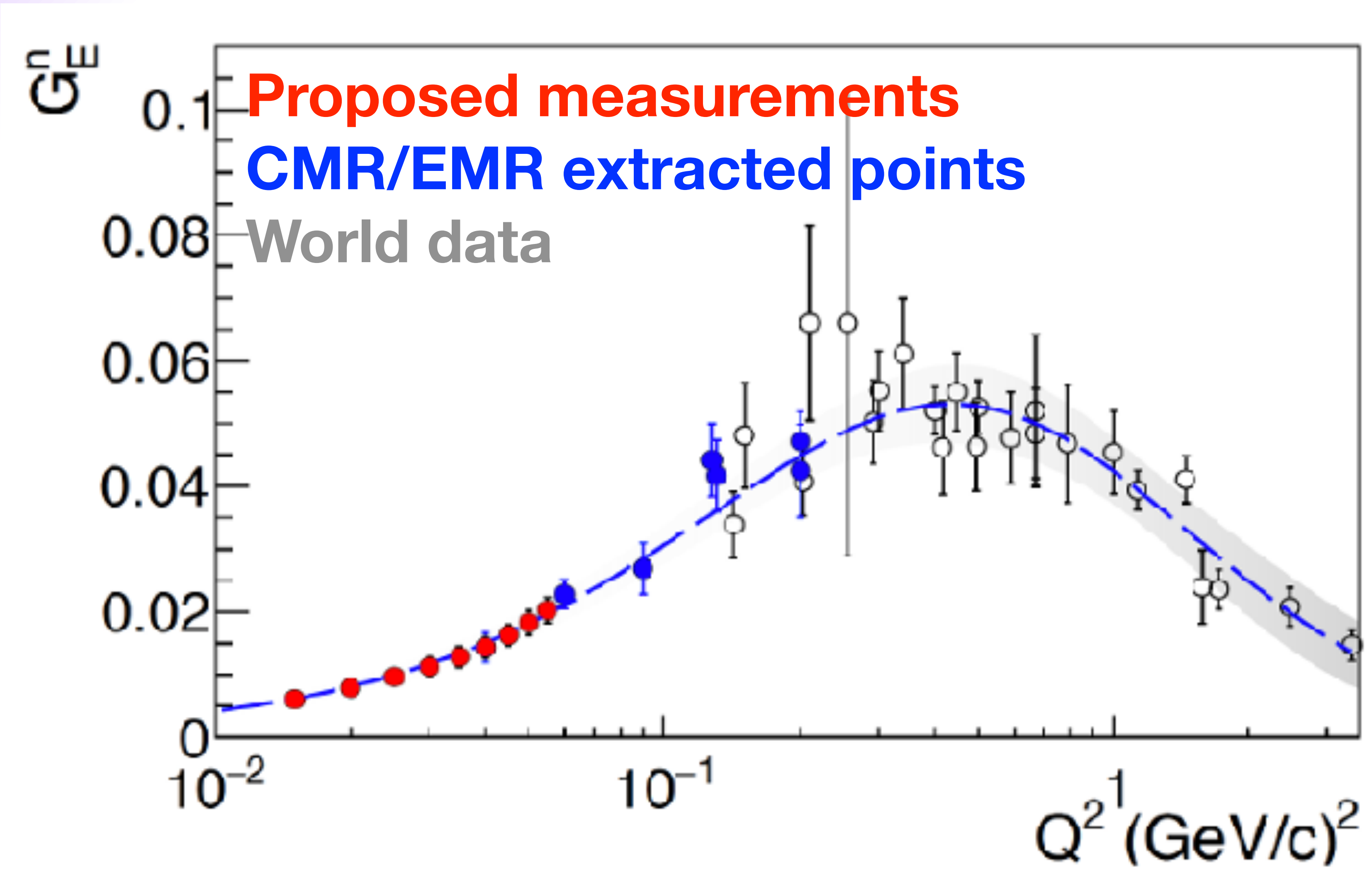


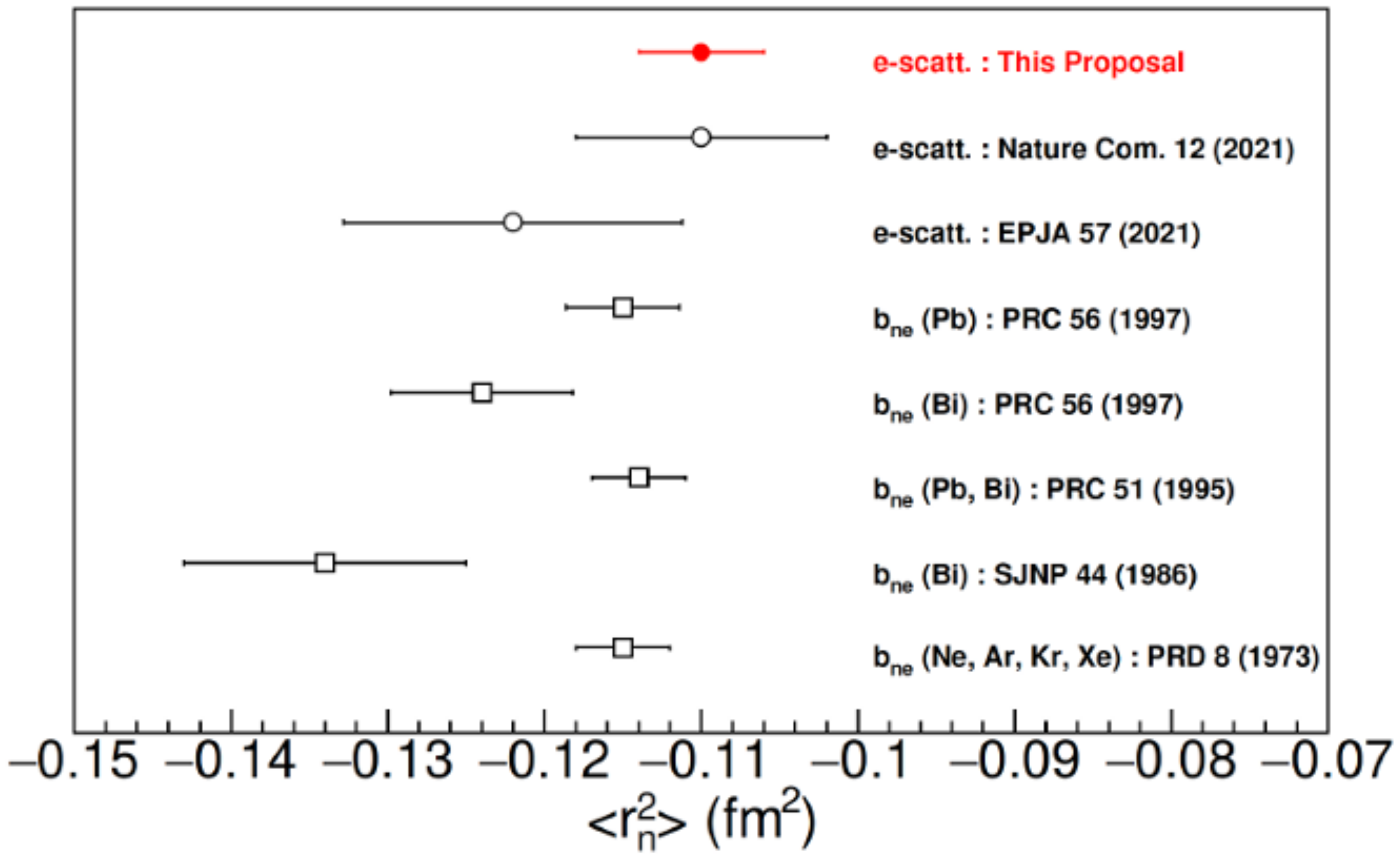


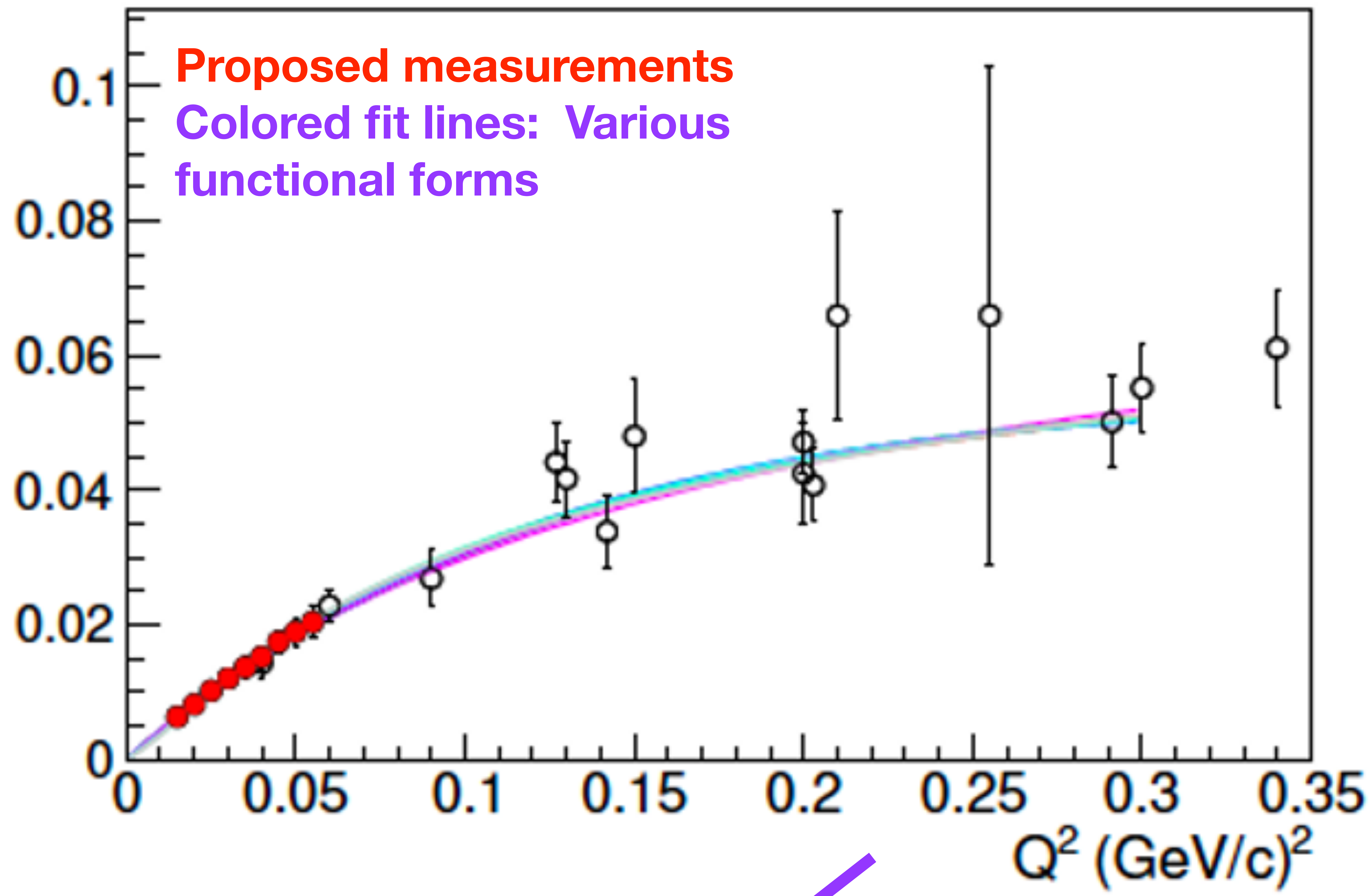
Resolution	2% - 3%
Acceptance	1%
Scattering angle	0.4% - 0.6%
Beam energy	0.7% - 1.2%
Beam charge	1%
Target density	0.5%
Detector efficiencies	0.5%
Target cell background	0.5%
Target length	0.5%
Dead-time corrections	0.5%
Total	2.8% - 3.8%

- High precision in very low Q^2 region that is sparsely populated
  - Region where pion-cloud effects are expected to be prominent

$\langle r_n^2 \rangle$ extraction through direct G_n^E fitting





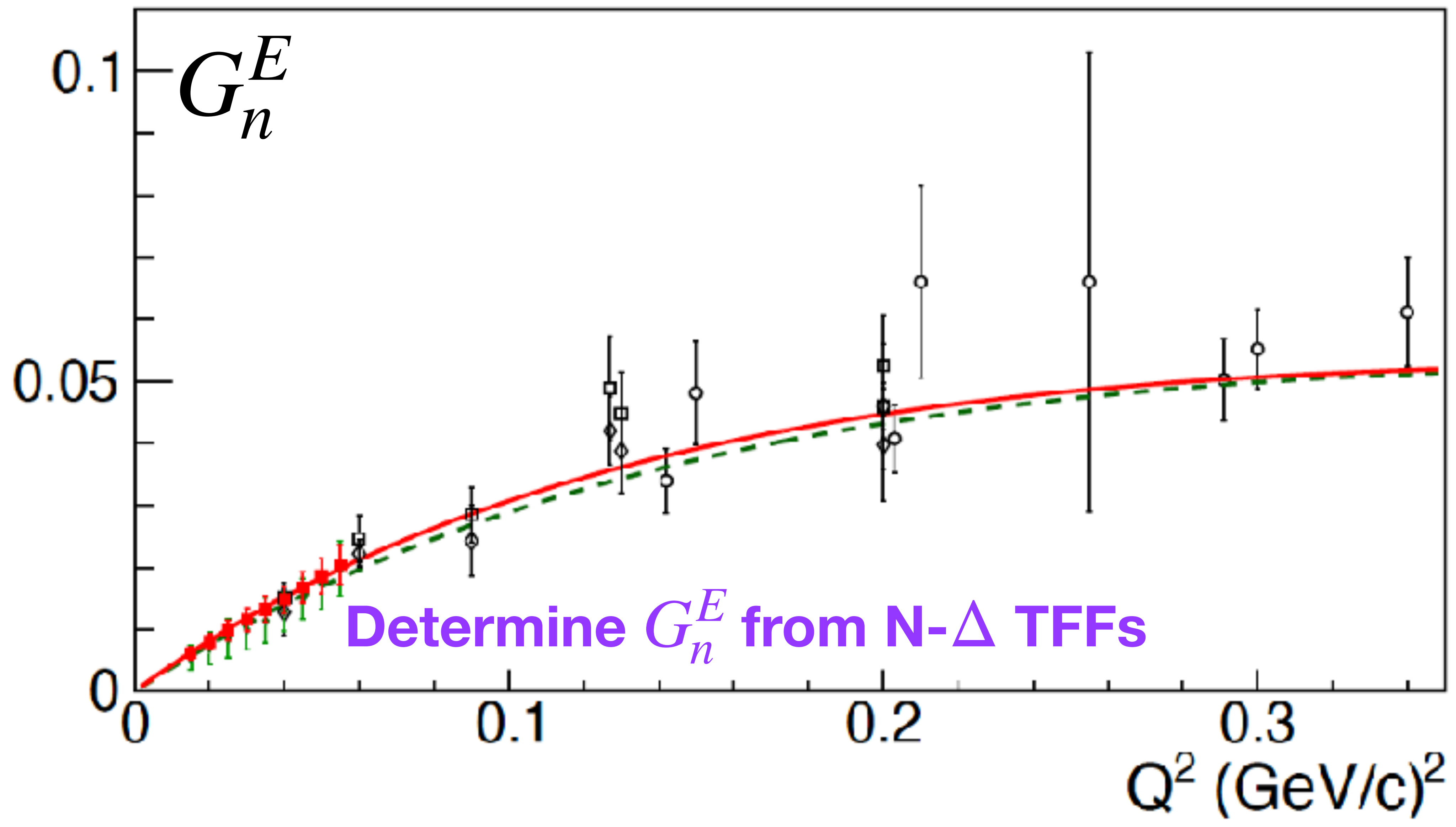


$$\langle r_n^2 \rangle = -6 \frac{dG_E^n(Q^2)}{dQ^2}\bigg|_{Q^2 \to 0}$$

Extract radius through fit of slope as $Q^2 \to 0$

Projected precision: ~ 3.7% !!!

$\langle r^2_{n,p} \rangle$ extraction and flavor decomposition



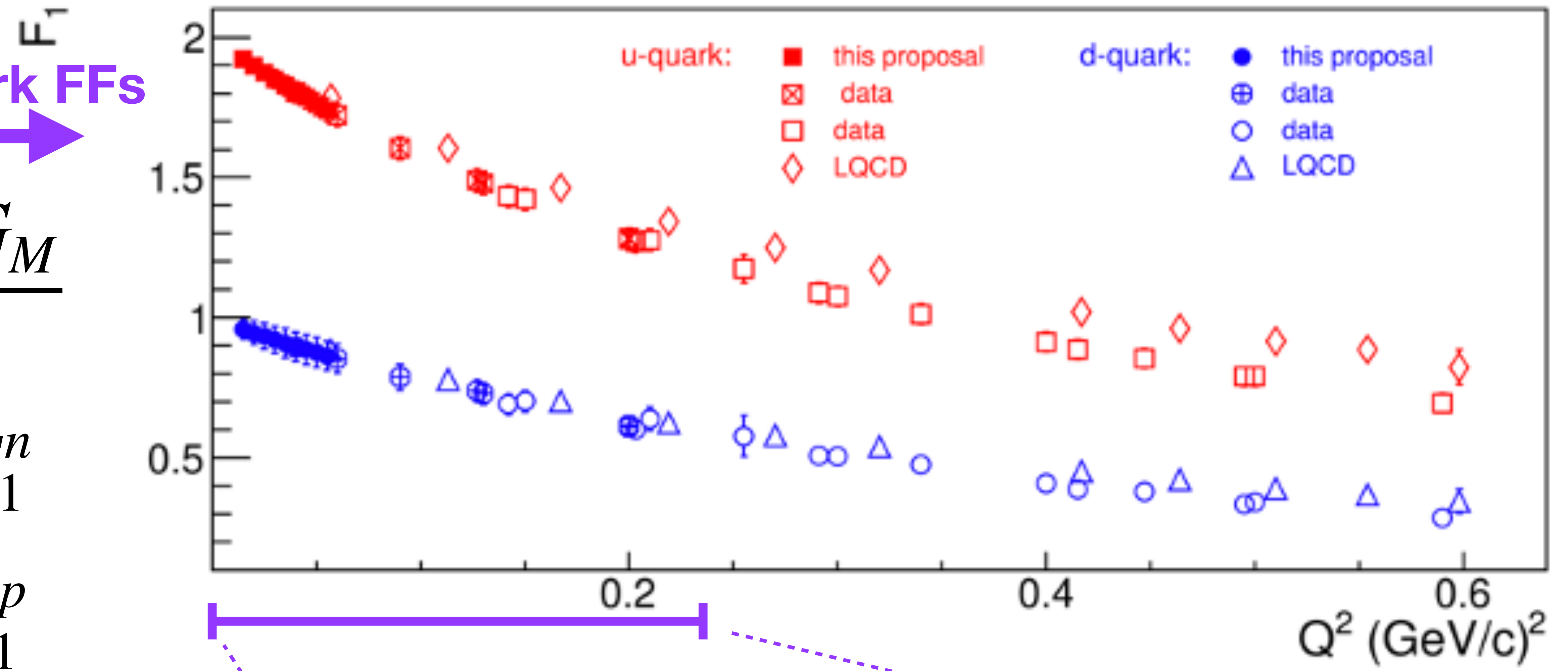
Determine G_n^E from N-Δ TFFs

Decompose quark FFs

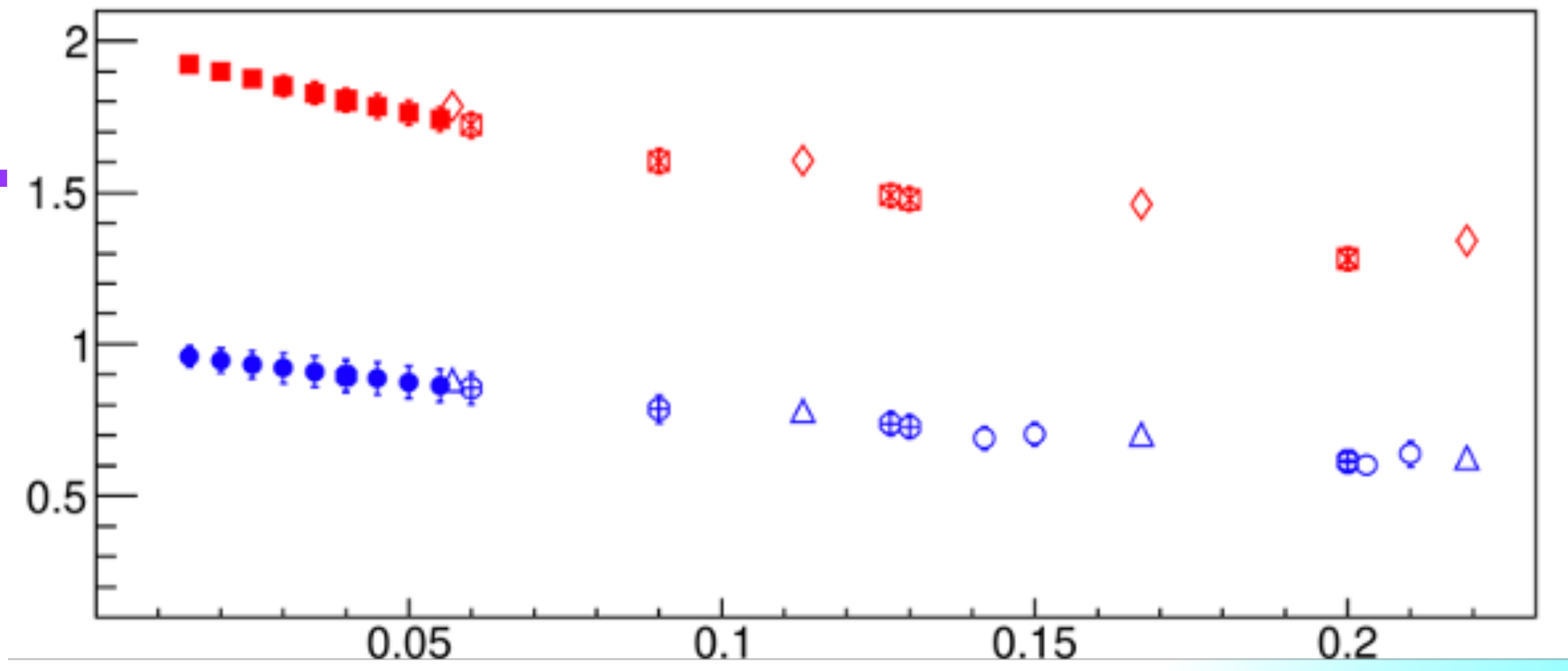
$$F_1 = \frac{G_E + \tau G_M}{1+\tau}$$

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

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



Determine transverse flavor radii



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

Recover nucleon radii

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

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

Summary

- **Proposed: A precise measurement (~3.7%) of the neutron charge radius.**
  - A very basic system property; sensitive to the internal structure & dynamics of the nucleon
  - Traditional method of extraction shows discrepancies which indicates unaccounted / underestimated systematics
    - PDG world data average value is elusive
    - Cross check with a different method ensures the honesty of the measurement and is a scientific obligation, whenever possible.
- **Measurement of the N-Δ TFFs in a mostly unmeasured region where the mesonic cloud dynamics is predicted to be dominant and rapidly changing**
  - Offers a test-bed for ChEFT and LQCD calculations
  - Can constrain systematics from 1/Nc and BChPT calculations
- **Resolve the long-standing neutron-electron scattering length discrepancies**
  - Important in setting constraints for the existence of new forces in nature
- **Direct extraction of the u- and d-quark distributions TMSR**
- **Request:**
  - 9.5 days
  - Beam energy: 1.3 GeV (flexible within +/- 0.1 GeV)
  - Hall C standard setup

Thank you!