Measurement of the N→Δ Transition Form Factors at low Q^2

A proposal for Jlab PAC50

H. Atac, A. Camsonne, M. Jones, M. Paolone, N. Sparveris

H. Atac(spokesperson), M. Cardona , S. Jia, R. Li, N. Sparveris (spokesperson)
Temple University, Philadelphia, PA 19122, USA
W. Armstrong, S. Joosten, J. Kim, Z.E. Meziani, C. Peng, J. Xie, M.Zurek
Argonne National Laboratory, Lemont, IL 60439, USA
A. Camsonne (spokesperson), J.-P. Chen, S. Covrig Dusa, M. Diefenthaler, D.W. Higinbotham M. K. Jones (spokesperson), D. Mack, D. Meekins, B. Sawatzky, G. Smith, A. Tadepalli
Thomas Jefferson National Accelerator Facility, Newport News, VA, USA
M. Paolone (spokesperson), M. Sievert
New Mexico State University, Las Cruces, NM, USA
M. Katramatou, G. Petratos
Kent State University, Kent, OH 44240, USA
W. Lin, R. Gilman, O. Yeung
Rutgers University, Piscataway, NJ 08855, USA
A. Christopher, T. Gautam, M. Kohl, N. Lashley-Colthirst, J. Nazeer, B. Pandey T. Patel, M. Rathnayake, M. Suresh, L. Tang
Hampton University, Hampton, Virginia 23668, USA
M. Mihovilovi, S. Širca
University of Ljubljana, Slovenia Jožef Stefan Institute, 1000 Ljubljana, Slovenia
N. Kalantarians
Virginia Union University, VA 23220, USA
P. Markowitz
Florida International University, FL USA
E. Brash
Christopher Newport University, VA 23606, USA
A. Puckett
University of Connecticut, CT 06269, USA
M. Nycz
University of Virginia, VA 22904, USA
B. Duran
University of Tennessee, Knoxville, USA
D. Androi
University of Zagreb, Zagreb, Croatia
M. Elaasar
Southern University at New Orleans, LA 70126, USA
S. Wood
Old Dominion University, VA 23529, USA
A. Mkrtchyan, H. Mkrtchyan, V. Tadevosyan
A.I. Alikhanyan National Science Laboratory, Yerevan Physics Institute, Armenia
G. Niculescu, I. Niculescu
James Madison University, VA 22807, USA
D. Byer, H. Gao, B. Karki, V. Khachatryan, G. Matousek, E. Nieuwenhuizen A. Smith, B. Yu, Z. Zhao, J. Zhou
Duke University and Triangle Universities Nuclear Laboratory, NC 27708, USA

Measurement of the $N \rightarrow \Delta$ Transition Form Factors at low Q^2 ,0.015 to 0.055 $(GeV/c)^2$

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Temple University, Philadelphia, PA 19122, USA
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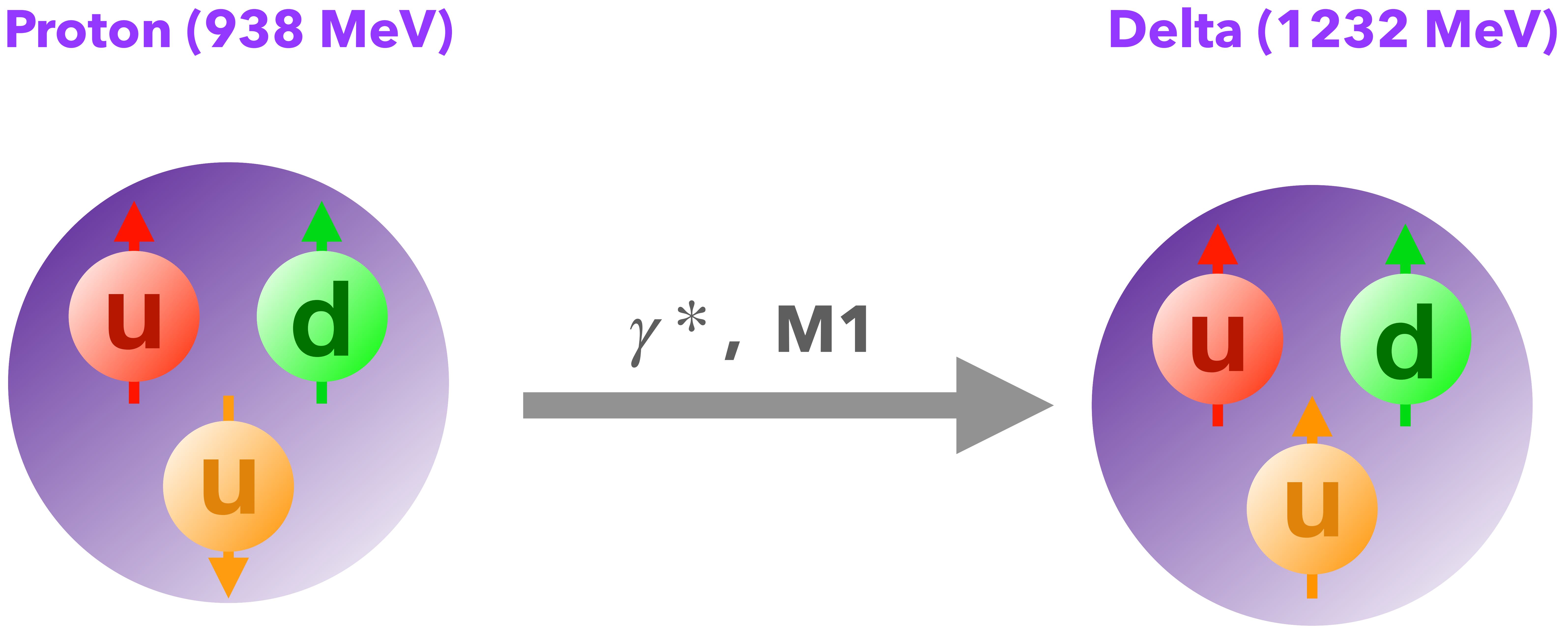
Measurement of the N→Δ Transition Form Factors at low Q^2

- **Follow-up to proposal PR12-21-001 submitted to PAC49:**
  - "The PAC regards the proposed measurements of p → Δ transition form factors at very small Q2 as very interesting. The PAC recommends to change the emphasis of the proposal and invites the proponents to submit a new proposal focusing on p → Δ transitions. This also should be reflected in the title. Such a proposal should emphasize the transition form factor measurements and the direct physics impact they will have."

- **Physics of interest:**
  - **The TFFs represent a central element of the nucleon dynamics and enhance the understanding of the baryon structure in QCD, extensions beyond hadronic physics.**

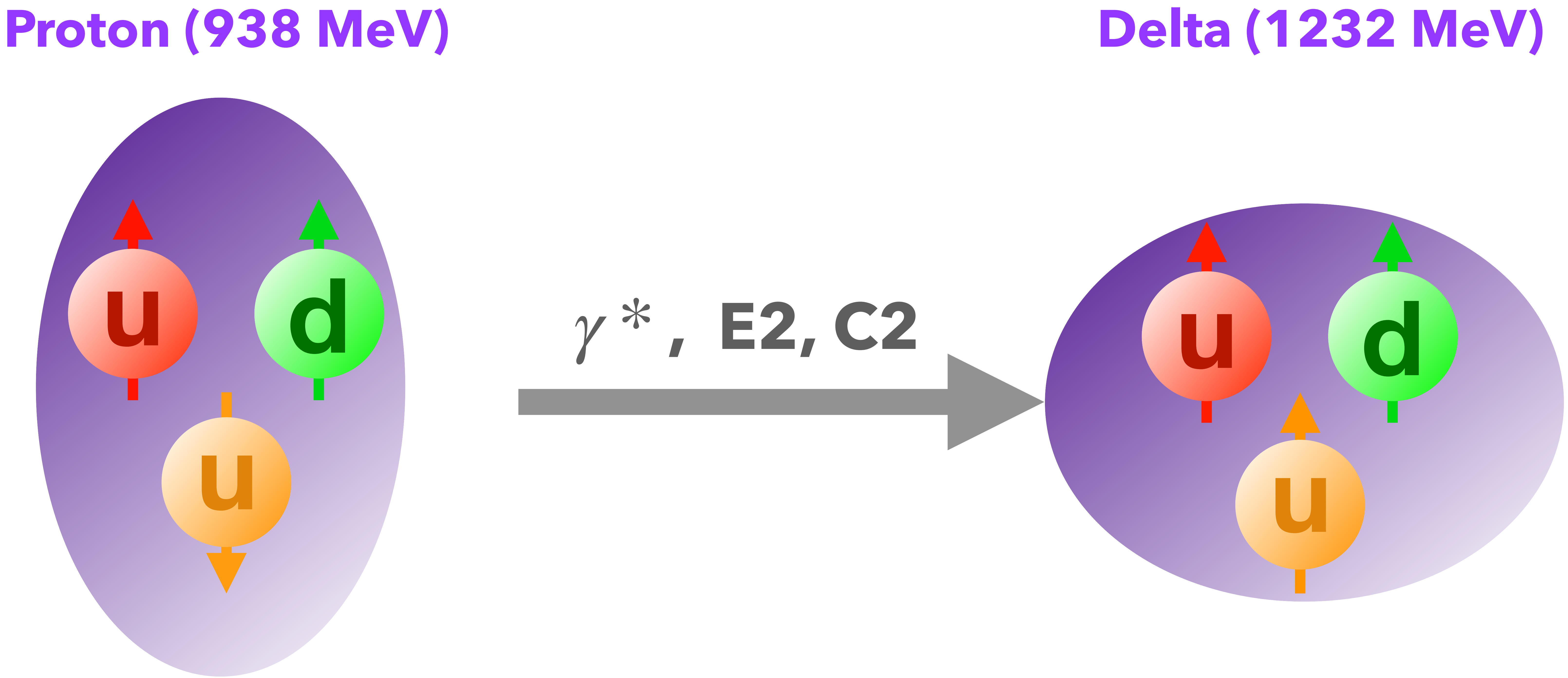
Extraction of the TFFs has been a central component of Jlab's experimental program!

The N-Δ transition



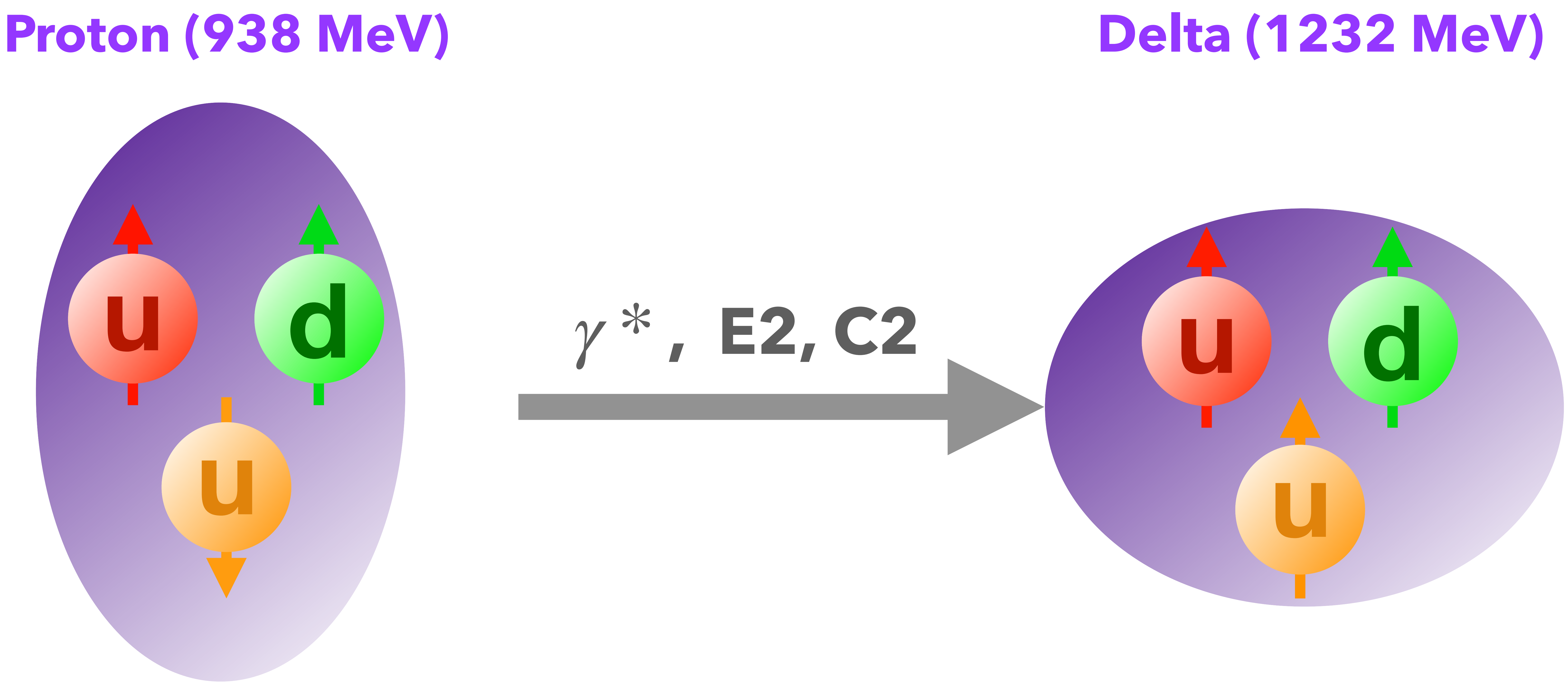
The dominant transition from proton to delta involves a dipole (M1) transition (spherical S-wave proton WF -> spherical S-wave Delta WF)

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



Proton (938 MeV)

Delta (1232 MeV)

γ^*, **E2, C2**

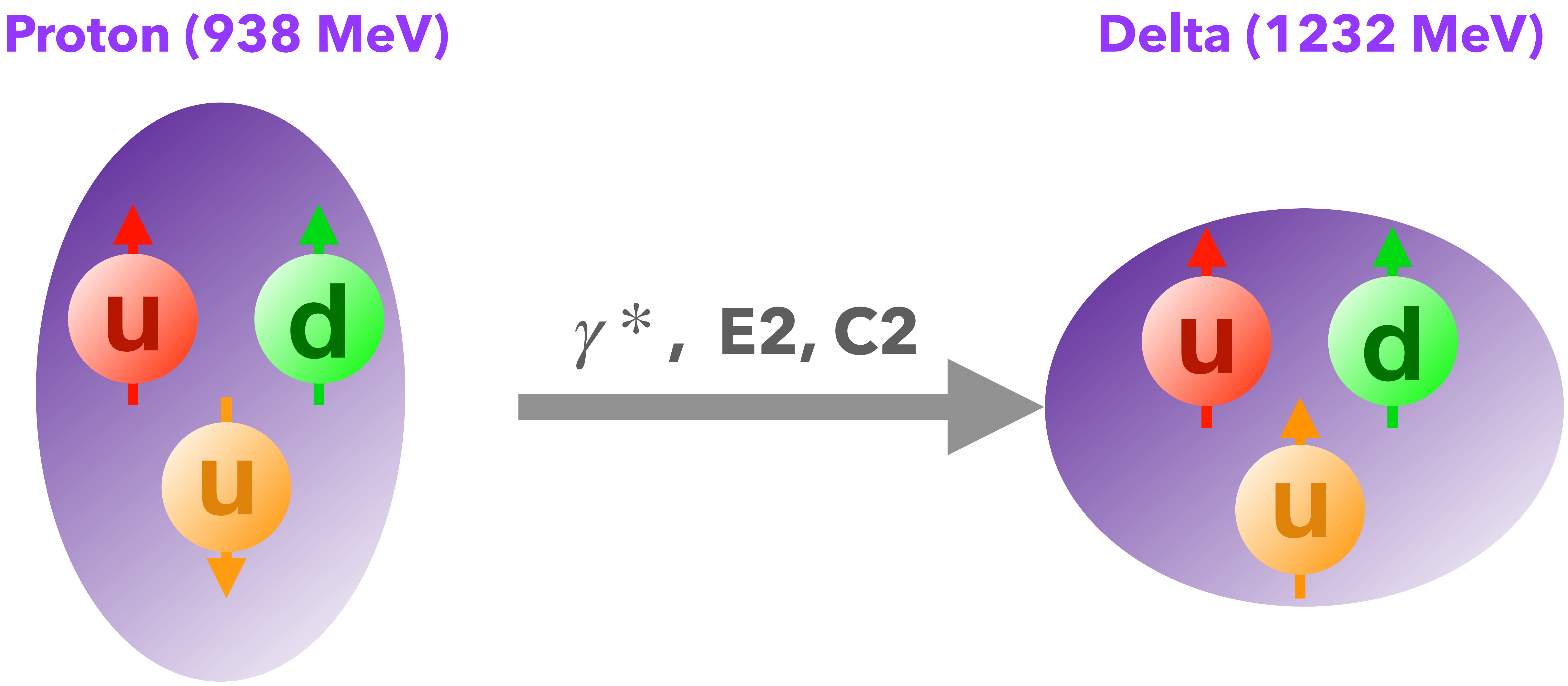
There also exists a quadrupole (E2 or C2) transition from proton to delta. (The quadrupole amplitudes are associated with the existence of non-spherical components in the proton and Delta WF)

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



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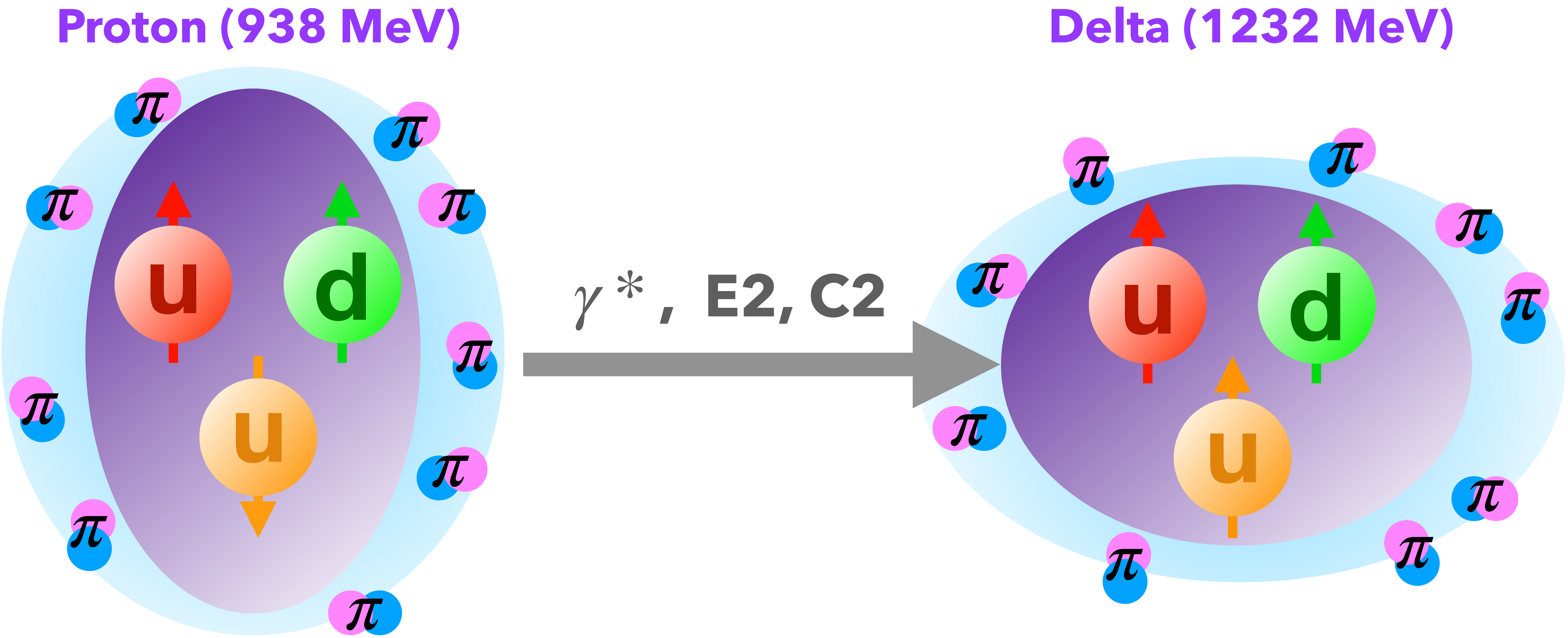
Non-central (tensor) interactions between quarks can account for some of the spherical deviation, but not all...

The N-Δ transition



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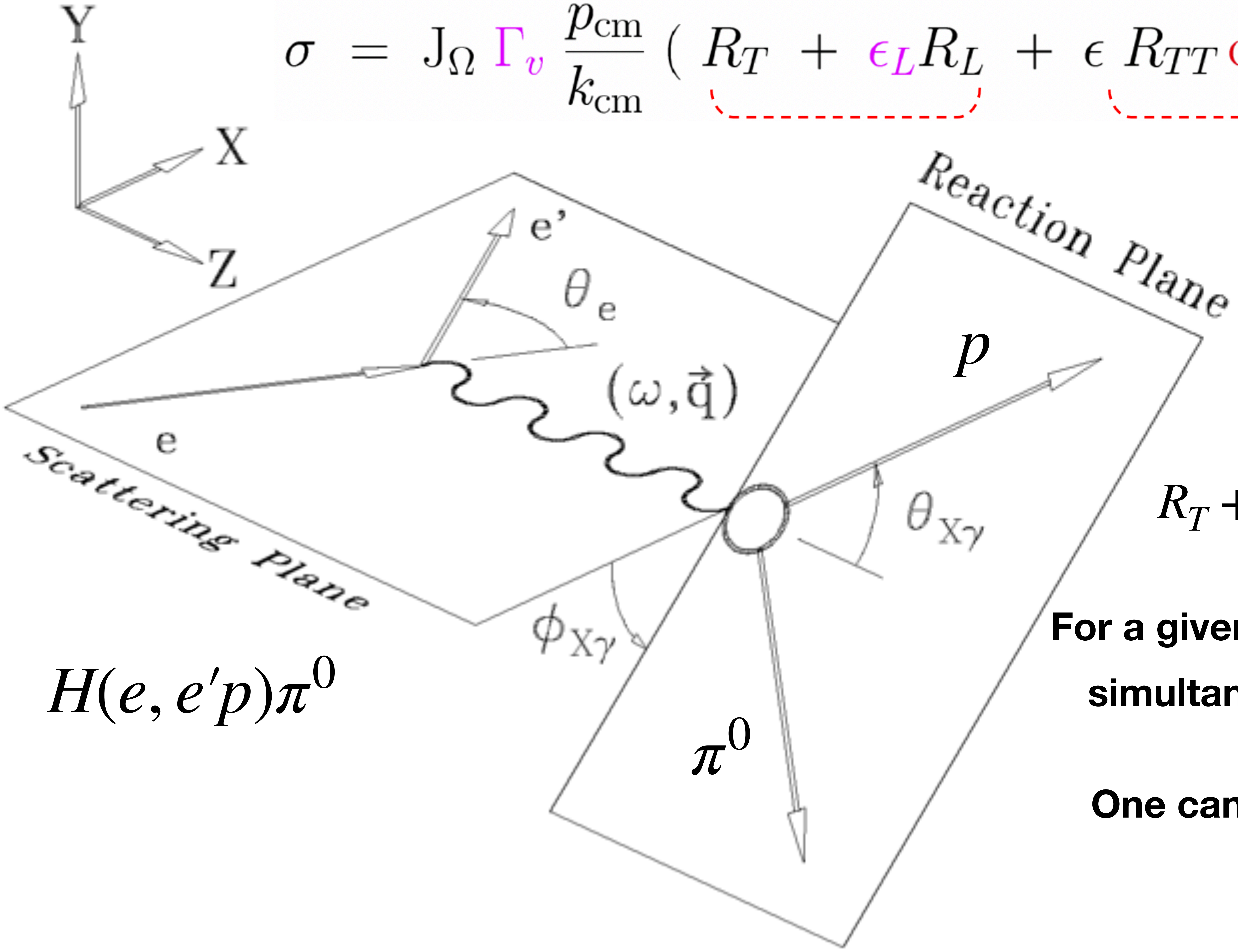
(The quadrupole amplitudes are associated with the existence of non-spherical components in the proton and Delta WF)

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.

Experimental Methodology

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



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

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

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

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

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

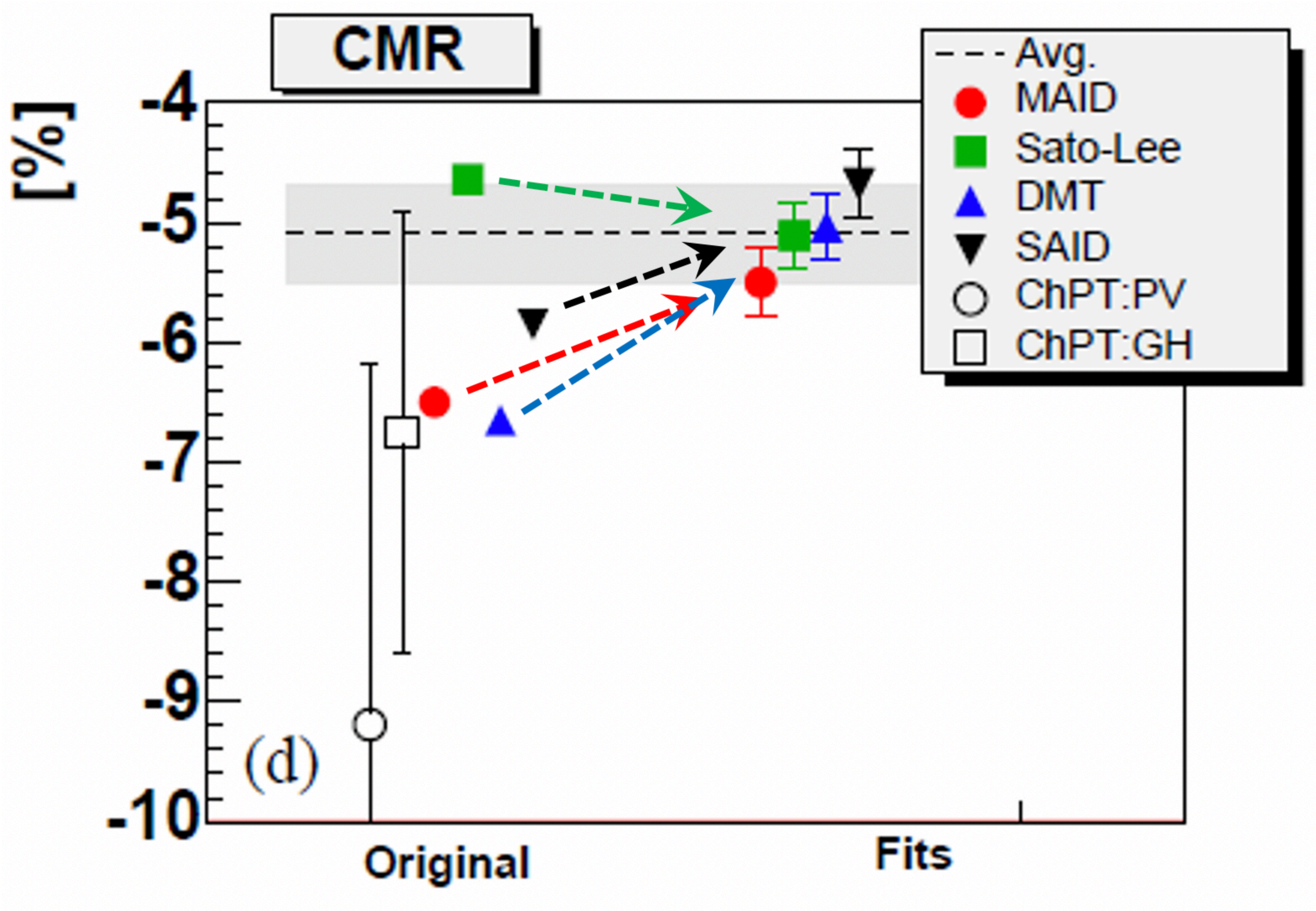
$$R_T + R_L = M1^2 + \ldots\Sigma_{\text{background}}$$

R_{TT} → **sensitive to the EMR**

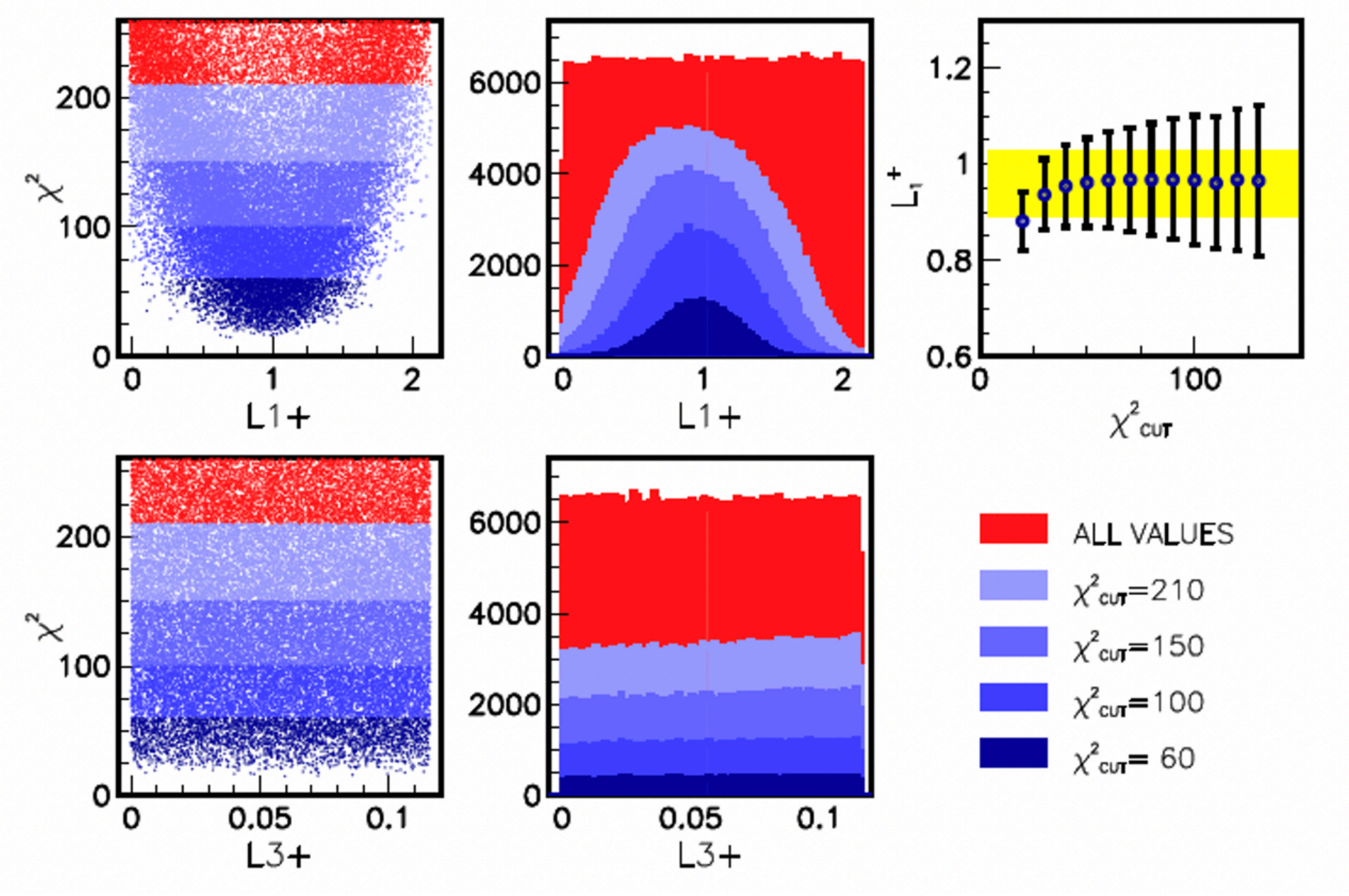
R_{LT} → **sensitive to the CMR**

$R_T + R_L$ → **sensitive to $M1$**

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



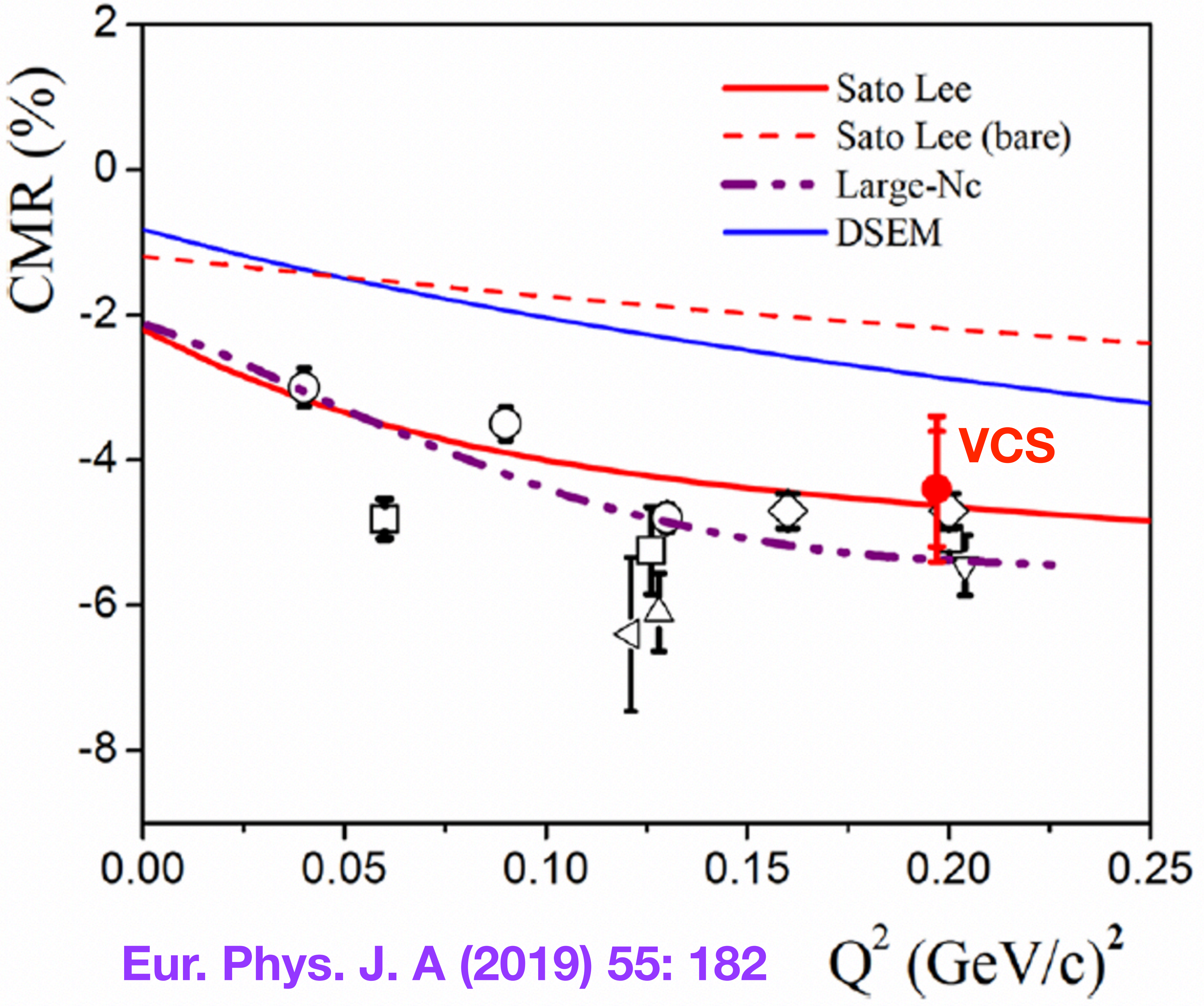
Use model independent statistical methods to identify and determine with maximal precision parameters that are sensitive to the data: AMIAS (Eur. Phys. J. A 56 (2020) 10, 270)



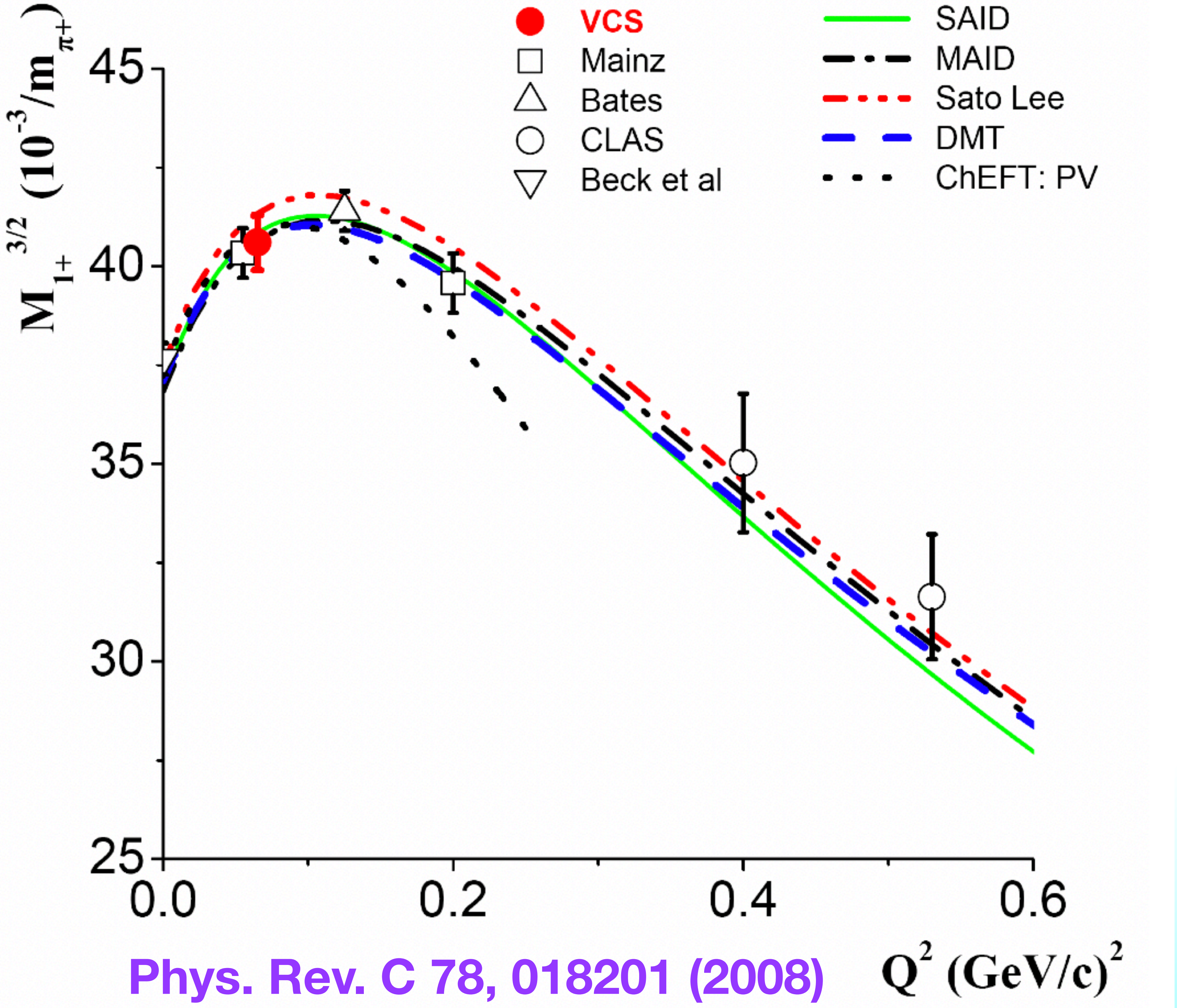
Cross-checks on Extraction Methods: VCS

$\Delta^+ \to N\pi$ ~ 99% **H(e,e'p)π^0 , H(e,e'π^+)n**
$\Delta^+ \to p\gamma$ < 1% **VCS: H(e,e' p)γ**

The excitation process is the same, but the backgrounds are very different:
Stringent test of the theoretical framework & control of theoretical model uncertainties



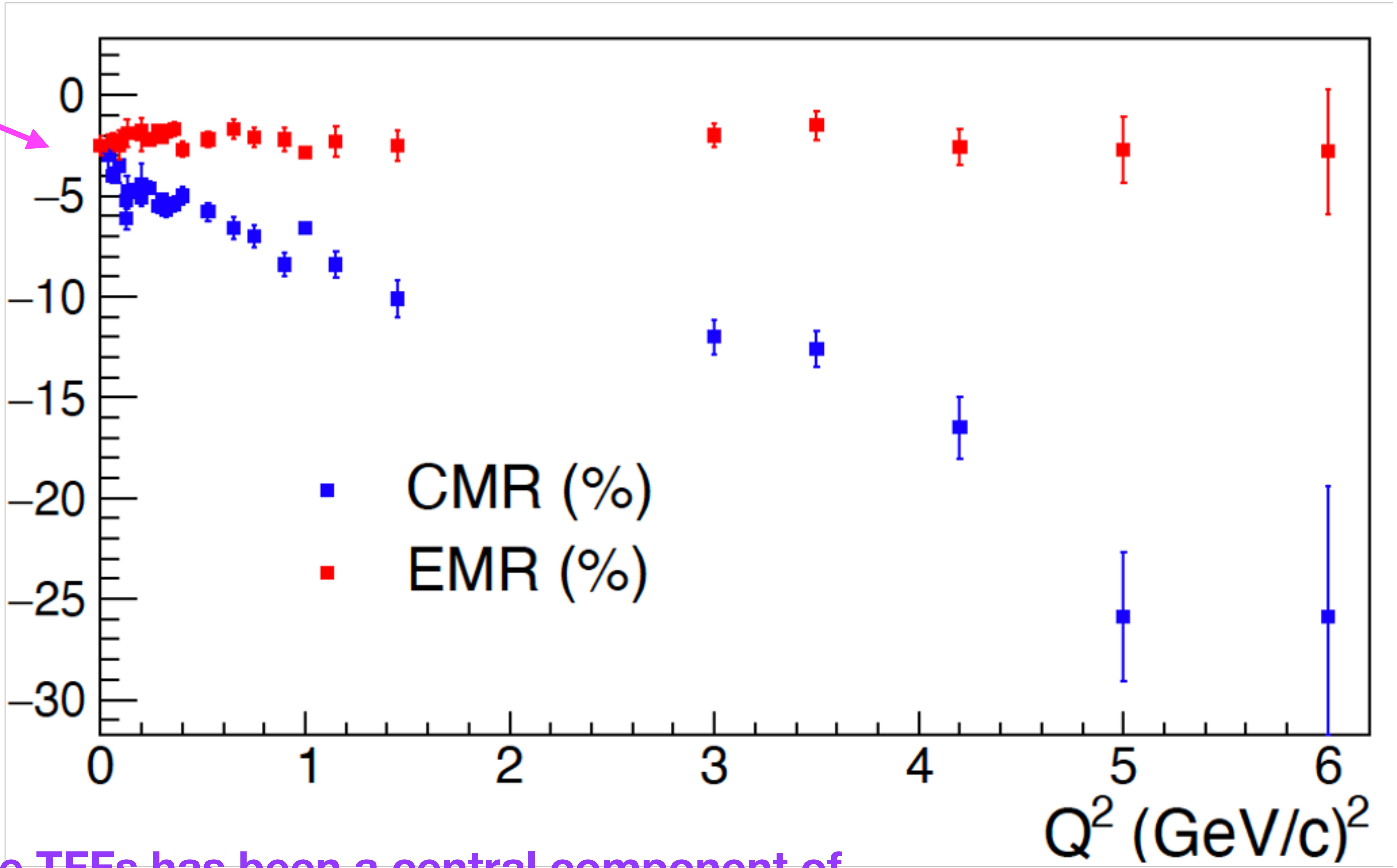
Eur. Phys. J. A (2019) 55: 182



Phys. Rev. C 78, 018201 (2008)

World data and status of TFFs

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

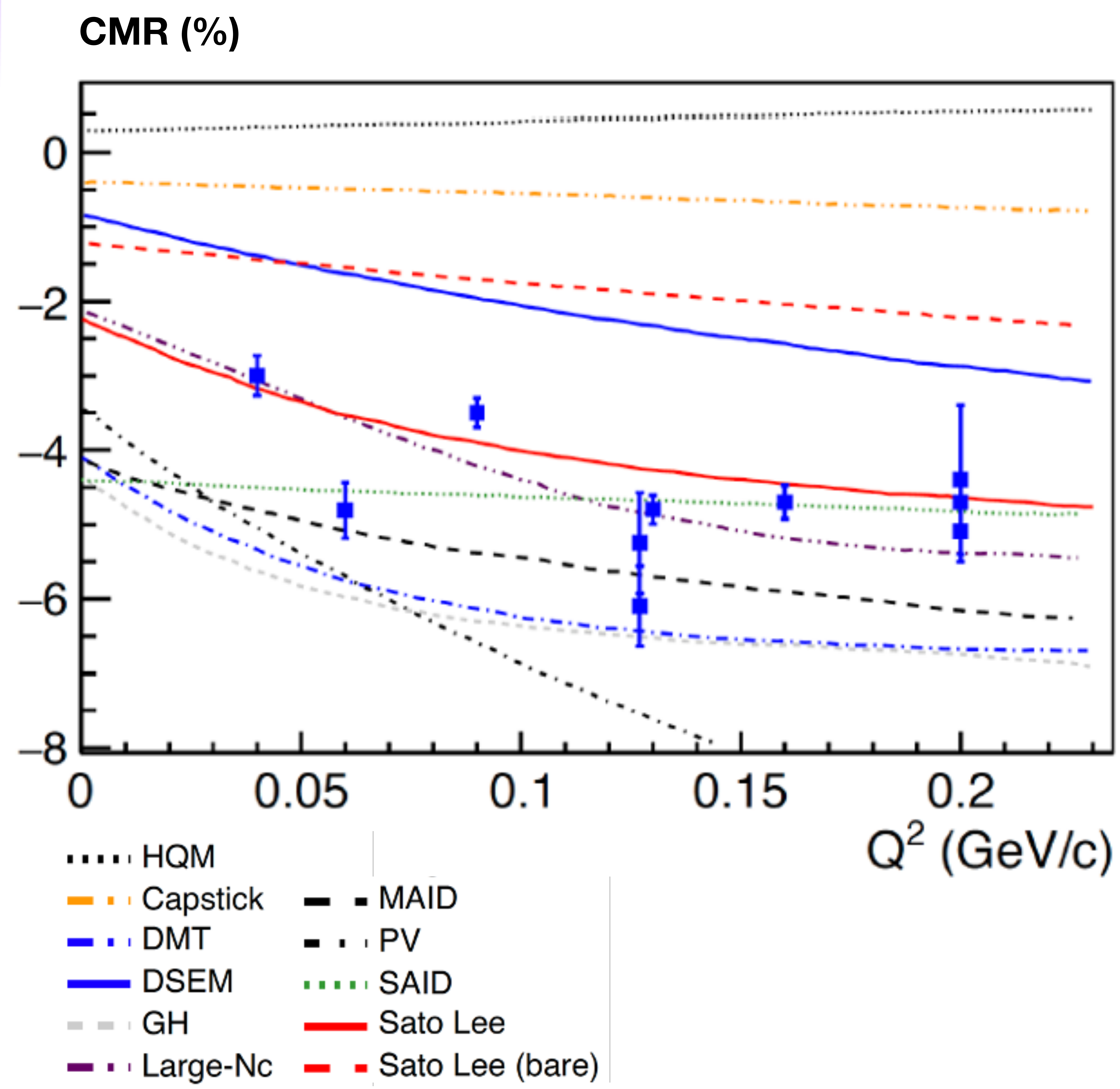


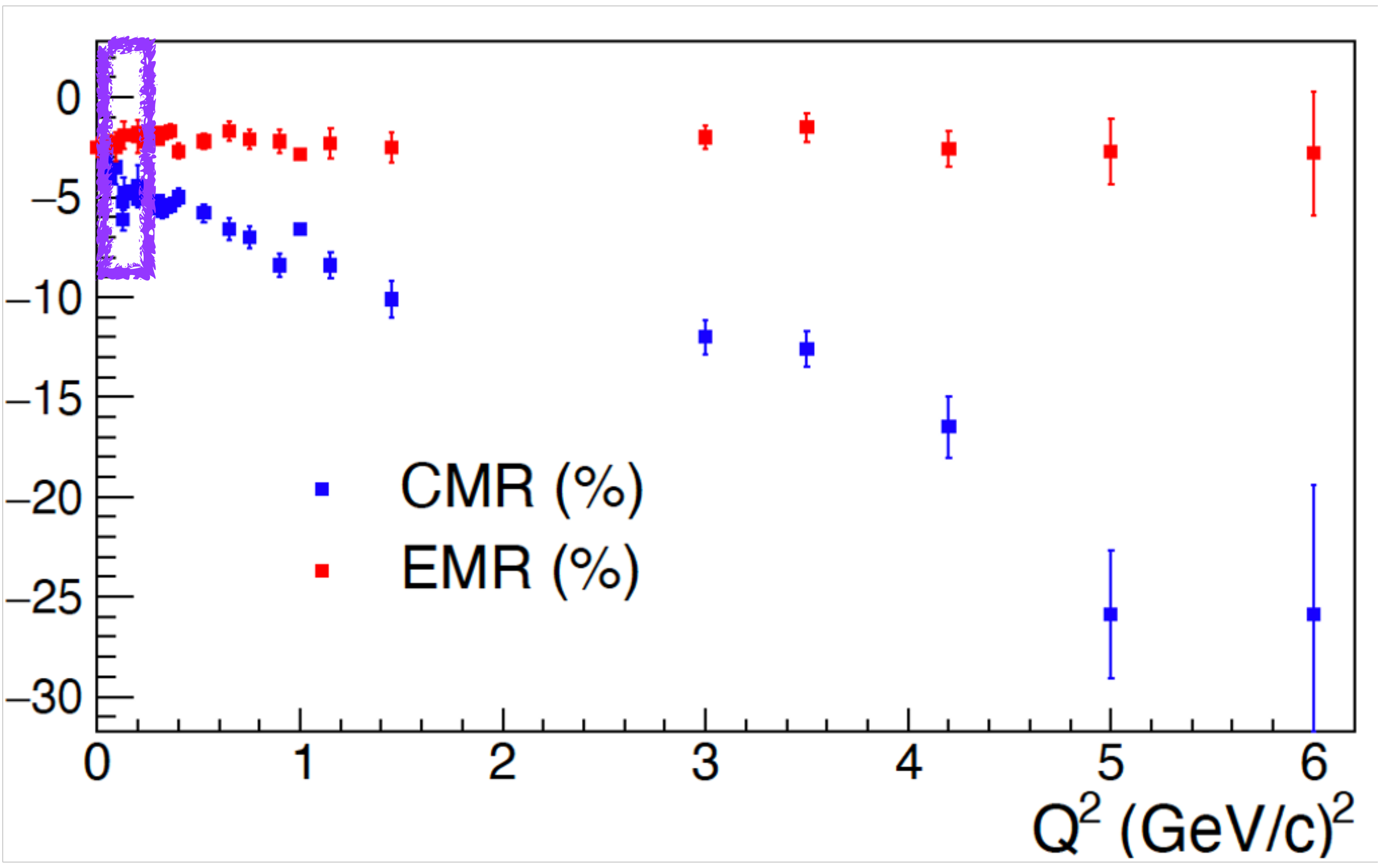
At large Q^2, no direct indication of EMR → 100% and CMR → constant (predicted in pQCD regime)

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)

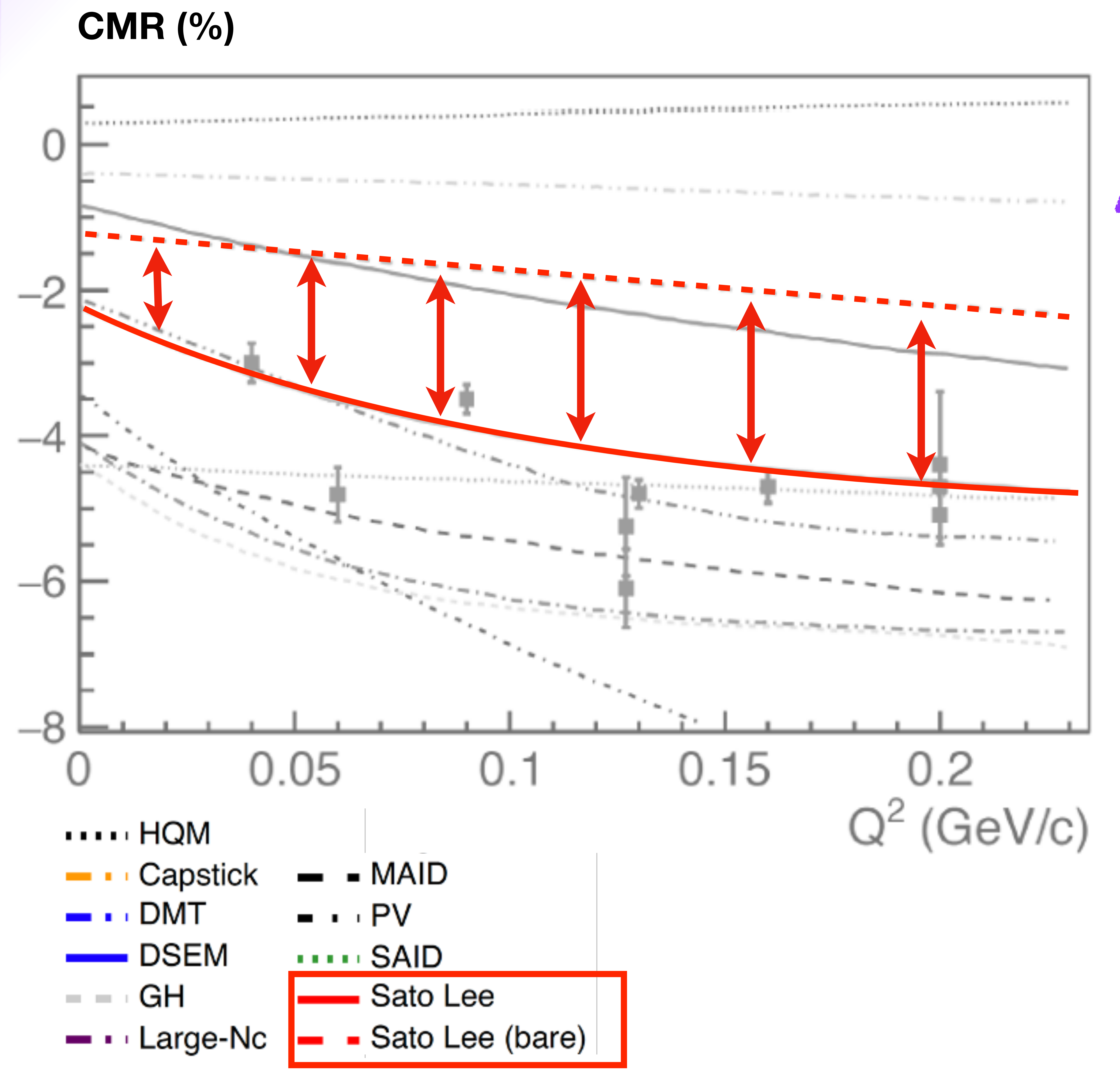
Low Q^2 N-Δ transition form factors

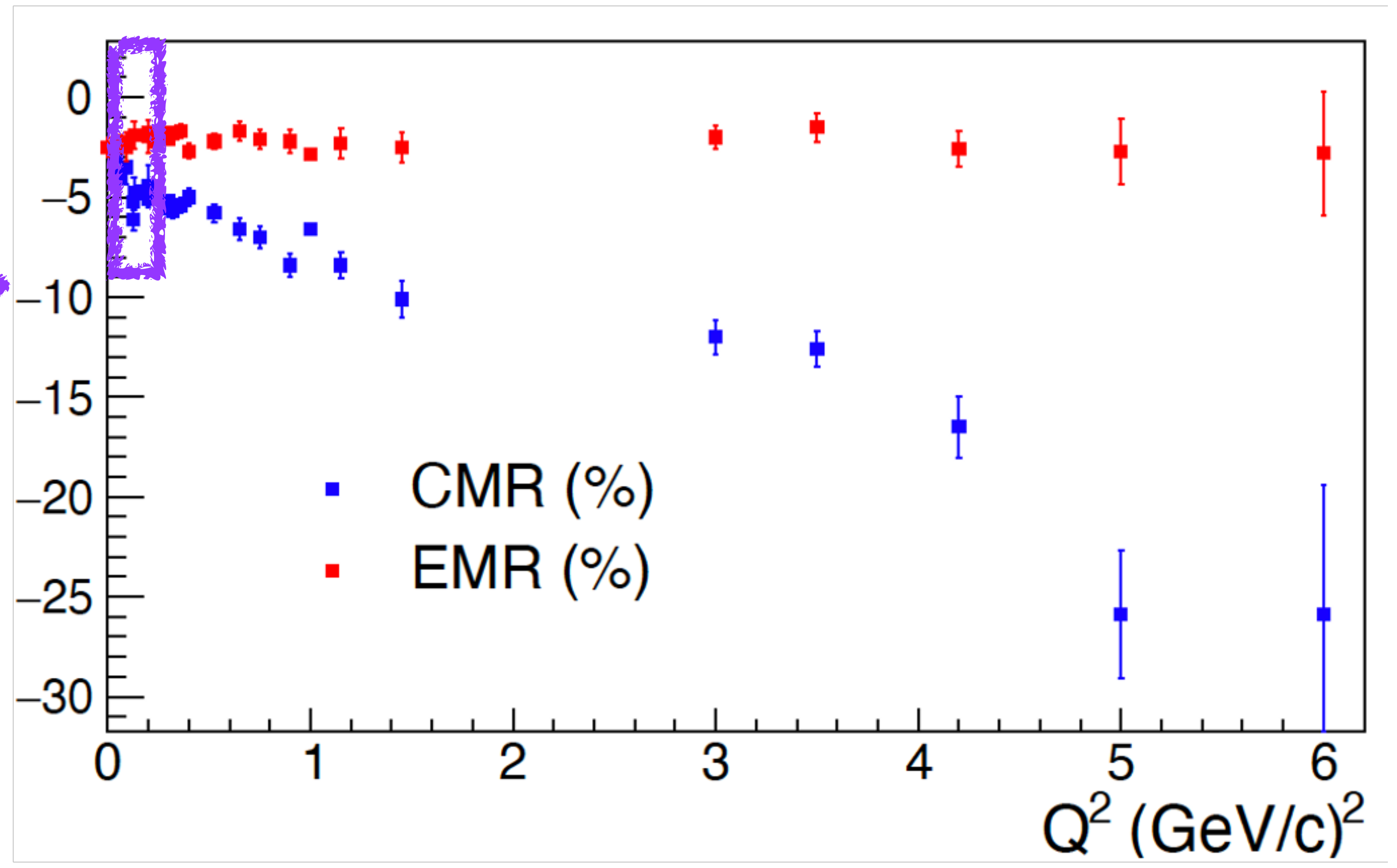




- **Low Q^2 landscape is an important region to measure:**
  - Mesonic cloud effects are predicted to be:
    - dominant in explaining the magnitude of the TFFs
    - changing most rapidly over all Q^2
  - Provides an excellent test bed for ChEFT and LQCD calculations
  - Relates the excitation mechanism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

Low Q² N-Δ transition form factors





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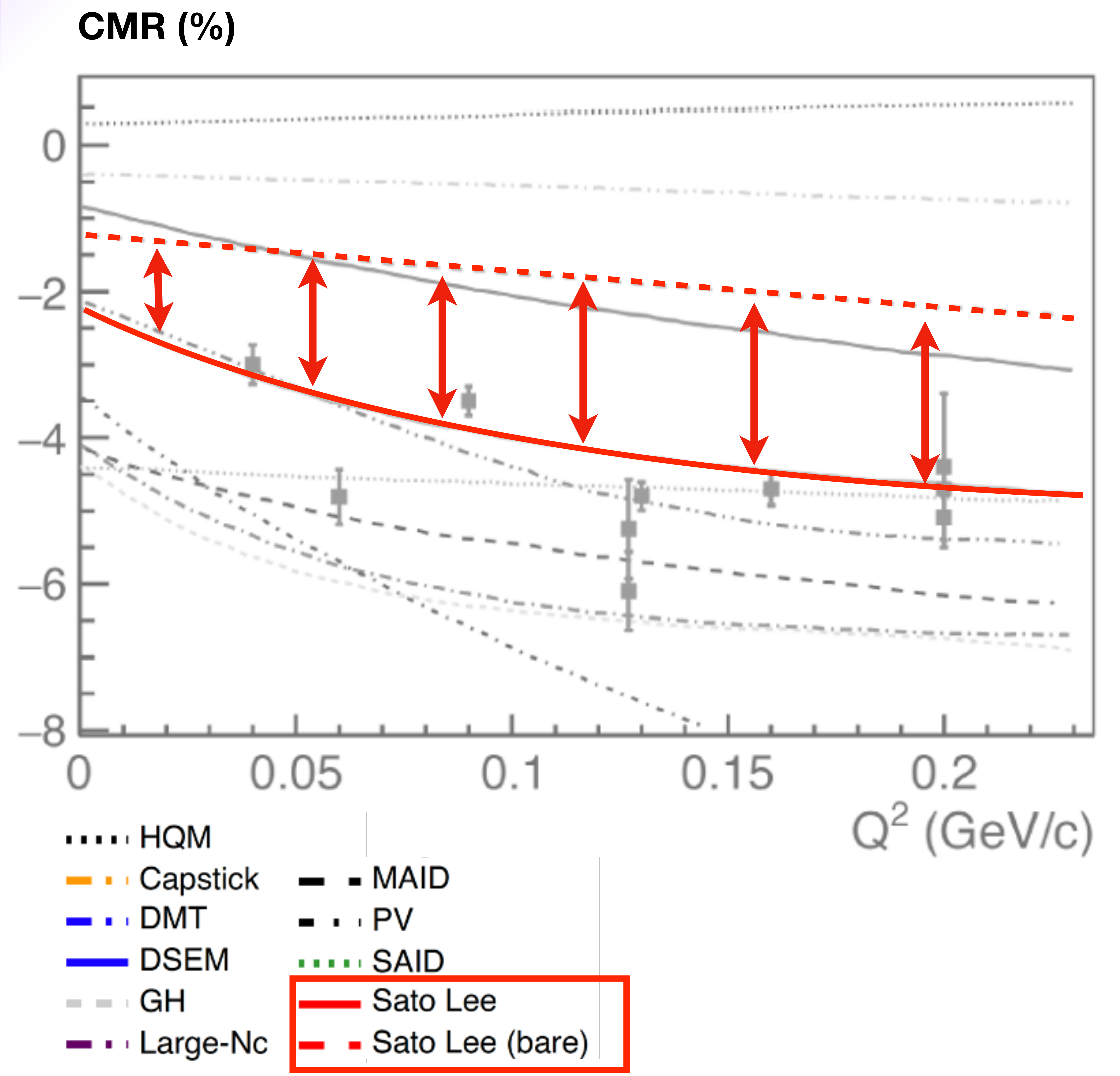
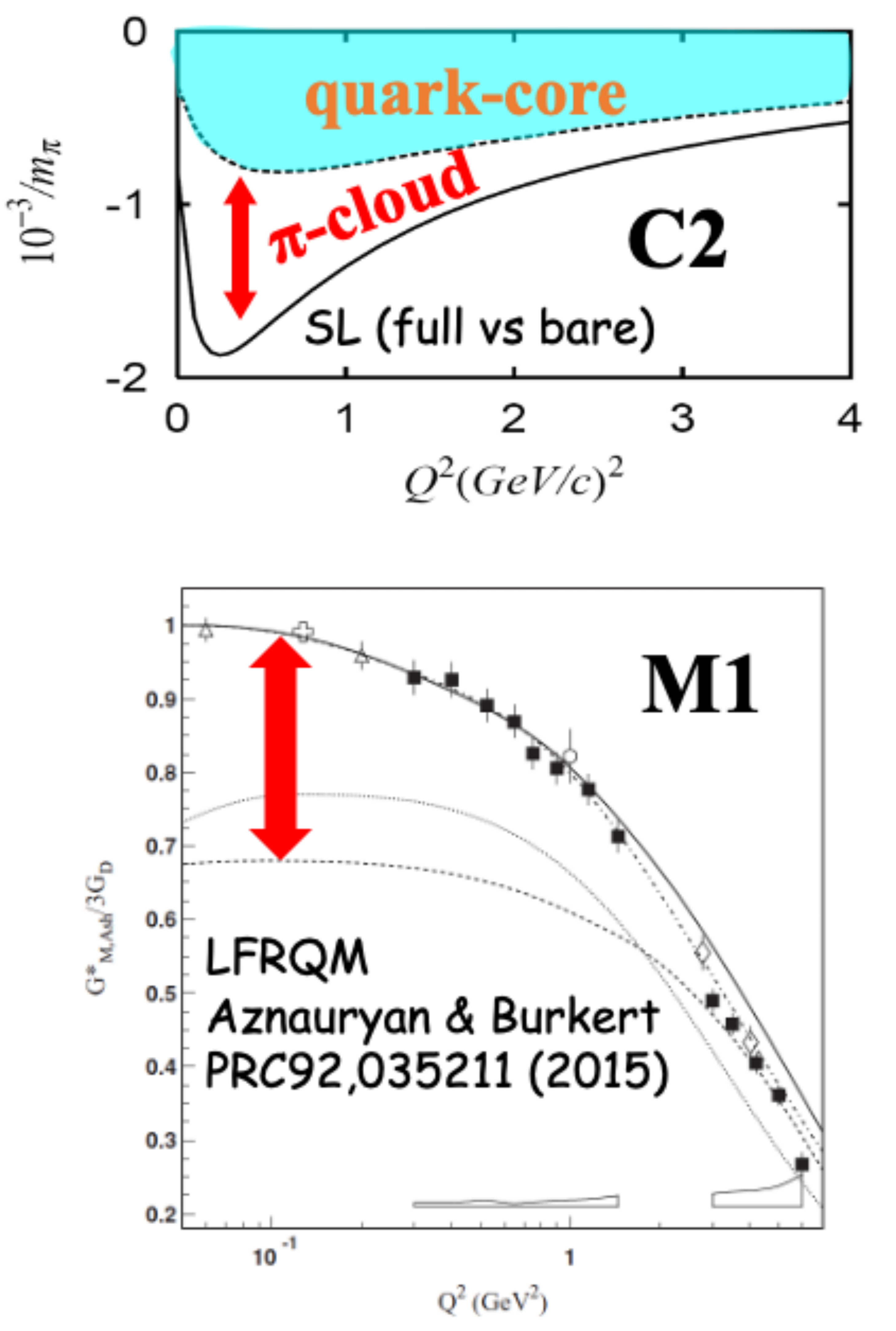


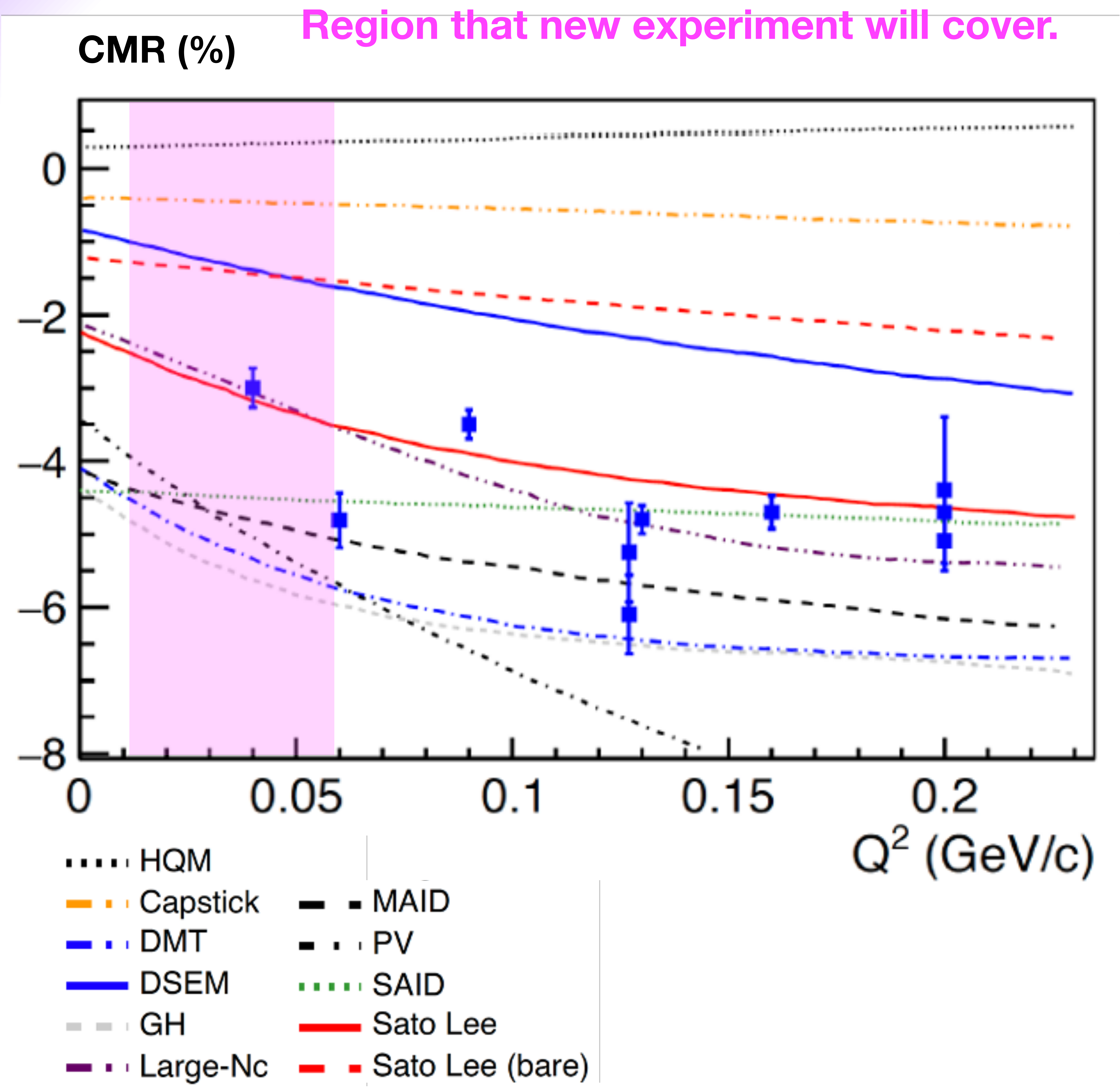


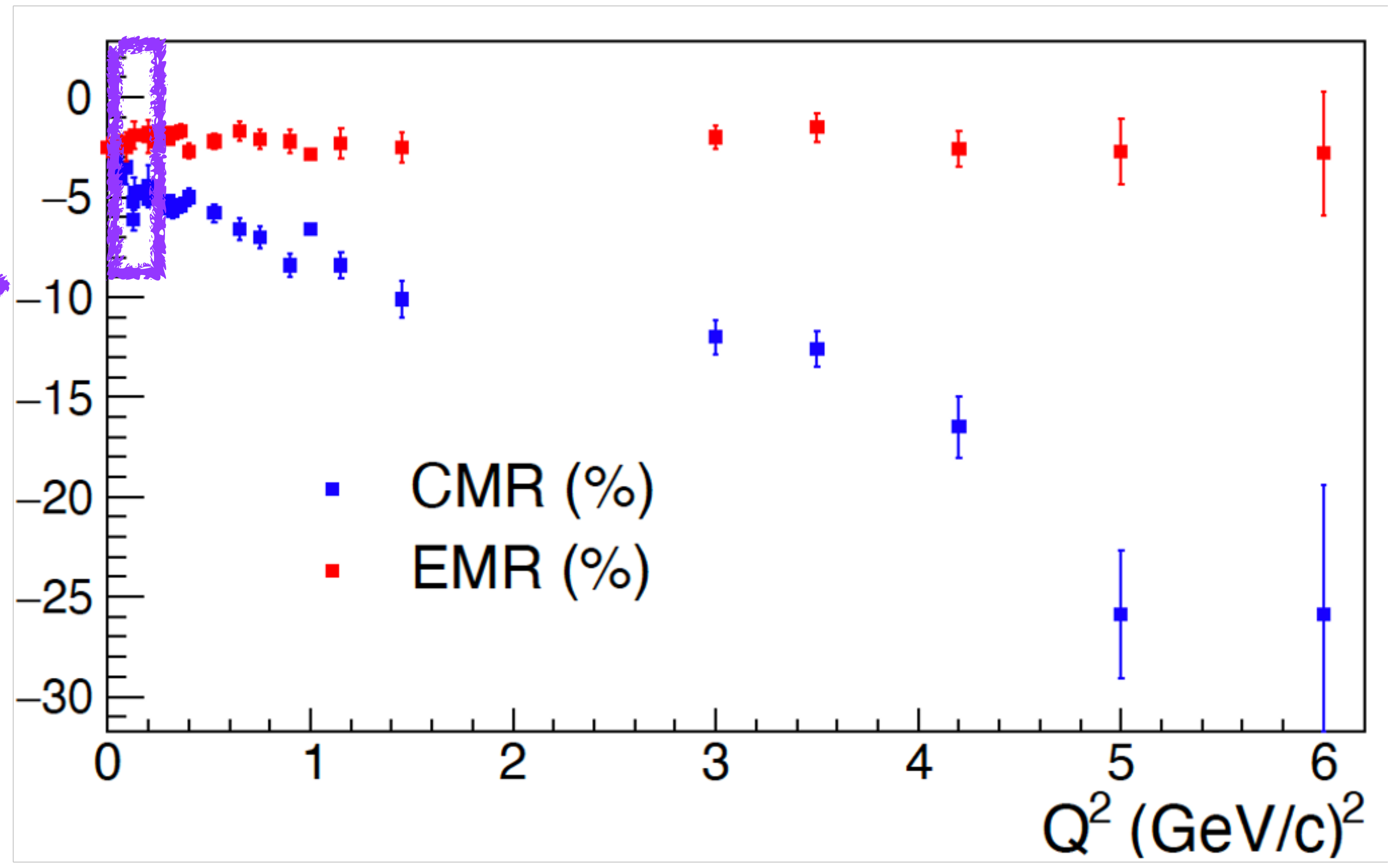
Signature of pion cloud

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 Q^2 N-Δ transition form factors


Region that new experiment will cover.



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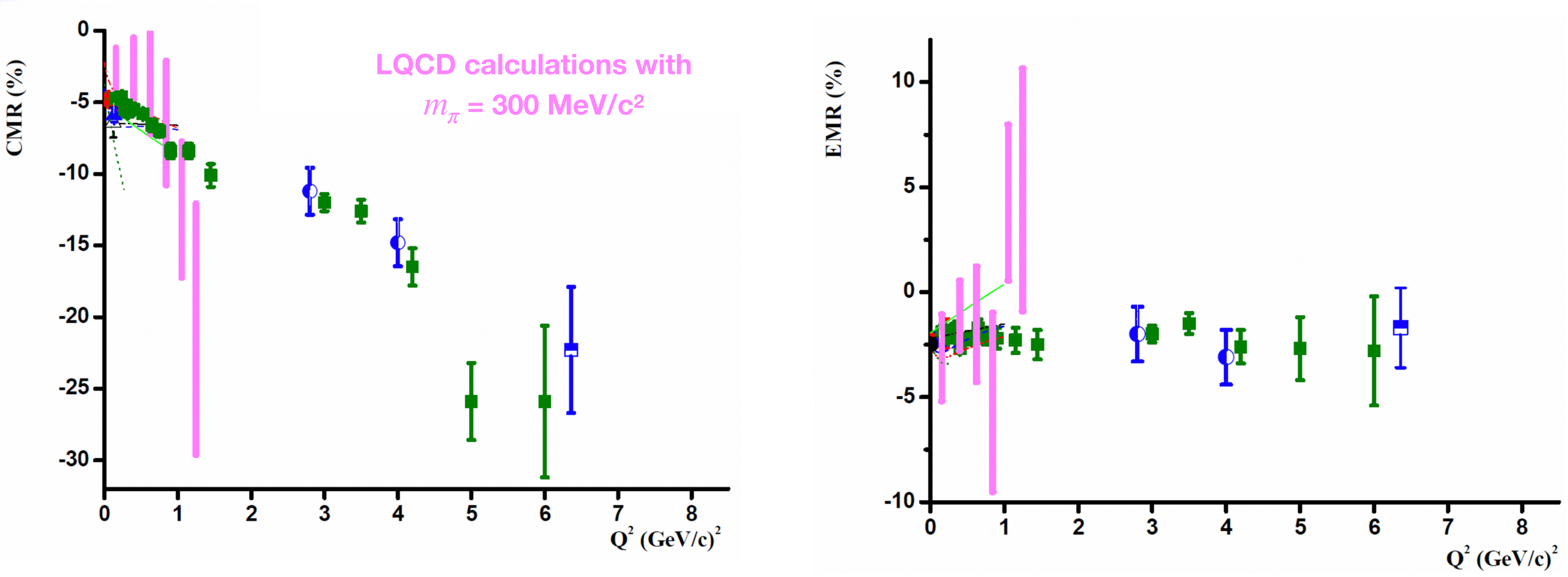
  - Sparsely measured region.

Lattice Calculations



- Updated LQCD calculations are in progress → new calculations will have a physical pion mass and uncertainties comparable to experiment.
  - Extended Twisted mass collaboration results expected within 2 years.
  - Efforts are partly motivated to understand baryon structure for neutrino scattering.
- Low Q^2 data will provide a precision benchmark for LQCD calculations.

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)

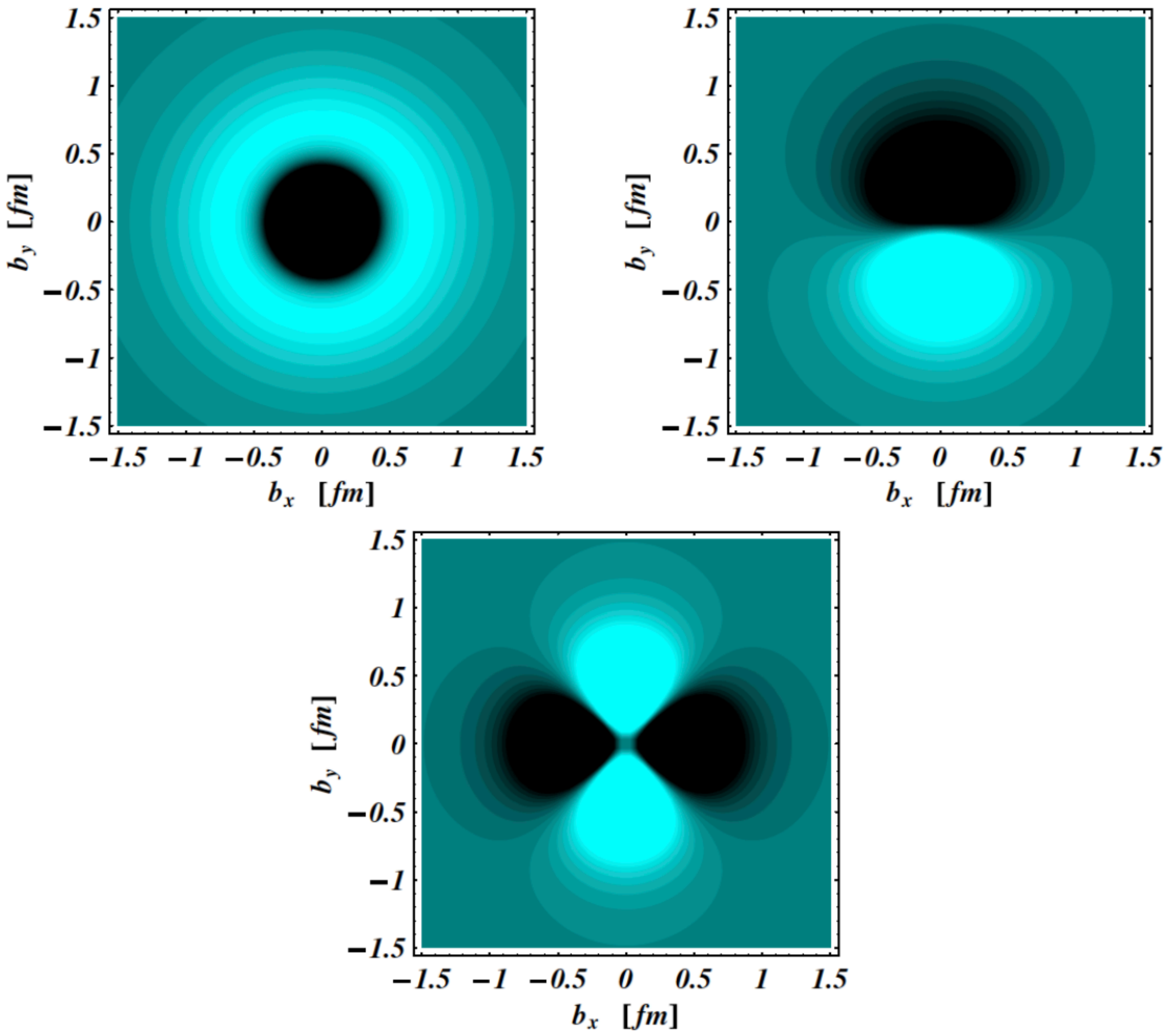


Fig. 18. Quark transverse charge density corresponding to the $p \to \Delta(1232)P_{33}$ e.m. transition. Upper left panel: p and Δ are in a light-front helicity +1/2 state ($\rho_0^{pP_{33}}$). Upper right panel: p and Δ are polarized along the x-axis ($\rho_T^{pP_{33}}$) as in Fig. 14. The lower panel 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)

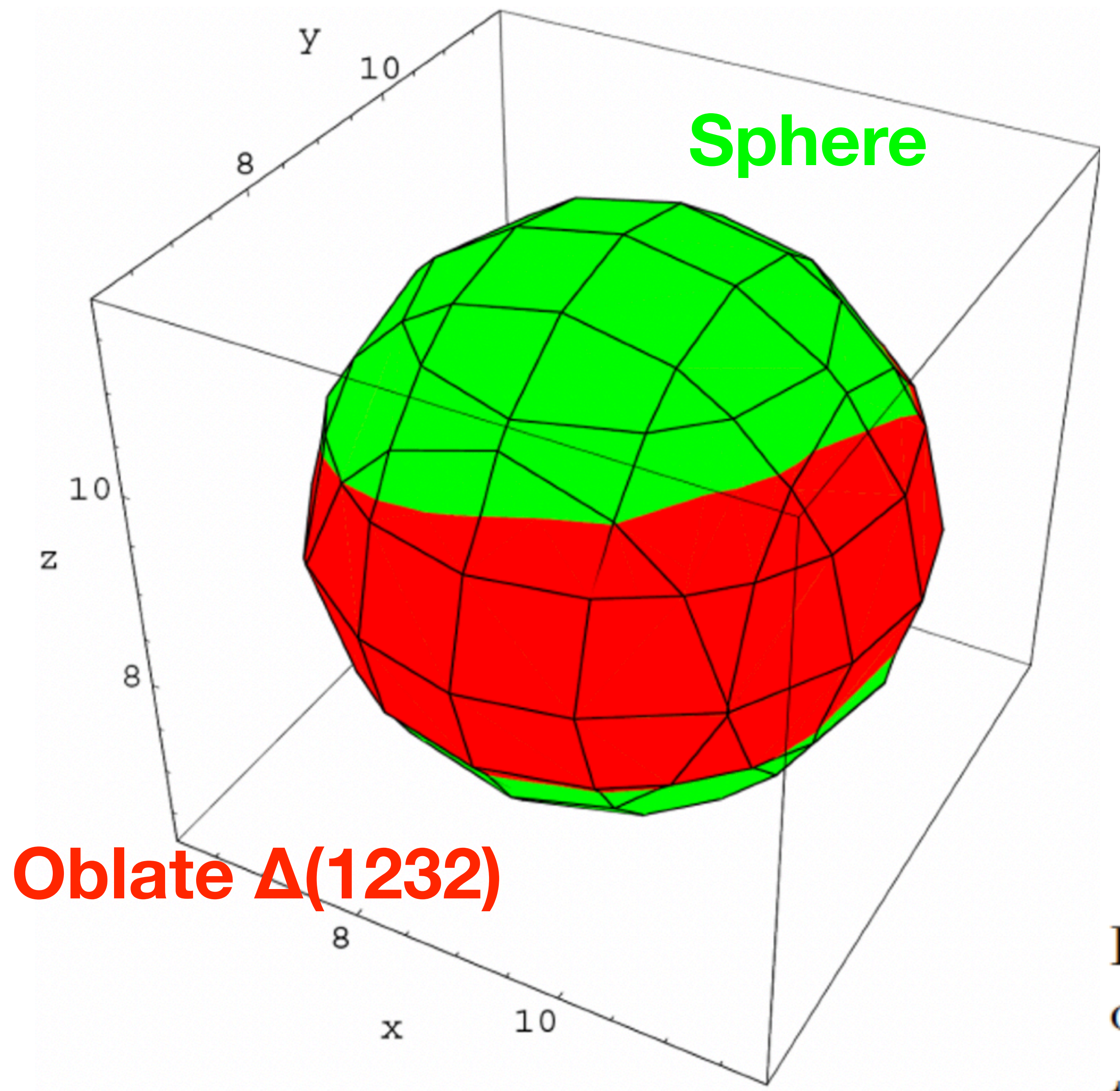


FIG. 18. Three-dimensional contour plot of the correlator (black): upper for the rho state with 0 spin projection (cigar shape) and lower for the Δ^+ state with +3/2 (slightly oblate) spin projection for two dynamical quarks at $\kappa = 0.156$. Values of the correlator (0.5 for the rho, 0.8 for the 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)

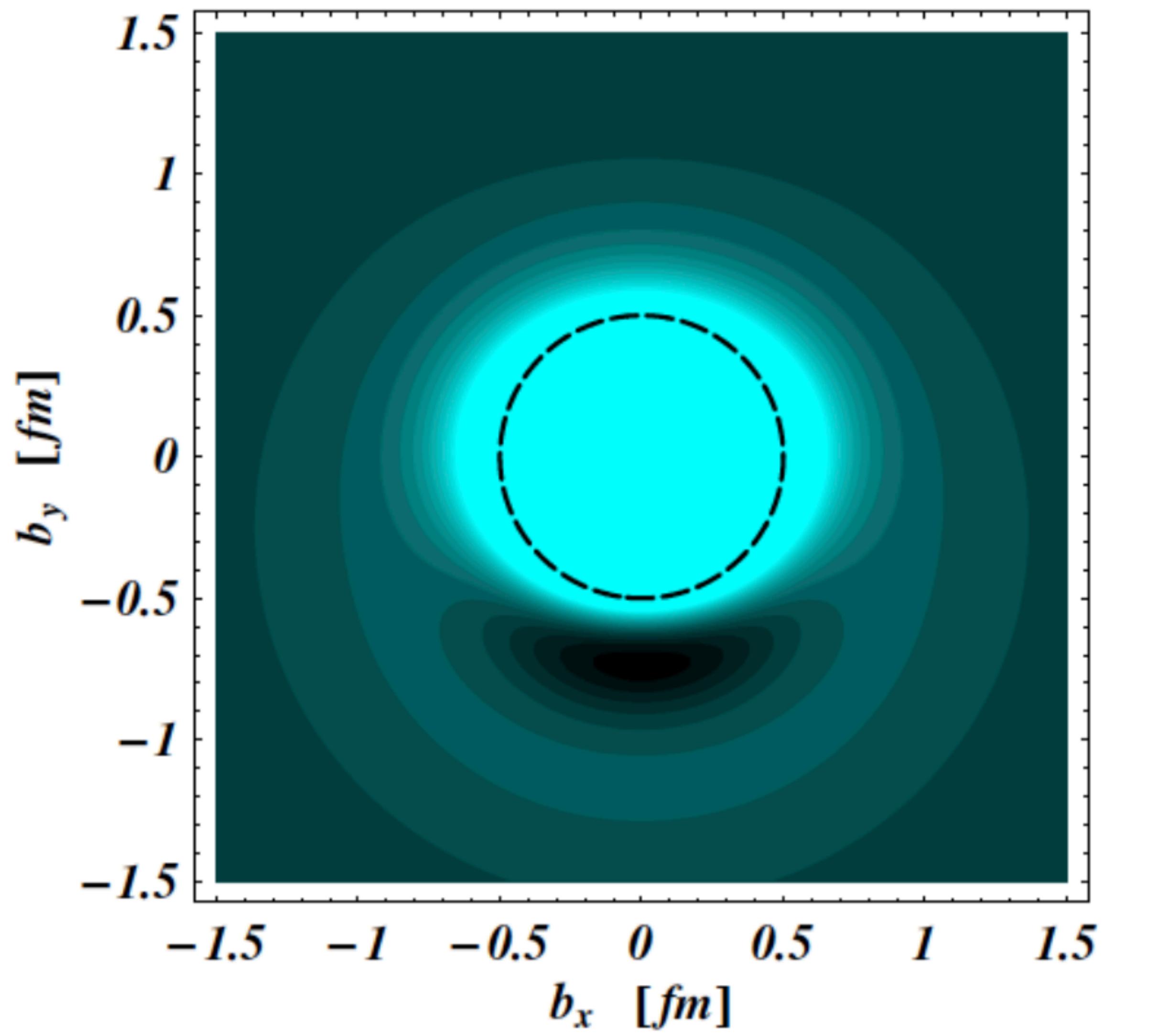
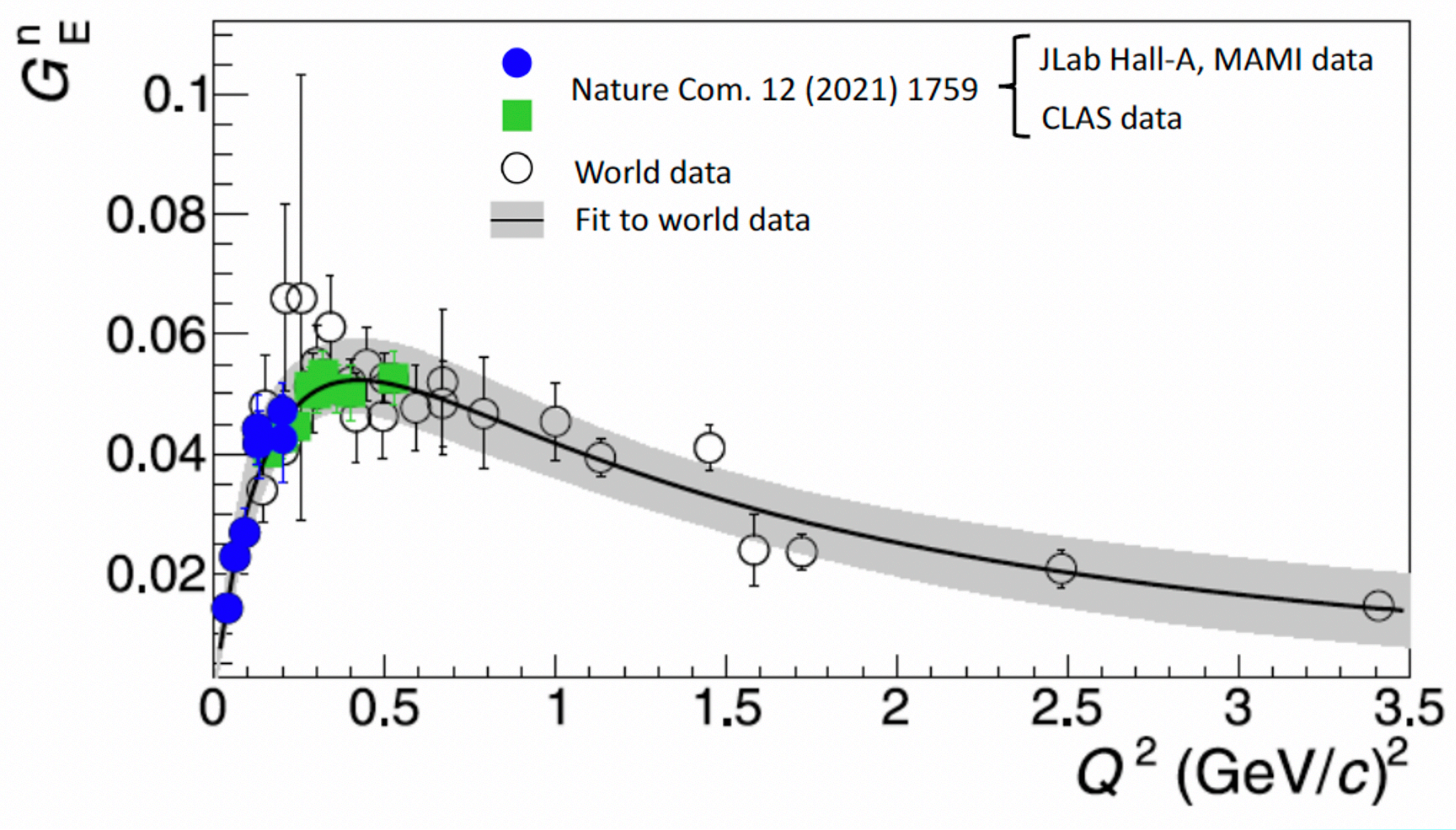


FIG. 10: Lattice QCD results for the quark transverse charge density $\rho^{\Delta}_{T\,\frac{3}{2}}$ in a $\Delta^+(1232)$ which is polarized along the positive x-axis. The light (dark) regions correspond to the largest (smallest) values of the density. In order to see the deformation more clearly, 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].

Connections to the neutron structure

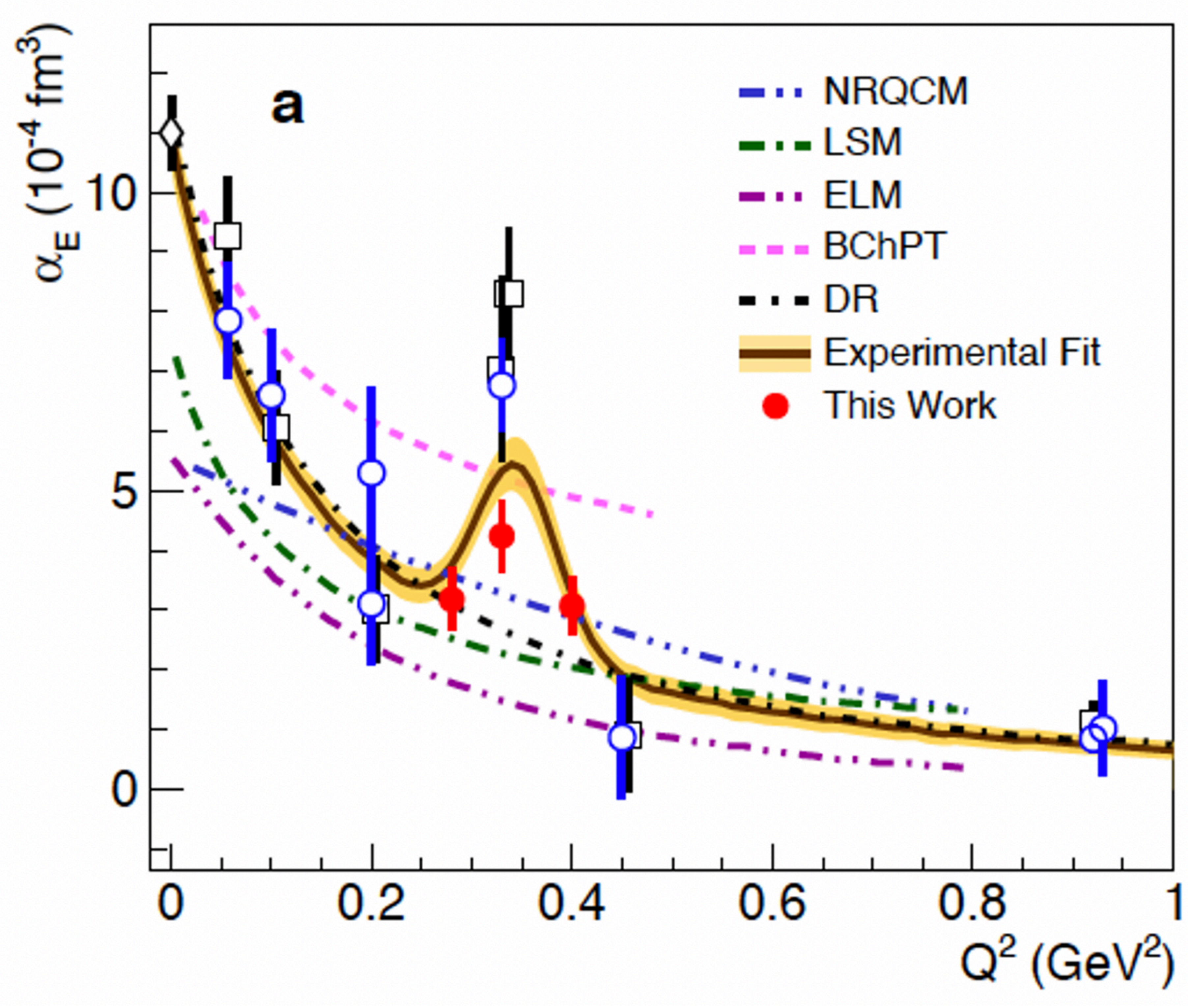
- There are long-known relations between the TFFs and the neutron FFs.
  - Pascalutsa, V. & Vanderhaeghen, M. : Phys. Rev. D 76 (2007) [Large-Nc]
  - Grabmayr, P. & Buchmann, A. J. : Phys. Rev. Lett. 86 (2001)   [CQM + 2-body currents]

- G_E^n extraction from TFFs show strong agreement with world data.
  - Allows access to low-Q² region where direct measurement of G_E^n is difficult.
  - The relations receive theoretical corrections that can be analyzed and confronted with experimental data e.g. they can be analyzed in a theoretical framework that combines ChPT with the 1/Nc expansion.

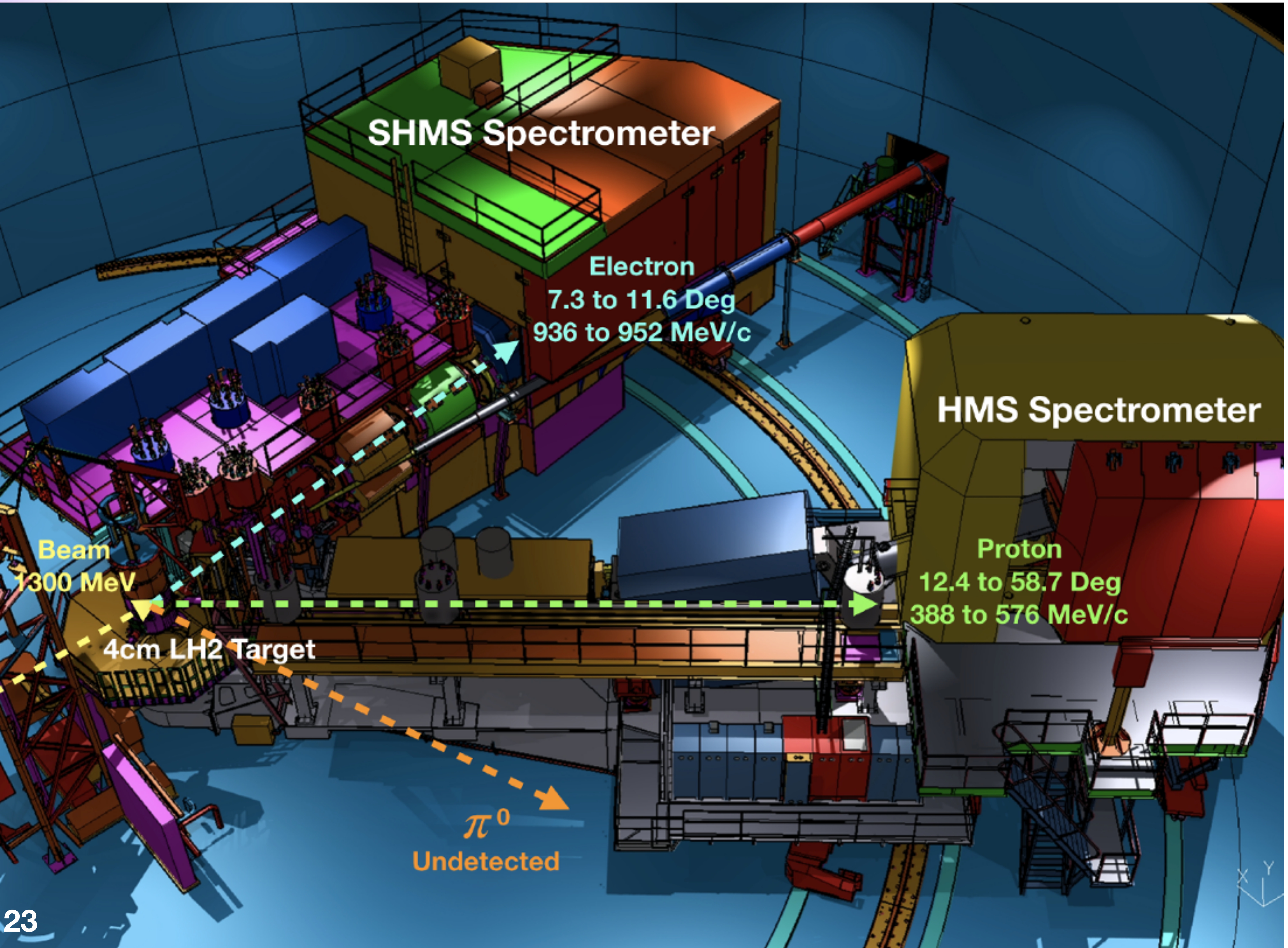


Impact on other domains of nuclear physics

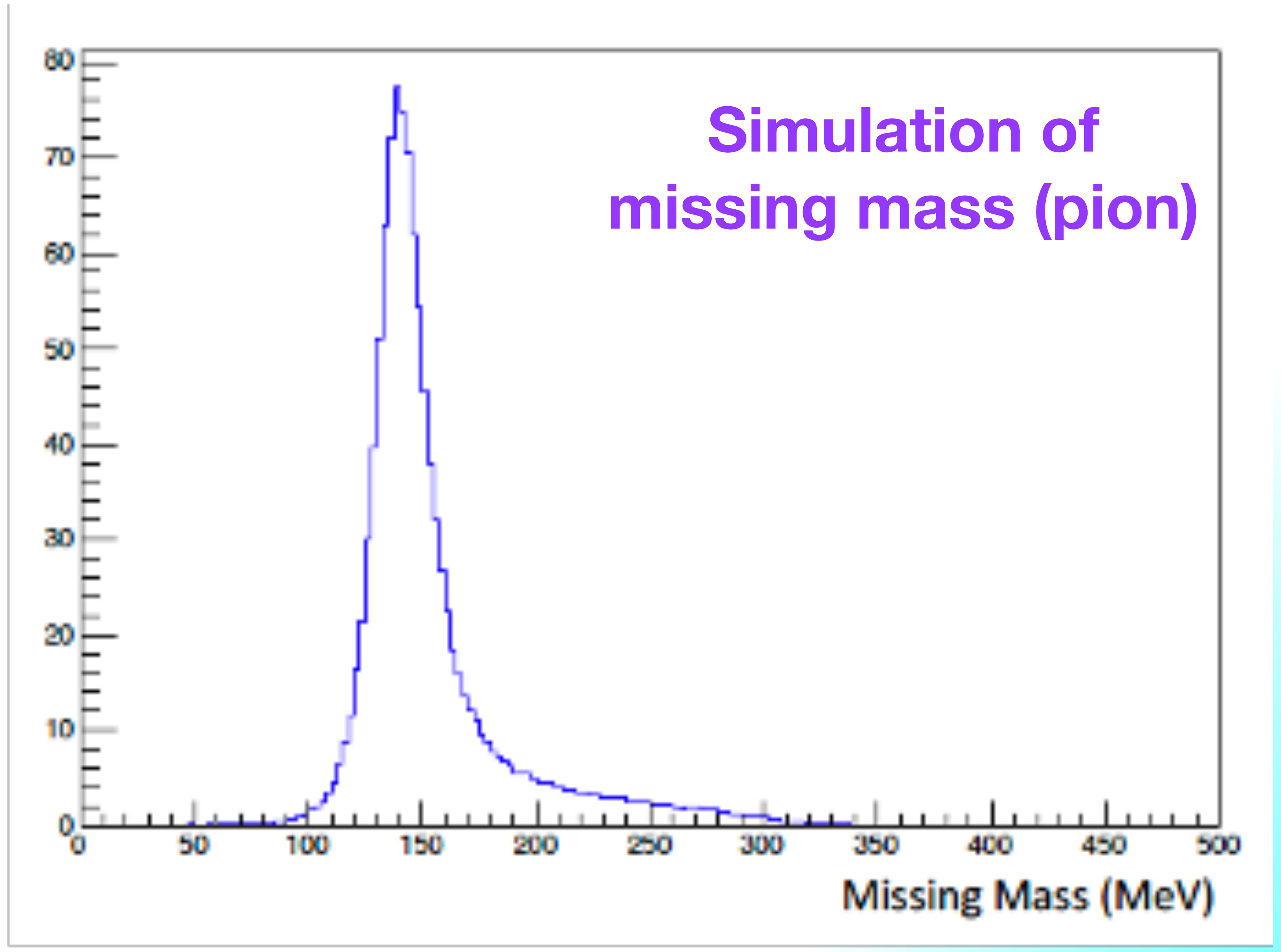
- Generalized polarizabilities (GPs) of the proton:
  - The TFFs enter as an input in the VCS cross section over the Δ resonance region – their precise knowledge is necessary for the precise extraction of the GPs from the measured cross sections
  - Physics of interest:
    - Electric polarizability 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.



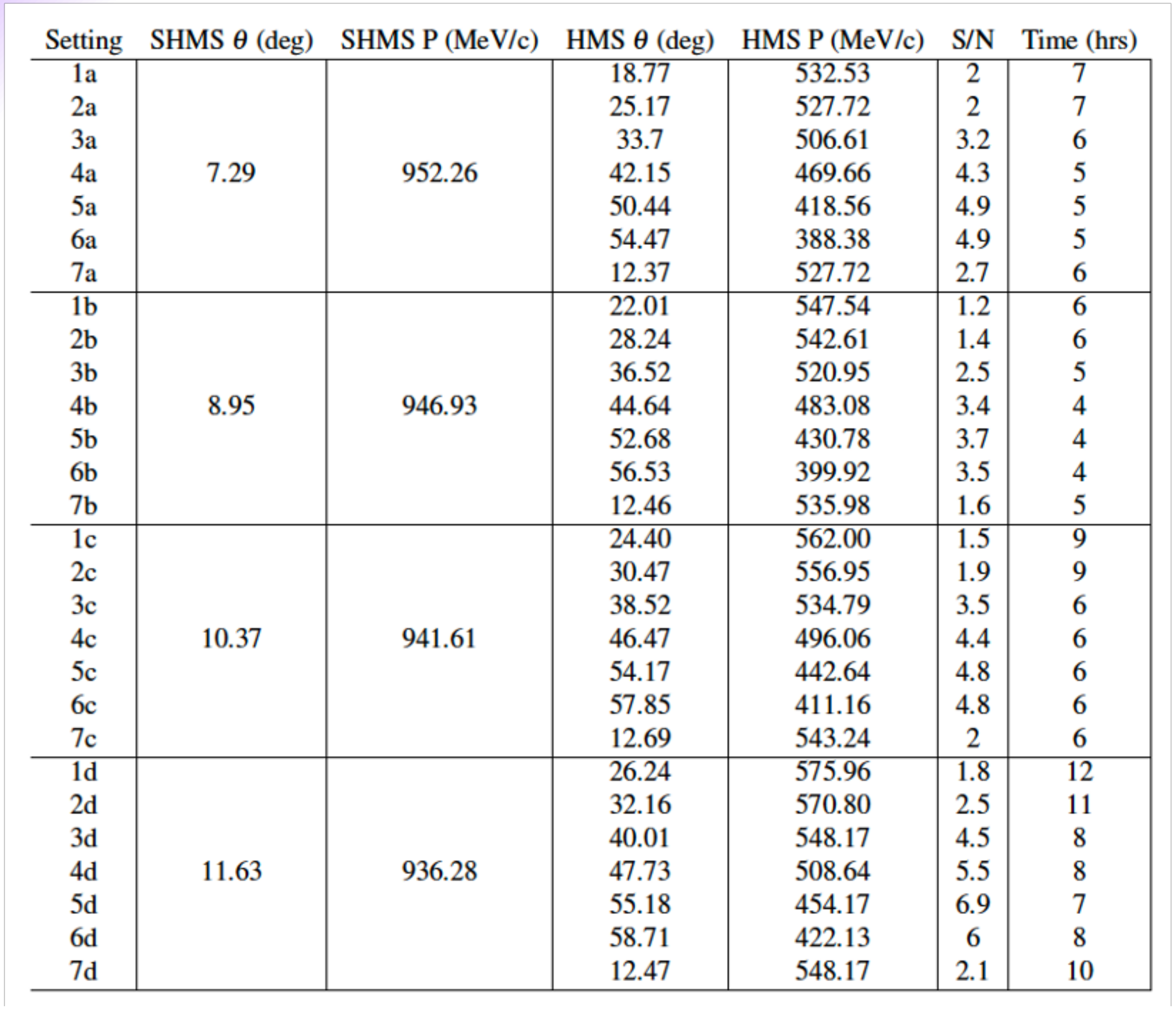
Experimental Setup



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

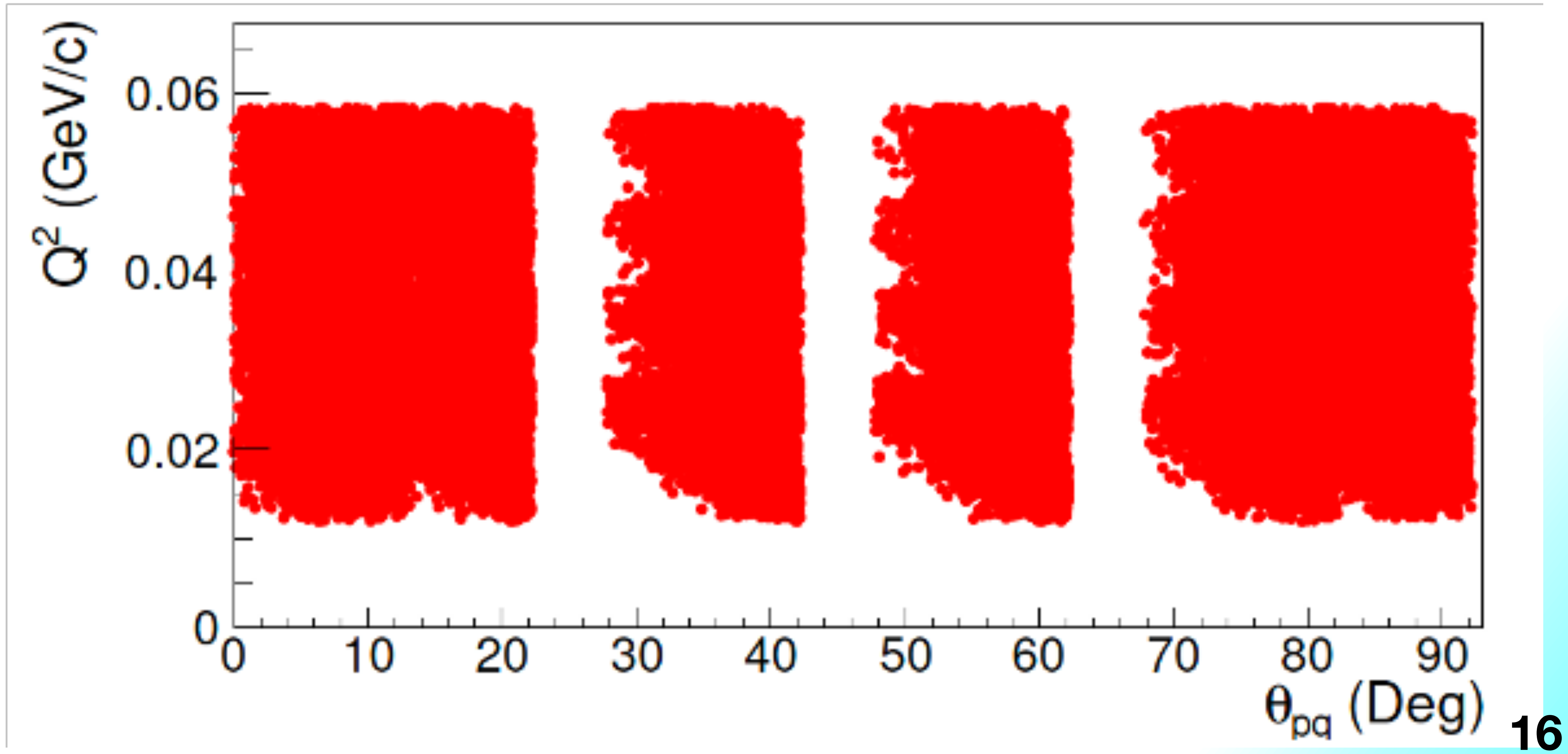


Measurement Settings



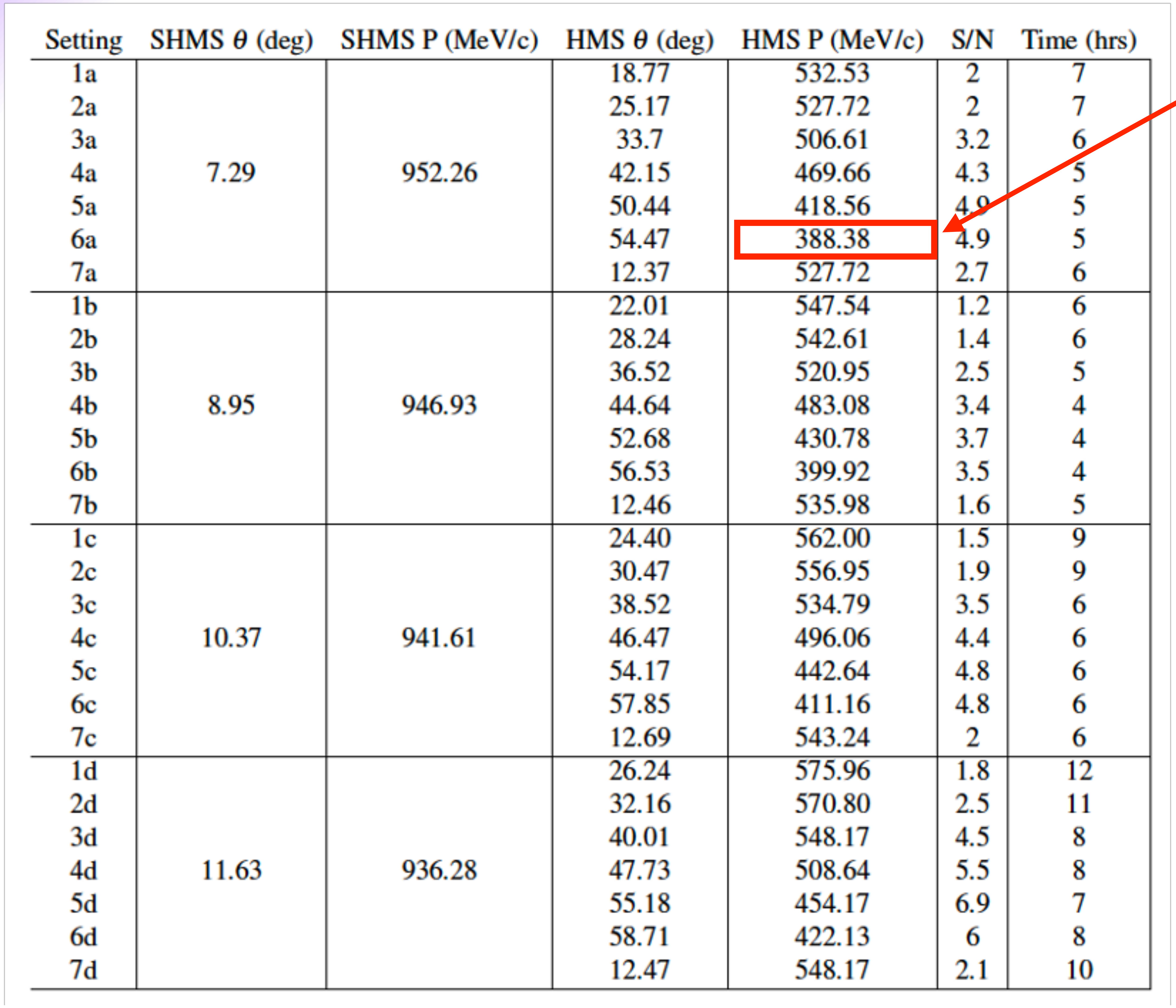
Setting	SHMS θ (deg)	SHMS P (MeV/c)	HMS θ (deg)	HMS P (MeV/c)	S/N	Time (hrs)
1a	7.29	952.26	18.77	532.53	2	7
2a			25.17	527.72	2	7
3a			33.7	506.61	3.2	6
4a			42.15	469.66	4.3	5
5a			50.44	418.56	4.9	5
6a			54.47	388.38	4.9	5
7a			12.37	527.72	2.7	6
1b	8.95	946.93	22.01	547.54	1.2	6
2b			28.24	542.61	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.
  - 8 days production
  - 3 days other (dummy, calibration, etc..)



Low Momentum HMS protons

Addressed with simulation and experimental tests performed in 2019 and 2021



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
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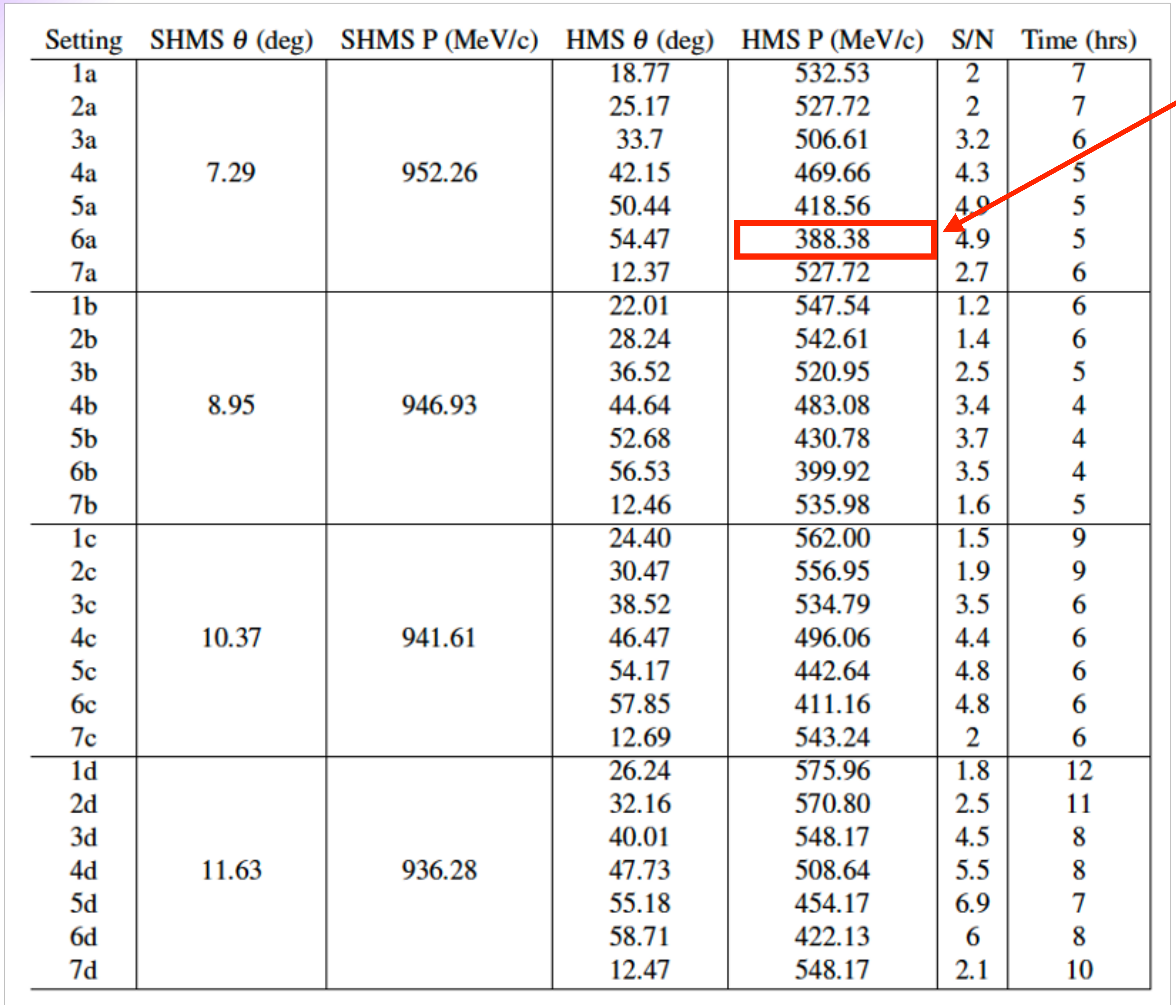
  - Lowest momentum setting to-date for proton detection in the HMS.
  - Protons are expected to be absorbed in the last scintillator plane.
  - The pulse heights in the scintillators will be larger than typical.
    - We plan on optimizing HV for pulse height.
    - We will determine efficiencies with dedicated single and coincident elastics runs.
  - HMS Q3 is at the lowest current of 19A with Q1 and Q2 at 40A and 50A.
    - Down to 250 MeV/c , the Q3 readback current was consistent with the set current at 0.01% level
  - Previous running at 440 MeV/c showed expected optics scaling.

Low Momentum HMS protons

Addressed with simulation and experimental tests performed in 2019 and 2021



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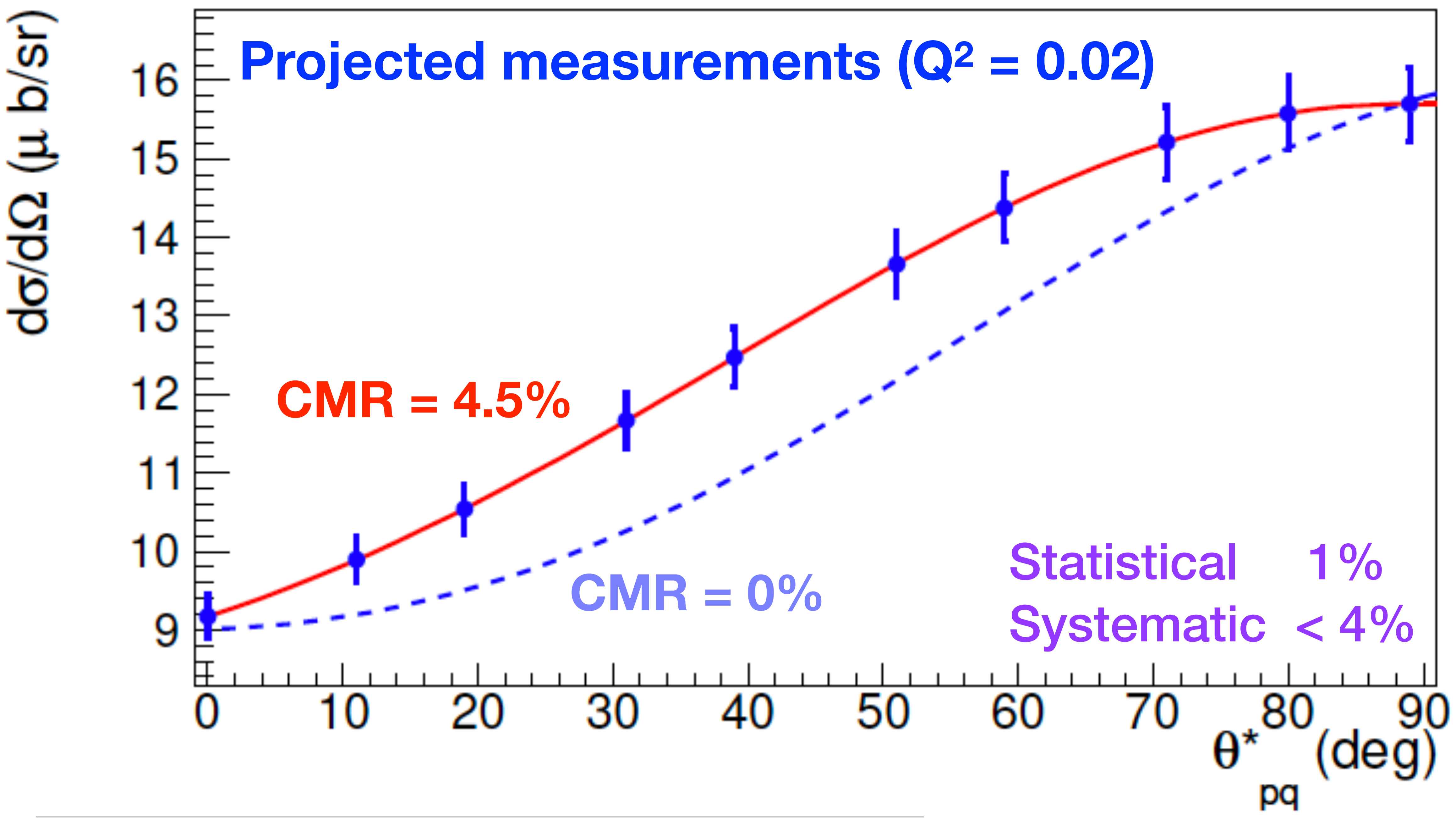
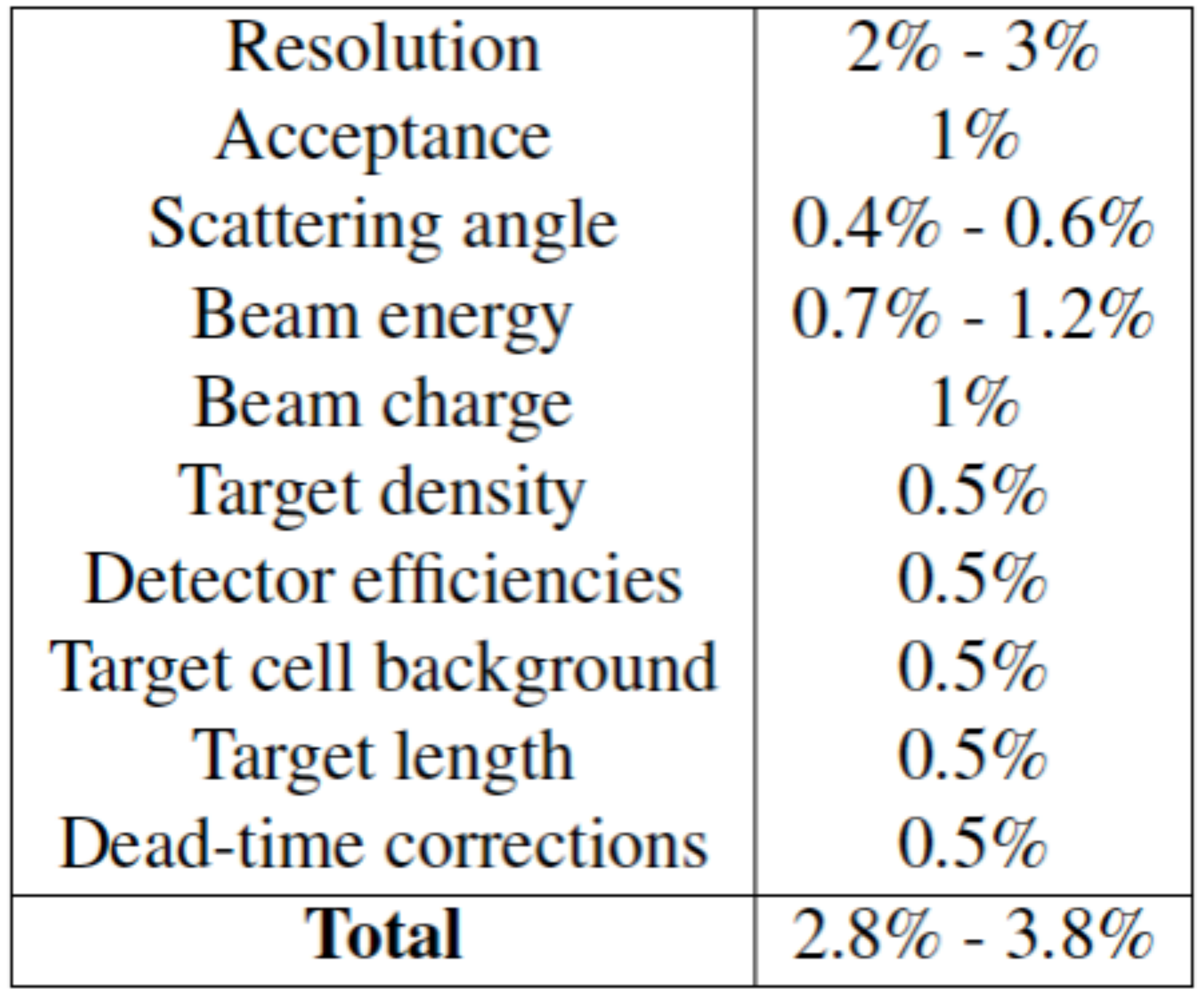
Only one setting out of 28. Worst case: impact of losing the setting is minimal.

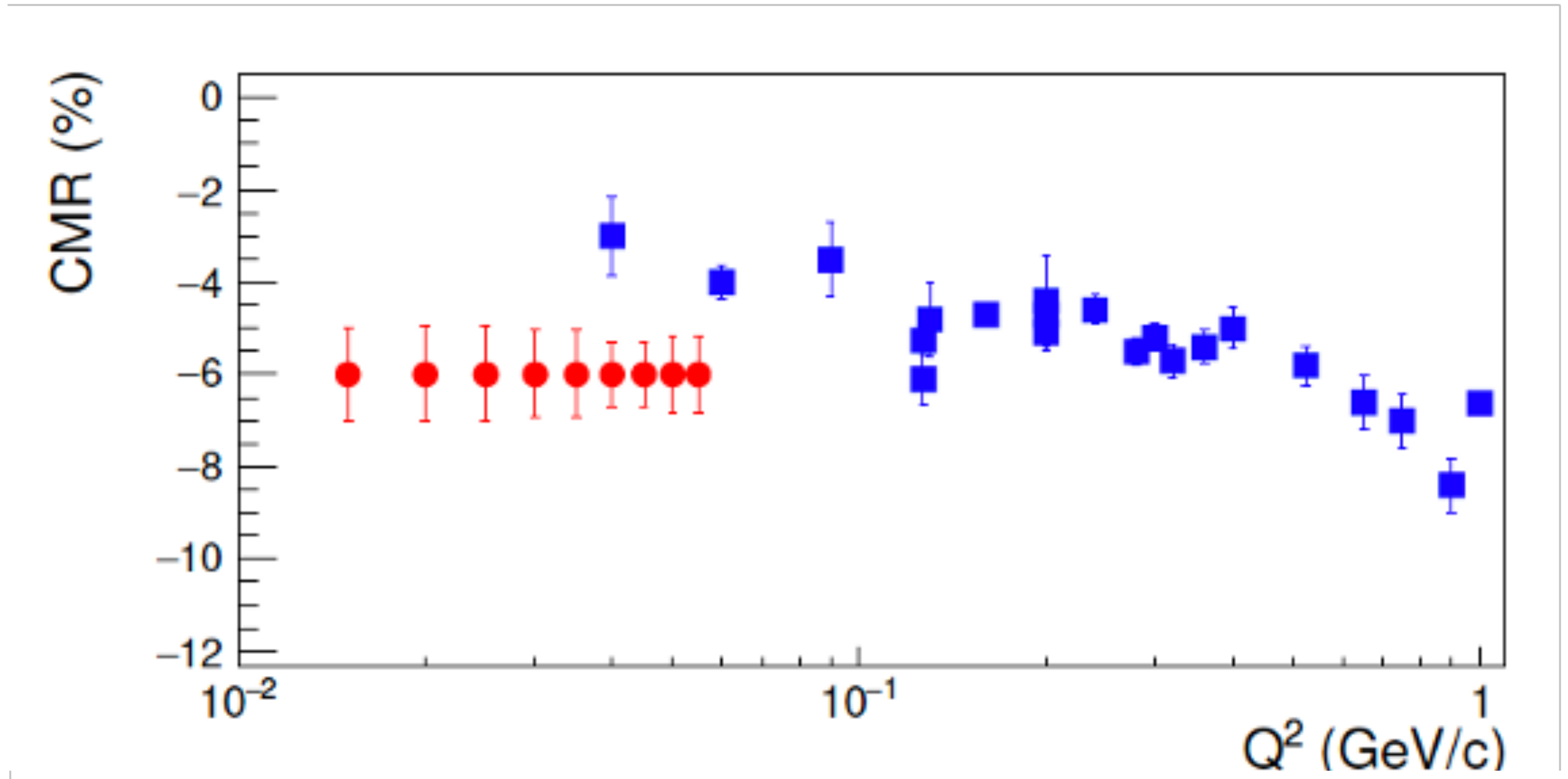
Projected CMR and EMR measurements

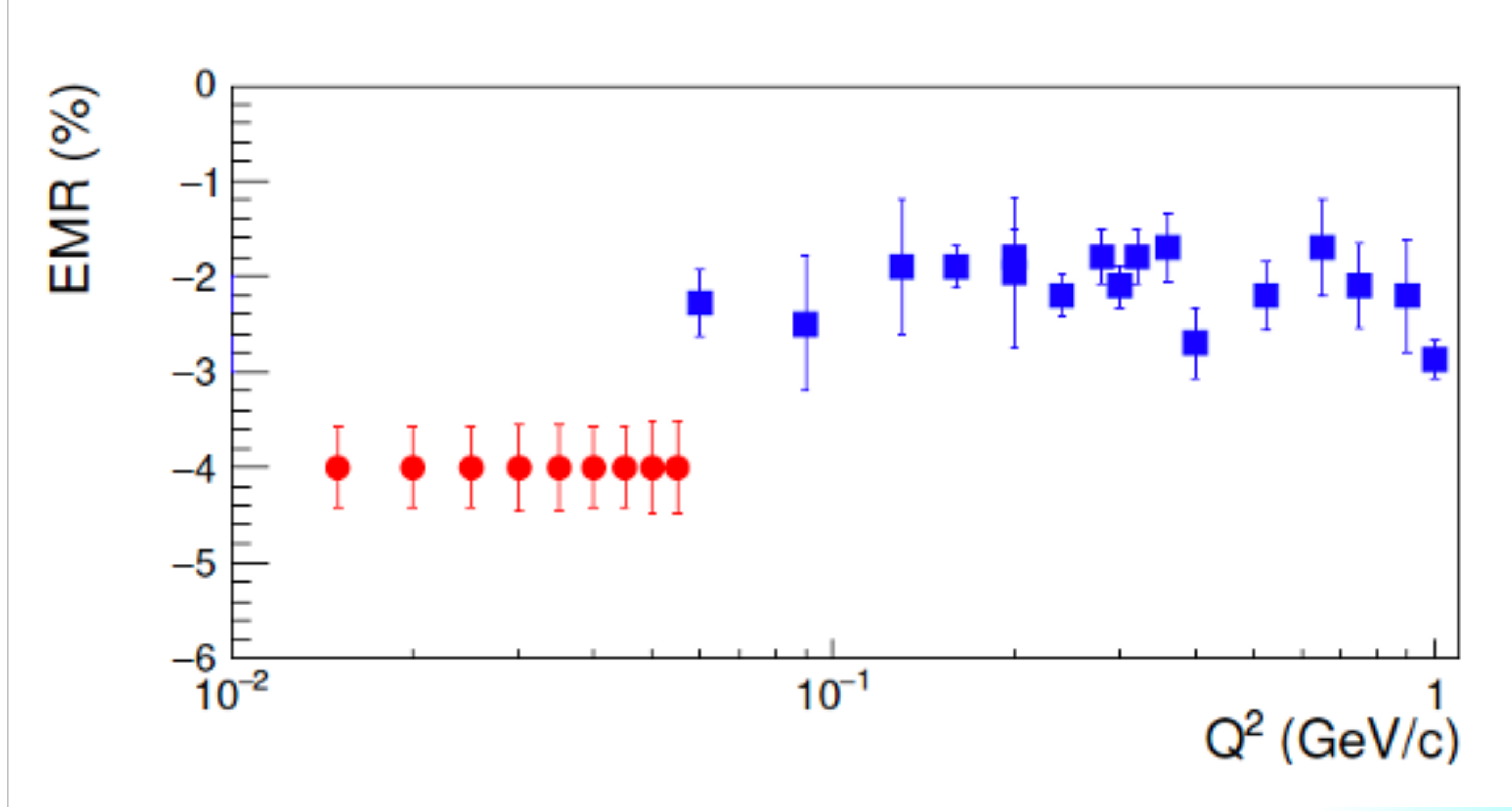




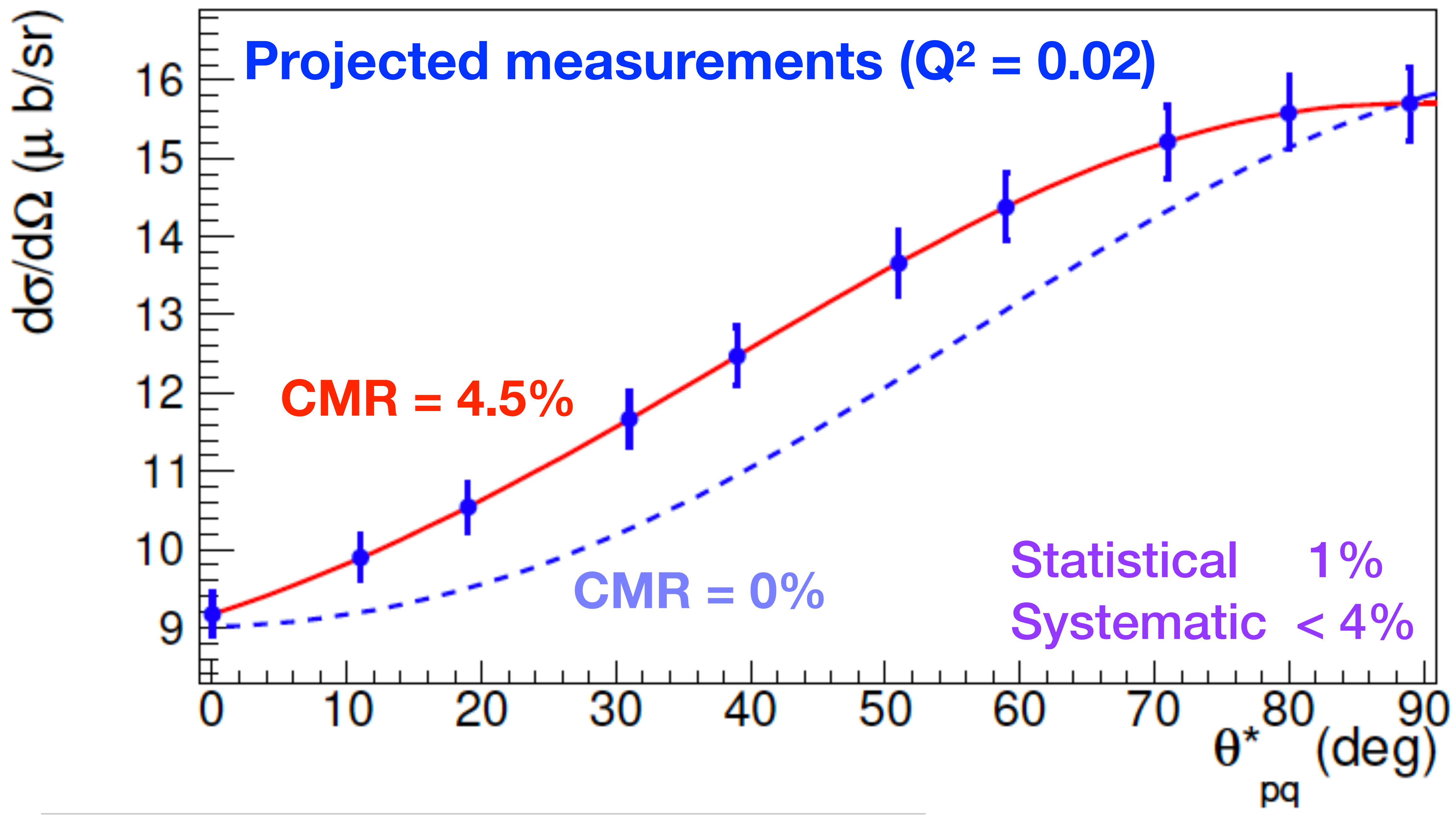
Resolution	2% - 3%
Acceptance	1%
Scattering angle	0.4% - 0.6%
Beam energy	0.7% - 1.2%
Beam charge	1%
Target density	0.5%
Detector efficiencies	0.5%
Target cell background	0.5%
Target length	0.5%
Dead-time corrections	0.5%
Total	2.8% - 3.8%

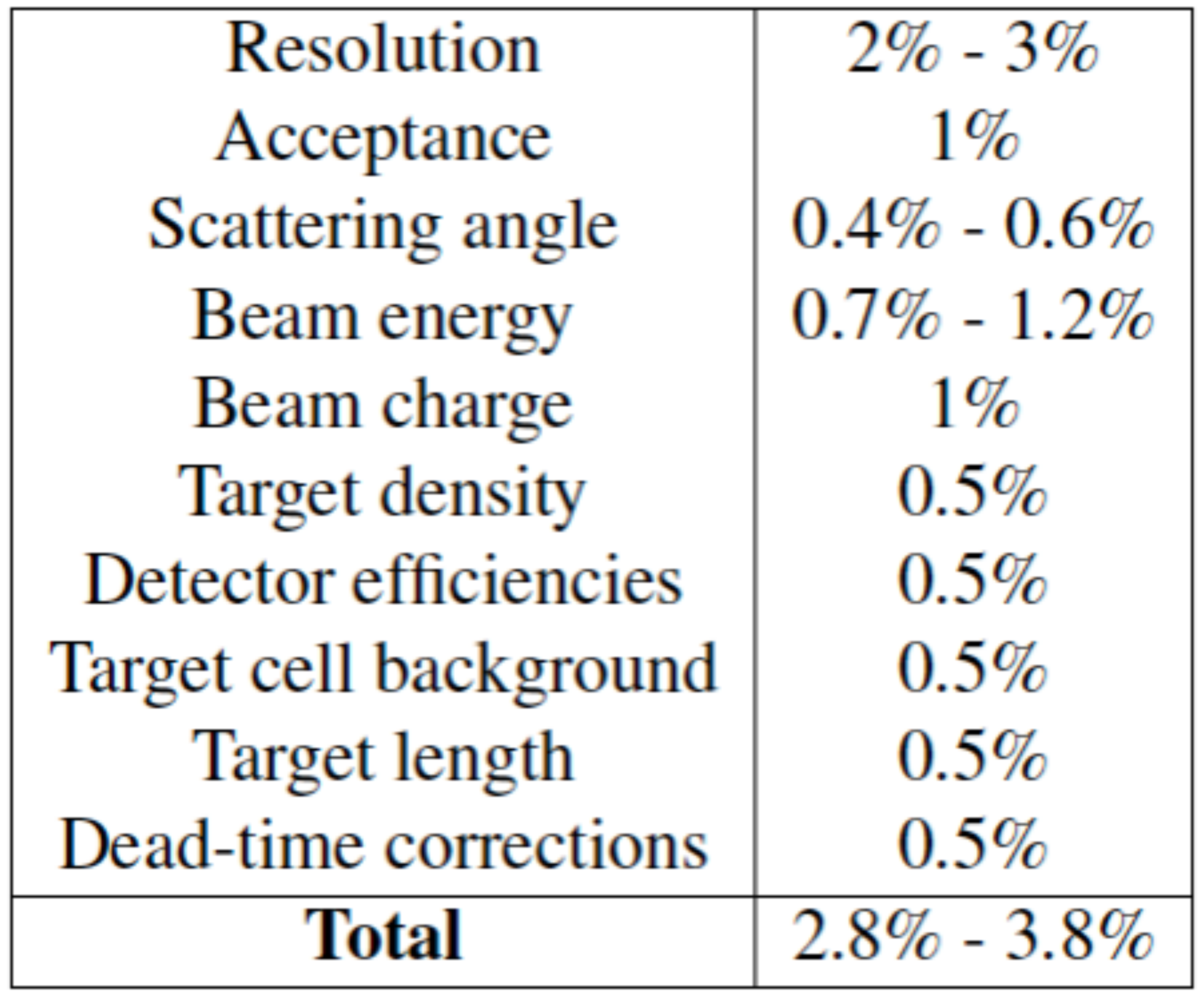
- High precision in very low Q^2 region that is sparsely populated
  - Region where pion-cloud effects are expected to be prominent





Projected CMR and EMR measurements





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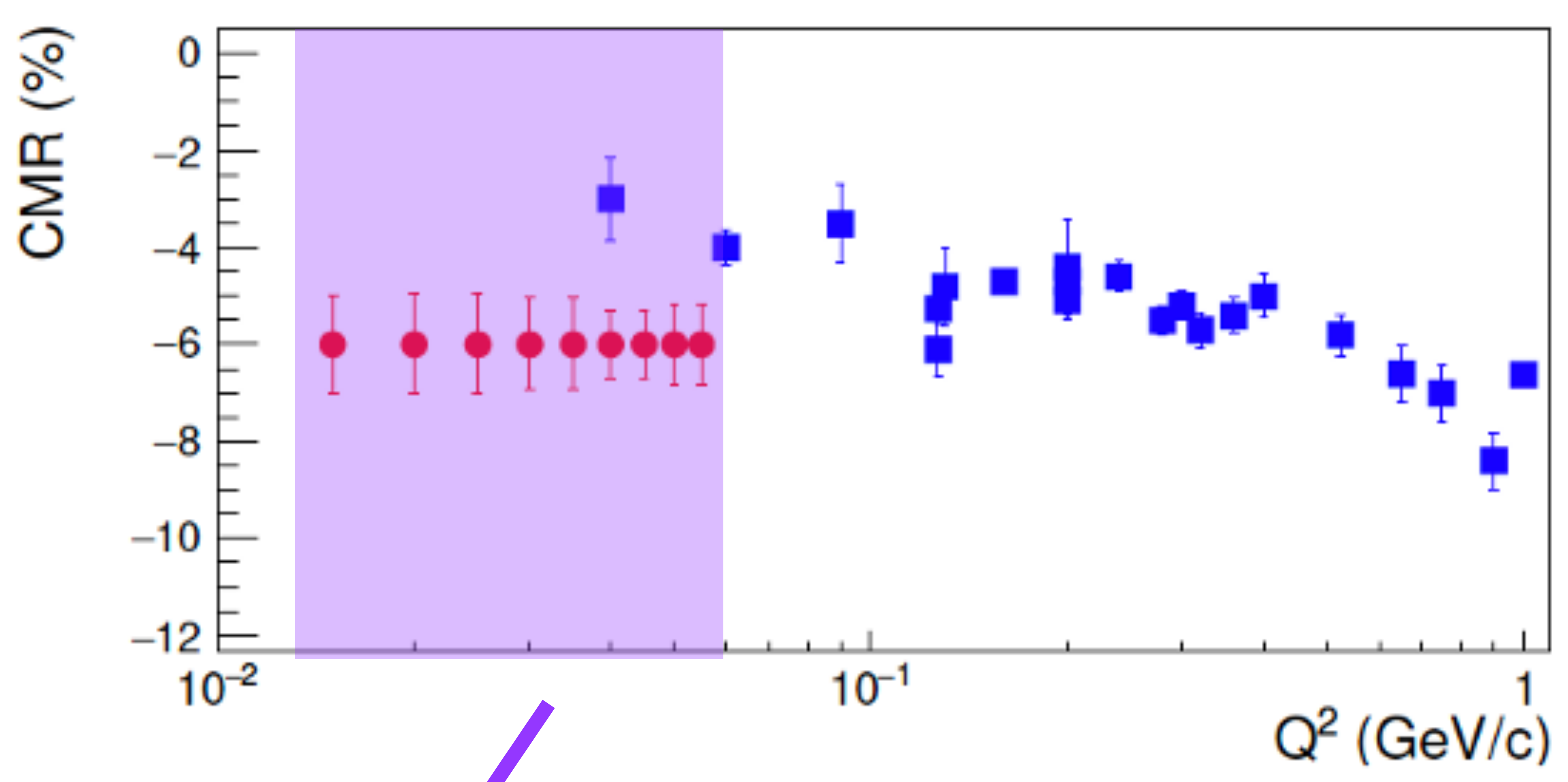
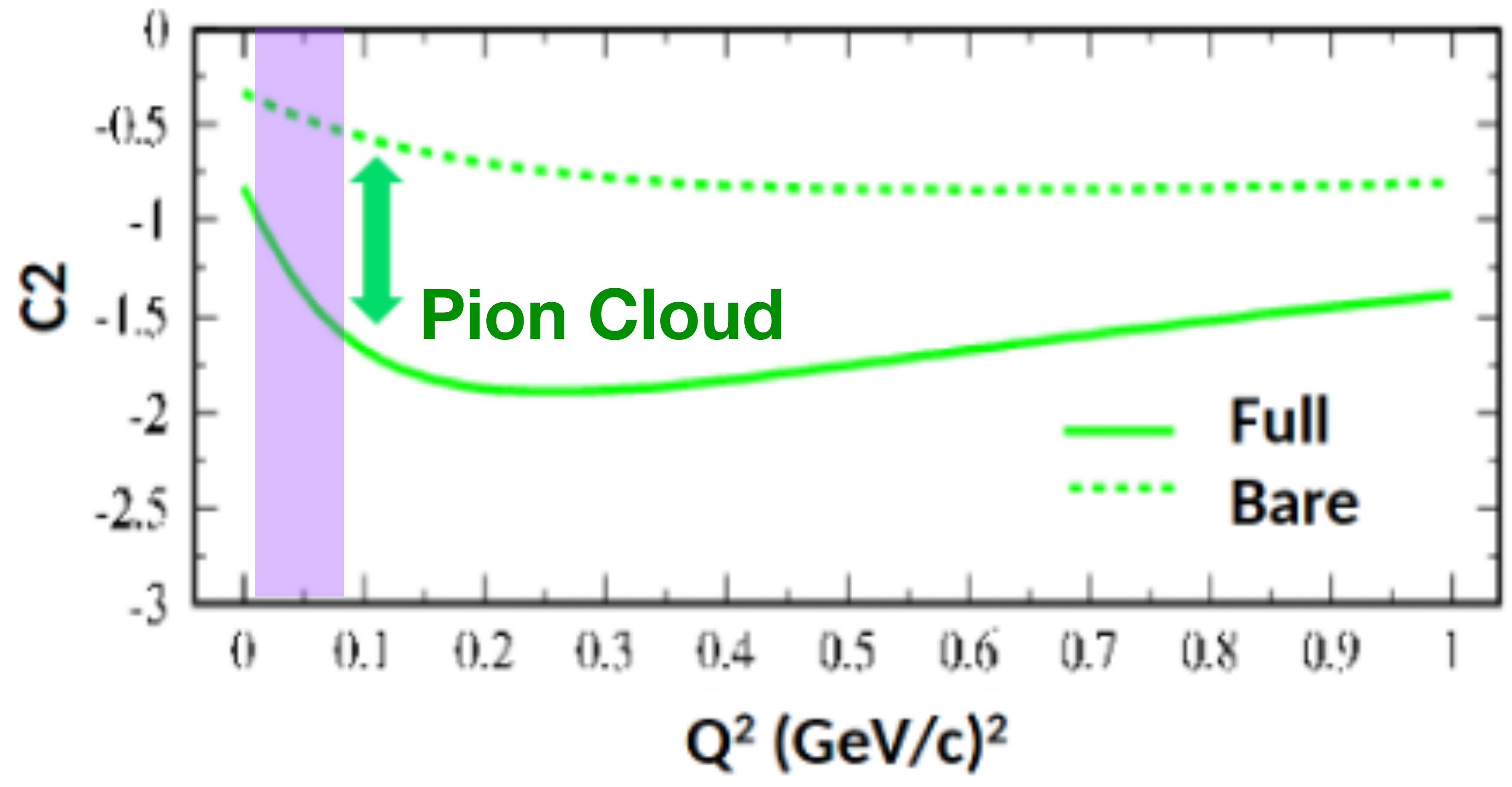
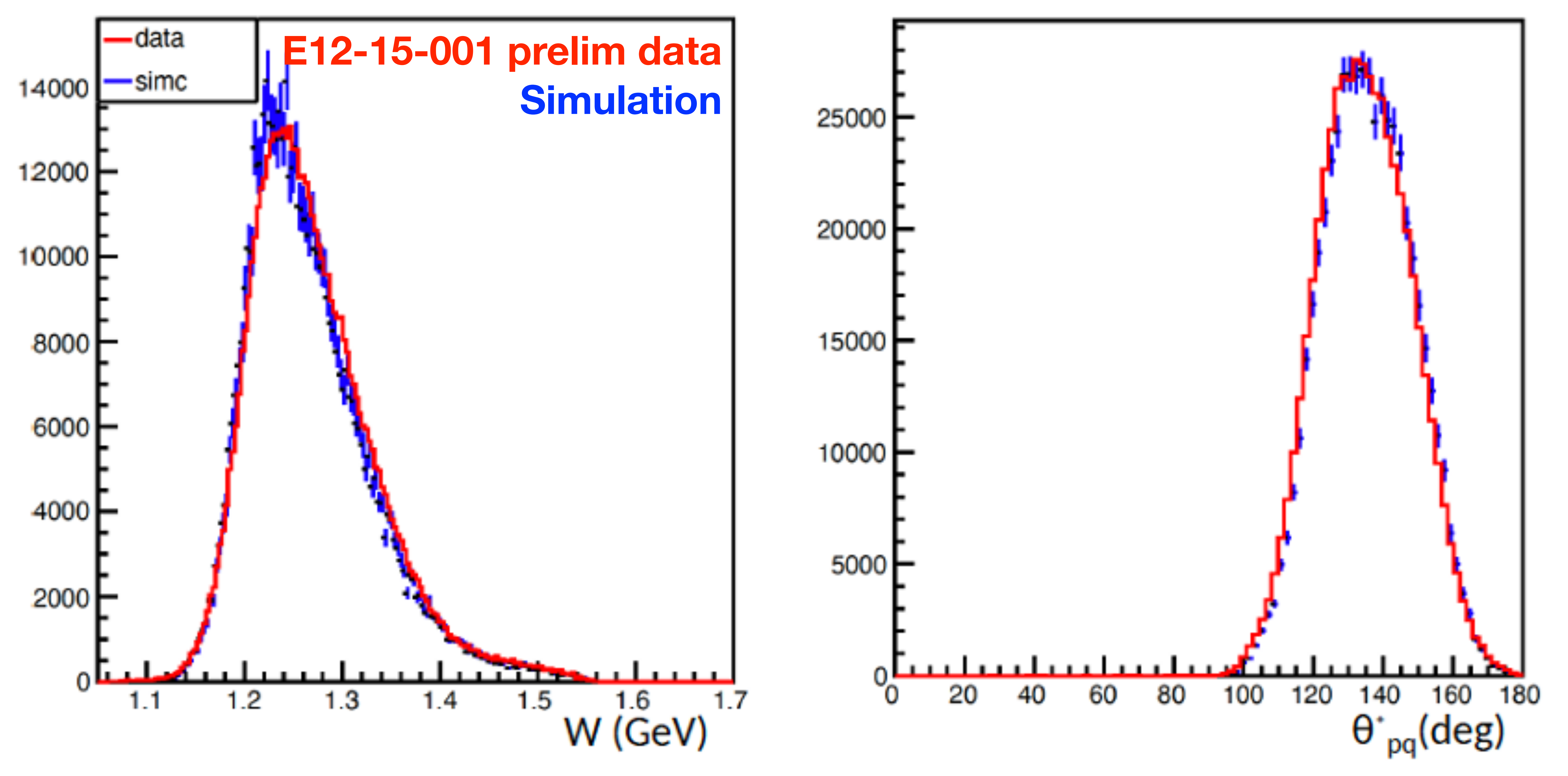


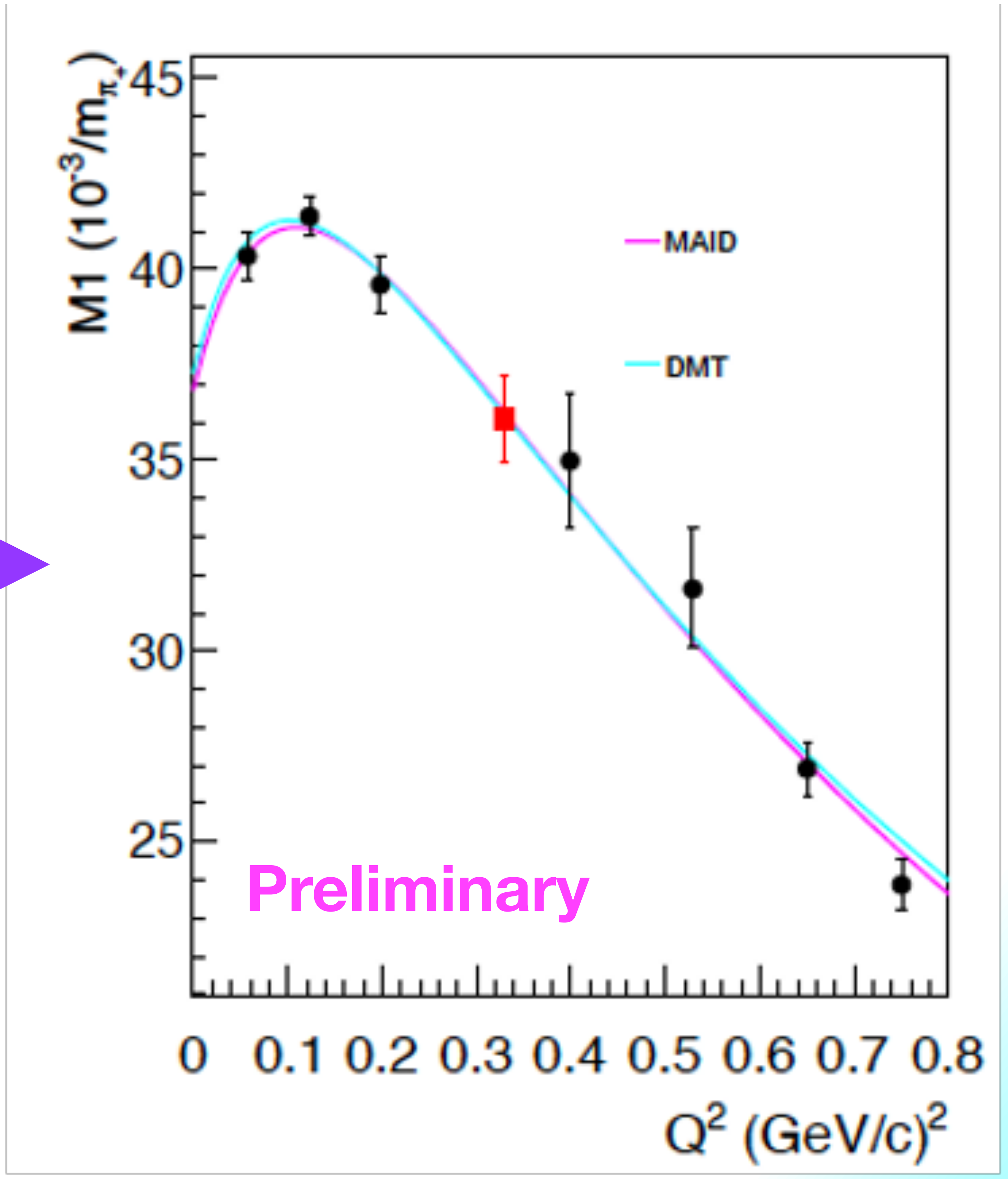


Readiness in experimental & theoretical methodology/tools

VCS Experiment E12-15-001 ran in Hall-C (2019) with a similar set-up at Q^2 = 0.33 (GeV/c)2

Main difference with proposed experiment: Lower Q^2 -> lower beam energy and lower central momentum settings





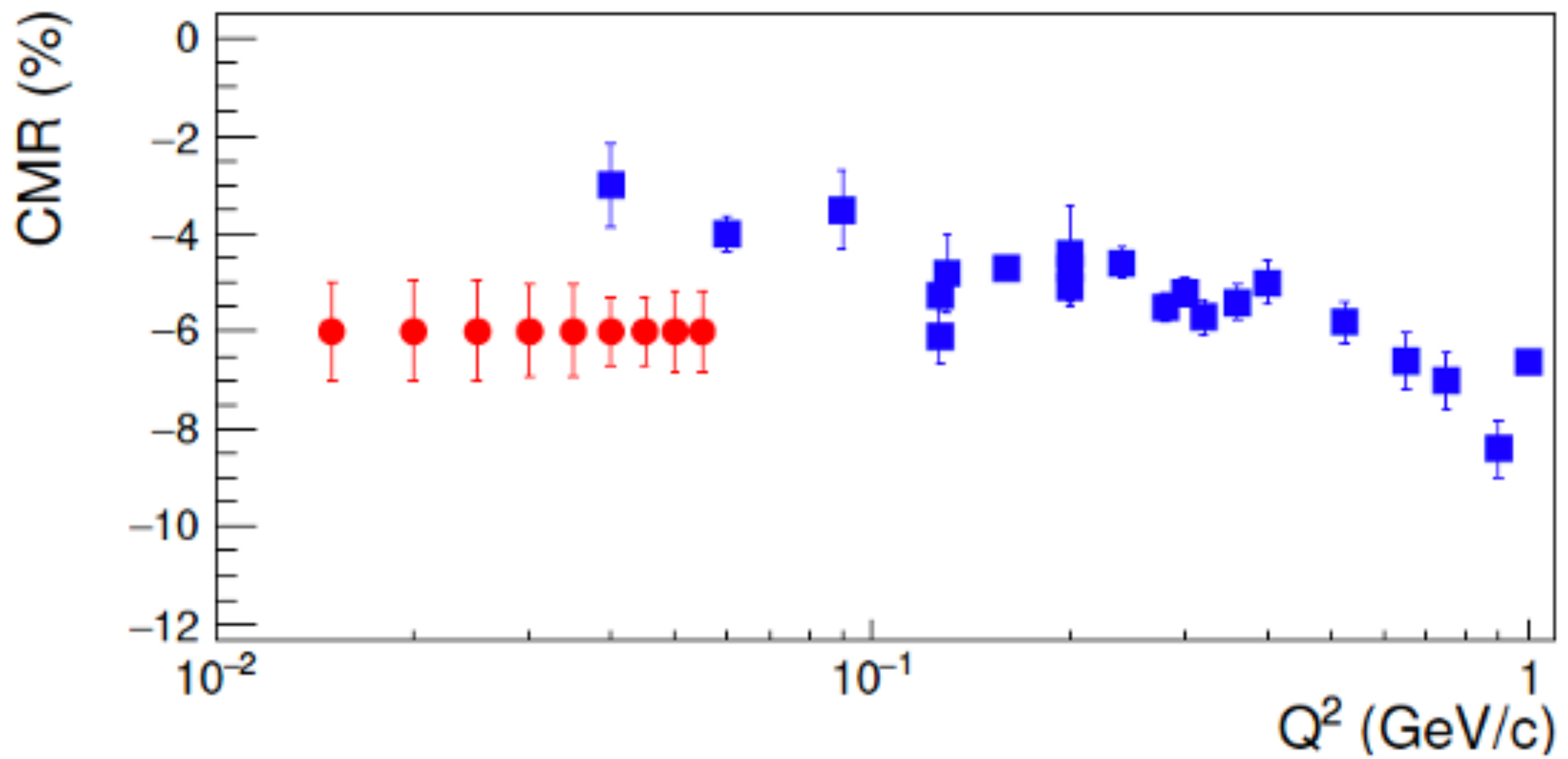
Collaboration has extensive experience extracting N-Δ transition measurements from Hall-C data (and beyond).

Measurement of the N→Δ Transition Form Factors at low Q^2

- **Exerts from the PAC50 theoretical report:**
  - *"In particular the results on the electric quadrupole moments of the N – Δ transition, which are the main focus of the experiment,* ***will be crucial*** *for further understanding the strong dynamics driving them, which to this day remains as a real challenge. Having the quadrupole form factors at low momenta will be very helpful for understanding the role of the pion through the rigorous implementation of chiral perturbation theory which has now been developed to include the Δ in a consistent way, namely respecting the constraints of the 1/Nc expansion. "*
  - *"...* ***the experiment has significant value*** *in that it will further enhance the determination of the N → Δ EM transition observables* ***in a domain where there is virtually no data****, and with it permit further understanding of the smaller effects due to the electric contributions. In particular, the current efforts to include in a rigorous way the Δ as a genuine degree of freedom in effective theory, in particular in chiral effective theory, will make good use of the results of this experiment. "*

Summary

- **The N→Δ TFFs represent a central element of the nucleon dynamics & has been an important part of Jefferson Lab's experimental program (Halls A, B & C)**
  - We will extend these measurements in the low Q^2 region:
    - Test bed for ChEFT calculations
    - High precision benchmark data for the Lattice QCD calculations
    - New constraints and input to the theoretical models
    - Insight to the mesonic-cloud dynamics within a region where they are dominant and rapidly changing
    - Insight to the origin of non-spherical components in the nucleon wave-function
    - Will test if the QCD prediction that CMR & EMR converge as $Q^2 \to 0$
- **N→Δ TFFs enter as an input in scientific problems that extend from hadronic to neutrino physics, and will advance our understanding of the baryon structure & beyond**
- **Request:**
  - 11 days (8 production, 3 calibration)
  - Beam energy: 1.3 GeV (flexible within +/- 0.1 GeV)
  - Hall C standard SHMS and HMS setup with a 4 cm LH2 target



Thank you!

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