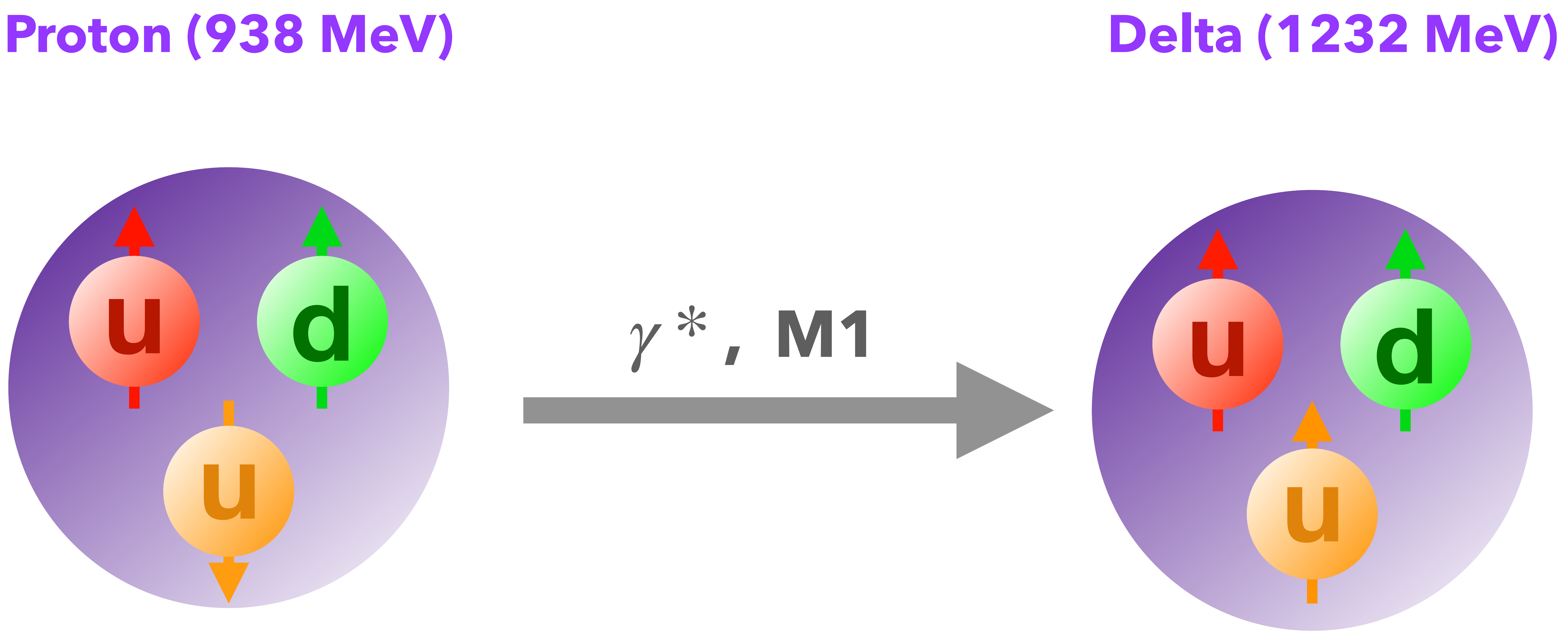
Upcoming Measurements of the $N \rightarrow \Delta$ Transition Form Factors at Jefferson Lab

Low-q workshop, Island of Crete, Greece, May 19 2023

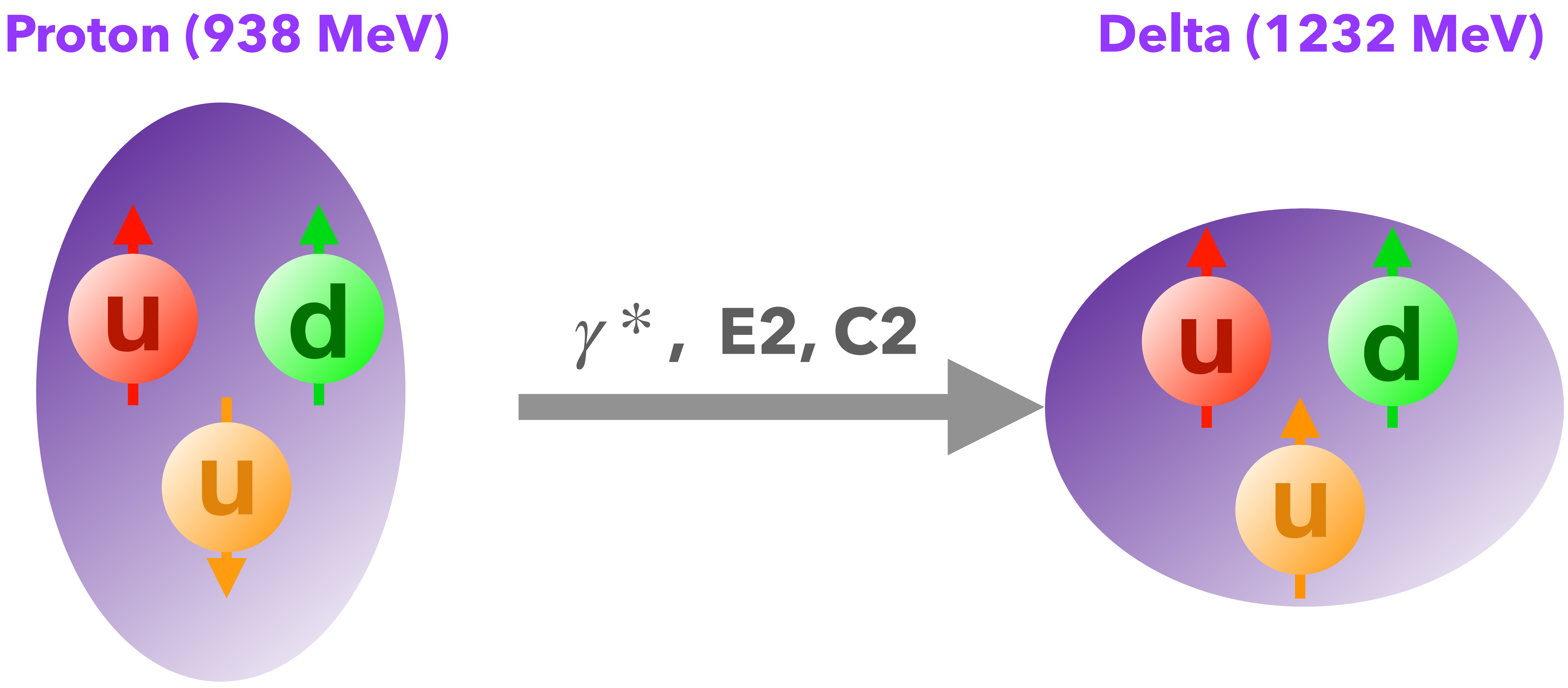
Michael Paolone, New Mexico State University

The N-Δ transition



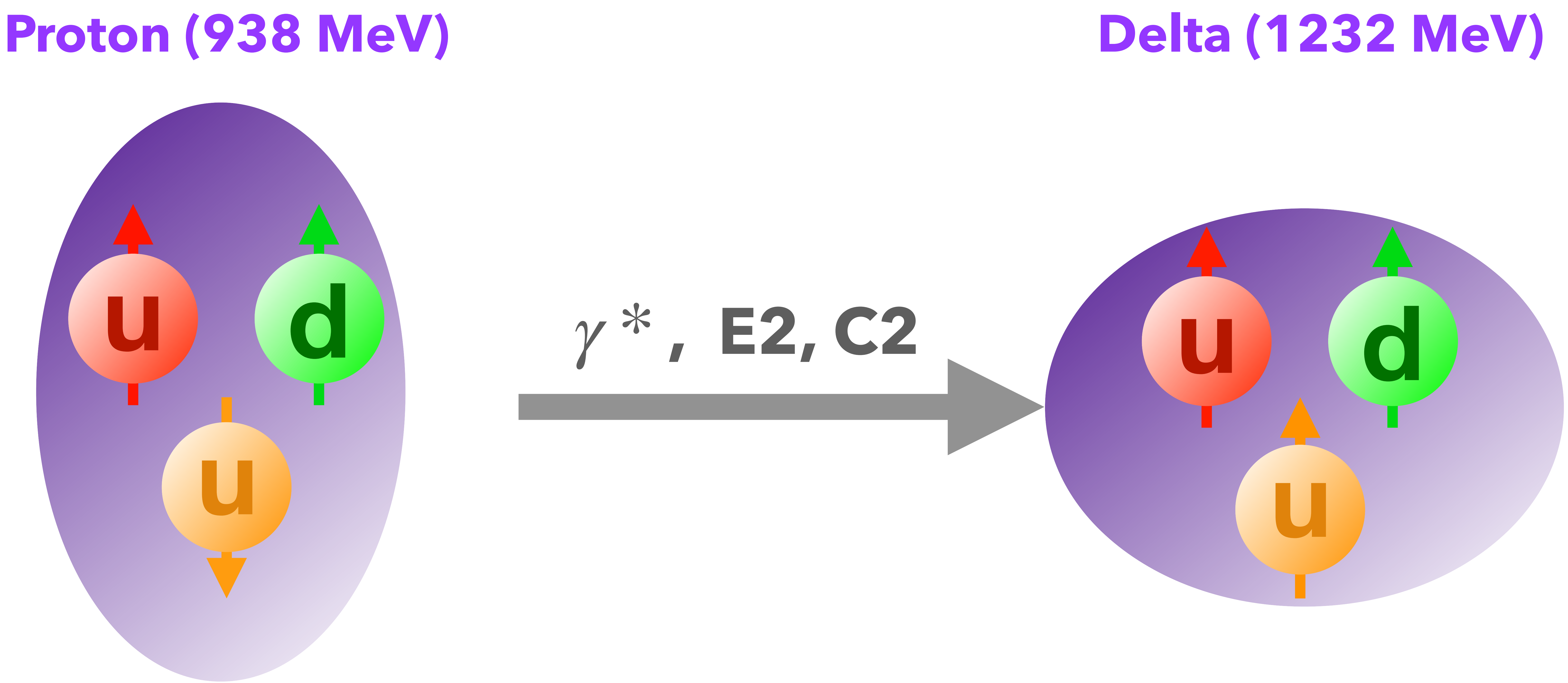
The dominant transition from proton to delta involves a dipole (M1) transition (spherical S-wave proton WF -> spherical S-wave Delta WF)

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



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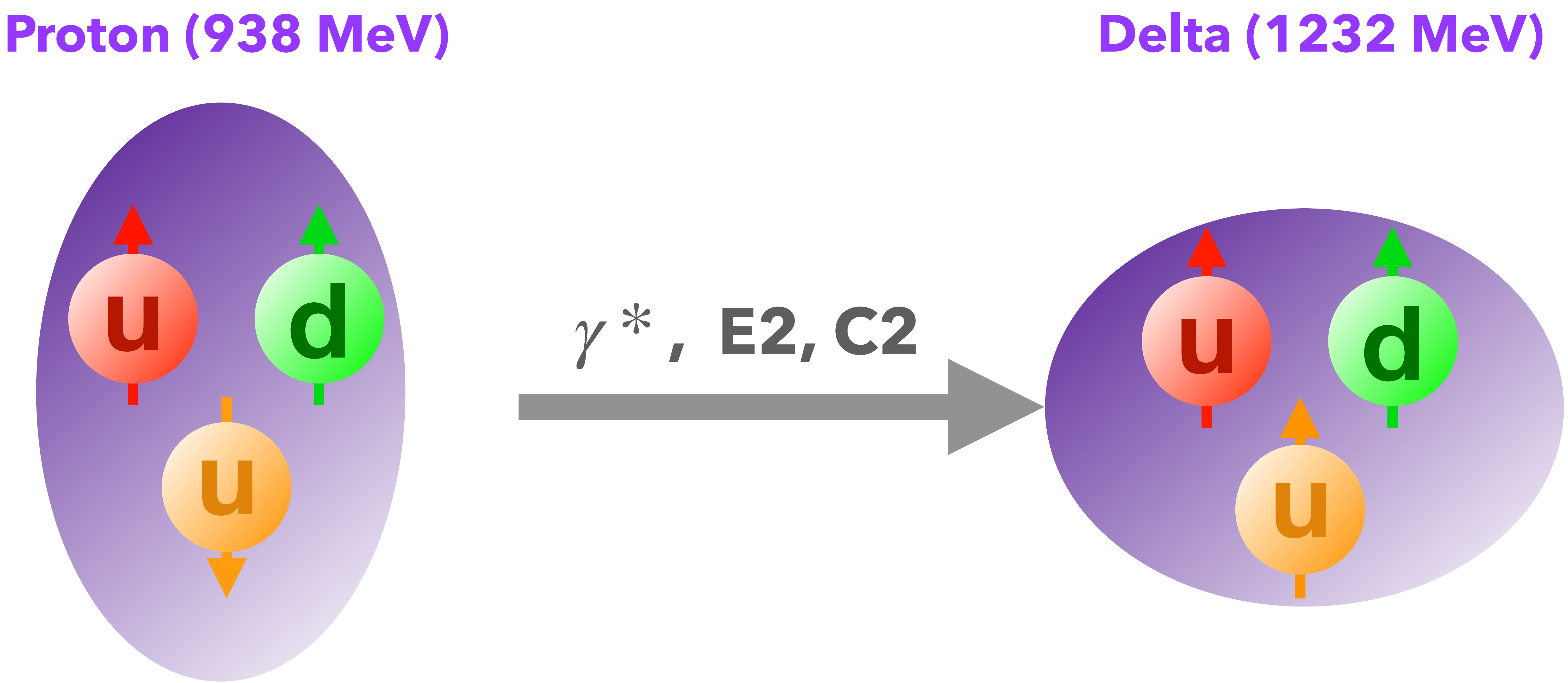
The quadrupole to dipole ratio (E2/M1 or C2/M1) is non-zero… Why?

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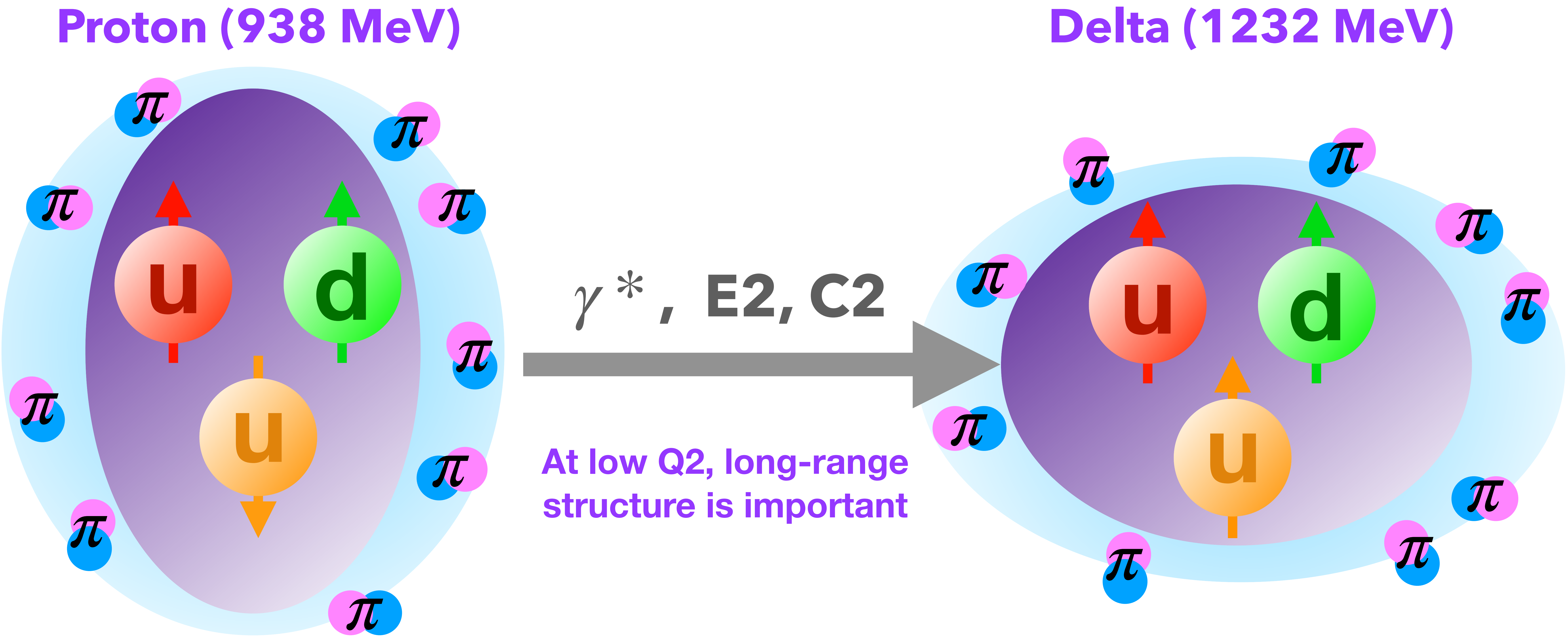
Non-central (tensor) interactions between quarks can account for some of the spherical deviation, but not all...

The N-Δ transition



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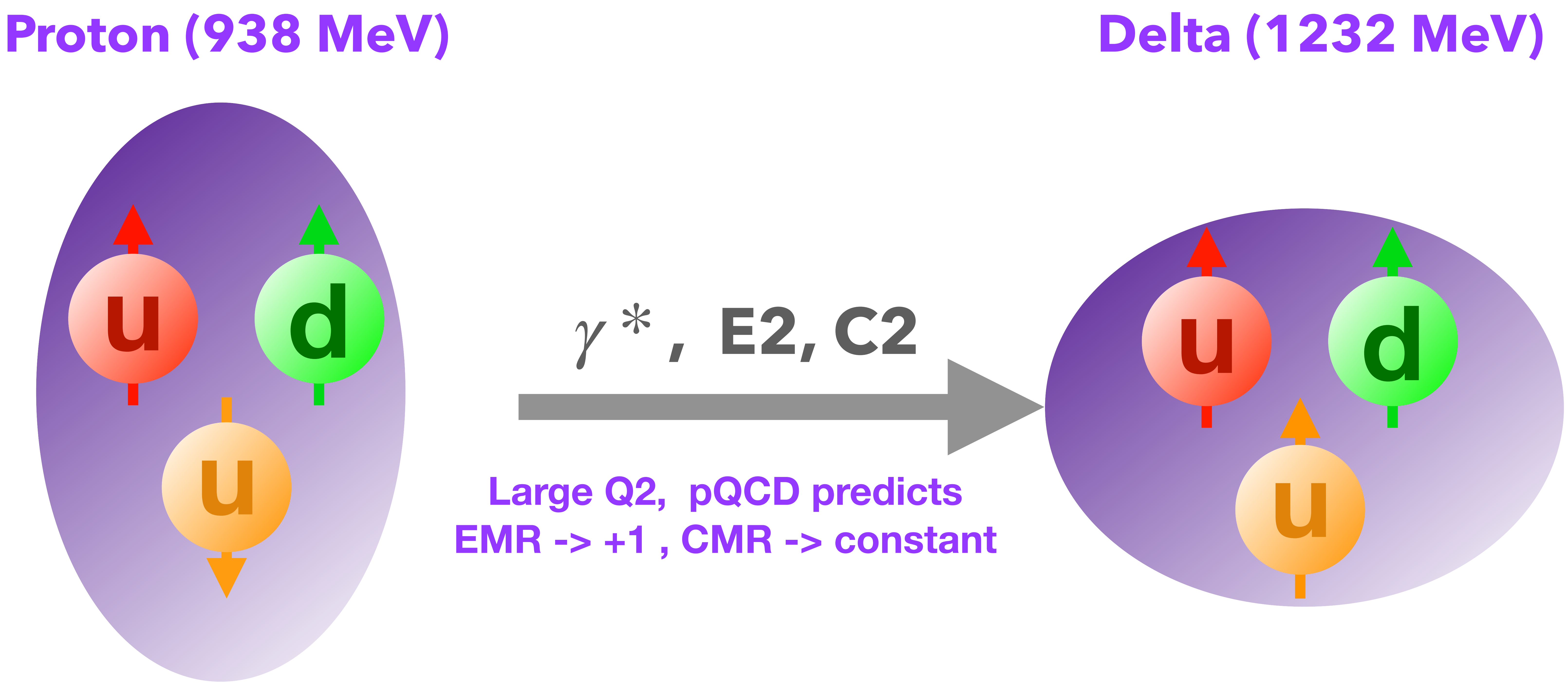
At low Q2, the dynamics of a meson cloud are important to describe the structure of the nucleon.

The N-Δ transition



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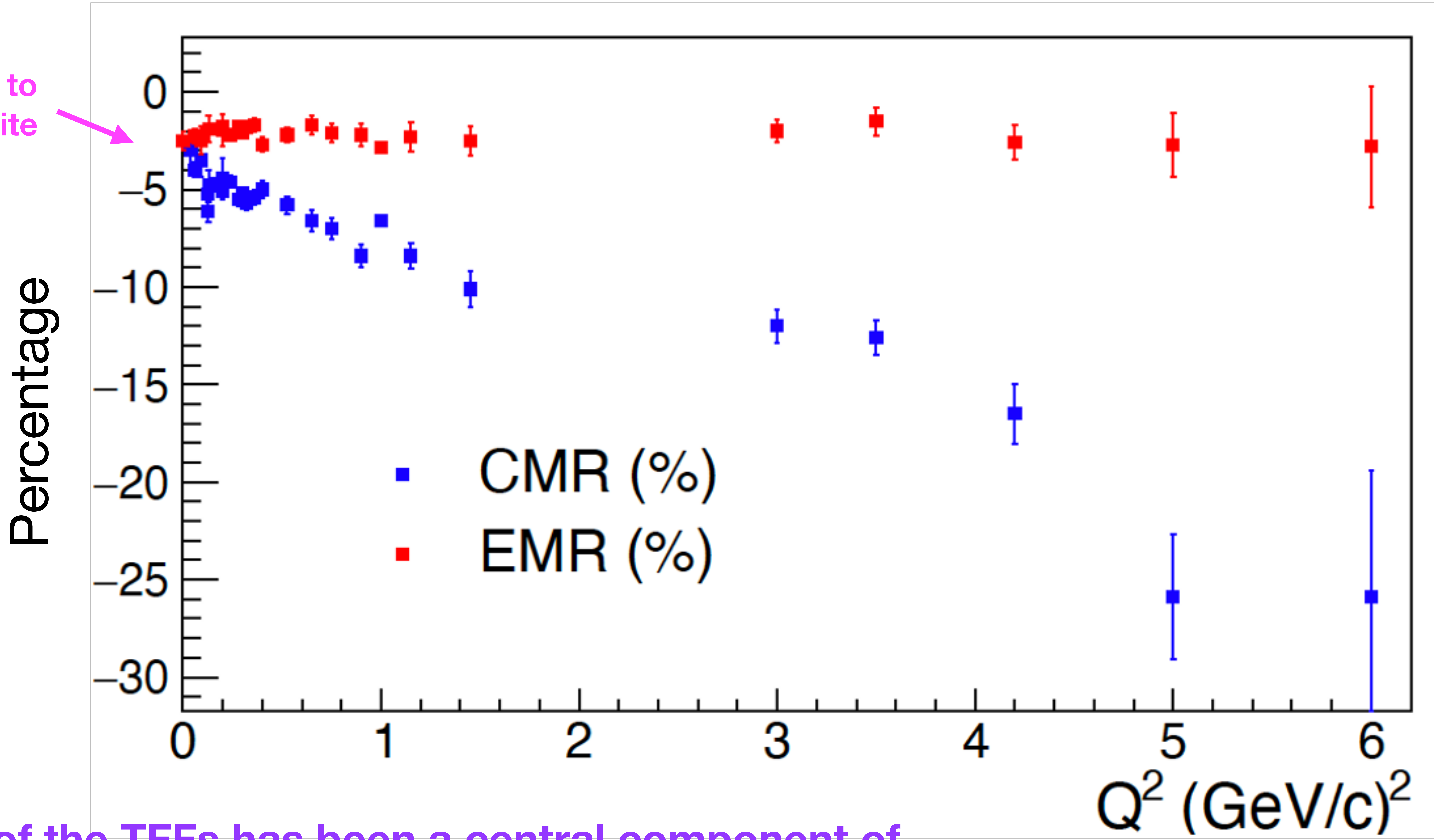
At high Q2, perturbative calculations should become more reliable and helicity conserving amplitudes are expected to dominate.

World data and status of TFFs

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

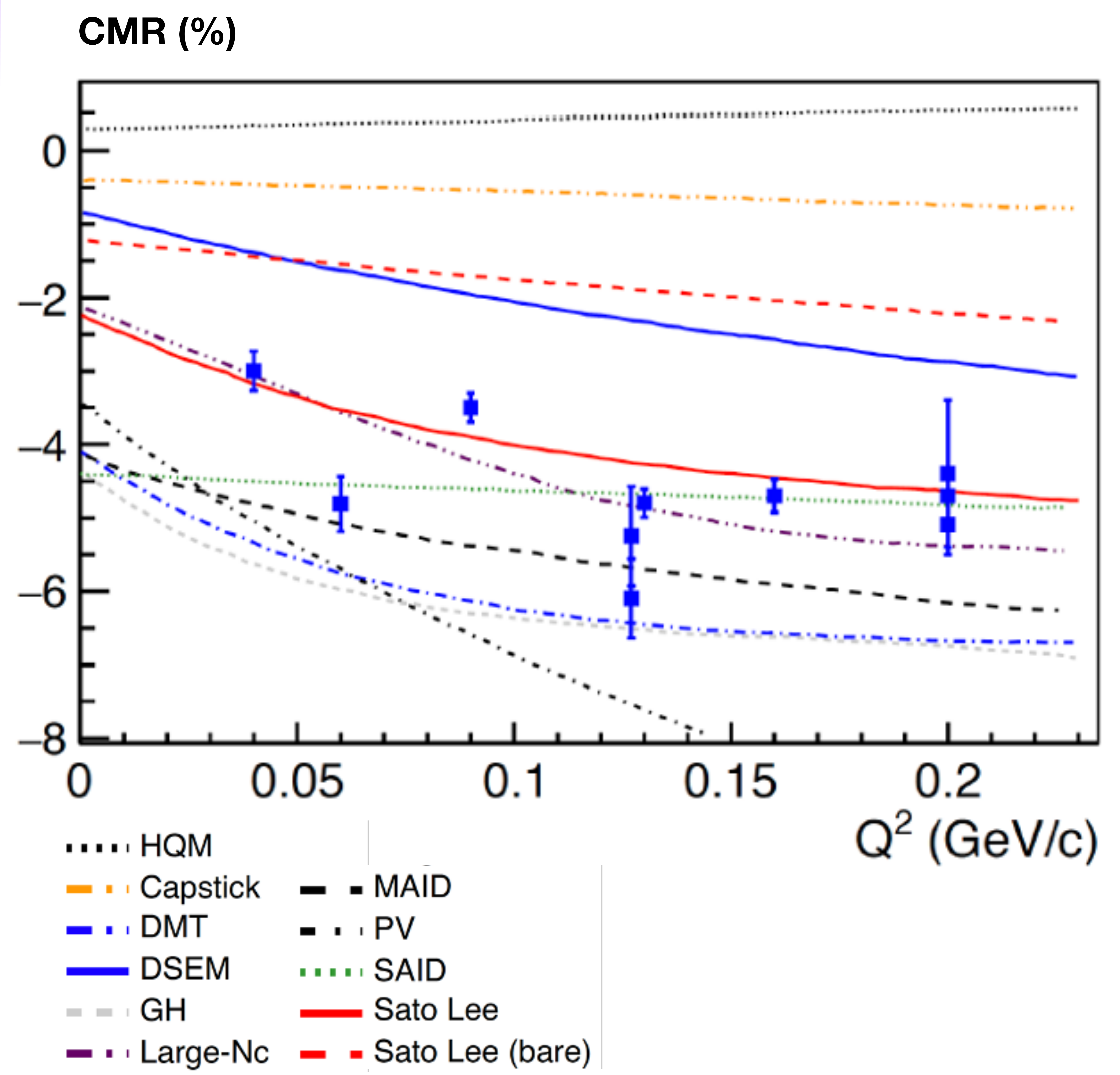


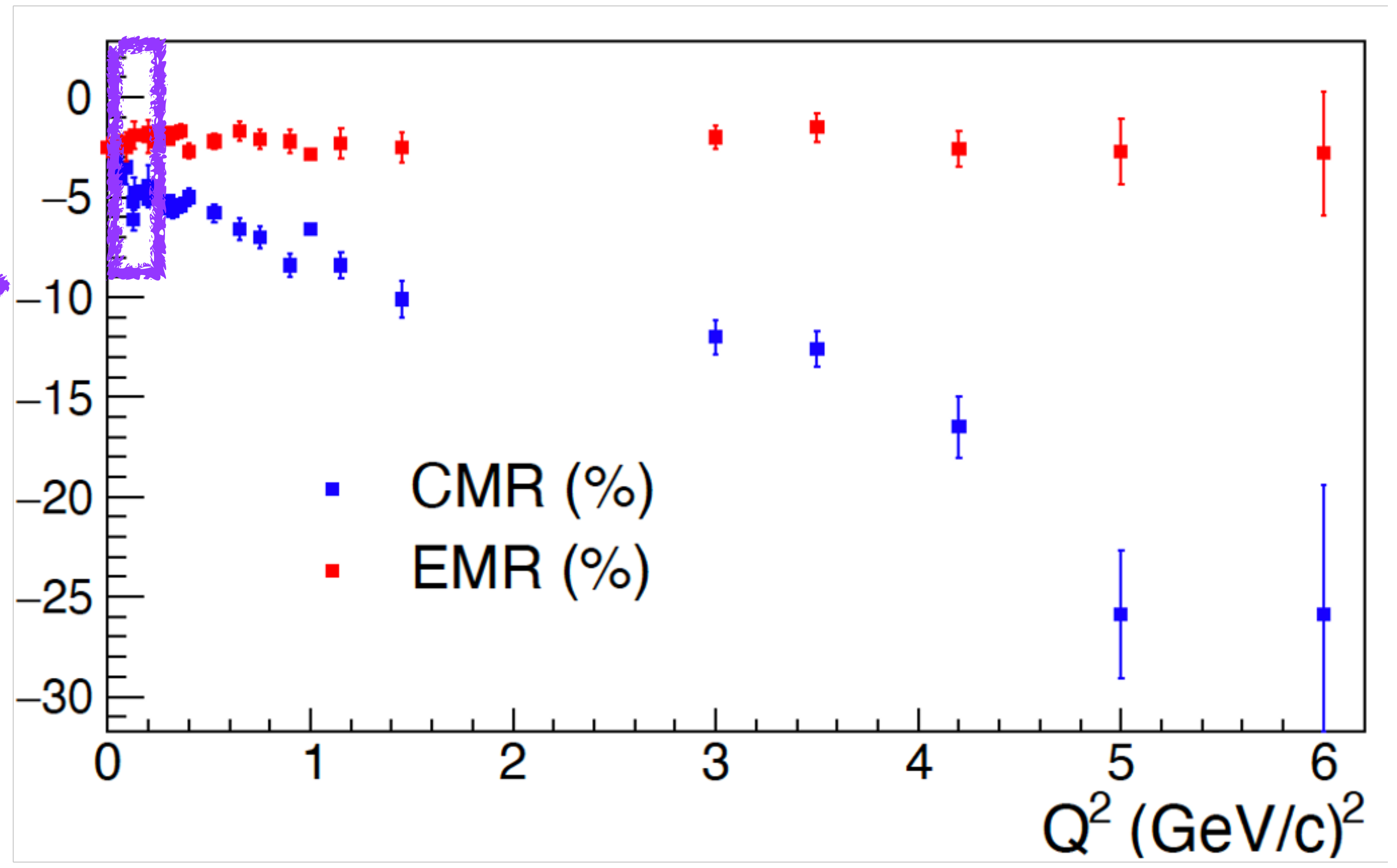
At large Q^2, no direct indication of EMR $\to$ 100% and CMR $\to$ constant (predicted in pQCD regime)

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 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.

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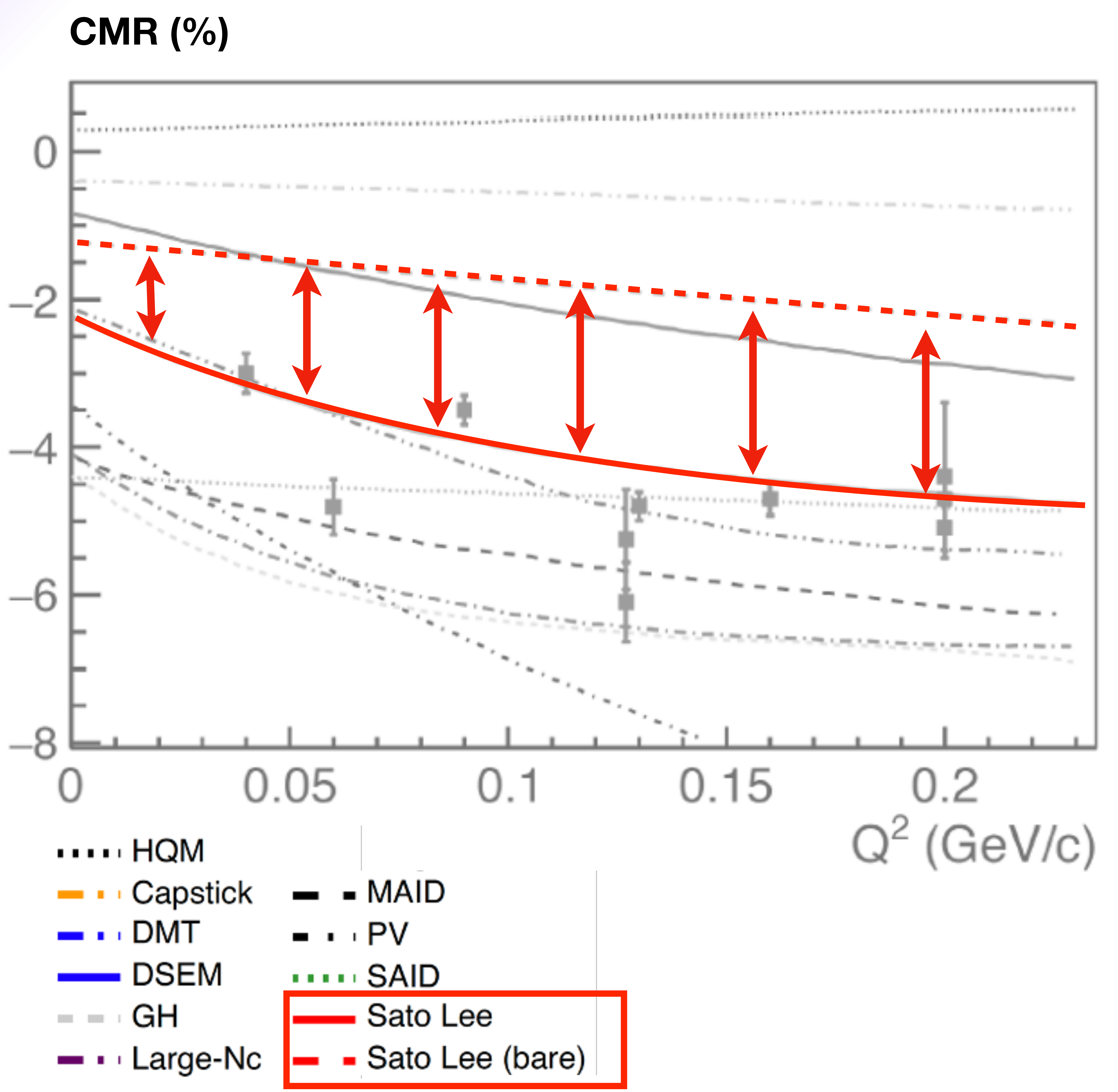

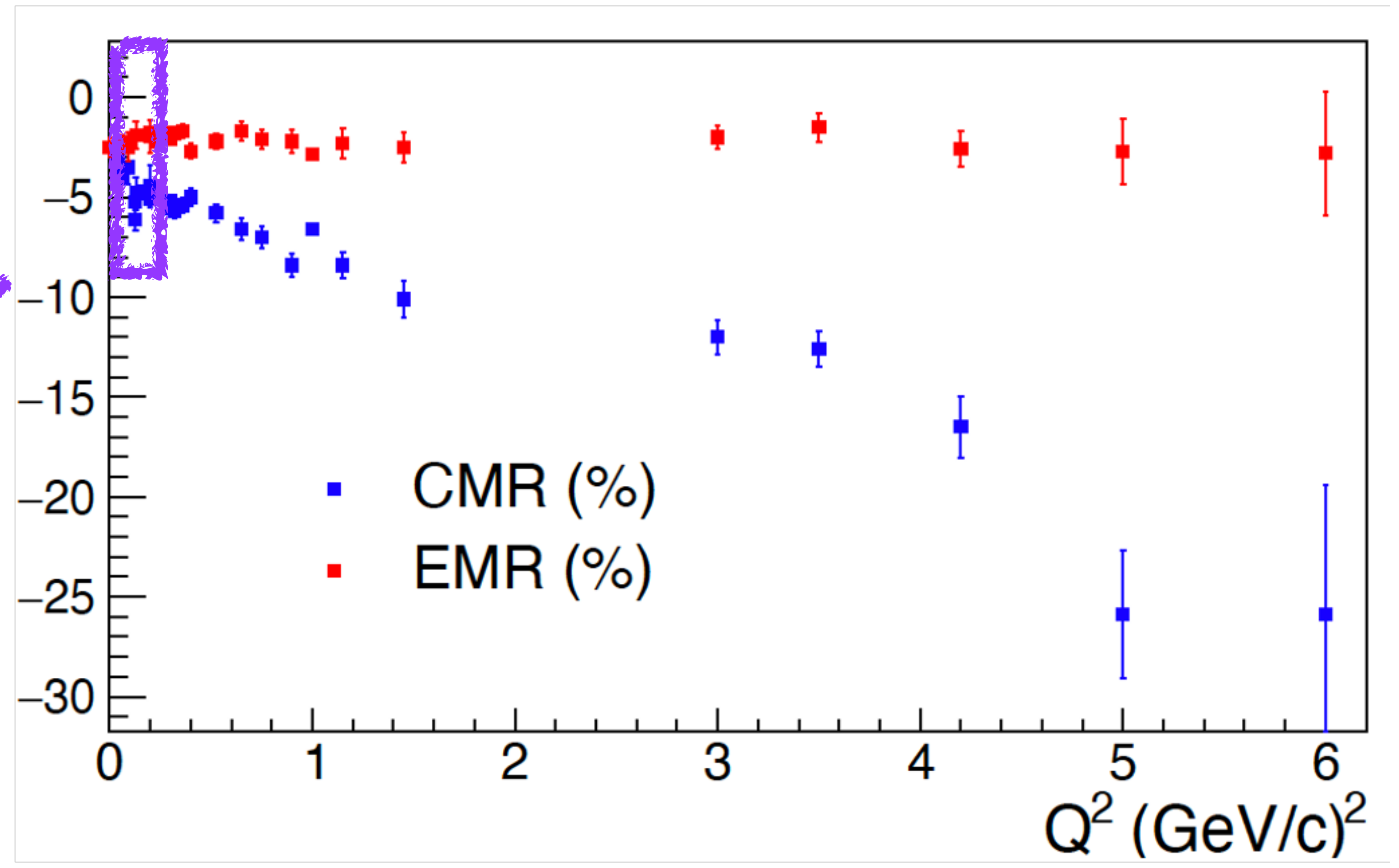

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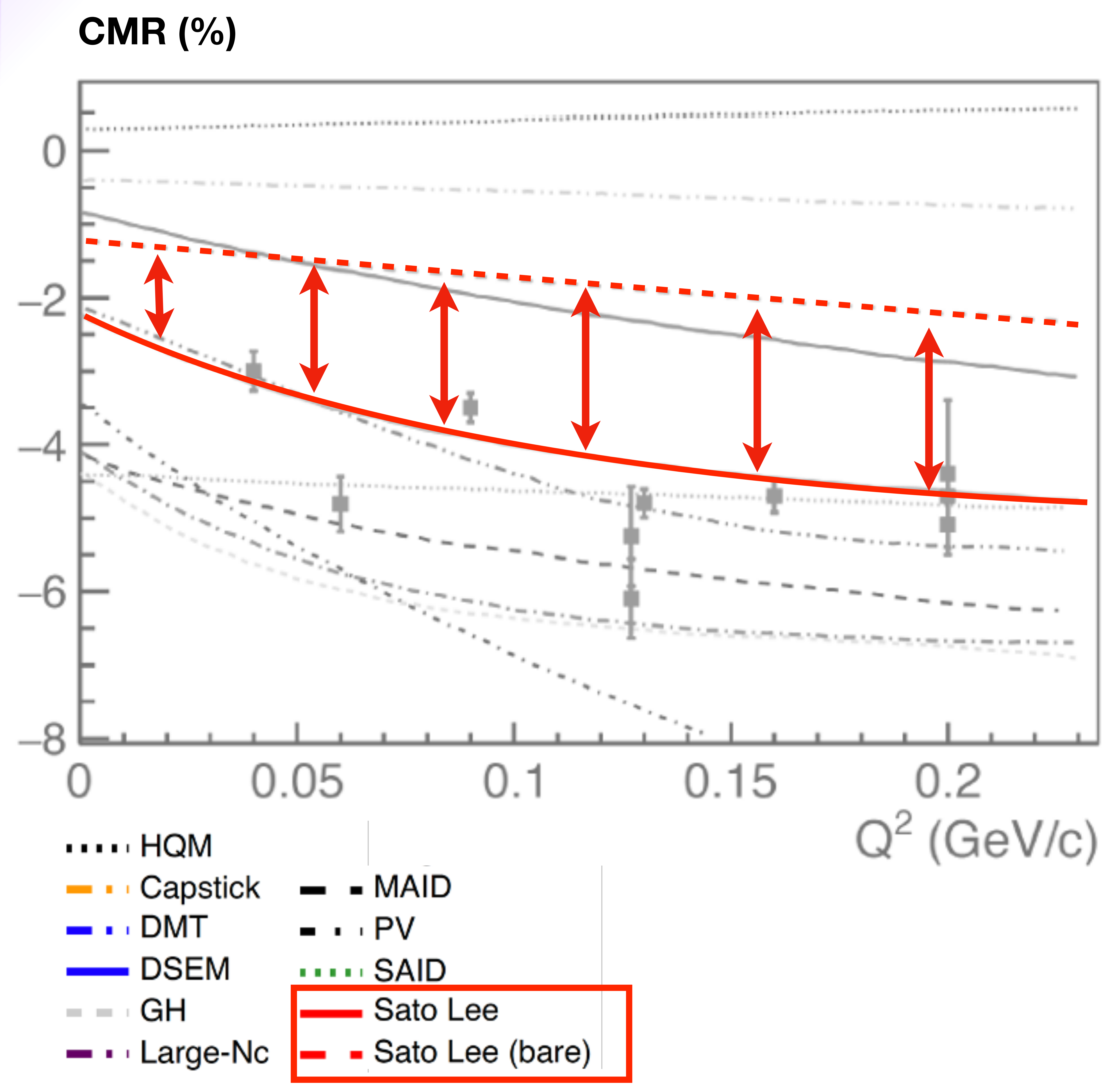
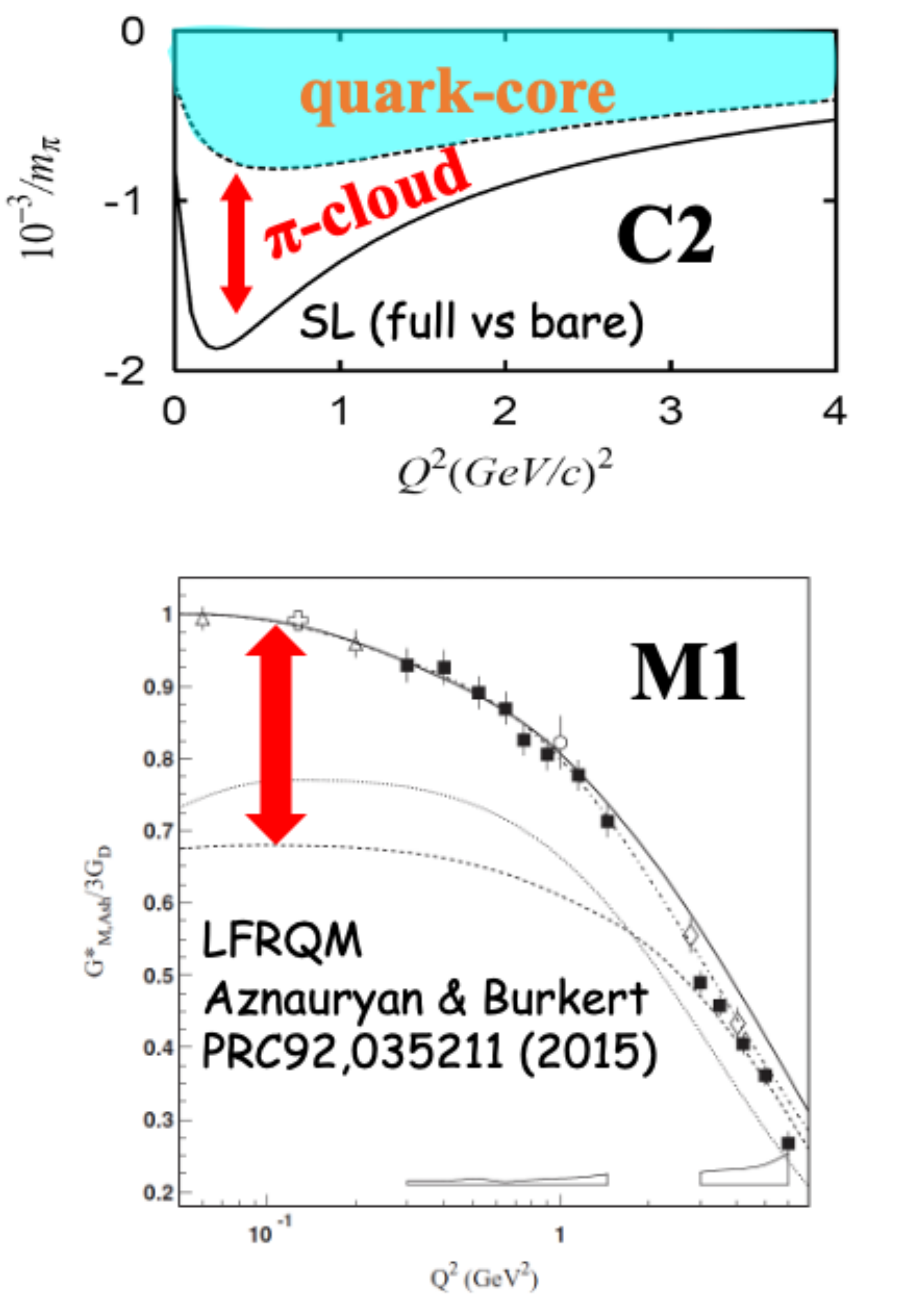




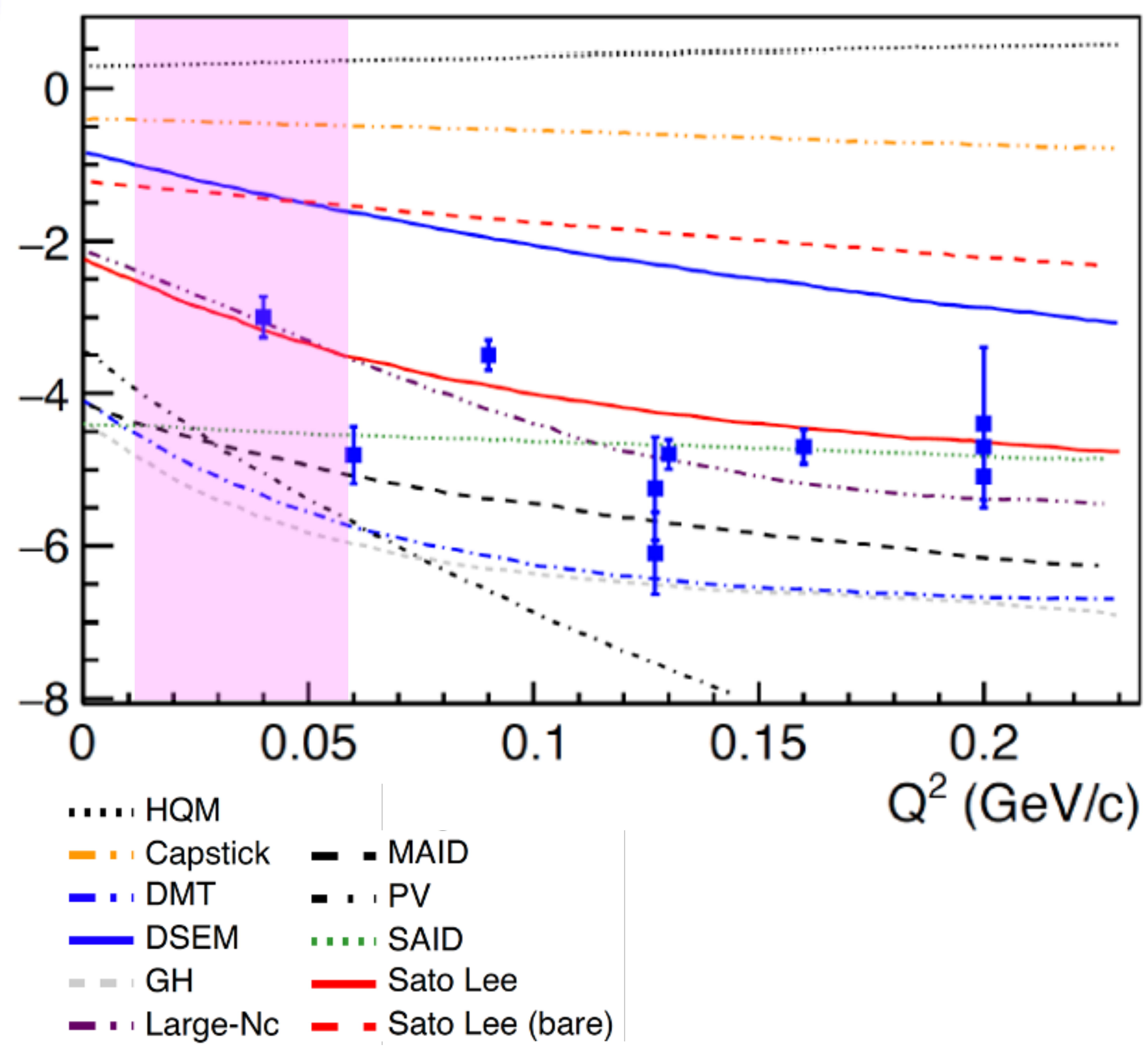
Signature of pion cloud

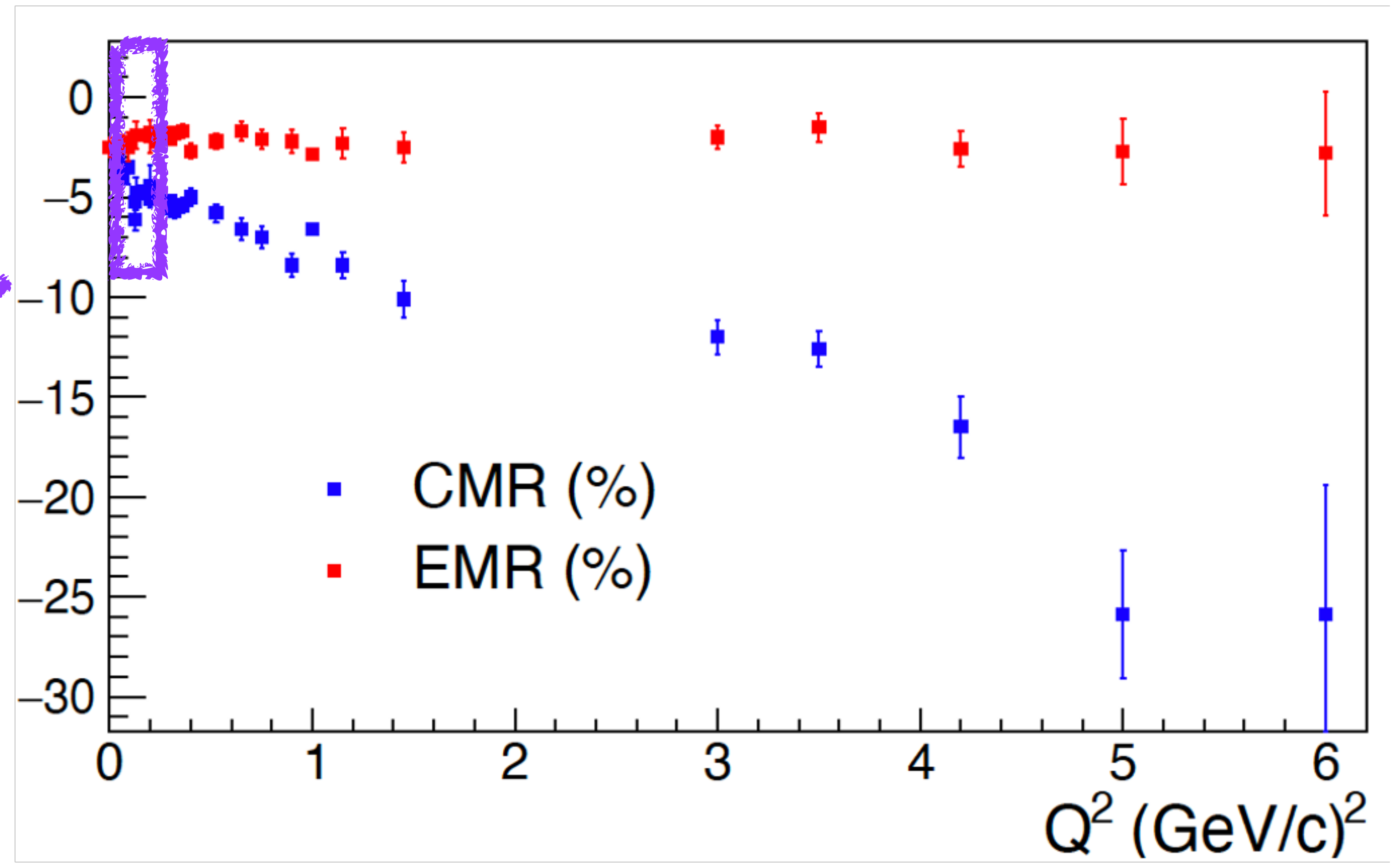
Dominant role of mesonic d.o.f. at large distance scale:

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

Low Q² N-Δ transition form factors

Region that new experiment will cover.





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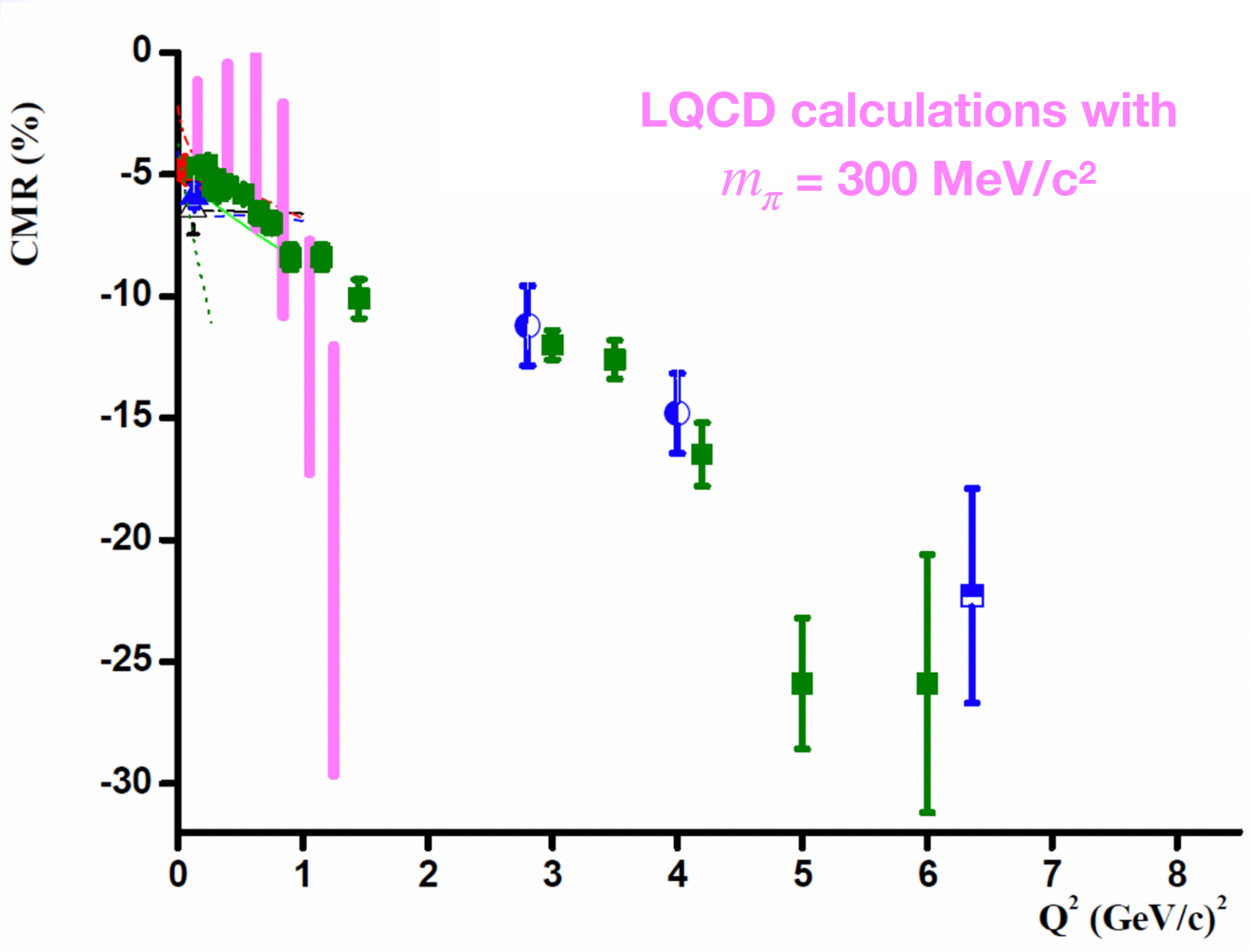
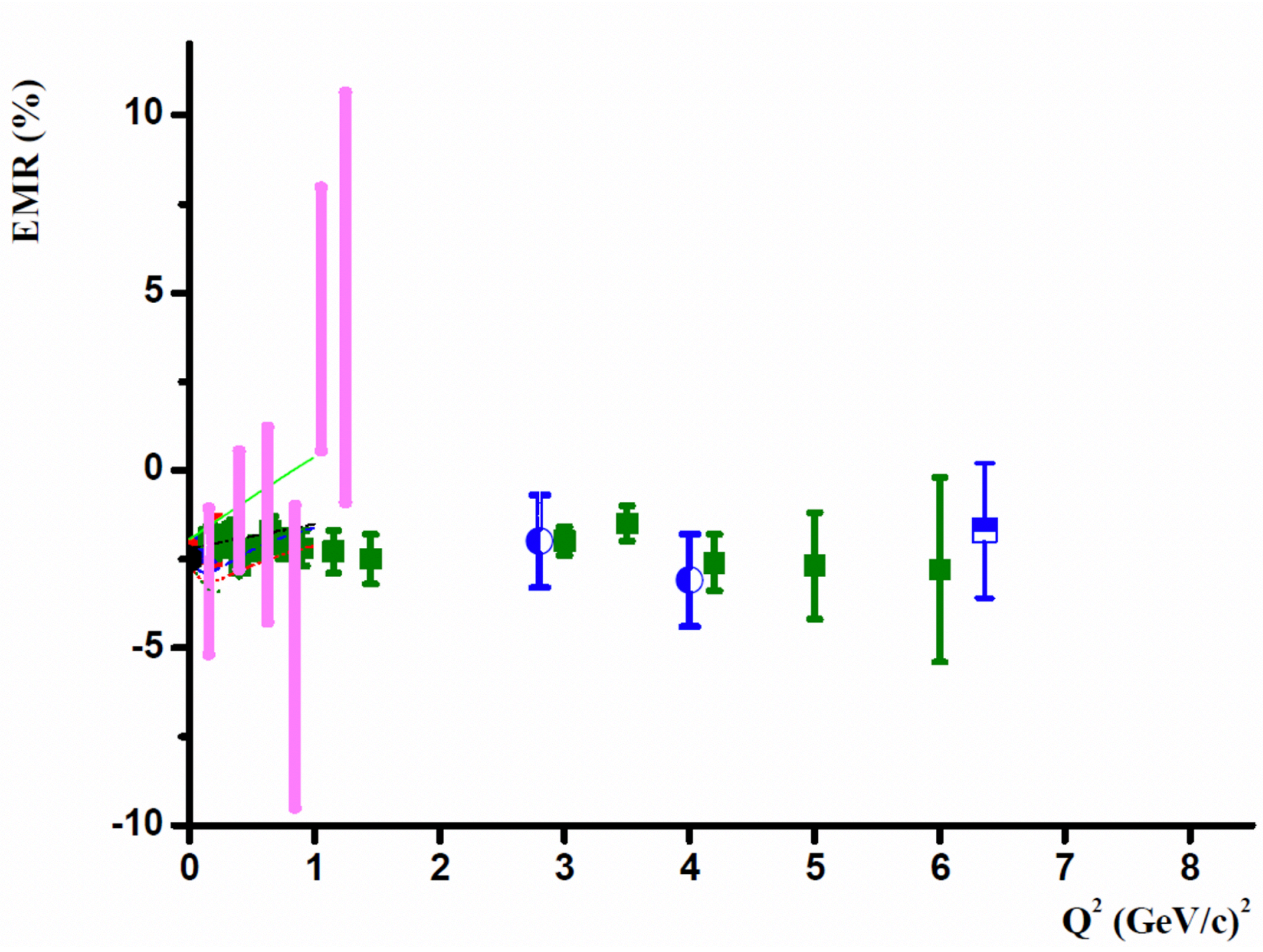
Lattice Calculations





- 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)

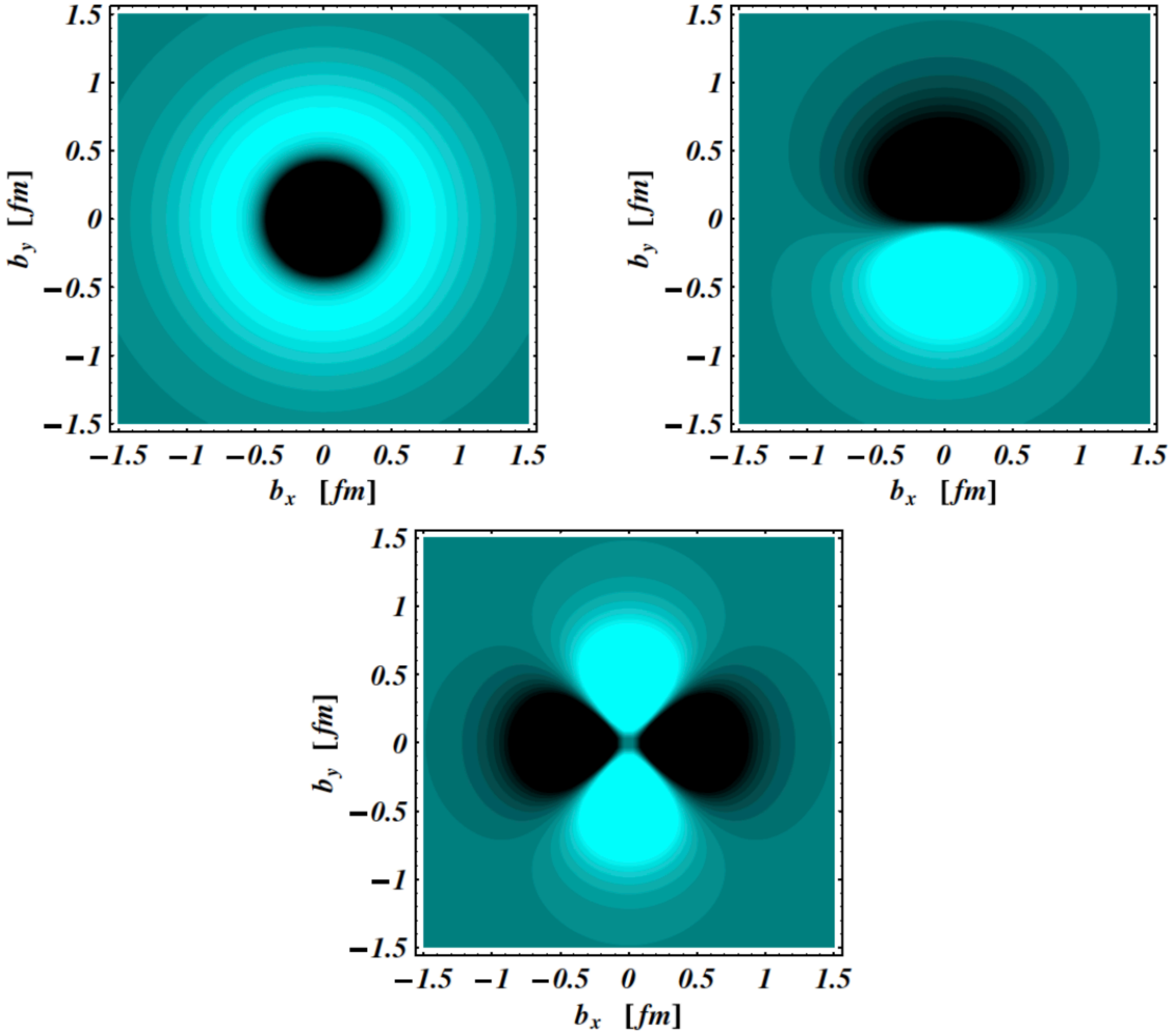


Fig. 18. Quark transverse charge density corresponding to the $p \to \Delta(1232)P_{33}$ e.m. transition. Upper left panel: p and Δ are in a light-front helicity +1/2 state ($\rho_0^{pP_{33}}$). Upper right panel: p and Δ are polarized along the x-axis ($\rho_T^{pP_{33}}$) as in Fig. 14. The lower panel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

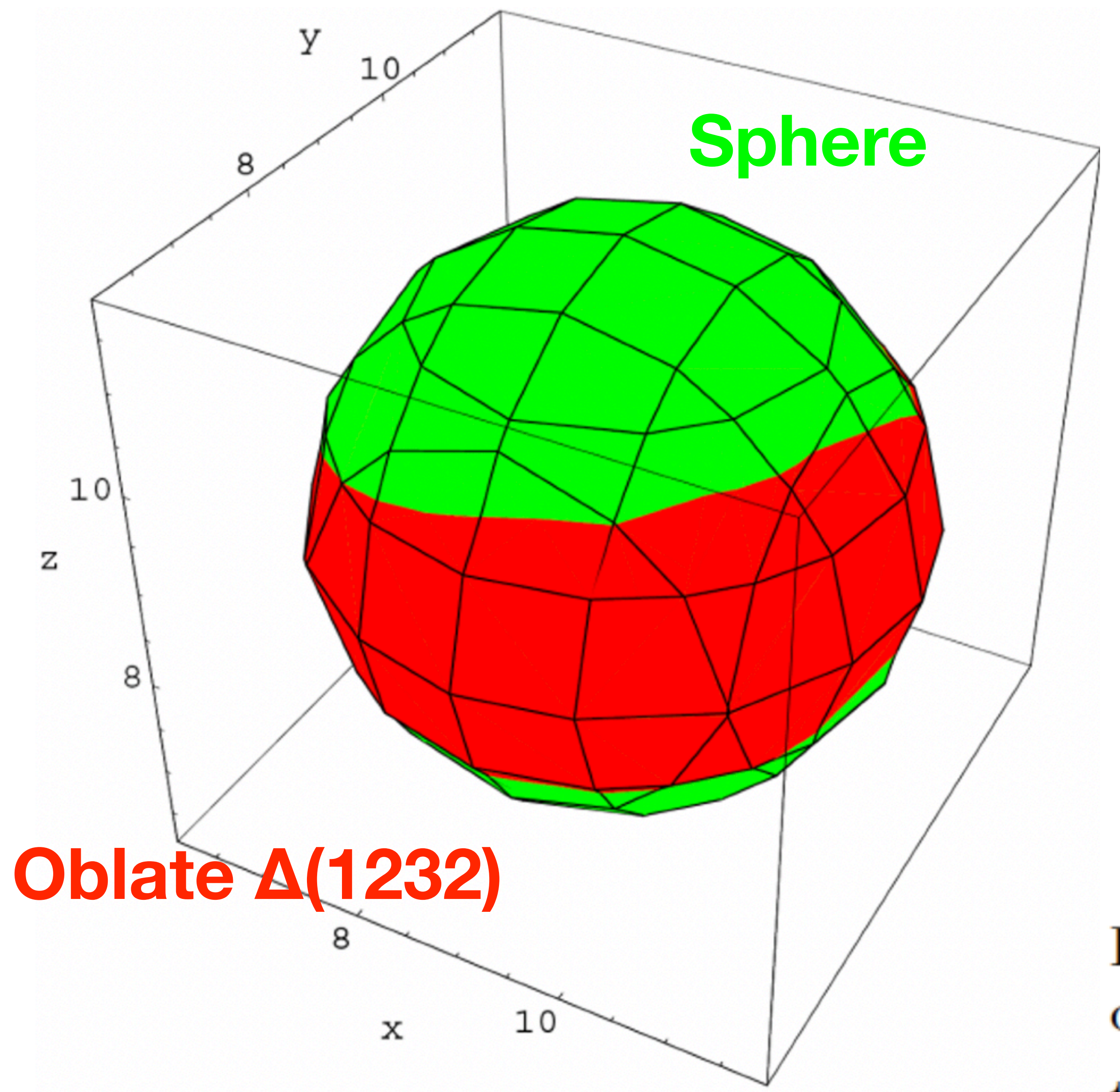


FIG. 18. Three-dimensional contour plot of the correlator (black): upper for the rho state with 0 spin projection (cigar shape) and lower for the Δ^+ state with +3/2 (slightly oblate) spin projection for two dynamical quarks at $\kappa = 0.156$. Values of the correlator (0.5 for the rho, 0.8 for the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

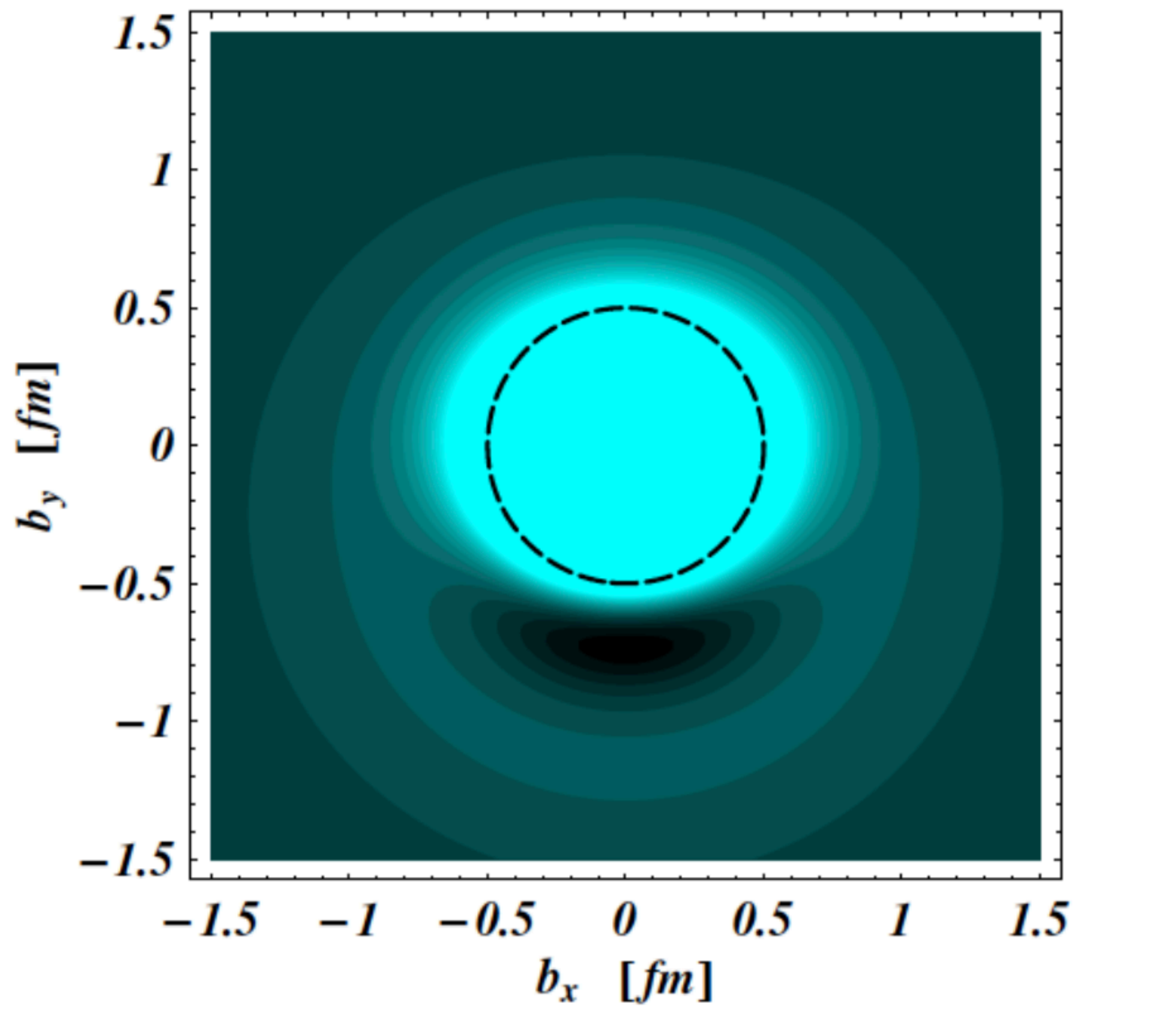
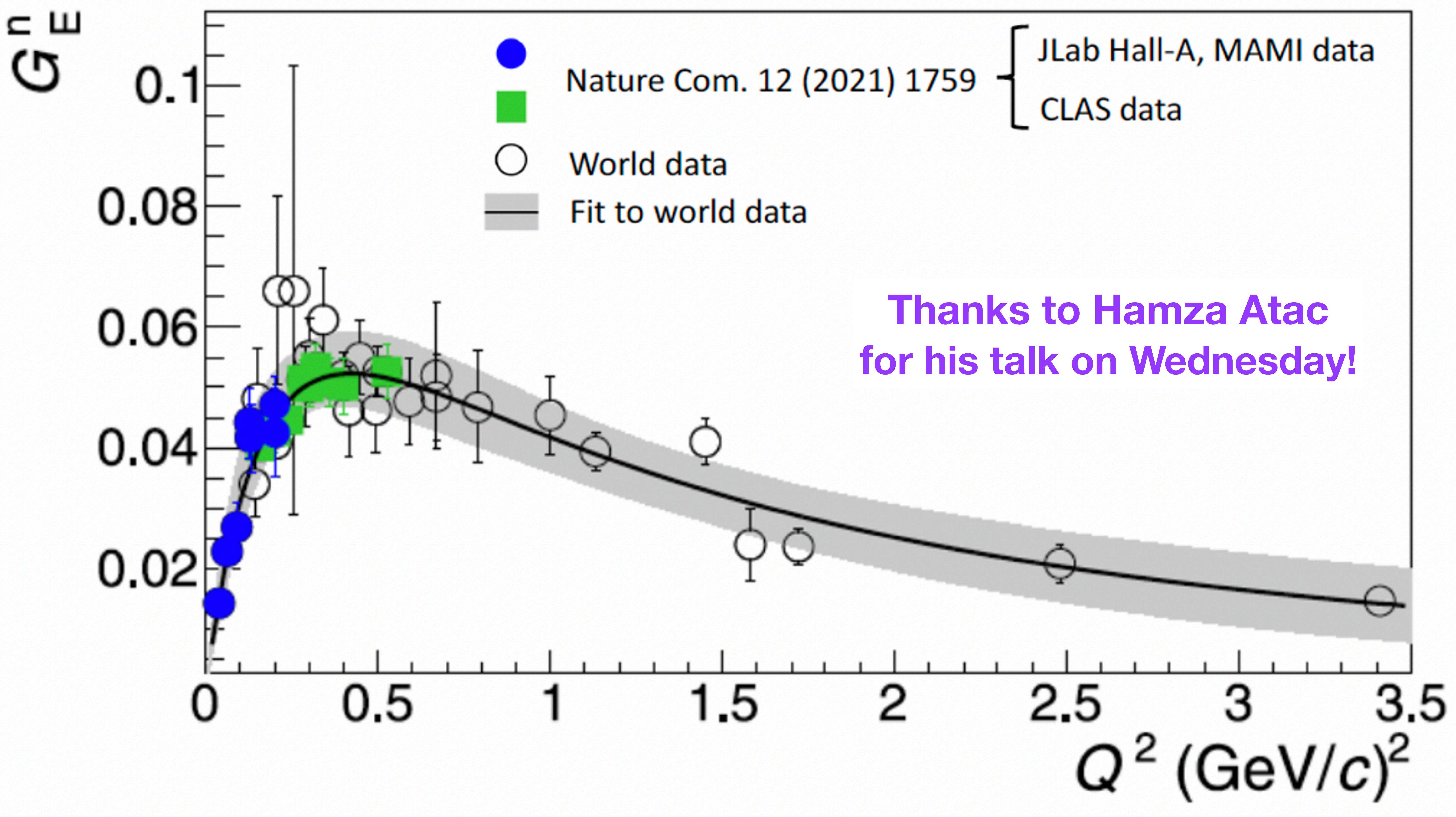


FIG. 10: Lattice QCD results for the quark transverse charge density $\rho^{\Delta}_{T\,\frac{3}{2}}$ in a $\Delta^+(1232)$ which is polarized along the positive x-axis. The light (dark) regions correspond to the largest (smallest) values of the density. In order to see the deformation more clearly,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

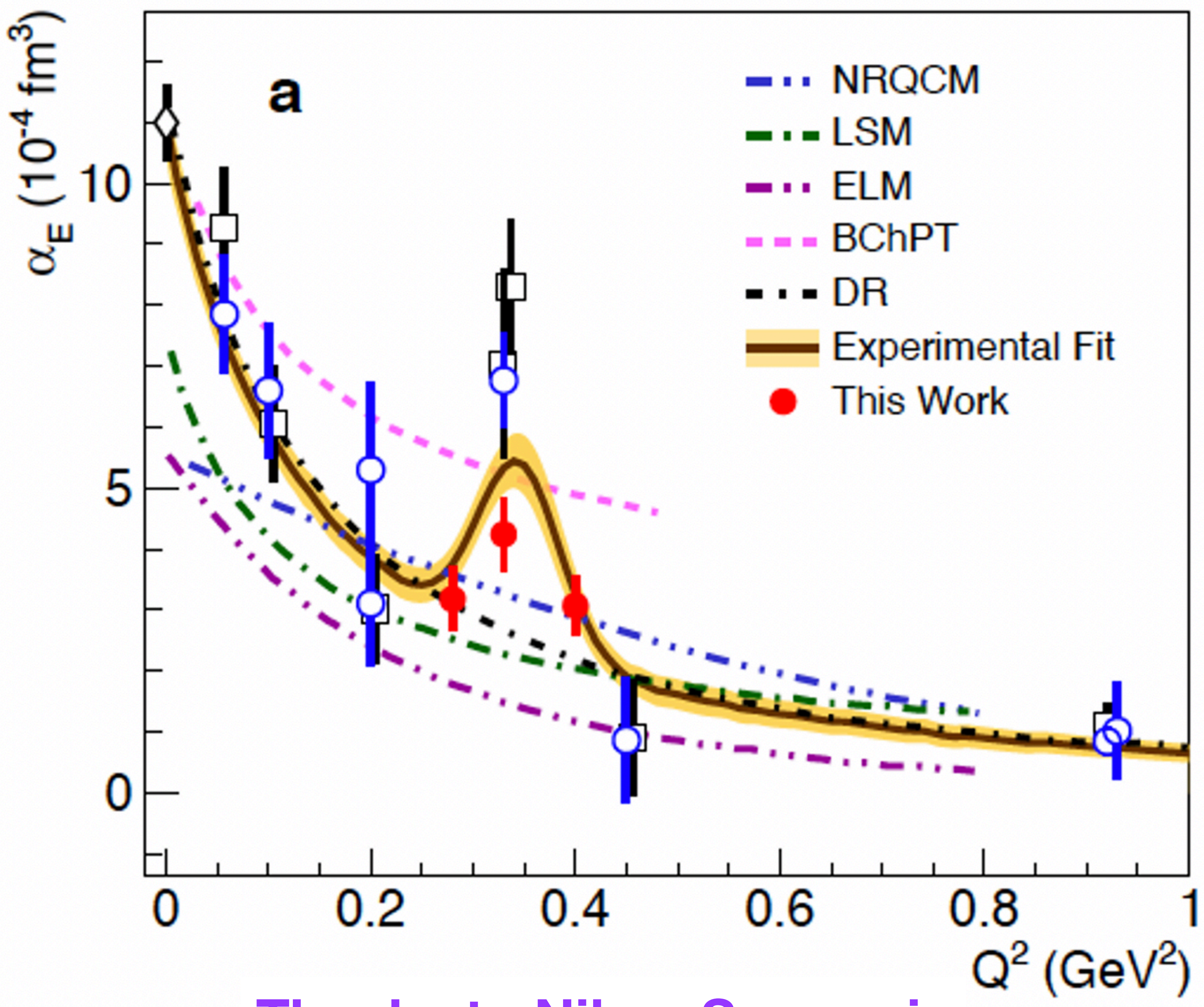
- G_E^n extraction from TFFs show strong agreement with world data.
  - Allows access to low-Q^2 region where direct measurement of G_E^n is difficult.
  - The relations receive theoretical corrections that can be analyzed and confronted with experimental data e.g. they can be analyzed in a theoretical framework that combines ChPT with the 1/Nc expansion.



Thanks to Hamza Atac for his talk on Wednesday!

Impact on other domains of nuclear physics

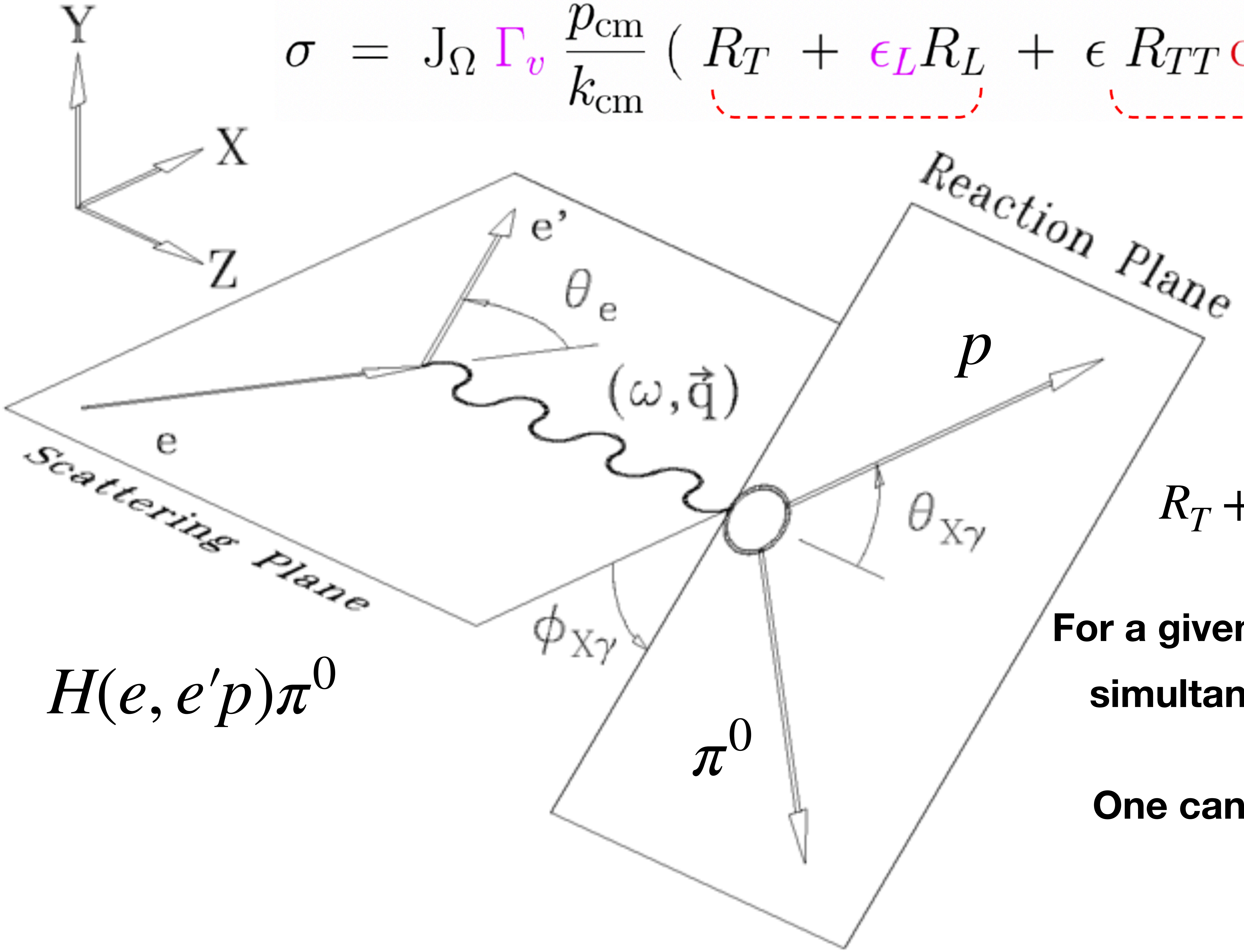
- Generalized polarizabilities (GPs) of the proton:
  - The TFFs enter as an input in the VCS cross section over the Δ resonance region – their precise knowledge is necessary for the precise extraction of the GPs from the measured cross sections
  - Physics of interest:
    - Electric polarizability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



Thanks to Nikos Sparveris for his talk on Monday!

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

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

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

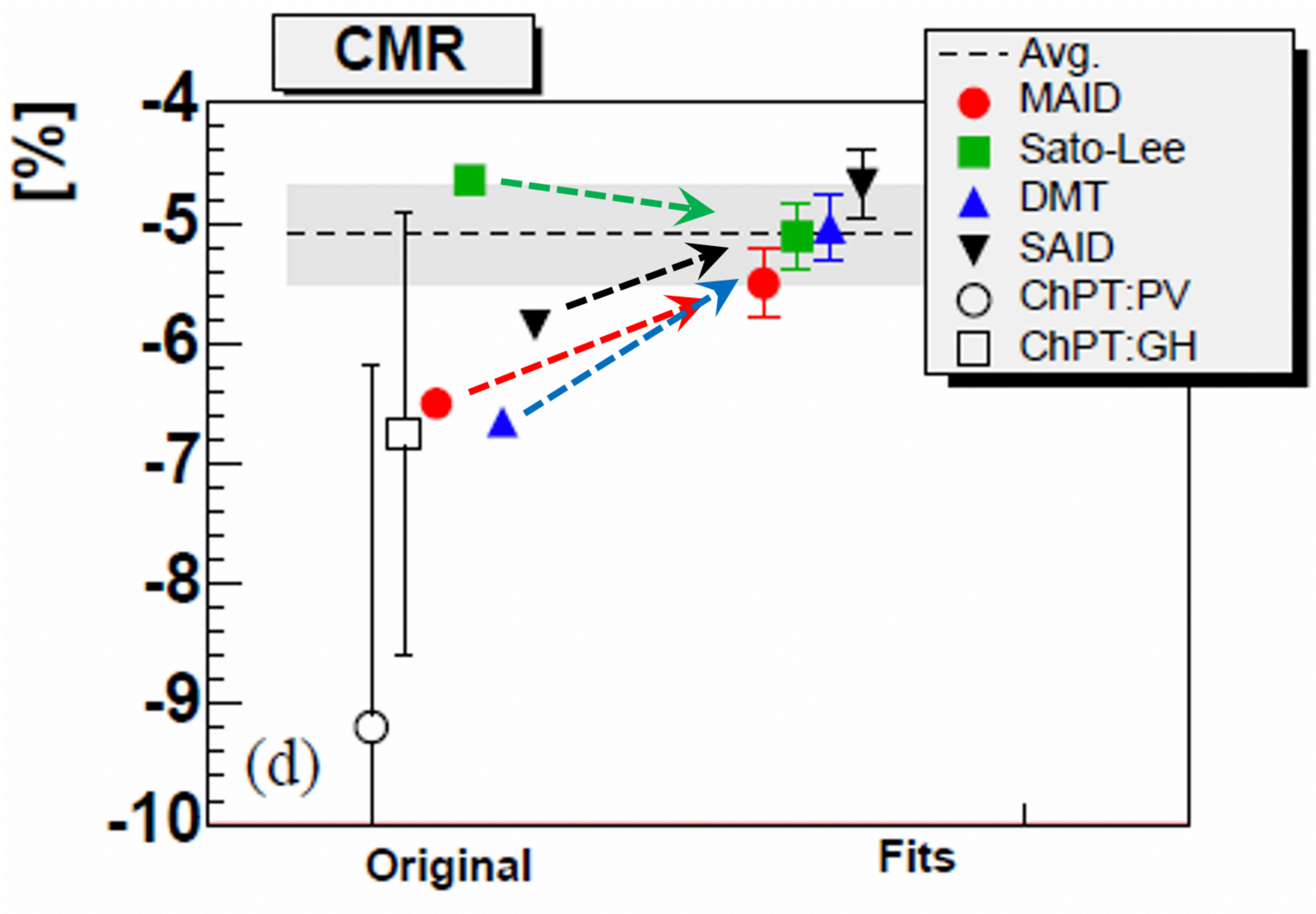
$$R_T + R_L = M1^2 + \ldots\Sigma_{\text{background}}$$

$R_{TT} \rightarrow$ **sensitive to the EMR**

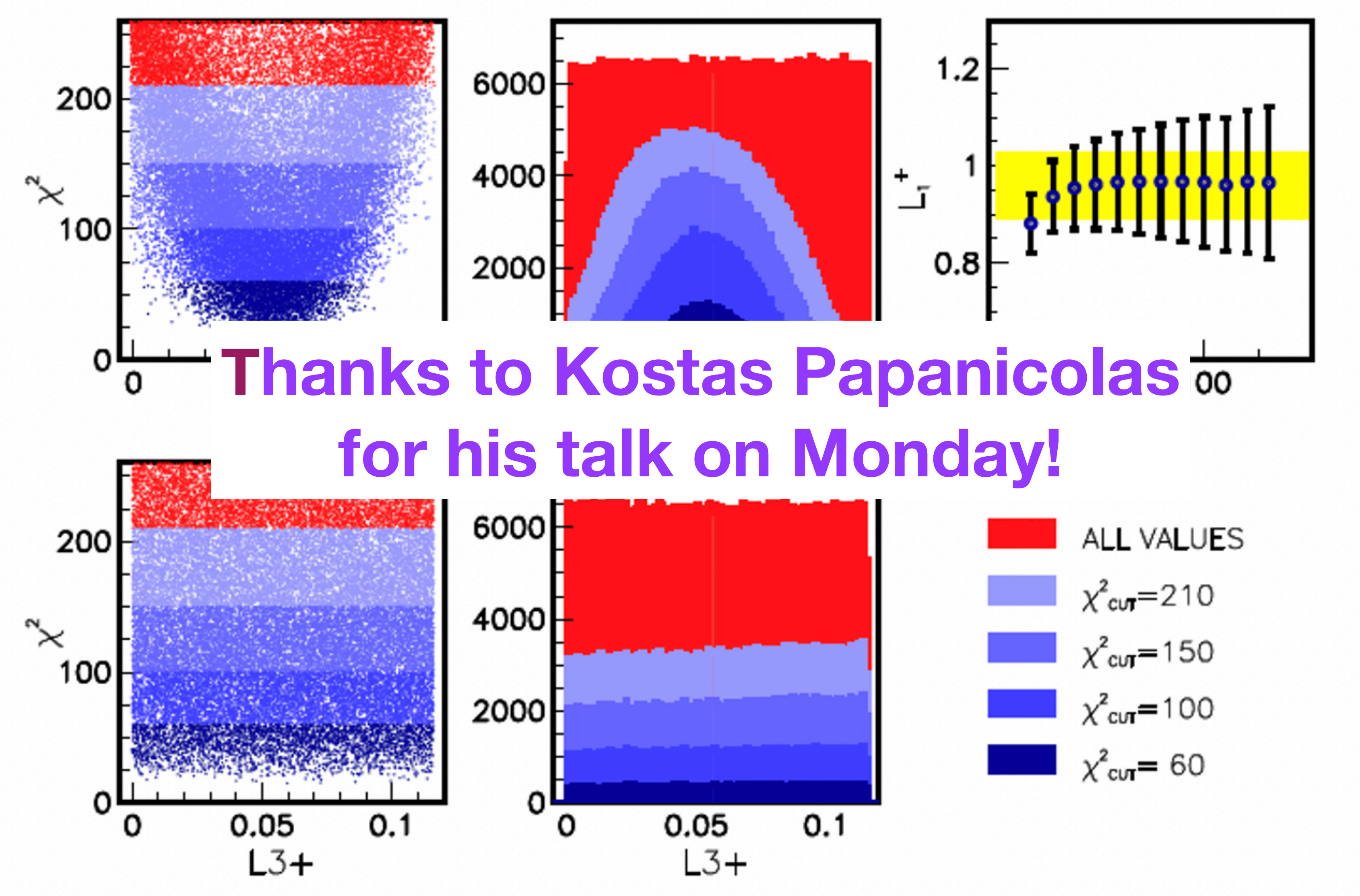
$R_{LT} \rightarrow$ **sensitive to the CMR**

$R_T + R_L \rightarrow$ **sensitive to $M1$**

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

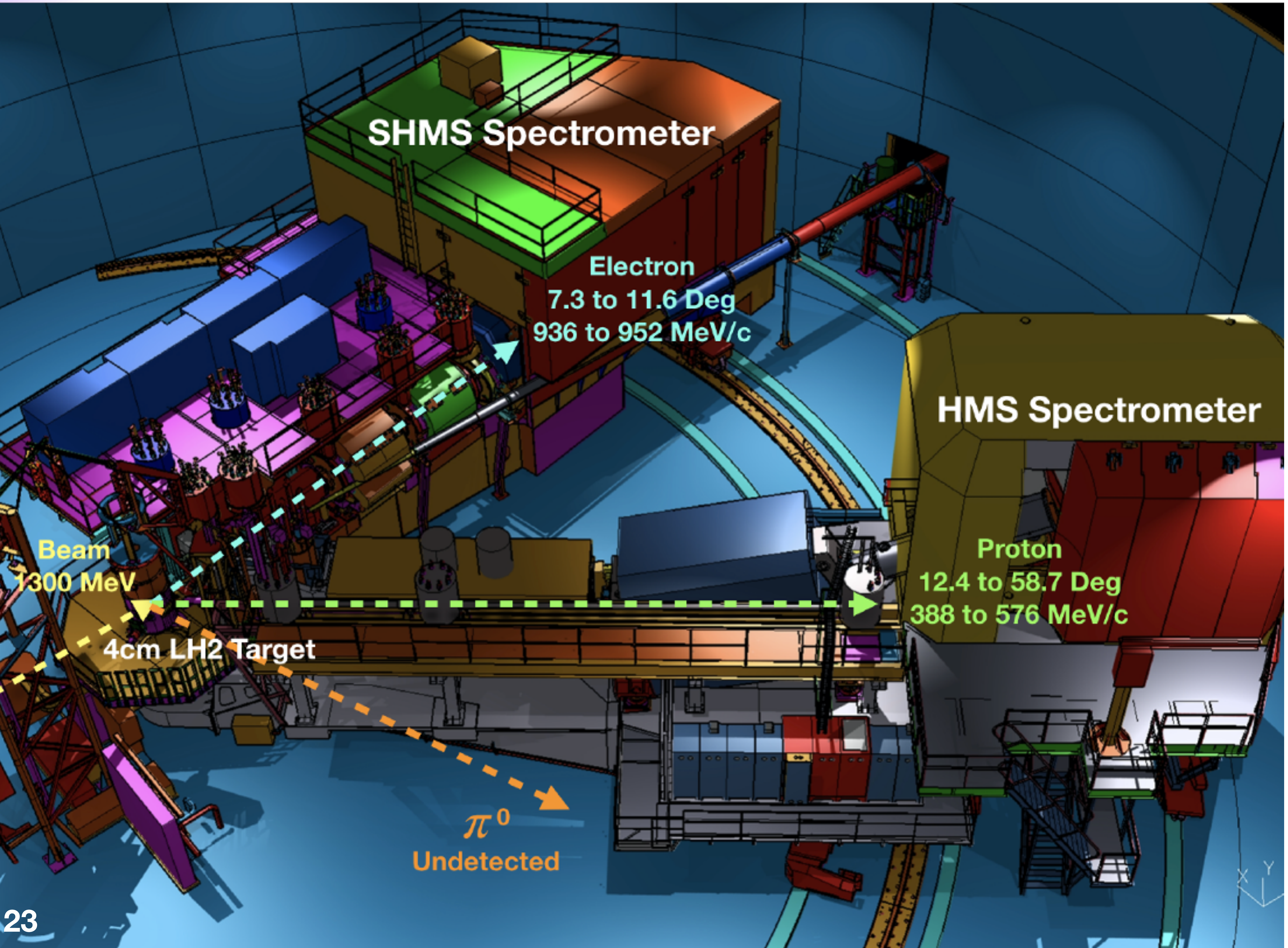


Use model independent statistical methods to identify and determine with maximal precision parameters that are sensitive to the data: AMIAS (Eur. Phys. J. A 56 (2020) 10, 270)

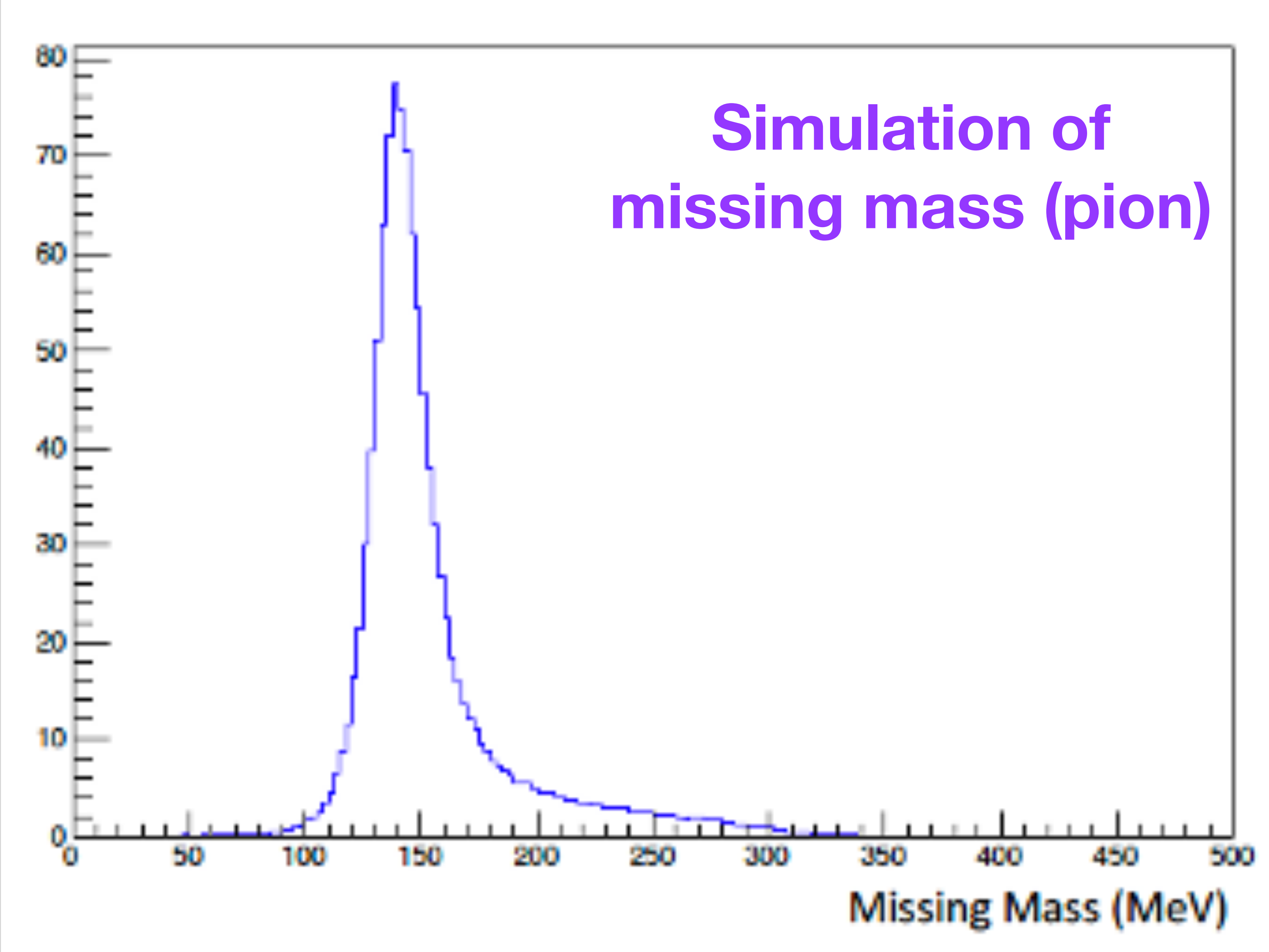


Thanks to Kostas Papanicolas for his talk on Monday!

Proposed to PAC49 and PAC50: low-Q2 TFF measurements in Hall-C



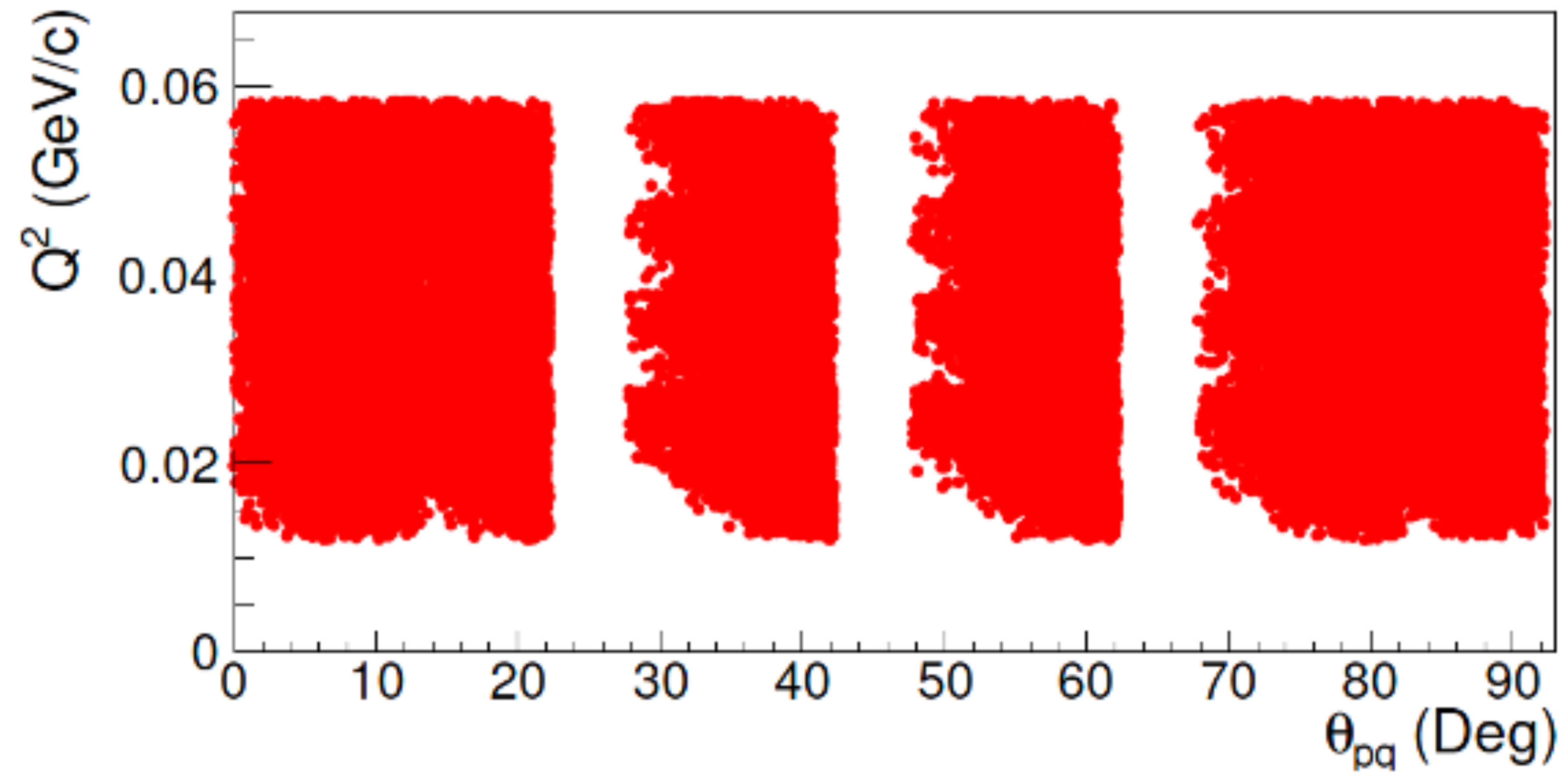
- **Standard Hall-C equipment**
  - 1300 MeV electron beam
  - Detect proton and electron in coincidence
  - Reconstruct pion from missing mass.



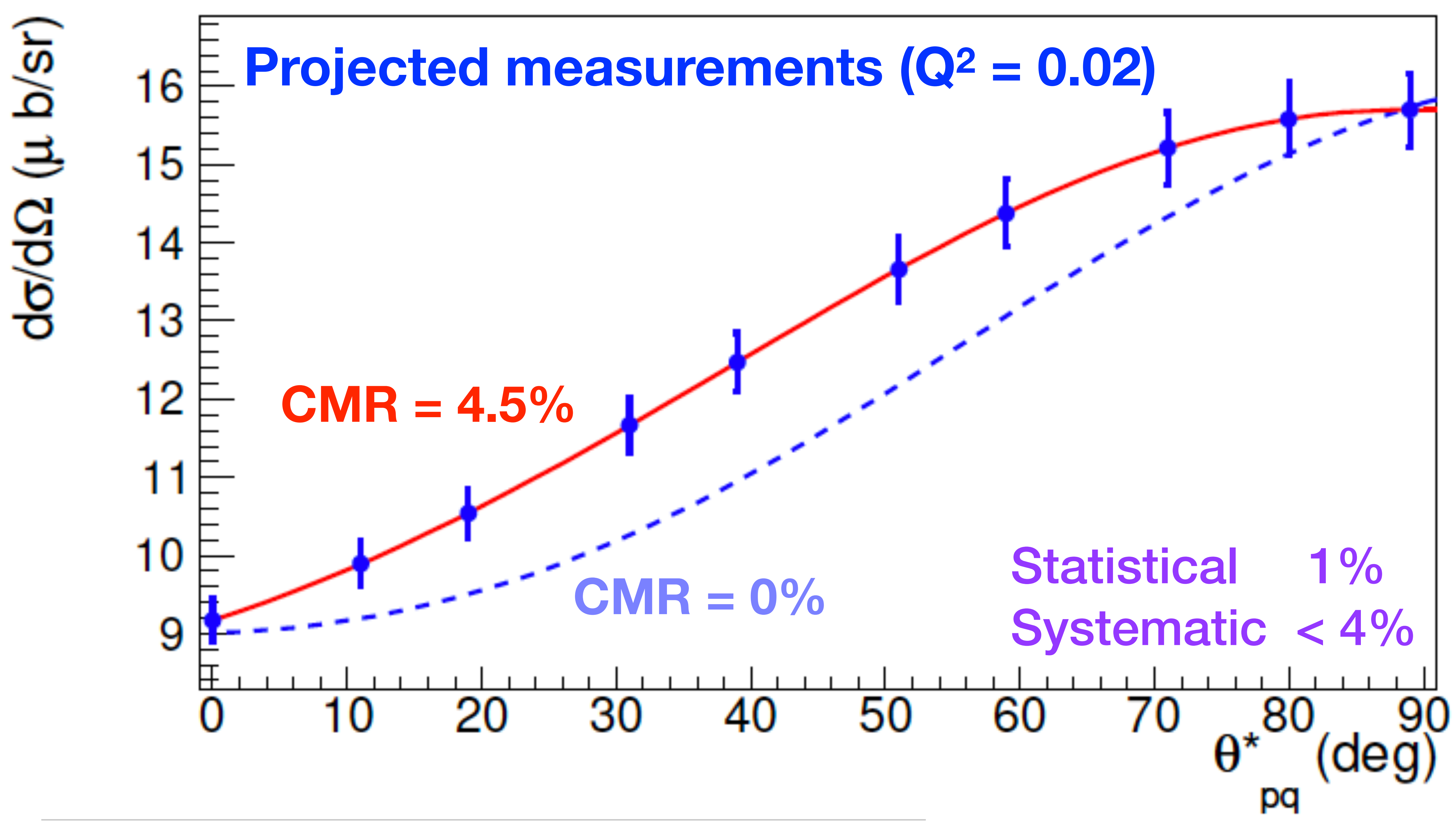
Measurement Settings

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..)

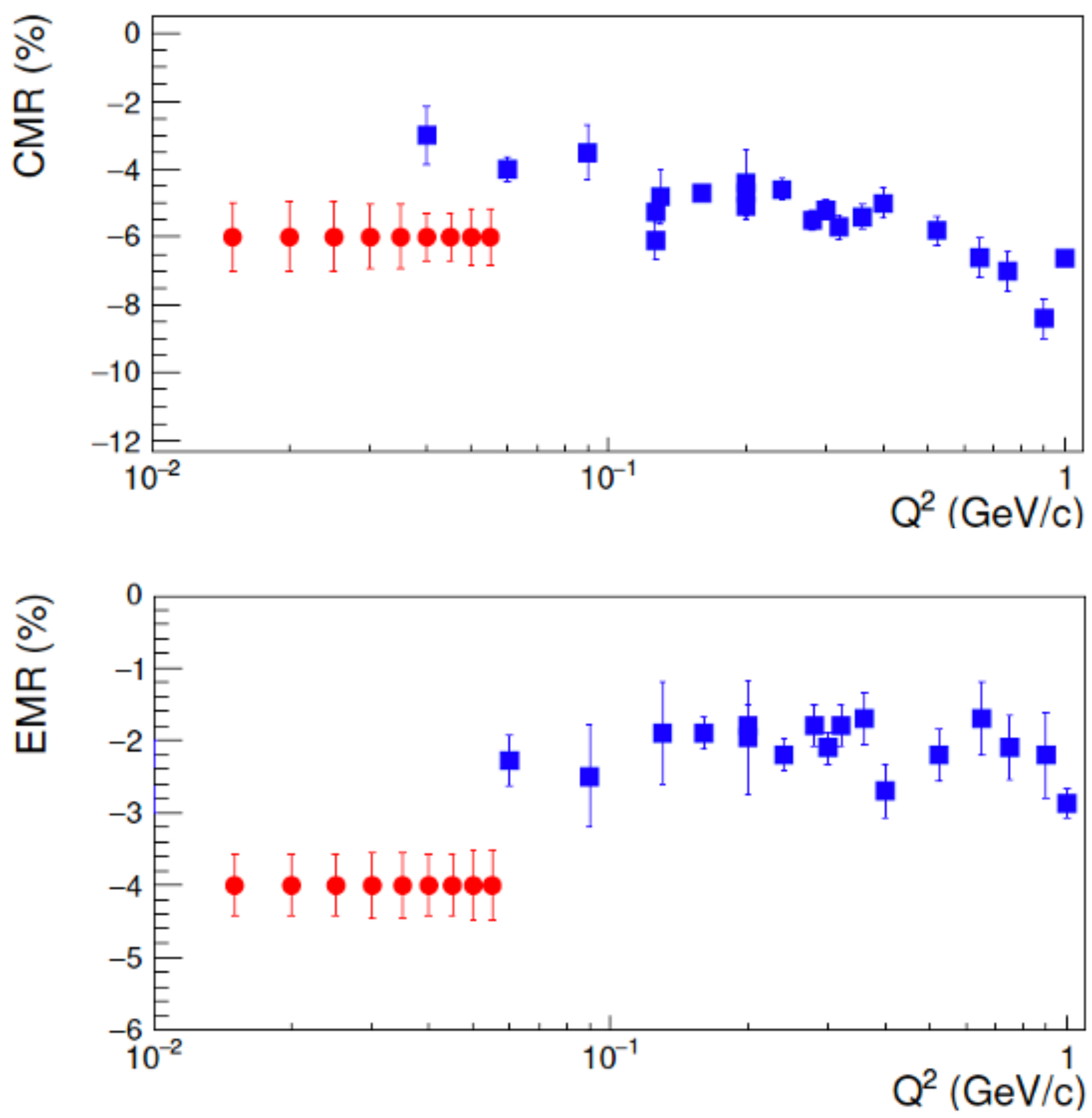


Projected CMR and EMR measurements



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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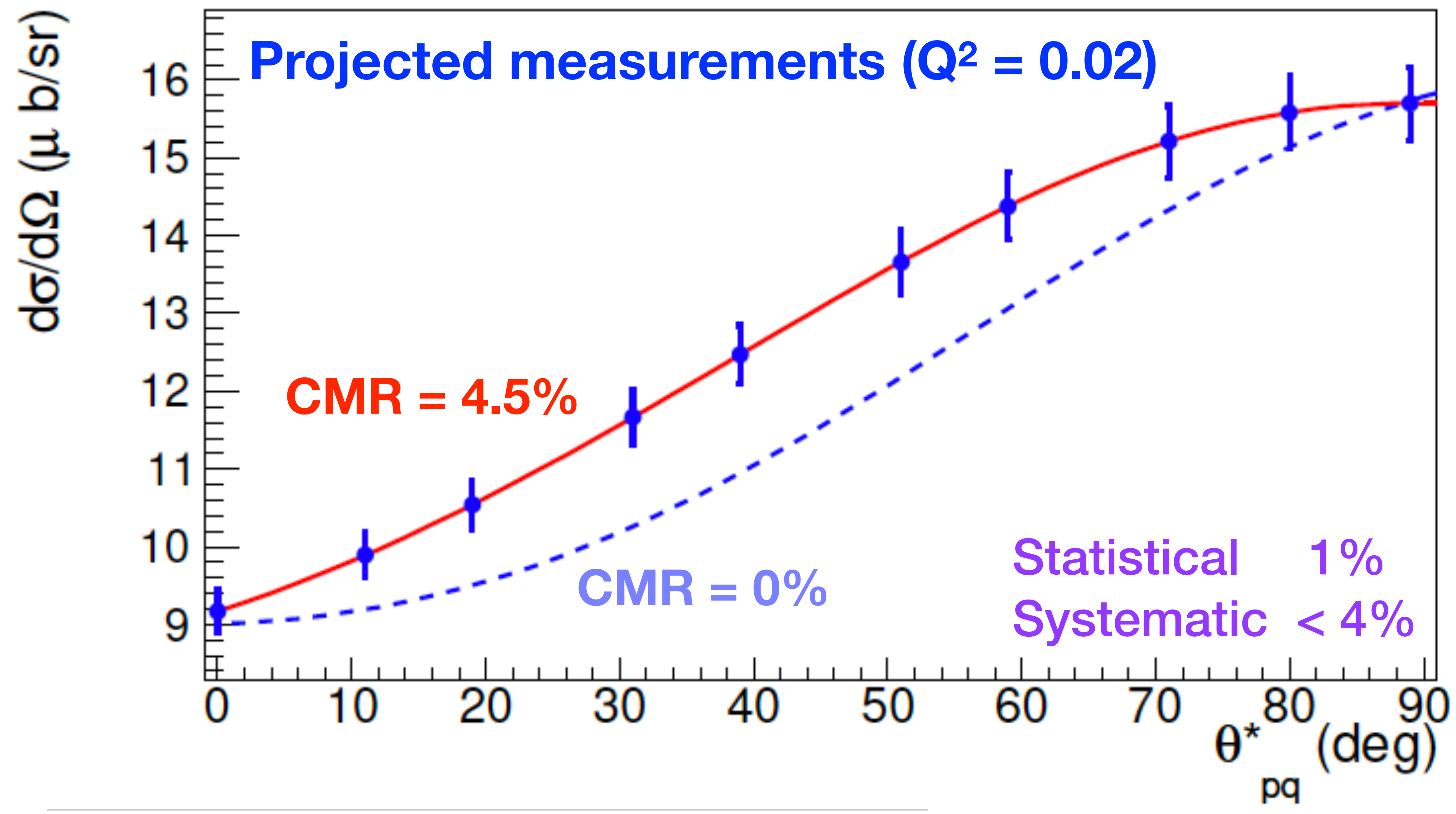

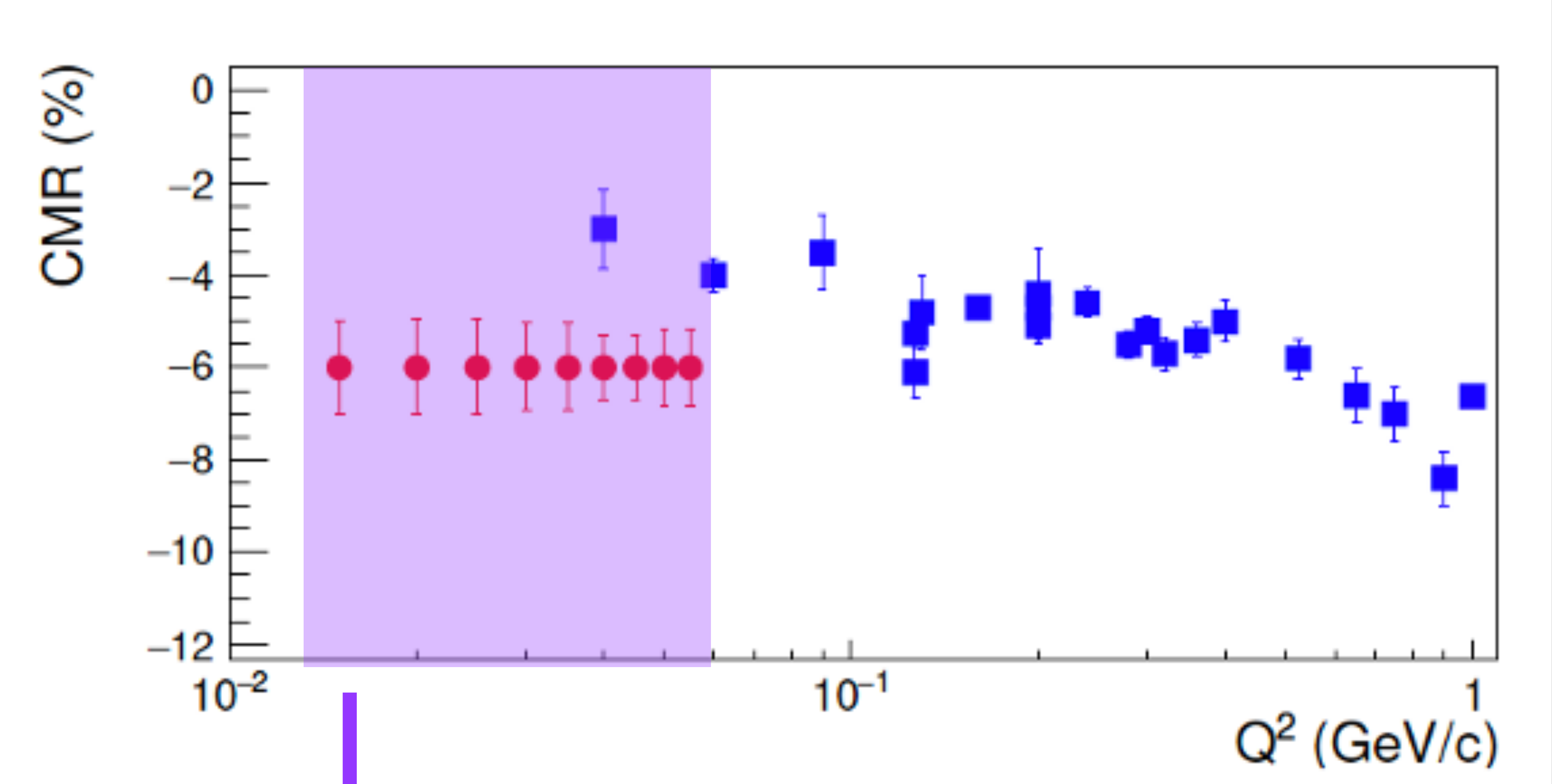

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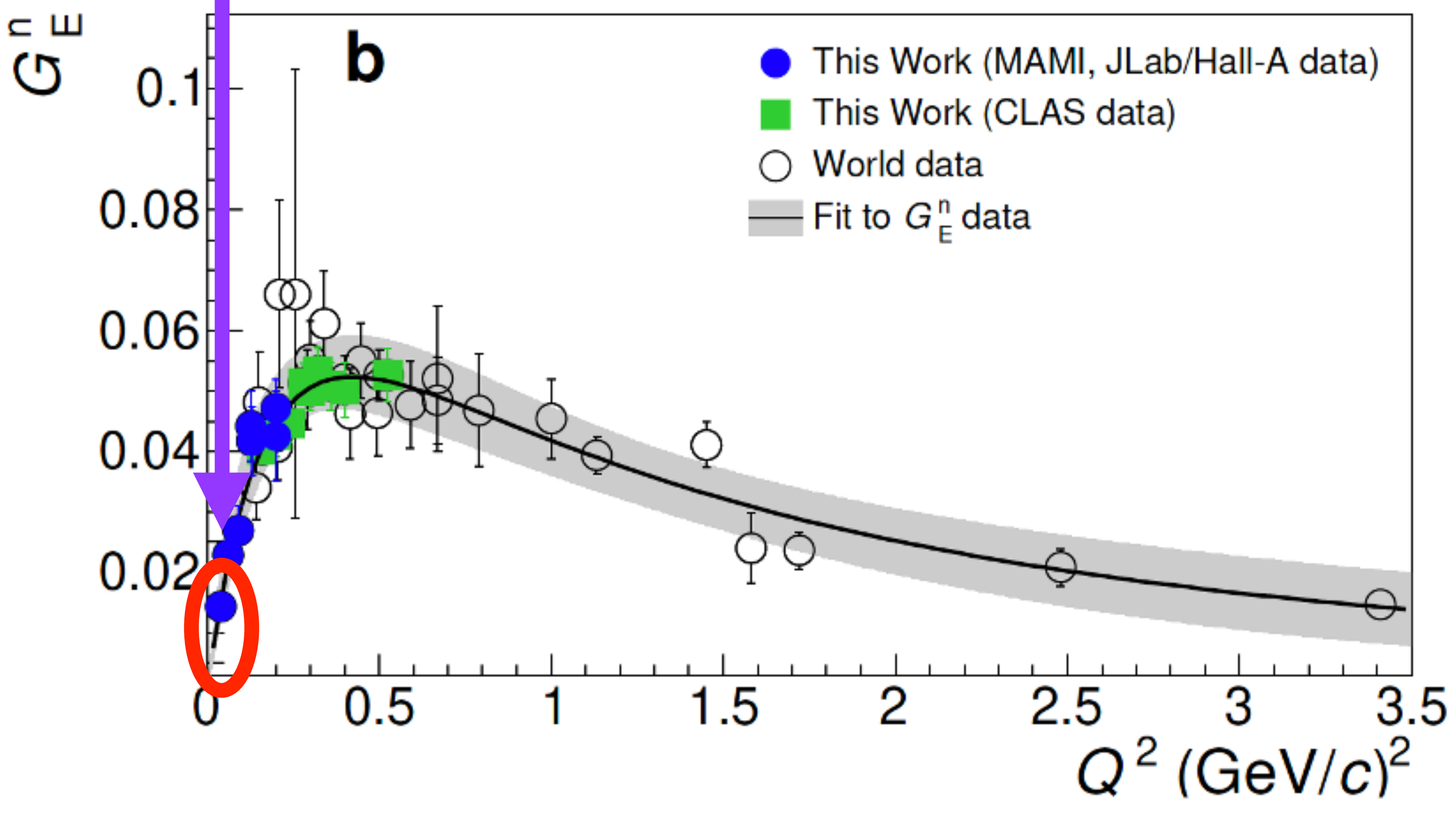
Proposed to PAC49: Extraction of Neuton Charge Radius



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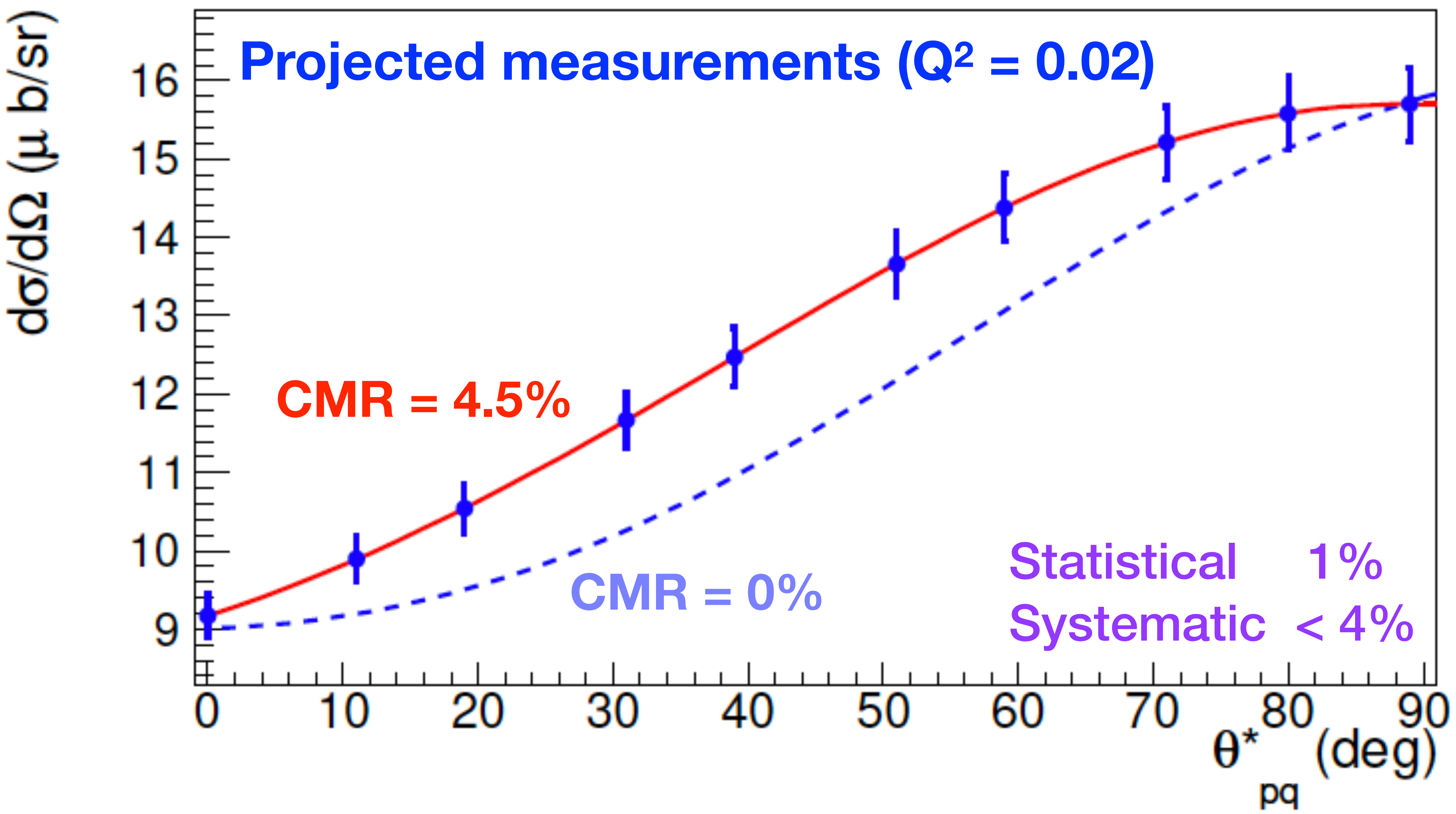

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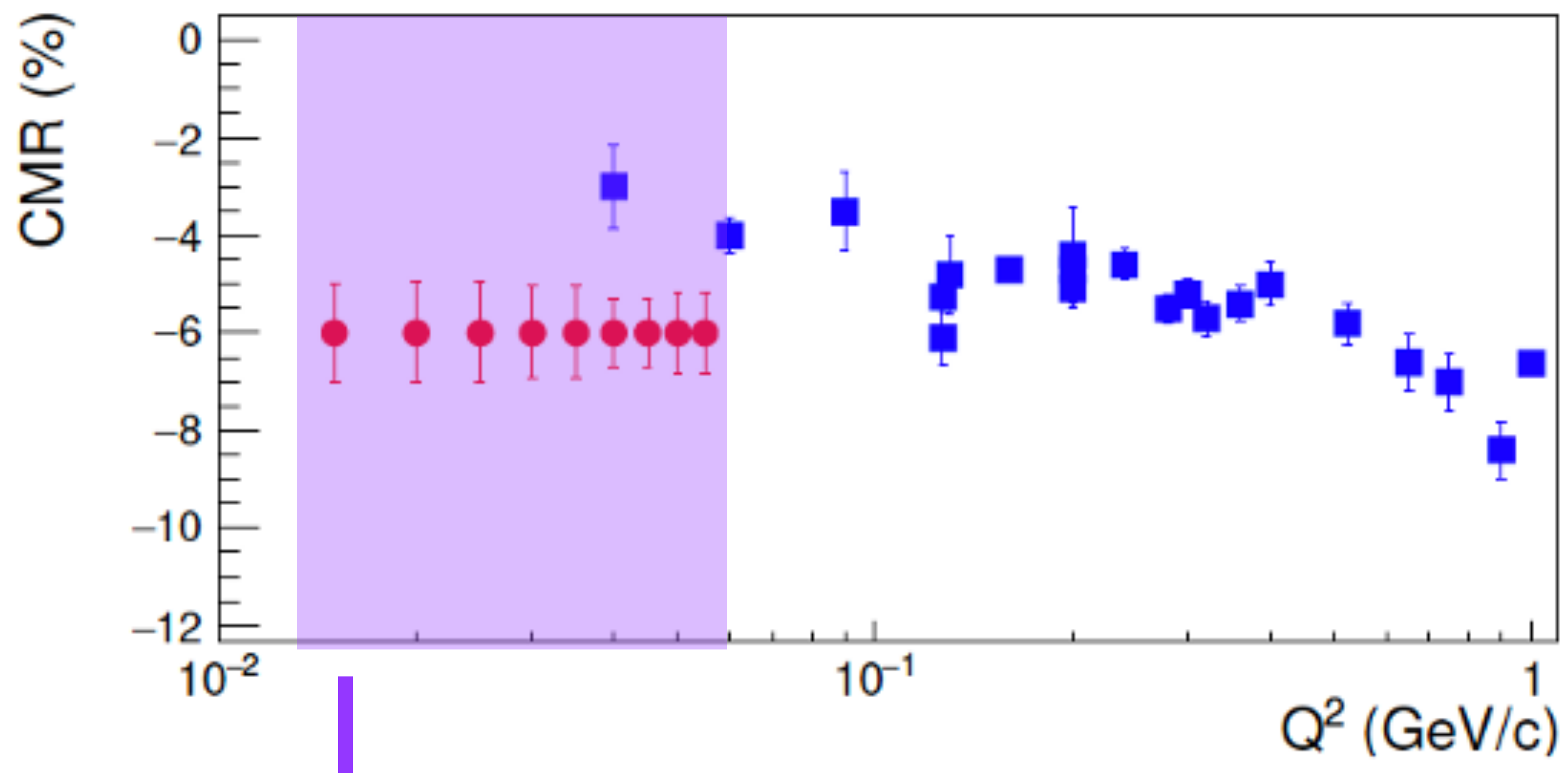

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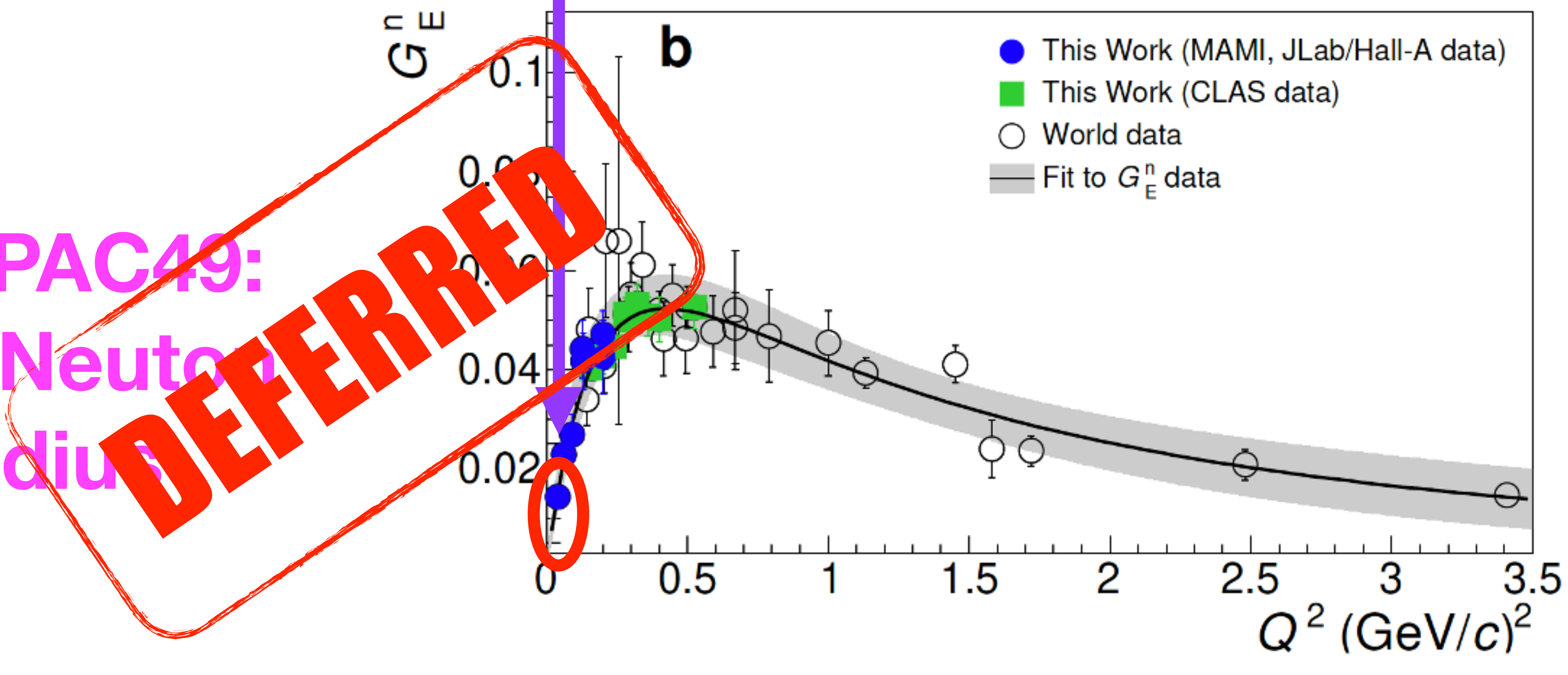
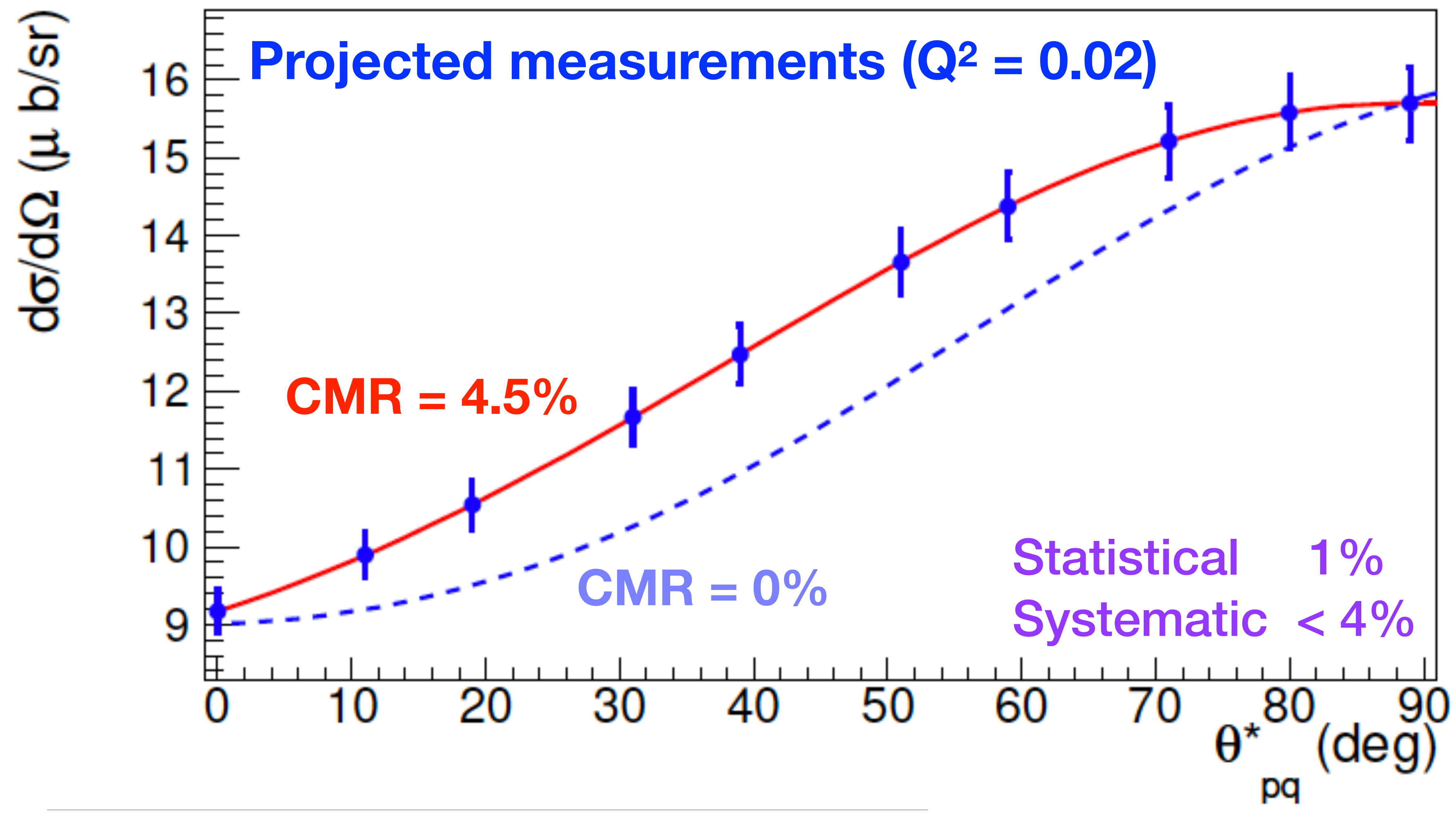
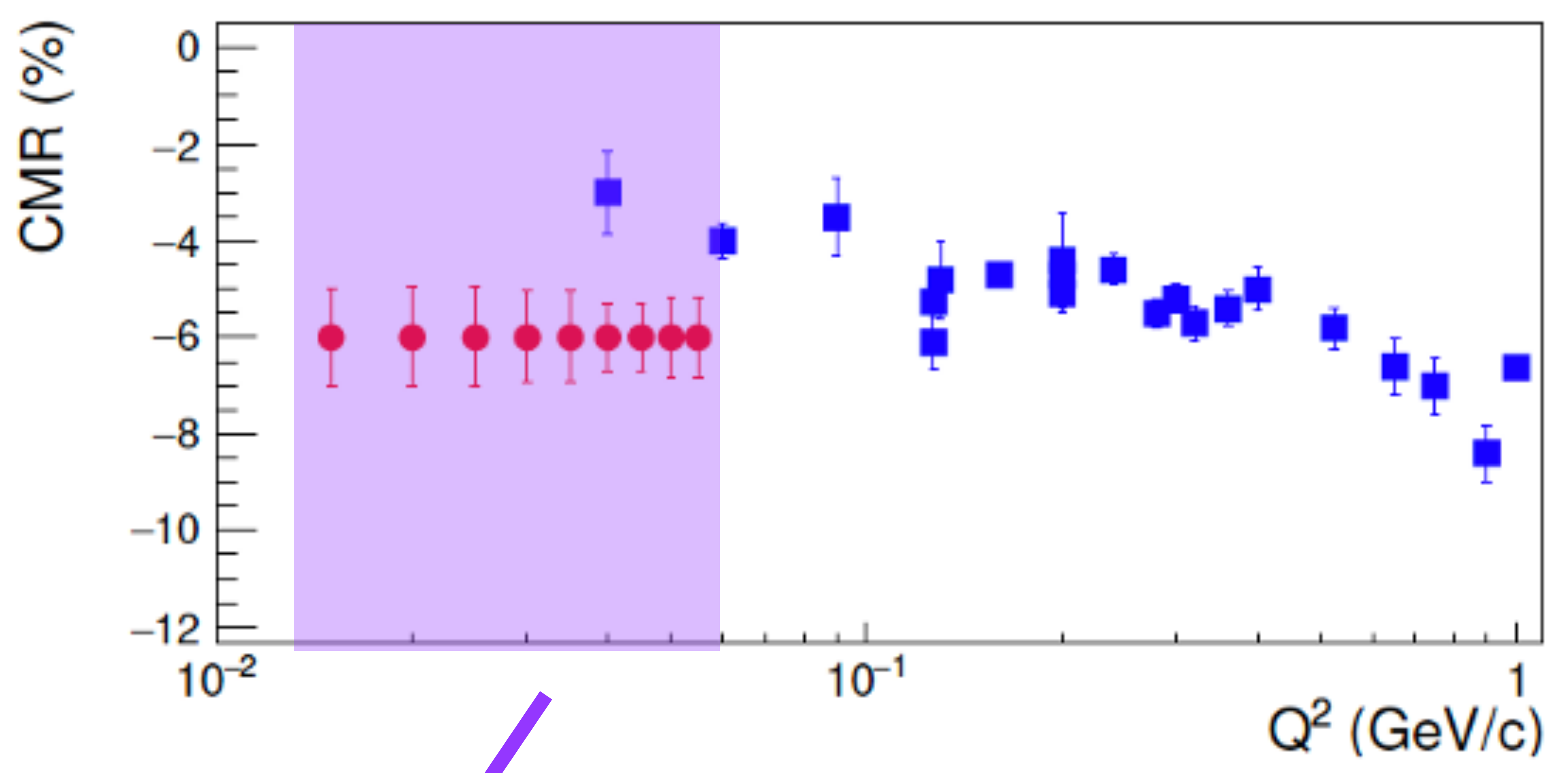


Projected CMR and EMR measurements





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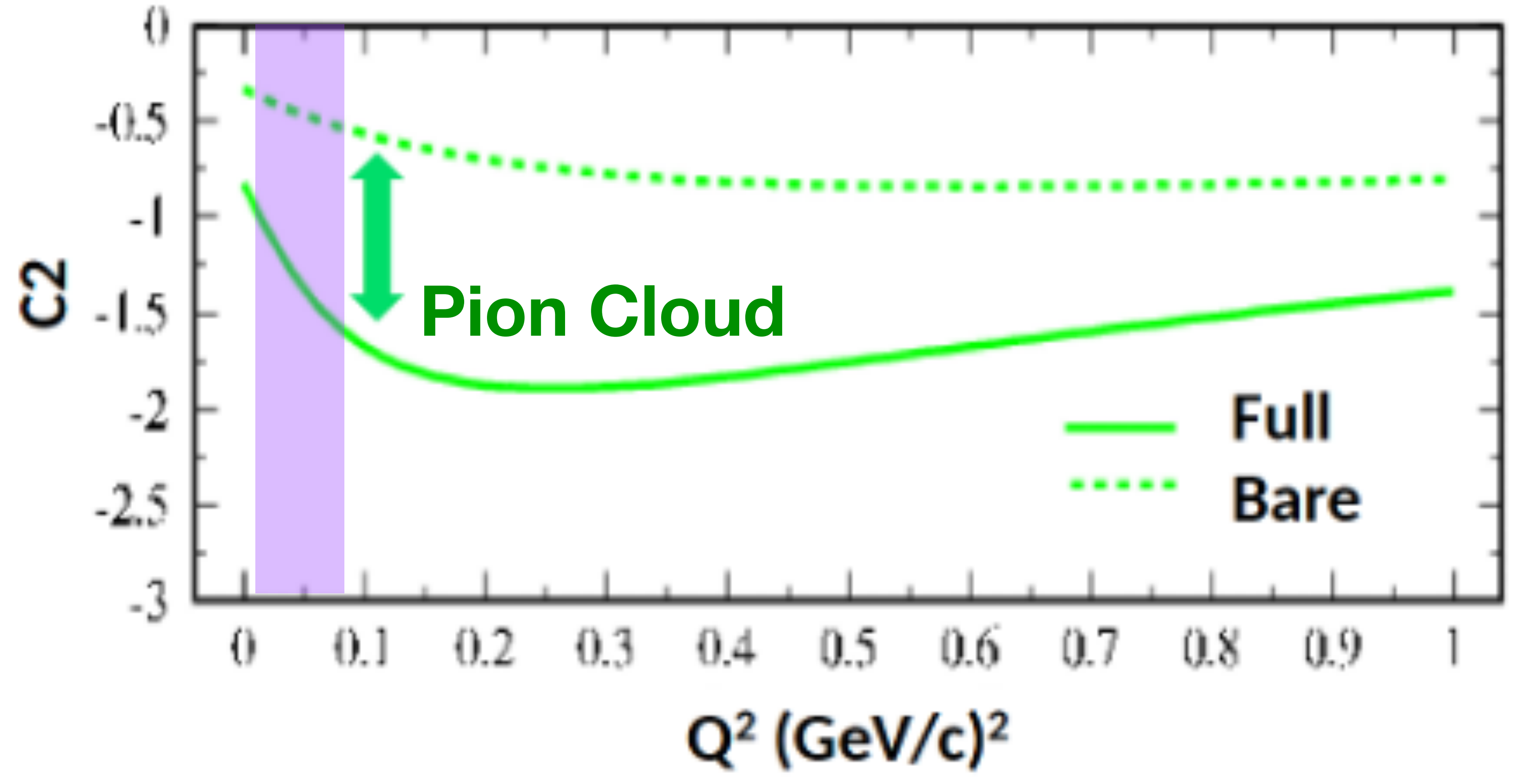
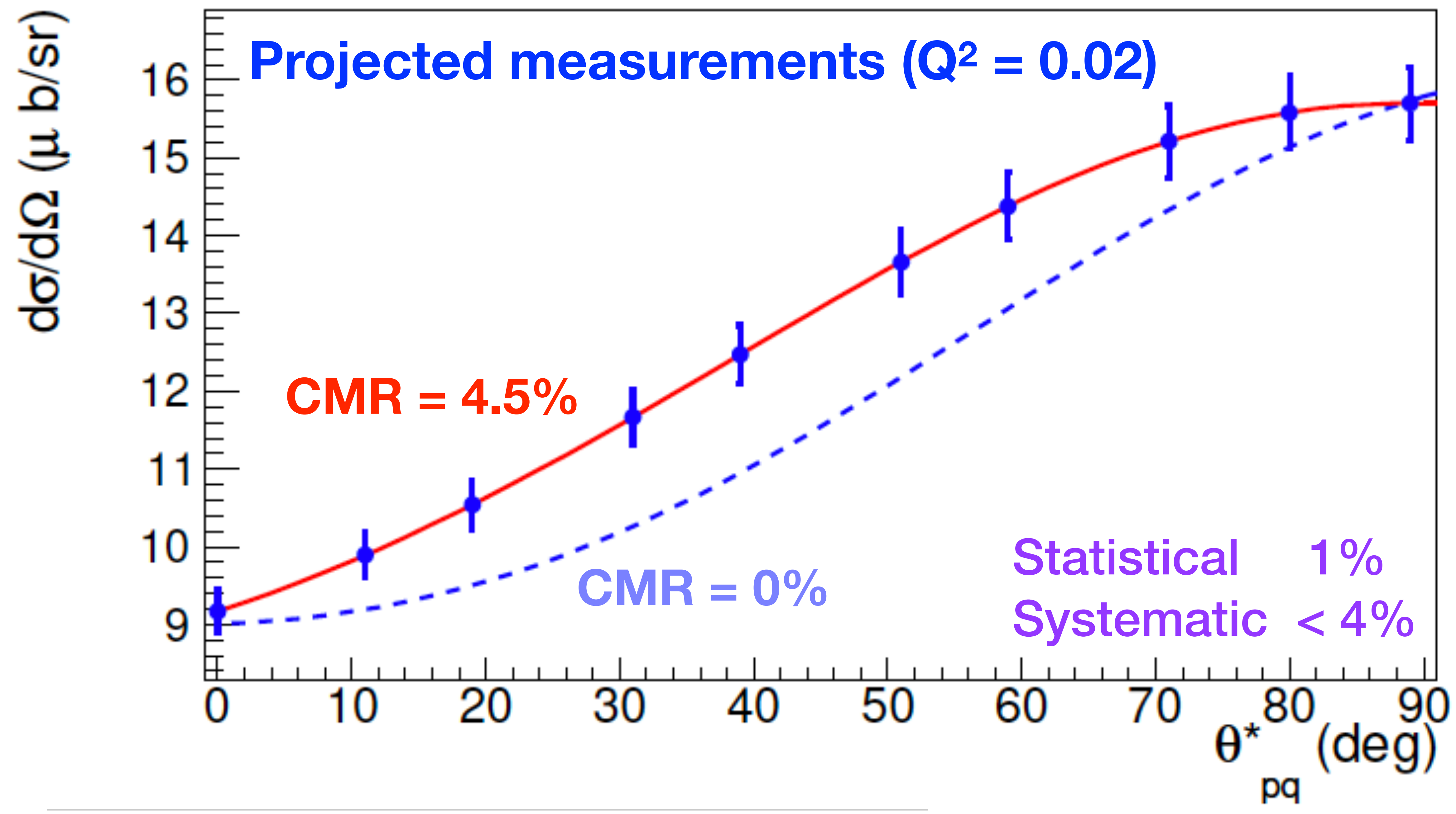
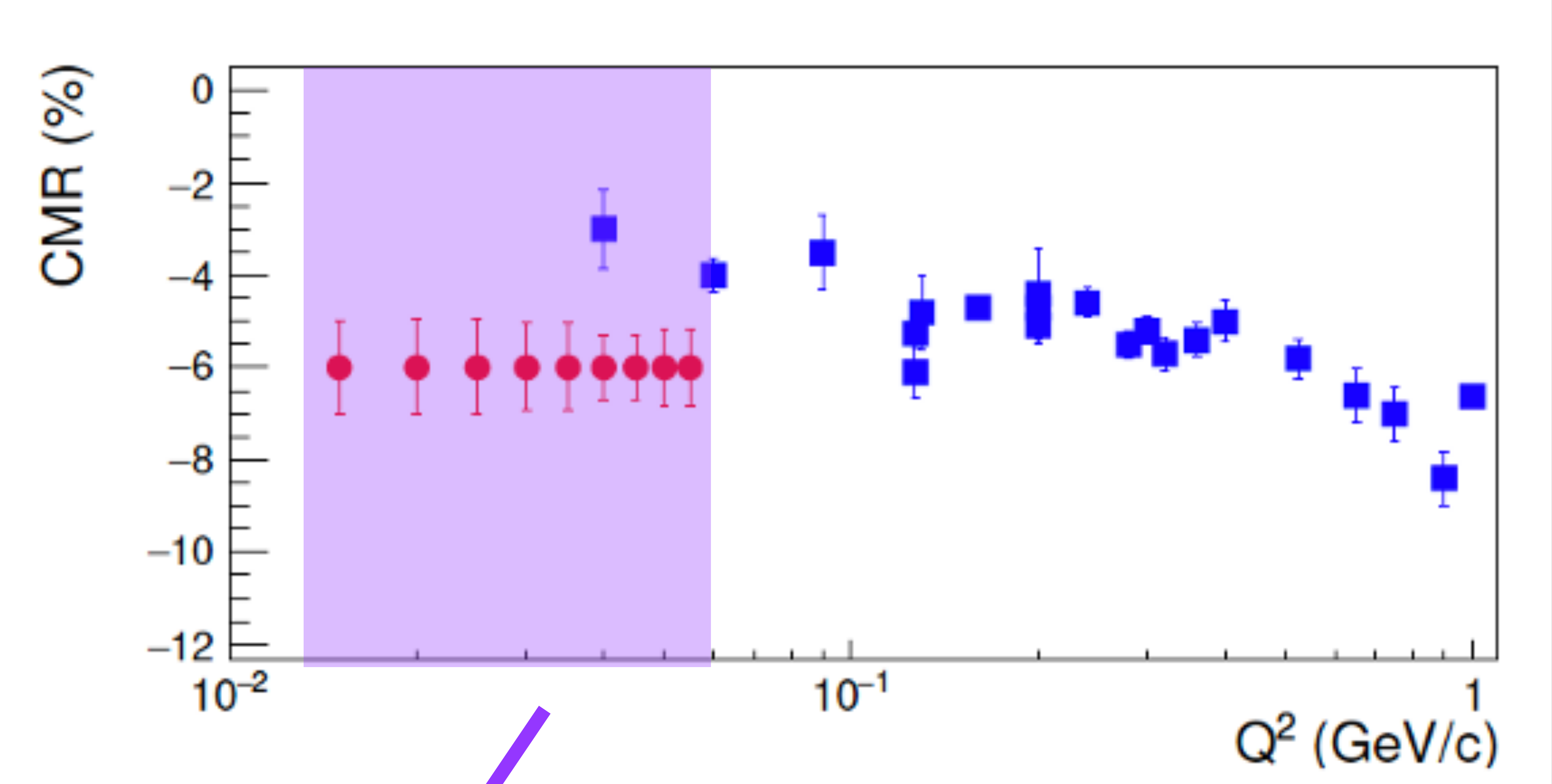
Total	2.8% - 3.8%

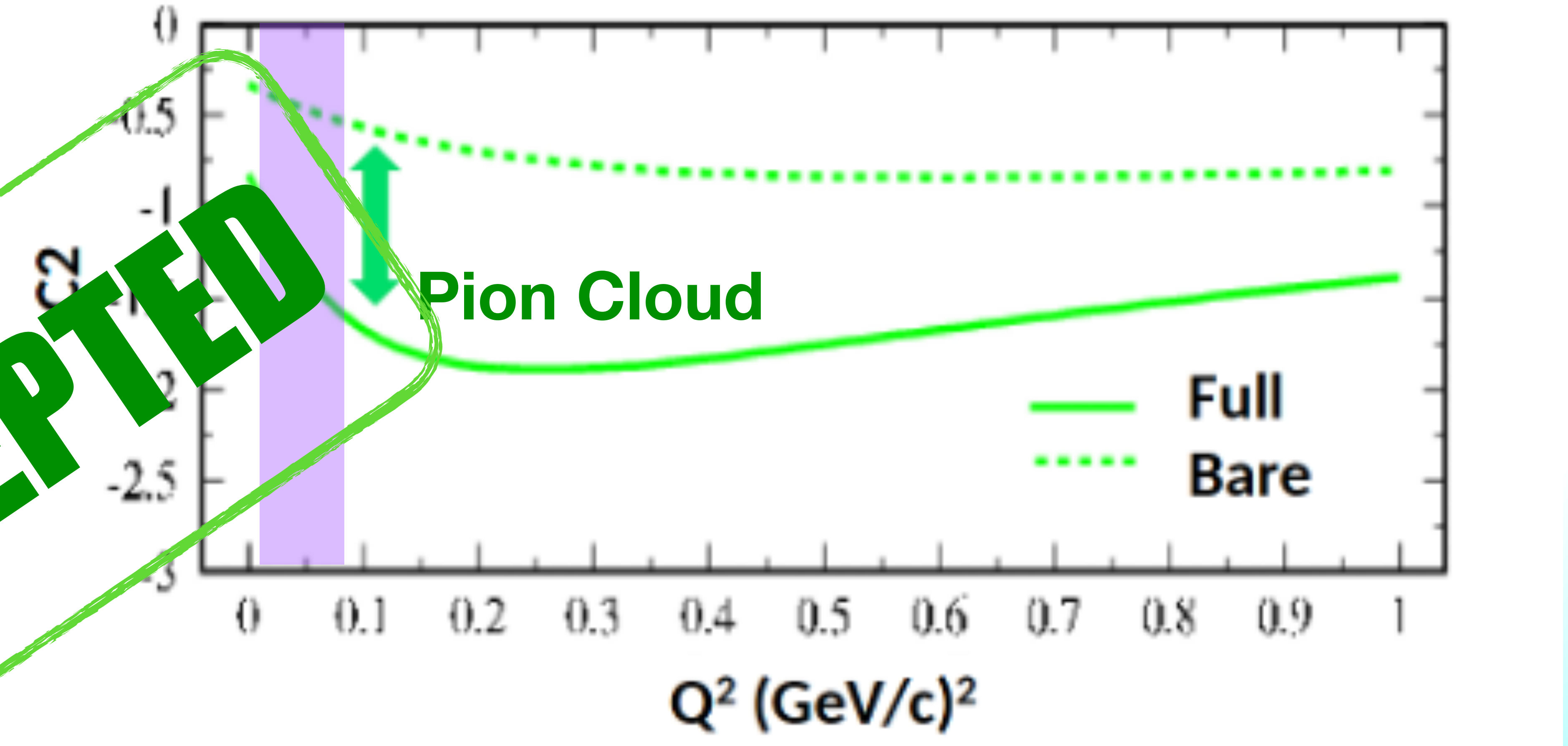
Proposed to PAC50: Extraction of TFFs at low Q2



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%

Proposed to PAC50:
Extraction of TFFs at
low Q2

ACCEPTED

11 days, to run sometime in the "near" future.

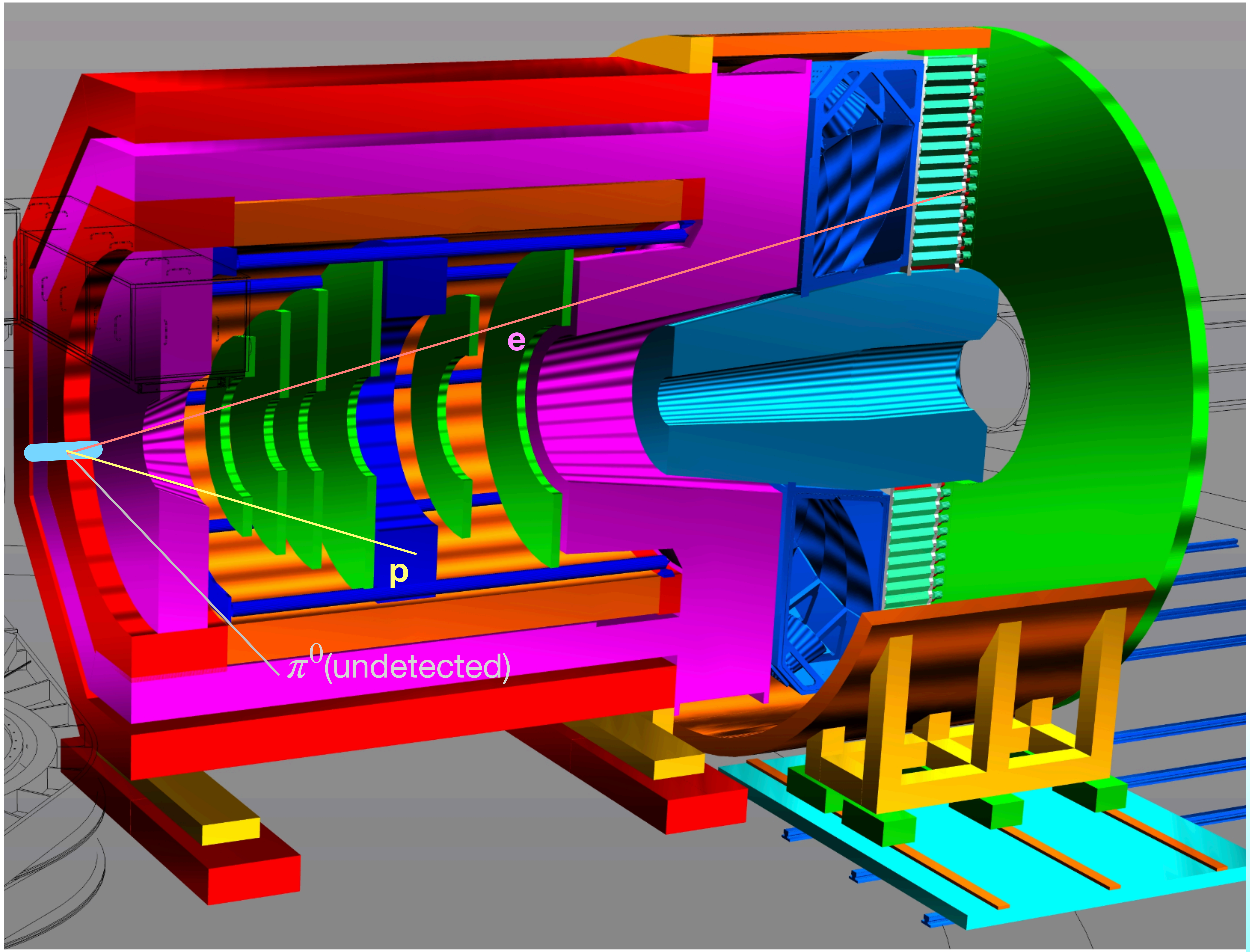
Future Analyses at JLab

- CLAS12 has single-pion production coverage up to Q2 = 12 GeV2 over a large range of W.
  - Program focused on large range Nucleon excitation resonances.
    - Specific sensitivity of expected data to EMR and CMR extraction is unclear.
      - How does low-luminosity affect rates at large Q2?
- SoLID:
  - Can detect azimuthal 2π with high luminosity:
    - Limited somewhat by polar angle acceptance and resolution

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



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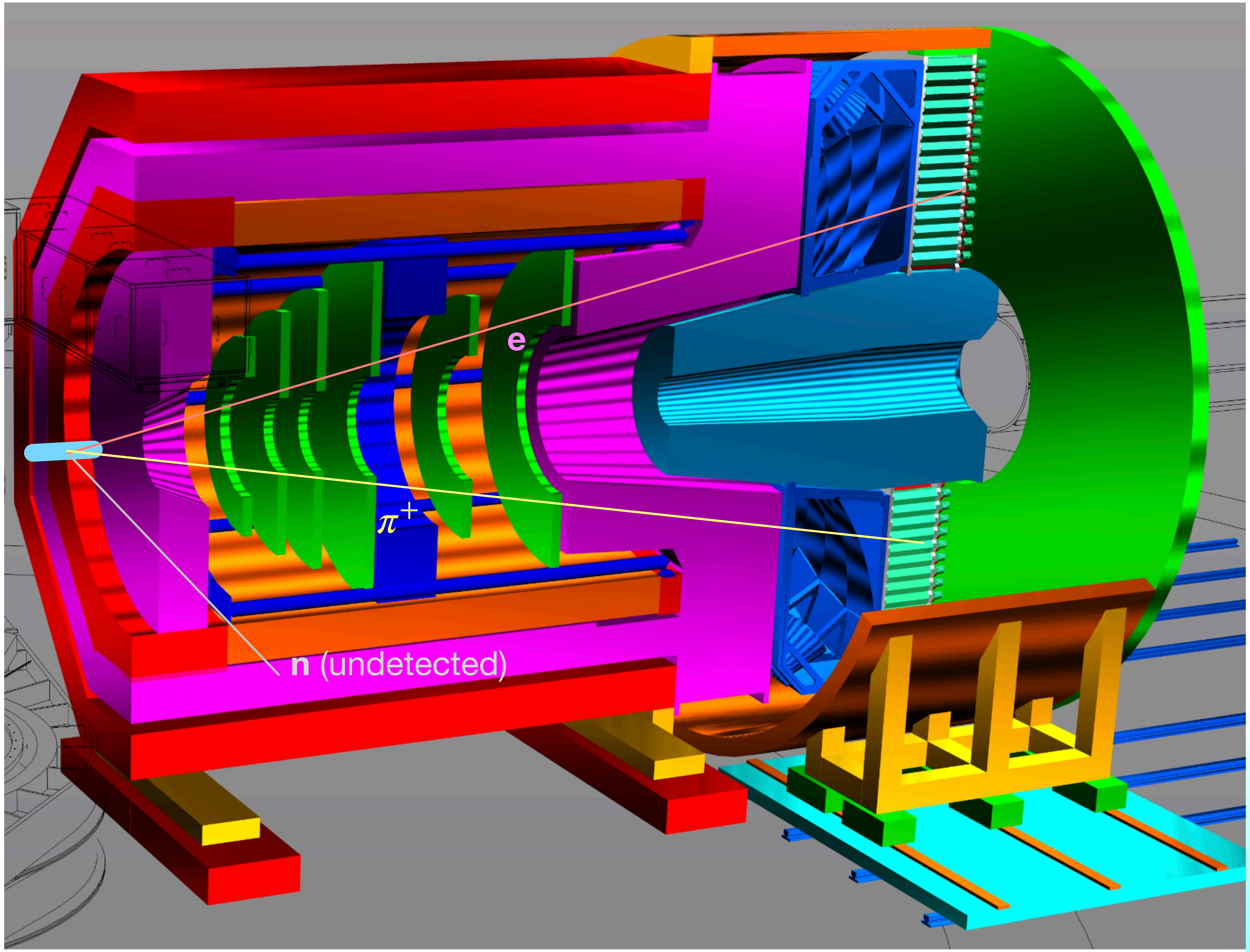

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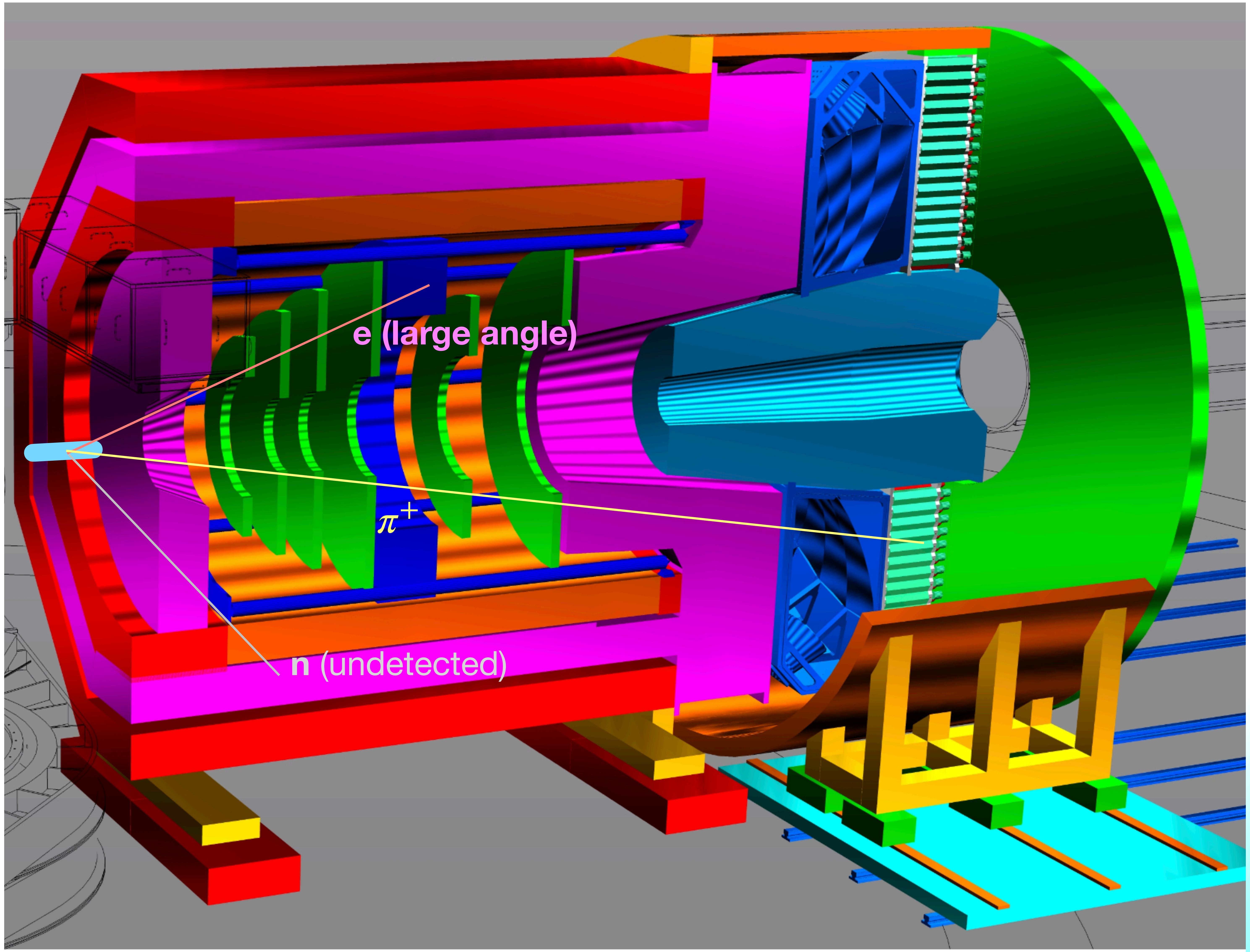
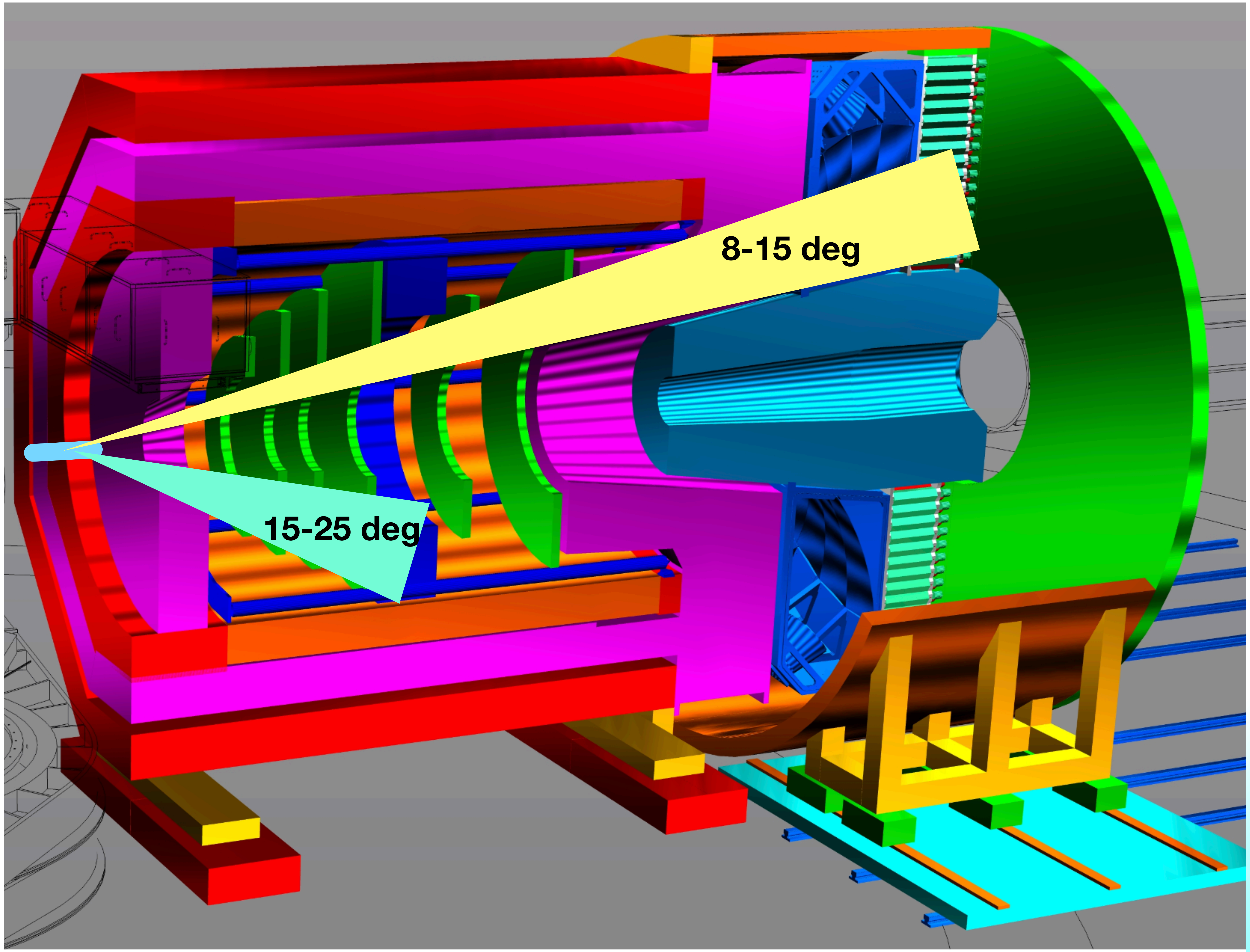


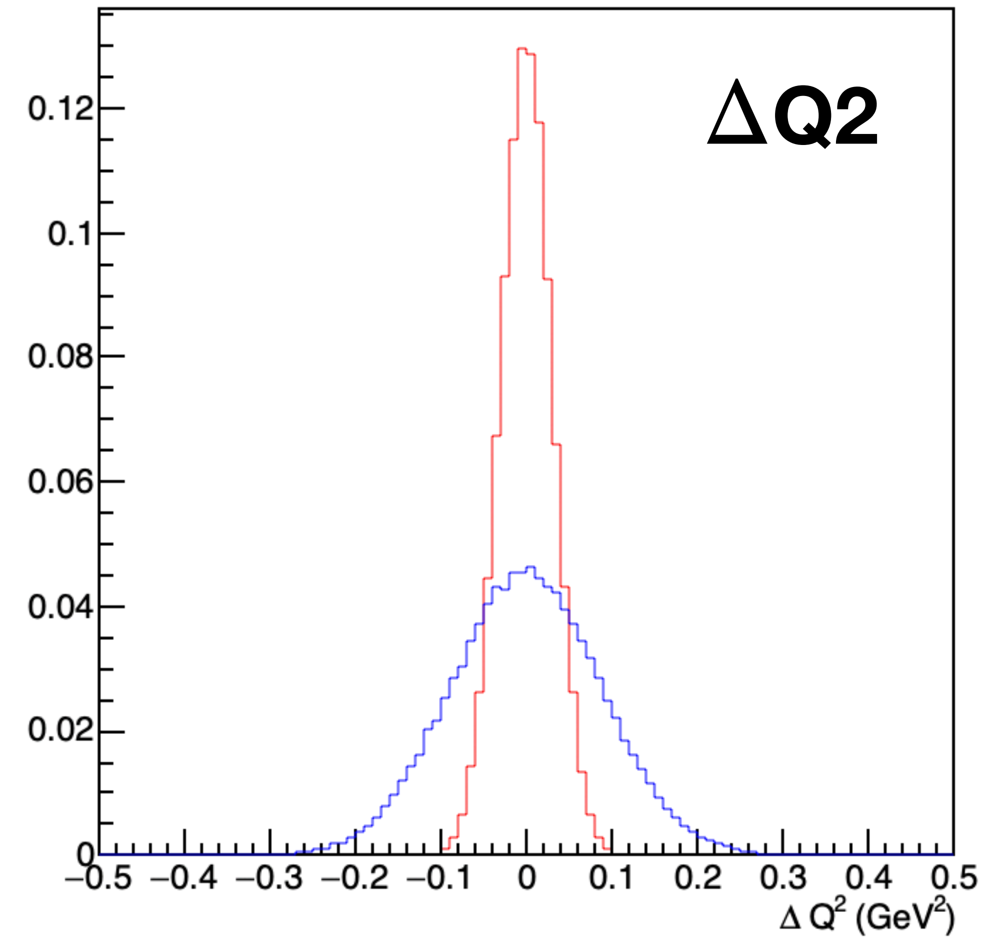
TFFs with SoLID at JLab (J/psi Set-up)

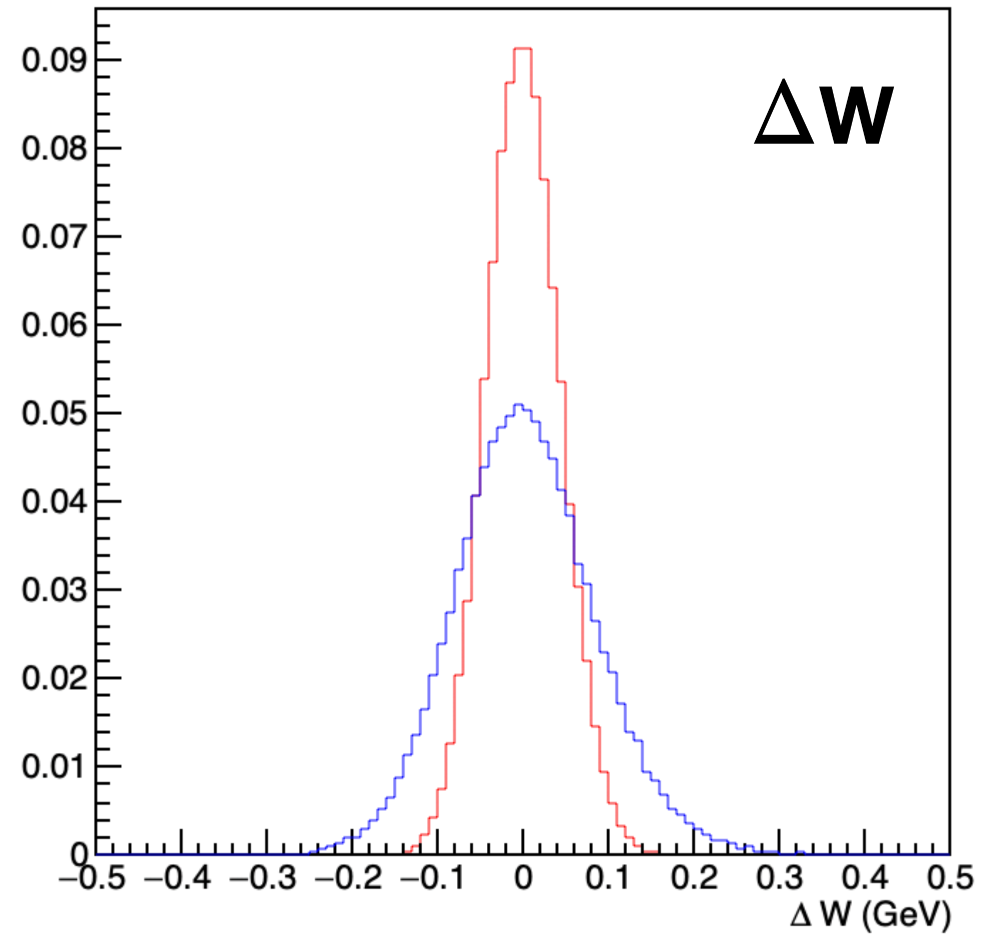
- Small angle electrons vs large angle electrons:
  - Advantages for small angle:
    - Better resolutions
    - LGC for PID
    - Standard Trigger Setup
    - Better systematics
  - Advantages for large angle:
    - Higher Q2 reach
    - Better θ_{cm} and ϕ_{cm} coverage

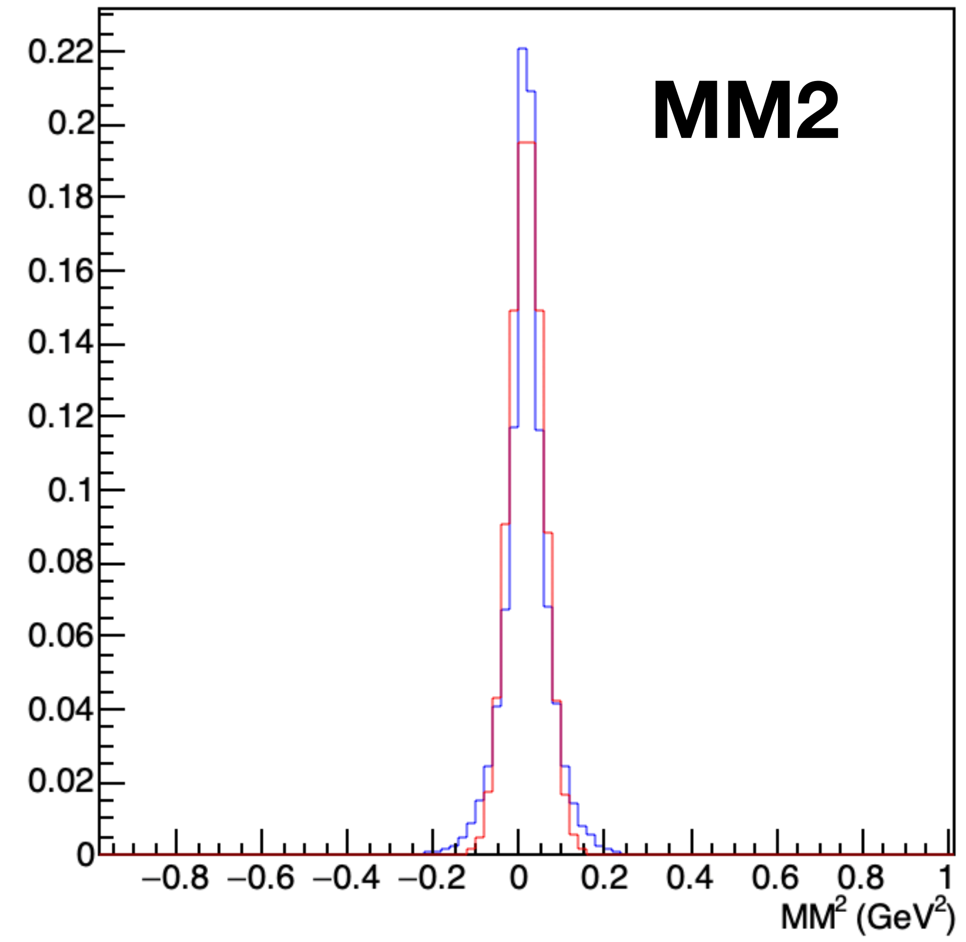


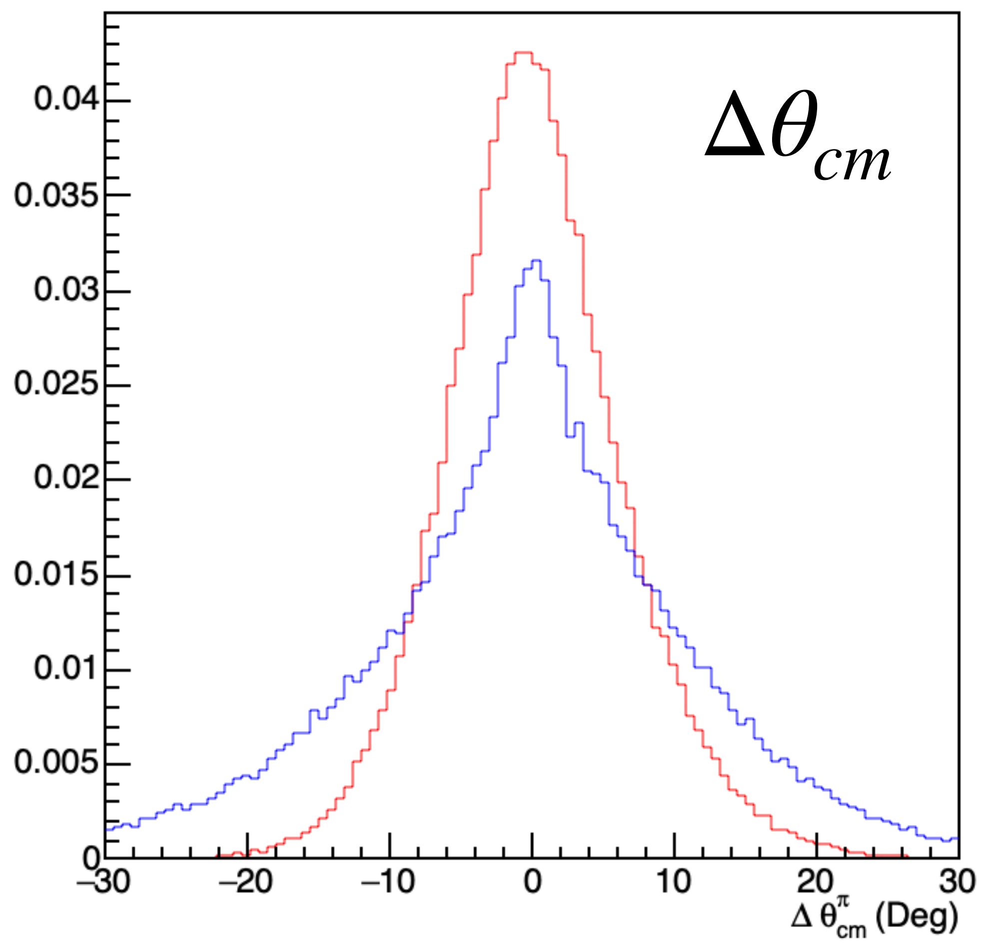
TFFs with SoLID at JLab (J/psi Set-up)

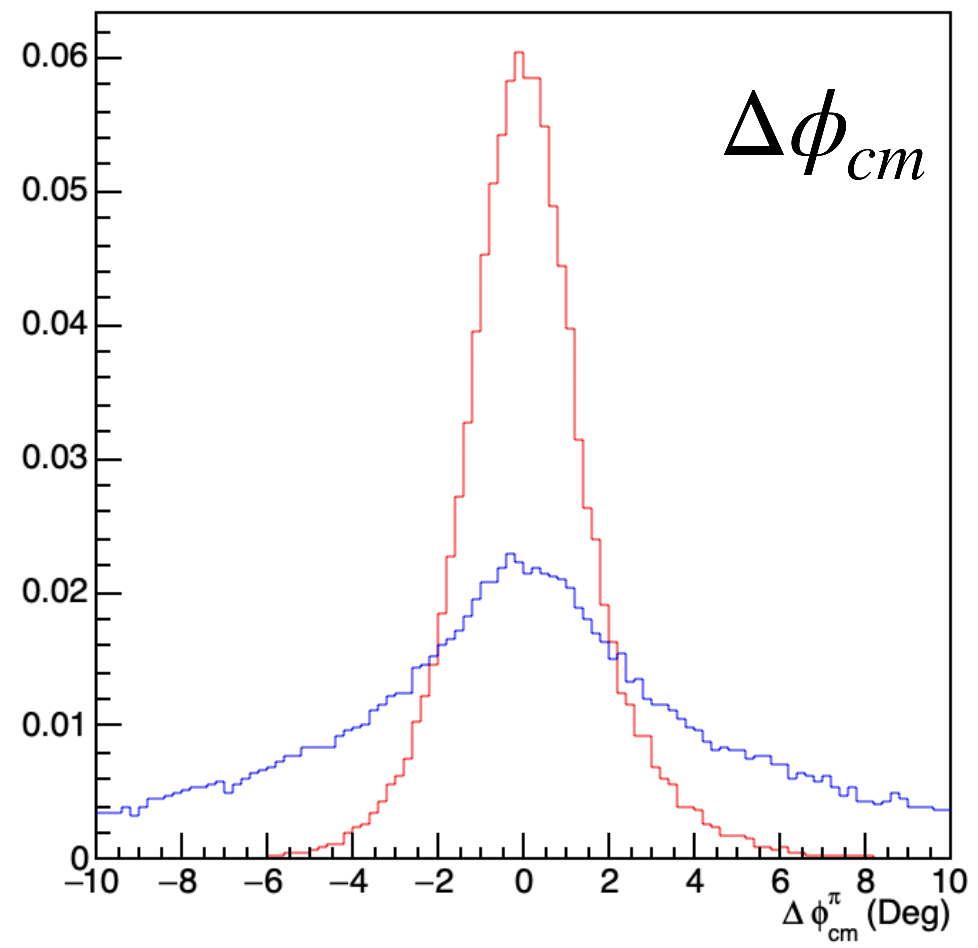
- Resolutions of large angle vs small angle electron detection (Tracking only)







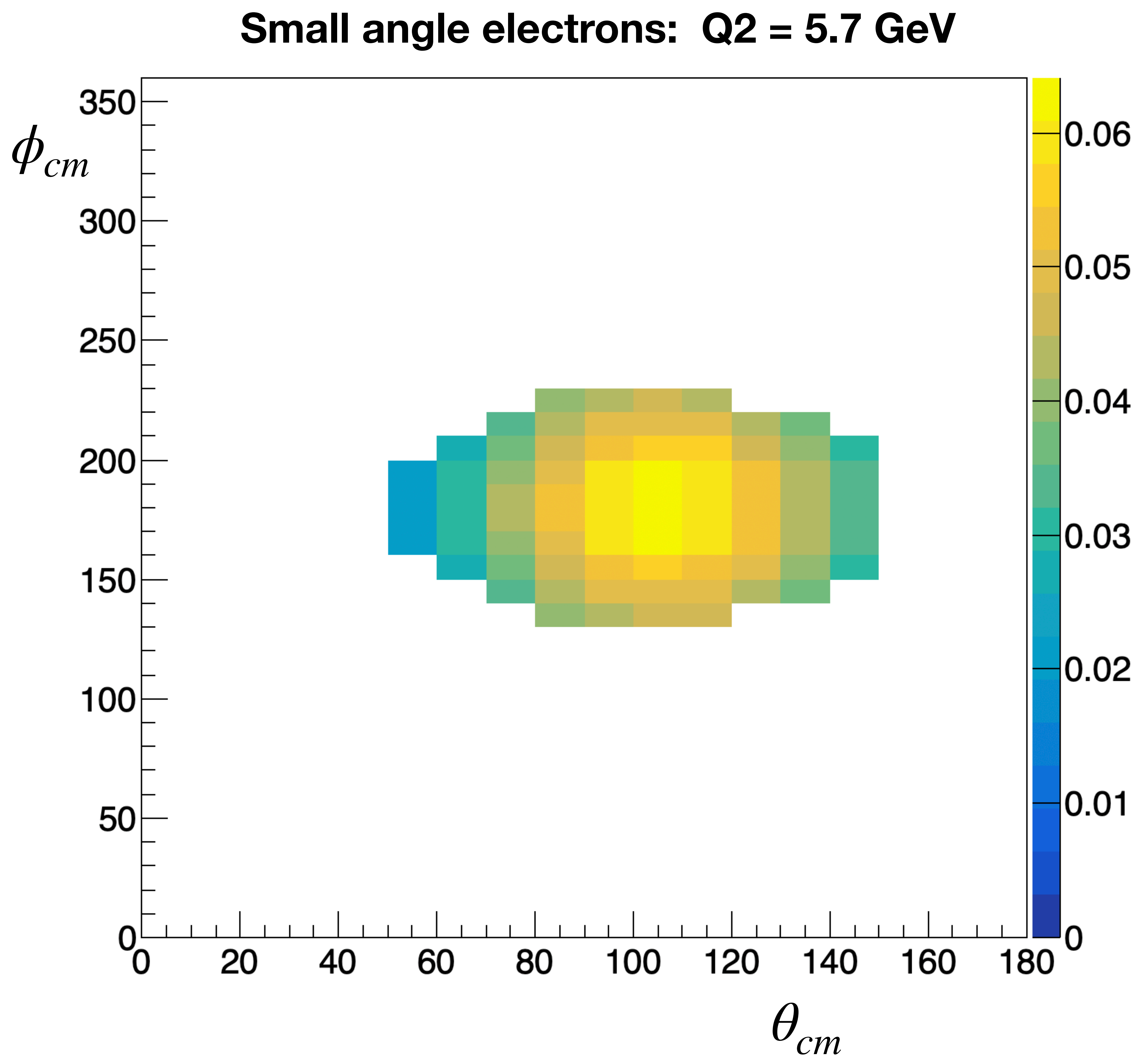


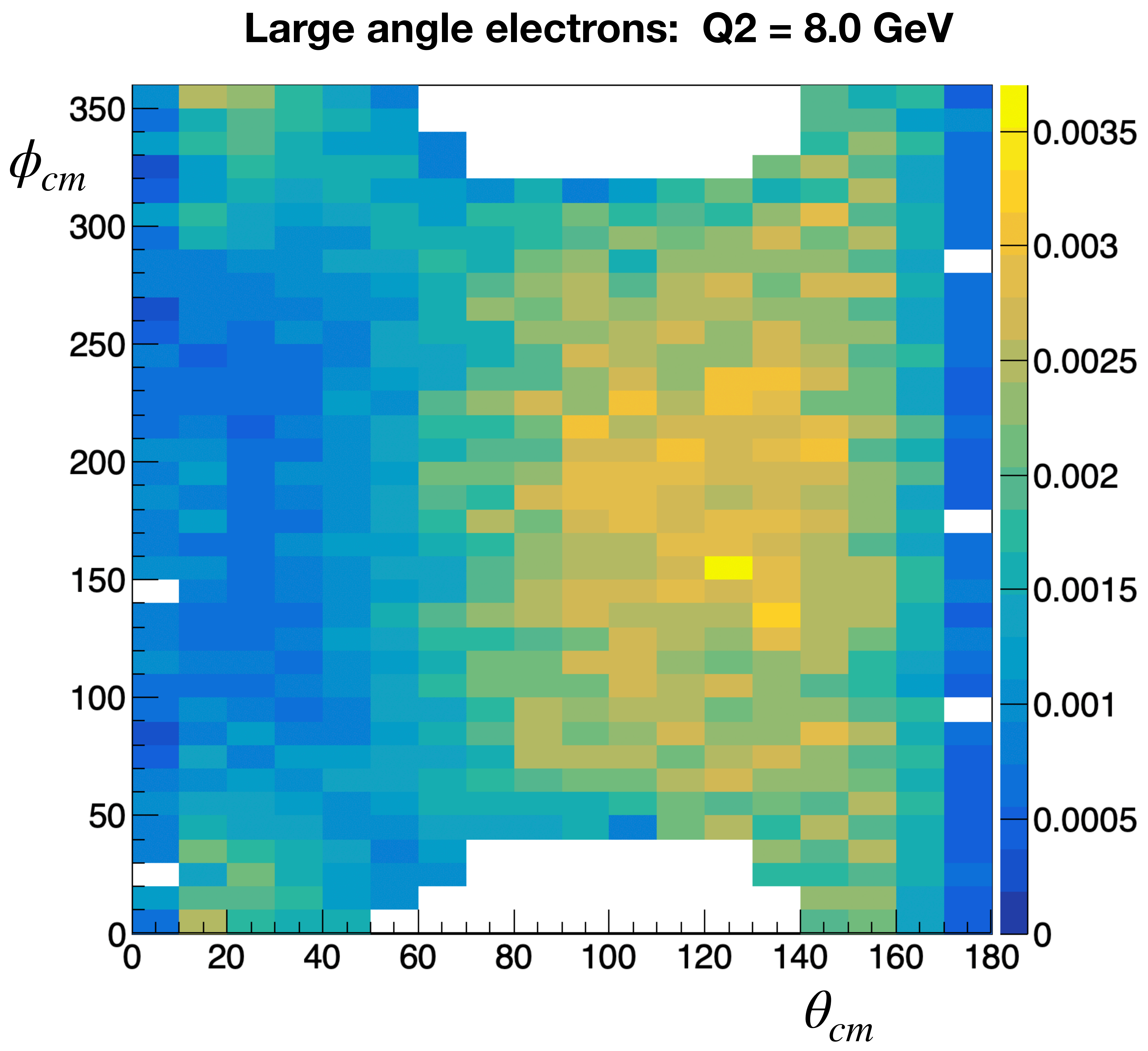


Small angle
Large Angle

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

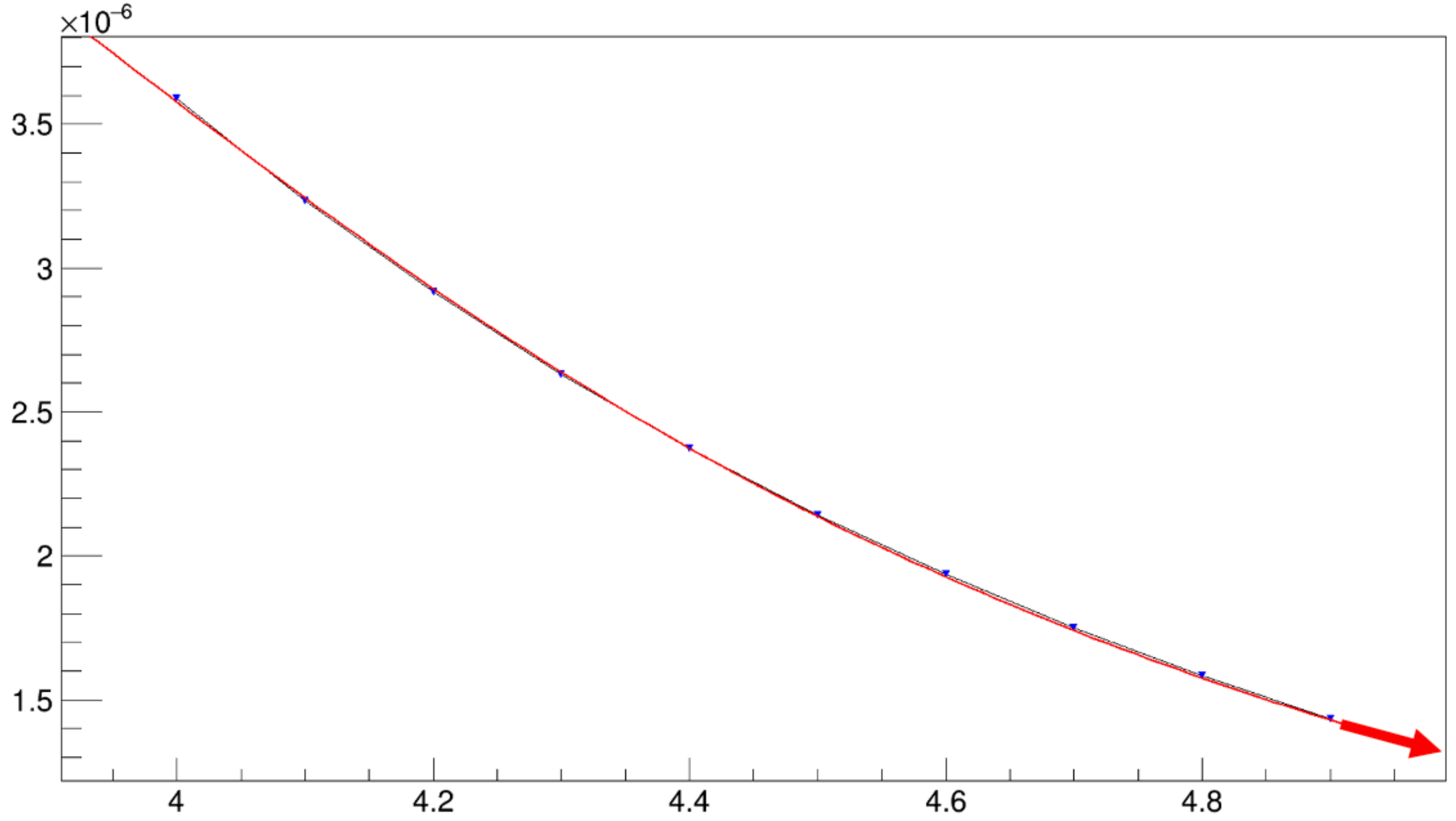
- θ_{cm} and ϕ_{cm} coverage





Cross-Section Extrapolations

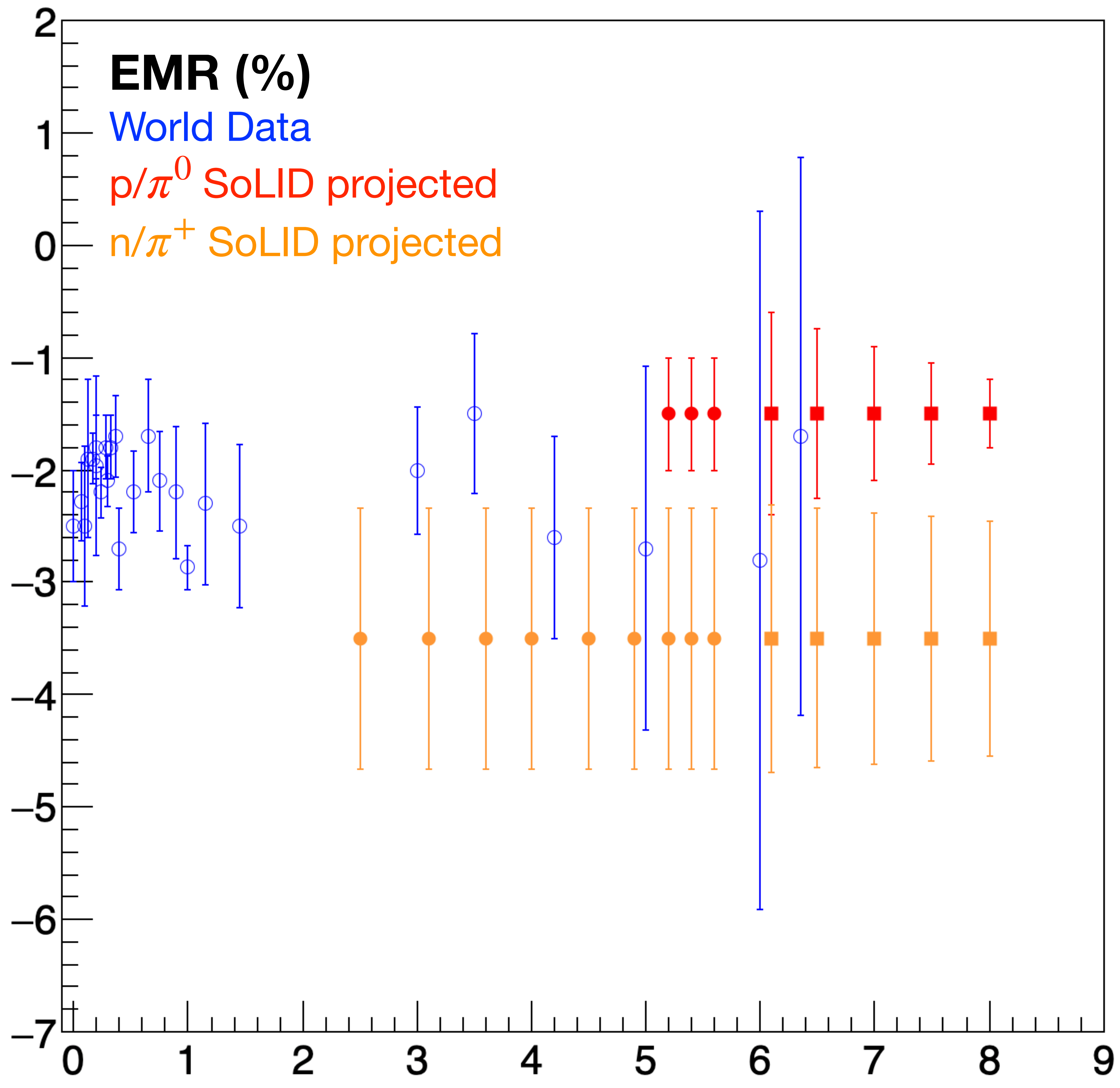
- MAID used for rate estimations, but only provides calculations up to Q2 = 5.0
  - For Q2 > 5.0
    - Fix W, theta_cm, pi_cm
    - Allow beam and scattered energy to scale to obtain cross-sections below Q2 = 5.0
    - Fit trend and extrapolate to higher Q2:

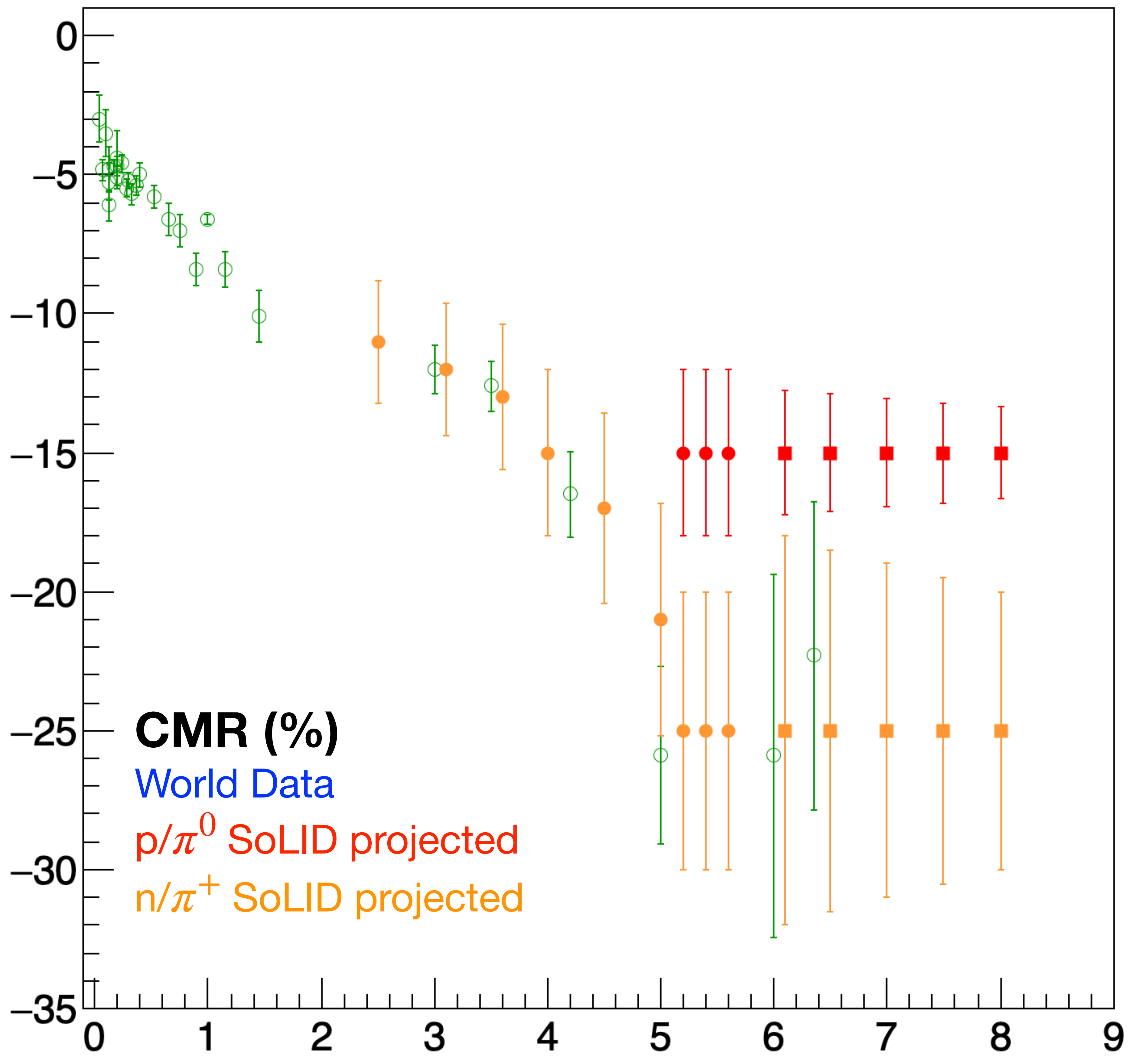


Where MAID and SAID disagree at Q2 = 5, take more conservative cross-section in estimates

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

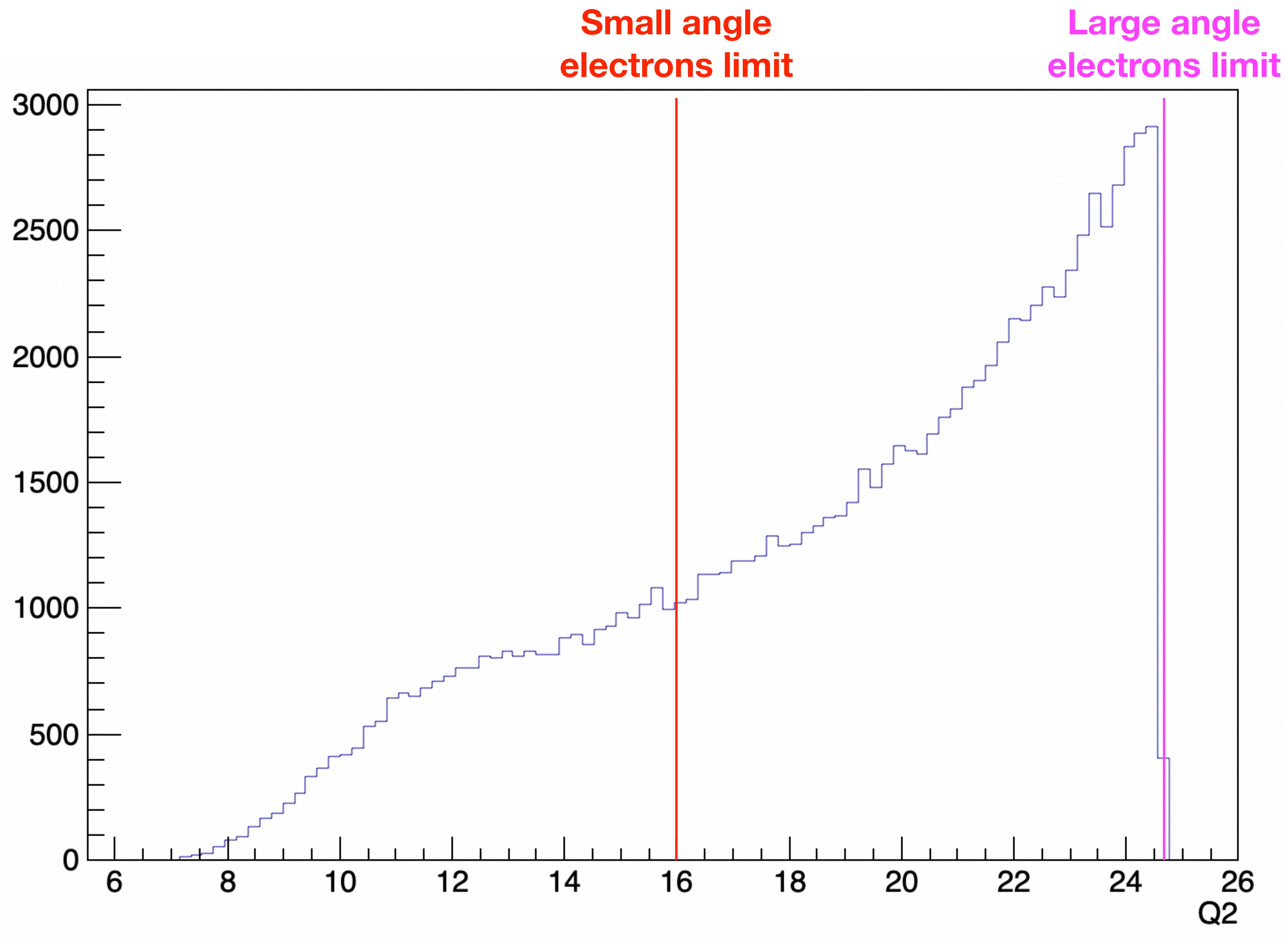
- Projections





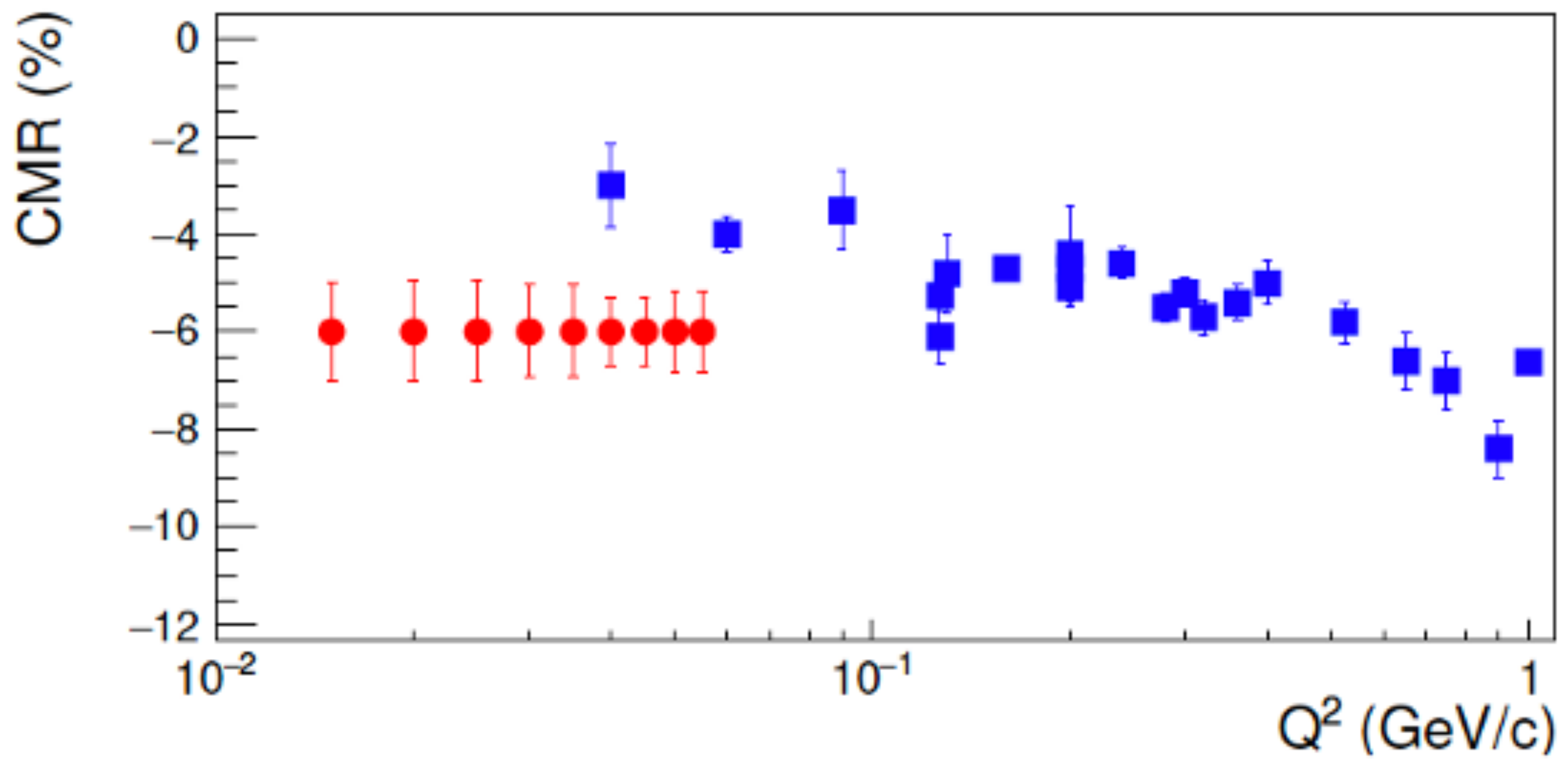
TFFs with SoLID at JLab @ 20 GeV

- Q2 reach



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)**
  - Newly approved experiment 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**
- **At SoLID:**
  - We can extend world data for high Q2 and test pQCD predictions while running parasitic with J/psi

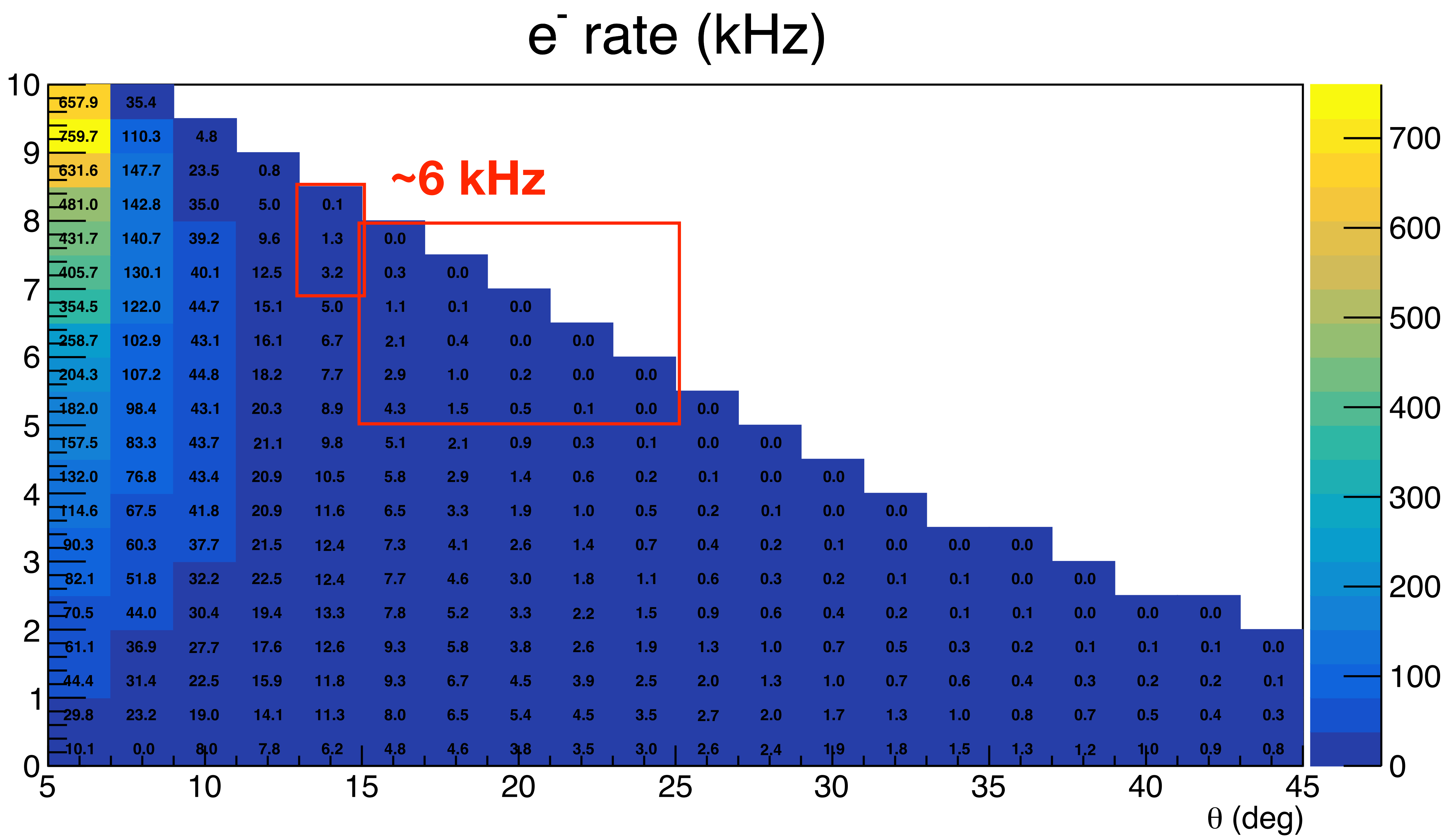


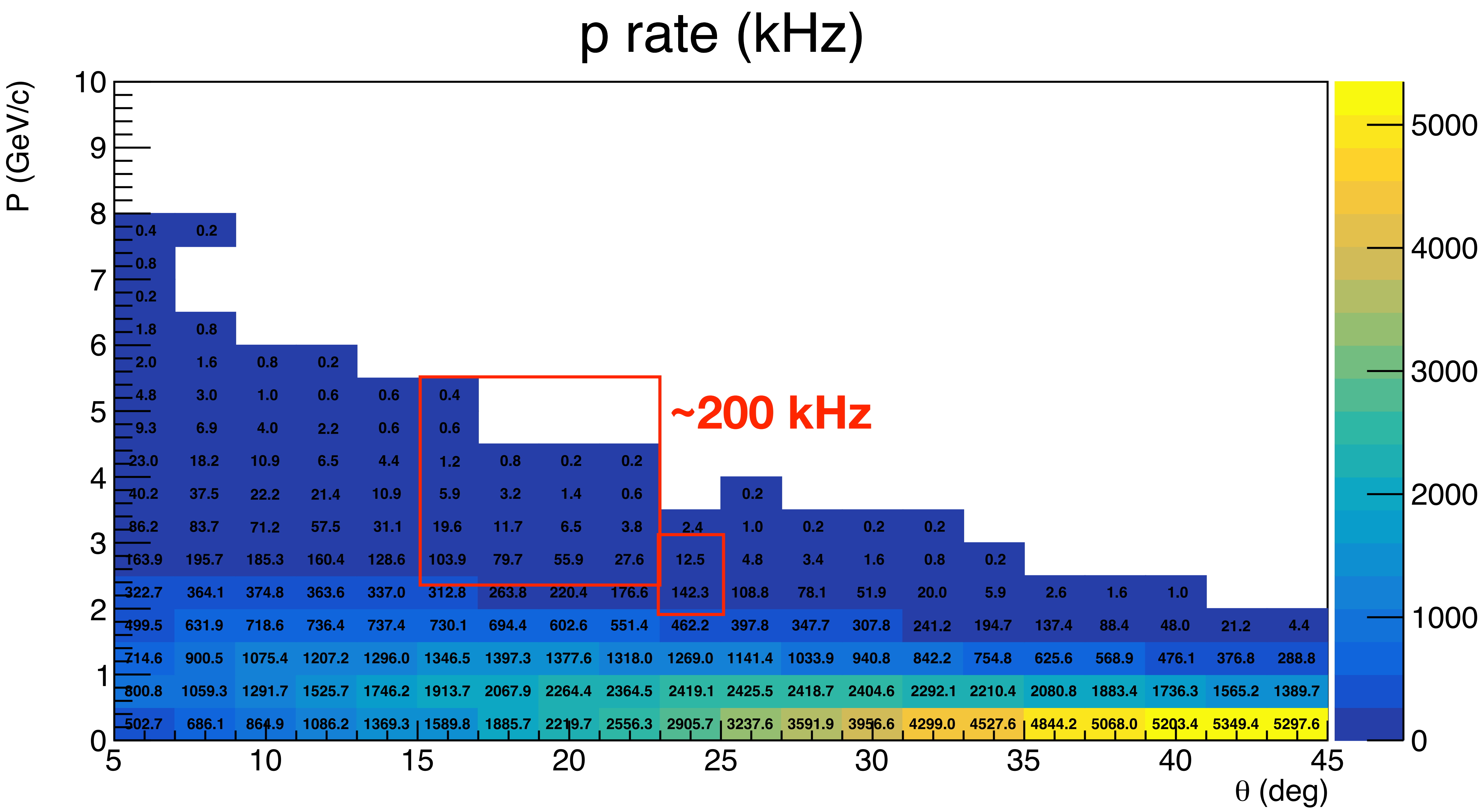
Thank you!

Backup Slides

Singles Rates

J/psi Configuration

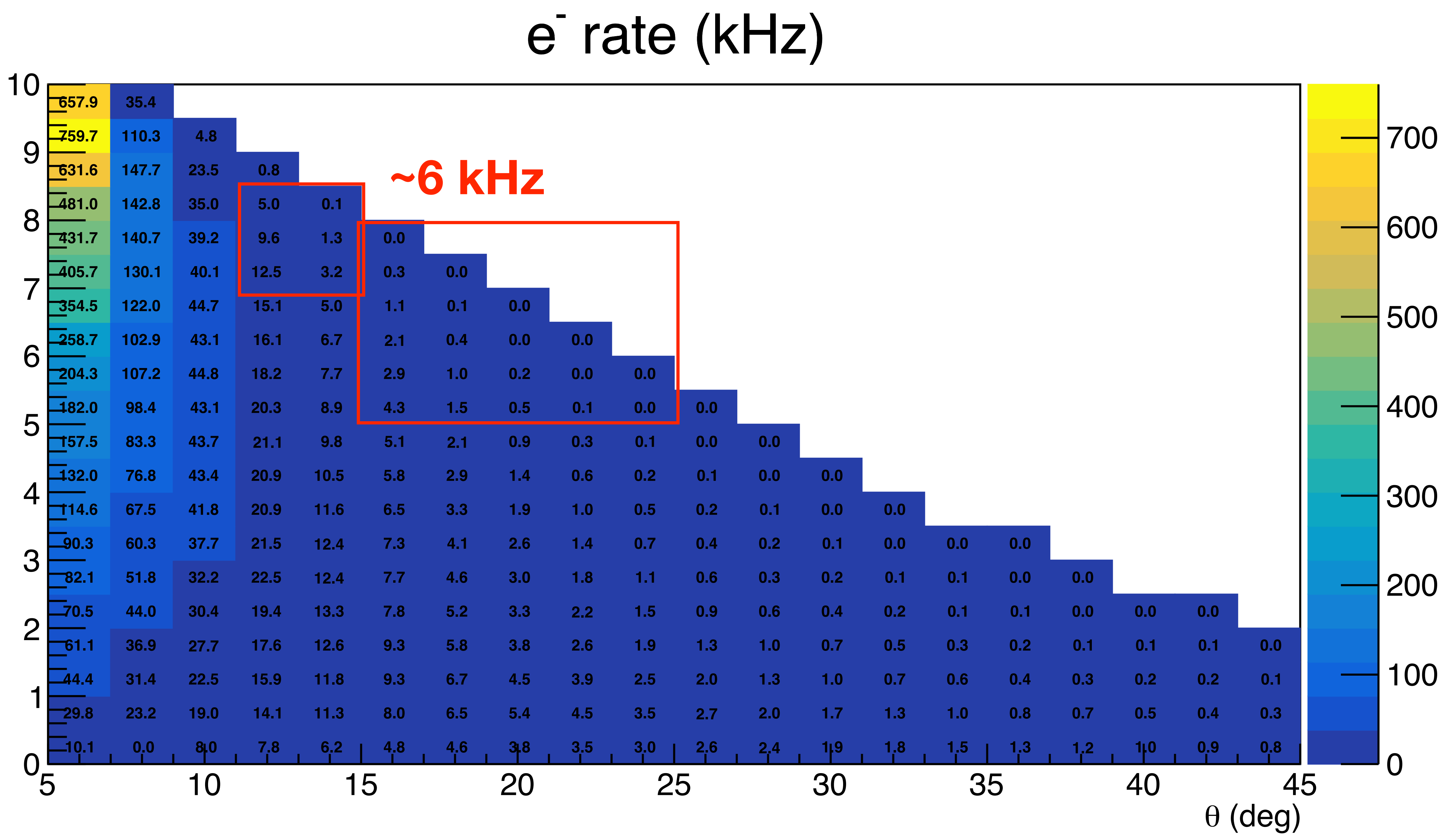


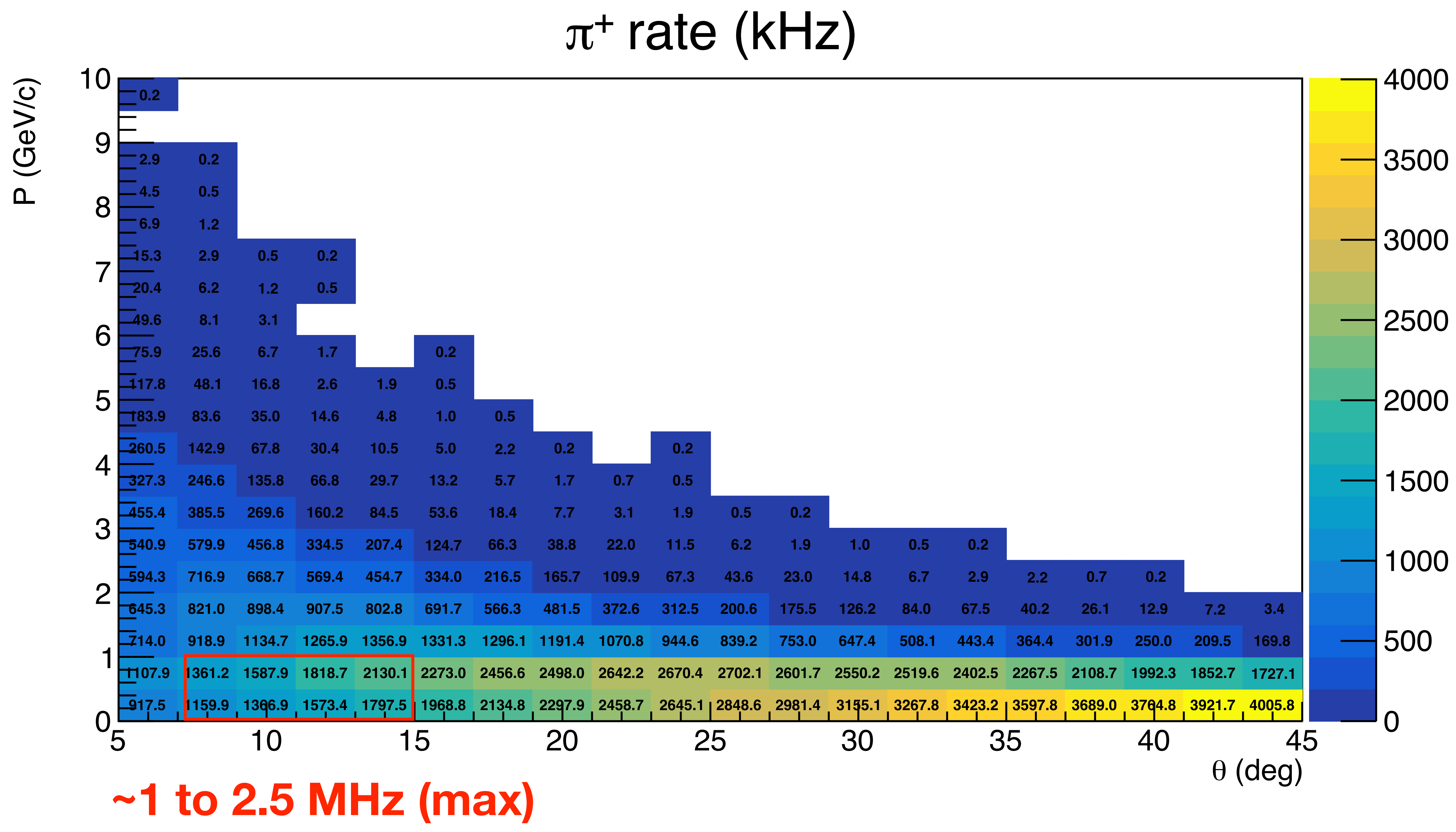


Maximum accidental rate with 100 ns trigger ~ 100 Hz BEFORE subdivision into theta/phi COM bins and missing mass cuts

Singles Rates

J/psi Configuration





Maximum accidental rate with 100 ns trigger ~ 1.5 kHz BEFORE subdivision into theta/phi COM bins and missing mass