Pion electroproduction and VCS at the Δ resonance region

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Nucleon excitation

A persistent thirty year effort

Goal Explore the extremely complicated many body dynamics of hadronic matter & the nucleon structure

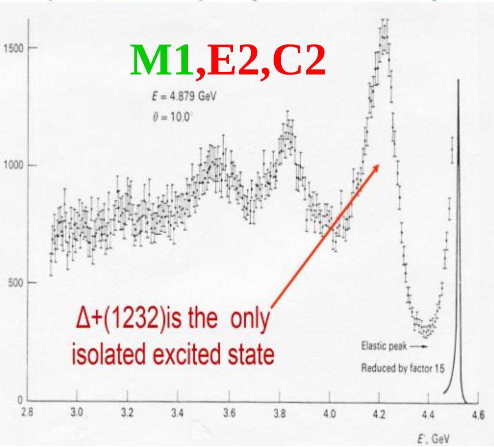
Presence of non-spherical components in the nucleon wave function: origin & dynamics

Exploring the shape of the fundamental building blocks of the Universe is a particularly fertile line of investigation for the understanding of the interactions of their constituents: the interquark interaction and the quark-gluon dynamics

Interplay of quark-gluon and pion-cloud d.o.f : study of the Q^2 dependence

Experiment all major facilities (Jlab, MAMI, Bates …)

Theory sophisticated phenomenology, dynamical models, ChEFT, Lattice QCD : establishing contact between QCD theory and experiment

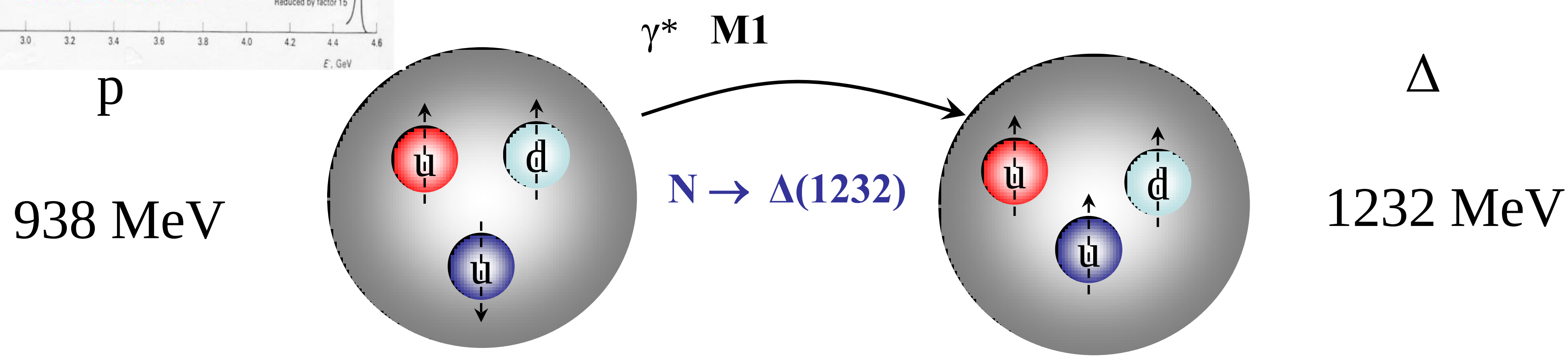


The signal

H(e,e'p)π^{o} ≈ 66%

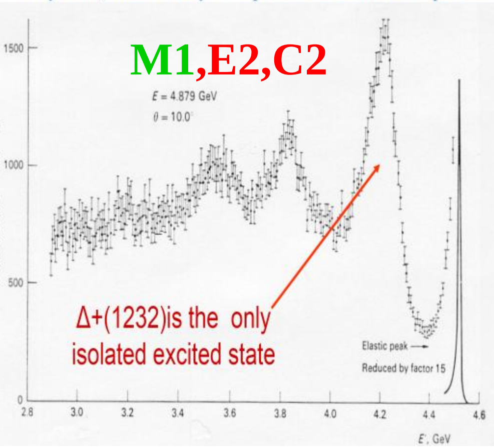
H(e,e'π^{+})n ≈ 33%

H(e,e'p)γ ≈ 0.6%



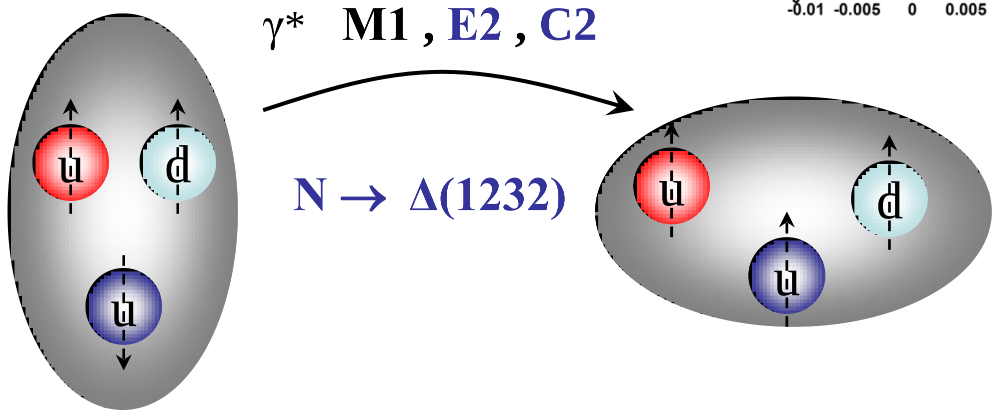
Spherical ⇒ M1

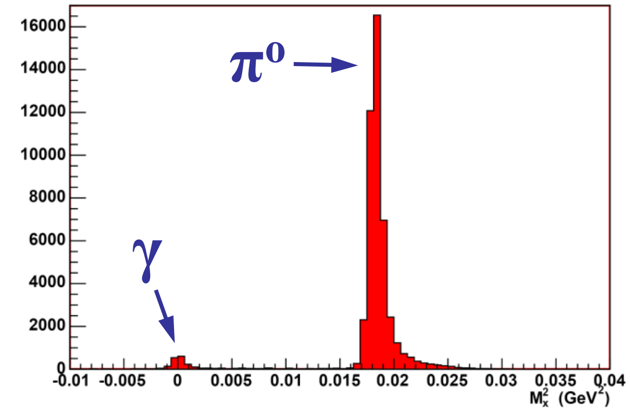
The signal



p

938 MeV





Δ

1232 MeV

Deformed ⇒ M1 , E2 , C2

Deformation signal

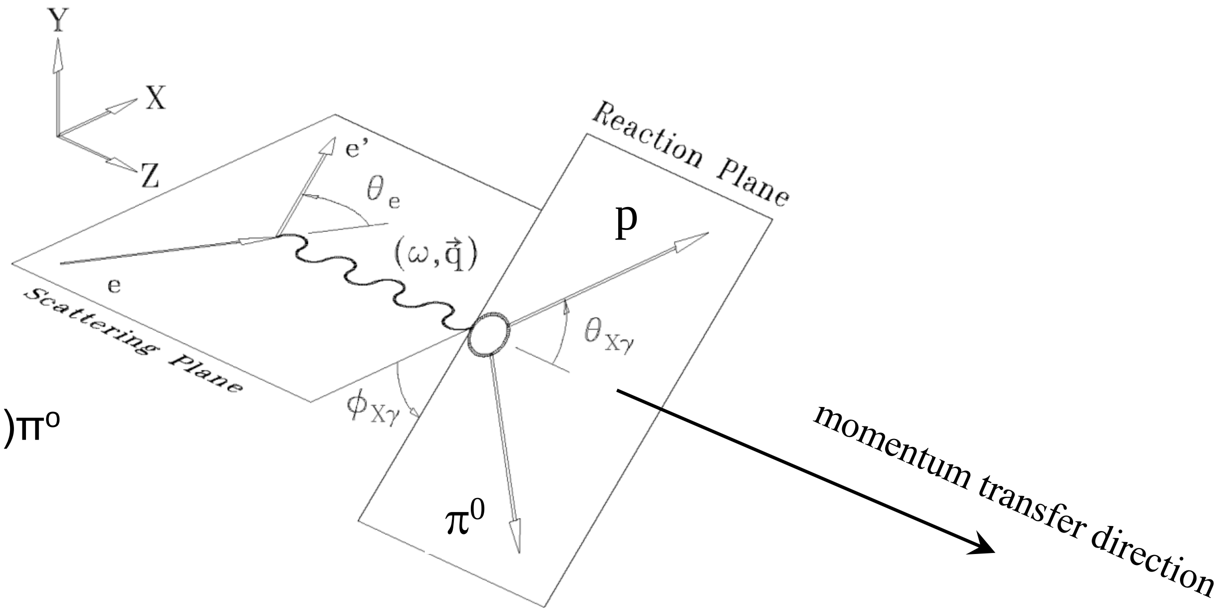
CMR = C2/M1

EMR = E2/M1

⇒ **non-spherical components in the nucleon wave function**

Methodology

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



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

R_T, R_L, R_{TT}, R_{LT} = **f(amplitudes(W,Q^2)** , g(**θ**)**)**

for fixed θ measure at 3 azimuthal angles Φ → extract $R_T + R_L$, R_{TT}, R_{LT} = **f(ampl.(W,Q^2)** , g(**θ**)**)**

explore θ from 0° to 180° → map $R_{[i]}$ vs θ $\xrightarrow{\text{fit}}$ extract **amplitudes(W,Q^2)**

Sensitivity to the amplitudes

R_{TT} = $3 \sin^2\theta$ ($E2^*M1 + (M1)^2 + \ldots \Sigma$(background))

R_{LT} = $-6 \cos\theta \sin\theta$ ($C2^*M1 + \ldots \Sigma$(background))

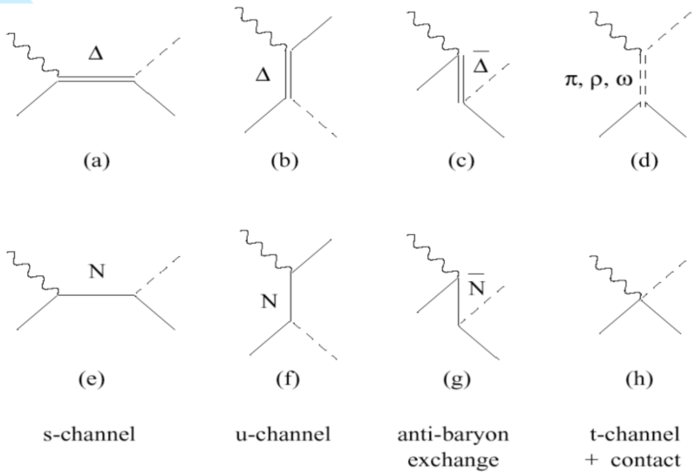
R_T+R_L = $(M1)^2 + \ldots \Sigma$(background)

R_{TT} → sensitivity to EMR

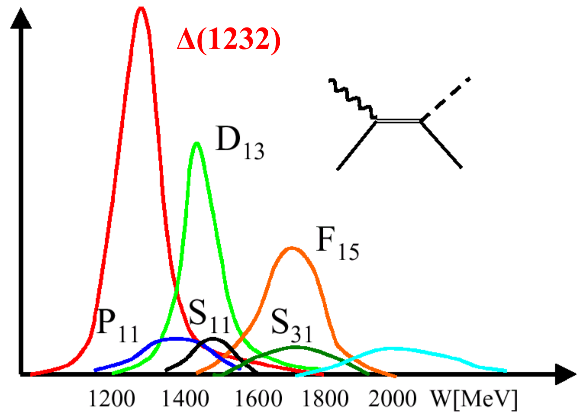
R_{LT} → sensitivity to CMR

R_T+R_L → sensitivity to M1

Background !

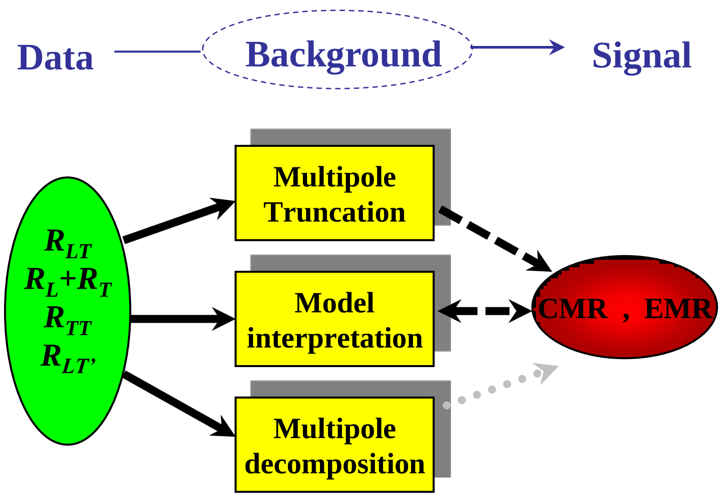


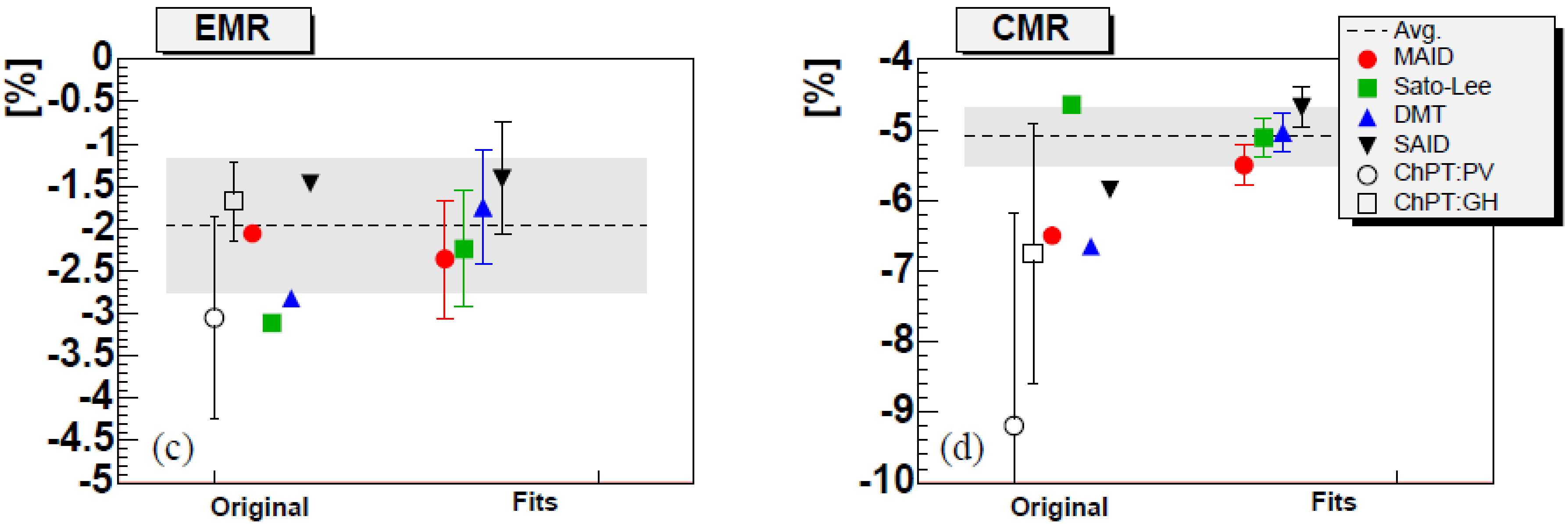
Tails of higher resonances



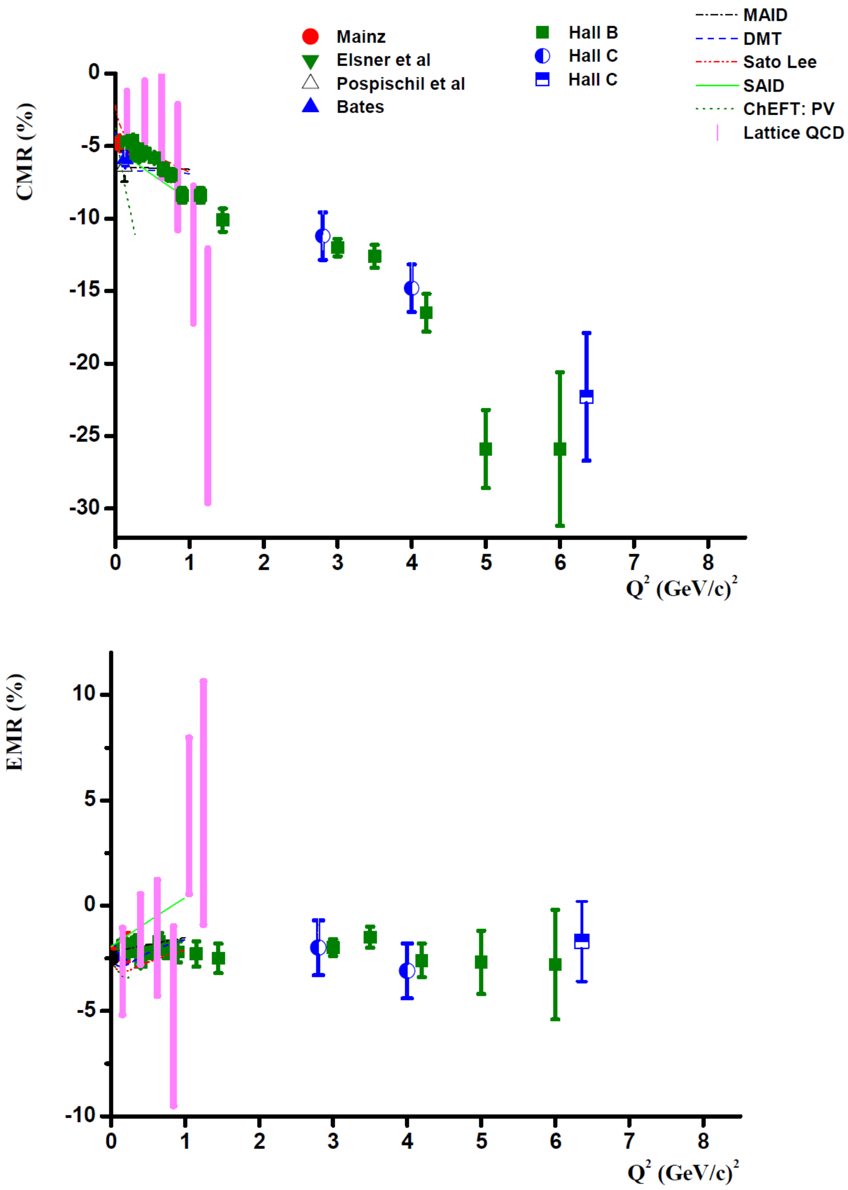
Interfering background amplitudes introduce model uncertainty

Model Uncertainty

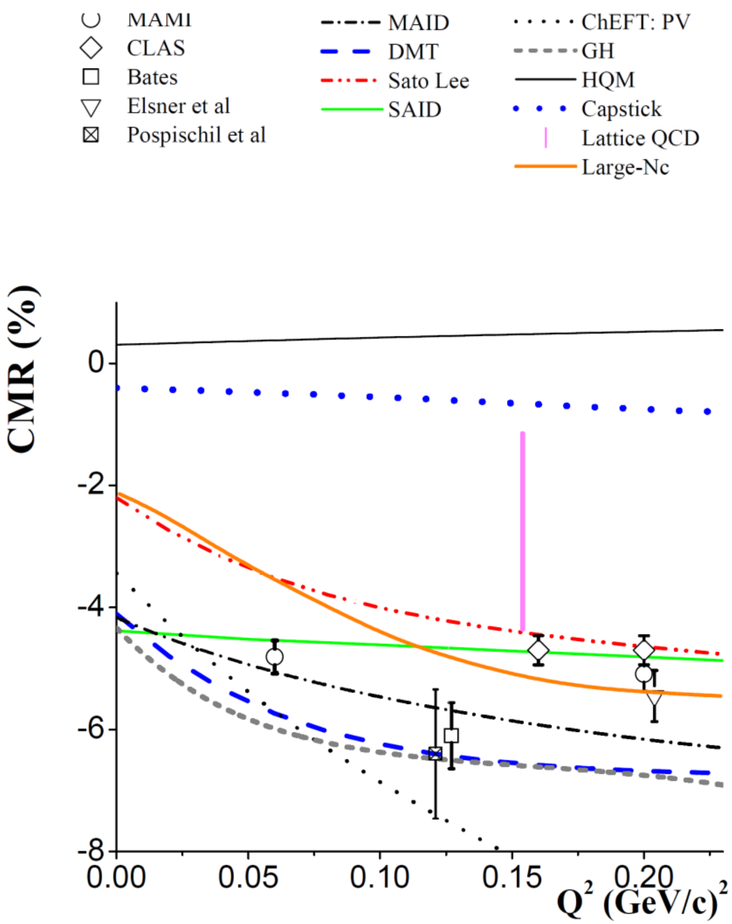




Experimental landscape

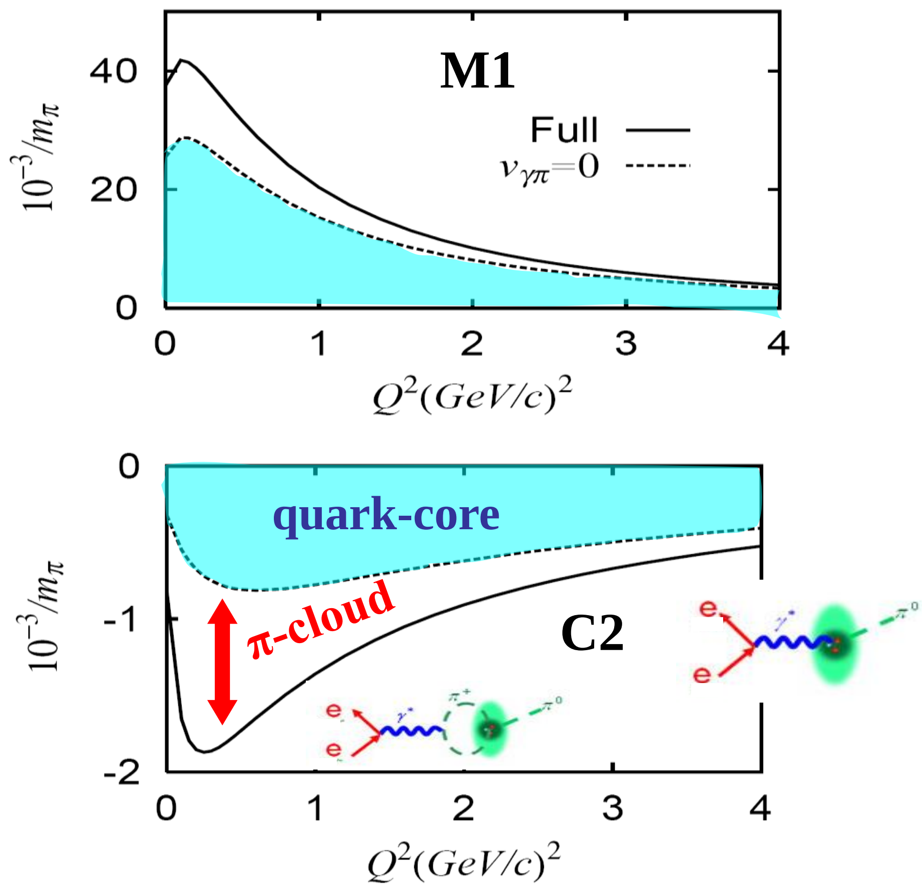


Dominance of mesonic cloud
at the low Q2 region



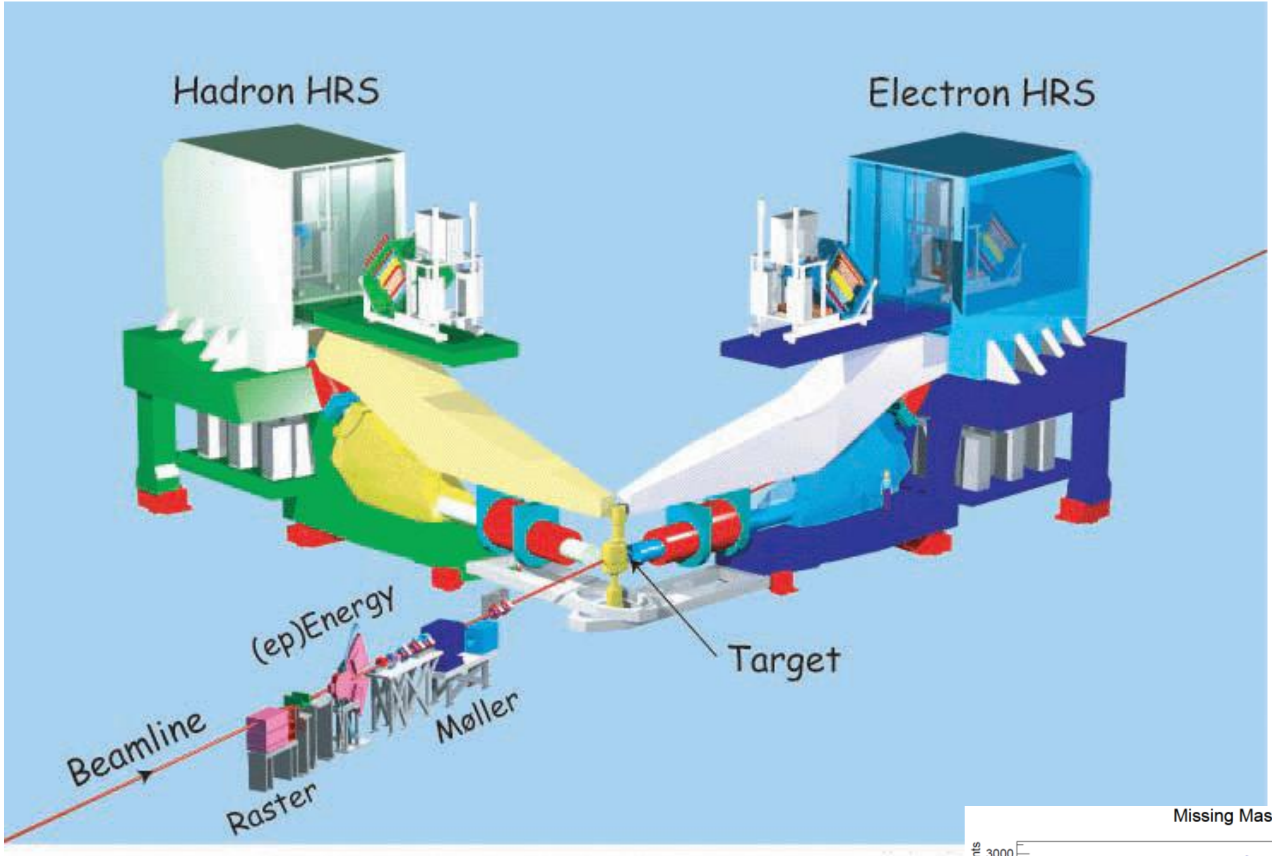
Sato-Lee calculation

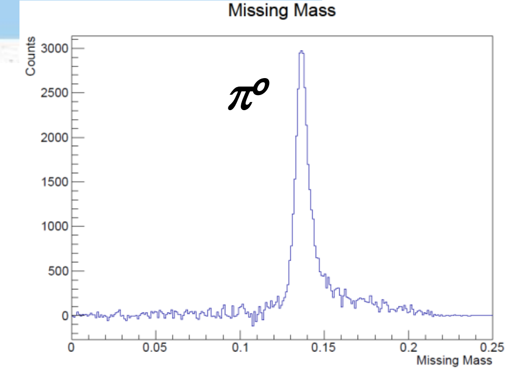
Dynamical calculation
quark core & pion cloud contributions



Jlab Hall-A : Experiment E08-010

Q^2=0.04 (GeV/c)^2 to 0.13 (GeV/c)^2





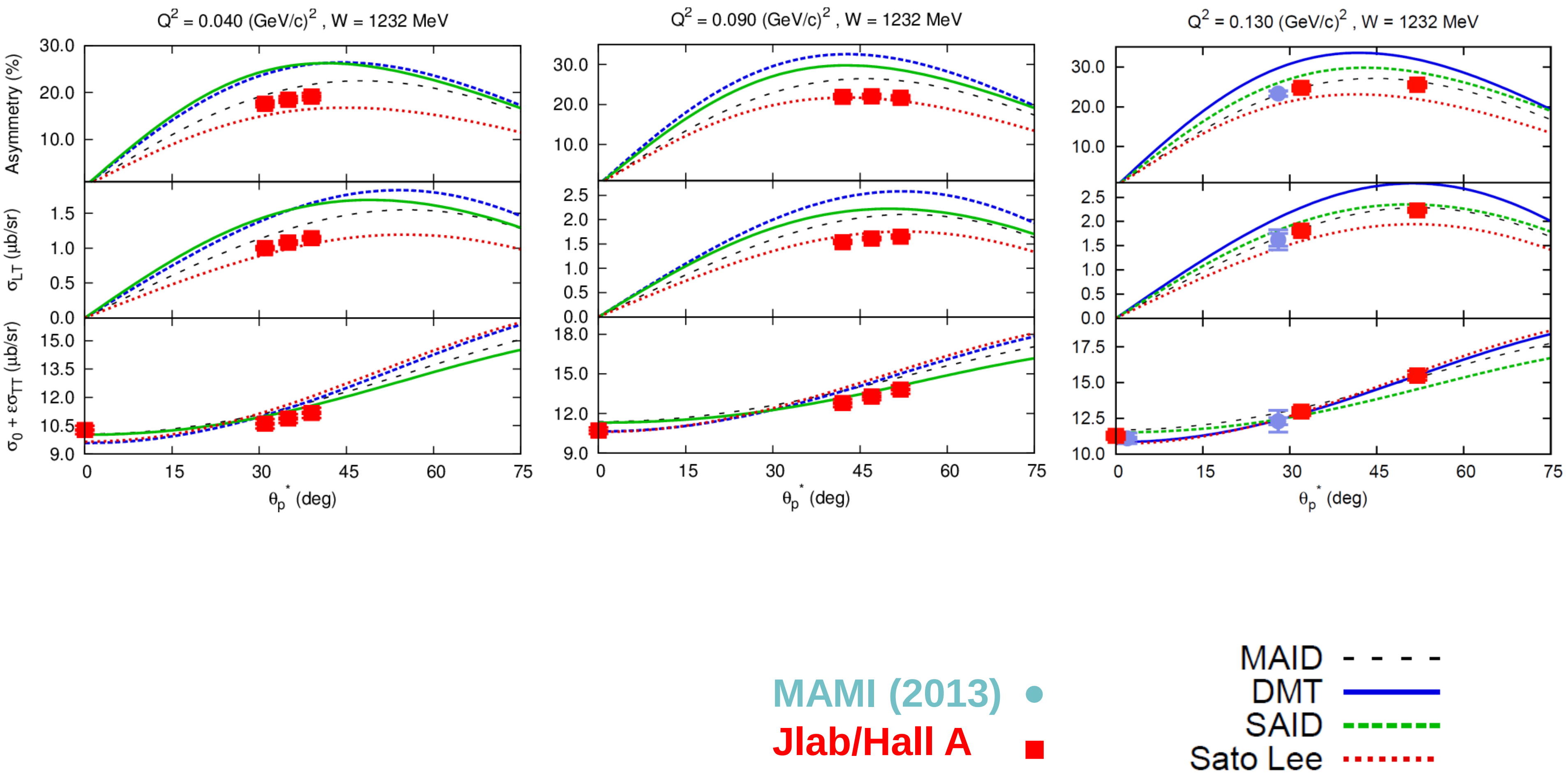
π^0 channel

E = 1.1 GeV

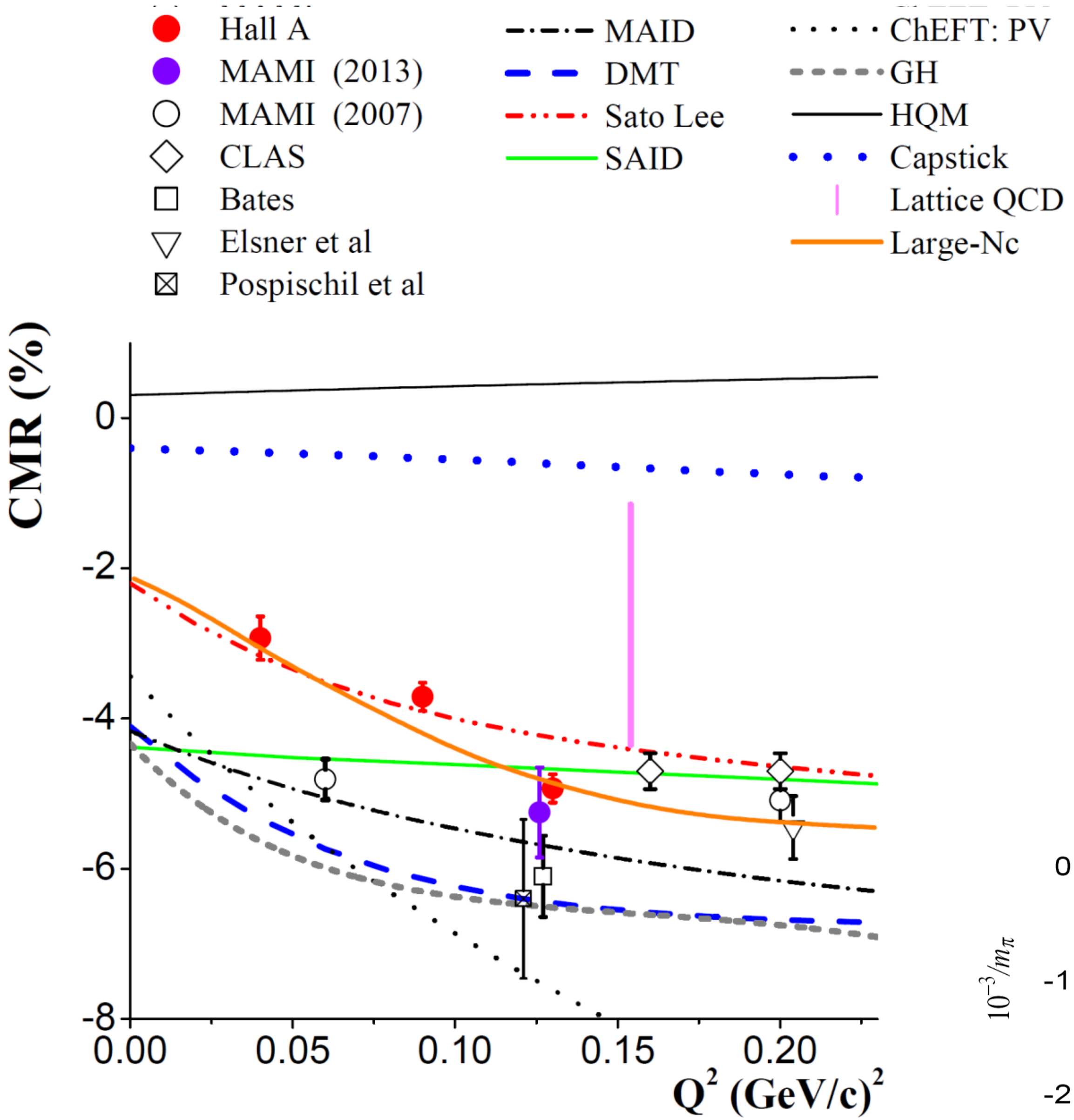
HRS measurements in coincidence

Data taking: February – March 2011

E08-010 results



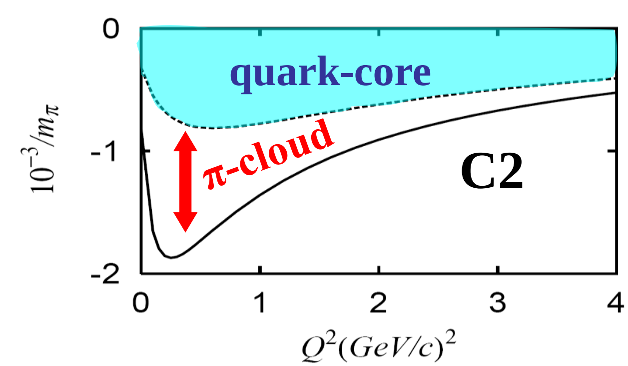
E08-010 results



Lattice QCD (m_π=300 MeV)
C. Alexandrou et al ,
Phys. Rev. D 83, 014501 (2011)

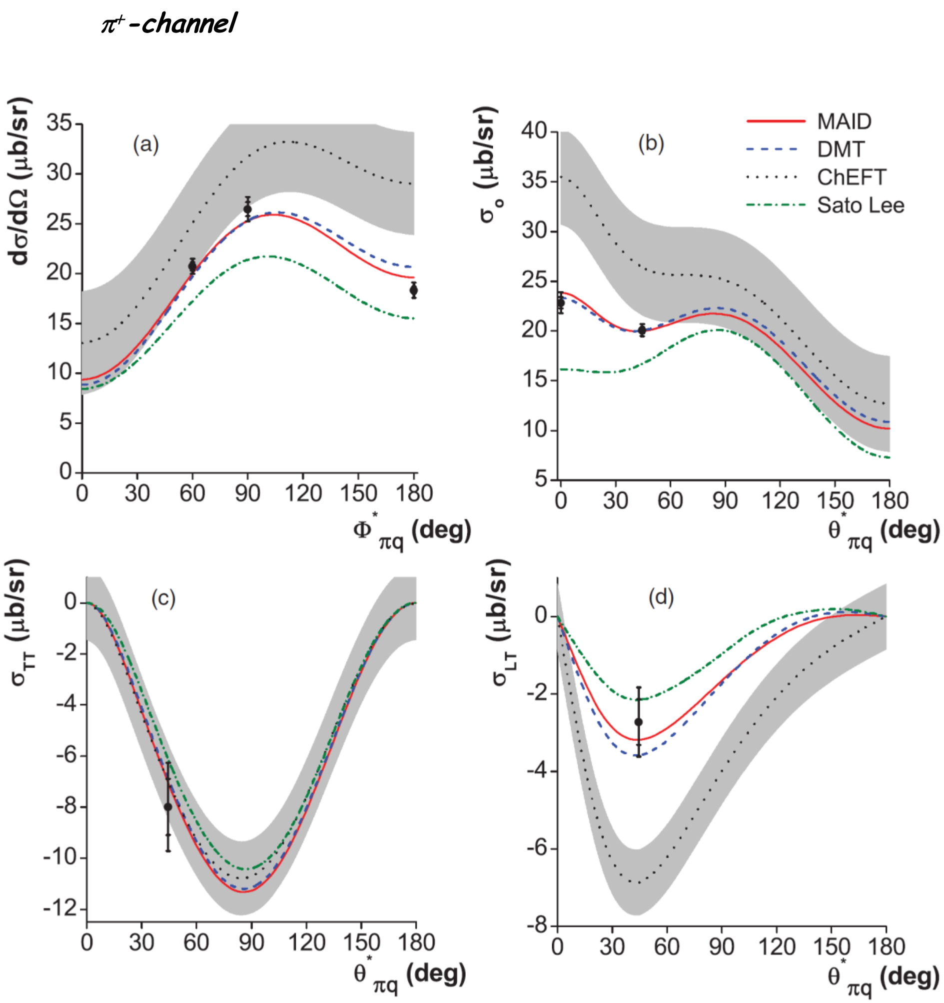
Large-Nc
Pascalutsa & Vanderhaeghen,
Phys. Rev. D 76, 111501 (2007)

Sato Lee
Phys. Rev. C 54, 2660 (1996)
Phys. Rev. C 63, 055201 (2001)



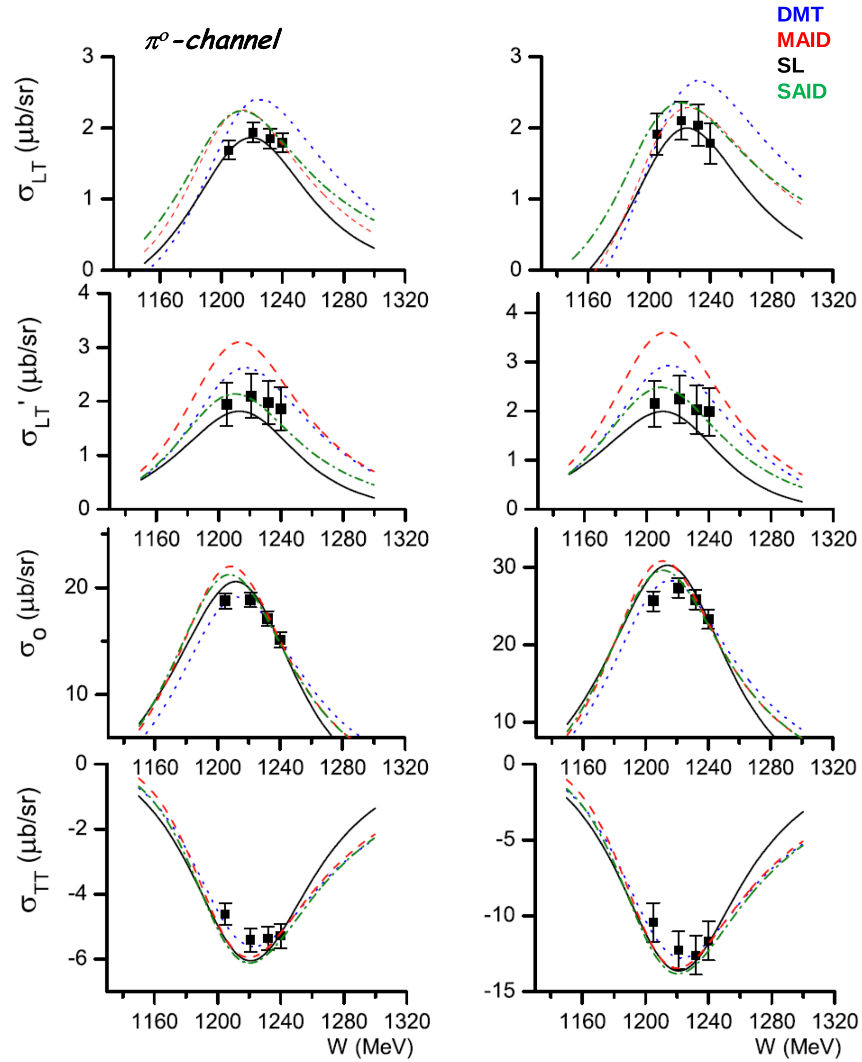
Q^2=0.13 (GeV/c)^2
(OOPS)

Phys. Rev. C 84, 028201 (2011)



Q^2=0.20 (GeV/c)^2
(MAMI)

Eur. Phys. J. A (2013) 49:136



What about the shape ?

Empirical transverse charge transition densities

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

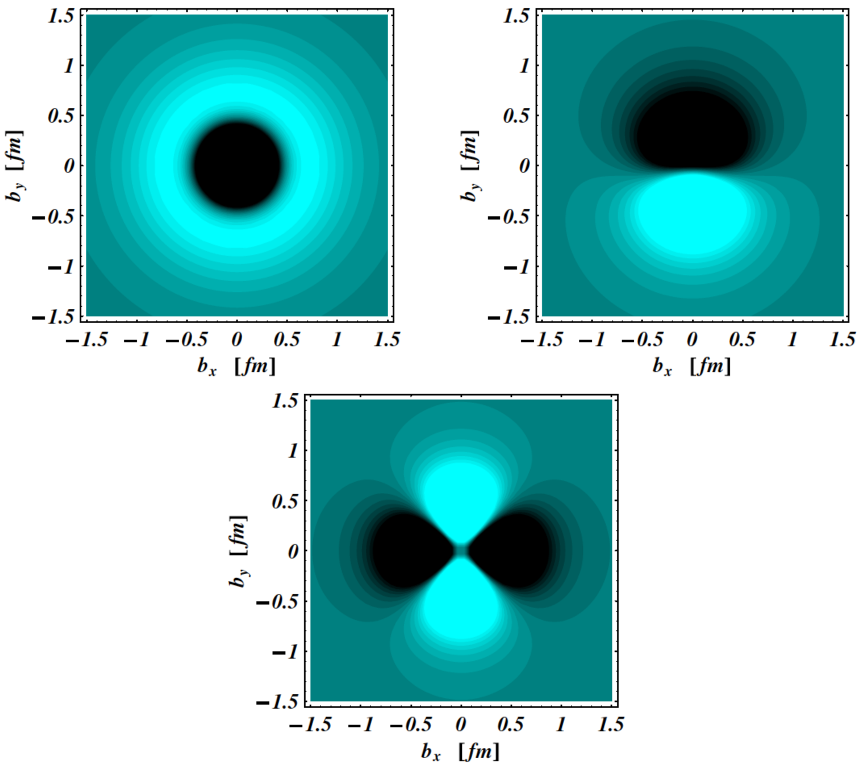


Fig. 18. Quark transverse charge density corresponding to the $p \to \Delta(1232)P_{33}$ e.m. transition. Upper left panel: p and Δ are in a light-front helicity $+1/2$ state ($\rho_0^{pP_{33}}$). Upper right panel: p and Δ are polarized along the x-axis ($\rho_T^{pP_{33}}$) as in Fig. 14. The lower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

Latice QCD

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

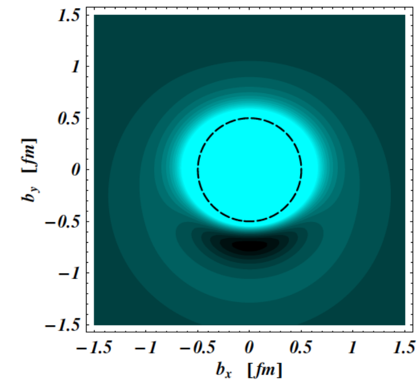
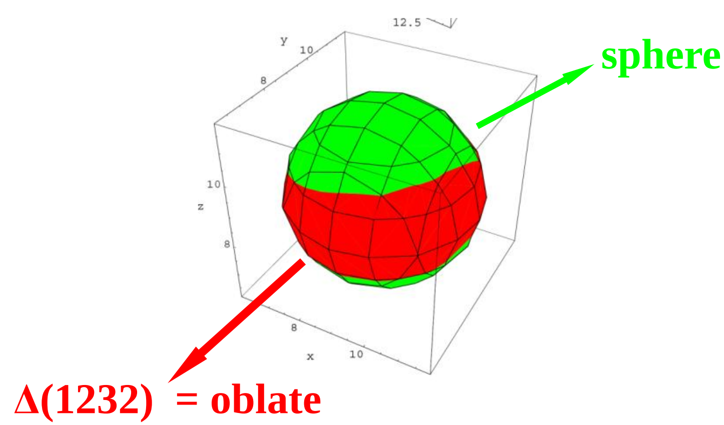
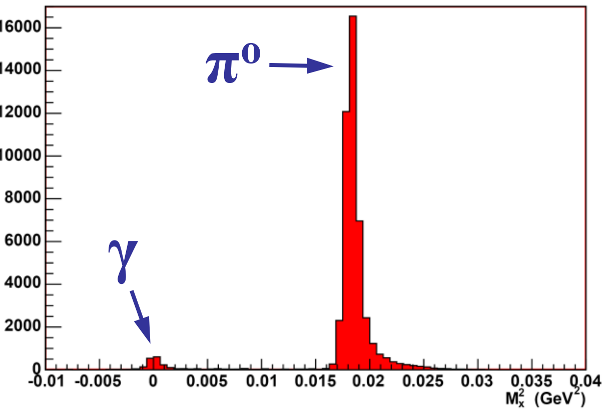


FIG. 10: Lattice QCD results for the quark transverse charge density $\rho^{\Delta}_{T\,\frac{3}{2}}$ in a $\Delta^+(1232)$ which is polarized along the positive x-axis. The light (dark) regions correspond to the largest (smallest) values of the density. In order to see the deformation more clearly,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

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



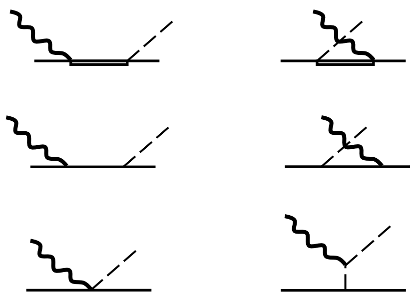
VCS @ Δ(1232)



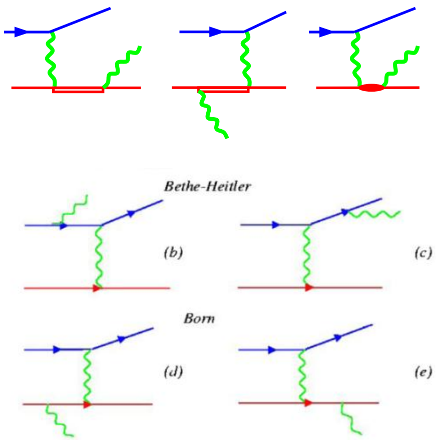
Quadrupole amplitudes have been explored so far only through the pion channel

VCS can also provide access:

The signal is the same in both cases, but the background contributions are different



π-channel



VCS

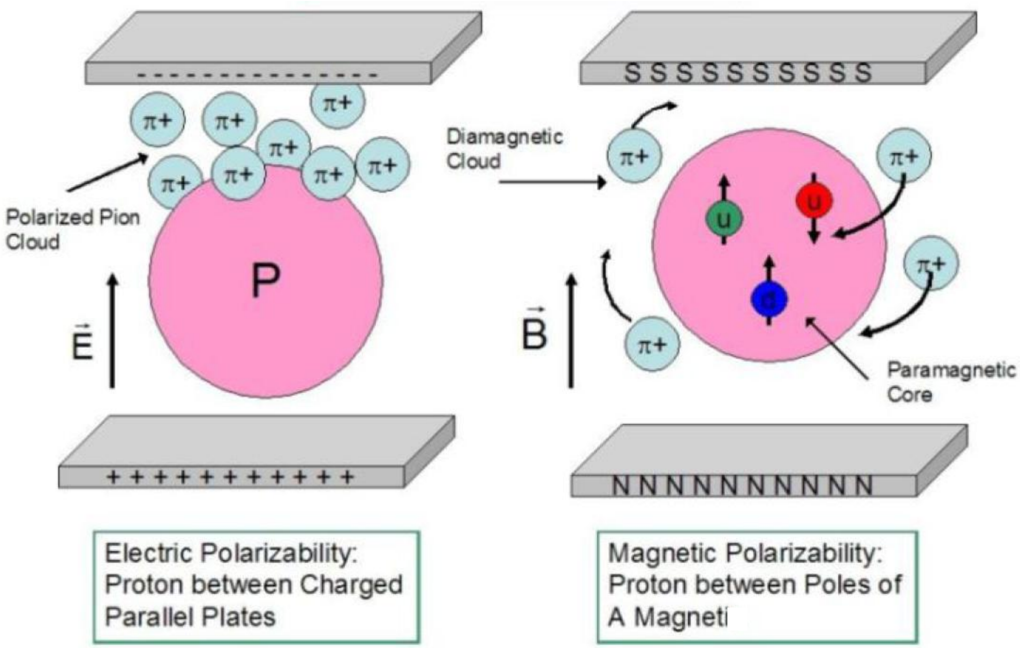
Test to the theoretical framework – control model uncertainties

Cross check (pion channel) world data

Simultaneous access to the protons Generalized Polarizabilities (α_E, β_M)

Proton Polarizabilities

a simplistic way to describe the polarizabilities



Electric Polarizability:

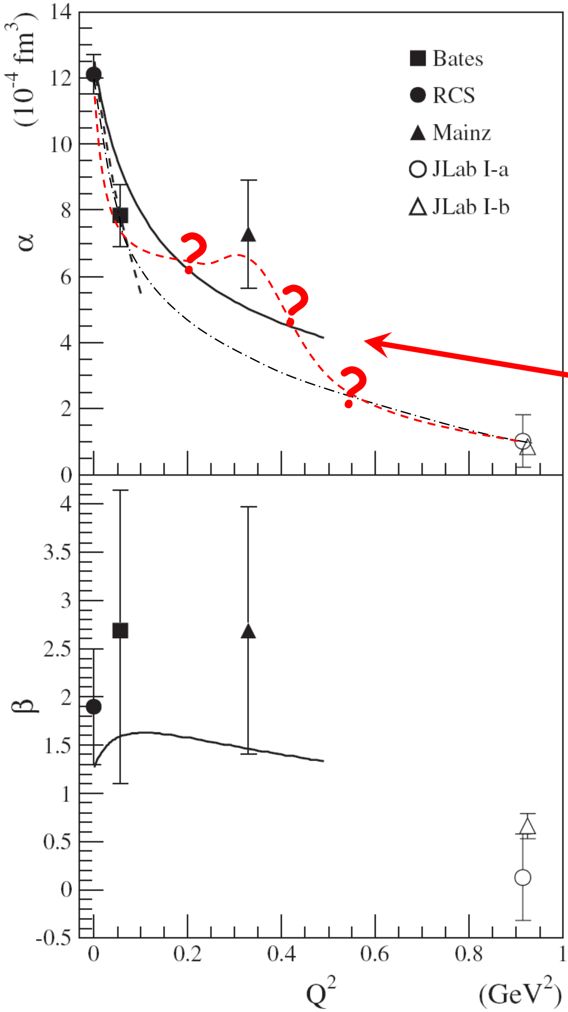
External field deforms the pion-cloud around the proton

Magnetic Polarizability:

Paramagnetic: proton spin aligns with the external magnetic field

Diamagnetic: π-cloud induction produces field counter to the external one

Proton G.Polarizabilities



first exploration of α_E and β_M

Bates/MIT (OOPS)
MAMI (A1)
JLab (Hall A)

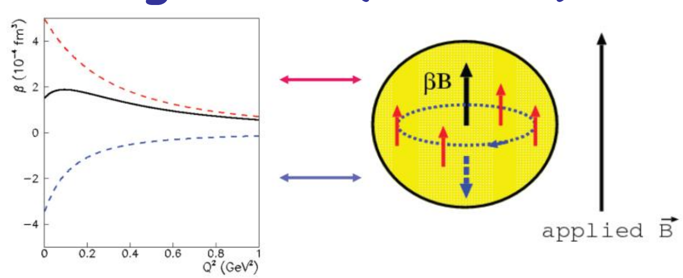
α_E does not follow the dipole form, $\approx 10^{-3}\ V_N$

explore further

β_M: small compared to α_E , low Q^2 maximum followed by a subsequent decrease

$\Rightarrow$

Interpreted as a cancellation of positive paramagnetism (core) and negative diamagnetism (π-cloud)

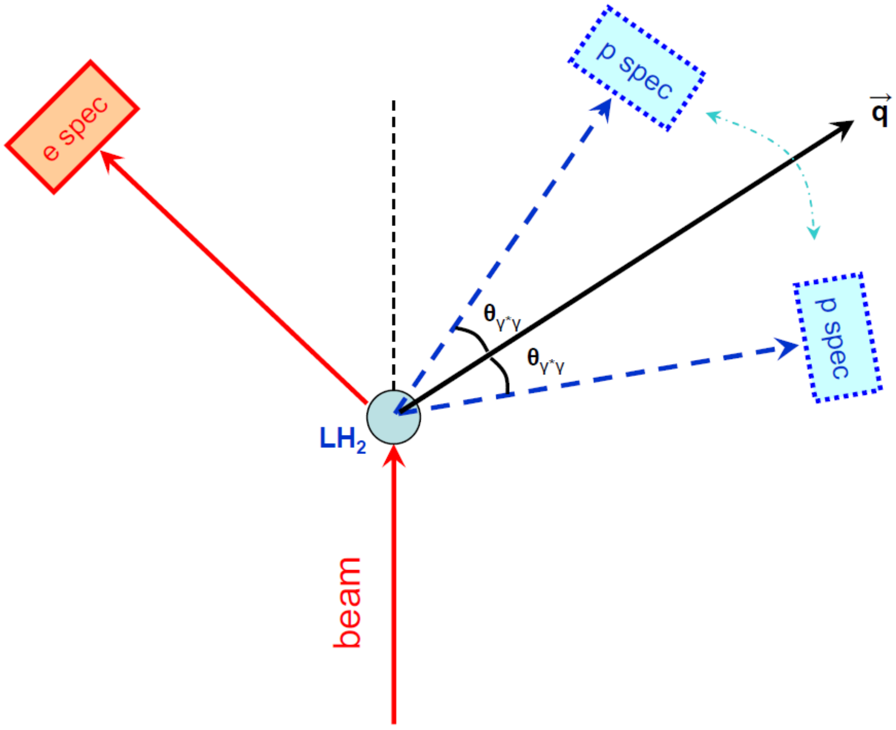


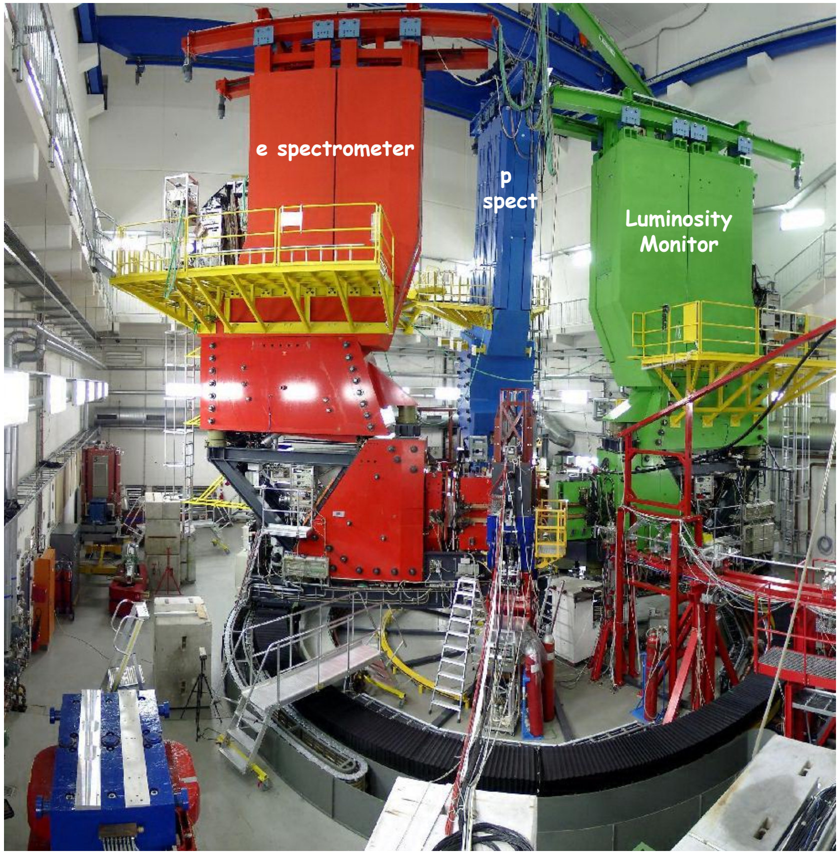
β_M : para- and diamagnetic contributions $\Rightarrow$
not a single dipole shape

VCS-Δ experiment: A1/03-12 @ MAMI/A1

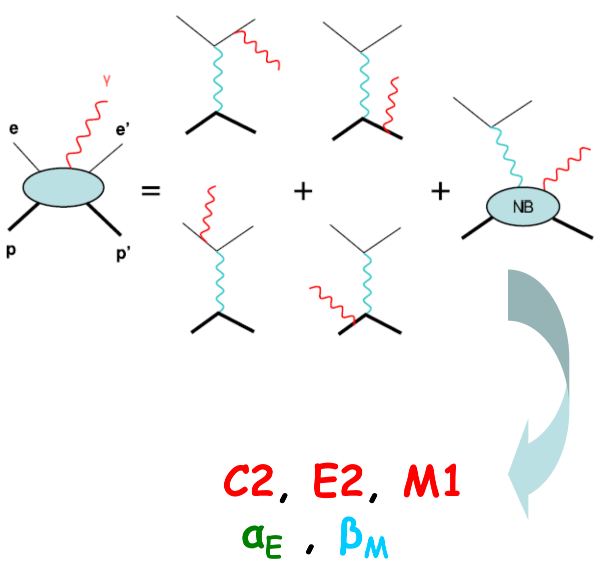
In plane azimuthal asymmetry $A_{[0,\pi]}$:
Excellent sensitivity to C2 & α_E

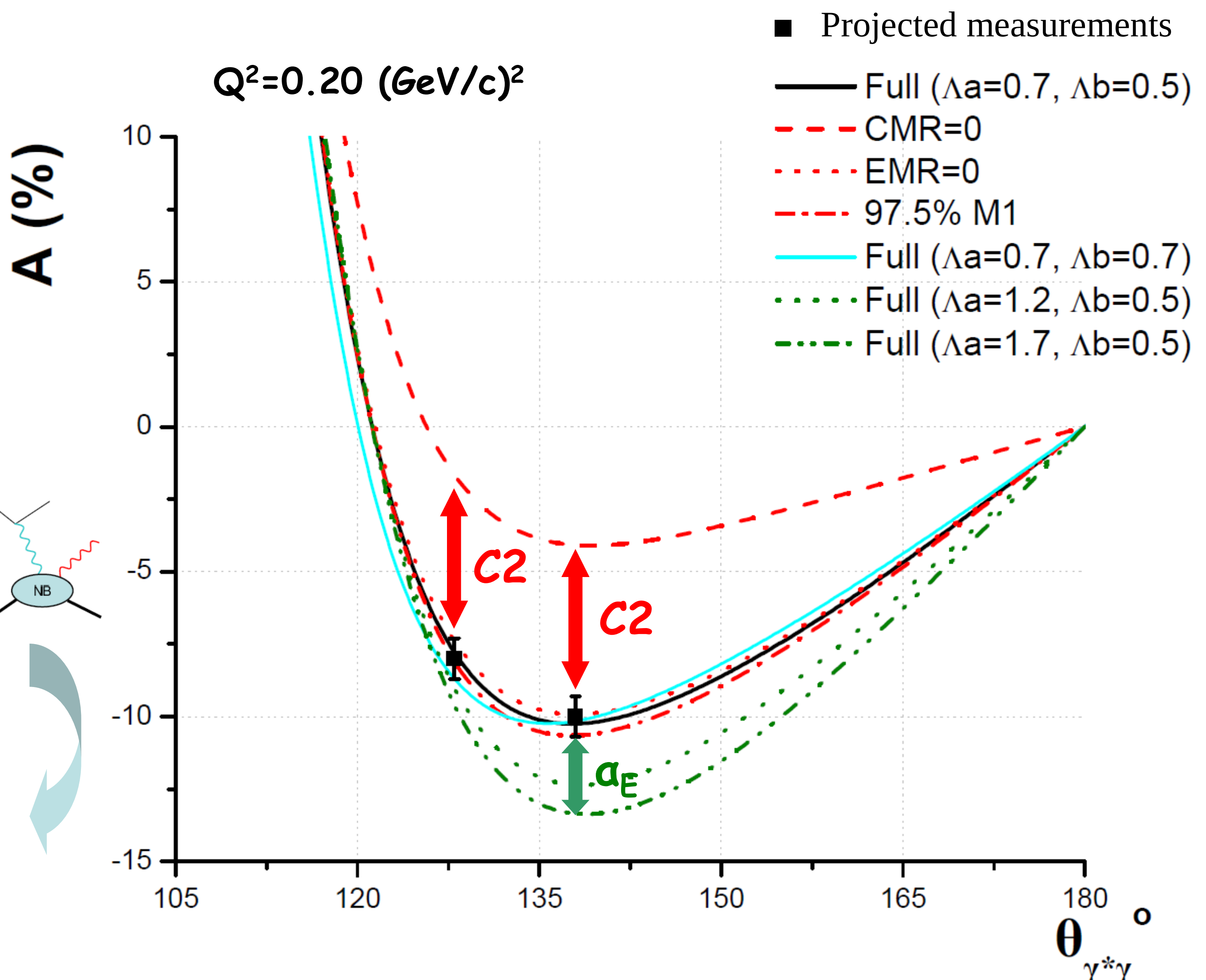
$$A = \frac{\sigma(\Phi=0) - \sigma(\Phi=180)}{\sigma(\Phi=0) + \sigma(\Phi=180)}$$



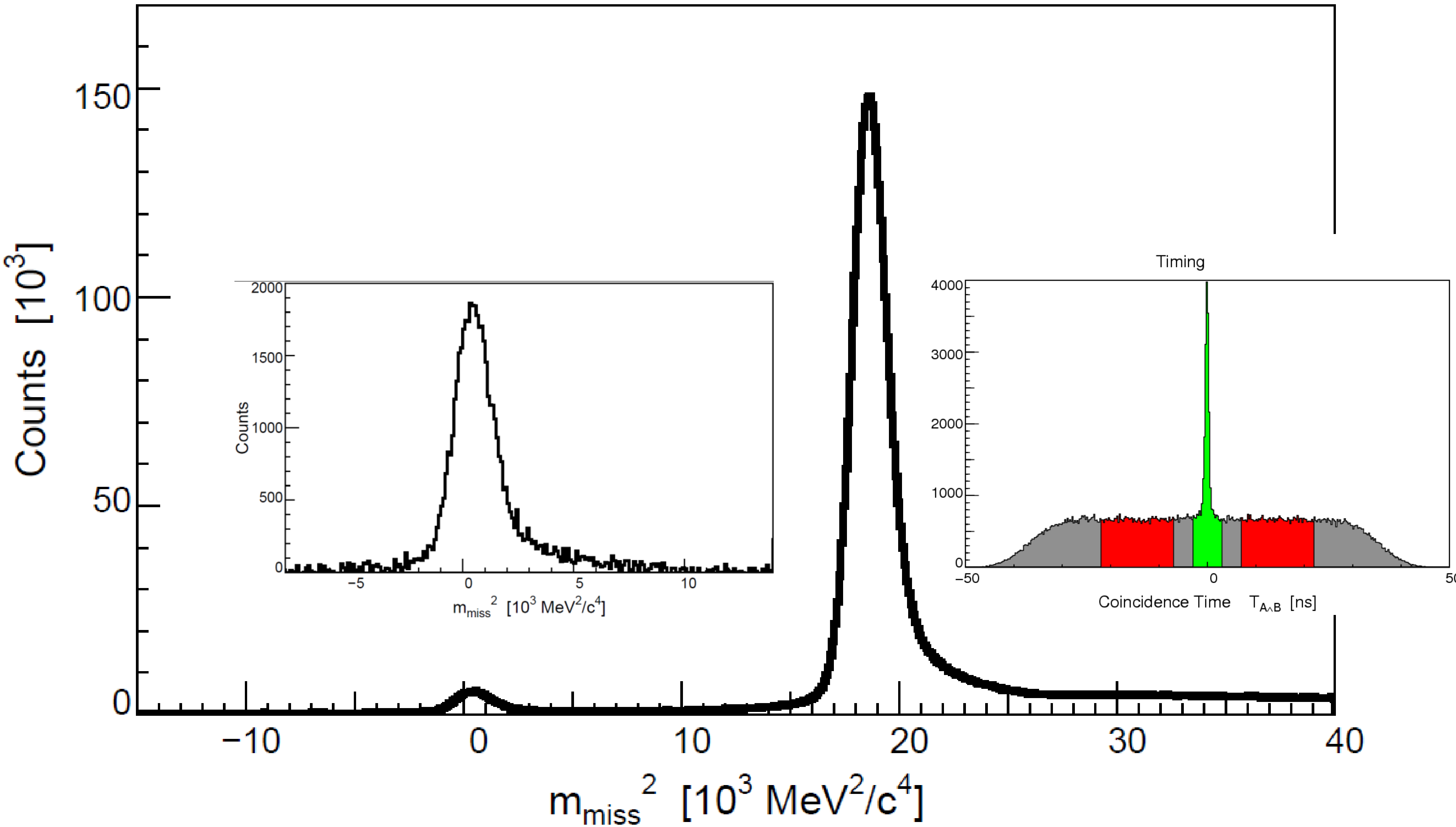


A1/03-12: E = 1.1 GeV
I = 15 μA
Data taking: September & October 2012



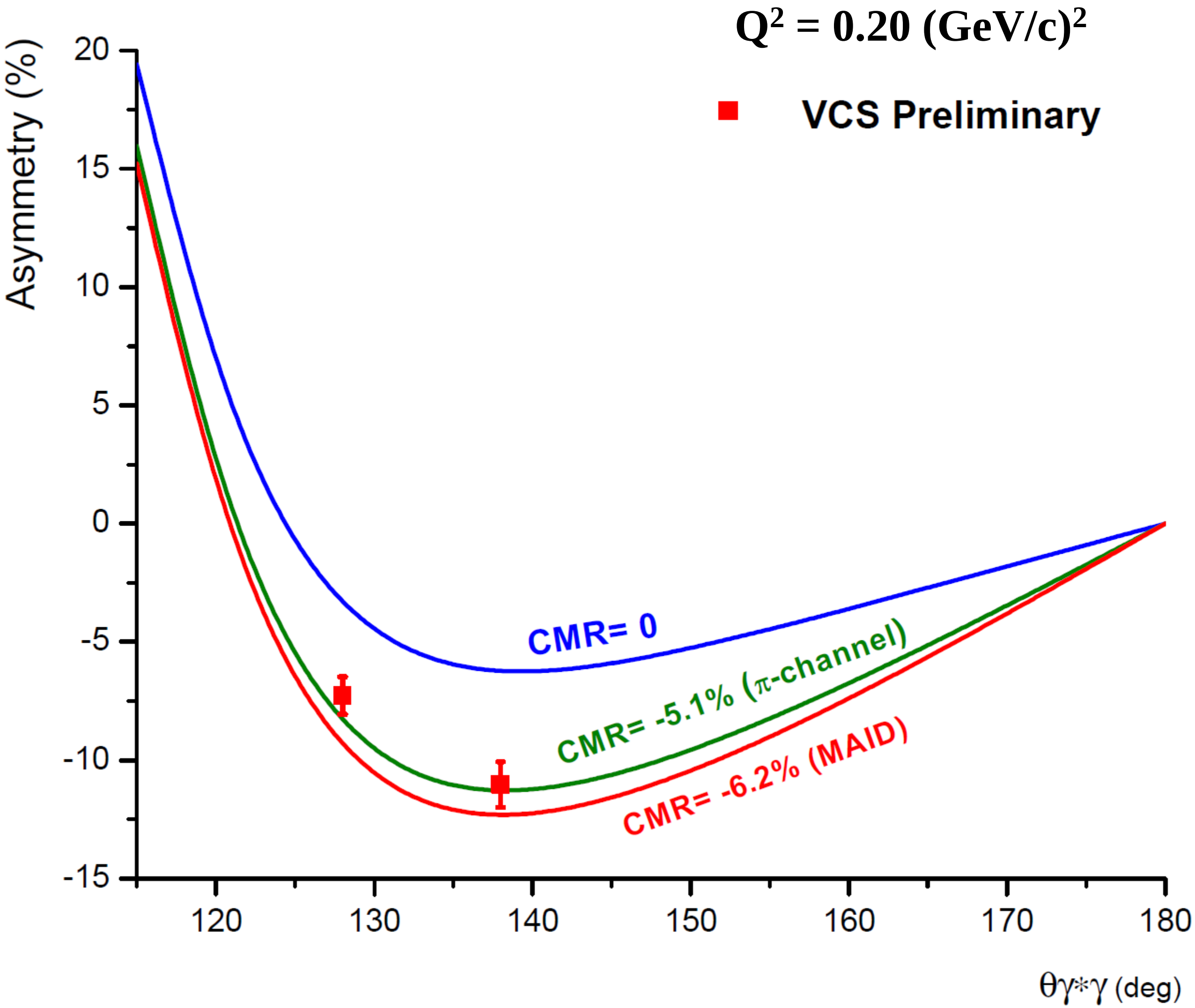


A1/03-12

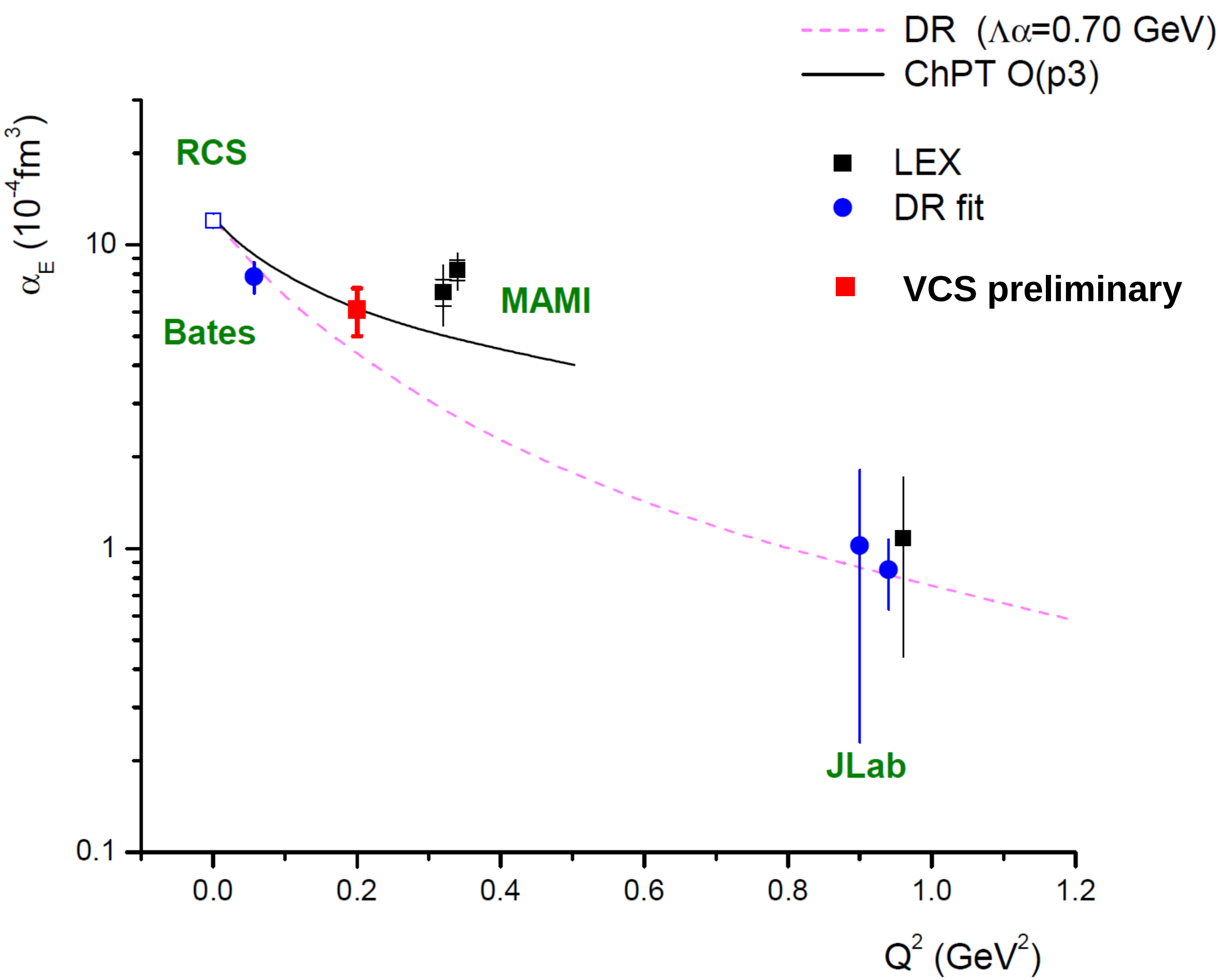


Counts [10^3]
150
100
50
0
−10
0
10
20
30
40
m_miss^2 [10^3 MeV^2/c^4]
Counts
2000
1500
1000
500
0
−5
0
5
10
m_miss^2 [10^3 MeV^2/c^4]
Timing
4000
3000
2000
1000
0
−50
0
50
Coincidence Time T_A∧B [ns]

A1/03-12 Preliminary Results



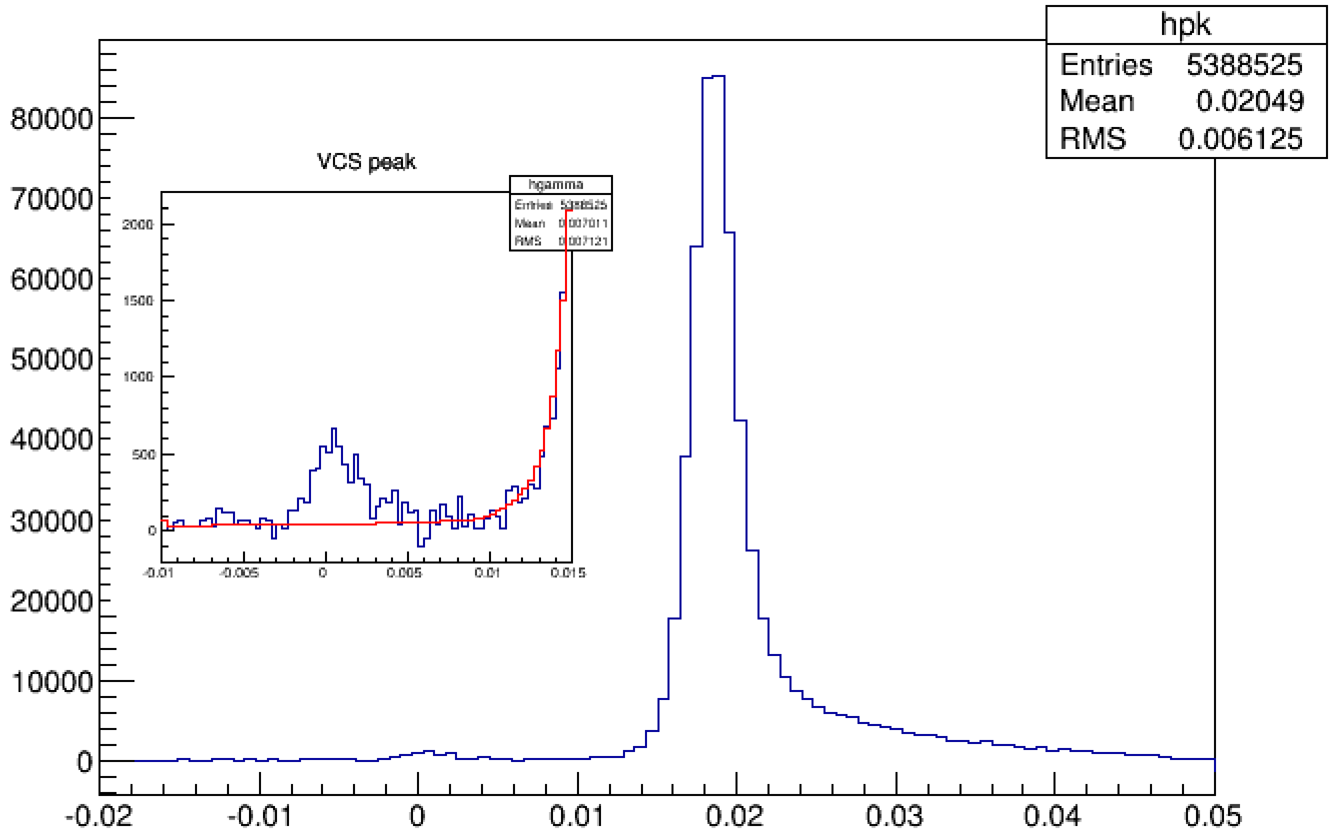
A1/03-12 Preliminary Results



Jlab Hall-A: E08-010

Q^2=0.04 $(GeV/c)^2$ to 0.13 $(GeV/c)^2$

parasitic access to VCS



Concluding Remarks

An intense experimental program has provided a detailed description of the first resonance excitation

New experimental results – strong constraints to theoretical calculations

The quadrupole transitions are pinned down on the order of a few % of the dominant magnetic dipole transition. A quantitative understanding of the small, non-zero values of these amplitudes from QCD is a particular challenge

Theory: successful Dynamical Models and contact with fundamental QCD,
We need improved theory !

The role of the mesonic cloud has been manifested at the long distance scales – dominance of quark d.o.f. at high Q^2

We now have rich and precise data base to get the signature (Q^2) of the pion cloud and to decode the interplay of the mesonic and quark-gluon d.o.f

Δ-VCS: a valuable line of investigation to address the model uncertainties, to cross check the world data, and to explore the GPs

IMPACT Getting close to decoding an important piece of the puzzle of the EM structure of the nucleon