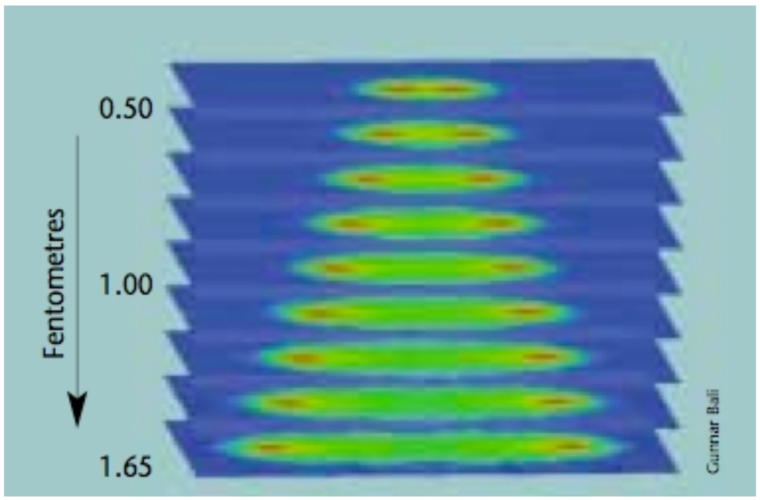
Chiral Dynamics with Pions, Nucleons, and Deltas

Daniel Phillips
Ohio University

Connecting lattice and laboratory



EFT

Picture credits: C. Davies, Jefferson Lab.

What is an Effective Field Theory?

- $\mathcal{M}=f(p/\Lambda)$ for $p \ll \Lambda$
- QFT with $\mathcal{L}=\mathcal{L}(p/\Lambda)$ + loops as a function of p/Λ
- $\mathcal{L}$ includes all possible terms at a given order
- Error estimates from size of omitted terms

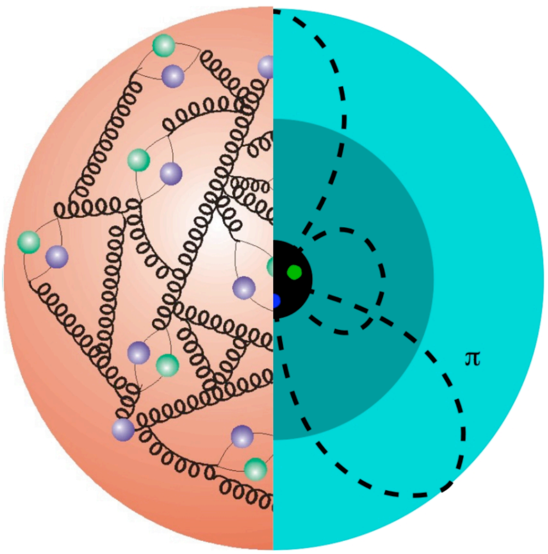
Chiral perturbation theory

•$\mathcal{L}= \mathcal{L}(N,\pi,\Delta)$

•Ratio of scales is $(p, m_{\pi}, M_{\Delta}-M_N)/\Lambda$,

$\Lambda=4\pi f_{\pi}$, m_{ρ}, M_N

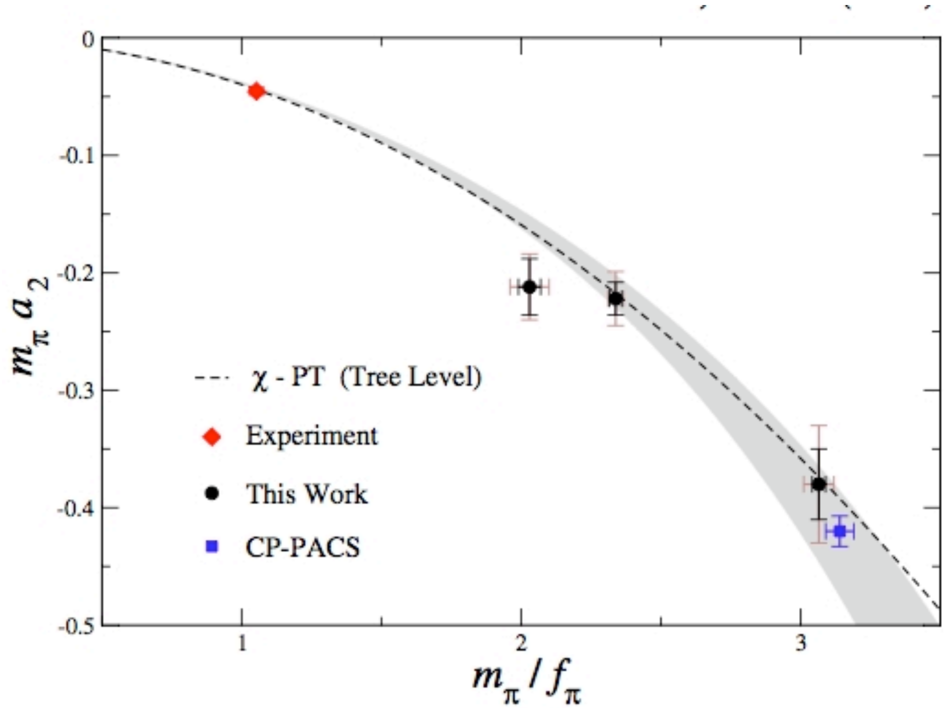
•$\mathcal{L}$ consistent with QCD symmetries and pattern of their breaking



Outline

- Progress and opportunities in Goldstone-boson dynamics….very briefly
- Progress and opportunities in chiral dynamics of baryons
  - Compton scattering (including VCS)
  - Neutron-proton differences in γN (Griesshammer)
  - π photo- and electro-production near t/hold (Weller)
  - πN scattering->isospin violation (Weller)
  - N->Δ transition
  - Δ magnetic dipole moment: Mainz experiment
  - Other resonances: Roper? S_{11}(1535)?

ππ scattering from full QCD



- Luescher method
- MILC lattices
- LHPC propagators
- Higher-order χPT corrections small

χPT predicts dependence on m_{π}, small momenta, lattice artefacts (partial quenching, finite volume)

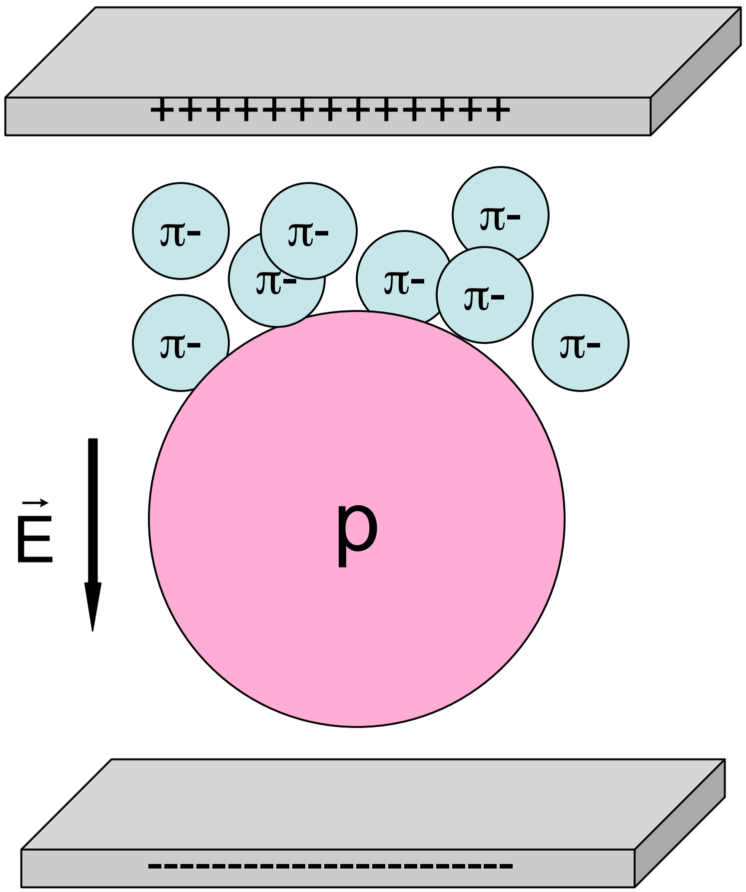
Beane, Bedaque, Orginos, Savage (NPLQCD), PRD (2006)

A=0: summary and future

- Lattice calculations from full QCD for $\pi\pi$, πK
- χPT a mature & precise theory: calculations to two loops=>relative error $(m_\pi/\Lambda)^4$
- Attempts to go beyond perturbation theory: data + dispersion relations + chiral constraints. Sheds light on scalar mesons?

- Standard model tests: K_{e3} decays and V_{us}
- Basic understanding of QCD: PRIMEX

Chiral structure of the nucleon I



- Electric polarizability

$$\vec{d} = 4\,\pi\,\alpha\,\vec{E}$$

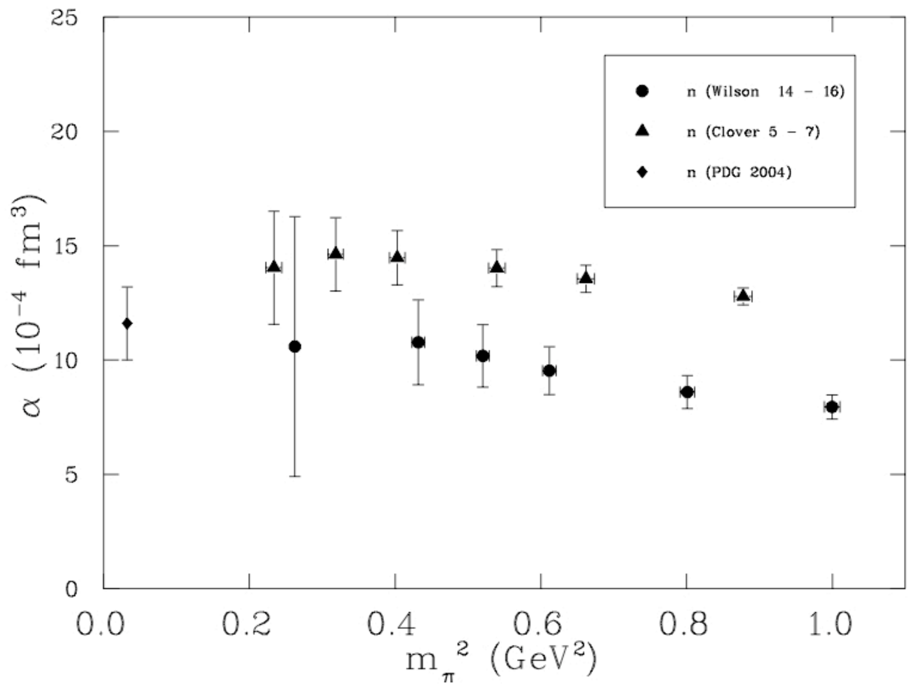
- Magnetic polarizability

$$\vec{\mu} = 4\,\pi\,\beta\,\vec{B}$$

Interplay of long-distance and short-distance effects

Picture credit: R. Miskimen

Polarizabilities on the lattice



Christensen, Wilcox, Lee, Zhou, PRD (2005)

From H=-2 π α E^2 - 2 π β B^2

Quenched calculation

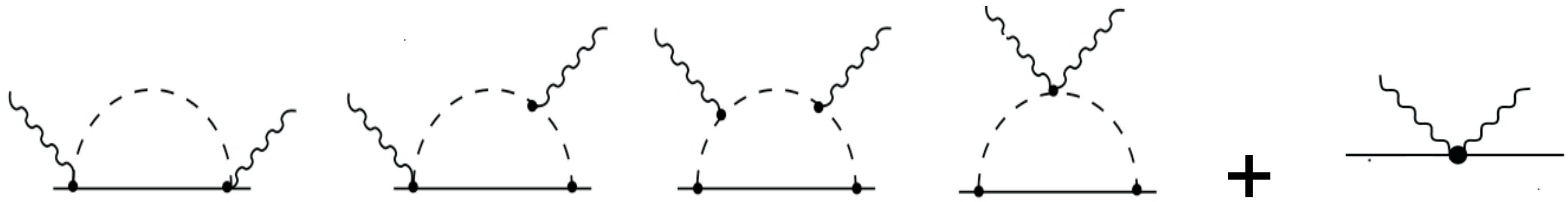
$$H = -2\pi \left(\gamma_{E1,E1} \sigma \cdot \vec{E} \times \dot{\vec{E}} + \gamma_{E1,E1} \sigma \cdot \vec{B} \times \dot{\vec{B}} - 2\gamma_{E2,M1} (\nabla_i E_j + \nabla_j E_i) \sigma_i B_j + 2\gamma_{M2,E1} (\nabla_i B_j + \nabla_j B_i) \sigma_i E_j \right)$$

Low-energy manifestations of nucleon spin structure

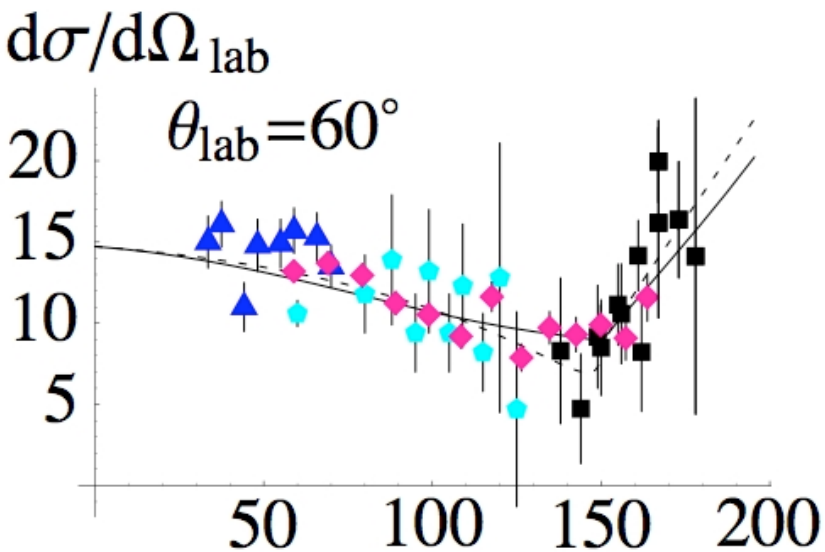
Computation of volume and m_π dependence of α, β, γ's

Detmold, Tiburzi, Walker-Loud, PRD (2006)

Measuring proton polarizabilites



Chiral Dynamics below pion threshold

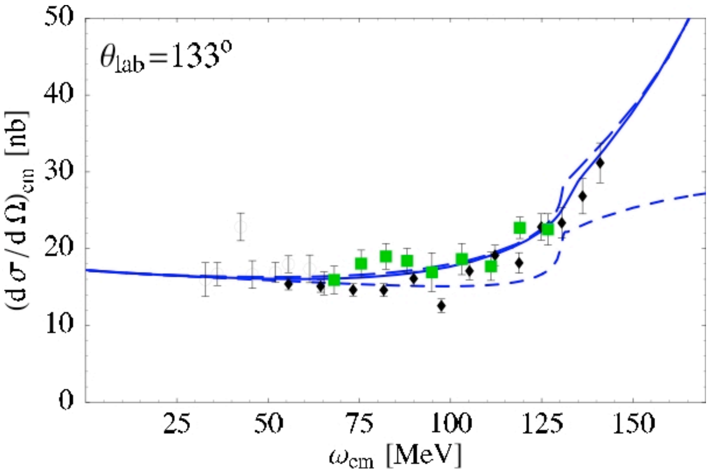


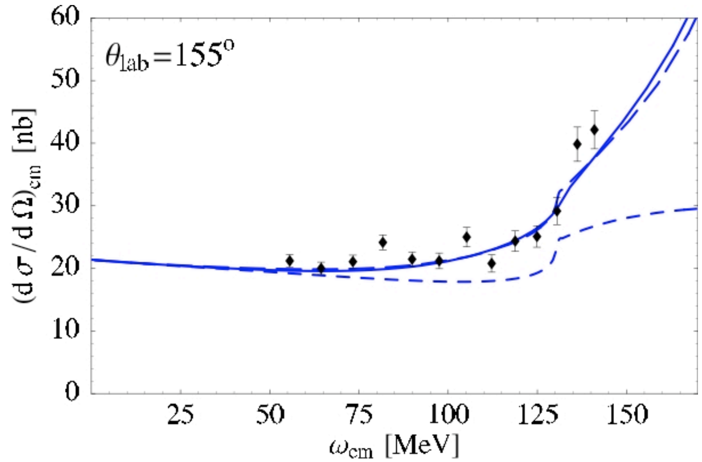
McGovern, PRC (2001)

- α, β, γ's predicted at $O(e^2P)$ in χPT
- α=10 β=12.5 x 10^{-4} fm^3
- Proton=neutron
- Short-distance effects enter at $O(e^2P^2)$
- To measure α, β, γ's need to go to ω>100 MeV

Extracting proton α, β, γ's

Hildebrandt, Griesshammer, Hemmert, Pasquini, EPJA (2004)





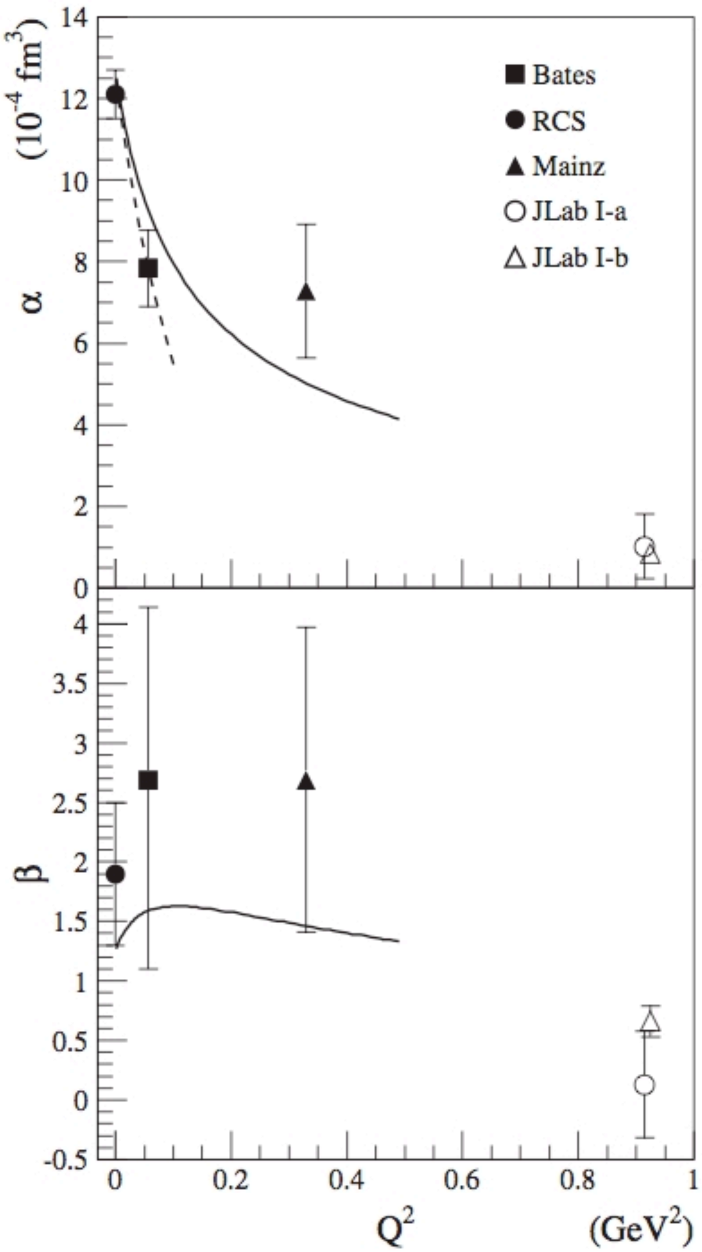
- Δ(1232) included in Lagrangian, loops
- Fit up to ω=200 MeV
- Marked Δ influence on magnetic response
- α, β in dcs, γ's in double-polarization observables

$$\alpha=(11.04 \pm 1.3 \pm 1.0) \times 10^{-4}\ \text{fm}^3$$
$$\beta=(2.76 \mp 1.3 \pm 1.0) \times 10^{-4}\ \text{fm}^3$$

More data needed: polarized data for γ's, but issues with α, β

Close to $O(e^2P)$ values!

Chiral dynamics in VCS



- VCS experiment at Bates
- Measured response functions P_{LL}-P_{TT}/ε, P_{LT}
- Using OOP spectrometer
- Extract $\alpha(q^2)$, $\beta(q^2)$
- $O(e^2P)$ χET predictions agree well with data within (admittedly large) error bars
- VCS future: smaller error bars? $\gamma(q^2)$? Where?

Bourgeois et al., PRL (2006)

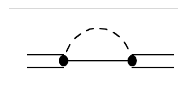
Compton scattering in the Δ region

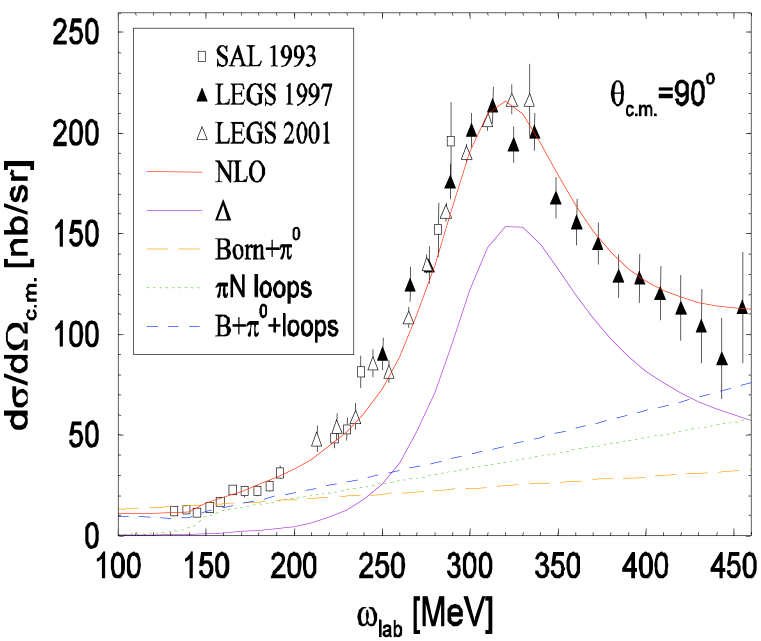
$m_\pi << \Delta << \Lambda_\chi$

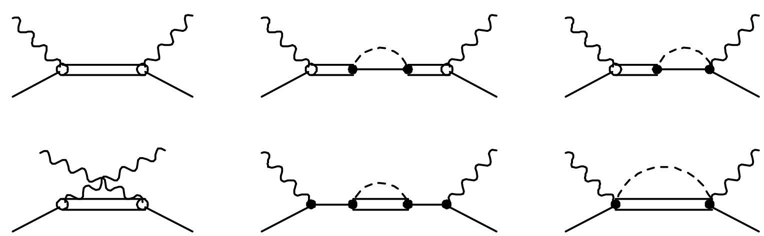
Pascalutsa, D.P., PRC (2003)

$\delta = \frac{\Delta}{\Lambda_\chi}, \ \frac{m_\pi}{\Lambda_\chi} = \delta^2$

$$\frac{1}{p-\Delta} = \begin{cases} p \text{ approx. } m_\pi, & 1/\Delta = O(1/\delta) \\ p \text{ approx. } \Delta, & 1/(p-\Delta-\Sigma) = O(1/\delta^3) \end{cases}$$

$\Sigma =$  $+ \ldots = O(p^3) = O(\delta^3)$

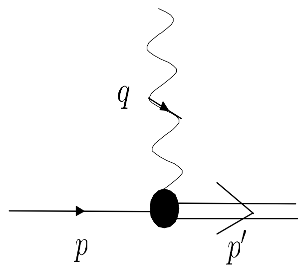




Courtesy V. Pascalutsa

N->Δ transition

3 electromagnetic transitions :



M1 -> G_M^*

E2 -> G_E^*

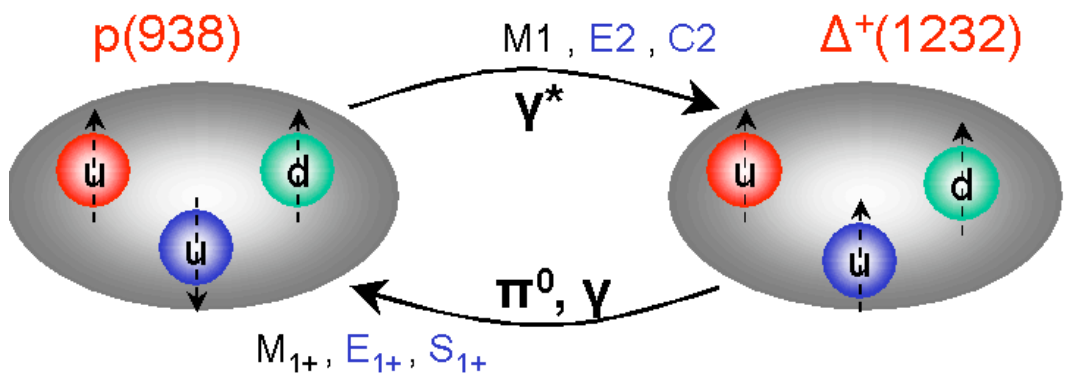
C2 -> G_C^*

Ratios:

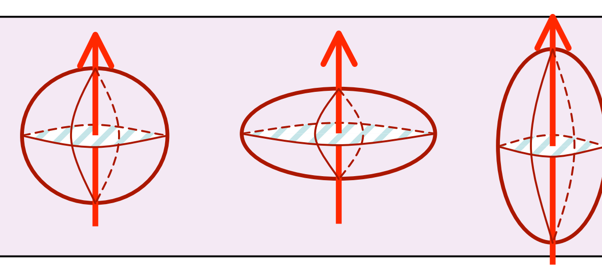
$$R_{EM} \equiv -\frac{G_E^*}{G_M^*}$$

$$R_{SM} \equiv -\frac{|\vec{q}|}{2\,M_\Delta}\,\frac{G_C^*}{G_M^*}$$

q : photon momentum in Δ rest frame

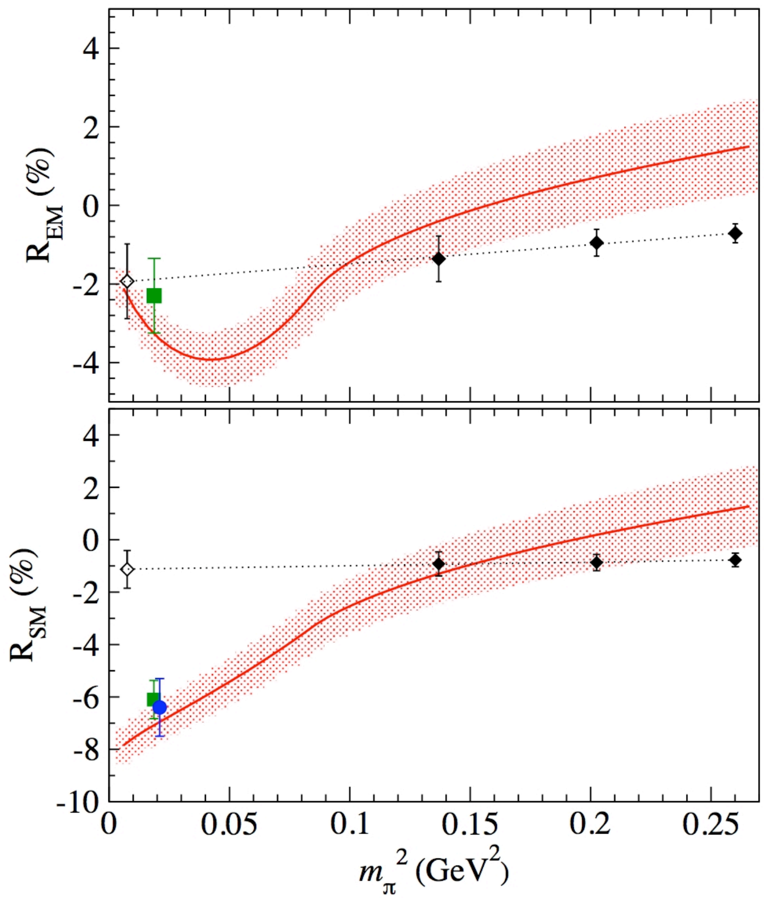


non-zero values for R_{EM} and R_{SM} : measure of non-spherical distribution of charges

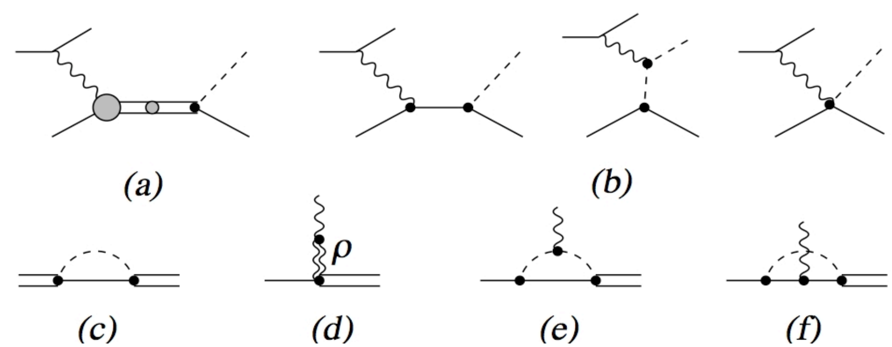


Courtesy V. Pascalutsa

Lattice results for R_{EM} and R_{SM}

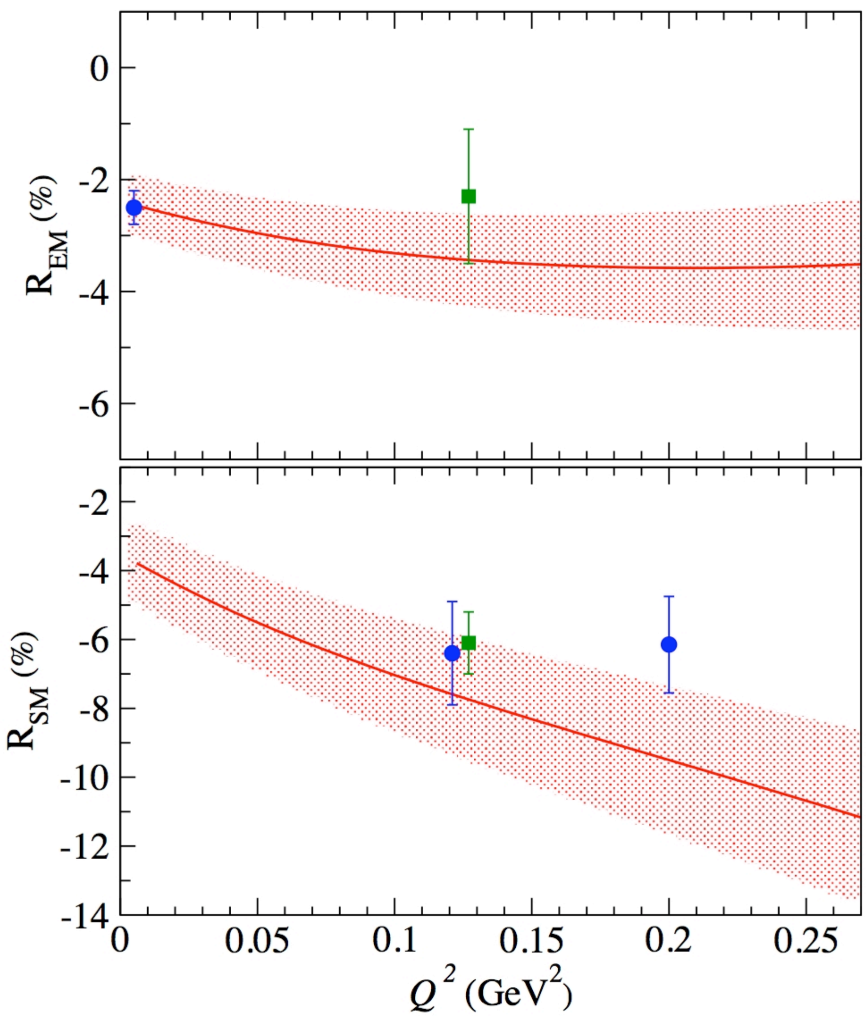


- Dependence on m_π calculable in χET
- NLO calculation in δ expansion
- Quenched lattice data



Lattice: C. Alexandrou et al., PRL (2005)
χET: Pascalutsa and Vanderhaeghen, PRL (2005)

R_{EM} and R_{SM} with Q^2



MIT-Bates [Sparveris et al. (2005)]

MAMI :

[Beck et al.(2000), Pospischil et al. (2001), Elsner et al. (2005)] + new 2006 data

NLO χET (LECs fixed from observables)

Pascalutsa and Vanderhaeghen, PRL(2005)

Summary and Outlook

Significant progress over last five years

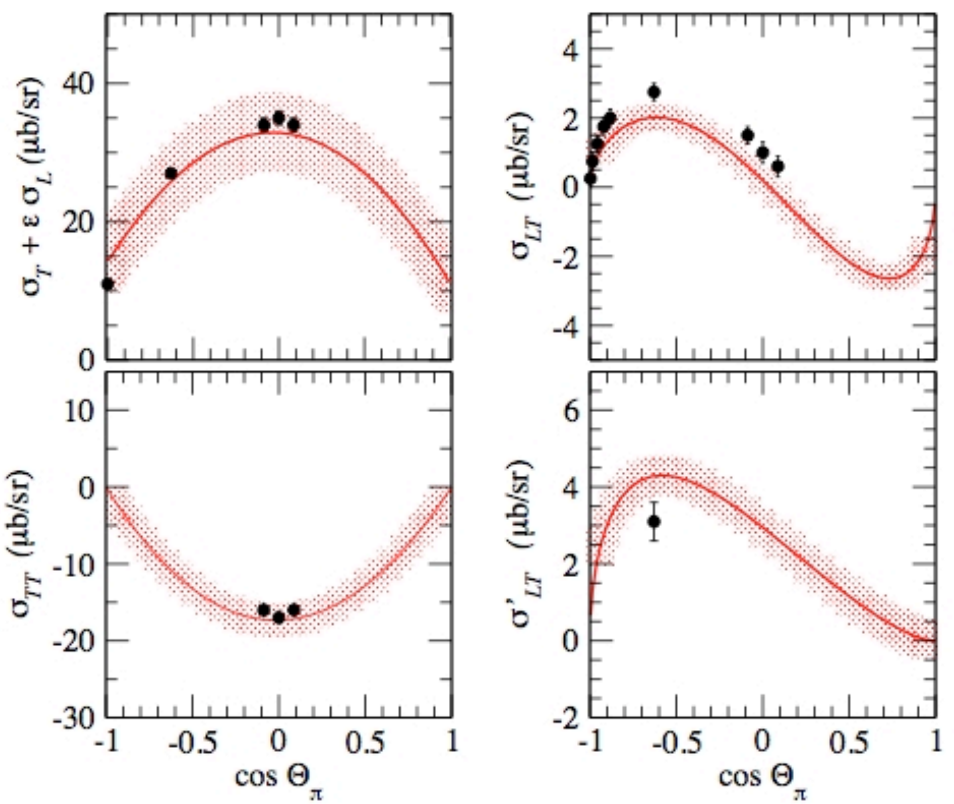
- What we need now:
  - More and better χET carried out to higher orders for more processes
  - More and better data

- What this will yield:
  - Input to few-nucleon calculations
  - Better constraints on physics beyond-the-pion-cloud

When used together with improved lattice data: rigorous connection of that short-distance physics to QCD

Thanks to the DoE for financial support

Electroproduction observables



Compton scattering (contd.)

- NLO in δ expansion
- LEGS data on beam asymmetry
- Pion cloud + Delta interference

Pascalutsa & D.P. (2003)