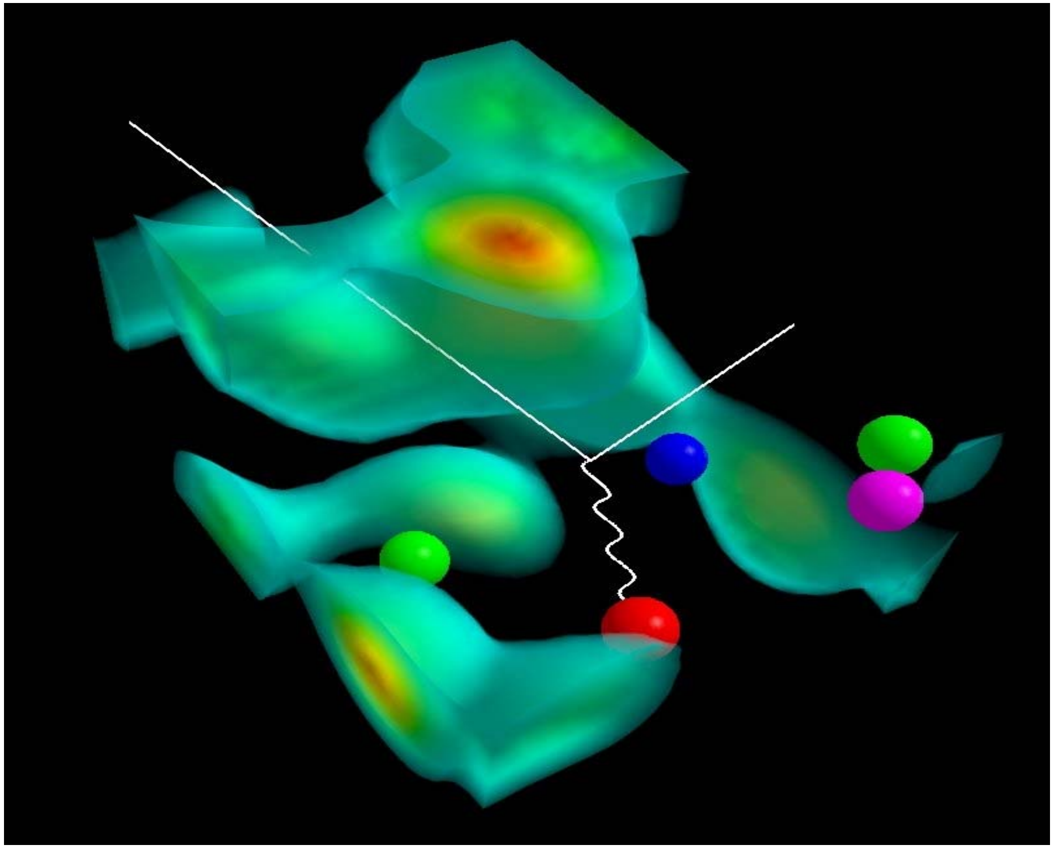
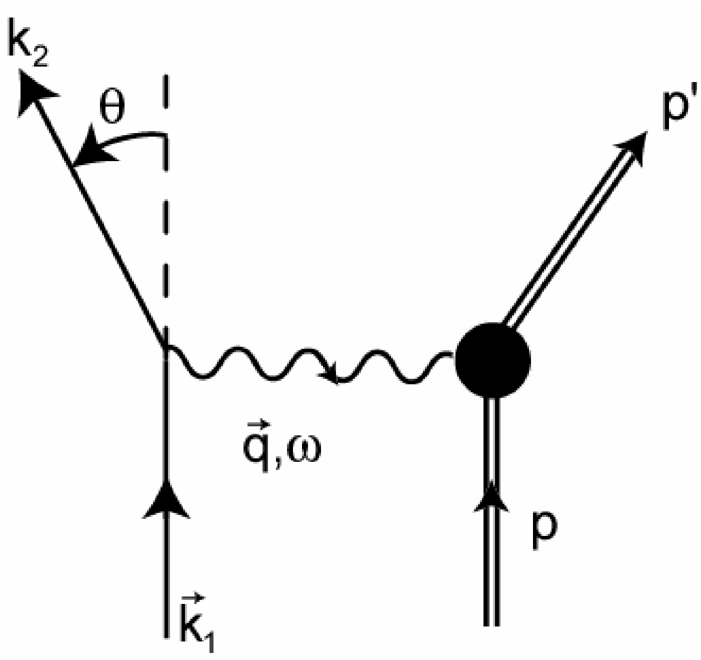
Electromagnetic Form Factors



Anthony W. Thomas

Workshop on Exclusive Reactions, JLab : May 24th 2007

Electron Scattering Provides an Ideal Microscope for Nuclear Physics



- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is "weak"
- Vary *q* to map out Fourier Transforms of charge and current densities:

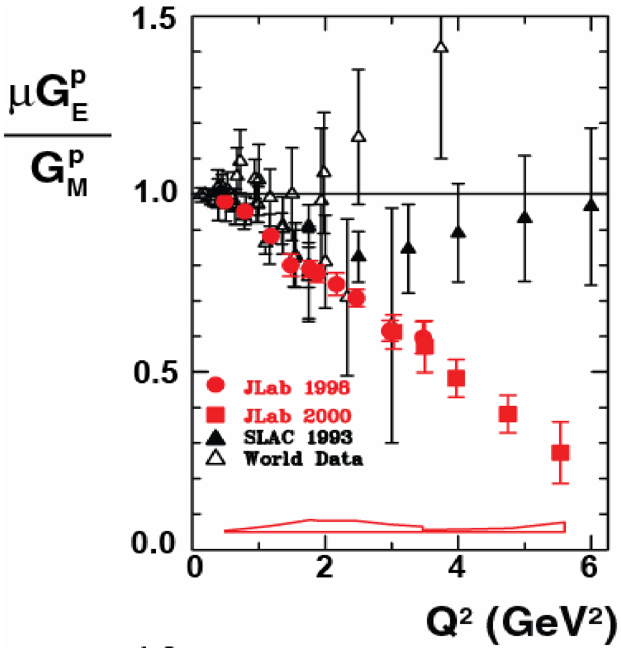
$\lambda \cong 2\pi/q$ **(1 fm ⇔ 1 GeV/c)**

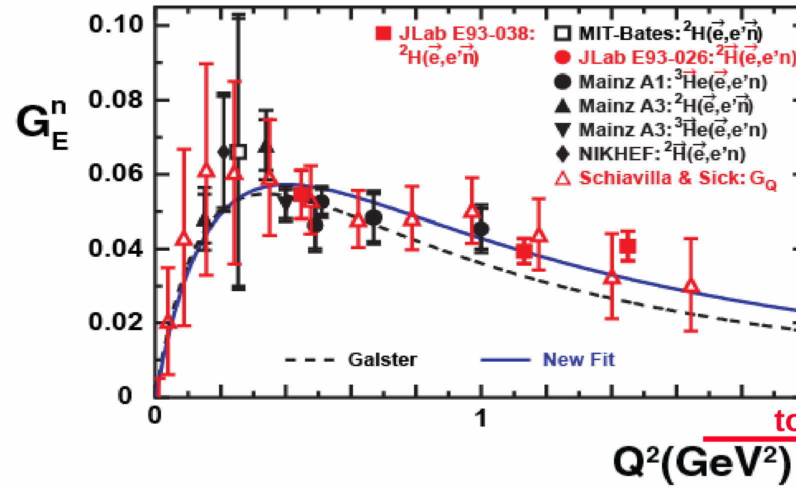
$$S_{fi} = \frac{-e^2}{\Omega}\,\bar{u}(k_2)\,\gamma^{\mu}\,u(k_1)\frac{1}{q^2}\int e^{iq\cdot x}\langle f|\hat{J}_{\mu}(x)|i\rangle d^4x$$

$Q^2 = -q^2 =$ 4-Momentum Transfer

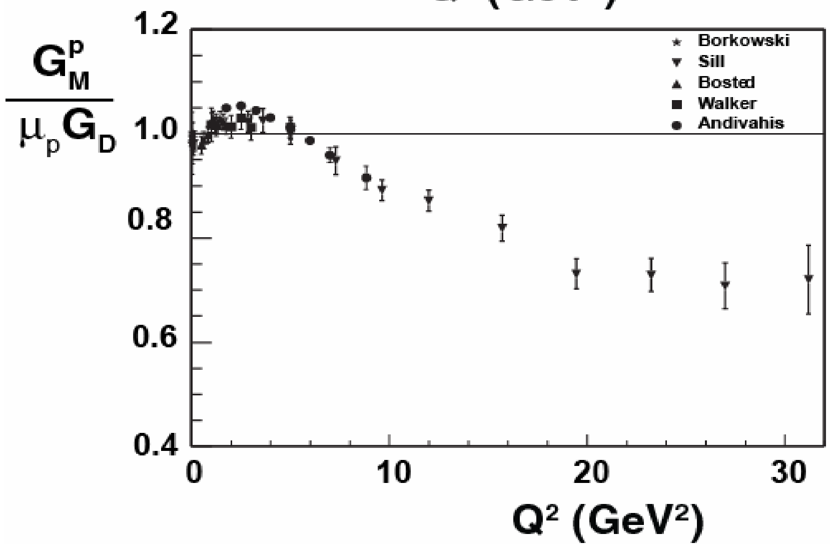
CEBAF's $\vec{e}$ and CW beams dramatically enhance the power of electron scattering

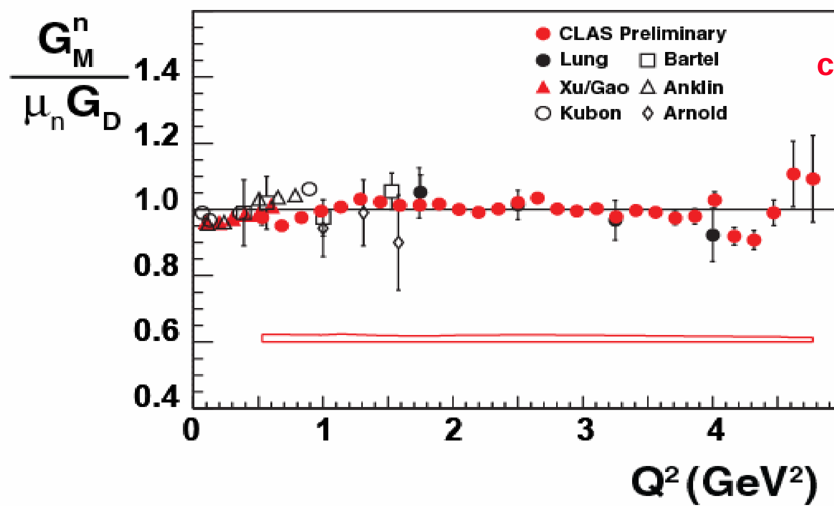
Overview of 6 GeV Form Factor Data



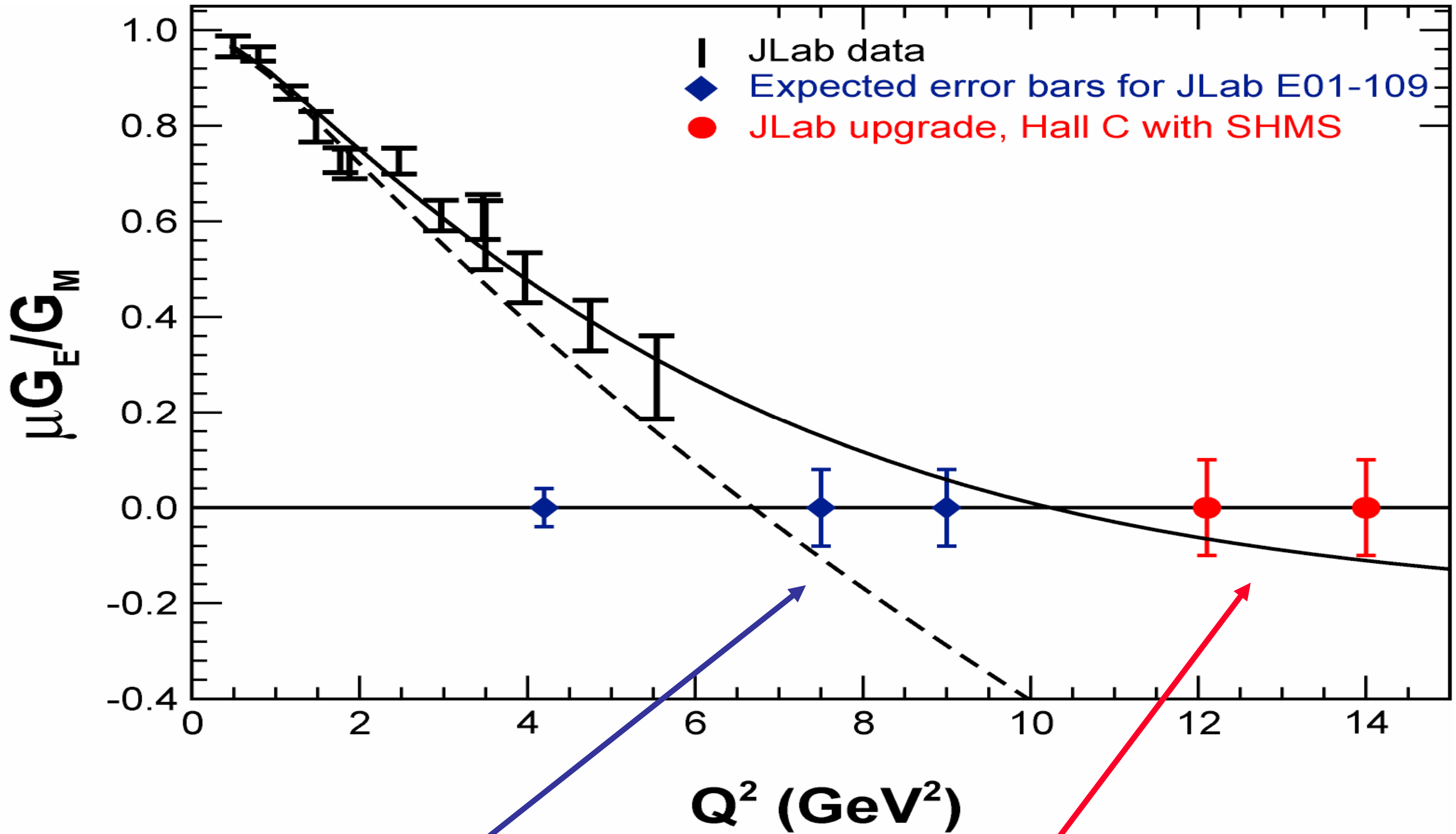


to 3.5 GeV²
(Hall A)
Data-taking just completed





Future Measurements on G_E^p



- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in FY08 (range of Q^2 for neutron will double over next 3-4 years)
- **With 12 GeV and SHMS in Hall C : similarly for G_M^n (and G_E^n)**

Lattice QCD

Inclusion of Pion Cloud

Improvements in Algorithms

Precise computations at Physical Pion Mass

Advances in high-performance computing

From D. Richards

JLab and National Effort

- Jefferson Laboratory co-equal partner with BNL and FNAL in lattice QCD effort.

FNAL
Weak matrix elements

BNL
RHIC Physics

JLAB
Hadronic Physics

SciDAC – R&D Vehicle
• Cluster Prototyping – Balint Joo and Roy Whitney • **Software R&D** – Balint Joo

Lattice QCD at JLab having critical impact on JLab's Nuclear Physics Program

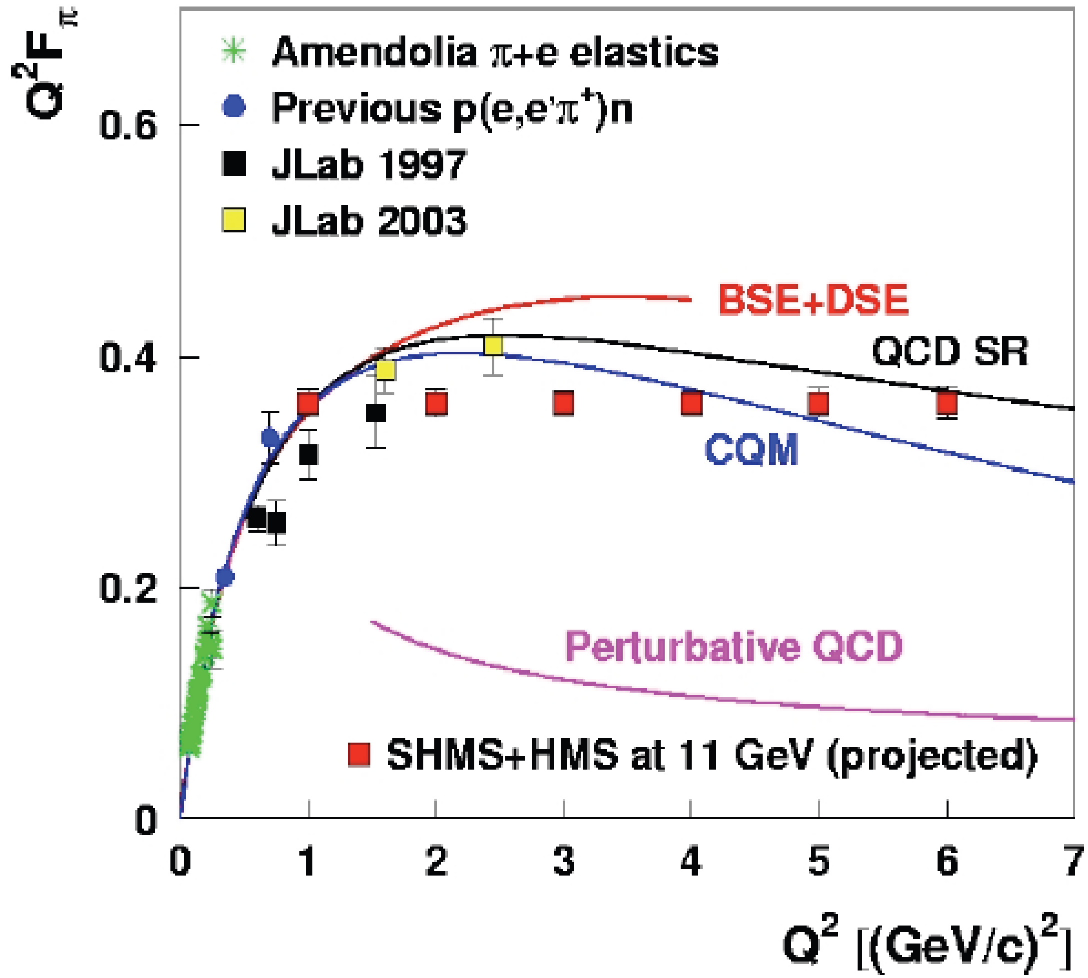
From D. Richards

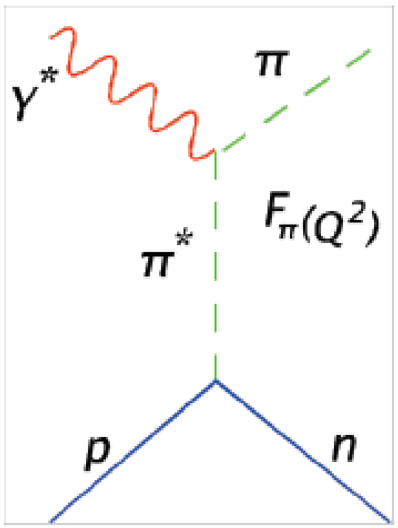
E01-004: New Pion Form Factor Data

Increase in coverage in Q^2

Data point at Q^2=1.60 GeV^2 to check model dependence of mass pole extrapolation

Possibility to rule out phenomenological calculations.



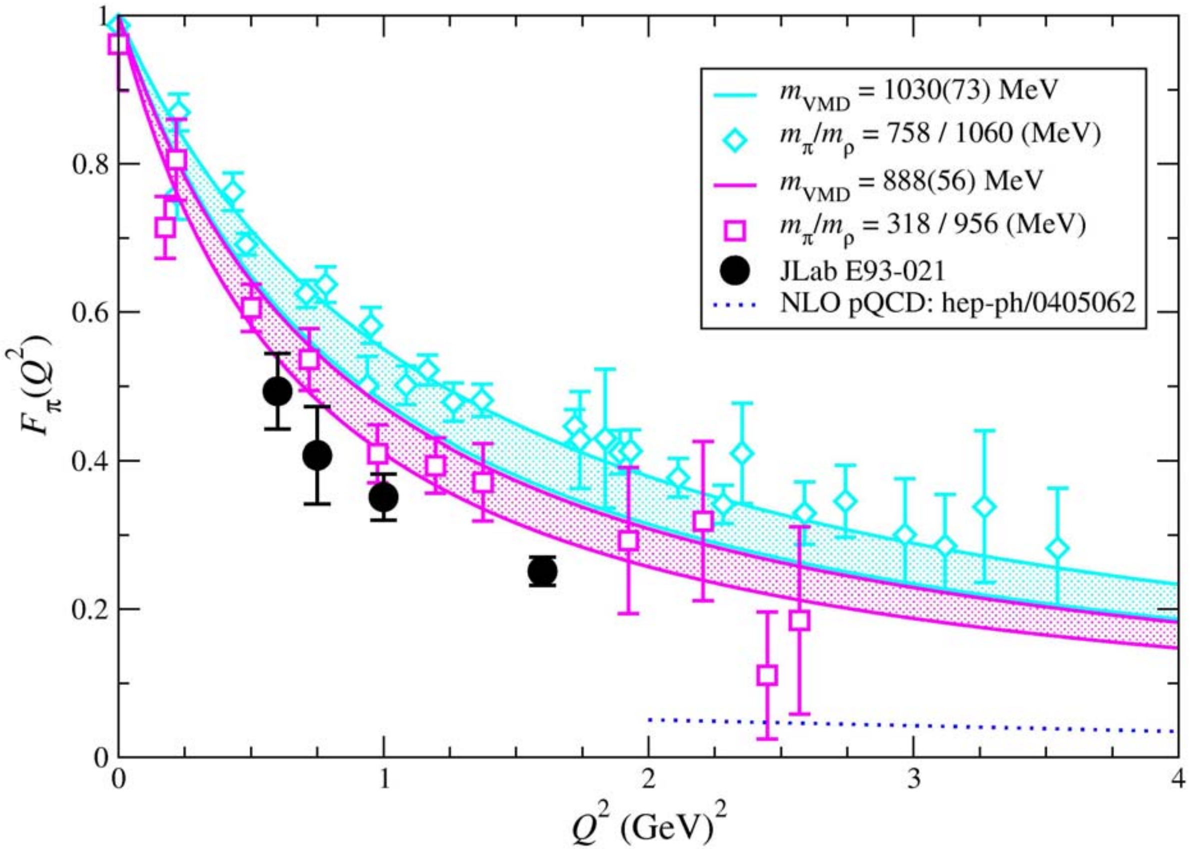


To reach regime of pQCD expectation

need higher energy of the 12 GeV Upgrade

from T. Horn

Pion Form Factor – Lattice QCD

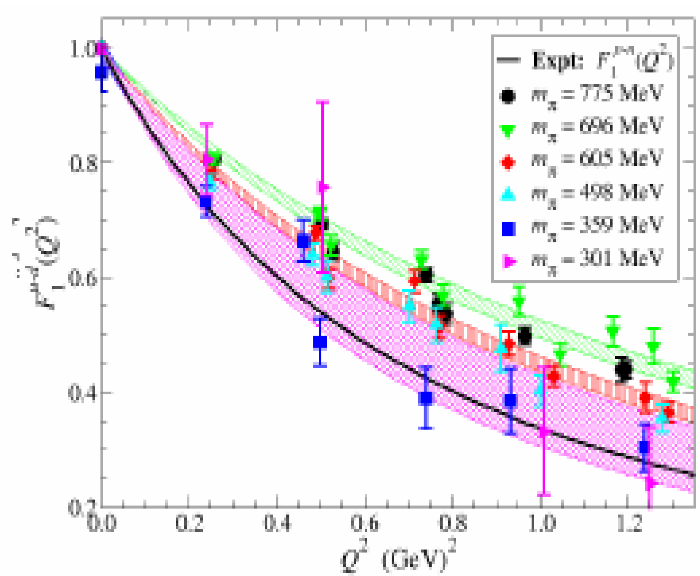


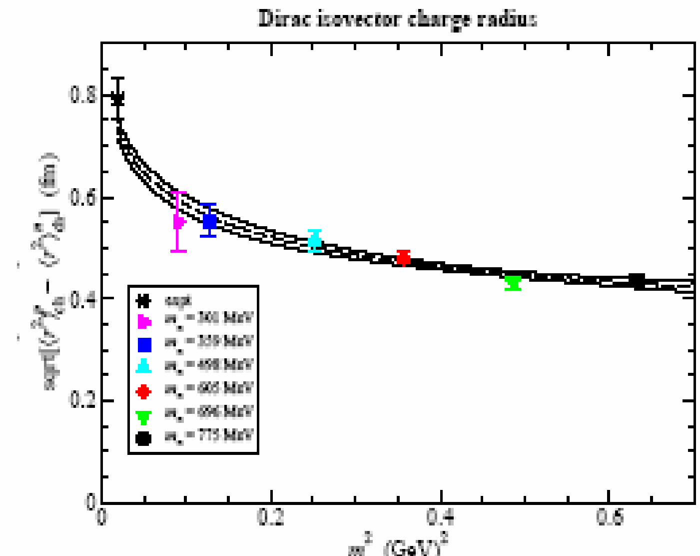
LHPC: Bonnet *et al*
hep-lat/0411028

- Pion Form factor vs Q^2 commensurate with experiment
- Future: pion GPDs and transition form factors

from D. Richards

Lattice: Proton EM Form Factors





- Lattice QCD computes the *isovector* form factor
- Hence obtain **Dirac charge radius** $\langle r^2 \rangle^{u-d}_{ch}$ assuming dipole form
- Chiral extrap. Using LNA and LA terms and finite-range regulator.

Leinweber, Thomas, Young, PRL 86, 5011

- As the pion mass approaches the physical value, the size approaches the correct value

$$\langle r^2 \rangle^{u-d}_{ch} = a_0 - 2\frac{(1+5g_A^2)}{(4\pi f_\pi)^2}\frac{1}{2}\log\left(\frac{m_\pi^2}{m_\pi^2+\Lambda^2}\right)$$

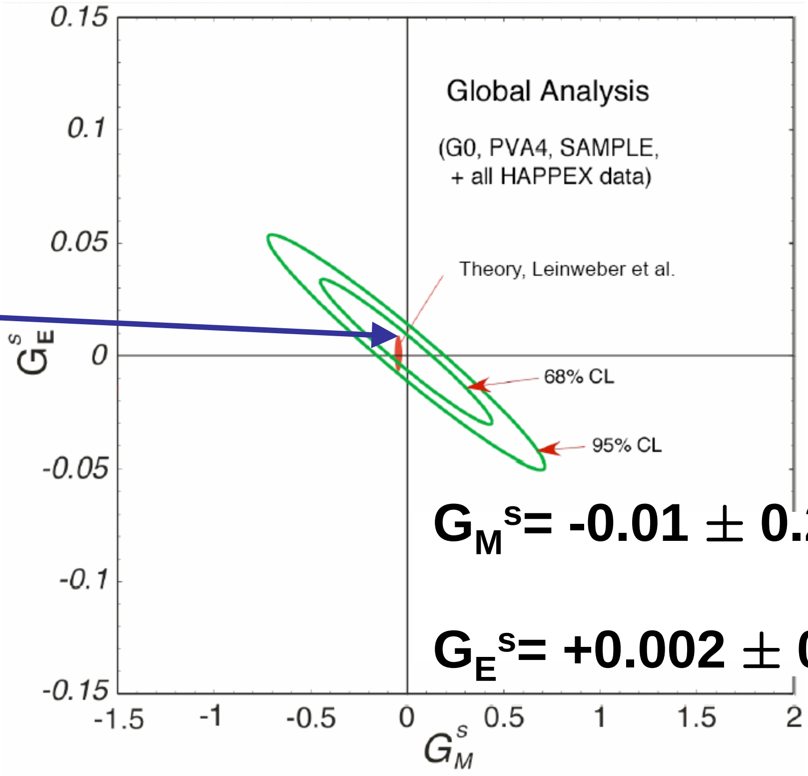
From D. Richards

Strange Quark Form Factors

Strange-quark contribution to EM form factors

– dominated by HAPPEX and G0

Lattice QCD supplemented with constraints of charge symmetry:
Leinweber et al. PRL 97 (2006) and PRL 94 (2005)



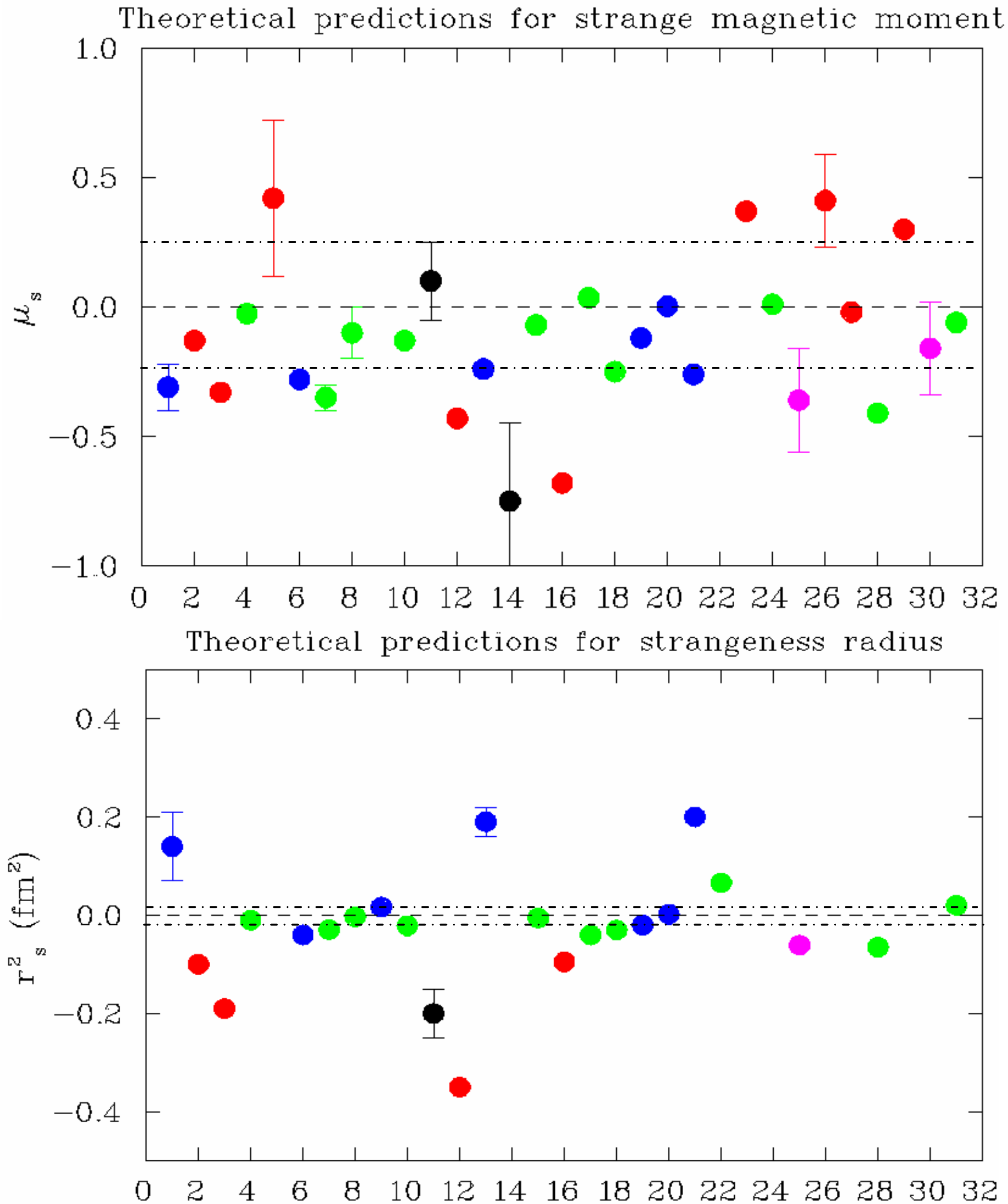
$G_M^s = -0.01 \pm 0.25\mu_N$

$G_E^s = +0.002 \pm 0.018$

Ab initio computations of strange-quark contribution, at $Q^2 = 0$ and Q^2 away from 0

Analysis of data by Young et al., PRL 97 (2006)

Early Theoretical predictions at $Q^2 = 0$



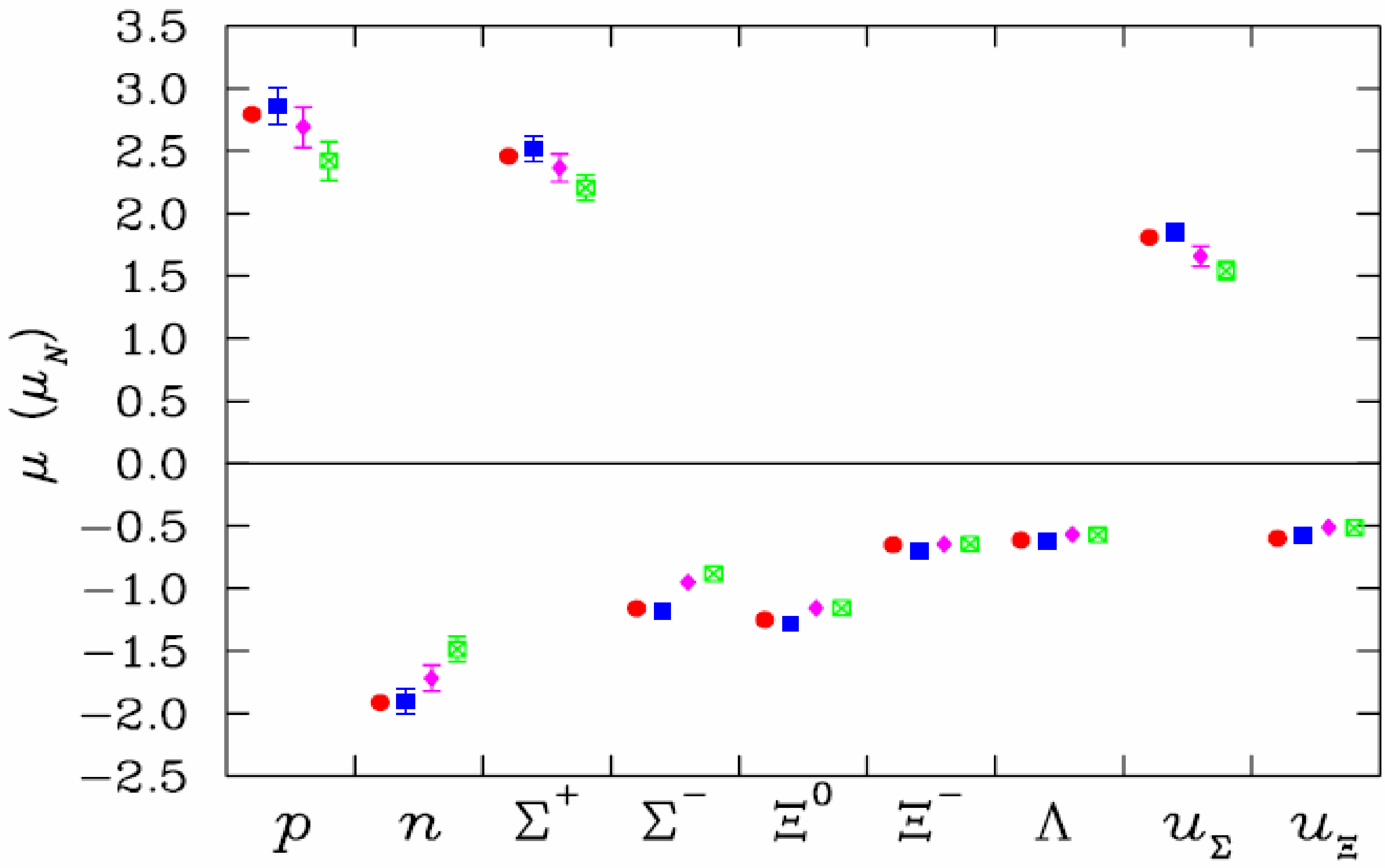
$$\mu_s \equiv G_M^s(Q^2 = 0)$$

Non-zero value of G^s_E or G^s_M requires spatial separation of s and $\bar{s}$

$$r_s^2 \equiv -6\left[\frac{dG_E^s}{dQ^2}\right]_{Q^2=0}$$

from Mark Pitt

Octet Magnetic Moments



Leinweber et al., PRL 94 (2005) 212001

"Back of the Envelope" Estimates

Nowhere that current quark masses enter dynamics
- always constituent quark masses

- Hence s-sbar pair costs 1.0-1.1 GeV plus KE

- K - Λ costs 0.65 GeV plus KE (and coupling $\sim \pi$ N)
  (K- Σ much smaller $\Rightarrow$ ignore)

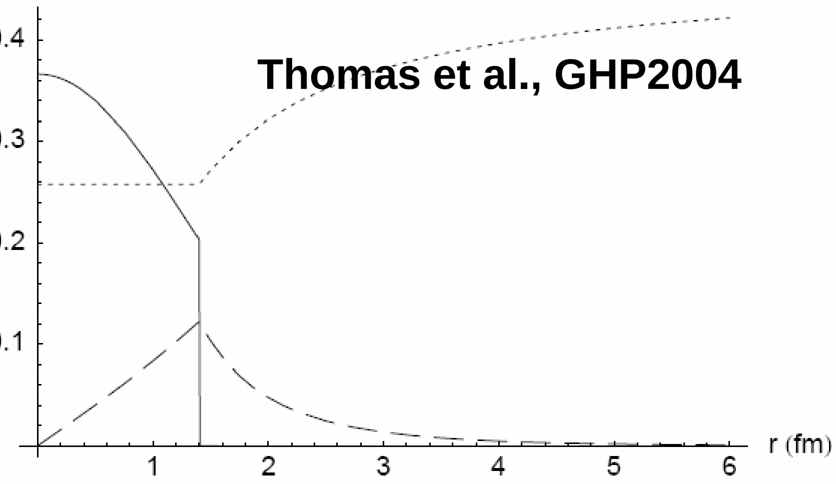
- Lots of evidence that $P_{\pi N} \sim 20\% \Rightarrow P_{K\Lambda} \sim 5\%$

$$G_M^s \approx -3 \times P_{K\Lambda} \times [2/3\,(+0.61 + 1/3) + 1/3(-0.61 + 0)]$$

$$\approx -0.067\ \mu_N$$

Thomas & Young, nucl-th/0509082

Strangeness Radius



Meson cloud surface peaked

- Core has mean-square radius $\sim (0.7\ R)^2$
- Meson cloud $\sim (R + 0.2)^2$
- Hence: $-3 \langle r^2 \rangle_s \sim$

$$-3 \times (+\ 1/3)\ P_{K\,\Lambda}\ [\ -\ 0.49\ R^2\ +\ (R + 0.2)^2\ ]$$

$$\varepsilon\ (-0.02,\ -0.04)\ \text{fm}^2 \text{ for } R\ \varepsilon\ (0.8, 1.0)\ \text{fm}$$

- Hence: $G_E^s\ (0.1\ \text{GeV}^2) \sim (+0.01,\ +0.02)$

More Chiral Physics

Noted above that N π probability is of order 20% (take 21%)

$\Rightarrow$ p $\sim$ 79% bare p + 14% bare n π^+ + 7% bare p π^0

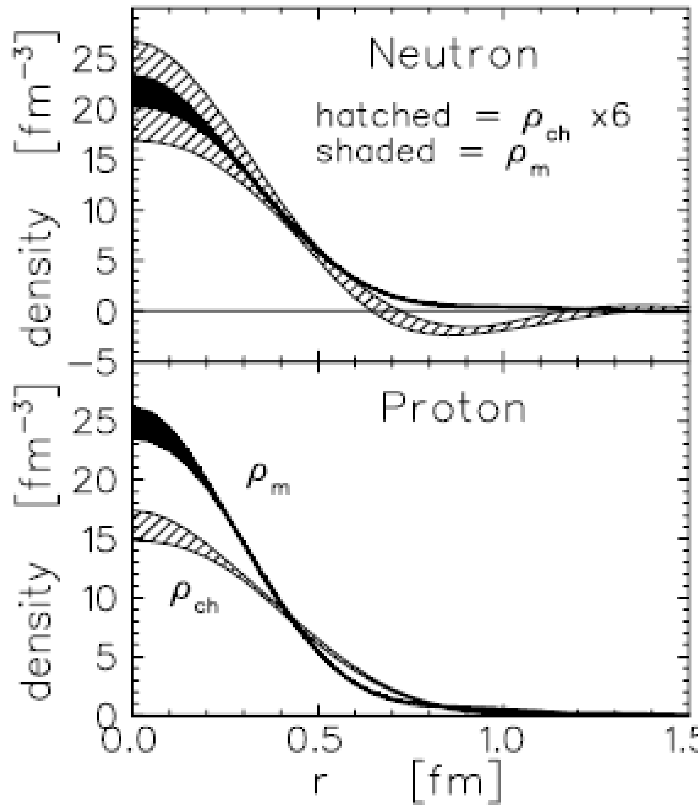
n $\sim$ 79% bare n + 14% bare p π^- + 7% bare n π^0

Let bare p charge density at r=0 be x (and bare n zero $\Rightarrow$ ratio of physical charge densities of n/p at r=0 is:

0.14x / (0.79x + 0.07x)

$\sim$ 1/6

Modulo corrections from non-zero bare n charge density, Δ π etc..



Densities from J.J. Kelly AIPCP 675

Chiral Extrapolation of Lattice data at high-Q^2 ?

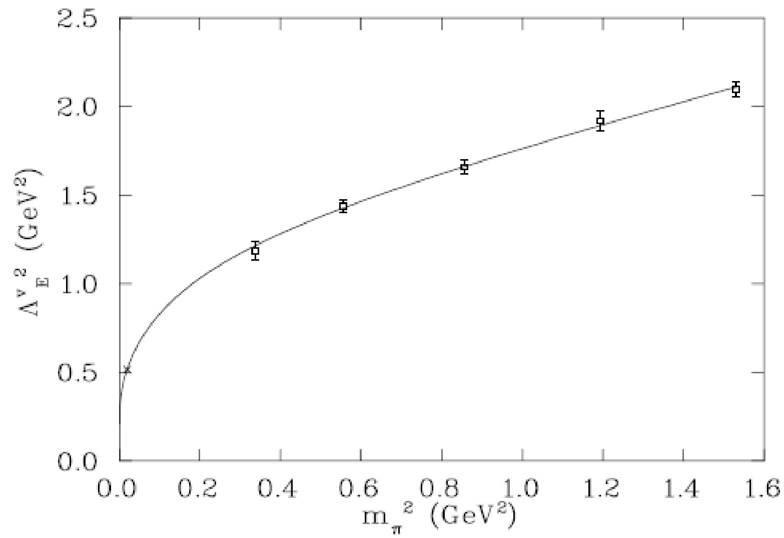
- Body of lattice data for electromagnetic form factors is growing (notably QCDSF and LHPC)
- Q^2 as high as 3 GeV^2 hopefully 10 GeV^2 within 5 years
- Currently quenched (primarily) and $a \to 0$ and $L \to \infty$ errors not totally under control and finally m_π relatively large
- How do we extrapolate to physical pion mass, while preserving the well known chiral properties of QCD?

Initial Approach: Build Chiral Behavior into Dipole Forms

$$G(Q^2) = \frac{G(0)}{(1 + Q^2/\Lambda^2)^2}$$

Relates Λ to radius through low-Q^2 expansion

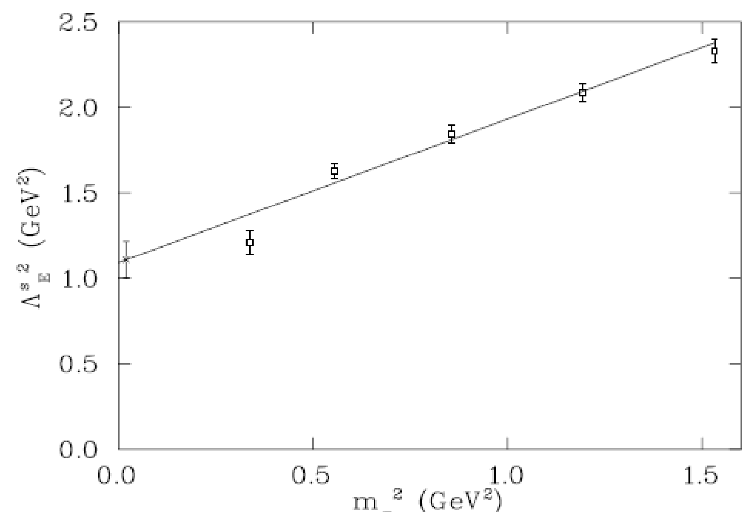
Fit Λ as function of m_π to lattice QCD data



-Iso-vector exhibits rapid chiral variation near physical pion mass

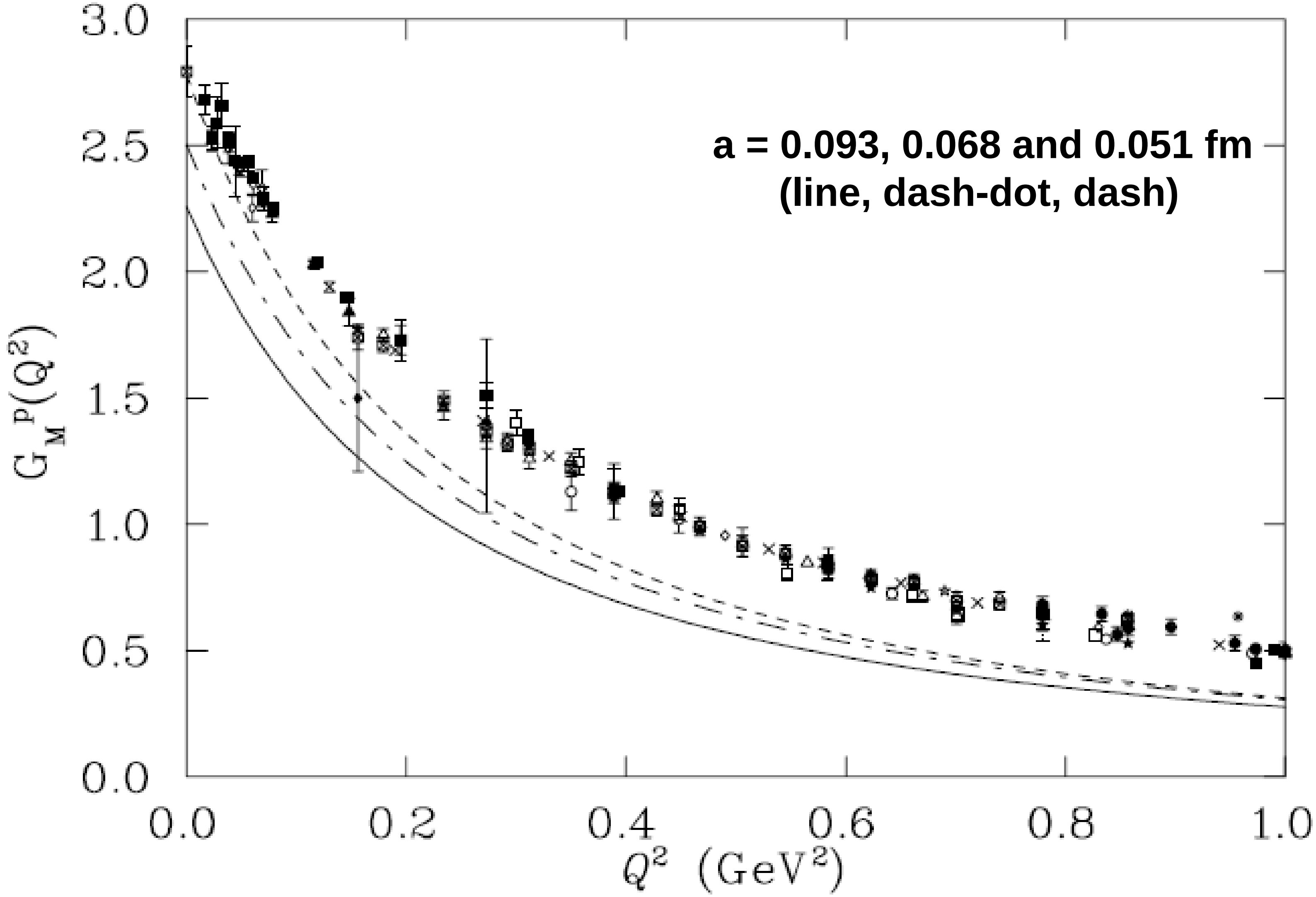
$$(\Lambda^v_E)^2 = \frac{12(1 + B_1 m_\pi^2)}{B_0 + \frac{\chi_2}{2}\ln(\frac{m_\pi^2}{m_\pi^2 + \mu^2})}$$; μ = 0.41 GeV

- Iso-scalar essentially a straight line

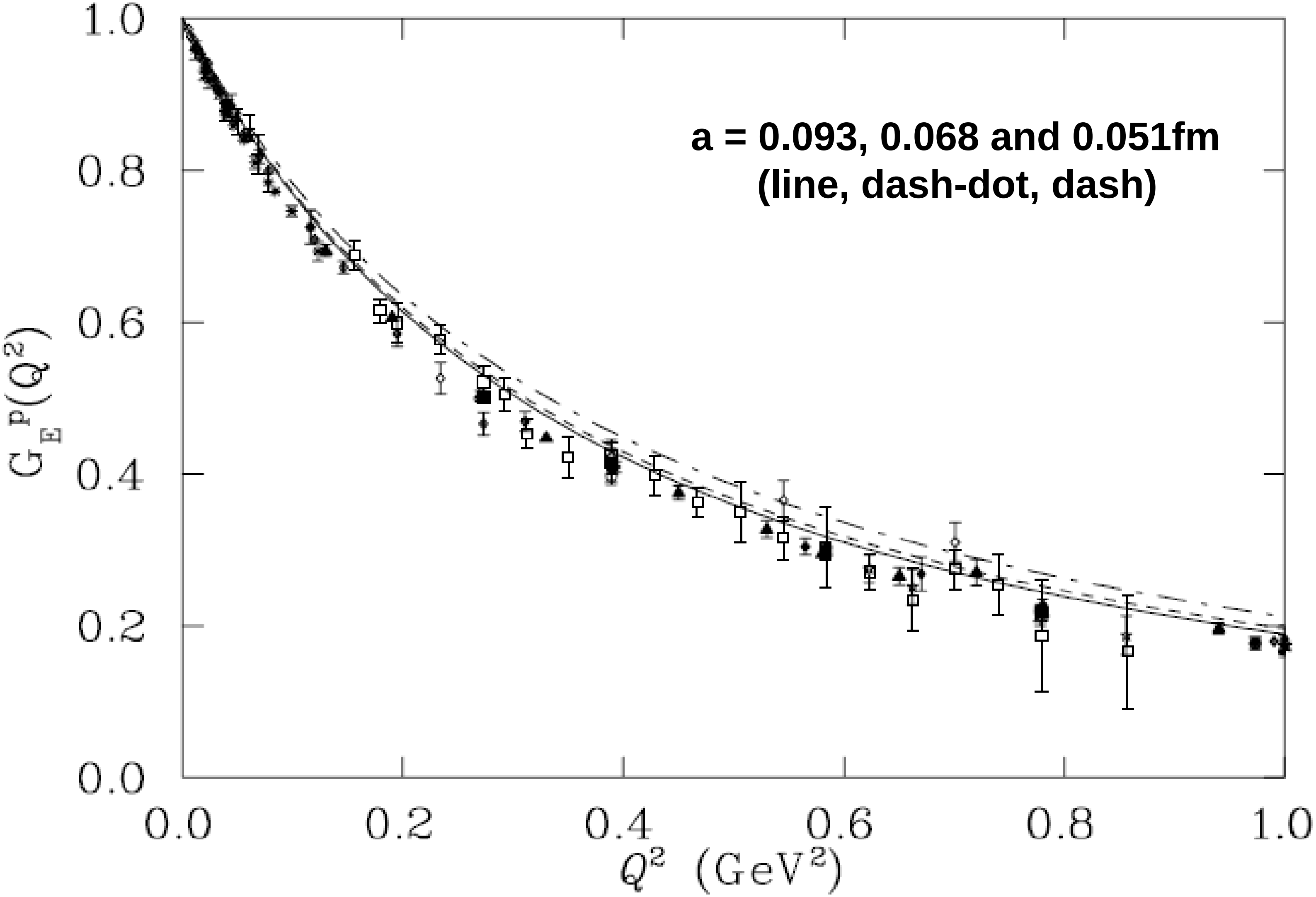


Ashley et al., EPJ A19 (2004)

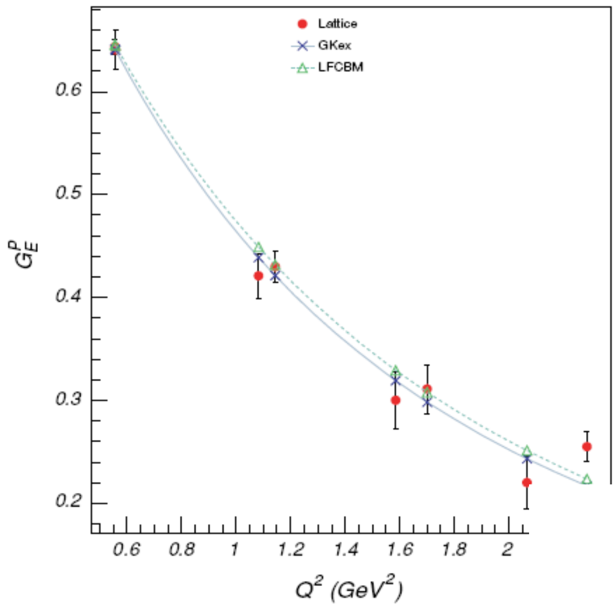
Comparison of Extrapolated Form Factors with Data

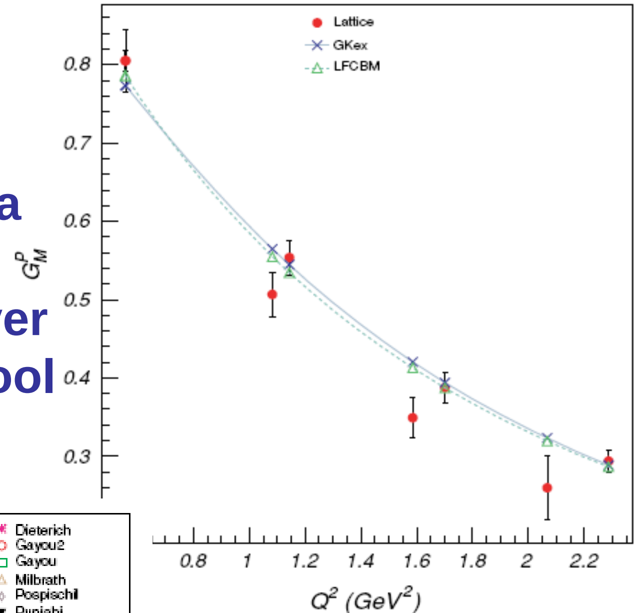


Comparison of Extrapolated Form Factors with Data

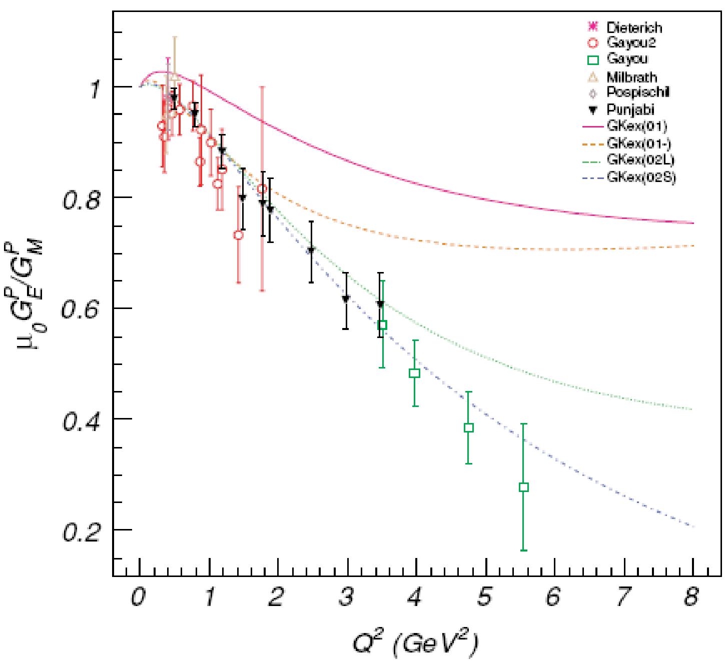


2: Vector Meson Dominance: Gari-Krümpelmann form





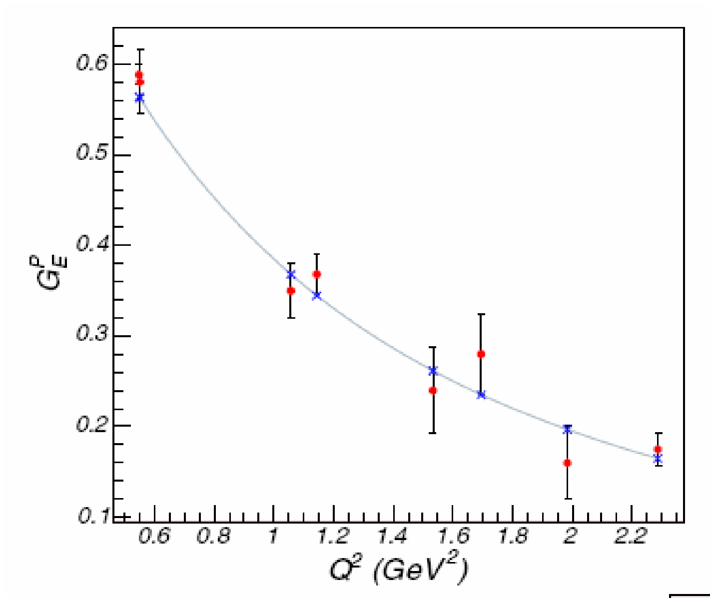
Can fit both exptl. data and lattice data BUT no use whatsoever as an extrapolation tool

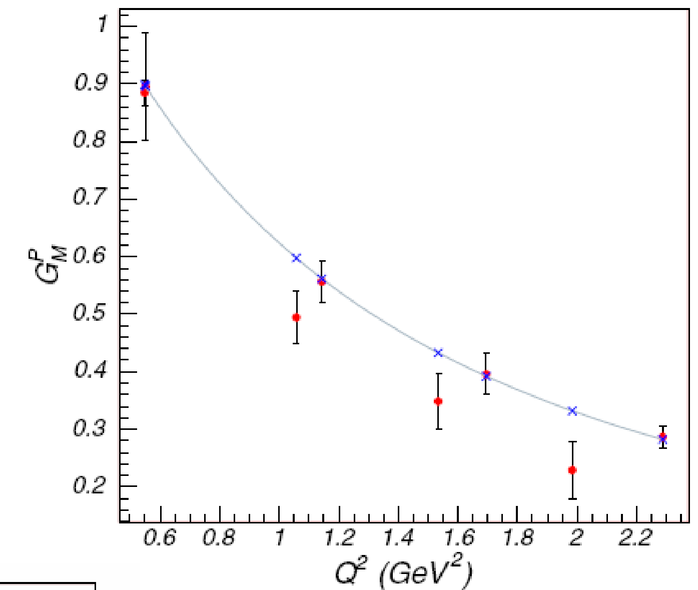


Lattice data: QCDSF – Phys Rev D71 (2005)

Extrapolation: Matevosyan et al., Phys Rev C72 (2005)

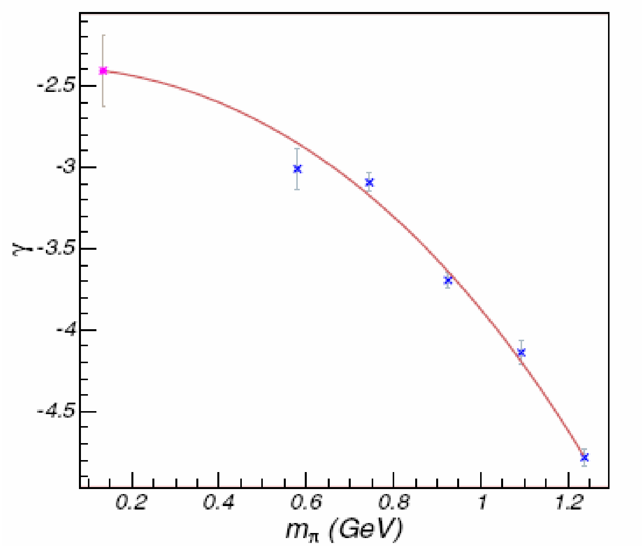
3: Light-Front Cloudy Bag Model





$$\Phi(M_0) = N\left(M_0^2 + \beta^2\right)^{\gamma}$$

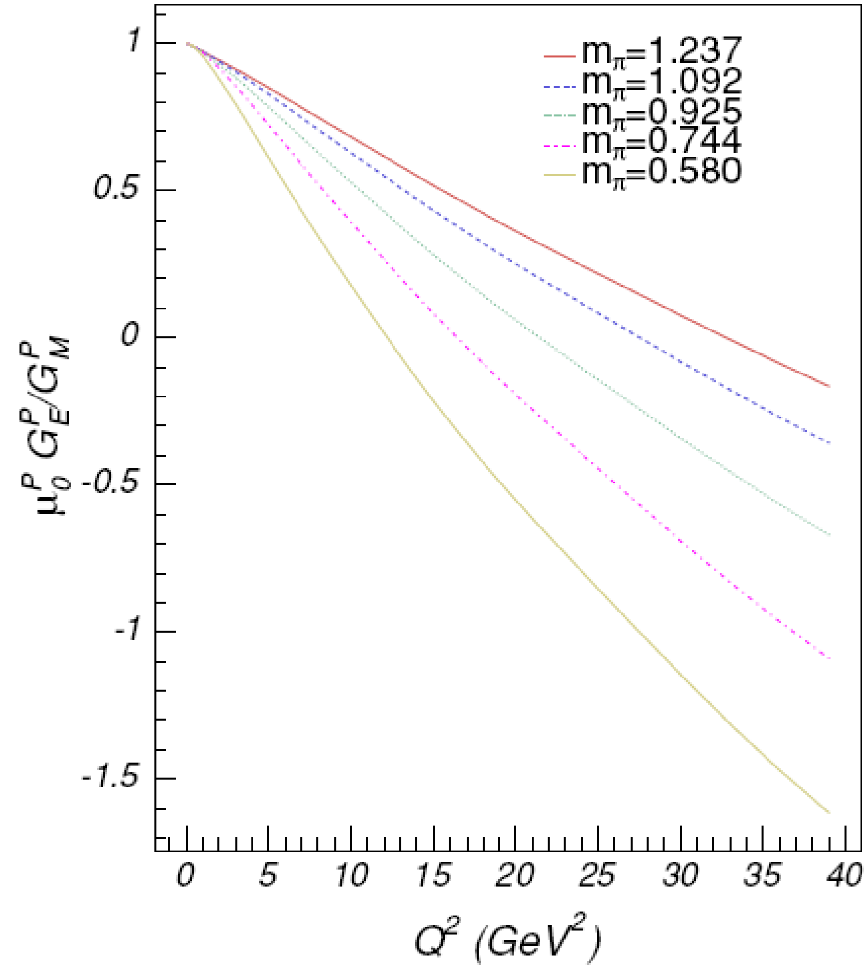
$$M_0^2 = \frac{K_\perp^2}{\eta(1-\eta)} + \frac{k_\perp^2 + M^2}{\eta\xi(1-\xi)} + \frac{M^2}{1-\eta}$$

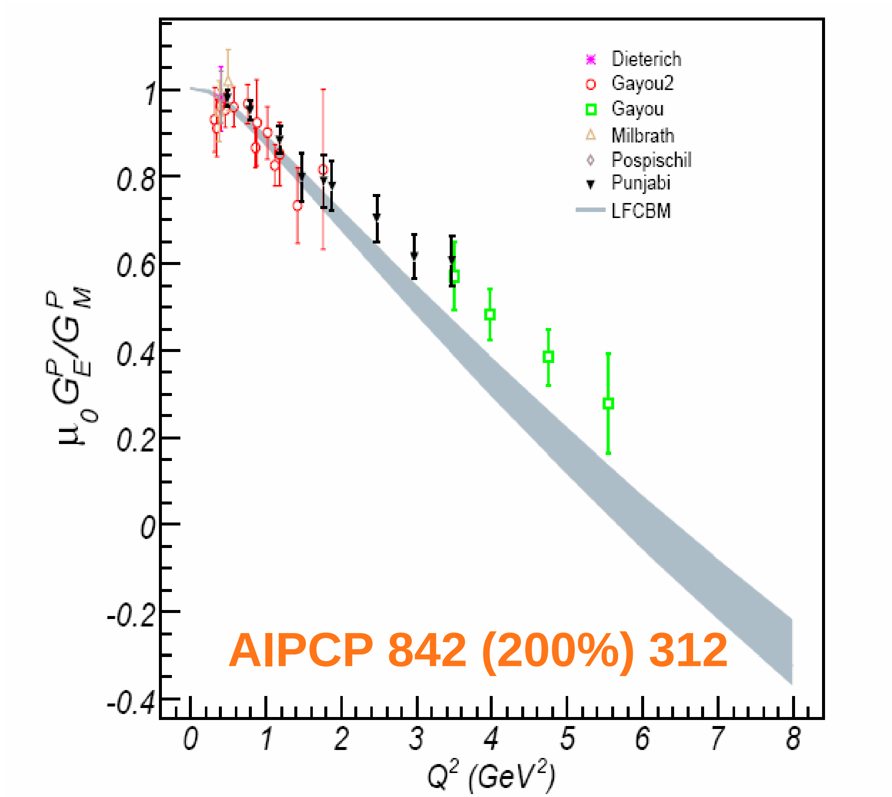


Matevosyan et al., Phys Rev C71 (2005)

L-F CBM (cont.)

Much better than VMD: does have predictive power BUT no way to estimate model dependence

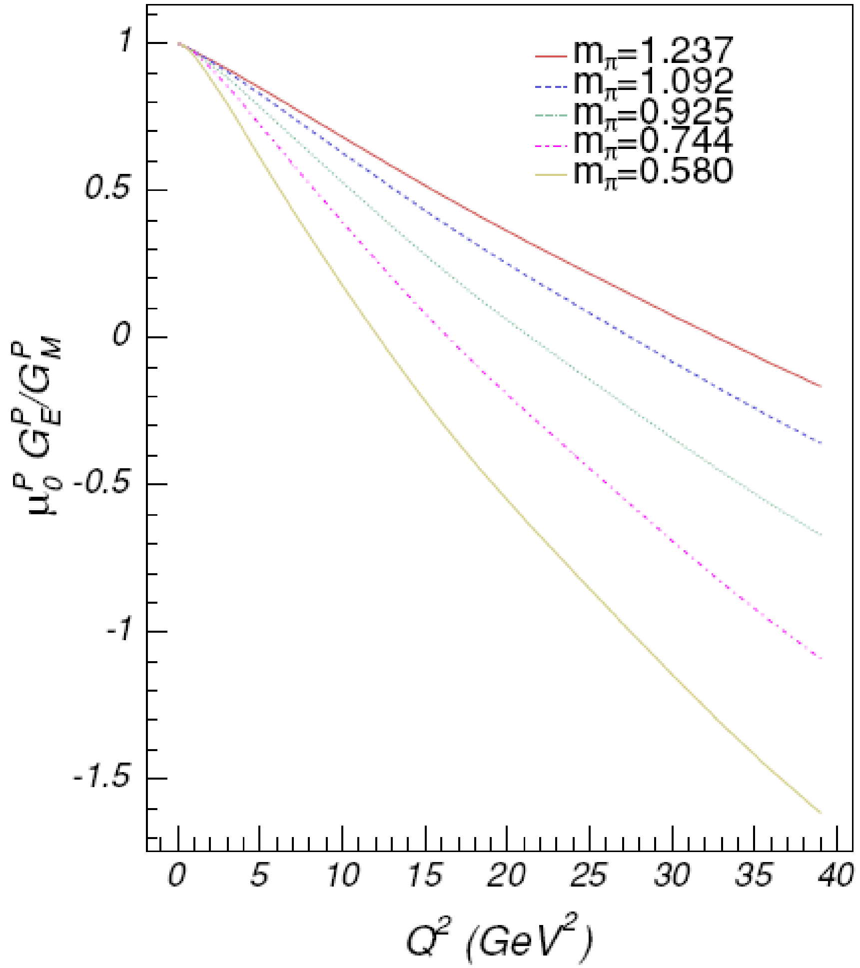




N.B. Errors from chiral extrapolation only…

L-F CBM (cont.)

Much better than VMD: does have predictive power BUT no way to estimate model dependence

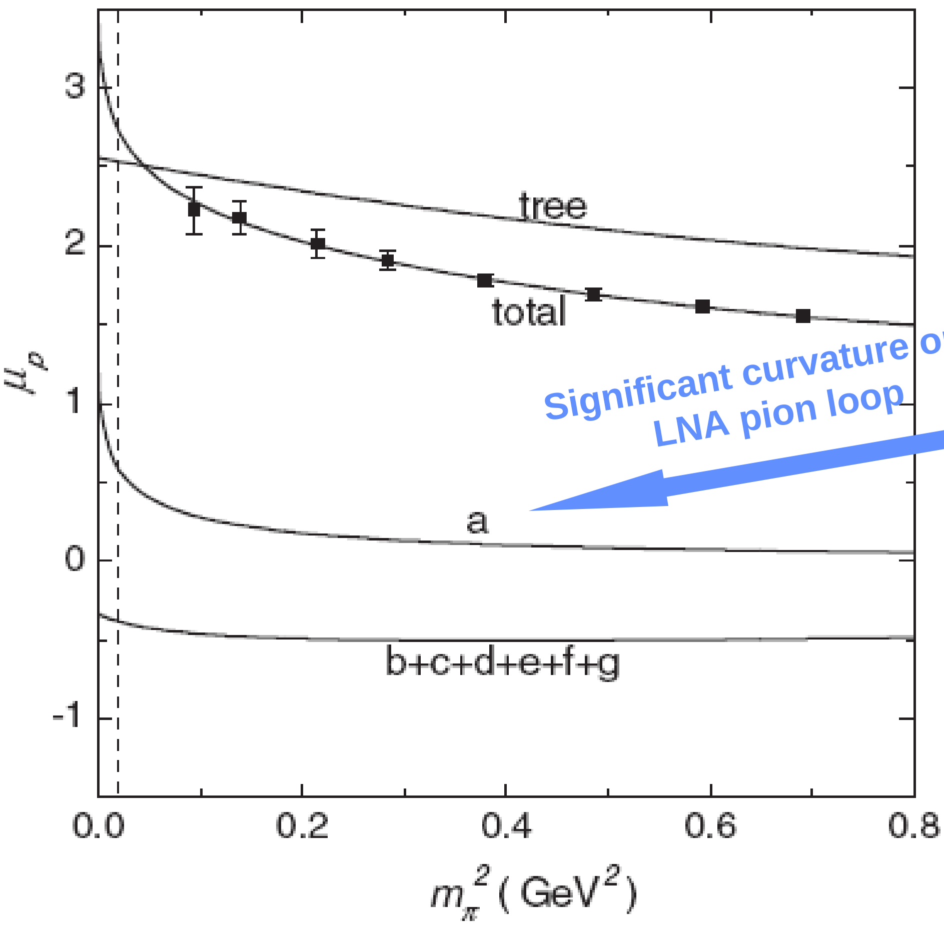


N.B. Errors from chiral extrapolation only…

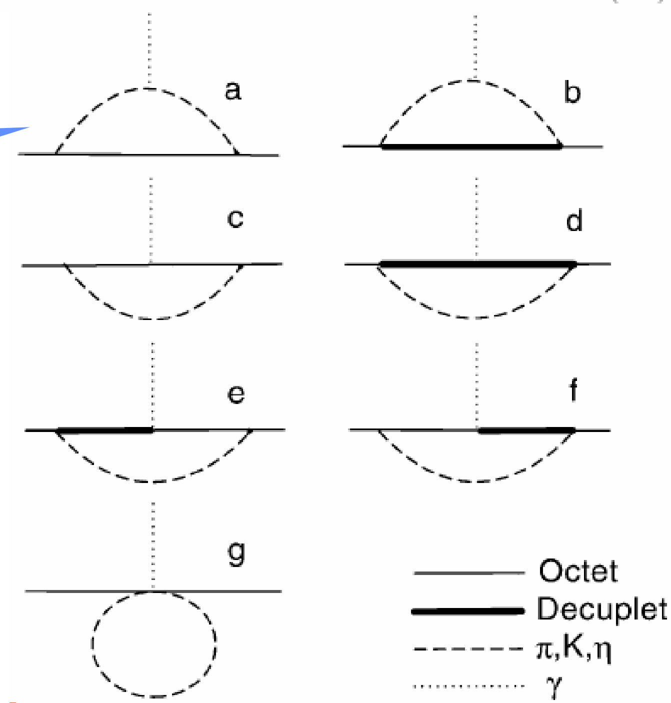
4: Systematic Expansion – Model Independent

$$\mu_p(m_\pi^2) = a_0^p + a_2^p m_\pi^2 + a_4^p m_\pi^4 + \sum_{k=a}^{g} G_M^{p(1k)}(Q^2 = 0, m_\pi^2), \quad (37)$$

$$\mu_n(m_\pi^2) = a_0^n + a_2^n m_\pi^2 + a_4^n m_\pi^4 + \sum_{k=a}^{g} G_M^{n(1k)}(Q^2 = 0, m_\pi^2), \quad (38)$$



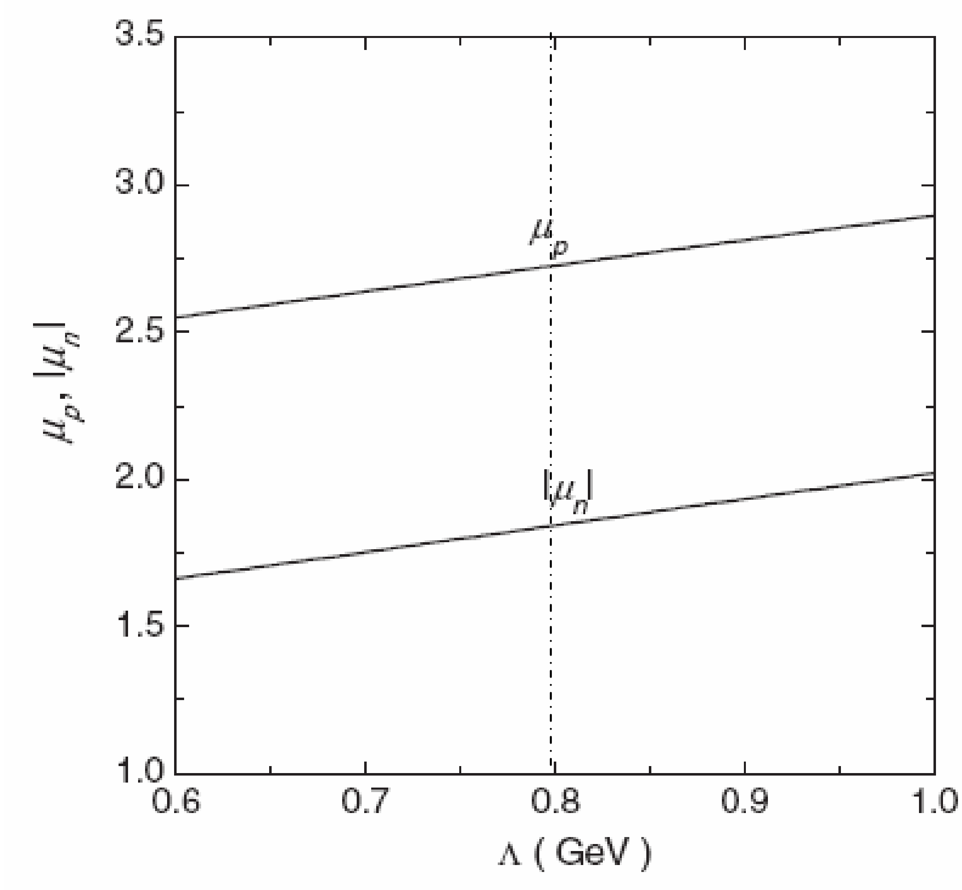
Significant curvature only from LNA pion loop



Wang et al., Phys Rev D75 (2007)
- lattice data Boinepalli et al., Phys Rev D74 (2006)

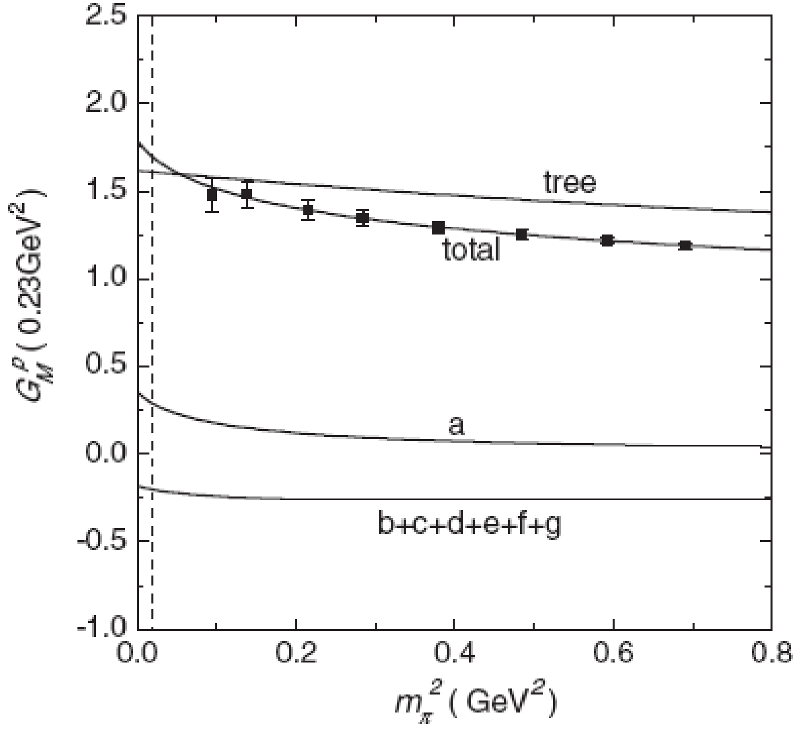
Finite Range Regulator

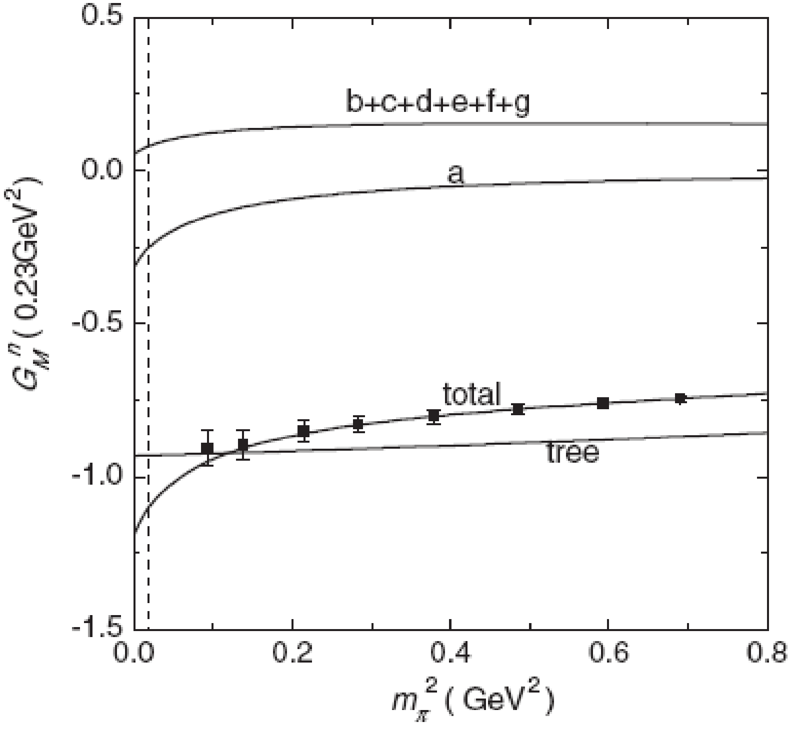
Suppresses meson loops for meson mass >0.4 GeV <u>and</u> high Q^2 but until data good enough to fix it $\rightarrow$ adds small error



Apply same approach at each fixed Q^2

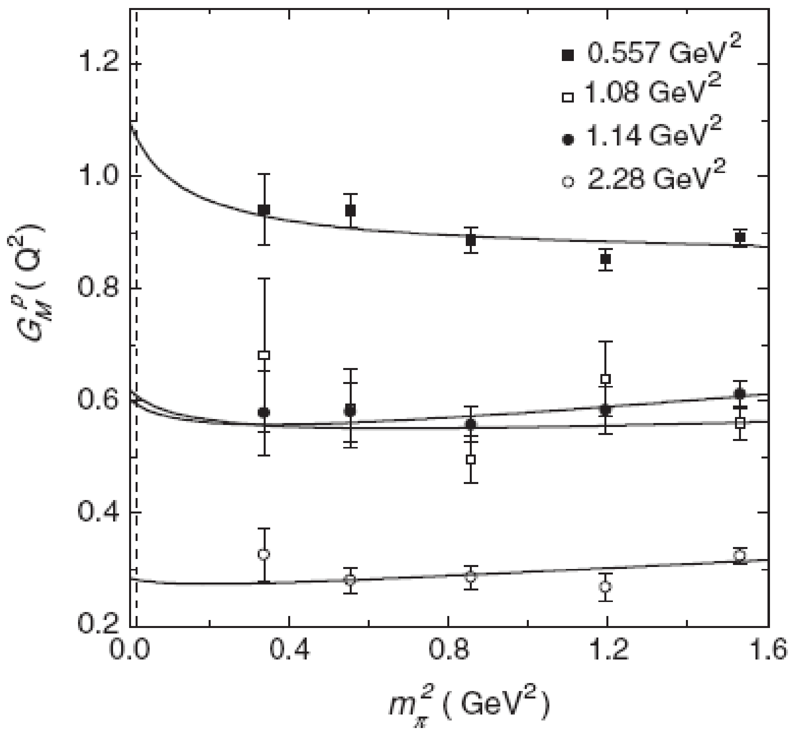
Fit a_0, a_2 etc to data as function of m_π at each Q^2 - above 0.23 GeV^2 data cannot fix a_4 or higher (yet!)

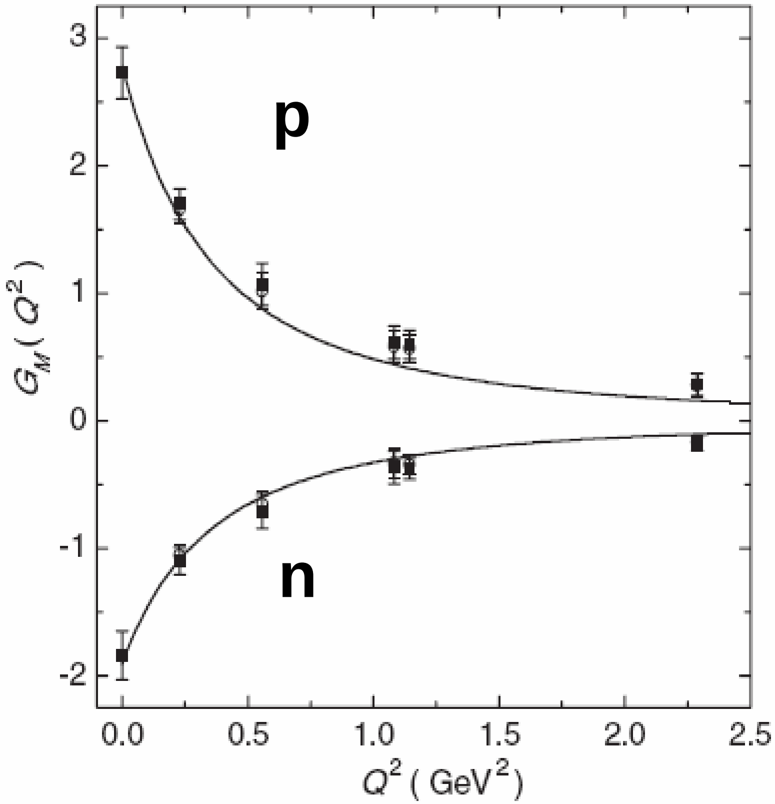




Data from CSSM group: Boinepalli et al.

Pion Loops Suppressed for Higher Q^2

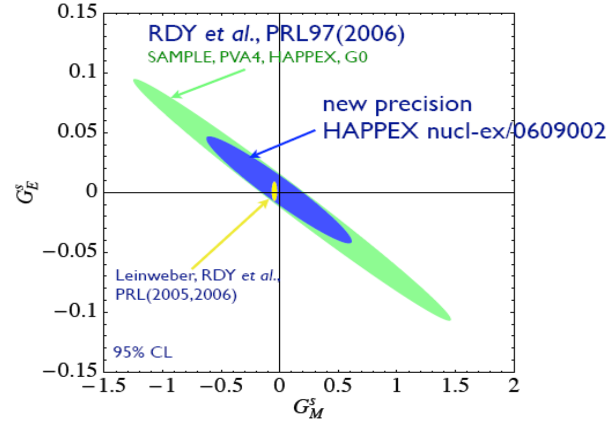




Lattice data QCDSF

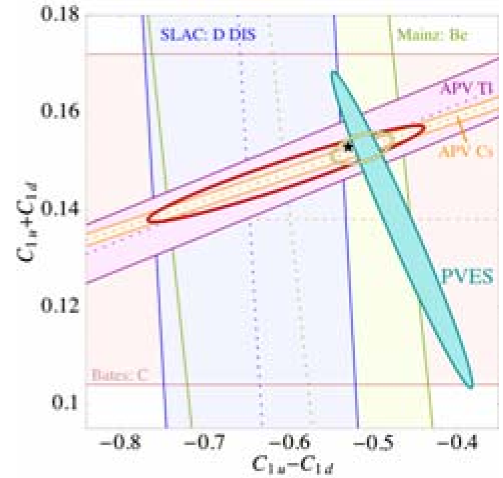
Comparison with data to 2.5 GeV^2 already quite impressive
- recall caveat on lattice errors

Summary



- There has been tremendous experimental progress, led by JLab - <u>including</u> flavor decomposition

- 12 GeV Upgrade promises to take this to as high as 14 GeV^2



- Prospects for accurate lattice data with known systematic errors very good over next 5 years

- Systematic expansion in powers of pion mass, supplemented by FRR pion loops seems very promising