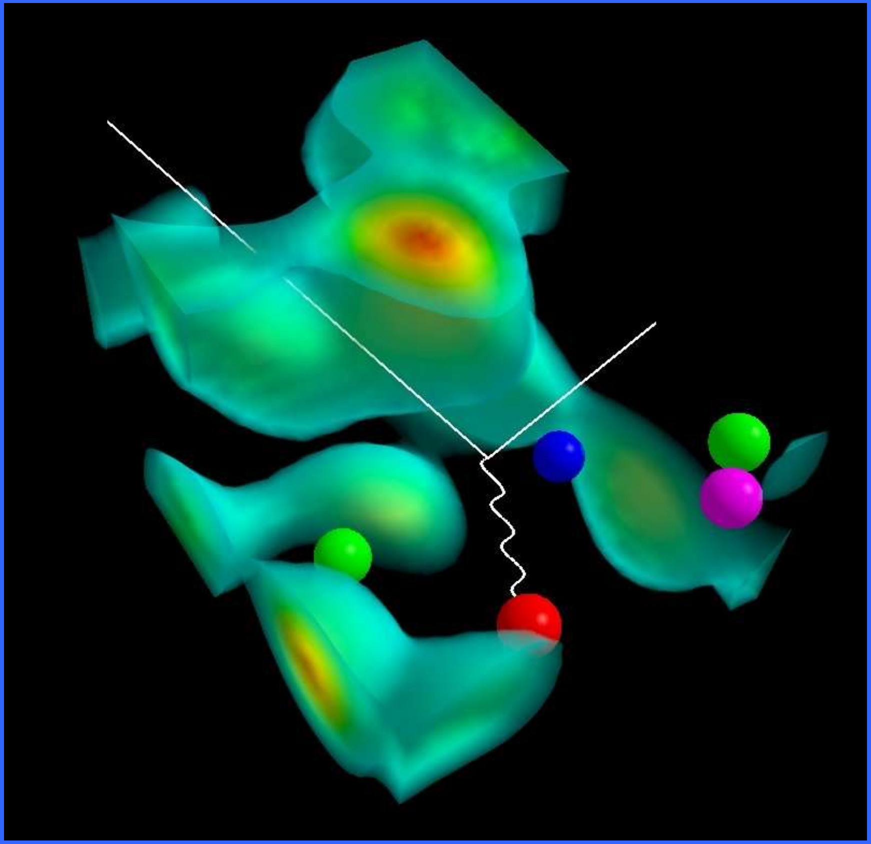
Baryon Structure and Spectroscopy



Anthony W. Thomas

Workshop on Baryon Spectroscopy

ANL : August 29th, 2005

Outline

- The QCD Vacuum
- Quarks to Hadrons
- Measurements of Nucleon Form Factors
- Latest Results on Strangeness
- Modeling Hadron Structure
- Baryon Excited States

Powerful Qualitative New Insights From Lattice QCD

QCD sum rules :

$$\left\langle 0 \left| \frac{\alpha_s}{\pi} G^i_{\mu\nu} G^{\mu\nu}_i \right| 0 \right\rangle = \left\langle 0 \left| \frac{2\alpha_s}{\pi} (B^2 - E^2) \right| 0 \right\rangle = (350 \pm 30\ \mathrm{MeV})^4,$$

- Non-trivial topological structure of vacuum linked to dynamical chiral symmetry breaking
- There are regions of positive and negative topological charge
- BUT they clearly are <u>NOT spherical</u>
- NOR are they weakly interacting!

Quark Condensate

$$\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = \langle \bar{s}s \rangle = -(225 \pm 25 \text{ MeV})^3$$

at a renormalization scale of about 1 GeV.

σ commutator measures chiral symmetry breaking
$\approx$ valence + pion cloud +

volume * (difference of condensate in & out of N)

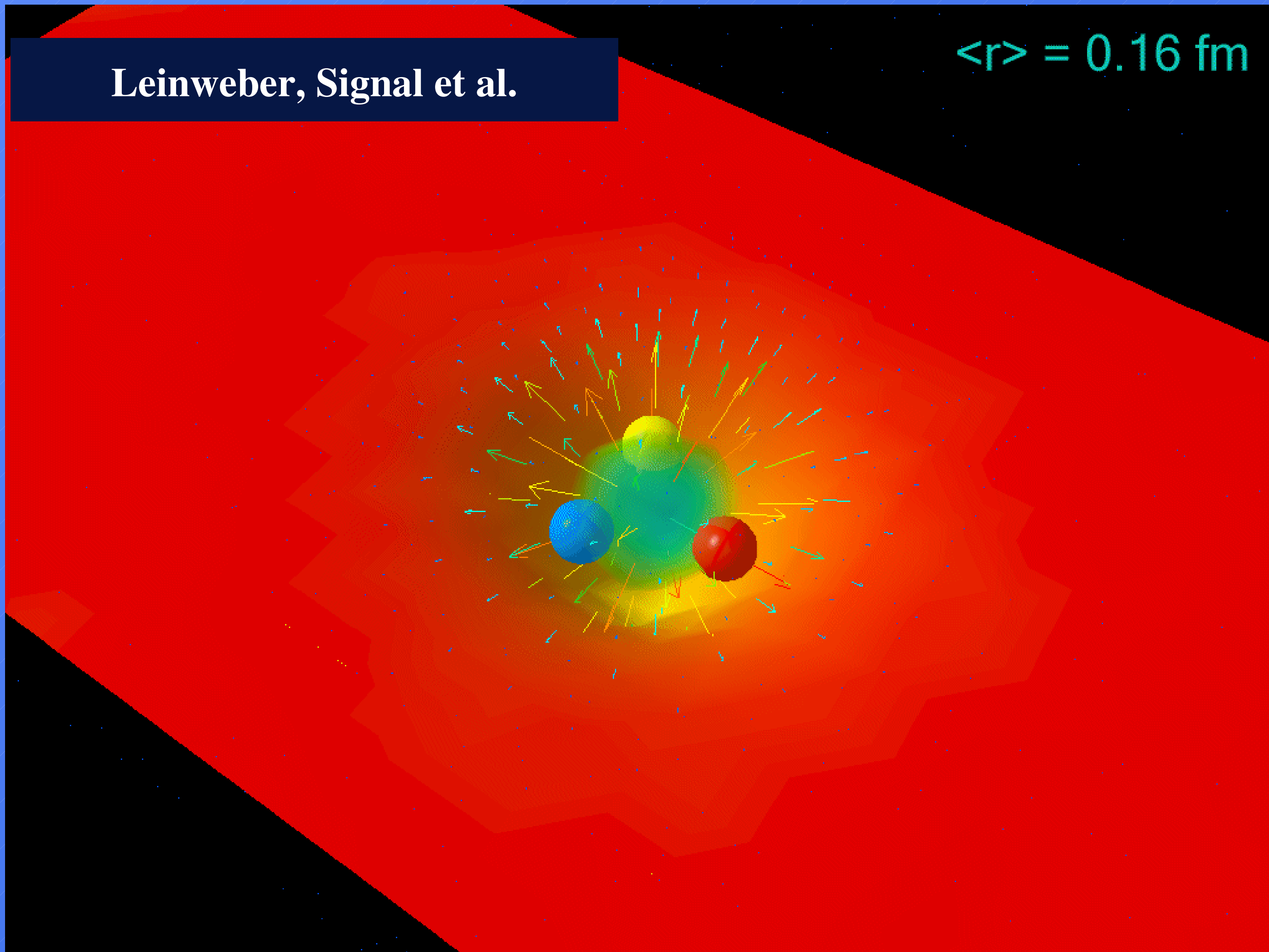
and last term is as big as 20 MeV (or more)
i.e. presence of nucleon "cleans out" vacuum to some extent

Hence: Model independent LO term for in-medium condensate

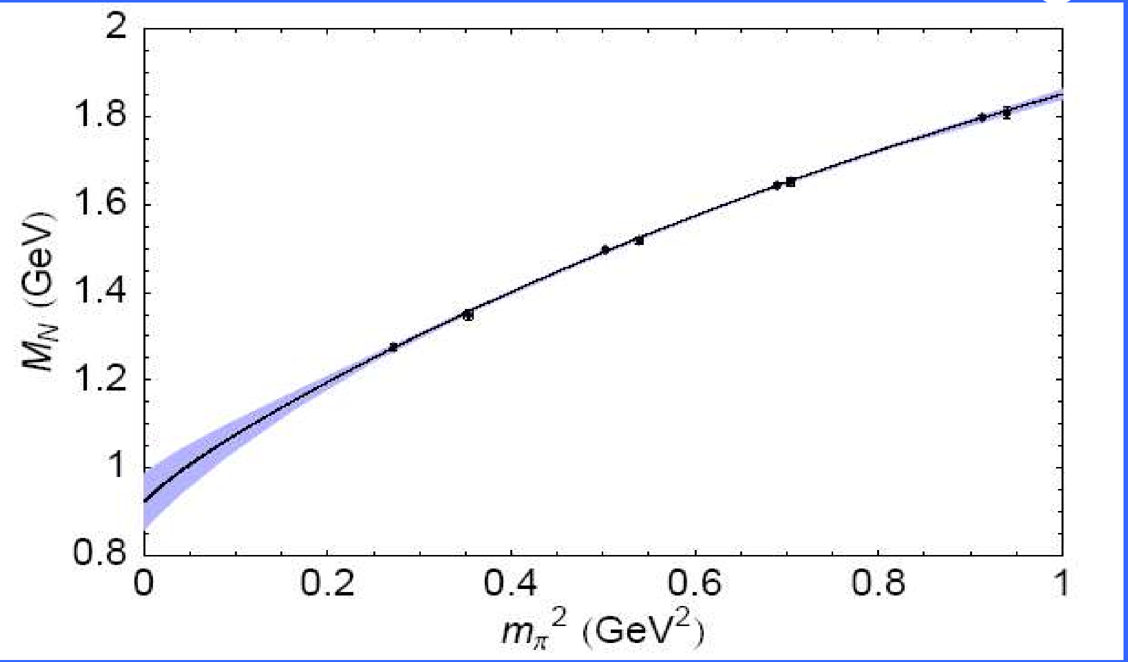
$$\frac{Q(\rho_B)}{Q_0} \simeq 1 - \frac{\sigma_N}{f_\pi^2 m_\pi^2} \rho_B$$

BUT this has no new physics at all!

Lattice QCD Simulation of Vacuum Structure



’al Extrapolation Under Control when Coefficients Known – e.g. for the nucleon



FRR give same answer to <<1% systematic error!

	Bare Coefficients				Renormalized Coefficients			
Regulator	a_0^Λ	a_2^Λ	a_4^Λ	Λ	c_0	c_2	c_4	m_N
Monopole	1.74	1.64	−0.49	0.5	0.923(65)	2.45(33)	20.5(15)	0.960(58)
Dipole	1.30	1.54	−0.49	0.8	0.922(65)	2.49(33)	18.9(15)	0.959(58)
Gaussian	1.17	1.48	−0.50	0.6	0.923(65)	2.48(33)	18.3(15)	0.960(58)
Sharp cutoff	1.06	1.47	−0.55	0.4	0.923(65)	2.61(33)	15.3(8)	0.961(58)
Dim. Reg. (BP)	0.79	4.15	+8.92	–	0.875(56)	3.14(25)	7.2(8)	0.923(51)

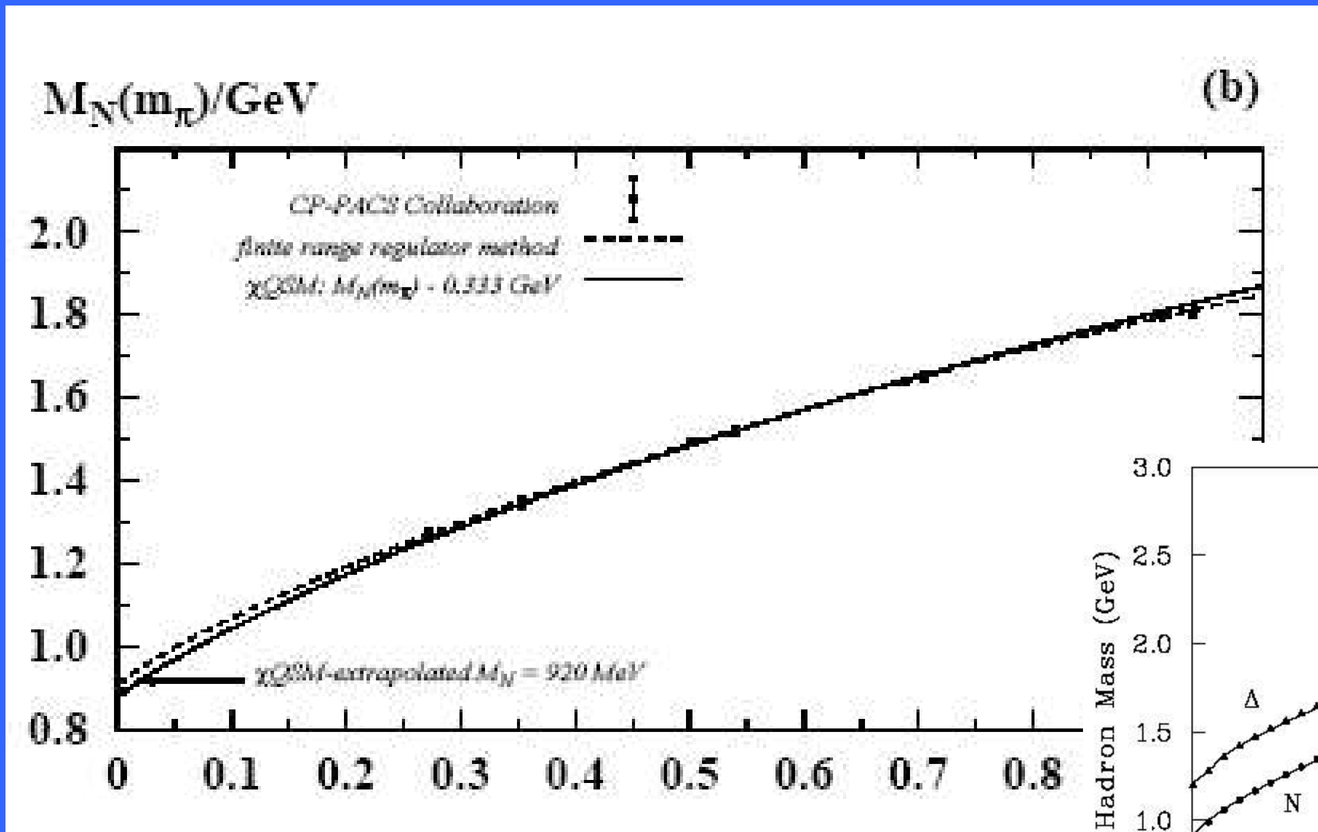
Leinweber et al., PRL 92 (2004) 242002

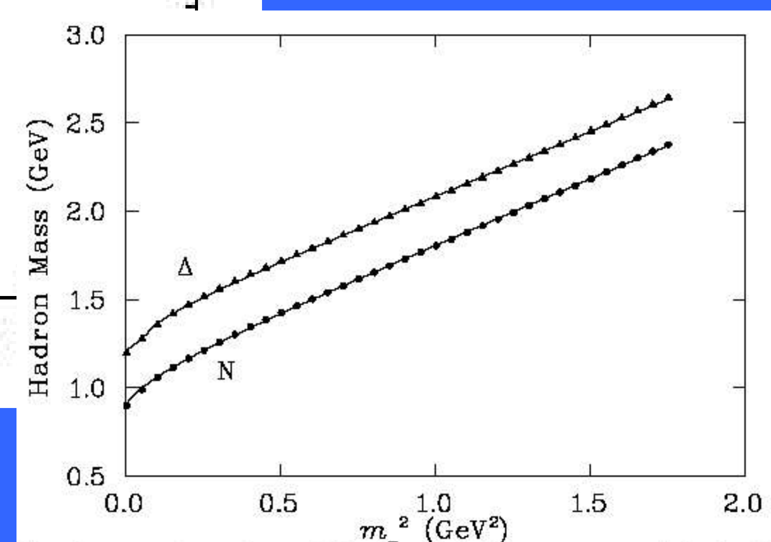
Convergence from LNA to NLNA is Rapid – Using Finite Range Regularization

Regulator	LNA	NLNA
Sharp	968	961
Monopole	964	960
Dipole	963	959
Gaussian	960	960
Dim Reg	784	884

M_N in MeV

Comparison with χ QSM

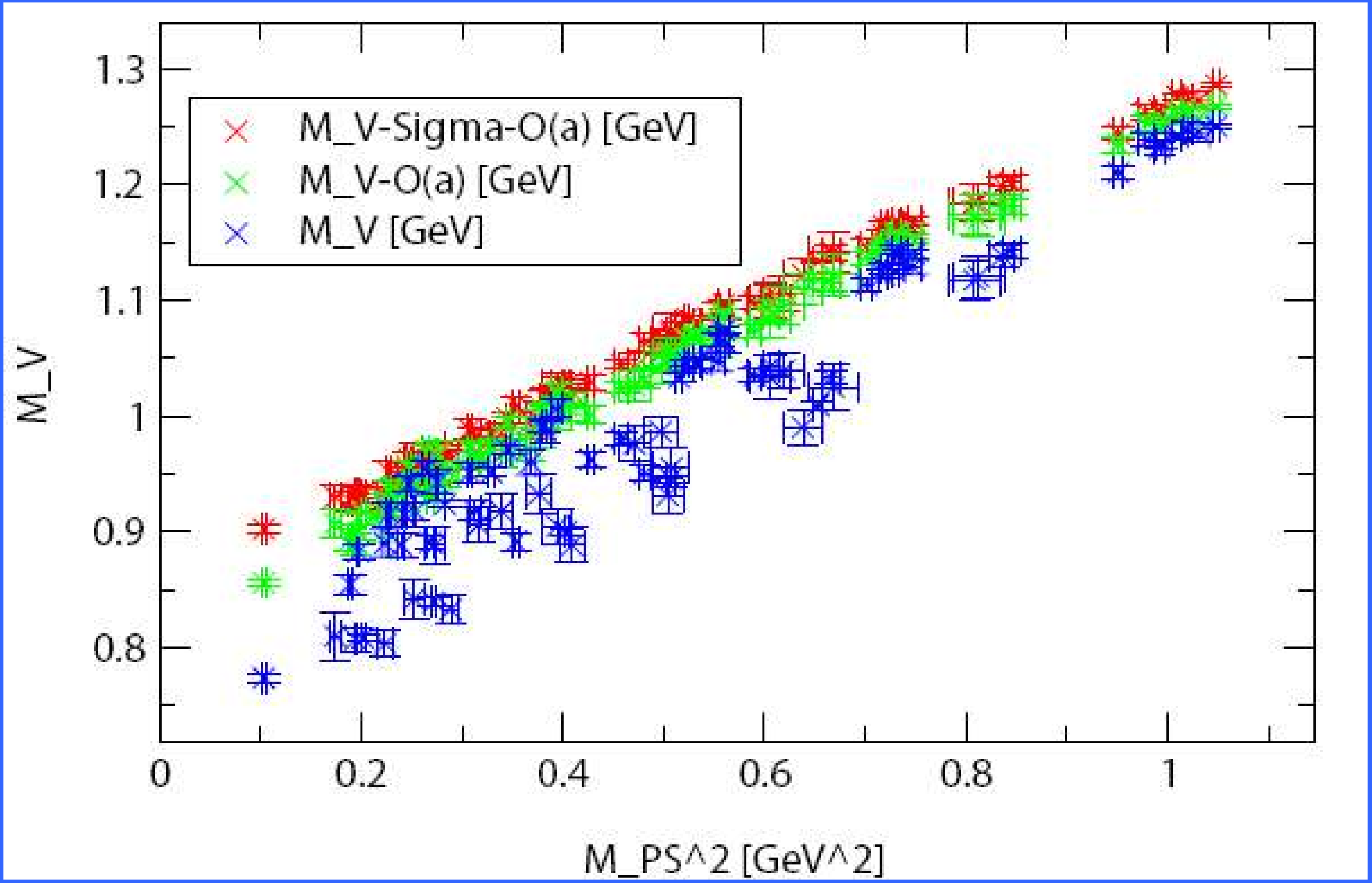




Goeke *et al.*, hep-lat/0505010

CBM: Leinweber et al., Phys.Rev.D61:074502,2000

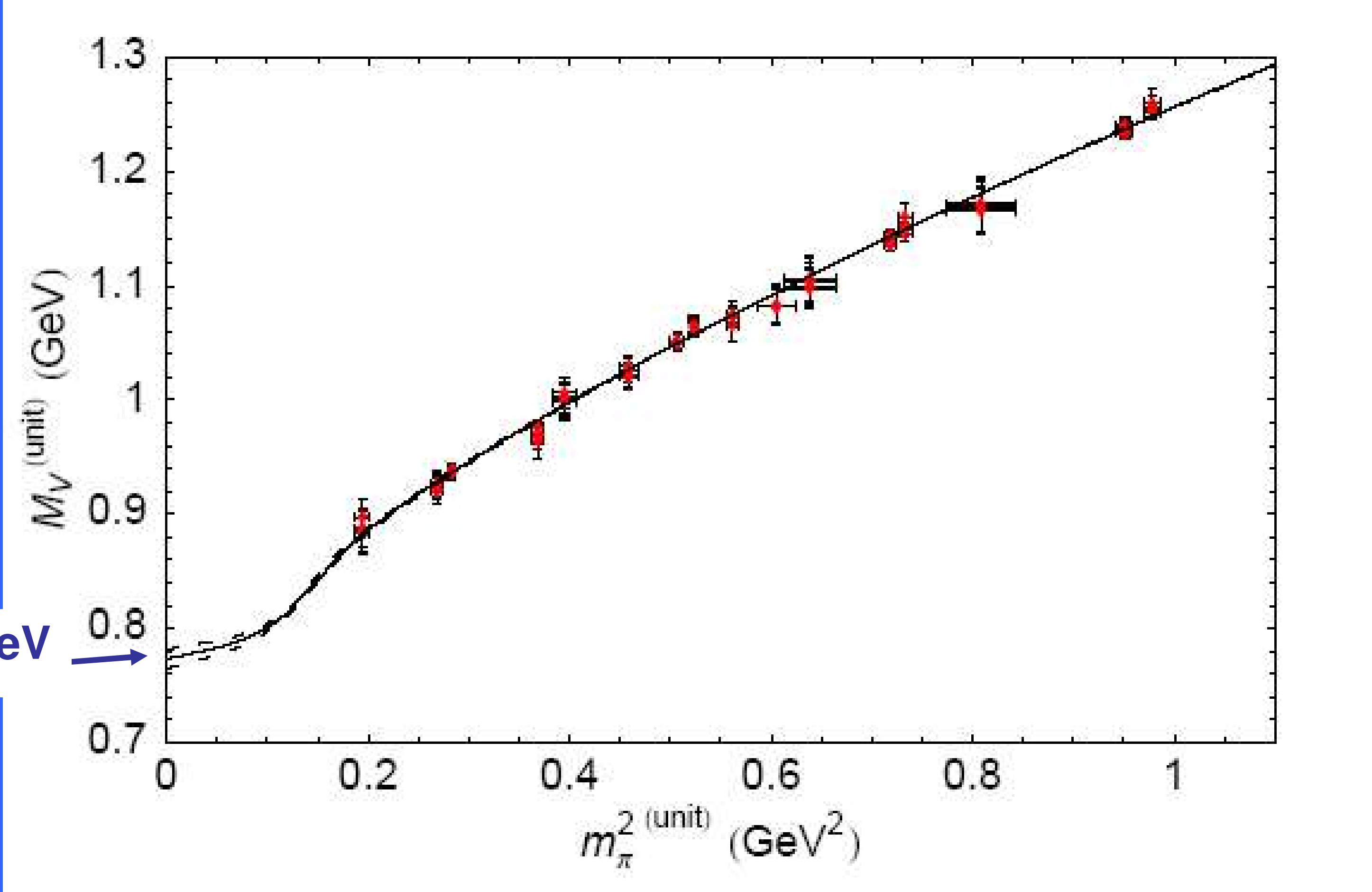
Analysis of pQQCD ρ data from CP PACS



$$\sqrt{(M_V^{deg})^2 - \Sigma_{TOT}} = (a_0^{cont} + X_1 a + X_2 a^2) + a_2 (M_{PS}^{deg})^2 + a_4 (M_{PS}^{deg})^4 + a_6 (M_{PS}^{deg})^6$$

Infinite Volume Unitary Results

All 80 data points drop onto single, well defined curve



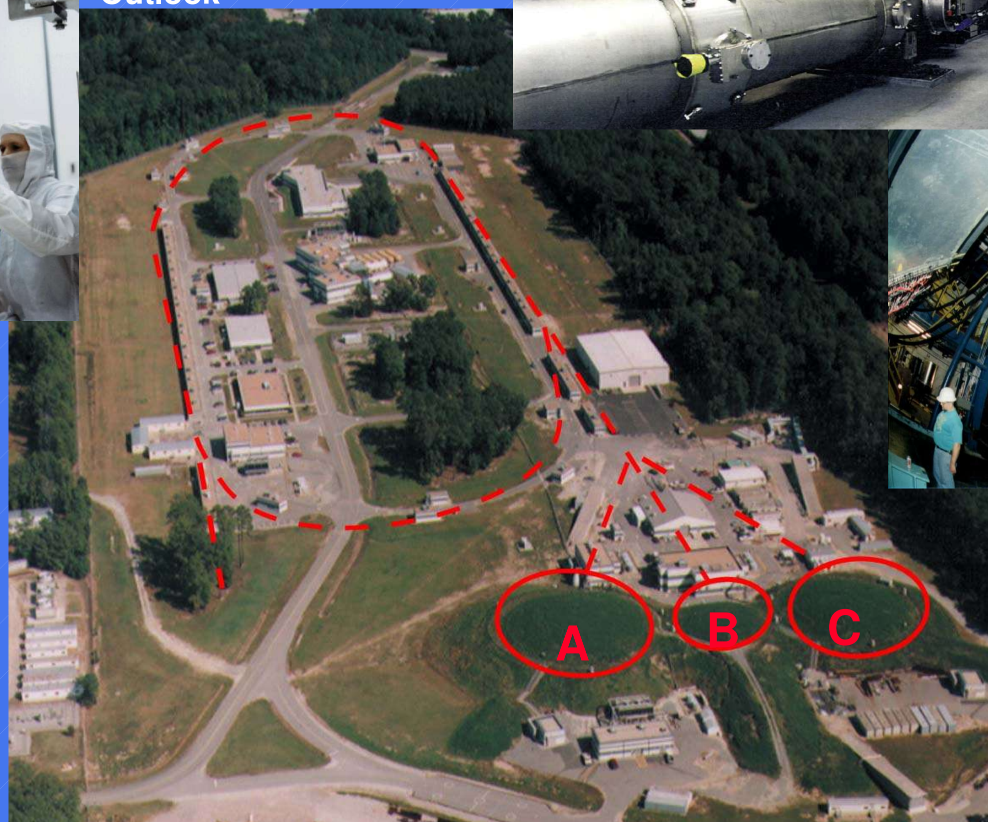
777 ± 7 MeV

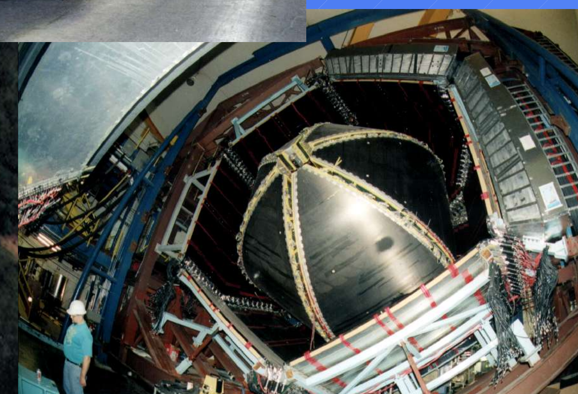
Allton, Young *et al.*, hep-lat/0504022

JLAB: Unique Capabilities for Investigating QCD in the Non-Perturbative Regime

JLab is a world leader in SRF technology: SNS, 12 GeV Upgrade, FEL, RIA, and others in the Office of Science 20-Year Facilities Outlook

Superconducting rf (SRF) technology makes the circulating accelerator feasible



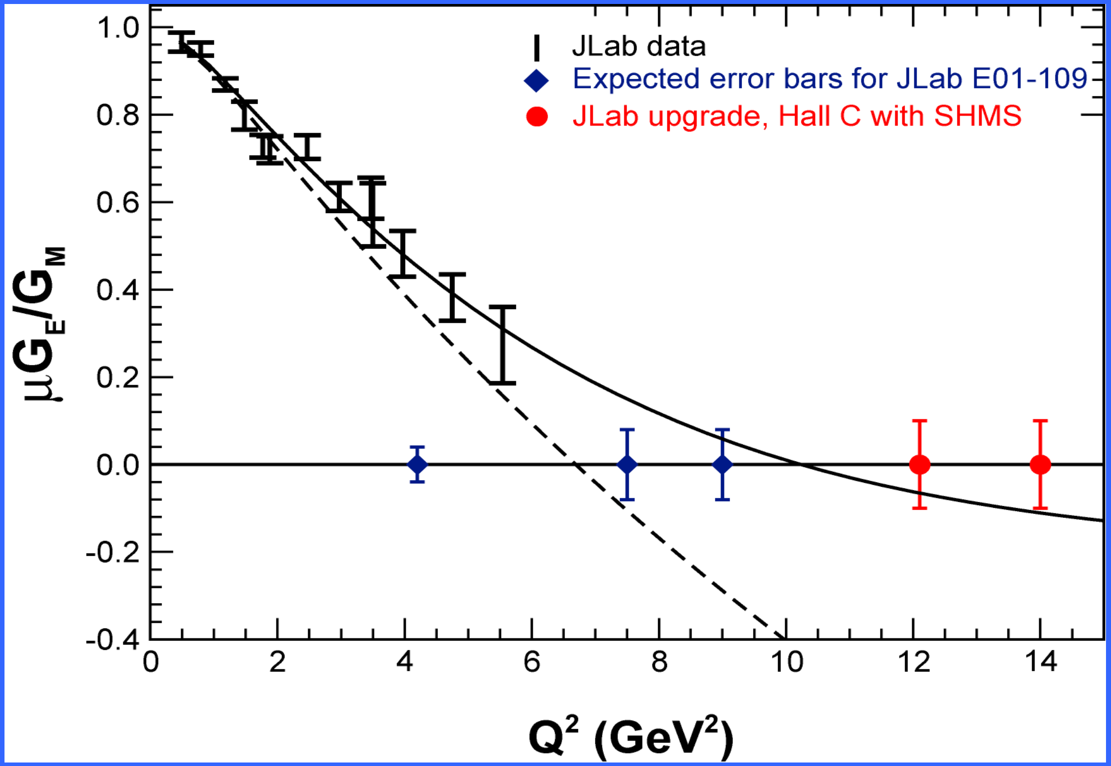


Providing ~2300 international users with a unique electron beam, three experimental halls, and computational and theory support

High luminosity, high resolution detectors in Halls A, B, and C.

Precision Tests of Nucleon Structure

- Astonishing discovery concerning proton electric form factor



- But what about contribution from non-valence quarks

- especially strange quarks ?

Strangeness Widely Believed to Play a Major Role – Does It?

- As much as 100 to 300 MeV of proton mass:

$$M_N = \langle N(P)| -\frac{9\,\alpha_s}{4\,\pi}\,\mathrm{Tr}(G_{\mu\nu}G^{\mu\nu}) + m_u\bar{\psi}_u\psi_u + m_d\bar{\psi}_d\psi_d + m_s\bar{\psi}_s\psi_s |N(P)\rangle$$

$$\Delta M_N^{s-\mathrm{quarks}} = \frac{y\,m_s}{m_u + m_d}\,\sigma_N$$

$y = 0.2 \pm 0.2$

45 ± 8 MeV (or 70?)

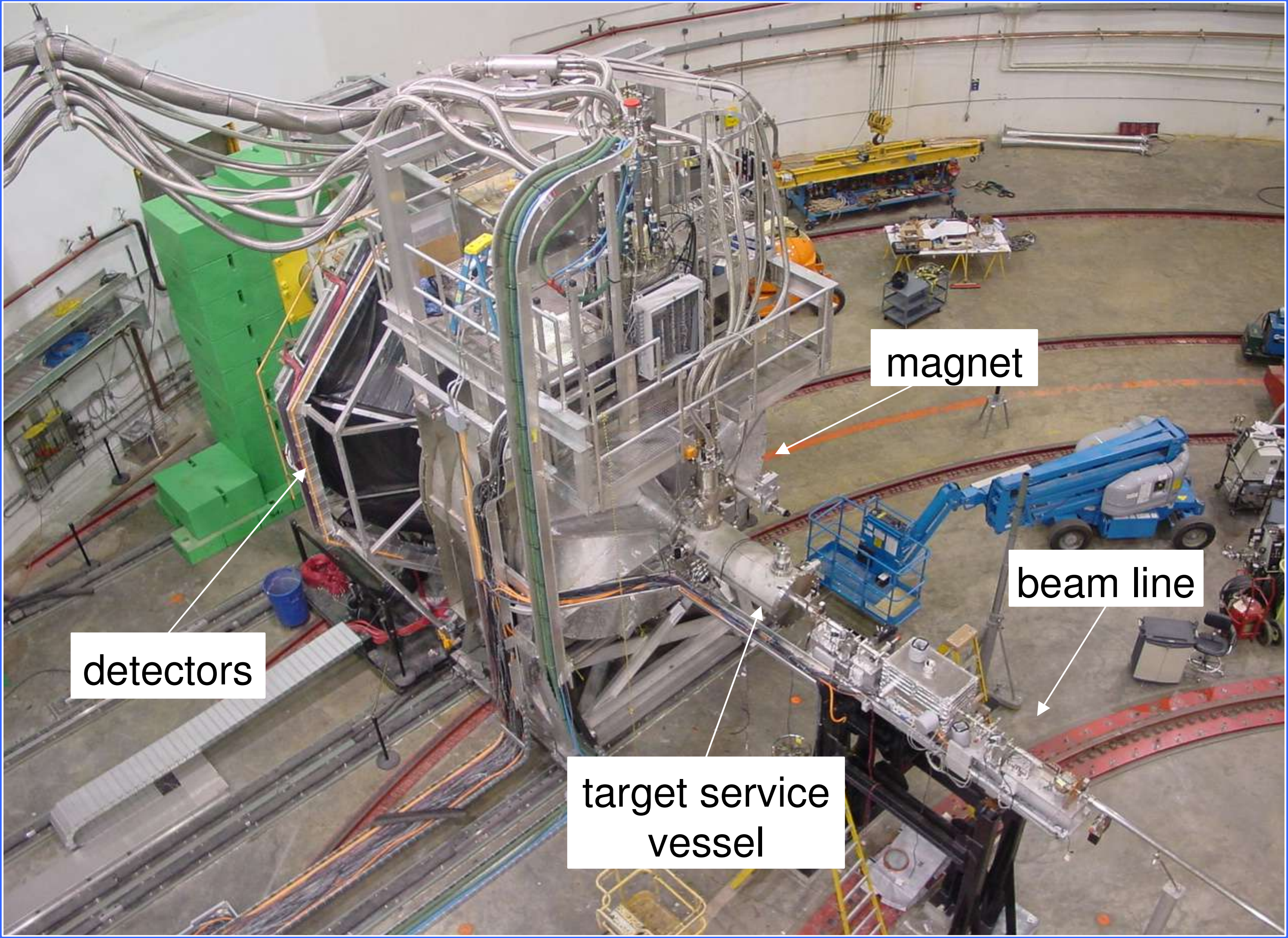
Hence 110 ± 110 MeV (increasing to 180 for higher σ_N)

- Through proton spin crisis:
  As much as 10% of the spin of the proton

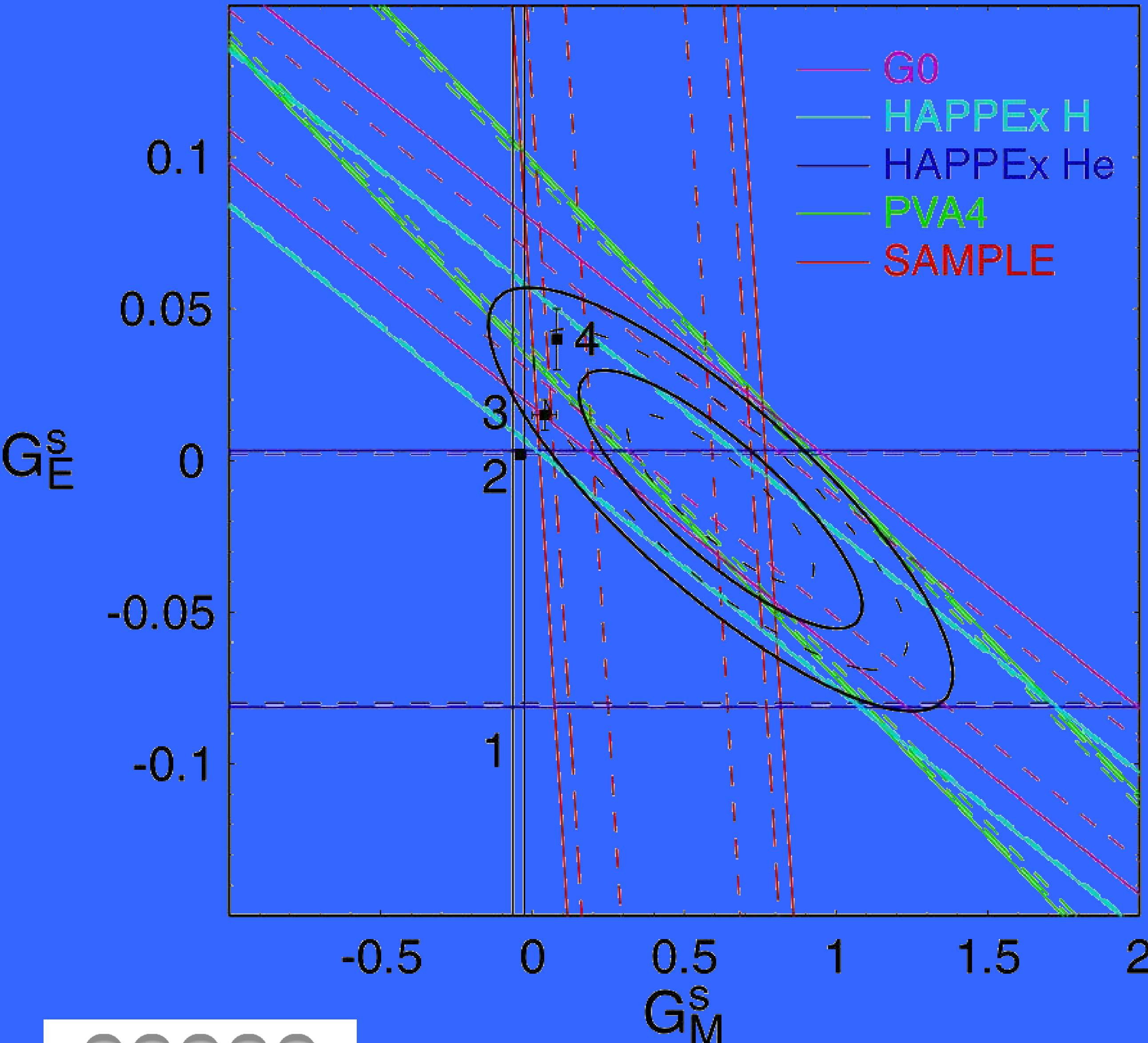
- HOW MUCH OF THE MAGNETIC FORM FACTOR?

A4 at Mainz

G0 Experiment at Jefferson Lab



World Data @ $Q^2 = 0.1$ GeV^2



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

Contours

----- 1σ, 2σ

—— 68.3, 95.5% CL

Theories

8. **Leinweber, et al. PRL 94 (05) 212001**
9. Lyubovitskij, et al. PRC **66** (02) 055204
10. Lewis, et al. PRD **67** (03) 013003
11. Silva, et al. PRD **65** (01) 014016

Significance & Comparison with Lattice QCD

- Size and sign of the strange magnetic moment is astonishing!

- Experimental isoscalar nucleon moment is 0.88 μ_N

c.f. this result which is (Beck) - 0.54 μ_N : i.e. - 60% !!

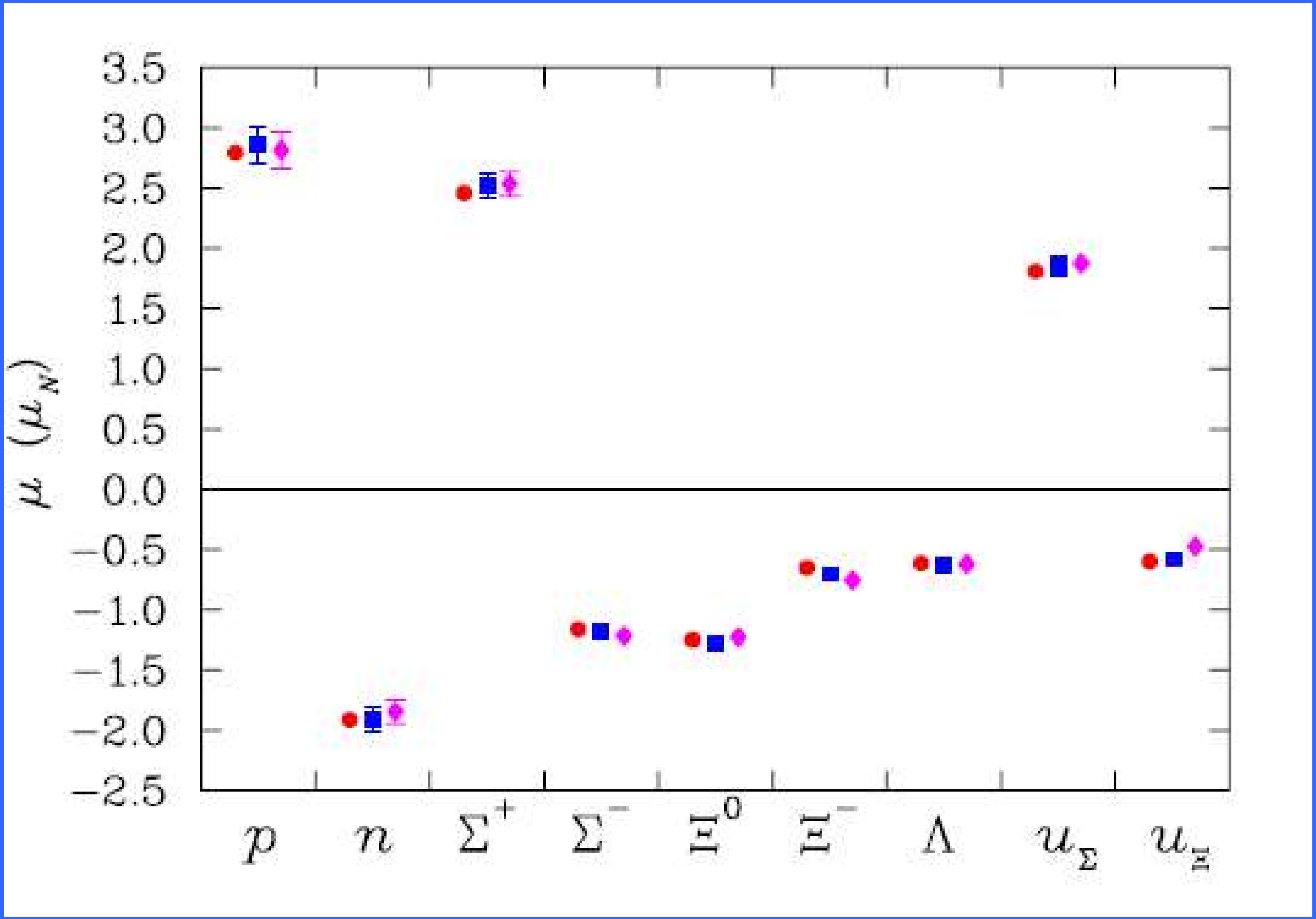
- Also remarkable versus lattice QCD which gives

$+0.03 \pm 0.01\ \mu_N$ (Leinweber et al., PRL 94 (2005) 212001)

- Sign would require violation of universality of

valence quark moments by $\sim$ 70% !

Convergence LNA to NLNA Again Excellent (Effect of Decuplet)



“Back of the Envelope” Estimate

- 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 ⇒ ignore)

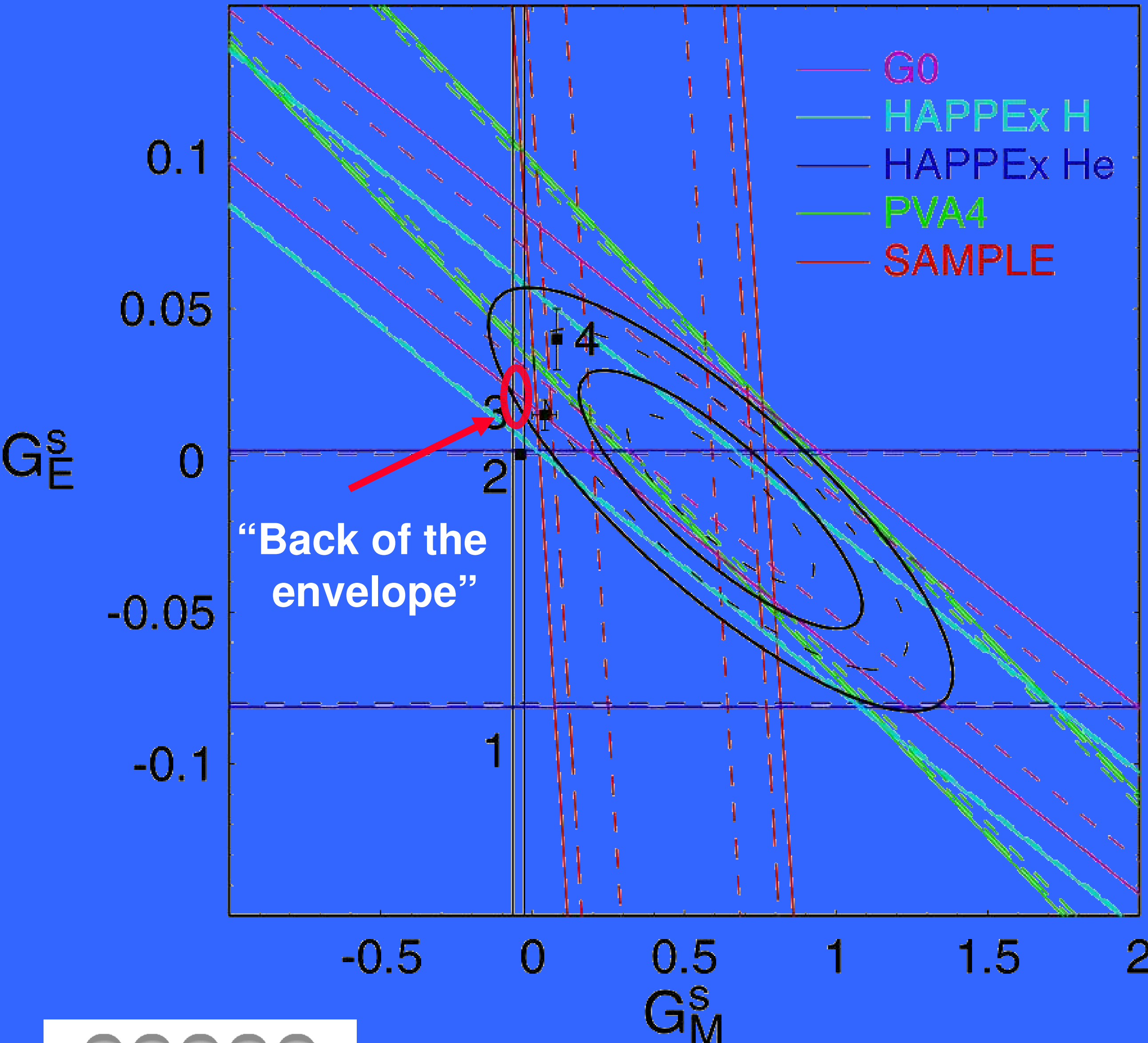
- Lots of evidence that $P_{\pi N} \sim 20\% \Rightarrow P_{K\Lambda} \sim 5\%$

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

$$\approx -0.067\ \mu_N$$

Remarkably close to lattice estimate!

World Data @ $Q^2 = 0.1\ GeV^2$



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31$

$\pm 0.62\ 2\sigma$

<u>Contours</u>

----- 1σ, 2σ

—— 68.3, 95.5% CL

<u>Theories</u>

8. Leinweber, et al. PRL **94** (05) 212001
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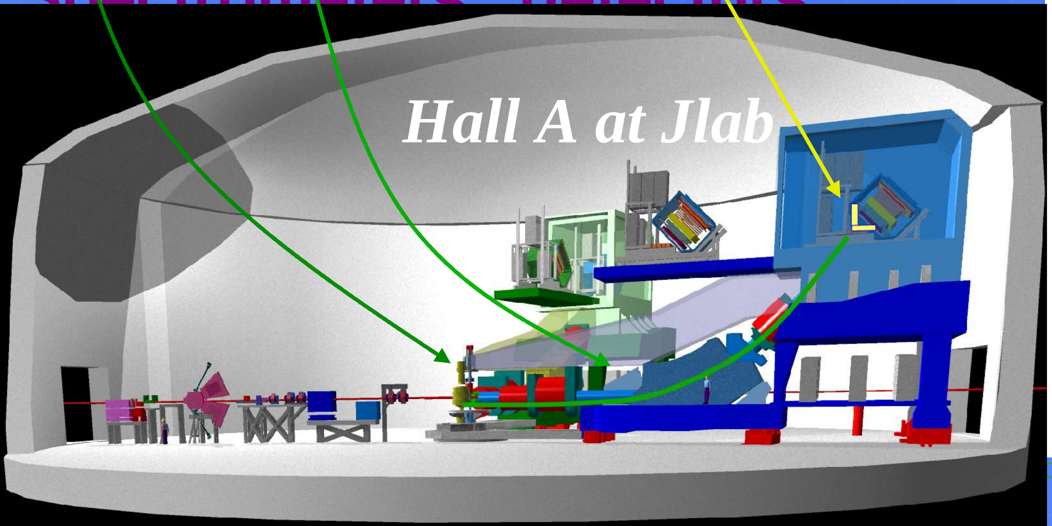
HAPPEx: Parity Violation on ^{1}H and ^{4}He

3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ (GeV/c)^2$

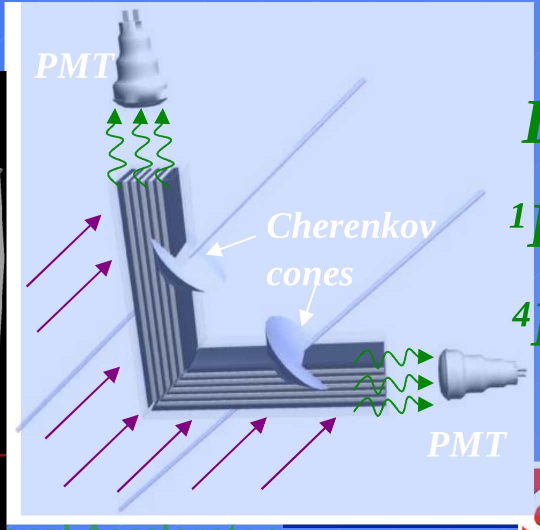
target	A_{PV} $G^s = 0$ (ppm)	Stat. Error (ppm)	Syst. Error (ppm)	sensitivity
^{1}H	-1.6	0.08	0.04	$\delta(G^s_E + 0.08 G^s_M) = 0.010$
^{4}He	+7.8	0.18	0.18	$\delta(G^s_E) = 0.015$

Septum magnets (not shown)

High Resolution Spectrometers detectors



Brass-Quartz integrating detector



Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz

Background ≤ 3%

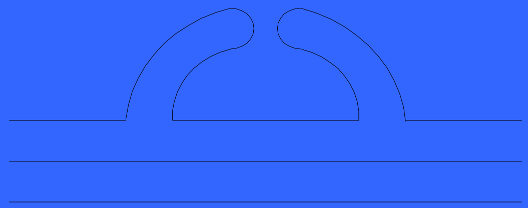
Office of Science U.S. DEPARTMENT OF ENERGY

Baryon Masses in Quenched QCD

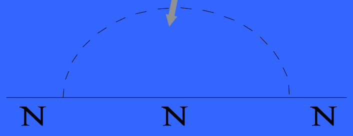
Chiral behaviour in QQCD quite different from full QCD

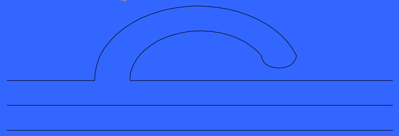
η' is an additional Goldstone Boson , so that:

$$m_N = m_0 \cancel{+ c_1 m_\pi} + c_2 m_\pi^2 + c_3 m_\pi^3 + c_4 m_\pi^4 + m_\pi^4 \ln m_\pi + \ldots..$$



Contribution from η' and π





LNA term now ~ $m_q^{1/2}$

origin is η' double pole

Extrapolation Procedure for Nucleon in QQCD

Coefficients of non-analytic terms again model independent

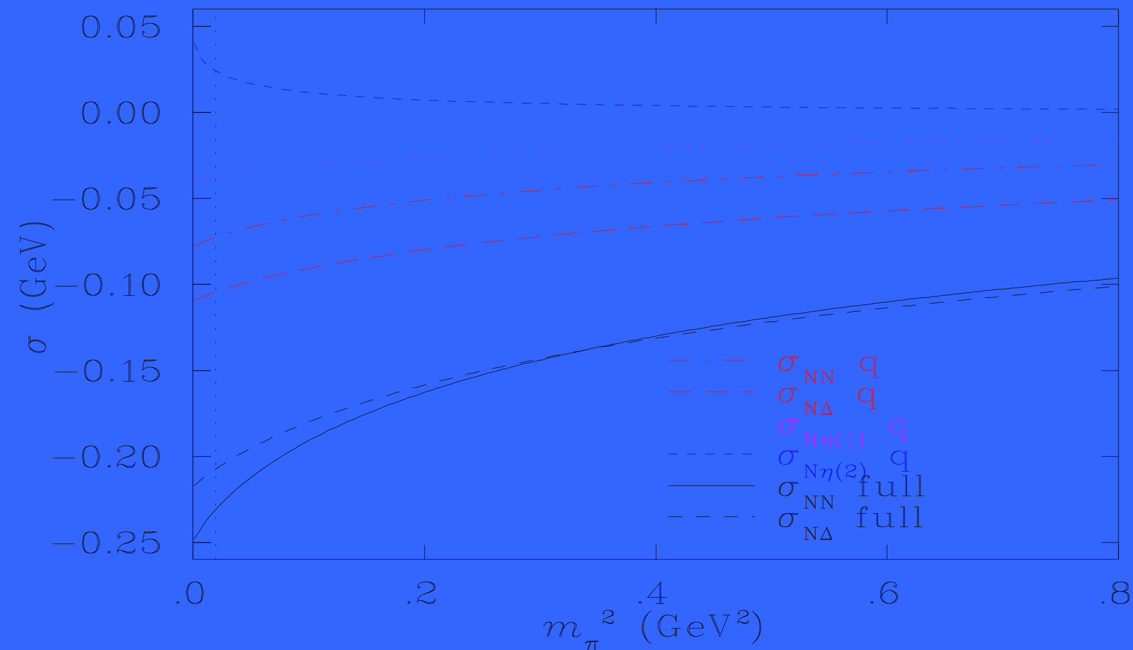
(Given by: Labrenz & Sharpe, Phys. Rev., D64 (1996) 4595)

Let:

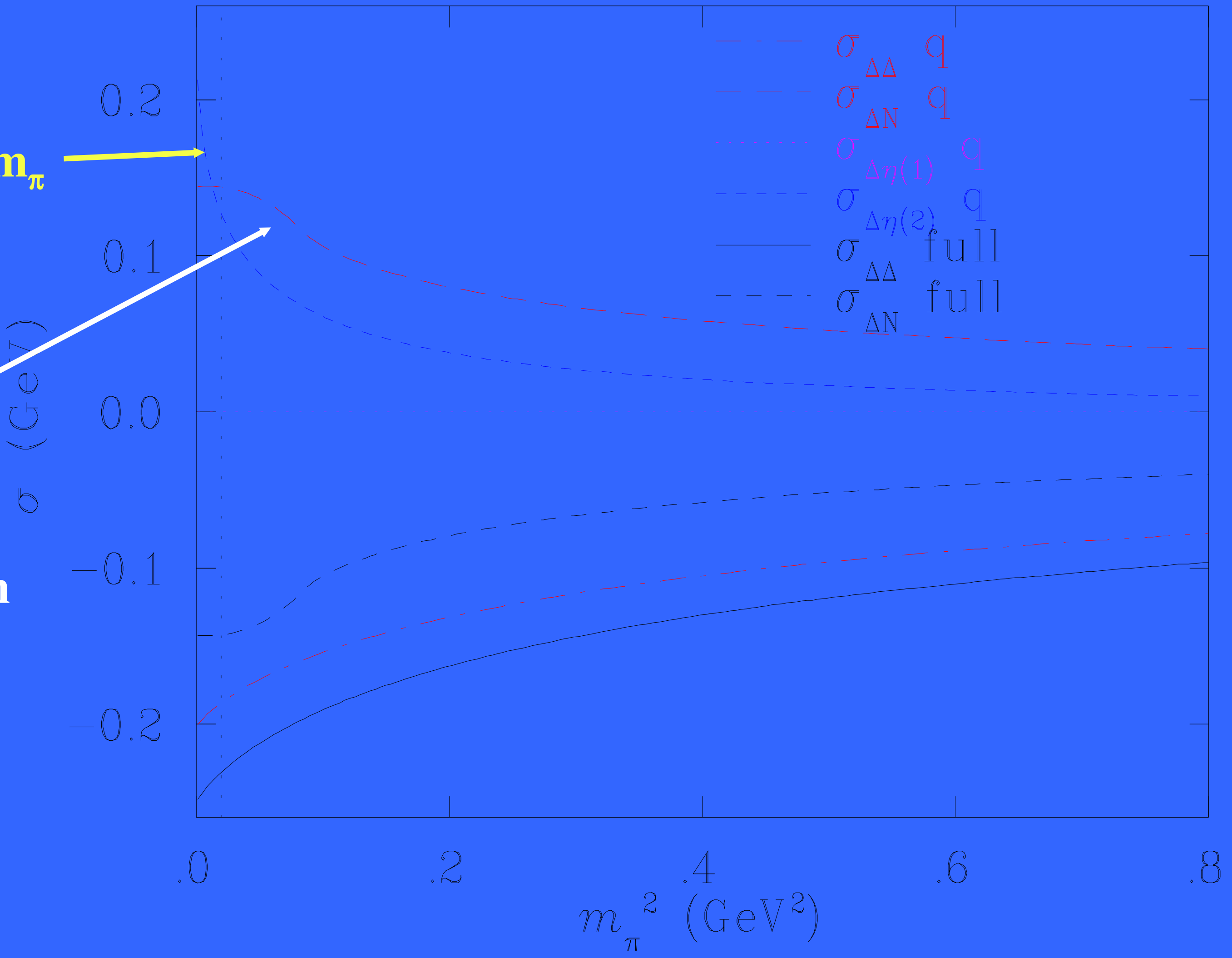
$$m_N = \alpha' + \beta' m_\pi^2 + \sigma_{QQCD}$$

with same Λ as

full QCD



Δ in QQCD

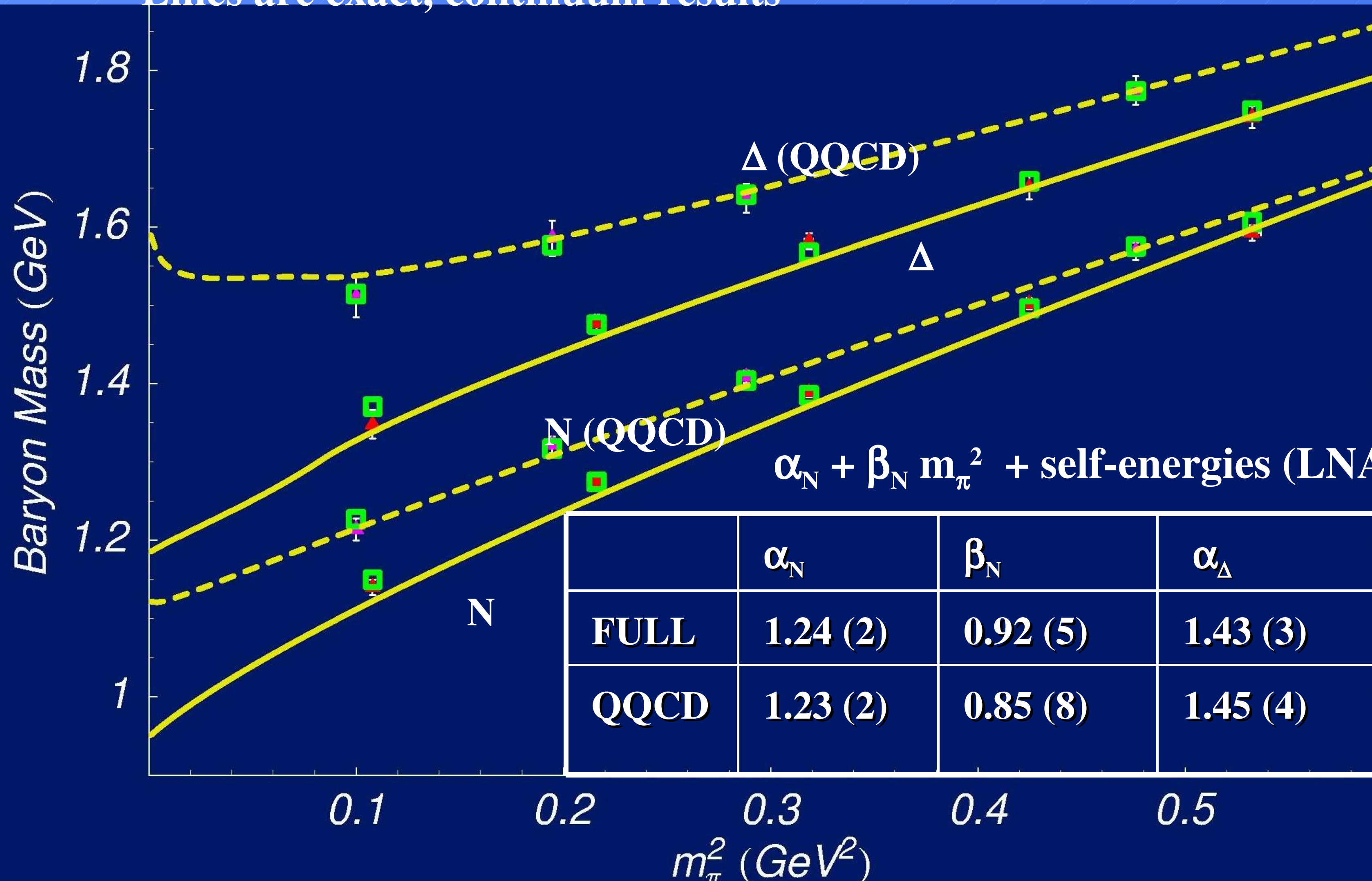


Δ → N π contribution

has opposite sign in QQCD (repulsive)

Overall σ_{QQCD} is repulsive !

- Lattice data (from MILC Collaboration) : red triangles
- Green boxes: fit evaluating σ’s on <u>same finite grid as lattice</u>
- Lines are exact, continuum results

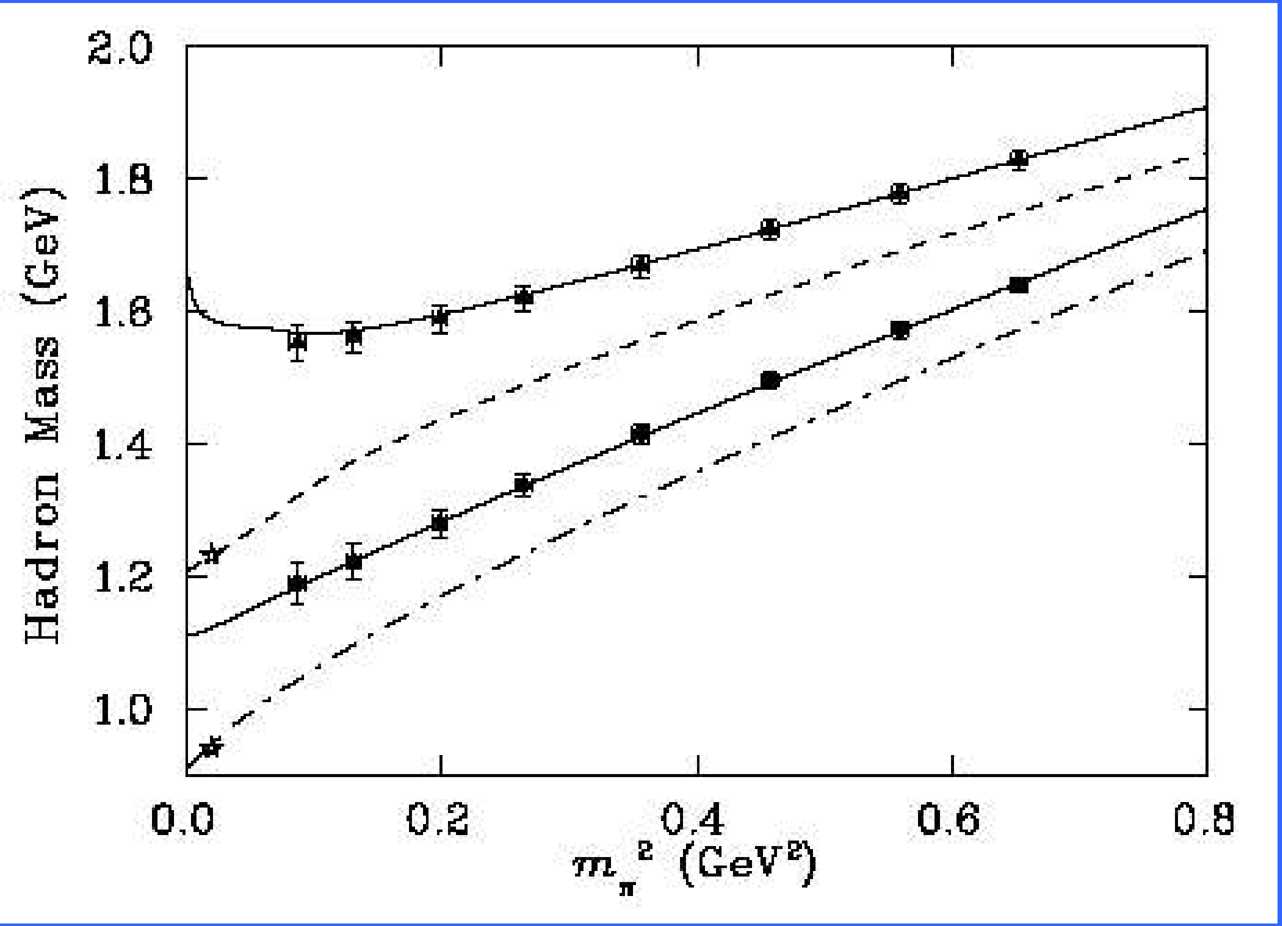


$\alpha_N + \beta_N m_\pi^2$ + self-energies (LNA+NLNA)

	α_N	β_N	α_Δ	β_Δ
FULL	1.24 (2)	0.92 (5)	1.43 (3)	0.75 (8)
QQCD	1.23 (2)	0.85 (8)	1.45 (4)	0.71 (11)

Young *et al.*, hep-lat/0111041; Phys. Rev. D66 (2002) 094507

Confirmation of Predicted Behavior of Δ



Zanotti et al., hep-lat/0407039

Decuplet-Octet Mass Splitting (QQCD)

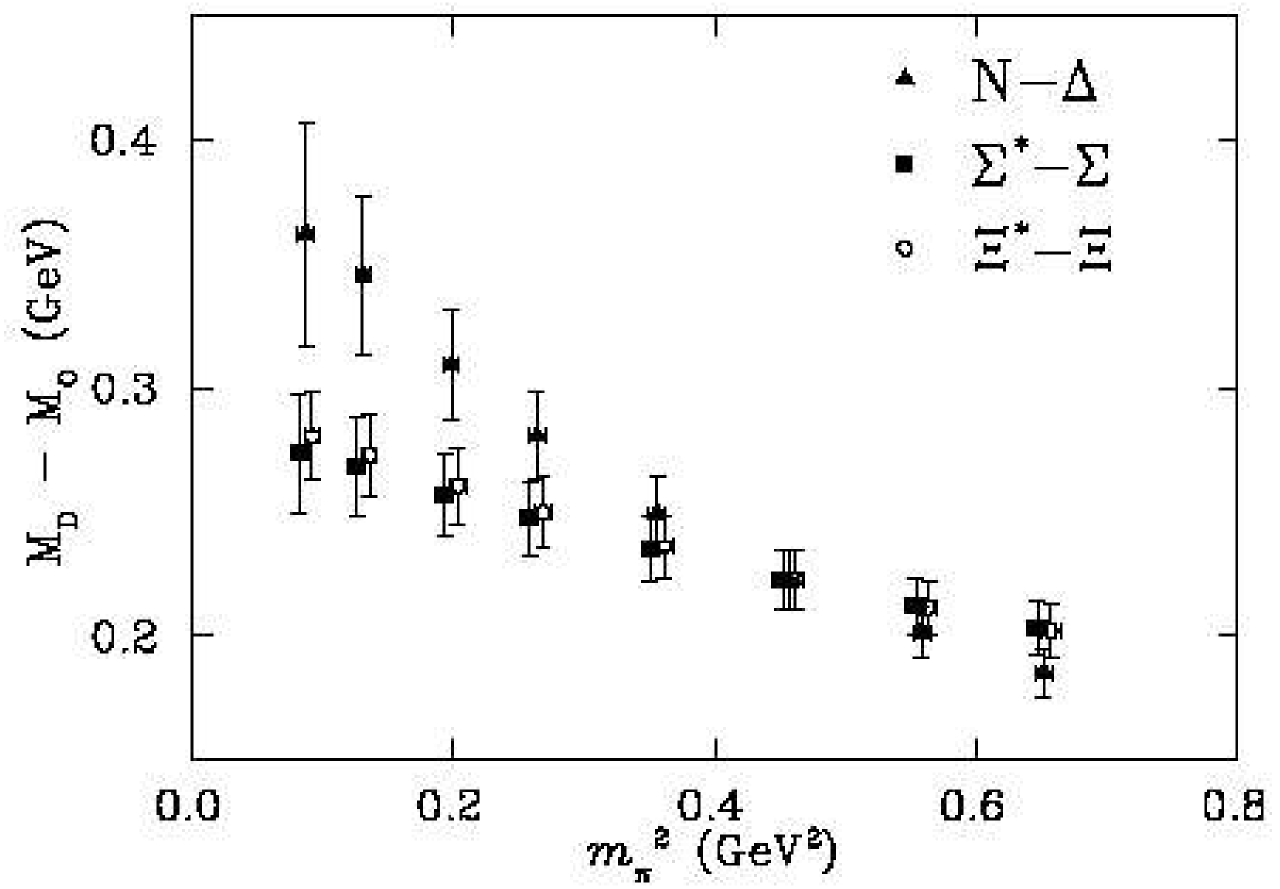


Fig. 13. Decuplet (M_D) - octet (M_O) baryon mass splittings for the FLIC-fermion action on a $20^3 \times 40$ lattice with $a = 0.132$ fm.

Zanotti et al., hep-lat/0407039

These results suggest following conjecture

IF lattice scale is set using static quark potential (e.g. Sommer scale)

(insensitive to chiral physics)

Suppression of Goldstone loops for $m_\pi >$ implies:

Analytic terms (e.g. + $m_\pi^2 + \gamma\, m_\pi^4$)

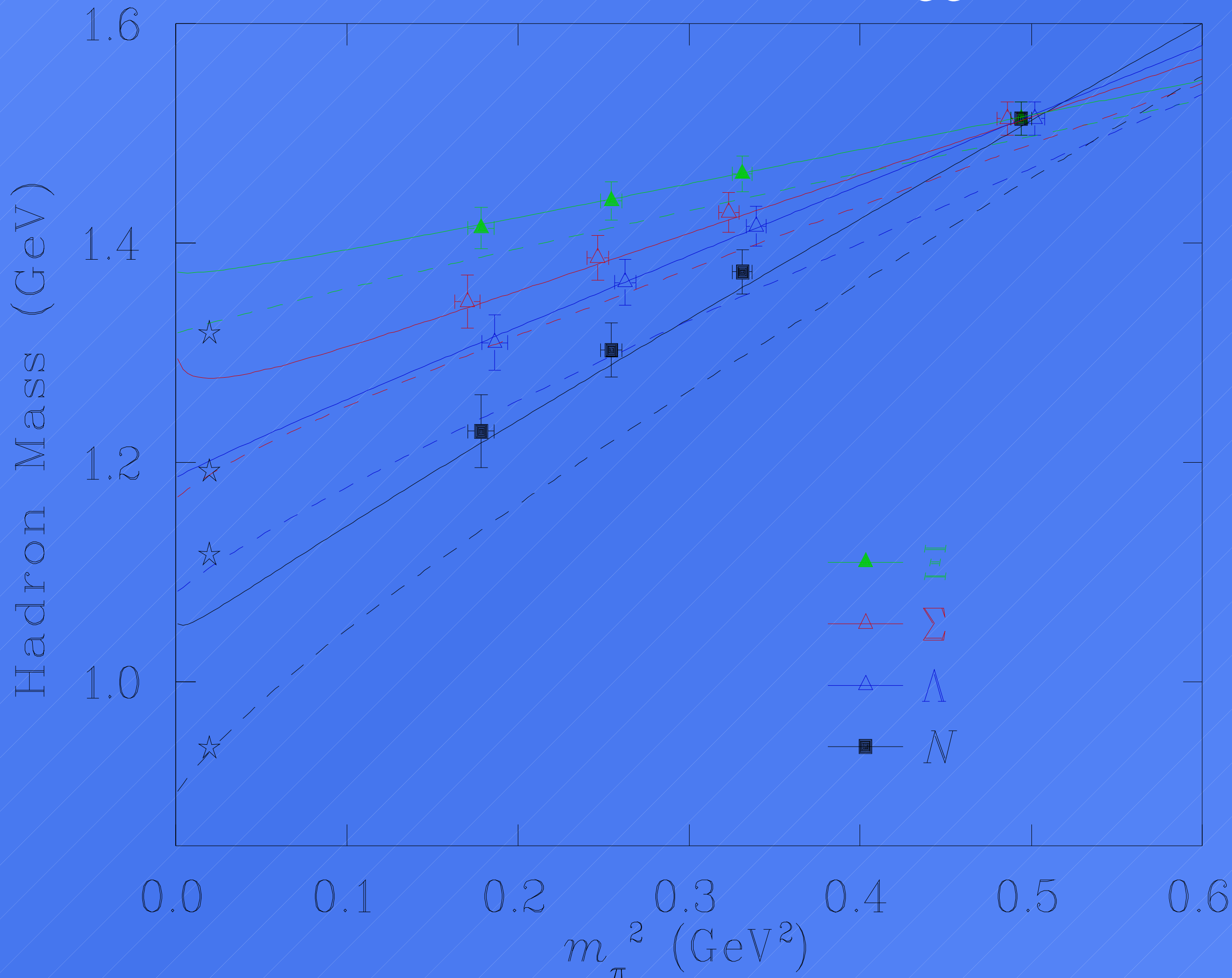
representing "hadronic core" are the same in QQCD & QCD

Can then correct QQCD results by replacing LNA & NLNA behaviour in QQCD by corresponding terms in full QCD

Quenched QCD is then no longer an "uncontrolled approximation" !

Octet Masses

Fit quenched data with : + m_π^2 + σ_{QQCD} ; then $\sigma_{QQCD} \rightarrow \sigma_{QCD}$



Errors for:
- **Stats**
- **a→ 0**
- **finite L**

NOT SHOWN

(Preliminary results from CSSM group: Young, Zanotti et al.)

Towards a New Quark Model

- Traditionally Constituent Quark Models <u>for light quarks</u> OMIT effects of Goldstone boson loops!

- OR assume they are included in effective parameters

- Simply not tenable any longer !

- Pion loops: $\delta M_N \sim 300$ MeV /// value for δM_Δ

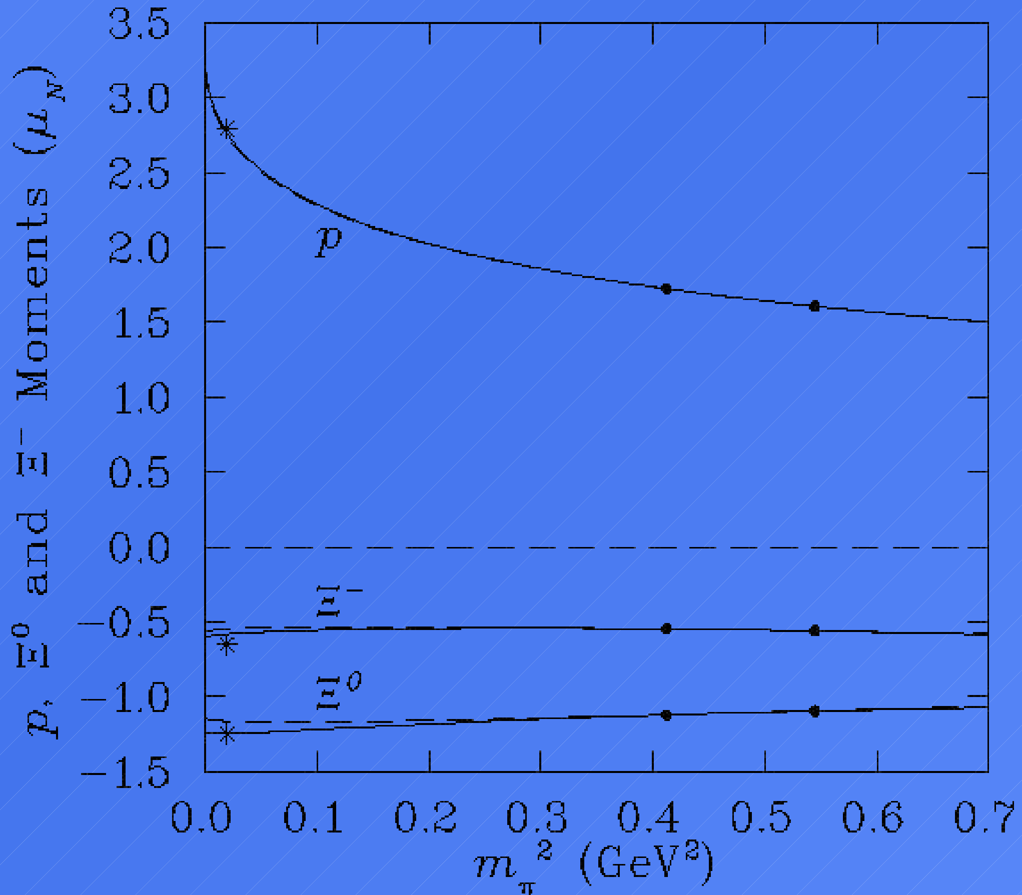
- LNA term in n: $\mu_n = \alpha\, m_\pi \sim 0.6\, \mu_N$ is 1/3rd of physical μ_n!

- LNA term in $\langle r^2\rangle_p$ is ~ 1 fm ^{2} at m_π ^{phys}

- LNA terms *depend on hadron* and [illegible]n ONLY come from Goldstone loops

Chiral Extrapolation Connects CQM to Physical Data

- Calculate CQM magnetic moments at M (strange) +/- 20 MeV (use exact SU(6) symmetry)
- Use Pade approximant to extrapolate to physical quark mass



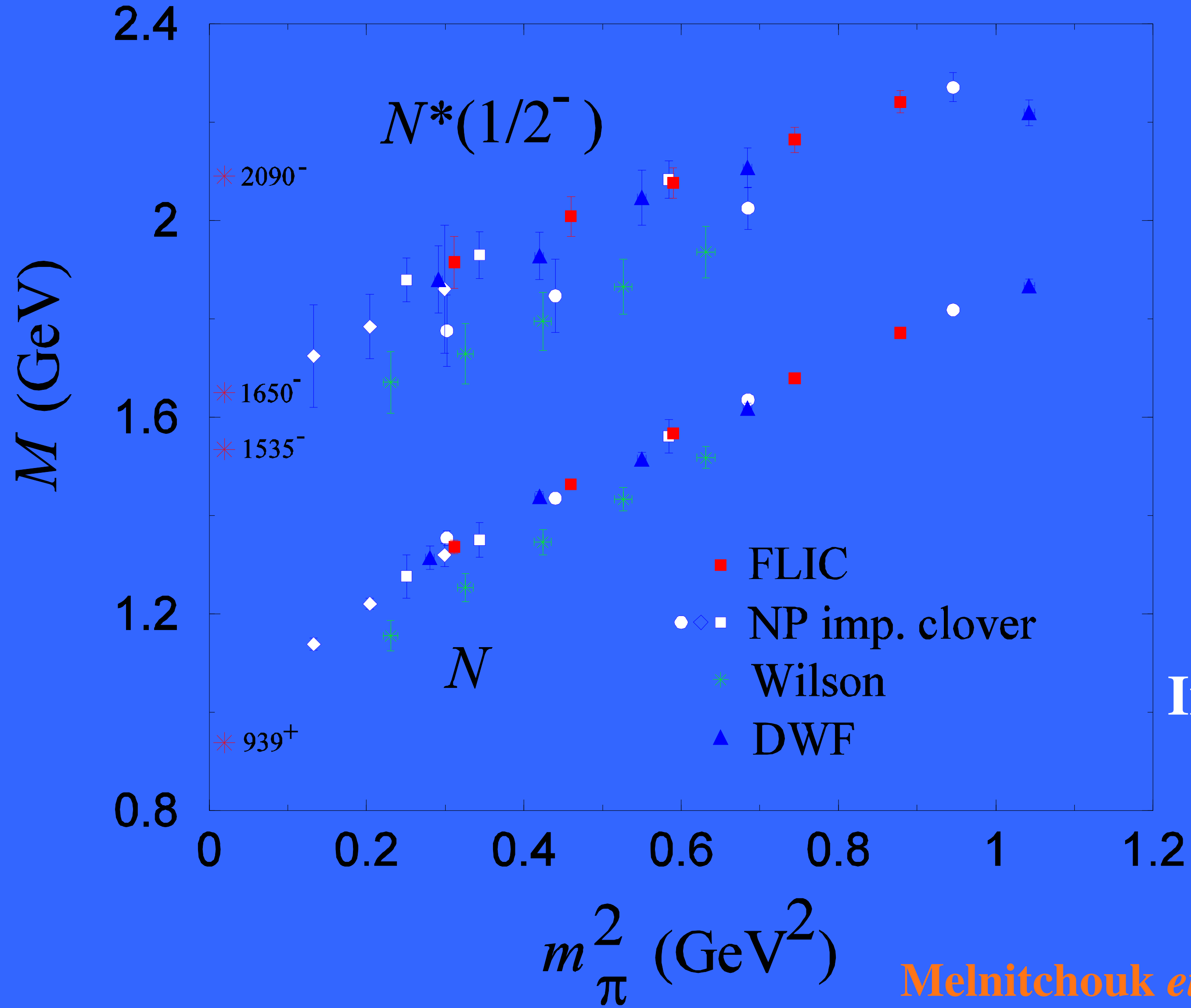
Cloet et al., Phys. Rev. C65 (2002) 062201

Test for ALL hadron models!

The availability of information from (lattice) QCD on the behaviour of hadron properties
as a function of current quark mass
suggests a very useful test for all models !!

- let Goldstone boson masses scale as for GMOR
- let "constituent quark mass" $M \sim M_0 + c\, m_q$
- calculate variation of all hadron masses with m_q
- masses must be linear above 50 MeV!
- magnetic moments must ~ 1/M above 50 MeV!
- etc… and compare with lattice data directly
- **EXTREMELY POWERFUL CONSTRAINTS!**

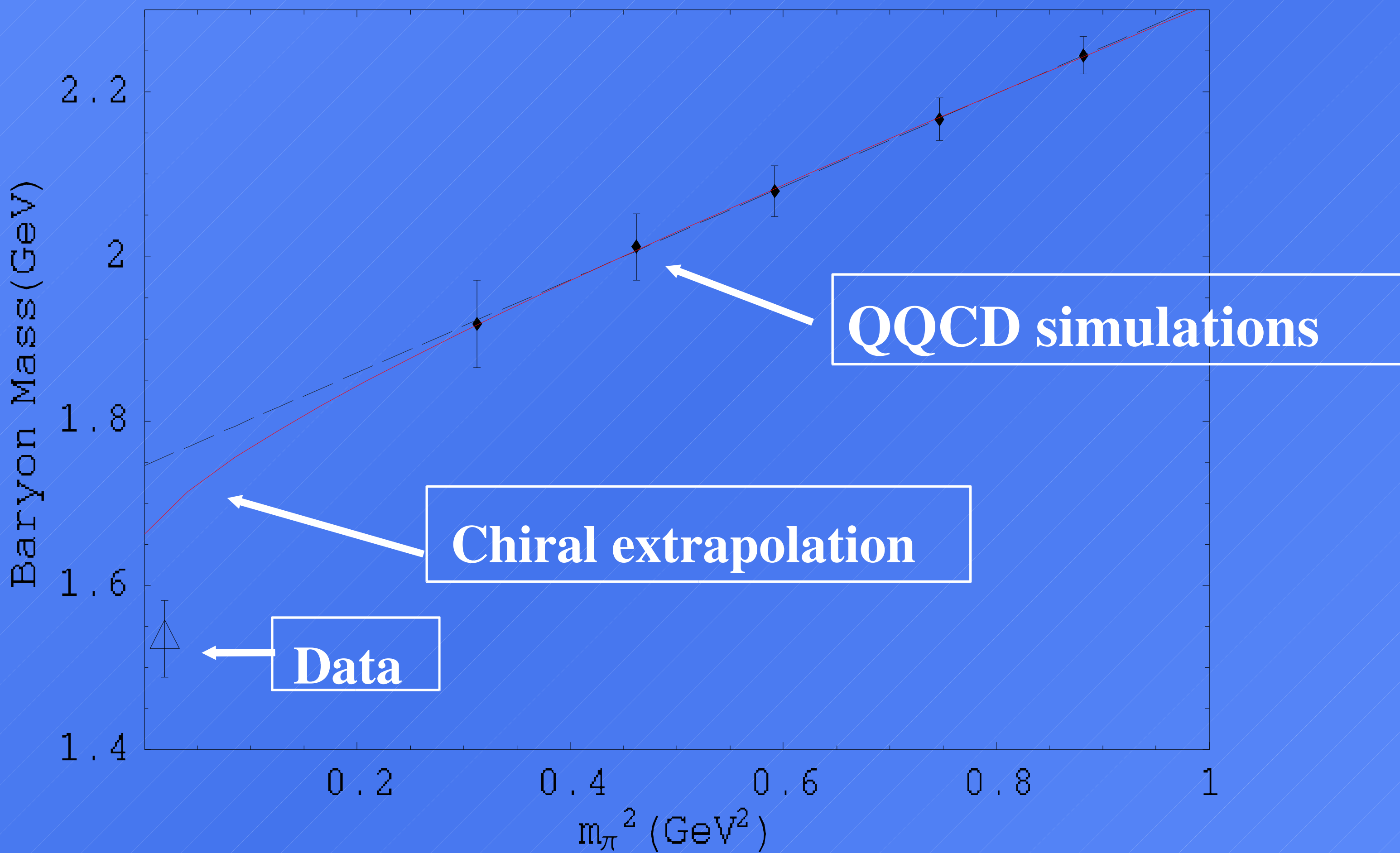
Caution in Interpreting Lattice Output



Actions?
(gluon & fermion)
Lattice Spacing?
Lattice Volume?
’al Extrapolation?
QQCD?
p QQCD?
Interpolating Field?
Plateau clear?
MEM?

Melnitchouk *et al.*

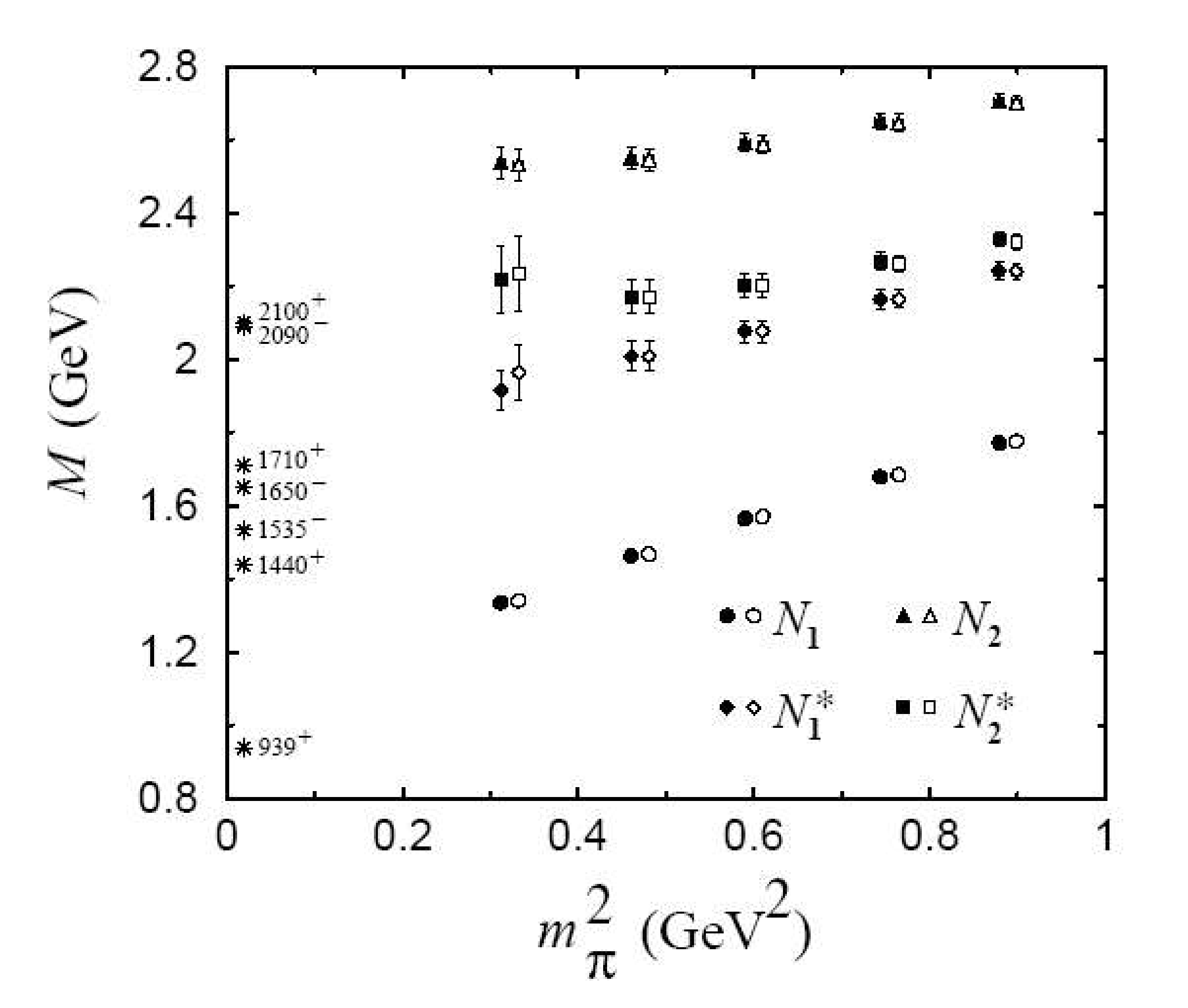
Baryon Spectroscopy: N*(1535) ½ ⁻



Red line is chiral extrapolation : couplings from Capstick & Morel

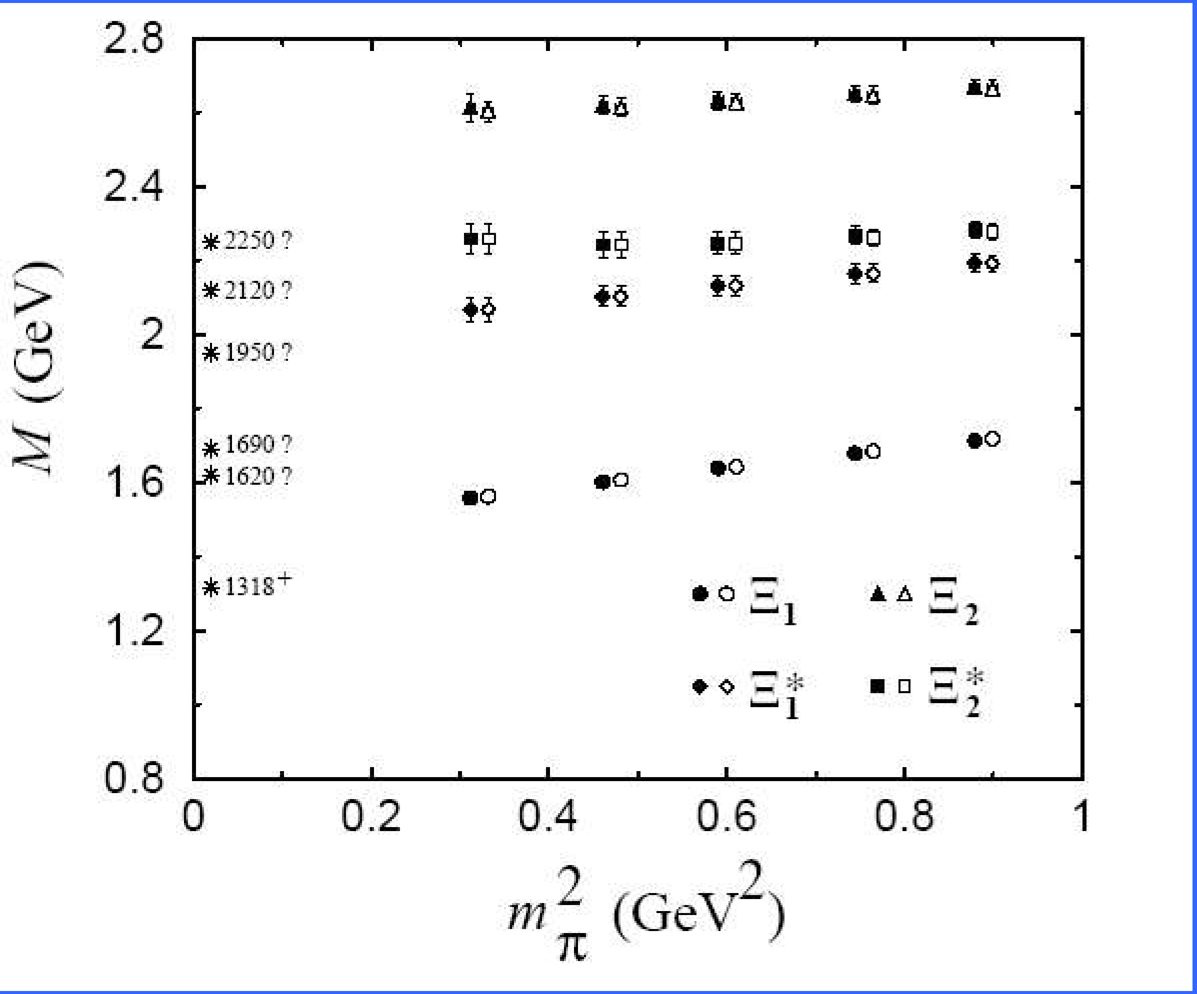
[Future: correct QQCD → QCD]

Oscillator-type Spectrum



Melnitchouk et al., hep-lat/0202022

Ξ Baryons



Operated by the Southeastern Universities Research Association for the U.S. Department of Energy

Spin 3/2 Non-Strange Baryons

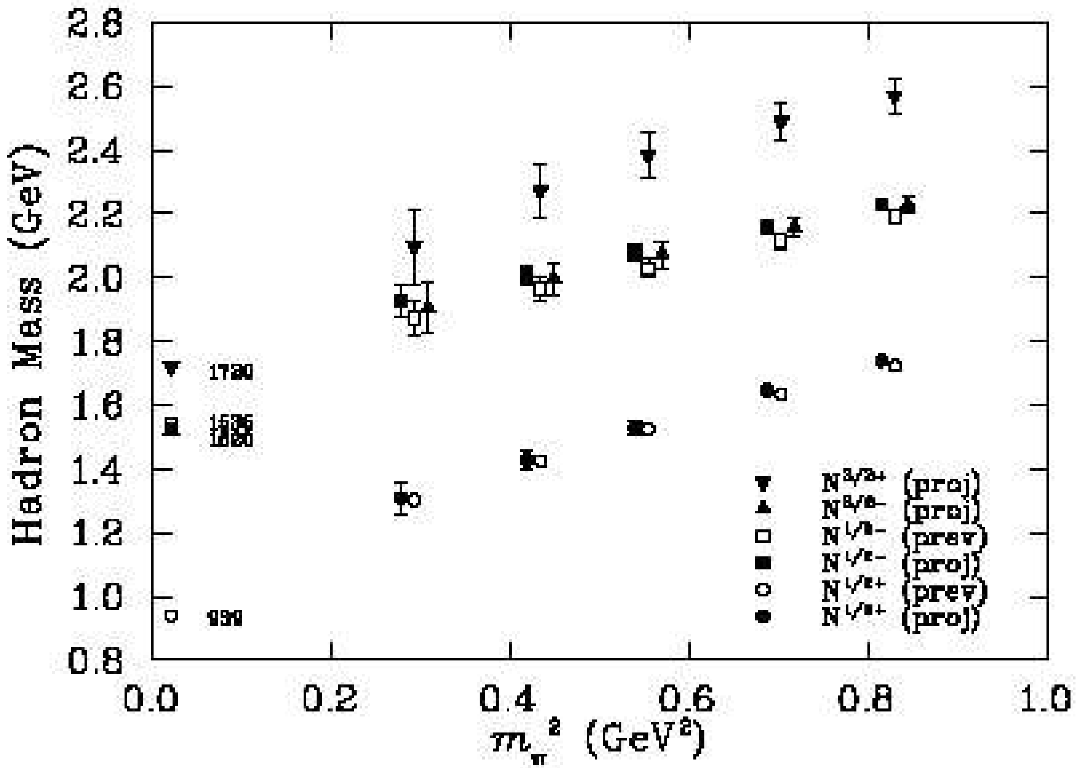
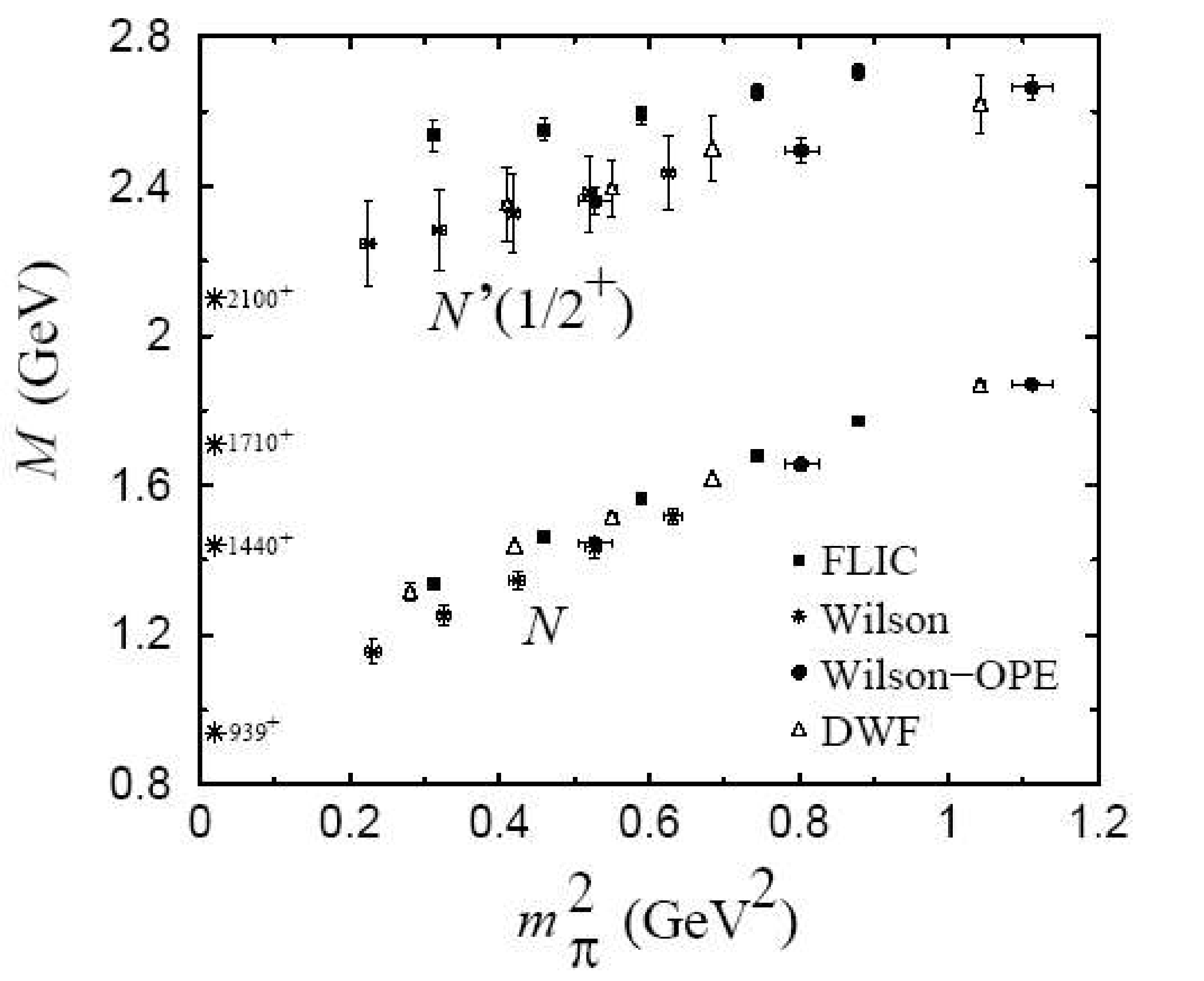


FIG. 5: Masses of the spin projected $N\frac{3}{2}^-$ (filled triangles), $N\frac{3}{2}^+$ (filled inverted triangles), $N\frac{1}{2}^+$ (filled circles), and $N\frac{1}{2}^-$ (filled squares) states. For comparison, previous results from the direct calculation of the $N\frac{1}{2}^+$ (open circles) and $N\frac{1}{2}^-$ (open squares) from Ref. [9] are also shown. The empirical values of the masses of the $N\frac{1}{2}^+$(939), $N\frac{1}{2}^-$(1535), $N\frac{3}{2}^-$(1520) and $N\frac{3}{2}^+$(1720) are shown on the left-hand-side at the physical pion mass.

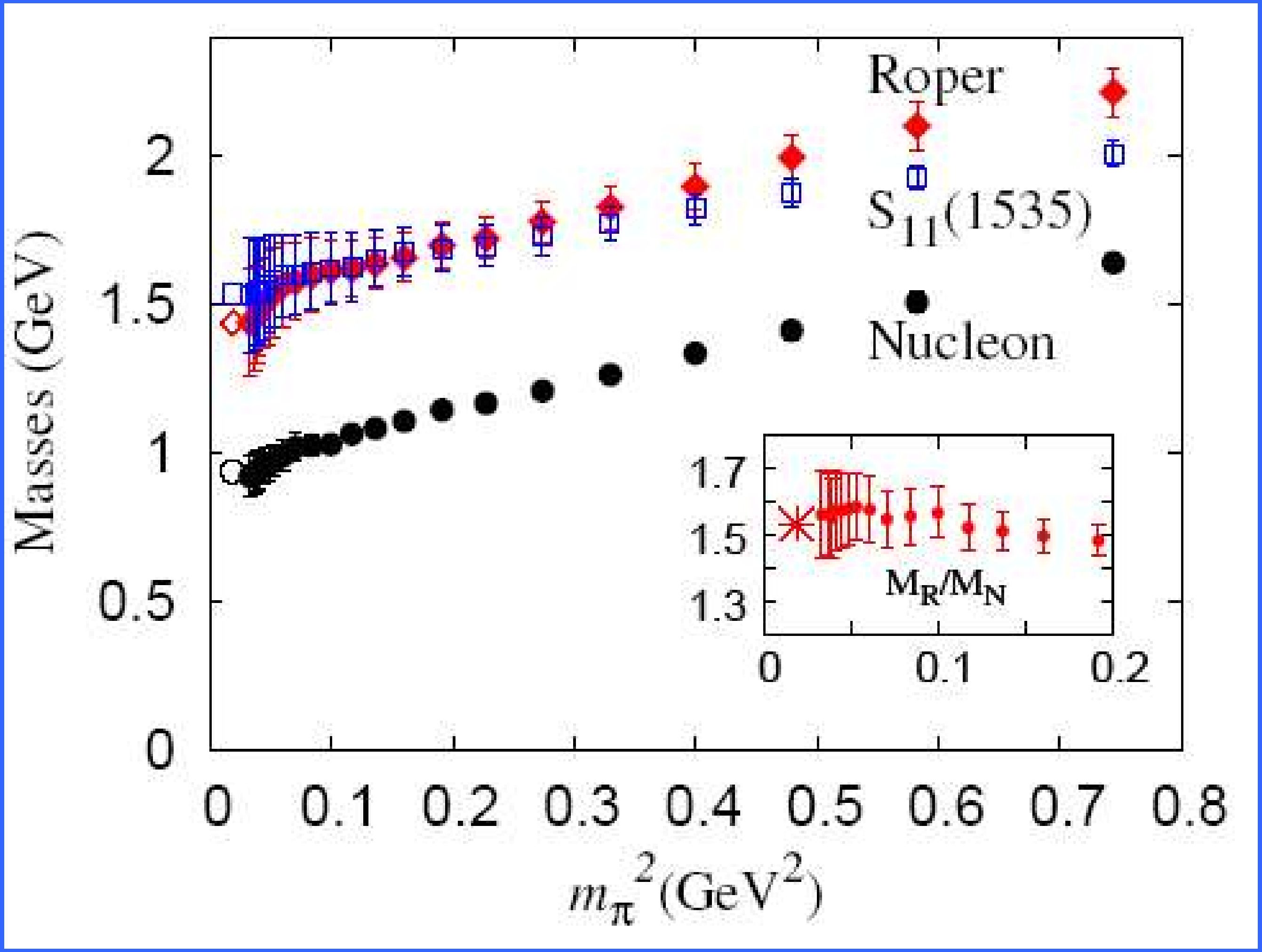
Zanotti et al., hep-lat/0304001

First Positive Parity Excited State?



Leinweber et al., hep-lat/0406032

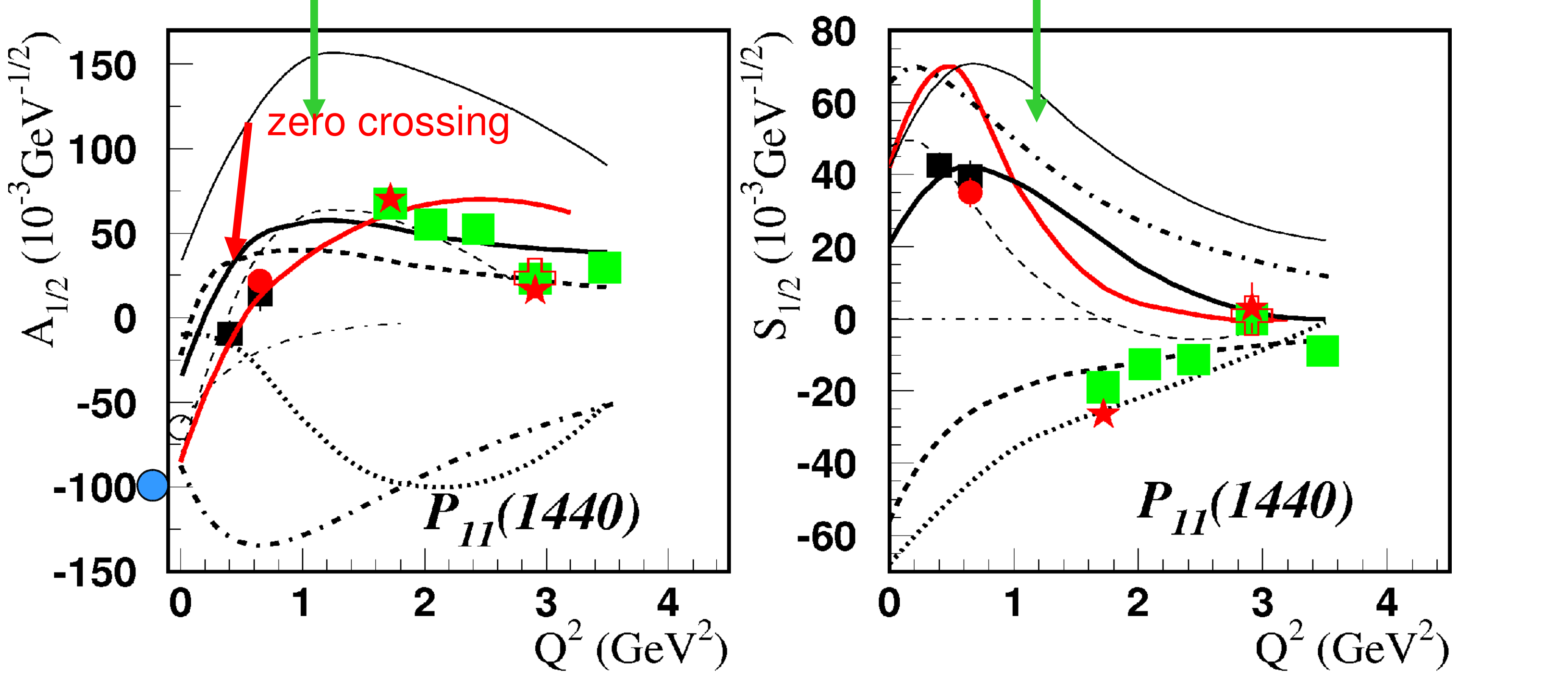
Roper Still a Mystery



Mathur et al., hep-lat/0306199

Transition form factor γp P_{11}(1440)

- Transition from meson-cloud behavior to quark core behavior ?



- UIM analysis of CLAS $p\pi^0$, $n\pi^+$, data
- Low Q^2 behavior consistent with meson-cloud model
- High Q^2 behavior consistent with small quark core
- Roper amplitudes not consistent with gluonic excitation??

Form Factors

Origin of Cloudy Bag Model was observation that (in 1979) there were two ways to generate the Δ

- Iterate crossed π N Born graphs (Chew-Low mechanism)
- Quark Model State which couples to π N

In general any resonance can be generated by multiple scattering with phenomenological interactions

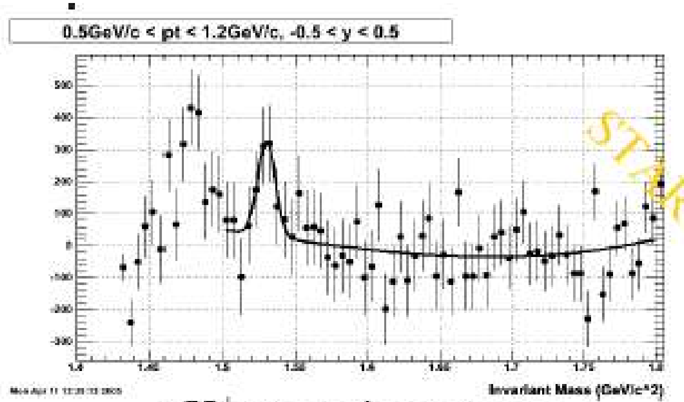
BUT by requiring that the pion-baryon form factors come from the same underlying quark model there is a unique answer – 3-quark state dominates

We now know that these form factors must be such that pion couplings are suppressed when $m_{\pi} > 500$ MeV

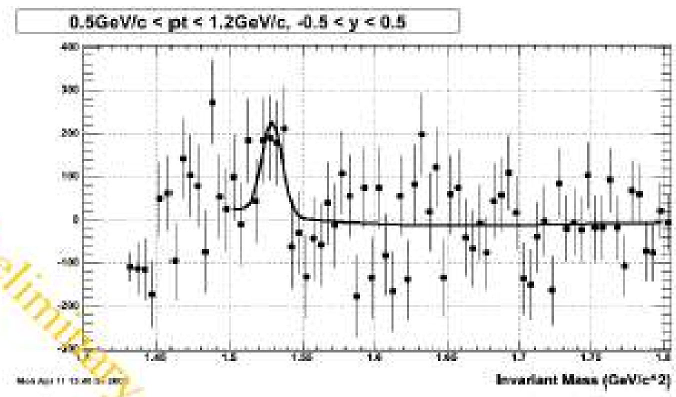
Pentaquark Publicity 2003

New Claims Since April 2005

- STAR Collaboration (Θ^{++})
  - Ma, APS Meeting, Tampa, FL April 2005.
  - Huang, International Conference on QCD and Hadronic Physics, Beijing, June 20, 2005.



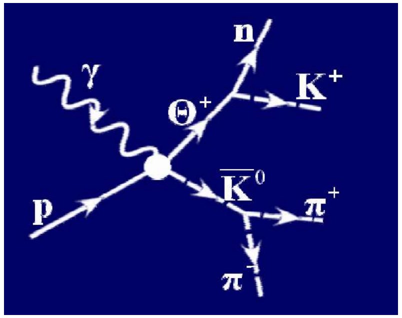
pK^+ Invariant mass



$\overline{p}K^-$ Invariant mass

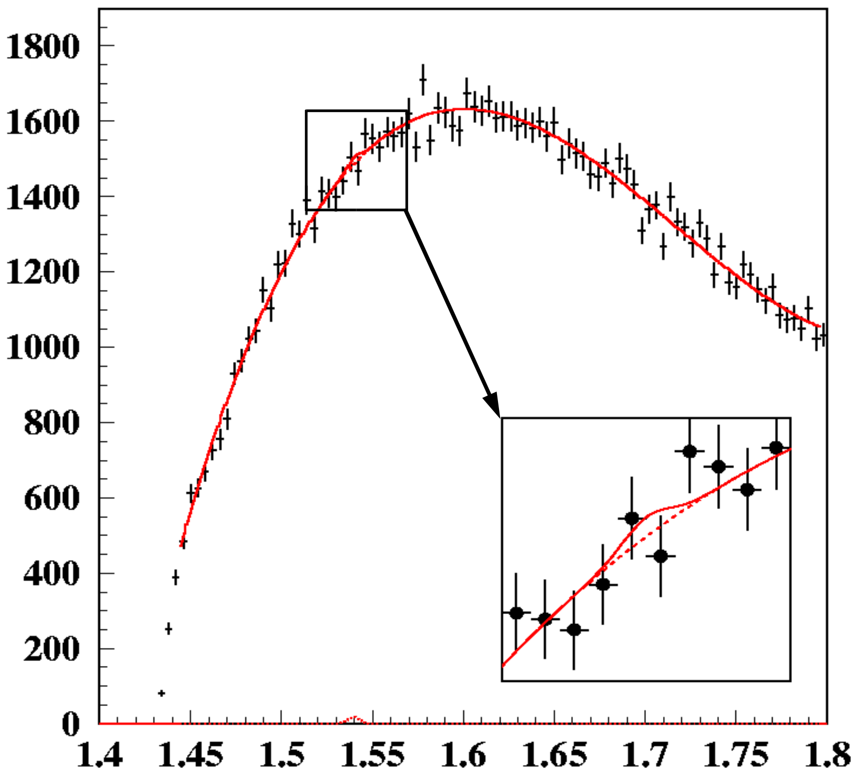
- SPring-8 $\gamma d \rightarrow \Theta^+ \Lambda(1520)$
  - Nakano, International Conference on QCD and Hadronic Physics, Beijing, June 20, 2005.

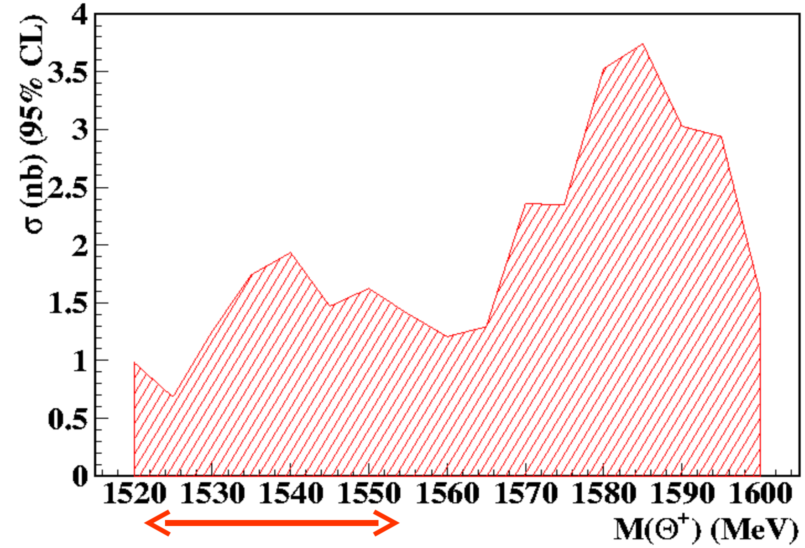
2005 JLab Search on p



$p \rightarrow K_S K^+ n$

► The new data show no signal





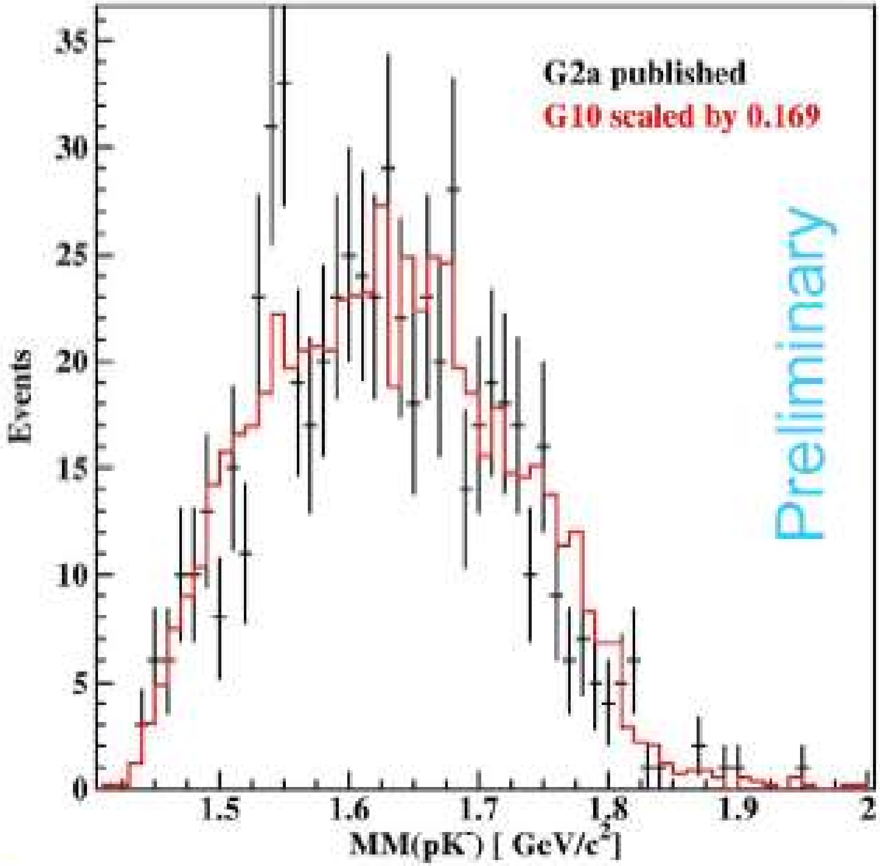
Upper limits (95% CL) :

~~$\sigma_{\gamma p \rightarrow \Theta^+ K^0}$ < 2 nb~~ @ 1520 - 1555 MeV

< 4 nb @ 1560 - 1600 MeV

g11: Tampa

High Statistics CLAS result - g10



- Two distributions statistically consistent with each other:
  - 26% c.l. for null hypothesis from the Kolmogorov test (two histograms are compatible).
  - Reduced χ^2**=1.15** for the fit in the mass range from 1.47 to 1.8 GeV/c^2
- G10 mass distribution can be used as a background for refitting the published spectrum.

Comparison of g11 with SAPHIR

Observed Yields

SAPHIR

$N(\Theta^+)/N(\Lambda^*) \sim 9\%$

CLAS

$N(\Theta^+)/N(\Lambda^*) < 0.5\%$ (95% CL)

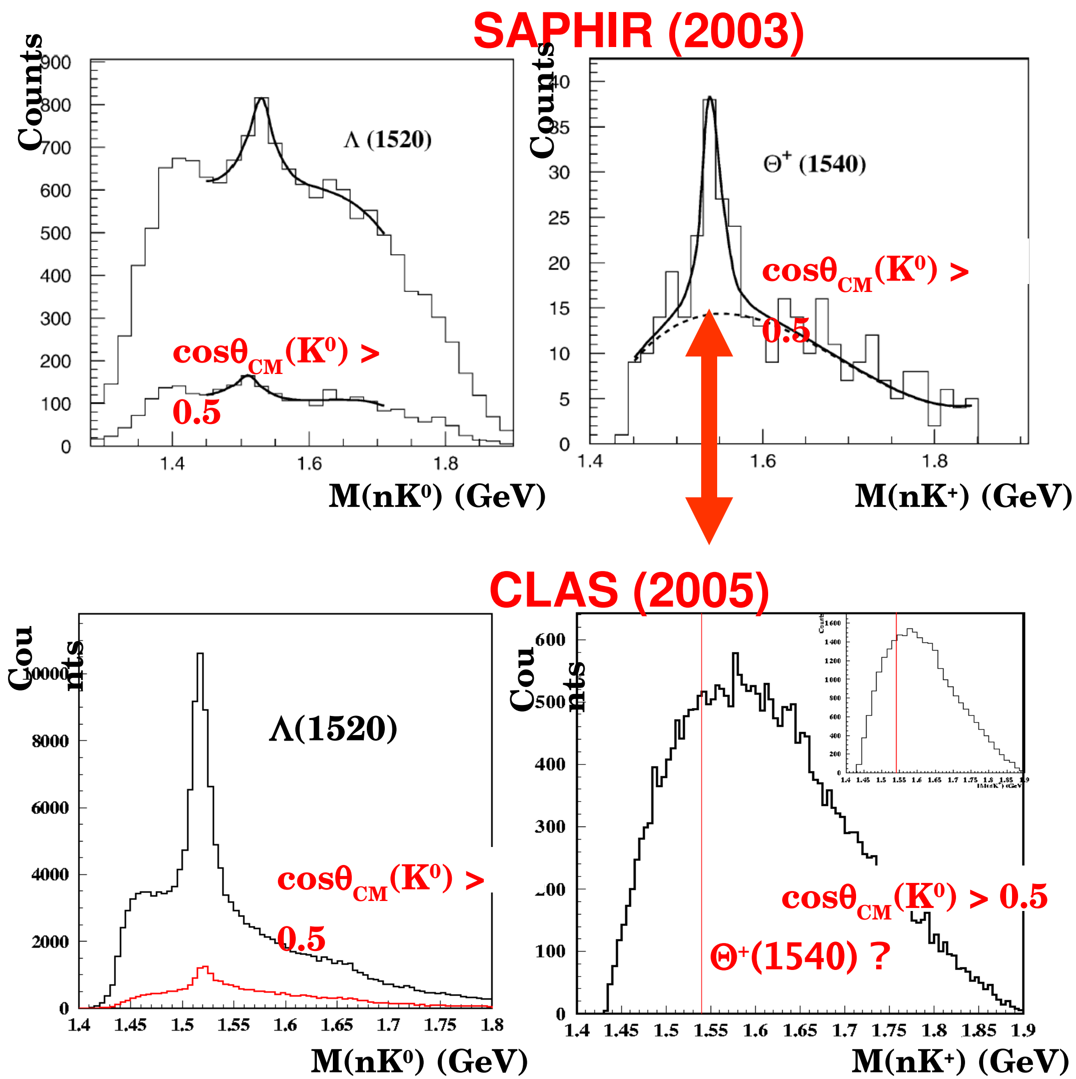
Cross Sections

SAPHIR

$\sigma_{\gamma p \to \Theta^+ K^0} \sim 200\ (50)$ nb

CLAS

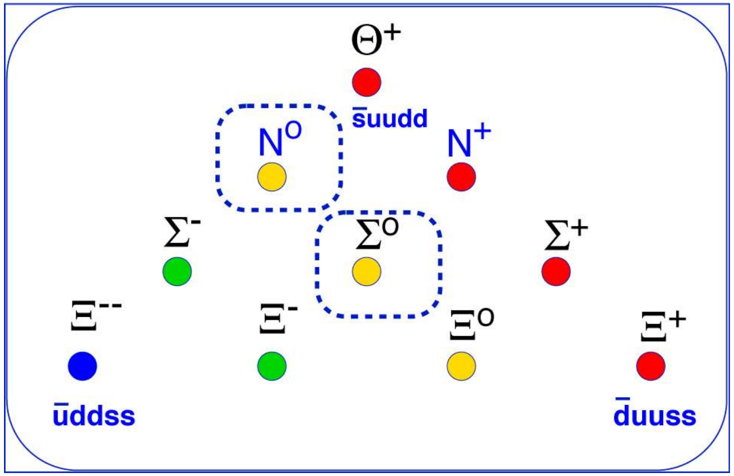
$\sigma_{\gamma p \to \Theta^+ K^0} < 2$ nb (95% CL)



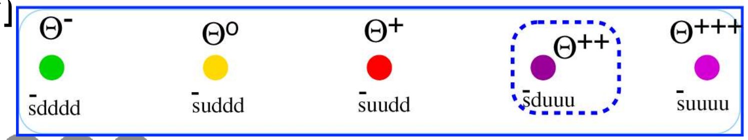
High Resolution Search for Q$^+$(1540) Partners in JLab/Hall A

Search for narrow resonances in the mass range 1.5-1.8 GeV/c^2, motivated by popular pentaquark models:

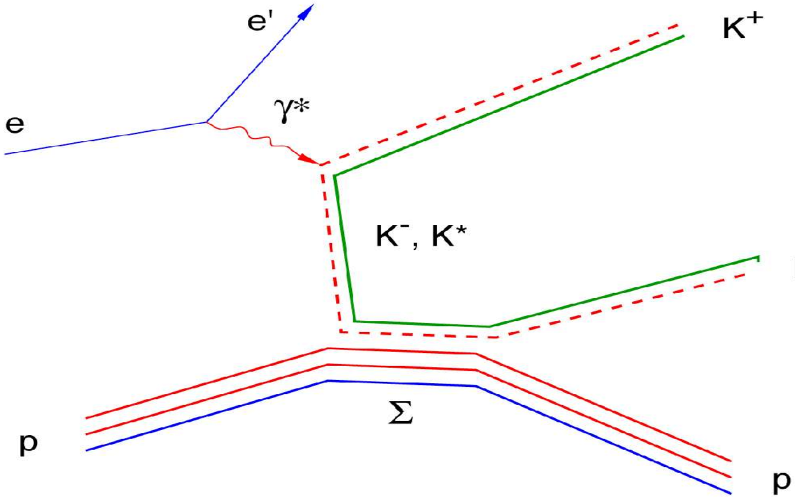
Anti-decuplet (Diakonov 1997)

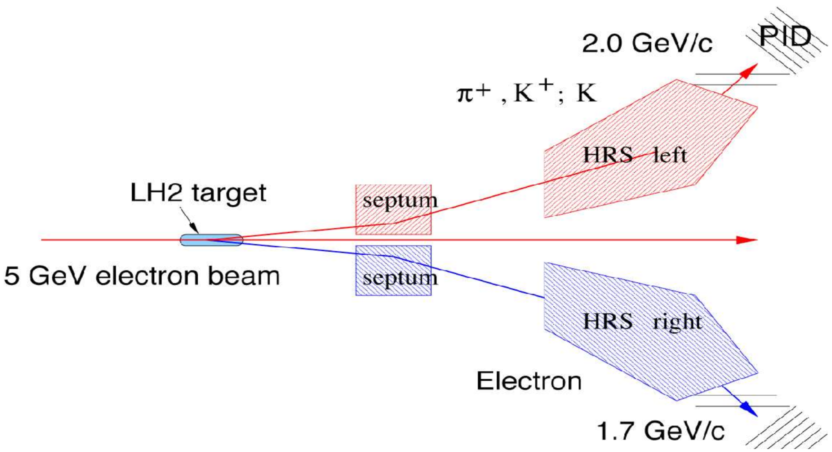


Isoten

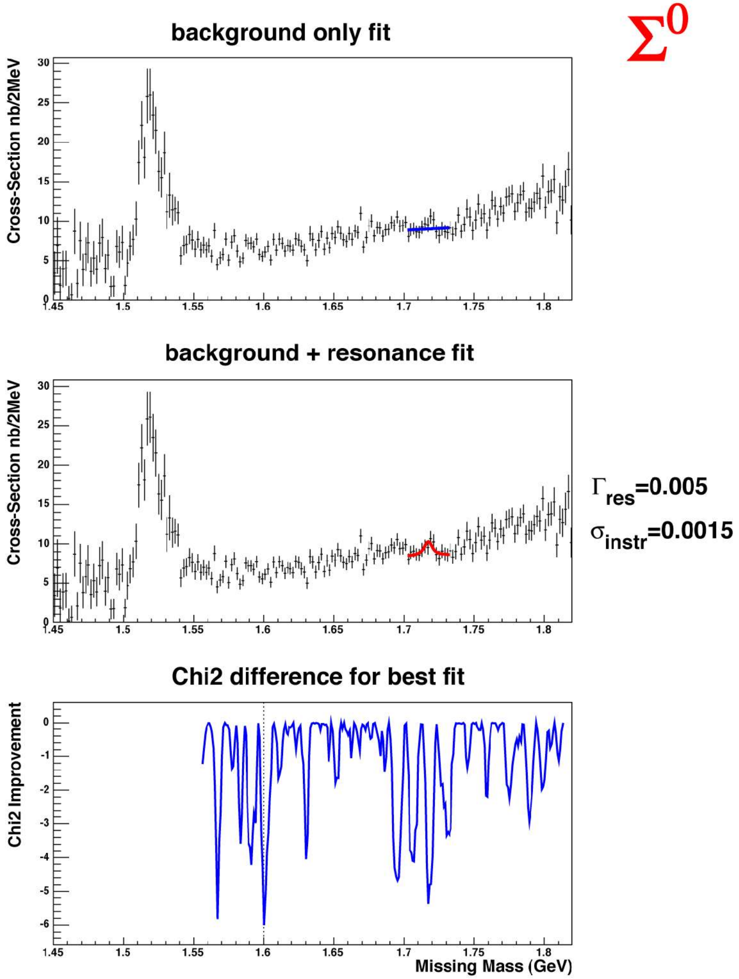


Missing mass technique

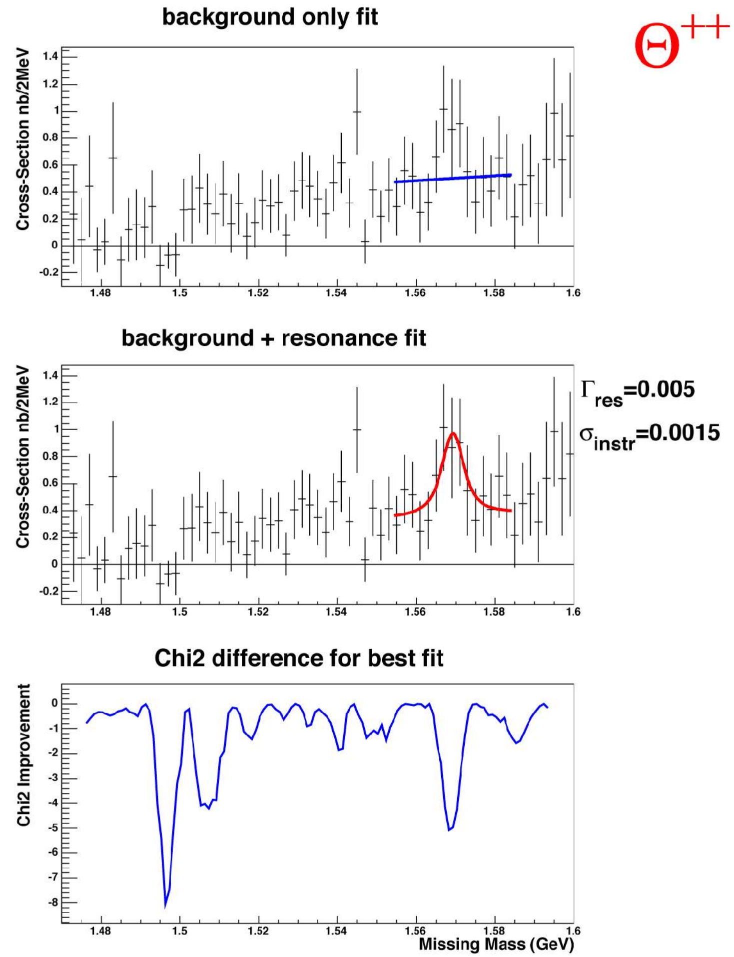




Σ^0 Search



Θ^{++} Search



Upper limit on production xsect

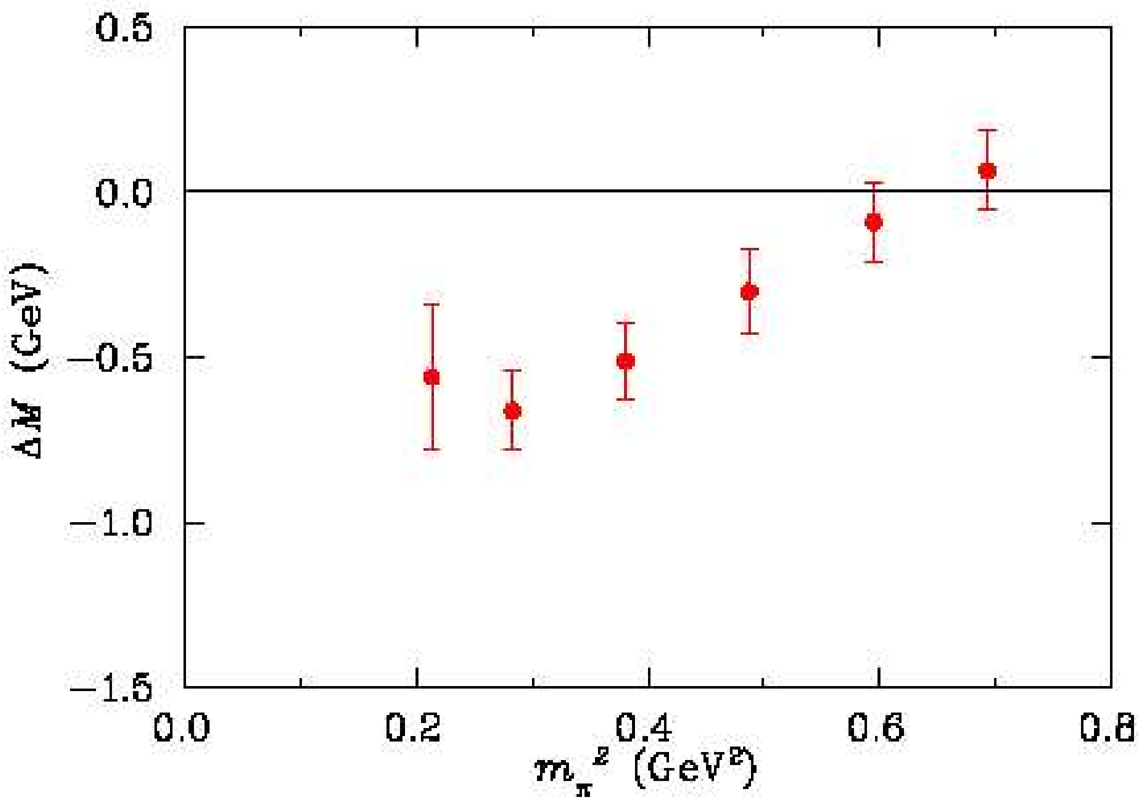
$$\sigma_{\gamma^* p \to K^+ \Sigma^0} < 8 \ nb$$

$$\sigma_{\gamma^* p \to K^- \Theta^{++}} < 3 \ nb$$

and just in case you think you understand…

Lattice QCD study* of spin-3/2 pentaquark show mass compared with p-wave NK system

Clear indication of attraction (and possibly interesting chiral behavior)



* hep-lat/0405015: Lasscock et al. [CSSM- Jlab Collaboration]

Excited-Baryon Analysis Center

A proposal for the establishment of an excited-baryon analysis center at JLab

HP 2009

- Role: **To develop theoretical tools (e.g. coupled channel; EFT) to analyze existing & future CLAS (and other) data**

- Scientific relevance:
  - i) **identify new baryon resonances**
  - ii) **measure couplings & transition form factors**
  - iii) **comparison with LQCD**
  - iv) **deepen understanding of how QCD is realized**

- Critical theoretical issues:
  - i) **background-resonance separation**
  - ii) **incorporation of multi-particle final states**
  - iii) **importance of unitarity, analyticity…**

Proposed Structure of EBAC

S&T Review 2003: "A critical need in the overall JLab program is to have a systematic effort dedicated to analysis of photo- and electro-production of baryons and mesons. The theory group, in concert with the needs of the experimental collaborations, has begun to formulate a plan to establish an N^* Analysis Center.

We applaud this long-needed initiative."

After 2004 S&T Review: proposal to DOE

- Senior theorist with a broad knowledge of hadronic and electromagnetic interactions, reaction theory, and the methods used in phenomenological analysis

- Mid- and junior-level staff positions and term/visiting positions for theorists and experimentalists to advance the program and to interface with relevant groups. Strong workshop/visitor program.

- Independent, expert Scientific Advisory Board