Science Vision: Present Status, Future Opportunities

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Chief Scientist

Science & Technology Review: Aug 30 – Sept 1, 2005

Outline

- Jefferson Lab in Context of Nuclear Physics World-wide

- 6 GeV: Exciting Science and a Natural Transition to the 12 GeV Upgrade

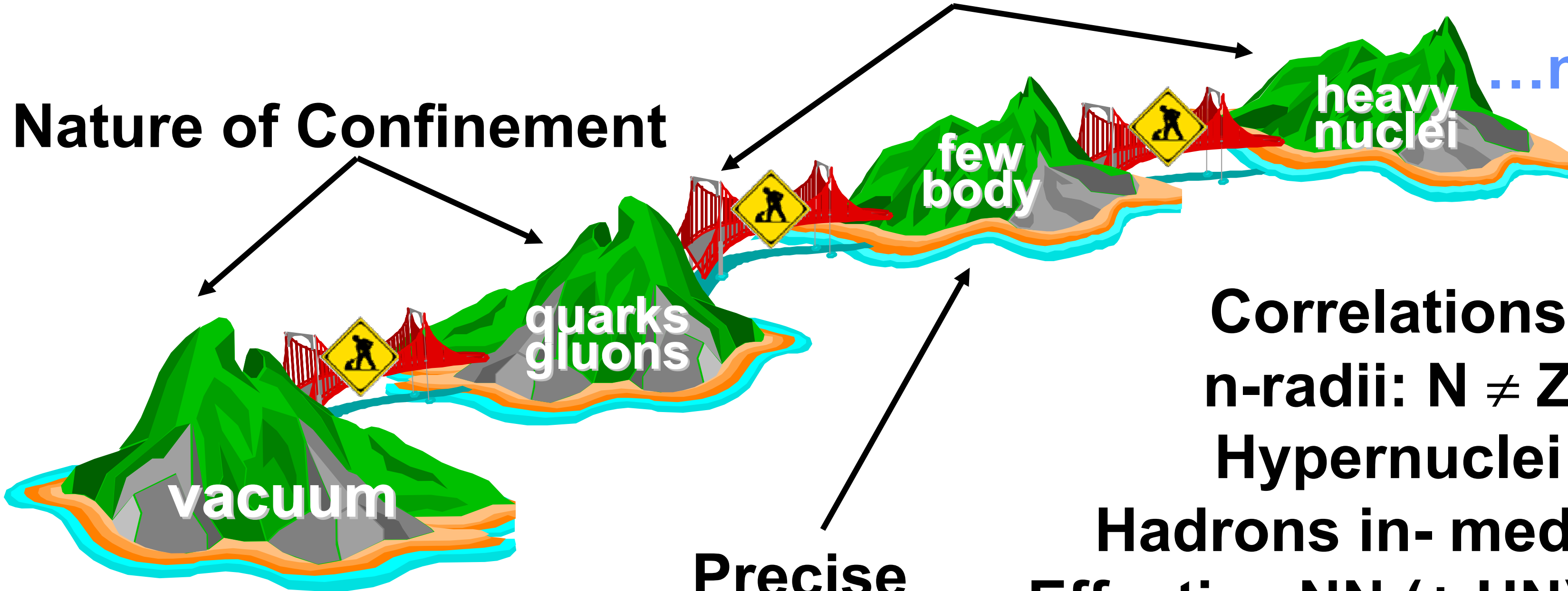
- Highlights of Current program
  - Pentaquarks?
  - SIDIS; duality
  - Form factors
  - Strangeness content of nucleon
  - Transition Form Factors; baryon spectroscopy
  - Λ Hypernuclei

- Synergy with theory
  - notably Lattice QCD

JLab Central to *all* of Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



…n-stars

Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

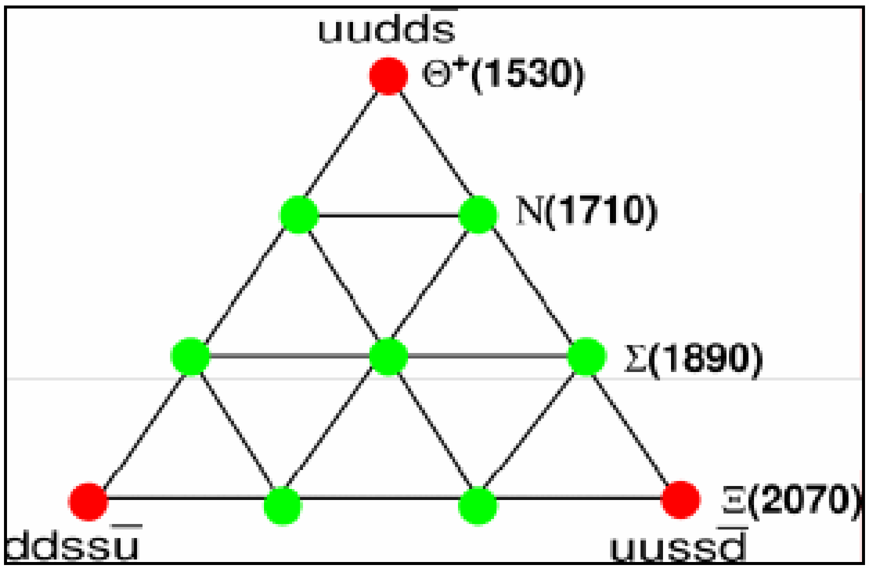
Precise
few-nucleon
calculations

Exotic mesons
and baryons

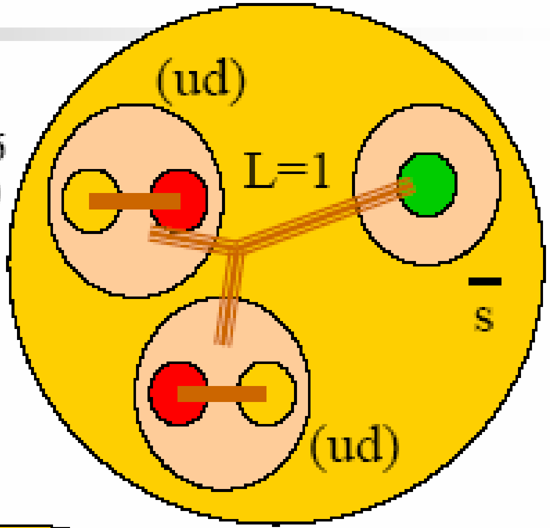
Pentaquark Structure

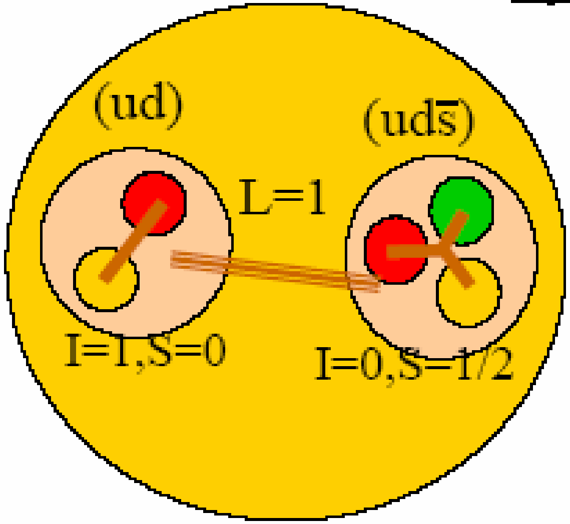
Pentaquarks:
rotational excitations of the soliton [rigid core surrounded by chiral (meson) fields]

Diakonov *et al.*, *Z. Phys* A **359**, 305 (1997).



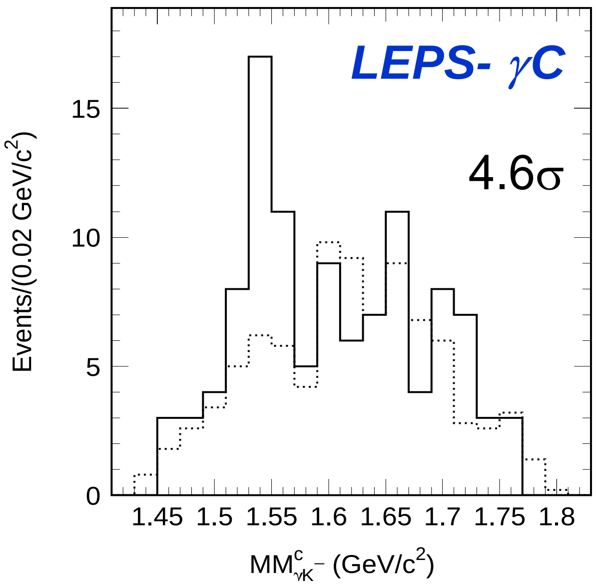
JW hep-ph/0307341
JM hep-ph/0308286
SZ hep-ph/0310270

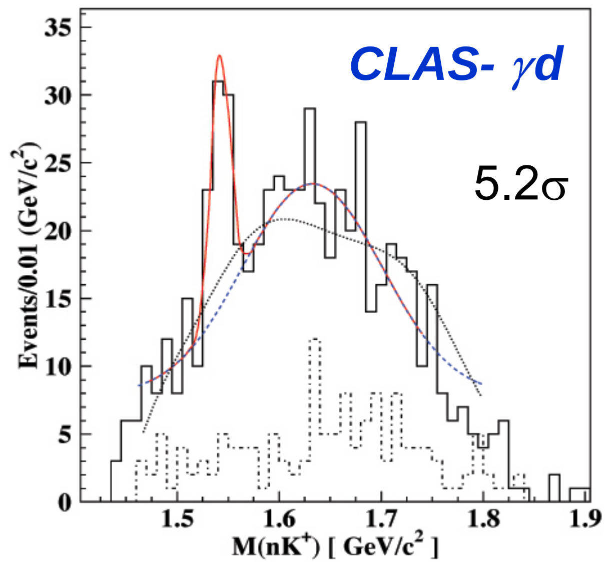




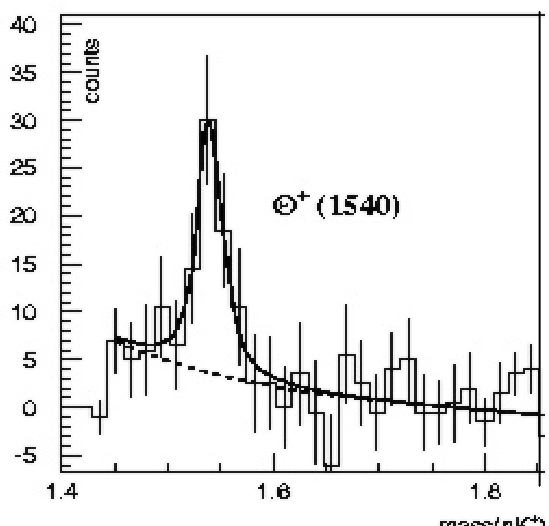
Karliner, Lipkin, hep-ph/0307243

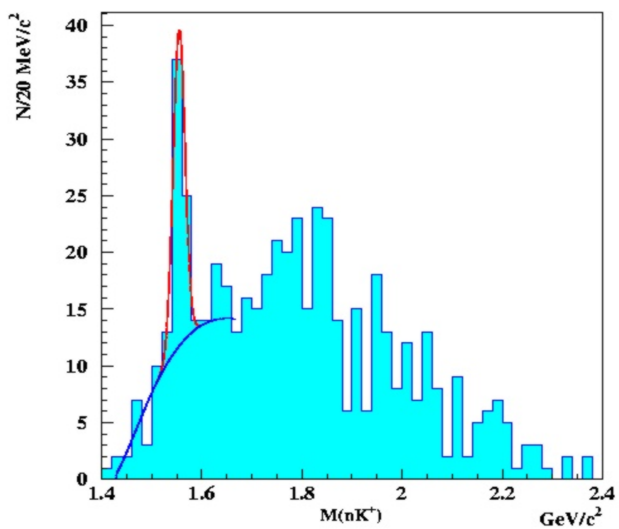
Positive Results for Θ^+ in "1st Round"





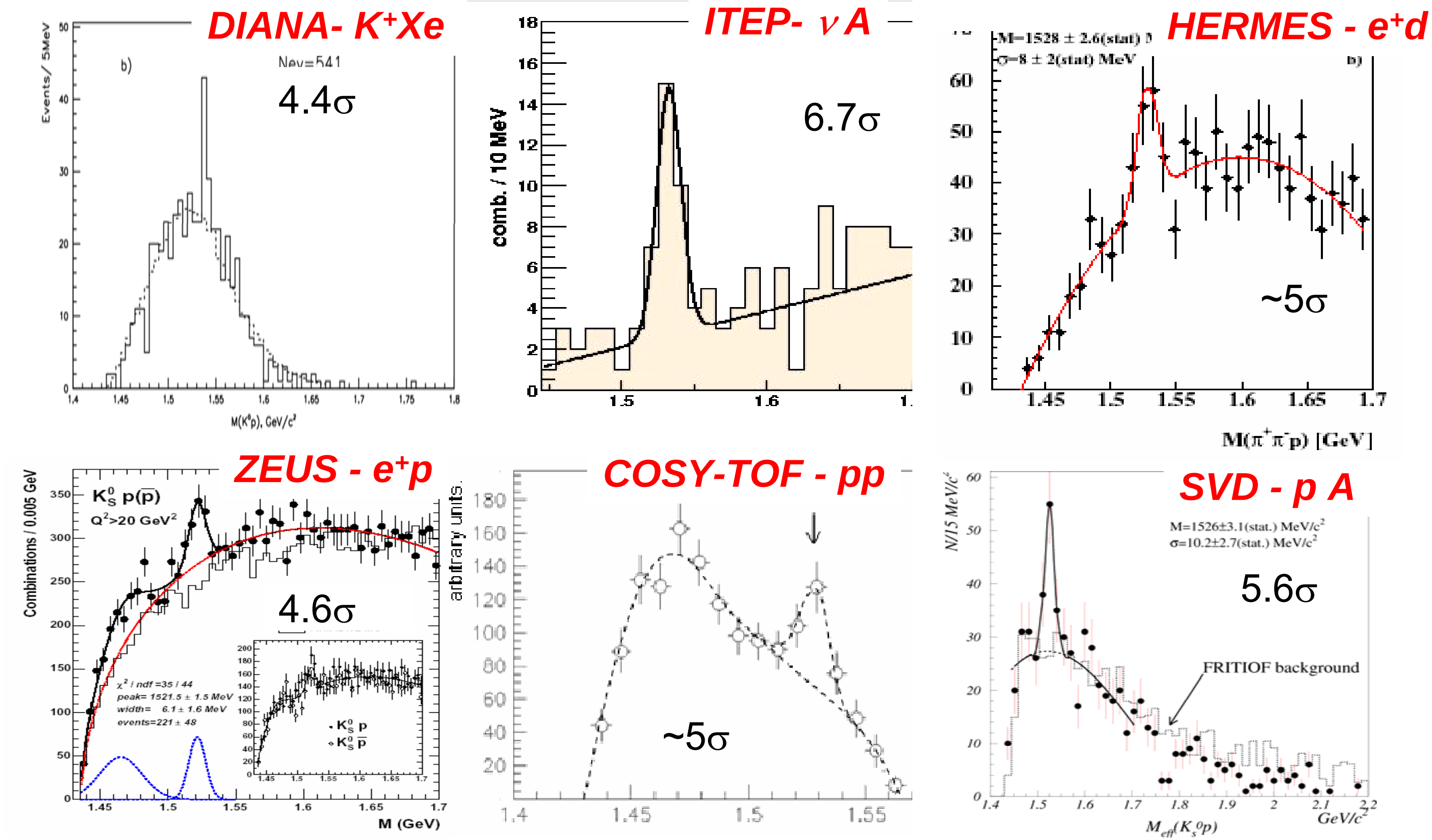
In K⁺ n mode





Further Evidence in "1st Round"

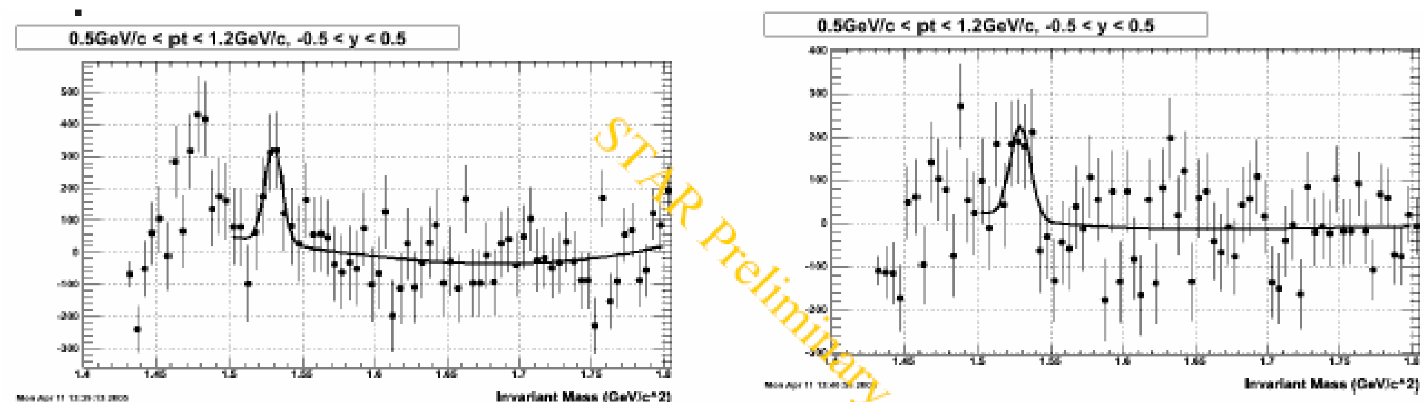
K^0p Evidence (published) from 6 experiments



Pentaquark Publicity 2003

New Claims Since April 2005

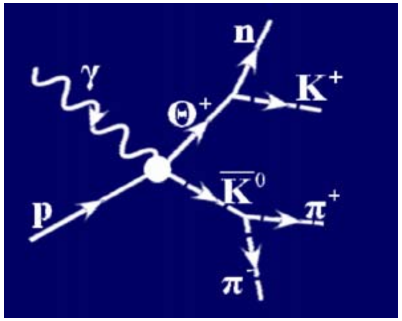
- STAR Collaboration (Θ^{++})
  - Ma, APS Meeting, Tampa, FL April 2005.
  - Huang, International Conference on QCD and Hadronic Physics, Beijing, June 20, 2005.



pK^+ Invariant mass | $\bar{p}K^-$ Invariant mass

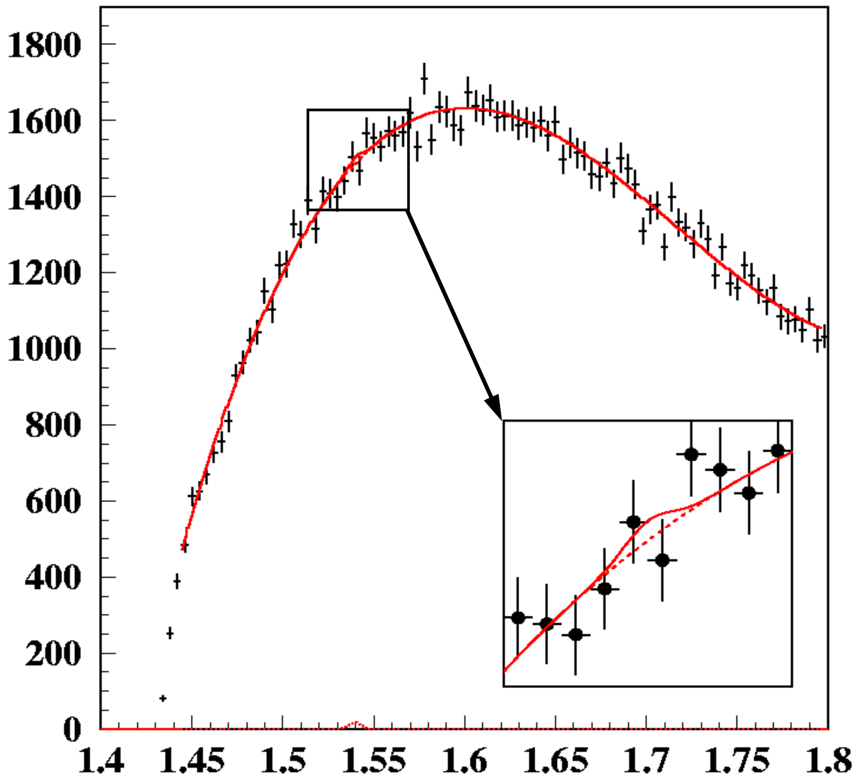
- SPring-8 $\gamma d \rightarrow \Theta^+ \Lambda(1520)$
  - Nakano, International Conference on QCD and Hadronic Physics, Beijing, June 20, 2005.

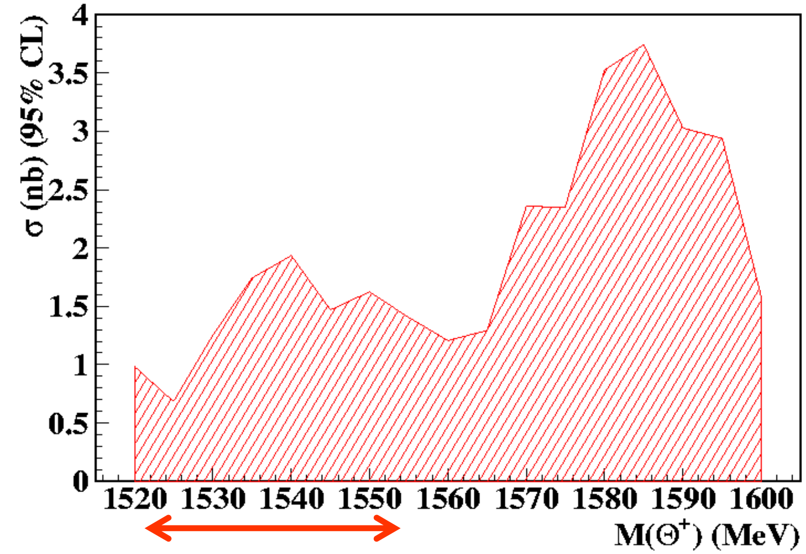
2005 JLab Search on p



$\gamma p \rightarrow K_S K^+ n$

- The new data show no signal





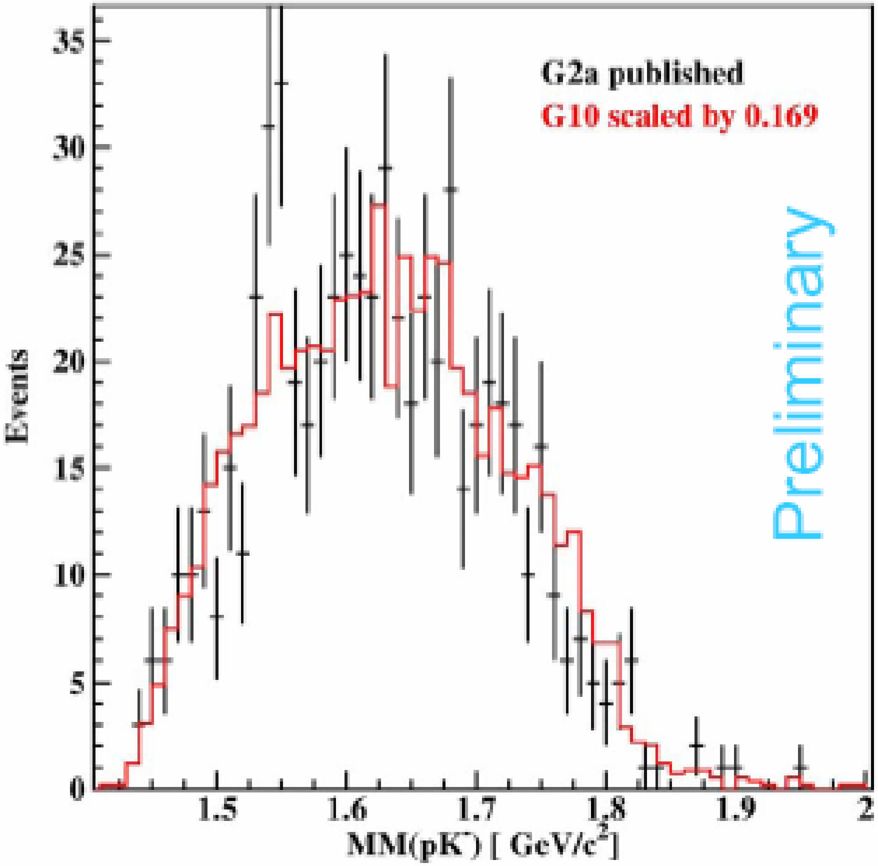
Upper limits (95% CL) :

$\sigma_{\gamma p \rightarrow \Theta^+ K^0}$ < 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)

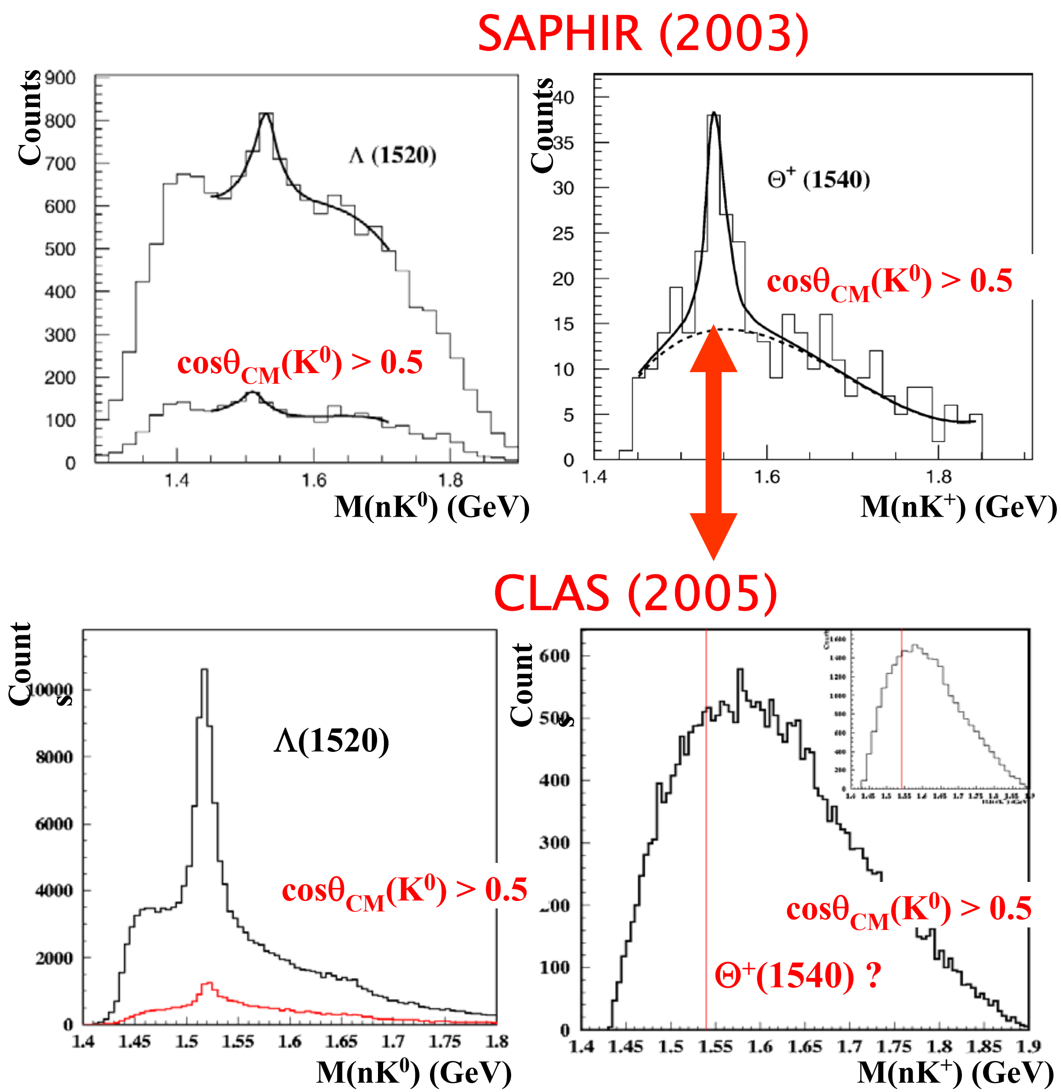
Cross Sections

SAPHIR

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

CLAS

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

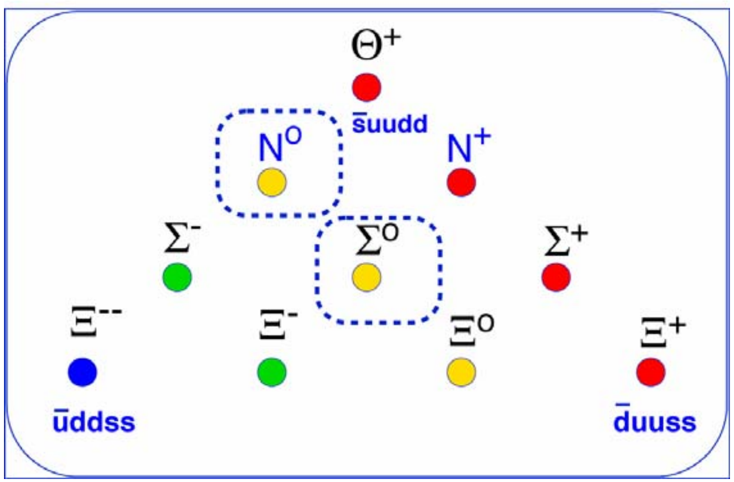


Pentaquark Publicity 2005

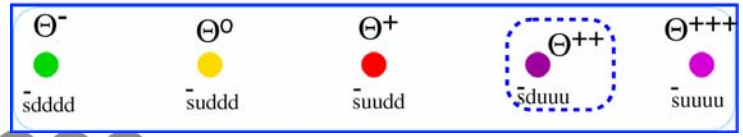
High Resolution Search for Q^+(1540) Partners in JLab/Hall A

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

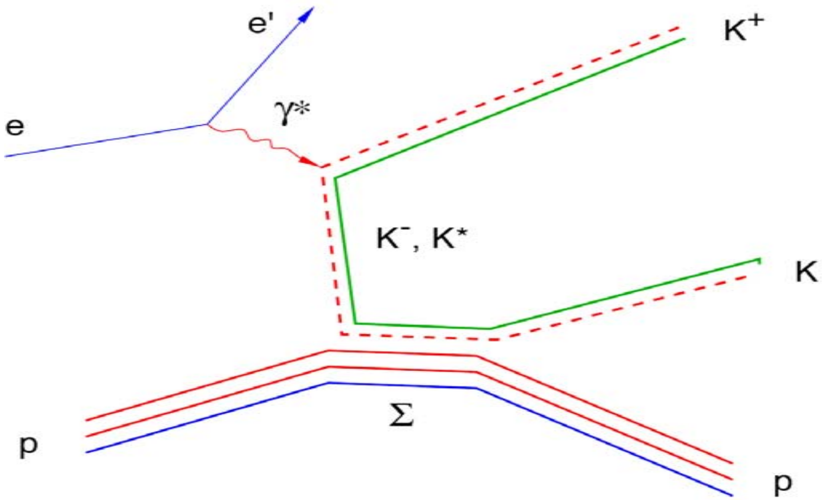
Anti-decuplet (Diakonov 1997)

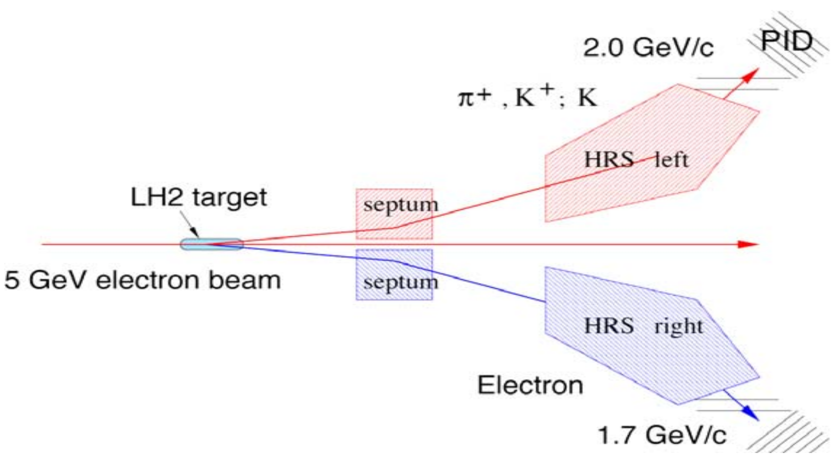


Isotensor multiplet (Capstick 2003)

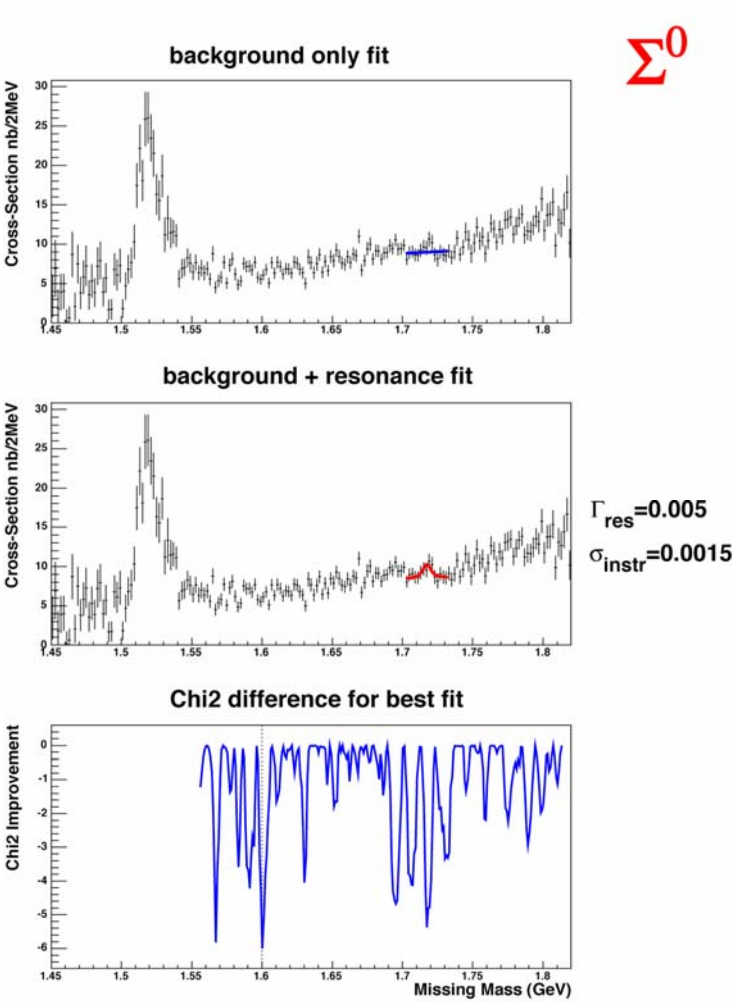


Missing mass technique

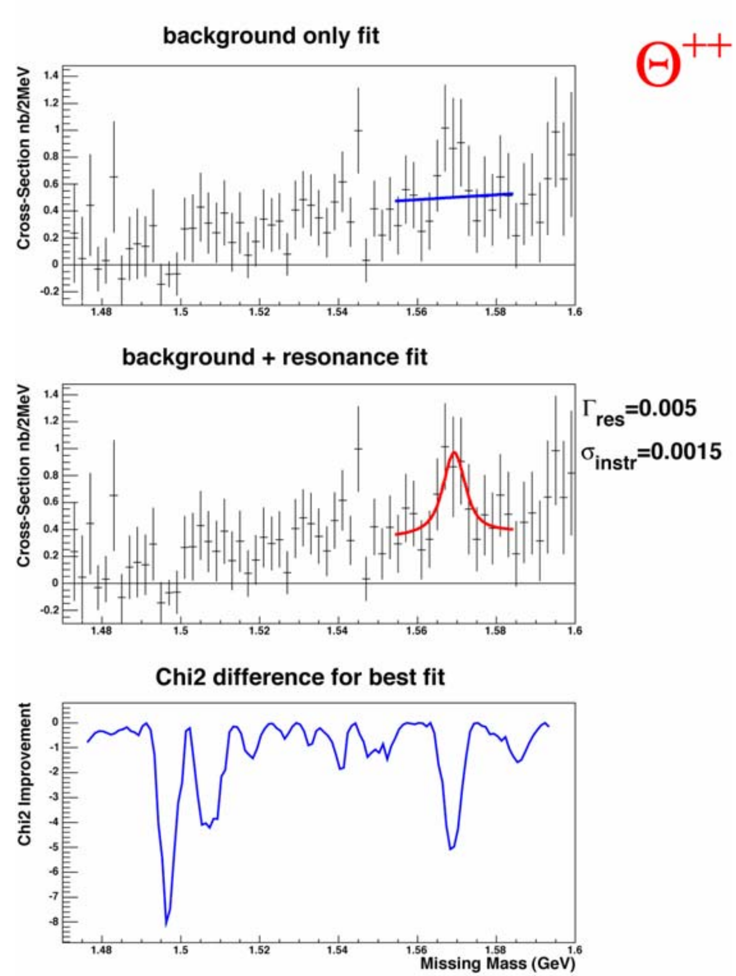




Σ^0 Search



Θ^{++} Search



Upper limit on production xsect

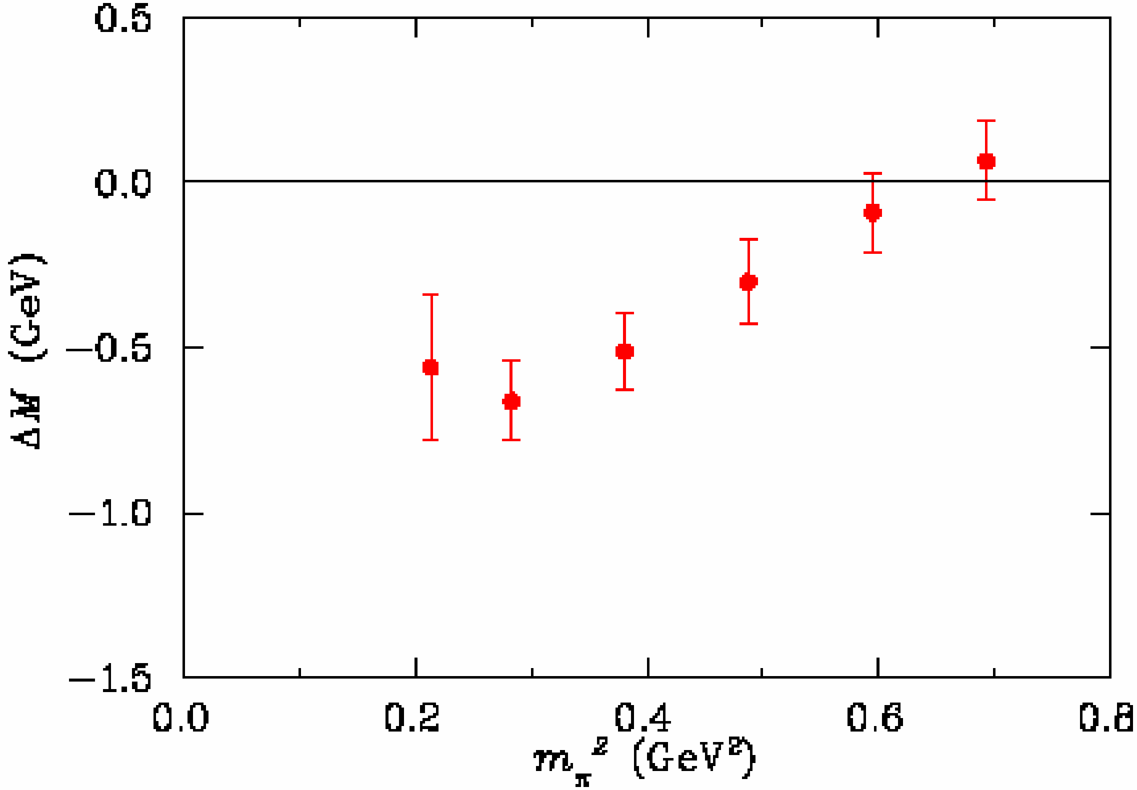
$$\sigma_{\gamma^* p \to K^+ \Sigma^0} < 8\ \text{nb}$$

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

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)



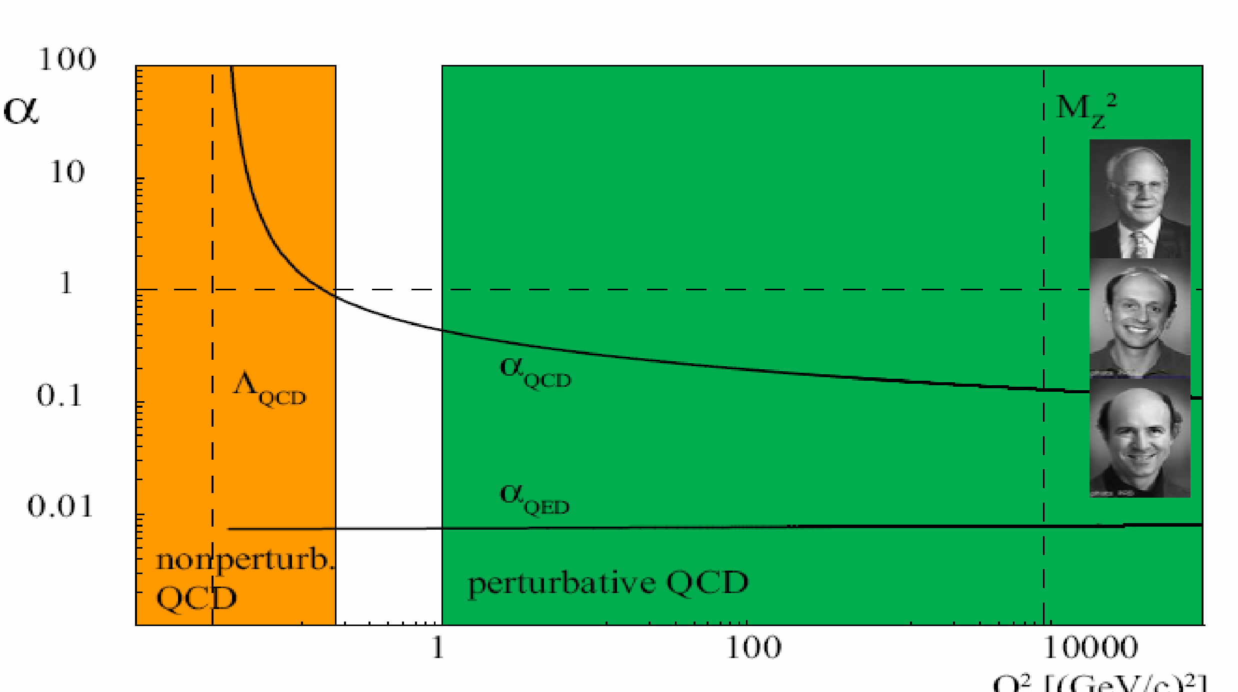
* hep-lat/0405015: Lasscock et al. [CSSM- Jlab Collaboration]

Pentaquark Summary

- Existence or otherwise is a CRUCIAL question in strong interaction physics

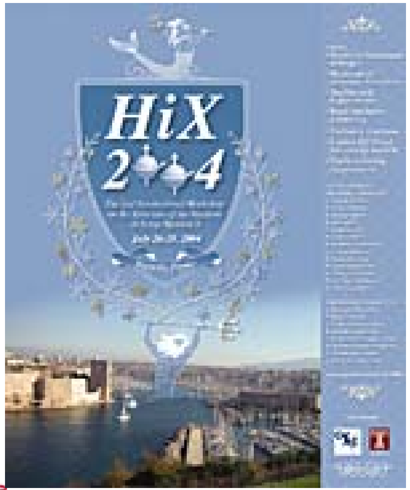
- Wilczek, Jaffe: That we cannot say whether such such exotica exist or not shows HOW LITTLE WE UNDERSTAND NON-PERTURBATIVE QCD

- Jefferson Lab is the ideal facility to definitively answer this question!



Marciana Marina, Isola d'Elba, Italy.

Electron-Nucleus Scattering VIII Workshop, June 21-25, 2004



6 GeV Highlights Leading to the 12 GeV Upgrade

- **Parton Distribution Functions**
- **Form Factors**
- **Generalized Parton Distributions**
- **Exotic Meson Spectroscopy:**
  Confinement and the QCD vacuum
- **Nuclei at the level of quarks and gluons**
- **Tests of Physics Beyond the Standard Model**

Revolutionize Our Knowledge of Spin and Flavor Dependence of Valence PDFs

- **In over 35 years of study of DIS no-one has had the facilities to map out the crucial valence region**

- **Region is fundamental to our understanding of hadron structure: i.e. how nonperturbative QCD works!**

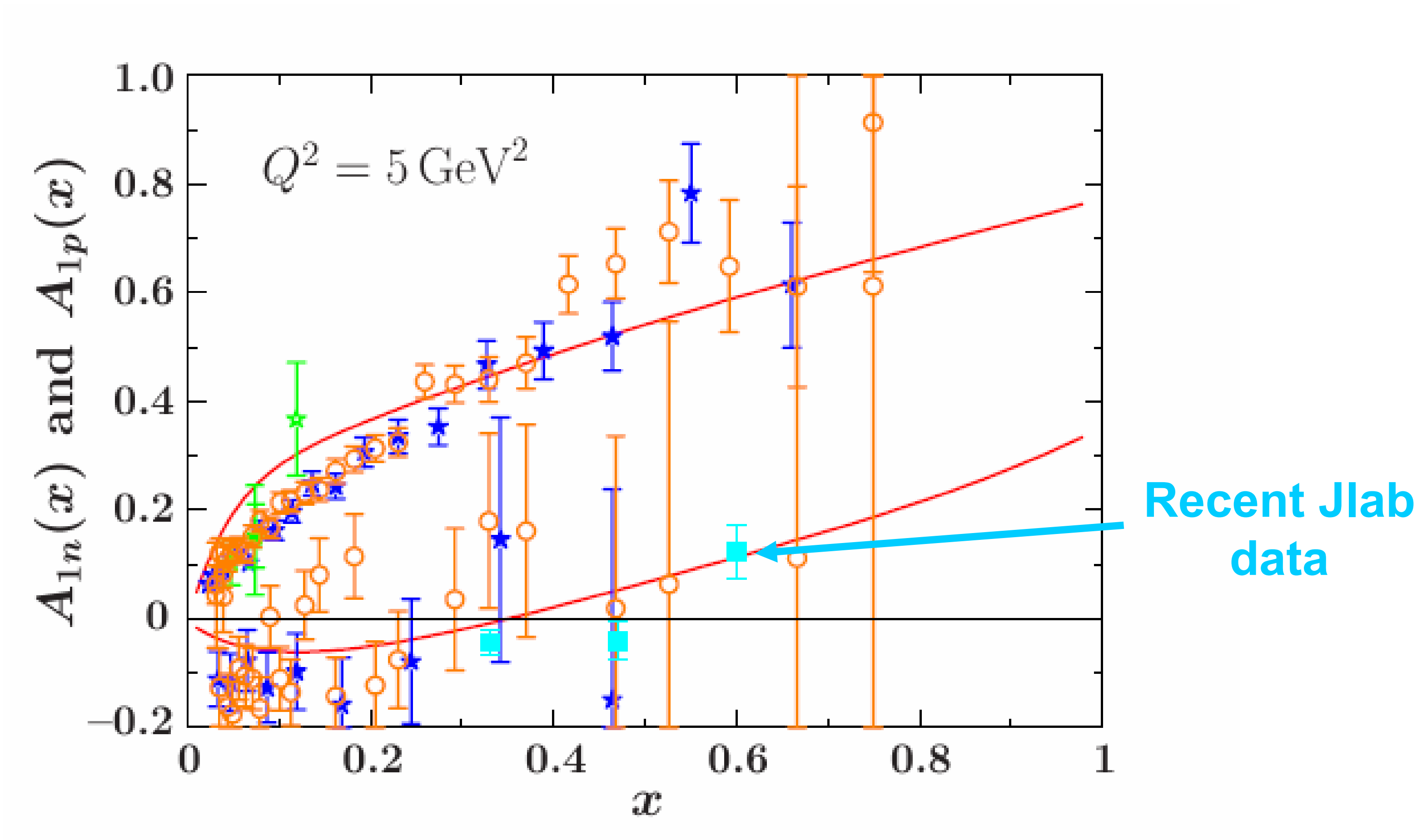
Role of di-quark correlations?

Role of hard scattering: pQCD / LCQCD guidance?

Breaking of SU(6) symmetry?

Moments of PDFs (and GPDs) from Lattice QCD….

Proton and Neutron Asymmetry

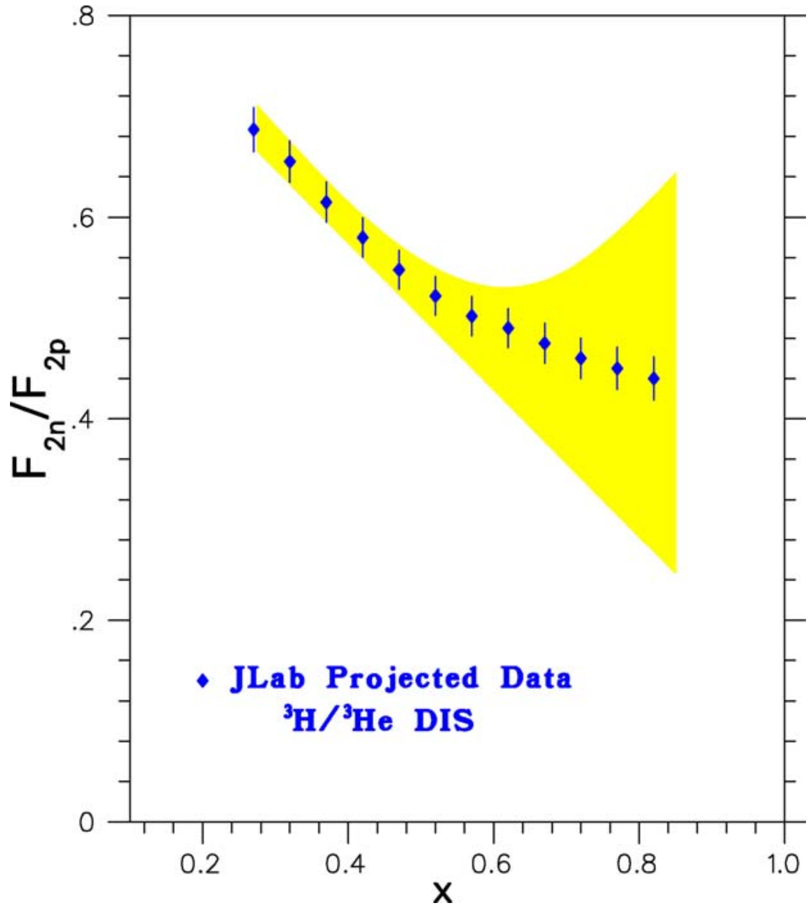


c.f. covariant NJL model, with confinement

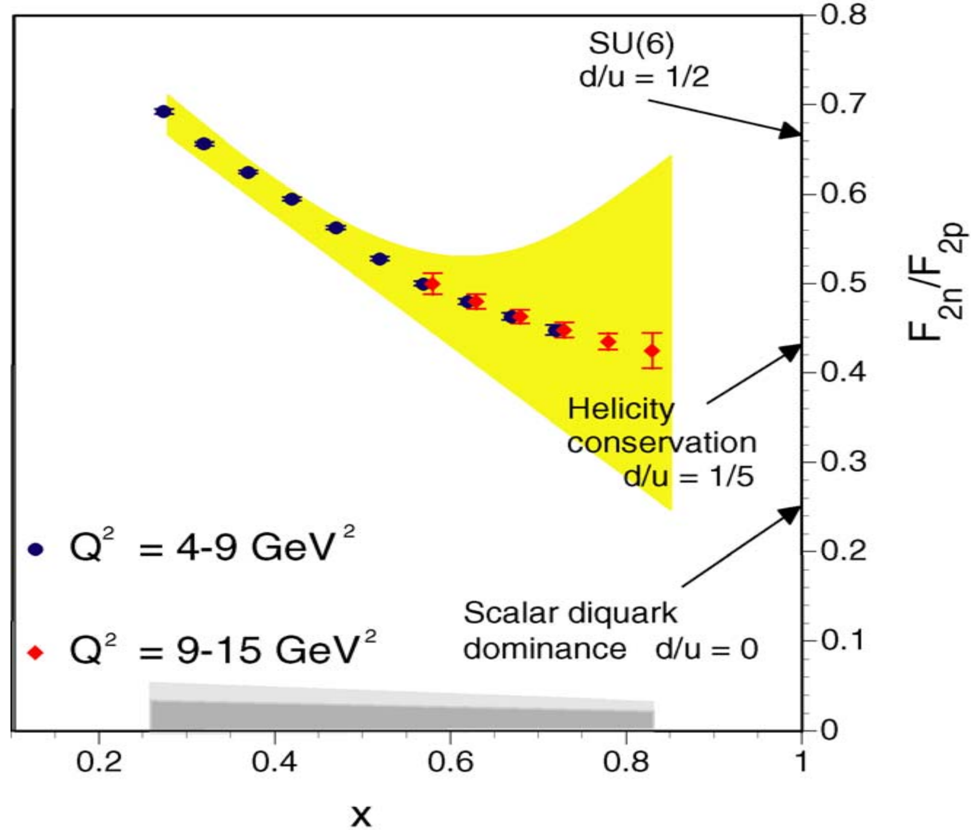
Cloet, Bentz, AWT, (Phys. Lett. B621 (2005) 246)

12 GeV : Unambiguous Flavor Structure x! 1

Hall C 11 GeV with HMS

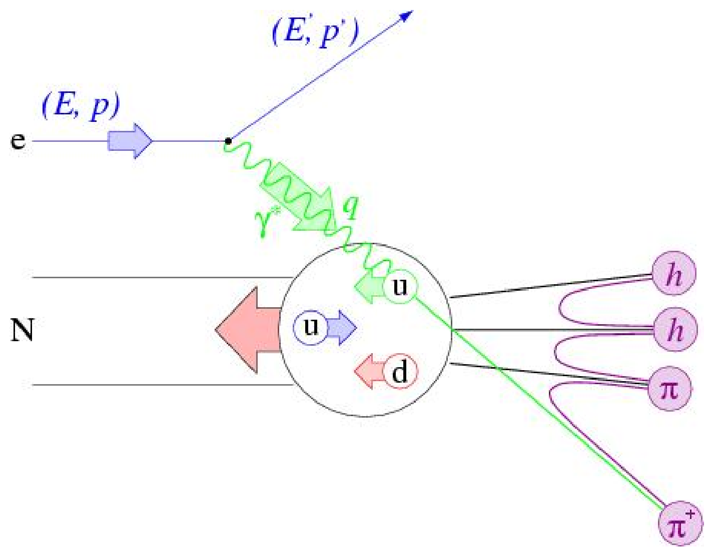


HallB 11 GeV with CLAS12



Initial investigation with BONUS early 06

Flavor Decomposition: semi-inclusive DIS



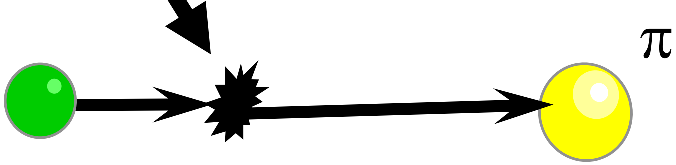
DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks

$$\sum e_q^2 (q + \bar{q})$$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

$$\sum e_q^2 \, q(x) \, D_{q \to M}(z)$$



(e,e') $W^2 = M^2 + Q^2 (1/x - 1)$

For M_m small, $\vec{p}_m$ collinear with $\vec{\gamma}$, and $Q^2/\nu^2 \ll 1$

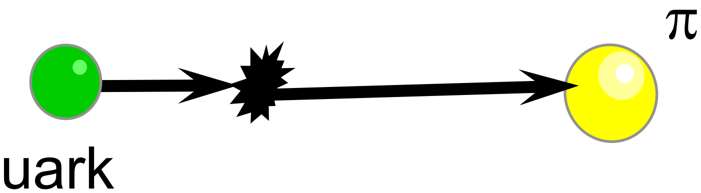
(e,e'm) $W'^2 = M^2 + Q^2 (1/x - 1)(1 - z)$

$z = E_m/\nu$

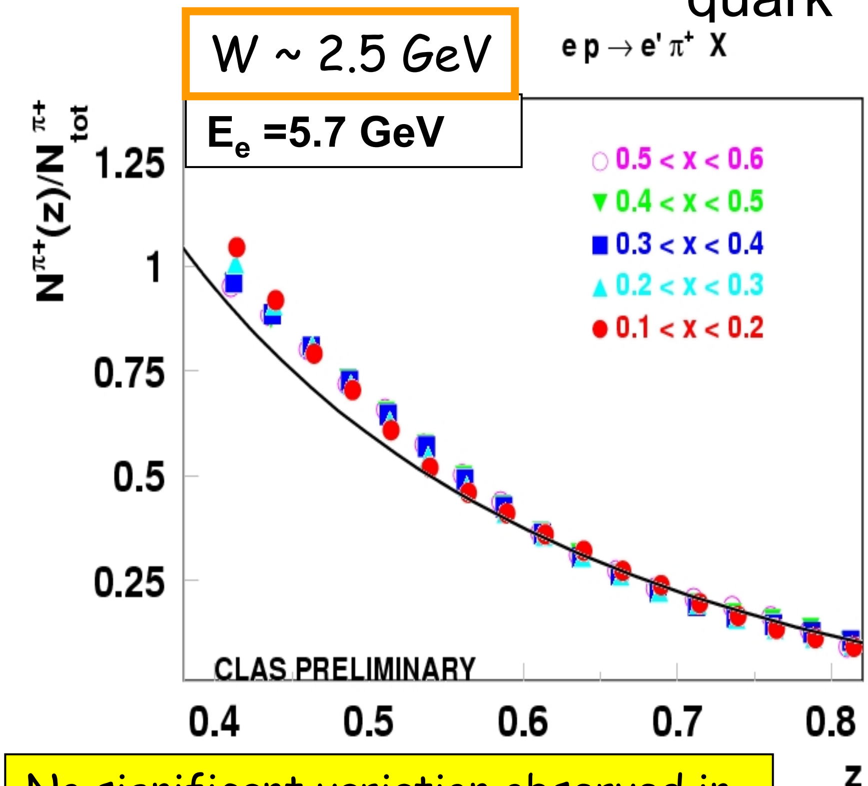
Low-Energy Factorization?

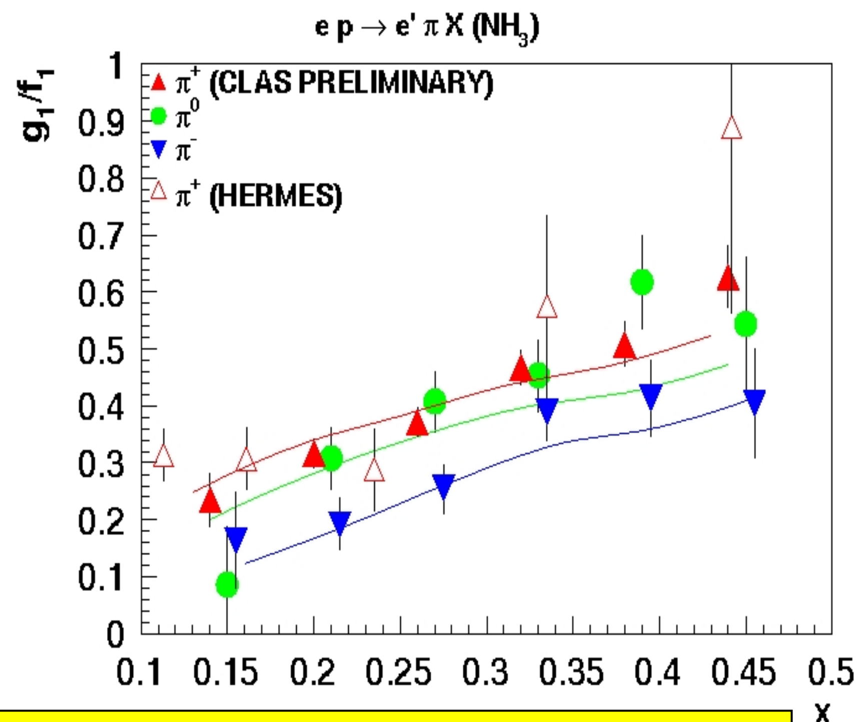
CLAS Collaboration,
H. Avakian et al.

$$\sum_q e_q^2 q(x)\, D_{q\to M}(z)$$



Collinear Fragmentation



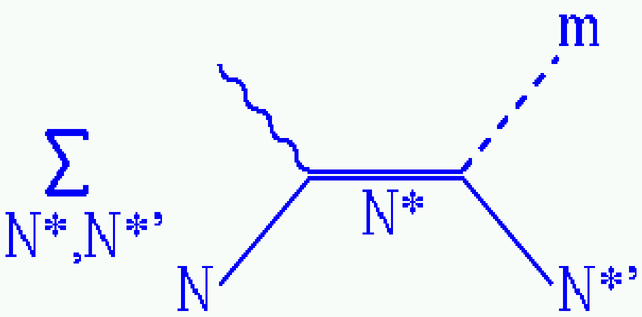


No significant variation observed in z distributions of π^+ for different **x** ranges ($0.4 < z < 0.7$, $M_X > 1.5$ GeV)

x dependence of CLAS A_1^p (A_2=0) consistent with HERMES data (at x3 higher Q^2) and with PEPSI (LUND)MC.

Duality in Meson Electroproduction

hadronic description | quark-gluon description



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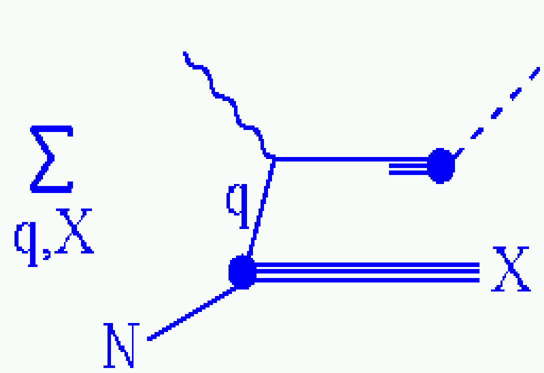


$$\sum_{N'^*} \left| \sum_{N^*} F_{\gamma^* N \to N^*}(Q^2, W^2)\, \mathcal{D}_{N^* \to N'^* M}(W^2, W'^2) \right|^2 \quad \sum_q e_q^2\, q(x)\, D_{q \to M}(z)$$

Transition Form Factor | Decay Amplitude | Fragmentation Function

Requires non-trivial cancellations of decay angular distributions

If duality is not observed, factorization is questionable

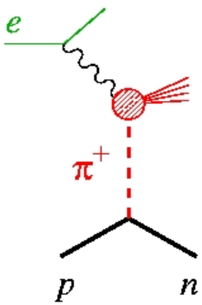
Duality and factorization possible for $Q^2, W^2 \leq 3$ GeV^2 (Close and Isgur, Phys. Lett. B509, 81 (2001); Close and Melnitchouk, Phys.Rev.C68:035210,2003)

Flavor asymmetry of proton sea: Quarks or mesons?

HP 2013

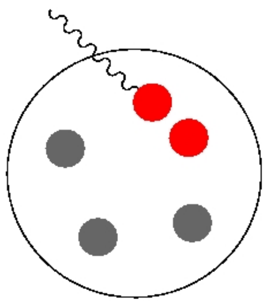
...New: Polarization!

Full list of OMB Milestones in Larry Cardman's talk



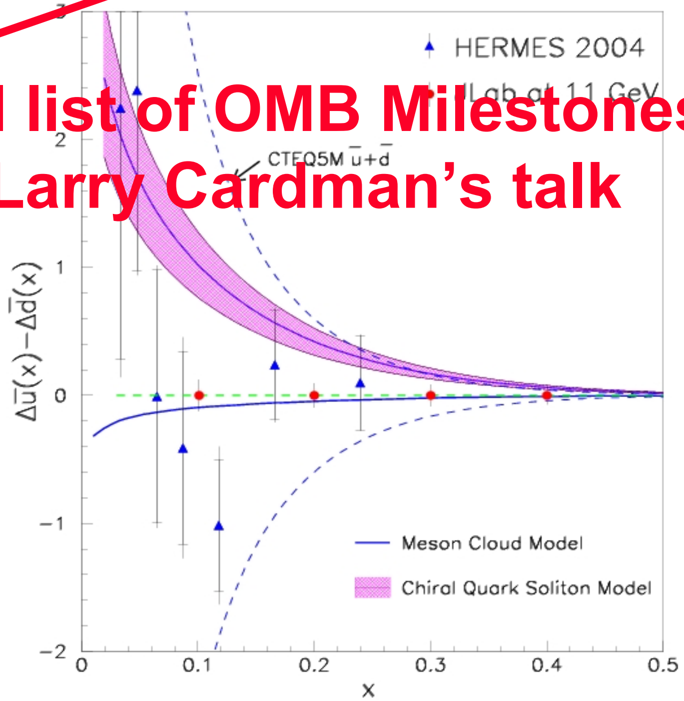
pion cloud

$$\Delta\bar{u} - \Delta\bar{d} = 0$$



$q\bar{q}$ pair
(Pauli blocking)

$$\Delta\bar{u} - \Delta\bar{d} > 0$$



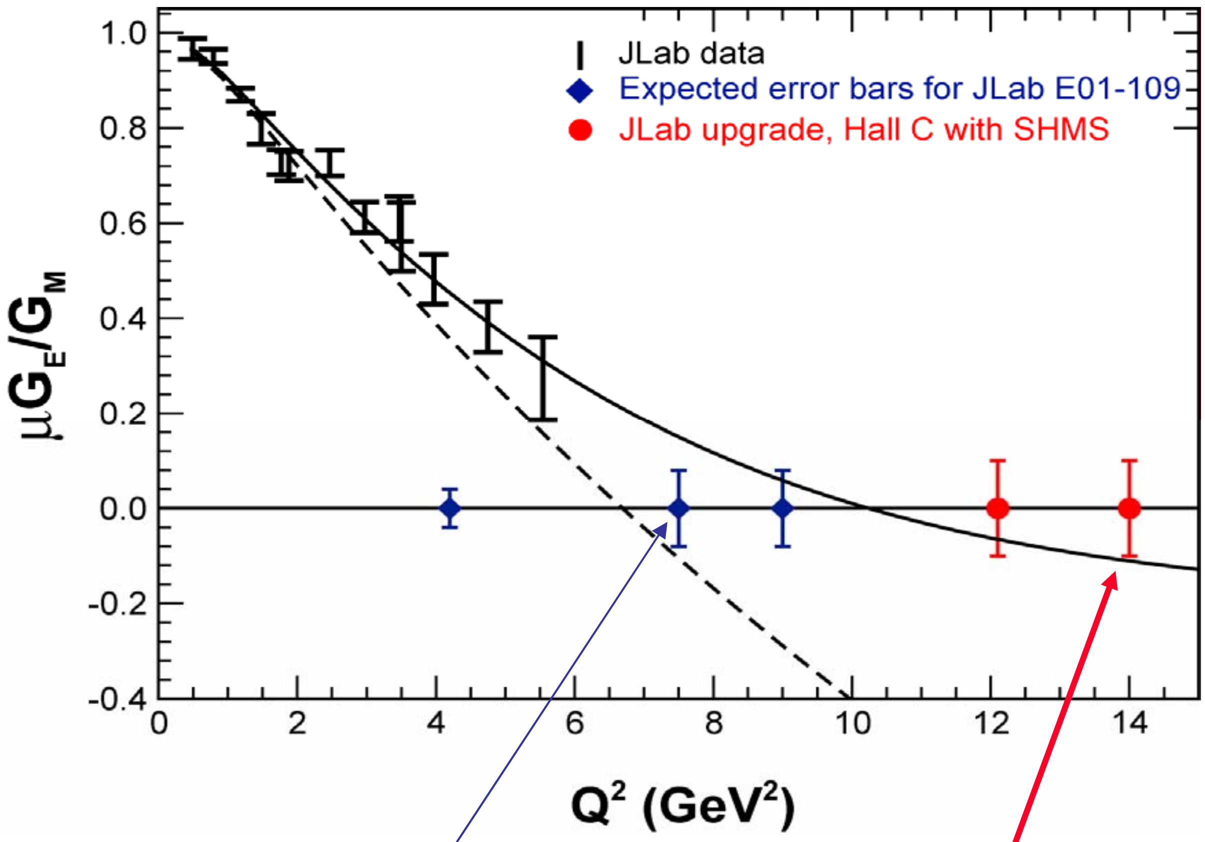
...Can be answered by initial SIDIS measurements in 2009 and fully with 12 GeV

[Thomas 83; Schreiber *et al.*, 90; Diakonov *et al.* 96; Fries, Schaefer, Weiss 03]

6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- **Form Factors**
- Generalized Parton Distributions
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

Revolutionize Our Knowledge of Distribution of Charge and Current in the Nucleon



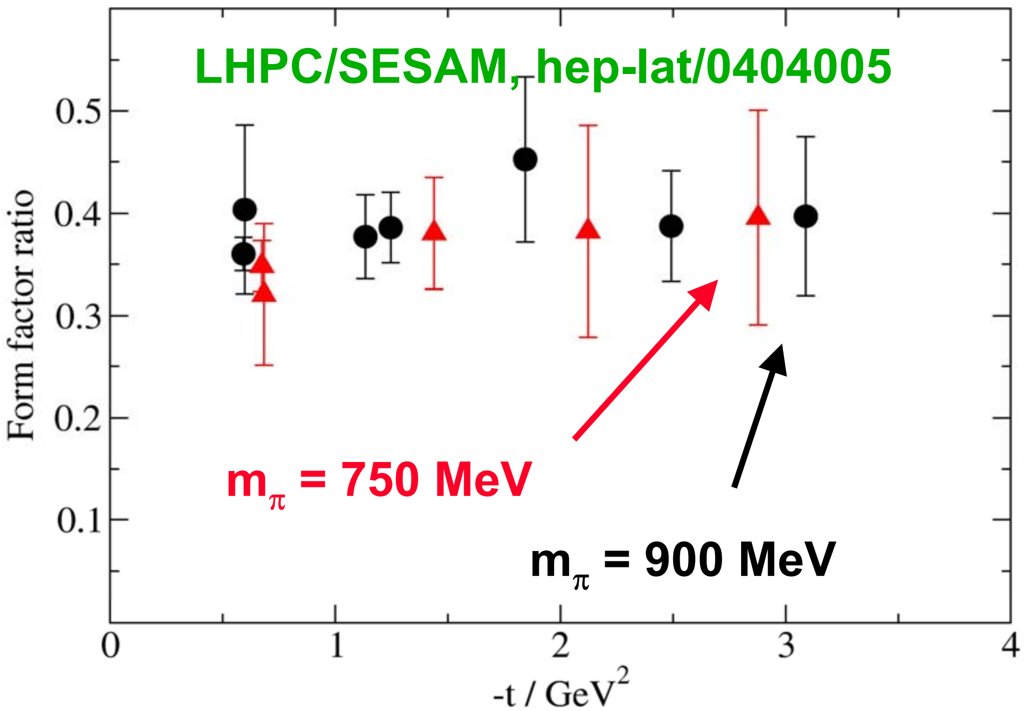
HP 2010

David Richards to discuss 2 γ corrections

- Perdrisat *et al*. E01-109 — will increase range of Q^2 by 50% in 2007 (range of Q^2 for n will double over next 3-4 years)
- With 12 GeV and SHMS in Hall C

Elastic Nucleon Form Factors $G^{p(n)}_{E,M}(Q^2)$

- **Magnetic Moments ($Q^2 = 0$) known experimentally to high precision**
  - — **Lattice computation to physical quark masses and large volumes**
- **Large Q^2 behavior controlled by lattice spacing *a***
  - — **Need to work on fine lattice**

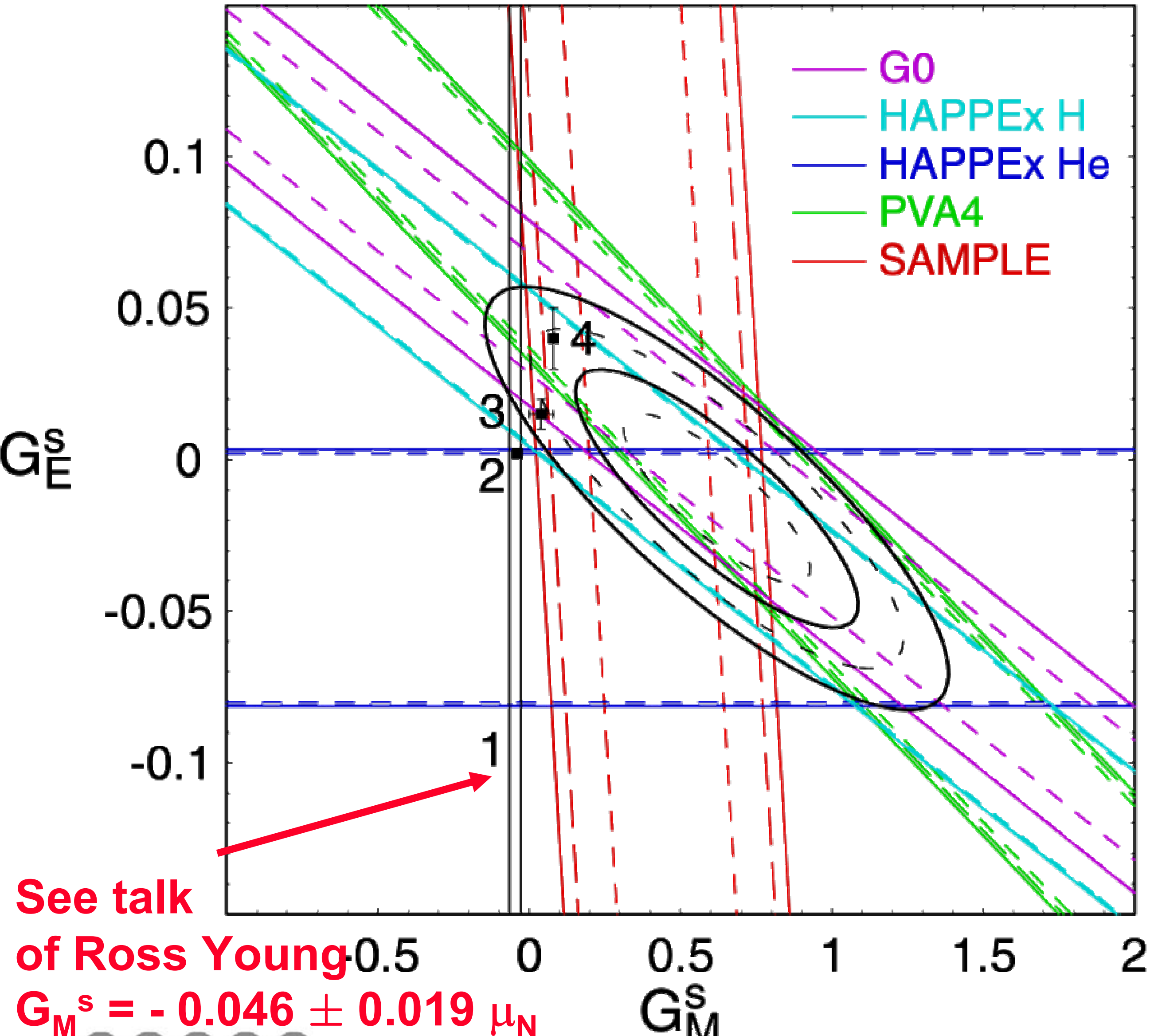


- **Importance of pQCD corrections**
  Brodsky
- **pQCD computation**
  Belitsky, Ji, Yuan

$$\frac{Q^2 F_2(Q^2)}{\log^2(Q^2/\Lambda^2) F_1(Q^2)} \simeq \text{const}$$

- **$Q^2 \simeq 6$ GeV^2 by 2010**
- **$Q^2 \simeq 10$ GeV^2 by 2012**

Strange Quark Form Factors at $Q^2 = 0.1\ GeV^2$



$G_E^s = -0.013 \pm 0.028$

$G_M^s = +0.62 \pm 0.31\ \mu_N$

See talk of Ross Young

$G_M^s = -0.046 \pm 0.019\ \mu_N$

Theories

1. Leinweber, et al. PRL **94** (05) 212001
2. Lyubovitskij, et al. PRC **66** (02) 055204
3. Lewis, et al. PRD **67** (03) 013003
4. 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 (G0) - 0.54 μ_N : i.e. - 60% !!

- Also remarkable versus lattice QCD which gives +0.03 $\pm$ 0.01 μ_N (Leinweber et al., PRL 94 (2005) 212001)

- Sign would require violation of universality of valence quark moments by $\sim$ 70% !

MORE DETAIL: TALK OF Ross Young…

Parity Violating Studies on ^{1}H and ^{4}He

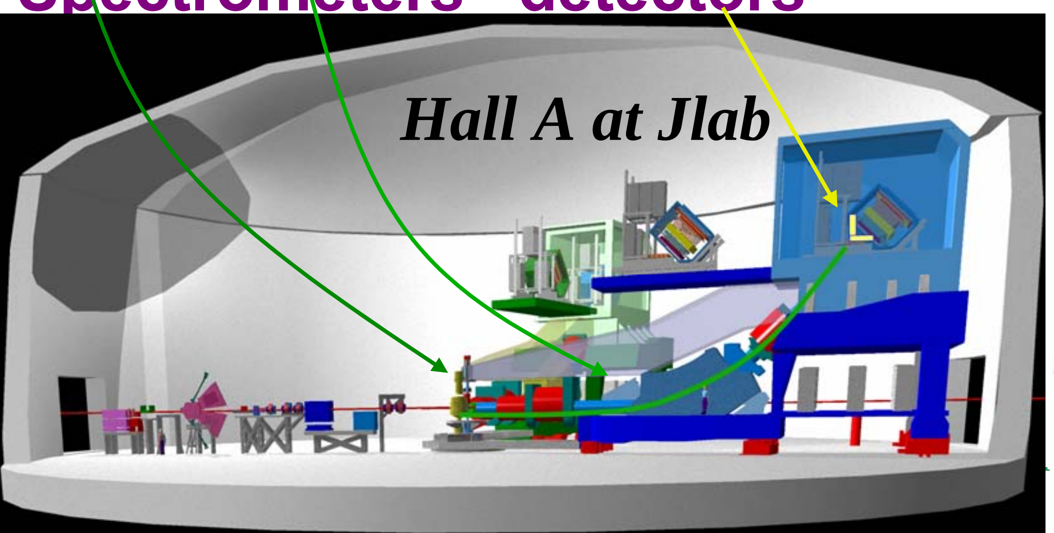
3 GeV beam in Hall A $\theta_{lab} \sim 6°$ $Q^2 \sim 0.1\ (GeV/c)^2$

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	$\delta(G^s_E) = 0.015$

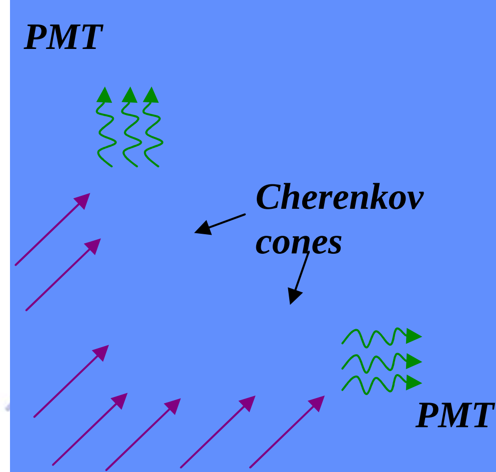
Septum magnets (not shown)

High Resolution

Spectrometers detectors



Brass-Quartz integrating detector



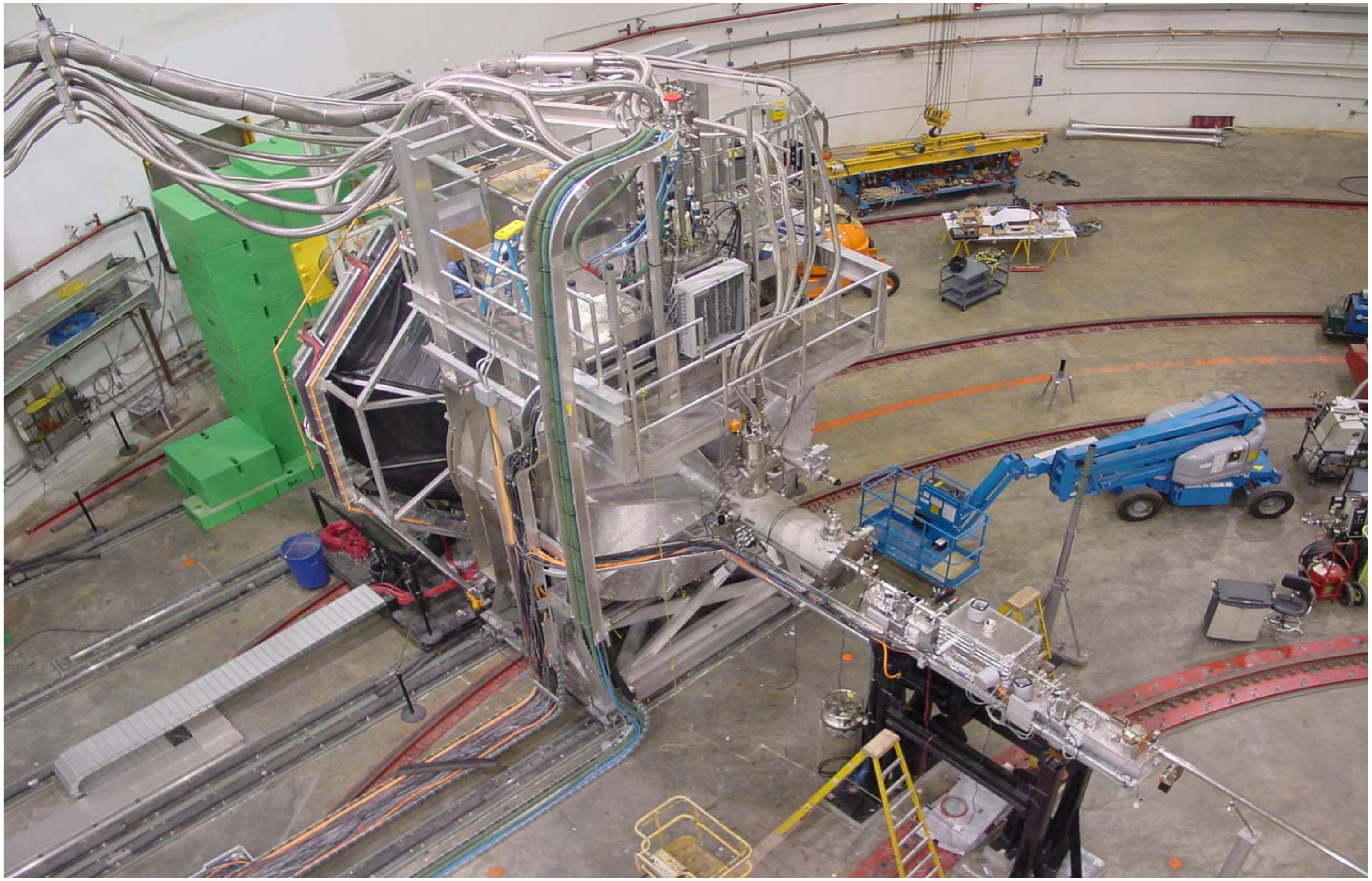
Elastic Rate:

^{1}H: 120 MHz

^{4}He: 12 MHz

Background ≤ 3%

G0 Experiment in Hall C

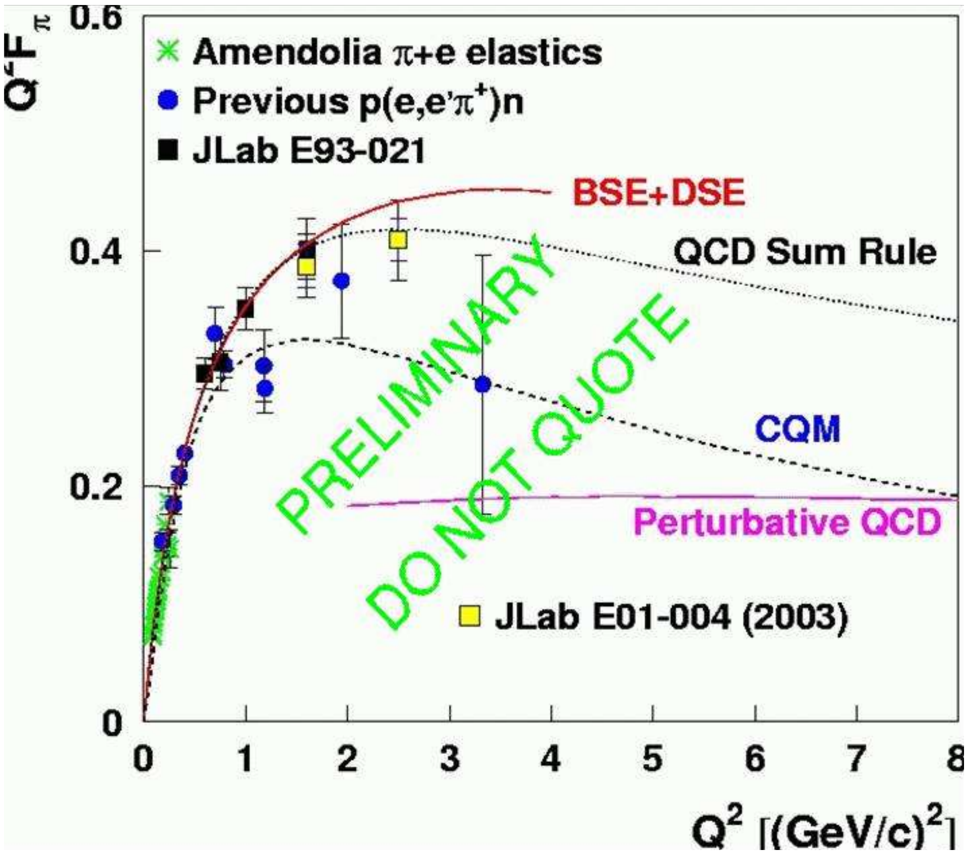


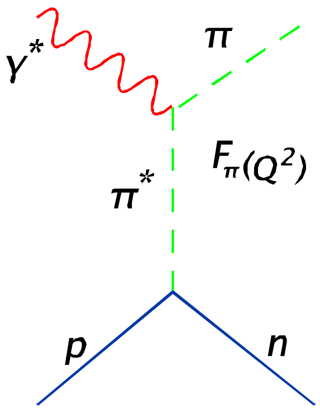
G0 and HAPPEx will <u>define</u> these form factors up to 1 GeV^2 over the next 2 years

2010

E01-004: New Pion Form Factor Data

- Increase in dynamic 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.

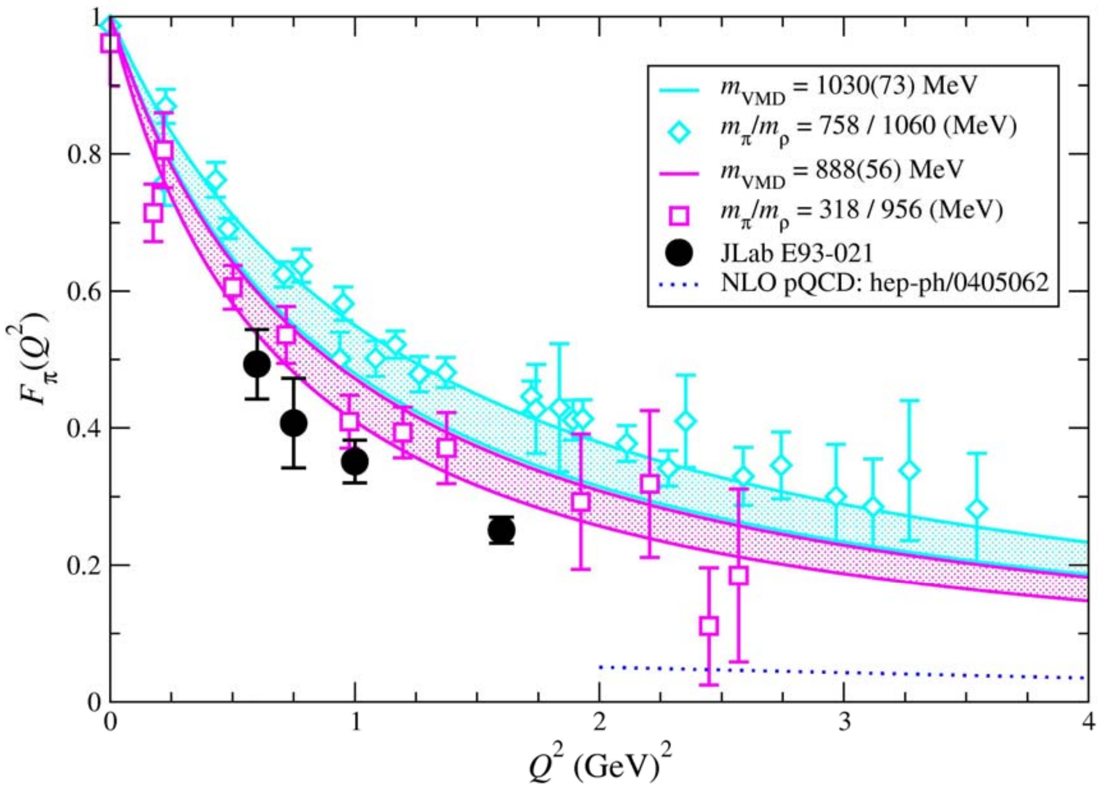




Outer uncertainties reflect present status of analysis, the inner bars reflect anticipated final uncertainties.

To reach regime of pQCD expectation require higher energy electron of the 12 GeV Upgrade

Pion Form Factor – Lattice QCD



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

- **Pion Form factor over Q^2 commensurate with experiment**
- **Pion GPD's and transition form factors**

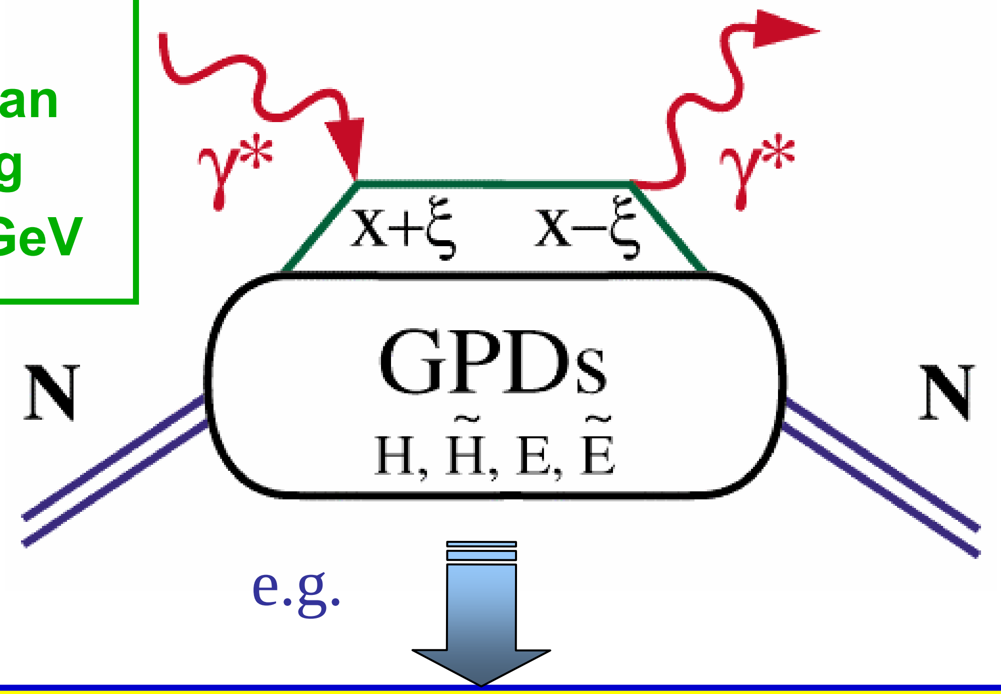
6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
- **Generalized Parton Distributions**
- Exotic Meson Spectroscopy:
  Confinement and the QCD vacuum
- Nuclei at the level of quarks and gluons
- Tests of Physics Beyond the Standard Model

Studies of the Generalized Parton Distributions (GPDs): New Insight into Hadron Structure

See talk of Larry Cardman for promising results at 6 GeV

HP 2008



X. Ji & A. Radyushkin (1996)

Quark angular momentum (Ji's sum rule)

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

6 GeV Highlights Leading to the 12 GeV Upgrade

- Parton Distribution Functions
- Form Factors
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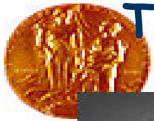
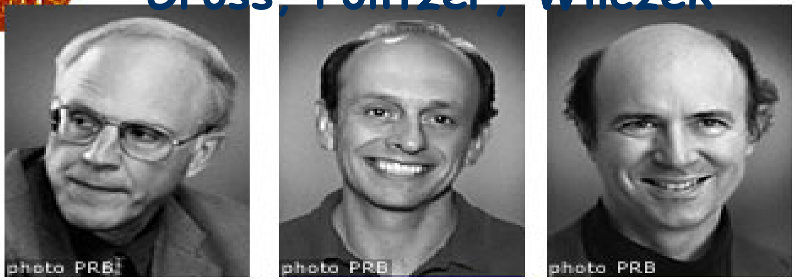
QCD: Unsolved in Nonperturbative Regime



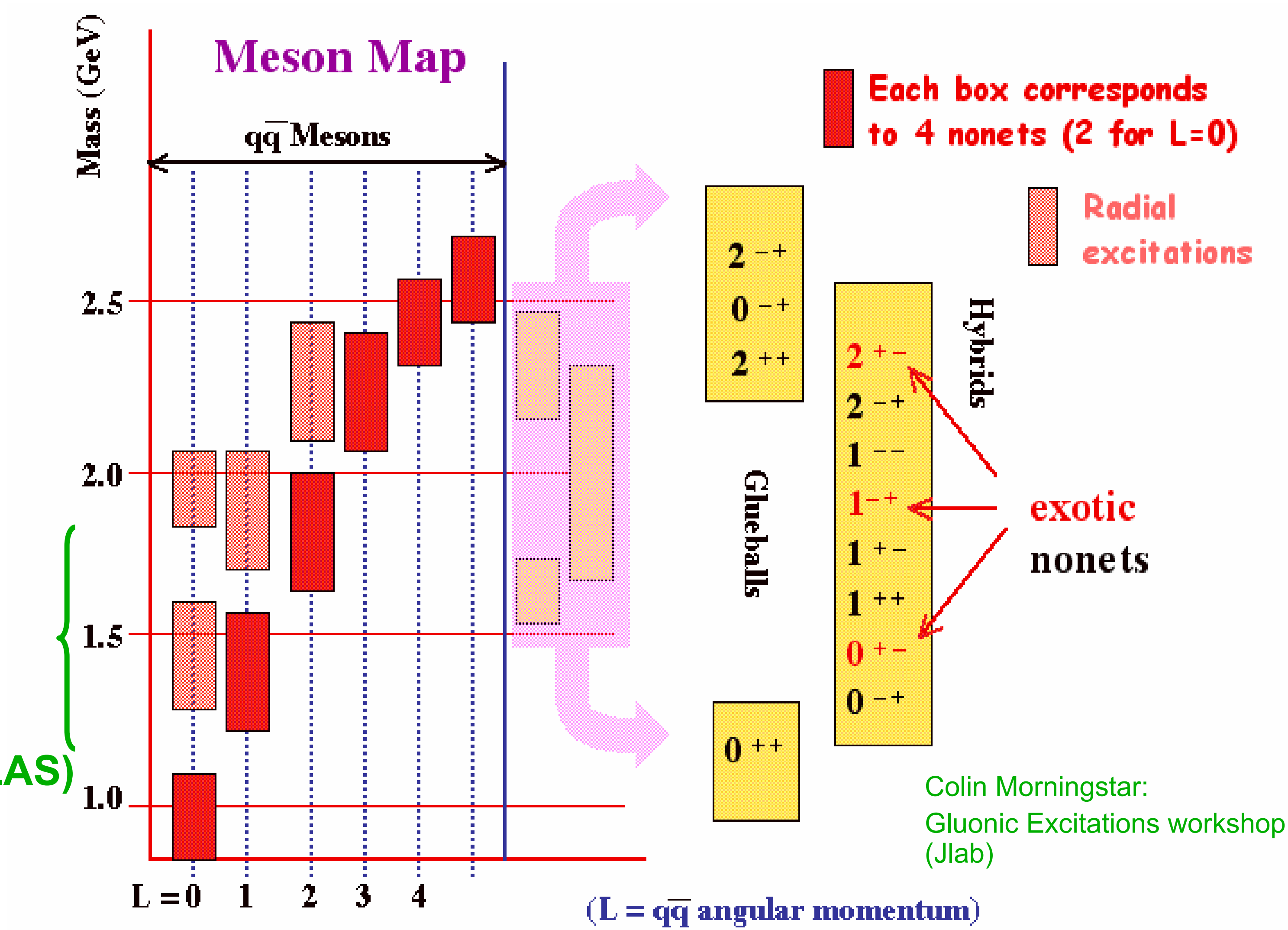
The Nobel Prize in Physics 2004
Gross, Politzer, Wilczek



- **2004 Nobel Prize awarded for “asymptotic freedom”**
- **BUT in nonperturbative regime QCD is still unsolved**
- **One of the top 10 challenges for physics!**
- **Is it right/complete?**
- **Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?**

JLab at 12 GeV is uniquely positioned to answer!

Glueballs and hybrid mesons



Initial search FY07 – G12 (CLAS)

Colin Morningstar:
Gluonic Excitations workshop, 2003 (Jlab)

Photo-couplings and Transition FF: H $\to \gamma$ M

- **Photo-couplings between hybrid and conventional mesons need to be calculated!**
- **GlueX proposal to produce hybrid mesons using real photons supported by flux-tube model calculations**
  - No suppression of conventional-hybrid photo-couplings for hybrids near 2 GeV

$$\Gamma(\pi^{+}_{1H} \to a_2^{+}\gamma) \sim \mathcal{O}(100)\mathrm{keV}$$
$$\Gamma(b^{+}_{JH} \to \rho^{+}\gamma) \sim \mathcal{O}(1000)\mathrm{keV}$$

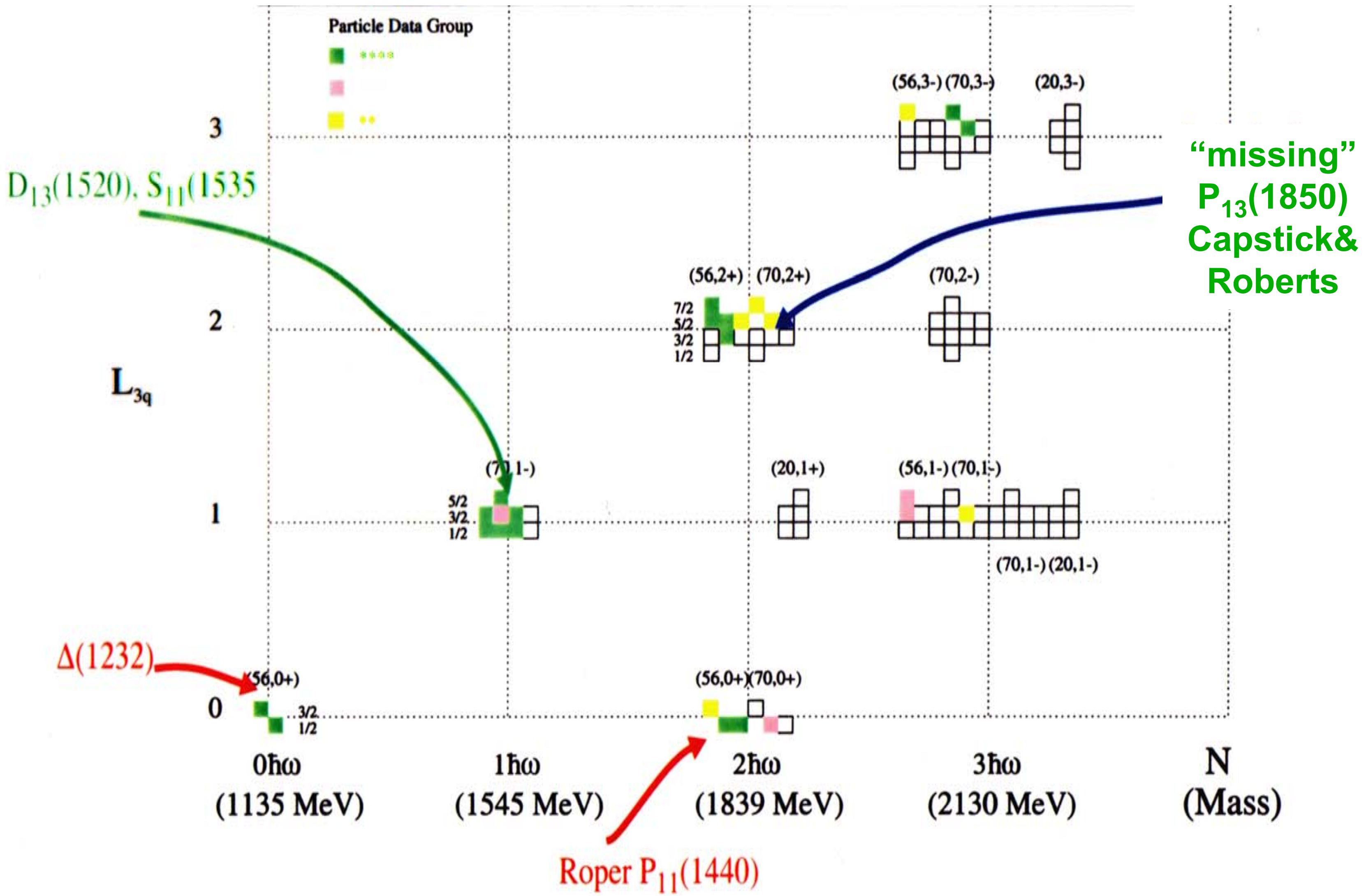
Close and Dudek, PRL91, 142001 (2003); PRD 69 034010 (2004)

$$(\mathrm{c.f.}\ \Gamma(b_1^{+} \to \rho^{+}\gamma) = 230 \pm 60\mathrm{keV})$$

Investigate and attempt to verify prediction using lattice QCD

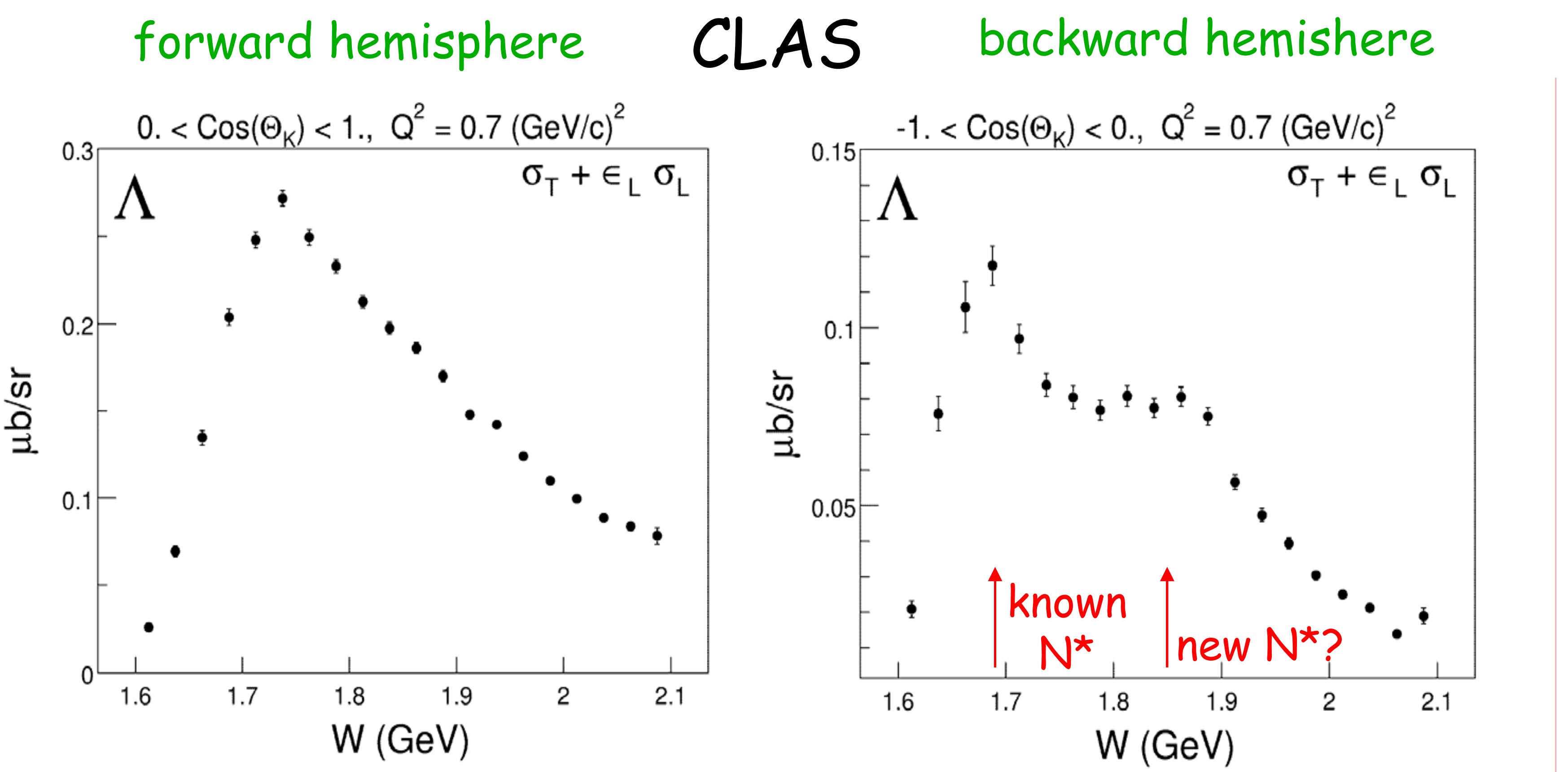
Report on PWA collaboration with Gluex and Lattice work: David Richards

Baryon Spectroscopy: e.g. "Missing States"

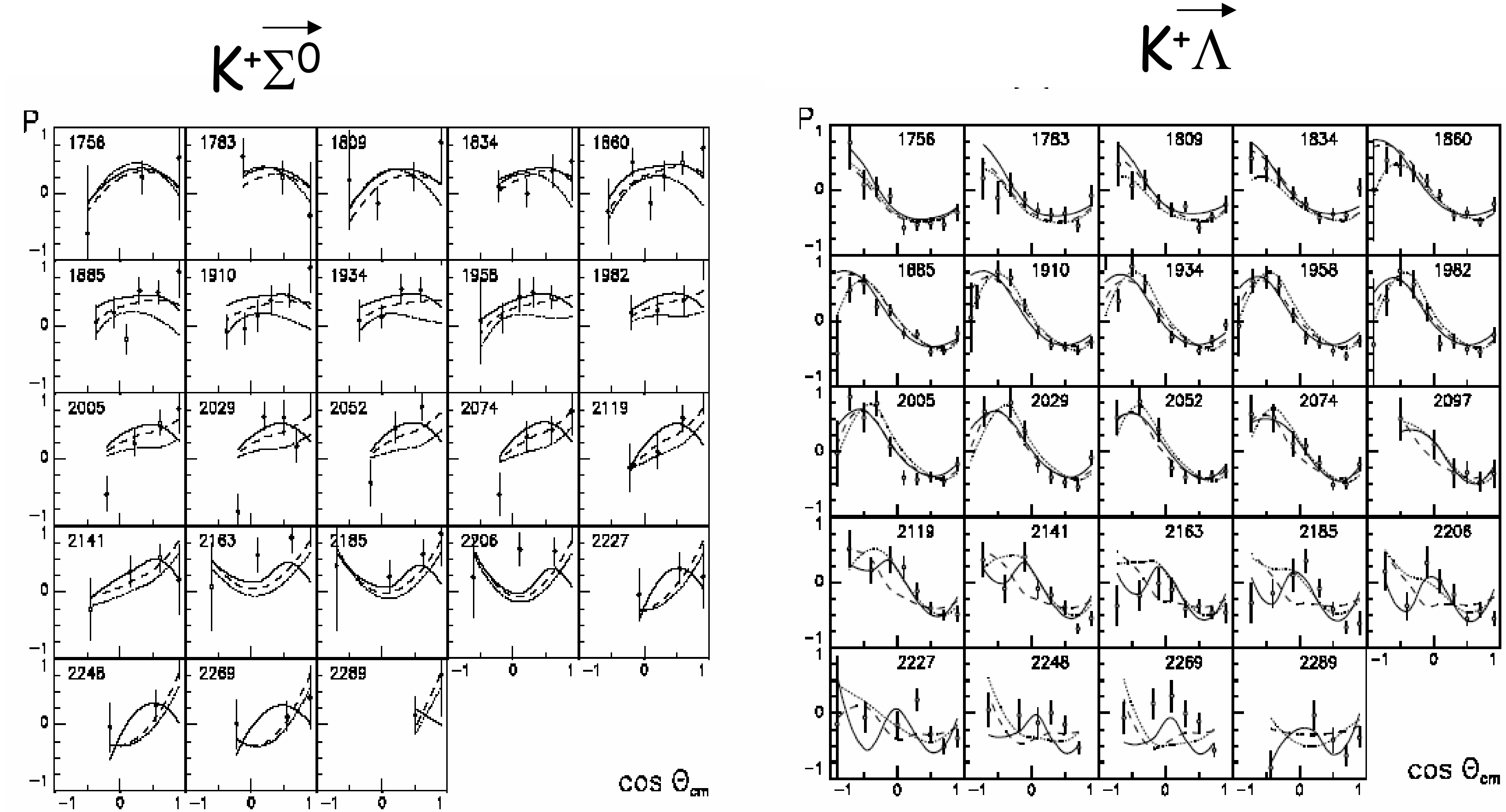


New N* state in KΛ/KΣ production ?

- **Possible new nucleon state near 1840 MeV visible in photo- and electroproduction total cross section data.**



New states in $K^+\Lambda$ and $K^+\Sigma$ photoproduction

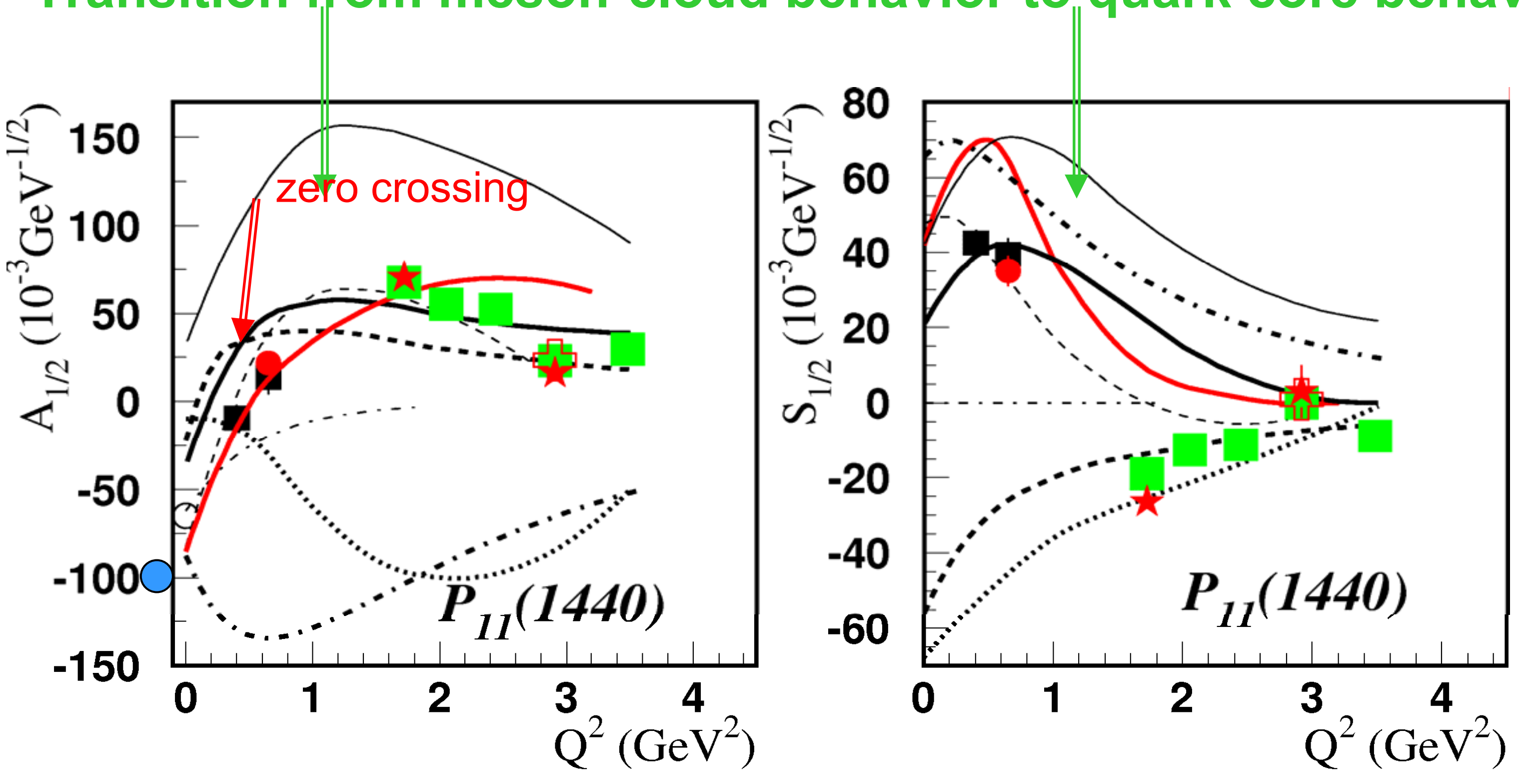


- Analysis finds new P_{11} state at 1840 MeV, and G = 140 MeV

- A P_{11} state @ 1840 MeV is consistent with symmetric quark model
- It is inconsistent with diquark-quark symmetry

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

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**

Collaboration with ANL Theory Group

Proposed Time Table

- Pose the results from homework problems on website by the end of June
- Invite other groups to send in their results by August 15
- Present a summary of the comparisons at the second workshop (Aug.29 -sept 2) of Argonne Theory Institute

  $\rightarrow$

  Develop a plan for future collaborations and/or communcations between different groups.
- Inform the organizers of 2005 N^* meeting at Florida State University (Oct. 12-15, 2005)

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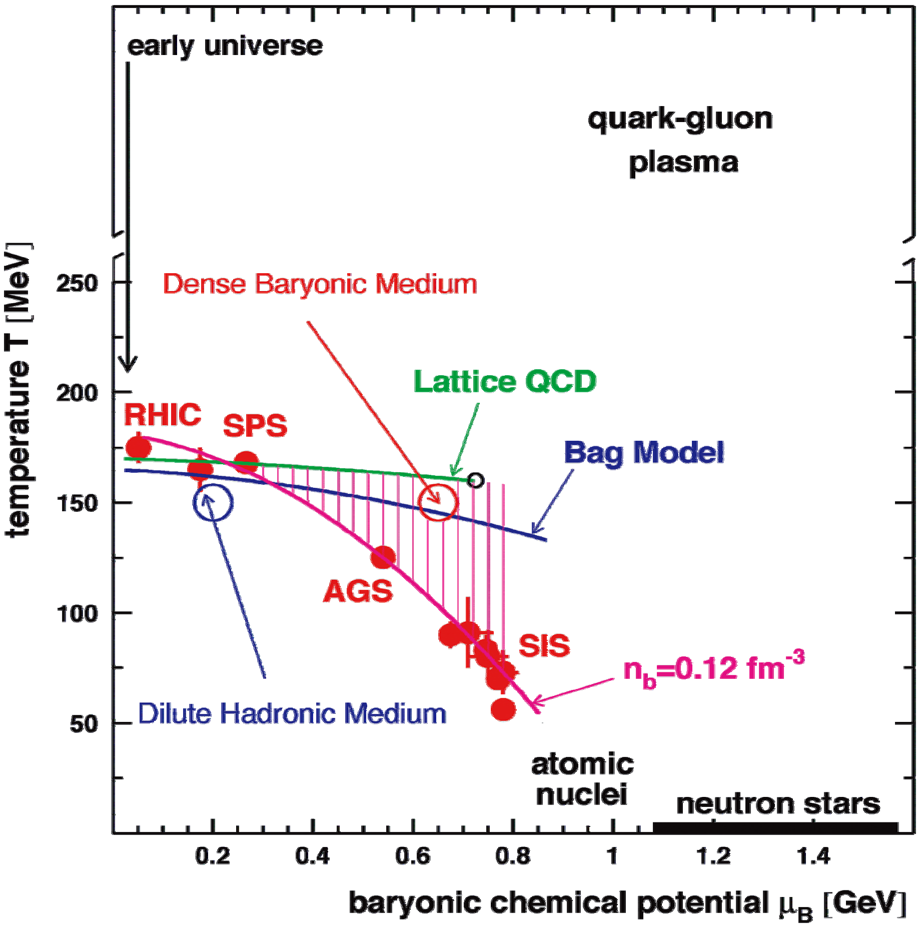
Major Challenges for Nuclear Physics

- **Origin of Nuclear Saturation**

- **EOS … as ρ ↑ ; as T ↑**
  as S ↑ ; as N-Z ↑



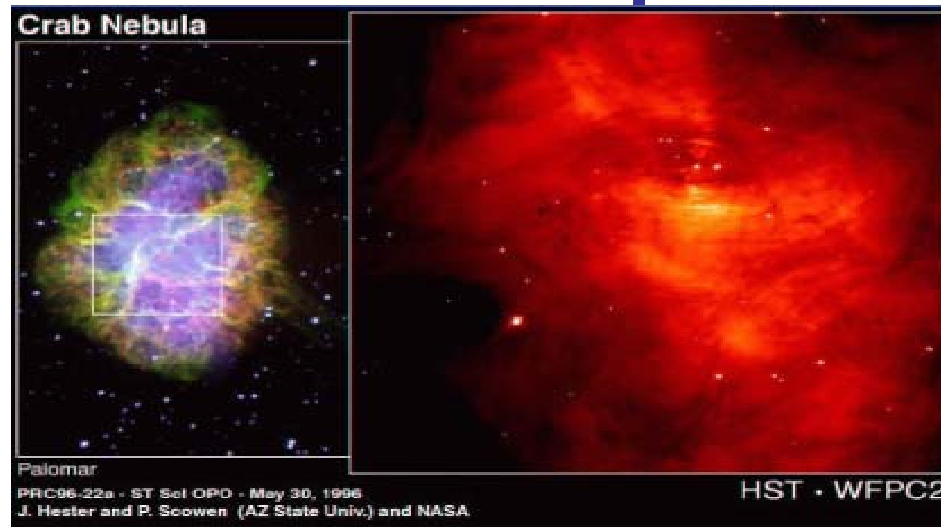
- **Phase Transition to:**
  - **quark matter (QM), superconducting QM, strange condensate**
  - **related to nuclear astrophysics; n-stars….**

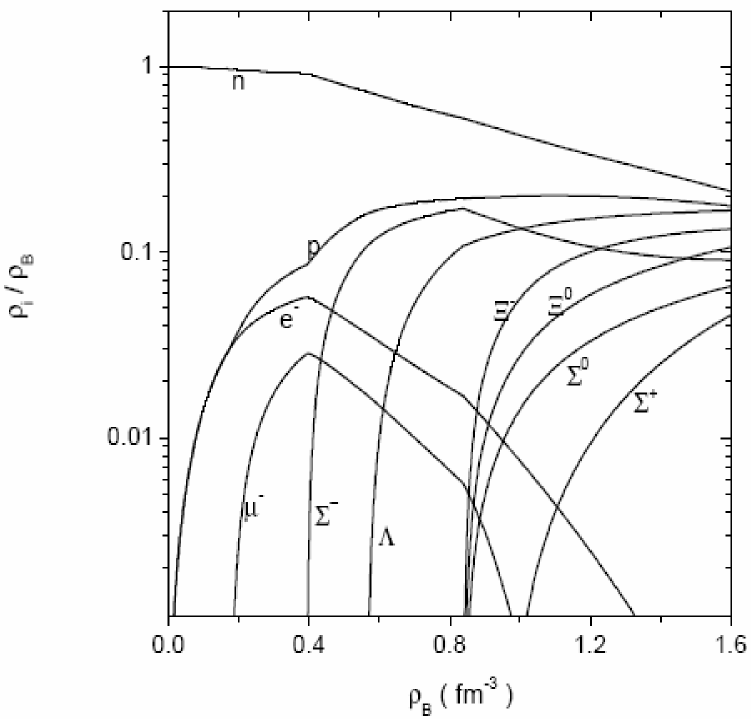
Neutron Star Composition

Hyperons enter at just 2-3 ρ_0

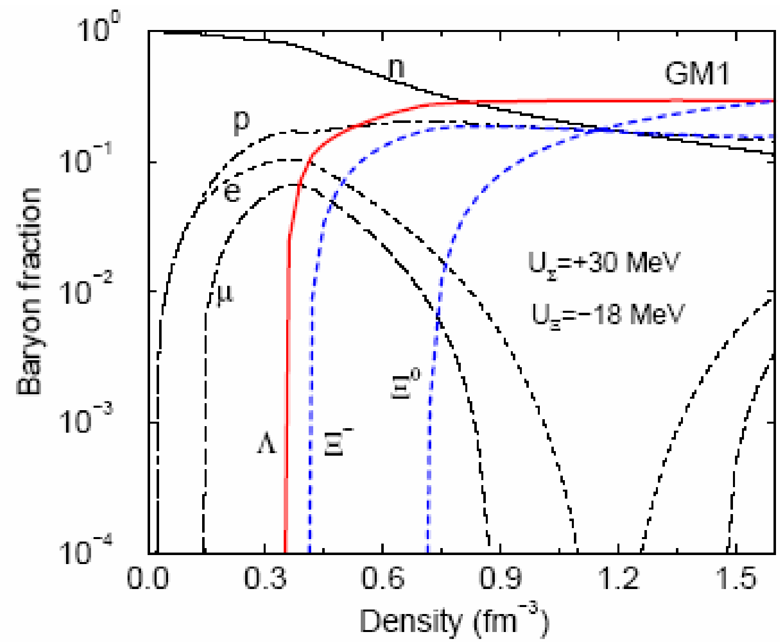
Hence need effective Σ-N and Λ-N forces in this density region!

Hypernuclear data is important input





?



Nuclear Physics: The Core of Matter, The Fuel of Stars

(NAS/NRC Report, 1999)

Science Chapter Headings:

The Structure of the Nuclear Building Blocks

The Structure of Nuclei

Matter at Extreme Densities

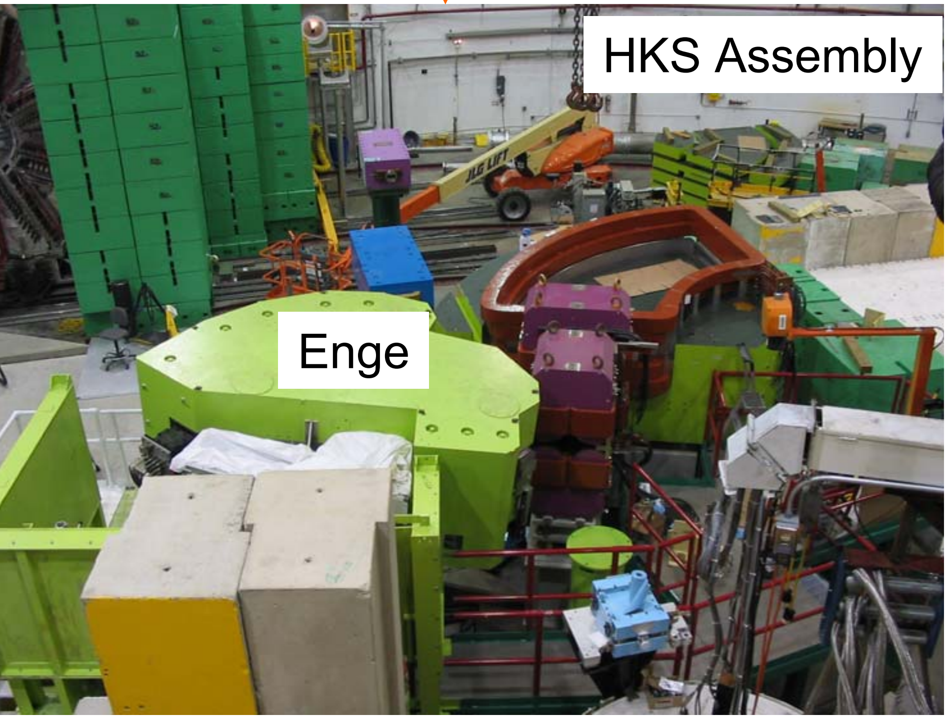
The Nuclear Physics of the Universe

Symmetry Tests in Nuclear Physics

Present Installation: HKS

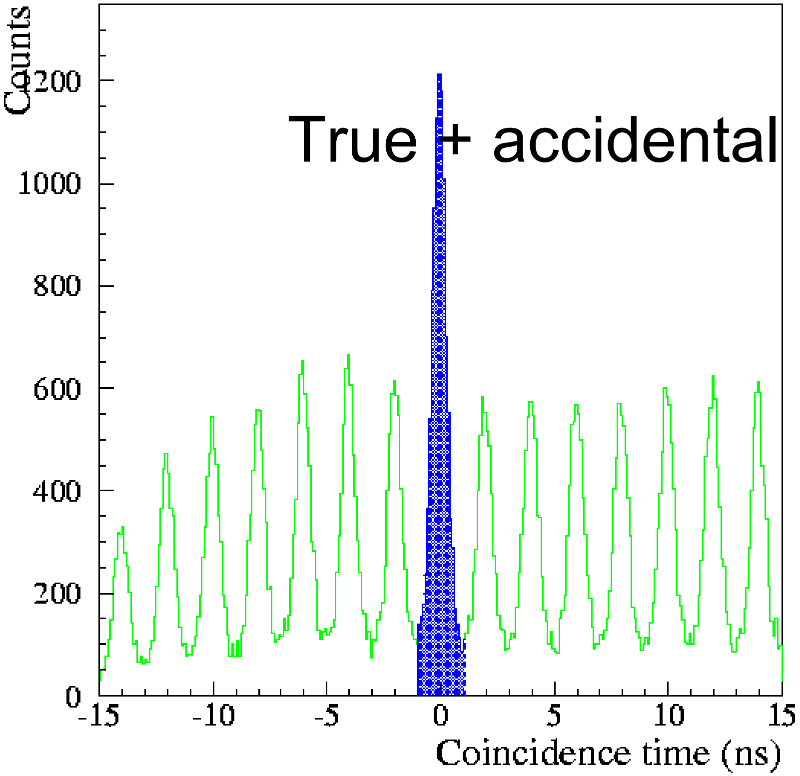
Present Hypernuclear Spectroscopy equipment combination is beam splitter, Enge (e^-), HKS (K^+)

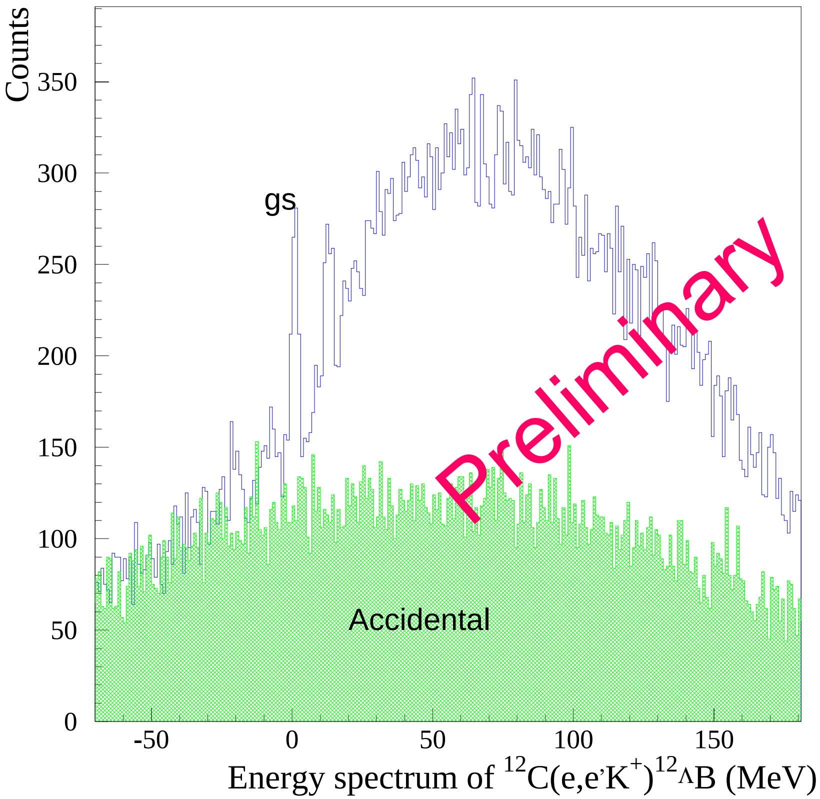
Installation ongoing in Hall C (April 13)



Installation completed (early June)

Carbon ($^{12}{}_{\Lambda}B$) data





$^{12}{}_{\Lambda}B$ g.s

~ 600 counts (~20/hr) ~1 MeV -> 400 keV

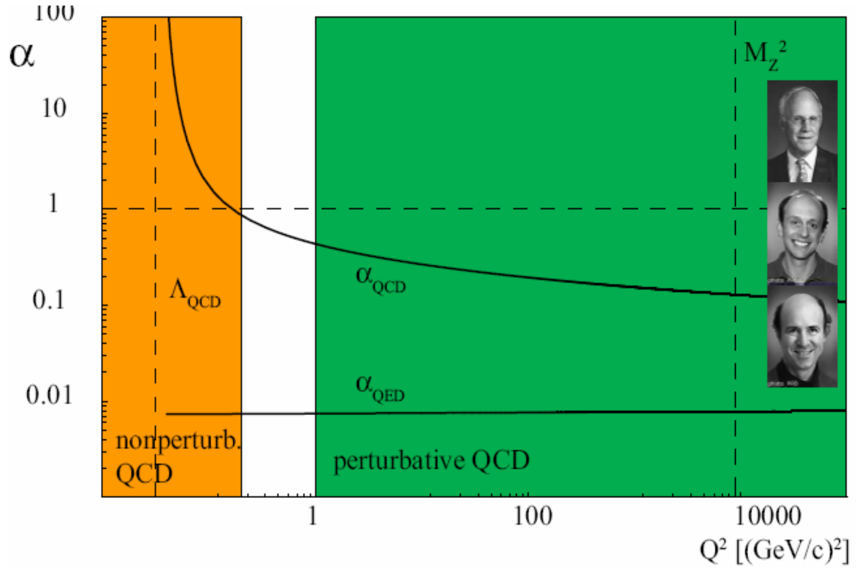
(Previous exp. (E89-009) 165 counts with 900 keV.

HallA 300 counts with 700 keV.)

Time Frame for 12 GeV & Advances in Lattice QCD ⇒ Wonderful synergy!

That is: Our growing ability to use lattice QCD to calculate the unambiguous consequences of nonperturbative QCD is beautifully matched to the capacity of Jlab at 12 GeV to measure the corresponding observables with precision!

….and hence really test if QCD is the complete theory of the strong interaction



Advances in Lattice QCD

Inclusion of Pion Cloud

Actions with exact chiral symmetry

Precise computations at Physical Pion Mass

Advances in high-performance computing

Computational Advances

- **Cluster Trends**
  - 1 Tflop-scale clusters currently offering $1/Mflops price-performance
  - Cluster hardware price-performance increasing at least as fast as Moore's Law (performance/price doubling every 18 months)
- **Ramped funding model tuned to physics goals**

	'05	'06	'07	'08	'09	'10	'11
$M/yr (new)		1.0	1.5	2.0	2.5	3.0	3.0
Tflops-year	0.5	2.5	5	10	18	34	55

(In addition to $1.2m of base JLab and SciDAC funding)

Optimal Lattice Hadron Program

- **Program of lattice studies with milestones linked to 12 GeV** – *White Paper to DOE, Feb '05*.

"Coarse"
a = 0.11 fm

m_π (MeV)	$L^3 \times L_t$	$m_\pi L$	Tflops-yrs
> 350	$24^3 \times 64$	4.6	1.0
	$32^3 \times 64$	6.2	2.8
300	$32^3 \times 64$	5.3	4.4
	$36^3 \times 64$	6	6.9
250	$36^3 \times 64$	5	12
	$40^3 \times 64$	5.5	18
210	$48^3 \times 64$	5.5	60
350	$30^3 \times 64$	4.7	7.3
300	$36^3 \times 64$	4.9	23
250	$48^3 \times 64$	5.4	117

Tflop-year
$\sim m_\pi^{-7} a^{-6}$

"fine"
a = 0.09 fm

more detail: David Richards

FEL Program Development

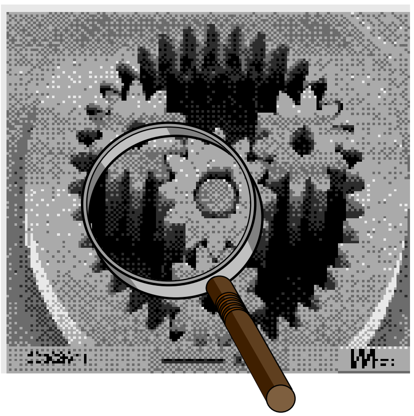
- THz User Working Group 9/2004
- DOE-BES/NIH/NSF report on THz opportunities 12/2004
- User meeting 3/2005
- Laser Biosciences Workshop 6/2005
- IRMMW meeting 9/2005
- Laser Precision Micro-fabrication Workshop 4/2005

- 150 users at User meeting March 2005 from > 30 groups

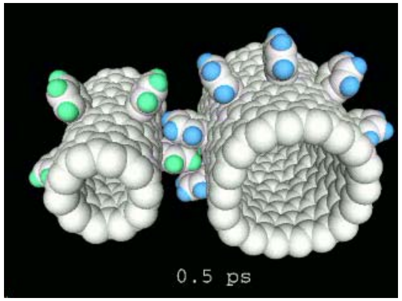
Forefront Condensed Matter and Life Sciences

Nano-Fluids **(talk by G. Williams)**

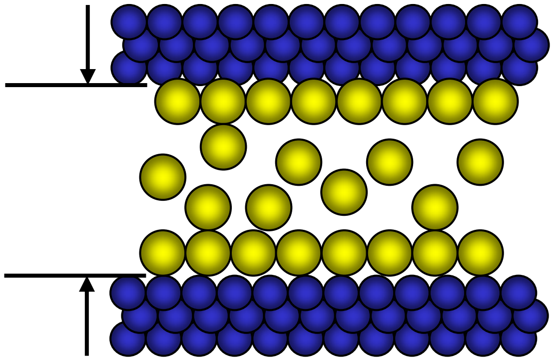
in New Technologies, in Chemistry, Bio Medicine, Geology



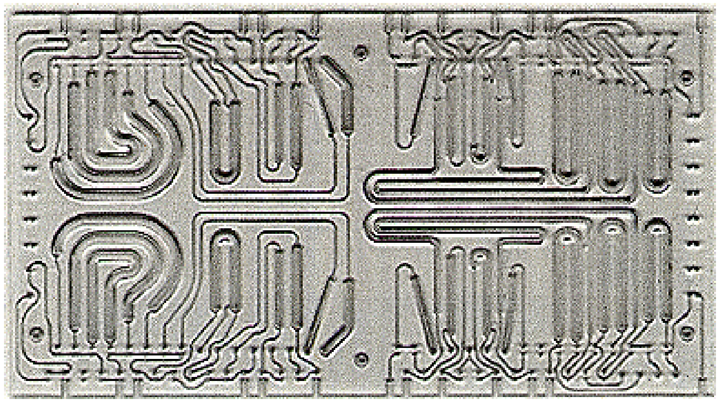
From Micro- to Nano-Gears



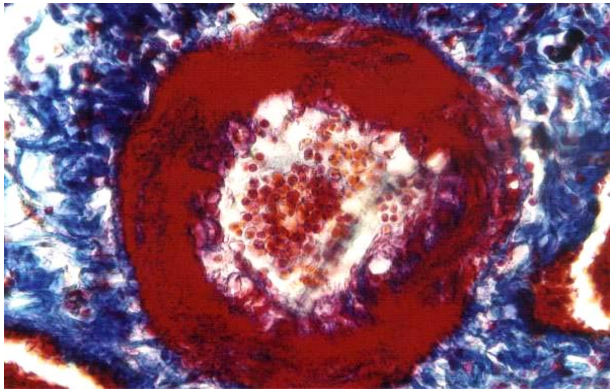
Nano Tubes



Lubrication in Nano Slits



Chemistry Lab of Tomorrow: On a Chip

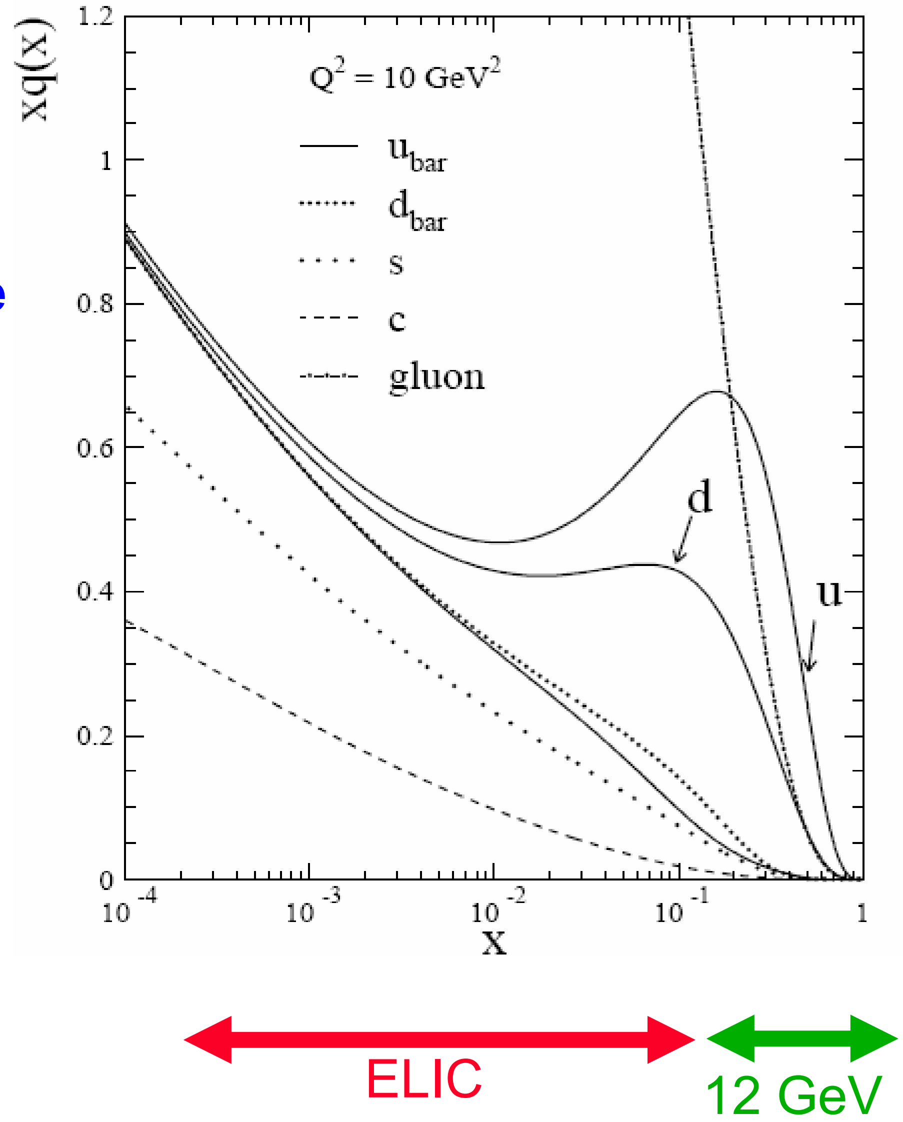


Blood/Fat Flow in Capillaries

CEBAF II/ELIC

Science addressed:

- **What is the gluonic structure of atomic nuclei?**
- **How is the structure of the quark-anti-quark sea (spin & flavor) modified in nuclei?**
- **Modification of the QCD vacuum in-medium?**



DOE Reviews in 2005

- **Science Review:**

The overall proposed program represents an impressive coherent framework of research directed towards one of the top frontiers of contemporary science

- **DOE Independent Project (Lehman) Review:**

No impediment to CD-1 !