# Measurements of R and the Longitudinal and Transverse Structure Functions in the Nucleon Resonance Region and Quark-Hadron Duality

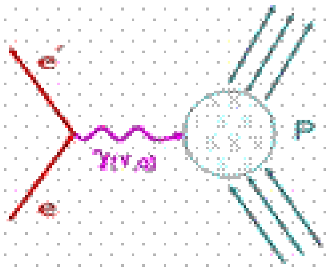
Rolf Ent, DIS2004

- -Formalism: R, 2x$F_1$, $F_2$, $F_L$
- -E94-110: L/T Separation at JLab
- -Quark-Hadron Duality
  - -Or: Why does DIS care about the Resonance Region?
- -If time left: Duality in nuclei/$g_1$
- -Summary

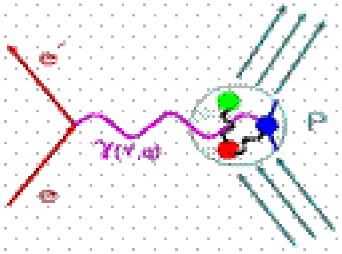
# Inclusive e + p → e’ + X scattering

## Single Photon Exchange

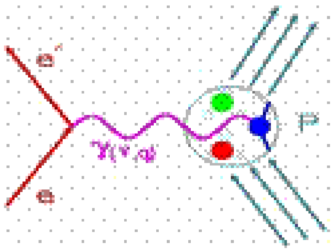
<u>Elastic</u>




<u>Resonance</u>




<u>DIS</u>




$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \varepsilon\sigma_L)$$

Where $\Gamma$ : flux of transversely polarized virtual photons

$\varepsilon$ : relative longitudinal polarization

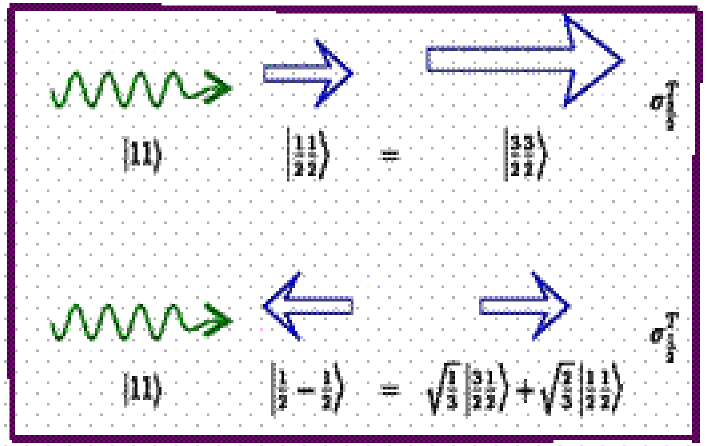
Alternatively:
$$\frac{d\sigma}{d\Omega dE'} = \sigma_{mott}\left(F_2/\nu + 2F_1 \tan^2(\theta/2)/M\right)$$

$$\sigma_{mott} = \frac{\alpha^2\cos^2(\theta/2)}{4E^2\sin^4(\theta/2)} \qquad R = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{2xF_1} \qquad F_L = \left(1 + \frac{4M^2x^2}{Q^2}\right)F_2 - 2xF_1$$

# Resonance Region L-Ts Needed For

**Extracting spin structure functions from spin asymmetries**

$$A_1 = \frac{\sigma_{/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{\sigma_{1/2} - \sigma_{3/2}}{2\sigma_T}$$



$$\frac{\Delta A_1}{A_1} \simeq \varepsilon\delta R \text{ (for R small)}$$

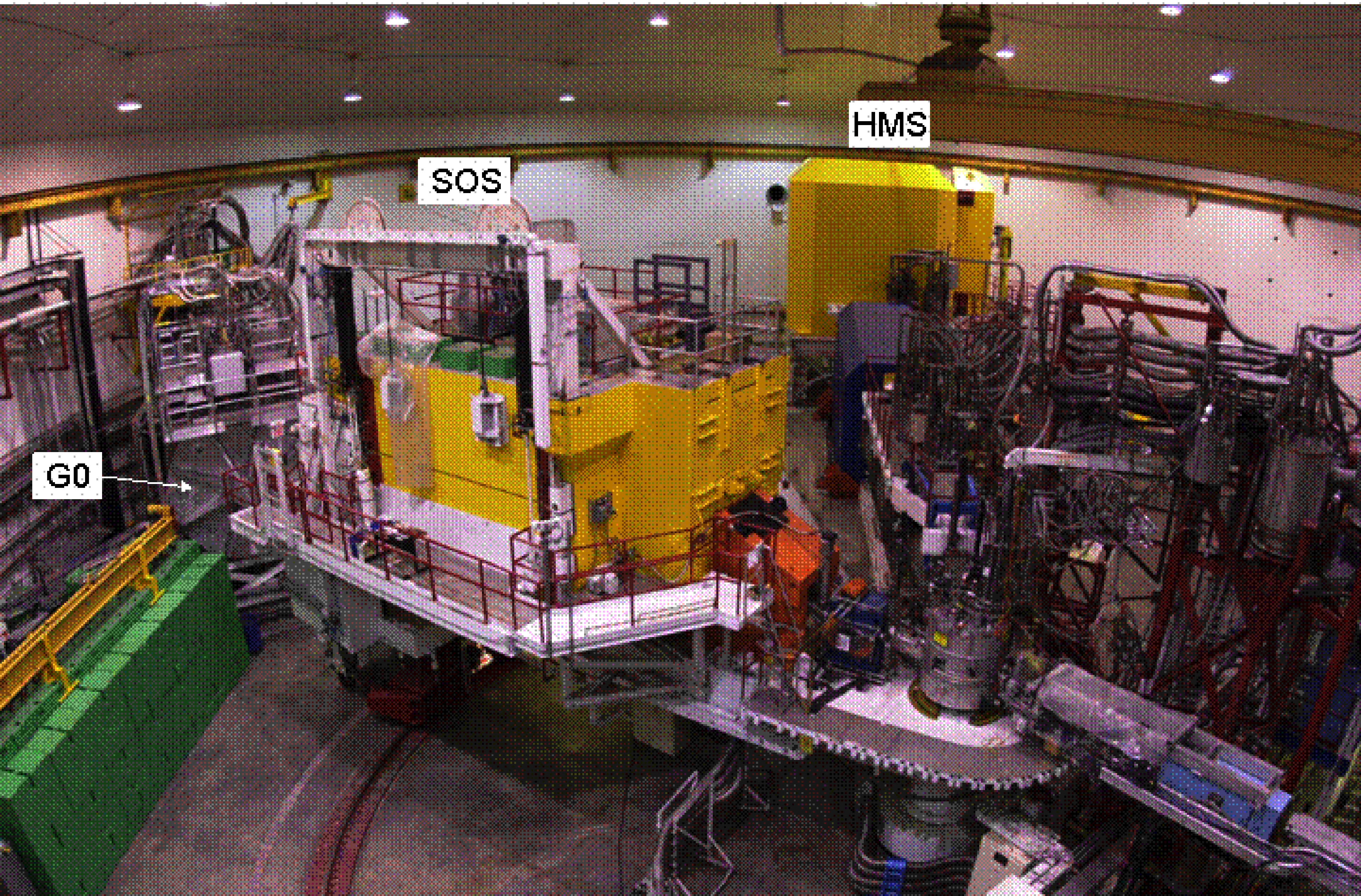
$$g_1 = \frac{F_1(A_1 - \gamma A_2)}{1 + \gamma^2}$$

$$\simeq \frac{F_2(1 + \varepsilon R)}{1 + R}$$

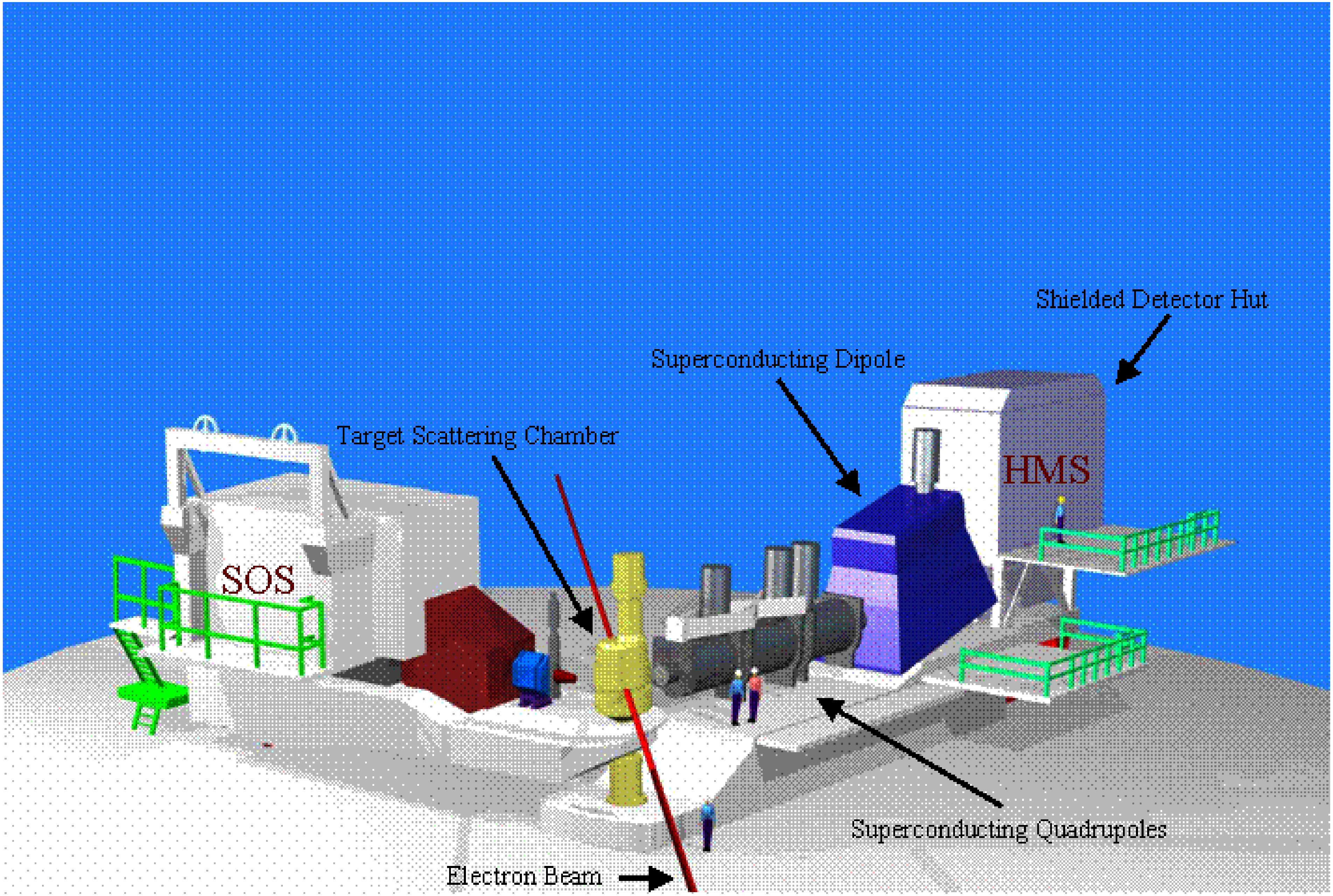
(Only insensitive to R if $F_2$ in relevant $(x,Q^2)$ region was truly measured at $\varepsilon = 1$)

From measurements of $F_1$ and $A_1$ extract $\sigma_{1/2}$ and $\sigma_{3/2}$!
(Get complete set of transverse helicity amplitudes)

# E94-110 Experiment performed at JLab-Hall C

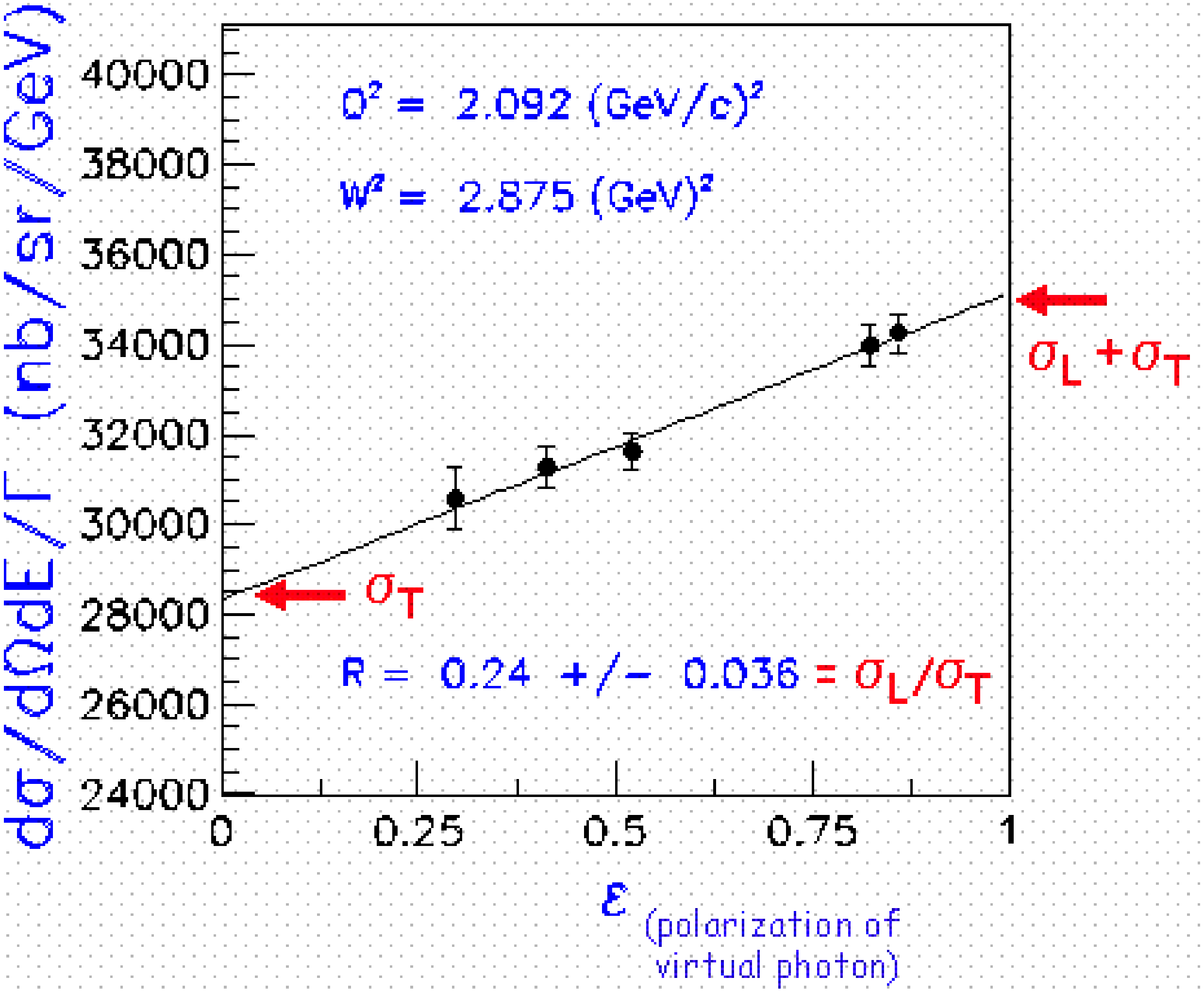


# JLab-HALL C


Shielded Detector Hut
Superconducting Dipole
Target Scattering Chamber
HMS
SOS
Superconducting Quadrupoles
Electron Beam

# Rosenbluth Separations

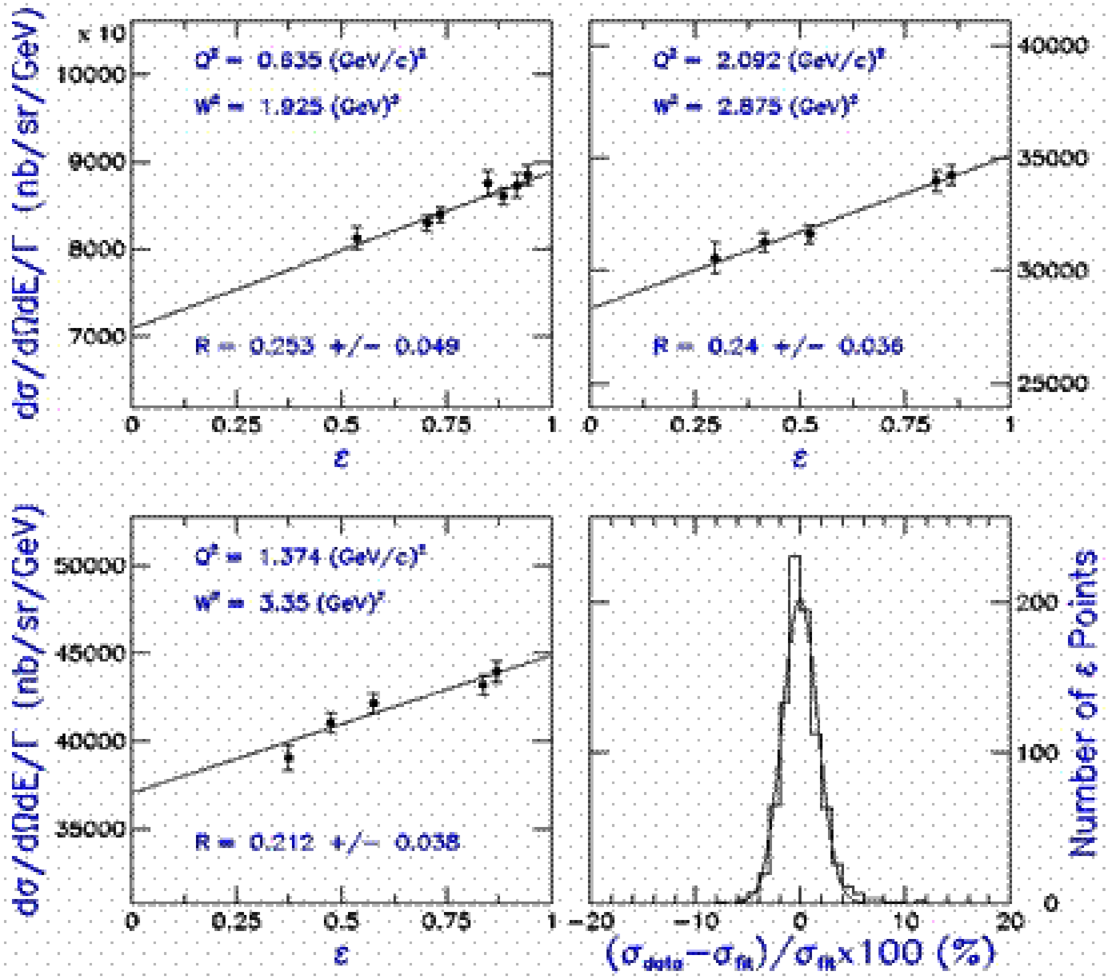
**Hall C E94-110: a global survey of longitudinal strength in the resonance region…..**



# Rosenbluth Separations

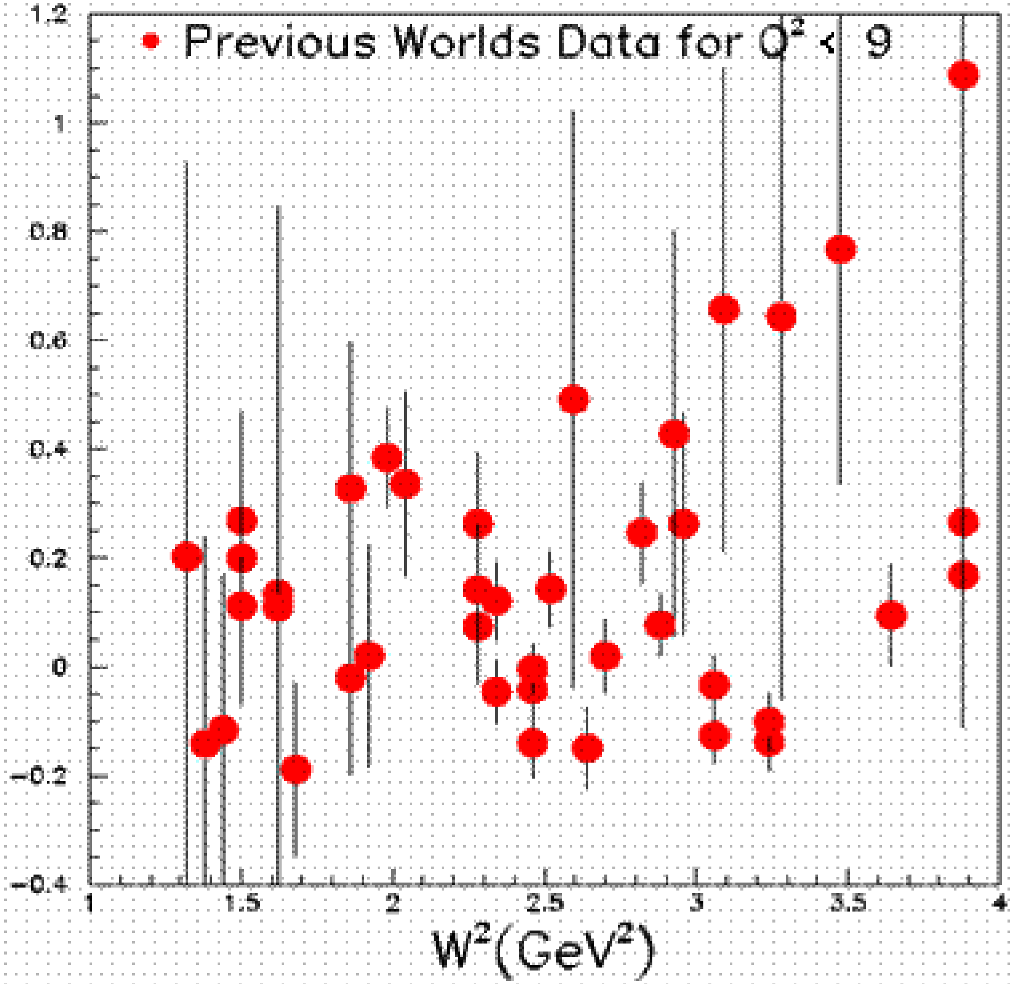
Hall C E94-110: a global survey of longitudinal strength in the resonance region......

- Spread of points about the linear fits is Gaussian with σ ~ 1.6 % consistent with the estimated point-point experimental uncertainty (1.1-1.5%)
  - a systematic "tour de force"



# World's L/T Separated Resonance Data

$R = \sigma_L / \sigma_T$



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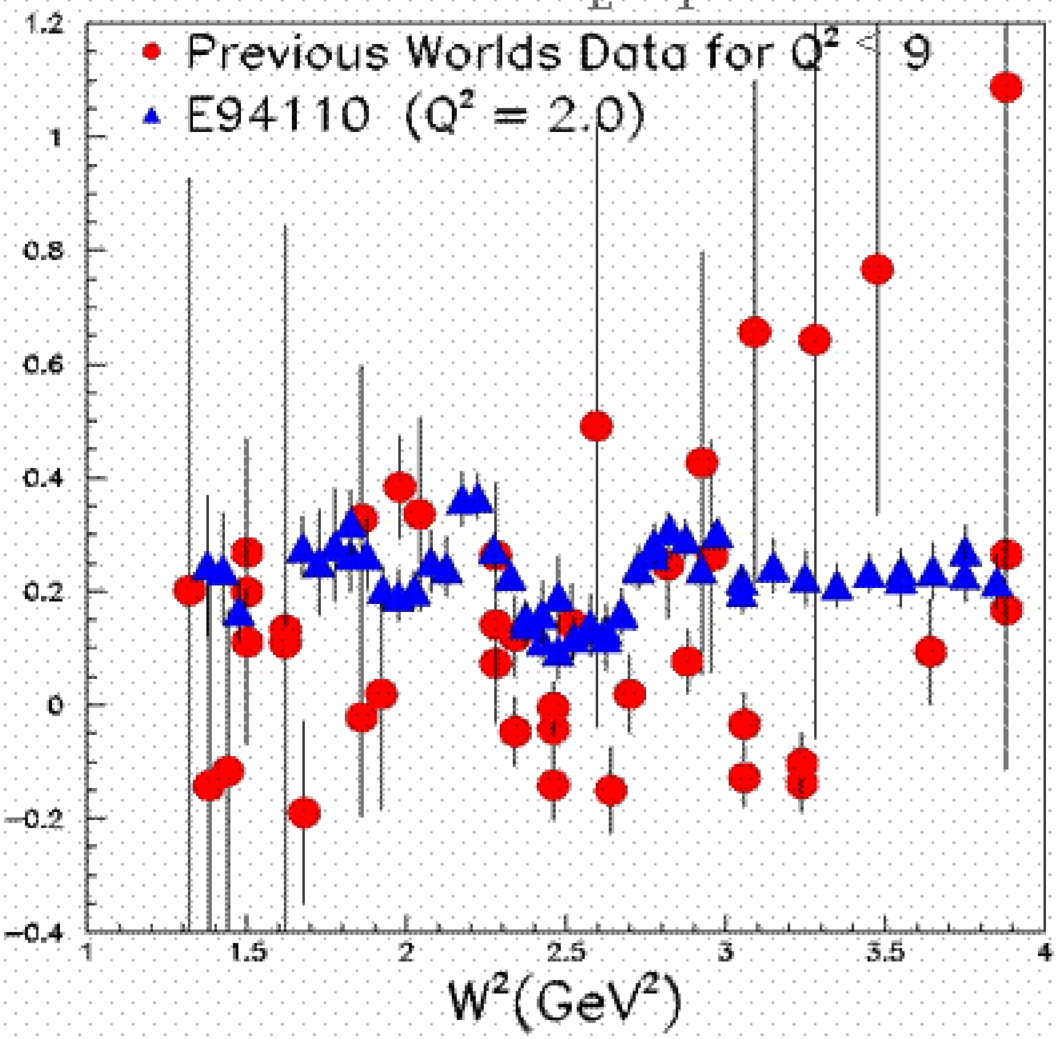


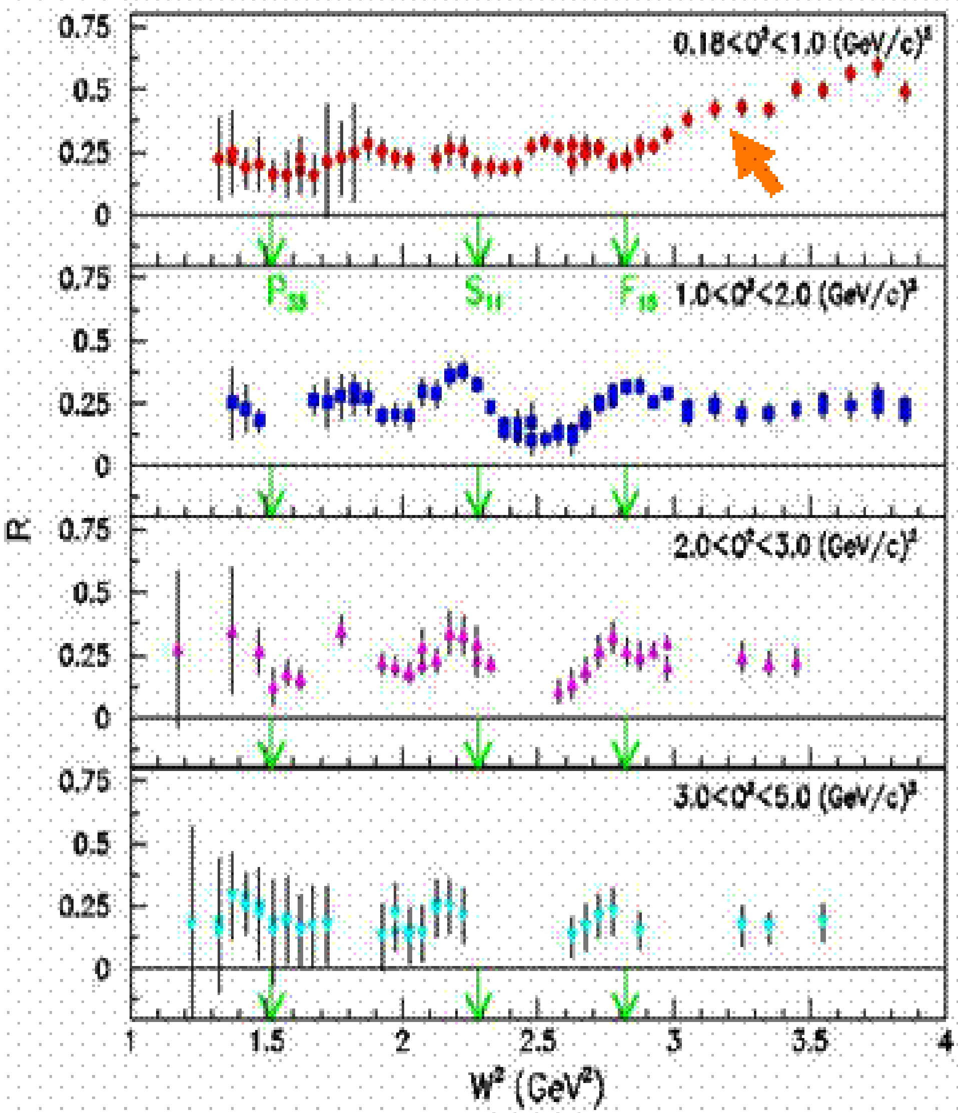

Now able to study the $Q^2$ dependence of individual resonance regions!

Clear resonant behaviour can be observed!

Use R to extract

$F_2$, $F_1$, $F_L$

# E94-110 Rosenbluth Extractions of R




- Clear resonant behaviour is observed in R for the first time!

→ Resonance longitudinal component NON-ZERO.

→ Transition form factor extractions should be revisited.

- Longitudinal peak in second resonance region at lower mass than $S_{11}$(1535 MeV)

→ $D_{13}$(1520 MeV) ? $P_{11}$(1440 MeV)?

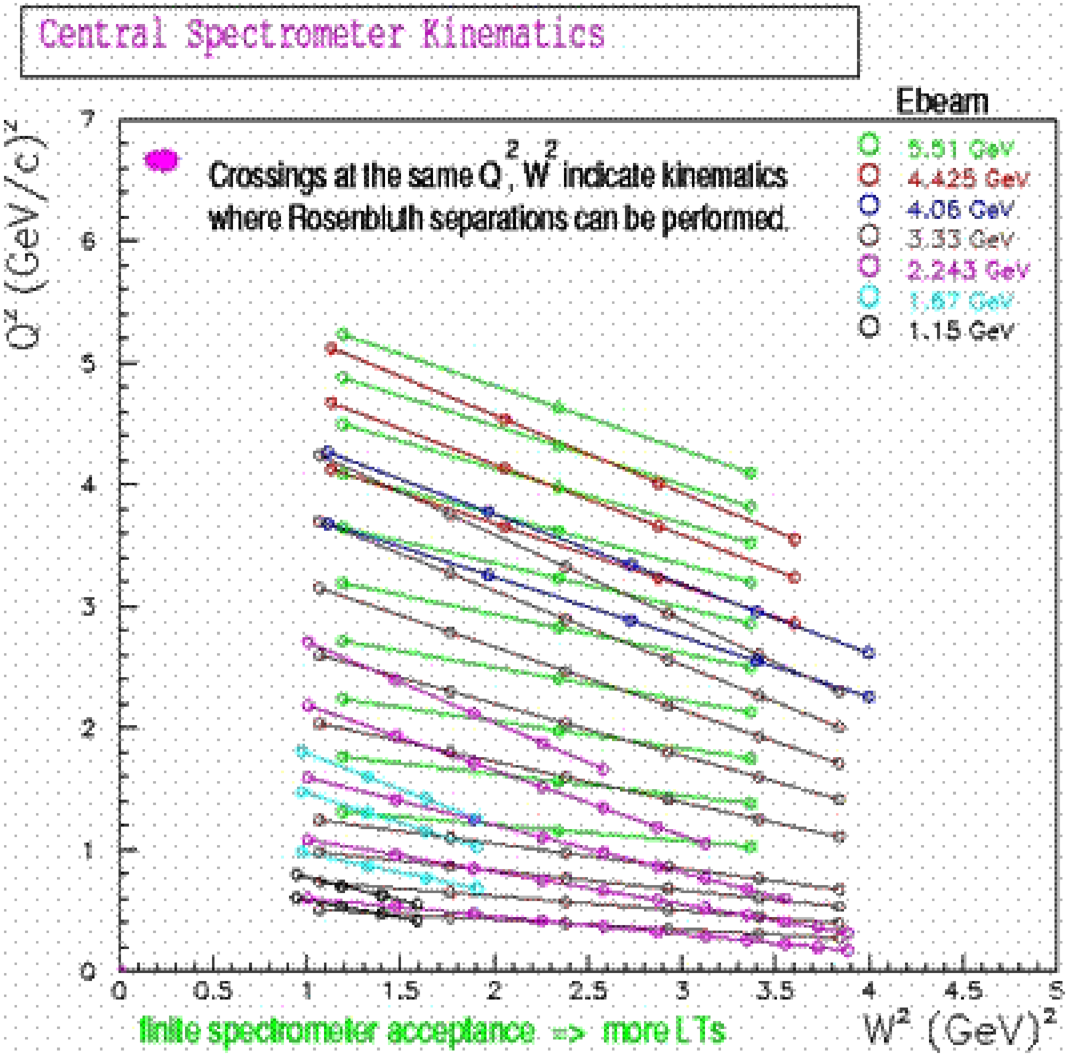
- R is large at low Q high W (low x)

→ Was expected $R \to 0$ as $Q^2 \to 0$

→ $R \to 0$ also not seen in recent SLAC DIS analysis (R1998)

# Kinematic Coverage of Experiment

$$\sigma_R = (d\sigma/\Gamma) = \sigma_T(W^2,Q^2) + \varepsilon\sigma_L(W^2,Q^2)$$

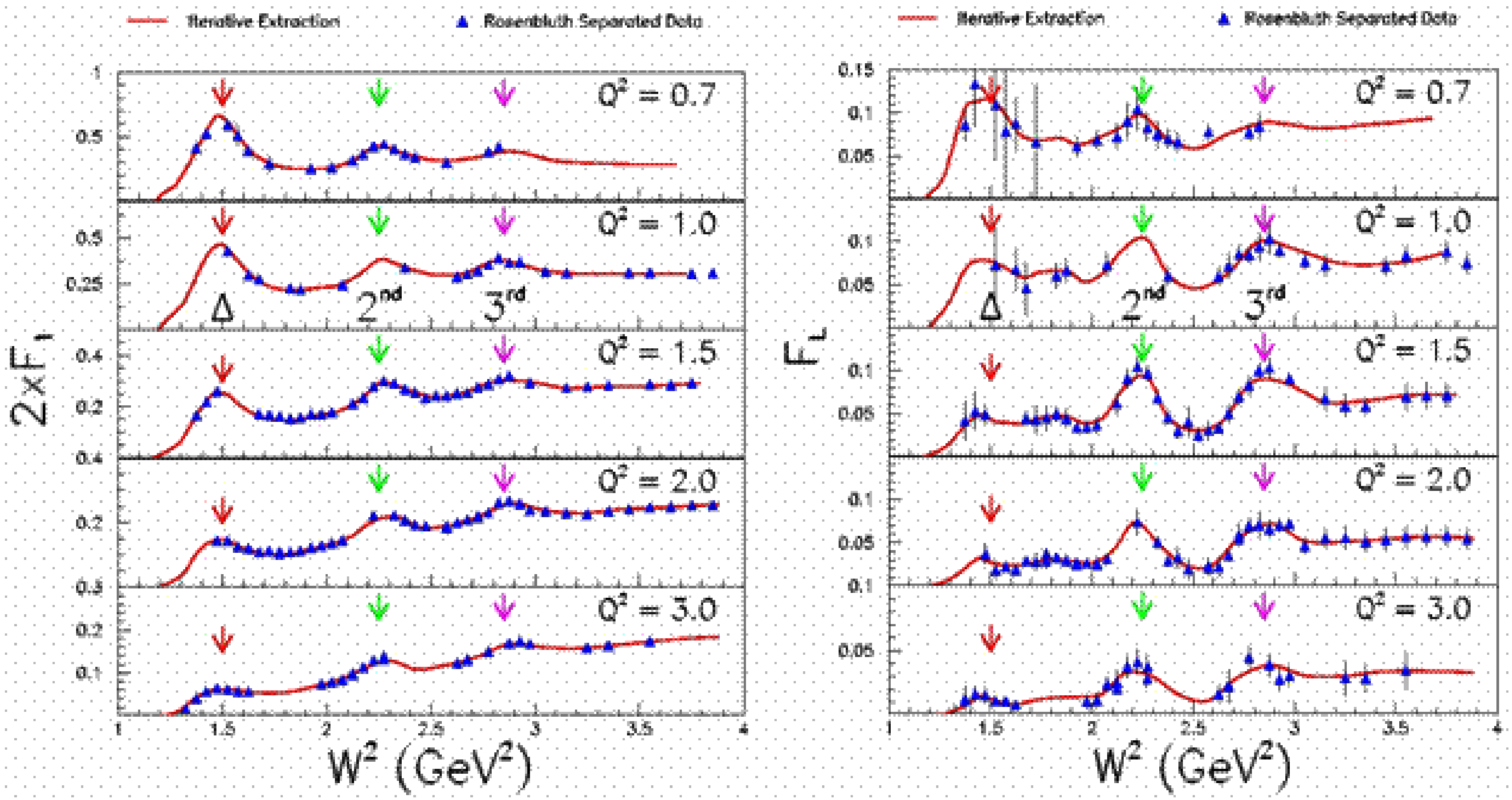



2 Methods employed for separating Structure Functions:

- Rosenbluth-type separations where possible (some small kinematic evolution is needed)
- Iteratively fit $F_2$ and R over the entire kinematic range.

Also perform cross checks with elastic and DIS (comparing with SLAC data)

# L-T Separated Structure Functions

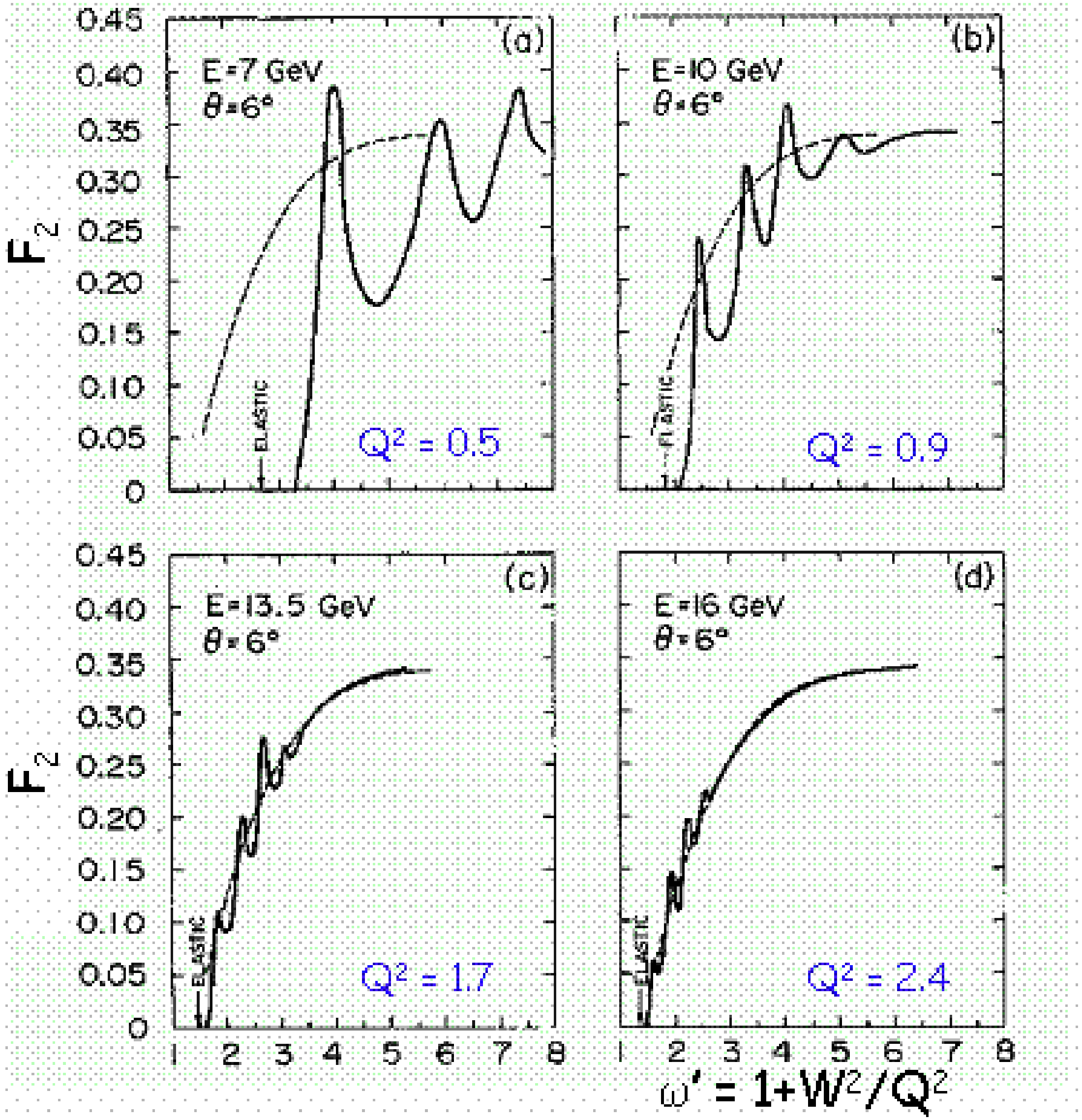



- Good agreement between methods (→ model available for use!)
- Very strong resonant behaviour in $F_L$!
- Evidence of different resonances contributing in different channels?

# Duality in the $F_2$ Structure Function

*First observed ~1970 by Bloom and Gilman at SLAC by comparing resonance production data with deep inelastic scattering data*

- *Integrated $F_2$ strength in Nucleon Resonance region equals strength under scaling curve. Integrated strength (over all $\omega'$) is called Bloom-Gilman integral*




Shortcomings:

- Only a single scaling curve and no $Q^2$ evolution (Theory inadequate in pre-QCD era)
- No $\sigma_L/\sigma_T$ separation → $F_2$ data depend on assumption of $R = \sigma_L/\sigma_T$
- Only moderate statistics

# Duality in the $F_2$ Structure Function

*First observed ~1970 by Bloom and Gilman at SLAC*

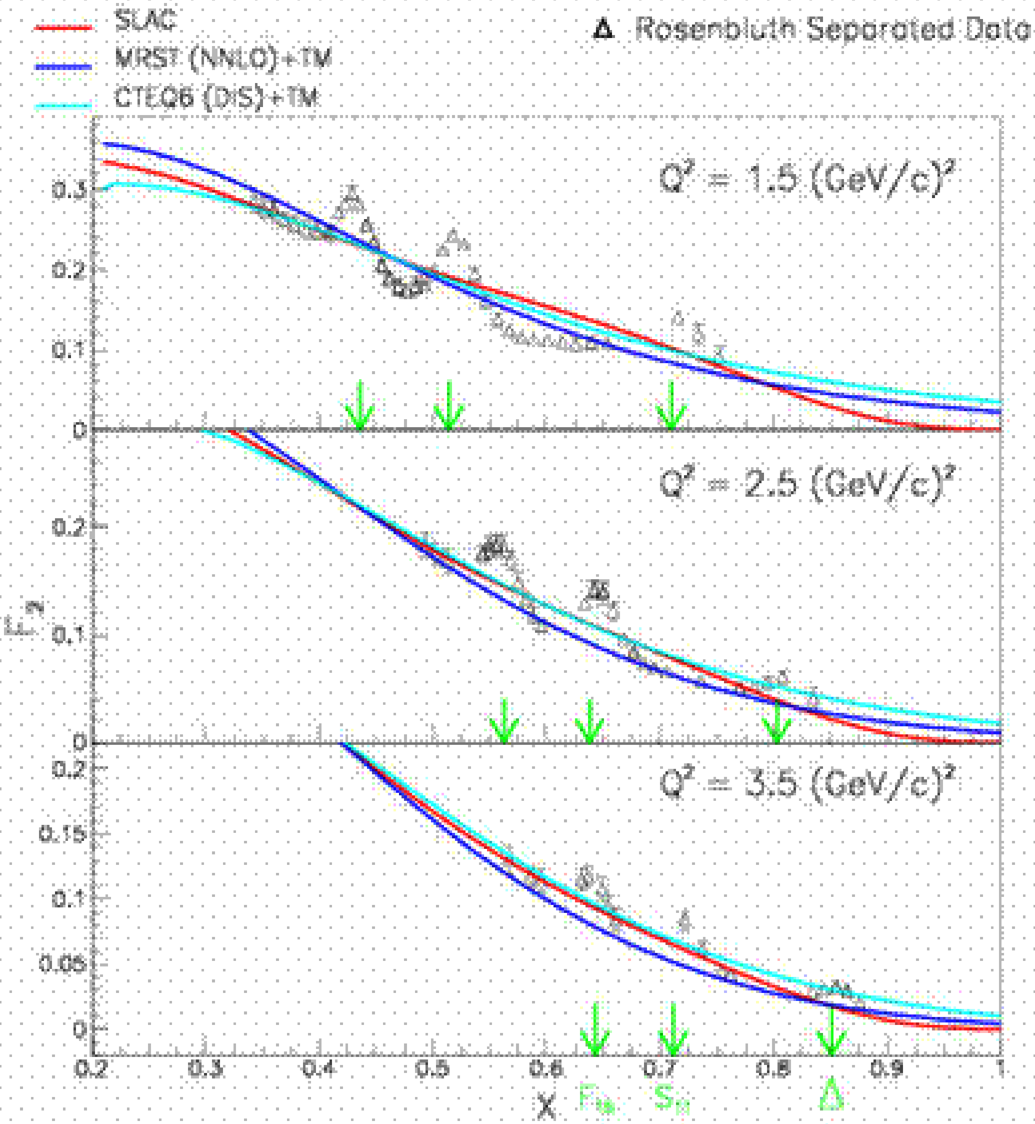
Now can truly obtain $F_2$ structure function data, and compare with DIS fits or QCD calculations/fits (CTEQ/MRST)

Use Bjorken x instead of Bloom-Gilman's $\omega'$

- **Bjorken Limit: $Q^2$, $\nu \rightarrow \infty$**
- **Empirically, DIS region is where logarithmic scaling is observed: $Q^2 > 5$ GeV$^2$, $W^2 > 4$ GeV$^2$**
- **Duality: Averaged over W, logarithmic scaling observed to work also for $Q^2 > 0.5$ GeV$^2$, $W^2 < 4$ GeV$^2$, resonance regime**

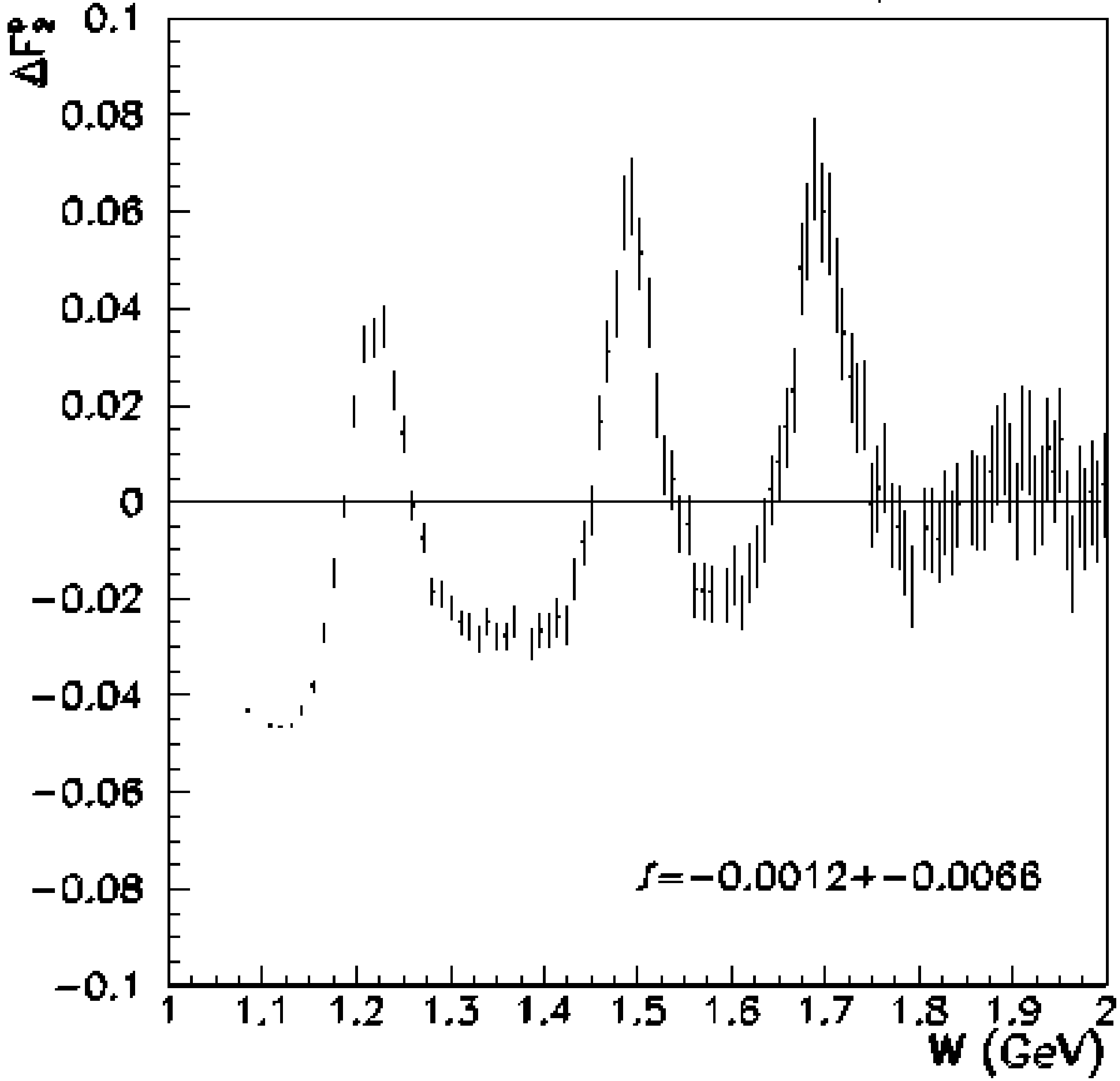
**(note: $x = Q^2/(W^2-M^2+Q^2)$)**

- **JLab results: Works quantitatively to better than 10% at such low $Q^2$**

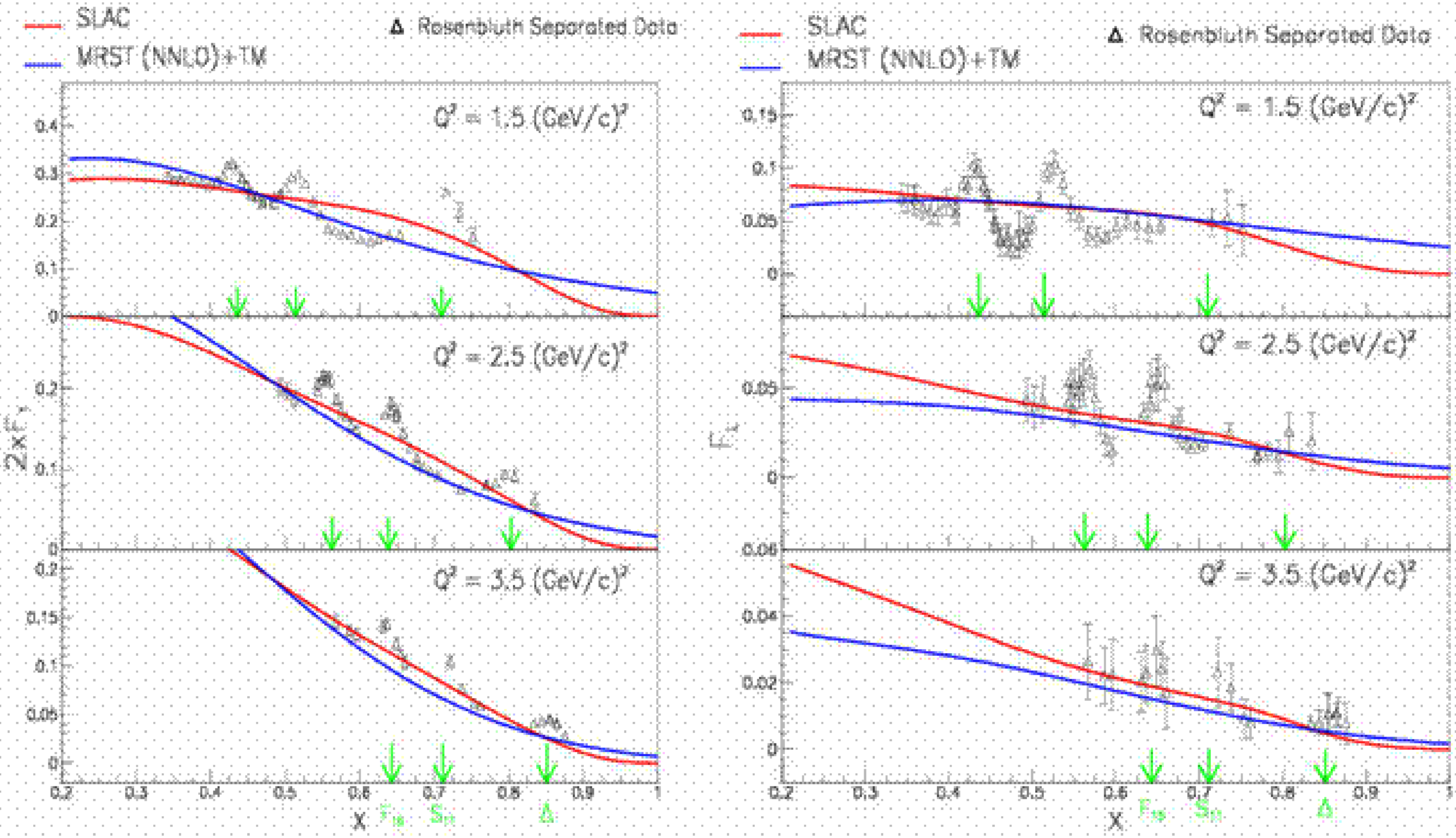


# Numerical Example: Resonance Region $F_2$
## w.r.t. Alekhin Scaling Curve

E=4 GeV, Θ=24 Deg (Q² ~ 1.5 GeV²)

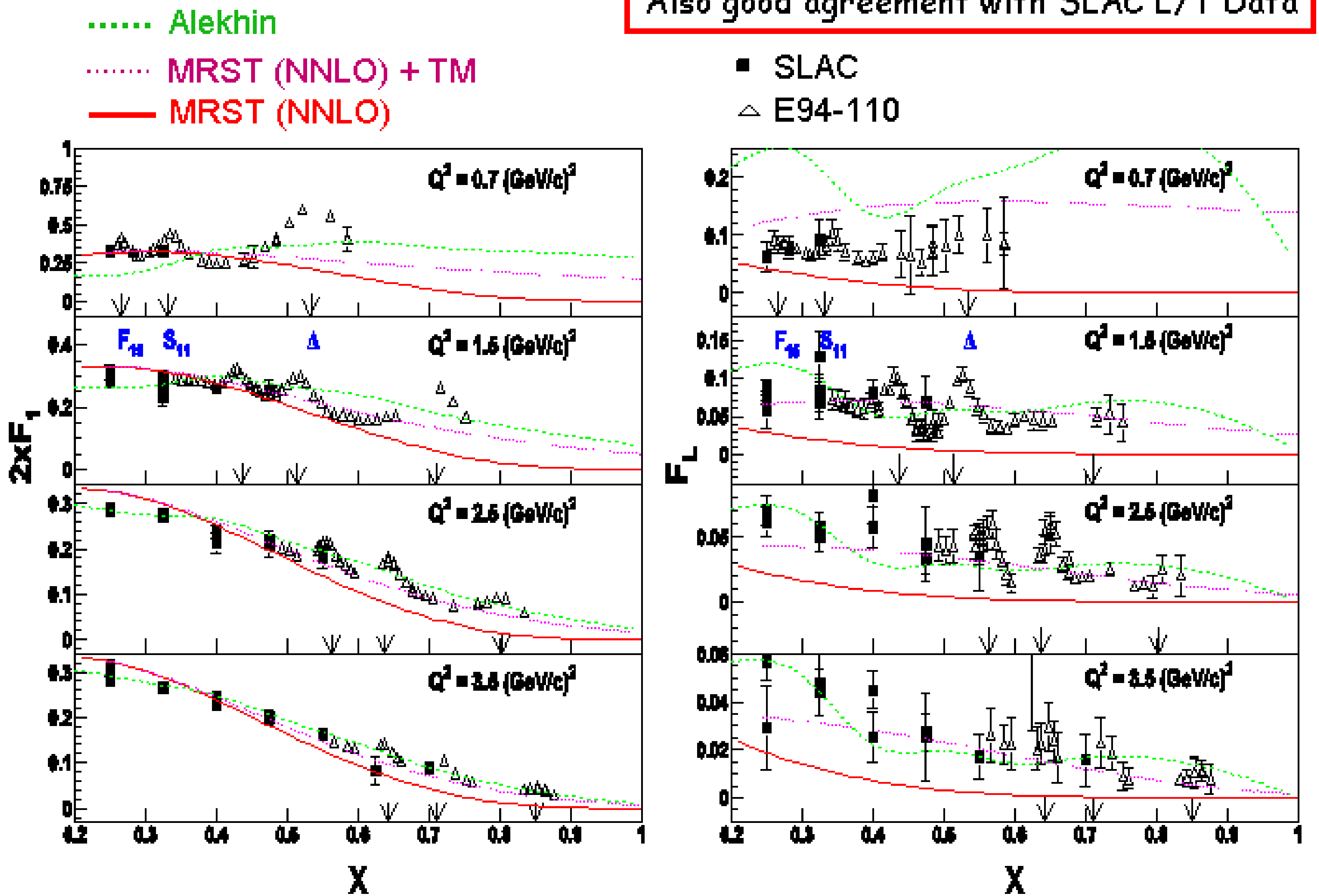


# Duality in $F_T$ and $F_L$ Structure Functions




Duality works well for both $F_T$ and $F_L$ above $Q^2 \sim 1.5$ (GeV/c)$^2$

Also good agreement with SLAC L/T Data



# Quark-Hadron Duality

***complementarity between quark and hadron descriptions of observables***

**At high enough energy:**

Hadronic Cross Sections averaged over appropriate energy range

Perturbative Quark-Gluon Theory

$$\sum_{\text{hadrons}} = \sum_{\text{quarks+gluons}}$$

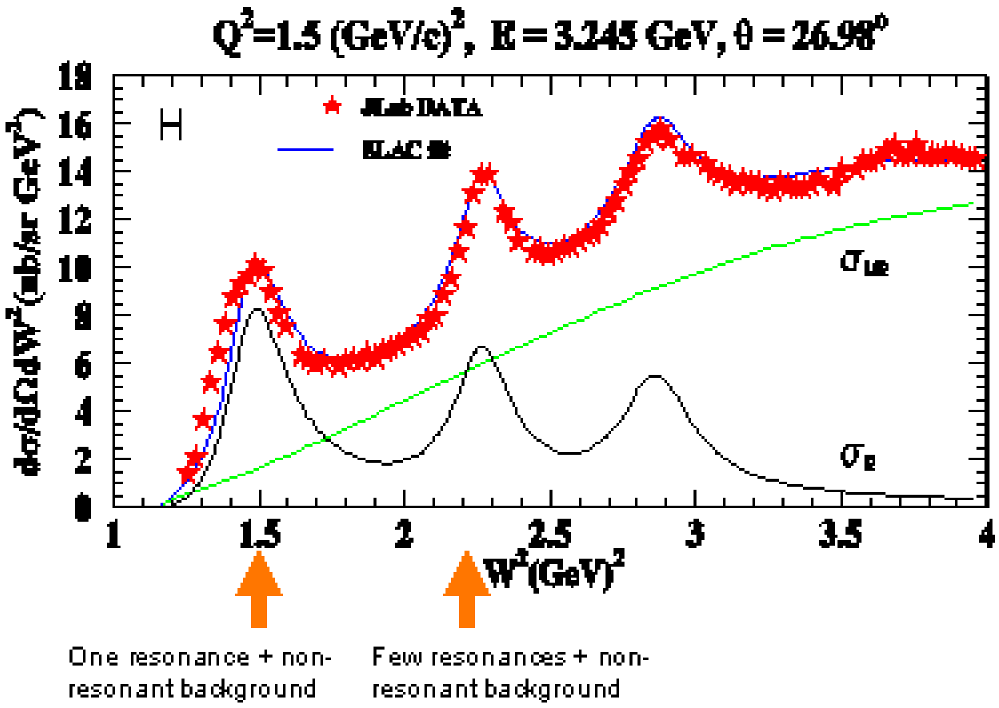
***Can use either set of complete basis states to describe physical phenomena***

***But why also in limited local energy ranges?***

If one integrates over all resonant and non-resonant states, quark-hadron duality should be shown by any model. This is simply unitarity.

However, quark-hadron duality works also, for $Q^2 > 0.5$ (1.0) $GeV^2$, to better than 10 (5) % for the $F_2$ structure function in both the N-Δ region and the N-$S_{11}$ region!

*(Obviously, duality does not hold on top of a peak! -- One needs an appropriate energy range)*




Why does local quark-hadron duality work so well, at such low energies?

~ quark-hadron transition

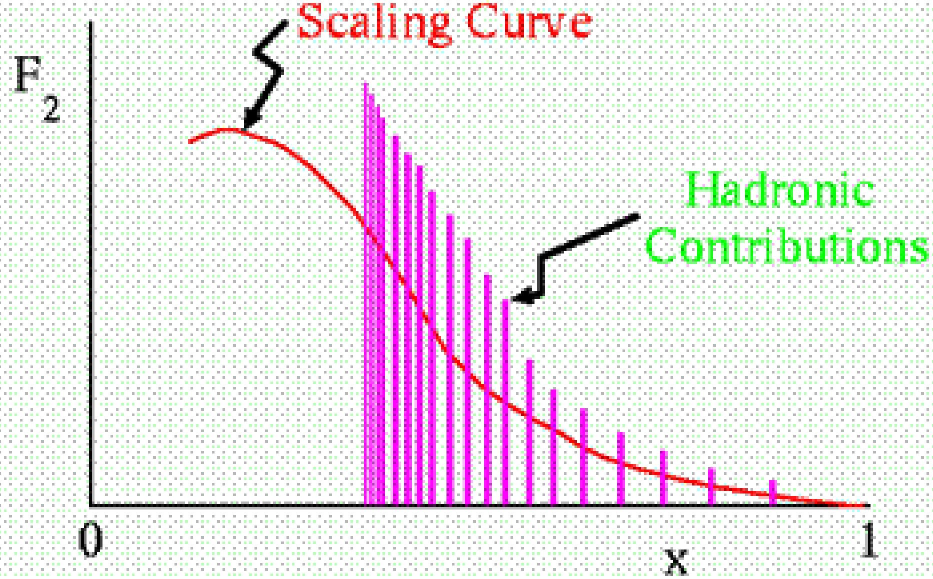
Confinement is local ….

# Quark-Hadron Duality - Theoretical Efforts

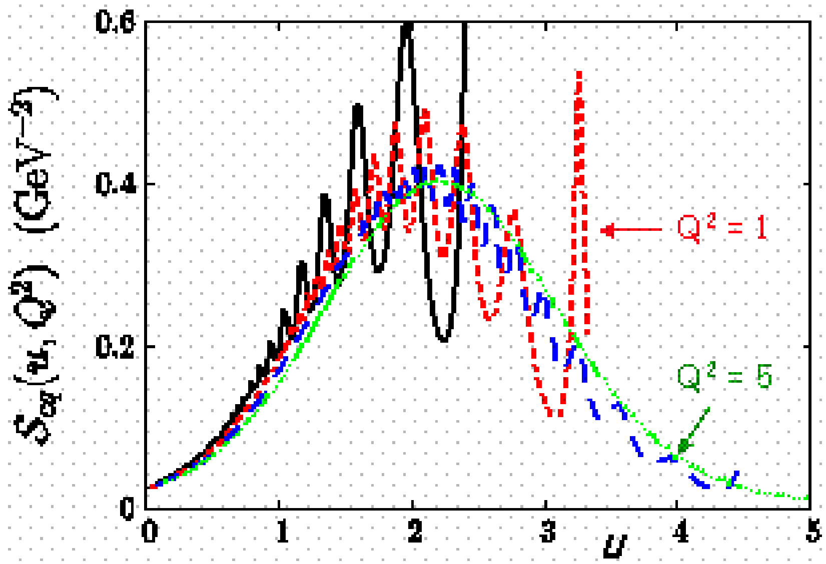
N. Isgur et al : $N_c \to \infty$

$q\bar{q}$ infinitely narrow resonances

$qqq$ only resonances




One heavy quark, Relativistic HO




Scaling occurs rapidly!

- Distinction between Resonance and Scaling regions is spurious
- Bloom-Gilman Duality must be invoked even in the Bjorken Scaling region
  → Bjorken Duality

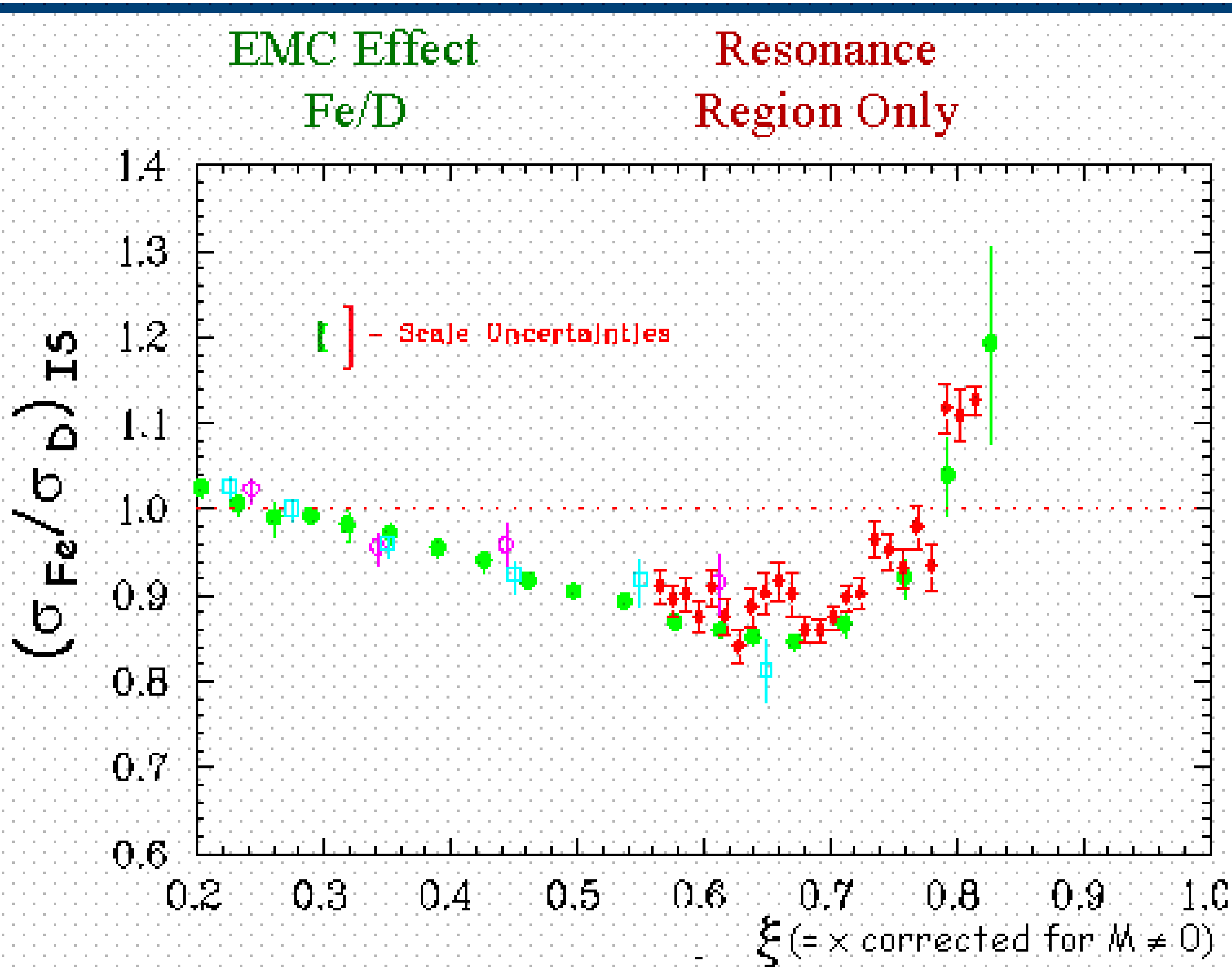
F. Close et al : SU(6) Quark Model

How many resonances does one need to average over to obtain a complete set of states to mimic a parton model?

→ 56 and 70 states o.k. for closure

→ Similar arguments for e.g. DVCS and semi-inclusive reactions

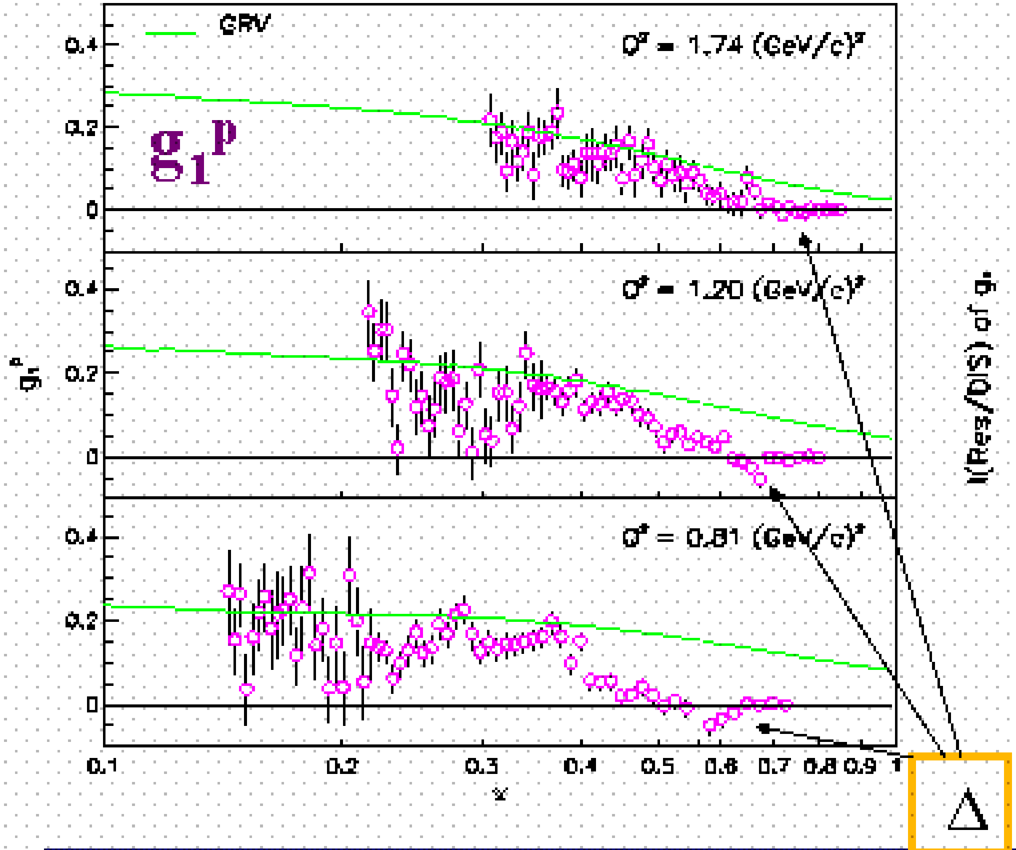
# Duality "easier" established in Nuclei




Nucleons have Fermi motion in a nucleus → **The nucleus does the averaging for you!**

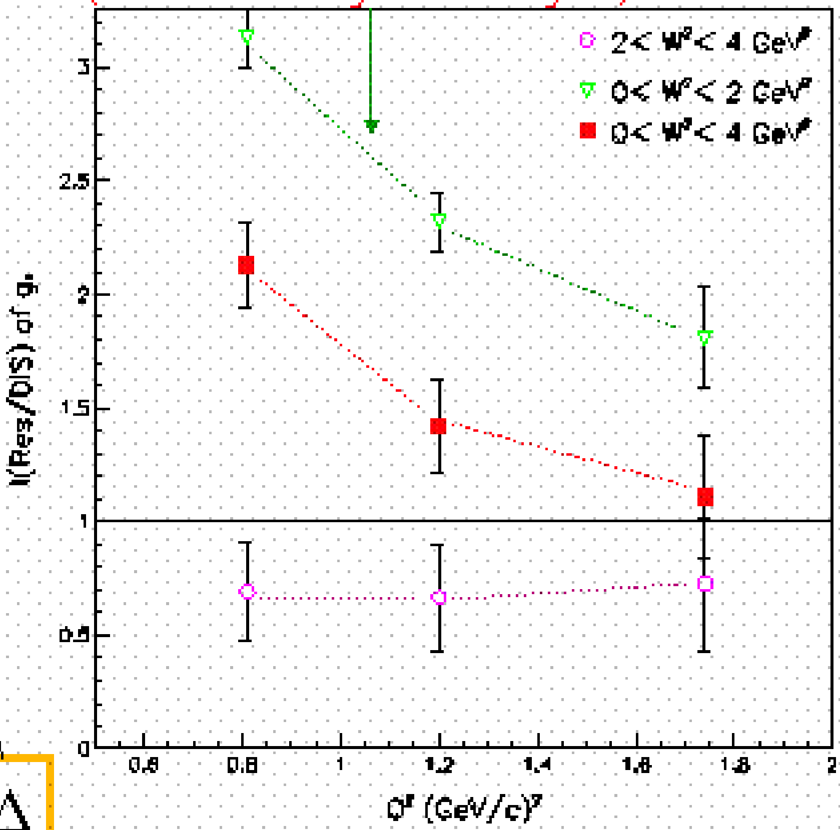
# ... but tougher in Spin Structure Functions

CLAS EG1




Pick up effects of both N and Δ

(the Δ is not negative enough...)



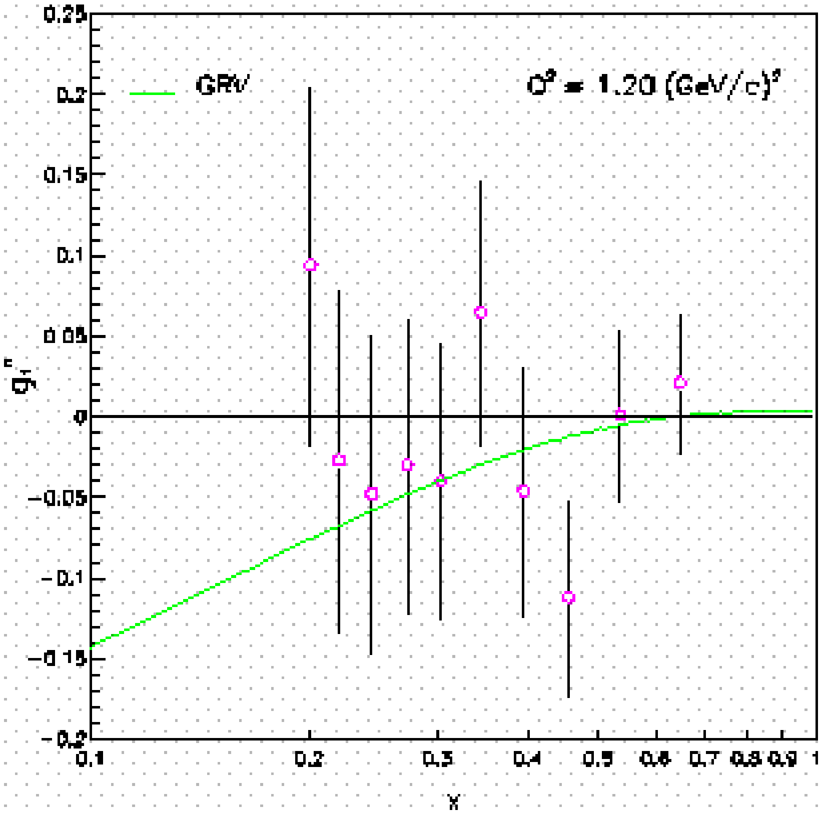

**CLAS: N-Δ transition region turns positive at $Q^2$ = 1.5 (GeV/c)$^2$**

**Elastic and N-Δ transition cause most of the higher twist effects**

# ... but tougher in Spin Structure Functions (cont.)

SLAC E143: $g_1^p$ and $g_1^d$ data combined

$g_1^n$




Hint of overall negative $g_1^n$ even in resonance region at $Q^2 = 1.2\ (GeV/c)^2$
Duality works better for neutron than proton? – Under investigation

# Summary

- Performed precision inclusive cross section measurements in the nucleon resonance region (~ 1.6% pt-pt uncertainties)
- R exhibits resonance structure (first observation)
  - Significant longitudinal resonant component observed.
- Prominent resonance enhancements in R and $F_L$ different from those in transverse and $F_2$
- Quark-hadron duality is observed for ALL unpolarized structure functions.
  - Quarks and the associated Gluons (the Partons) are tightly bound in Hadrons due to Confinement. Still, they rely on camouflage as their best defense:
    a limited number of confined states acts as if consisting of free quarks → Quark-Hadron Duality, which is a non-trivial property of QCD, telling us that contrary to naïve expectation quark-quark correlations tend to cancel on average
- Observation of surprising strength in the longitudinal channel at Low $Q^2$ and $x \sim 0.1$

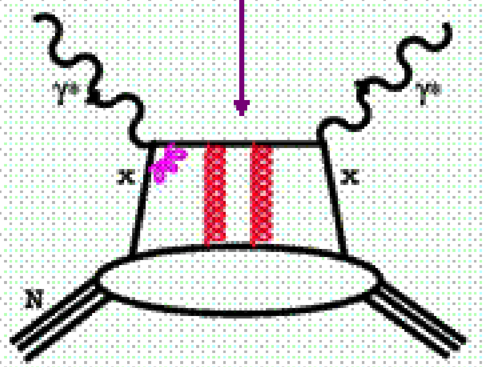
# QCD and the Operator-Product Expansion

- Moments of the Structure Function $M_n(Q^2) = \int_0^1 dx\ x^{n-2} F(x,Q^2)$

  If n = 2, this is the Bloom-Gilman duality integral!
- Operator Product Expansion

$$M_n(Q^2) = \sum_{k=1}^{\infty} (nM_0^{\,2}/\,Q^2)^{k-1} B_{nk}(Q^2)$$

higher twist    logarithmic dependence




- Duality is described in the Operator Product Expansion

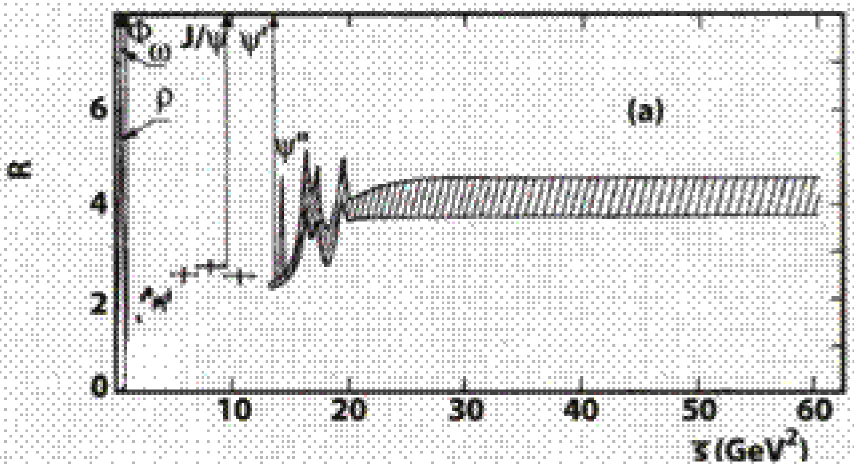
  *as higher twist effects being small or canceling*

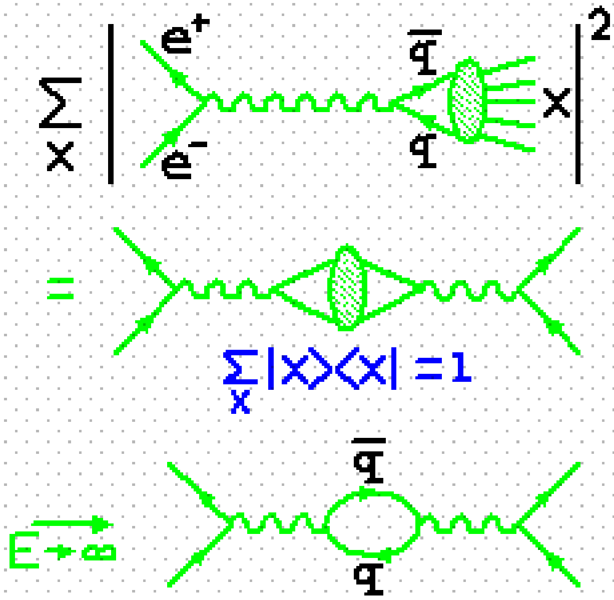
**DeRujula, Georgi, Politzer (1977)**

# Example: $e^+e^- \longrightarrow$ hadrons

Textbook Example

$$R = \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



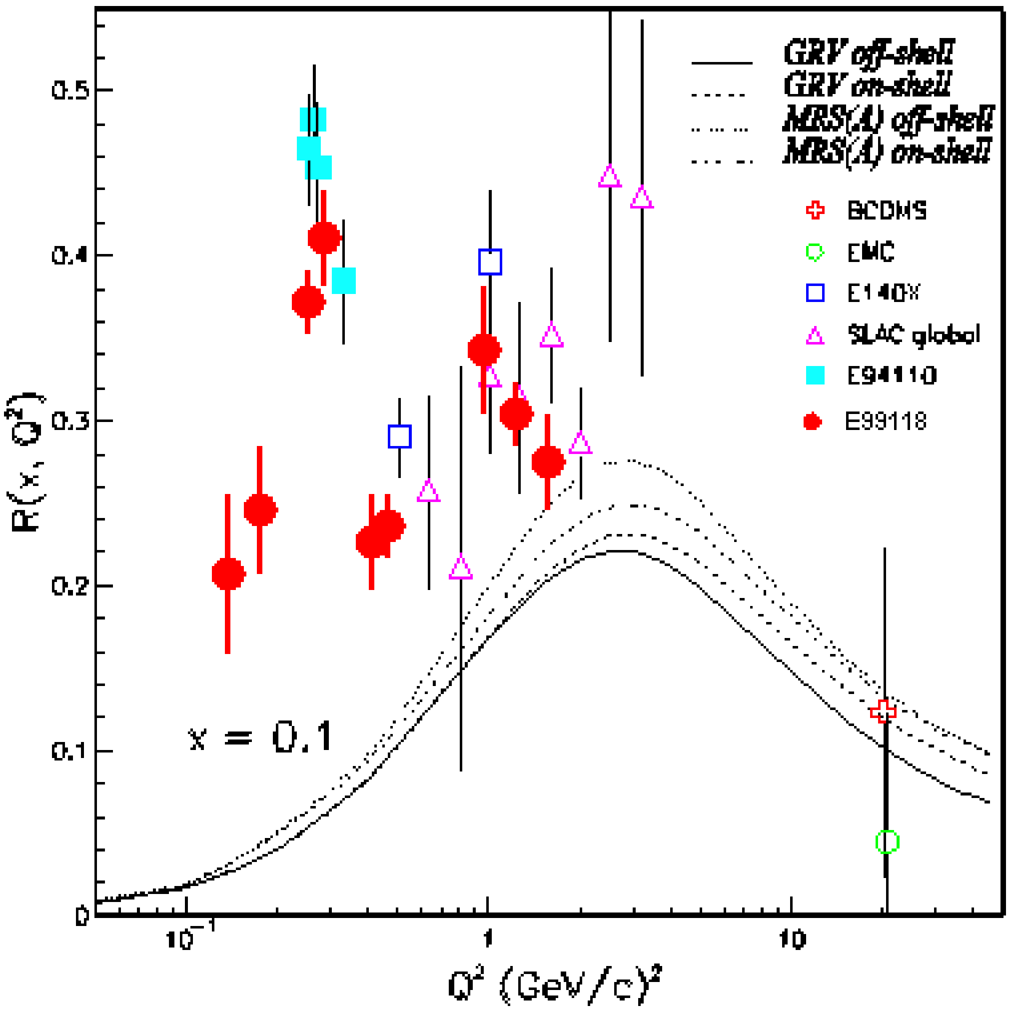




$$\lim_{E\to\infty} \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_q e_q^2$$

Only evidence of hadrons produced is narrow states oscillating around step function

## Preliminary: Still ΔR = 0.1 point-to-point

(mainly due to bin centering assumptions to x = 0.1)



# Model Iteration Procedure

Starting model is used for input for radiative corrections and in bin-centering the data in θ

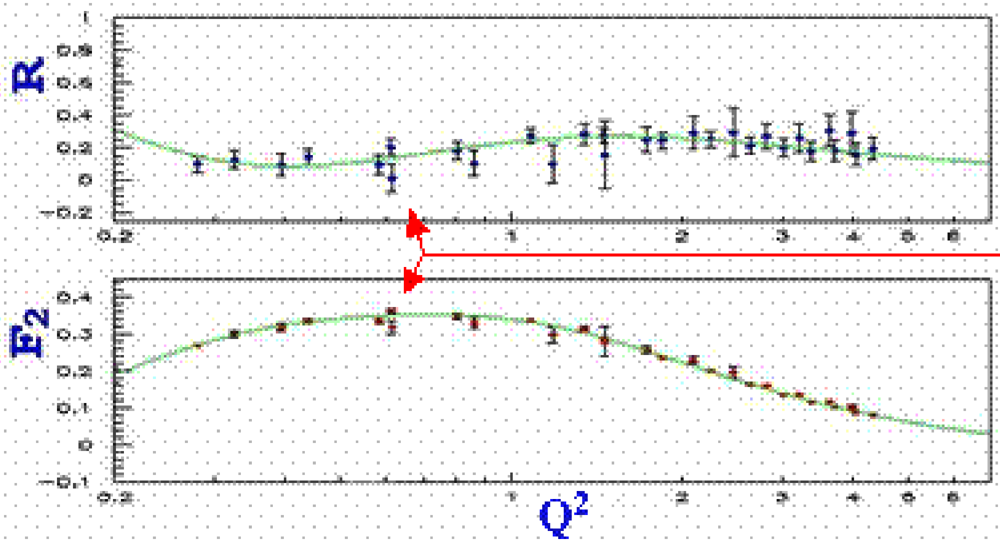
$\sigma^{exp}$ is extracted from the data

Model is used to decompose $\sigma^{exp}$ into $F_2^{exp}$ and $R^{exp}$

$Q^2$ dependence of both $F_2$ and $R$ is fit for each $W^2$ bin to get new model

# Example SF Iteration

3rd Resonance Peak, Iteration 0:

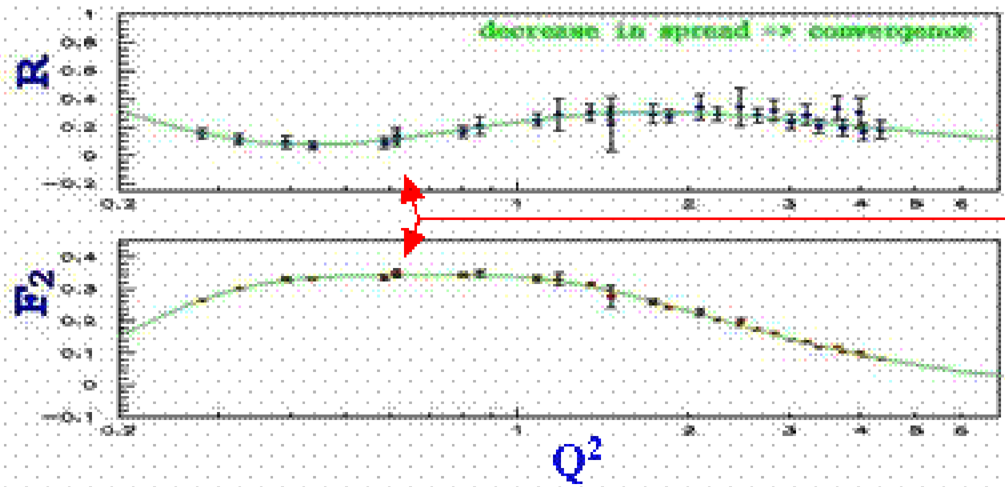



Measurements at different $\varepsilon$ are inconsistent $\Rightarrow$

started with wrong splitting of strength!

3rd Resonance Peak, Iteration 2:

Iteration results in shuffling of strength



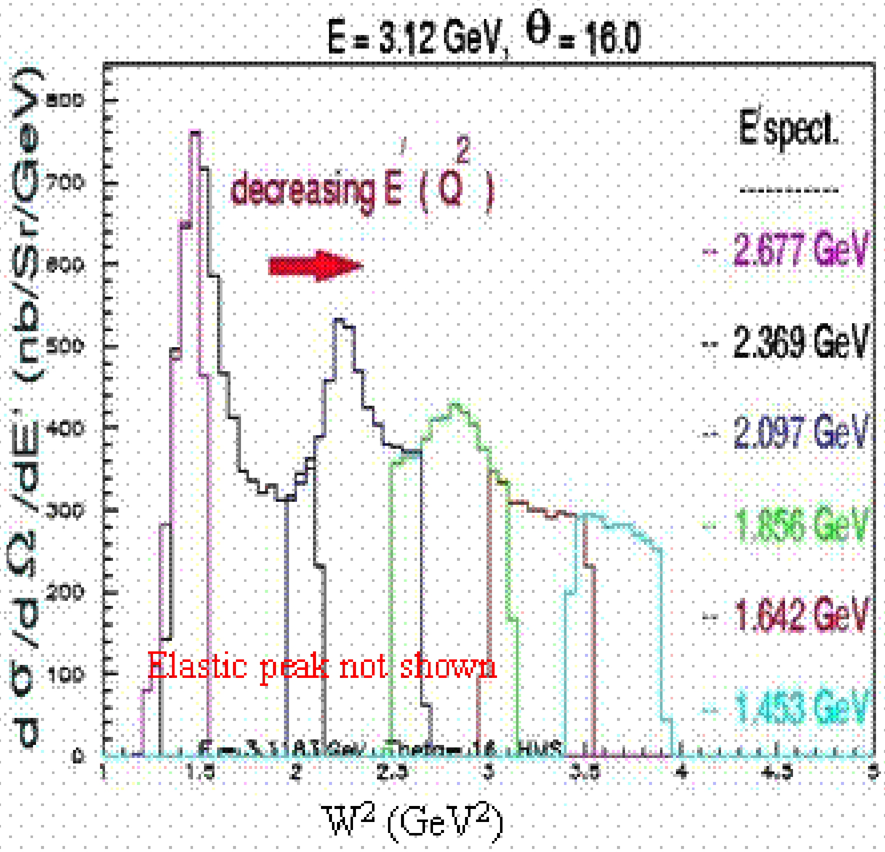

Consistent values of the separated structure functions for all $\varepsilon$ !

# Point-to-Point Systematic Uncertainties for E94-110

| Quantity | Uncertainty | $\delta_\sigma(\%)$ |
|---|---|---|
| Beam energy | $\sim 5 \times 10^{-4}$ | 0.30 |
| Scattered $e^-$ energy | $\sim 5 \times 10^{-4}$ | 0.25 |
| Scattering $e^-$ angle | $\sim 0.2$ mrad | 0.26 |
| Target density (relative) | 0.05% | 0.05 |
| Beam charge (relative) | 0.1% | 0.1 |
| Dead Time Correction | 0.2% | 0.2 |
| Detector Efficiency | 0.55% | 0.55 |
| $e+/e-$ background | 0.2% | 0.2 |
| Acceptance | 0.7% | 0.7 |
| Model Dependence | 0.6% | 0.6 |
| Radiative Correction ($\epsilon$) | 1.05% | 1.05 |
| Total point-to-point | | 1.6 |

**Total point-to-point systematic uncertainty for E94-110 is 1.6%.**

# Experimental Procedure and CS Extraction

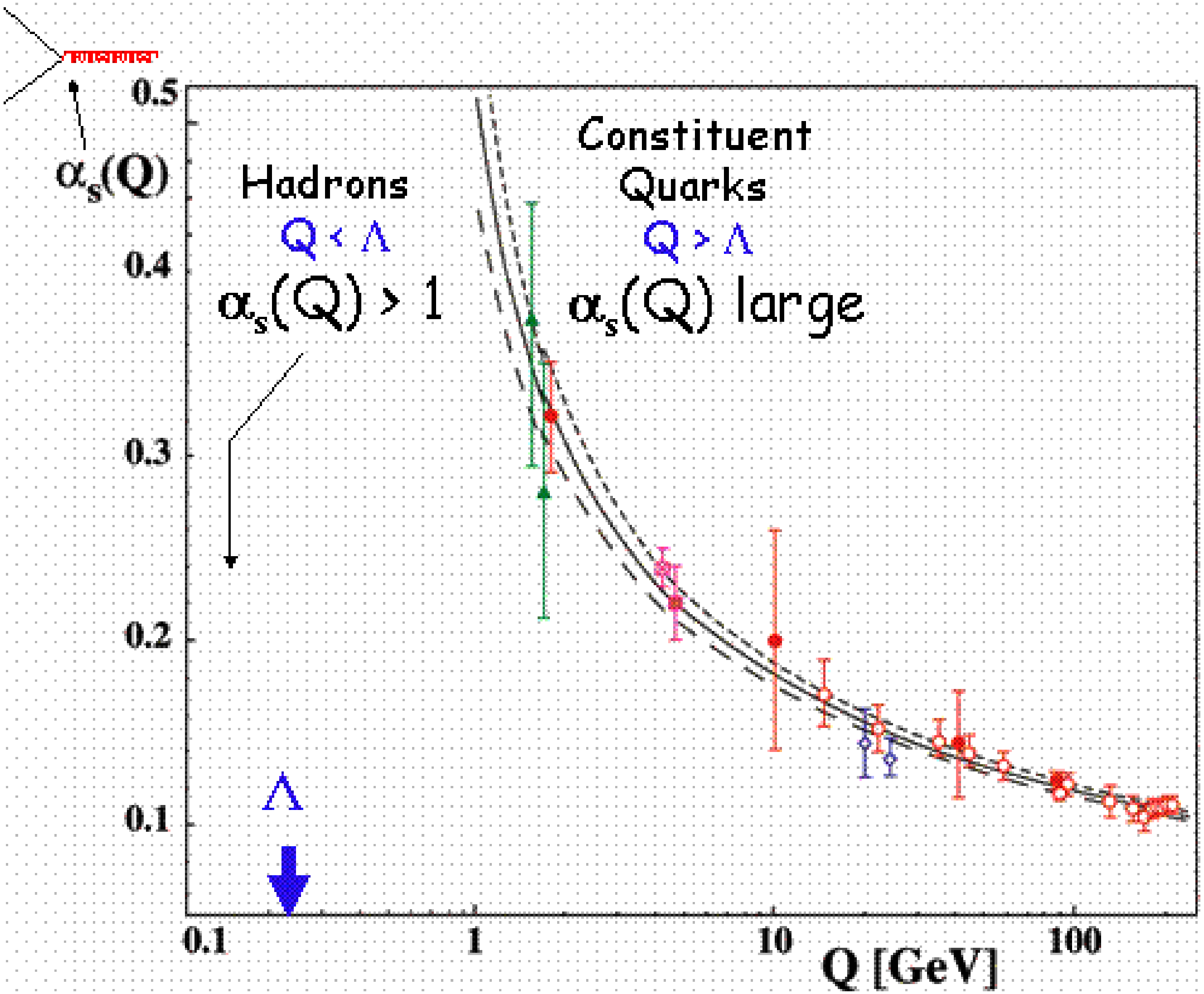



- At fixed $E_{beam}$, $\theta_c$, scan E' from elastic to DIS. ($dp/p$ =+/-8%, $d\theta$ =+/-32 mrad)
- Repeat for each $E_{beam}$, $\theta_c$ to reach a range in $\varepsilon$ for each $W^2$, $Q^2$.

## Cross Section Extraction

- Acceptance correct $e^-$ yield bin-by-bin ($\delta$, $\theta$).
- Correct yield for detector efficiency.
- Subtract scaled dummy yield bin-by-bin, to remove $e^-$ background from cryogenic target aluminum walls.
- Subtract charge-symmetric background from $\pi^0$ decay via measuring $e^+$ yields.
- bin-centering correction.
- radiative correction.

# QCD and the Parton-Hadron Transition




One parameter, $\Lambda_{QCD}$, ~ Mass Scale or Inverse Distance Scale where $\alpha_s(Q)$ = infinity

"Separates" Confinement and Perturbative Regions

Mass and Radius of the Proton are (almost) completely governed by

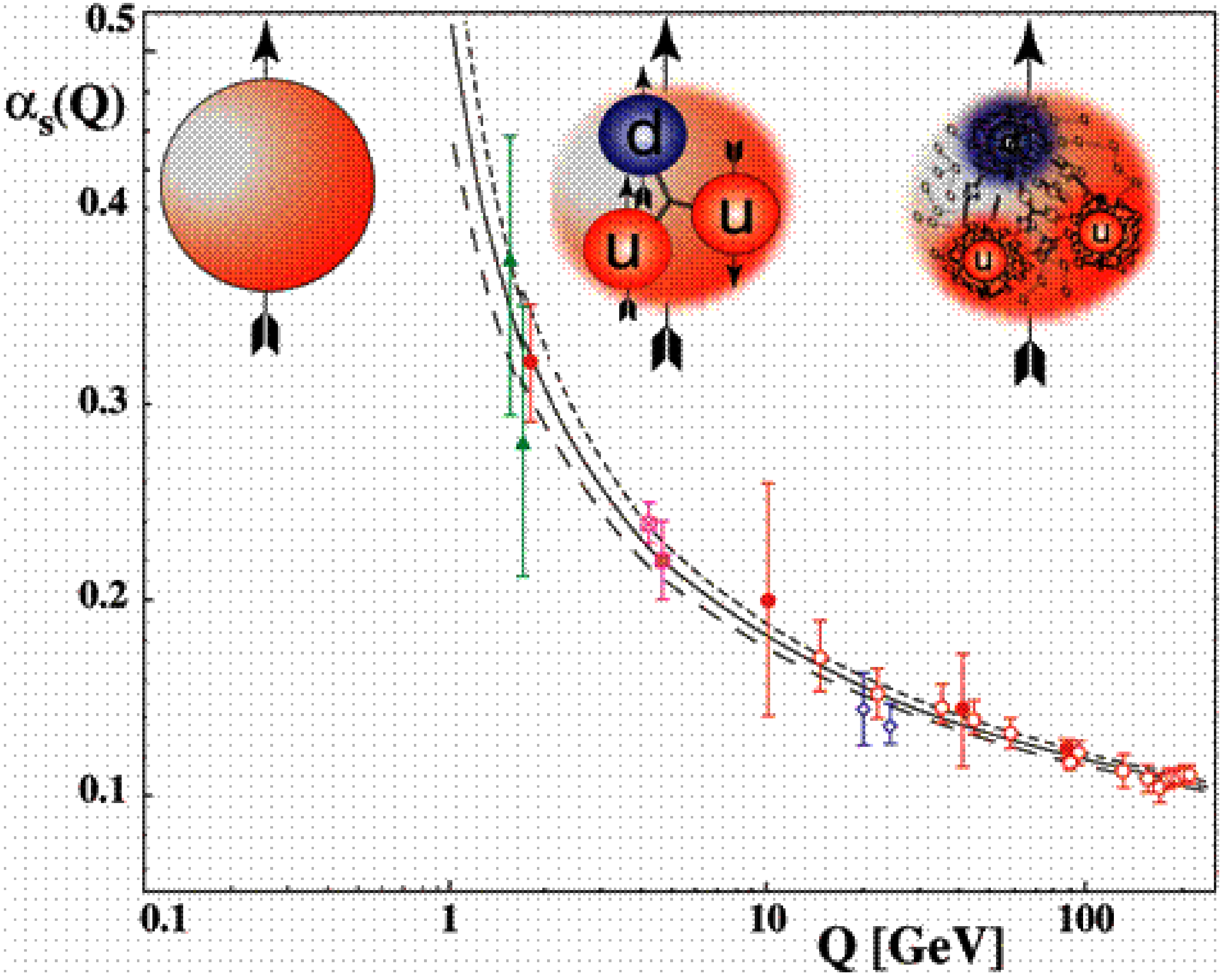
$\Lambda_{QCD} \approx 213$ MeV

Asymptotically Free Quarks

Q >> Λ

$\alpha_s(Q)$ small

# QCD and the Parton-Hadron Transition

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