Exploring Hadrons with Electromagnetic Probes: Structure, Excitations, Interactions
Jefferson Lab, November 3, 2017

Connecting resonance and deep-inelastic phenomena through quark-hadron duality

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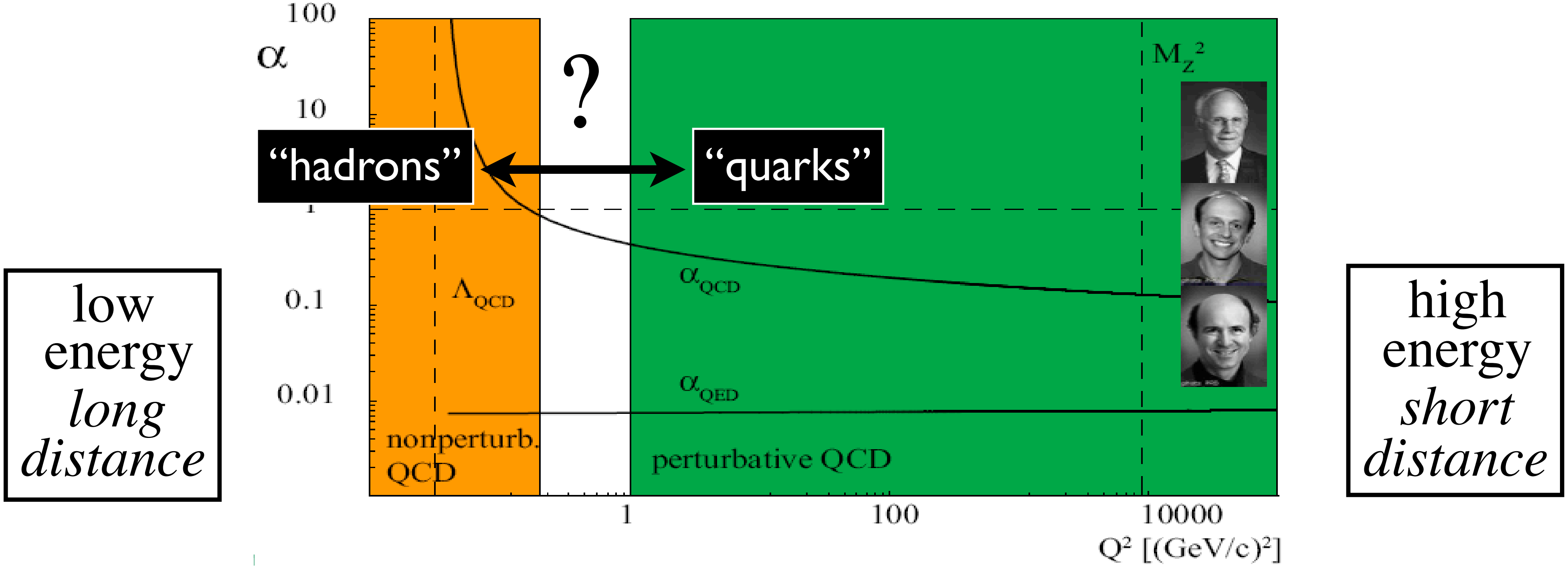
Outline

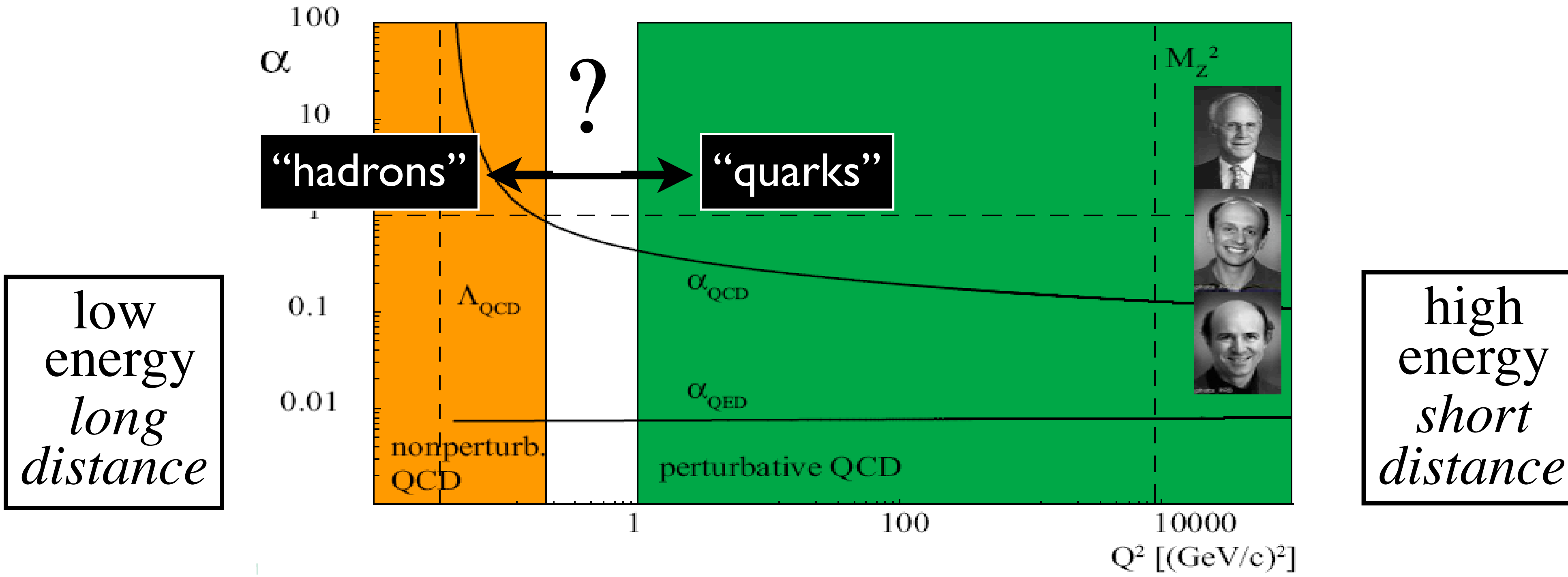
- Historical perspective
- Duality in QCD
  - $\longrightarrow$ resonances & higher twists
- Local duality
  - $\longrightarrow$ truncated moments
  - $\longrightarrow$ insights from models
- Applications of duality
  - $\longrightarrow$ global PDF analysis
  - $\longrightarrow$ single-hadron production
- Outlook



- Duality hypothesis: complementarity between *quark* and *hadron* descriptions of observables

$$\sum_{hadrons} = \sum_{quarks}$$

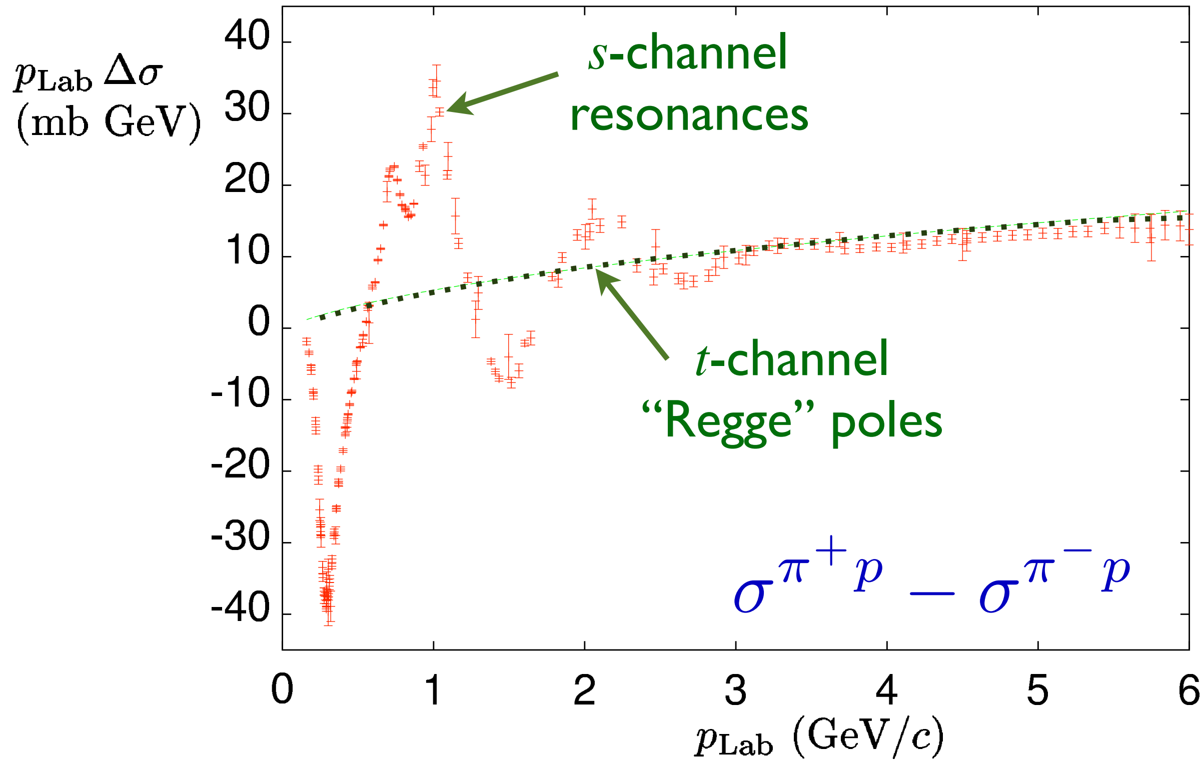
$\longrightarrow$ can use either set of *complete* basis states to describe physical phenomena



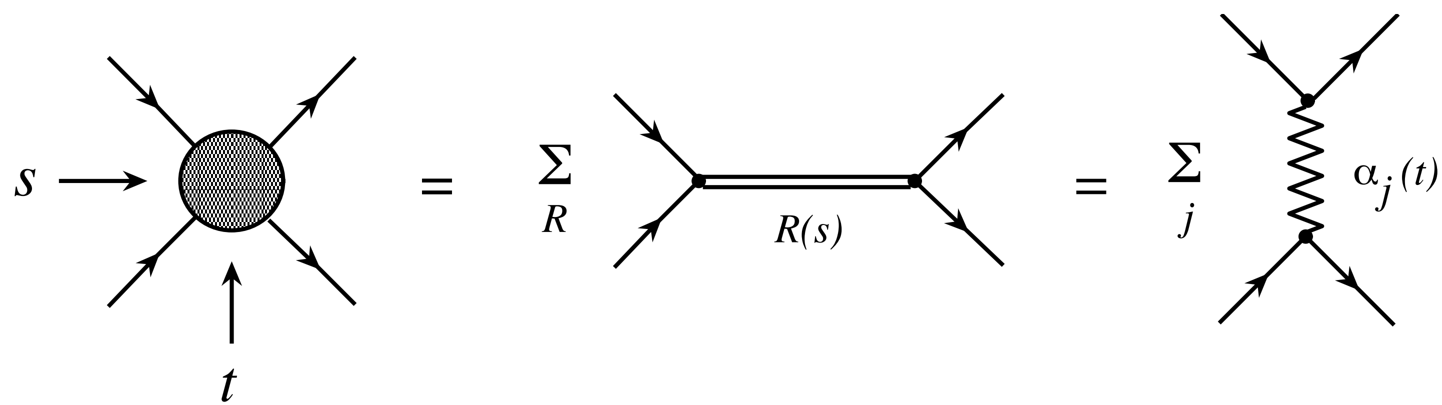
- In practice, at *finite energy* typically access only *limited* set of basis states

- Question is not “*why* duality exists”, but
  — *how* it arises?
  — how can we make *use* of it (in a controlled way)?

Duality in hadron-hadron scattering



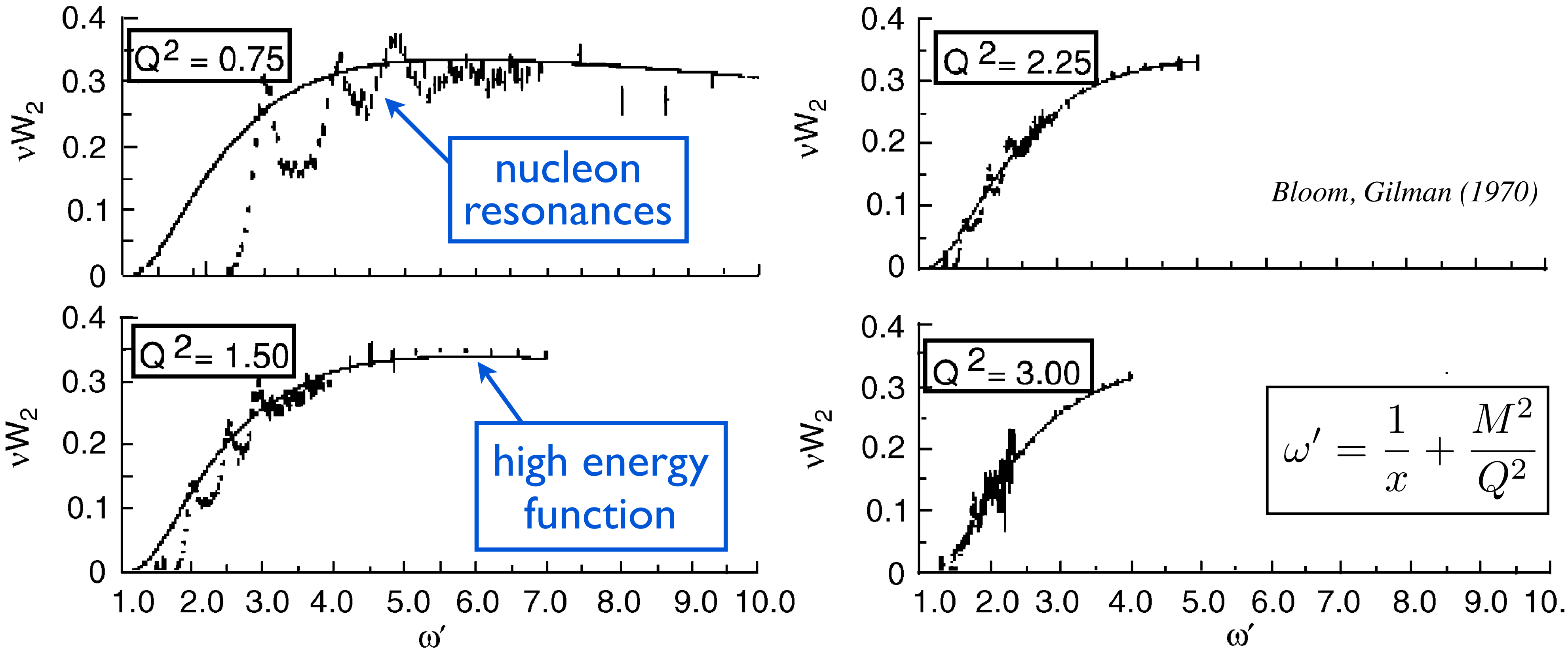
Igi (1962)
Dolen, Horn, Schmidt (1968)



$s - t$ channel duality

Duality in electron-proton scattering

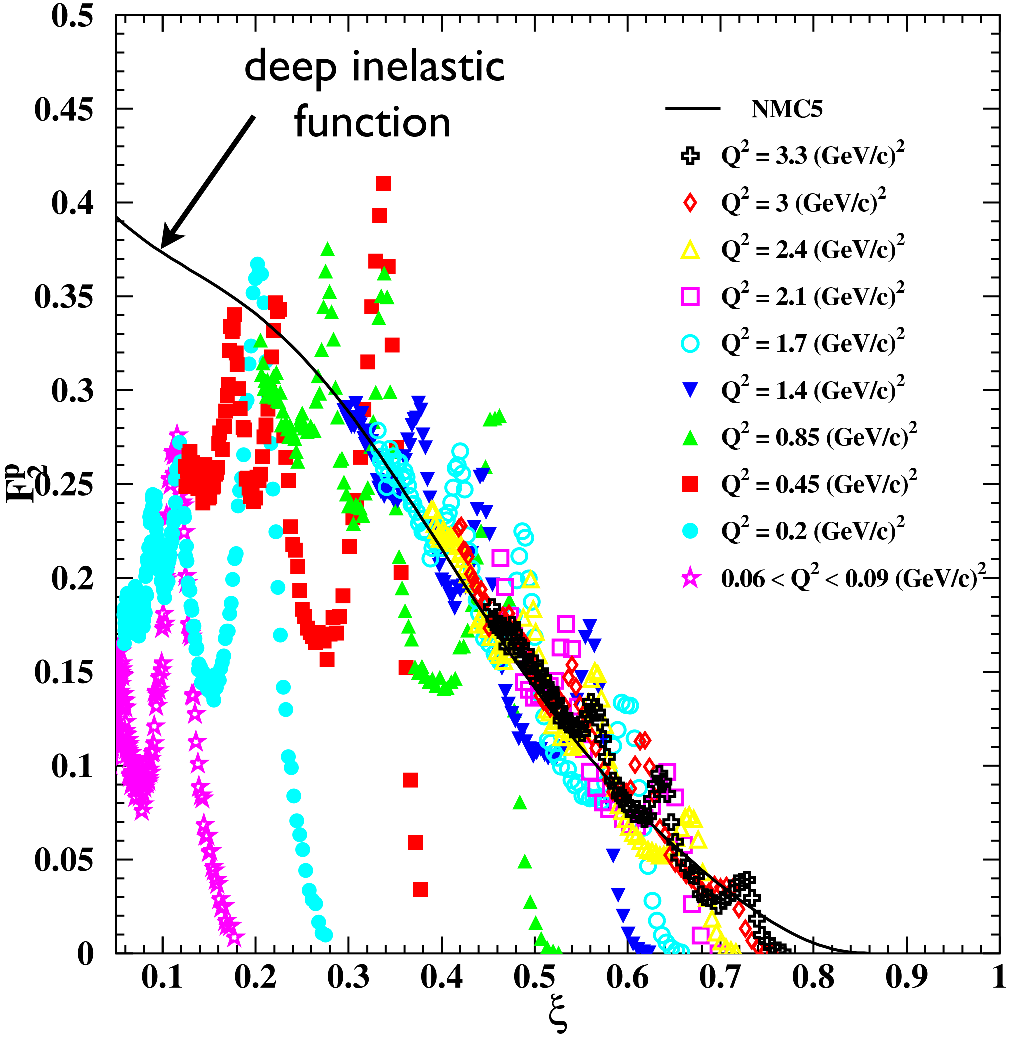
"Bloom-Gilman duality"



"hadrons" $$\frac{2M}{Q^2}\int_0^{\nu_m} d\nu\ \nu W_2(\nu, Q^2) = \int_1^{\omega'_m} d\omega'\ \nu W_2(\omega')$$ "quarks"

finite-energy sum rules

Duality in electron-proton scattering



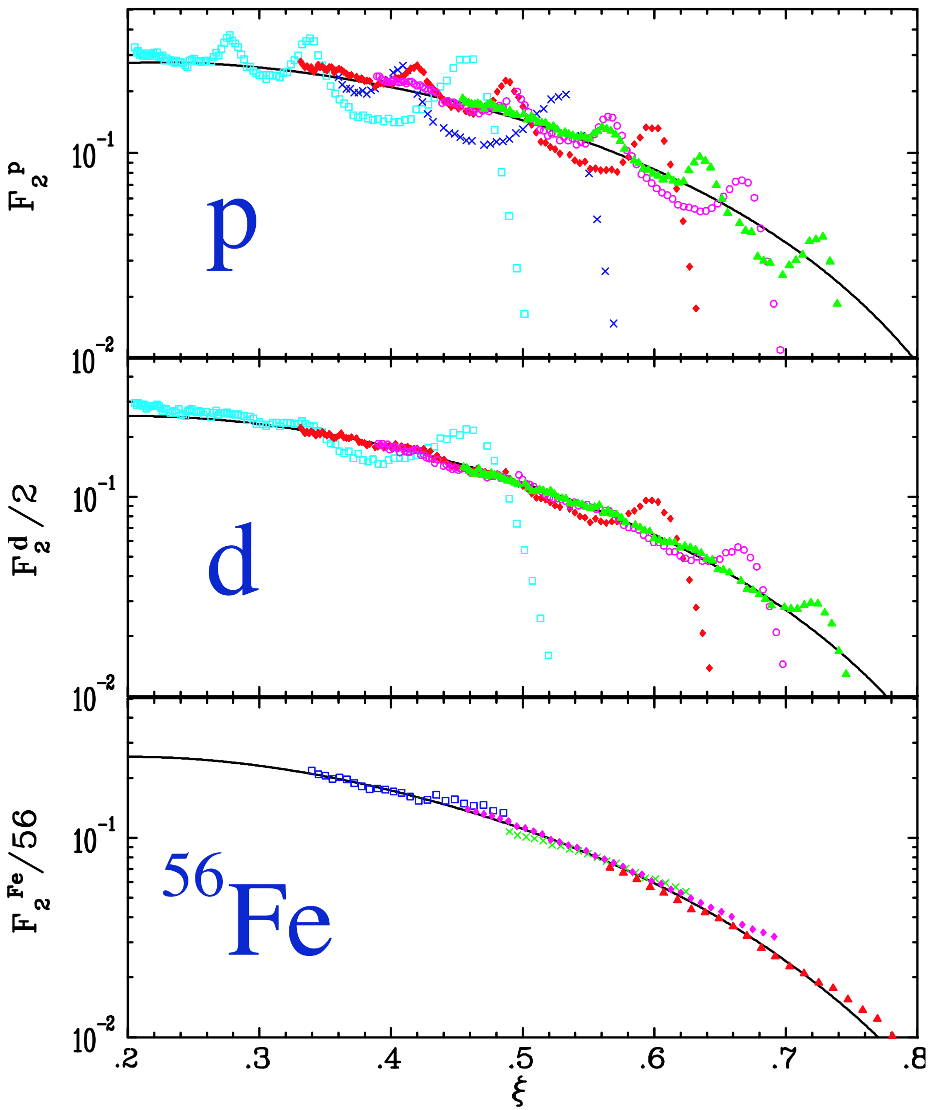
Niculescu et al. (2000)

$$\xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}}$$

- average over resonances
  (strongly Q^2 dependent)

  $\approx$ Q^2 independent scaling function

Duality in electron-nucleus scattering

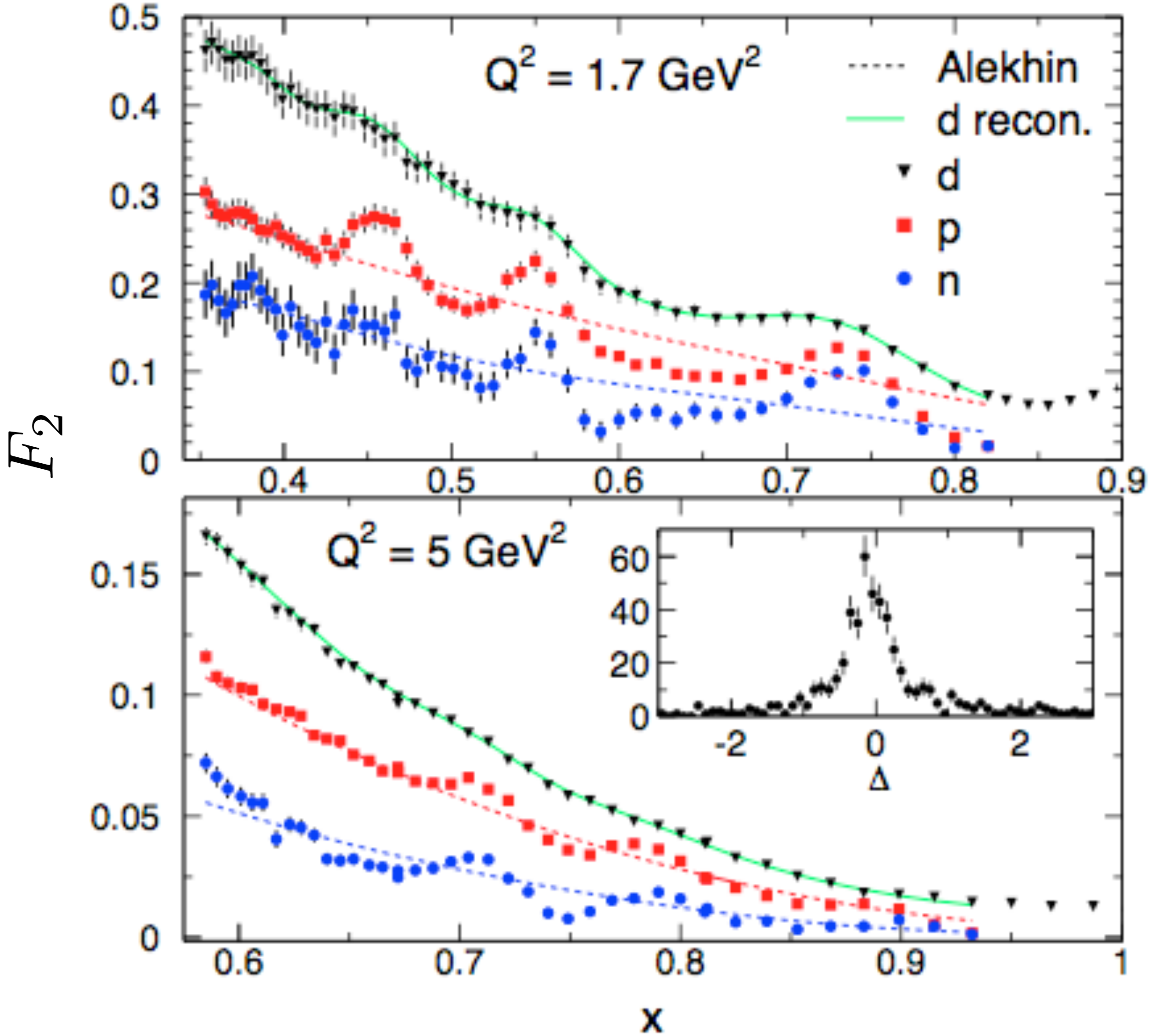


WM, Ent, Keppel (2005)

- further resonance averaging from Fermi smearing in *nuclear* structure functions

Duality in electron-neutron scattering

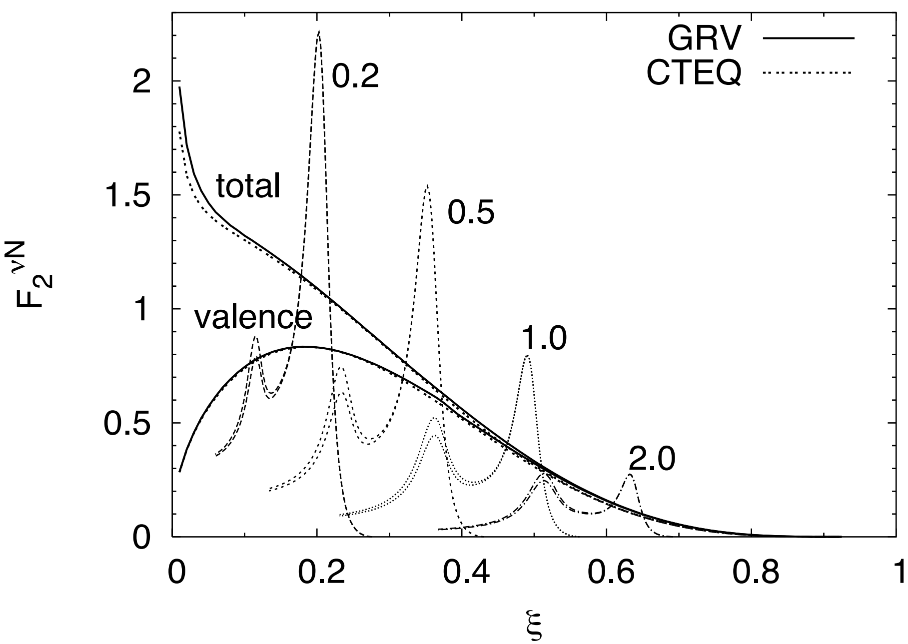
No free neutron targets, but (new) iterative method allows neutron resonance structure function to be extracted

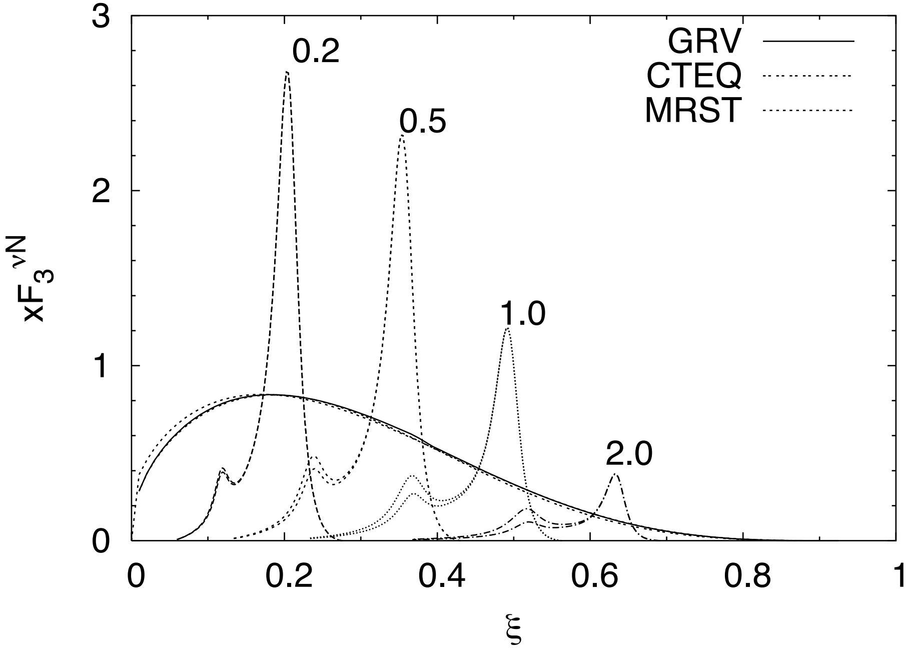


Malace, Kahn, WM, Keppel (2010)

- evidence for duality also in neutron!

Duality in neutrino-nucleon scattering





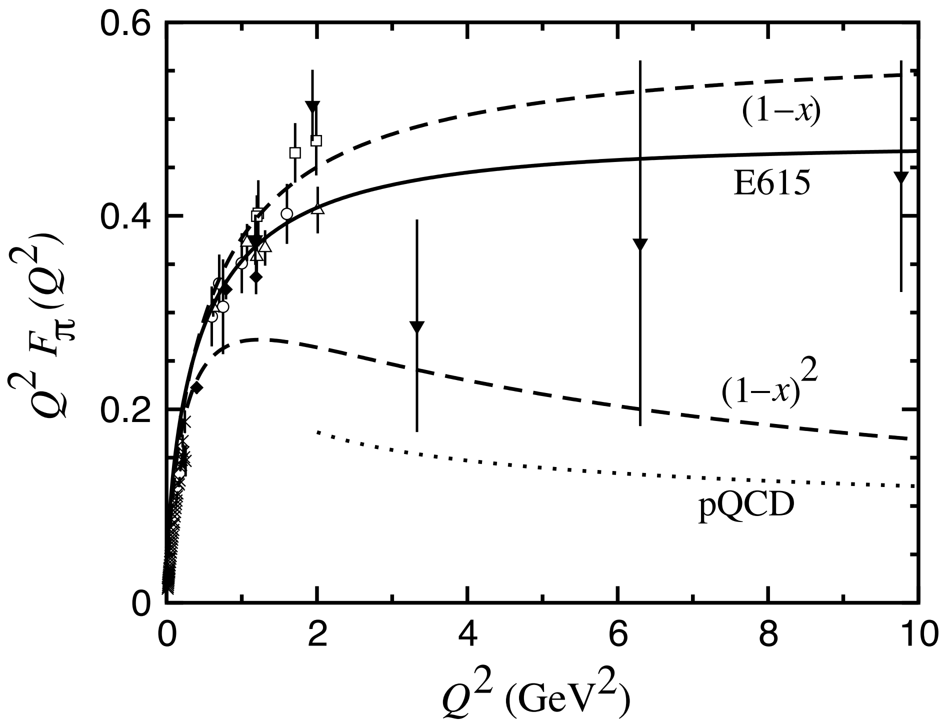
Lalakulich, WM, Paschos (2007)

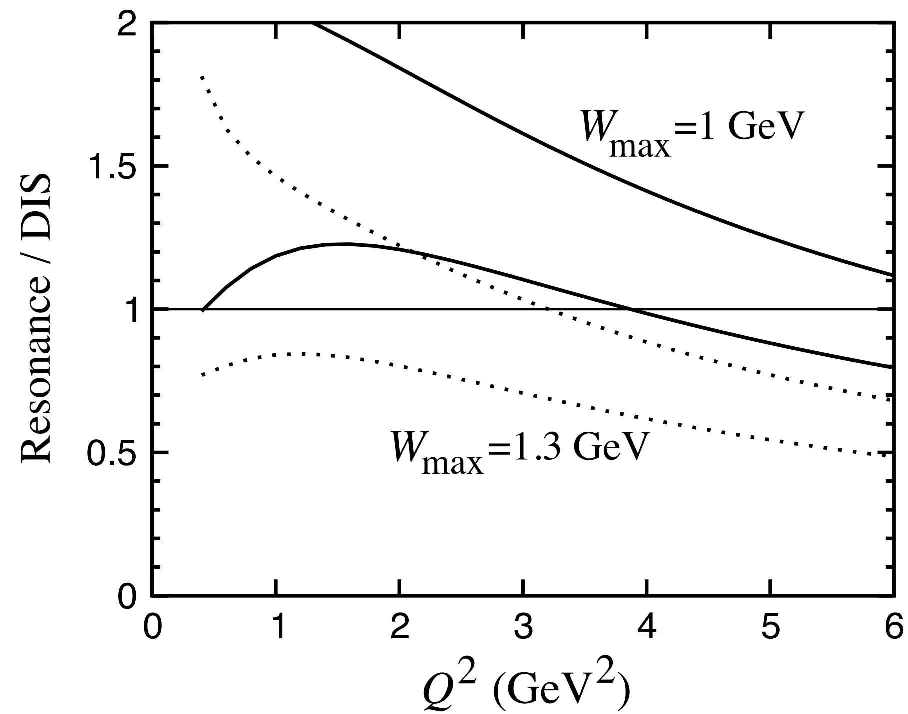
- indications of duality in neutrino structure functions from models of weak transition matrix elements from resonance neutrino-production data (FNAL, ANL)

Duality in electron-pion scattering (?)

Extend finite-energy sum rule to threshold region

$$\left[F_\pi(Q^2)\right]^2 \approx \int_1^{\omega_{\max}} d\omega\ \nu W_2^\pi(\omega) \qquad \omega = 1/x\,, \quad \omega_{\max} = 1 + (W_{\max}^2 - m_\pi^2)/Q^2$$





→ Q^2 dependence of FF correlated with $x \to 1$ behavior of SF

→ nontrivial relation between L and T cross sections?

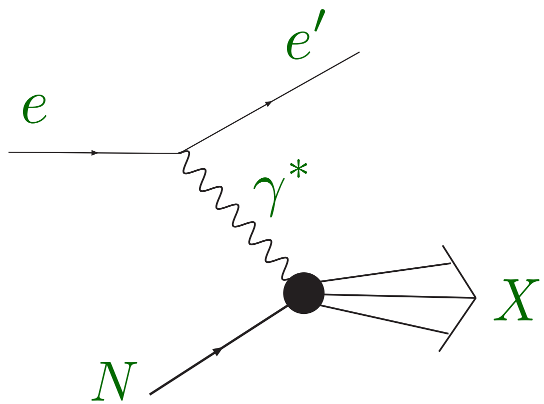
→ $F_\pi^2 + \left(1 + \frac{m_\rho^2 - m_\pi^2}{Q^2}\right) F_{\pi\rho}^2$

Duality in QCD

– global duality –

Duality and QCD

- Kinematics of inclusive deep-inelastic scattering (DIS)



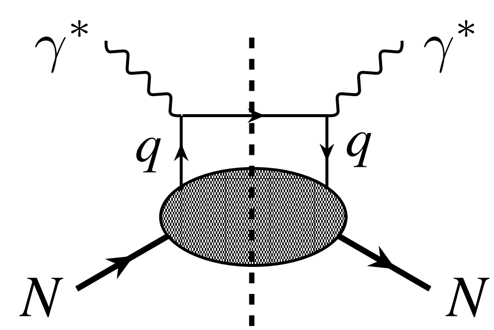
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$\nu = E - E'$$
$$Q^2 = \vec{q}^{\,2} - \nu^2$$
$$W^2 = M^2 + Q^2\frac{(1-x)}{x}$$

$$x = \frac{Q^2}{2M\nu}$$

- In *deep-inelastic* region $(W \gtrsim 2\ \mathrm{GeV},\ Q^2 \gtrsim 1\ \mathrm{GeV}^2)$ structure functions given by parton distributions

$$F_2(x,Q^2) \stackrel{\mathrm{LO}}{=} x\sum_q e_q^2\, q(x,Q^2)$$



Duality and QCD

- Operator product expansion in QCD

$\longrightarrow$ expand *moments* of structure functions in powers of $1/Q^2$

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x,Q^2)$$

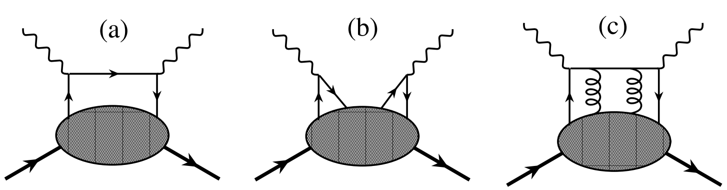
$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" τ

$e.g.\ \ \langle N|\,\overline{\psi}\,\gamma^+\psi\,|N\rangle$

$\langle N|\,\overline{\psi}\,\widetilde{G}^{+\nu}\gamma_\nu\,\psi\,|N\rangle$

etc.



$\tau = 2$ $\qquad \tau > 2$

$\tau = \mathrm{dimension} - \mathrm{spin}$

Duality and QCD

- Operator product expansion in QCD

  $\longrightarrow$ expand *moments* of structure functions in powers of $1/Q^2$

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x, Q^2)$$
$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

- If moment $\approx$ independent of Q^2

  $\longrightarrow$ "higher twist" terms $A_n^{(\tau>2)}$ small

- Duality $\longleftrightarrow$ suppression of higher twists

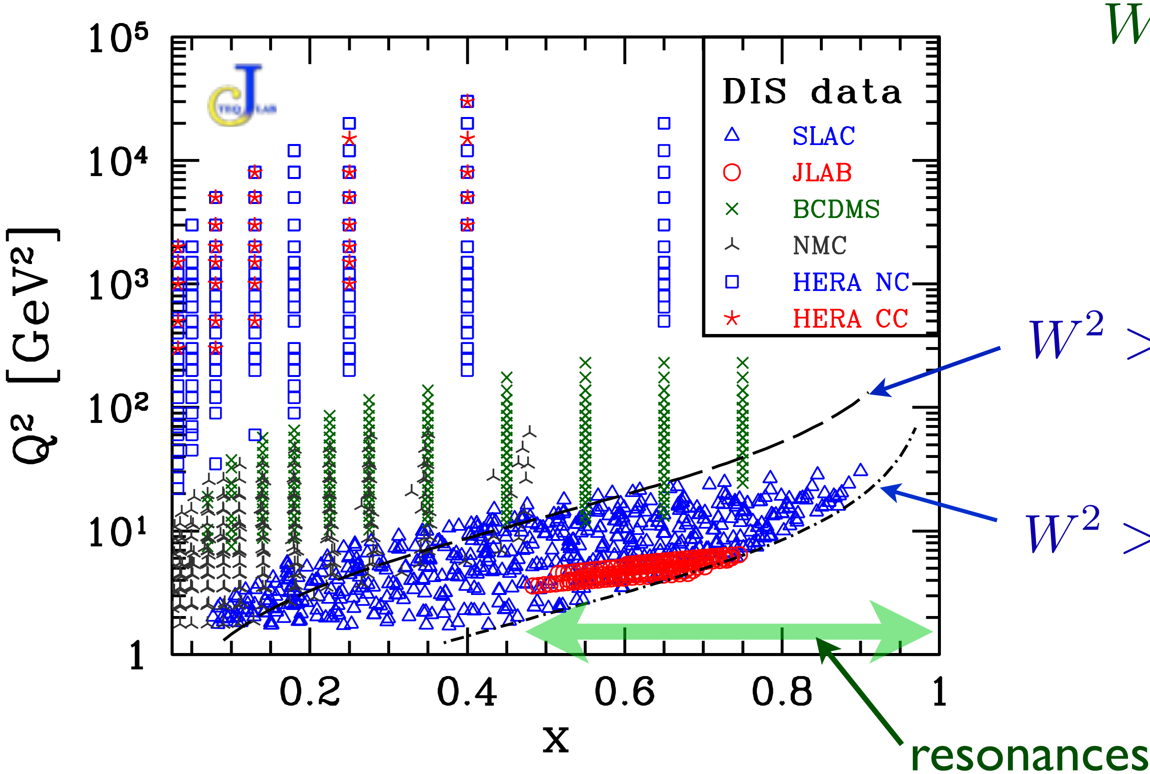
Duality and QCD

- <u>Note</u>: at finite Q^2, from kinematics *any* moment of *any* structure function (of *any* twist) must, by definition, include the resonance region

$$W^2 = M^2 + Q^2 \frac{(1-x)}{x} \quad \Longrightarrow \quad x_{\rm res} = \frac{Q^2}{W_{\rm res}^2 - M^2 + Q^2}$$

$$W_{\rm res} = 2 \text{ GeV} \quad \Longrightarrow \quad x_{\rm res} \approx 0.24$$

$$\text{at } Q^2 = 1 \text{ GeV}^2$$



Duality and QCD

- Note: at finite Q^2, from kinematics *any* moment of *any* structure function (of *any* twist) must, by definition, include the resonance region

- Resonance and DIS regions intimately connected
$\longrightarrow$ resonances an *integral* part of scaling structure function

  e.g. in large-N_c limit, spectrum of zero-width resonances is "maximally dual" to quark-level (smooth) structure function

Local Duality

— truncated moments —

Truncated moments

- Complete moments can be studied via twist expansion

  $\longrightarrow$ Bloom−Gilman duality has a precise meaning

  (*i.e.*, duality violation = higher twists)

- Rigorous connection between local duality & QCD difficult

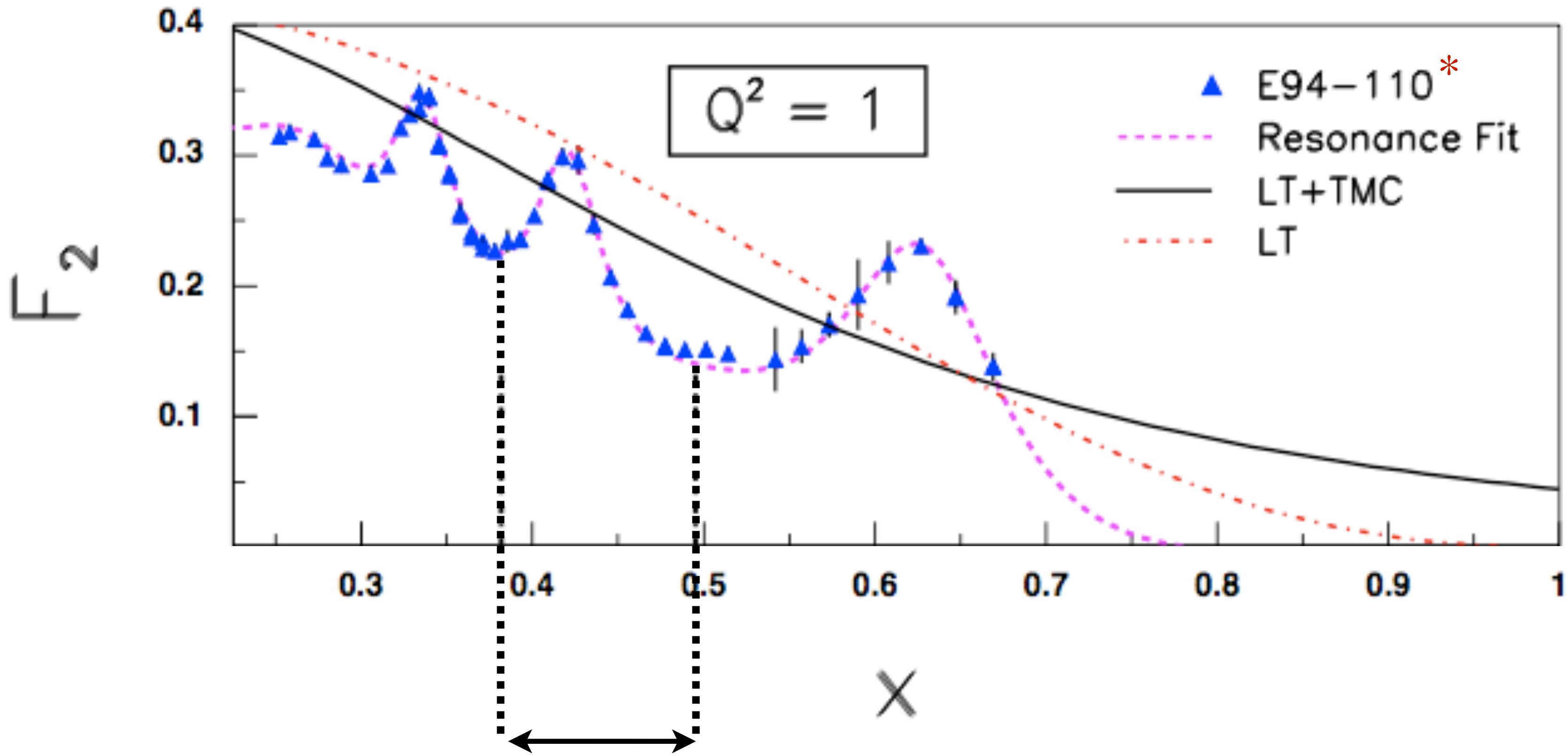
  $\longrightarrow$ need prescription for how to average over resonances

- *Truncated* moments allow study of restricted regions in x (or W) within pQCD in well-defined, systematic way

$$\overline{M}_n(\Delta x, Q^2) = \int_{\Delta x} dx\ x^{n-2}\ F_2(x, Q^2)$$

Forte, Magnea (1999)
Psaker, Malace, Keppel, WM (2008)

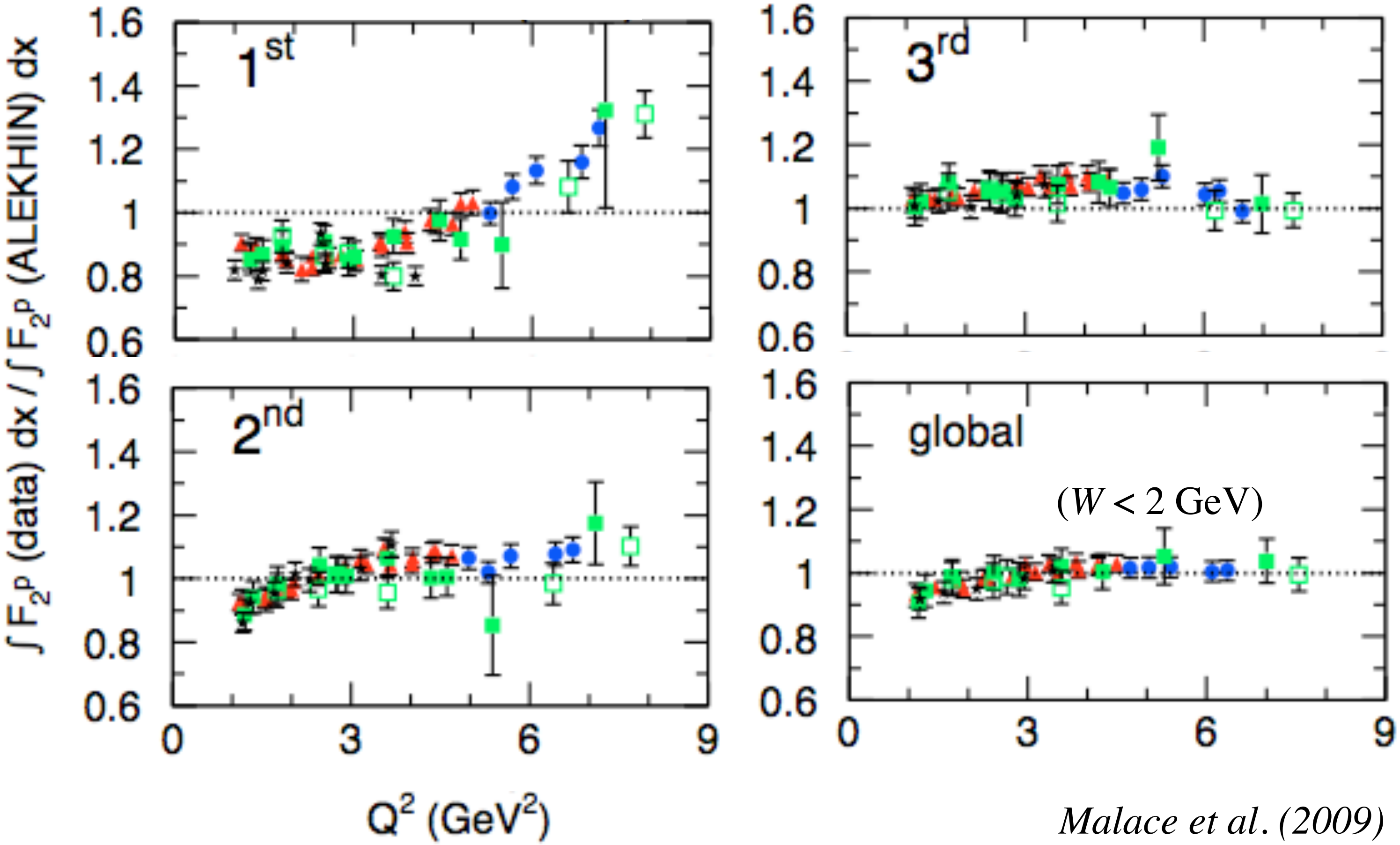
Truncated moments



* JLab Hall C

how much of this region is *leading twist* ?

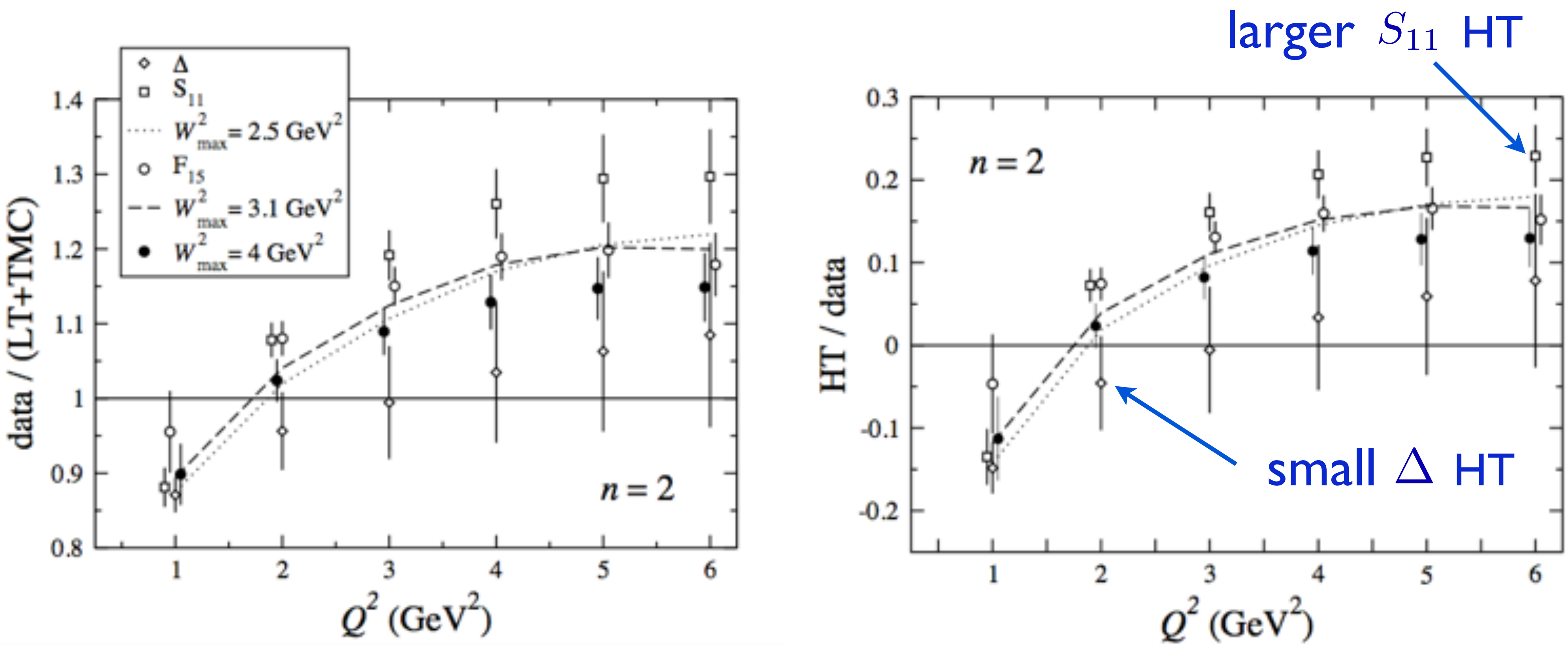
Truncated moments



Malace et al. (2009)

→ duality appears in various resonance regions

Truncated moments



→ higher twists < 10–15% for $Q^2 > 1\ \mathrm{GeV}^2$

Resonances & twists

- Total "higher twist" is *small* at scales $Q^2 \sim \mathcal{O}(1\ \mathrm{GeV}^2)$
- On average, nonperturbative interactions between quarks and gluons not dominant (at these scales)

  $\longrightarrow$ nontrivial interference between resonances

- Can we understand this dynamically, at quark level?
- Can we use resonance region data to learn about *leading twist* structure functions (and *vice versa*)?

  $\longrightarrow$ expanded data set has potentially significant implications for global quark distribution studies

Local Duality

— insights from models —

Scaling functions from resonances

- Earliest attempts predate QCD

→ *e.g.* harmonic oscillator spectrum $M_n^2 = (n+1)\Lambda^2$
including states with spin = 1/2, ..., n+1/2
(n even: I = 1/2, n odd: I = 3/2)

Domokos et al. (1971)

→ at large Q^2 magnetic coupling dominates

$$G_n(Q^2) = \frac{\mu_n}{(1 + Q^2 r^2/M_n^2)^2}$$

$$r^2 \approx 1.41$$

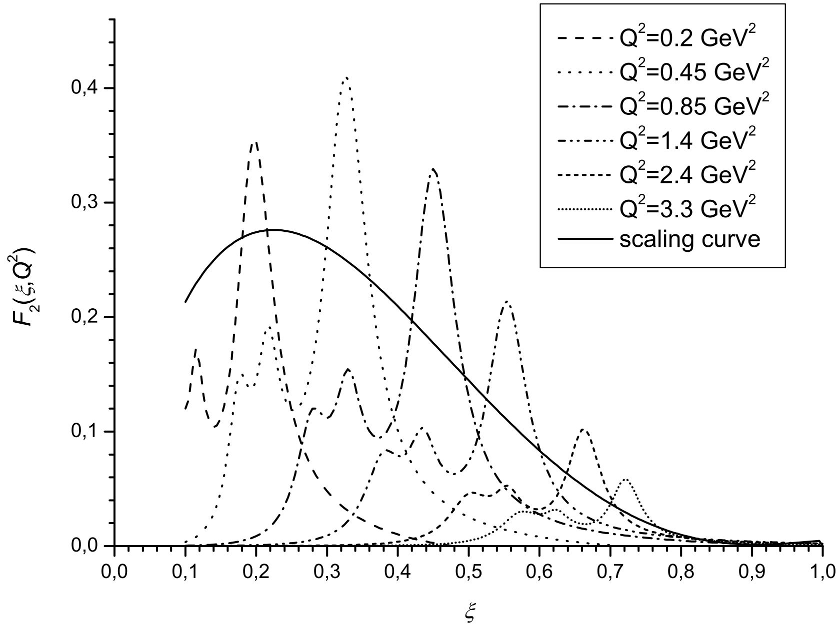
→ in Bjorken limit, $\sum_n \longrightarrow \int dz\,, \quad z \equiv M_n^2/Q^2$

$$F_2 \sim (\omega' - 1)^{1/2}(\mu_{1/2}^2 + \mu_{3/2}^2)\int_0^\infty dz\, \frac{z^{3/2}(1 + r^2/z)^{-4}}{z + 1 - \omega' + \Gamma_0^2 z^2}$$

→ scaling function of $\omega' = \omega + M^2/Q^2 \qquad (\omega = 1/x)$

Scaling functions from resonances

- Phenomenological analyses at finite Q^2



21 isospin-1/2 & 3/2 resonances (mass < 2 GeV)

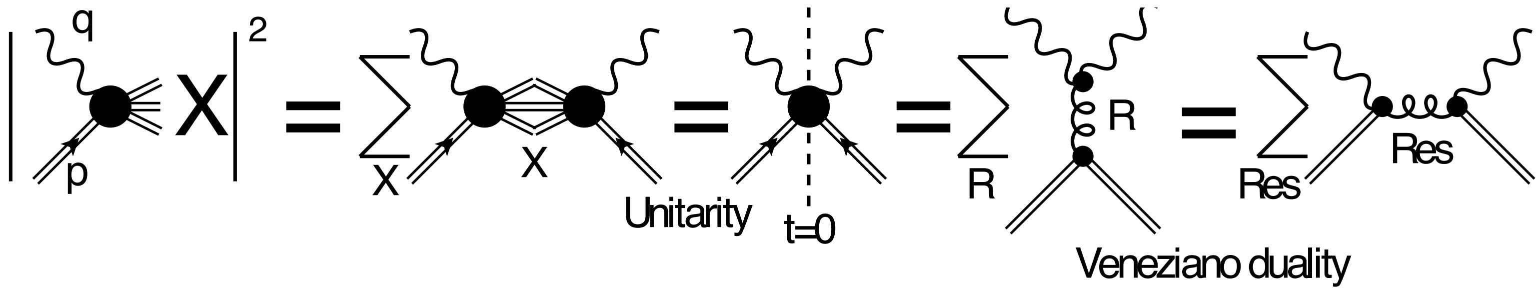
Davidovsky, Struminsky (2003)

⟶ valence-like structure of dual function suggests "two-component duality":

- valence (Reggeon exchange) dual to resonances $F_2^{(\mathrm{val})} \sim x^{0.5}$
- sea (Pomeron exchange) dual to background $F_2^{(\mathrm{sea})} \sim x^{-0.08}$

Scaling functions from resonances

- Explicit realization of Veneziano & Bloom-Gilman duality



$$V(s,t) = \frac{\Gamma(1-\alpha(s))\Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s)-\alpha(t))}$$

$\rightarrow \; s^{\alpha(t)}$ high s, low $|t|$

⟶ Veneziano model not unitary,
has no imaginary parts

⟶ generalization of narrow-resonance approximation,
with nonlinear, complex Regge trajectories

$$D(s,t) = \int_0^1 dz \left(\frac{z}{g}\right)^{-\alpha_s(s(1-z))-1} \left(\frac{1-z}{g}\right)^{-\alpha_t(tz)-1}$$

"dual amplitude with Mandelstam analyticity" (DAMA) model

Jenkovszky et al.

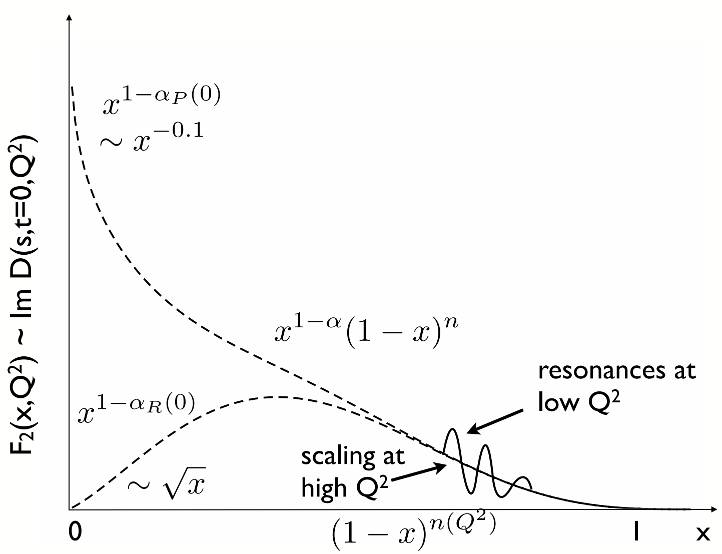
Scaling functions from resonances

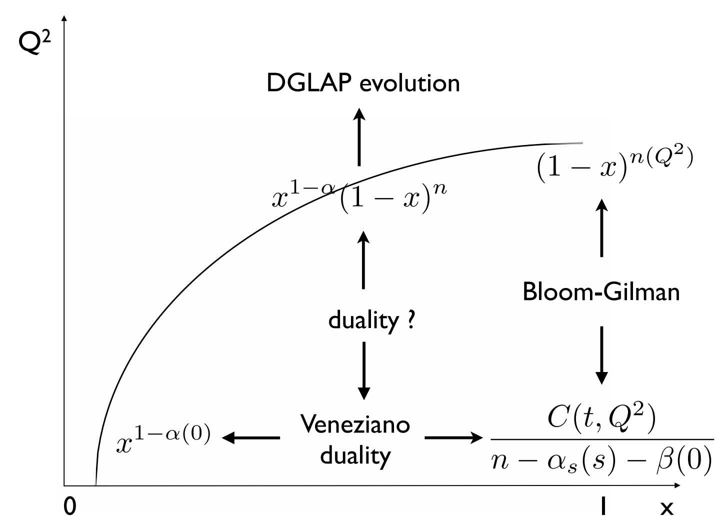
- Explicit realization of Veneziano & Bloom-Gilman duality

→ for large x and Q^2, have power-law behavior

$$F_2 \sim (1-x)^{2\alpha_t(0)\ln 2g/\ln g}$$

where parameter g can be Q^2 dependent





Jenkovszky, Magas, Londergan, Szczepaniak (2012)

Applications of Duality

CTEQ-JLab (CJ) global PDF analysis

- Global QCD analysis of high-energy scattering data, including large-x, low-Q^2 region

- Systematically study effects of Q^2 & W cuts

cut0: $Q^2 > 4\ \mathrm{GeV}^2, \quad W^2 > 12.25\ \mathrm{GeV}^2$

cut1: $Q^2 > 3\ \mathrm{GeV}^2, \quad W^2 > 8\ \mathrm{GeV}^2$

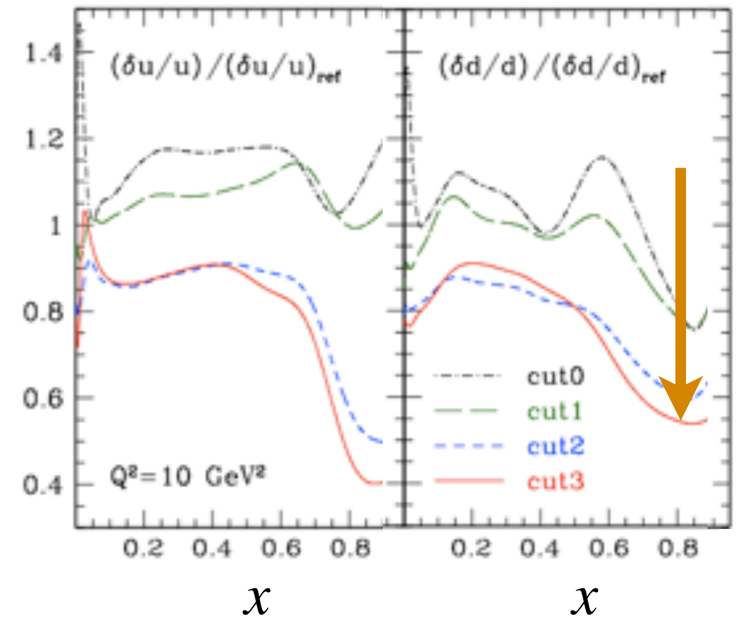
cut2: $Q^2 > 2\ \mathrm{GeV}^2, \quad W^2 > 4\ \mathrm{GeV}^2$

cut3: $Q^2 > m_c^2\ , \quad W^2 > 3\ \mathrm{GeV}^2$

factor 2 increase in DIS data from cut0 $\rightarrow$ cut3

$\longrightarrow$ larger database with weaker cuts significantly reduced errors, especially at large x

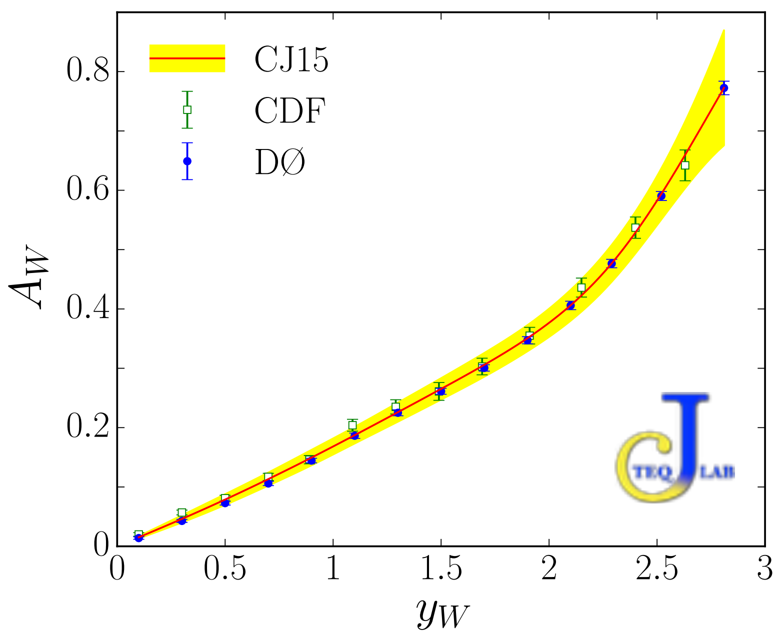
$\longrightarrow$ up to $\sim 40\text{–}60\%$ error reduction when cuts extended into near-resonance region



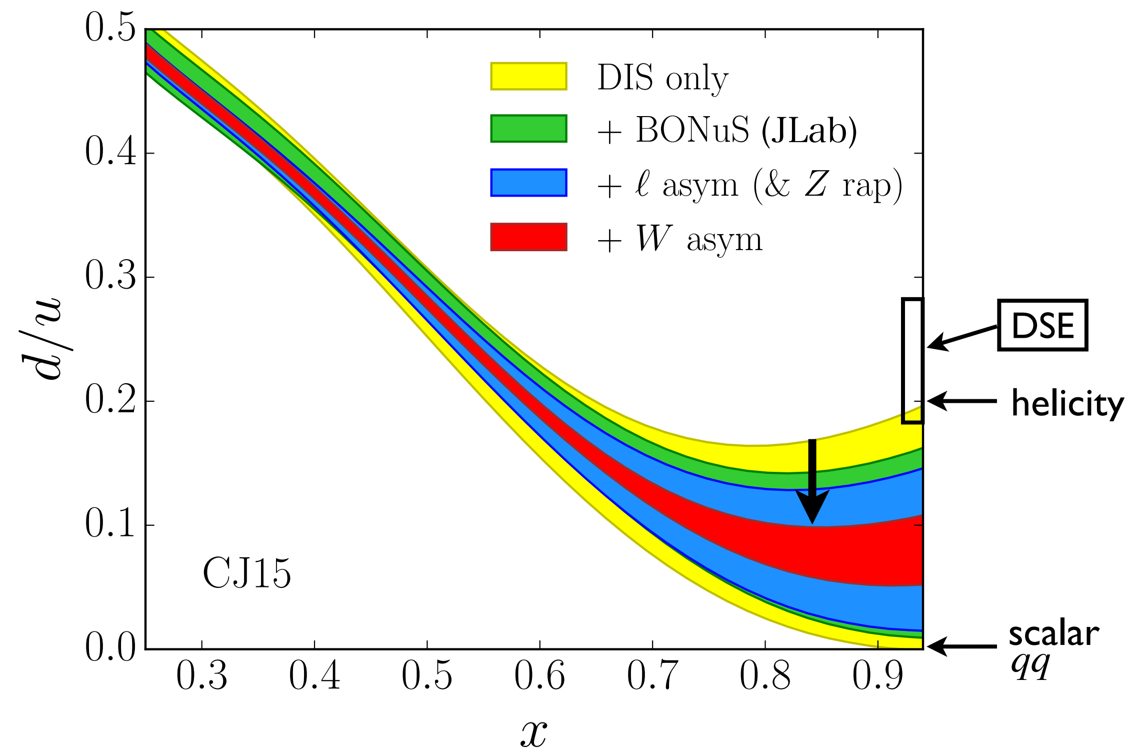
CTEQ-JLab (CJ) global PDF analysis

- Valence d/u ratio at high x

→ significant reduction of PDF errors with new JLab tagged neutron & FNAL W-asymmetry data



Accardi, WM, Owens (2016)



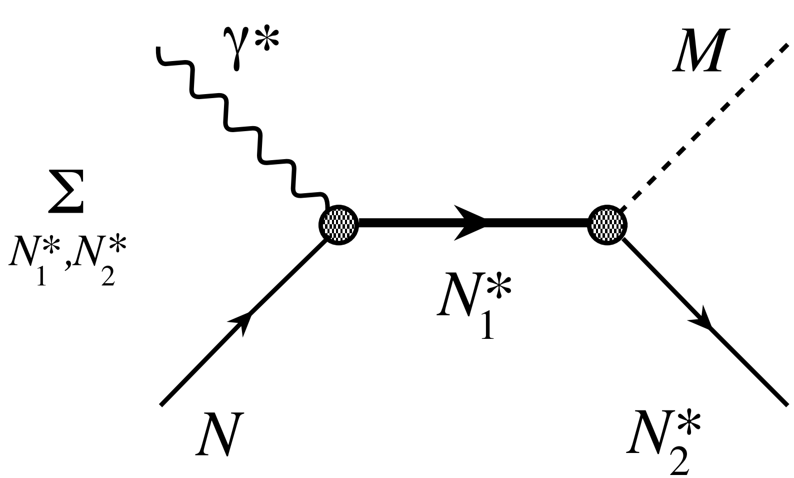
→ extrapolated ratio at $x = 1$

$$d/u \;\to\; 0.09 \pm 0.03$$

→ upcoming experiments at JLab (MARATHON, BONuS, SoLID) will determine d/u up to $x \sim 0.85$

Duality in (semi-inclusive) meson production

- Extend duality to less inclusive processes, such as meson electroproduction



s-channel resonance excitation and decay

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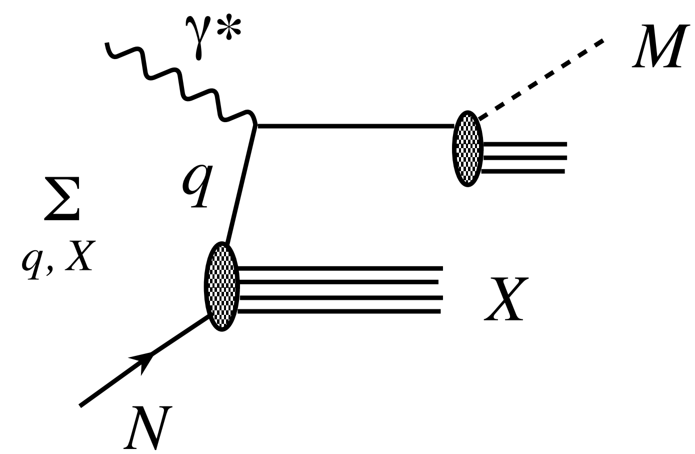

parton level scattering and fragmentation

$$\sum_{N_2^*} \left| \sum_{N_1^*} F_{\gamma N \to N_1^*}(Q^2, M_1^*)\, \mathcal{D}_{N_1^* \to N_2^* M}(M_1^*, M_2^*) \right|^2 = \sum_q e_q^2\, q(x, Q^2)\, D_q^M(z, Q^2)$$

Afanasev, Carlson, Wahlquist (2000)
Hoyer (2002)
Close, WM (2009)

Outlook

- Confirmation of duality (experimentally & theoretically) suggests origin in dynamical cancelations between resonances

  $\longrightarrow$ explore more realistic descriptions based on phenomenological $\gamma^* N N^*$ form factors ($\longrightarrow$ CLAS N^* program)

  $\longrightarrow$ incorporate nonresonant background in same framework

- Practical application of duality

  $\longrightarrow$ use resonance region data to constrain PDFs at high x

  $\longrightarrow$ application to other processes, *e.g.*, semi-inclusive DIS, DVCS / GPDs, ...