University of New Hampshire
Colloquium, March 19, 2012

Quark-Hadron Duality in Electron-Nucleon Scattering

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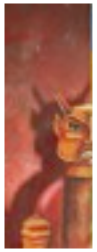
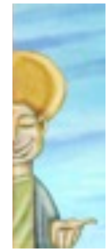
Jefferson Lab



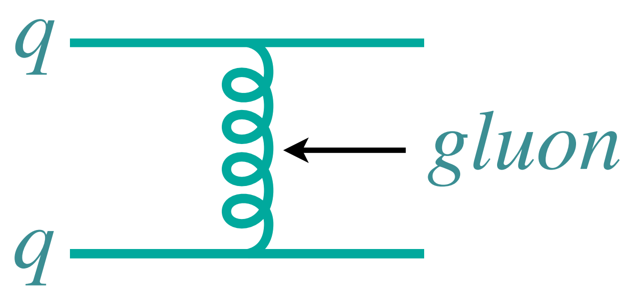
Outline



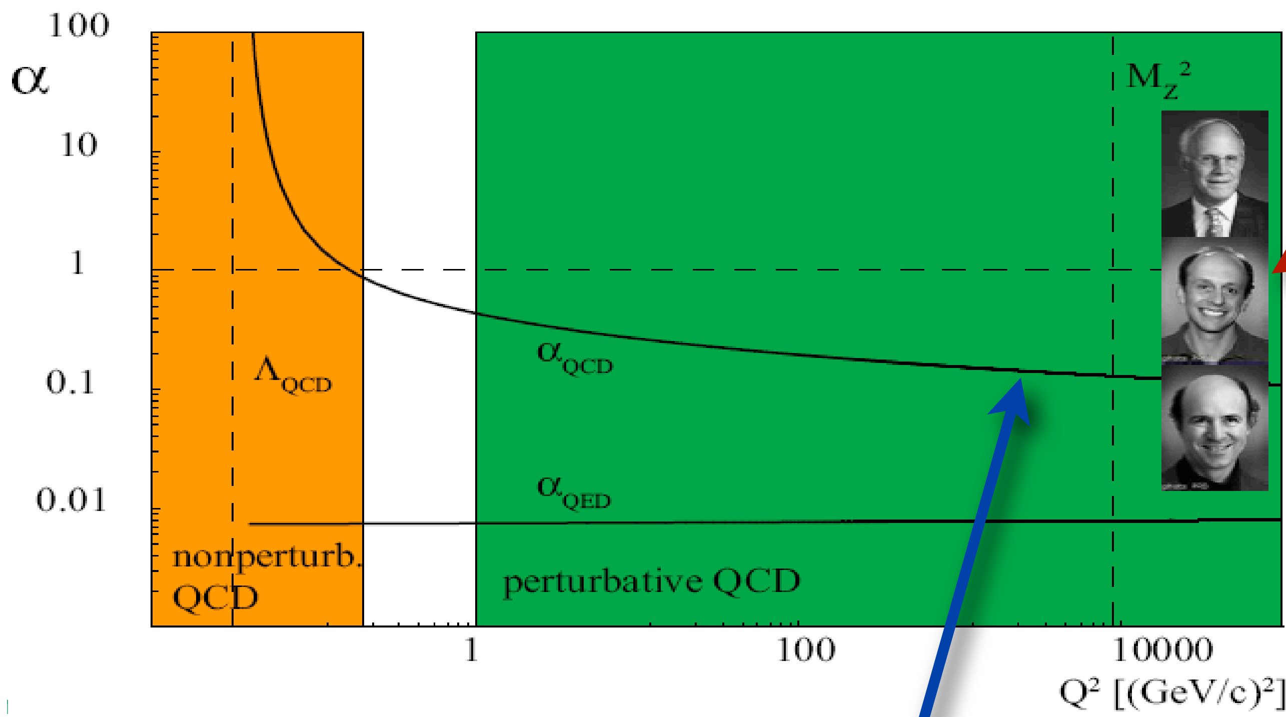
- Historical perspective
  - → examples from Nature
- Duality and Quantum ChromoDynamics
  - → twists and moments
  - → nonperturbative models
- Implications for quark distributions
- Outlook

- Strong nuclear force described (in principle) by theory of Quantum ChromoDynamics (QCD)

→ governed by size of quark-gluon coupling constant α_{QCD} (or α_s)



→ in practice, full understanding of *hadron & nuclear* structure and interactions in terms of *quarks & gluons* remains a challenge even after 40 years!



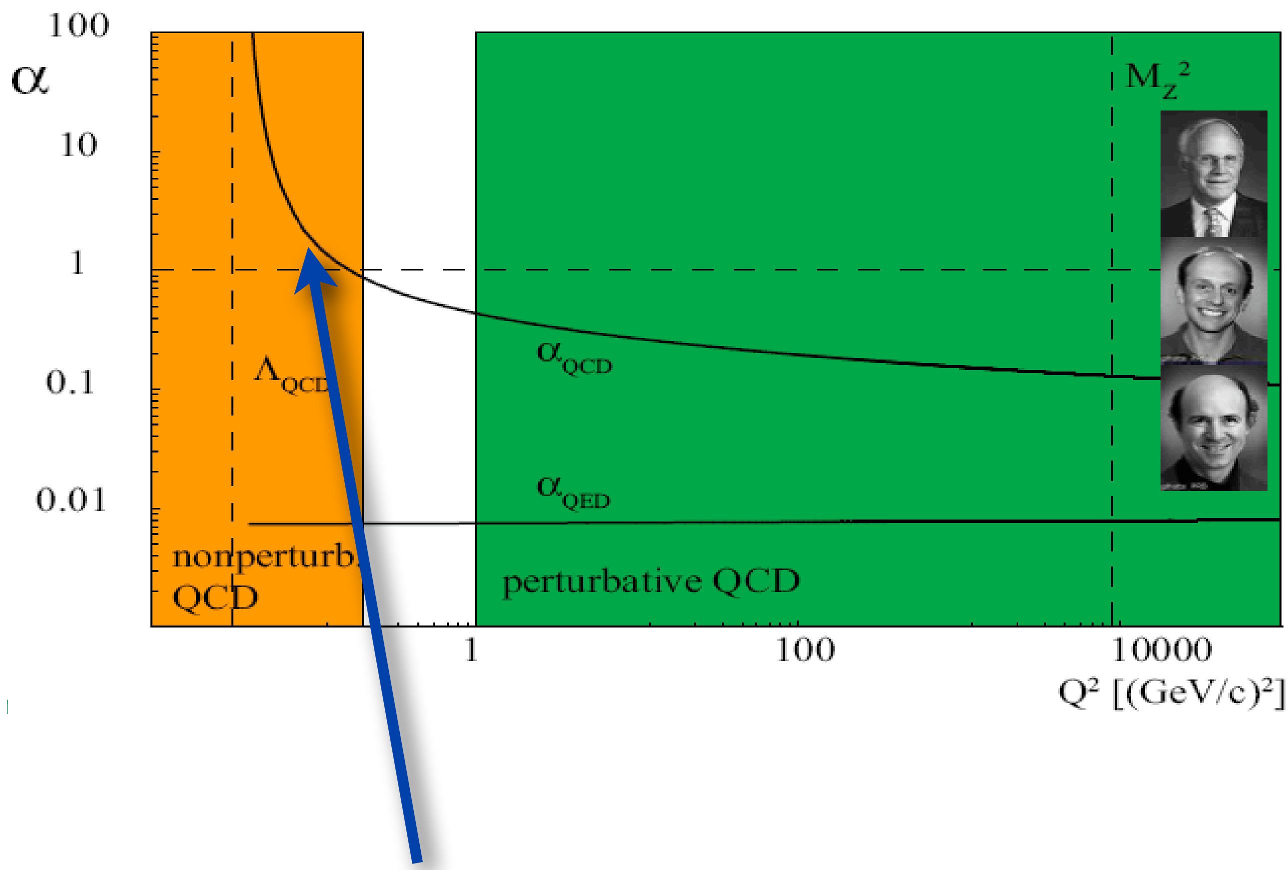
Nobel Prize (2004): discovery of "asymptotic freedom" (1973)

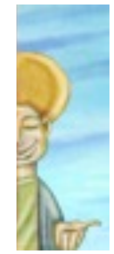
high energy *short distance*

"strong" coupling constant α_s small

→ calculate physical observables in terms of quarks and gluons using perturbation theory

low energy
long distance



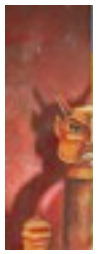


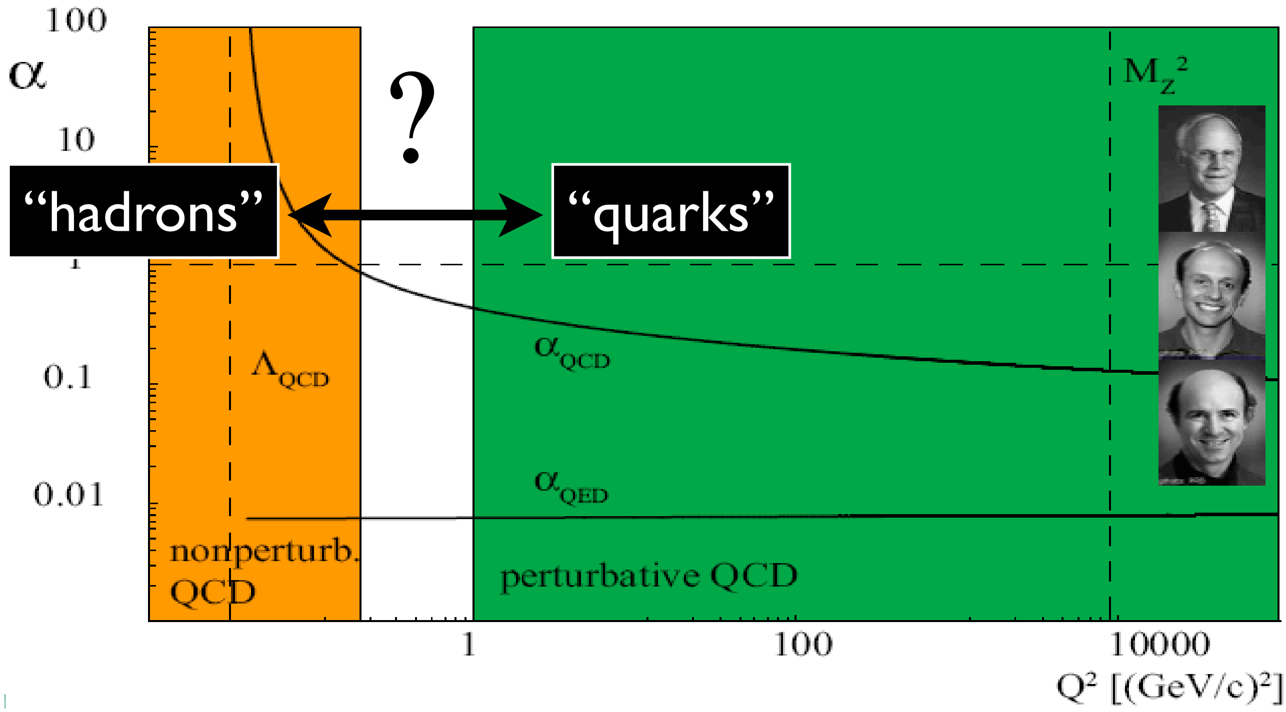
high energy
short distance

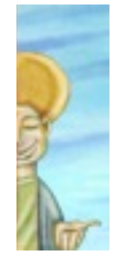
α_s large, cannot describe observables in terms of quarks perturbatively

⟶ requires nonperturbative methods such as *lattice* QCD

⟶ meson & baryon degrees of freedom prominent







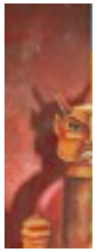
low energy *long distance*

high energy *short distance*

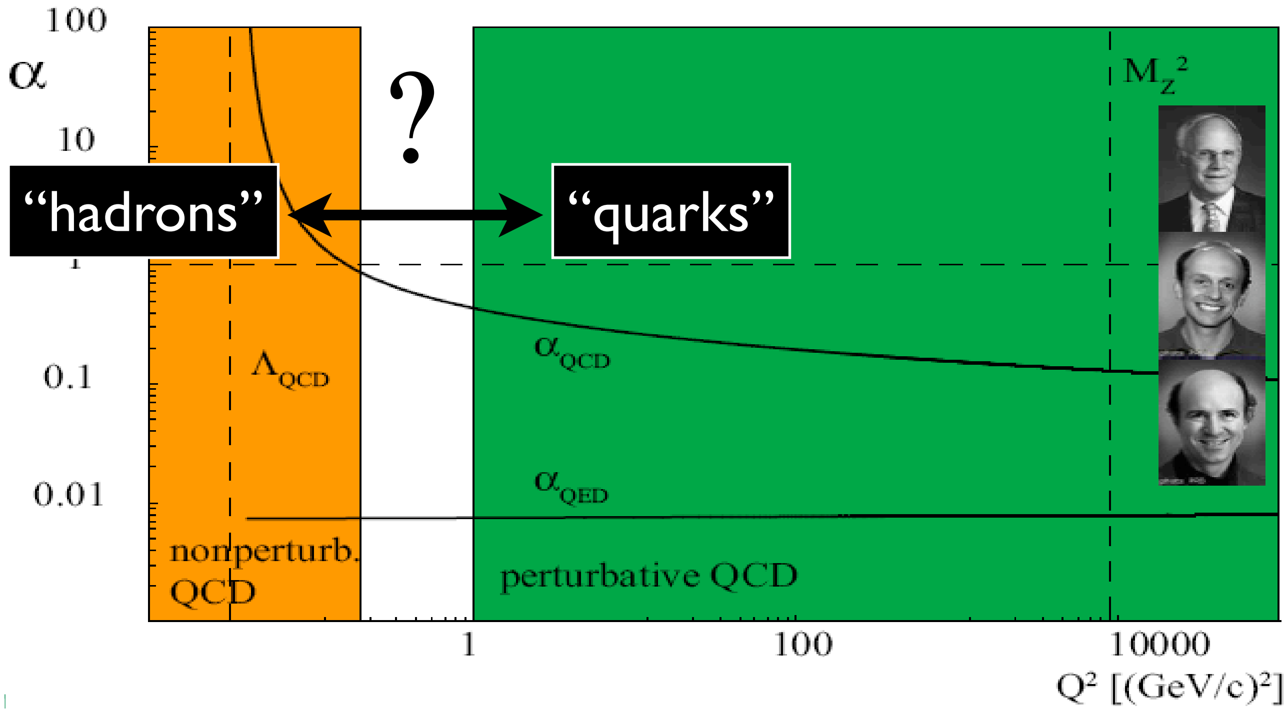
- Duality hypothesis: complementarity between *quark* and *hadron* descriptions of observables

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

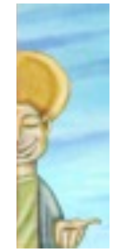
→ can use either set of *complete* basis states to describe physical phenomena



low energy
long distance



high energy
short distance



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

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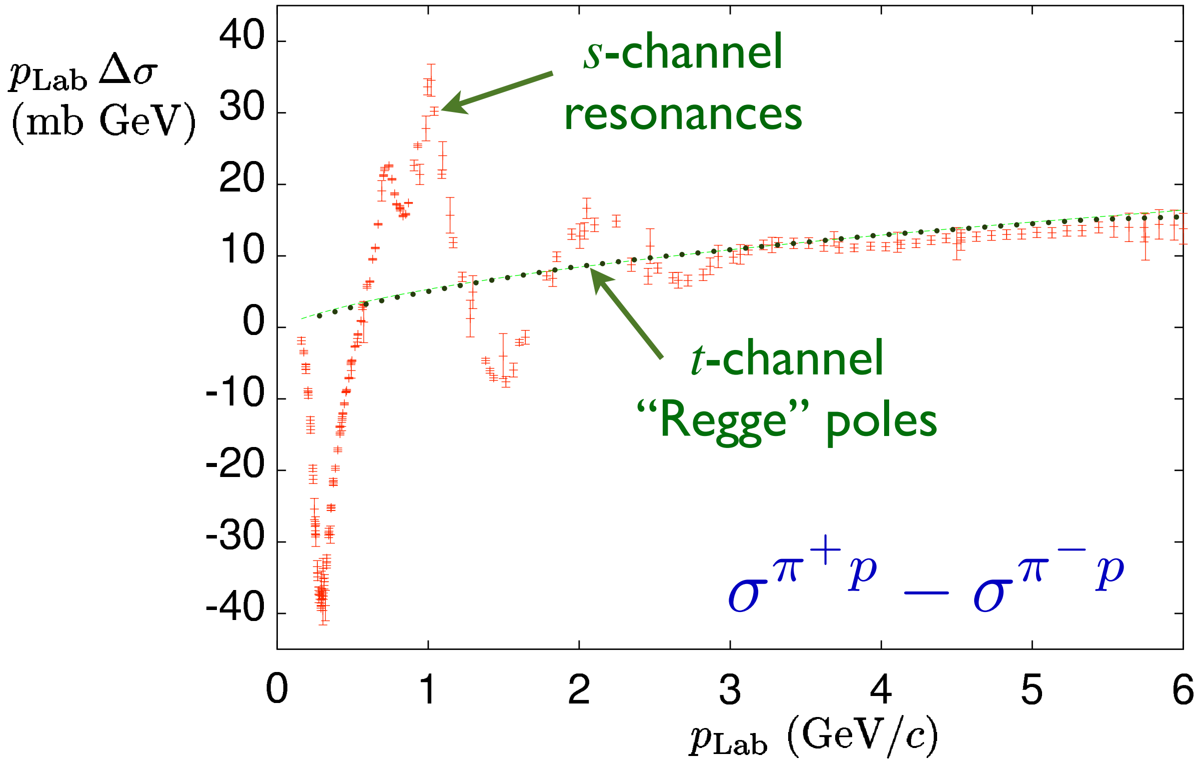
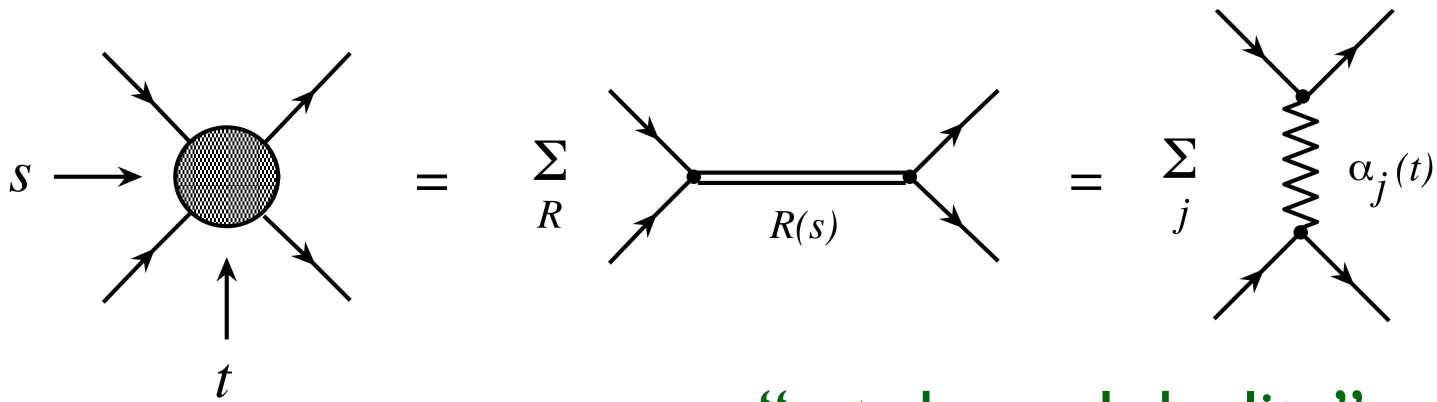
- Question is not *why* duality exists, but *how* it arises where it exists

Duality in hadron-hadron scattering

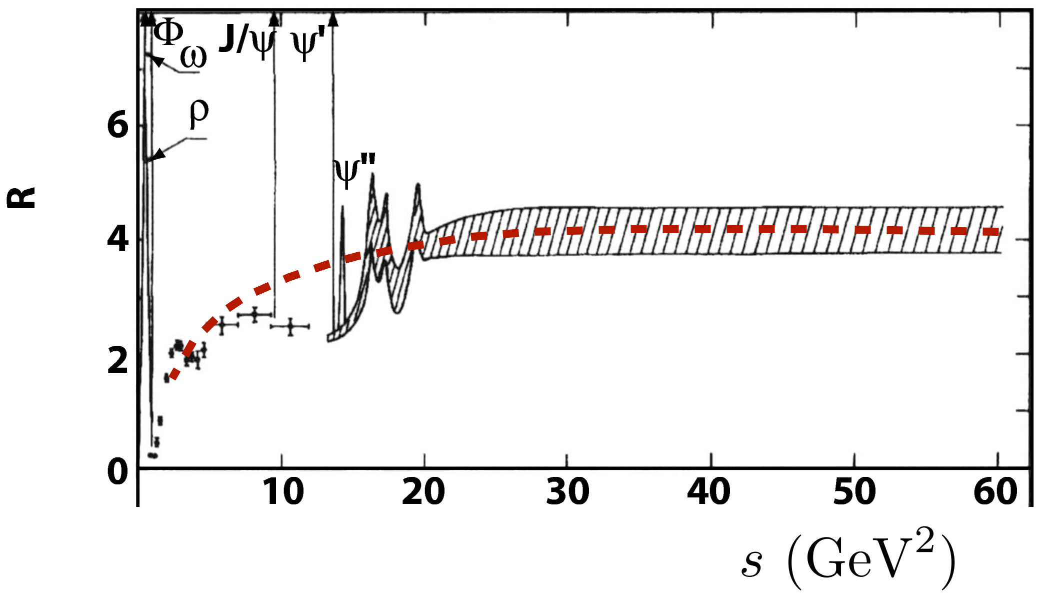


Igi (1962)
Dolen, Horn, Schmidt (1968)



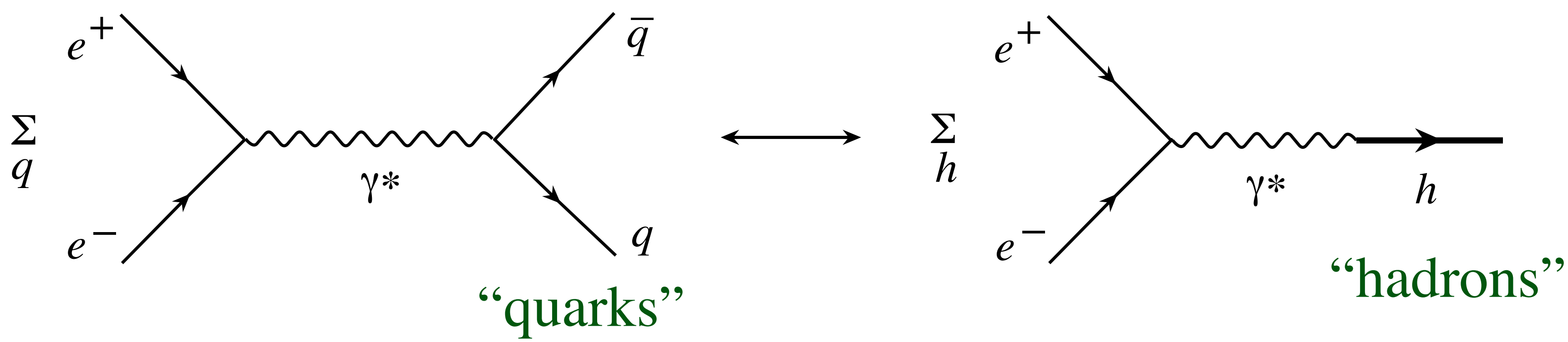
"s-t channel duality"

Duality in $e^+ e^-$ annihilation

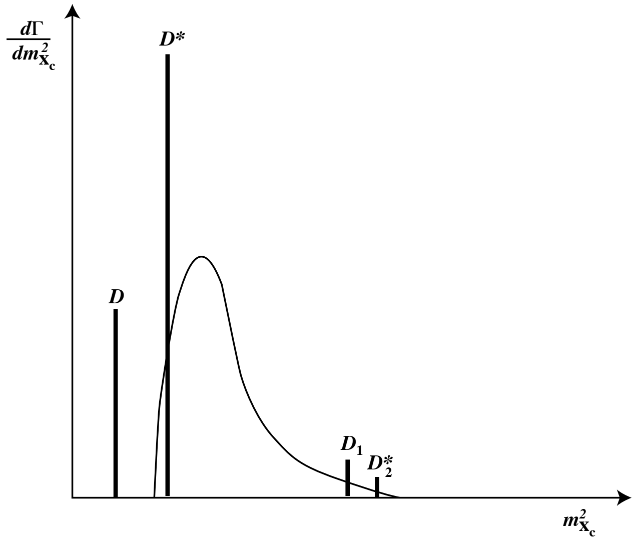


$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

→ total hadronic cross section at high energy averages resonance cross section



Duality in heavy meson decays



$$Q \to Q' \, l \, \bar{\nu}_l$$

$$\Gamma^q = \frac{G_F^2 \delta m^5}{15\pi^2} |V_{QQ'}|^2$$

$$(Q\bar{q}) \to X_{Q'} \, l \, \bar{\nu}_l$$

$$\Gamma^{\rm PS} = \frac{G_F^2 \delta m^5}{60\pi^2} |V_{QQ'}|^2$$

$$\Gamma^{\rm V} = \frac{G_F^2 \delta m^5}{20\pi^2} |V_{QQ'}|^2$$

$$m_Q + m_{Q'} \gg m_Q - m_{Q'} \gg \Lambda_{\rm QCD}$$

$$\delta m = m_Q - m_{Q'} \approx M_{(Q\bar{q})} - M_{Q'\bar{q}}$$

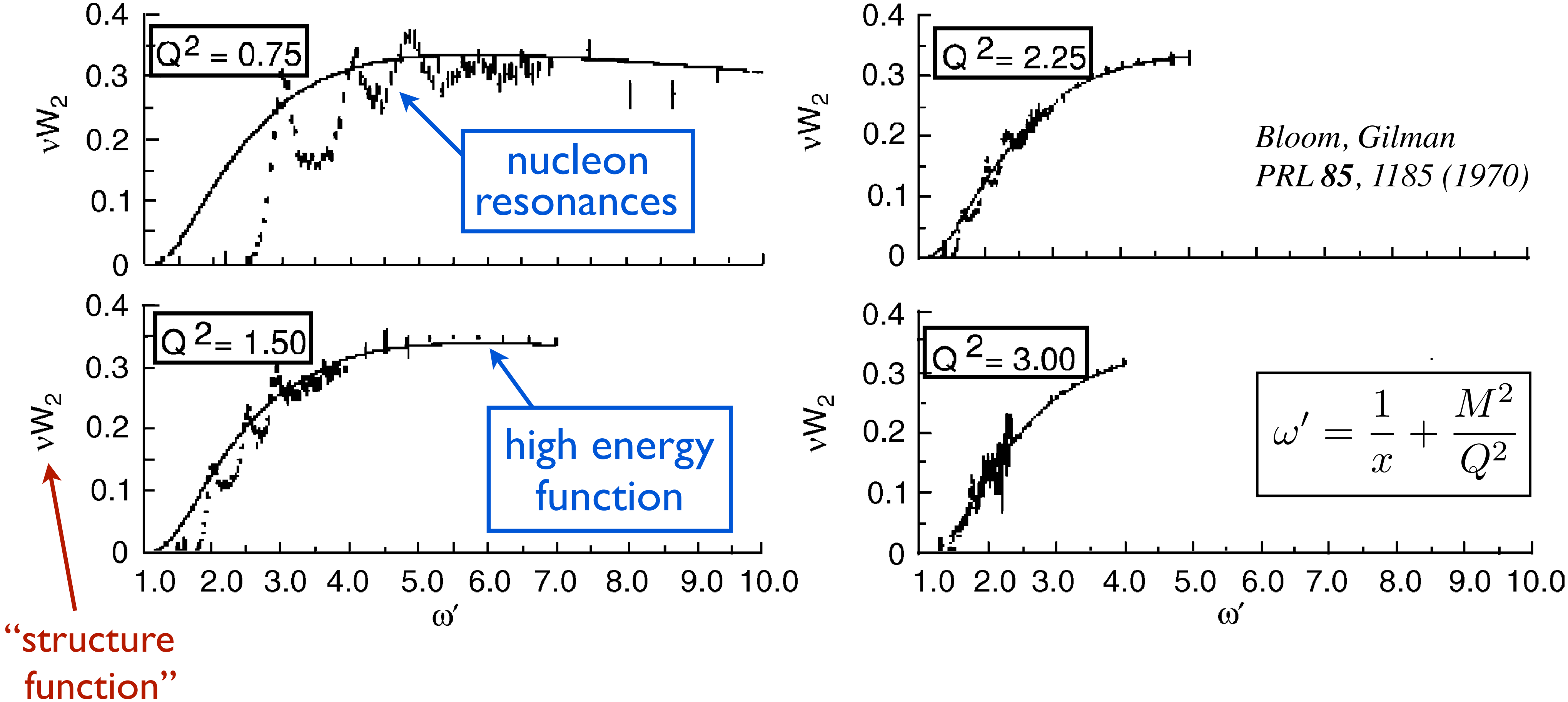
→ sum over hadronic-level decay rates
= quark-level decay rate

$$\Gamma^{\rm PS} + \Gamma^{\rm V} \longleftrightarrow \Gamma^q$$

*Voloshin, Shifman, SJNP **41**, 120 (1985); Isgur, PLB **448**, 111(1999)*

Duality in electron-nucleon scattering

"Bloom-Gilman duality"

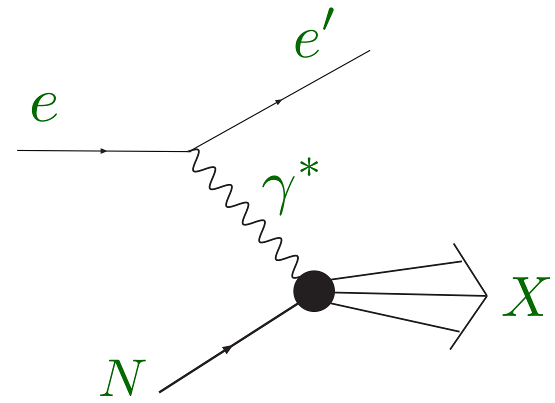


$$\frac{2M}{Q^2}\int_0^{\nu_m} d\nu\ \nu W_2(\nu, Q^2) = \int_1^{\omega'_m} d\omega'\ \nu W_2(\omega')$$

"hadrons" "quarks"

Electron-nucleon scattering

- Inclusive cross section for $eN \to eX$



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

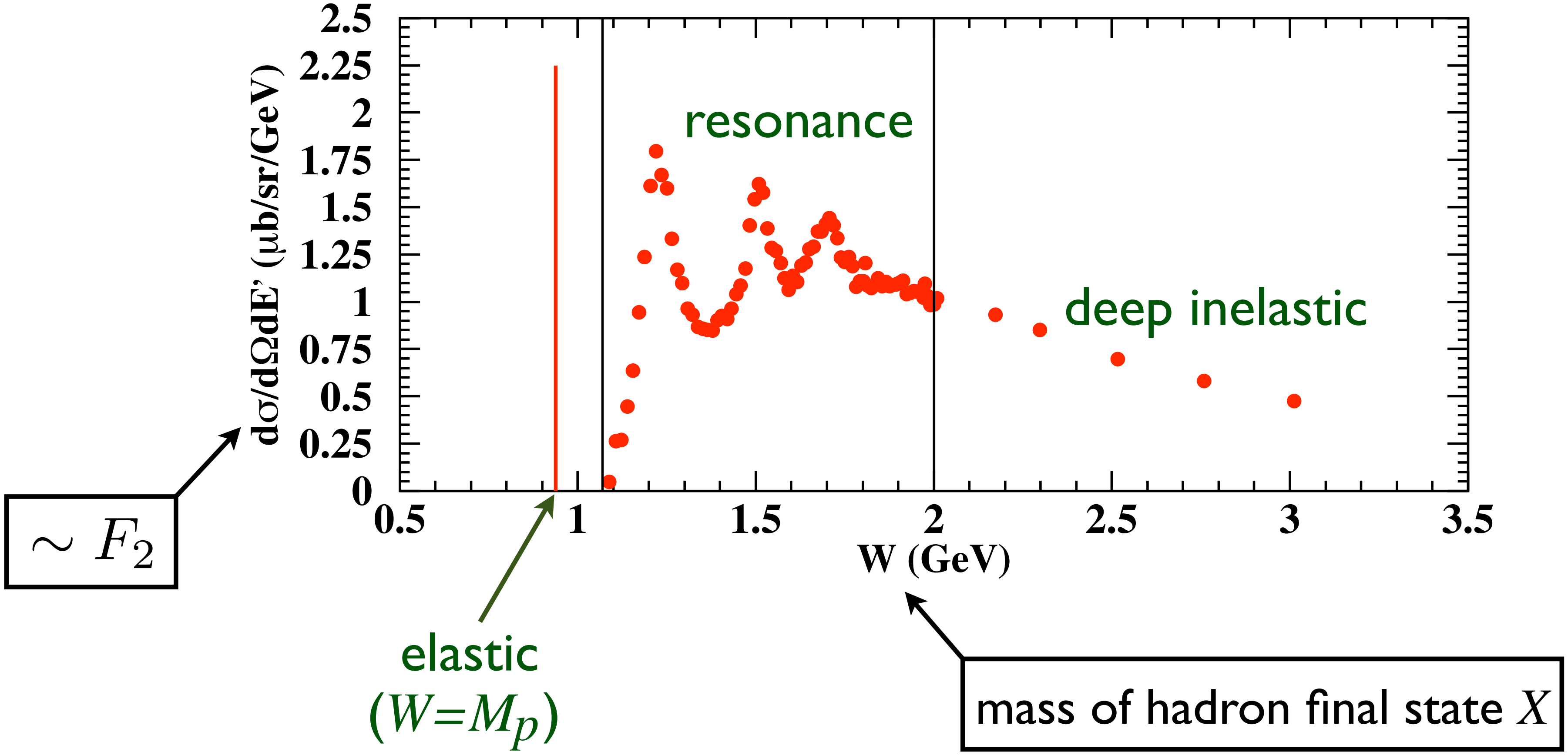
$$\left.\begin{aligned} \nu &= E - E' \\ Q^2 &= \vec{q}^{\,2} - \nu^2 = 4EE'\sin^2\frac{\theta}{2} \end{aligned}\right\} \quad x = \frac{Q^2}{2M\nu}$$

Bjorken scaling variable

- F_1 , F_2 structure functions

$\longrightarrow$ contain all information about structure of nucleon

Electron-nucleon scattering



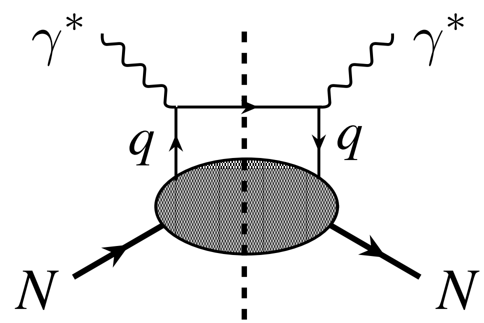
Bjorken variable in terms of Q^2 & W : $x = \dfrac{Q^2}{W^2 - M^2 + Q^2}$

- In *deep-inelastic* region $(W \gtrsim 2\ \text{GeV},\ Q^2 \gtrsim 1\ \text{GeV}^2)$, structure function given by quark & antiquark ("parton") distributions

$$F_2(x,Q^2) = x \sum_q e_q^2\, q(x,Q^2)$$
$$= \frac{4}{9} x(u+\bar{u}) + \frac{1}{9} x(d+\bar{d}) + \frac{1}{9} x(s+\bar{s}) + \cdots$$

→ $q(x,Q^2)$ = probability to find quark type "q" in nucleon, carrying momentum fraction x

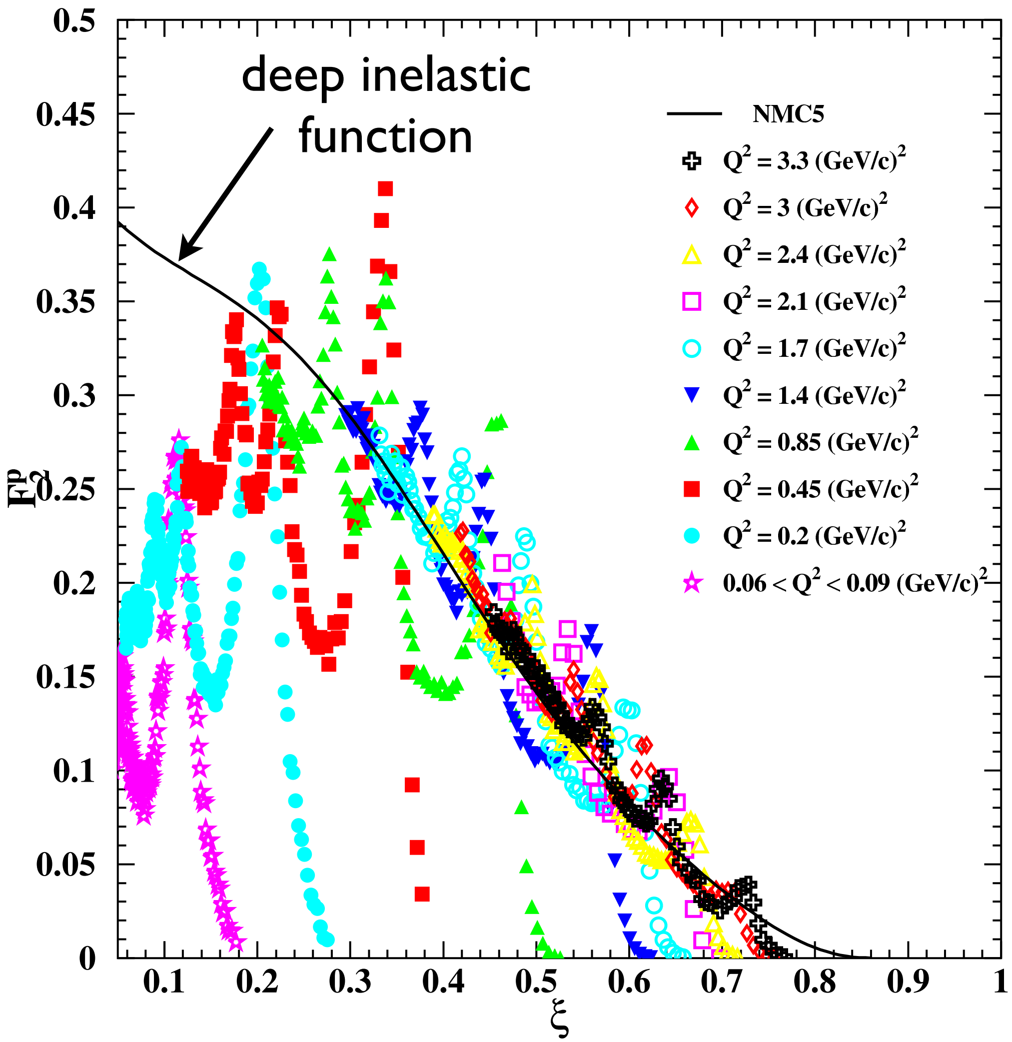
"PDF"



- In *resonance* region ($W \lesssim 2\ \text{GeV}$), or at low Q^2 ($Q^2 \lesssim 1\ \text{GeV}^2$) can no longer resolve individual quark structure

→ see *gross features* of hadron (complex, multi-parton effects)

Duality in electron-nucleon scattering



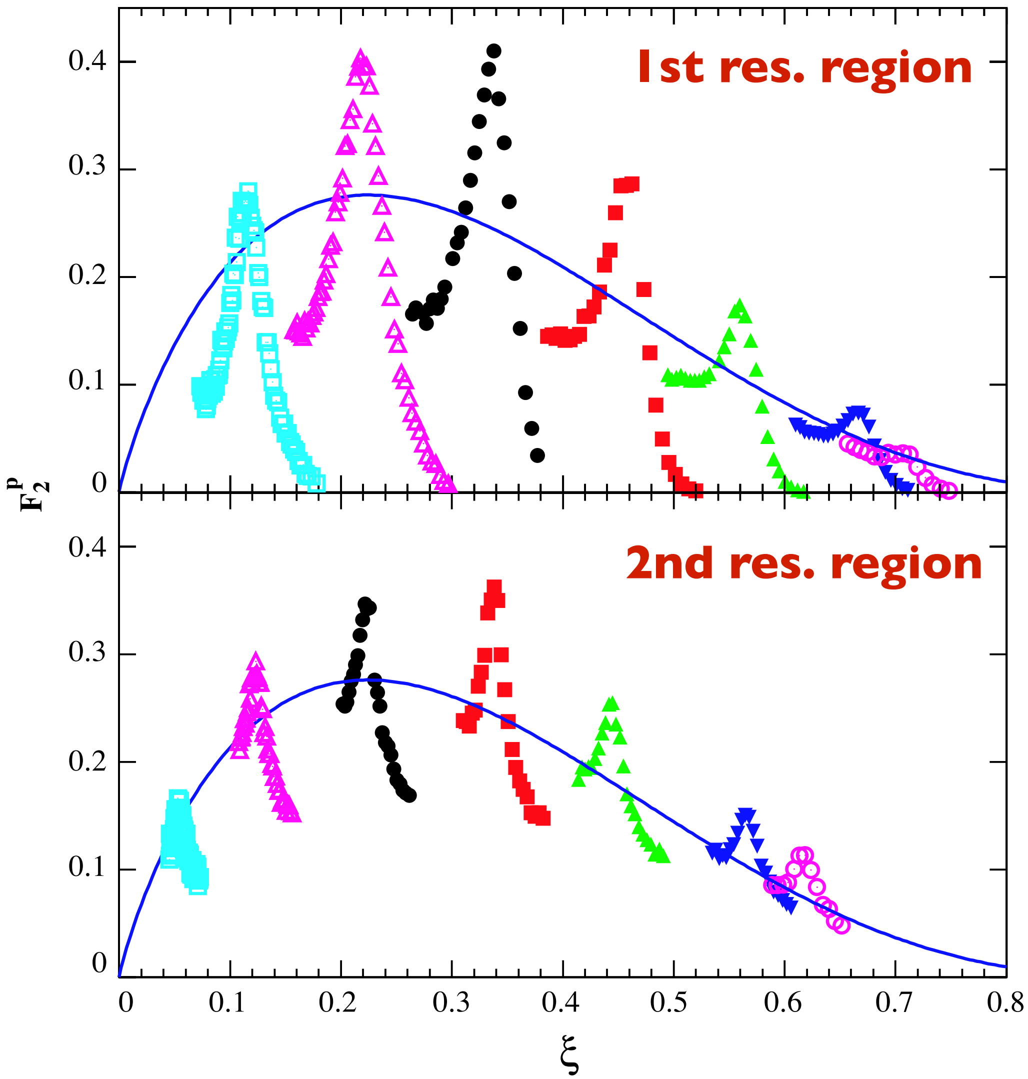
Niculescu et al., PRL ***85****, 1182 (2000)*
WM, Ent, Keppel, PRep. ***406****, 127 (2005)*

average over
(strongly Q^2 dependent)
resonances
$\approx Q^2$ independent
scaling function

"Nachtmann" scaling variable

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

Duality in electron-nucleon scattering



→ also exists *locally* in individual resonance regions

Duality and QCD

- Operator product expansion

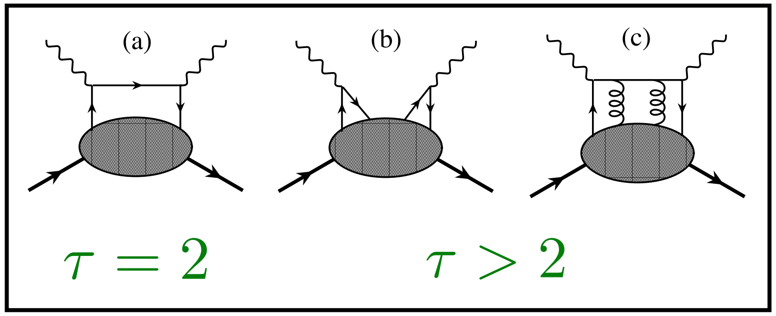
→ expand *moments* of structure functions in powers of $1/Q^2$

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

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

matrix elements of operators with specific "twist" τ

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



Duality and QCD

- Operator product expansion

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

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

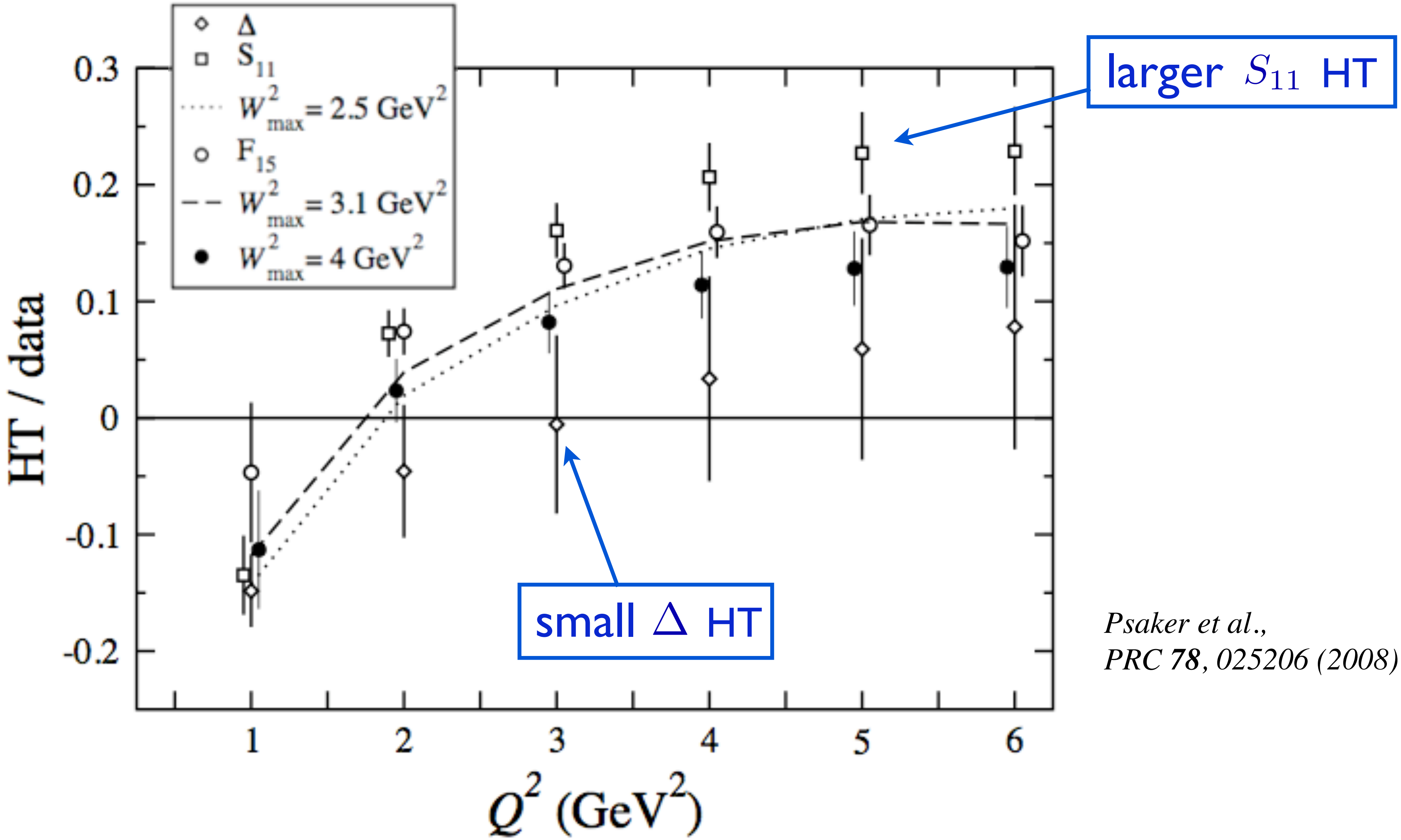
de Rujula, Georgi, Politzer
Ann. Phys. ***103****, 315 (1975)*

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

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

- Duality $\longleftrightarrow$ suppression of higher twists

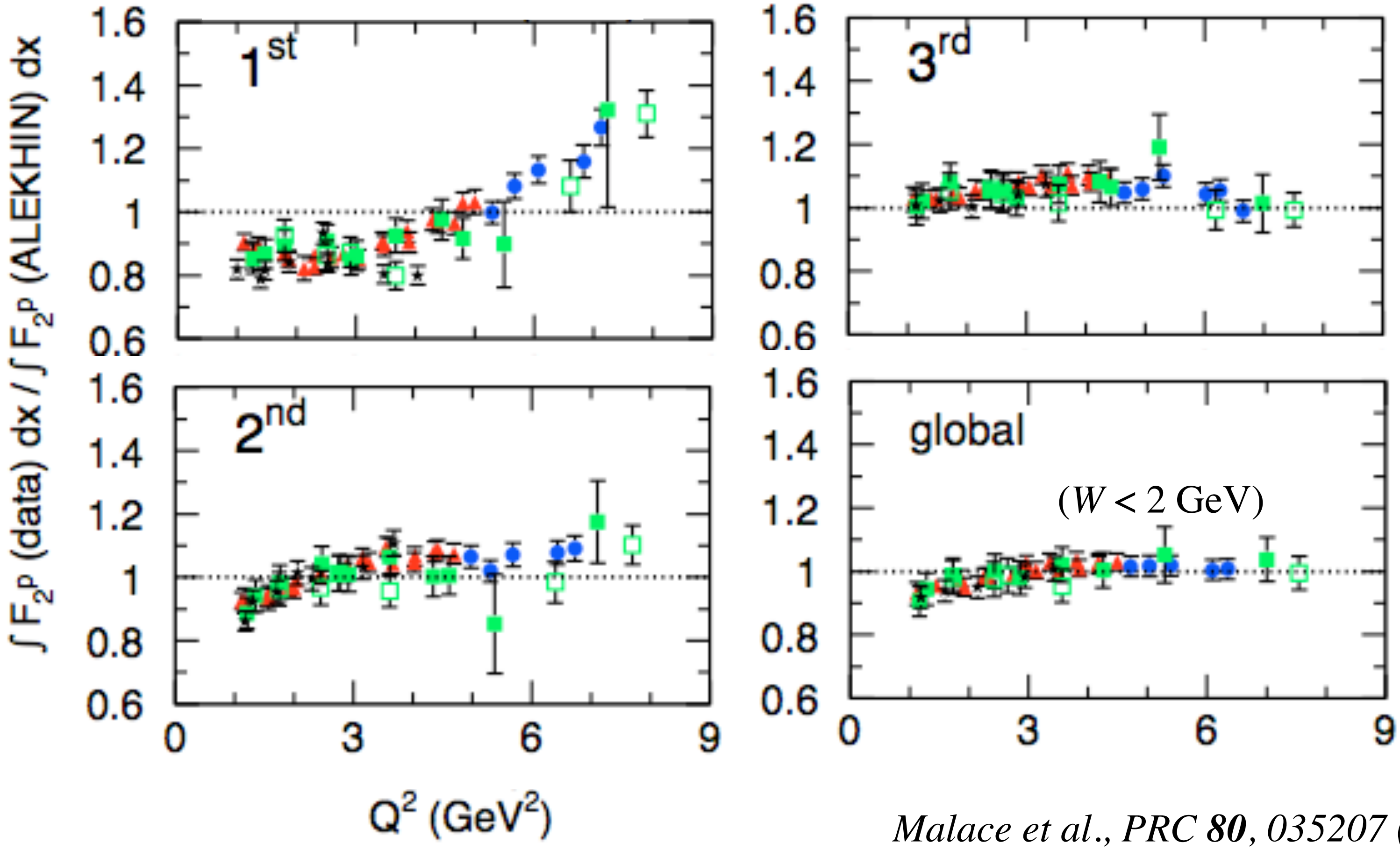
Analysis of JLab F_2^p resonance region data



Psaker et al., *PRC* ***78***, *025206 (2008)*

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

Analysis of (latest) JLab F_2^p resonance region data



Malace et al., PRC ***80****, 035207 (2009)*

→ higher twists $< 10\text{–}15\%$ 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)

  → nontrivial interference between resonances

- Can we understand this dynamically, at quark level?

  → is duality an accident?

- Can we use resonance region data to learn about *leading twist* structure functions?

  → expanded data set has potentially significant implications for global quark distribution studies

- Consider simple quark model with spin-flavor symmetric wave function

<u>low energy</u>

→ *coherent* scattering from quarks $$d\sigma \sim \left(\sum_i e_i\right)^2$$

<u>high energy</u>

→ *incoherent* scattering from quarks $$d\sigma \sim \sum_i e_i^2$$

- For duality to work, these must be equal

→ how can <u>*square of a sum*</u> become <u>*sum of squares*</u>?

Dynamical cancellations

→ *e.g.* for toy model of two quarks bound in a harmonic oscillator potential, structure function given by

$$F(\nu,\mathbf{q}^2)\ \sim\ \sum_n \left|G_{0,n}(\mathbf{q}^2)\right|^2\ \delta(E_n - E_0 - \nu)$$

→ charge operator $\Sigma_i\ e_i \exp(i\mathbf{q}\cdot\mathbf{r}_i)$ excites *even* partial waves with strength $\propto (e_1+e_2)^2$ *odd* partial waves with strength $\propto (e_1-e_2)^2$

→ resulting structure function

$$F(\nu,\mathbf{q}^2)\ \sim\ \sum_n \left\{(e_1+e_2)^2\ G^2_{0,2n} + (e_1-e_2)^2\ G^2_{0,2n+1}\right\}$$

→ if states degenerate, *cross terms* $(\sim e_1 e_2)$ *cancel* when averaged over nearby *even and odd parity* states

*Close, Isgur, PLB **509**, 81 (2001)*

Dynamical cancellations

→ duality is realized by summing over at least one complete set of *even* and *odd* parity resonances

*Close, Isgur, PLB **509**, 81 (2001)*

→ in NR Quark Model, even & odd parity states generalize to **56** (L=0) and **70** (L=1) multiplets of spin-flavor SU(6)

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
F_1^p	$9\rho^2$	$8\lambda^2$	$9\rho^2$	0	λ^2	$18\rho^2+9\lambda^2$
F_1^n	$(3\rho+\lambda)^2/4$	$8\lambda^2$	$(3\rho-\lambda)^2/4$	$4\lambda^2$	λ^2	$(9\rho^2+27\lambda^2)/2$

λ (ρ) = (anti) symmetric component of ground state wave function

*Close, WM, PRC **68**, 035210 (2003)*

Dynamical cancellations

→ in SU(6) limit $\lambda = \rho$, with relative strengths of $N \to N^*$ transitions

$SU(6):$	$[\mathbf{56}, \mathbf{0}^+]^\mathbf{2}\mathbf{8}$	$[\mathbf{56}, \mathbf{0}^+]^\mathbf{4}\mathbf{10}$	$[\mathbf{70}, \mathbf{1}^-]^\mathbf{2}\mathbf{8}$	$[\mathbf{70}, \mathbf{1}^-]^\mathbf{4}\mathbf{8}$	$[\mathbf{70}, \mathbf{1}^-]^\mathbf{2}\mathbf{10}$	*total*
F_1^p	9	8	9	0	1	27
F_1^n	4	8	1	4	1	18

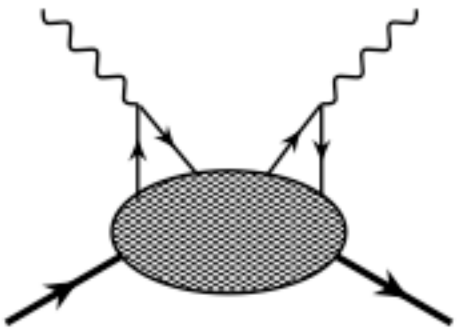
→ summing over all resonances in $\mathbf{56}^+$ and $\mathbf{70}^-$ multiplets

$$\frac{F_1^n}{F_1^p} = \frac{18}{27} = \frac{2}{3}$$

→ at the quark level, n/p ratio is

$$\frac{F_1^n}{F_1^p} = \frac{4d+u}{d+4u} = \frac{6}{9} = \frac{2}{3} \quad ! \qquad \text{if } u = 2d$$

Accidental cancellations of charges?



cat's ears diagram (4-fermion higher twist $\sim 1/Q^2$)

$$\propto \sum_{i \neq j} e_i \, e_j \sim \Big(\sum_i e_i \Big)^2 - \sum_i e_i^2$$

↑ *coherent* ↑ *incoherent*

proton $\quad \mathrm{HT} \sim 1 - \left(2 \times \frac{4}{9} + \frac{1}{9}\right) = 0\ !$

neutron $\quad \mathrm{HT} \sim 0 - \left(\frac{4}{9} + 2 \times \frac{1}{9}\right) \neq 0$

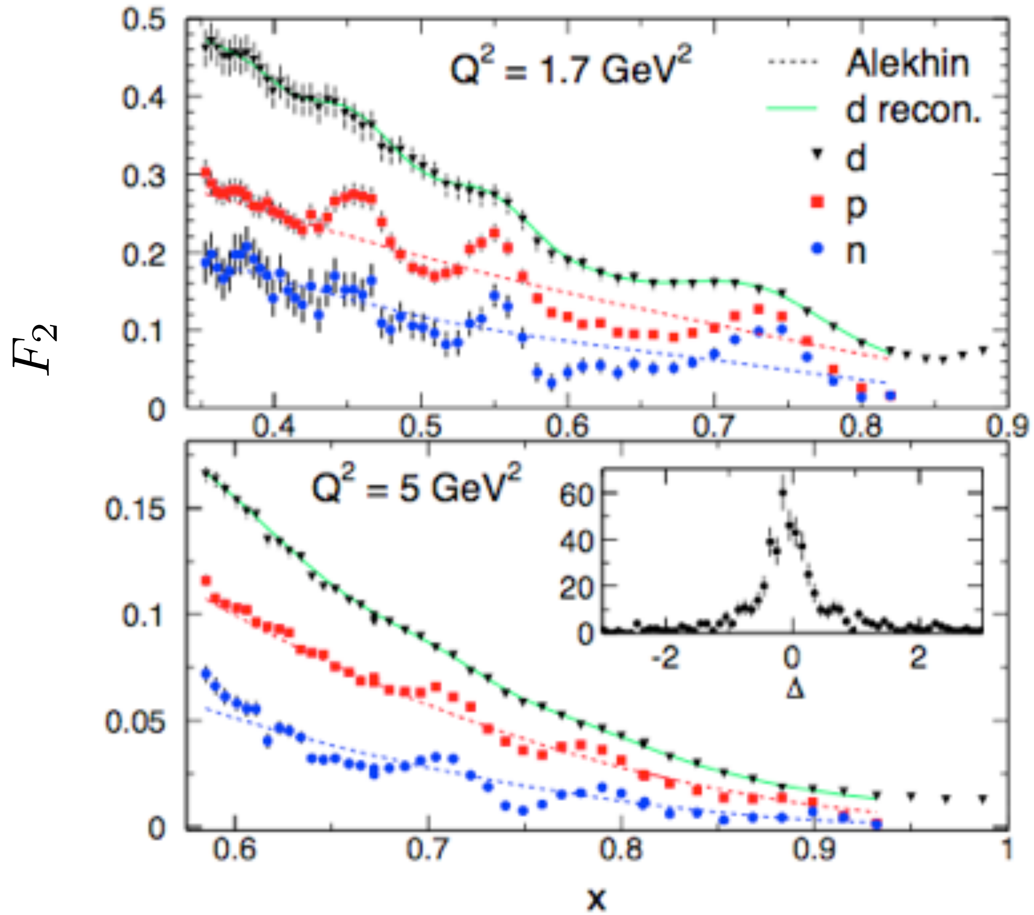
Brodsky
hep-ph/0006310

→ duality in proton a *coincidence!*

→ should *not* hold for neutron

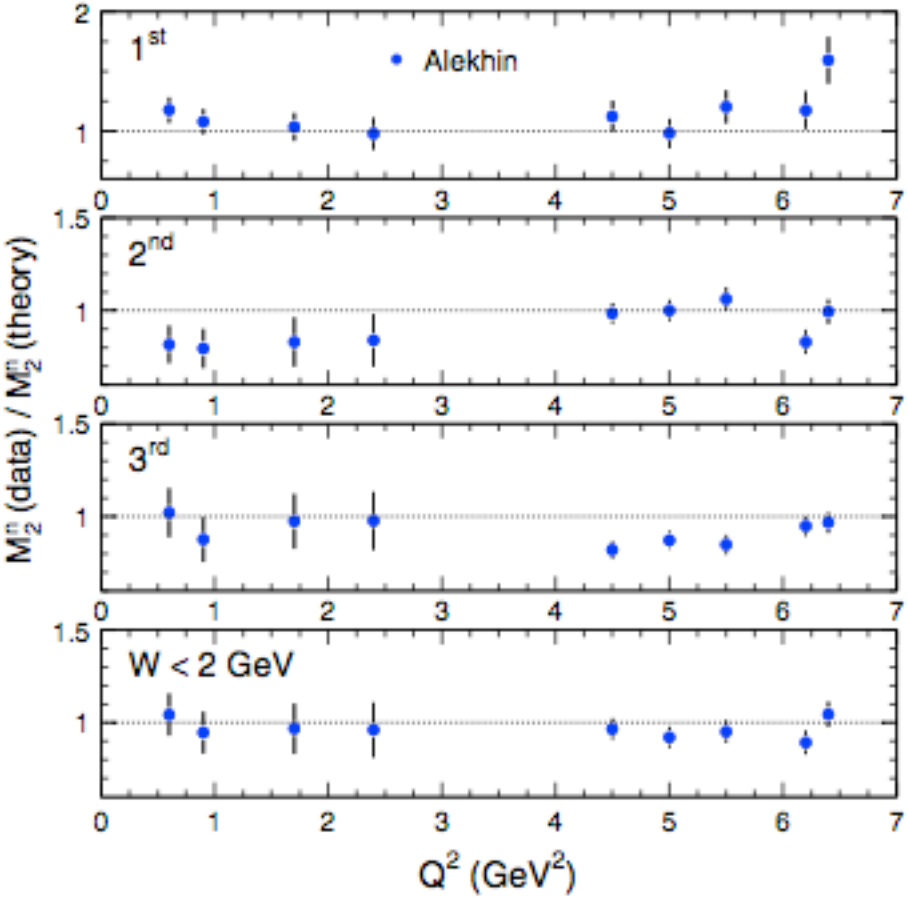
Neutron: the smoking gun

- Duality in *neutron* more difficult to test because of absence of free neutron targets
- New extraction method (using iterative procedure for solving integral convolution equations) has allowed first determination of F_2^n in resonance region & test of neutron duality



Malace, Kahn, WM, Keppel
PRL ***104****, 102001 (2010)*

Neutron: the smoking gun



→ "theory": fit to $W > 2$ GeV data

Alekhin et al., 0908.2762 [hep-ph]

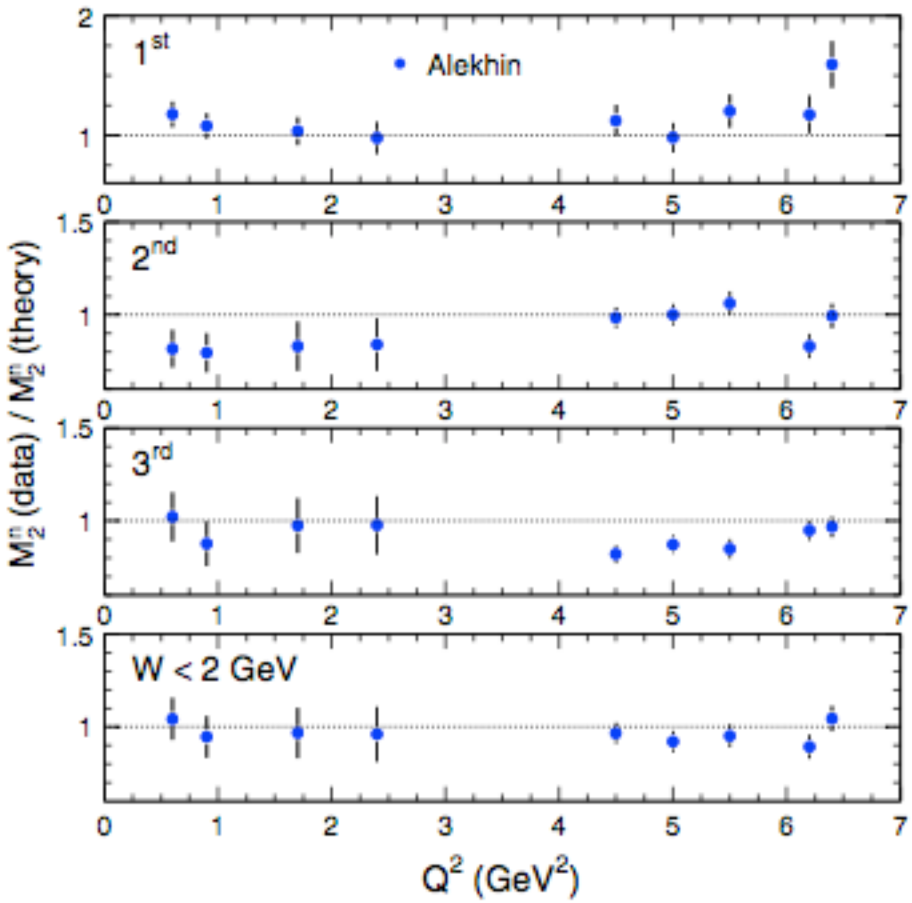
→ *locally*, violations of duality in resonance regions $< 15-20\%$ (largest in Δ region)

→ *globally*, violations $< 10\%$

Malace, Kahn, WM, Keppel
PRL ***104****, 102001 (2010)*

⇨ duality is *<u>not</u> accidental*, but a general feature of resonance−scaling transition!

Neutron: the smoking gun



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⇨ use resonance region data to learn about *leading twist* structure functions?

CTEQ-JLab (CJ) global PDF analysis *

- New global NLO analysis of expanded set of p and d data (DIS, pp, pd) including large-x, low-Q^2 region

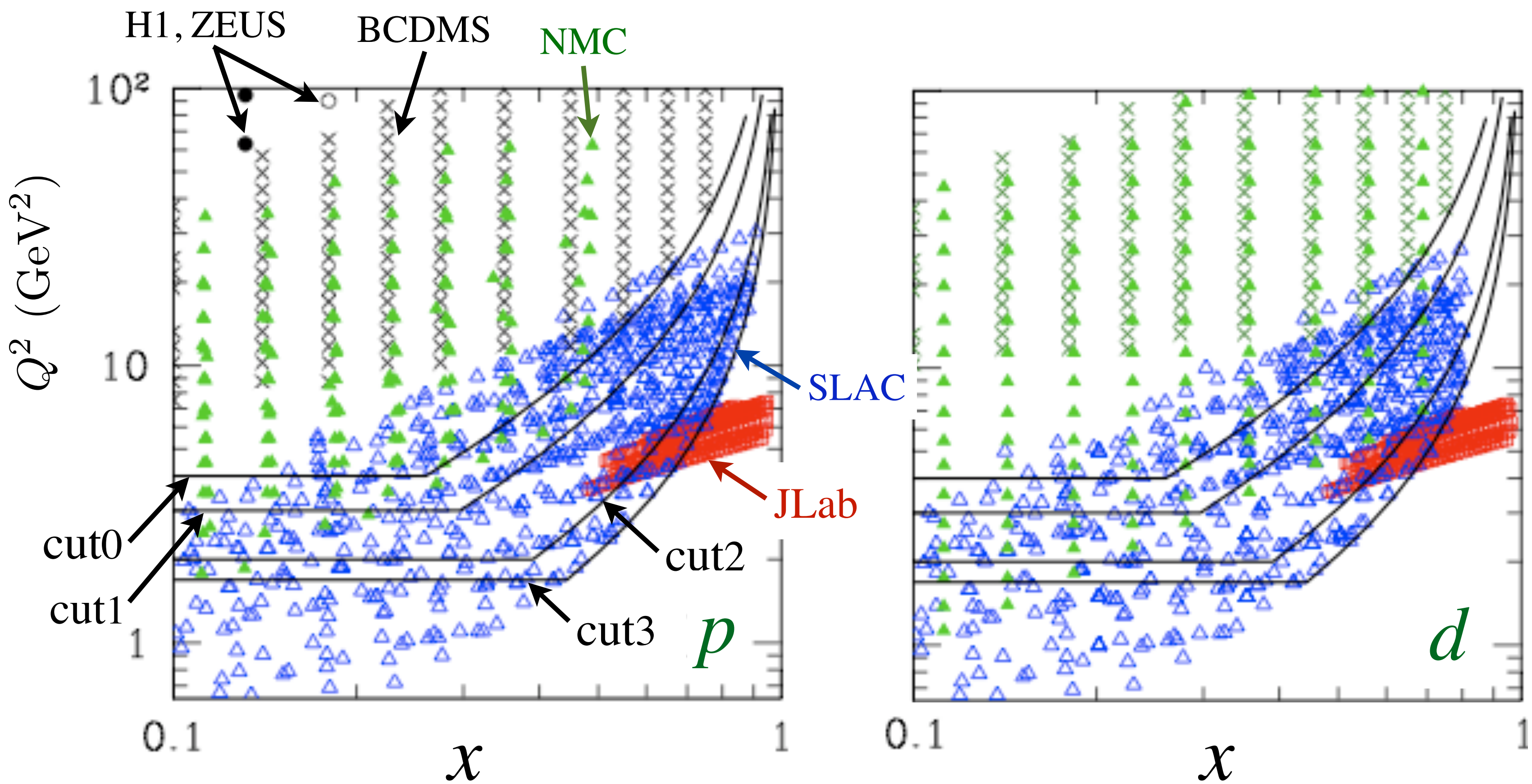
- Systematically study effects of Q^2 & W cuts
  → down to $Q \sim m_c$ and $W \sim 1.7$ GeV

- Correct for *nuclear* effects in the deuteron, subleading $1/Q^2$ corrections (target mass, higher-twists)

- Dependence on choice of PDF parametrization

* CJ collaboration: A. Accardi, J. Owens, WM (theory)
E. Christy, C. Keppel, P. Monaghan, L. Zhu (expt.)
http://www.jlab.org/CJ/

CJ kinematic cuts



cut0: $Q^2 > 4$ GeV^2, $W^2 > 12.25$ GeV^2

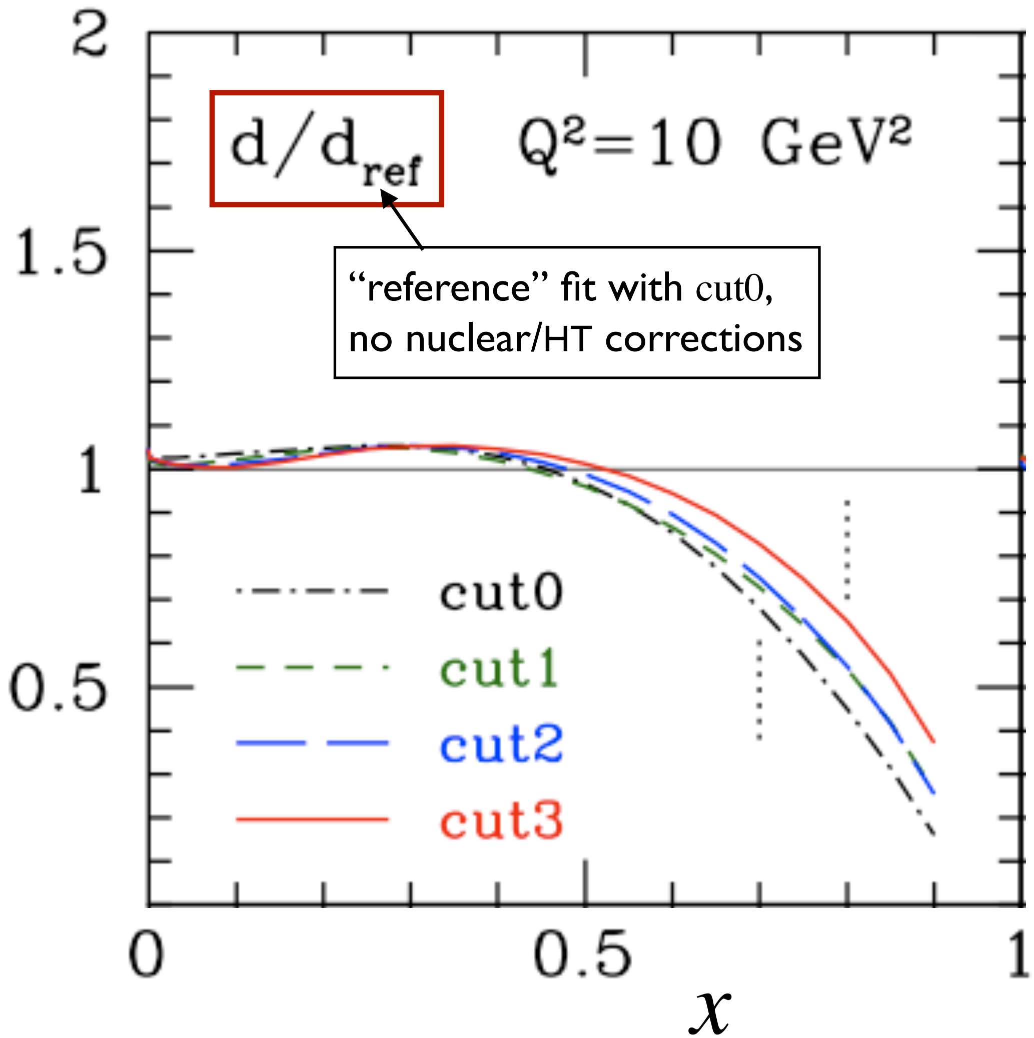
cut1: $Q^2 > 3$ GeV^2, $W^2 > 8$ GeV^2

cut2: $Q^2 > 2$ GeV^2, $W^2 > 4$ GeV^2

cut3: $Q^2 > m_c^2$, $W^2 > 3$ GeV^2

<u>factor 2 increase</u> in DIS data from cut0 → cut3

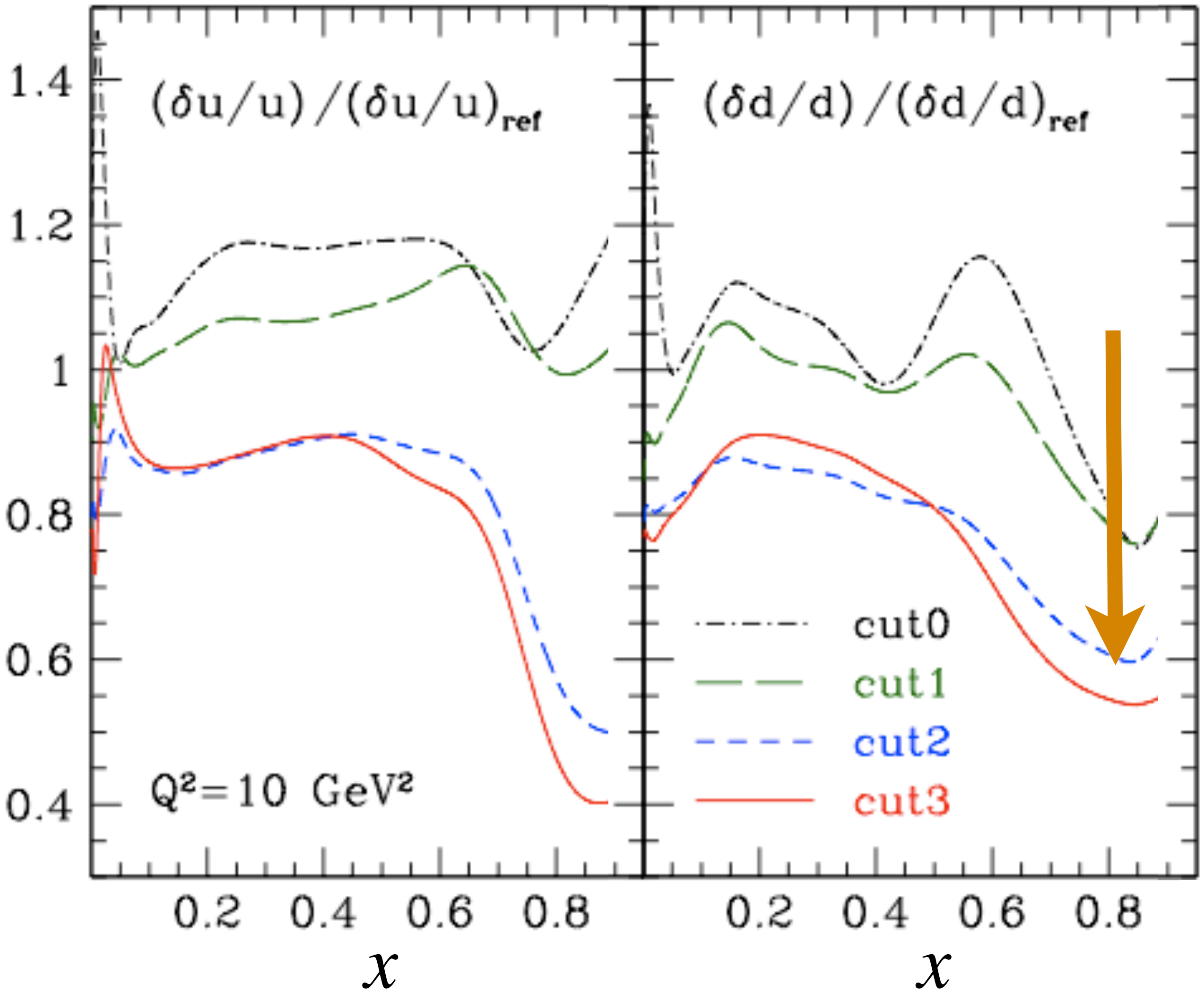
- PDFs remarkably *stable* with respect to cut reduction, as long as finite-Q^2 corrections included



Accardi et al.
PRD ***81****, 034016 (2010)*

→ d quark behavior driven by nuclear corrections at high x

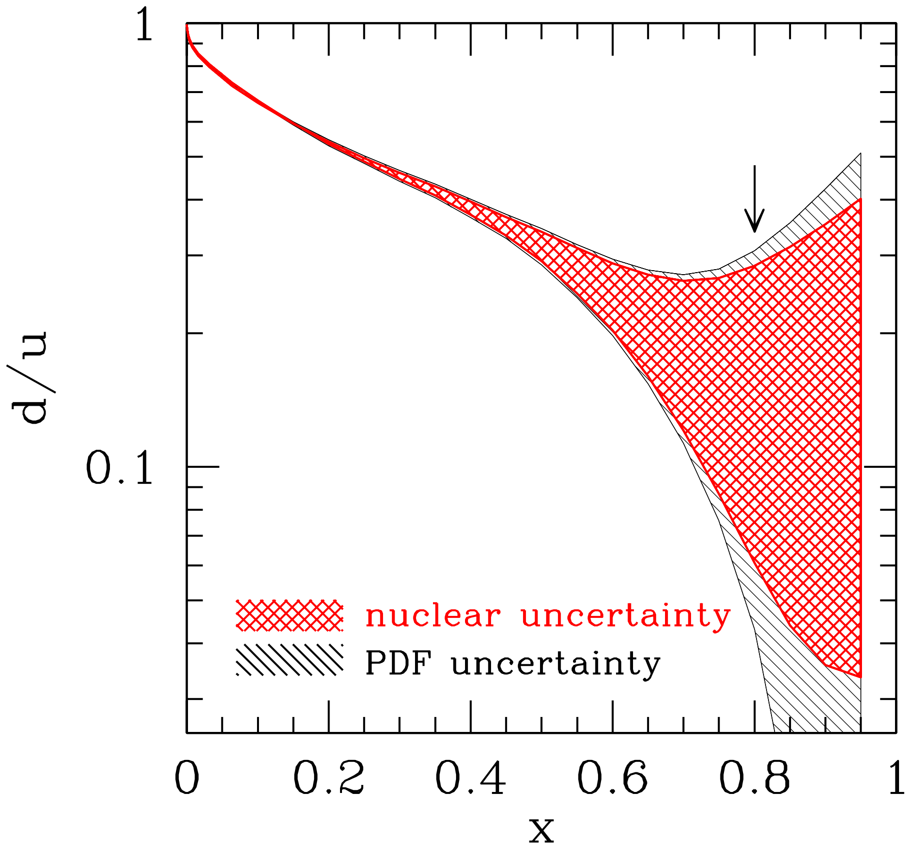
- Larger database with weaker cuts leads to significantly reduced errors, especially at large x

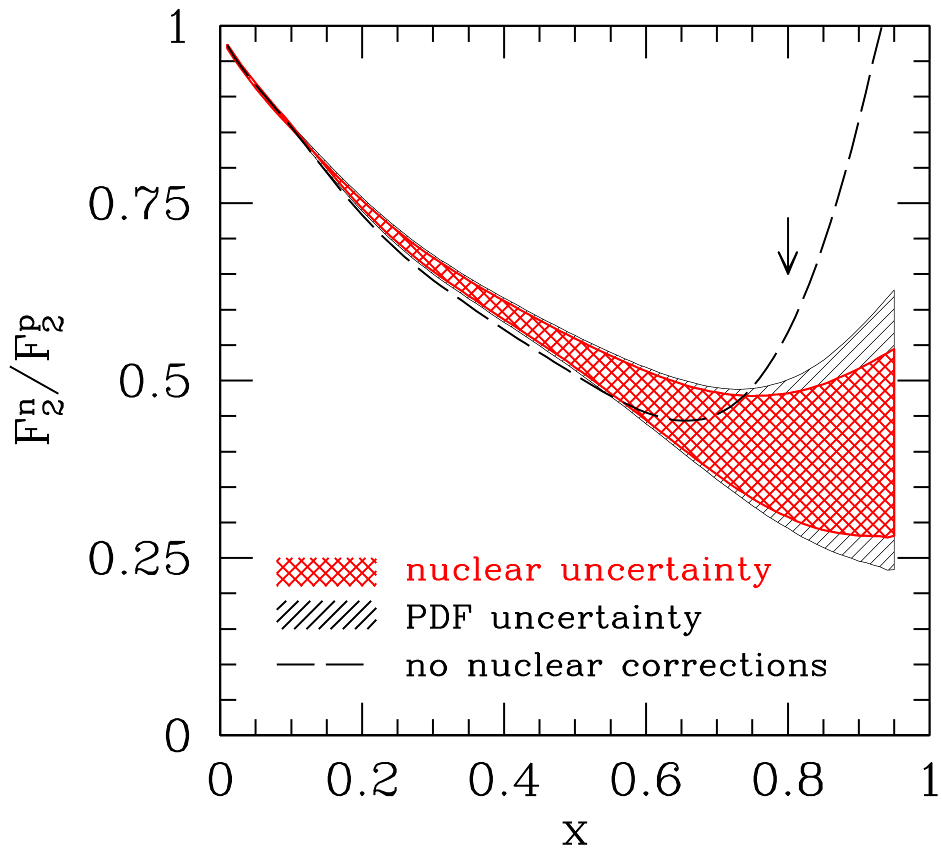


Accardi et al.
PRD ***81****, 034016 (2010)*

→ up to 40–60% error reduction when cuts extended into resonance region

- Vital for large-x analysis, which currently suffers from large uncertainties (mostly due to nuclear corrections)





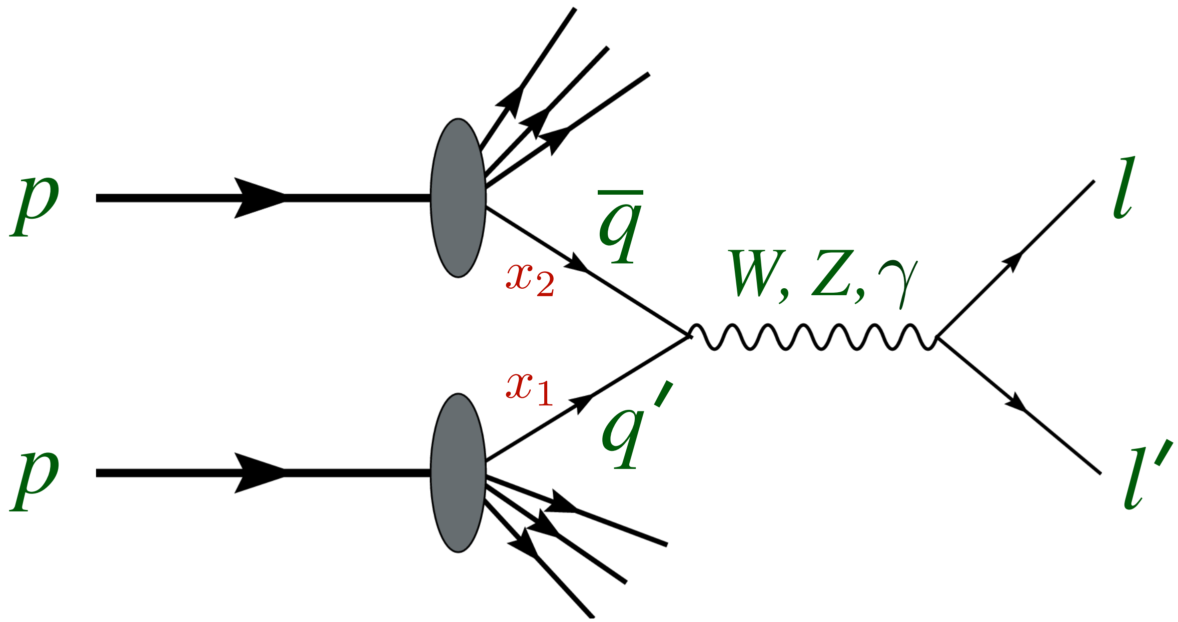
*Accardi et al., PRD **84**, 014008 (2011)*

→ uncertainty in d feeds into larger uncertainty in g at high x (important for LHC physics!)

Brady et al., arXiv:1110.5398

Large Hadron Collider (CERN)

pp collisions
at $\sqrt{s} = 7$ TeV



Heavy Z', W' boson production

- Some extensions of Standard Model predict heavy versions of W, Z bosons

→ Sequential Standard Model (SSM)
(assume same couplings as SM W, Z bosons)

→ Grand Unified Theories *e.g.* E_6 — *London, Rosner (1986)*

$$\mathrm{E}_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\chi \to \mathrm{SU}(5) \times \mathrm{U}(1)_\psi \times \mathrm{U}(1)_\chi$$

→ more exotic scenarios, *e.g.*

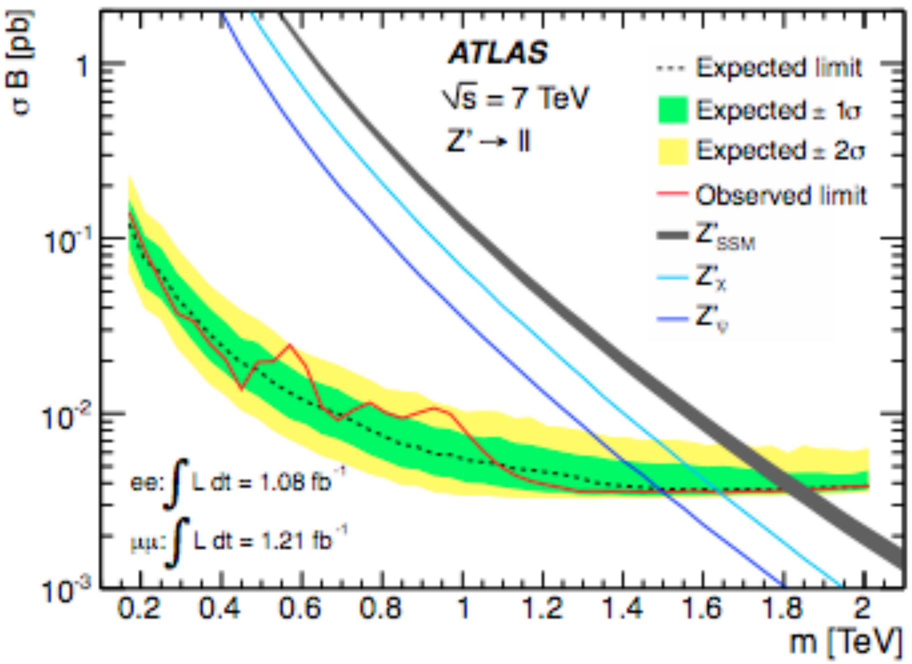
- scalar excitations in R-parity violating supersymmetric models — *Hewett, Rizzo (1998)*
- spin-1 Kaluza-Klein excitations of SM bosons in presence of extra dimensions — *Antoniadis (1990)*
- spin-2 excitations of the graviton — *Randall, Sundrum (1999)*

Heavy Z', W' boson production

- Current limits on masses (for SSM; lower for other models)

$$\longrightarrow \quad M_{Z'} > 1.83 \text{ TeV}$$

$$M_{W'} > 2.15 \text{ TeV}$$ ATLAS @ LHC



arXiv:1108.1582 [hep-ex]

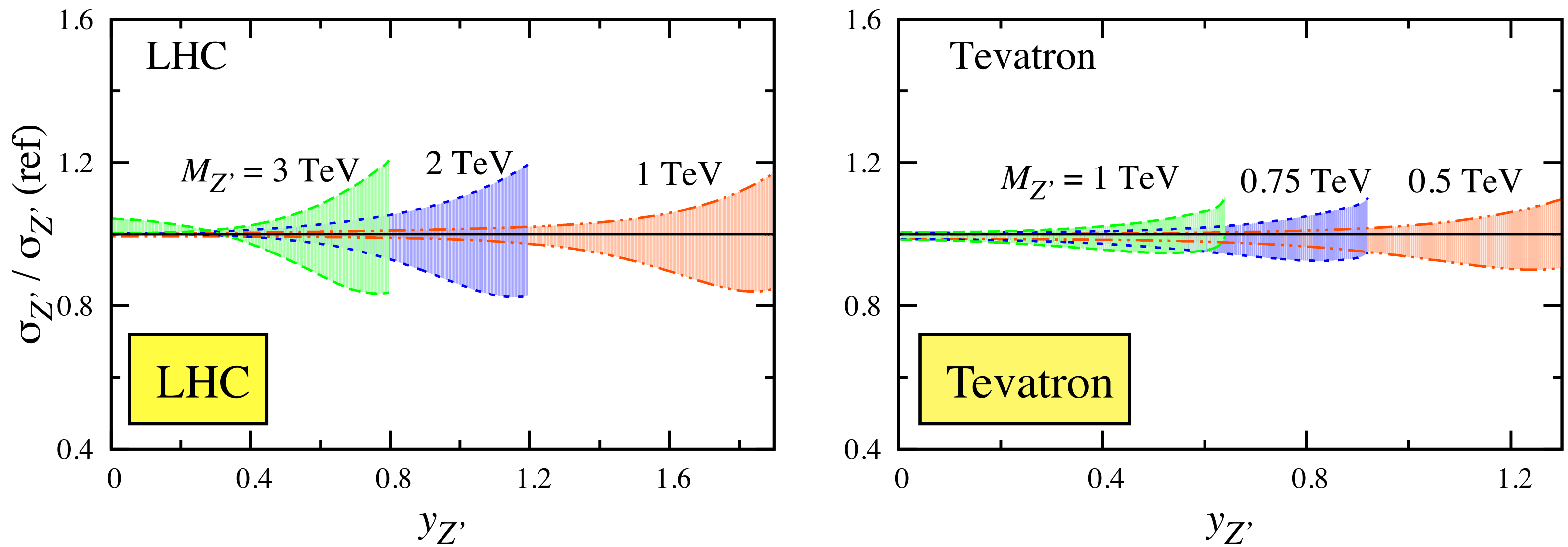
Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass)

  - for Z' production

couplings similar for u and d

$$\frac{d\sigma^{pp}}{dy} \sim \sum_q \left[(g_V^q)^2 + (g_A^q)^2 \right] \Big(q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2) \Big)$$



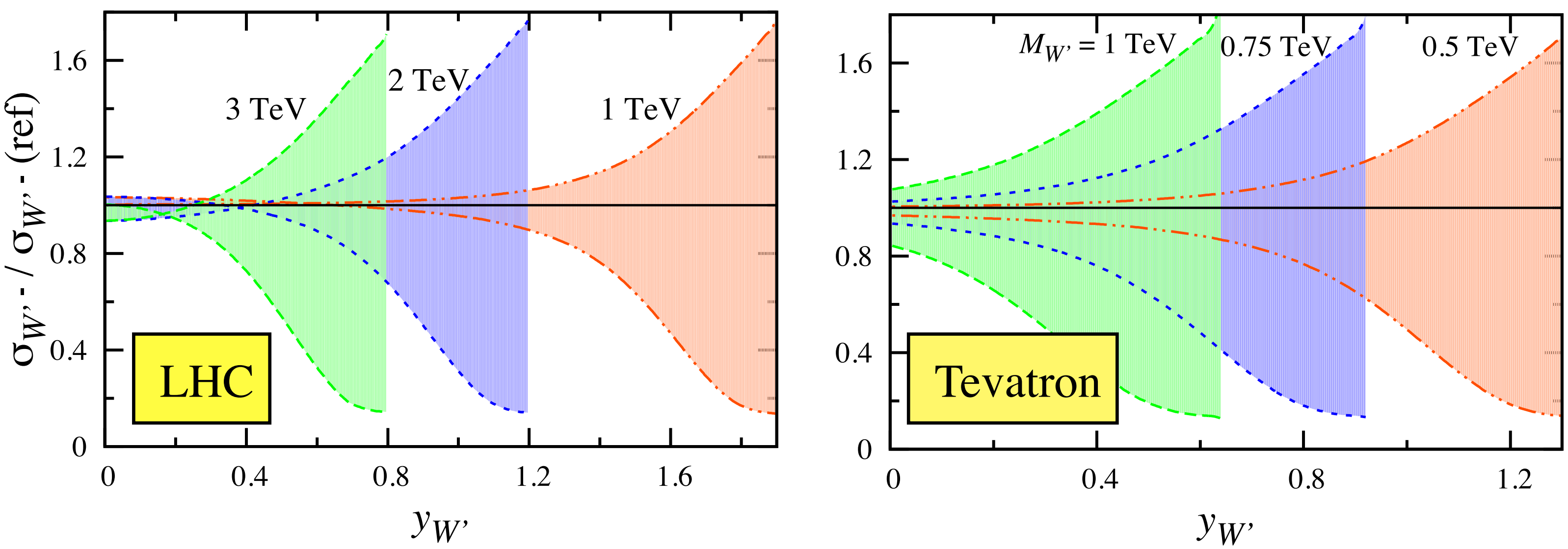
→ dominated by $u * \bar{u}$
– rel. small uncertainties

→ dominated by $u * u$
– well constrained

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
(since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

  - for W'^{-} production



→ dominated by $d * \bar{u}$ → dominated by $d * u + u * d$

$> 100\%$ uncertainties at large y !

Summary

- Remarkable confirmation of quark-hadron duality in *proton* and *neutron* structure functions

  → duality-violating higher twists $\sim 10-15\%$ in few-GeV range

- Confirmation of duality in *neutron* suggests origin in dynamical cancellations of higher twists

  → duality *not* due to accidental cancellations of quark charges

- Practical application of duality

  → use resonance region data to constrain *leading twist* PDFs (global PDF analysis underway)

  → stable fits at low Q^2 and large x with significantly reduced uncertainties

The End