BONuS / TDIS Collaboration Meeting
Jefferson Lab, December 12, 2016

New developments in tagged structure functions and PDF determination

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After almost 100 years of nuclear physics, what do we know about the nucleon?

→ it has finite size

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} \times F^2(Q^2)$$

elastic form factor

Hofstadter (1955)

→ from slope of form factor at low Q^2
r.m.s. charge radius $\sim 0.75 \times 10^{-15}\mathrm{m}$

(precise value currently under hot debate!)

→ at high Q^2 inelastic cross section looks point-like

$$\frac{d^2\sigma}{d\Omega dE'} = \left.\frac{d^2\sigma}{d\Omega dE'}\right|_{\text{point}} \left(2F_1 \tan^2\frac{\theta}{2} + F_2\right)$$

structure functions

Friedman, Kendall, Taylor (1969)

- At high energies, scattering from point-like constituents of nucleon

→ "partons" *(Feynman, 1970)* = quarks *(Gell-Mann, Zweig, 1964)* 

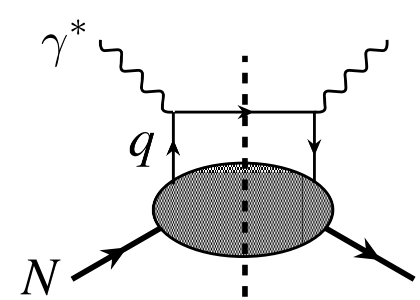
+ gluons *(Gell-Mann… 1972)*

- Measurement of structure functions in DIS reveals how nucleon is made up of quarks & gluons

→ in Feynman's parton model, structure functions given by parton distribution functions (PDFs)

$$F_2 = x \sum_q e_q^2 \, q(x)$$

$q(x)$ = probability distribution to find quark q in nucleon with momentum fraction x

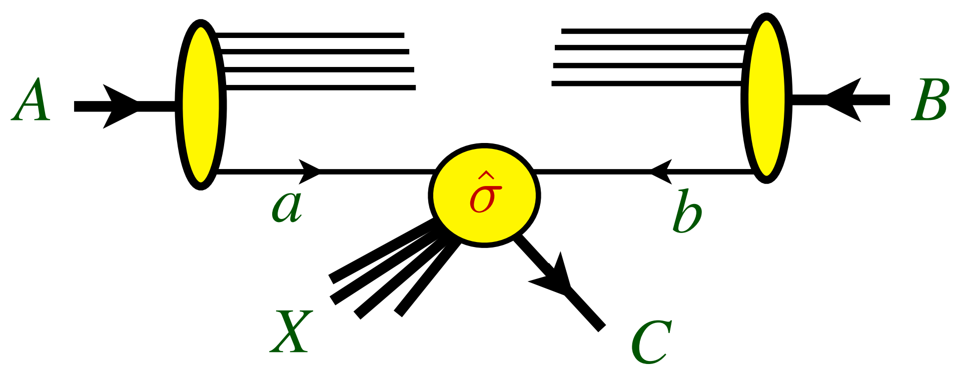


In QCD, parton distributions are universal (process-independent)

→ established formally through factorization theorems ($e.g.$ collinear, TMD, …)

Collins, Soper, Sterman ("CSS"), 1980s

→ allows high-energy cross sections to be factorized into "hard scattering partonic cross sections" (calculated from QCD using perturbation theory), and "soft" matrix elements (parametrized via PDFs)

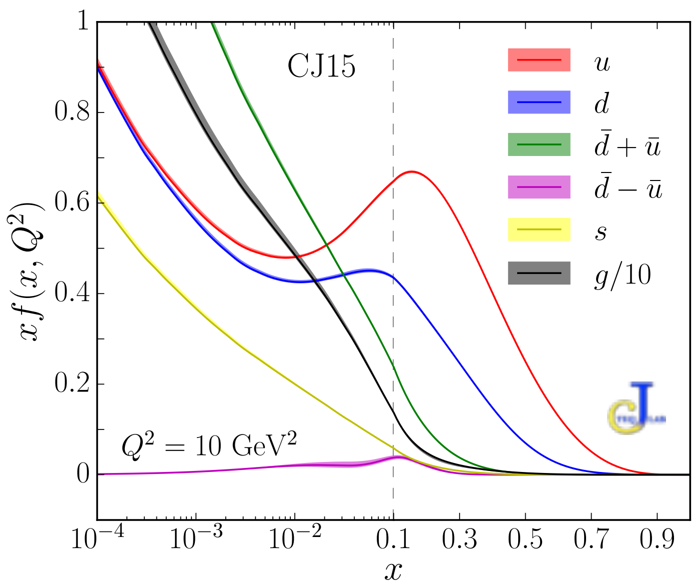


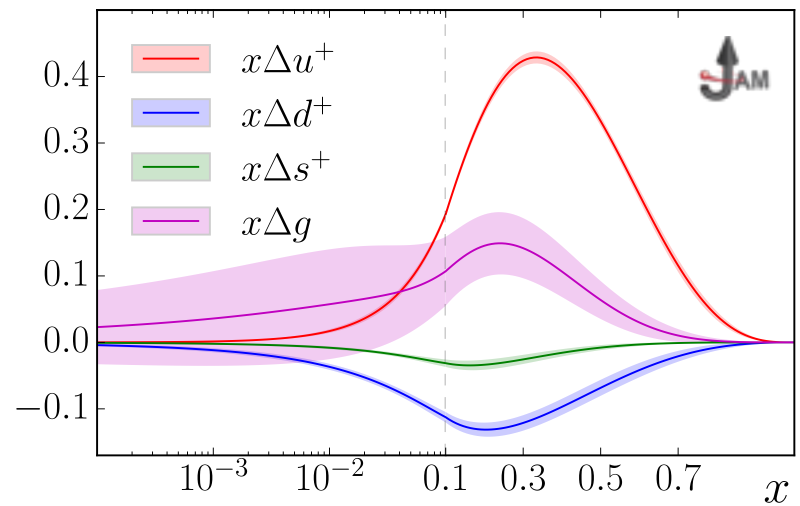
$$\sigma_{AB\to CX}(p_A, p_B) = \sum_{a,b} \int dx_a\, dx_b\, \boxed{f_{a/A}(x_a,\mu)}\, \boxed{f_{b/B}(x_b,\mu)} \times \hat{\sigma}_{ab\to CX}(x_a p_A, x_b p_B, Q/\mu)$$

- Universality of PDFs allows data from many different processes (DIS, SIDIS, weak boson/jet production in pp, Drell-Yan, …) to be analyzed simultaneously

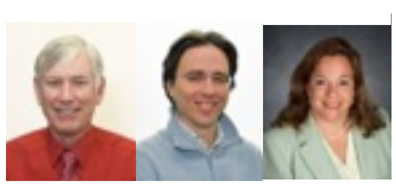
$\longrightarrow$ global QCD analyses of spin-averaged $(f = f^{\uparrow} + f^{\downarrow})$ and spin-dependent $(\Delta f = f^{\uparrow} - f^{\downarrow})$ PDFs

$\longrightarrow$ $e.g.$ CTEQ-JLab (CJ), JLab Angular Momentum (JAM) Collaborations

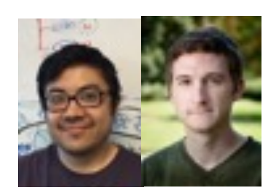




CJ ***(Owens, Accardi, Keppel, WM…)***



JAM ***(Sato, Ethier, WM…)***



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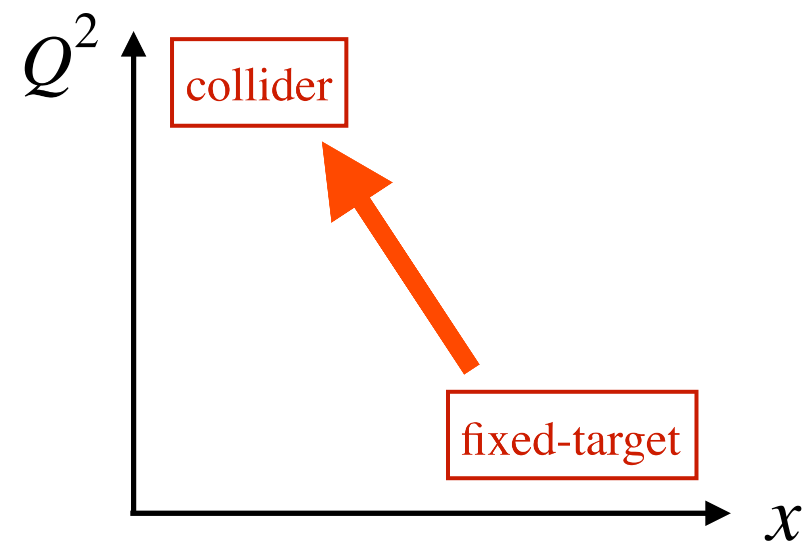
  → global QCD analyses of spin-averaged $(f = f^{\uparrow} + f^{\downarrow})$ and spin-dependent $(\Delta f = f^{\uparrow} - f^{\downarrow})$ PDFs

- Precision PDFs needed to
  (1) understand basic structure of QCD bound states
  (2) compute backgrounds in searches for BSM physics

  → Q^2 evolution feeds
  low x, high Q^2 ("LHC")
  from high x, low Q^2 ("JLab")



CJ15 global PDF analysis

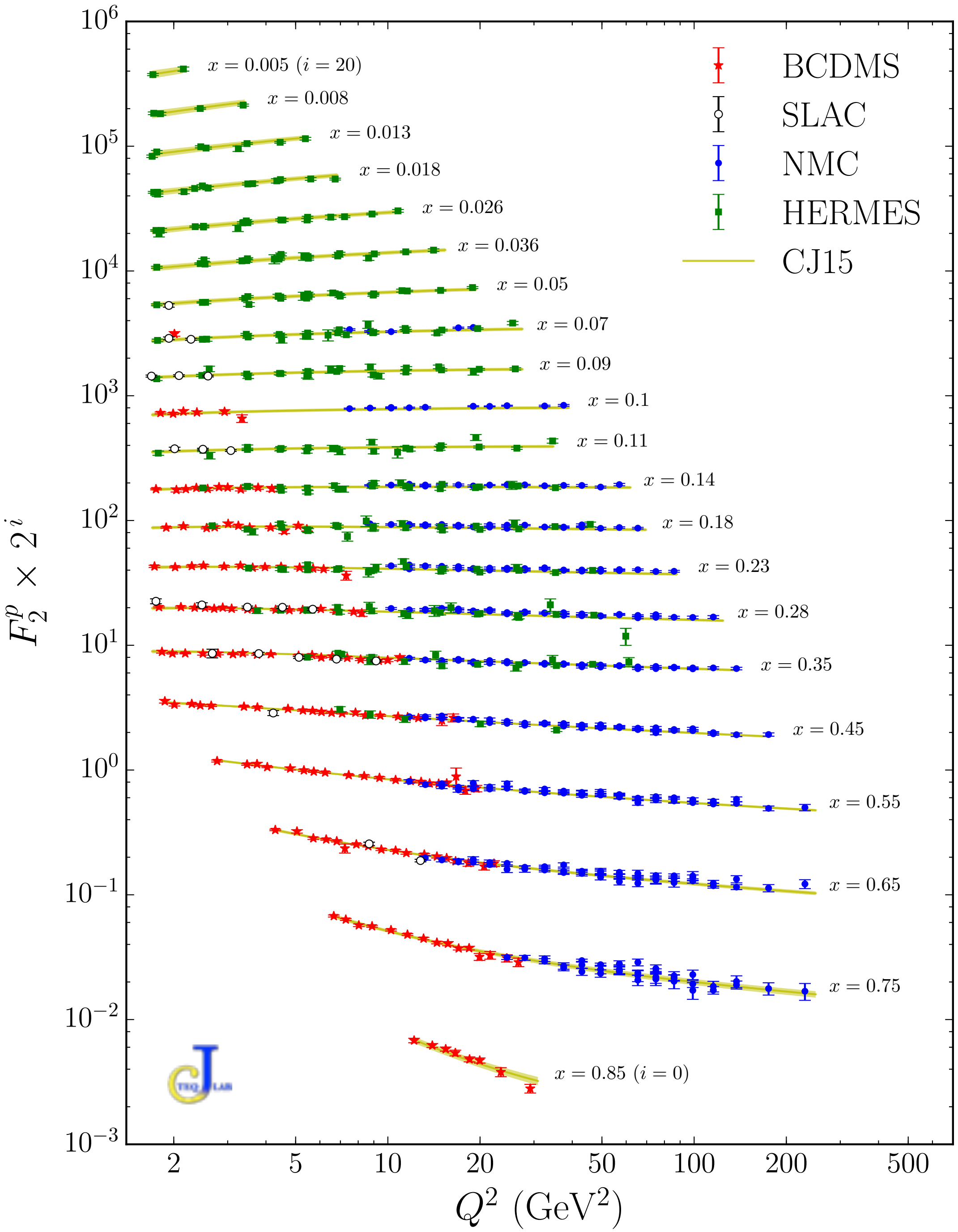
- NLO analysis of expanded set of proton & deuterium data
  - → include high-x region $(x > 0.5)$
- High-x region requires use of data at lower W & Q^2
- Analysis of high-x data requires careful treatment of subleading $1/Q^2$ corrections
  - → target mass corrections, higher twist effects
- Correct for nuclear effects in deuteron (binding + off-shell)
  - → binding + Fermi motion (well known), nucleon off-shell (less well known)
  - → impact on d/u ratio in large-x region

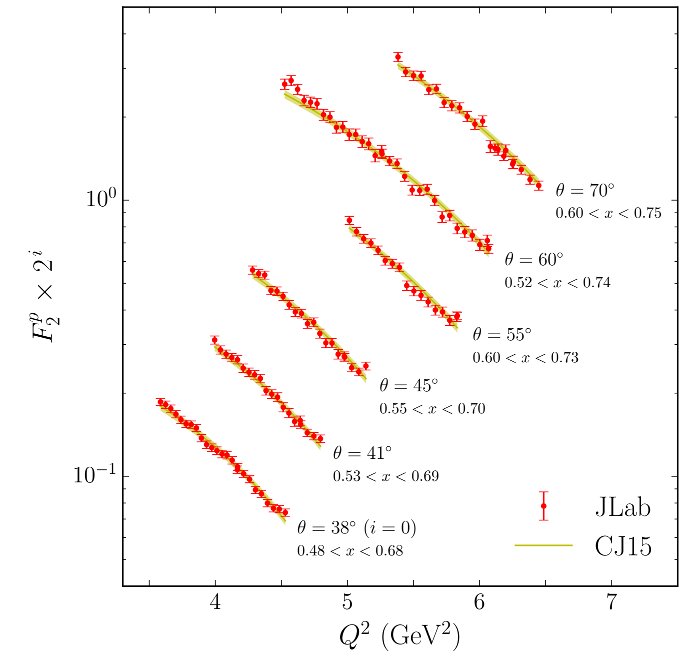
Accardi et al., PRD 93, 114017 (2016)

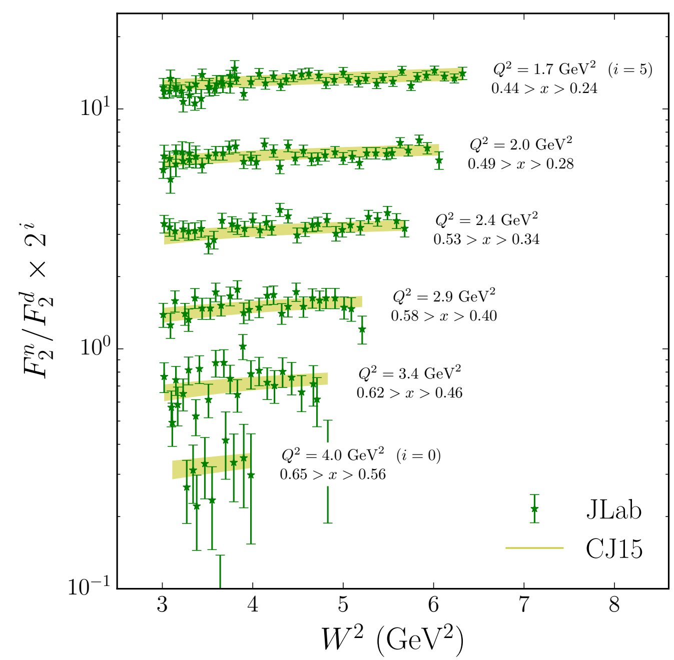
data sets used in fit

Observable	Experiment	# points	χ^2 LO	NLO	NLO (OCS)	NLO (no nucl)	NLO (no nucl/D0)	
DIS F_2	BCDMS (p) [81]	351	430	**438**	436	440	427	
	BCDMS (d) [81]	254	297	**292**	289	301	301	
	SLAC (p) [82]	564	488	**434**	435	441	440	
	SLAC (d) [82]	582	396	**376**	380	507	466	
	NMC (p) [83]	275	431	**405**	404	405	403	
	NMC (d/p) [84]	189	179	**172**	173	174	173	
	HERMES (p) [86]	37	56	**42**	43	44	44	
	HERMES (d) [86]	37	51	**37**	38	36	37	
	Jefferson Lab (p) [87]	136	166	**166**	167	177	166	
	Jefferson Lab (d) [87]	136	131	**123**	124	126	130	
DIS F_2 tagged	Jefferson Lab (n/d) [21]	191	218	**214**	213	219	219	⟵ BONuS F_2^n/F_2^d
DIS σ	HERA (NC e^-p) [85]	159	325	**241**	240	247	244	
	HERA (NC e^+p 1) [85]	402	966	**580**	579	588	585	
	HERA (NC e^+p 2) [85]	75	184	**94**	94	94	93	
	HERA (NC e^+p 3) [85]	259	307	**249**	249	248	248	
	HERA (NC e^+p 4) [85]	209	348	**228**	228	228	228	
	HERA (CC e^-p) [85]	42	44	**48**	48	45	49	
	HERA (CC e^+p) [85]	39	56	**50**	50	51	51	
Drell-Yan	E866 (pp) [29]	121	148	**139**	139	145	143	
	E866 (pd) [29]	129	207	**145**	143	158	157	
W/charge asymmetry	CDF (e) [88]	11	11	**12**	12	13	14	
	DØ (μ) [17]	10	37	**20**	19	29	28	⟵ D0 A_l
	DØ (e) [18]	13	20	**29**	29	14	14	
	CDF (W) [89]	13	16	**16**	16	14	14	
	DØ (W) [19]	14	39	**14**	15	82	—	⟵ D0 A_W
Z rapidity	CDF (Z) [90]	28	100	**27**	27	26	26	
	DØ (Z) [91]	28	25	**16**	16	16	16	
jet	CDF (run 2) [92]	72	33	**15**	15	23	25	
	DØ (run 2) [93]	110	23	**21**	21	14	14	
γ+jet	DØ 1 [94]	16	17	**7**	7	7	7	
	DØ 2 [94]	16	34	**16**	16	17	17	
	DØ 3 [94]	12	34	**25**	25	24	25	
	DØ 4 [94]	12	76	**13**	13	13	13	
total		4542	5894	**4700**	4702	4964	4817	
total + norm			6022	**4708**	4710	4972	4826	
χ^2/datum			1.33	**1.04**	1.04	1.09	1.07	

~ 4500 data points, with χ^2 per datum = 1.04





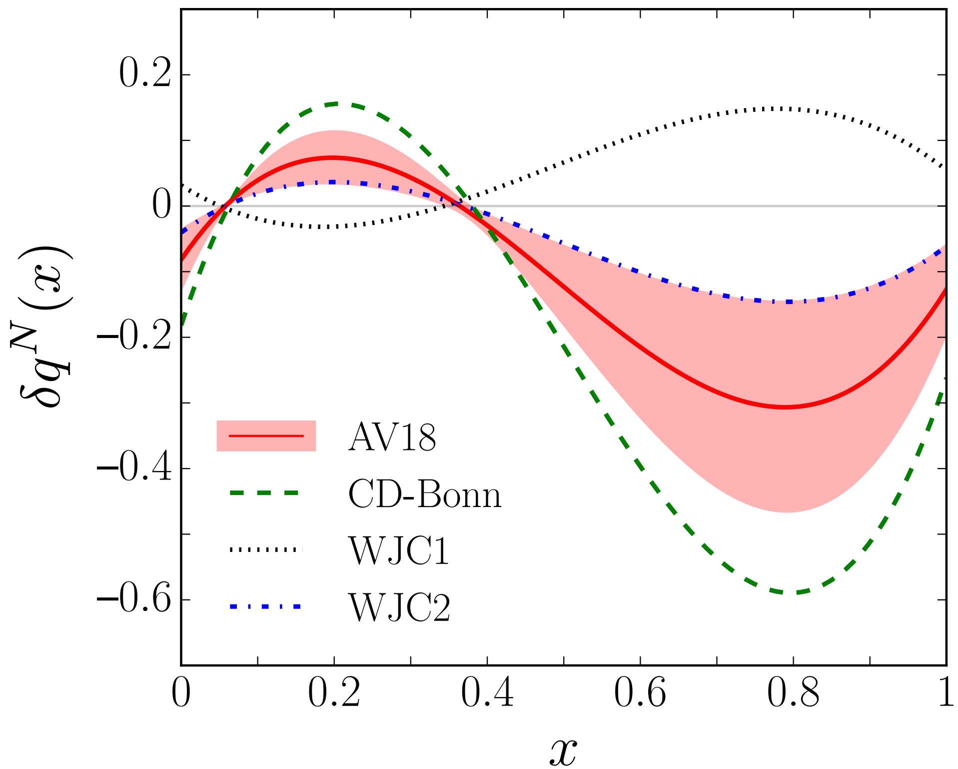


→ excellent description over orders of magnitude in x and Q^2

Nuclear corrections

- Nucleon off-shell correction parametrized phenomenologically

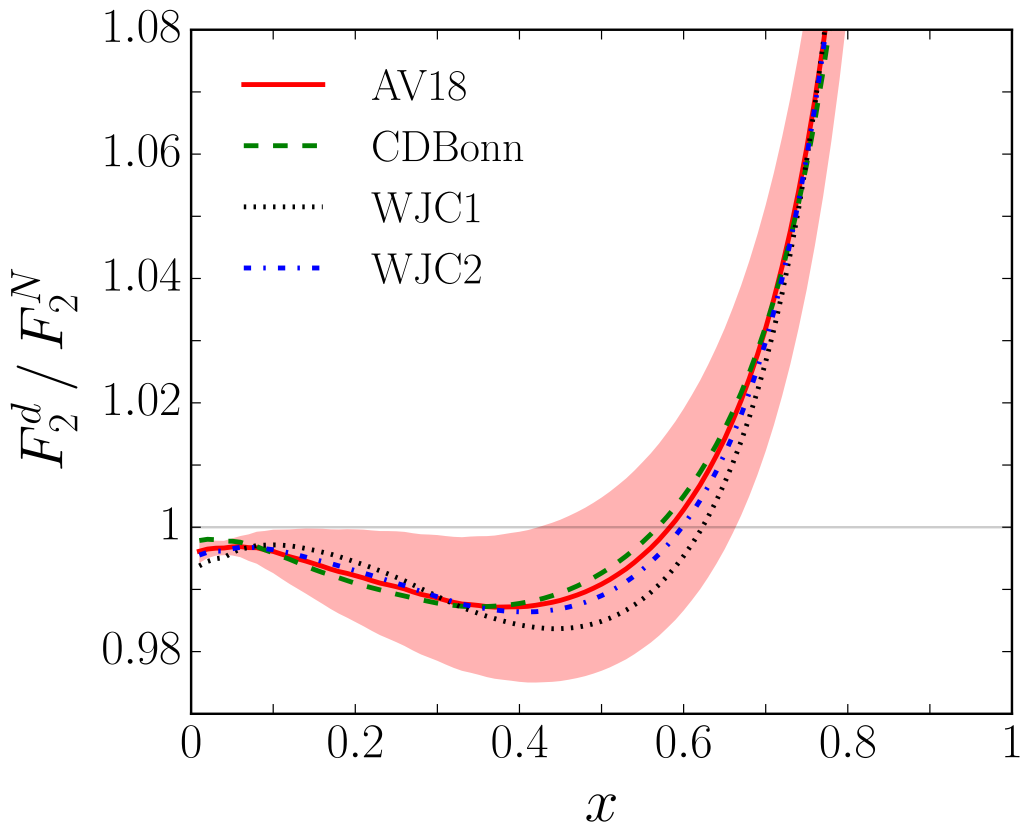
$$\delta q^N = C_N(x - x_0)(x - x_1)(1 + x - x_0)$$



→ fitted off-shell corrections weakly dependent on deuteron wave function, except for WJC-1 (hardest momentum distribution – largest tail)

Nuclear corrections

- Nuclear "EMC ratio" in deuterium

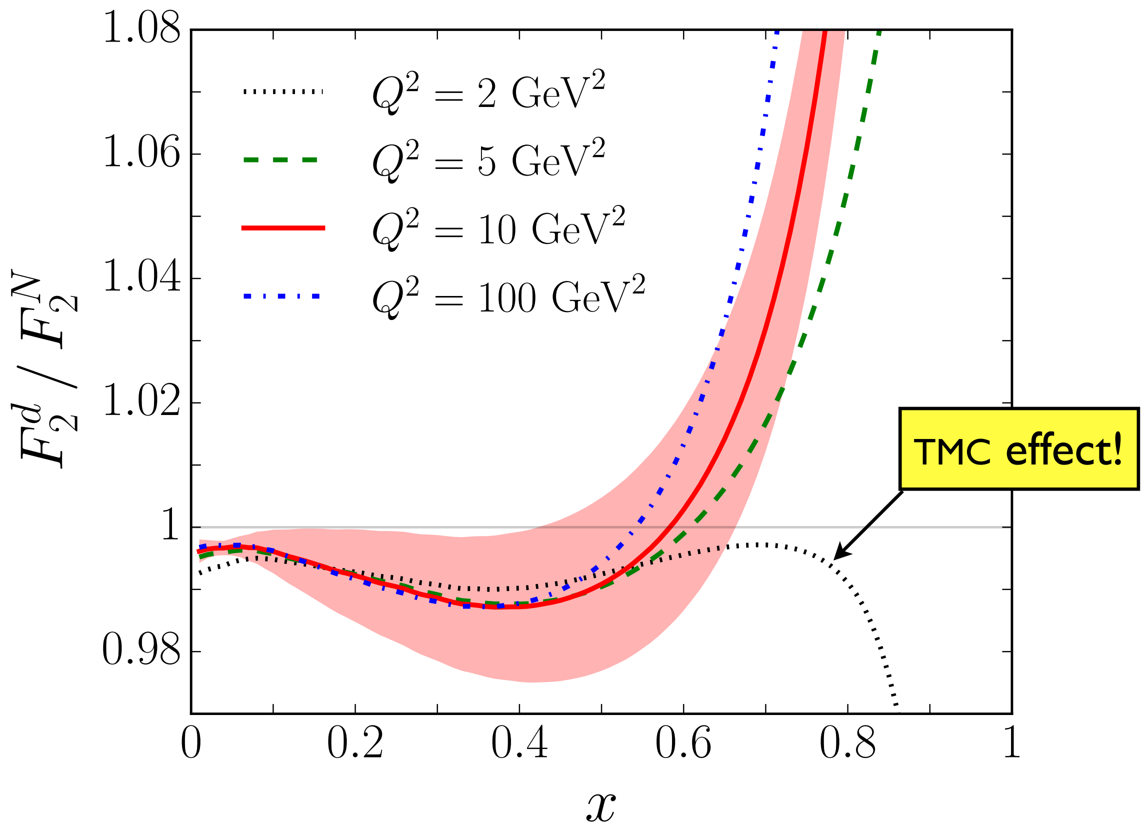


→ observables sensitive only to combined smearing (wave function) *and* off-shell corrections

→ no evidence for "antishadowing" at $x \sim 0.1$

Nuclear corrections

- Nuclear "EMC ratio" in deuterium



→ ratio has significant Q^2 dependence at low Q^2 from target mass effects – problematic to use universal ratio $R = F_2^d / F_2^N$ for all kinematics

Valence quark PDFs

- Valence d/u ratio at high x of particular interest

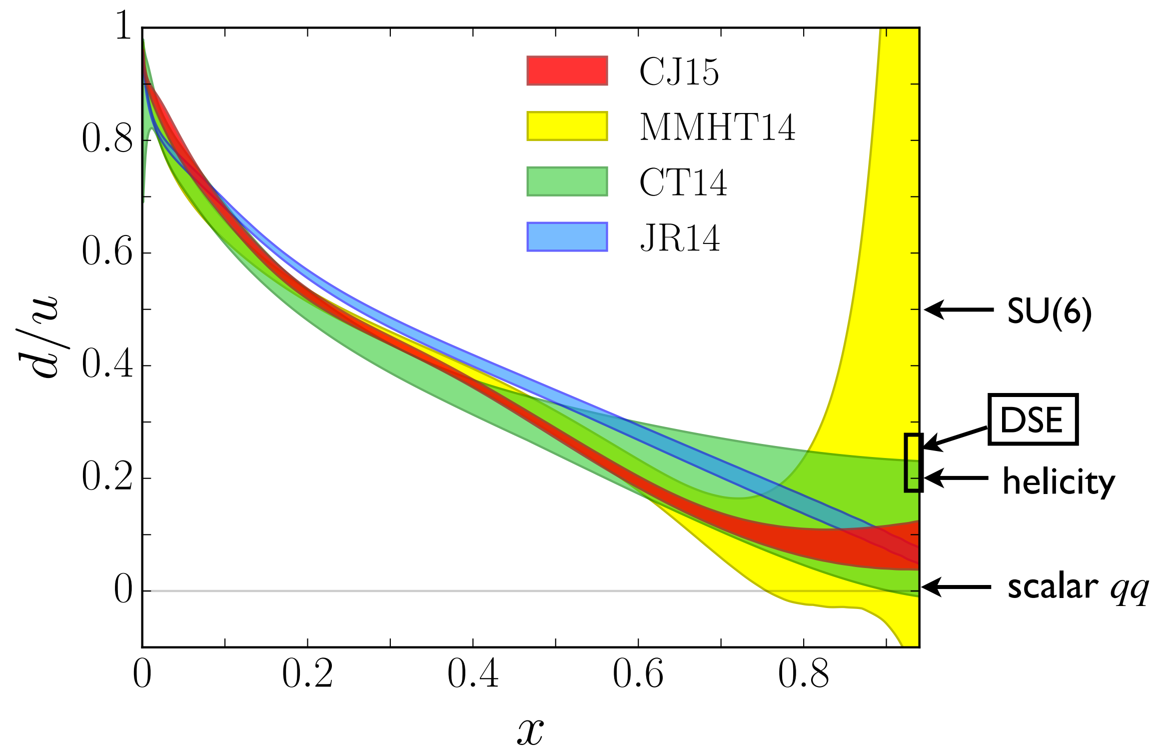
$\longrightarrow$ testing ground for nucleon models in $x \to 1$ limit

- $d/u \to 1/2$
  SU(6) symmetry

- $d/u \to 0$
  $S = 0$ qq dominance
  (color-hyperfine interaction)

- $d/u \to 1/5$
  $S_z = 0$ qq dominance
  (perturbative gluon exchange)

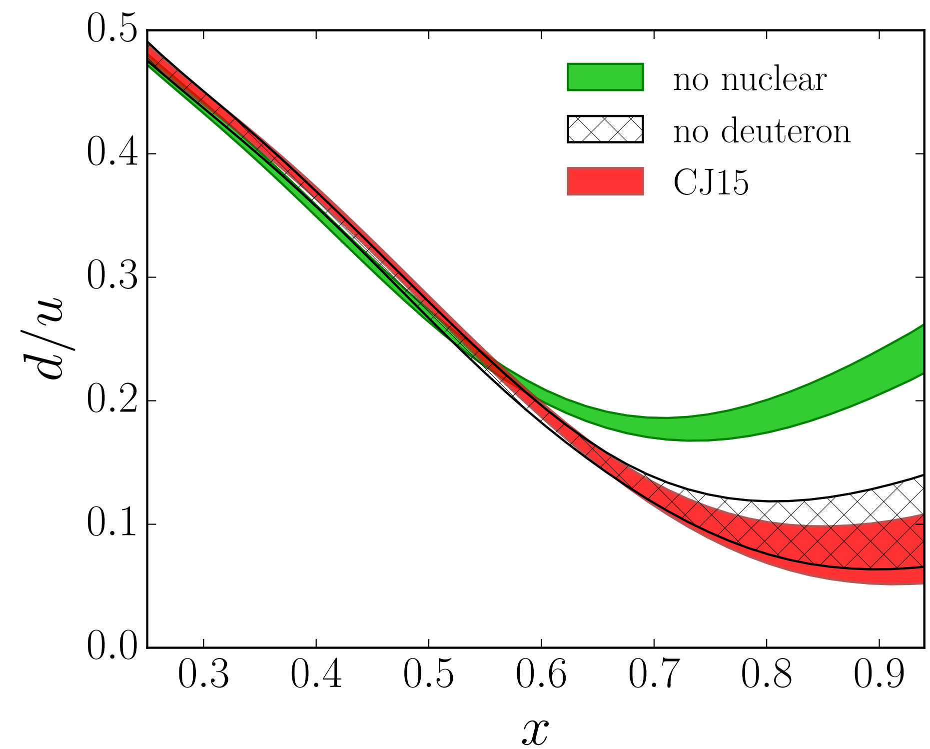
- $d/u \to 0.18 - 0.28$
  DSE with qq correlations



$\longrightarrow$ considerable uncertainty at high x from deuterium corrections (no free neutrons!)

Valence quark PDFs

- Valence d/u ratio at high x of particular interest
  - → nuclear corrections vital at large x
  - → omission would lead to significant overestimate of d/u at $x > 0.6$
  - → deuterium data reduces uncertainties (at all x)

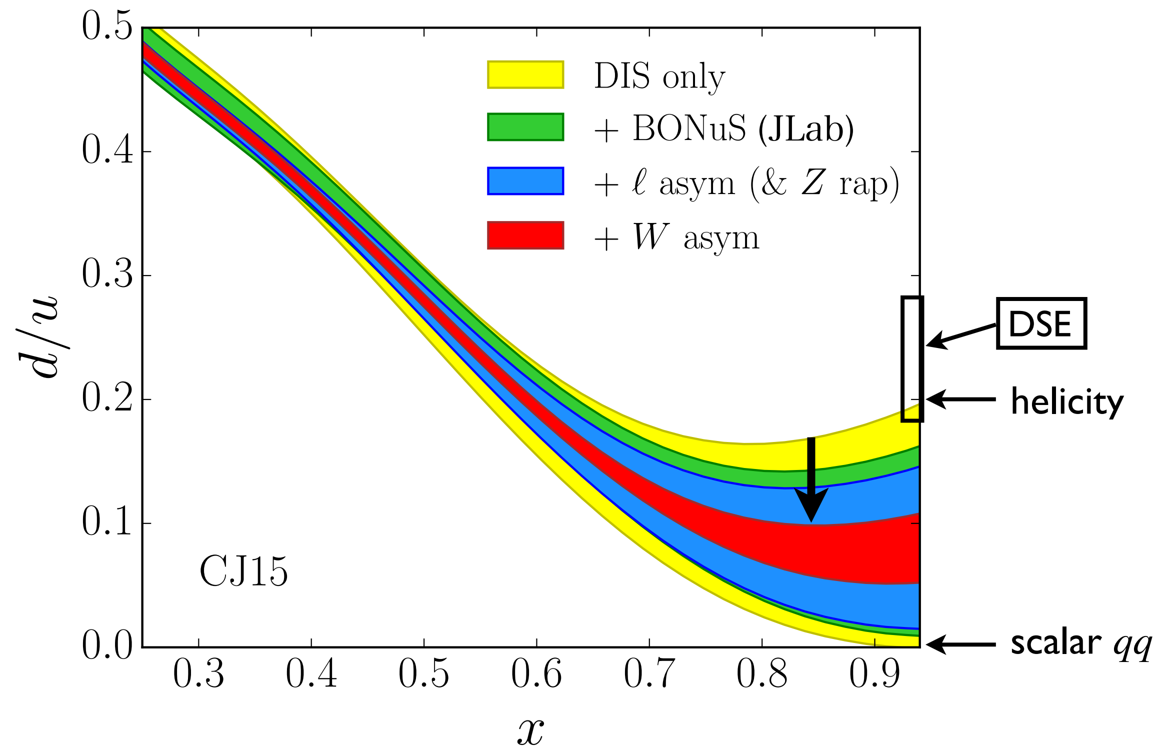


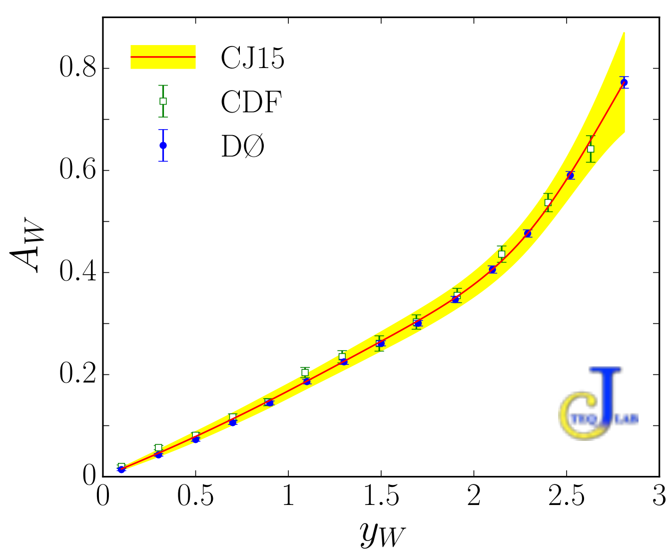
→ **note**: errors are 90% CL with no "tolerance" factor

Valence quark PDFs

- Valence d/u ratio at high x of particular interest

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





→ extrapolated ratio at $x = 1$

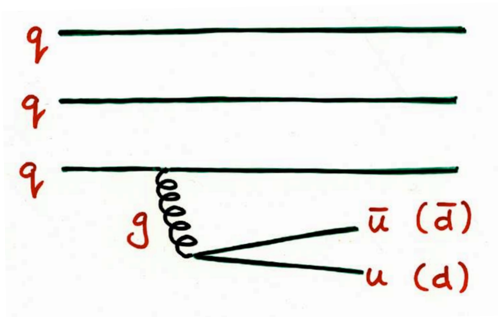
$$d/u \;\rightarrow\; 0.09 \pm 0.03$$

does not match any model!

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

Light quark sea

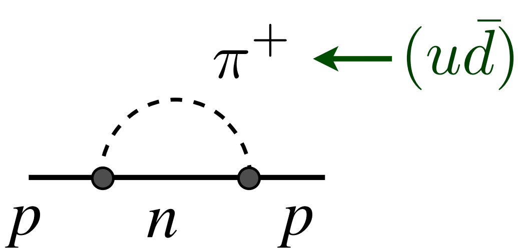
- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)



$\rightarrow$ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

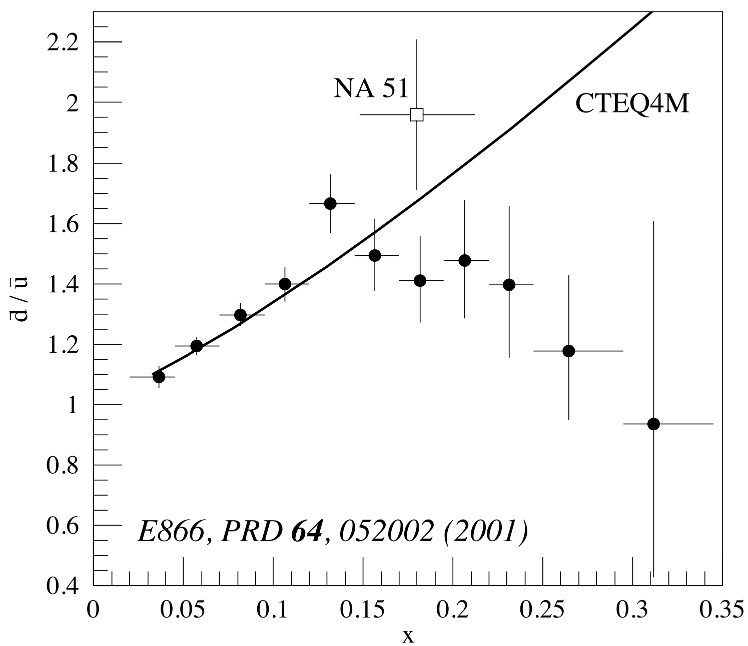
- In 1980s Thomas argued that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

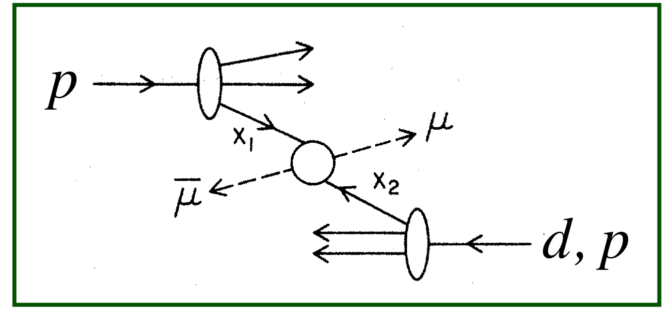


$$\rightarrow \boxed{\bar{d} > \bar{u}}$$

Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments





$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\, \bar{q}(x_2) \;+\; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

$\longrightarrow$ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

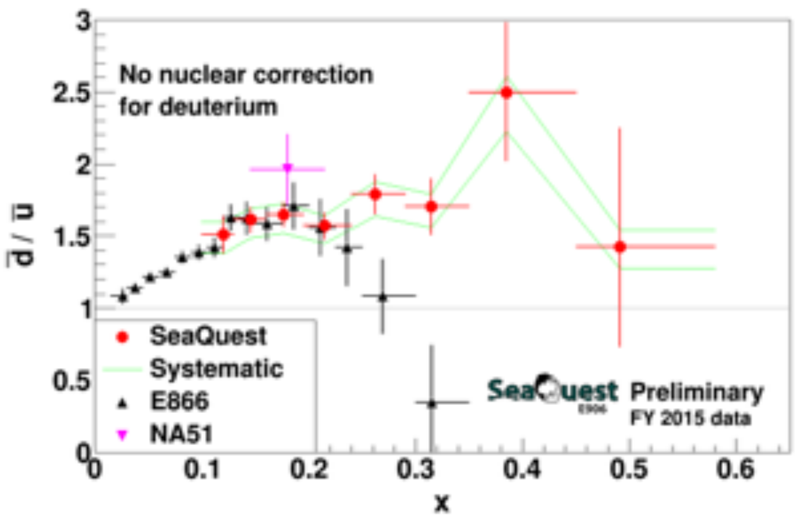
$$(\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)\,(x)$$

pion distribution in nucleon

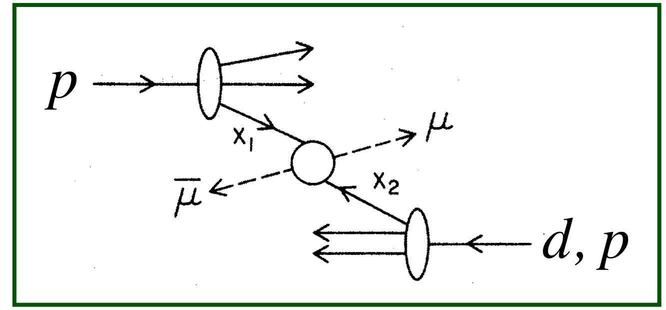
pion PDF

Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments



P. Reimer (2016)



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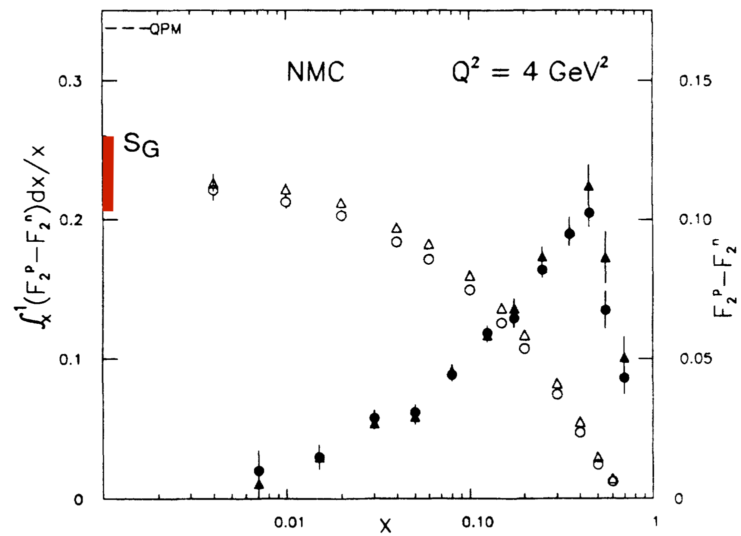


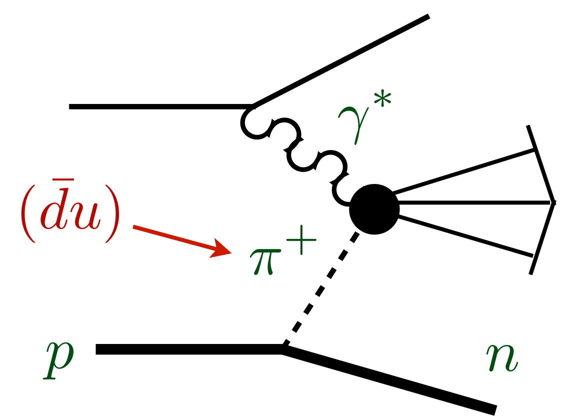
NMC (1994)

$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,(\bar{d} - \bar{u})$$

$$= 0.235(26)$$

violation of Gottfried sum rule!

→ Sullivan process — DIS from pion cloud of the nucleon



Sullivan (1972)

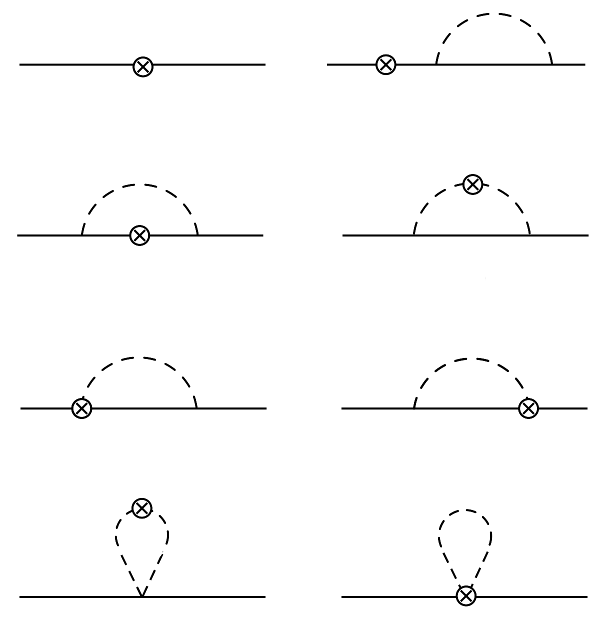
Chiral effective theory

- Early calculations used phenomenological models — more recently rigorous connection with QCD established via effective chiral field theory

$$\mathcal{L}_{\rm eff} = \frac{g_A}{2f_\pi}\,\bar\psi_N \gamma^\mu \gamma_5\,\vec\tau\cdot\partial_\mu\vec\pi\,\psi_N - \frac{1}{(2f_\pi)^2}\,\bar\psi_N\gamma^\mu\,\vec\tau\cdot(\vec\pi\times\partial_\mu\vec\pi)\,\psi_N$$

Weinberg (1967)

→ lowest order πN interaction includes pion rainbow and tadpole contributions



→ matching quark- and hadron-level operators

$$\mathcal{O}_q^{\mu_1\cdots\mu_n} = \sum_h c_{q/h}^{(n)}\;\mathcal{O}_h^{\mu_1\cdots\mu_n}$$

yields convolution representation

$$q(x) = \sum_h \int_x^1 \frac{dy}{y}\, f_h(y)\, q_v^h(x/y)$$

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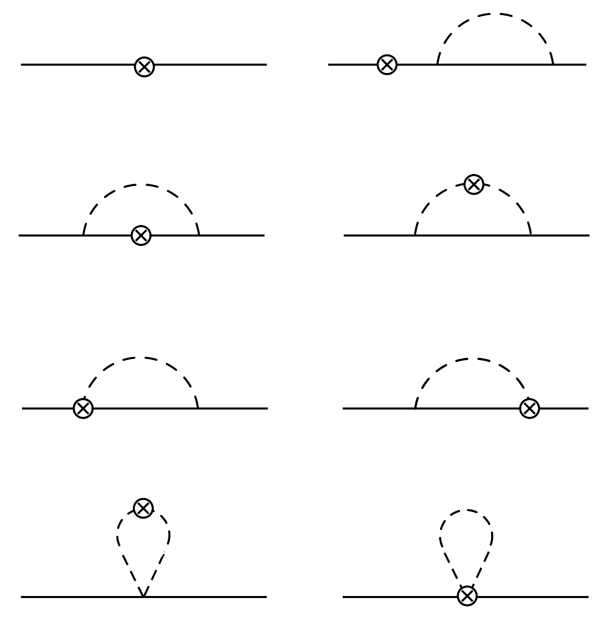
Weinberg (1967)

→ expanding PDF moments in powers of m_π, coefficients of leading nonanalytic (LNA) terms are model-independent!

Thomas, WM, Steffens (2000)
Chueng Ji, WM, Thomas (2012)



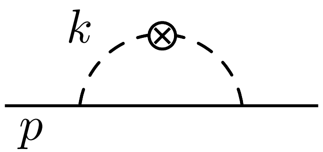
→ nonanalytic behavior vital for chiral extrapolation of lattice data on PDF moments

$$\langle x \rangle_{u-d}^{\rm LNA} \sim m_\pi^2 \log m_\pi^2$$

Detmold et al. (2001)

Pion splitting functions

- Spitting functions for various diagrams computed in chiral theory $e.g.$ pion rainbow diagram



$$f_\pi(y) = f^{(\text{on})}(y) + f^{(\delta)}(y)$$

has on-shell $(y = k^+/p^+ > 0)$ and $\delta(y)$ contributions!

$$f^{(\text{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \, \frac{y(k_\perp^2 + y^2 M^2)}{[k_\perp^2 + y^2 M^2 + (1-y)m_\pi^2]^2}$$

$$f^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2} \int dk_\perp^2 \, \log\left(\frac{k_\perp^2 + m_\pi^2}{\mu^2}\right) \delta(y)$$

- For point-like nucleons and pions, integrals divergent

$\longrightarrow$ finite size of nucleon provides natural regularization scale (but does not prescribe form of regularization)

$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$ $k_\perp$ cutoff

$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ t monopole

$\mathcal{F} = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ t exponential

$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$ s-dep. exponential

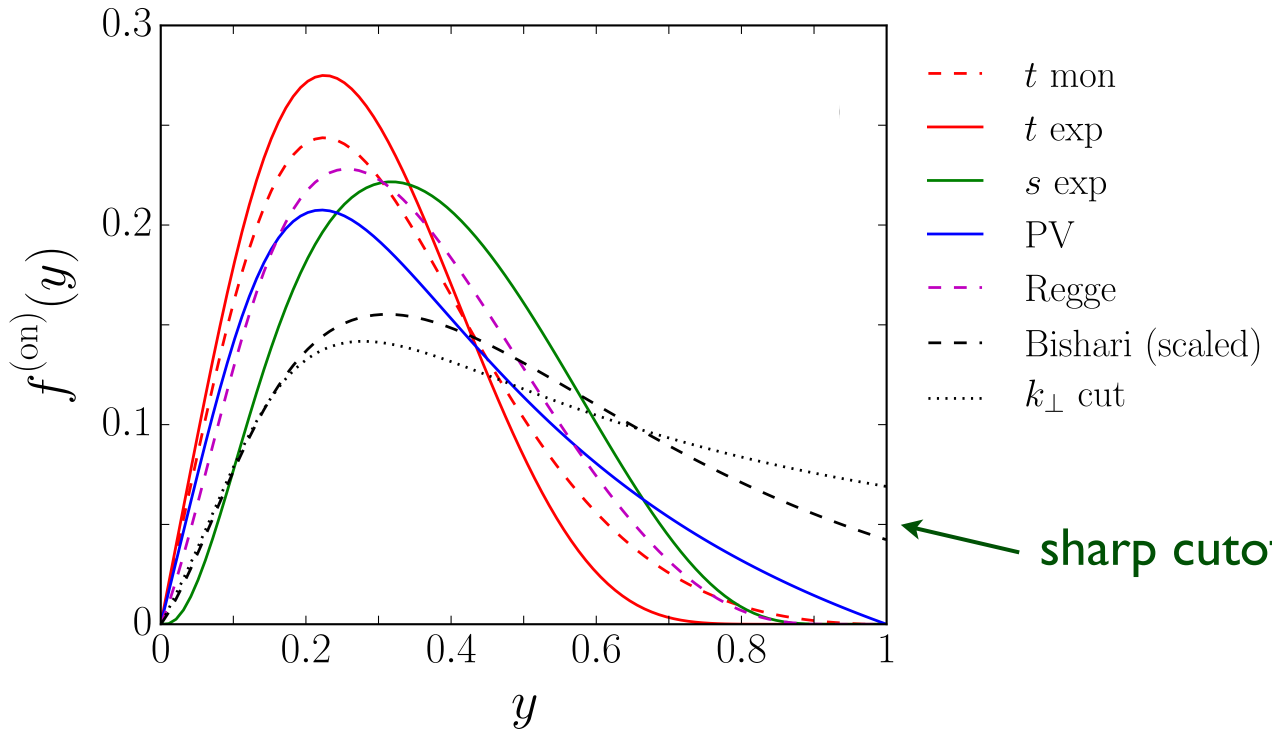
$\mathcal{F} = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$ Pauli-Villars

$\mathcal{F} = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ Regge

Pion splitting functions

- Detailed shape of splitting function depends on regularization, but common general features

e.g. on-shell function



sharp cutoffs

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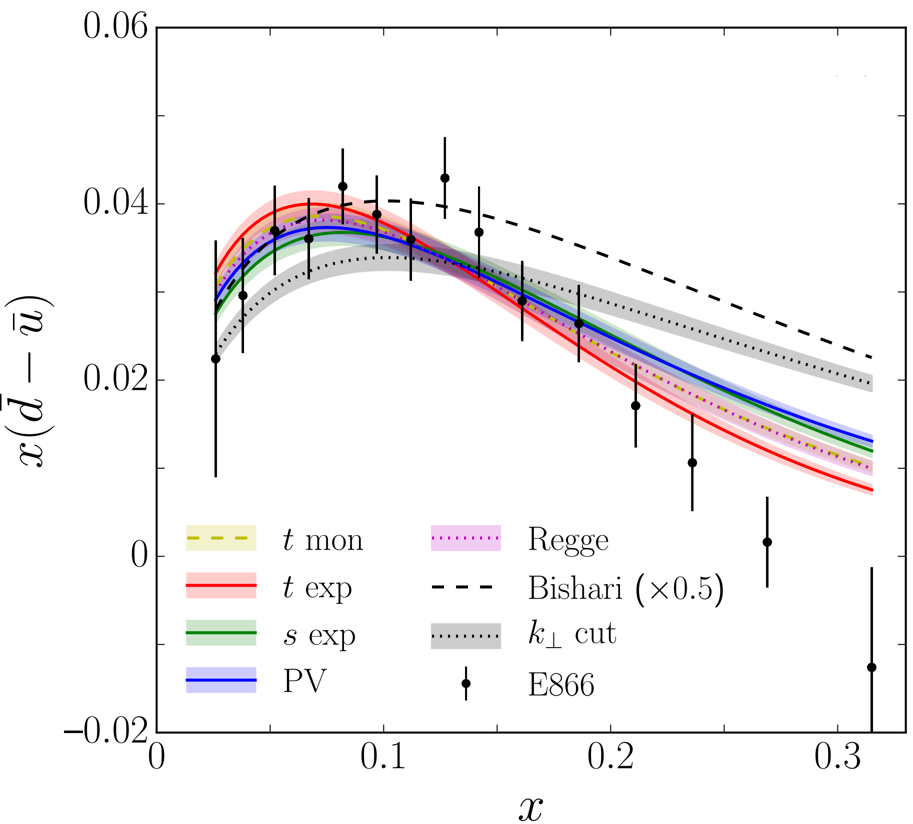
Pion splitting functions

- E866 $\bar{d} - \bar{u}$ data can be fitted with range of regulators



average pion "multiplicity"

$$\langle n \rangle_{\pi N} = 3 \int_0^1 dy \, f_N^{(\mathrm{on})}(y)$$

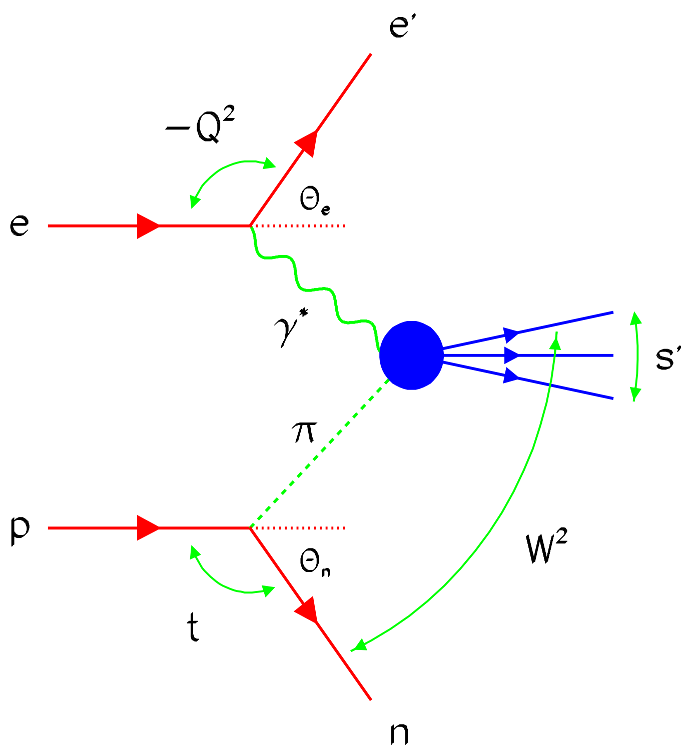
$$\sim \; 0.25 - 0.3$$

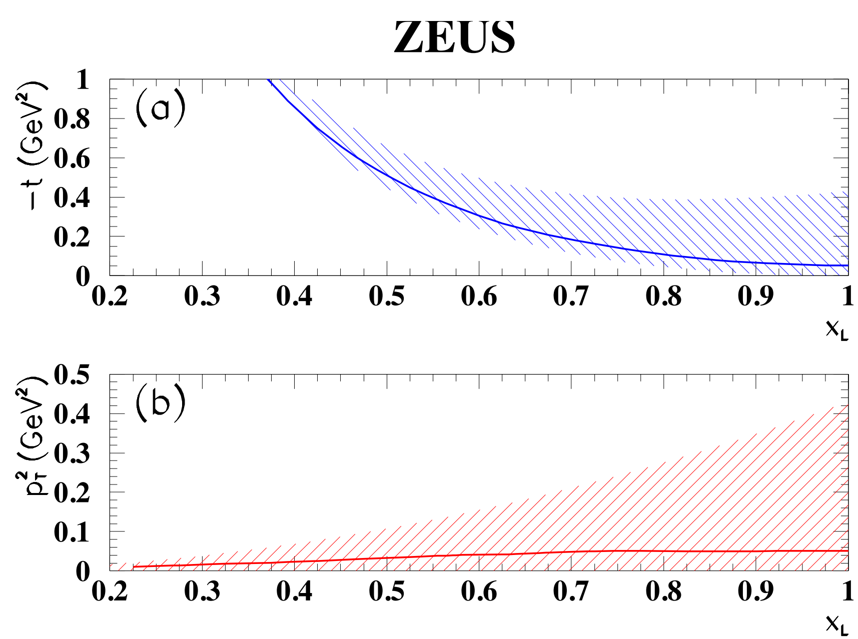
$\longrightarrow$ with exception of $k_\perp$ cutoff and Bishari models, all others give reasonable fits, $\chi^2 \lesssim 1.5$

$\longrightarrow$ are there other data that can be more discriminating?

Leading neutron production at HERA

- ZEUS & H1 collaborations measured spectra of neutrons produced at very forward angles, $\theta_n < 0.8$ mrad





$x_L \approx 1 - y$

→ can data be described within same framework as E866 asymmetry?

→ simultaneous fit never previously been performed!

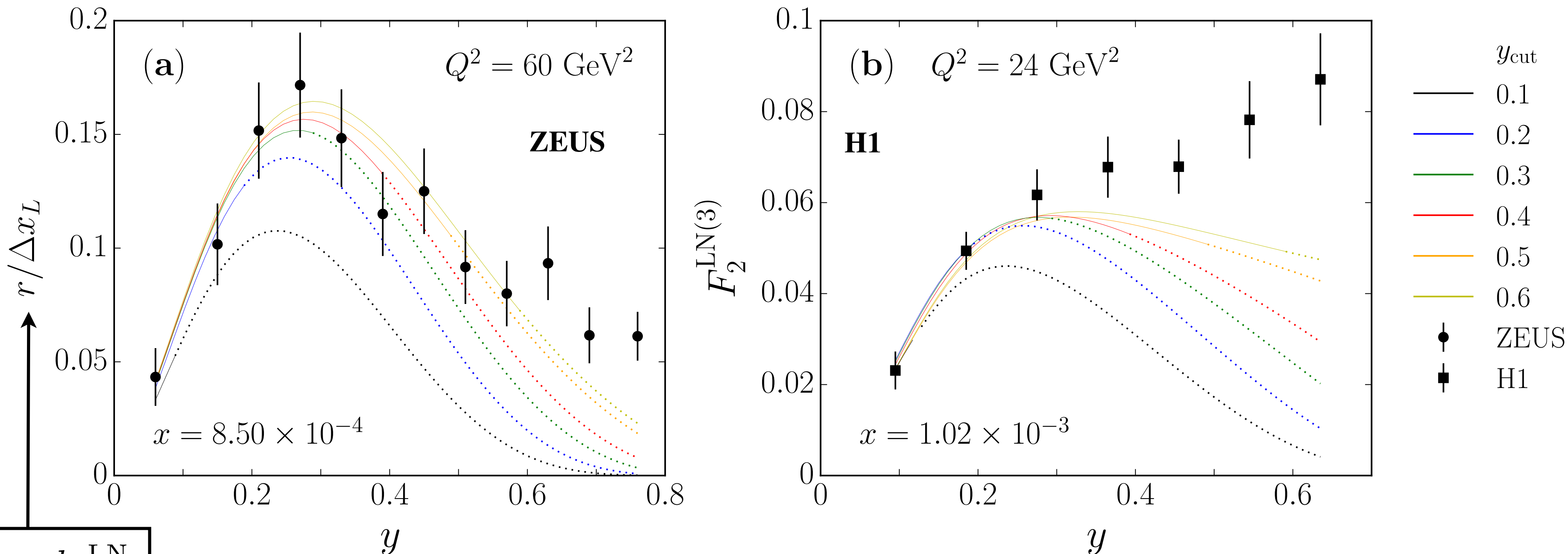
Leading neutron production at HERA

- Measured LN differential cross section (integrated over $p_\perp$)

$$\frac{d^3\sigma^{\mathrm{LN}}}{dx\, dQ^2\, dy} \;\sim\; F_2^{\mathrm{LN}(3)}(x, Q^2, y)$$

$\boxed{2 f_N^{(\mathrm{on})}(y)\, F_2^{\pi}(x/y, Q^2)}$ for π exchange

e.g.

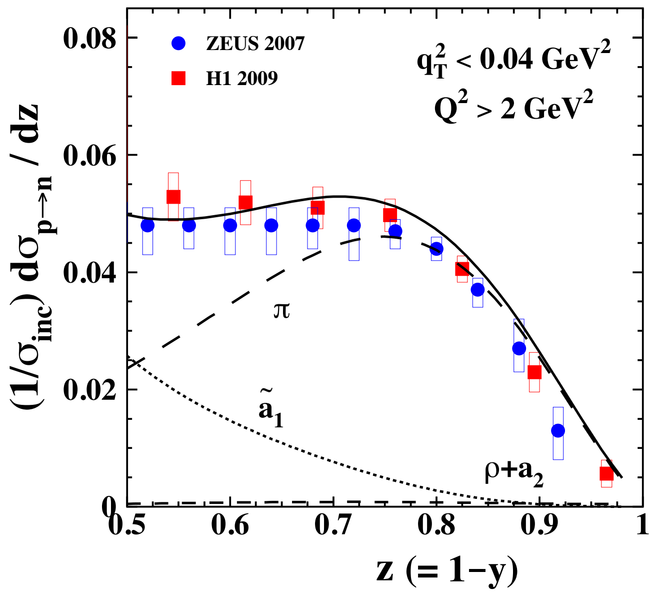


$$\boxed{r = \frac{d\sigma^{\mathrm{LN}}}{d\sigma^{\mathrm{inc}}}}$$

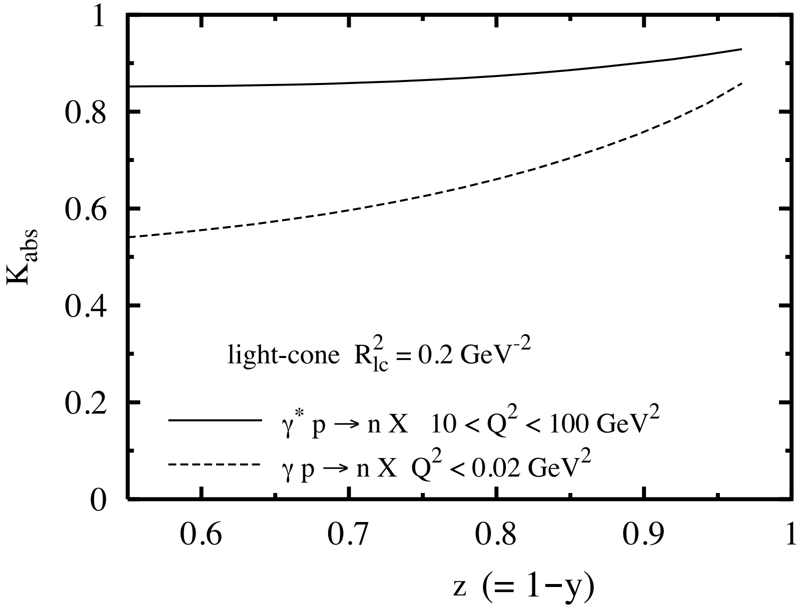
$\longrightarrow$ quality of fit depends on range of y fitted

Leading neutron production at HERA

- At large y non-pionic mechanisms contribute
  ($e.g.$ heavier mesons, absorption)



Kopeliovich et al. (2012)

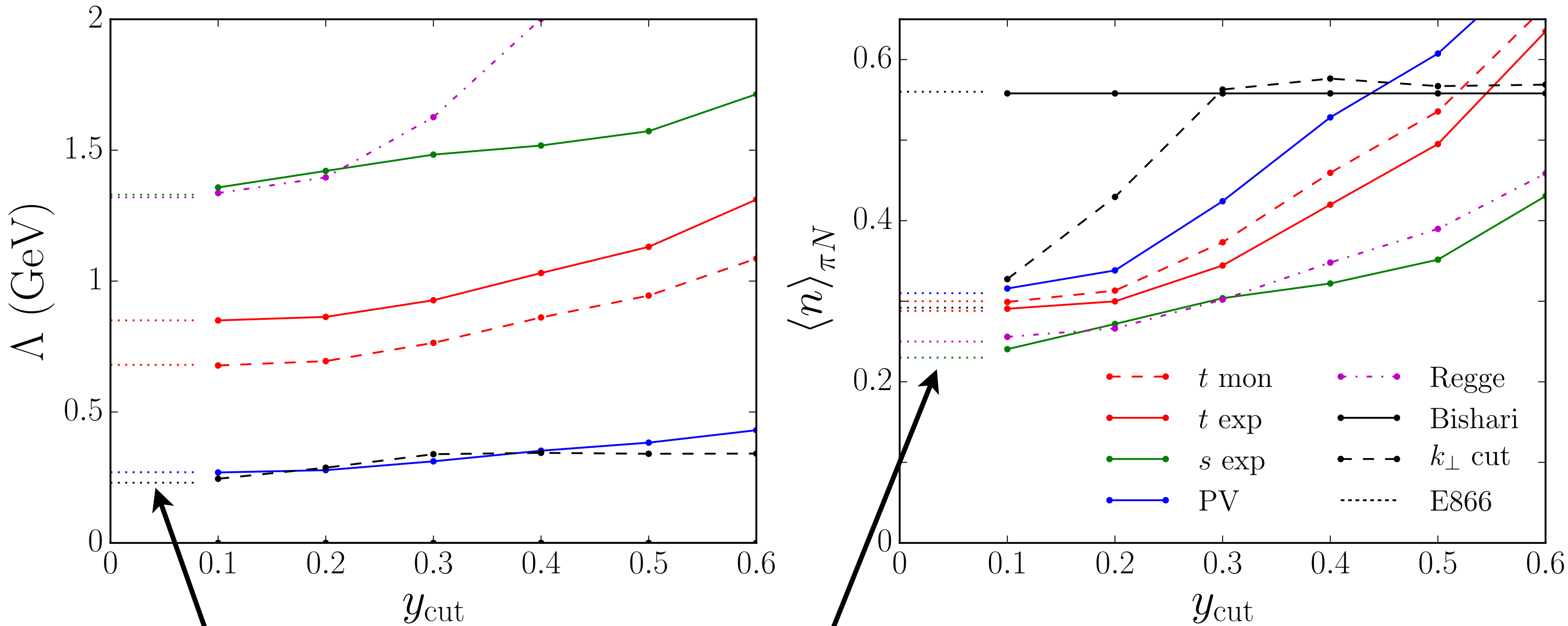


D'Alesio, Pirner (2000)

- To reduce model dependence, fit the value of $y_{\rm cut}$
  up to which data can be described in terms of π exchange

Leading neutron production at HERA

- Fit requires higher momentum pions with increasing $y_{\rm cut}$

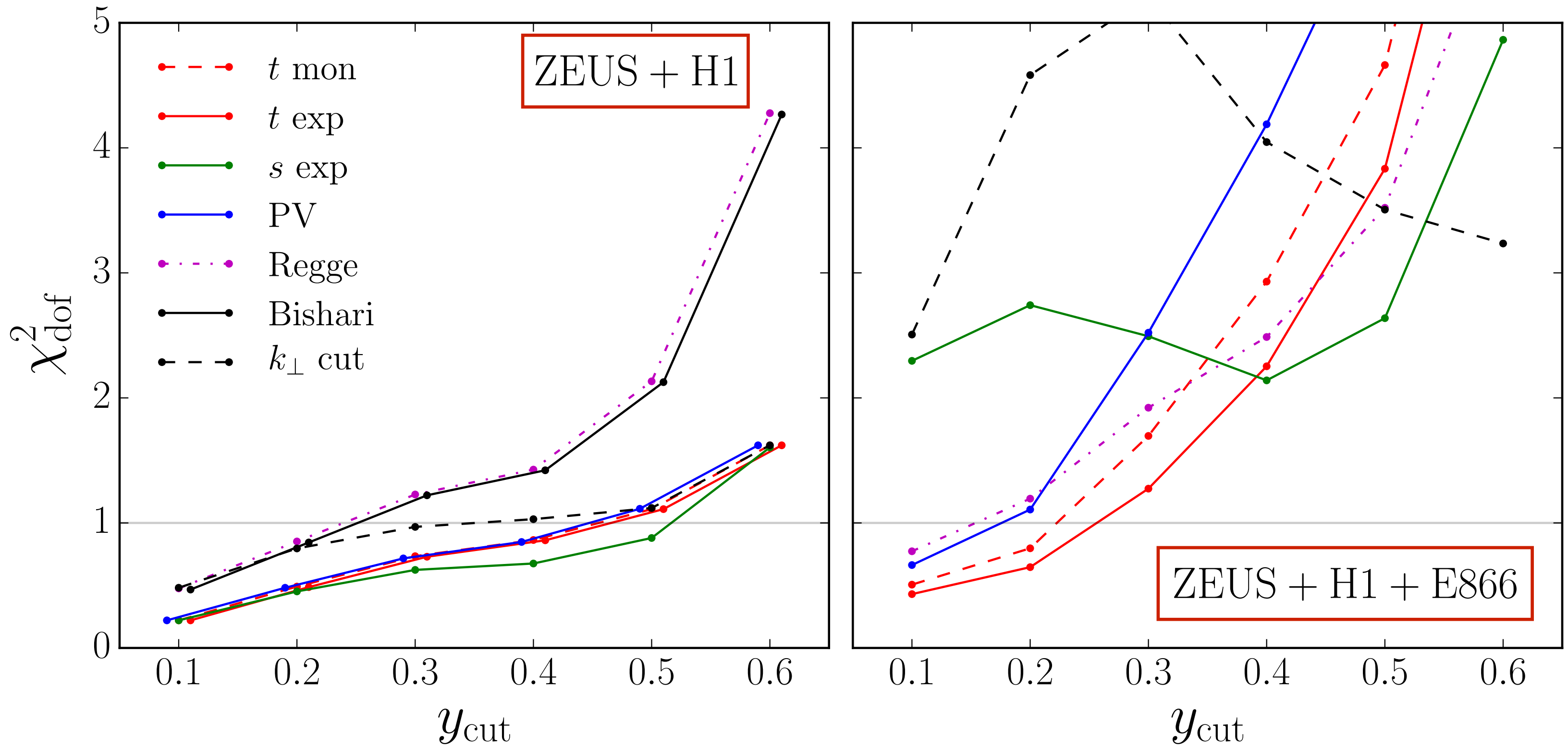


values from fit to E866 data only

$\longrightarrow$ larger values of $y_{\rm cut}$ more in conflict with E866 data

Leading neutron production at HERA

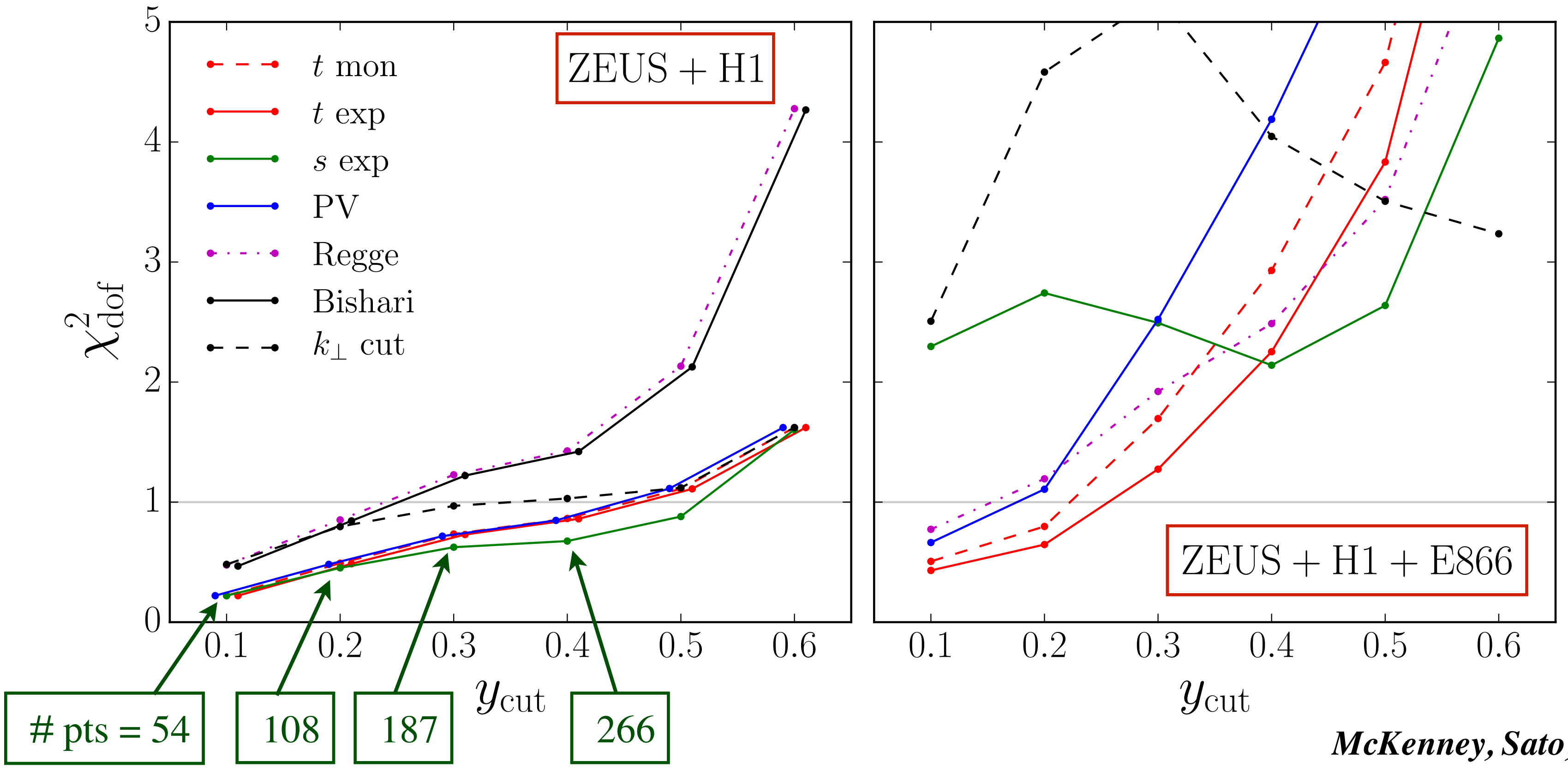
- Combined fit to HERA LN and E866 Drell-Yan data



McKenney, Sato, WM, Ji (2016)

Leading neutron production at HERA

- Combined fit to HERA LN and E866 Drell-Yan data

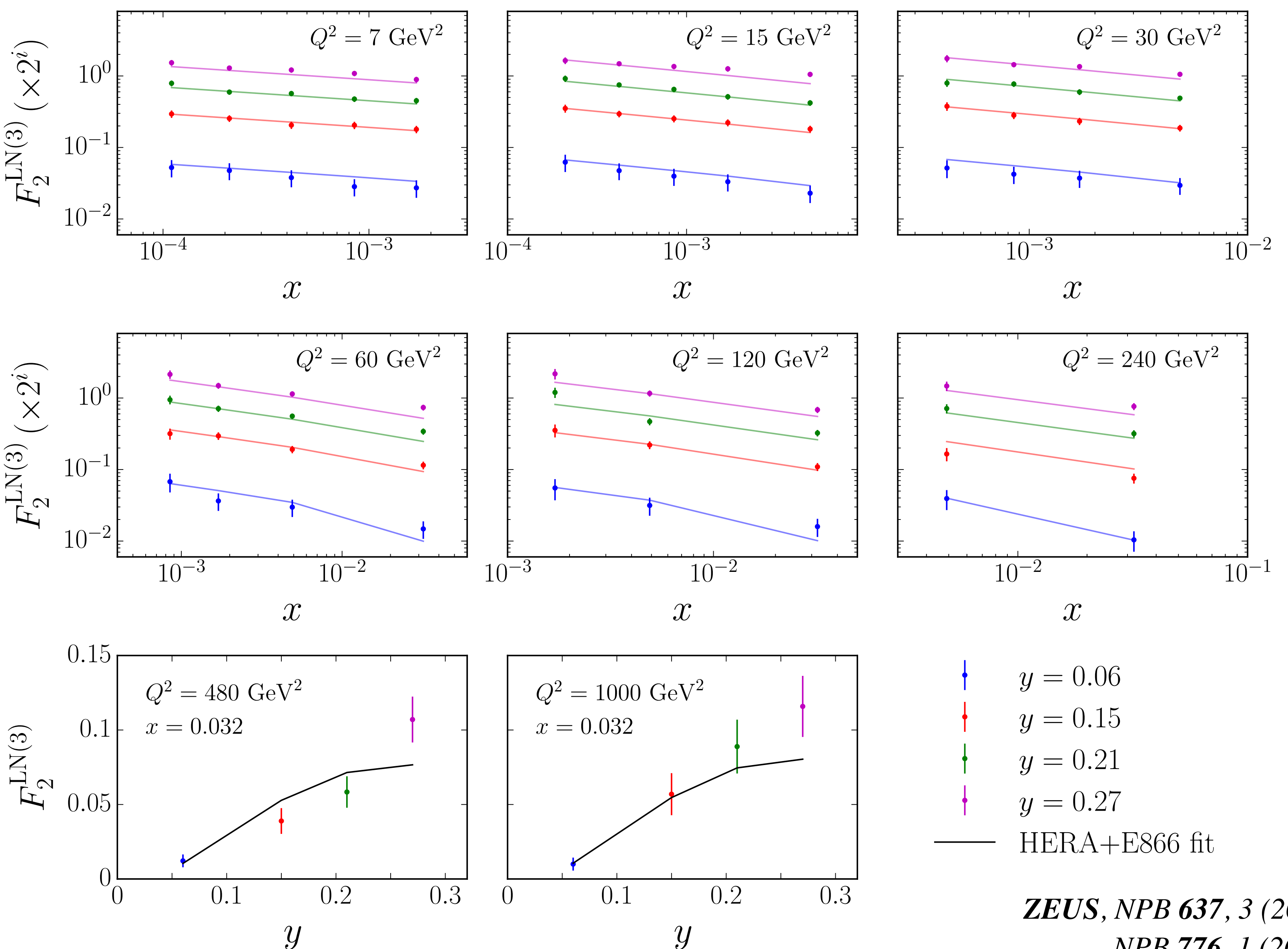


McKenney, Sato, WM, Ji (2016)

→ best fits for largest number of points afforded by t-dependent exponential (and t monopole) regulators

Leading neutron production at HERA

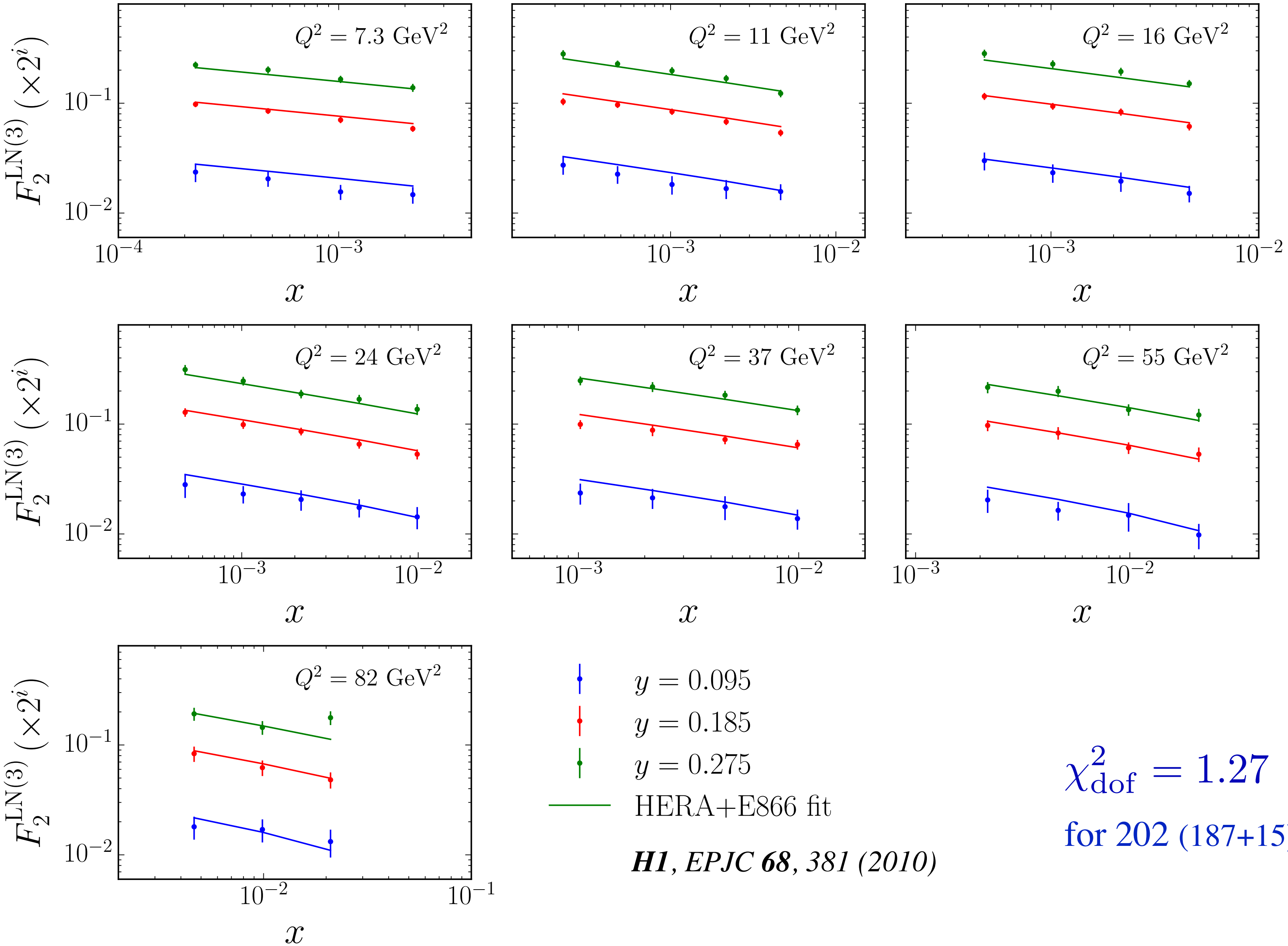
- Fit to ZEUS LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



ZEUS, *NPB* ***637***, *3 (2002)*
NPB ***776***, *1 (2007)*

Leading neutron production at HERA

- Fit to H1 LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)

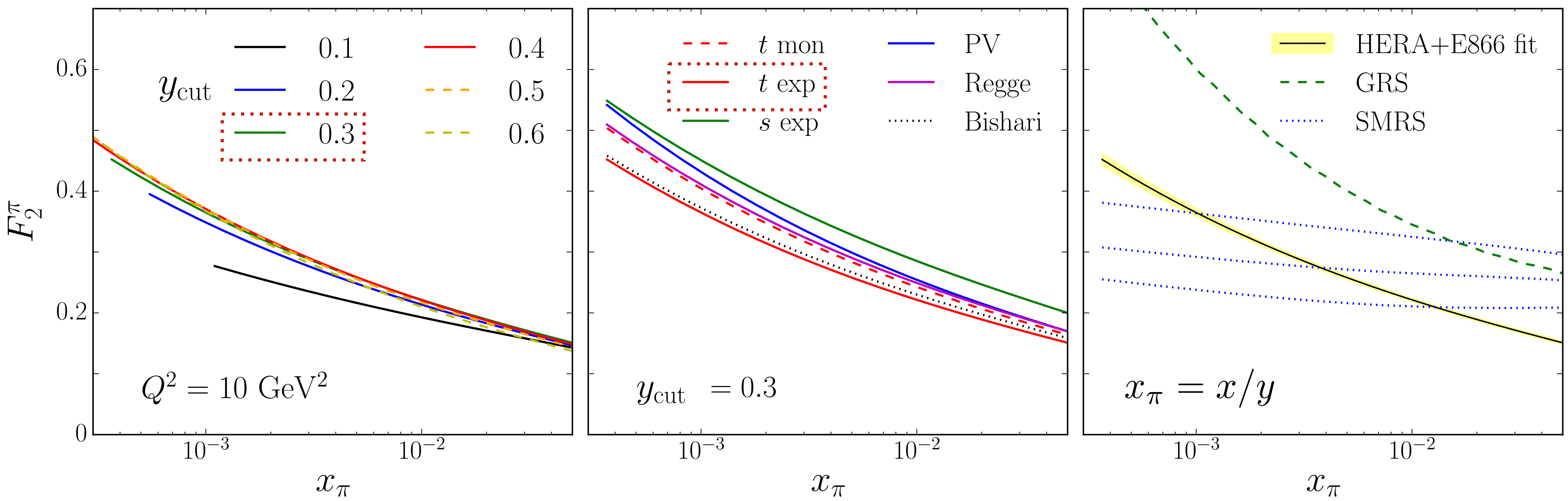


***H1**, EPJC **68**, 381 (2010)*

$\chi^2_{\rm dof} = 1.27$

for 202 (187+15) points

Extracted pion structure function



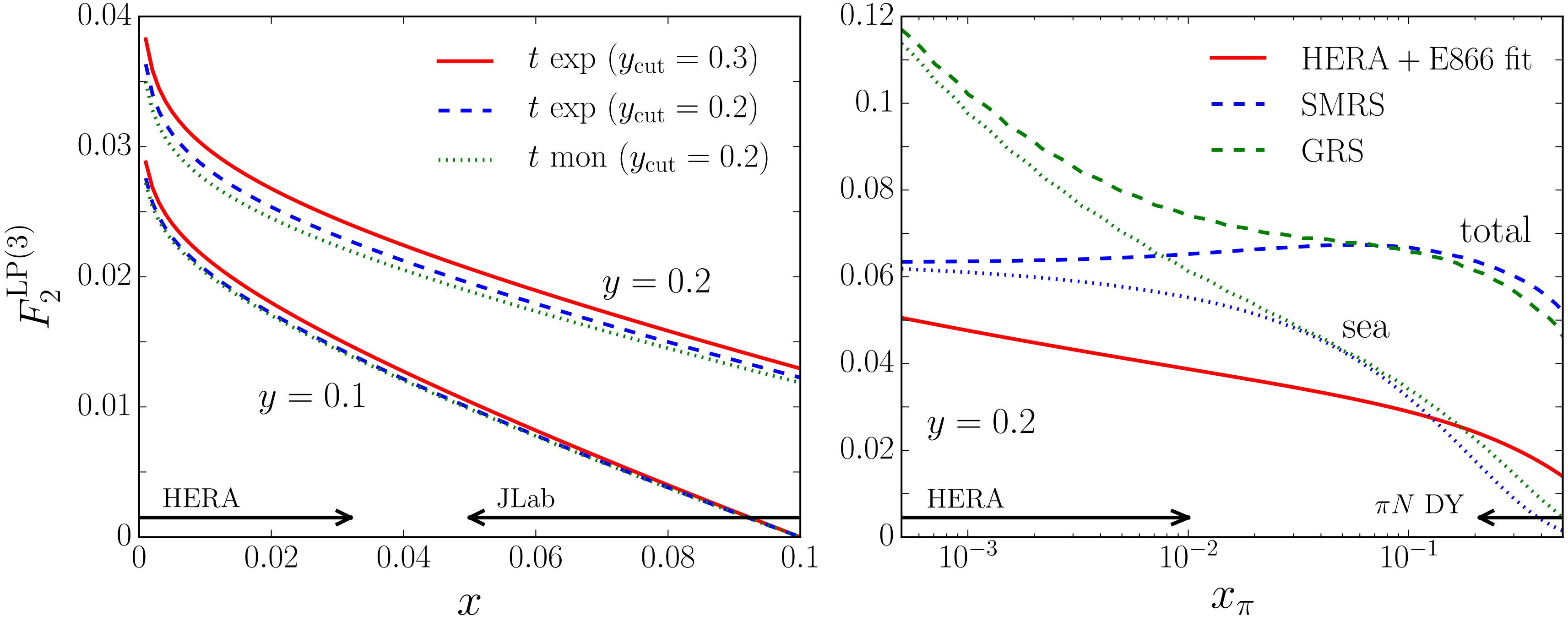
$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$
$$\eta \sim \log(\log Q^2)$$

McKenney, Sato, WM, Ji (2016)

→ stable values of F_2^π at $4\times 10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined fit

→ shape similar to GRS fit to πN Drell-Yan data (for $x_\pi \gtrsim 0.2$), but smaller magnitude

Predictions at TDIS kinematics



McKenney, Sato, WM, Ji (2016)

→ JLab TDIS experiment can fill gap in x_π coverage between HERA and πN Drell-Yan kinematics

Outlook

- Combined analysis can be extended by including πN DY data

  $\longrightarrow$ constrain large-x_π region $(x_\pi \gtrsim 0.2)$

- Generalize parametrization by fitting individual pion valence and sea quark PDFs, rather than F_2^π

- Medium-term goal is to use all data sensitive to pion structure (including TDIS, EIC) to constrain pion PDFs over full range $10^{-4} \lesssim x_\pi \lesssim 1$

  $\longrightarrow$ global analysis under way of HERA LN, Drell-Yan $\pi N + pd/pp$ (+ future JLab TDIS data) to determine pion PDFs at all x

  Patrick Barry, Chueng Ji, Nobuo Sato, WM (2016)

- Longer-term goal is to *simultaneously* fit nucleon and pion PDFs!