XIIth Quark Confinement & the Hadron Spectrum
Thessaloniki, August 29, 2016

PDFs from Jefferson Lab to the LHC

Wally Melnitchouk

Jefferson Lab

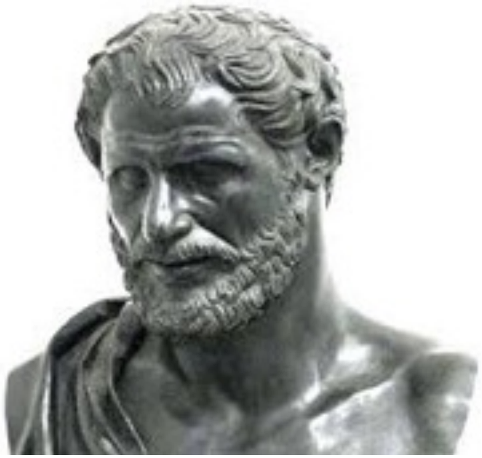
JLab Angular Momentum (JAM) collaboration: http://www.jlab.org/JAM

CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ

Quest to understand nature in terms of fundamental building blocks — “atoms” — is ancient!

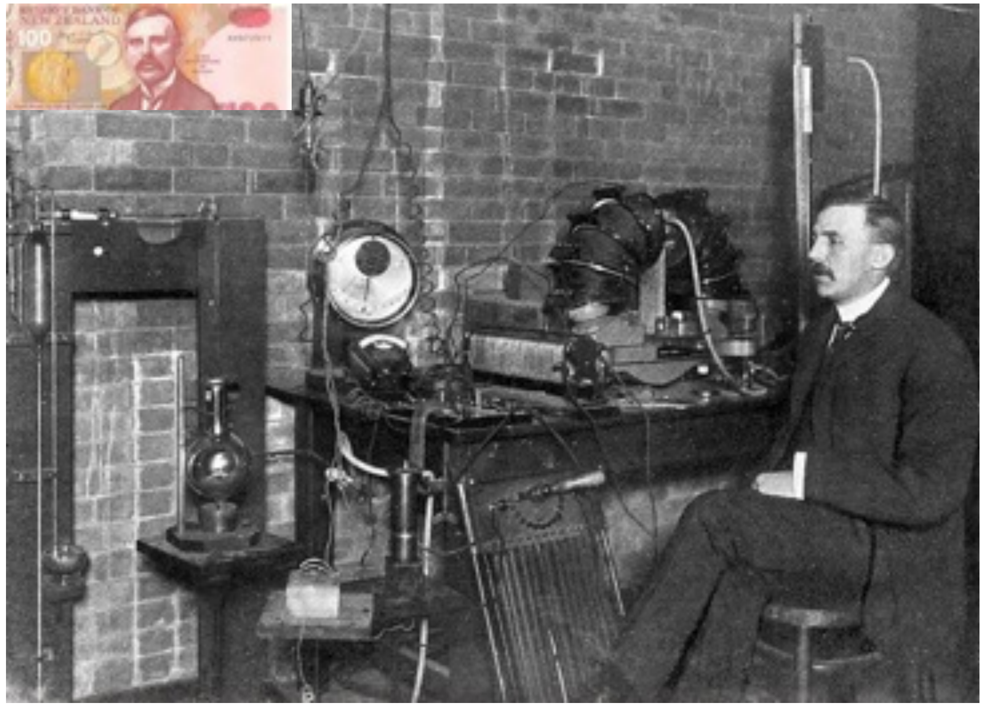
→ circa 5th century BC, not far from here…

Leucippus



Democritus

23 centuries later, experimental discovery of atomic nucleus

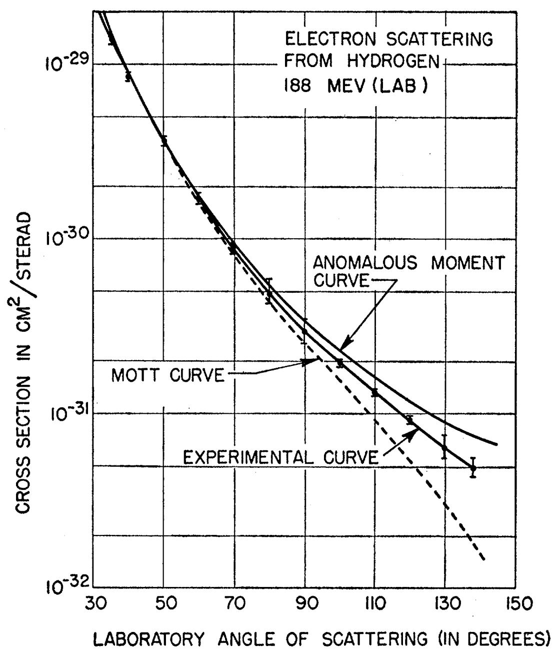


Rutherford (1911)

… followed by discoveries of proton ***(Rutherford, 1917)*** and neutron ***(Chadwick, 1932)***

Almost 100 years later, what do we know about the nucleon?

→ it has finite size



Hofstadter (1955)

elastic $e\,p \to e\,p$
scattering cross section

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

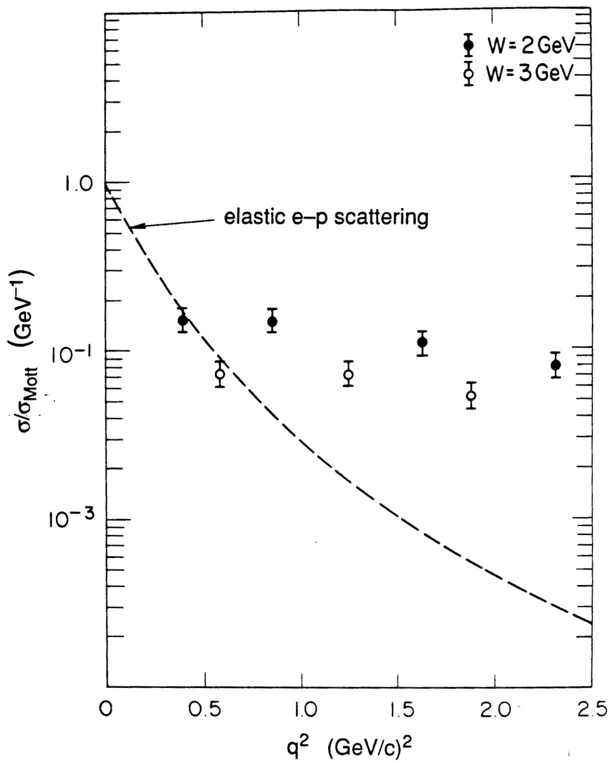
→ from slope of form factor $F(Q^2)$ vs. momentum transfer squared Q^2, obtained r.m.s. charge radius

$$\sim 0.75 \times 10^{-15}\mathrm{m}$$

(precise value currently under hot debate!) → ***R. Hill talk Tue. 9:30***

Almost 100 years later, what do we know about the nucleon?

→ remarkably, at higher Q^2 inelastic cross section exhibits point-like behavior!



Friedman, Kendall, Taylor (1969)

deep-inelastic $e\,p \to e\,X$ scattering (DIS) cross section

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

structure functions

→ how can nucleon have finite-size and point-like properties at the same time?

- At high energies, scattering *<u>is</u>* point-like… but from *constituents* of nucleon

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

  + gluons ***(Gell-Mann… 1972)***

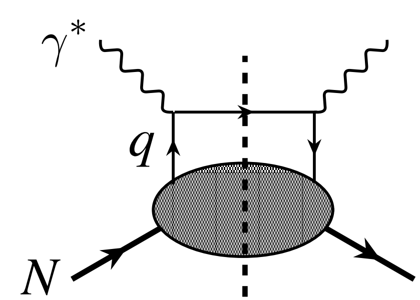
  

- Measurement of structure functions in DIS reveals how nucleon is made up of quarks & gluons

  → 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 functions which are 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)

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$(e.g.$ collinear, TMD, $\ldots)$

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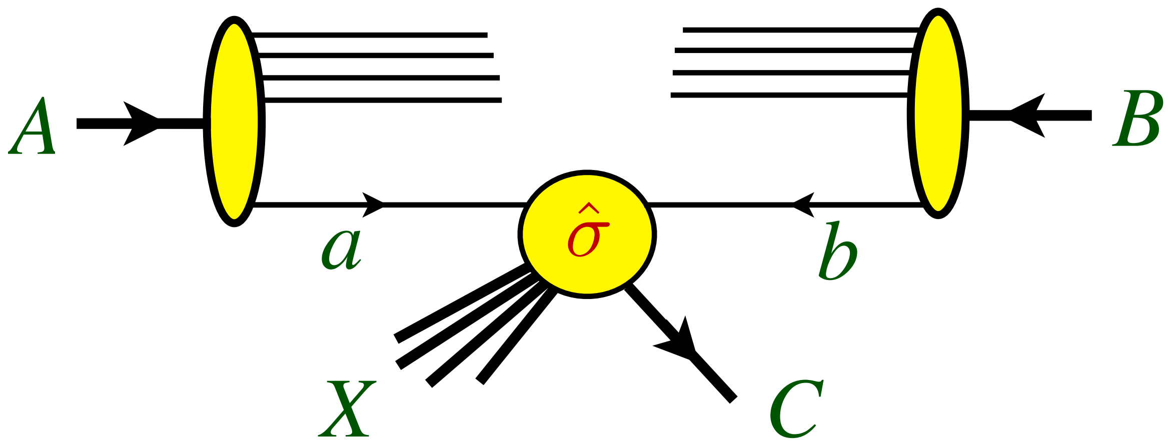
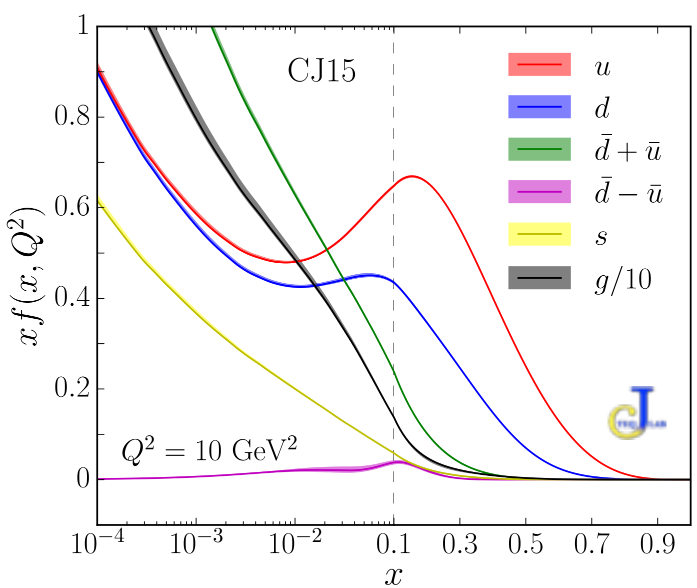


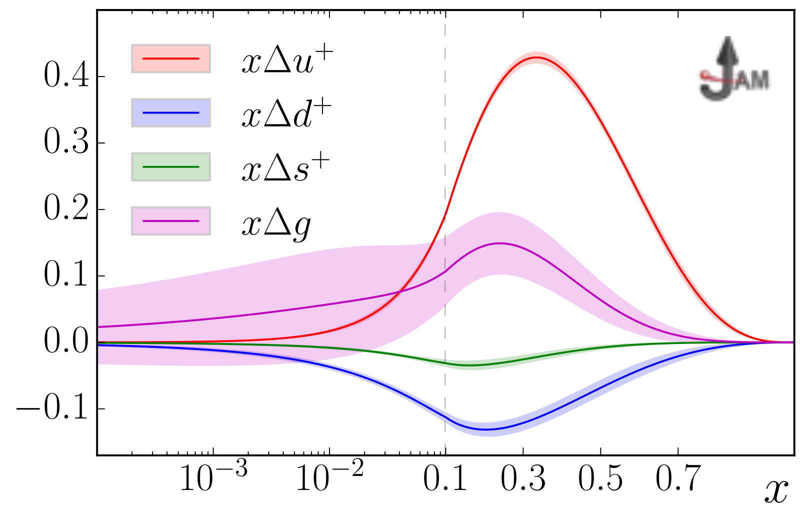
$$\sigma_{AB\to CX}(p_A, p_B) = \sum_{a,b} \int dx_a\, dx_b \boxed{f_{a/A}(x_a, \mu)}\, \boxed{f_{b/B}(x_b, \mu)}$$
$$\times\ \hat{\sigma}_{ab\to CX}(x_a p_A, x_b p_B, Q/\mu)$$

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

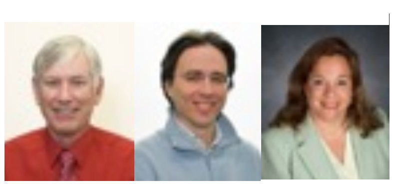
$\longrightarrow$ global QCD analyses of spin-averaged $(f = f^{\uparrow} + f^{\downarrow})$ and spin-dependent $(\Delta f = f^{\uparrow} - f^{\downarrow})$ PDFs

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





CJ (Owens, Accardi, Keppel, WM...)



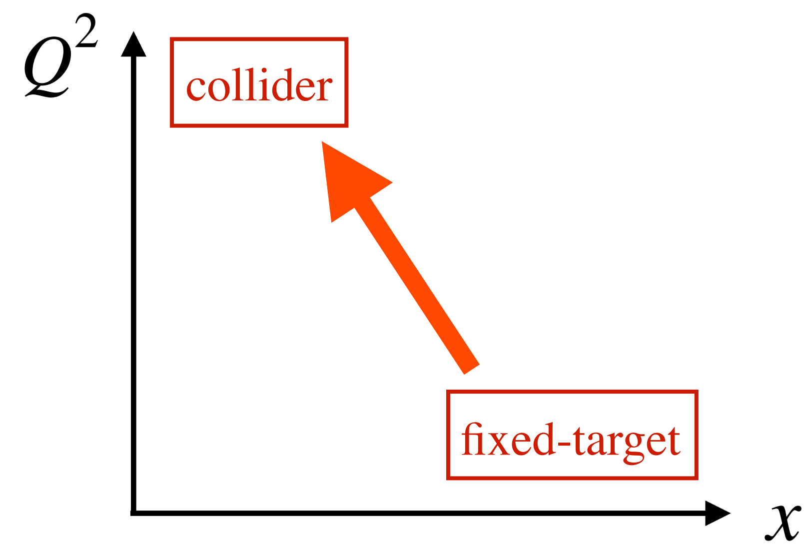
JAM (Sato, Ethier, WM...)

- 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

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

  $\longrightarrow$ Q^2 evolution feeds
  low x, high Q^2 ("LHC")
  from high x, low Q^2 ("JLab")



Valence quarks & QCD models

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

→ 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)

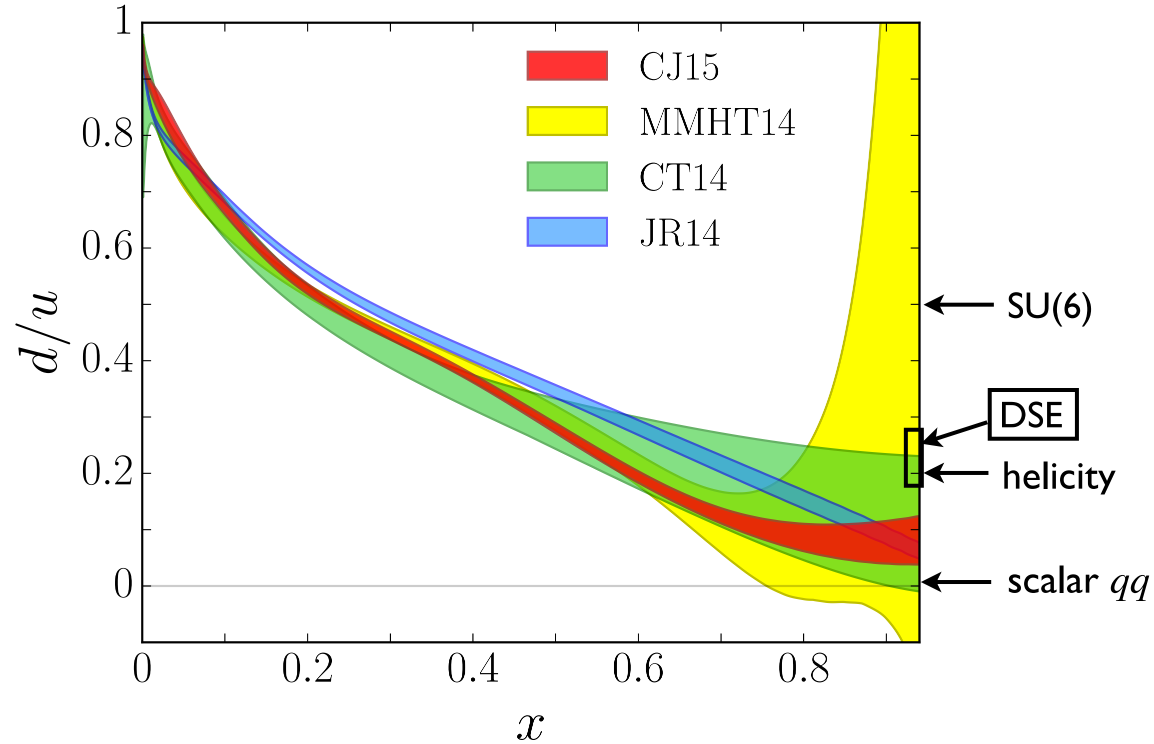
- $d/u \to 1/5$

  $S_z = 0$ qq dominance
  (perturbative gluon exchange)

- $d/u \to 0.18 - 0.28$

  DSE with qq correlations

Roberts

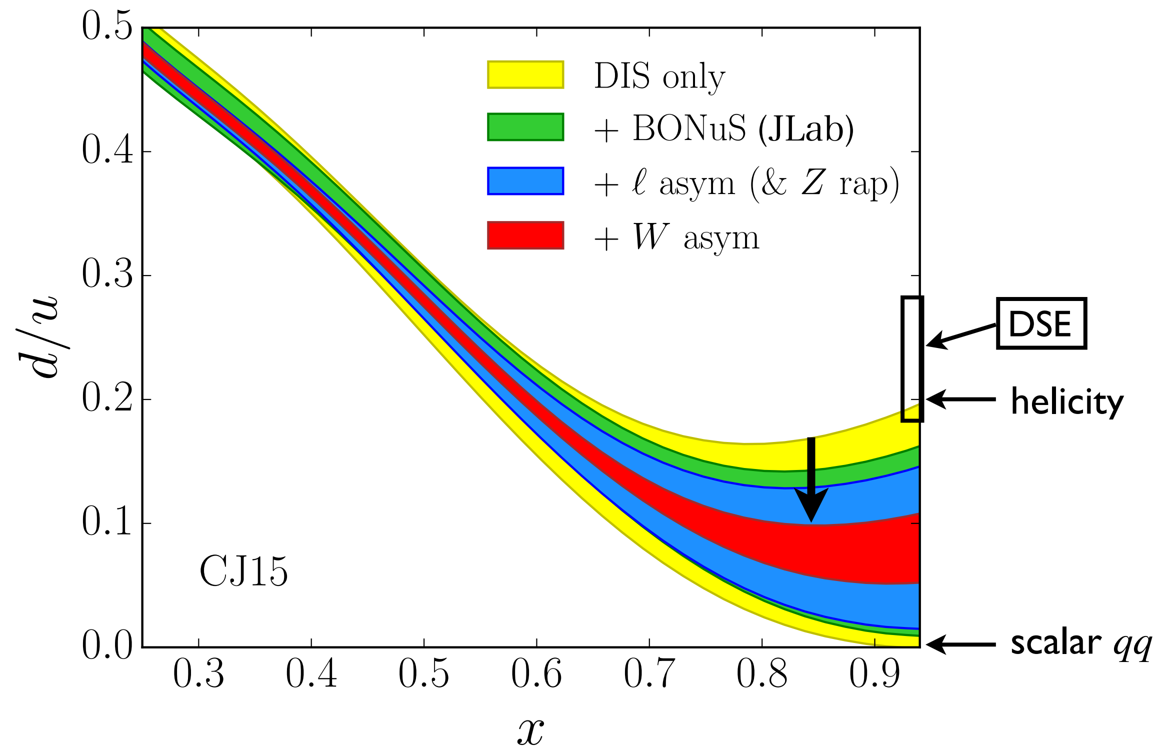


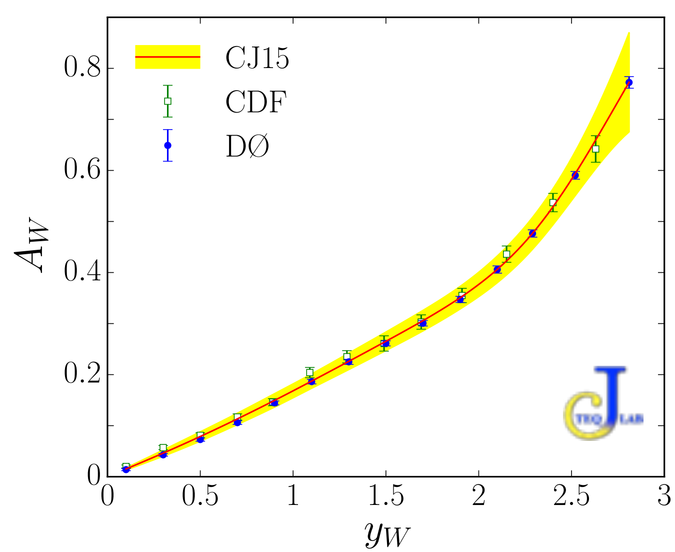
→ considerable uncertainty at high x from deuterium corrections (no free neutrons!)

Valence quarks & QCD models

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

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





Accardi et al. (2016)

→ extrapolated ratio at $x = 1$

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

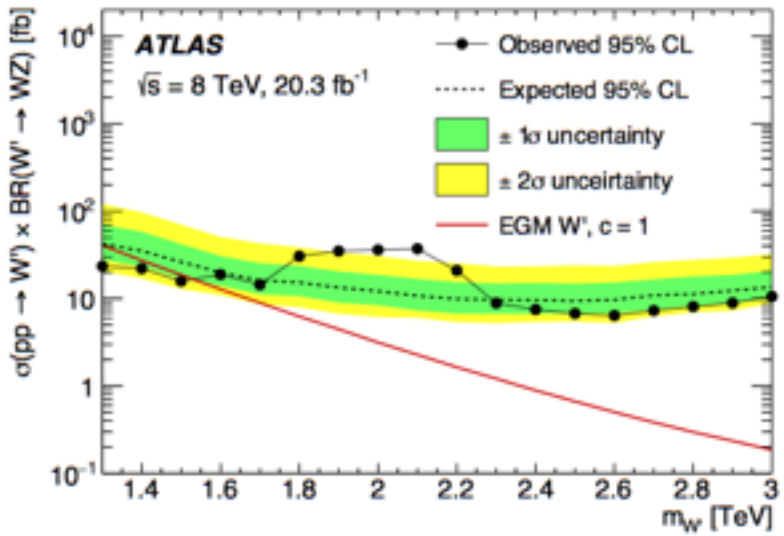
does not match any model!

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

Valence quarks & BSM searches

- Observation of new physics signals requires accurate determination of QCD backgrounds, which depend on PDFs

→ $e.g.$ Higgs boson, or heavy W' boson production at LHC



- $3.4\,\sigma$ excess in WZ diboson channel at ~ 2 TeV
- extended gauge model $W' \to WZ$ with $M < 1.5$ TeV excluded at 95% c.l.

→ for W'^- production, parton luminosity is

$$\mathcal{L}_{W'^-} \sim x_1 x_2 \left[\cos^2\theta_C \left(d(x_1)\bar{u}(x_2) + s(x_1)\bar{c}(x_2) \right) + \sin^2\theta_C \left(s(x_1)\bar{u}(x_2) + d(x_1)\bar{c}(x_2) \right) \right] + (x_1 \leftrightarrow x_2)$$

$\sim d(x_1)\bar{u}(x_2)$ at large rapidity $y_{W'}$

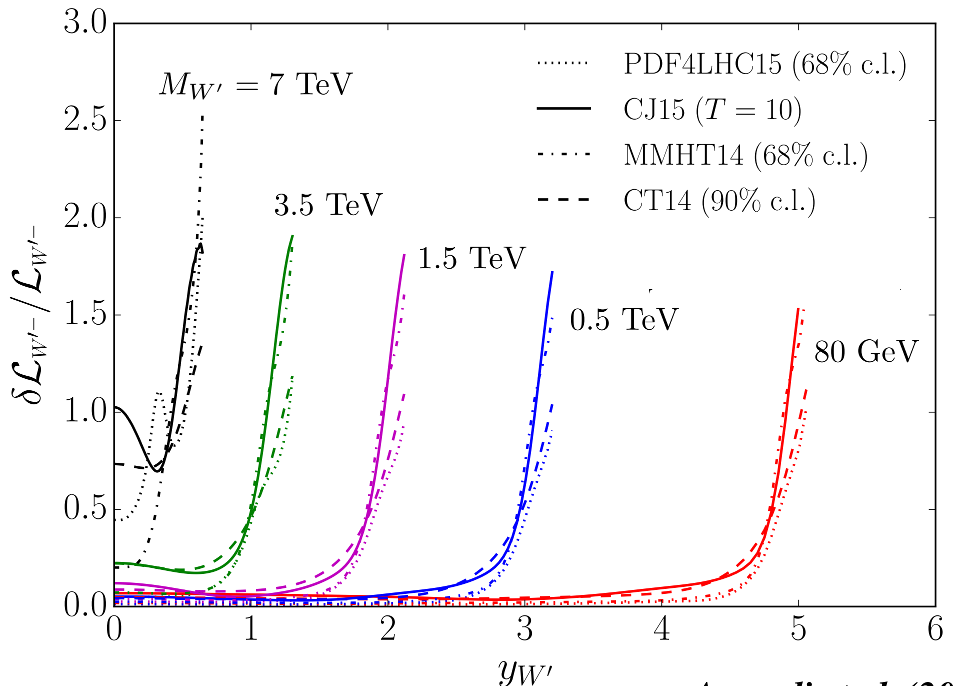
$$x_{1,2} = \frac{M_{W'}}{\sqrt{s}} e^{\pm y_{W'}}$$

Valence quarks & BSM searches

- Observation of new physics signals requires accurate determination of QCD backgrounds, which depend on PDFs

→ large-x uncertainties scale with mass

relative uncertainty in luminosity

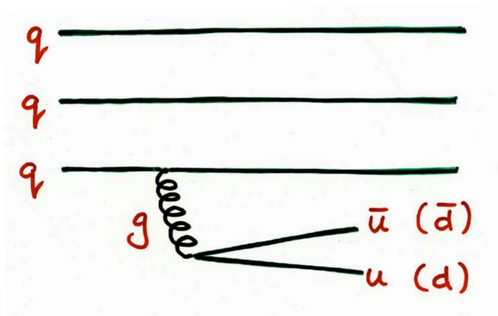


Accardi et al. (2016)

→ PDF uncertainty small at low $y_{W'}$, rises dramatically at large $y_{W'}$, for all $M_{W'}$

Light quark sea

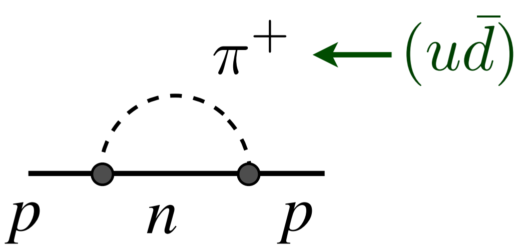
- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)



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

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

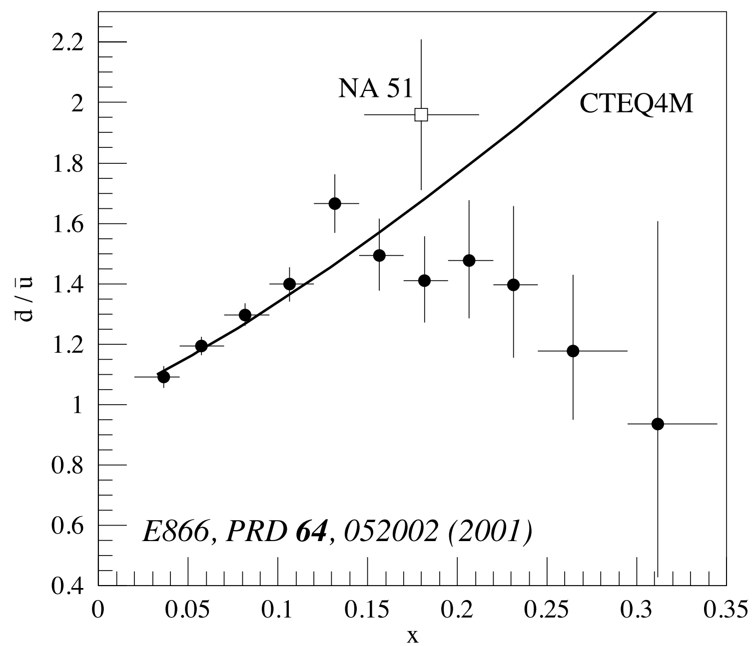
- In 1984 Thomas made audacious suggestion that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

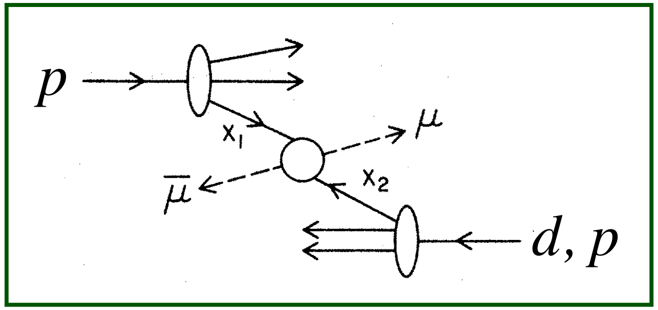


$\rightarrow$ $\boxed{\bar{d} > \bar{u}}$

Light quark sea

- Asymmetry spectacularly confirmed (more than a decade later) in high-precision DIS and Drell-Yan experiments





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

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

→ firmly established 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

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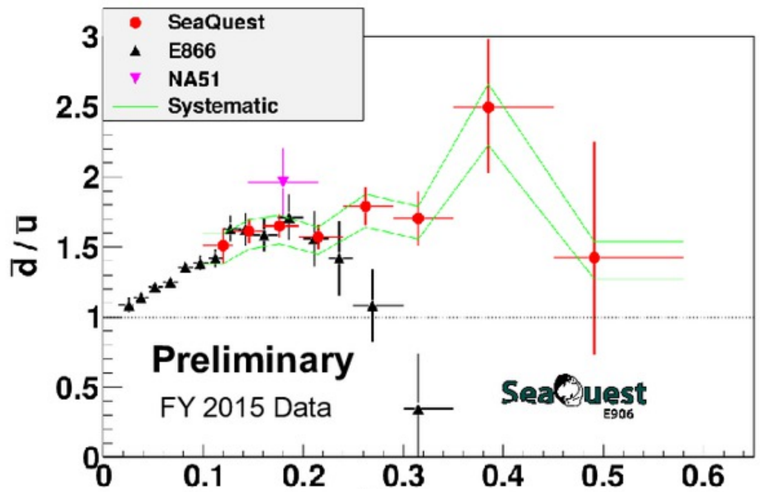
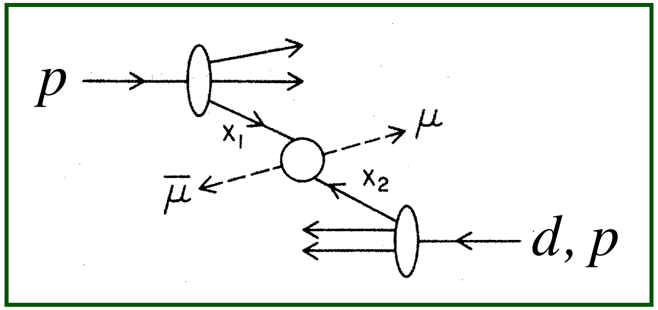


B. Kerns (April 2016)



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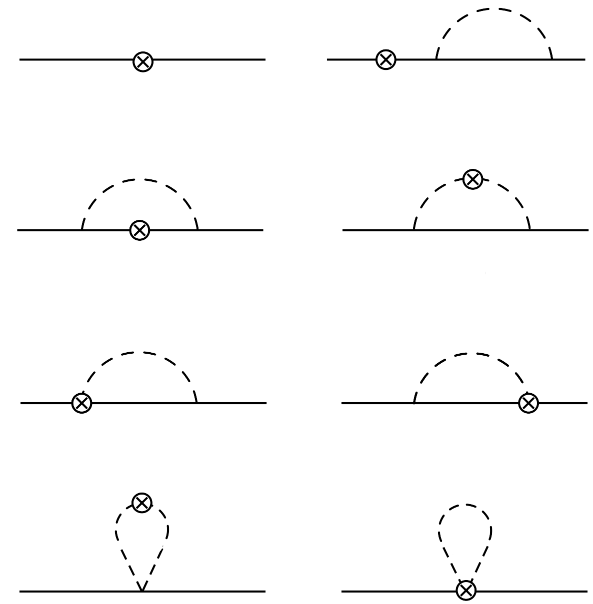
Light quark sea

- 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

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

Xiangdong Ji (2001)

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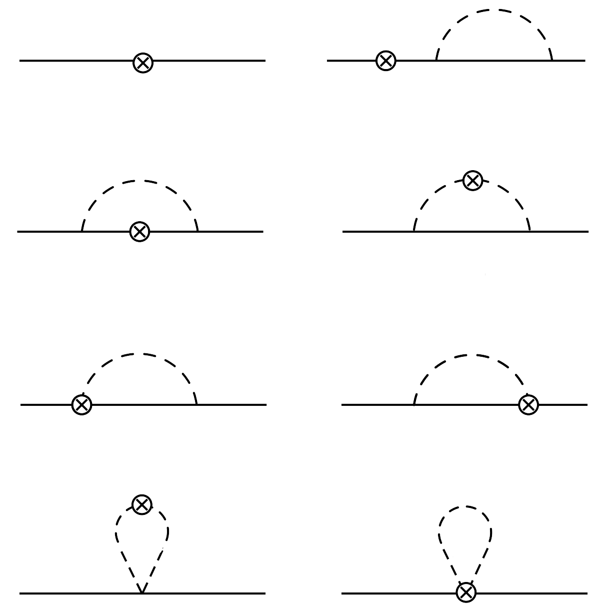

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Stelios Kazantzidis (?)

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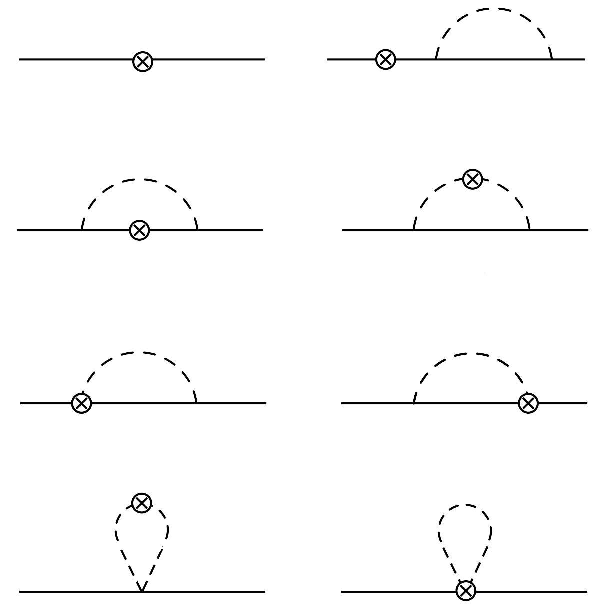
Weinberg (1967)

→ 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)



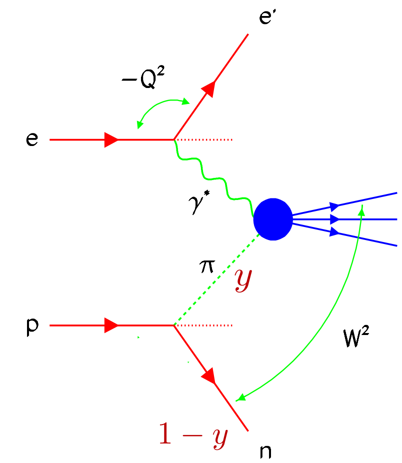
→ **Chueng Ji talk Mon. 15:00**

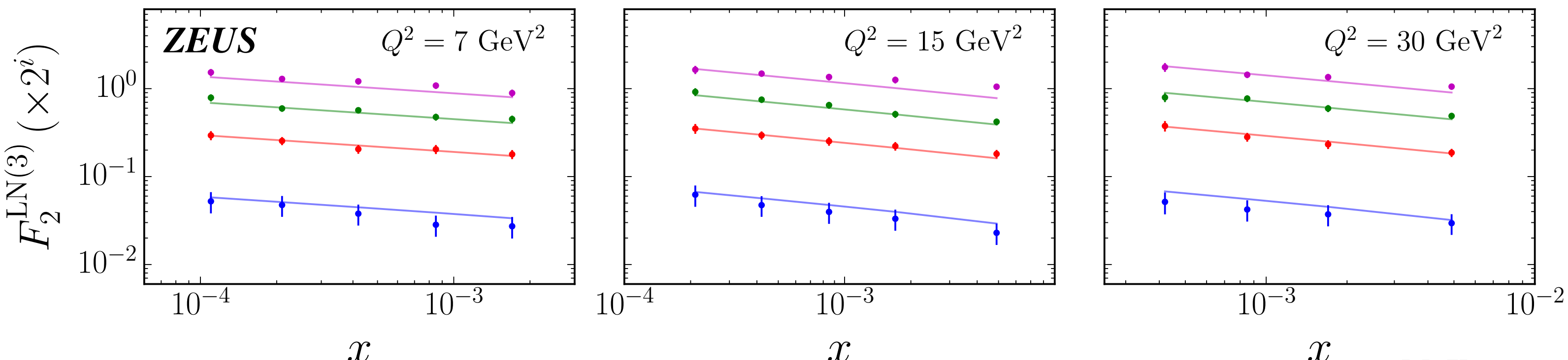
Light quark sea

- Drell-Yan $\bar{d} - \bar{u}$ data can be described using range of UV regulators (shapes of pion momentum distributions)

→ semi-inclusive production of "leading neutrons" at HERA can discriminate between different shapes

$$\frac{d^3\sigma^{\rm LN}}{dx\, dQ^2\, dy} \sim F_2^{\rm LN(3)}(x, Q^2, y) = f_\pi(y)\, F_2^\pi(x/y, Q^2)$$





McKenney et al. (2016)

→ best fit to ZEUS & H1 data prefers t-dependent exponential regulator

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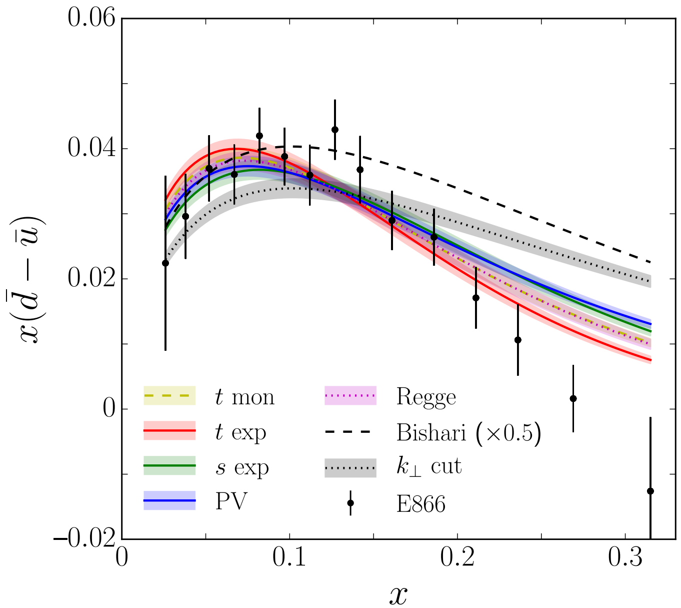

→ constrain shape of F_2^π at $10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined HERA + Drell-Yan fit

McKenney, Sato, WM, Chueng Ji (2016)

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

Barry, Chueng Ji, WM, Sato (2016)

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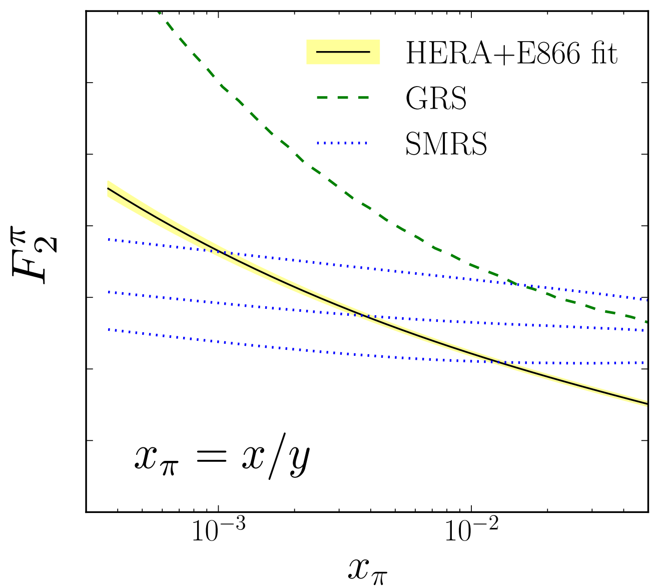

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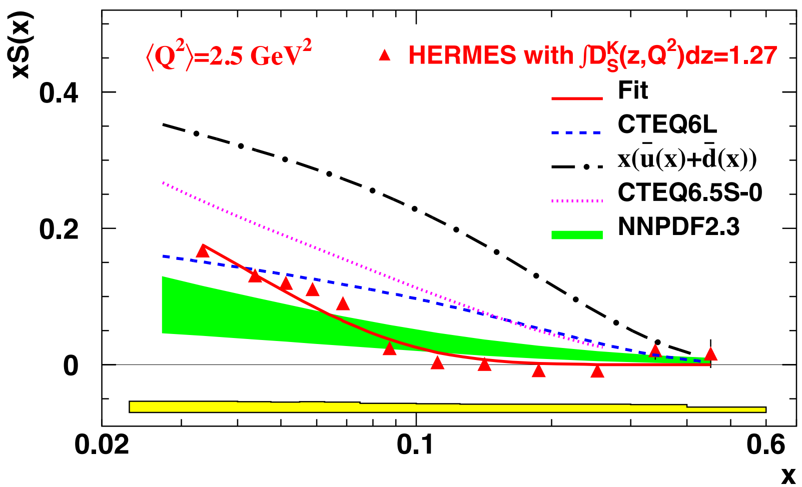
Barry, Chueng Ji, WM, Sato (2016)

Strange quarks

- Strange quark PDFs most directly determined from dimuon production in (anti)neutrino-nucleus DIS $(W^+ s \to c\ /\ W^- \bar{s} \to \bar{c})$

$\longrightarrow$ but significant uncertainty from nuclear corrections, semileptonic branching ratio uncertainty

$\longrightarrow$ tension with HERMES semi-inclusive K-production data



historically, strange to nonstrange ratio

$$\kappa = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$$

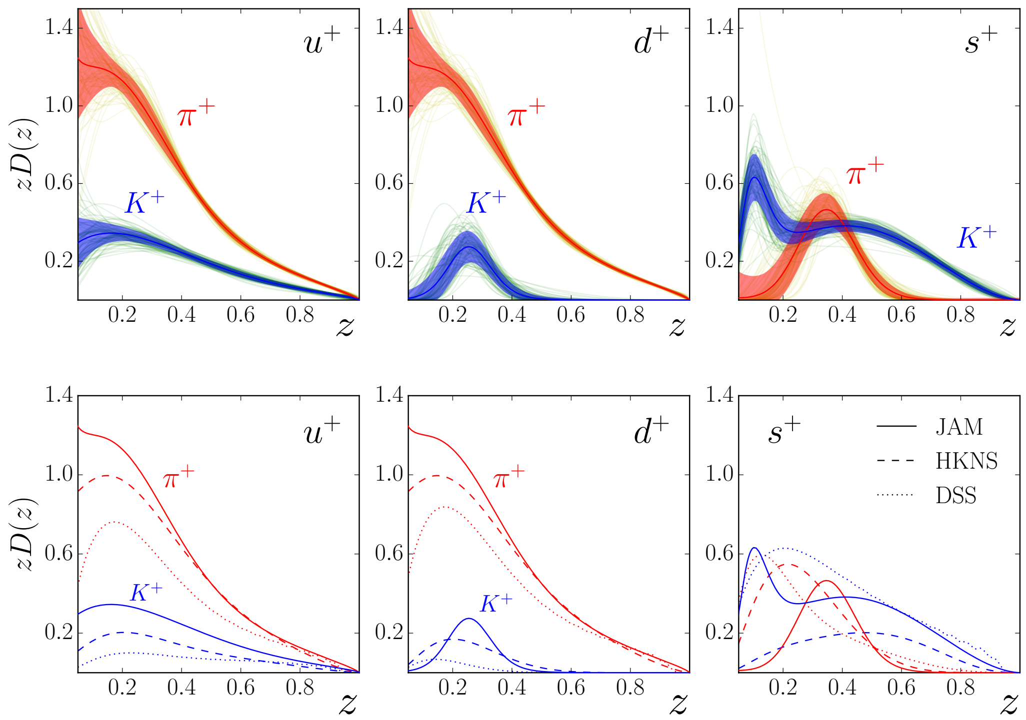
$$\sim\ 0.2 - 0.5$$

... but uncertainty from K fragmentation functions

Strange quarks

- Fragmentation functions (FFs) determined from single-inclusive meson production in e^+e^- annihilation

→ new "iterative Monte Carlo" (IMC) global analysis (including new Belle & BaBar data) suggests differences with previous extractions

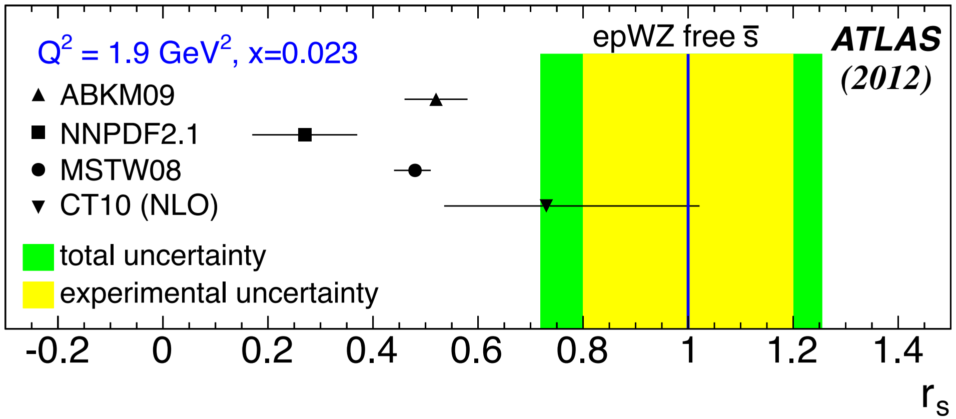


Nobuo Sato et al. (2016)
(arXiv this week)

→ SIDIS data also constrain fragmentation functions, but require simultaneous PDF + FF fit (currently in progress)

Strange quarks

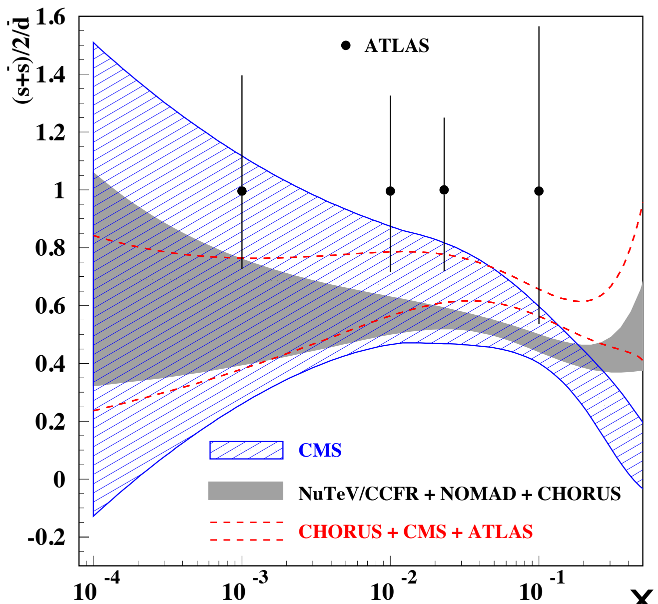
- Alternatively, probe strange PDF in W/Z production at LHC $pp \to W(Z) + X$ free of nuclear effects



→ surprisingly large strangeness

$$r_s = (s + \bar{s})/2\bar{d}$$
$$= 1.00^{+0.25}_{-0.28}$$

→ more recent reanalysis of neutrino DIS (CHORUS, NOMAD) and ATLAS data does not support enhanced strange PDF



Alekhin et al. (2015)

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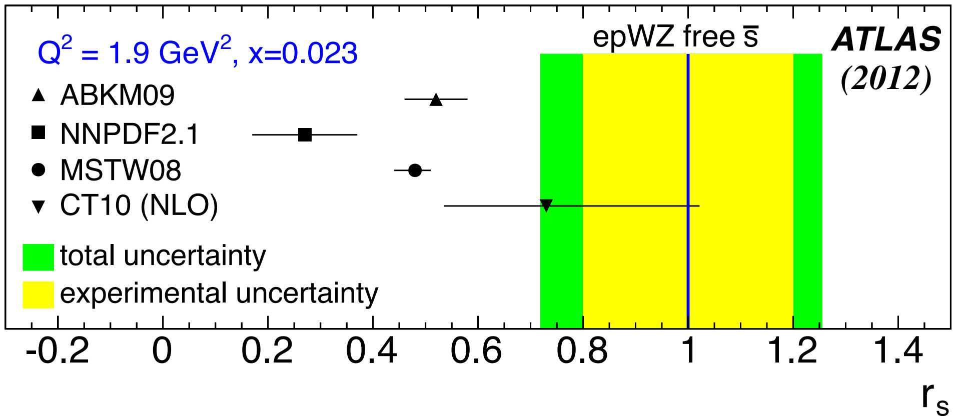

→ surprisingly large strangeness

$$r_s = (s + \bar{s})/2\bar{d}$$
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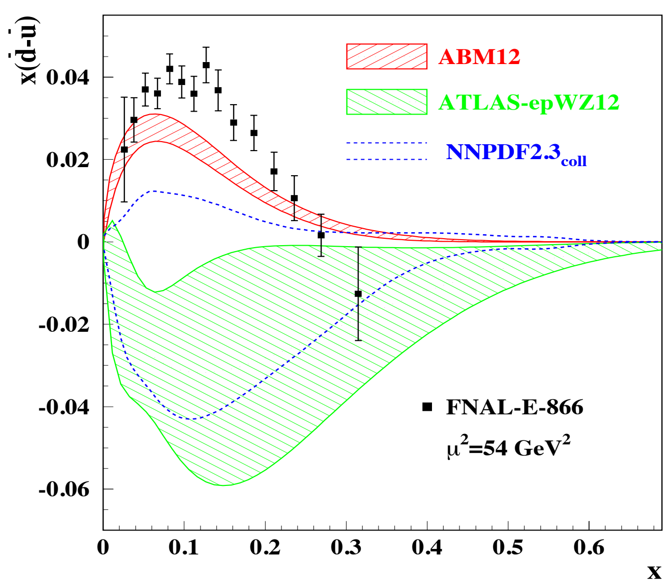
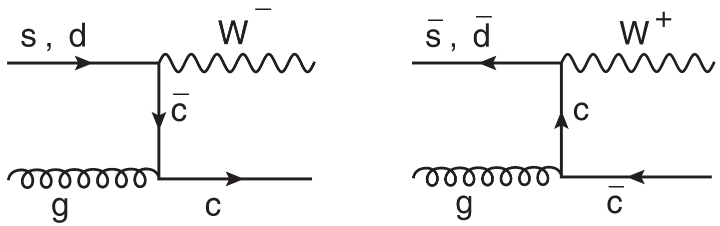
→ suggests effect related to underestimated $\bar{d}$ PDF
— collider data alone cannot (yet) disentangle flavors



Alekhin et al. (2015)

Strange quarks

- More reliable determination may come from associated production of W + charm jet events



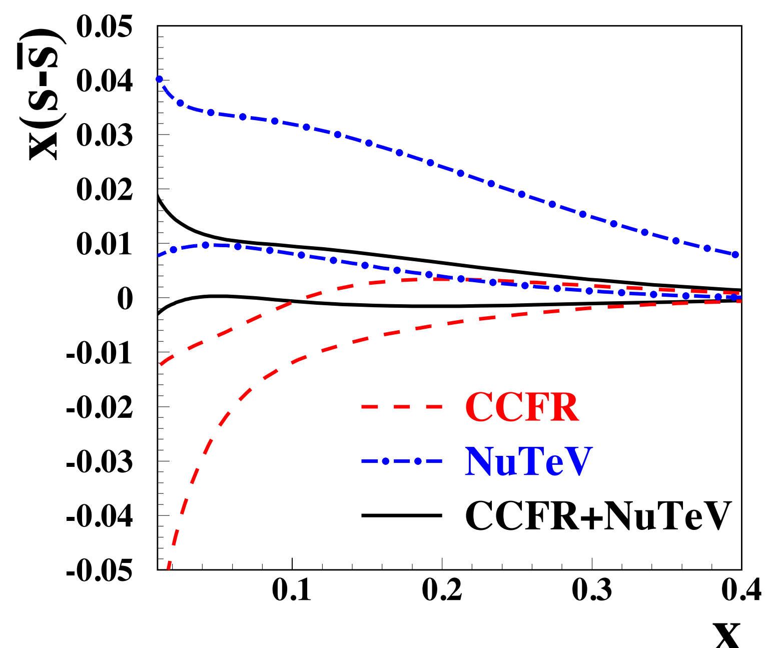
→ discriminate between s and $\bar{s}$ in the proton!

→ some indication from (anti)neutrino DIS from NuTeV experiment

$$S^- = \int_0^1 dx\, x(s - \bar{s})$$
$$= (2.0 \pm 1.4) \times 10^{-3}$$

NuTeV (2007)

… but global analysis including other data is inconclusive



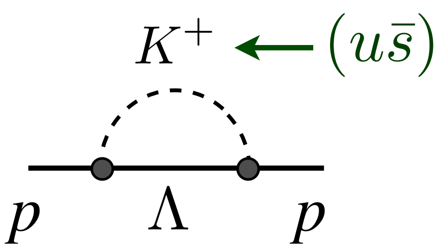
Alekhin et al. (2013)

Strange quarks

- Strange−antistrange asymmetry important indicator of nonperturbative physics

→ predicted from chiral SU(3) symmetry breaking via "kaon cloud"

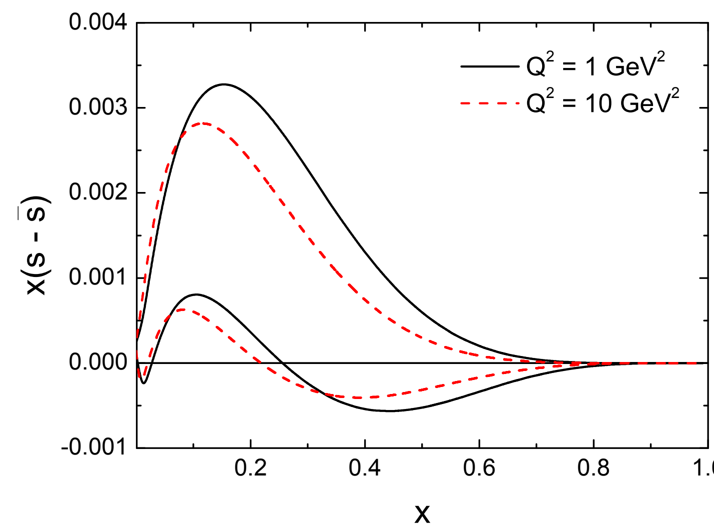
Signal, Thomas (1987)



… but shape more difficult to constrain

- Recent chiral effective theory analysis
  (including rainbow, tadpole & Kroll-Ruderman)
  favors small positive moment

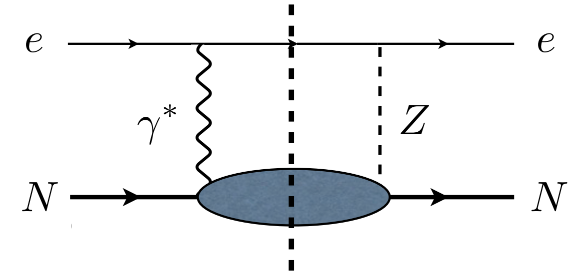
$$S^- \lesssim 1 \times 10^{-3}$$



Xuangong Wang et al. (2016)

Strange quarks

- Parity-violating DIS measurements ($e.g.$ SoLID at JLab12) will allow strange contribution to be isolated, when combined with e.m. p and n DIS data at low/intermediate x



→ at leading order

$$F_2^{\gamma p} = \frac{4}{9}x(u+\bar{u}) + \frac{1}{9}x(d+\bar{d}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma n} = \frac{4}{9}x(d+\bar{d}) + \frac{1}{9}x(u+\bar{u}+s+\bar{s}) + \cdots$$

$$F_2^{\gamma Z,p} = \left(\frac{1}{3} - \frac{8}{9}\sin^2\theta_W\right) x(u+\bar{u}) + \left(\frac{1}{6} - \frac{2}{9}\sin^2\theta_W\right)(d+\bar{d}+s+\bar{s}) + \cdots$$

$$\approx \frac{1}{9}x(u+\bar{u}+d+\bar{d}+s+\bar{s}) + \cdots \quad \text{for } \sin^2\theta_W \approx 1/4$$

→ 3 equations with 3 unknowns;
order of magnitude greater sensitivity of γZ to strange PDF

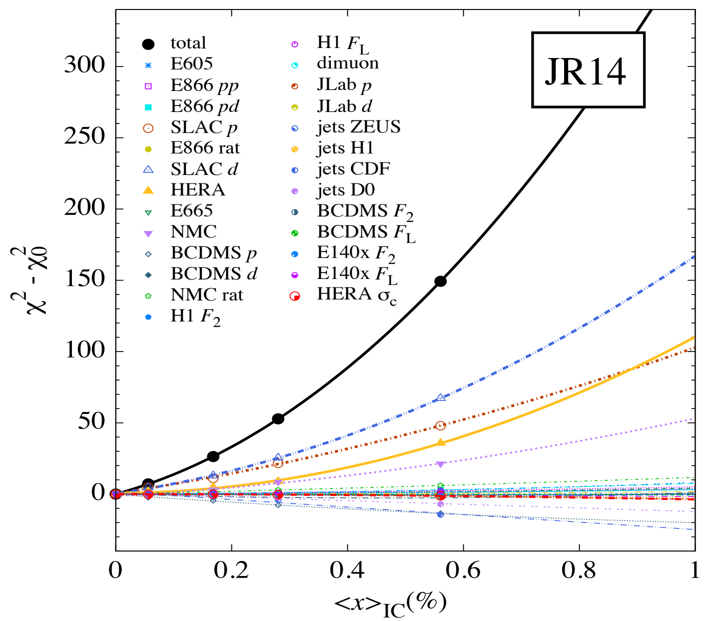
→ V x A term also sensitive to $s - \bar{s}$

$$F_3^{\gamma Z,p} = \frac{2}{3}(u-\bar{u}) + \frac{1}{3}(d-\bar{d}+s-\bar{s}) + \cdots$$

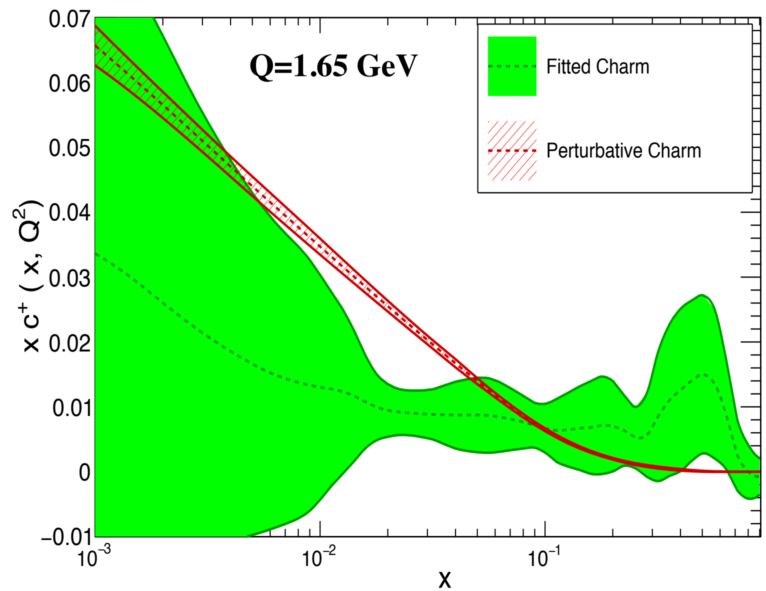
Charm in the nucleon

- Global PDF analyses find no evidence for large "intrinsic charm" (IC)

→ different upper limits obtained depend on definition of tolerance & treatment of nonperturbative effects (thresholds, masses, …)



Jimenez-Delgado et al. (2015)



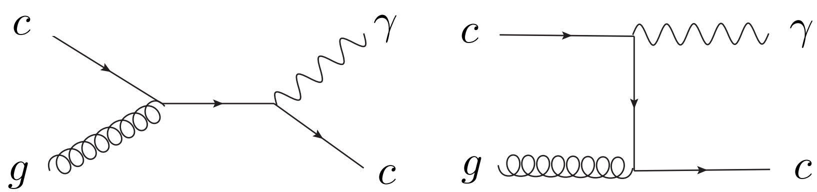
NNPDF (2016)

- with standard fitting technology momentum carried by "IC" $\langle x \rangle_{\rm IC} < 0.1\%$ at 5σ CL

- with "FONNL-B" HQ scheme, $\langle x \rangle_{\rm IC} < 1\%$ at 1σ CL, but can go < 0 at low x to fit EMC F_2^c data

Charm in the nucleon

- Associated prompt photon + charm production
  $pp \to \gamma + c + X$ may reveal "intrinsic" charm component



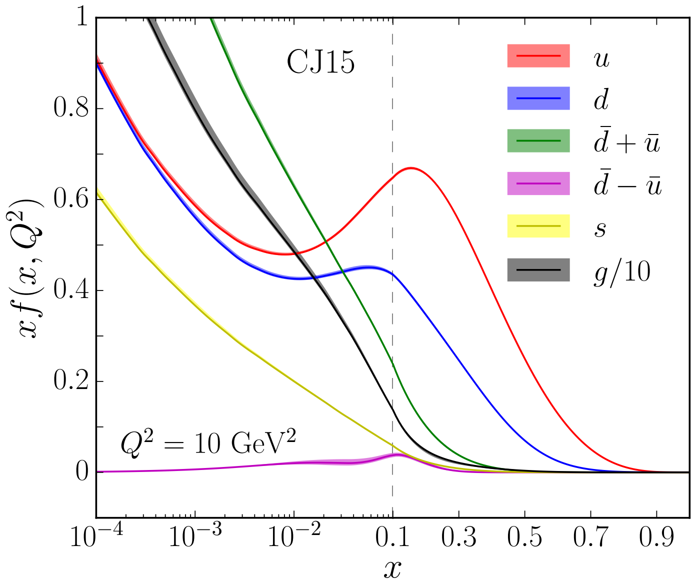
***Bednyakov et al.* (2014)**

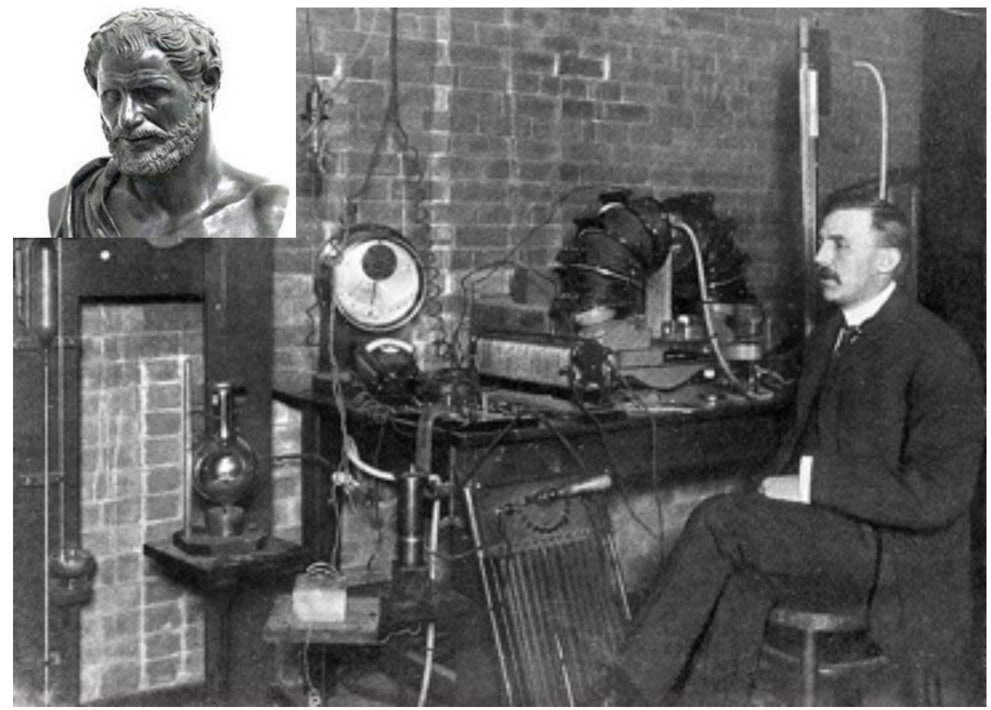
→ "smoking gun" would be observation of asymmetric distributions $c(x) \neq \bar{c}(x)$

→ ***Tim Hobbs talk***
Tue. 18:30

Outlook and new directions

- Study of PDFs has brought together essential elements of nuclear and high-energy physics





nucleon structure

BSM physics

neutrino oscillations

astrophysics

chiral physics

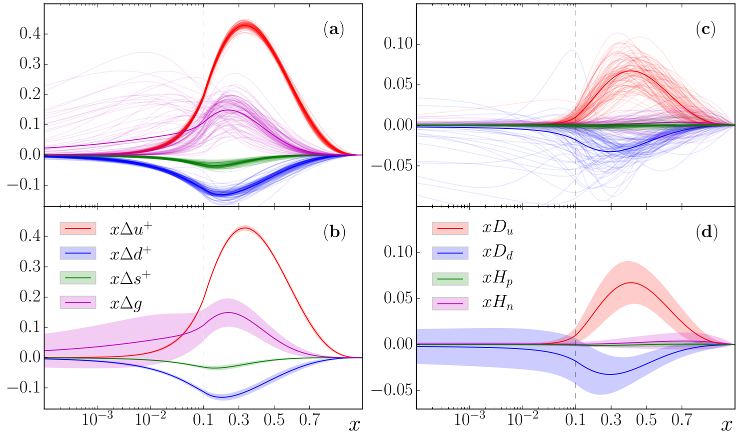
quark-hadron duality

Outlook and new directions

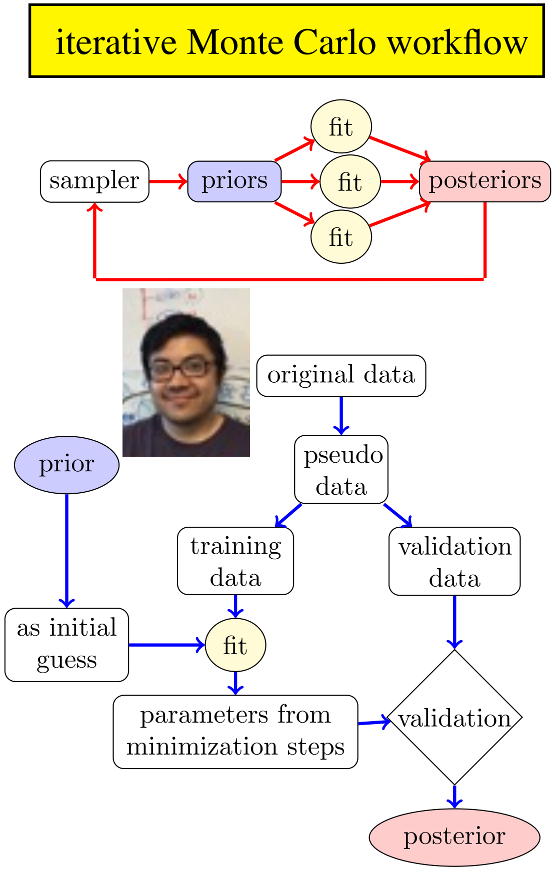
New approach to global QCD analysis — "IMC"

→ minimize bias from choice of initial parameters

→ statistically rigorous PDF uncertainties, without assumptions about "tolerance" or Gaussianity



Sato et al. (2016)



→ ultimate goal of simultaneous fit of unpolarized and polarized PDFs and fragmentation functions in sight
(eventually generalize to TMDs)

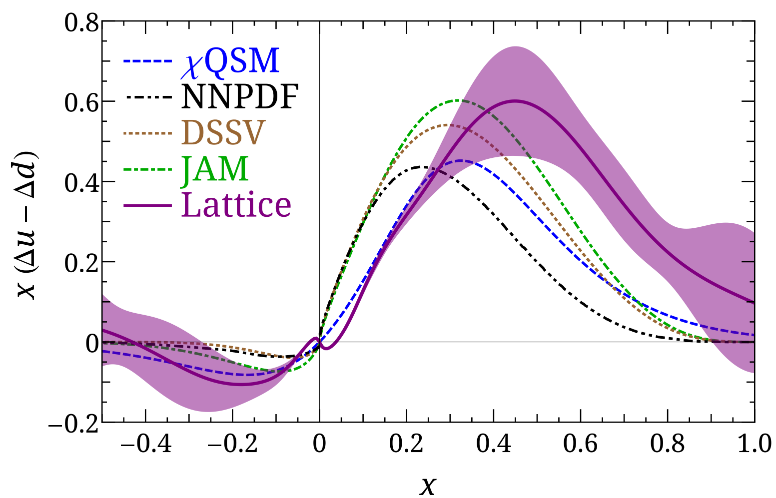
Outlook and new directions

PDFs on the lattice

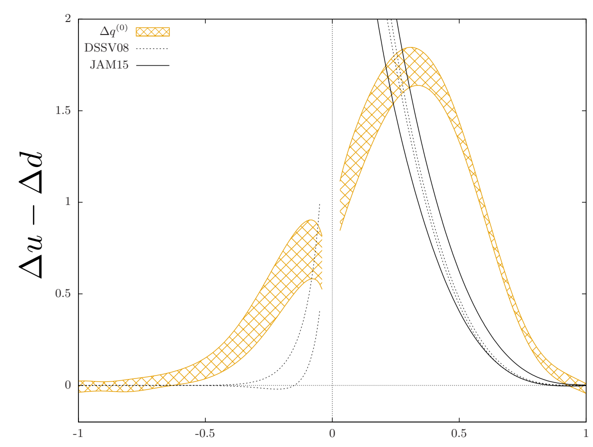
⟶ compute light-cone correlations of parsons by boosting matrix elements of spatial correlations to large momentum — large momentum effective field theory (LaMET)

Xiangdong Ji (2013)

⟶ challenges to overcome, but first computations promising



H.-W. Lin, J.-W. Chen et al. (2015-16)



Alexandrou et al. (2016)

Το τέλος.

Ευχαριστώ!