*New Directions in Subatomic Physics*
*CSSM Adelaide, March 8, 2016*

# Parton distributions from JLab to LHC

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*arXiv:1602.03154 [hep-ph]*
*arXiv:1601.07782 [hep-ph]*

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

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

# Outline

- New insights from global PDF analysis – "CJ15" PDFs

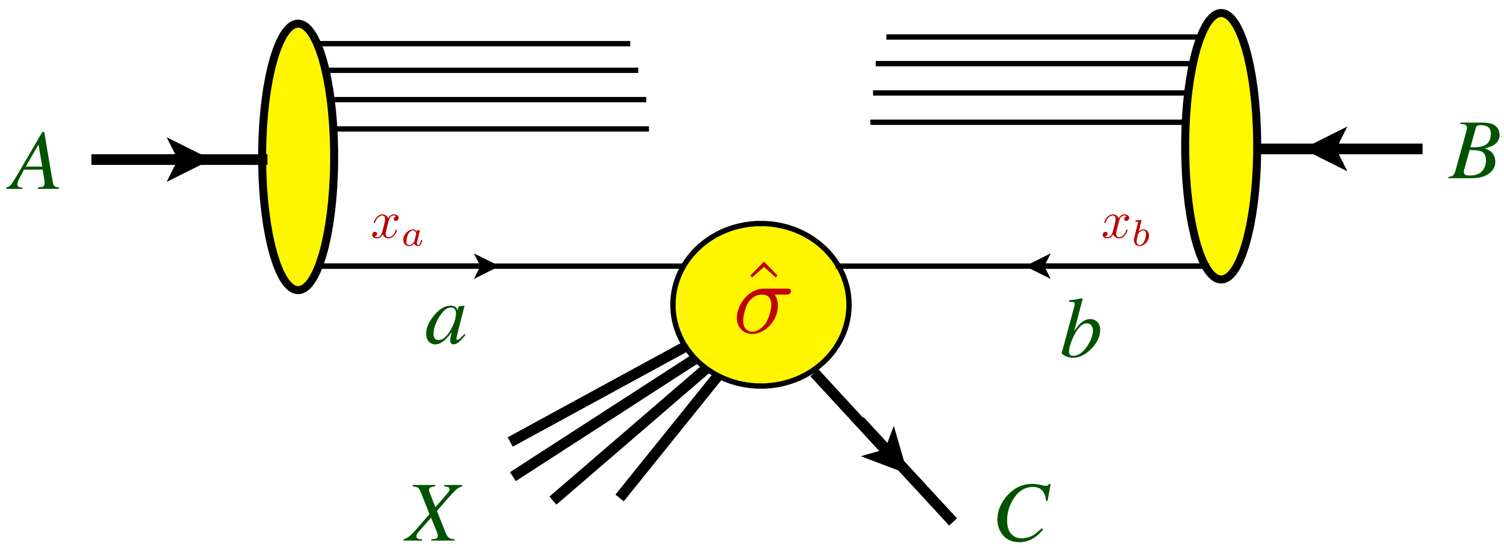
- High-$x$ PDFs
  - → impact of new $W$ asymmetry data on $d/u$ ratio
  - → implications for new particle searches

- Sea quarks
  - → strange & charm quark PDFs

- New directions
  - → "iterative Monte Carlo" analysis

# Parton distributions in hadrons

- Inclusive particle production $A\,B \to C\,X$

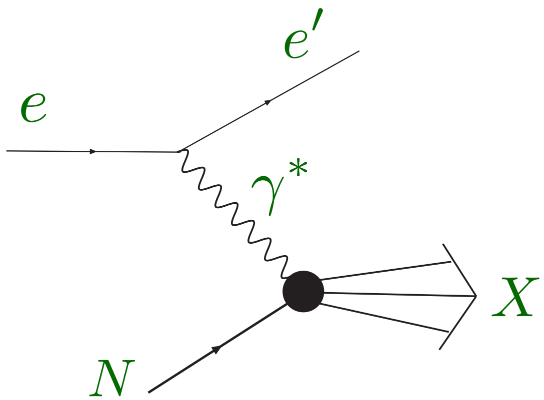



$$\sigma_{AB\to CX}(p_A, p_B) = \sum_{a,b} \int dx_a\, dx_b\, f_{a/A}(x_a, \mu)\, f_{b/B}(x_b, \mu) \times \sum_n \alpha_s^n(\mu)\, \hat{\sigma}^{(n)}_{ab\to CX}(x_a p_A, x_b p_B, Q/\mu)$$

→ universal functions $f_{a/A}$ characterize internal structure of bound state $A$

# Parton distributions in hadrons

- Most information on parton distribution functions (PDFs) obtained from inclusive deep-inelastic scattering (DIS)

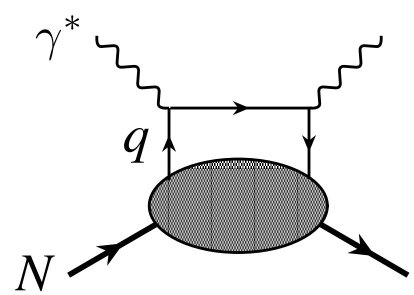



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

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

- At leading order (LO) in pQCD, structure functions given in terms of PDFs

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



# Parton distributions in hadrons

- PDFs extracted in global QCD analyses of data from deep-inelastic $l$-$h$ scattering, dilepton/weak boson/jet production in $h$-$h$ scattering, ...

- Typically parametrized as

$$x f(x,\mu) = N x^{\alpha} (1-x)^{\beta} P(x)$$

with polynomial $e.g.\ P(x) = 1 + \epsilon\sqrt{x} + \eta\, x$

- Needed to understand basic structure of QCD bound states – and for backgrounds in searches for physics beyond the Standard Model at high-energy colliders

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

# Parton distributions in hadrons

- Several groups dedicated to global PDF analysis

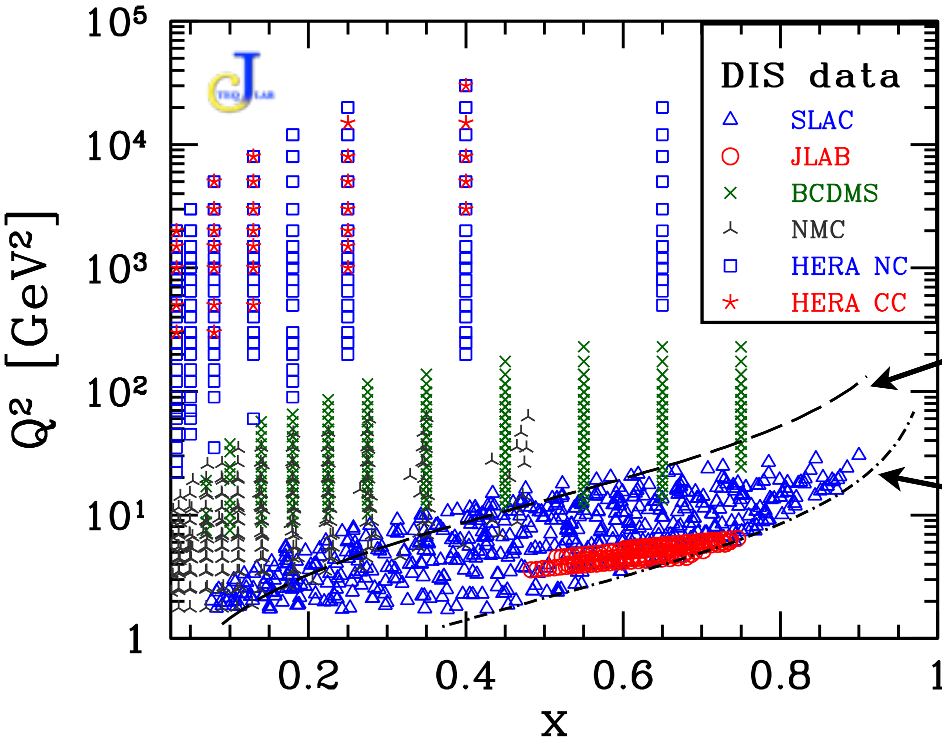
  - CTEQ (Coordinated Theoretical-Experimental Project on QCD)
    - CT (CTEQ-Tung et al.) US-based, LHC focus
    - CJ (CTEQ-JLab) includes high $x$, low $Q^2$
    - nCTEQ nuclear PDFs
  - MMHT (Martin, Thorne et al.) UK-based, strong data cuts
  - ABM (Alekhin-Bluemlein-Moch) DESY-based, LHC focus
  - JR (Jimenez-Delgado–Reya) dynamically generated from low $Q^2$
  - HERAPDF uses only H1 & ZEUS data
  - NNPDF uses "neural networks", strong data cuts

→ all use NLO QCD corrections, some use NNLO (partially known)

# 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 $W$ & $Q^2$




$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

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

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

→ factor 2 increase in # of DIS data points when relax strong cut (excludes most SLAC, all JLab data) → weak cut

# CJ15 global PDF analysis

- NLO analysis of expanded set of proton & deuterium data
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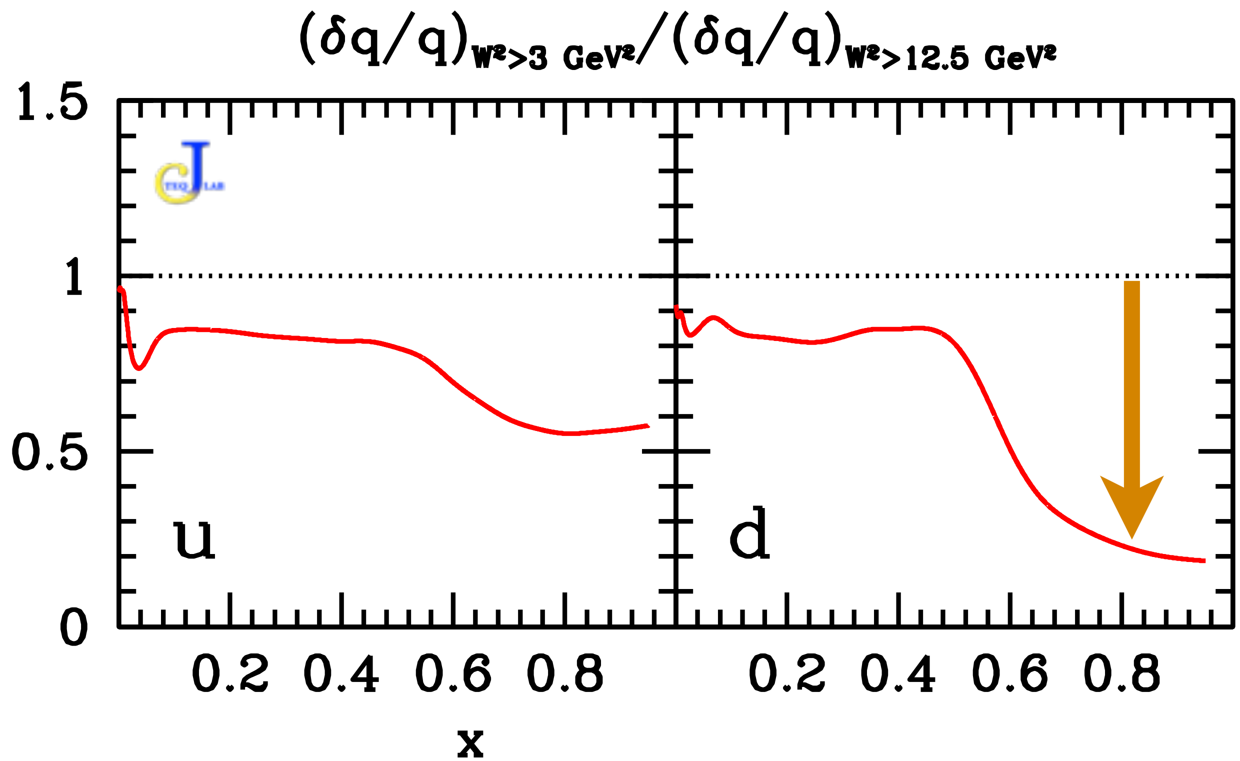



→ significant error reduction at high $x$

# 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

## data sets used in fit

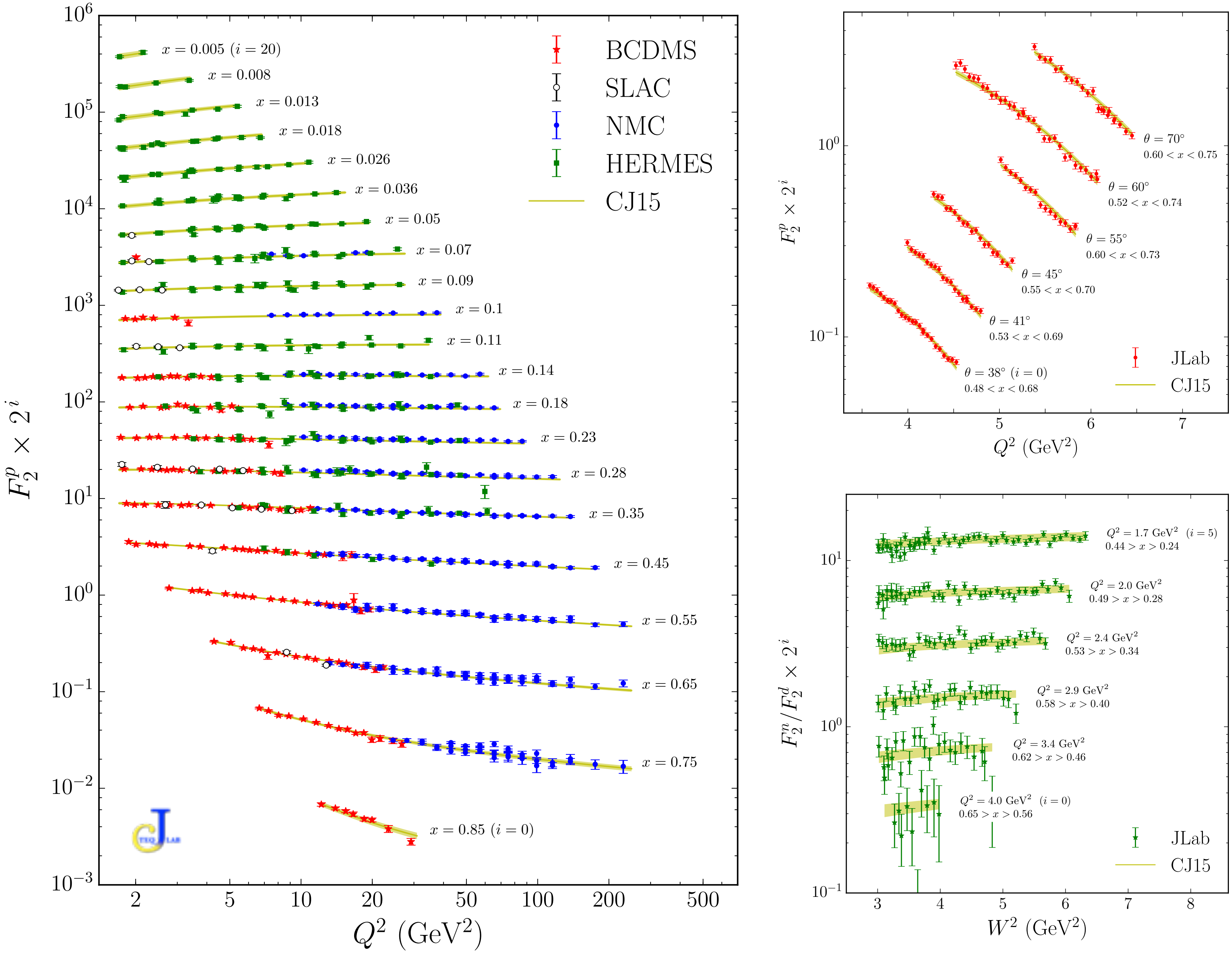
| Observable | Experiment | # points | $\chi^2$ LO | NLO | NLO (OCS) | NLO (no nucl) | NLO (no nucl/D0) |
|---|---|---|---|---|---|---|---|
| DIS $F_2$ | BCDMS ($p$) [81] | 351 | 430 | **438** | 436 | 440 | 427 |
| | BCDMS ($d$) [81] | 254 | 297 | **292** | 289 | 301 | 301 |
| | SLAC ($p$) [82] | 564 | 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 |
| DIS $\sigma$ | 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 ($\mu$) [17] | 10 | 37 | **20** | 19 | 29 | 28 |
| | 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 | — |
| $Z$ 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 |
| $\gamma$+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 |
| $\chi^2$/datum | | | 1.33 | **1.04** | 1.04 | 1.09 | 1.07 |

← BONuS $F_2^n/F_2^d$

← D0 $A_l$

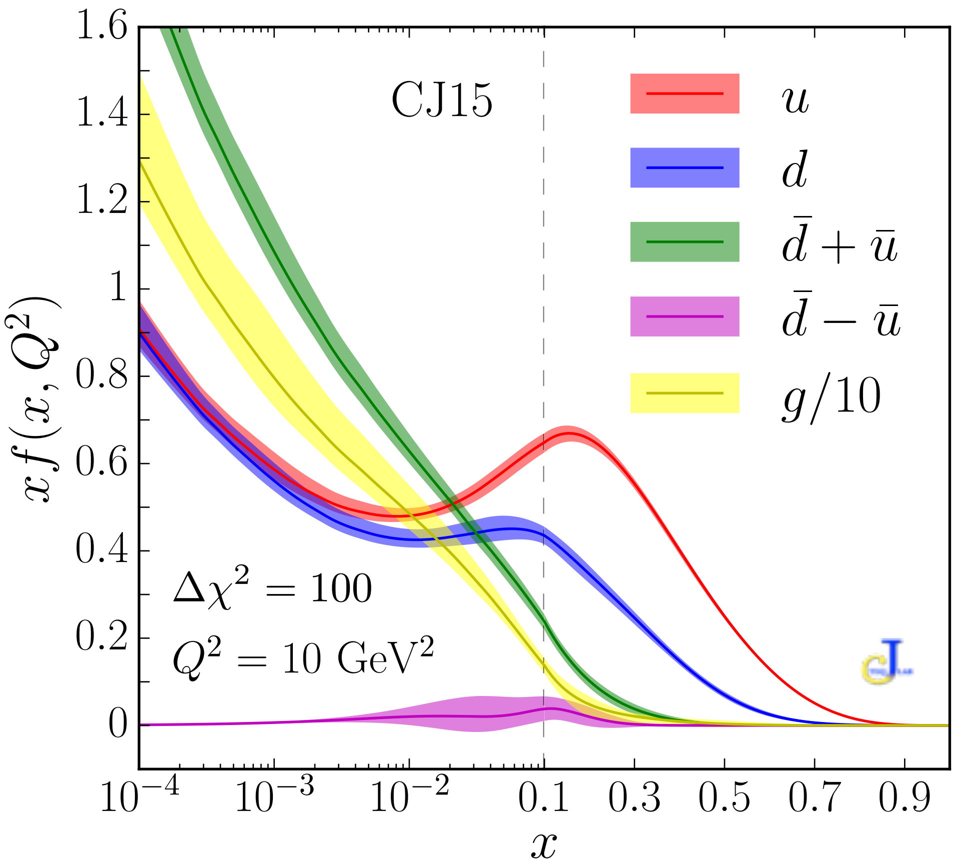
← D0 $A_W$

→ ~ 4500 data points, with $\chi^2$ per datum = 1.04




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

# CJ15 PDFs, using standard Hessian error propagation




→ $\chi^2$ for parameters $\vec{p}$

$$\chi^2(\vec{p}) = \sum_i \frac{(\mathrm{data}_i - \mathrm{thy}_i(\vec{p}))^2}{\sigma^2_{\mathrm{uncor},i} + \sigma^2_{\mathrm{cor},i}}$$

Hessian matrix

$$H_{ij} = \frac{1}{2} \frac{\partial\chi^2(\vec{p})}{\partial p_i \partial p_j}\Big|_{\vec{p}=\mathrm{best}}$$

→ often introduce "tolerance" $T = \Delta\chi^2$ to account for tensions between data sets

→ NLO fit gives $\chi^2$/dat = 1.04; LO fit worse, $\chi^2$/dat = 1.33 (cannot accommodate $Q^2$ dependence of data at LO)

→ fit uses $\Lambda^{(5)}_{\mathrm{QCD}} = 0.2268\ \mathrm{GeV}$, or $\alpha_s(M_Z) = 0.1180$

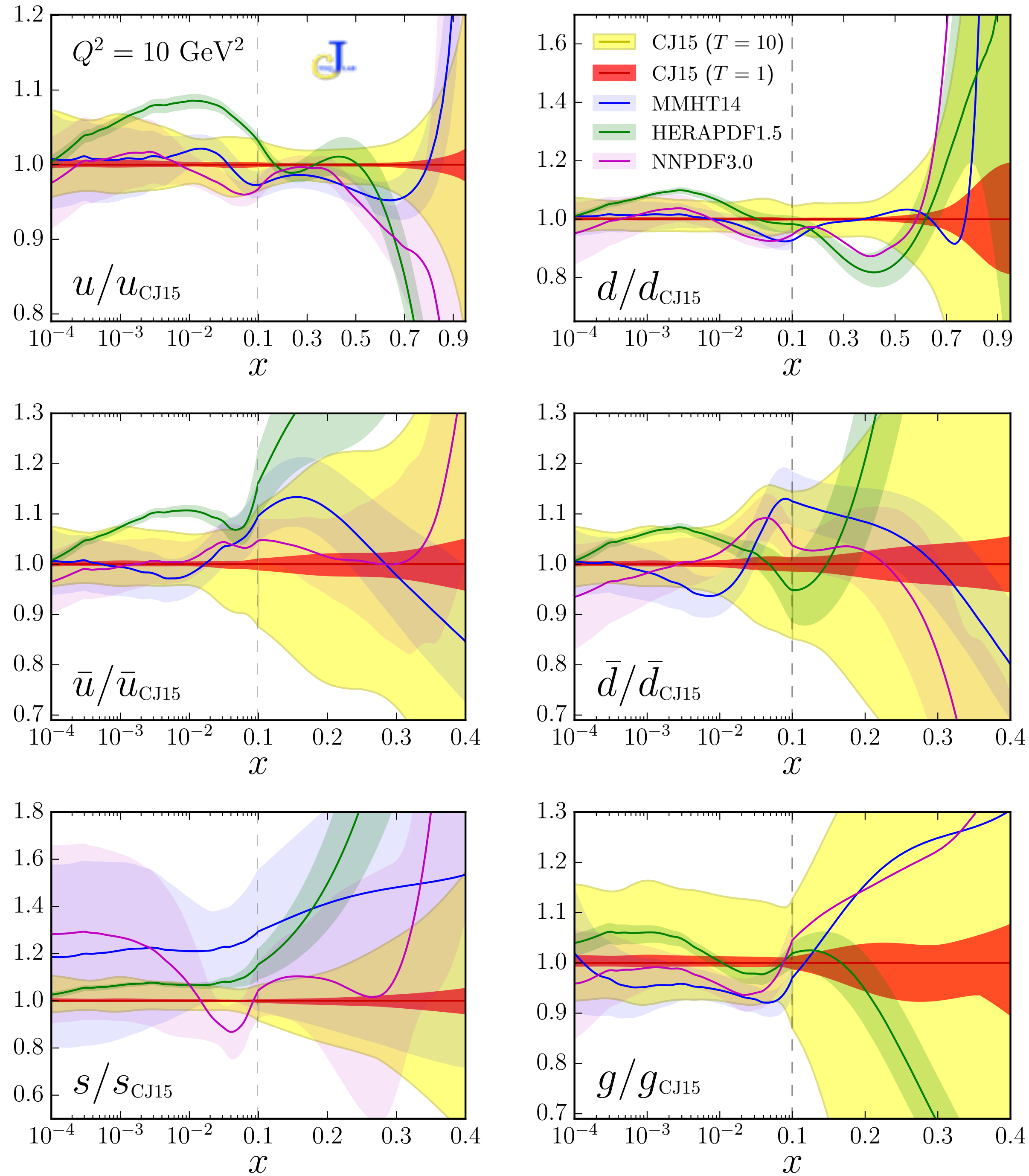
# ■ *cf.* other PDFs

→ MMHT & NNPDF errors comparable to CJ15 with $T$=10

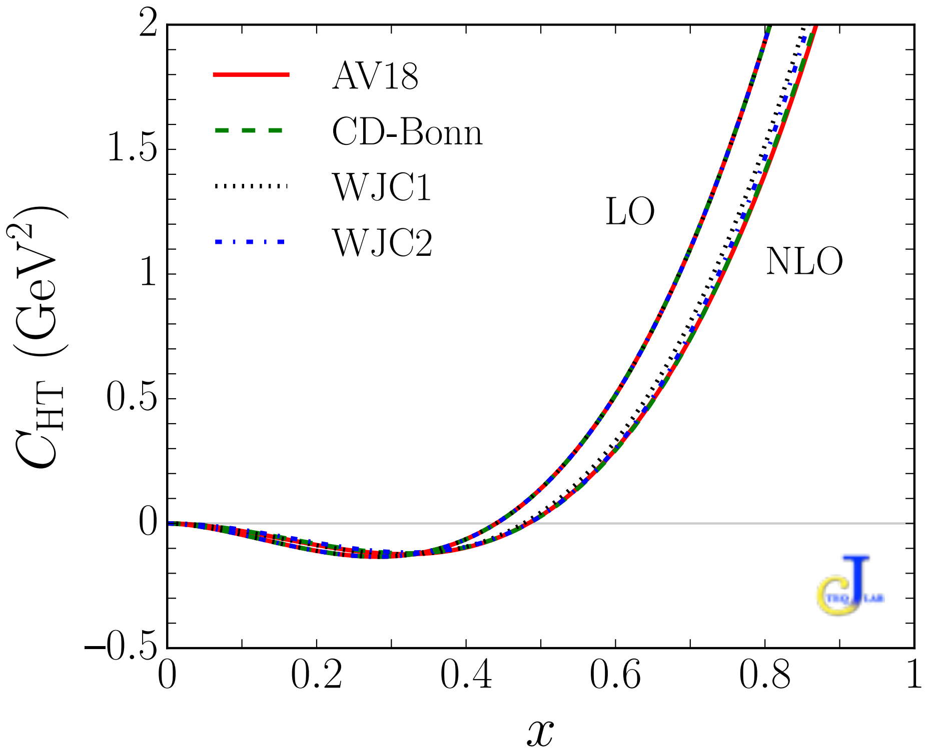
→ HERAPDF1.5 errors comparable to $T$=1 (uses $\Delta\chi^2 = 1$)

→ much larger uncertainty at high $x$ for $d$-quark than for $u$-quark PDF (no free-neutron data)

→ strange-quark not well constrained (CJ15 takes $\kappa = (s+\bar{s})/(\bar{u}+\bar{d}) \sim 0.4$)



- At low $Q^2$, cannot accommodate $Q^2$ dependence without power corrections (target mass and higher twists)




$$F_2(x,Q^2) = F_2^{(\rm TMC)}(x,Q^2)\left(1+\frac{C_{\rm HT}(x)}{Q^2}\right)$$

$$C_{\rm HT} = h_0\, x^{h_1}(1+h_2 x)$$

$h_{0,1,2}$ fit parameters

**deuteron wave functions from *NN* scattering**

AV18: *Wiringa et al., PRC* ***51****, 38 (1995)*

CD-Bonn: *Machleidt, PRC* ***63****, 024001 (2001)*

WJC: *Gross, Stadler, PRC* ***82****, 034004 (2010)*

→ corrections large at high $x$ and low $Q^2$

→ crucial for extracting correct PDFs at high $x$

# Nuclear corrections

- Deuteron PDFs related to bound nucleon PDFs at $x \gg 0$

$$q^d(x,Q^2) = \int \frac{dz}{z} dp^2 \, f_{N/d}(z,p^2)\, \widetilde{q}^N(x/z,p^2,Q^2)$$

nucleon momentum distribution in deuteron ("smearing function") → $f_{N/d}$

PDF in bound (off-shell) nucleon → $\widetilde{q}^N$

→ $z = \dfrac{p \cdot q}{p_d \cdot q} \approx 1 + \dfrac{p_0 + \gamma p_z}{M} \qquad \left[ p_0 = M + \varepsilon, \quad \varepsilon = \varepsilon_d - \dfrac{\vec{p}^{\,2}}{2M} \right]$

momentum fraction of deuteron carried by nucleon

→ at finite $Q^2$, smearing function depends on $\gamma = \sqrt{1 + 4M^2x^2/Q^2}$

# Nuclear corrections

- Expand off-shell nucleon PDF about on-shell $(p^2 = M^2)$ limit

$$\widetilde{q}^N(x,p^2) = q^N(x)\left[1 + \frac{(p^2 - M^2)}{M^2}\,\delta q^N(x)\right]$$

$$\delta q^N = \left.\frac{\partial \log \widetilde{q}^N}{\partial \log p^2}\right|_{p^2=M^2}$$

- Deuteron PDF sum of on- and off-shell contributions $q^d = q^{d(\mathrm{on})} + q^{d(\mathrm{off})}$, where

$$q^{d(\mathrm{on})}(x,Q^2) = \int \frac{dz}{z} f^{(\mathrm{on})}(z)\, q^N(x/z,Q^2)$$

$$q^{d(\mathrm{off})}(x,Q^2) = \int \frac{dz}{z} f^{(\mathrm{off})}(z)\, \delta q^N(x/z,Q^2) q^N(x/z,Q^2)$$

on-shell & off-shell smearing functions

$$f^{(\mathrm{on})}(z) = \int dp^2\, f_{N/d}(z,p^2)$$

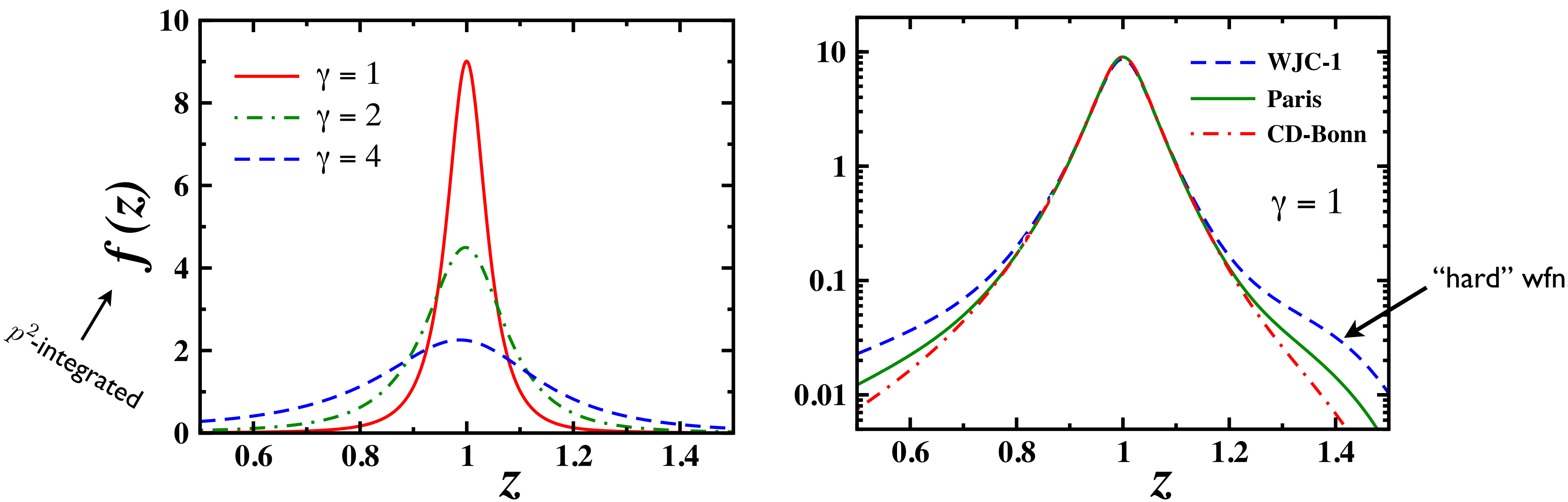
$$f^{(\mathrm{off})}(z) = \int dp^2\, \frac{p^2 - M^2}{M^2} f_{N/d}(z,p^2)$$

*Ehlers et al., PRD **90**, 014010 (2014)*

# Nuclear corrections

- Smearing function in the deuteron computed in "weak binding approximation" – expand in powers of $\vec{p}^2/M^2$

$$f_{N/d}(z,p^2) = \frac{1}{(2\pi)^3}\,\frac{1}{\gamma^2}\left[1+\frac{\gamma^2-1}{z^2}\left(1+\frac{2\varepsilon}{M}+\frac{\vec{p}^2}{2M^2}(1-3\hat{p}_z^2)\right)\right]|\psi_d(p)|^2$$

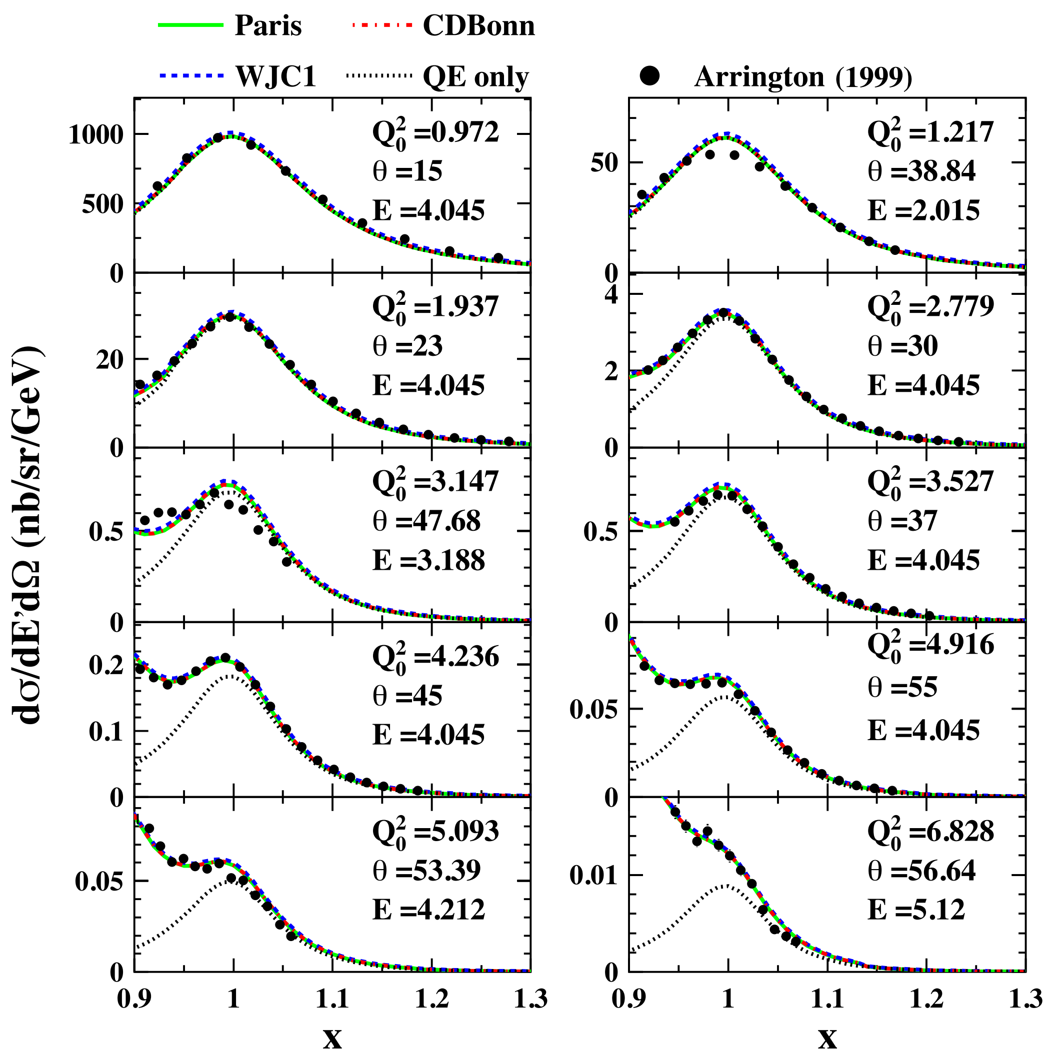



→ effectively more smearing for larger $x$ and lower $Q^2$

→ greater wave function dependence at large $z$ (→ large $x$)

# Nuclear corrections

- Smearing functions tested in quasi-elastic *ed* scattering




$$\sigma_{(\mathrm{QE})} \sim f_{N/d}(y,\gamma) \times G_N(Q^2)$$

elastic $eN$ form factors

*Ethier et al.*
*PRC* ***89****, 065203 (2014)*

→ good description of QE data at low and high $Q^2$

# Nuclear corrections

- Nucleon off-shell correction parametrized phenomenologically

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

*Kulagin, Petti, NPA* ***765***, *126 (2006)*

→ fit 2 of $\{C, x_0, x_1\}$ for given deuteron wave function; fix third parameter from normalization condition

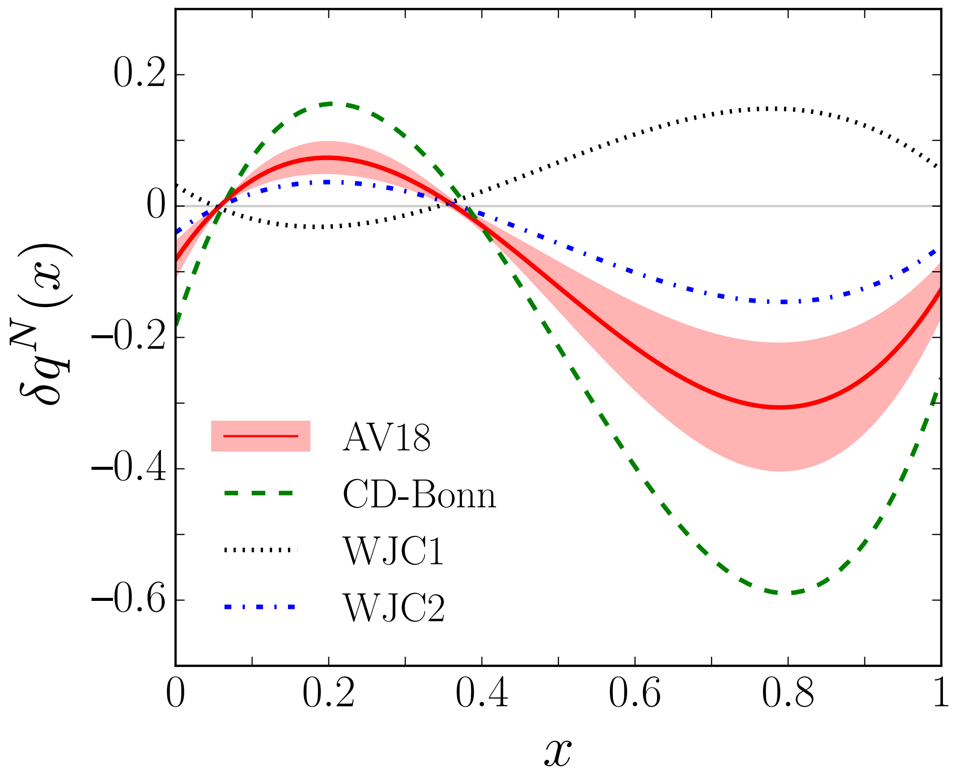
$$\int_0^1 dx\, \delta q^N(x) \Big( q^N(x) - \bar{q}^N(x) \Big) = 0$$

# Nuclear corrections

- Nucleon off-shell correction parametrized phenomenologically

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

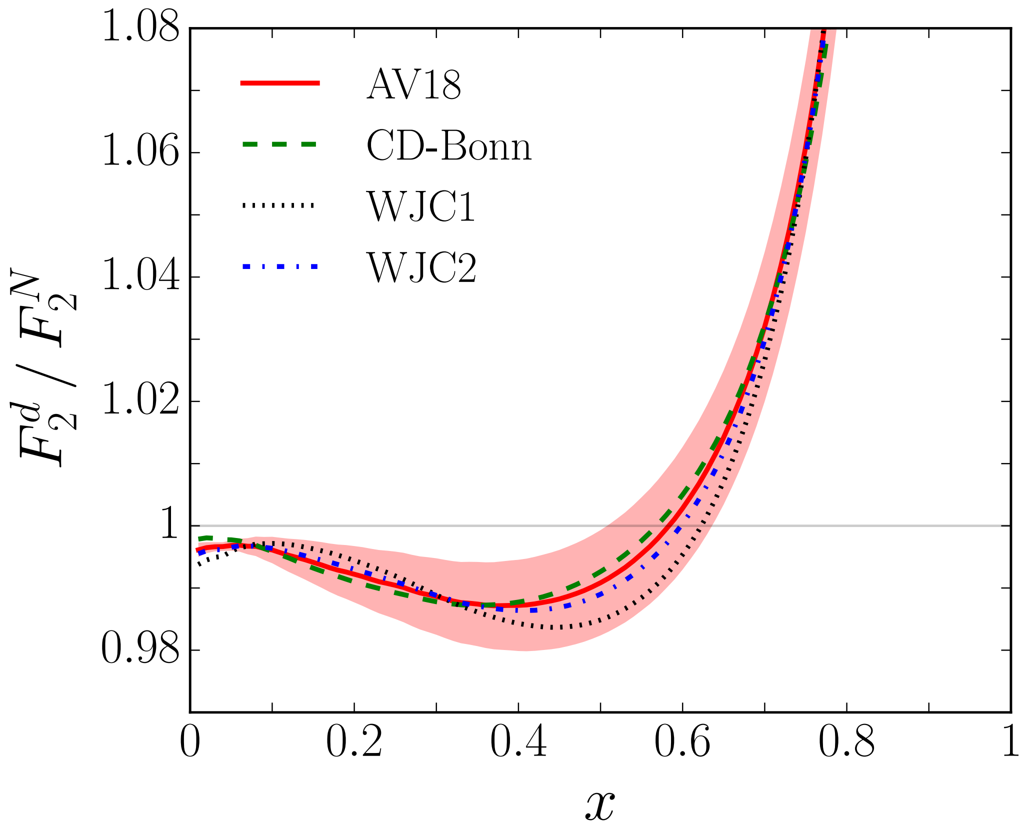
*Kulagin, Petti, NPA **765**, 126 (2006)*




→ 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

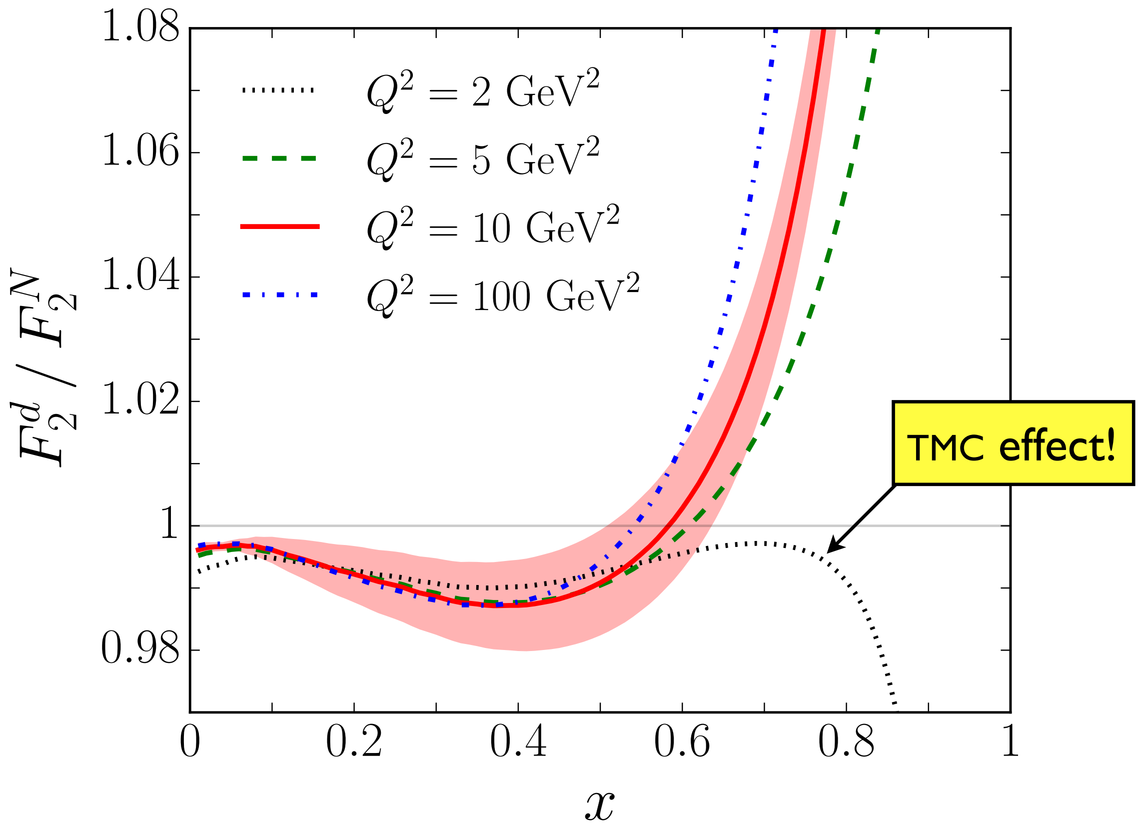



→ observables sensitive only to combined smearing (wave function) *and* off-shell corrections

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

# Nuclear corrections

- Nuclear "EMC ratio" in deuterium



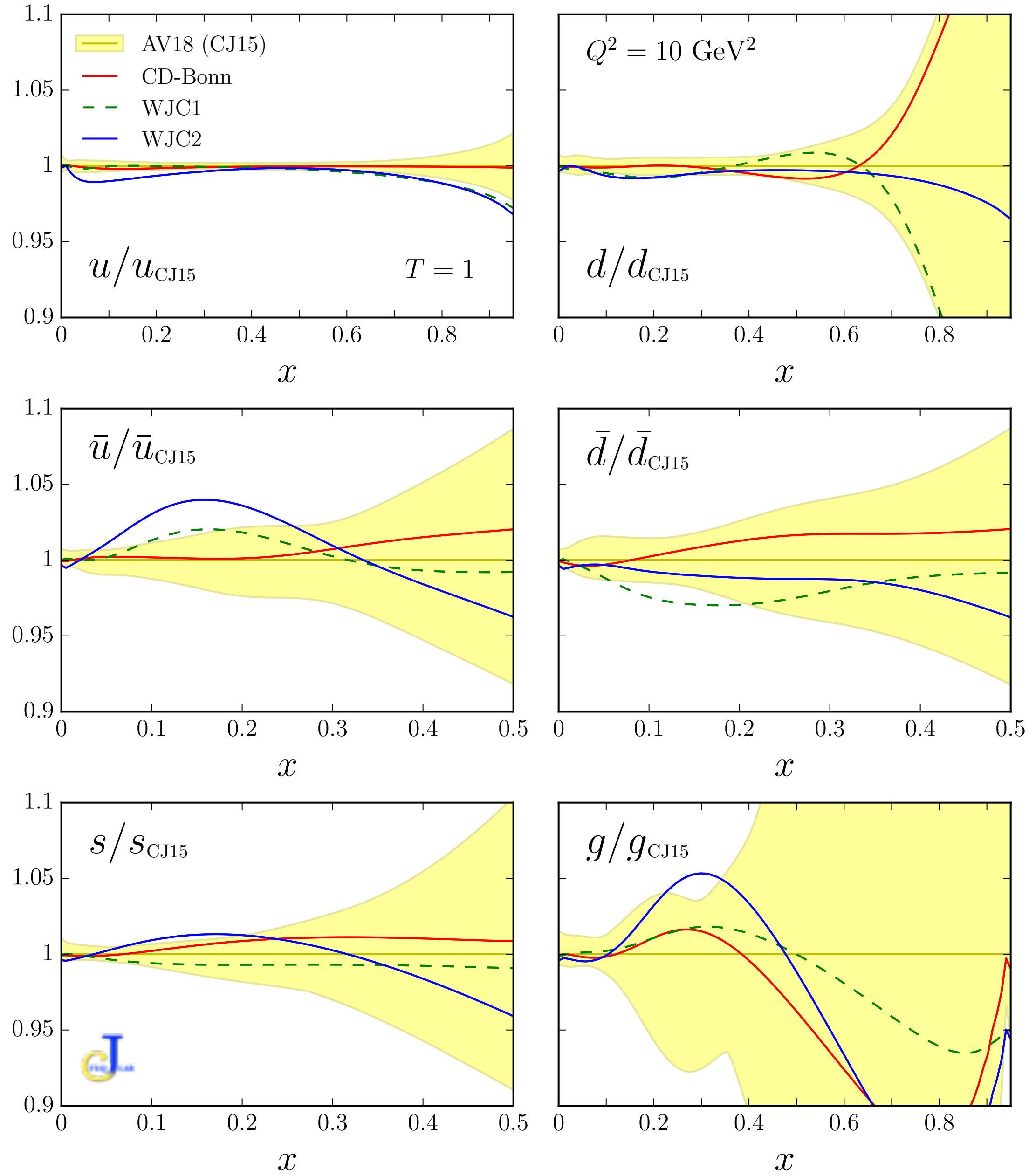

→ ratio has significant $Q^2$ dependence at low $Q^2$ from target mass effects – problematic to use universal ratio $R = F_2^d/F_2^N$ for all kinematics

# Nuclear corrections & CJ15 PDFs

→ large uncertainty for $d$ PDF — no free-$n$ data, large nuclear uncertainties in deuterium at $x > 0.5$

→ $\chi^2$ for AV18 & CD-Bonn wfns. almost indistinguishable — off-shell correction compensates for wfn.

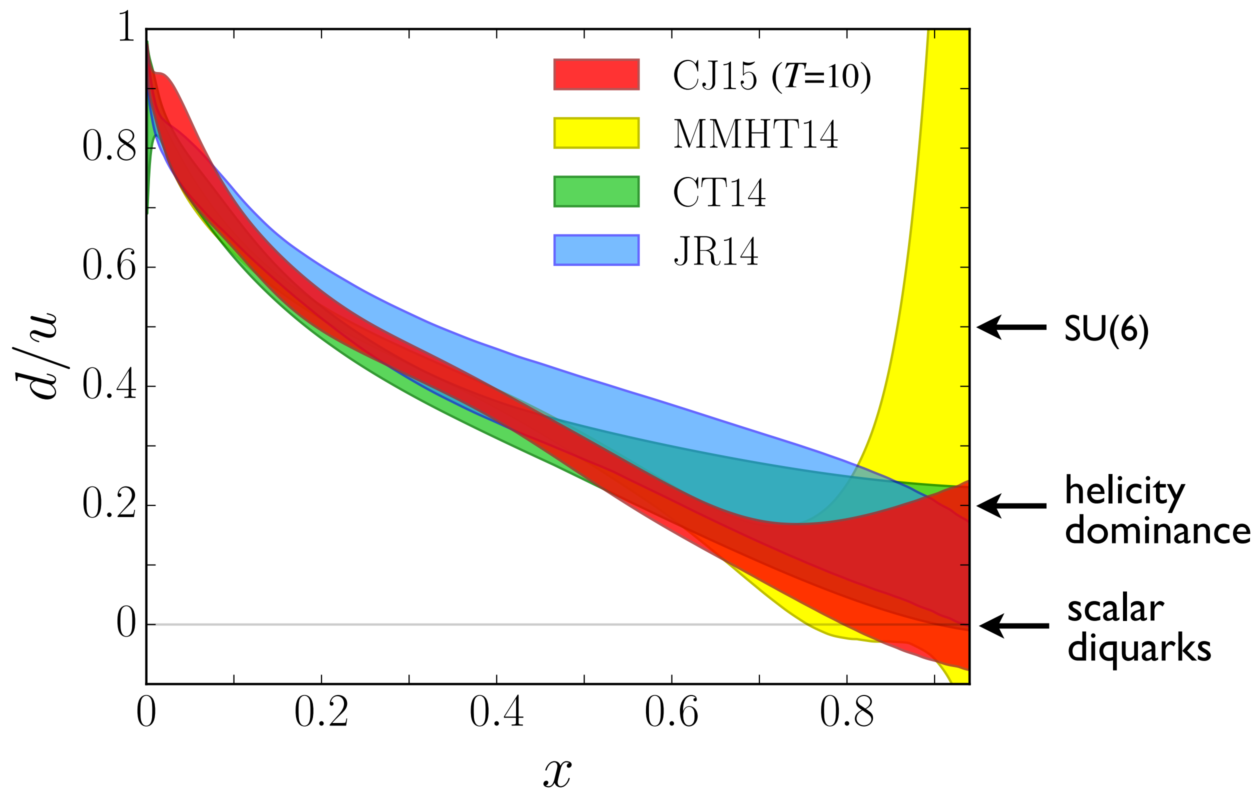
→ $\chi^2$ for (harder) WJC-1 slightly larger — $d$ PDF suppressed at high $x$



# Nuclear corrections & CJ15 PDFs

→ $d/u$ 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

- $d/u \to 1/5$

  $S_z=0$ $qq$ dominance (pQCD-inspired)

- $d/u \to \dfrac{4\,\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2} \approx 0.22$

  local quark-hadron duality

# Nuclear corrections & CJ15 PDFs

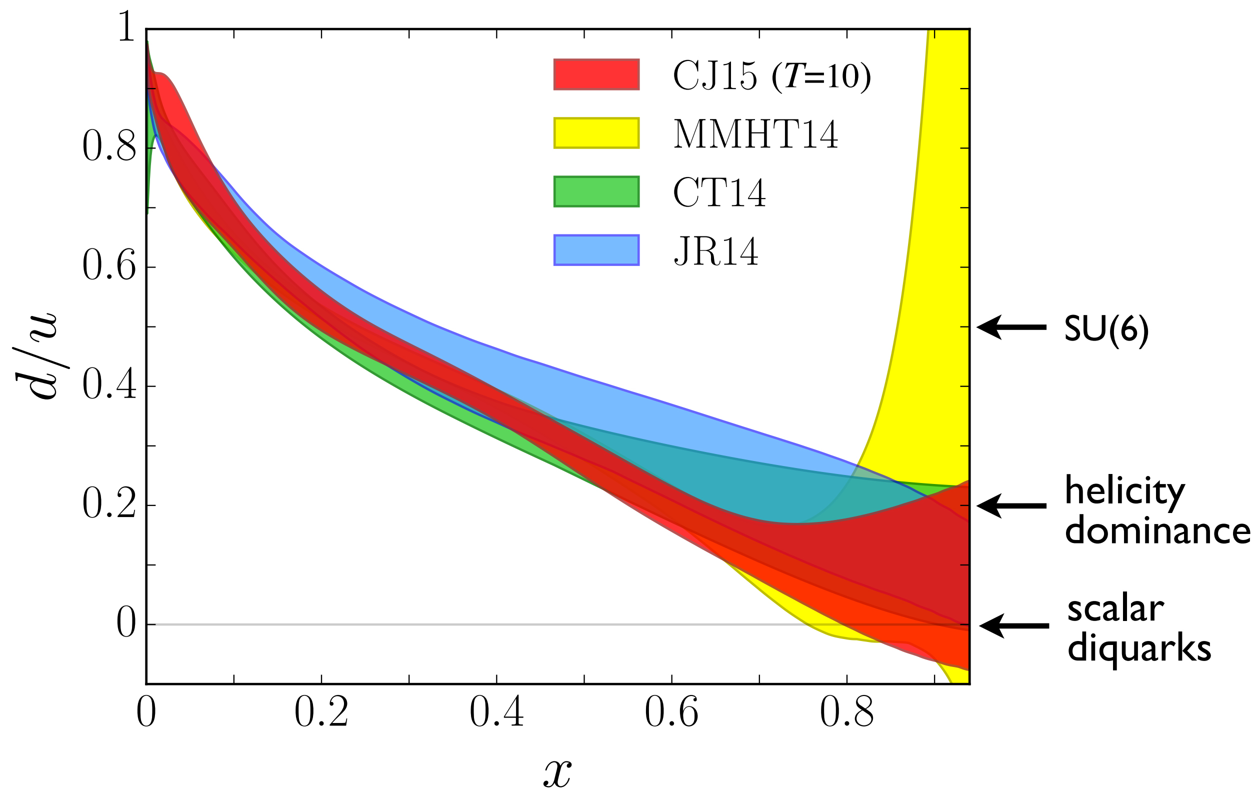
→ $d/u$ ratio at high $x$ of particular interest

→ more flexible parametrization

$$d \rightarrow d + b\,x^c\,u$$

allows finite, nonzero $x = 1$ limit

— standard PDF form $\sim (1-x)^\beta$ gives 0 or $\infty$ unless $\beta_d = \beta_u$



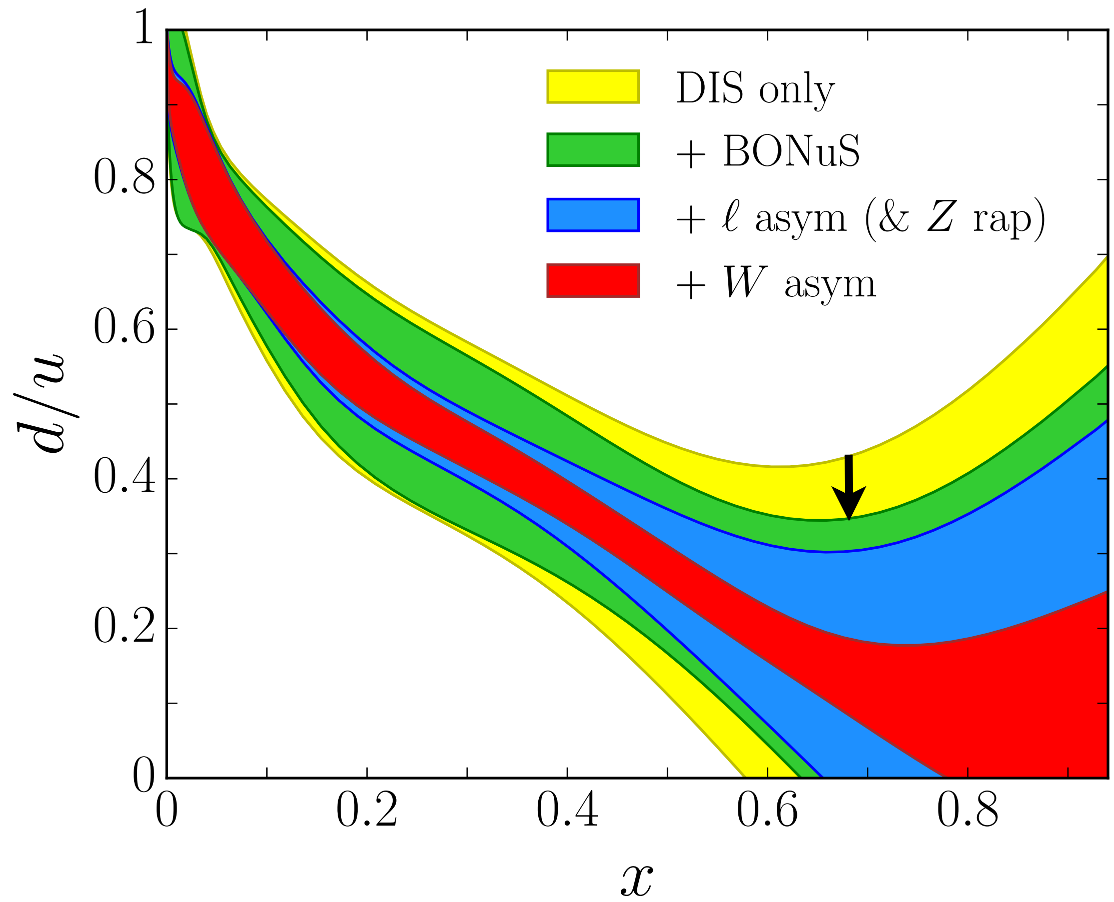

MMHT14: fitted deuteron correction, "standard" $d$ parametrization

CT14: flexible $d$ parametrization, no nuclear corrections

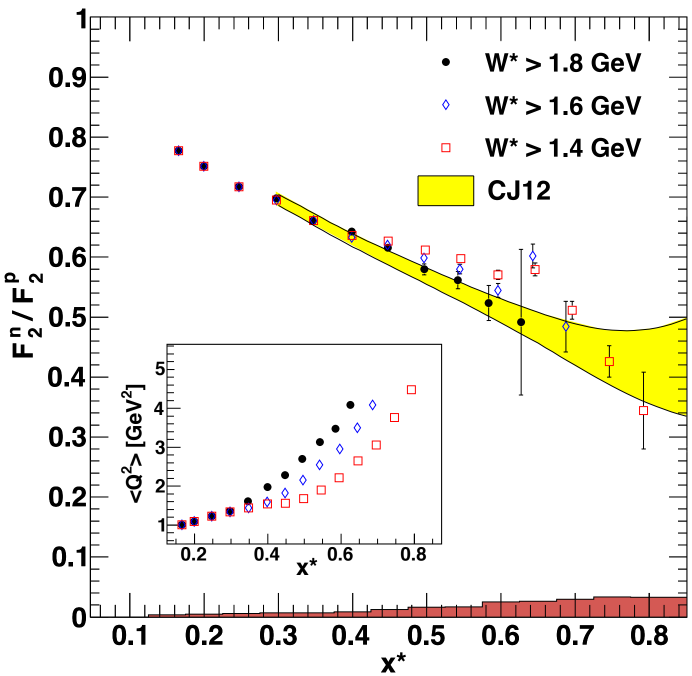
JR14: similar deuteron correction, no lepton/$W$ asymmetry data

# Effect of data sets of $d/u$

→ new JLab (BONuS) data reduces error at $x \sim 0.6$



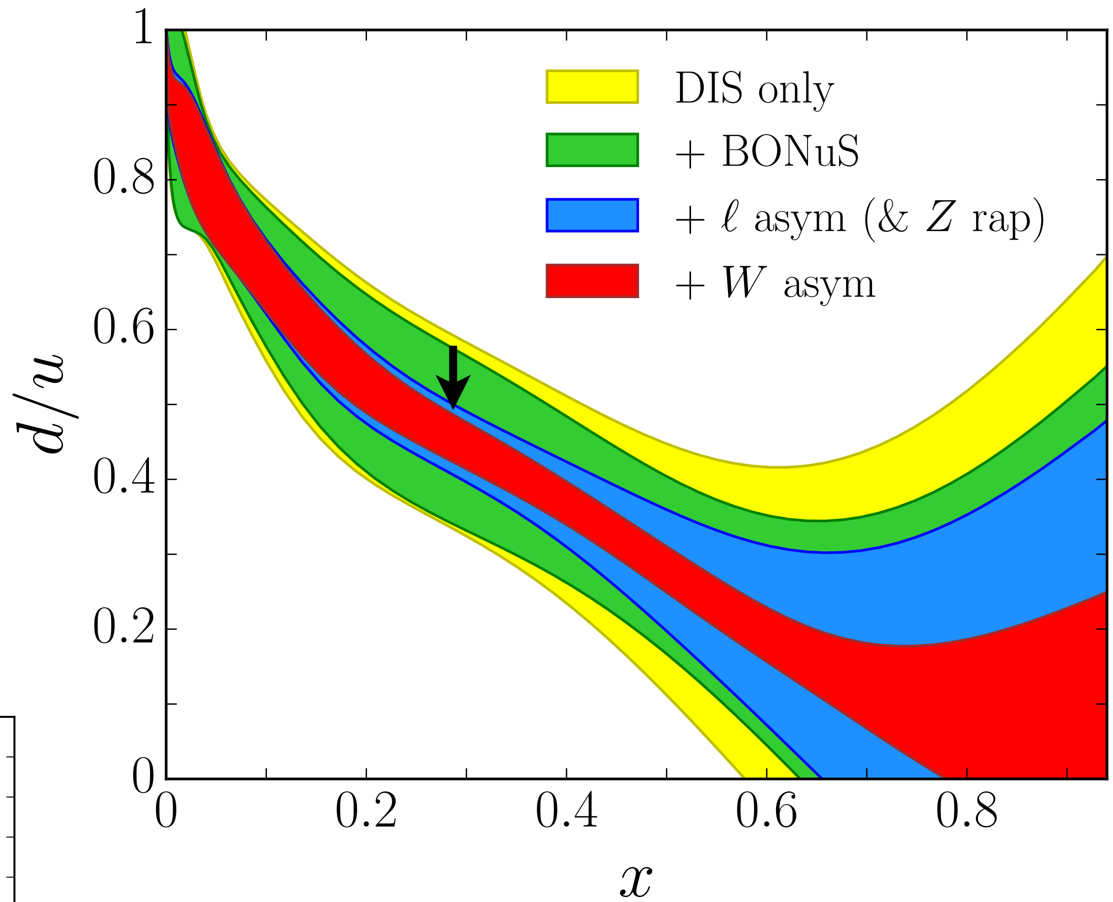

BONuS: spectator proton tagging in semi-inclusive *ed* DIS

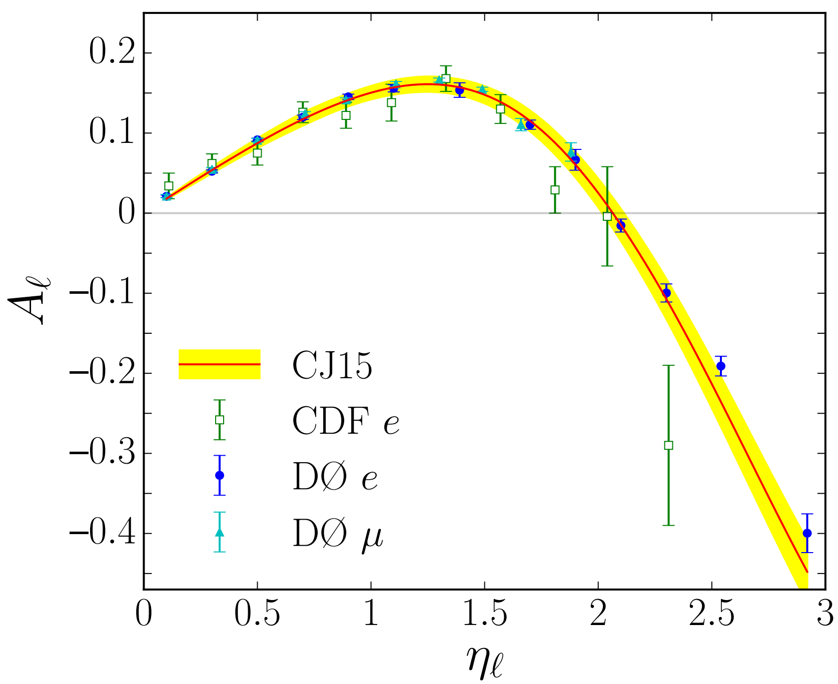



*Baillie et al.*
*PRL **108**, 142001 (2012)*

# Effect of data sets of $d/u$

- → new JLab (BONuS) data reduces error at $x \sim 0.6$
- → significant reduction from new DØ lepton asymmetry data
  (little effect from $Z$ rapidity data)



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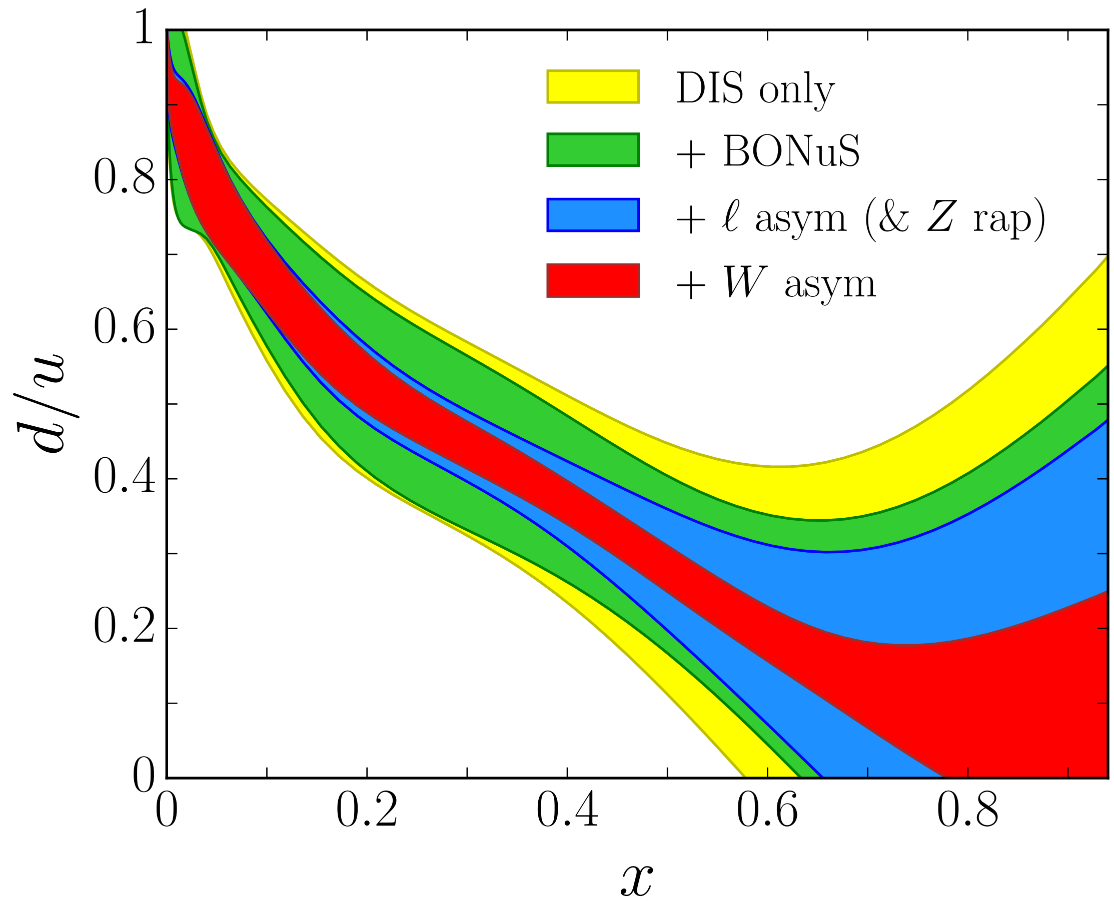


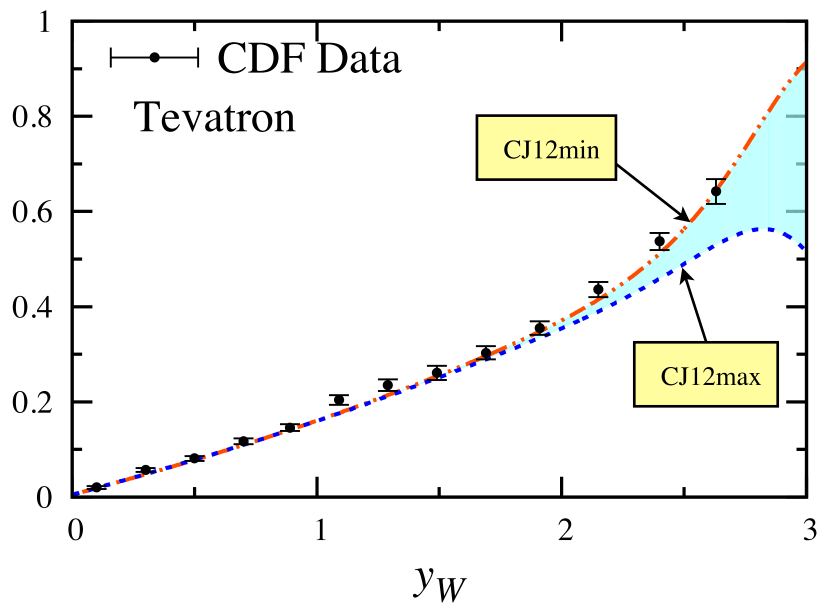


→ $W$ asymmetry at large $W$ rapidity more sensitive to $d/u$ at high $x$

→ earlier CDF data preferred smaller ("CJ12min") nuclear corrections

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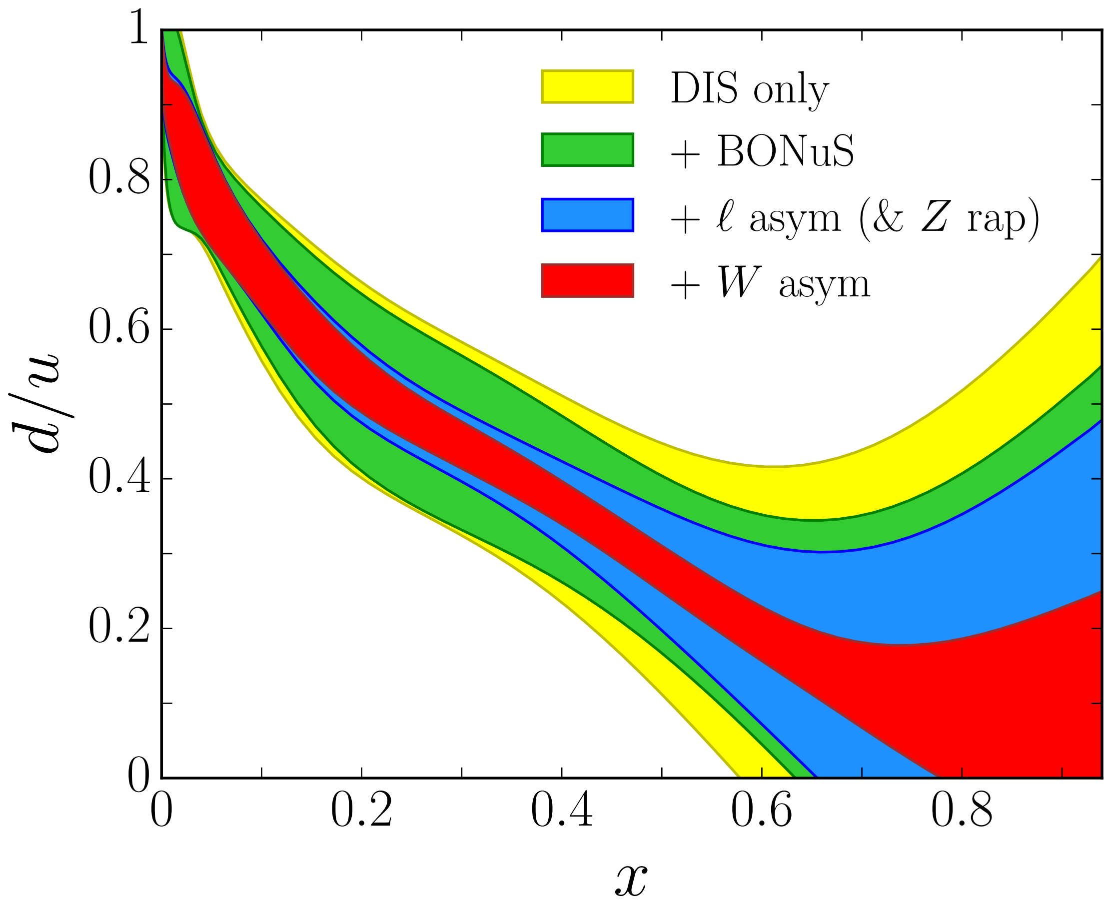


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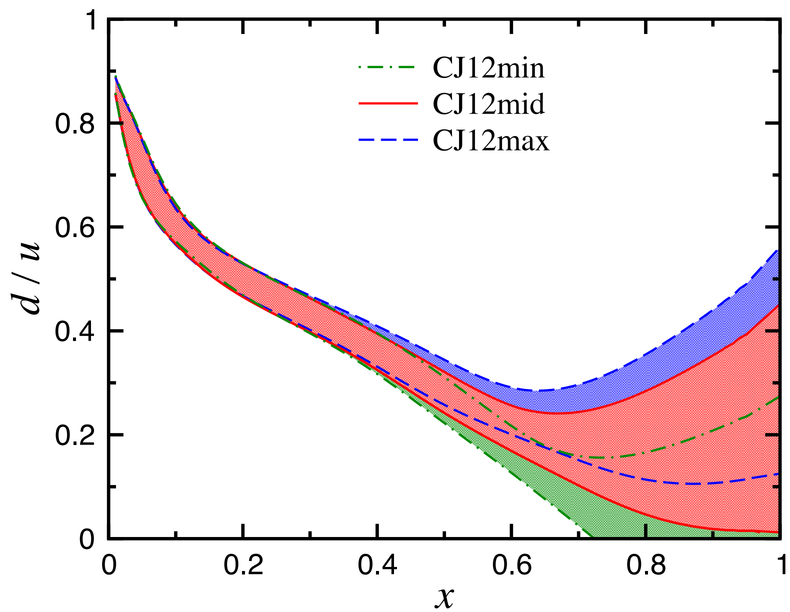

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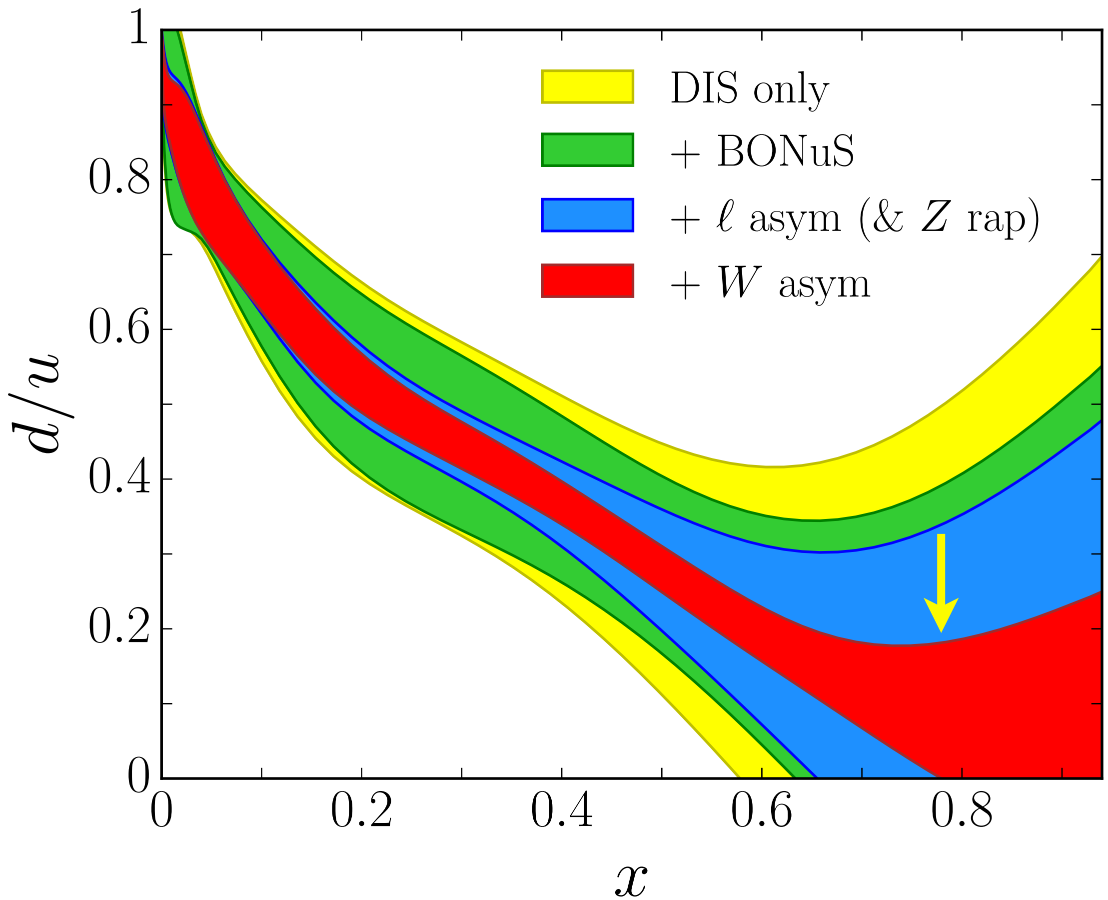
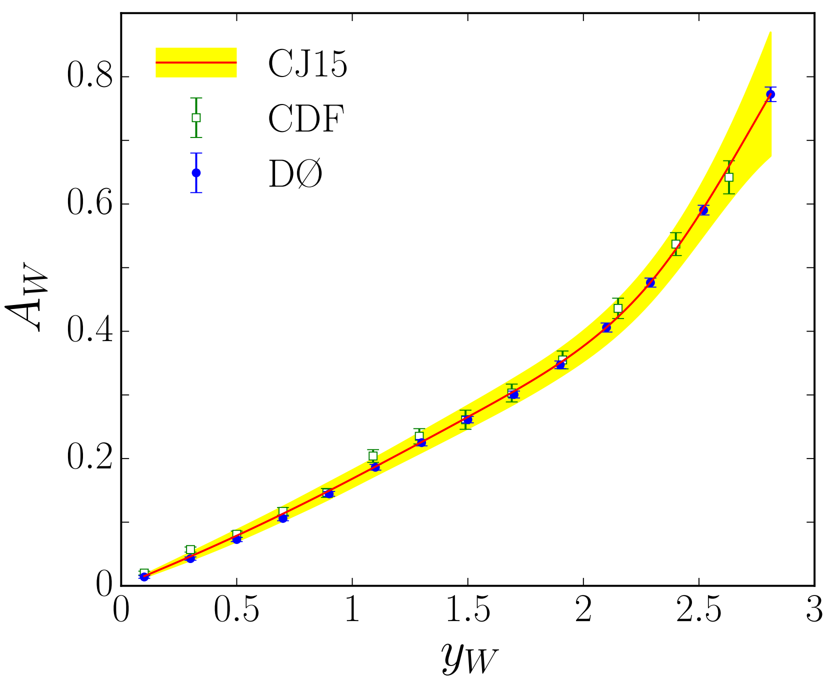


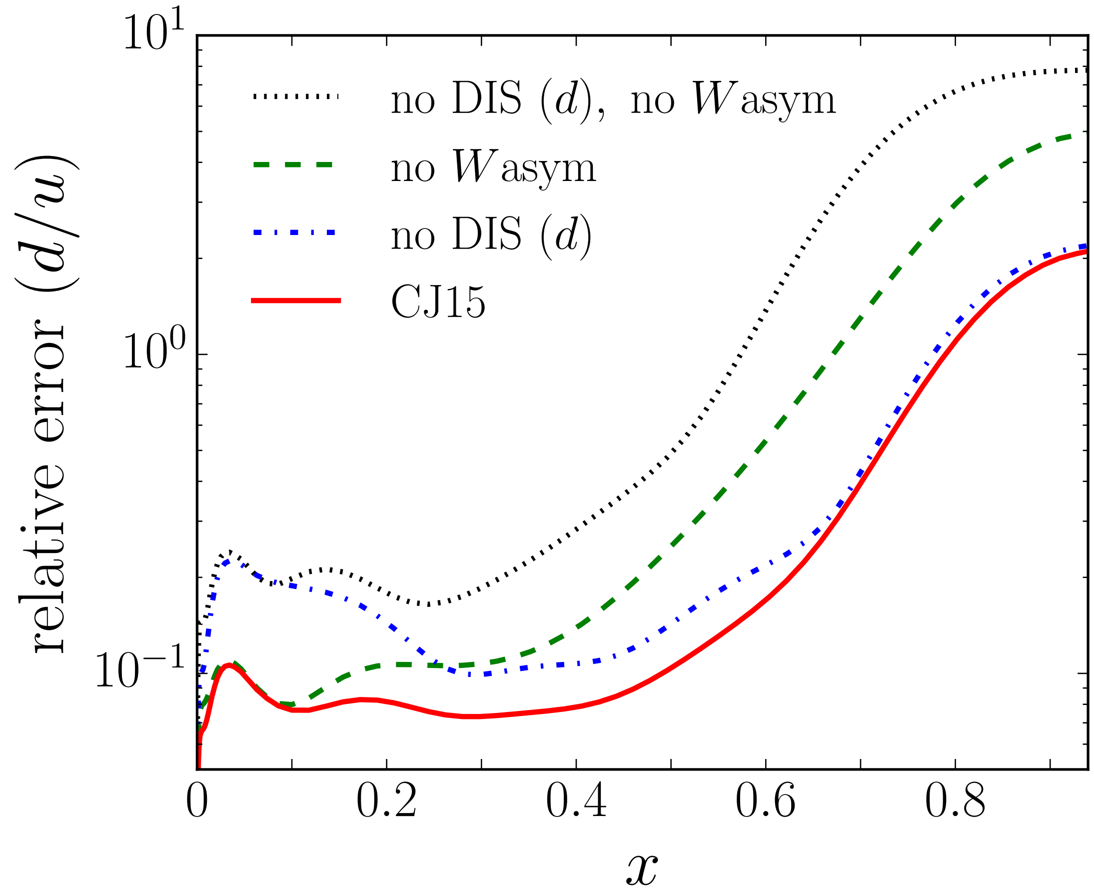

→ $W$ asymmetry at large $W$ rapidity more sensitive to $d/u$ at high $x$

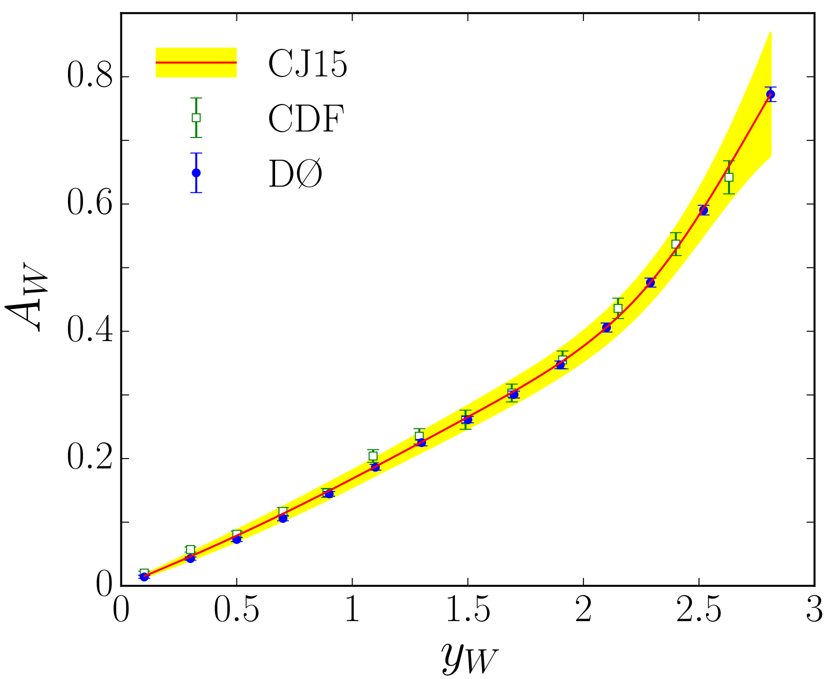
→ new DØ data reduce uncertainties at $x \sim 0.6 - 0.7$, strongly favor models with small (but nonzero) nuclear corrections

# Effect of data sets of $d/u$

→ new JLab (BONuS) data reduces error at $x \sim 0.6$

→ significant reduction from new DØ lepton asymmetry data
(little effect from $Z$ rapidity data)




→ $W$ asymmetry at large $W$ rapidity more sensitive to $d/u$ at high $x$

→ new DØ data reduce uncertainties at $x \sim 0.6 - 0.7$, strongly favor models with small (but nonzero) nuclear corrections

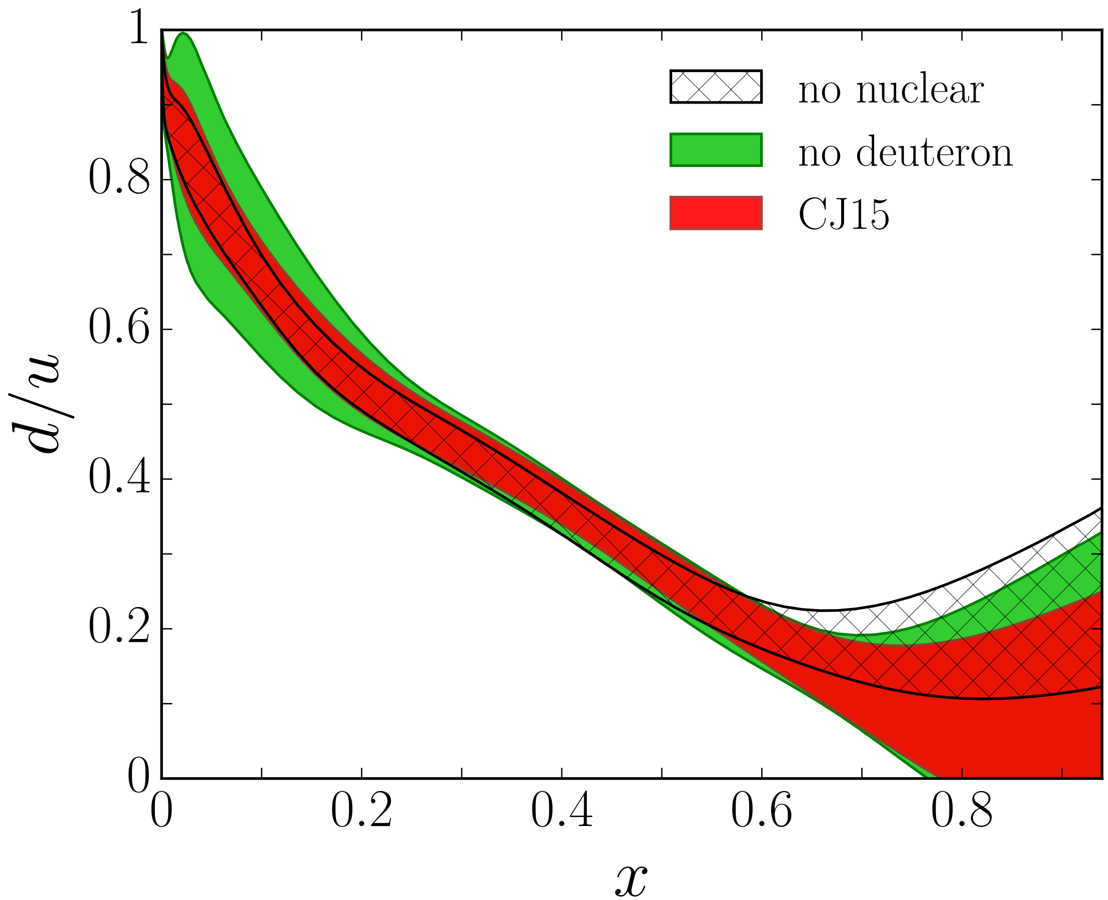
# Effect of data sets of $d/u$

→ deuterium data, and proper treatment of nuclear corrections, are important for *accuracy* and *precision* of $d/u$ determination at $x > 0.6$

→ using all available data, extrapolated ratio at $x = 1$ is (for $T$=10)

$$d/u \rightarrow 0.10 \pm 0.15$$

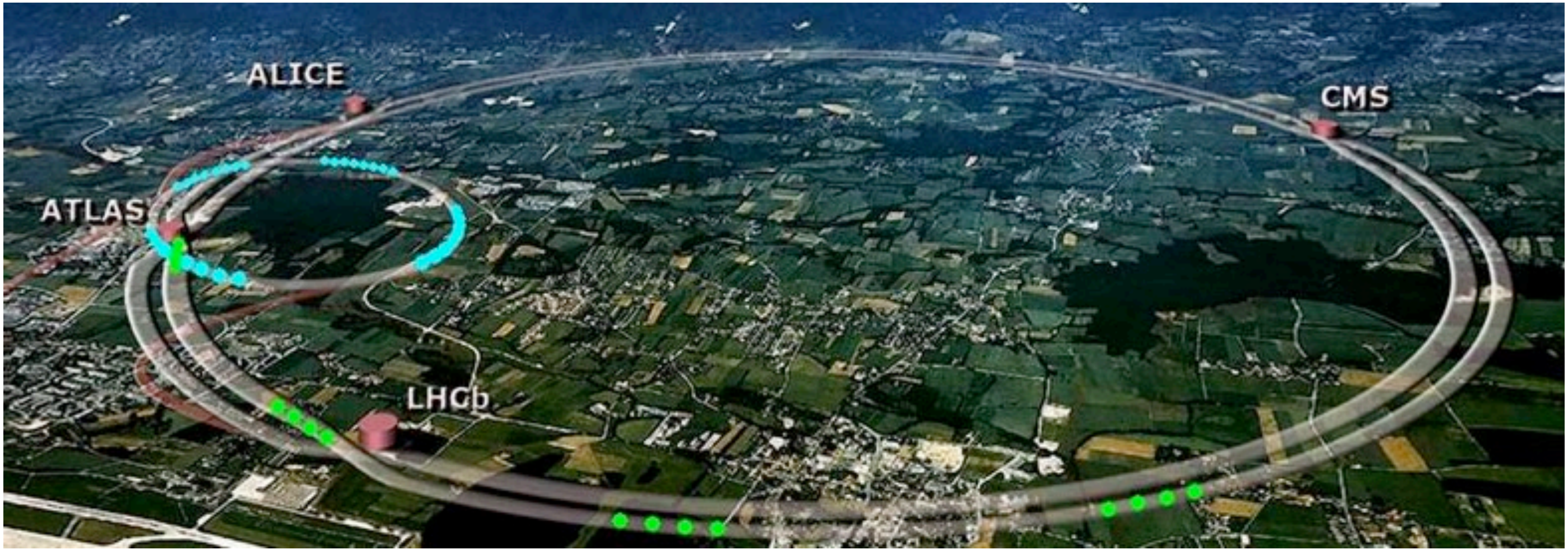
*cf.* $d/u \rightarrow 0.22 \pm 0.23$ in previous CJ12 analysis



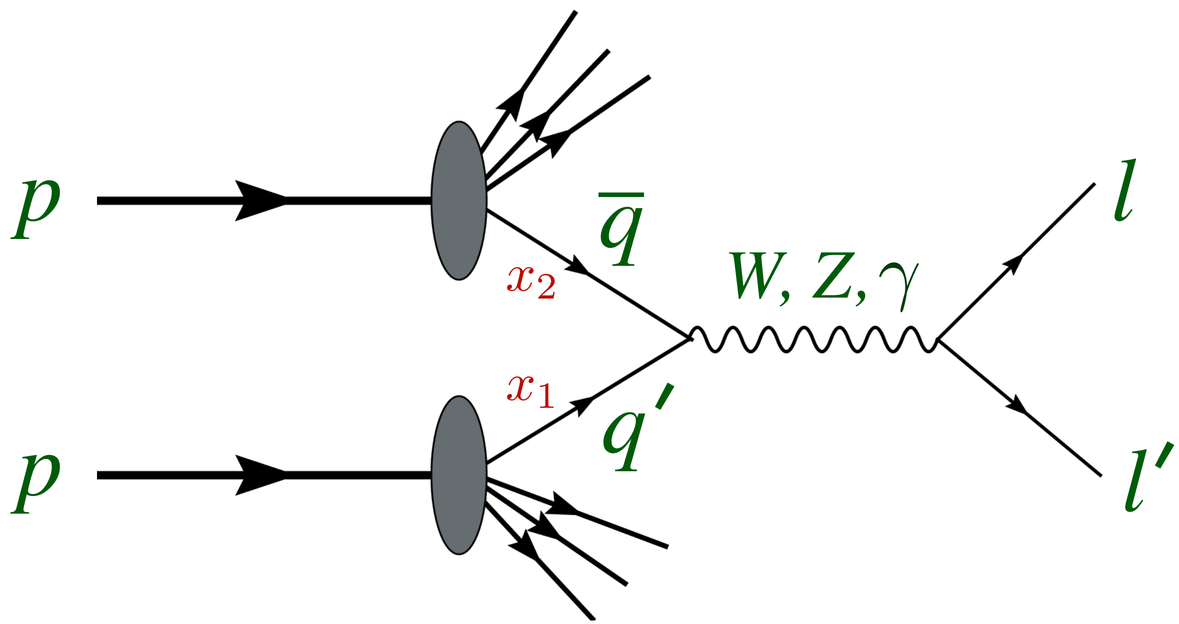

→ cannot yet distinguish between helicity & scalar diquark models

→ upcoming experiments at JLab will determine $d/u$ up to $x \sim 0.8$

# Implications for new particle searches




$e.g.$ heavy boson production



# Implications for new particle searches

- 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 $e.g.$ $\mathrm{E}_6$ *London, Rosner (1986)*

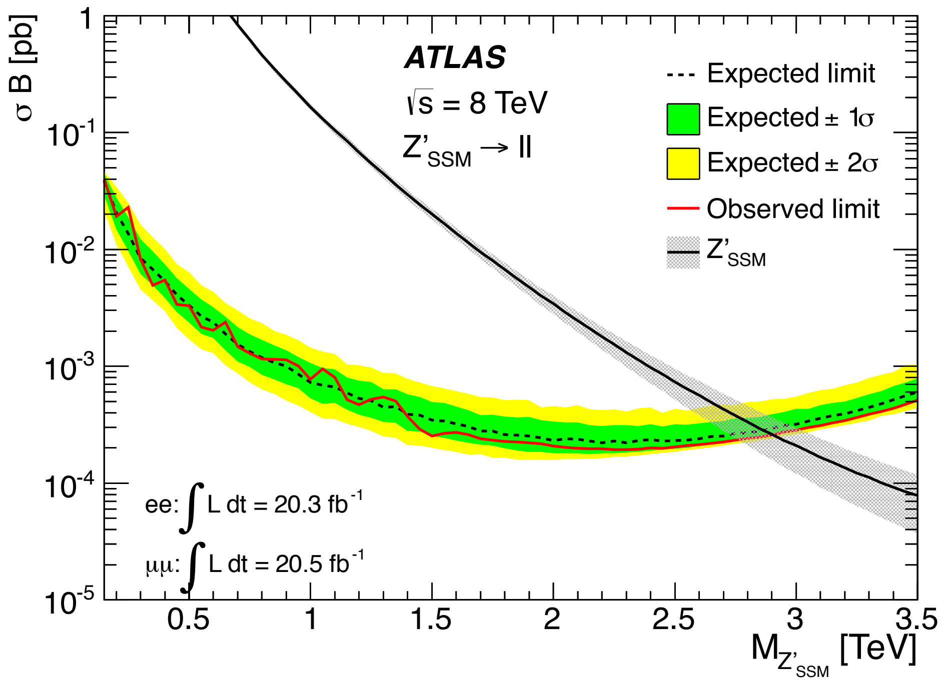
$$\mathrm{E}_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\chi \to \mathrm{SU}(5) \times \mathrm{U}(1)_\psi \times \mathrm{U}(1)_\chi$$

→ 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)*

# Implications for new particle searches

- Current limit on $Z'$ mass in dilepton production

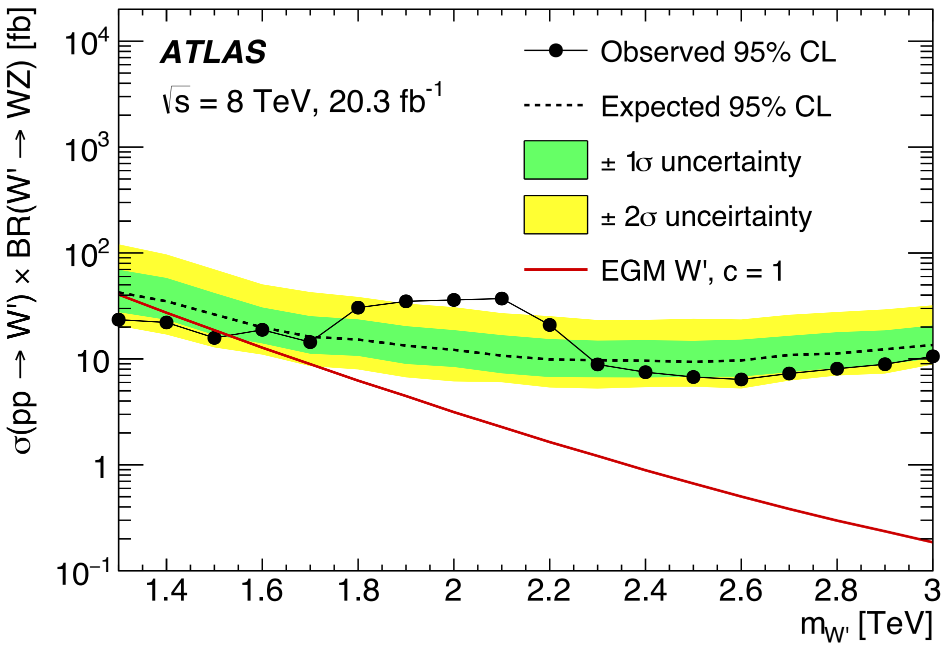



*ATLAS*
*PRD* ***90****, 052005 (2014)*

→ $M_{Z'} > 2.9\ \mathrm{TeV}$ in SSM (lower for other models)

# Implications for new particle searches

- Hint of signal in diboson $(W' \to WZ)$ channel?




*ATLAS*
*EPJC* ***72***, *2241 (2012)*

→ $3.4\ \sigma$ excess in $WZ$ channel at ~ $2$ TeV
($2.5\ \sigma$ in all $WW$, $WZ$, $ZZ$ channels)

→ extended gauge model (EGM) $W' \to WZ$
with mass < $1.5$ TeV excluded at 95% CL

# Implications for new particle searches

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

→ for $W'^{-}$ production, parton luminosity

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

→ since $x_{1,2} = (M_{W'}/\sqrt{s})\, e^{\pm y_{W'}}$, at large rapidity $y_{W'}$

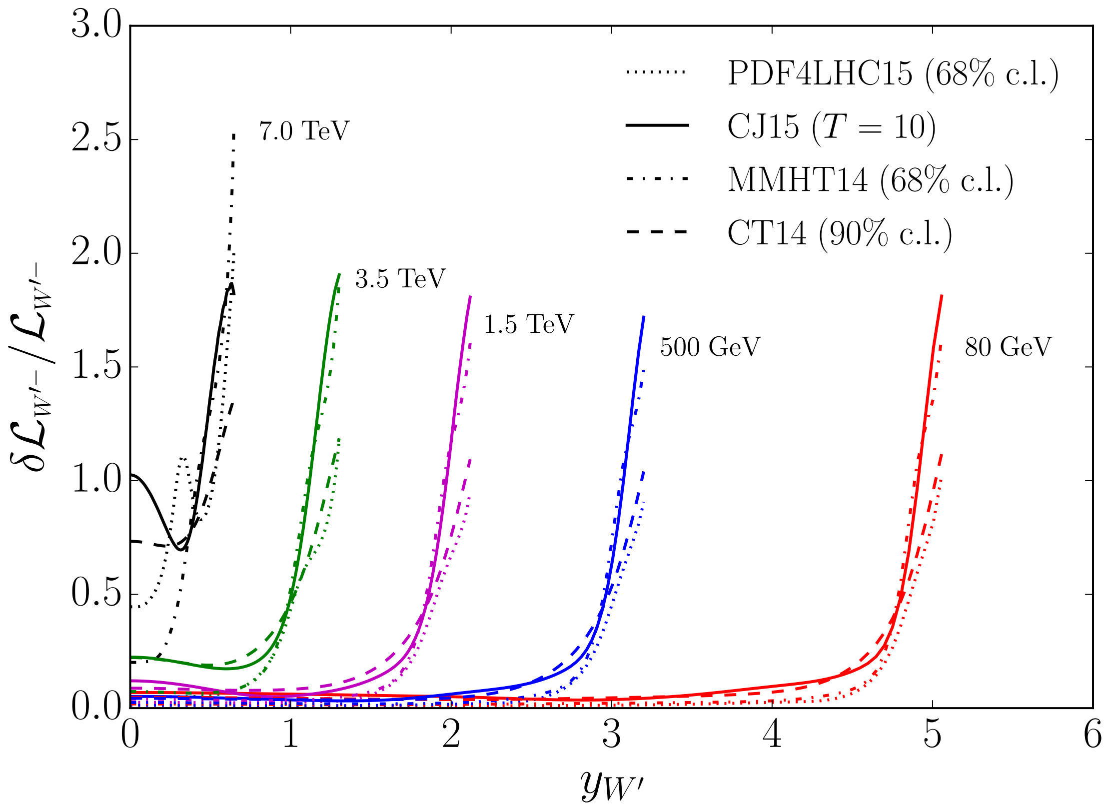
$$\mathcal{L}_{W'^{-}} \sim d(x_1)\bar{u}(x_2)$$

→ large-$x$ uncertainties scale with mass

# Implications for new particle searches

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

relative uncertainty in luminosity

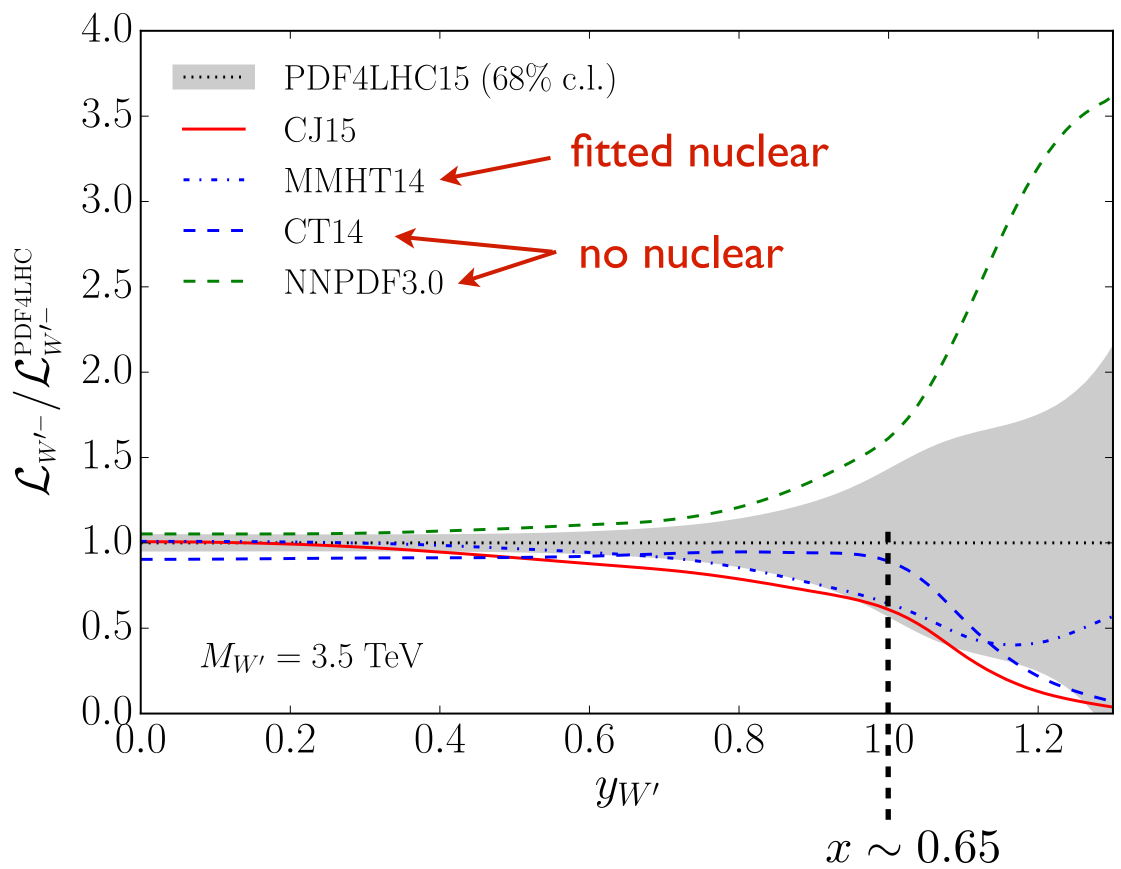



→ PDF uncertainty small at low $y_{W'}$, rises dramatically at large $y_{W'}$, for all $M_{W'}$

# Implications for new particle searches

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

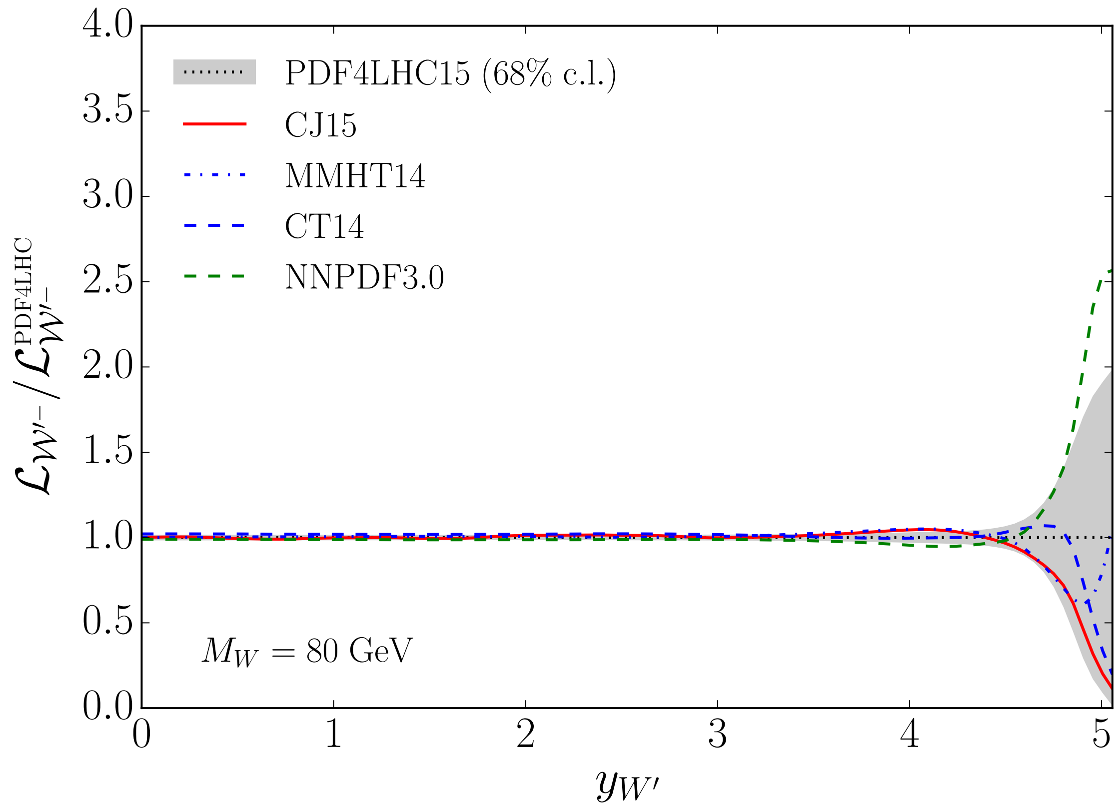
luminosity relative to “averaged” PDF set




→ PDFs that exclude low-$W$ data are unconstrained for $y_{W'} \approx 1$

# Implications for new particle searches

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



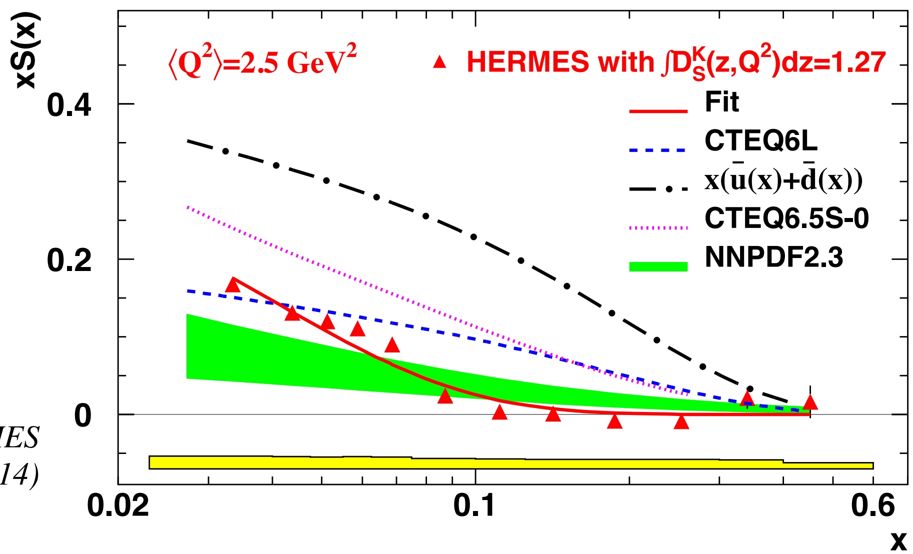

→ PDF uncertainty for SM $W$ restricted to very high $y_{W'}$

# Strange quark PDFs

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

→ significant uncertainty from nuclear corrections, semileptonic branching ratio uncertainty

→ tension with HERMES semi-inclusive $K$-production data




*HERMES*
*PRD* ***89****, 097101 (2014)*

historically, strange to nonstrange ratio

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

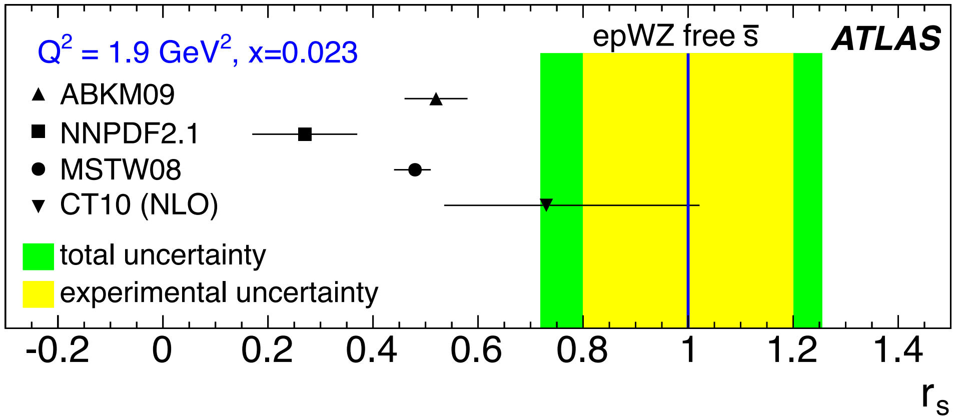
$$\sim \; 0.2 - 0.5$$

... but uncertainty from $K$ fragmentation functions

→ nuclear effects eliminated in $W$ production at LHC!

# Strange quark PDFs

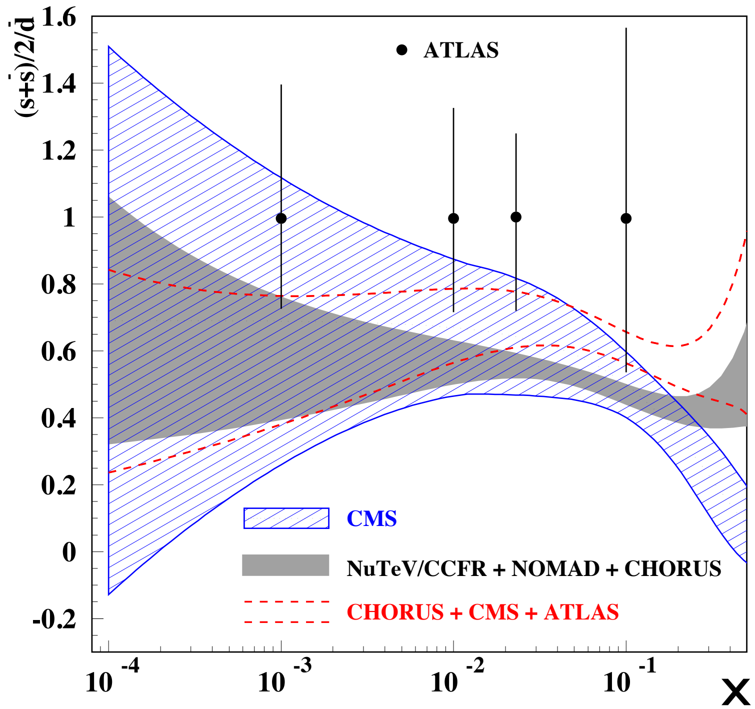
- Surprisingly larger than expected strangeness from ATLAS $pp \to W(Z) + X$ data at low $x$




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

*ATLAS, PRL **109**, 012001 (2012)*

- Recent global analysis including CHORUS & NOMAD data does not support enhanced strange PDF




*Alekhin et al., PRD **91**, 094002 (2015)*

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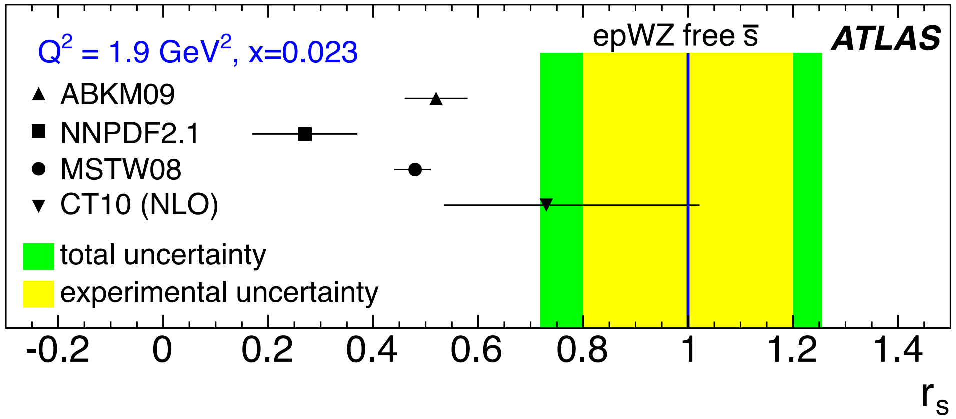
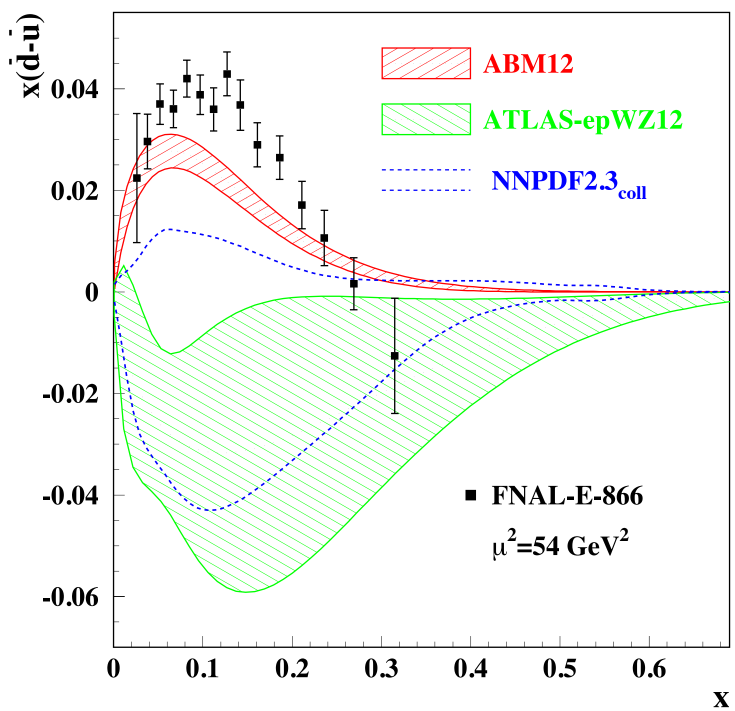



$$r_s = (s + \bar{s})/2\bar{d}$$
$$= 1.00^{+0.25}_{-0.28}$$

*ATLAS, PRL **109**, 012001 (2012)*

- Recent global analysis including CHORUS & NOMAD data does not support enhanced strange PDF

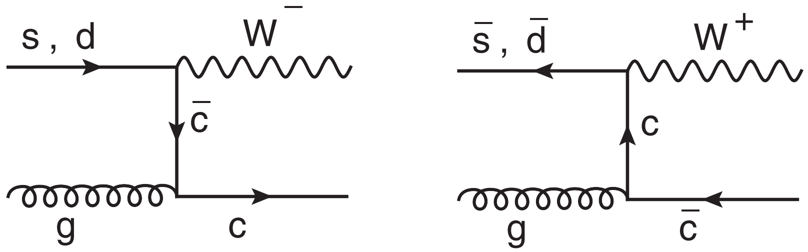
→ suggests effect related to underestimated $\bar{d}$ PDF
— collider data alone cannot (yet) disentangle flavors




*Alekhin et al., PRD **91**, 094002 (2015)*

# Strange quark PDFs

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



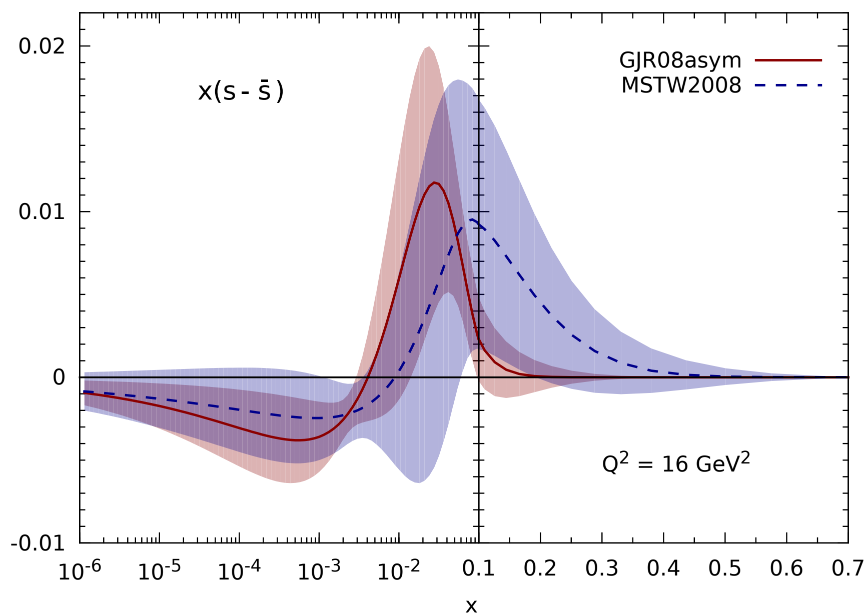

*CMS, JHEP* ***02****, 013 (2014)*
*ATLAS, JHEP* ***05****, 068 (2014)*

→ allow discrimination between $s$ and $\bar{s}$ !

- Strange−antistrange asymmetry predicted ~ 30 years ago from chiral SU(3) symmetry breaking

*Signal, Thomas, PLB* ***191****, 205 (1987)*

→ important indicator of nonperturbative physics, but empirically inconclusive




*Jimenez-Delgado et al., JPG* ***40****, 093102 (2013)*

# Strange quark PDFs

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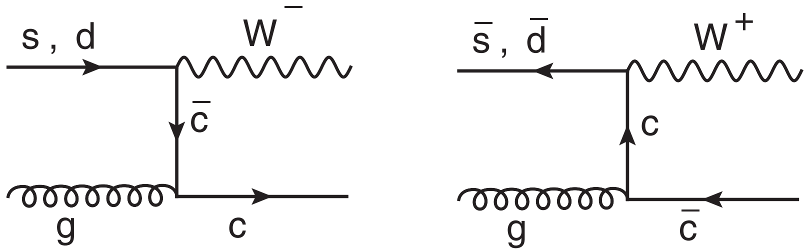


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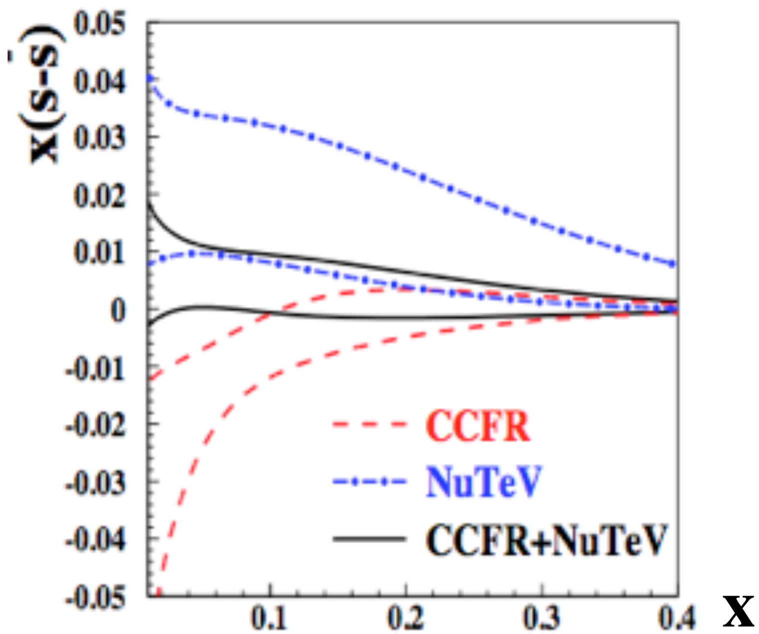
→ allow discrimination between $s$ and $\bar{s}$ !

- Strange−antistrange asymmetry predicted $\sim 30$ years ago from chiral $\mathrm{SU}(3)$ symmetry breaking

*Signal, Thomas, PLB* **191***, 205 (1987)*

→ NuTeV found

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




*Alekhin et al., PLB* **675***, 433 (2009)*

# Strange quark PDFs

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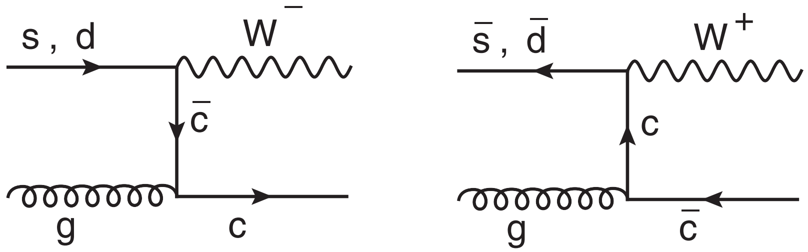


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*ATLAS, JHEP **05**, 068 (2014)*

→ allow discrimination between $s$ and $\bar{s}$ !

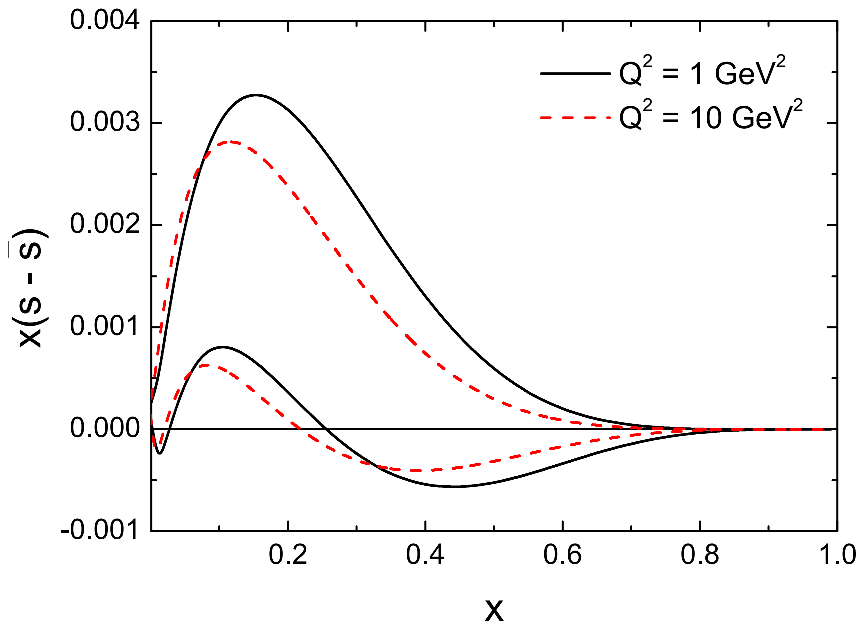
- Strange−antistrange asymmetry predicted ~ 30 years ago from chiral SU(3) symmetry breaking

*Signal, Thomas, PLB **191**, 205 (1987)*

→ ongoing Adelaide analysis

$$S^- \in [-0.1, 1.1] \times 10^{-3}$$

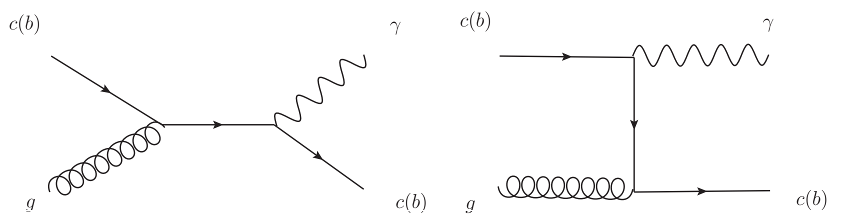
$\chi$EFT + phenomenology




*X. Wang et al. (2016)*

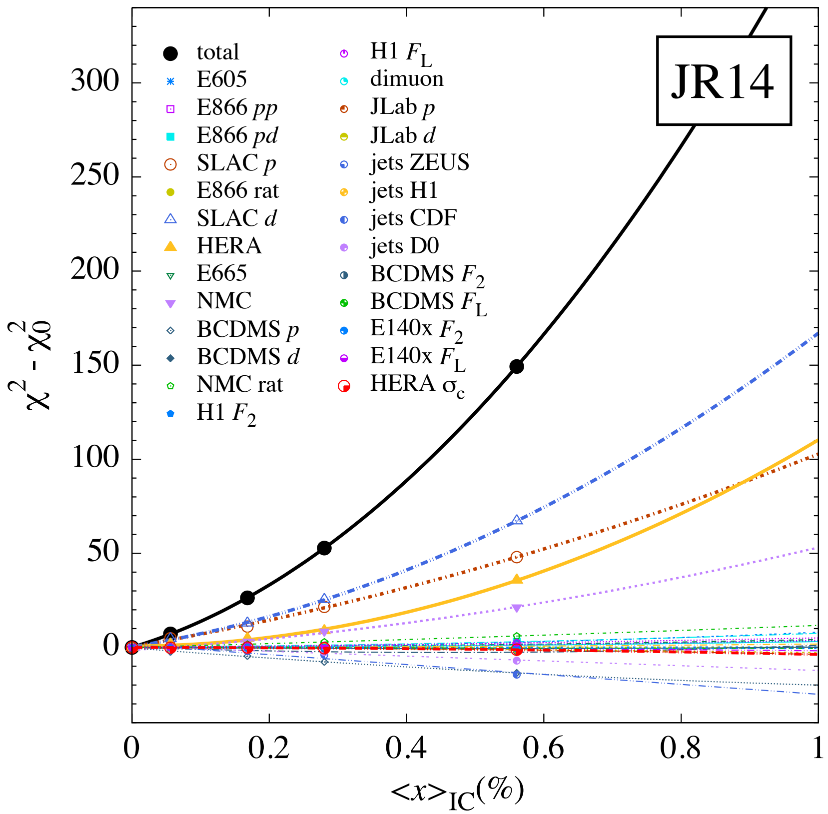
# Charm quark PDFs

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




*Bednyakov et al.*
*PLB **728**, 602 (2014)*

- Global analysis of full data set – no evidence for large "IC"



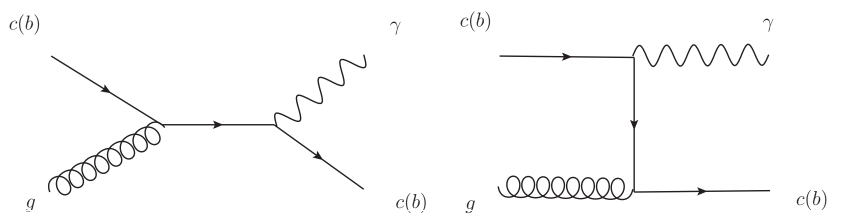

- momentum carried by "IC" $\langle x \rangle_{\rm IC} < 0.1\%$ at $5\sigma$ CL for $\Delta\chi^2 = 1$

- for $\Delta\chi^2 = 100$ (tolerance $T$=10) would have $\langle x \rangle_{\rm IC} \lesssim 0.4\%$

*Jimenez-Delgado et al.*
*PRL **114**, 082002 (2015)*

# Charm quark PDFs

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




*Bednyakov et al.*
*PLB* ***728****, 602 (2014)*

- Global analysis of full data set − no evidence for large "IC"

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

# New directions

- Standard fitting technology – perform single fit, assuming basic parametric form, with parameters obtained minimizing $\chi^2$, errors propagated using Hessian or Lagrange multiplier methods

  → some parameters may need fixing – introduces arbitrariness due to correlations, leading to overfitting

  → with imperfect data, will have many solutions with multiple local $\chi^2$ minima

  → experience can allow judicious choices for starting parameters to ensure stable fits, or tune # of free parameters to reduce # of solutions

  → strategy fails if data are scarce, or fitting new distributions with limited phenomenological information

# New directions

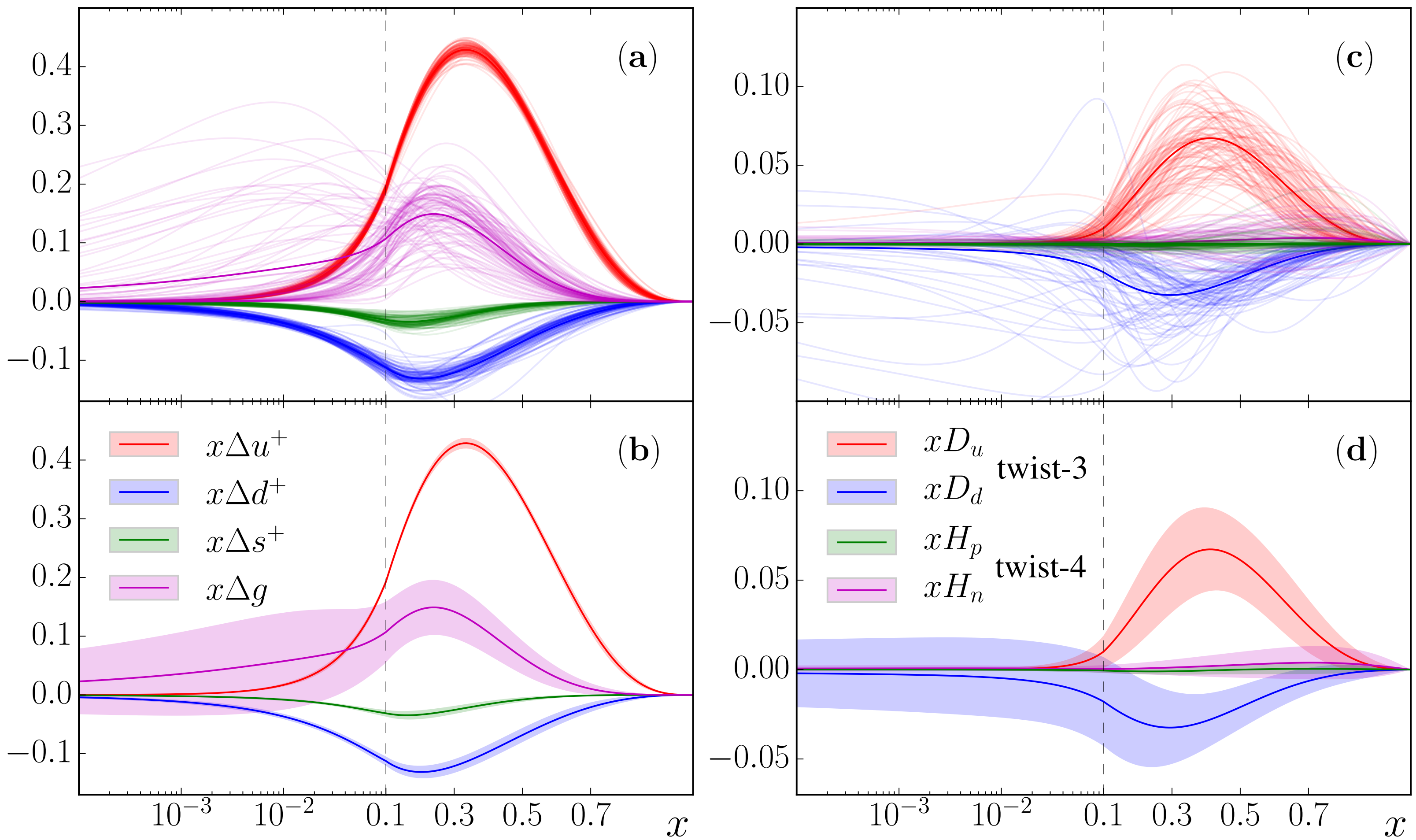
- Alternative strategy – “iterative Monte Carlo” (IMC) fitting
  - → retain basic parametric form, but maximally explore parameter space using MC sampling
  - → transform “priors” from initial flat MC sampling into “posteriors” for next iteration; repeat until convergence
  - → cross validation (random data partition) & bootstrap (resampling) avoids overfitting
  - → free of biases from guessing (or fixing) initial parameters
  - → gives statistically rigorous PDF uncertainties, without assumptions about “tolerance” or Gaussianity
  - → recently applied (for first time) to spin-PDF analysis (“JAM15”)

    *Nobuo Sato et al., arXiv:1601.07782 [hep-ph]*

# New directions

- Alternative strategy – "iterative Monte Carlo" (IMC) fitting

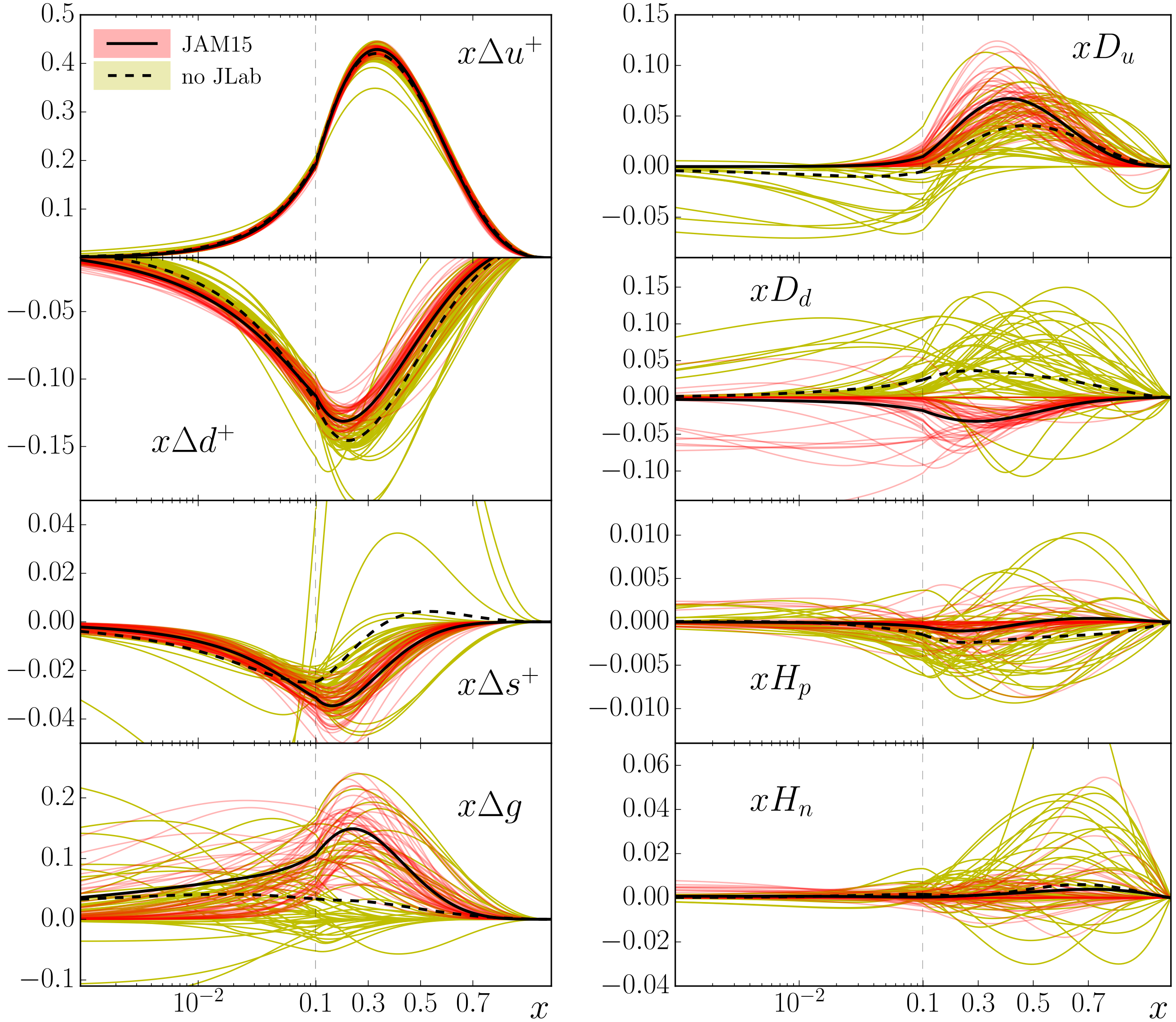
random sample of 100 from 8000 IMC fits



# New directions

- Alternative strategy – "iterative Monte Carlo" (IMC) fitting

random sample of 50 from 8000 IMC fits



# New directions

- Alternative strategy – "iterative Monte Carlo" (IMC) fitting

- Ultimate goal – apply IMC method to simultaneous fit of unpolarized and polarized PDFs, and fragmentation functions!

Happy 60th, Tony!