Pure Proton Data Questions
Light-Flavor Sea Antiquark Asymmetry

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PPP16 Workshop

In collaboration with USTC and CTEQ-TEA members

CTEQ – Tung et al. (TEA)
in memory of Prof. Wu-Ki Tung

References

arXiv:

2510.08941; 2505.17608; 2209.13143; 2202.13628;

2512.197789; 2512.23792 (CT25)

Talks:

DIS 2026 by Wenhao Ma;

Seminar at SJTU (China) by Siqi Yang;

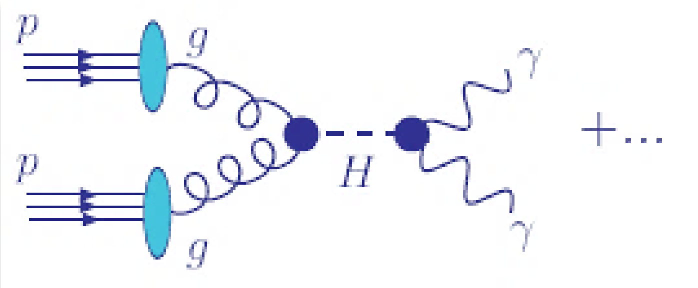
DIS 2026 by Pavel Nadolsky (CT25)

USTC group:

Liang Han, Minghui Liu, Wenhao Ma, MingZhe Xie, Siqi Yang

QCD Factorization Theorem and PDFs

$$\sigma_{pp\to H\to\gamma\gamma X}(Q) = \sum_{a,b=g,q,\bar{q}} \int_0^1 d\xi_a \int_0^1 d\xi_b \hat{\sigma}_{ab\to H\to\gamma\gamma}\left(\frac{x_a}{\xi_a}, \frac{x_b}{\xi_b}, \frac{Q}{\mu_R}, \frac{Q}{\mu_F}; \alpha_s(\mu_R)\right)$$
$$\times f_a(\xi_a,\mu_F) f_b(\xi_b,\mu_F) + O\left(\frac{\Lambda_{QCD}^2}{Q^2}\right)$$



$\hat{\sigma}$ is the hard cross section; computed order-by-order in $\alpha_s(\mu_R)$
$f_a(x,\mu_F)$ is the distribution for parton a with momentum fraction x, at scale μ_F

$$f_{a/h}(x,Q)$$

Unpolarized collinear parton distribution functions (PDFs) $f_{a/h}(x,Q)$ are associated with probabilities for finding a parton a with the "+" momentum xp^+ in a hadron h with the "+" momentum p^+ for $p^+ \to \infty$, at a resolution scale $Q > 1$ GeV .

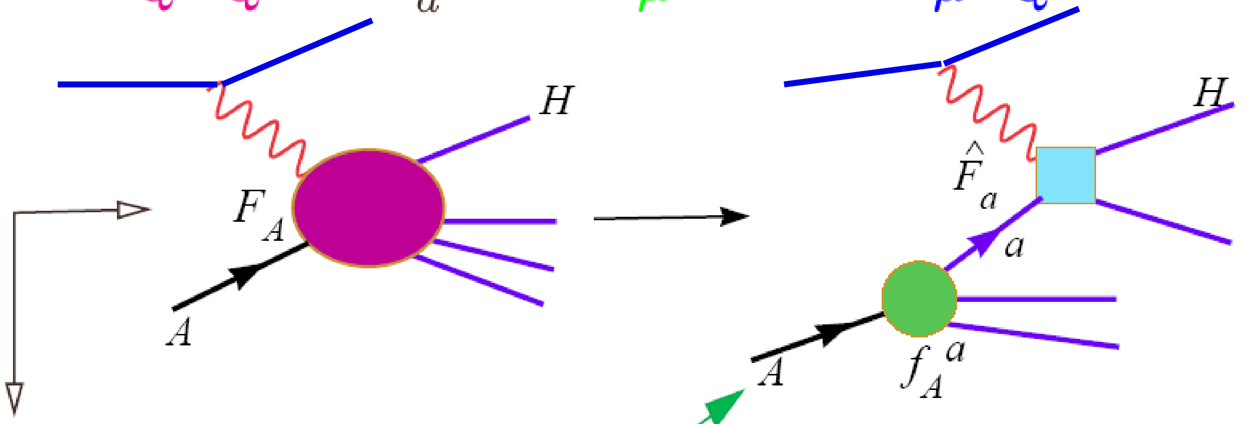
The (unpolarized) collinear PDFs describe long-distance dynamics of (single parton scattering) in high-energy collisions.

Lepton-hadron Sc.

C T E Q

Master Equation for QCD Parton Model – the Factorization Theorem

$$F_A^\lambda\left(x,\frac{m}{Q},\frac{M}{Q}\right) = \sum_a f_A^a\left(x,\frac{m}{\mu}\right) \otimes \hat{F}_a^\lambda\left(x,\frac{Q}{\mu},\frac{M}{Q}\right) + \mathcal{O}\left(\left(\frac{\Lambda}{Q}\right)^2\right)$$



Experimental Input

Theory Input

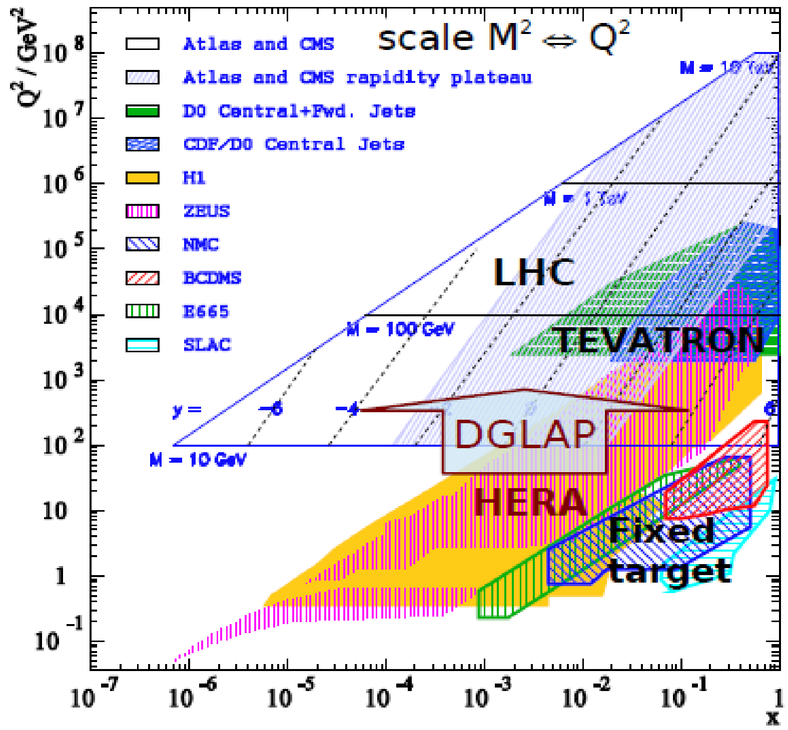
Hard Cross-section
perturbative, calculable
(may contain $\alpha_s^n \mathrm{Log}^n(M/Q)$)

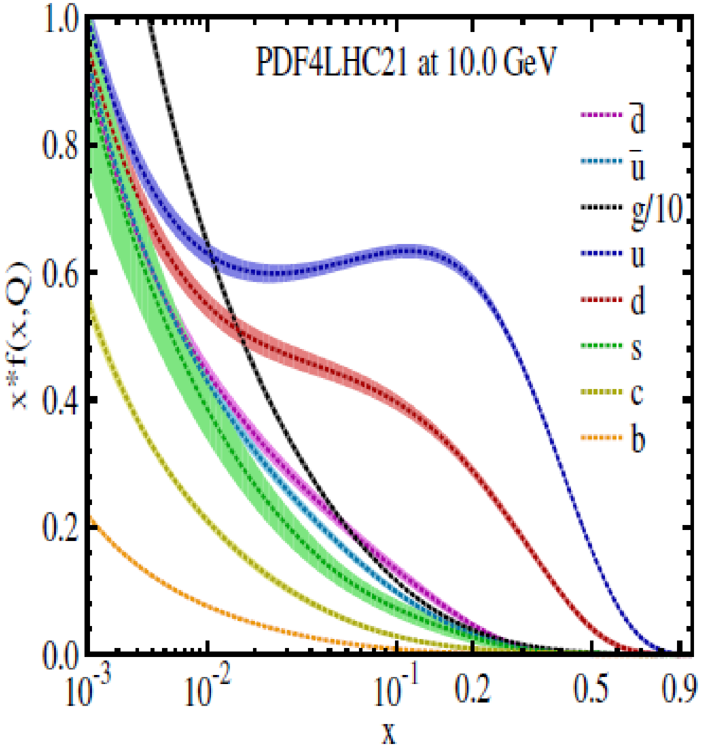
universal Parton Dist. Fn.
Non-Perturbative Parametrization at Q_0
DGLAP Evolution to Q

Extracted by global analysis

Global analysis of PDFs

- PDFs are usually extracted from global analysis on variety of data, e.g., DIS, Drell-Yan, jets and top quark productions at fixed-target and collider experiments, with increasing weight from LHC, together with SM QCD parameters [see 1709.04922, 1905.06957 for recent review articles]





parameter variations

$\alpha_S(M_Z)$

Mc, Mb, Mt

QCD/EW corrections

nuclear corrections

EW parameters

New Physics

- diversity of the analysed data are important to ensure flavor separation and to avoid theoretical/experimental bias; possible extensions to include EW parameters and possible new physics for a self-consistent determination

- alternative approach from lattice QCD simulations, for various PDF moments or PDFs directly calculated in x-space with large momentum effective theory or pseudo-PDFs [2004.03543]

Global QCD analysis for PDFs

CTEQ

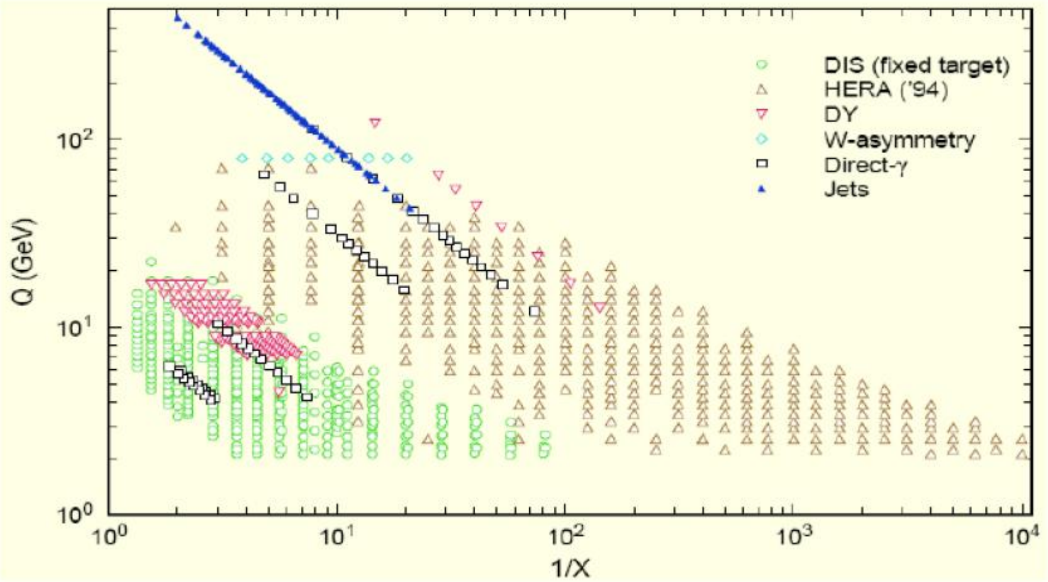
Input DPFs at Q_0

$\varphi_{f/h}\left(x,\{a_j\}\right)$

Vary $\{a_j\}$

Minimize Chi²

DGLAP



$\varphi_{f/h}(x)$ at $Q>Q_0$

QCD calculation

Comparison with Data at various x and Q

Procedure: Iterate to find the best set of $\{a_j\}$ for the input DPFs

CT18 NNLO high-energy neutrino-nucleon DIS cross sections from 10^2 to 10^7 GeV

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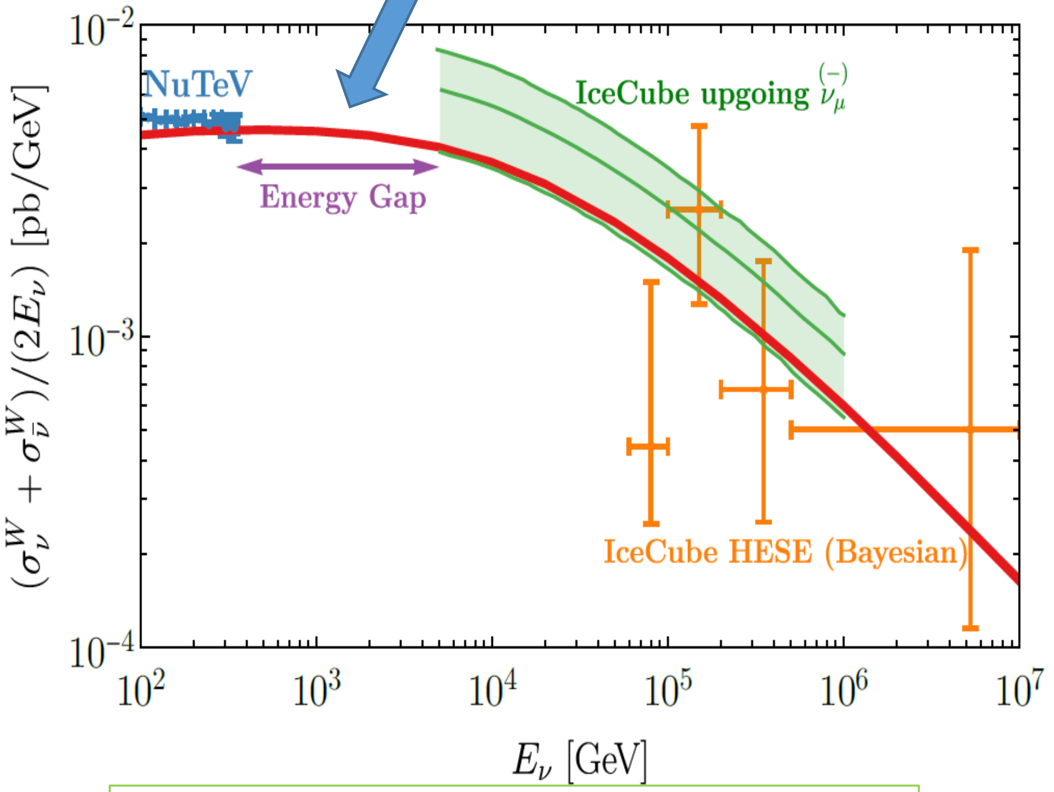
arXiv:2303.13607

To be filled by FASER measurement at the LHC

We published the first GM NNLO calculation for charged current DIS processes in arXiv:2107.00460, which is needed for

- DUNE (Deep underground neutrino exp)
- EIC (Electron-Ion Collider)
- IceCube Neutrino Observatory
- FASER (Forward search exp at the LHC; the first observation of collider neutrino events)

arXiv:2303.14185



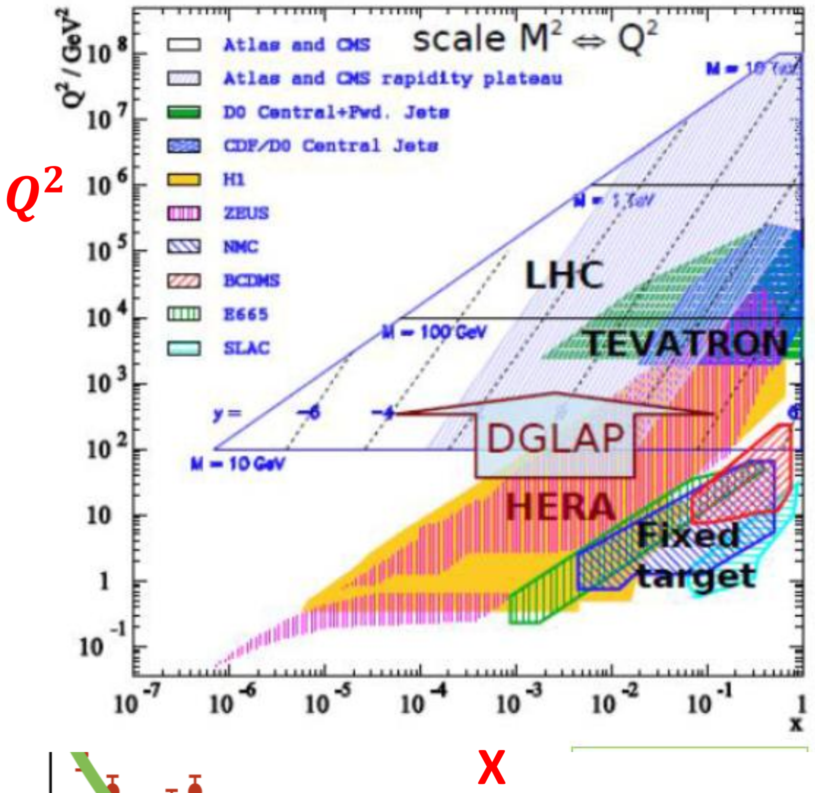
At low E_ν the contributions from quasi-elastic (QE) scattering and resonance (RES) production are important, and not included in this comparison.

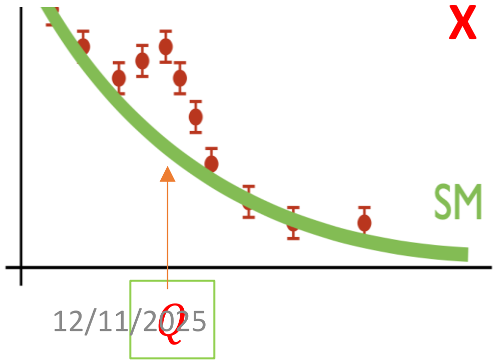
Future data can further constrain PDFs.

(See talk by Keping Xie, Pheno23)

Some basics about PDFs: relevant kinematics in (x, Q^2)

C T E Q





$$\sigma(Q) \simeq \sum_{i,j} f_{i/p}(x_1, Q) \otimes f_{j/p}(x_2, Q) \otimes \hat{\sigma}_{ij}(x_1, x_2; Q)$$

- Parton Distribution Function $f(x, Q)$
- Given a heavy resonance with mass Q produced at hadron collider with c.m. energy $\sqrt{S}$
- What's the typical x value?

$$<x> = \frac{Q}{\sqrt{S}}$$ at central rapidity (y=0)

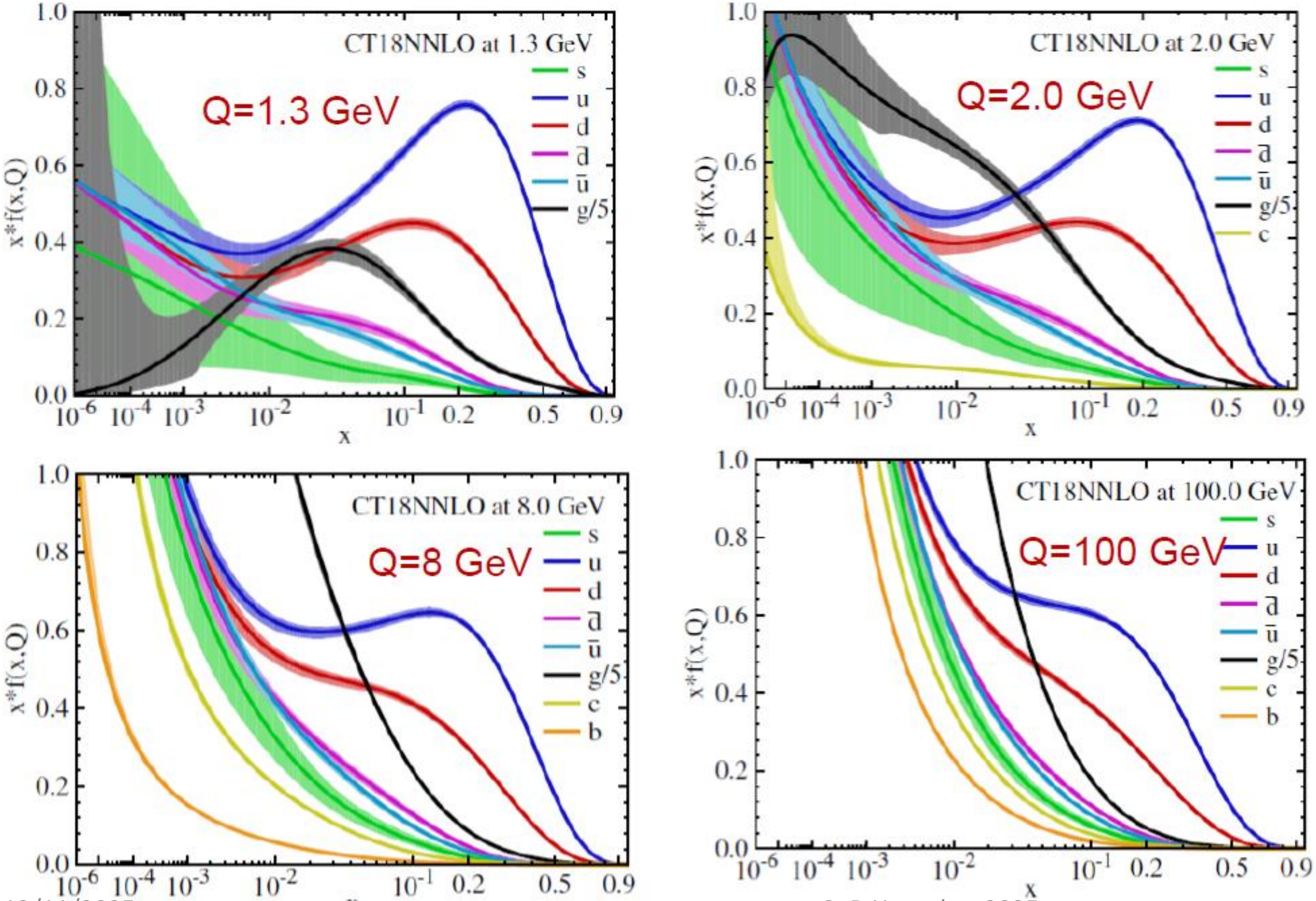
- Generally, $x_1 = \frac{Q}{\sqrt{S}} e^{y}$ and $x_2 = \frac{Q}{\sqrt{S}} e^{-y}$

$$x_1 + x_2 = 2\frac{Q}{\sqrt{S}}\cosh(y) \Rightarrow y_{max} : x_1 + x_2 = 1$$

PDF uncertainties vary as Q via DGLAP evolution

arXiv: 1912.10053

CT18 NNLO PDFs



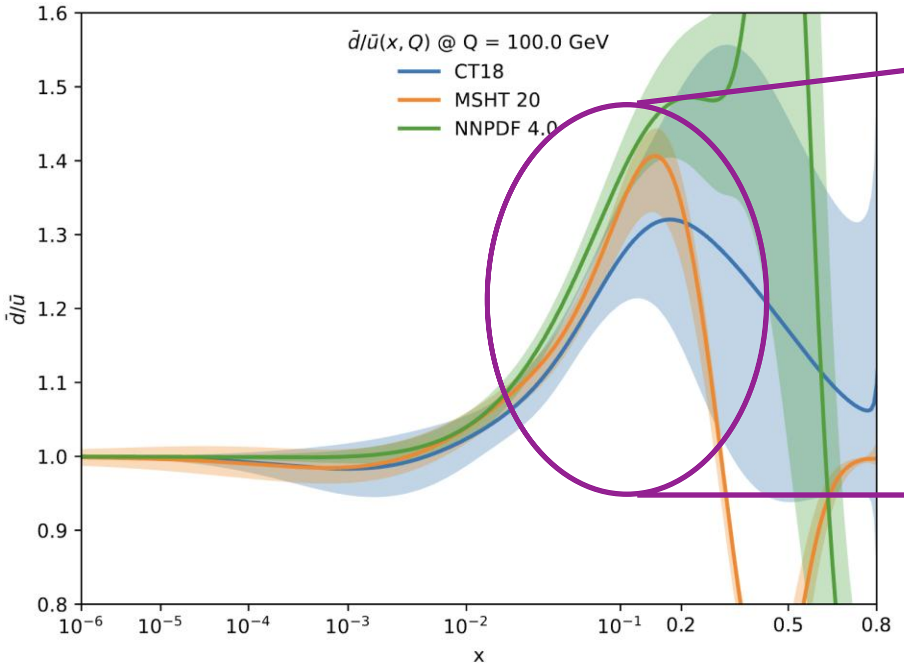
- ➢ Faster DGLAP evolution at low Q values.
- ➢ Smaller PDF error bands at higher Q values.
- ➢ At high Q, perturbaive contribution becomes more important than the non-perturbative part of PDF.

Relatively low energy data, such as HERA I+II, remain crucial for PDF global analysis.

SU(2) Flavor Asymmetry of Light antiquarks: $\bar{u}$ and $\bar{d}$

CTEQ

- Perturbative mechanism (gluon splitting): $\bar{d}(x) \simeq \bar{u}(x)$, with higher order corrections in QCD
- Non-perturbative mechanism: SU(2) flavor asymmetry $\bar{d}(x) \neq \bar{u}(x)$, much larger than pQCD contributions



$\bar{d}/\bar{u}$ ratio in moderon PDF global analyses

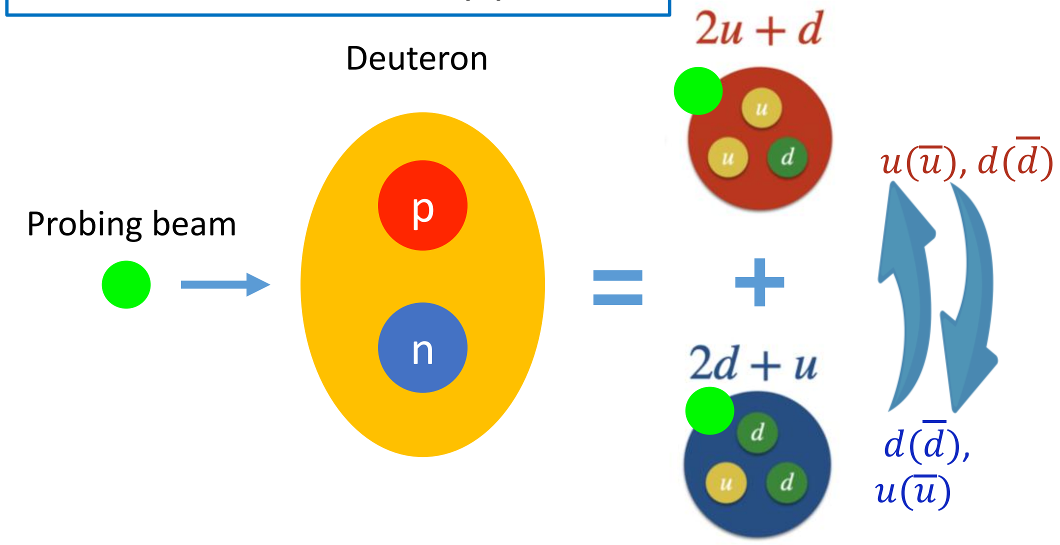
In the past decades, the ratio of $\bar{d}/\bar{u}$ in the proton is determined to have a rising-up structure at $x \sim 0.1$, known as the SU(2) flavor asymmetry, which becomes an important evidence of non-perturbative mechanism of the generation of light quarks

SU(2) Flavor Asymmetry of Light antiquarks: $\overline{u}$ and $\overline{d}$

The only constraint comes from high energy deuteron measurements

- Pure proton interactions: ideal way, but very difficult, since $\overline{d}$ and $\overline{u}$ contributions are indistinguishable in inclusive experimental observables
- Deuteron data: currently, the only data providing direct constraint on $\bar{d}/\bar{u}$.

Conventional two-body picture:



In the past, $\overline{d}/\overline{u}$ was determined by comparing the deuteron-interaction to the proton-interaction under same kinematic configuration, based on two important assumptions:

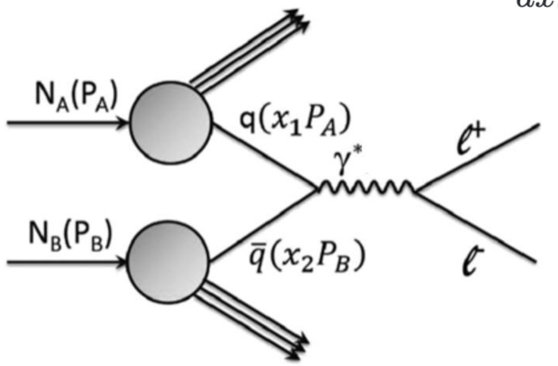
i. the classic deuteron structure picture: $\sigma(D) = \sigma(p) + \sigma(n)$ + "small deuteromn nuclear corrections"

ii. the proton-neutron isospin symmetry: $u_n(\overline{u}_n) = d_p(\overline{d}_p)$, $d_n(\overline{d}_n) = u_p(\overline{u}_p)$

NuSea and SeaQuest experiments

Drell-Yan process with deuteron target

➢ Proton-deuteron interaction vs. proton-proton interaction



$$\frac{d^2\sigma}{dx_b\,dx_t} = \frac{4\,\pi\,\alpha^2}{9\,s\,x_b\,x_t} \sum_q e_q^2 \left[q(x_b)\bar{q}(x_t) + \bar{q}(x_b)q(x_t)\right]$$

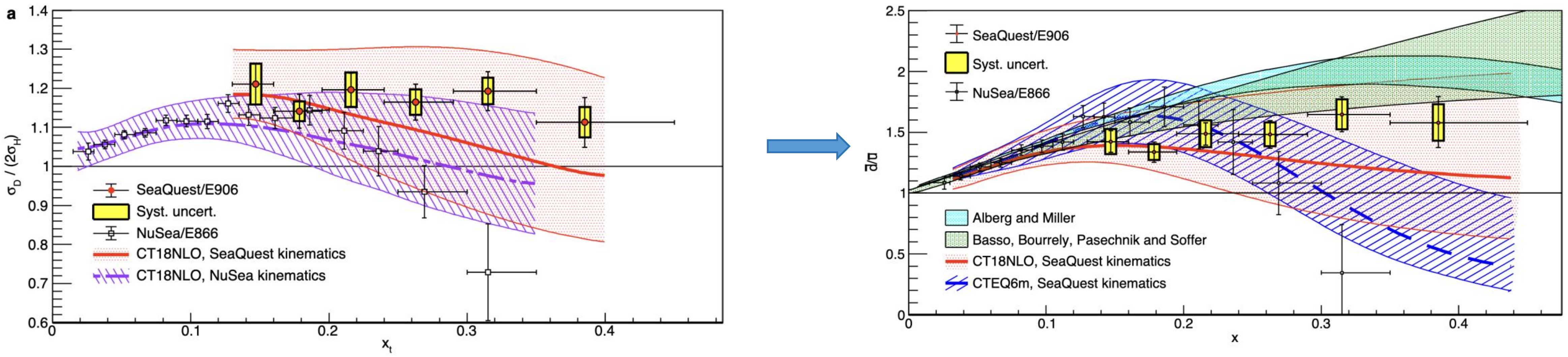
$$\begin{aligned}
\frac{\sigma_{pD}}{\sigma_{pp}} &= \frac{\sigma_{pp}+\sigma_{pn}}{\sigma_{pp}} = 1 + \frac{\sigma_{pn}}{\sigma_{pp}} \\
&\approx 1 + \frac{4u_p\bar{u}_n + d_p\bar{d}_n}{4u_p\bar{u}_p + d_p\bar{d}_p} = 1 + \frac{4u_p\bar{d}_p + d_p\bar{u}_p}{4u_p\bar{u}_p + d_p\bar{d}_p} \\
&= 1 + \frac{\frac{\bar{d}_p}{\bar{u}_p} + \frac{d_p}{(4u_p)}}{1 + \frac{d_p}{4u_p}\frac{\bar{d}_p}{\bar{u}_p}} \approx 1 + \frac{\bar{d}_p}{\bar{u}_p}
\end{aligned}$$

- High energy proton beam and stationary target → Anti-quarks come from target
- Target side: dominated by ($\bar{u}$ and $\bar{d}$) at $x_2 \sim \mathcal{O}(0.1)$ → s, c, b, g contributions suppressed
- Beam side: dominated by (u and d) valence quarks at $x_1 \geq 0.3$, and d is suppressed than u due to γ-exchanged → Detection at beam forward direction

NuSea/SeaQuest experimental results

Higher deuteron cross section

- The deuteron cross section is observed to be much higher
- Interpreted as SU(2) flavor asymmetry

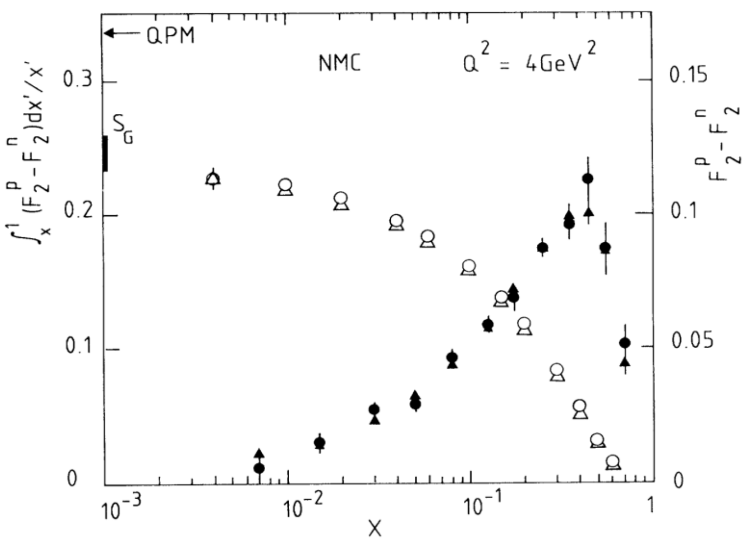


Nature Vol 590, 561-565, 2021

Other experimental results

Consistent conclusion from other deuteron measurements

➢ NMC inclusive DIS



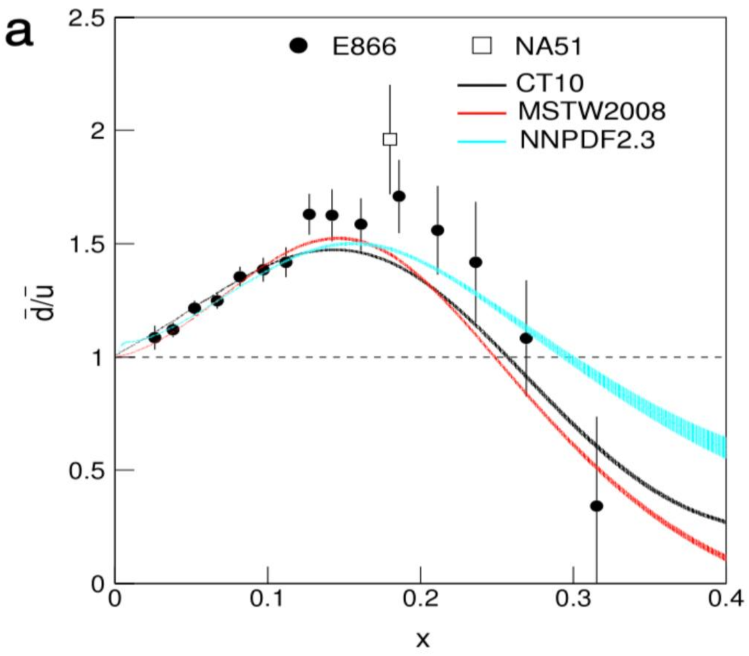
$$\int_0^1 dx\,[\bar{d}(x) - \bar{u}(x)] = 0.147 \pm 0.039$$

Muon 90-280GeV on H2/D2 targets

@ CERN SPS

Phys. Rev. Lett. 66 (1991) 2712

➢ NA51 Drell-Yan process

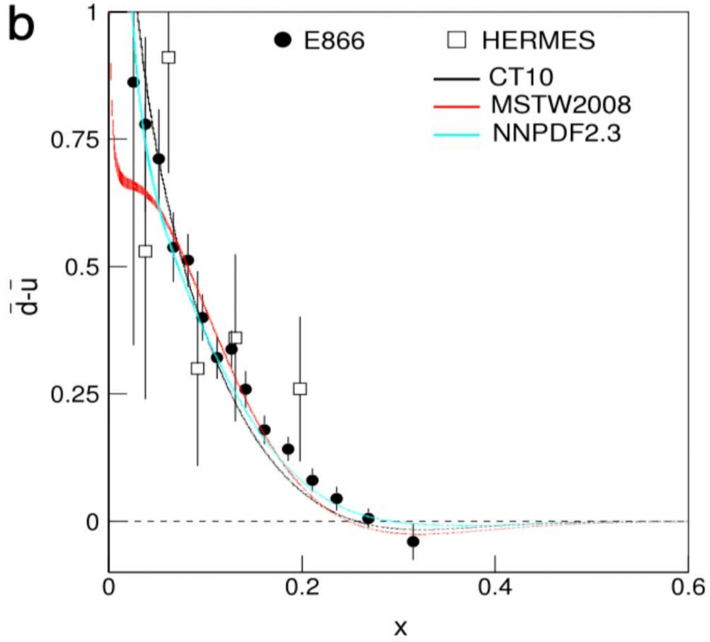


Proton 450GeV on H2/D2 targets

@ CERN SPS

Phys. Lett. B 332 (1994) 244

➢ HERMES semi-inclusive DIS



Positron 27.5GeV on H2/D2 targets

@ DESY HERA

Phys. Lett. B 81 (1998) 5519

Deuteron data provide the only direct constraint on $\bar{d}/\bar{u}$ at $x \sim 0.1$ in existing PDF global analysis

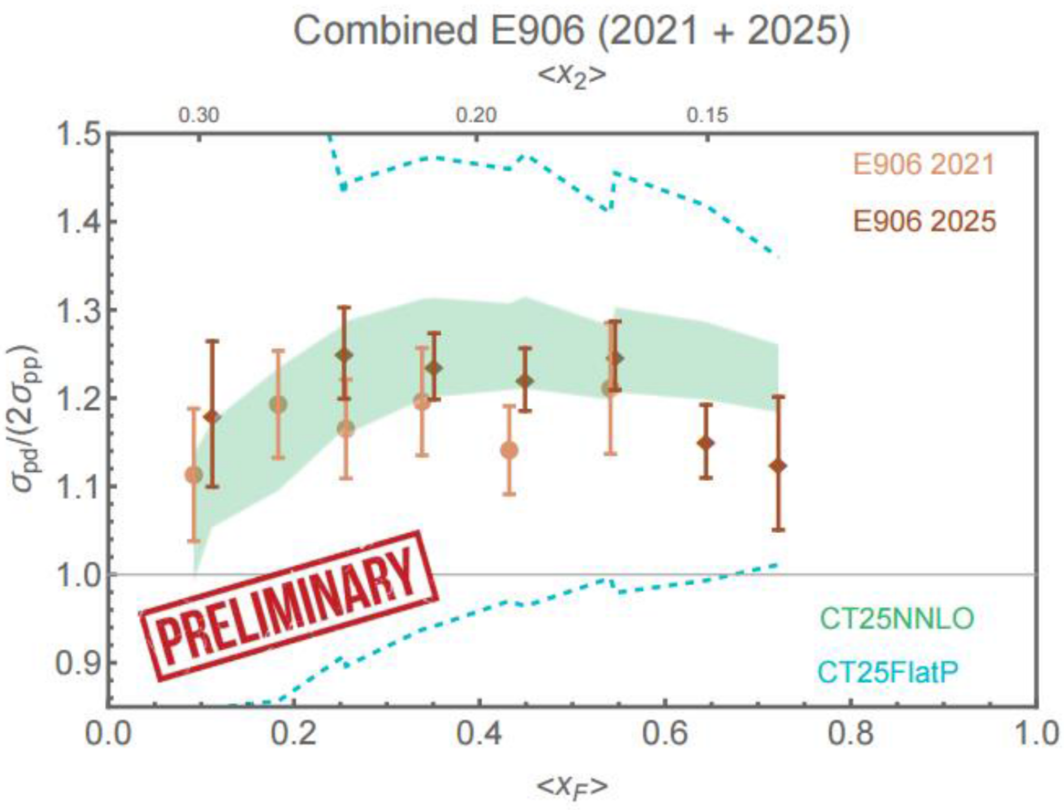
CTEQ

CT25FlatP fit: with all heavy nuclear and deuteron data removed from the CT25 dataset.

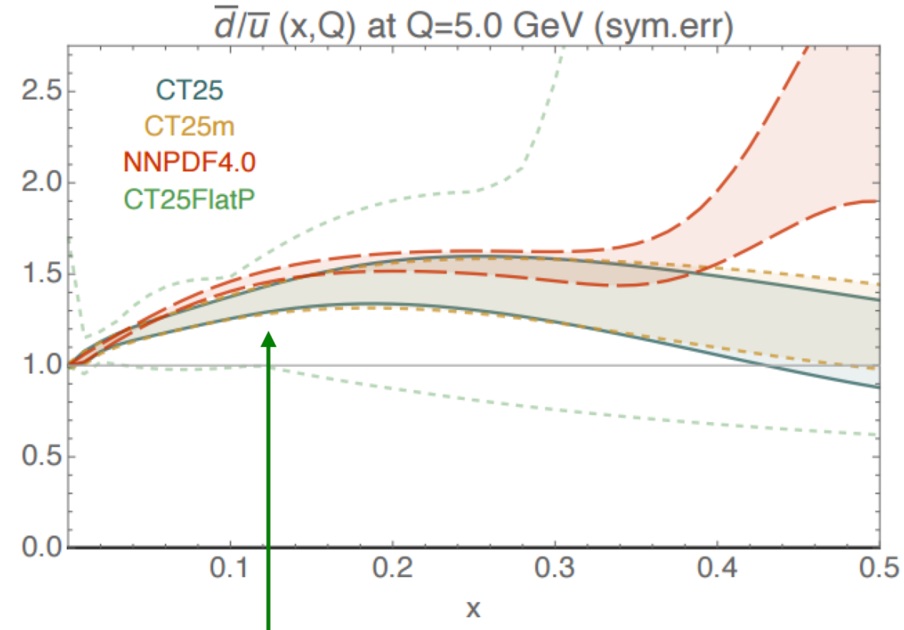
⇒ Large error band for $\bar{d}/\bar{u}$ at $x \sim 0.1$, still compatible with $\bar{d}/\bar{u} \sim 1$.

$\bar{d}/\bar{u}$ analysis with the CT25 proton-only flat prior (CT25FlatP)

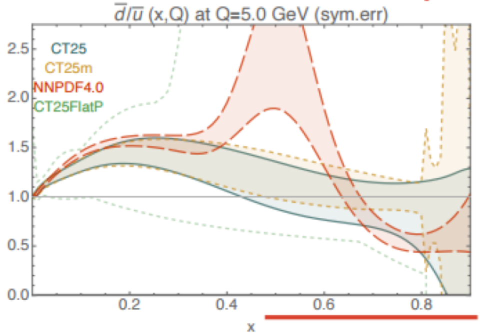
December 2025
CT25FlatP is not biased by the E906 data
CT25 includes E906 (2021)
Postdiction for E906 (2025) – excellent agreement with both E906 data sets



Underlying $\bar{d}/\bar{u}$ PDFs



Enhancement >1 present in CT25, not in CT25FlatP



Figures: A. Courtoy

Light antiquark ratio in pure proton data

C T E Q

Measurement of light quark ratio in pure proton data

Probe

Proton structure:
Measurement of SU(2) flavor asymmetry, unbiased from nuclear assumptions

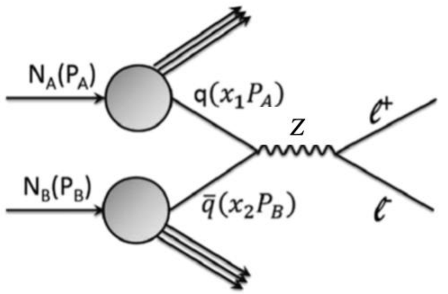
Deuteron structure:
tests on models of nuclear corrections

Today's talk

- Light quark ratio measured from $pp(p\bar{p})$ collisions
- Significantly different from previous deuteron results

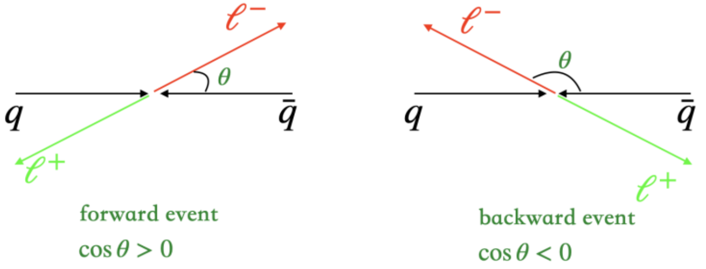
Z-exchanged neutral current interactions

- Flavor-dependent vector/axial vector couplings, so that $u(\overline{u})$ and $d(\overline{d})$ contributions can be separated
- Experimental observable: spatial asymmetry A_{FB} at Z pole

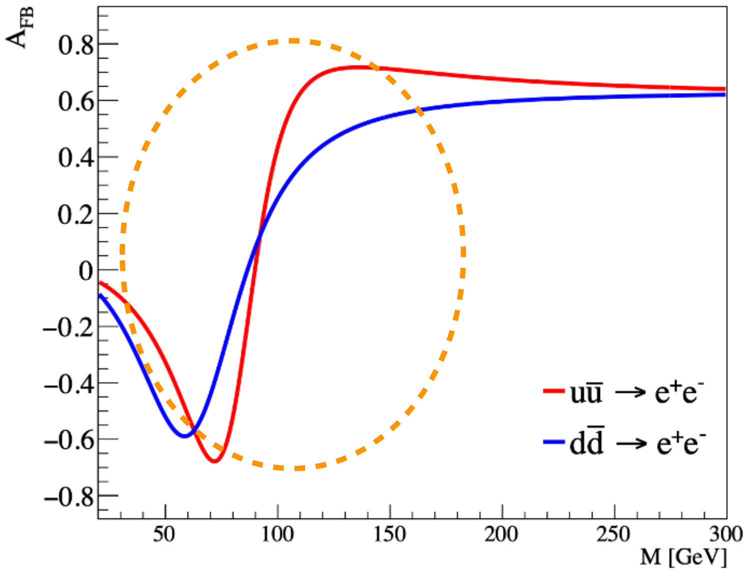


$$-\frac{g}{2\cos\theta_W}\sum_i \overline{\psi}_i\,\gamma^\mu(g_V^i - g_A^i\gamma^5)\,\psi_i\,Z_\mu$$

$$g_V^i \equiv t_{3L}(i) - 2q_i\sin^2\theta_W\ ,$$
$$g_A^i \equiv t_{3L}(i)\ ,$$

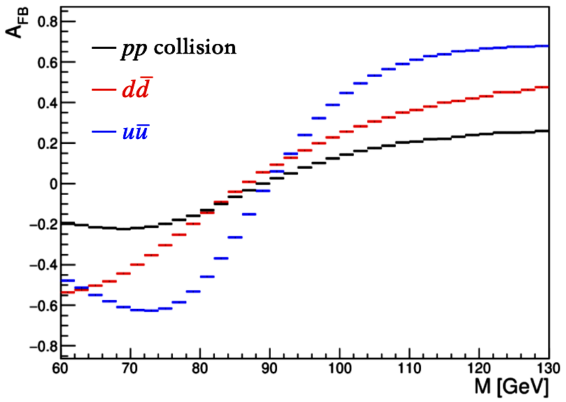


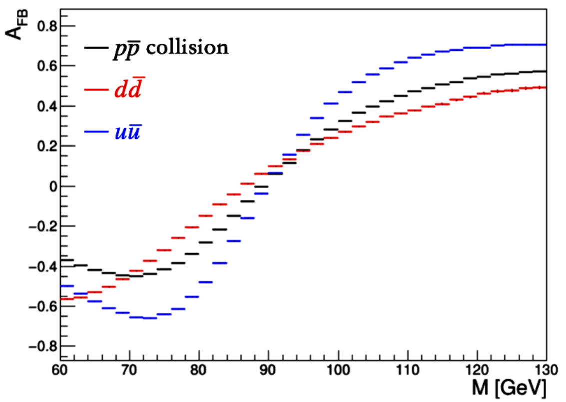
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



The up-type asymmetry A_{FB}^u is in different shape from the down-type asymmetry A_{FB}^d as a function of mass at the pole region of the Z boson

Proton Structure Parameters defined in the observed A_{FB} spectrum





- Observed A_{FB}^{h} = combination of A_{FB}^{u} and A_{FB}^{d}, weighted by the proton structure parameters C_u and C_d.
- It holds rigorously at all orders in QCD, in analogy to factorization for inclusive production in DIS processes.
- Implemented via ResBos, using CSS q_T resummation formalism.

$$A_{FB}^{h} = C_u[u(x);\bar{u}(x)] \times A_{FB}^{u}[\sin^2\theta_W] + C_d[d(x);\bar{d}(x)] \times A_{FB}^{d}[\sin^2\theta_W]$$

$$C_u(x_1,x_2) = \frac{\left[u(x_1)\bar{u}(x_2) - \bar{u}(x_1)u(x_2)\right]\mathcal{N}_u}{\sum_{q=u,d,s,c,b}\left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]\mathcal{N}_q}$$

$$C_d(x_1,x_2) = \frac{\left[d(x_1)\bar{d}(x_2) - \bar{d}(x_1)d(x_2)\right]\mathcal{N}_d}{\sum_{q=u,d,s,c,b}\left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]\mathcal{N}_q}$$

For LHC's pp collisions

$$C_u(x_1,x_2) = \frac{\left[u(x_1)u(x_2) - \bar{u}(x_1)\bar{u}(x_2)\right]\mathcal{N}_u}{\sum_{q=u,d,s,c,b}\left[q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)\right]\mathcal{N}_q}$$

$$C_d(x_1,x_2) = \frac{\left[d(x_1)d(x_2) - \bar{d}(x_1)\bar{d}(x_2)\right]\mathcal{N}_d}{\sum_{q=u,d,s,c,b}\left[q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)\right]\mathcal{N}_q}$$

For Tevatron's $p\bar{p}$ collisions

Chinese Phys. C 45 (2021) 053001

Eur. Phys. J. C82 (2022) 368

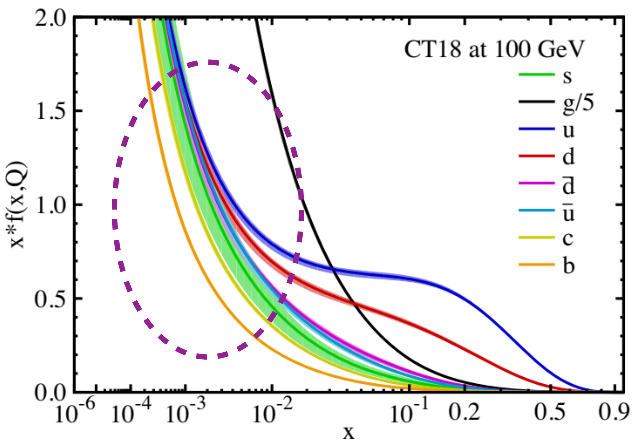
Phys. Rev. D106 (2022) 033001

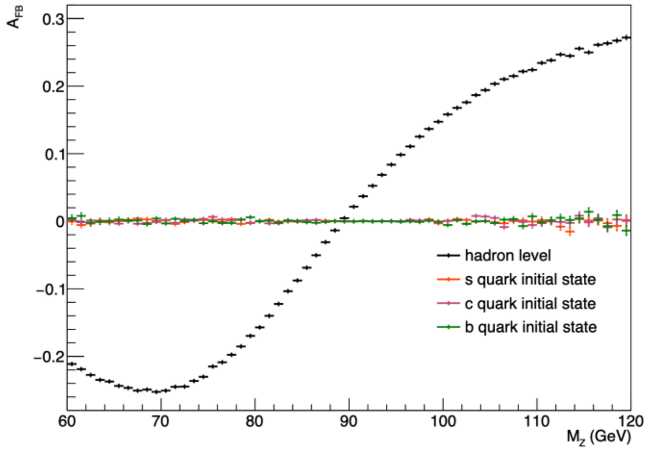
R-Parameter
defined through the observed A_{FB} spectrum

$$R = \frac{C_d}{C_u} \propto \frac{d(x_1)\bar{d}(x_2) - d(x_2)\bar{d}(x_1)}{u(x_1)\bar{u}(x_2) - u(x_2)\bar{u}(x_1)} \approx \frac{d(x_1) - \bar{d}(x_1)}{u(x_1) - \bar{u}(x_1)} \Rightarrow \frac{\bar{d}}{\bar{u}}$$

$$x_{1,2} = \frac{\sqrt{M^2 + Q_T^2}}{\sqrt{s}} \times e^{\pm Y}$$

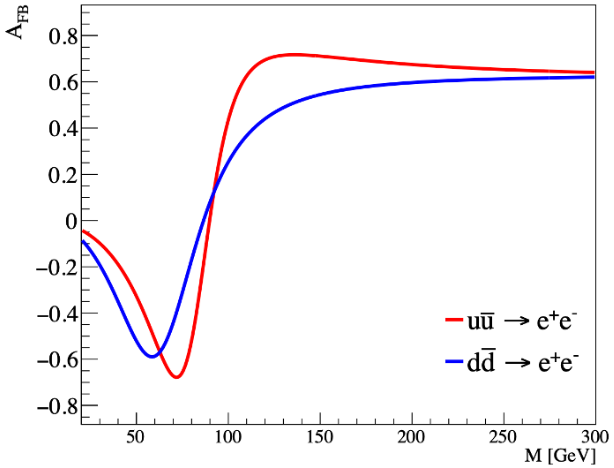
- Light quark distributions agree for $x_2 < 0.01$, so the contributions from x_2 cancel out in the ratio. The R parameter is dominated by the information at $x_1 \sim 0.1$.
- Contributions of s, c, and b quarks are greatly suppressed, since their quark and antiquark distributions are nearly identical.
- The influence of the R-parameter on the on $\frac{d}{u}$ and $\frac{\bar{d}}{\bar{u}}$ ratios shows an anti-correlation.

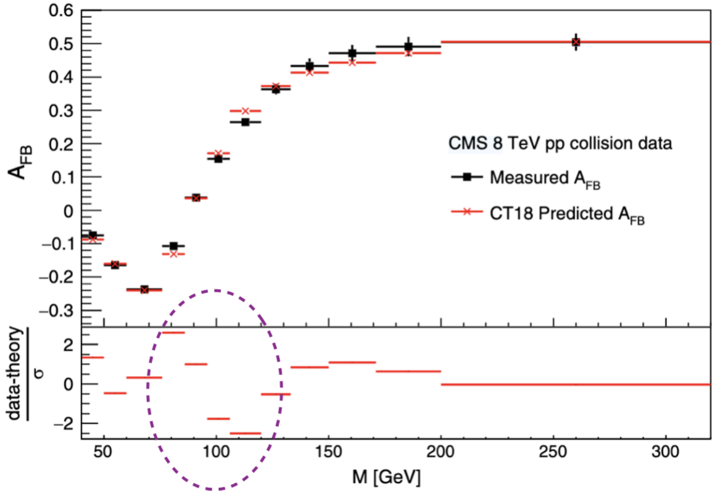




In conclusion: R is an experimental observable for pure proton interactions and is sensitive to the $\bar{d}/\bar{u}$ ratio.

The measured R parameter is a direct reflection of the observed A_{FB}

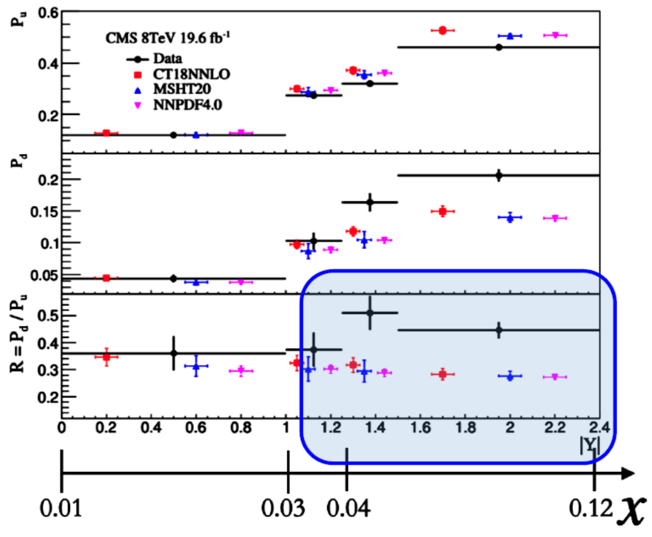




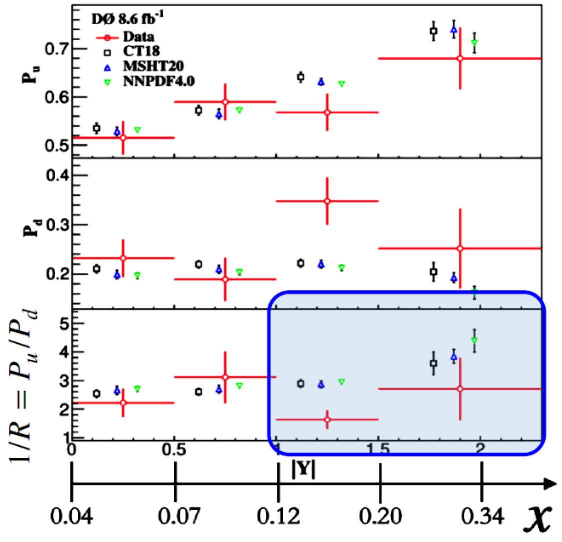
- A_{FB} is suppressed in the data with respect to the PDF predictions
- Since A_{FB}^{d} is less significant than A_{FB}^{u} ,the suppressed A_{FB} observation naturally reveals a higher weight of A_{FB}^{d} component, namely a lower $\bar{d}/\bar{u}$.

$$R = \frac{C_d}{C_u} \propto \frac{d(x_1) - \bar{d}(x_1)}{u(x_1) - \bar{u}(x_1)} \Longrightarrow \frac{\bar{d}}{\bar{u}} \downarrow$$

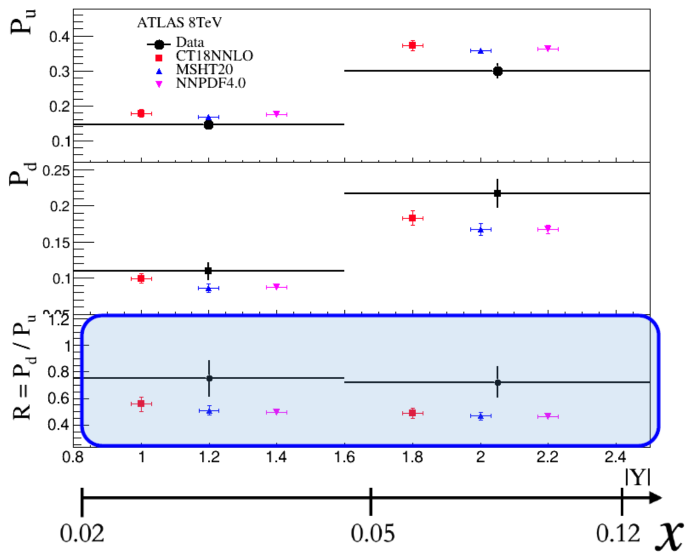
Experimental Data from CMS, D0 and ATLAS



R parameter fitted from A_{FB} spectrum measurement in CMS 8 TeV *pp* collision data



R parameter measured in D0 1.96 TeV $p\bar{p}$ collision data



R parameter fitted from A_{FB} spectrum measurement in ATLAS 8 TeV *pp* collision data (preliminary)

Experimental results consistently show a tendency that $\bar{d}/\bar{u}$ is lower than the current PDF predictions (which is constrained by the deuteron data)

Phys. Rev. D 107 (2023) 054008

Phys. Rev. D 110 (2024) L091101

Phys. Rev. D 113 (2026) L011504

Current experimental data, as of June 2026

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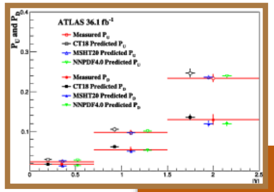
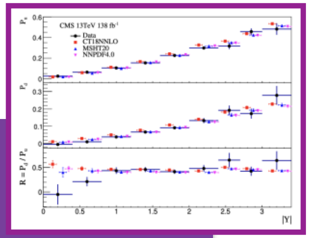
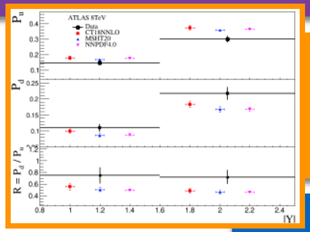
LHCb pp @ 13 TeV
Discrepancy observed ($> 2\sigma$, preliminary)



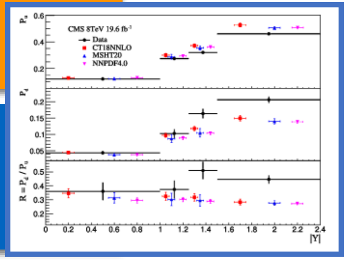
ATLAS pp @ 13 TeV
Consistent at small x region (preliminary)



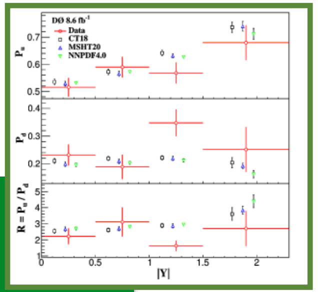
CMS pp @ 13 TeV
Discrepancy observed at high ZY region



ATLAS pp @ 8 TeV (preliminary)
Discrepancy observed ($> 2\sigma$)



CMS pp @ 8 TeV
Discrepancy observed ($> 4\sigma$)



D0 $p\bar{p}$ @ 1.96 TeV
Discrepancy observed ($>3.5\sigma$)

x_1

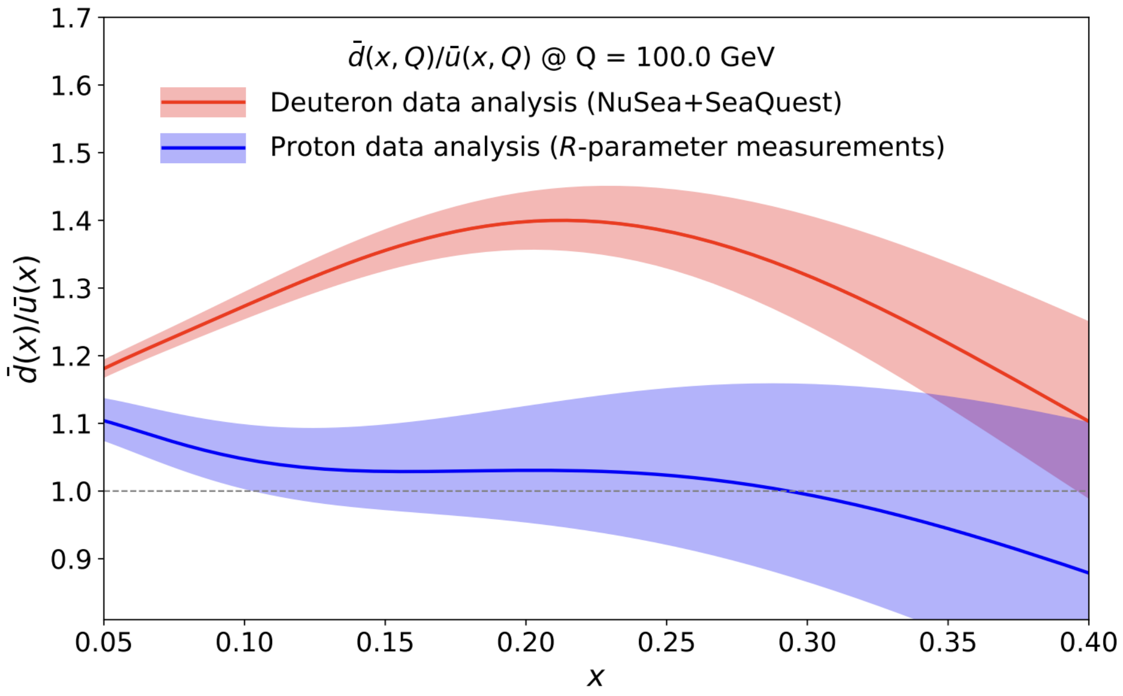
0.01 0.03 0.05 0.08 0.12 0.2 0.4

Comparing Global Analyses of Deuteron Data and Pure Proton Data

arXiv: 2510.08941

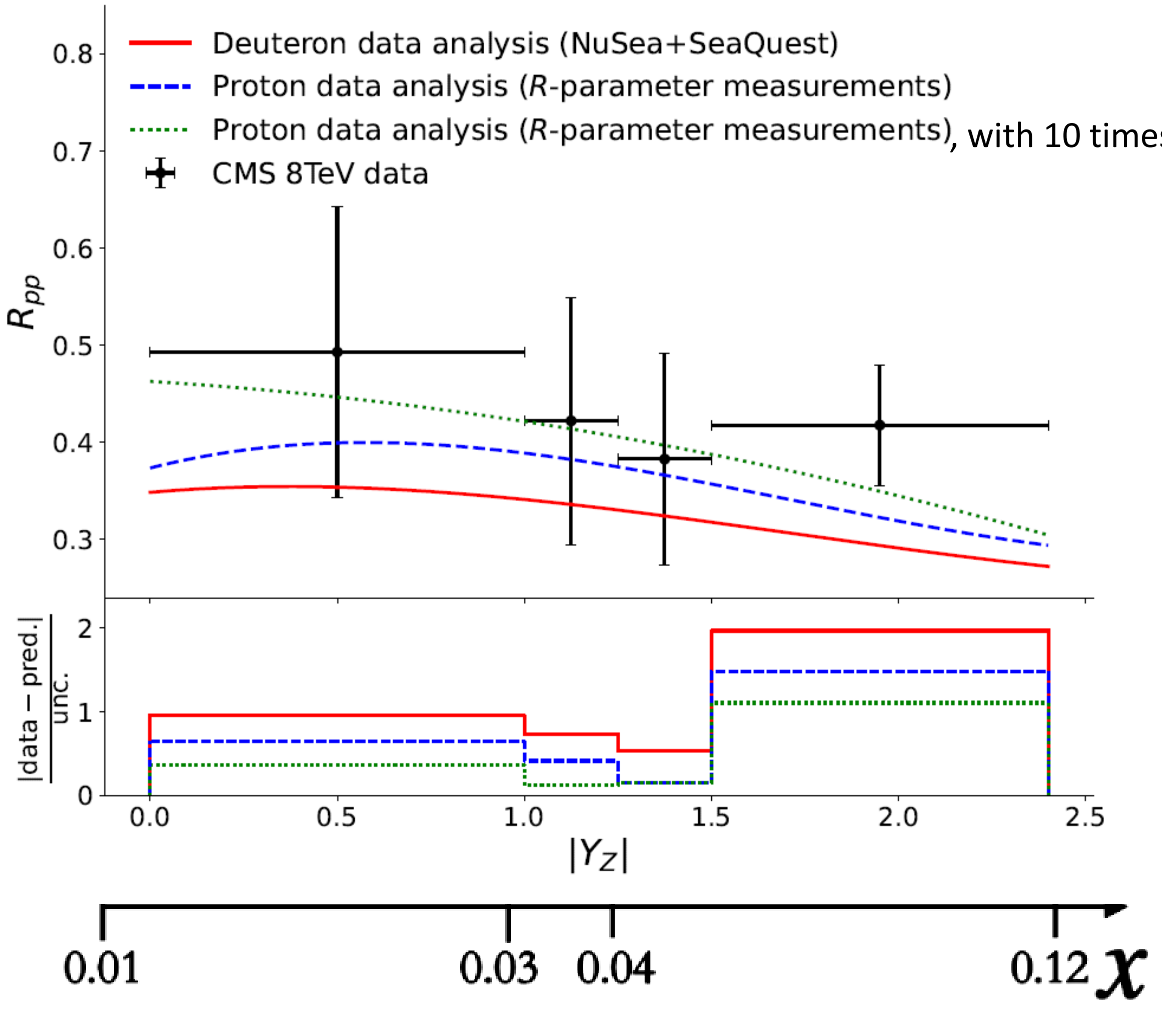
The R-parameter data (pure proton interaction) yield a $\bar{d}/\bar{u}$ ratio close to unity

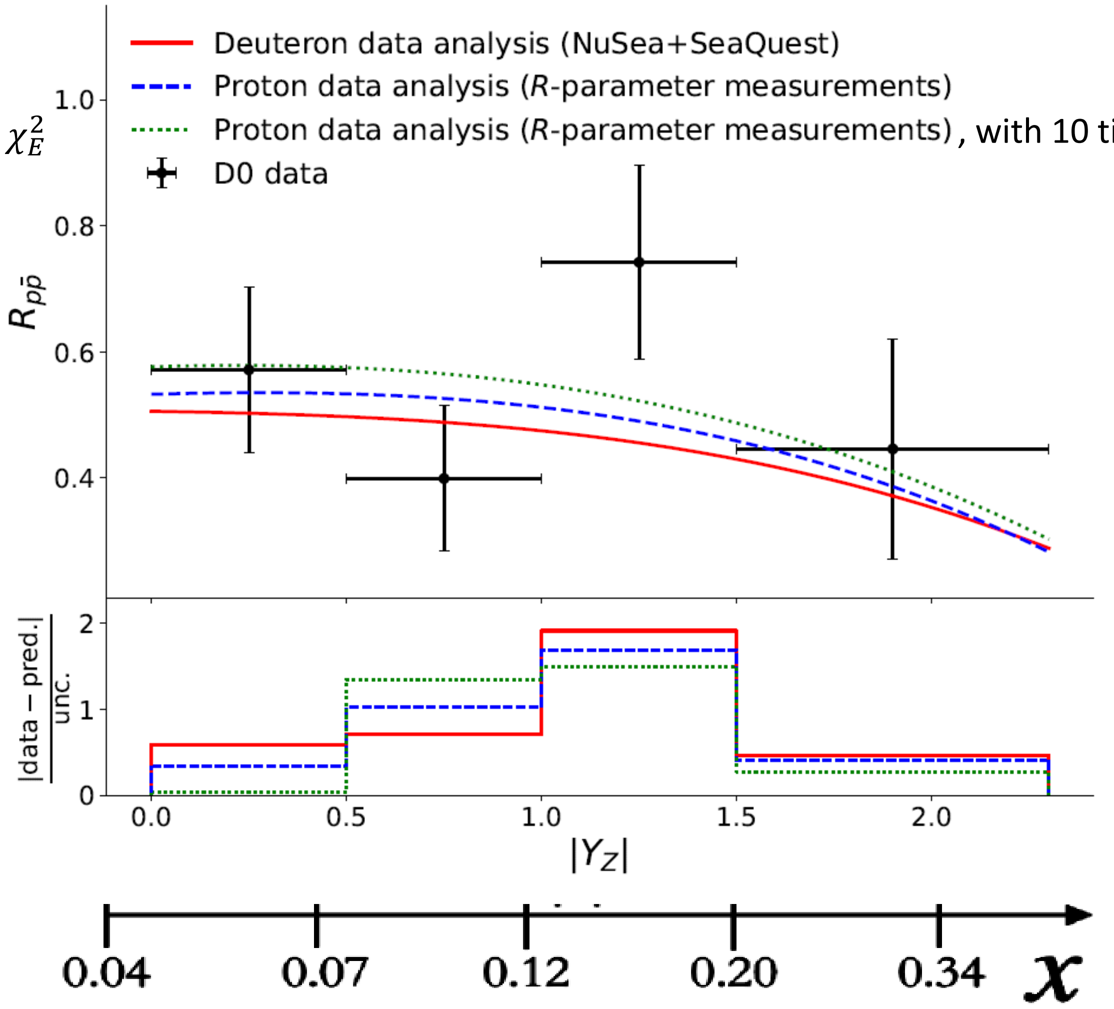
- **For proton structure:** indicating that the SU(2) flavor asymmetry of light antiquarks ($\bar{d}$ and $\bar{u}$) arising from nonperturbative QCD dynamics is unlikely to be sizable. (We note that a modest SU(2) flavor asymmetry can be perturbatively generated from higher order QCD corrections.)
- **For deuteron structure:** indicating that the high-energy deuteron cannot be described by the conventional picture of proton-deutron two-body bound state.



Global analysis:
- Following CT18 procedure
- With all other nuclear data removed
- Demonstrated with $\Delta\chi^2 = 1$

Comparison of the fitted R-parameter to the CMS and D0 data





A toy model for estimating the deuteron nuclear effect

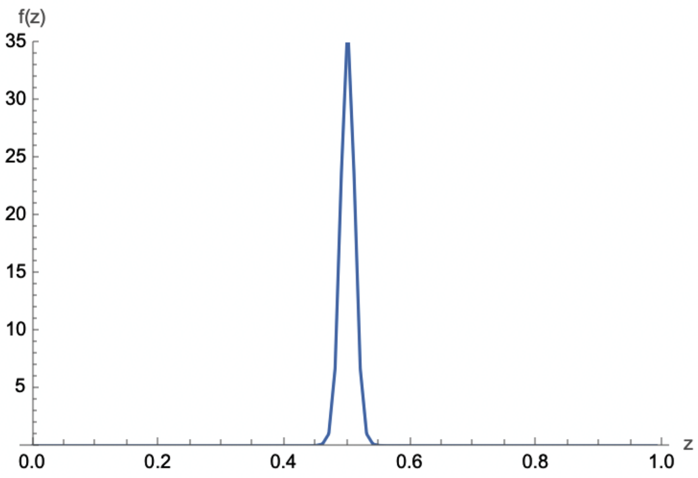
LMDF (longitudinal momentum distribution function) in the conventional picture of proton-deutron two-body bound state.

- Sharp peak: weak interaction between nucleons in deuteron (B.E. ~2 MeV)
- Peak at 0.5: nucleons in deuteron are proton and neutron, so they equally share the deuteron energy

$$\mathcal{F}_q^D(x, Q^2) = \frac{1}{2}\sum_N \int_x^1 \frac{dz}{z}\, \mathrm{LMDF}(z)\, \mathcal{F}_q^N\left(\frac{x}{z}, Q^2\right)$$

- $\mathcal{F}_q^D(x, Q^2)$: Overall distribution of quarks
- $\mathrm{LMDF}(z)$: Distribution of nucleons in the deuteron
- $\mathcal{F}_q^N\left(\frac{x}{z}, Q^2\right)$: PDF of quarks in nucleons (proton)

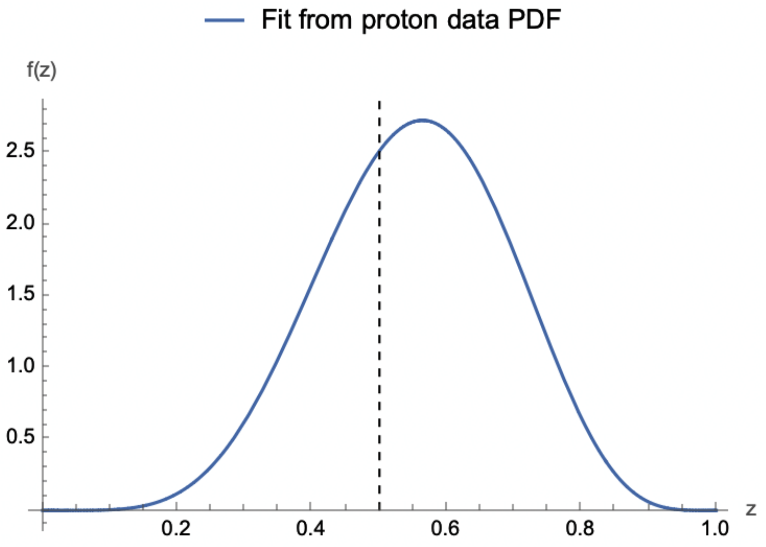
LMDF in classic picture



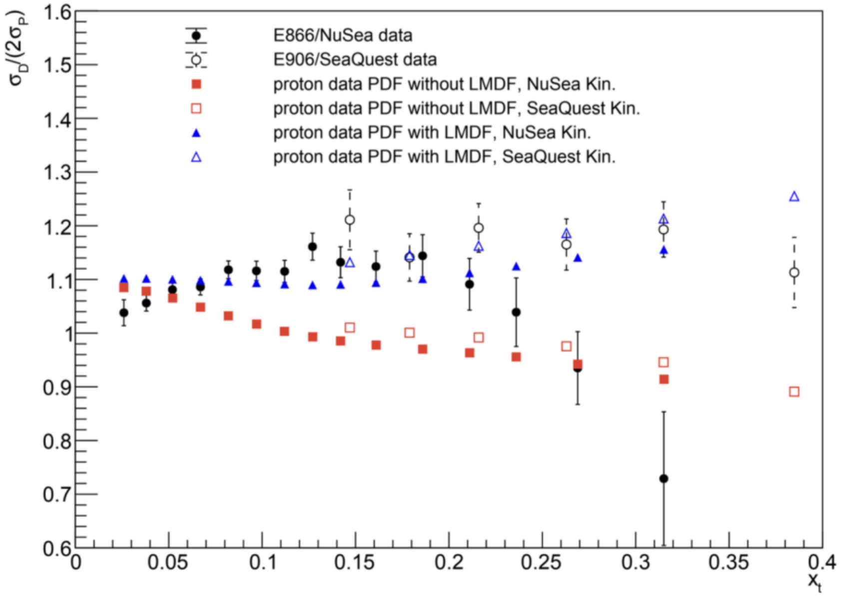
A toy model for estimating the deuteron nuclear effect

LMDF fitted from deuteron data, using pure proton PDF ($\bar{d}/\bar{u} \sim 1$ at $x \sim 0.1$)

- Significantly smeared: strong interaction between nucleons
- Shifted peak: not a simple proton-deutron two-body bound state.



Possible causes:
short-distance structure, hidden color, octet-cluster, meson cloud, six-quark bond state, etc.

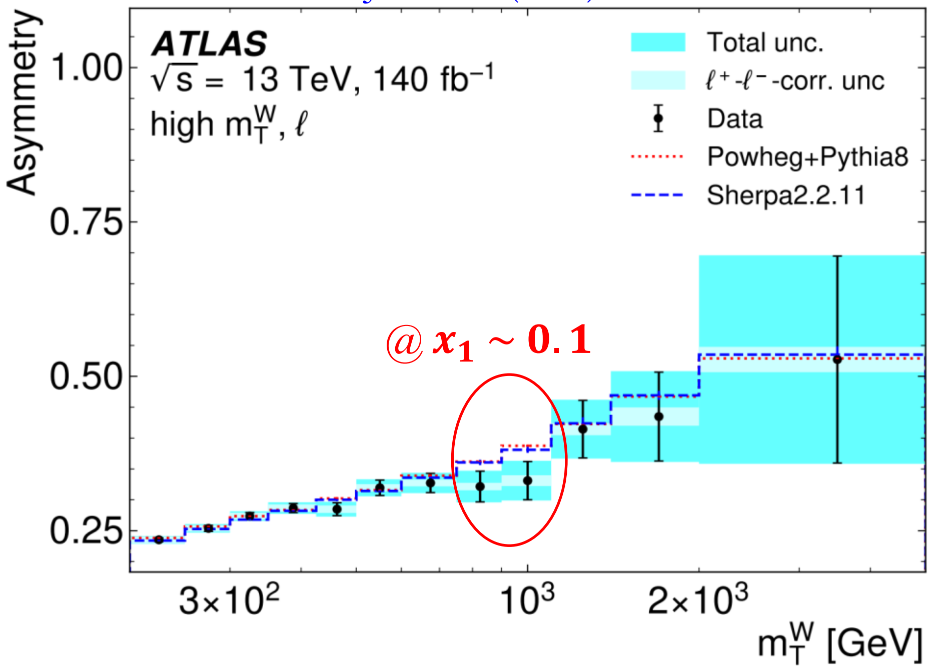


The pure proton PDF ($\bar{d}/\bar{u} \sim 1$)$\otimes$LMDF well explains the NuSea/SeaQuest data

Hints from other experimental data

- ATLAS $W^{\pm}$-asymmetry measurement. Reaching large x at TeV high m_T

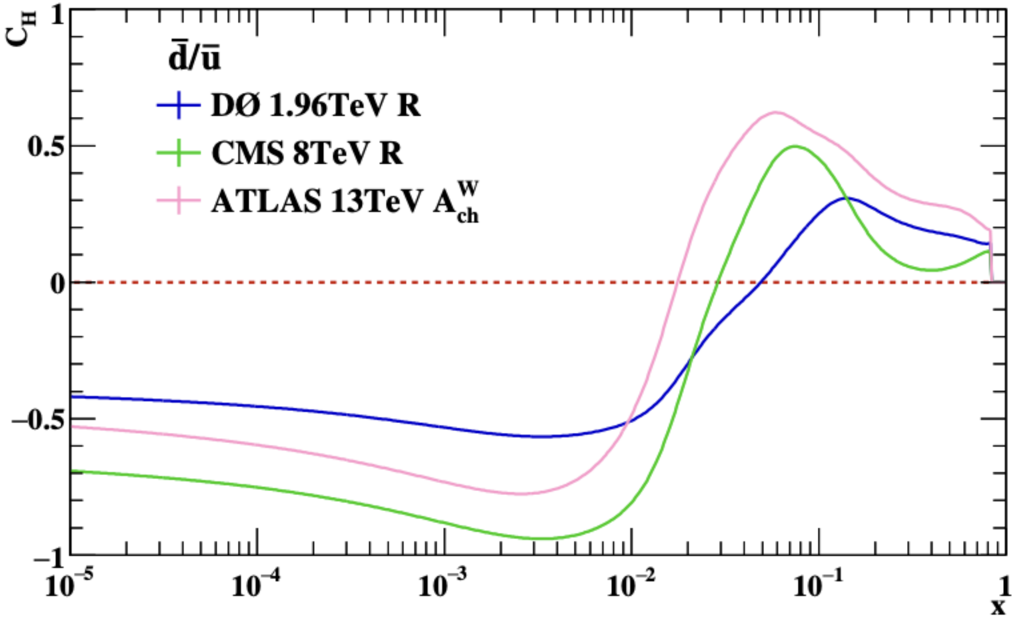
JHEP 07 (2025) 026



$$A_{ch}^{W} \equiv \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$$

- Correlation study of W/Z-asymmetry at hadron colliders:

Chin. Phys. C 50 (2026) 023107



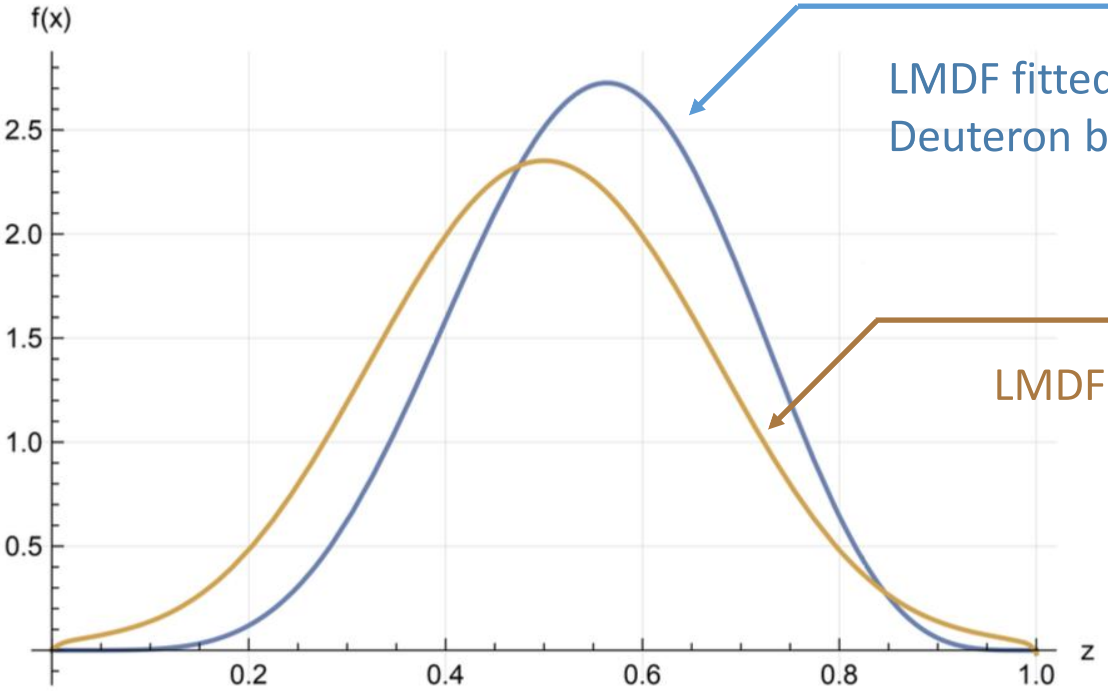
$$A_{ch}^{W} \propto \frac{u\bar{d}}{d\bar{u}} \Rightarrow \frac{\bar{d}}{\bar{u}}$$

Hints from other experimental data

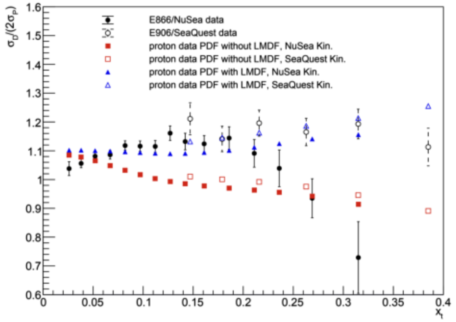
arXiv:2507.09886

- LMDF found to be with large smearing;

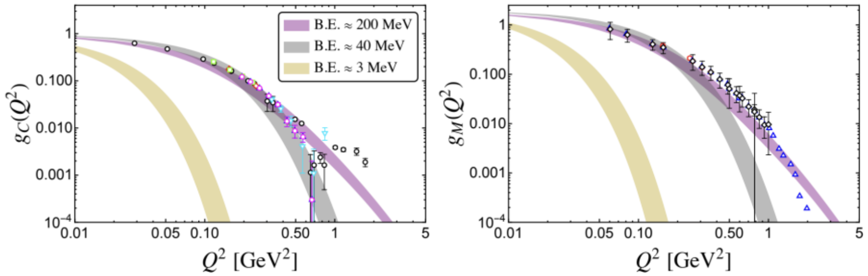
Model deuteron as single-singlet and octet-octet color clusters and compare to its electromagnetic form factors.



LMDF fitted from NuSea/SeaQuest data:
Deuteron breaks into quarks



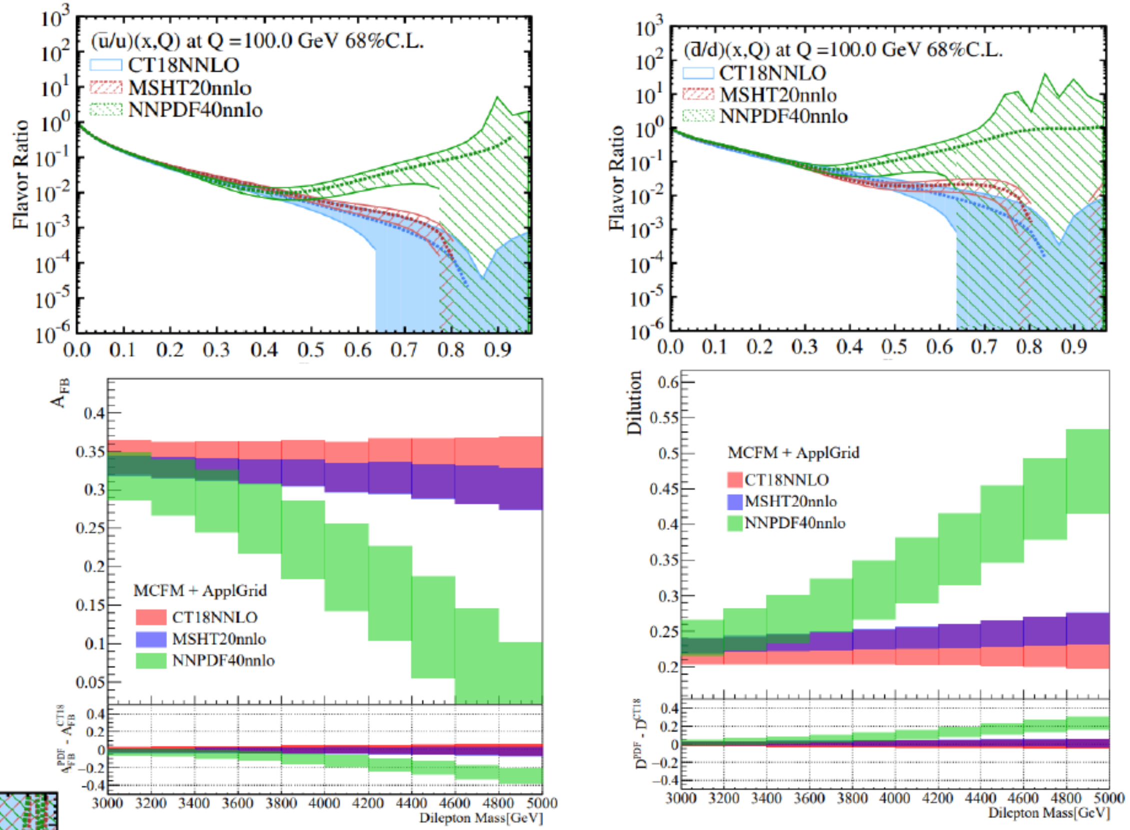
LMDF that describes electromagnetic form factors of deuteron

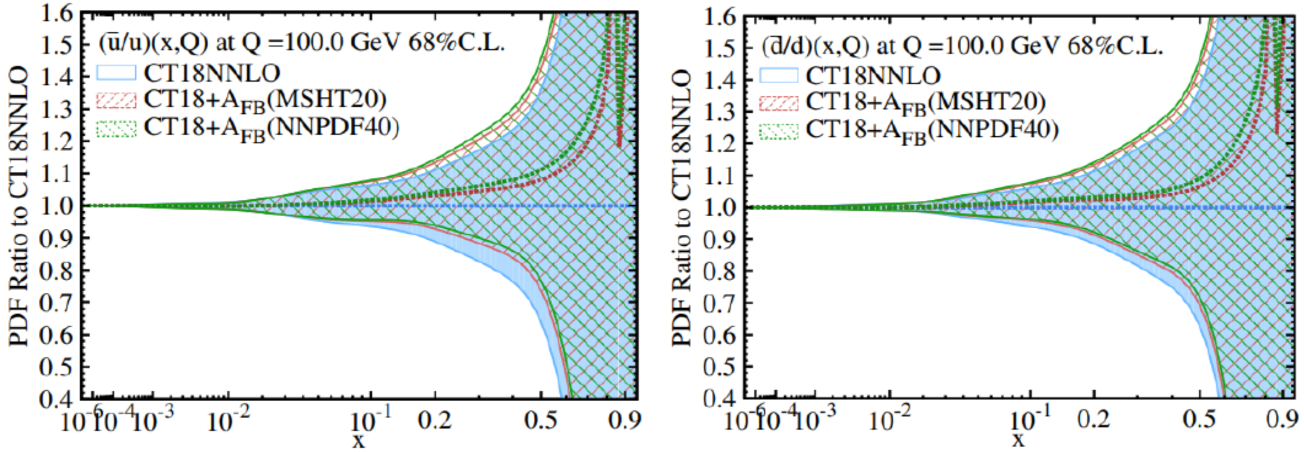


Impact of A_{FB} in the high-mass Drell-Yan process

Y. Fu et al., 2307.07839
C. Willis et al., 1809.09481

- A_{FB} at the LHC is sensitive to the energy dilution factor D (probability of $k_q^0 < k_{\bar{q}}^0$ in the Collins-Soper frame)
- $A_{FB}^h = \frac{N_F^h - N_B^h}{N_F^h + N_B^h} \approx (1 - 2D) A_{FB}^q$
- A_{FB} at high invariant mass region probes $\bar{u}/u$, $\bar{d}/d$ at $x > 0.2$





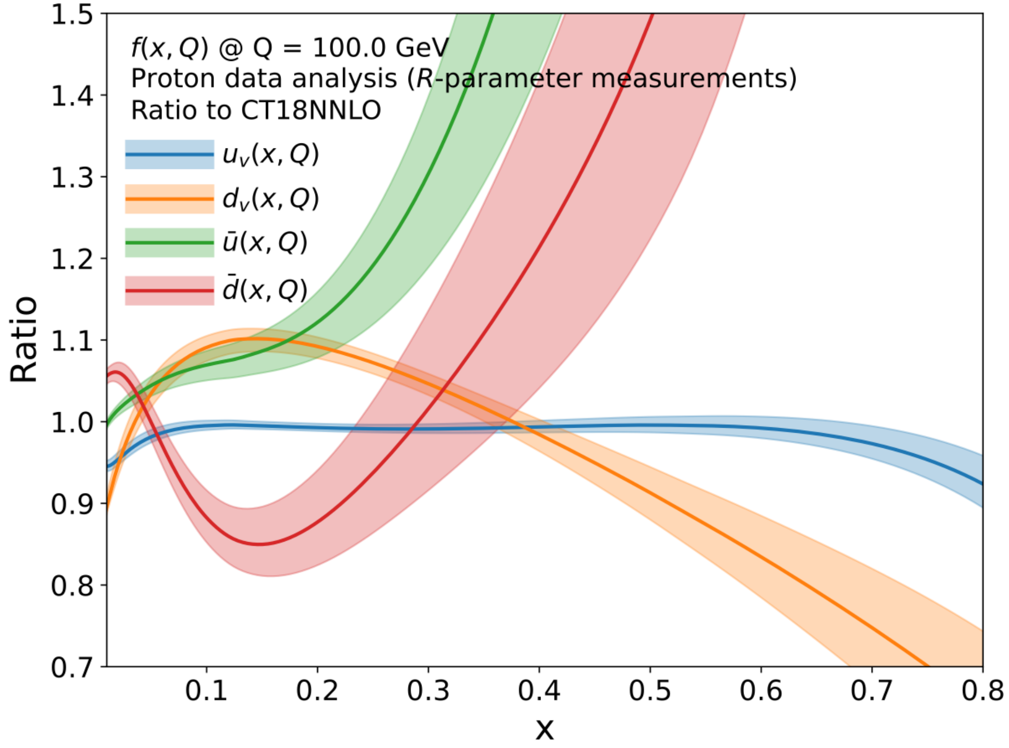
- CT18, MSHT20, and NNPDF4.0 predict very different $\bar{q}/q$ at $x > 0.2$
- The article quantified the potential effect of high-mass A_{FB} on large-x antiquarks

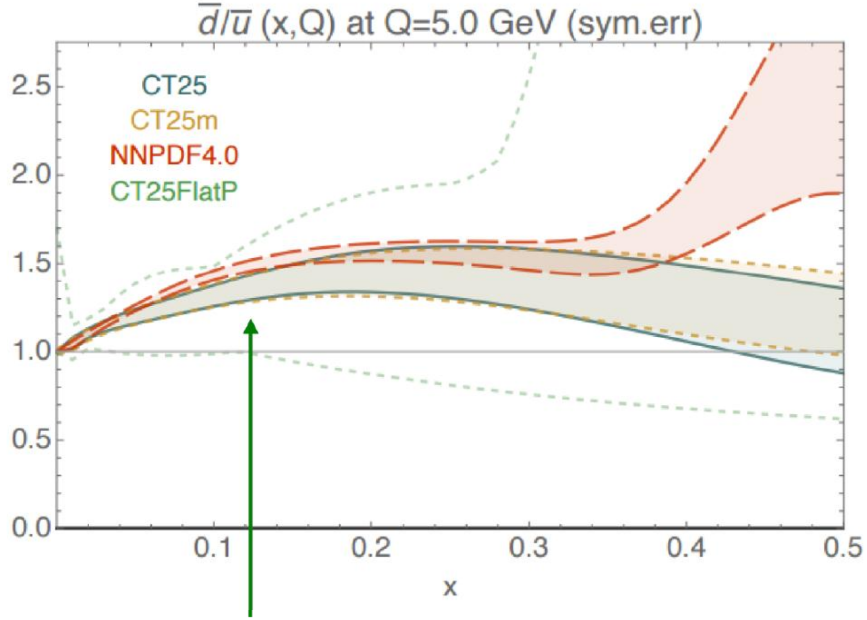
See also NNPDF (2209.08115), Fiaschi et al. (2211.06188)

The need of Global Analysis of Pure Proton Data

Proton structure in pure proton data

- For proton structure: avoid potential bias from nuclear data
- For nuclear structure: prior input to analyze high energy nuclear data
- Need new experimental observables and large-x measurements





Enhancement >1 present in CT25, not in CT25FlatP

New types of experimental observables are needed for global PDF analysis

	mixed quarks	x range
γ DIS	$u(x)+\bar{u}(x)+\frac{1}{4}d(x)+\frac{1}{4}\bar{d}(x)+\mathcal{O}(s,c,b,\cdots)$	$x\sim\mathcal{O}(0.001)$ to $\mathcal{O}(0.1)$
Z DIS (lower precision)	$u(x)+\bar{u}(x)+1.2d(x)+1.2\bar{d}(x)+\mathcal{O}(s,c,b,\cdots)$	$x\sim\mathcal{O}(0.1)$
W^+ DIS (lower precision)	$u(x)+\bar{d}(x)+\mathcal{O}(s,c,b,\cdots)$	$x\sim\mathcal{O}(0.01)$ to $\mathcal{O}(0.1)$
W^- DIS (lower precision)	$u(x)+\bar{d}(x)+\mathcal{O}(s,c,b,\cdots)$	$x\sim\mathcal{O}(0.01)$ to $\mathcal{O}(0.1)$
γ Drell-Yan Target	$u(x_1)\bar{u}(x_2)+\bar{u}(x_1)u(x_2)+1.2d(x_1)\bar{d}(x_2)+1.2\bar{d}(x_1)d(x_2)+\mathcal{O}(s,c,b,\cdots)$	$x_{1,2}\sim\mathcal{O}(0.1)$
Z Drell-Yan LHC	$u(x_1)\bar{u}(x_2)+\bar{u}(x_1)u(x_2)+1.2d(x_1)\bar{d}(x_2)+1.2\bar{d}(x_1)d(x_2)$ $+c\bar{c}(x_1,x_2)+1.2s\bar{s}(x_1,x_2)+1.2b\bar{b}(x_1,x_2)+\mathcal{O}(qg,\cdots)$	$x_1\sim\mathcal{O}(0.01)$ to $\mathcal{O}(0.1)$ $x_2\sim\mathcal{O}(0.0001)$ to $\mathcal{O}(0.01)$
Z Drell-Yan Tevatron (lower precision)	$u(x_1)u(x_2)+\bar{u}(x_1)\bar{u}(x_2)+1.2d(x_1)d(x_2)+1.2\bar{d}(x_1)\bar{d}(x_2)$ $+c\bar{c}(x_1,x_2)+1.2s\bar{s}(x_1,x_2)+1.2b\bar{b}(x_1,x_2)+\mathcal{O}(qg,\cdots)$	$x_1\sim\mathcal{O}(0.1)$ $x_2\sim\mathcal{O}(0.01)$
W^+ Drell-Yan LHC	$u(x_1)\bar{d}(x_2)+\bar{d}(x_1)u(x_2)+c(x_1)\bar{s}(x_2)+s(x_1)\bar{c}(x_2)+\mathcal{O}(q_i\bar{q}_j,qg,\cdots)$	$x_1\sim\mathcal{O}(0.01)$ to $\mathcal{O}(0.1)$ $x_2\sim\mathcal{O}(0.0001)$ to $\mathcal{O}(0.01)$
W^- Drell-Yan LHC	$d(x_1)\bar{u}(x_2)+\bar{u}(x_1)d(x_2)+s(x_1)\bar{c}(x_2)+c(x_1)\bar{s}(x_2)+\mathcal{O}(q_i\bar{q}_j,qg,\cdots)$	$x_1\sim\mathcal{O}(0.01)$ to $\mathcal{O}(0.1)$ $x_2\sim\mathcal{O}(0.0001)$ to $\mathcal{O}(0.01)$
W^+ Drell-Yan Tevatron	$u(x_1)d(x_2)+\bar{d}(x_1)\bar{u}(x_2)+c(x_1)s(x_2)+\bar{s}(x_1)\bar{c}(x_2)+\mathcal{O}(q_i\bar{q}_j,qg,\cdots)$	$x_1\sim\mathcal{O}(0.1)$ $x_2\sim\mathcal{O}(0.01)$
W^- Drell-Yan Tevatron	$d(x_1)u(x_2)+\bar{u}(x_1)\bar{d}(x_2)+s(x_1)c(x_2)+\bar{c}(x_1)\bar{s}(x_2)+\mathcal{O}(q_i\bar{q}_j,qg,\cdots)$	$x_1\sim\mathcal{O}(0.1)$ $x_2\sim\mathcal{O}(0.01)$

- Conventional experimental data are sensitive to the sum of contributions from different parton flavours..
- Need new data which are sensitive to the difference of contributions from different parton flavours, such as R-parameter derived from the A_{FB} experimental measurement.
- Improving the precision of conventional data yields far less benefit than introducing new types of data.

Conclusion

- Novel proton-only probe of light antiquark flavor structure using neutral-current Drell–Yan forward–backward asymmetry
- Pure proton data favor

$$\frac{\bar{d}}{\bar{u}} \sim 1 \quad \text{at} \quad x \sim 0.1$$

in tension with traditional deuteron-based extractions

- Possible interpretations:

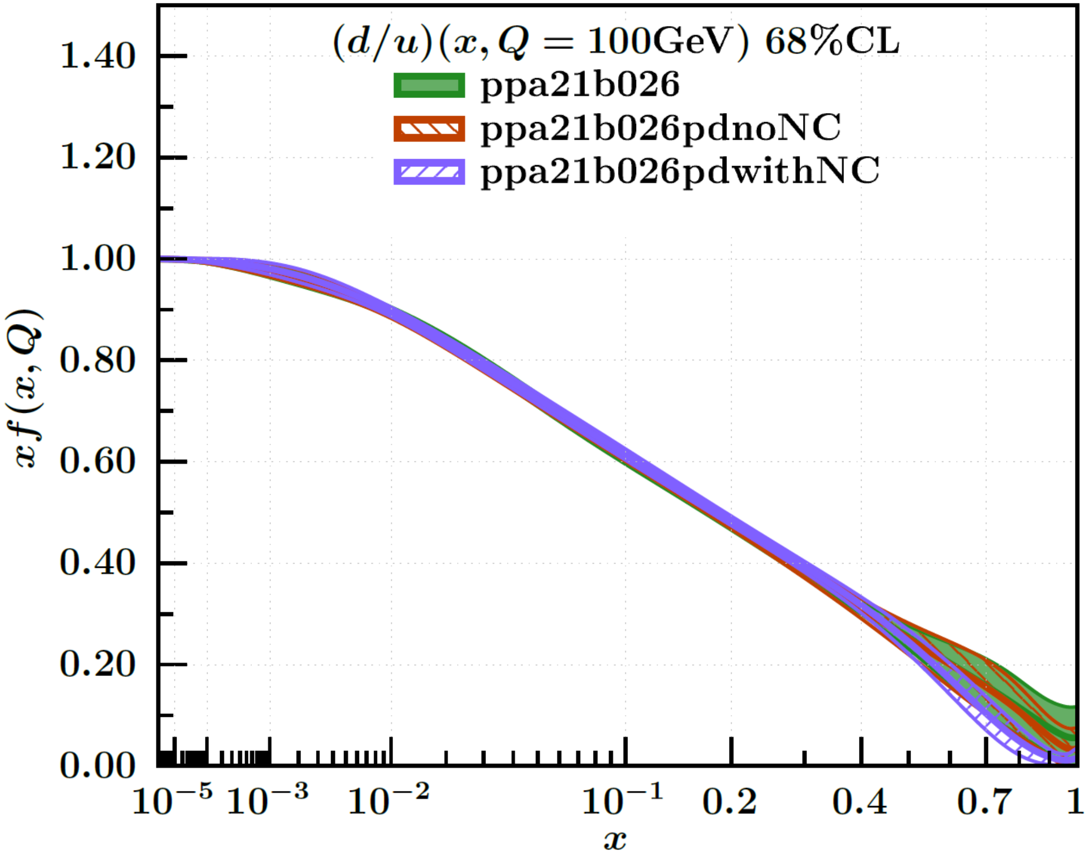
– reduced or absent SU(2) sea-quark asymmetry

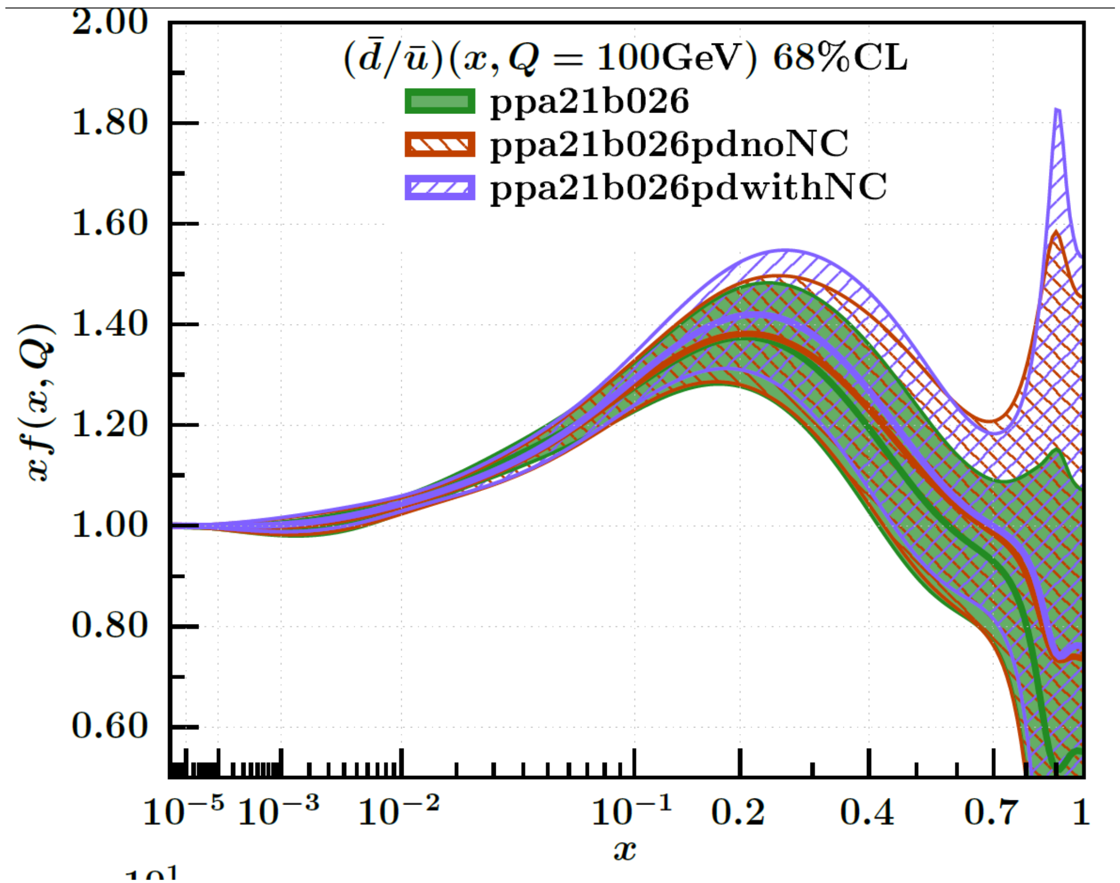
– underestimated nuclear corrections in deuteron data

- Motivates future proton-only PDF analyses and new (including charged current) precision Drell–Yan measurements, etc.

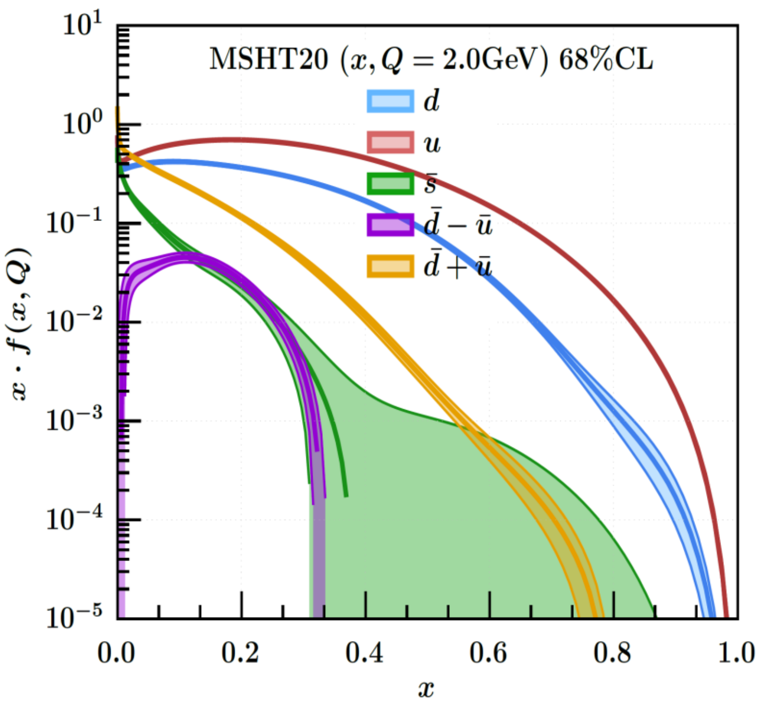
Backup slides

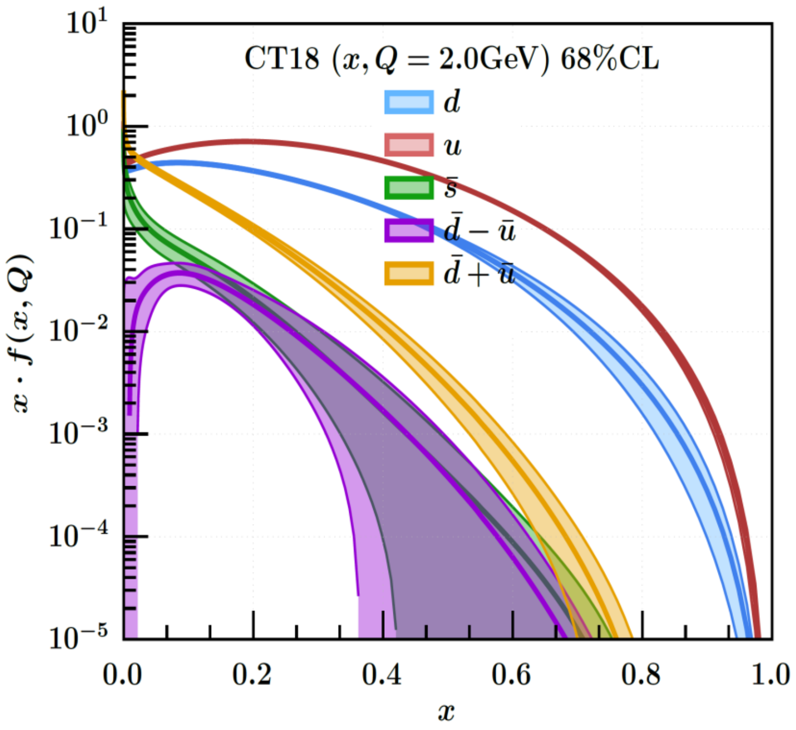
Effect of Deuteron nuclear corrections in CT25pd fit

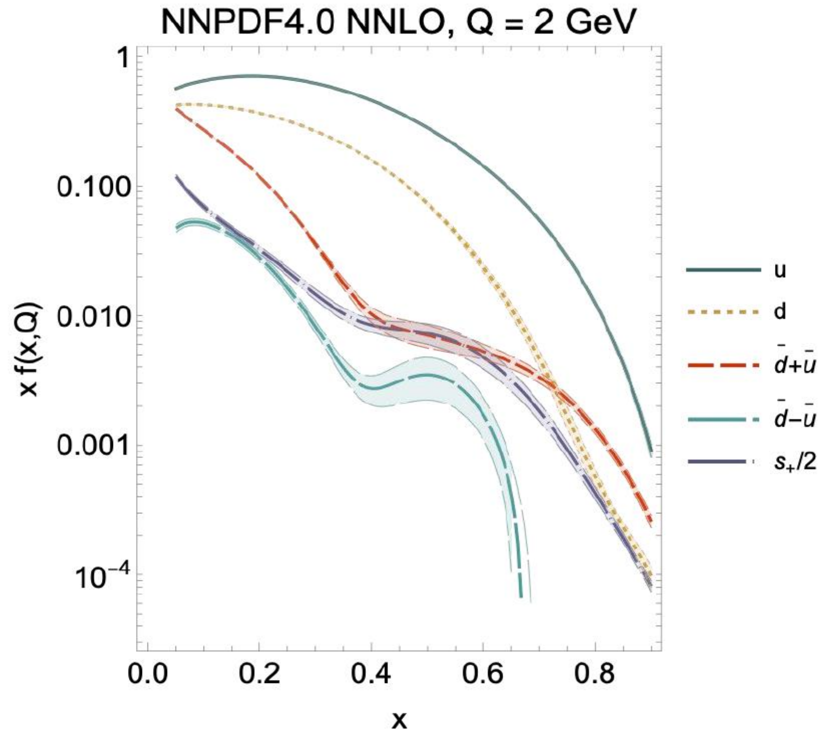




Compare MSHT20, CT18 and NNPDF4.0 PDFs







- MSHT20, CT18 and NNPDF4.0 predict very different sea quarks at large x.
- A_{FB} is sensitive to combinations of $\bar{u}/u$ and $\bar{d}/d$

High-sea scenario with non-smooth light-sea quarks, with sea PDFs that can be larger than valence PDFs at large x.

Smaller uncertainties.