Probing the light-quark ratio via forward-backward asymmetry

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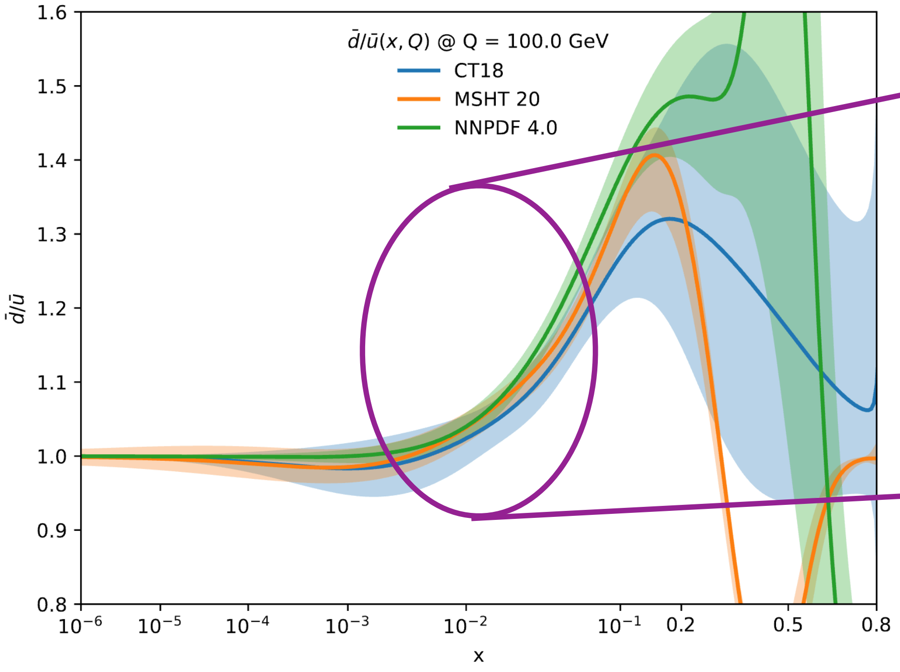
SU(2) flavor asymmetry of the light quark sea

How sea quarks generated inside the proton?

- Perturbative mechanism (gluon splitting): consistent light anti-quark distributions
- Non-perturbative mechanism: SU(2) flavor asymmetry $\bar{d}(x) \neq \bar{u}(x)$



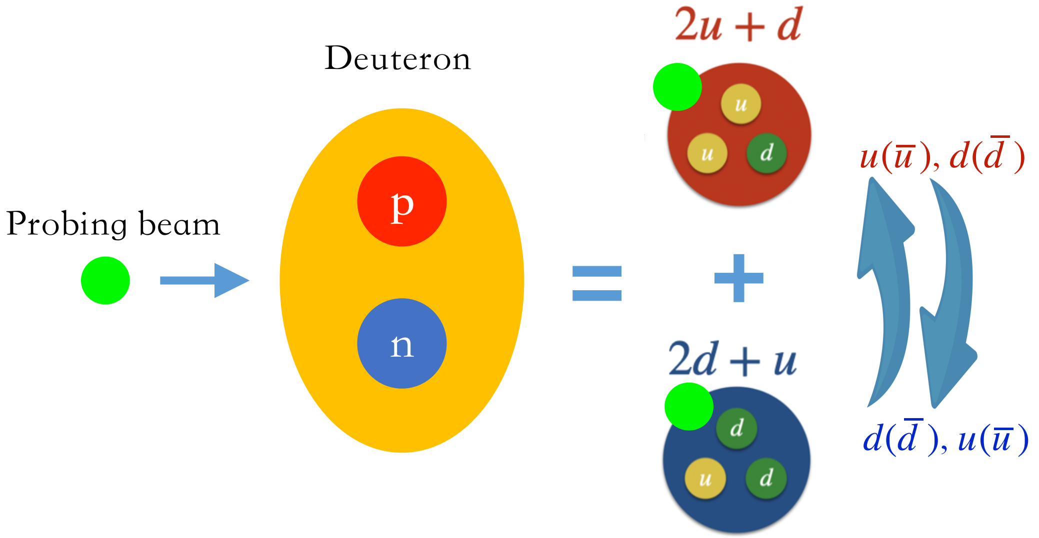
$\bar{d}/\bar{u}$ ratio in moderon PDF global analyses

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 the light quark sea

How to experimentally determine $\bar{d}/\bar{u}$?

- Pure proton interactions: ideal way, but very difficult, since $\bar{d}$ and $\bar{u}$ contributions are indistinguishable in inclusive experimental observables
- Nuclear data: currently the only direct constraints



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

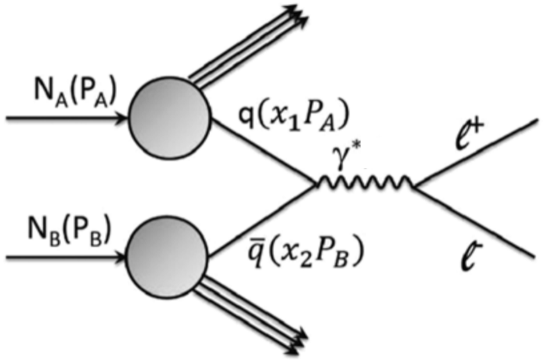
i. the classic deuteron structure picture: $\sigma(D) = \sigma(p) + \sigma(n)$

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

NuSea/SeaQuest experimental results

Drell-Yan process with deuteron target

➢ Proton-deuteron interaction vs. proton-proton interaction



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

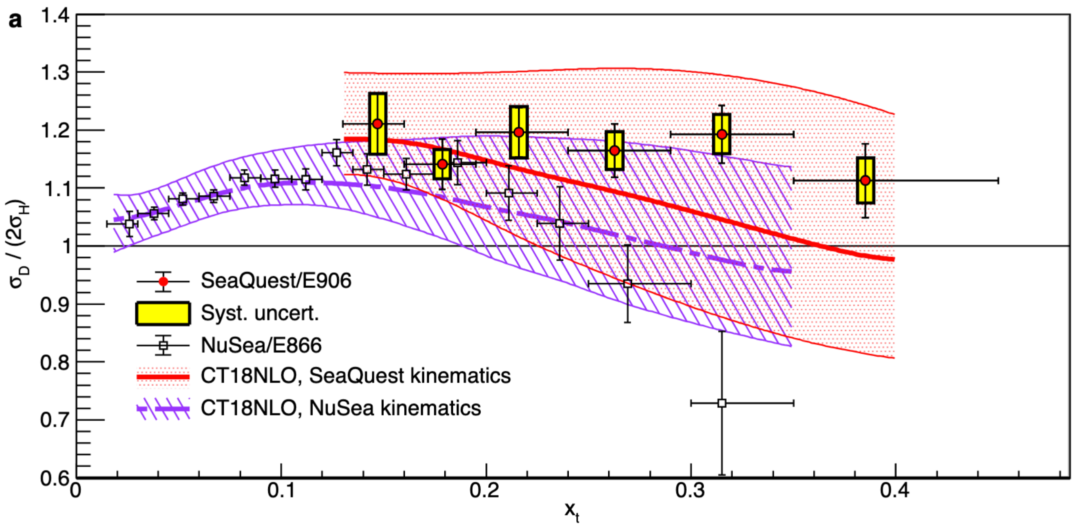
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{x_1 \gg x_2} \approx \frac{1}{2} \frac{\left[1 + \frac{1}{4}\frac{d(x_1)}{u(x_1)}\right]}{\left[1 + \frac{1}{4}\frac{d(x_1)}{u(x_1)}\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]} \left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right] \approx \frac{1}{2}\left[1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$$

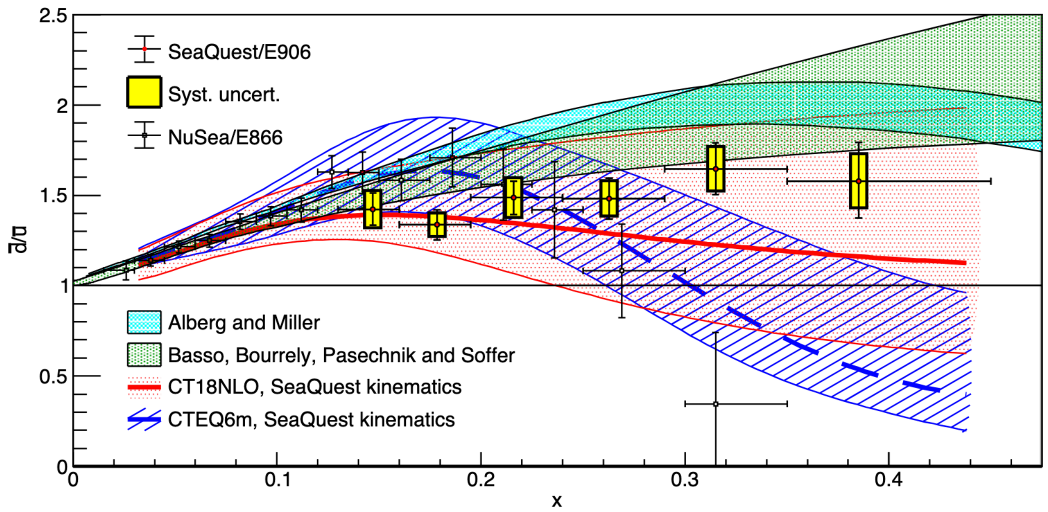
High energy proton beam and stationary target	→	Anti-quarks come from target
Kinematics designed at the peak of valence quarks $x_t \sim \mathcal{O}(0.1)$	→	s, c, b, g contributions suppressed
~10 GeV high energy interactions, γ-exchanged	→	d contribution suppressed

NuSea/SeaQuest experimental results

Higher deuteron cross section

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



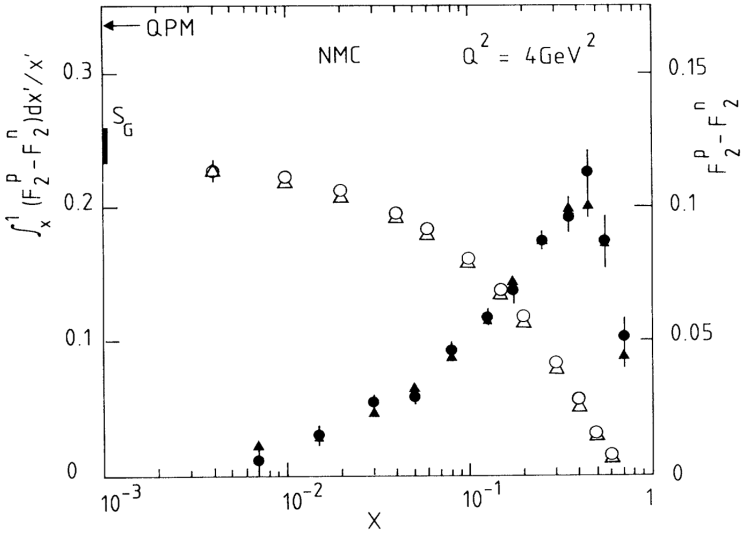


Nature Vol 590, 561-565, 2021

Other experimental results

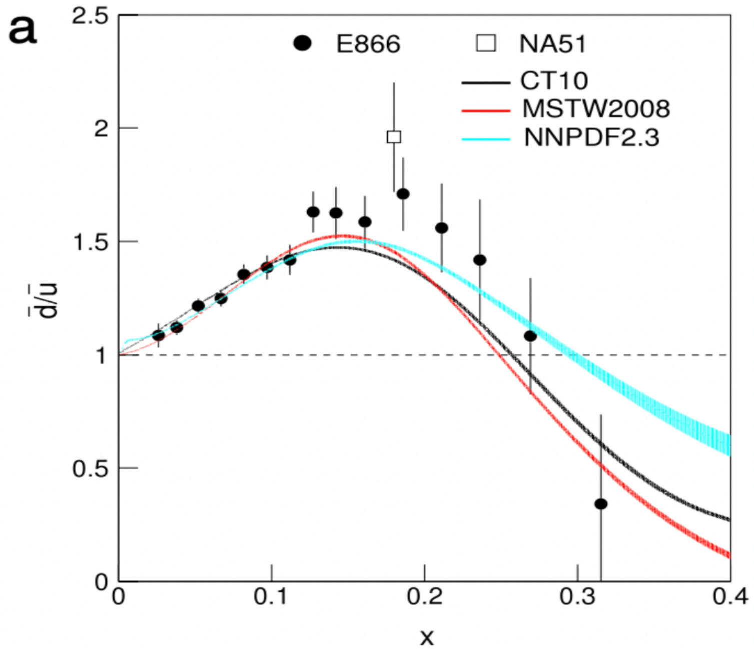
Consistent conclusion from other deuteron measurements

- ➢ NMC inclusive DIS
- ➢ NA51 Drell-Yan process
- ➢ HERMES semi-inclusive DIS

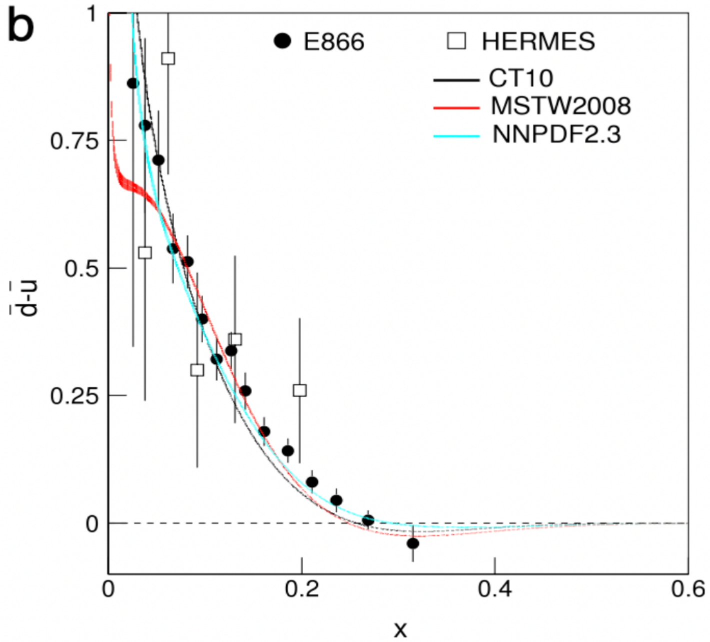


$$\int_0^1 dx\,[\bar{d}(x) - \bar{u}(x)] = 0.147 \pm 0.039,$$

Muon 90-280GeV on H2/D2 targets
@ CERN SPS
Phys. Rev. Lett. 66 (1991) 2712



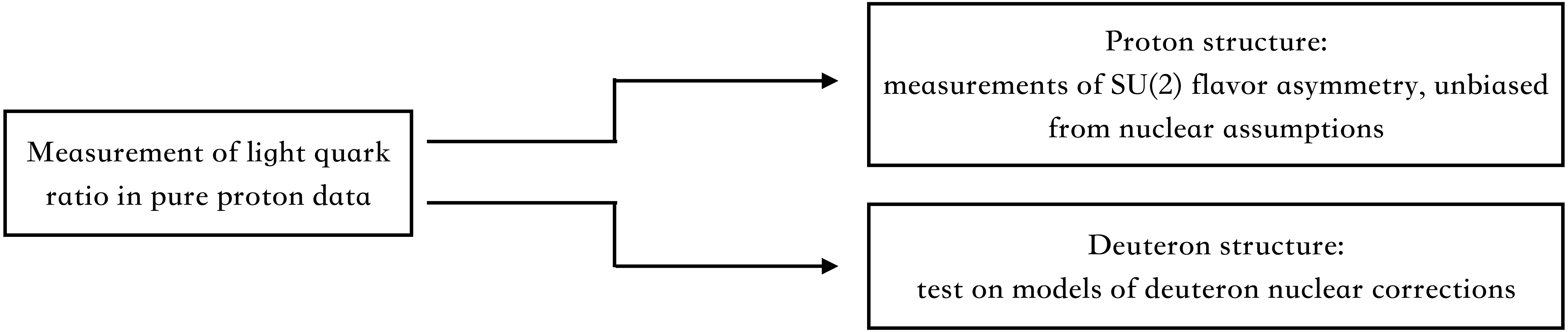
Proton 450GeV on H2/D2 targets
@ CERN SPS
Phys. Lett. B 332 (1994) 244



Positron 27.5GeV on H2/D2 targets
@ DESY HERA
Phys. Lett. B 81 (1998) 5519

Light quark ratio in pure proton data

- ➢ SU(2) flavor asymmetry: results from analyzing the deuteron data with certain deuteron nuclear corrections
- ➢ Deuteron data provide the only direct constraints on $\bar{d}/\bar{u}$ at $x \sim 0.1$ in existing PDF global analyses



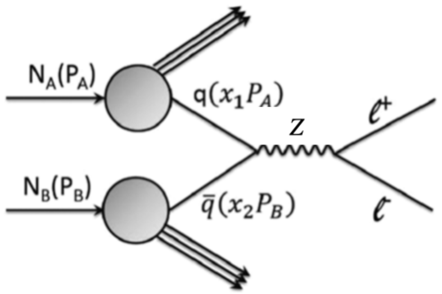
Today's talk

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

Weak interaction and flavor dependence

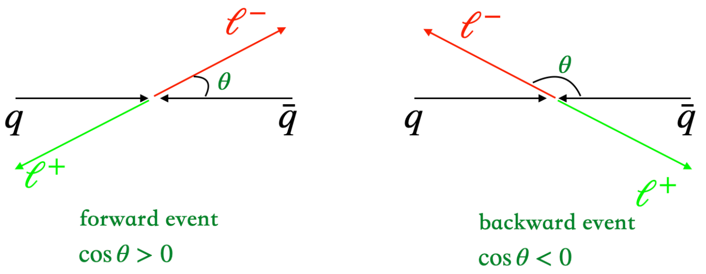
Z-exchanged neutral current interactions

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

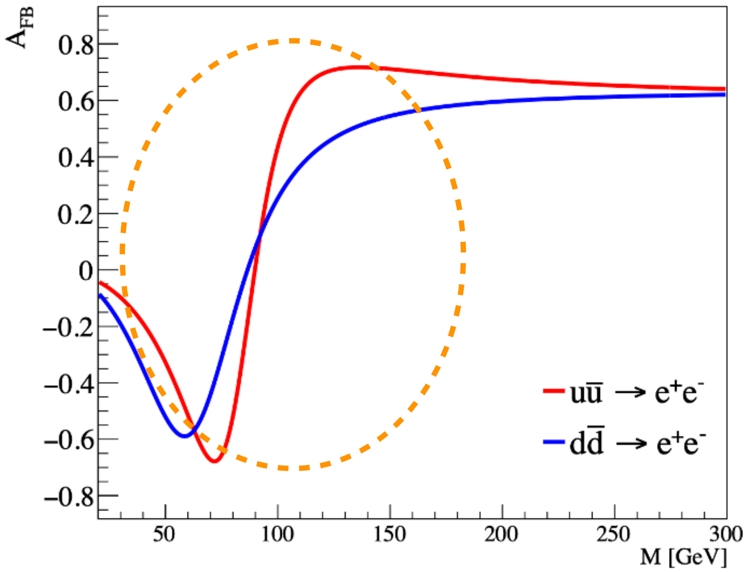


$$-\frac{g}{2\cos\theta_W}\sum_i \overline{\psi}_i\,\gamma^\mu(g_V^i - g_A^i\gamma^5)\,\psi_i\,Z_\mu$$

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



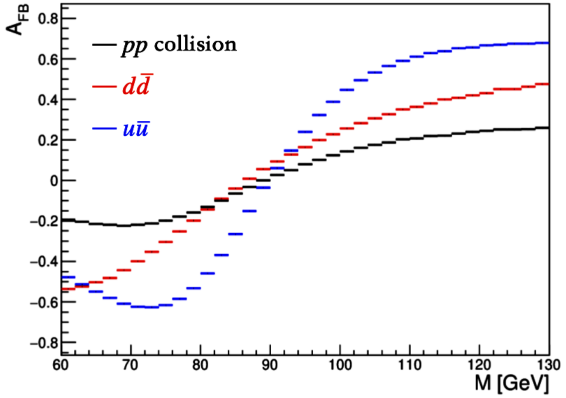
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

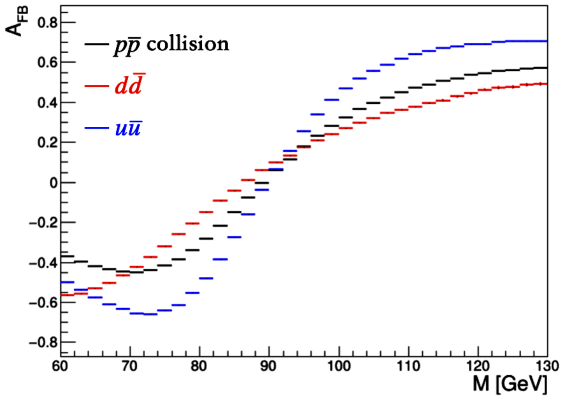


The up-type asymmetry A_{FB}^u is in different shape from the down-type asymmetry A_{FB}^d as a function of mass at the pole region of the Z boson

Factorization on A_{FB}

Proton structure parameters defined in the observed A_{FB} spectrum





$$A^h_{FB} = C_u[u(x);\bar{u}(x)] \times A^u_{FB}[\sin^2\theta_W] + C_d[d(x);\bar{d}(x)] \times A^d_{FB}[\sin^2\theta_W]$$

- Observed A_{FB} = combination of A^u_{FB} and A^d_{FB}
- Weighted by the structure parameter C_u and C_d
- Strictly holds beyond LO, by the factorization formalism

Phys. Rev. D106 (2022) 033001

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

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

For LHC's pp collisions

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

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

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

Note: $q(x)$ in this factorization is defined as the effective q_T-dependent parton distribution functions corresponding to quarks coupled to the Z boson in hard scattering

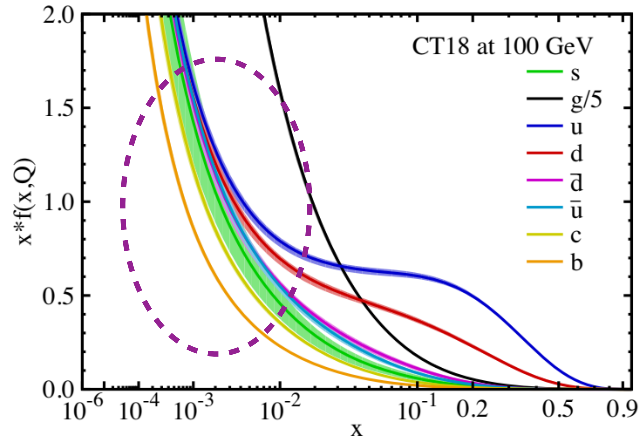
Factorization on A_{FB}

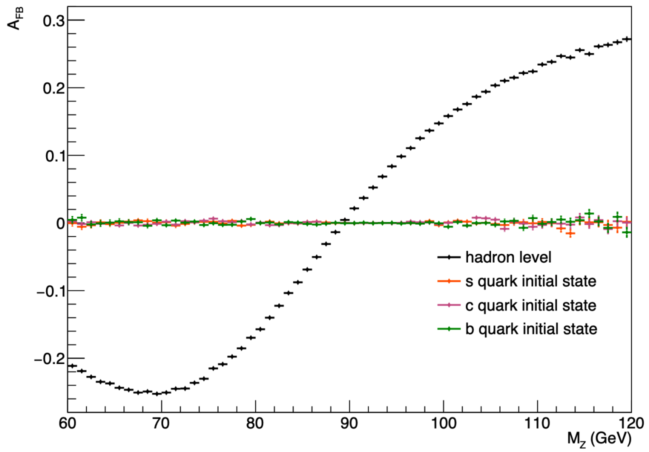
$$R = \frac{C_d}{C_u} \propto \frac{d(x_1)\bar{d}(x_2) - d(x_2)\bar{d}(x_1)}{u(x_1)\bar{u}(x_2) - u(x_2)\bar{u}(x_1)} \approx \frac{d(x_1) - \bar{d}(x_1)}{u(x_1) - \bar{u}(x_1)} \sim -\frac{\bar{d}}{\bar{u}}$$

$$x_{1,2} = \frac{\sqrt{M^2 + Q_T^2}}{\sqrt{s}} \times e^{\pm Y}, \ (x_1 > x_2)$$

- Light quark distributions are consistent at $x_2 < 0.01$ so that x_2 terms nearly cancelled in the ratio.

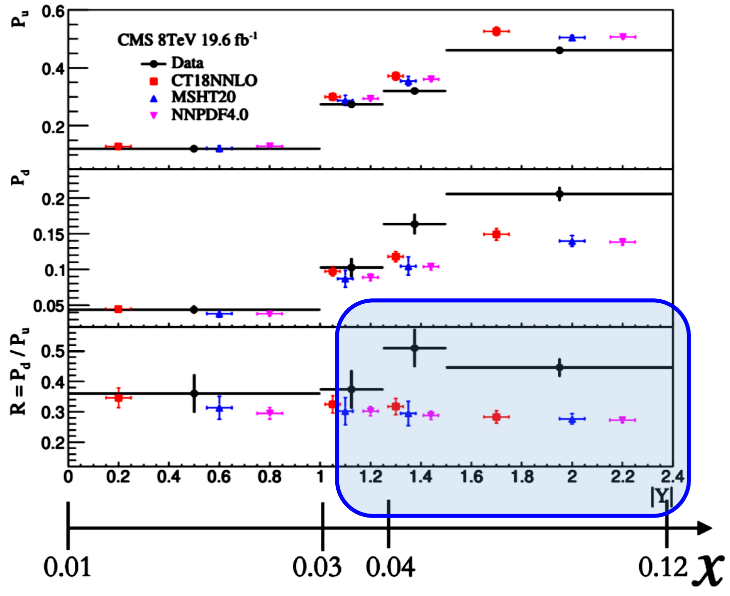
- Contributions of s, c, and b quarks are significantly suppressed as they have consistent anti-quark and quark distributions



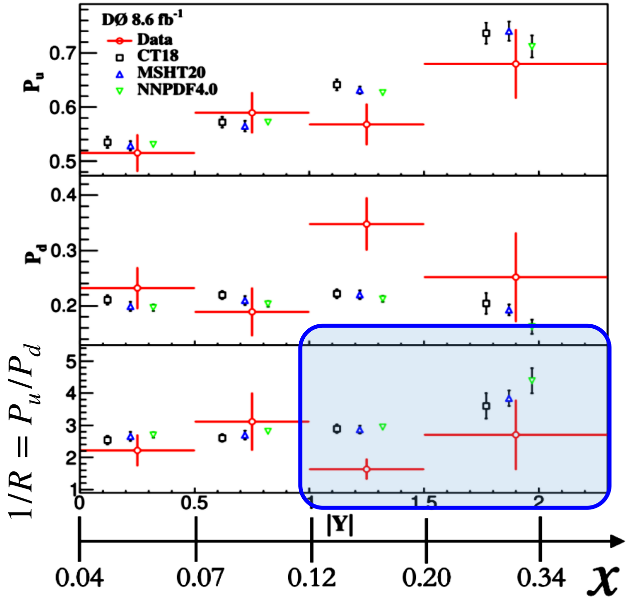


In conclusion: R is an experimental observable in pure proton interactions which provides almost direct constraint on $\bar{d}/\bar{u}$

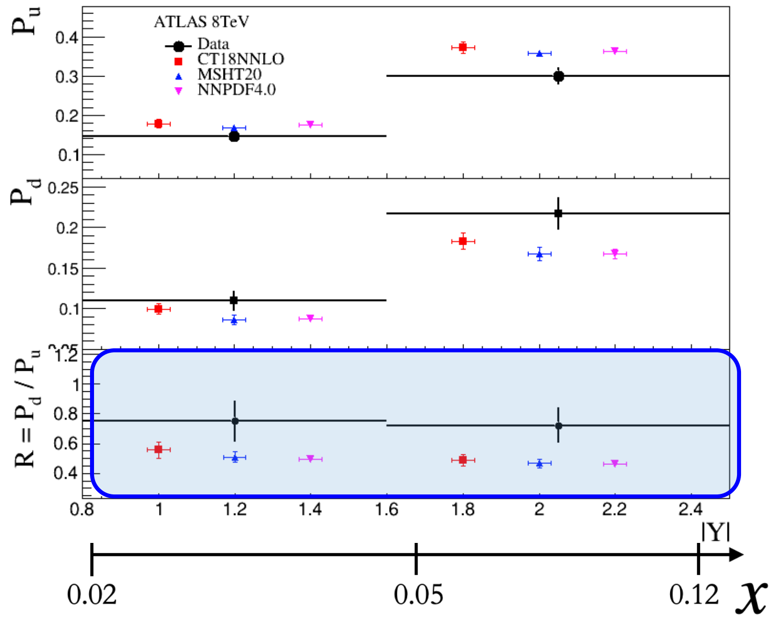
Experimental results



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



$1/R$ 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 (mainly constrained by the deuteron data)

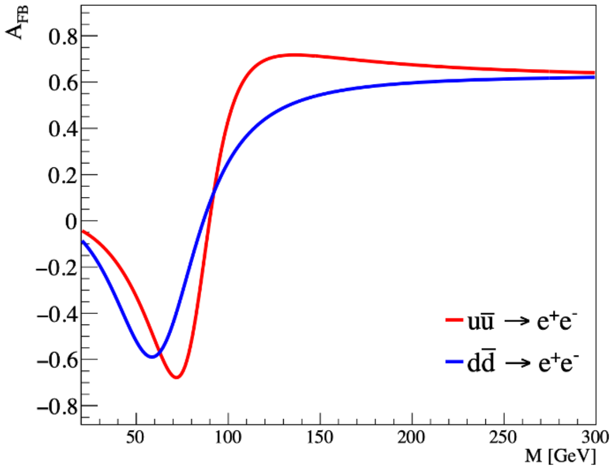
Phys. Rev. D 107 (2023) 054008

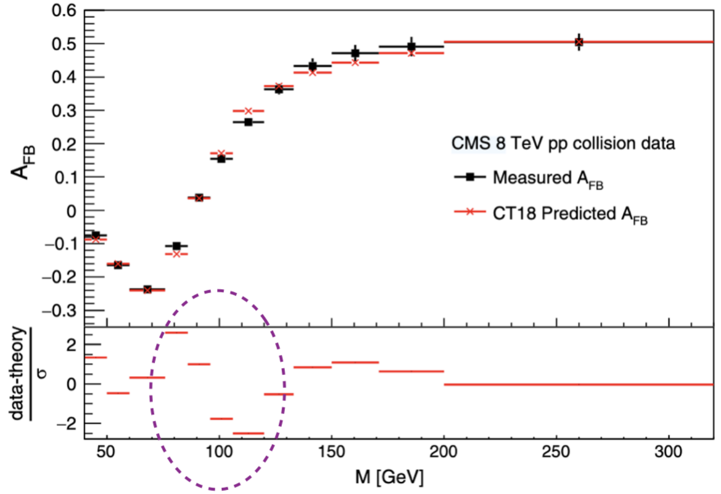
Phys. Rev. D 110 (2024) L091101

Phys. Rev. D 113 (2026) L011504

Experimental results

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





- ➢ A_{FB} is suppressed in the data with respect to the existing 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 $\bar{d}/\bar{u}$ and higher d/u

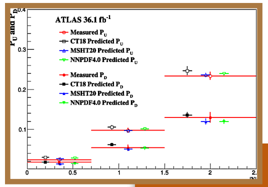
$$R = \frac{C_d}{C_u} \propto \frac{d(x_1) - \bar{d}(x_1)}{u(x_1) - \bar{u}(x_1)} \Longrightarrow \frac{\bar{d}}{\bar{u}} \downarrow \text{ and } \frac{d}{u} \uparrow$$

Negative correlation

Summary on the current A_{FB} measurements

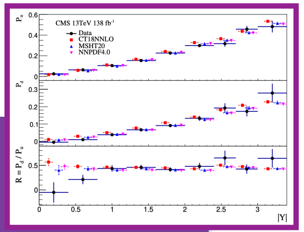
LHCb pp @ 13 TeV

on going, expected to provide independent checks for large x region



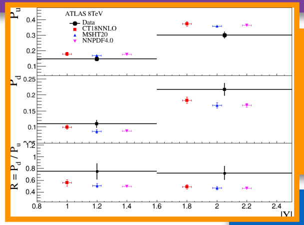
ATLAS pp @ 13 TeV

Consistent at small x region (preliminary)



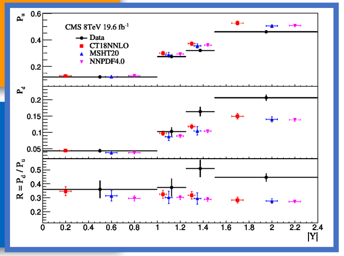
CMS pp @ 13 TeV

Discrepancy observed at high ZY region



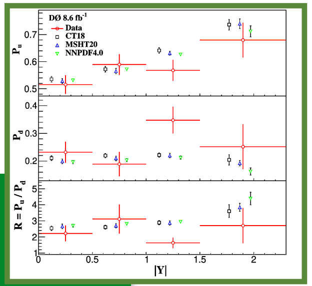
ATLAS pp @ 8 TeV (preliminary)

Discrepancy observed ($> 2\sigma$)



CMS pp @ 8 TeV

Discrepancy observed ($> 4\sigma$)



D0 $p\bar{p}$ @ 1.96 TeV

Discrepancy observed (>3.5σ)

x_1

0.01 0.03 0.05 0.08 0.12 0.2 0.4

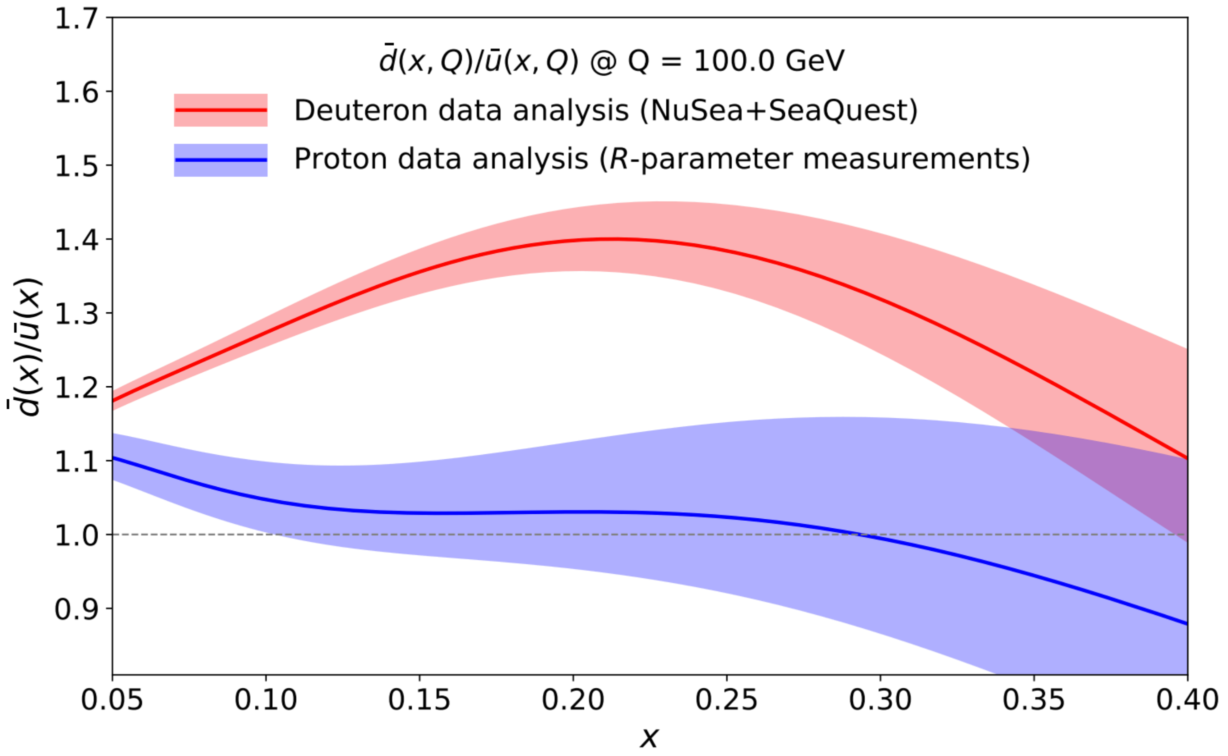
Global analysis of deuteron data and pure proton data

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

arXiv: 2510.08941

- For proton structure: indicating that the sea quarks generated under perturbative mechanisms, instead of SU(2) flavor asymmetry from non-perturbative dynamics

- For deuteron structure: an important evidence that the high energy deuteron might not be a classic proton+neutron system (with "small" deuteron nuclear corrections)



Global analysis:
fully follows CT18 procedure,
with all the other nuclear data removed
uncertainty bands are displayed for $\Delta\chi^2 = 1$

A rough estimation on the deuteron nuclear effects

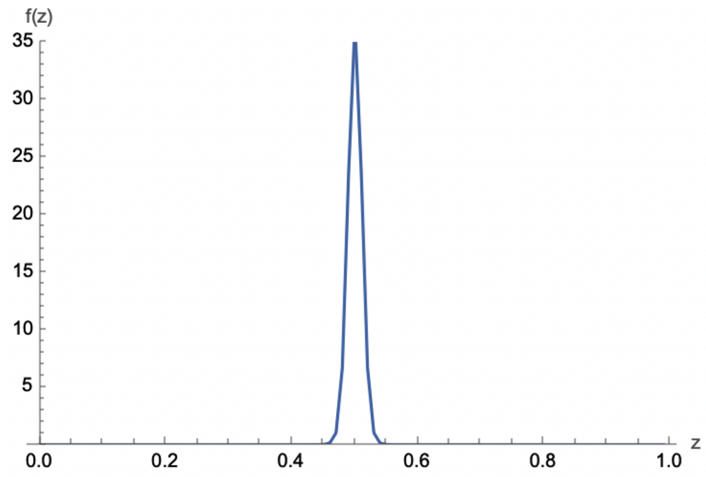
LMDF (longitudinal momentum distribution function) in classic deuteron structure picture

- ➢ Sharp peak: weak interaction between nucleons in deuteron (with binding energy ~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 in deuteron
- $\mathrm{LMDF}(z)$: Distribution of nucleons in deuteron
- $\mathcal{F}_q^N$: PDF of quarks in nucleons

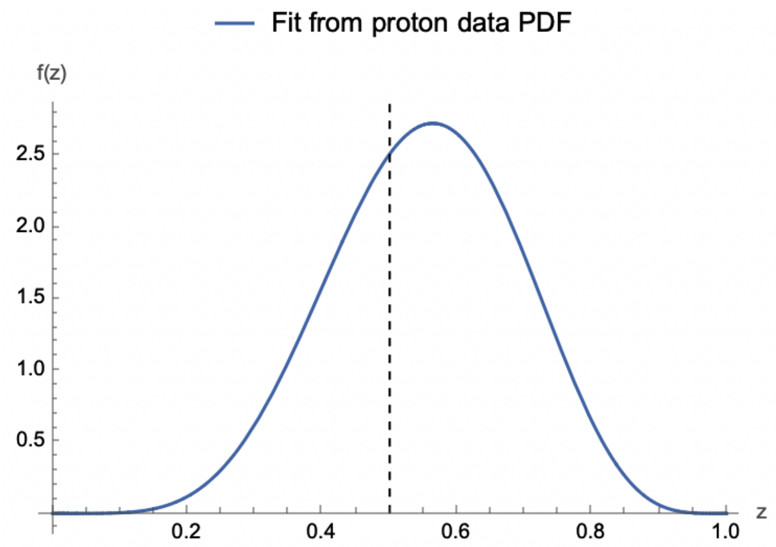
LMDF in classic picture



A rough estimation on the deuteron nuclear effects

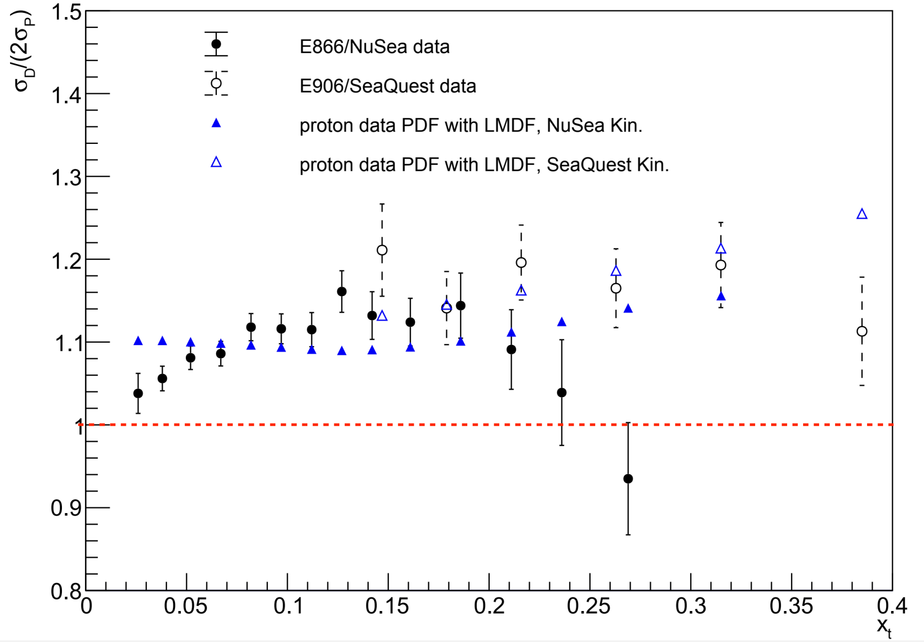
LMDF fitted from deuteron data, using pure proton PDF ($\bar{d}/\bar{u} \sim 1$)

- ➢ Significantly smeared: strong interaction between nucleons
- ➢ Shifted peak: not a simple proton+neutron structure



This could arise from:

short-distance structure, hidden color, octet-cluster, meson cloud, six-quark bond state, ⋯ ⋯



The pure proton PDF (R from A_{FB}, $\bar{d}/\bar{u} \sim 1$)⊗LMDF well explains the higher deuteron cross sections in NuSea/SeaQuest data

Conclusion

- Novel measurements (asymmetry of neutral-current Drell-Yan) of light quark ratio achieved in pure proton data

- Discrepancy observed compared to previous deuteron measurements:
  No SU(2) flavor asymmetry? Violation of assumptions of small deuteron nuclear corrections?

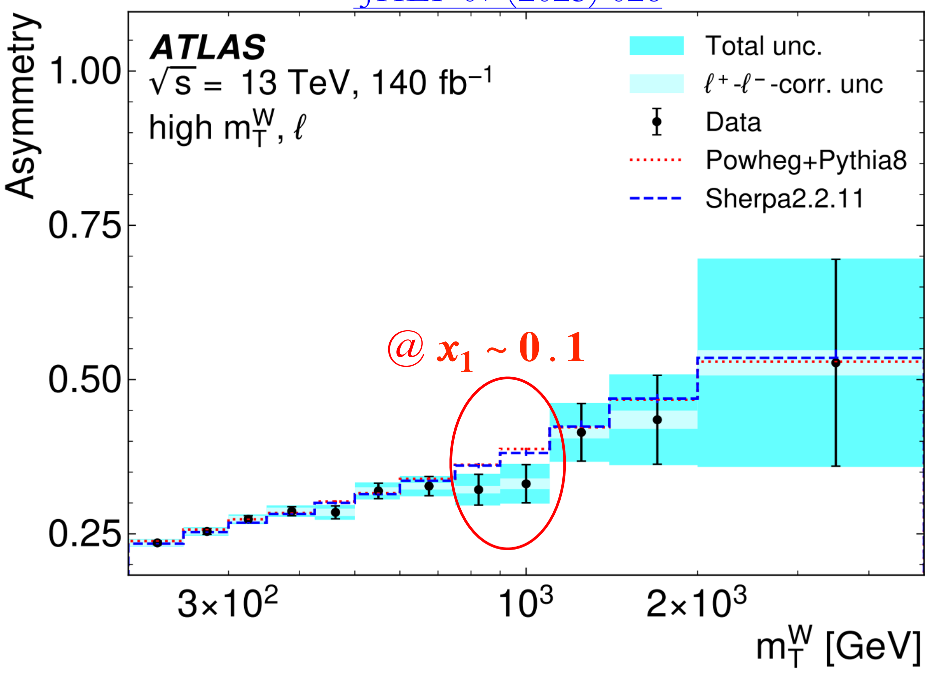
Thanks

Backup

Discrepancy with deuteron data

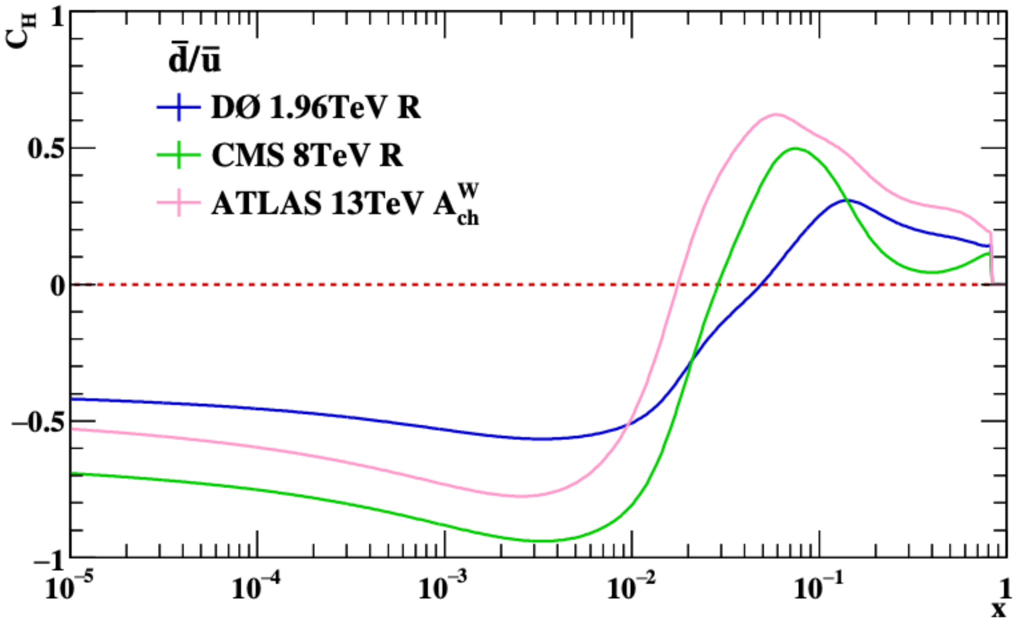
➢ ATLAS $W^{\pm}$-asymmetry measurement. Reaching large x at TeV high m_T

[JHEP 07 (2025) 026]



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

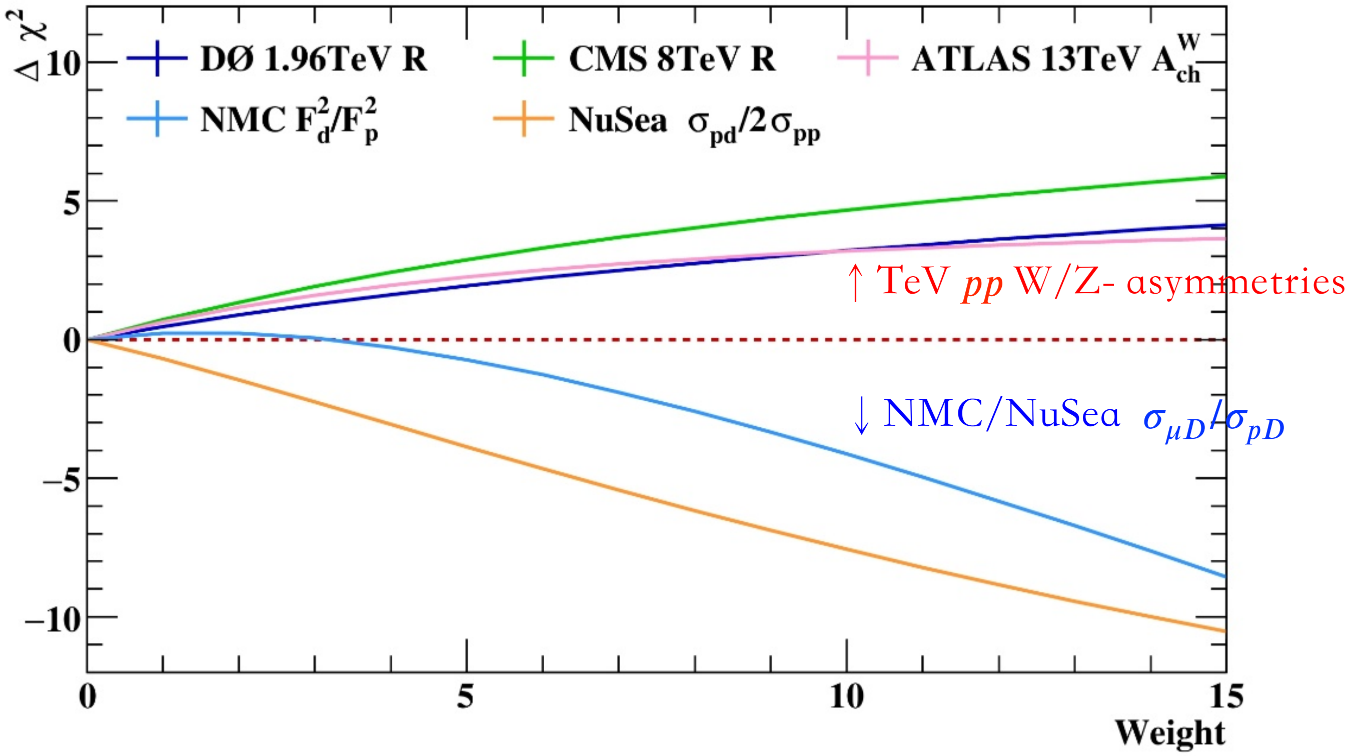
➢ Correlation study of W/Z-asymmetry at hadron colliders:



[Chin. Phys. C 50 (2026) 023107]

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

Discrepancy with deuteron data

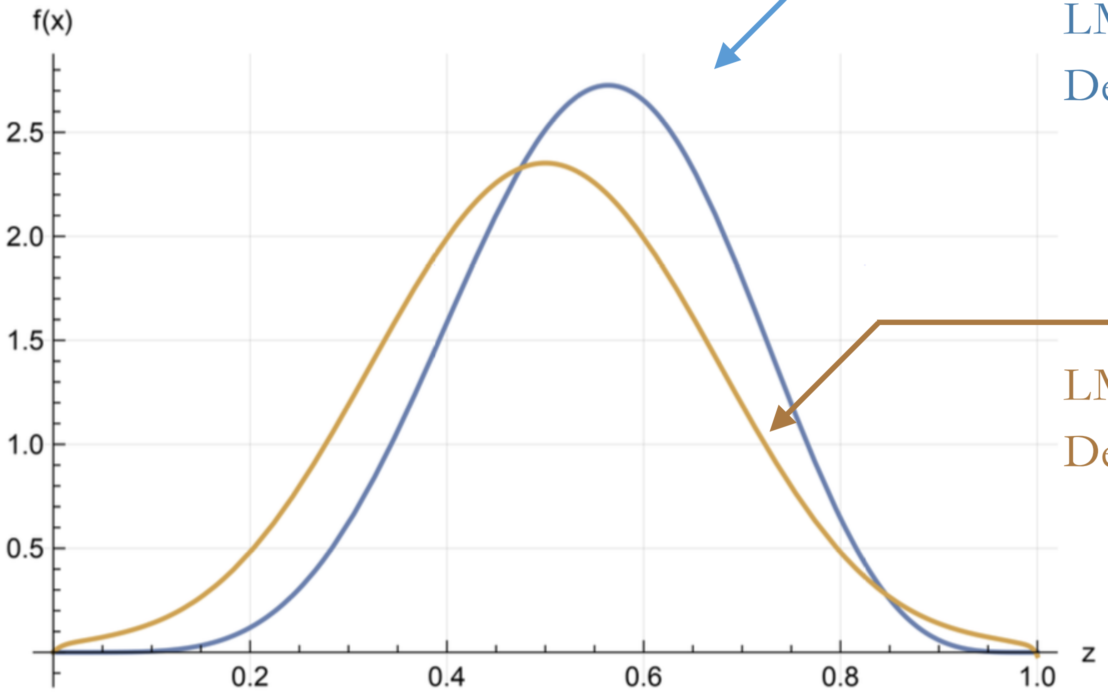


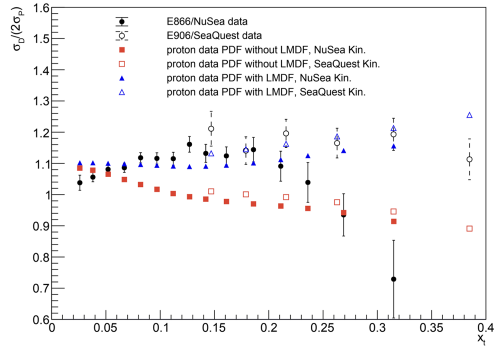
Chin. Phys. C 50 (2026) 023107

Cross checks with electromagnetic form factors

- LMDF fitting: large smearing

  consistent results from quark-level interactions and electromagnetic form factors





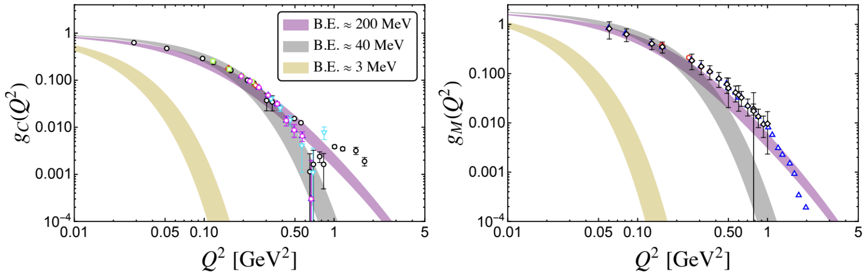
LMDF fitted from NuSea/SeaQuest data:

Deuteron breaks into quarks

LMDF fitted from electromagnetic form factors:

Deuteron overall shape

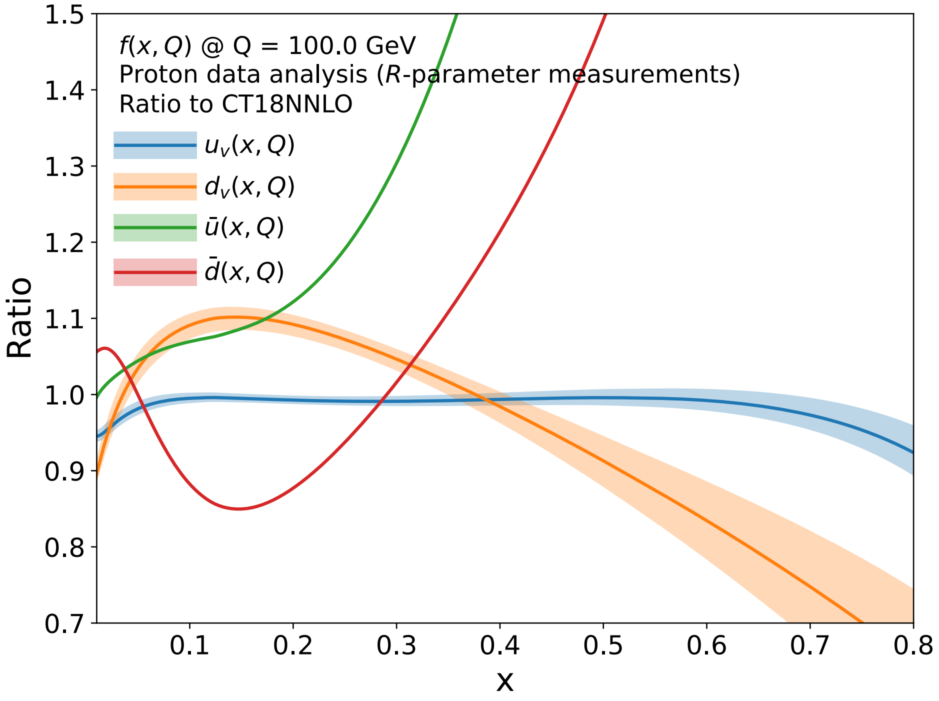
[Phys. Rev. D 113, 054008 (2026)]



What do we learn ?

Proton structure in pure proton data

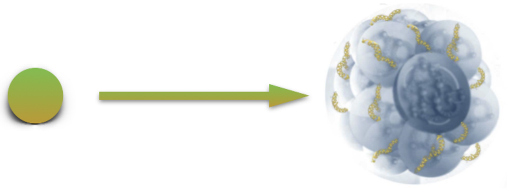
- ➢ For proton structure: avoid potential bias from nuclear data
- ➢ For nuclear structure: prior input to analyze high energy data
- ➢ Need new experimental observables and large x measurements



The proton PDFs would be significantly affected when nuclear data sets are removed.

What do we learn ?

Measurements on deuteron in Drell-Yan process



Why Drell-Yan?

With high energy hadron beam (or boosted forward kinematics), it is easy to individually probe anti-quarks and quarks inside deuteron

Probing anti-quarks in deuteron	Hadron beam → deuteron target
	Hadron → deuteron collision boosted toward deuteron direction
Probing quarks in deuteron	Deuteron beam → hadron target
	Hadron → deuteron collision boosted toward hadron direction