

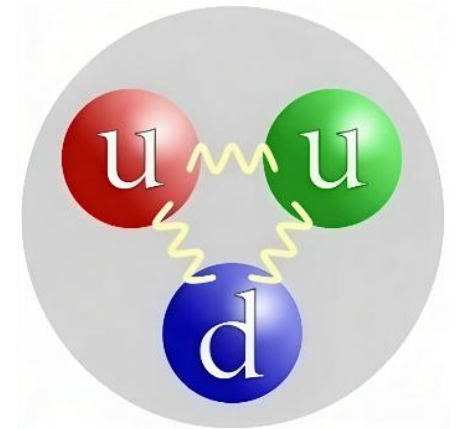


What could we learn from the W/Z asymmetries at hadron collider?

# LHC measurements: from electroweak to proton and nuclear structure

Liang Han

2026-04-30 presented at Bonn University



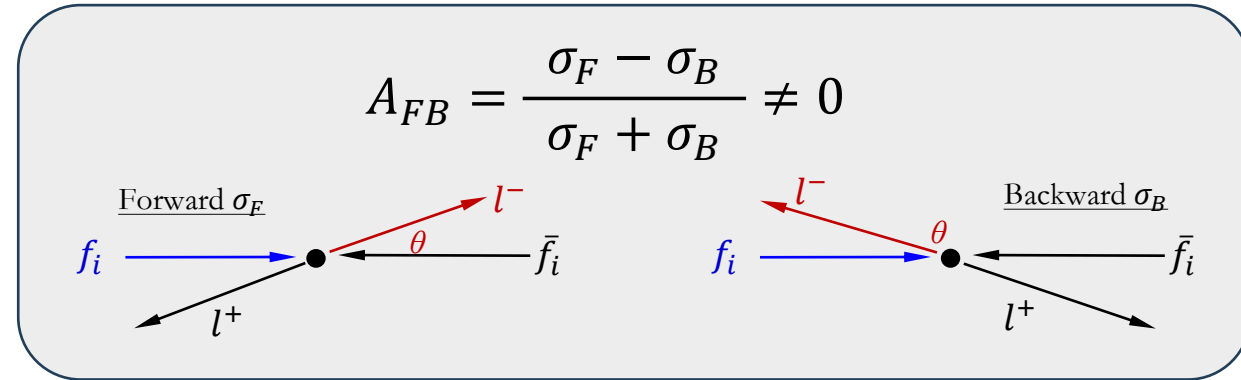
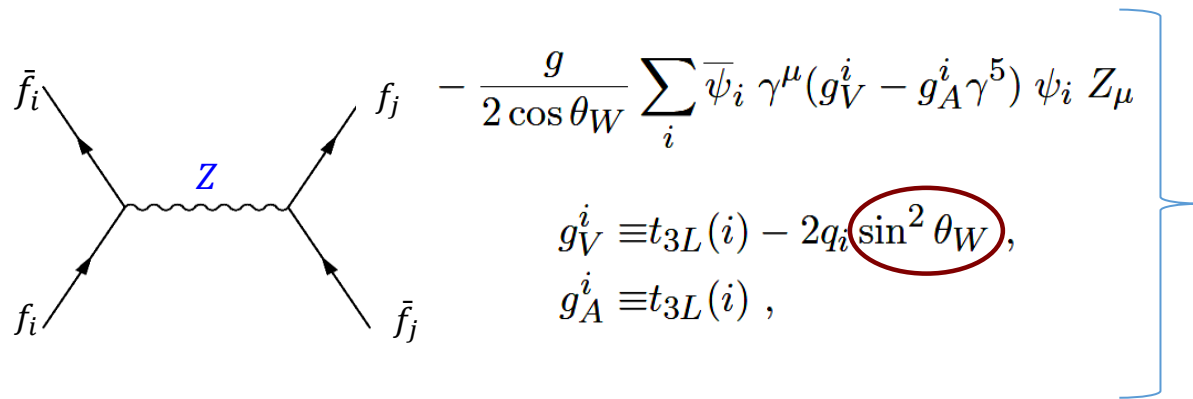


Prelude:

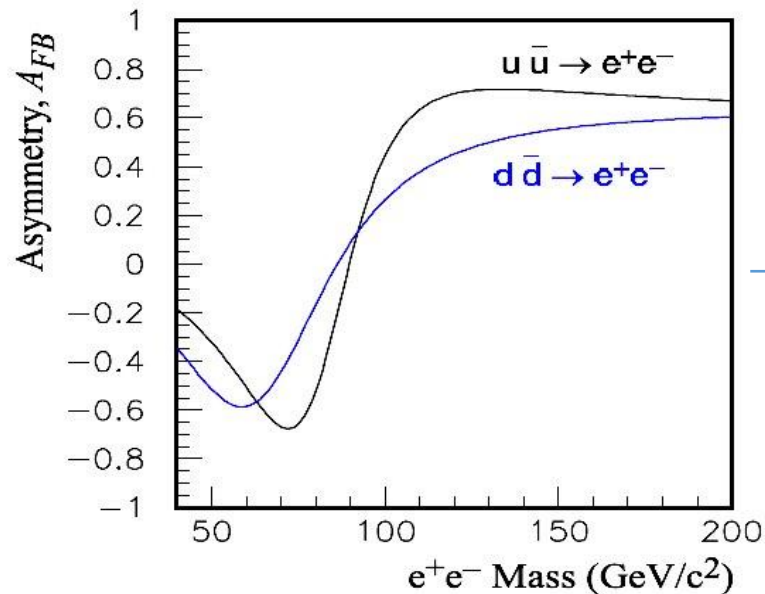
Electroweak asymmetry,  $A_{FB}$  and  $\sin^2 \theta_W$

# Electroweak asymmetry and $A_{FB}$ at the Z-pole

- Parity violation of Z-boson neutral current V-A coupling :



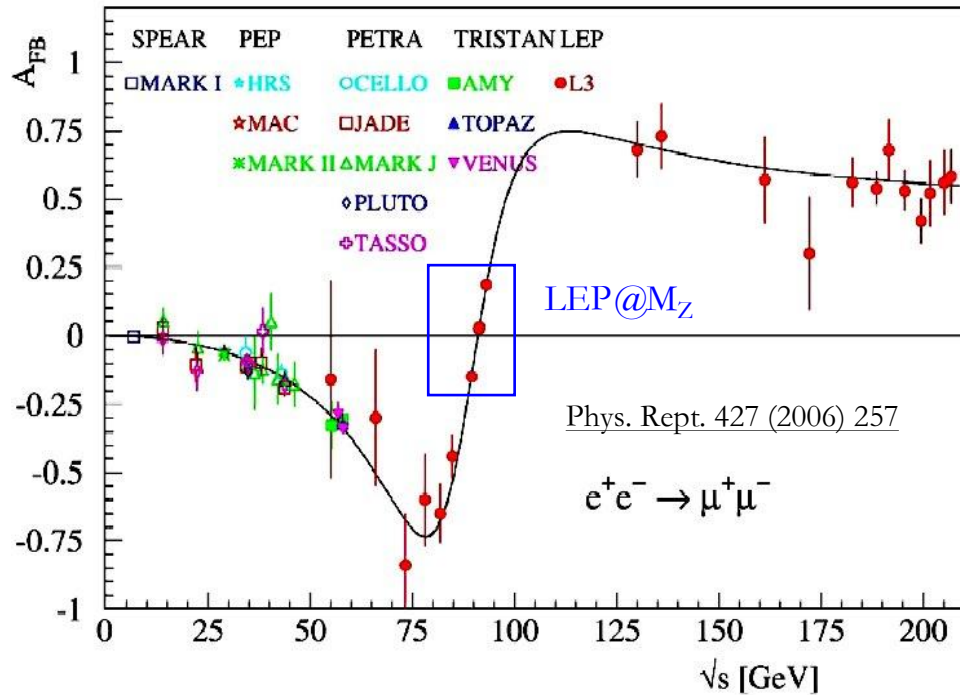
- The flavor dependence of neutral current asymmetry  $A_{FB}^u/A_{FB}^d$  around the Z-pole



$$\sigma[h_A h_B \rightarrow Z] = \int_0^1 \int_0^1 dx_1 dx_2 \sum_q \hat{\sigma}_q[q\bar{q} \rightarrow Z; x_1 x_2 s] \otimes f_{q/A}(x_1) \otimes f_{\bar{q}/B}(x_2) + (x_1 \leftrightarrow x_2)$$

# Precise measurements of $\sin^2\theta_W$ : LEP/SLD

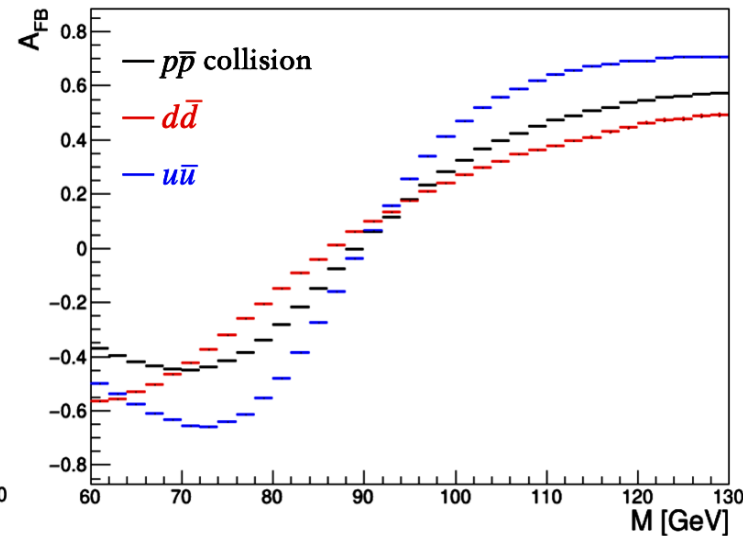
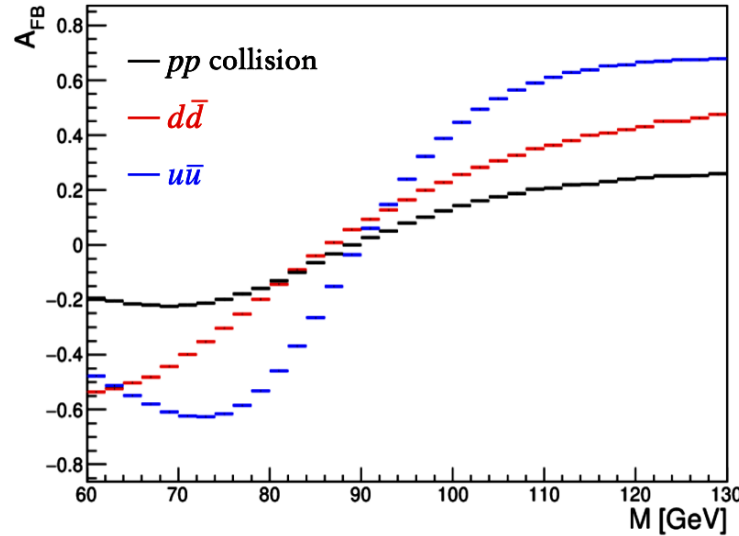
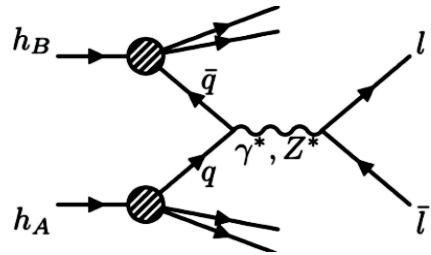
- Measurements at lepton colliders : relative precision of 0.1% achieved, limited with statistical uncertainties



The determination of $\sin^2\theta_W$	
LEP experiments	$0.23221 \pm 0.00029$
SLD experiment	$0.23098 \pm 0.00026$
LEP+SLD combined	$0.23153 \pm 0.00016$
Theory (PDG2024)	$0.23161 \pm 0.00004$ ( SM 2-loops )

# Precise measurements of $\sin^2\theta_W$ : Tevatron/LHC

- Measurements at hadron colliders : systematics dominated by the PDF-induced uncertainties



- Tevatron 1.96TeV  $p\bar{p}$  collision: [Phys. Rev. D 97\(2018\)112007](#)

$$\sin^2\theta_W[\text{Tevatron}] = 0.23148 \pm 0.00027 \text{ (stat.)} \pm 0.00005 \text{ (exp.)} \pm 0.00018 \text{ (PDF)}$$

- CMS 8TeV  $pp$  collision: [Eur. Phys. J. C78\(2018\)701](#)

$$\sin^2\theta_W[\text{CMS-8}] = 0.23101 \pm 0.00036 \text{ (stat.)} \pm 0.00018 \text{ (exp.)} \pm 0.00016 \text{ (QCD)} \pm 0.00031 \text{ (PDF)}$$

- CMS 13TeV  $pp$  collision: [Phys. Lett. B 866 \(2025\) 139526](#)

$$\sin^2\theta_W[\text{CMS-13}] = 0.23152 \pm 0.00010 \text{ (stat.)} \pm 0.00015 \text{ (exp.)} \pm 0.00008 \text{ (QCD)} \pm 0.00027 \text{ (PDF)}$$

# Observed $A_{FB}^h$ at hadron colliders and light quark ratio

- As a combination of  $A_{FB}^u$  and  $A_{FB}^d$ , the observed  $A_{FB}^h$  at hadron colliders should be sensitive to the relative weight between the light quark  $u(\bar{u})$  and  $d(\bar{d})$  inside proton

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

$\sin^2 \theta_W$



proton structure

- PDF-induced uncertainty on  $A_{FB}^h$  : the light quark ratio  $d(\bar{d})/u(\bar{u})$ , difficult to be experimentally constrained

Question: How are the light sea quark  $\bar{d}/\bar{u}$  of proton measured, and then described by PDFs ?



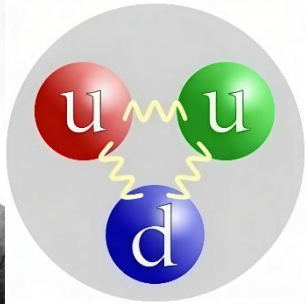
# Proton PDF, deuteron structure, and SU(2) flavour asymmetry

# The proton – from simple to comprehensive

- Proton: the lightest stable hadron, as a natural candidate to understand QCD and color confinement mechanism



Murray Gell-Mann  
(1929 - 2019)



Constituent Quark model

$p(uud)$

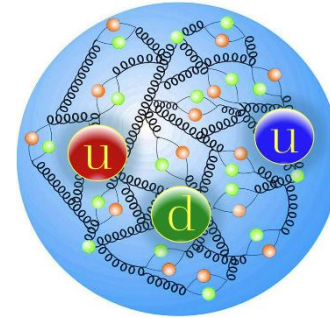
- High energy proton interactions:

$$\sigma = \sum_i q_i(x) \otimes \hat{\sigma}_q(q_i)$$

- Parton distribution function (PDF):

$$q_i(x) = a_0 x^{a_1 - 1} (1 - x)^{a_2} P_i(x; a_3, a_4, \dots)$$

The general form of non-perturbative parameterization as a function of parton  $i$  momentum ratio  $0 < x = \frac{E_i}{E_P} < 1$



Richard Feynman  
(1918 - 1988)

QCD-improved Parton model

$p(u_V d_V g u\bar{u} d\bar{d} s\bar{s} c\bar{c} \dots)$

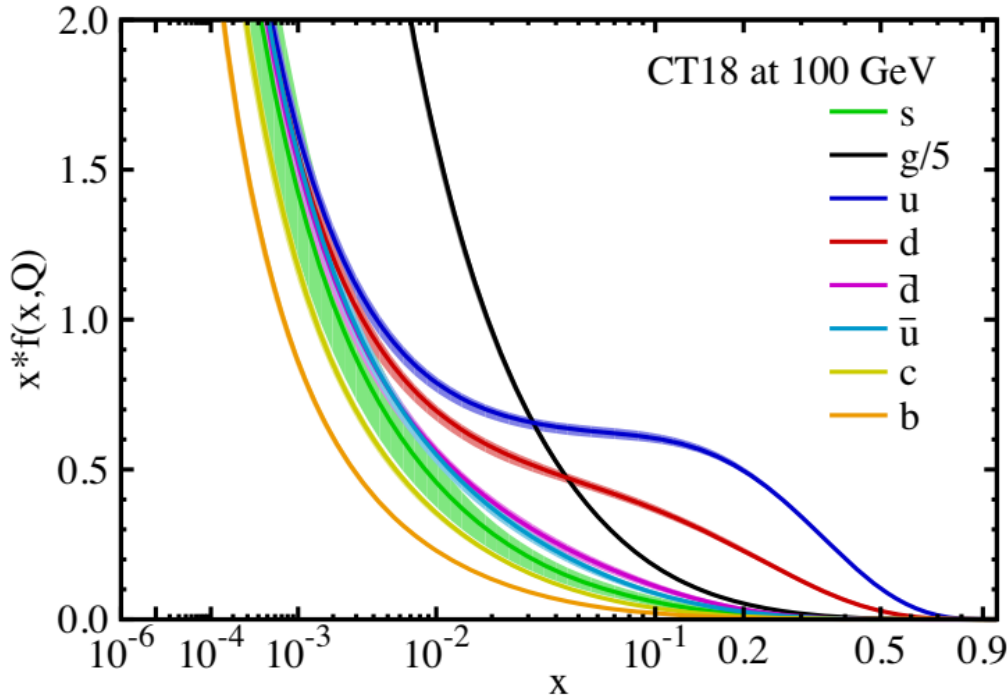
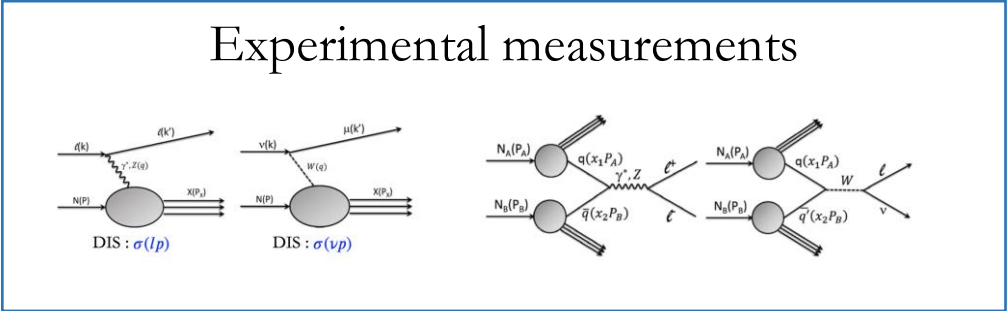
# QCD global analysis on PDFs

Factorized PDFs for  $u_V/d_V/\bar{u}/\bar{d}/s(\bar{s})/g$  at  $Q_0$  :

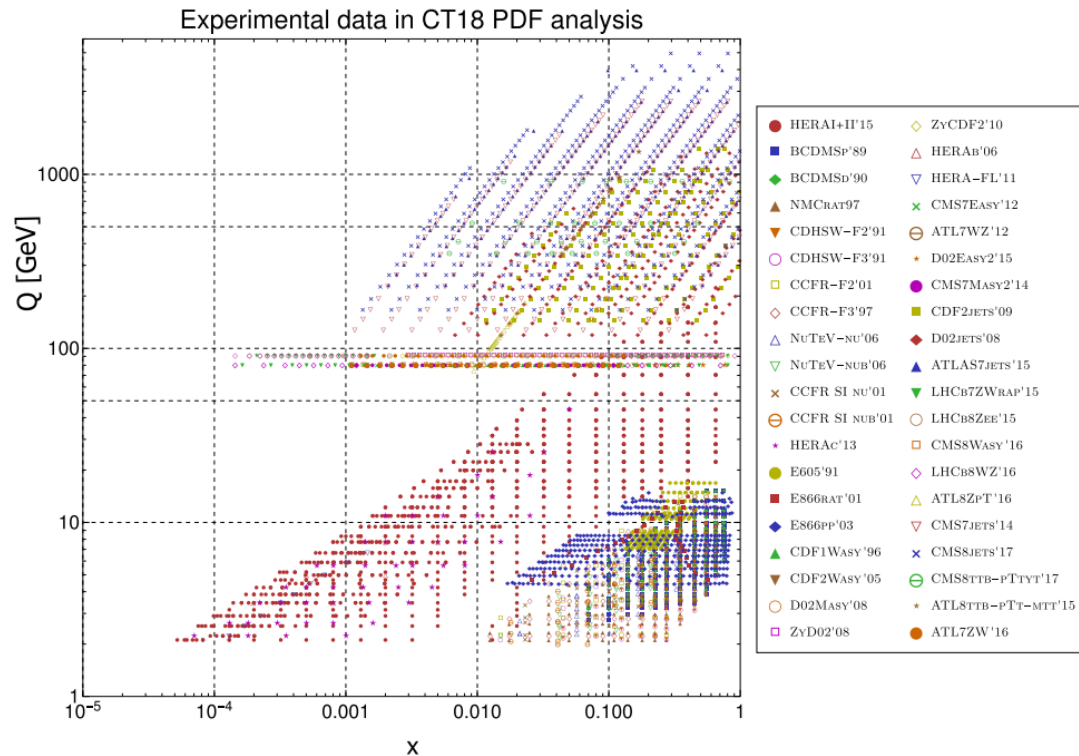
$$q(x) = a_0 x^{a_1} (1-x)^{a_2} \times \text{Pol}(x; a_i)$$

Perturbative evolution (DGLAP)  
Sum rules  
Hard process calculations

Predictions on physical observables  
Comparison with data  
QCD global analysis



# Two categories of experimental inputs



Constraints on quarks:

DIS

Drell-Yan

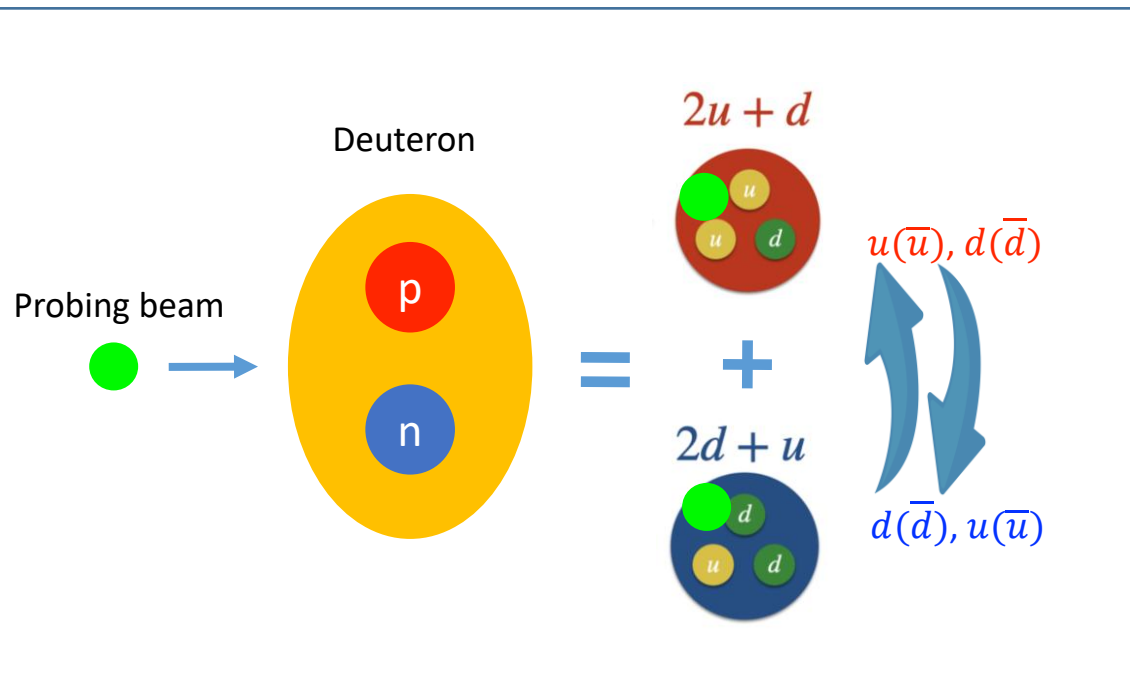
Constraints on gluons:

top and jet data

- Pure proton interactions: HERA/Tevatron/LHC, constraints on quarks and gluon in small  $x$  region
- Various nuclear interactions: fixed target experiments, constraints on the light quarks in large  $x$  region, with assumptions on nuclear structure

# An important nuclear observation: the $\bar{d}/\bar{u}$ ratio

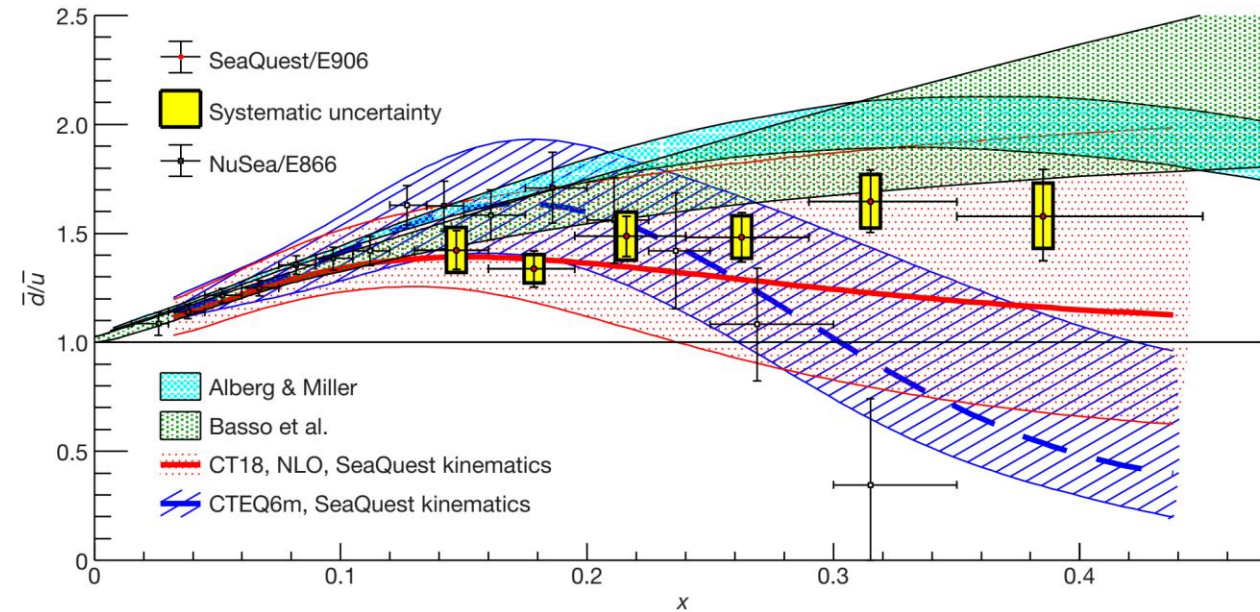
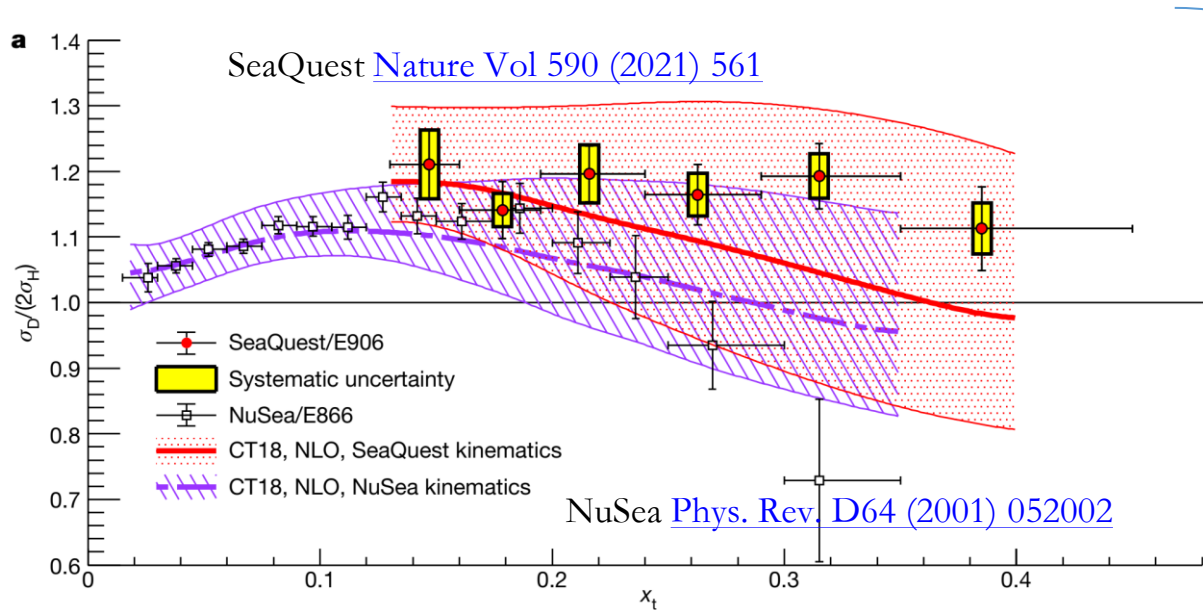
- How the sea quarks generated inside proton ?
  - Perturbative mechanism, i.e. gluon splitting  $\bar{d}/\bar{u} \sim 1$
  - Non-perturbative mechanism, i.e. SU(2) flavor asymmetry  $\bar{d} \neq \bar{u}$



- How to measure the light quark sea ?
  - Determined by comparing D-scatterings to p-ones under the same kinematic configuration
  - Assumptions :
    - ① Classic Deuteron picture as  $\sigma(D) = \sigma(p) + \sigma(n)$
    - ② Isospin symmetry between n-p as  $u_n(\bar{u}_n) = d_p(\bar{d}_p), d_n(\bar{d}_n) = u_p(\bar{u}_p)$

# Mystery: SU(2)-asymmetry of proton $\bar{d}/\bar{u}$ quark sea

- Excess of Deuteron scattering against proton  $\sigma_D/(2\sigma_H)$ : an unexpected higher deuteron cross section



Assumptions:

- Negligible nuclear effect, i.e.  $\sigma_{pD} \equiv \sigma_{pp} + \sigma_{pn}$
- Isospin symmetry, i.e.  $u_p \equiv d_n$ ,  $d_p \equiv u_n$ ,  
 $\bar{u}_p \equiv \bar{d}_n$ ,  $\bar{d}_p \equiv \bar{u}_n$ ,

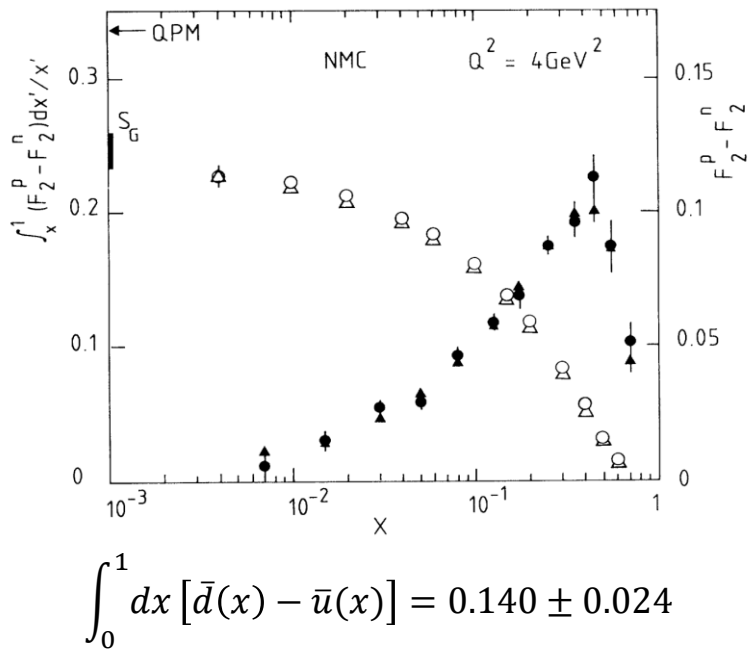
$$\frac{\sigma_{pD}}{\sigma_{pp}} \approx \left[ 1 + \frac{\bar{d}}{\bar{u}} \right]$$

SU(2) asymmetry of proton

$$\bar{d}/\bar{u} > 1 @ x \sim 0.1$$

# Mystery: SU(2)-asymmetry of proton $\bar{d}/\bar{u}$ sea-quark

➤ NMC inclusive DIS :

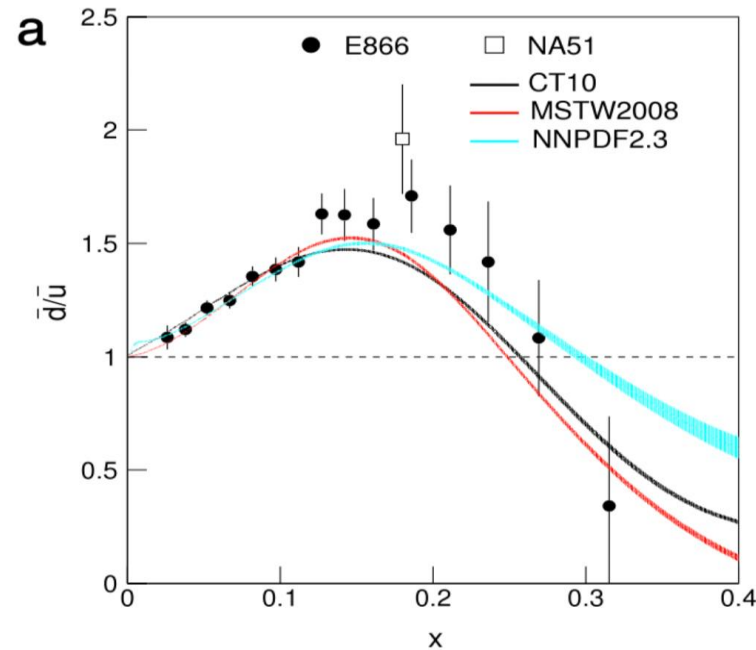


Muon 90-280 GeV on  $\text{H}_2/\text{D}_2$  targets

@ CERN SPS

[Phys. Rev. Lett. 66 \(1991\) 2712](#)

➤ NA51 Drell-Yan process

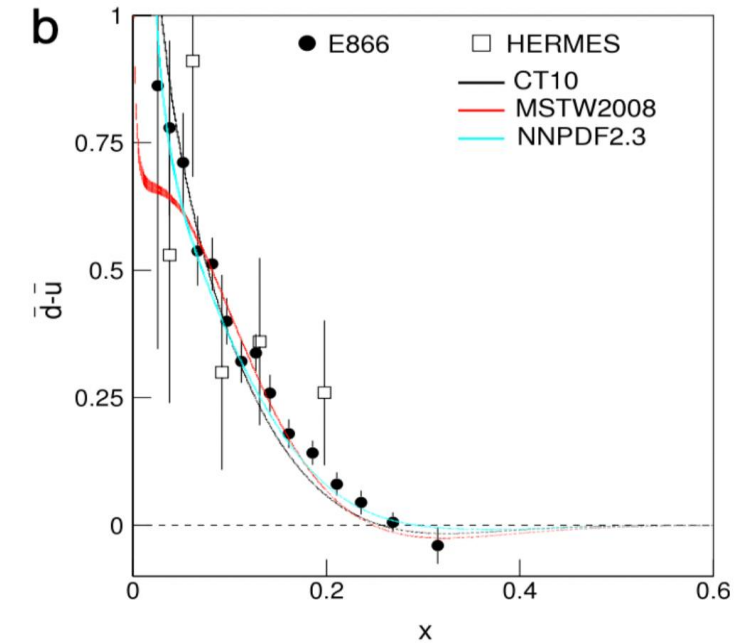


Proton 450 GeV on  $\text{H}_2/\text{D}_2$  targets

@ CERN SPS

[Phys. Lett. B 332 \(1994\) 244](#)

➤ HERMES semi-inclusive DIS

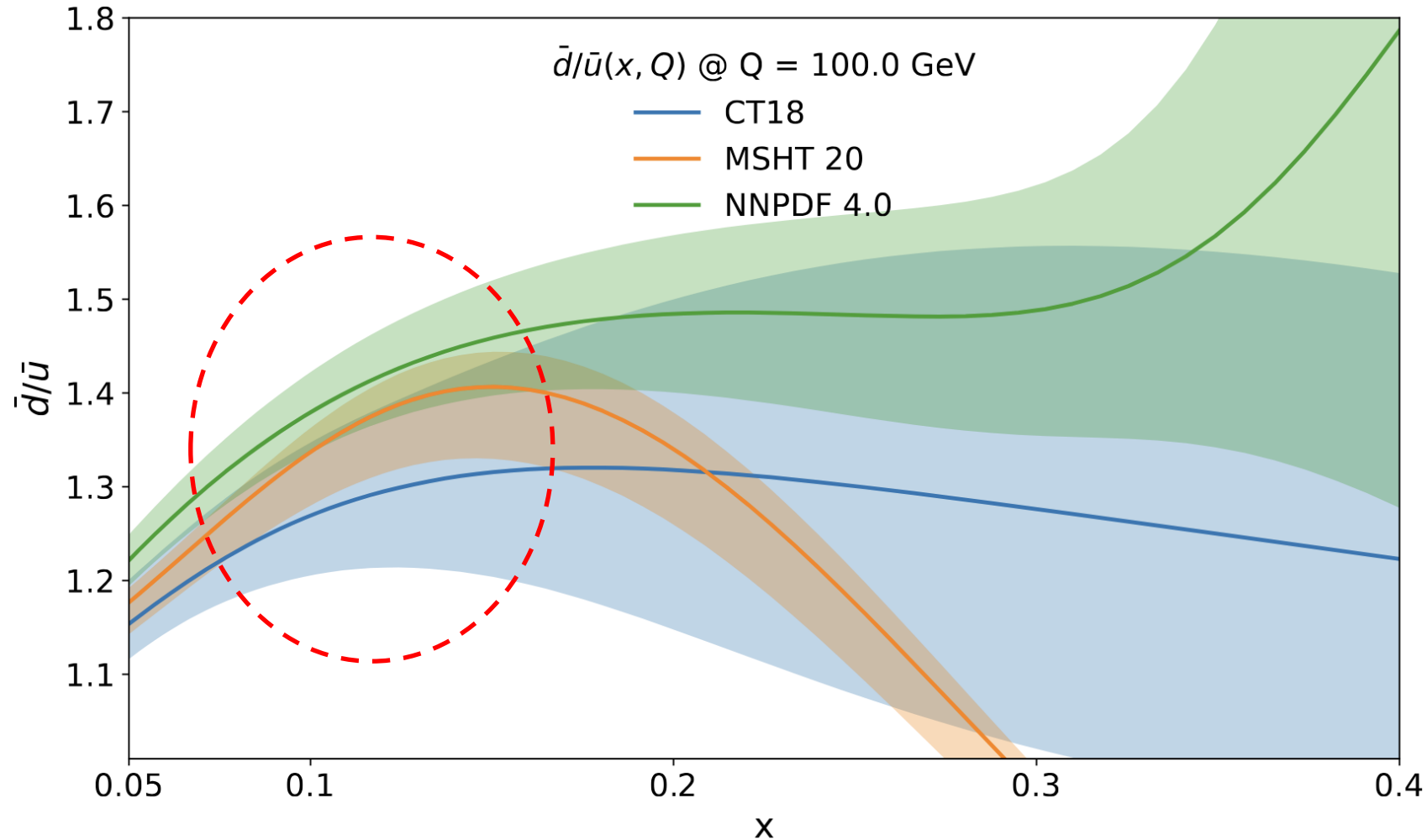


Positron 27.5 GeV on  $\text{H}_2/\text{D}_2$  targets

@ DESY HERA

[Phys. Lett. B 81 \(1998\) 5519](#)

# Modern PDF global fitting: the $\bar{d}/\bar{u}$ sea-quark of proton

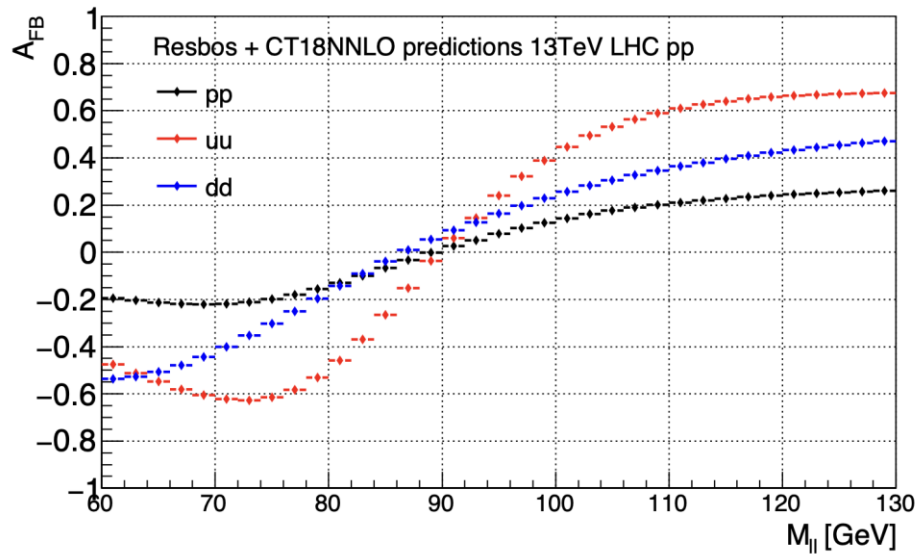


SU(2) flavor asymmetry of light quark sea in proton, determined by Deuteron scattering experiments.

Question: any way to verify the  $\bar{d}/\bar{u}$  asymmetry with unbiased pure proton data?

# Factorization and new proton structure observables

- The observed  $A_{FB}^h$  can be factorized, with well-defined proton structure parameters :



$$A_{FB}^h = C_u(Y, M, Q_T) \times A_{FB}^u(Y, M, Q_T; \sin^2 \theta_W) + C_d(Y, M, Q_T) \times A_{FB}^d(Y, M, Q_T; \sin^2 \theta_W)$$

- ① strictly holds at all orders  $\rightarrow$  define new observables
- ② decouple EW and proton  $\rightarrow$  joint fit for  $\sin^2 \theta_W$
- ③  $p$ -structure parameter  $C_u/C_d \rightarrow$  related to  $u/d$  respectively

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

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

For LHC  $pp$  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  $p\bar{p}$  collisions

[Chinese Phys. C 45 \(2021\) 053001](#)

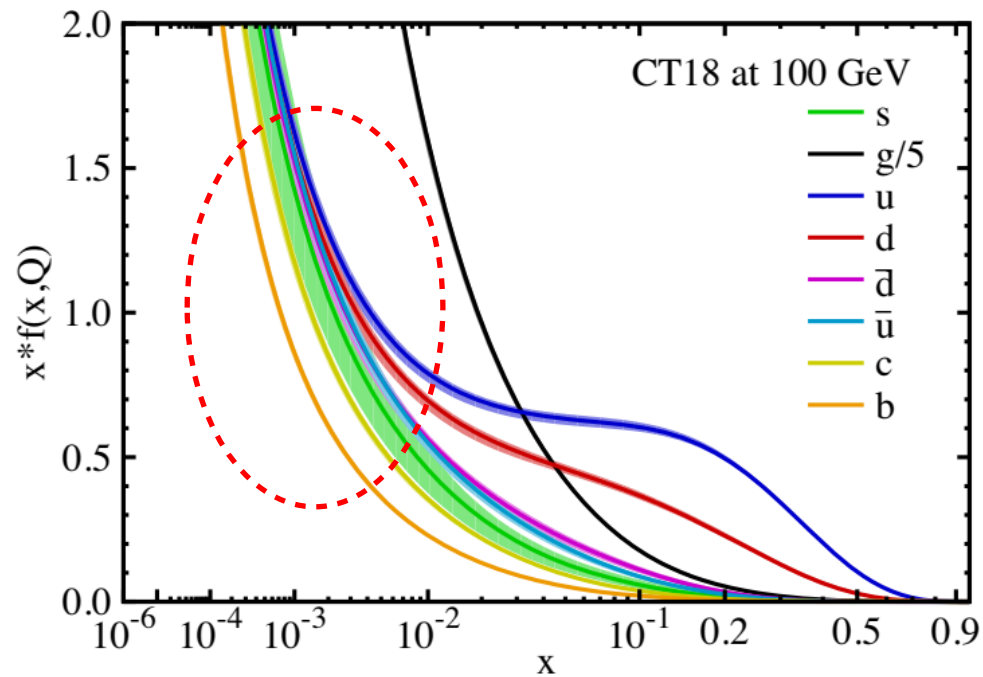
[Eur. Phys. J. C82 \(2022\) 368](#)

[Phys. Rev. D106 \(2022\) 033001](#)

# Factorization and new proton structure observables

- The light quark ratio at the Z-pole of hadron colliders :

$$R = \frac{C_d}{C_u} \propto \frac{d(x_1)\bar{d}(x_2) - d(x_2)\bar{d}(x_1)}{u(x_1)\bar{u}(x_2) - u(x_2)\bar{u}(x_1)} \approx \frac{d(x_1) - \bar{d}(x_1)}{u(x_1) - \bar{u}(x_1)} \equiv \frac{d_V(x_1)}{u_V(x_1)} \quad \text{where} \quad x_{1,2} = \frac{\sqrt{M^2 + Q_T^2}}{\sqrt{s}} e^{\pm Y}$$



- Typical  $x_1 \sim 0.1$  and  $x_2 < 0.01$ , and all light quark contributions are consistent as

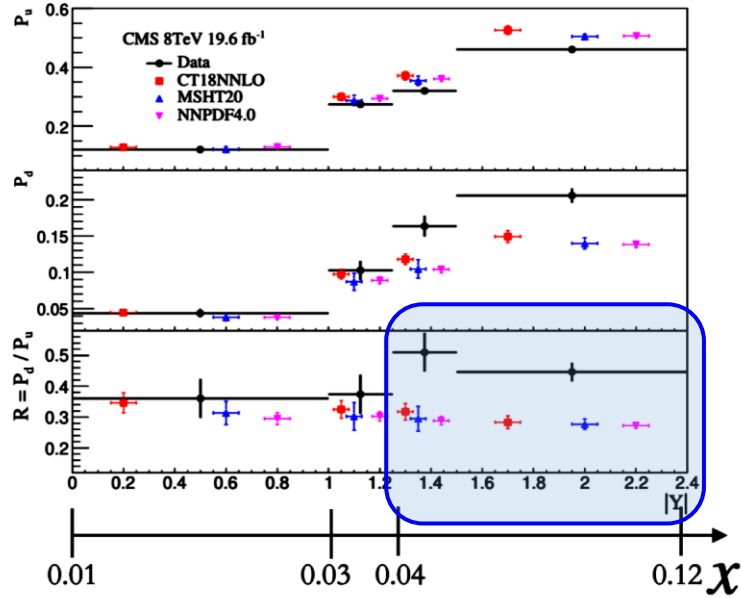
$$u(x_2) \approx \bar{u}(x_2) \approx d(x_2) \approx \bar{d}(x_2)$$

- The ratio of  $\bar{d}/\bar{u}$  and  $d/u$  are negatively correlated, due to the strict valence quark sum rule, therefore

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

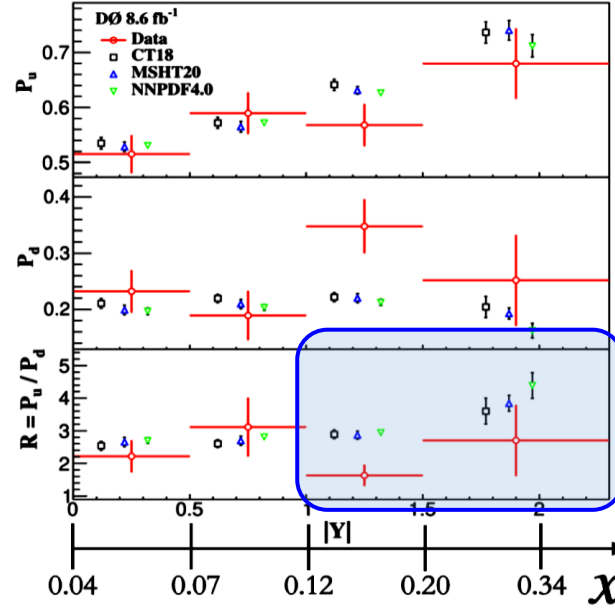
# The light quark ratio $R = C_d/C_u$ measurements at hadron colliders

➤ CMS 8 TeV  $pp A_{FB}^h$  fitting:



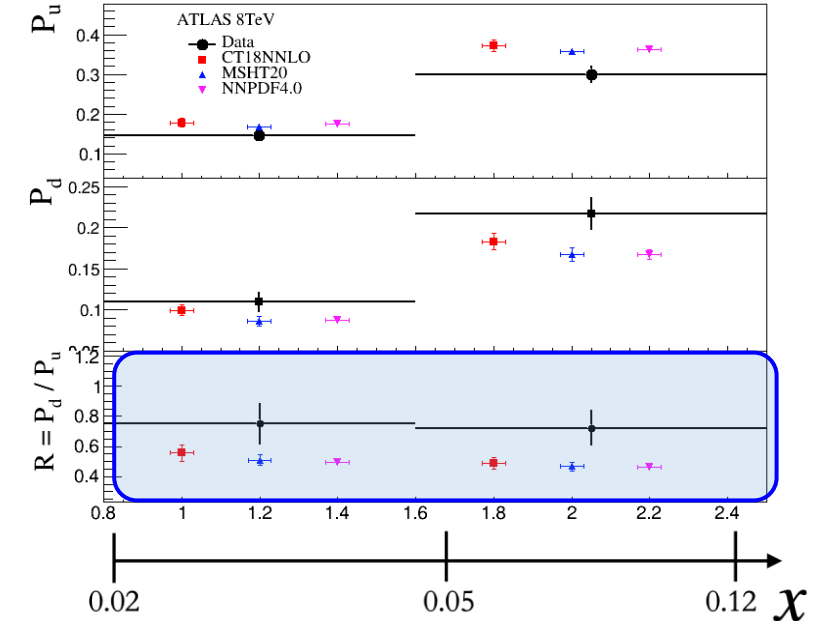
[Phys. Rev. D 113 \(2026\) L011504](#)

➤ DØ 1.96 TeV  $p\bar{p} A_{FB}^h$  measurement:



[Phys. Rev. D 110 \(2024\) L091101](#)

➤ ATLAS 8 TeV  $pp A_{FB}^h$  fitting:

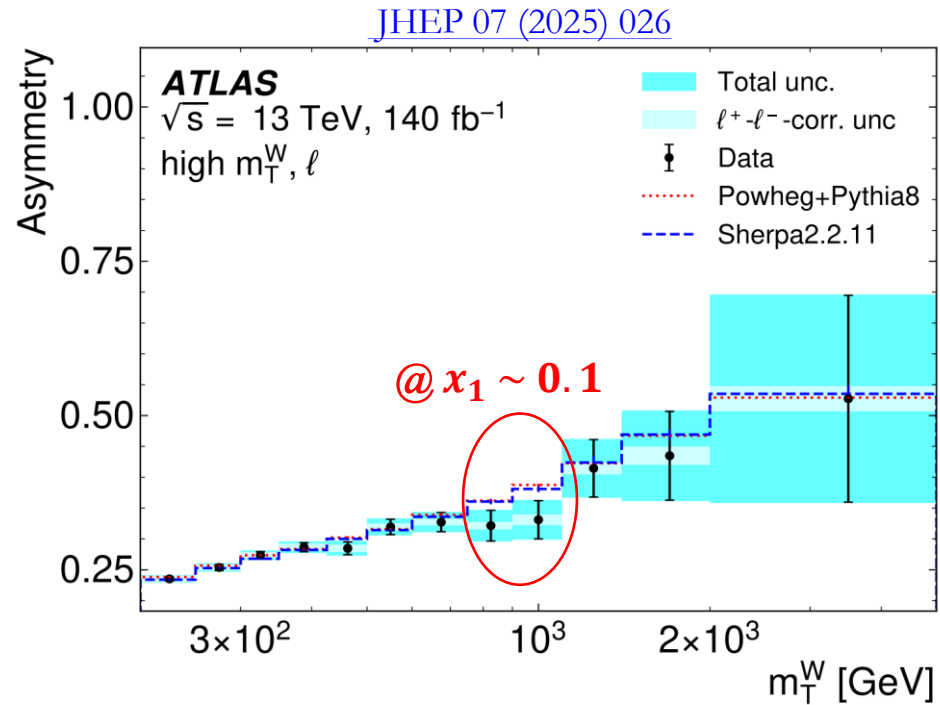


[Paper in preparation](#)

$R$ -observations at hadron collider indicate less  $\bar{d}$  @  $x > 0.1$  than PDF predictions

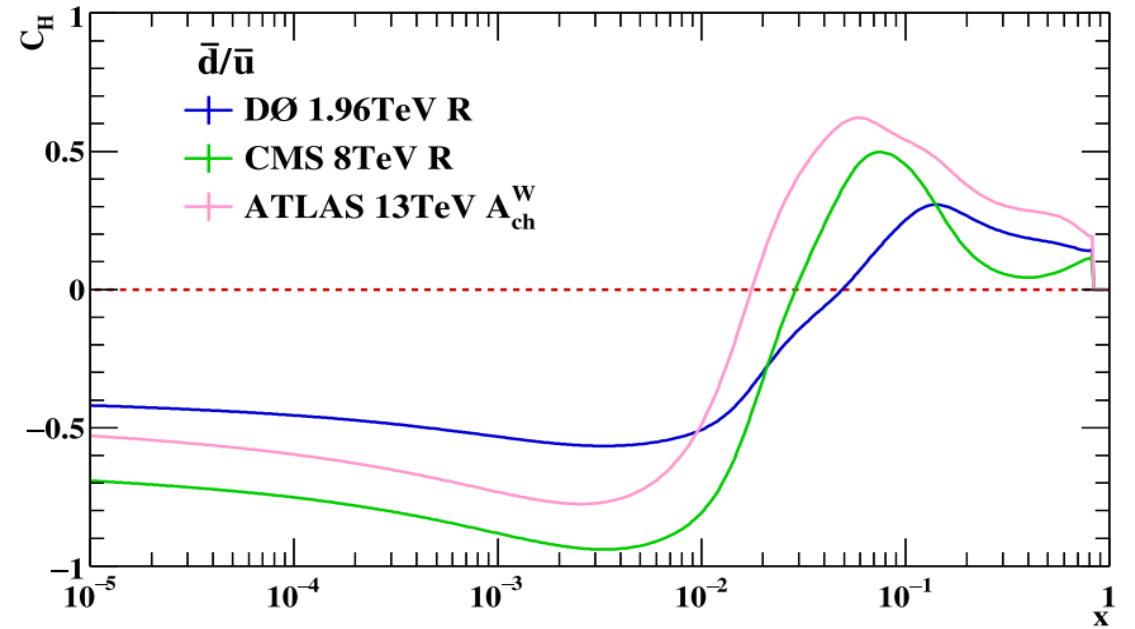
# Indirect evidence: W asymmetry at high $m_T$

- ATLAS  $W^\pm$ -asymmetry measurement:



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

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

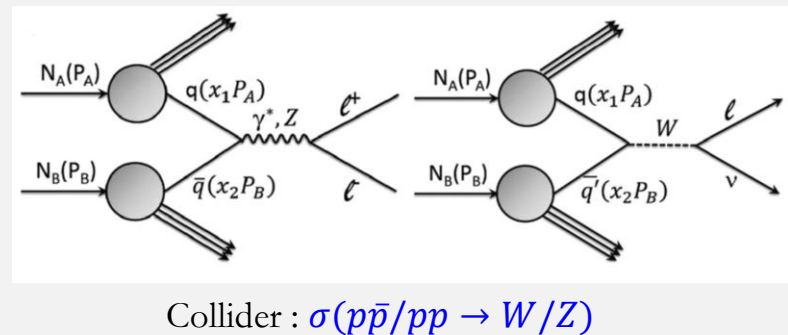
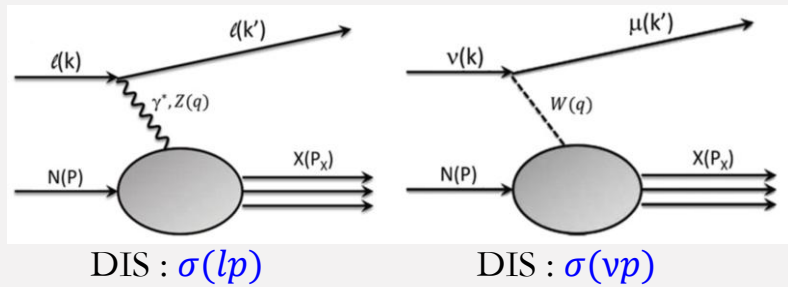


Chin. Phys. C 50 (2026) 023107

$$A_{ch}^W \propto \frac{(u + \bar{d}) - (\bar{u} + d)}{u + \bar{u} + \bar{d} + d} = \frac{u_V - d_V}{u + \bar{u} + \bar{d} + d}$$

# Global fitting of proton data PDF

- DGLAP evolution: APFELXX/HOPPET library;
- DIS: structure function/fixed target Drell-Yan @ NNLO;
- Collider: W/Z @ N3LL+NNLO, APPLGrid+ResBos2;
- Modular designed, written in C++;
- Consistency check with CT18: exactly the same ;
- Input-0 : [proton cross-sections](#) from HERA to LHC.



Input-1(a) :

NuSea + SeaQuest  $\sigma_{pD}/(2\sigma_{pp})$

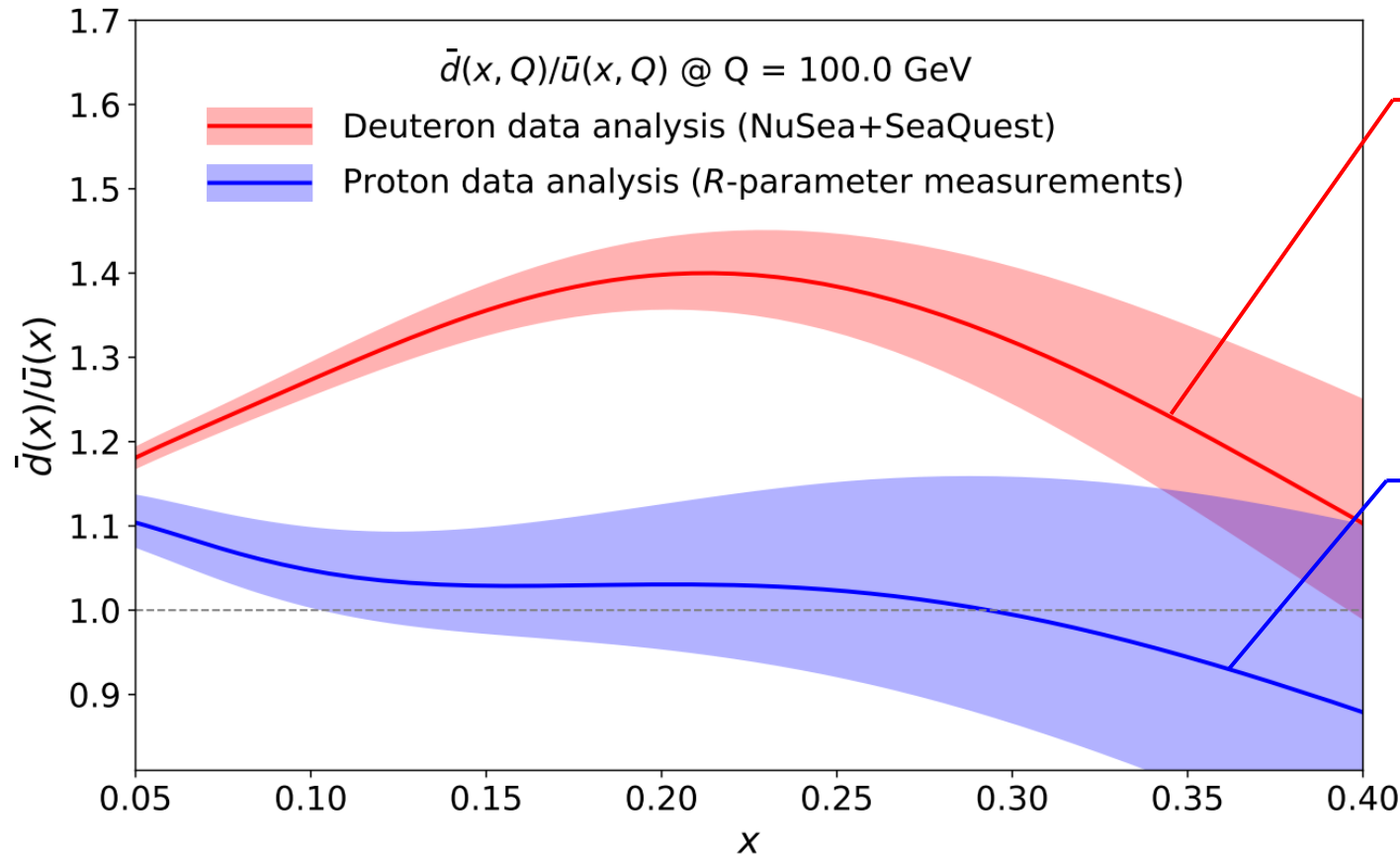
$$\bar{d}/\bar{u} > 1?$$

Input-1(b) :

CMS8 + DØ  $A_{FB}^h$  new observables

# Global analysis of deuteron data vs $A_{FB}^h$ measurements

- The R-parameter measurements of  $A_{FB}^h$  yield a light sea  $\bar{d}/\bar{u}$  ratio close to unity



Proton scattering  $\sigma_{lp/pp}$  baseline + NuSea/SeaQuest

- Deuteron: in high energy region, the classic D(n,p) picture may not be held

Proton scattering  $\sigma_{lp/pp}$  baseline + DØ/CMS  $A_{FB}^h-R$

- Proton: the sea quarks generated under pQCD, instead of SU(2) flavor asymmetry

[arXiv: 2510.08941](https://arxiv.org/abs/2510.08941)

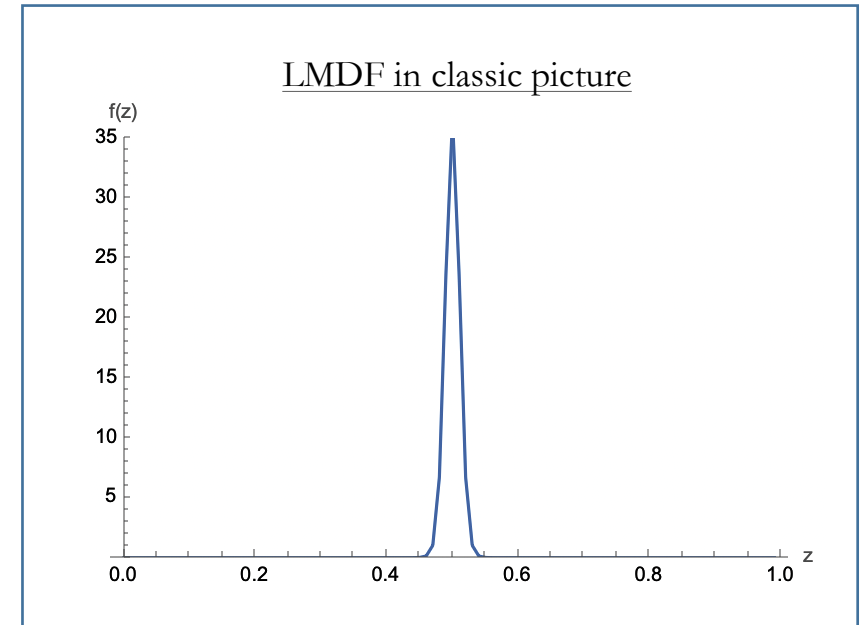
# A rough estimation of deuteron nuclear effect

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

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

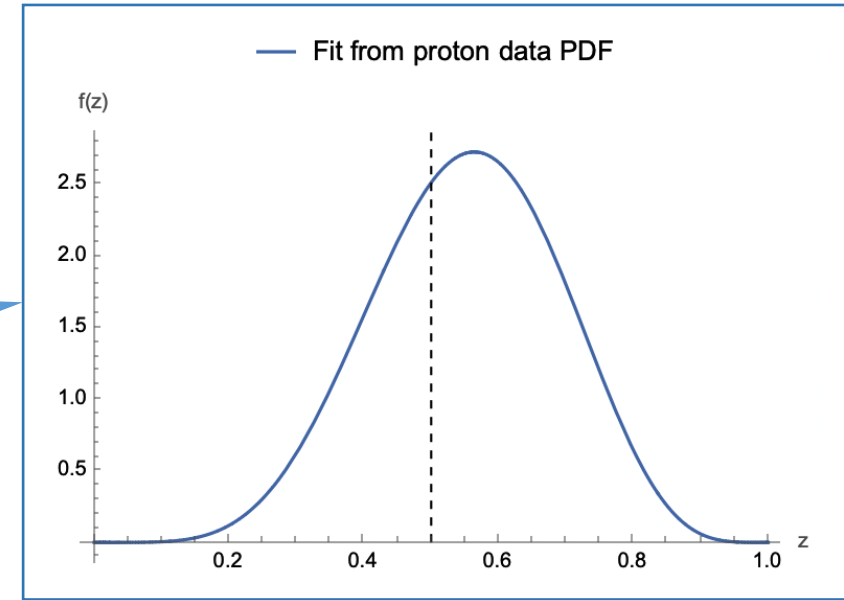
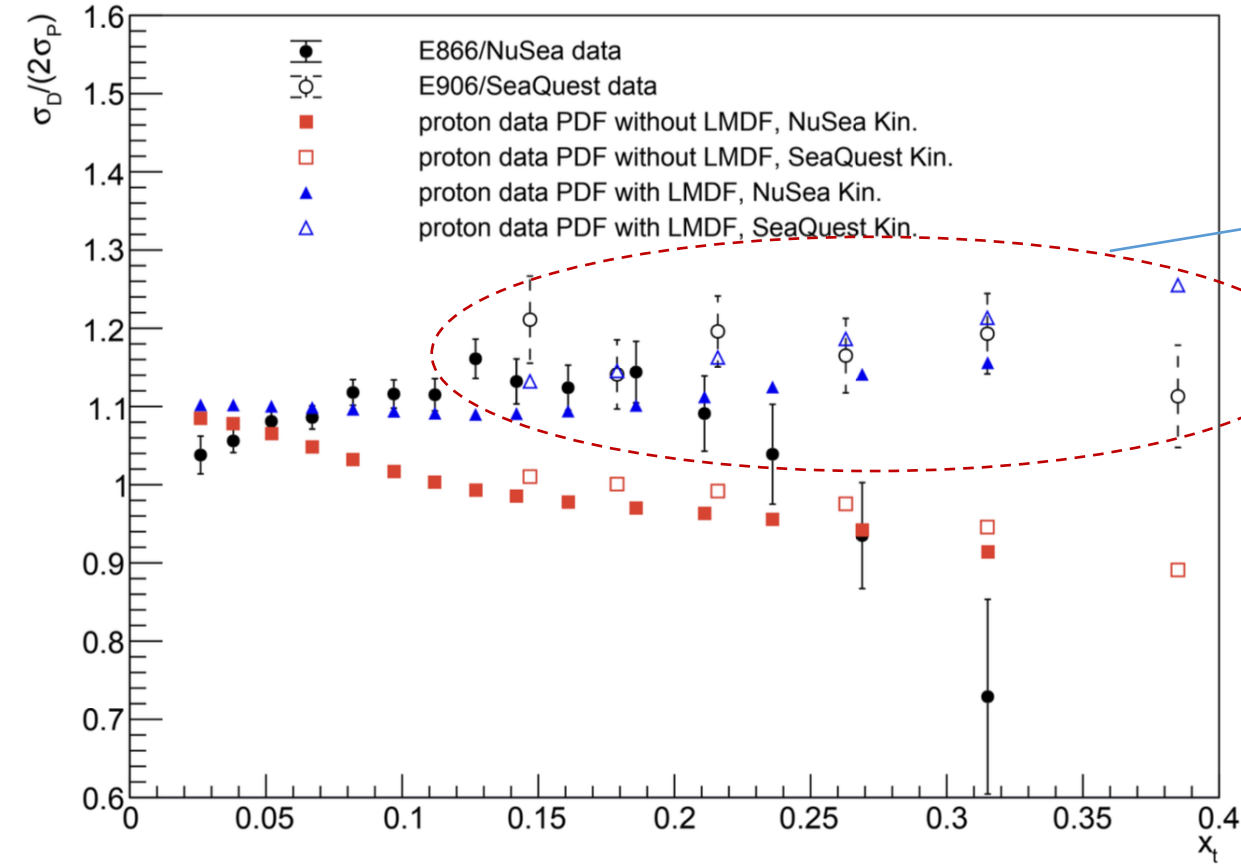
Overall distribution of quarks in deuteron      Nucleons in deuteron      PDF of quarks in proton

- Sharp peak: weak interaction between nucleons in deuteron (B.E.  $\sim 2$  MeV)
- Peak at  $1/2$ : nucleons in deuteron are proton and neutron, equally sharing the deuteron energy

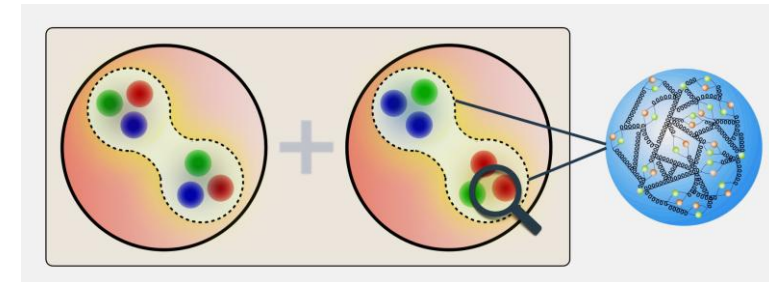


# A rough estimation of deuteron nuclear effect

- LMDF fitted with NuSea/SeaQuest with proton data PDF (i.e.  $\bar{d}/\bar{u} \sim 1$ )



- Significantly smeared: strong interaction between nucleons
- Peak shifted from 1/2: not a classic D(np) deuteron system





For the future: a new potential frontier

# Plan for proton data PDF : new LHC data input

- Pure proton scattering based PDF:

Baseline x-section «sum»
<u>DIS neutral current</u> $\sigma(\text{DIS } \gamma^*) \sim u(x) + d(x) + \bar{u}(x) + \bar{d}(x) + \dots$
<u>DIS charge current</u> $\sigma(\text{DIS } W^+) \sim u(x) + \bar{d}(x) + \dots$ $\sigma(\text{DIS } W^-) \sim d(x) + \bar{u}(x) + \dots$
<u><math>p\bar{p}</math> DY neutral current</u> $\sigma_{p\bar{p}}(\text{DY } Z/\gamma^*) \sim u(x_1)u(x_2) + d(x_1)d(x_2) + \dots$
<u><math>p\bar{p}</math> DY charge current</u> $\sigma_{p\bar{p}}(\text{DY } W^+) \sim u(x_1)d(x_2) + \dots$ $\sigma_{p\bar{p}}(\text{DY } W^-) \sim d(x_1)u(x_2) + \dots$
<u><math>pp</math> DY neutral current</u> $\sigma_{pp}(\text{DY } Z/\gamma^*) \sim u(x_1)\bar{u}(x_2) + \bar{u}(x_1)u(x_2) +$ $d(x_1)\bar{d}(x_2) + \bar{d}(x_1)d(x_2) + \dots$
<u><math>pp</math> DY charge current</u> $\sigma_{pp}(\text{DY } W^+) \sim u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2) + \dots$ $\sigma_{pp}(\text{DY } W^-) \sim d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2) + \dots$

+

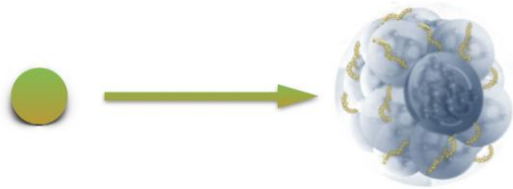
New W/Z-asymmetry «ratio/difference»
<u><math>p\bar{p} A_{FB}^h</math> proton parameters</u> $C_u(p\bar{p}) \sim u(x_1)u(x_2) - \bar{u}(x_1)\bar{u}(x_2)$ $C_d(p\bar{p}) \sim d(x_1)d(x_2) - \bar{d}(x_1)\bar{d}(x_2)$
<u><math>pp A_{FB}^h</math> proton parameters</u> $C_u(pp) \sim u(x_1)\bar{u}(x_2) - \bar{u}(x_1)u(x_2)$ $C_d(pp) \sim d(x_1)\bar{d}(x_2) - \bar{d}(x_1)d(x_2)$
<u><math>pp</math> high-MT W-asymmetry</u> $A_{ch}^W \sim u_V(x) - d_V(x)$
<u><math>pp W^+W^-</math> boost asymmetry</u> $A_{boost}^{W^+W^-} \sim q(x_1)\bar{q}(x_2) - \bar{q}(x_1)q(x_2)$
<u><math>pp W^+\gamma(Z)</math> boost asymmetry</u> $A_{boost}^{W^+\gamma(Z)} \sim u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)$
<u><math>pp W^-\gamma(Z)</math> boost asymmetry</u> $A_{boost}^{W^-\gamma(Z)} \sim d(x_1)\bar{u}(x_2) - \bar{u}(x_1)d(x_2)$

LHC Run3  
ATLAS  
CMS  
LHCb

# Proposal of high energy light nucleus experiments

- Study the deuteron structure in Drell-Yan process:

- $\mathcal{O}(10)$  GeV hadron-deuteron experiments:  $\gamma$ -exchanged neutral-current cross sections
- $\mathcal{O}(100)$  GeV hadron-deuteron experiments:  $Z$ -exchanged neutral-current  $A_{FB}$



## 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 $\rightarrow$ deuteron target
	hadron + deuteron collision boosted toward deuteron direction
Probing quarks in deuteron	deuteron beam $\rightarrow$ hadron target
	hadron + deuteron collision boosted toward hadron direction

# Thanks



- Precision  $\sin^2\theta_W$  measurements at hadron colliders are now limited by PDFs uncertainty
- The light quark ratio measurements have been achieved in pure proton data
- Discrepancy between deuteron and proton experiments was found:
  - No SU(2) flavor asymmetry of light quark sea in proton?
  - Non-classic nuclear structure of deuteron?
- Potential new frontier:
  - Proton structure from pure proton interactions at the LHC
  - New experiments on deuteron
  - Phenomenology studies
  - First principle calculation/Lattice QCD



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Backup slides

# Summary

## ● New observables

- ①  $A_{FB}^h$  factorization: simultaneous fitting  $\sin^2\theta_W$  and proton  $R = C_d/C_u \propto d_V/u_V$
- ②  $A_{boost}^{WV}$  asymmetry: sensitive to both  $\bar{q}(x_1)$  and  $q(x_2)$  information of proton

[Phys. Rev. D106 \(2022\) 033001](#)  
[Phys. Rev. D 106 \(2022\) L051301](#)

## ● New measurements

- ① CMS  $A_{FB}^h$  analysis: significant deviations of observed R at  $x_1 \sim 0.1$  from PDFs
- ② DØ  $A_{FB}^h$  measurement: confirmed the R deviation with different  $p\bar{p}$  collision
- ③ ATLAS  $A_{boost}^{WW}$  analysis: first measurement with limited statistics

[Phys. Rev. D 107 \(2023\) 054008](#)  
[Phys. Rev. D 110 \(2024\) L091101](#)  
[JHEP 08 \(2025\) 142](#)  
[Phys. Rev. D 113 \(2026\) L011504](#)

## ● New proton data PDF

- ① Baseline of proton  $\sigma_{lp}$  and  $\sigma_{pp}$  input + new  $A_{FB}^h$  versus  $\sigma_{pD}$  input options
- ② Pure proton show  $\bar{d}/\bar{u} \approx 1$ , negative to SU(2)-asymmetry of SeaQuest/NuSea

[Chin. Phys. C 50 \(2026\) 023107](#)  
[arXiv: 2510.08941](#)