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Proton structure information from A_{FB} of Drell-Yan process

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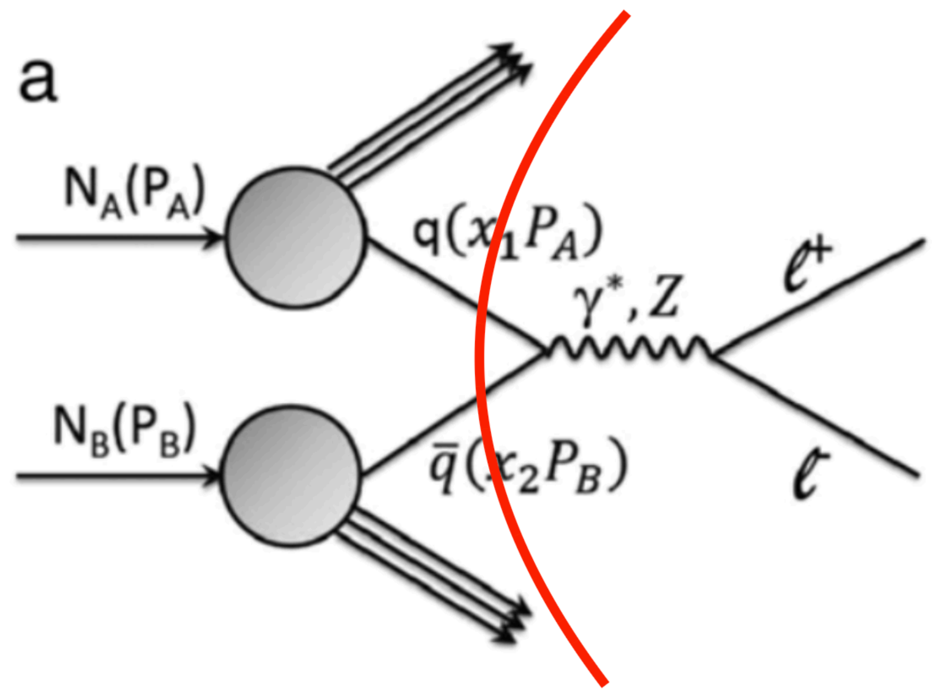
2025.11.4

Proton structure at high energy scale

- QCD improved parton model
  - Interactions between parsons can be ignored
  - Initial state parton information can be factorized into momentum-fraction x
    - Described by parton distribution function (PDF)



$$\sigma(p) = \sum_i \sigma(q_i) = \sum_i q_i(x) \otimes HardProcess(q_i; x)$$

PDF global analysis

Highly rely on the experimental measurements and QCD calculations

Low energy scale: non-perturbative quarks and gluon
$u(x), d(x), \bar{u}(x), \bar{d}(x), s(x), \bar{s}(x), g(x)$

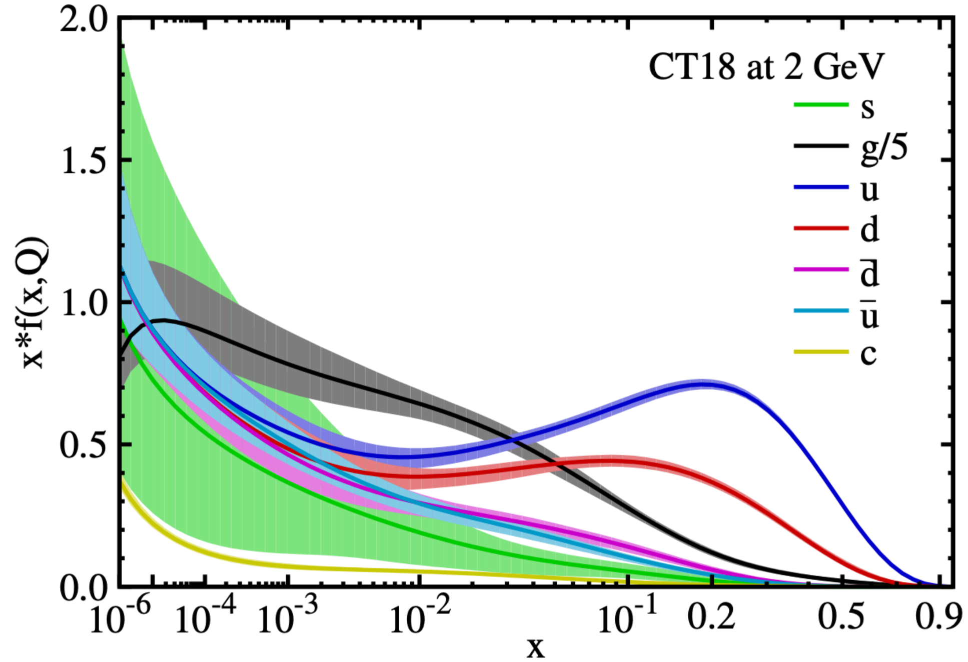
i.e $q(x) = x^{a_0}(1-x)^{a_1} \cdot P(x; a_i)$

→ Compare with experimental measurement and fit the non-perturbative part

+

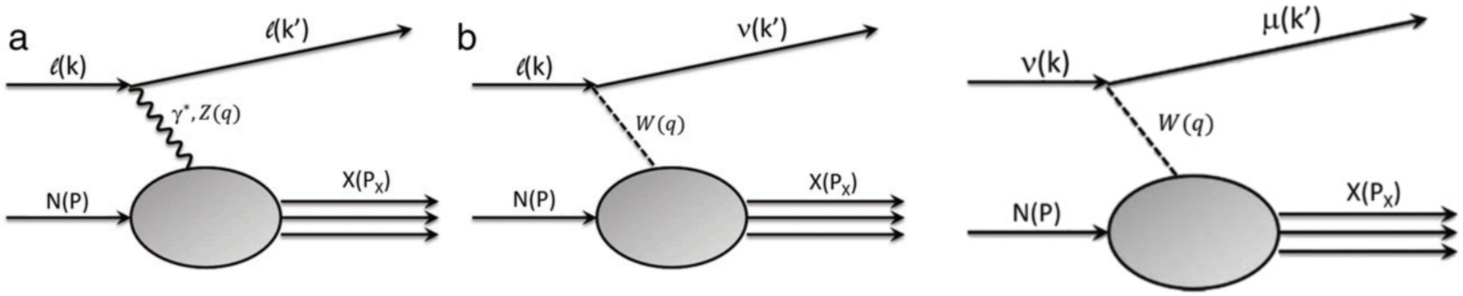
Perturbative QCD calculation
Evolute to any energy scale (DGLAP)
Heavy quarks $c(x), b(x)$
Sum rule

=

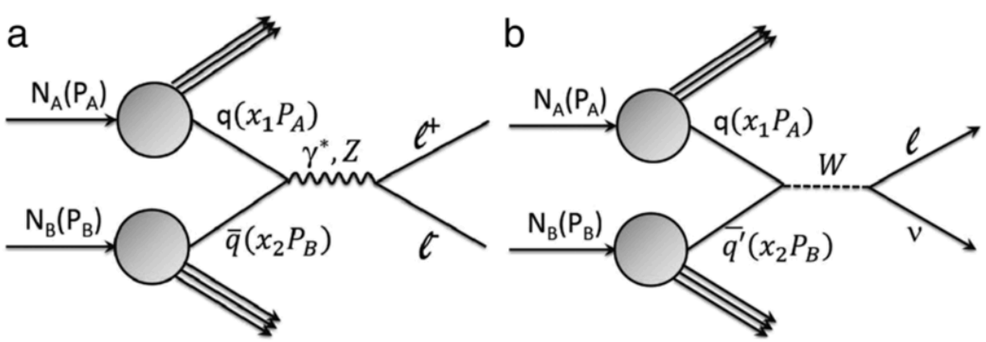


experimental input to PDF global fitting

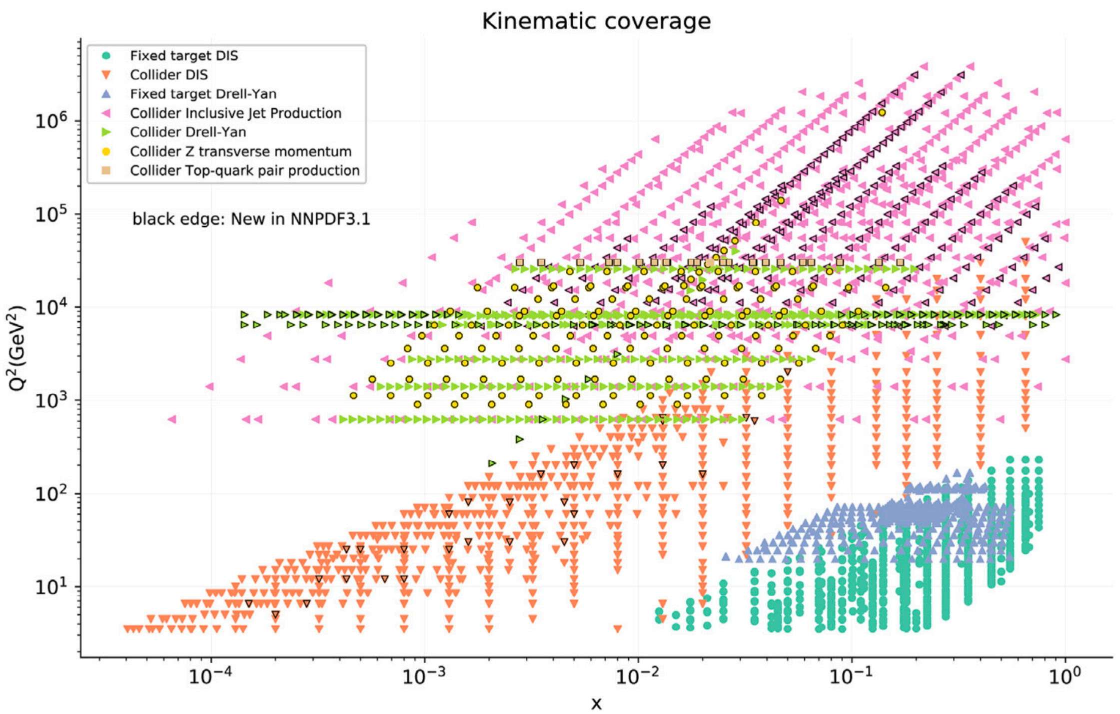
- Mainly DIS and Drell-Yan measurements, plus a few jet and top measurements



lepton(neutrino)-nucleon scattering



Neutral(charge)-current Drell-Yan process



Npt ~ 4000

- Experimental input covers large kinematic regions
  - Q: $O(1) \sim O(100)$ GeV
  - x: $O(10^{-4}) \sim 0.4$

Two quantities: sum or difference

- "Sum" quantity
  - Cross section measurements are measuring sum of quark distributions
  - In the past decades, "sum" quantity is measured from Drell-Yan and DIS cross sections, and then used to predict cross sections
  - Well measured from the cross sections

$$\sigma_{DIS} \sim \sigma_u u(x) + \sigma_d d(x) + \sigma_{\bar{u}} \bar{u}(x) + \sigma_{\bar{d}} \bar{d}(x) + \cdots$$

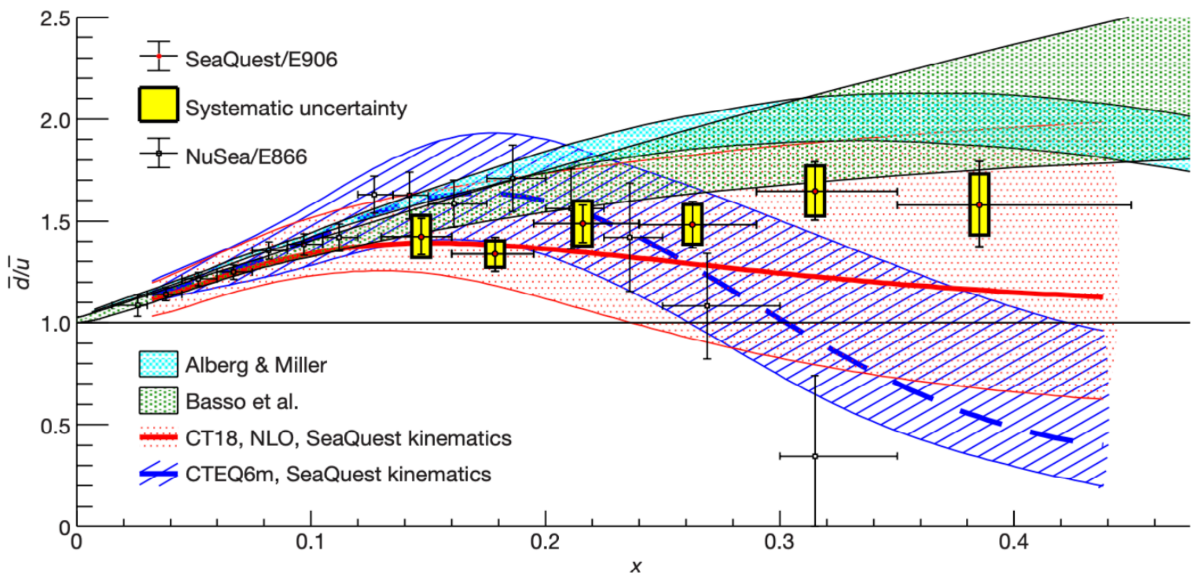
$$\sigma_{DY}^{pp} \sim \sigma_{u\bar{u}} u(x_1) \bar{u}(x_2) + \sigma_{d\bar{d}} d(x_1) \bar{d}(x_2) + \cdots$$

- "Difference" quantity
  - Relative difference between various quark distributions
  - Directly related to proton structure and QCD theory
  - Experimental measurement very limited

An example: flavor asymmetry

- Relative difference between different flavor quarks
  - Sea quark generation mechanism in proton: gluon splitting?
  - $\bar{d}/\bar{u} \neq 1$: SU(2) flavor asymmetry
  - $(s+\bar{s})/(\bar{d}+\bar{u}) \neq 1$: SU(3) flavor asymmetry

SU(2) flavor asymmetry: $\bar{d} \neq \bar{u}$



NuSea/SeaQuest pp/pD scattering

SU(3) flavor asymmetry: $(s+\bar{s}) \neq (\bar{d}+\bar{u})$

$$\kappa_s = \frac{\int_0^1 x[s(x,\mu^2)+\bar{s}(x,\mu^2)]dx}{\int_0^1 x[\bar{u}(x,\mu^2)+\bar{d}(x,\mu^2)]dx}$$

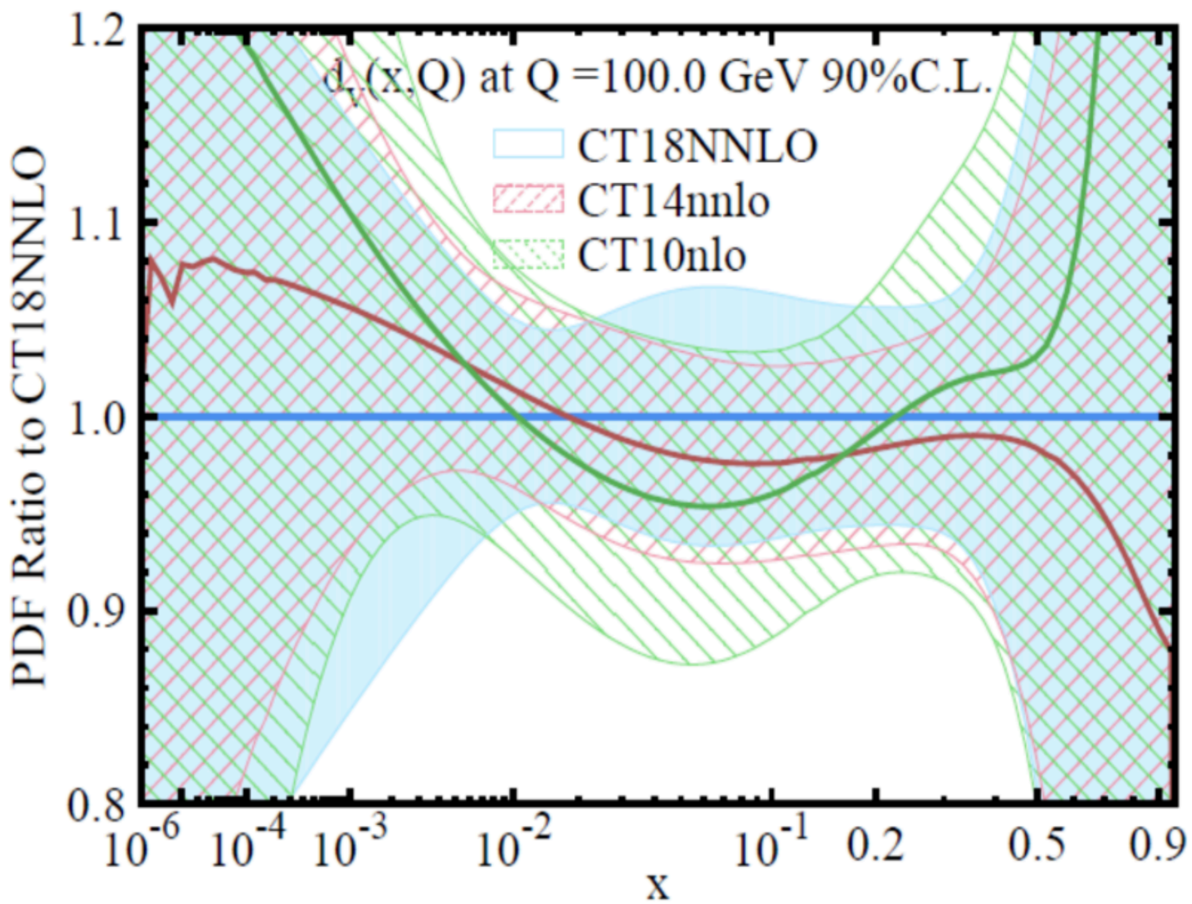
Experiment (year)	QCD order	κ_s
CDHS (1982)	LO	0.52 ± 0.09
CCFR (1993)	LO	$0.373^{+0.048}_{-0.041} \pm 0.018$
CCFR (1995)	NLO	$0.477^{+0.051}_{-0.050}{}^{-0.017}_{+0.036}$
CHARMII (1999)	LO	$0.388^{+0.074}_{-0.061} \pm 0.067$
NOMAD (2000)	LO	$0.48^{+0.09}_{-0.07}{}^{+0.17}_{-0.12}$
NuTeV (2001)	LO	$0.38 \pm 0.08 \pm 0.043$
NuTeV (2007)	NLO	
CHORUS (2008)	NLO	$0.33 \pm 0.05 \pm 0.05$
NOMAD (2013)	NNLO	0.591 ± 0.019

Some experiments showing less s quark

Obtain "difference" indirectly from "sum"?

- Difficult, as shown from valence d_V quark
  - From CT14 to CT18, lots of high precision LHC Drell-Yan measurements introduced, but the precision of d_V is not improved.
  - LHC Drell-Yan process contains large d quark contributions. However, these measurements are the sum of u, d, $\bar{u}$, $\bar{d}$…

$$\sigma_{DY}^{pp} \sim \sigma_{u\bar{u}} u(x_1)\bar{u}(x_2) + \sigma_{d\bar{d}} d(x_1)\bar{d}(x_2) + \cdots$$

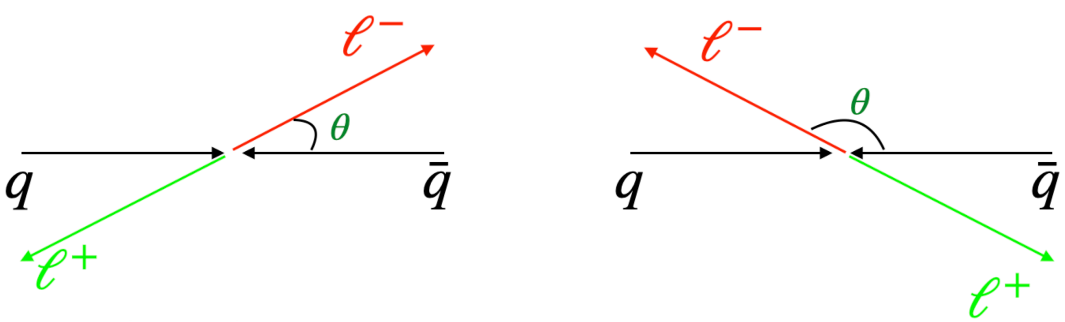


More direct measurement on the "difference" quantity is needed!

Precision of d_V is not improved!

Drell-Yan process and A_{FB}

- Originate from parity violation in weak interactions
  - $hh(q\bar{q}) \rightarrow Z/\gamma^* \rightarrow l^+l^-$



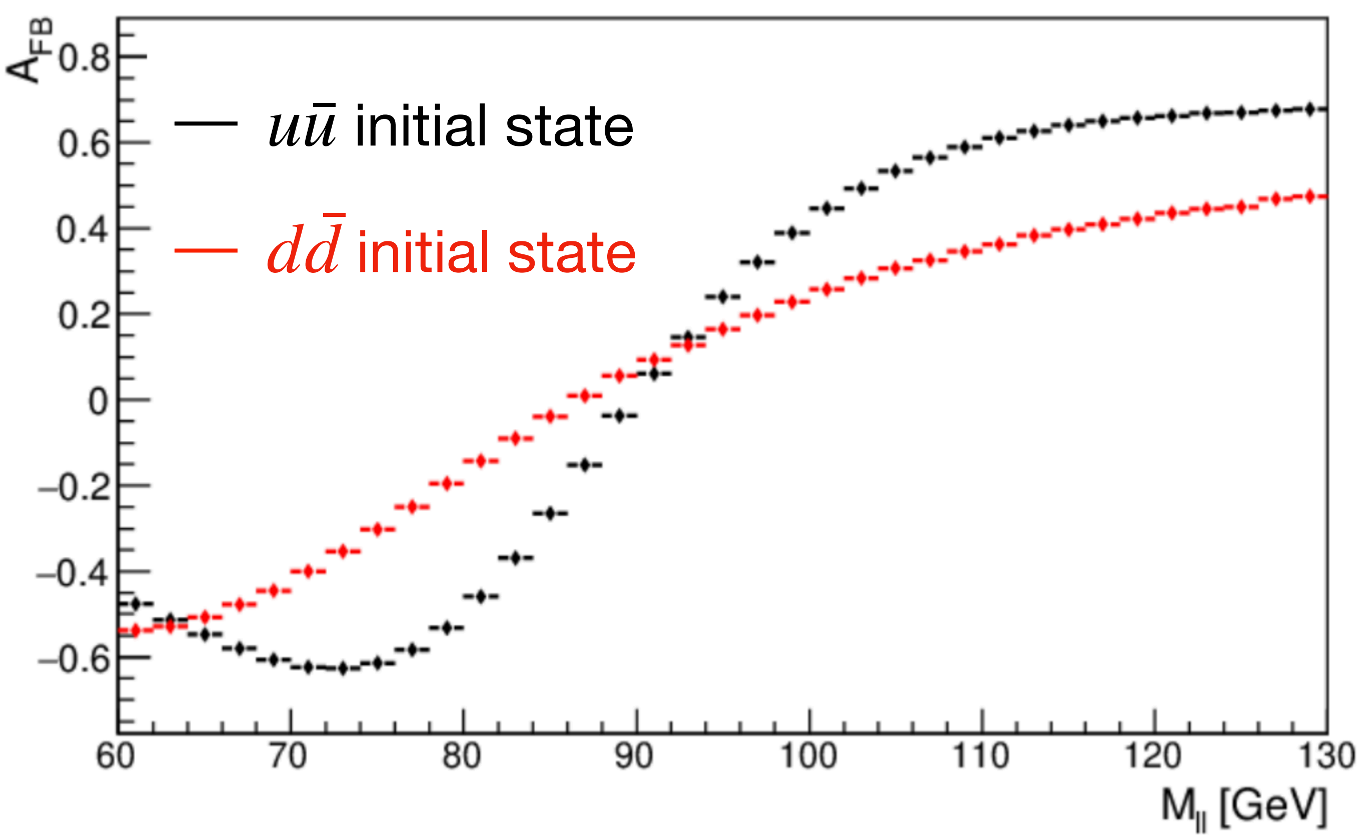
Forward event

$cos\theta > 0$

backward event

$cos\theta < 0$

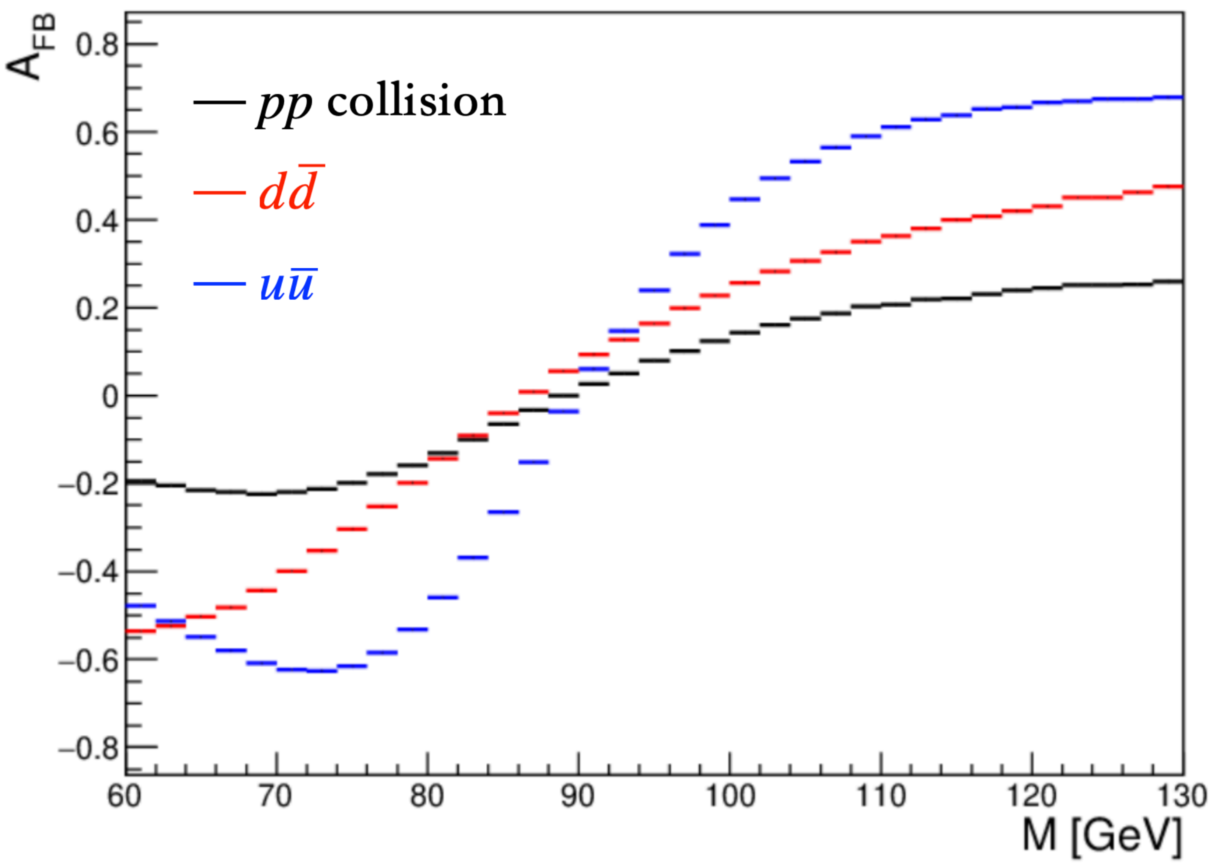
$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$



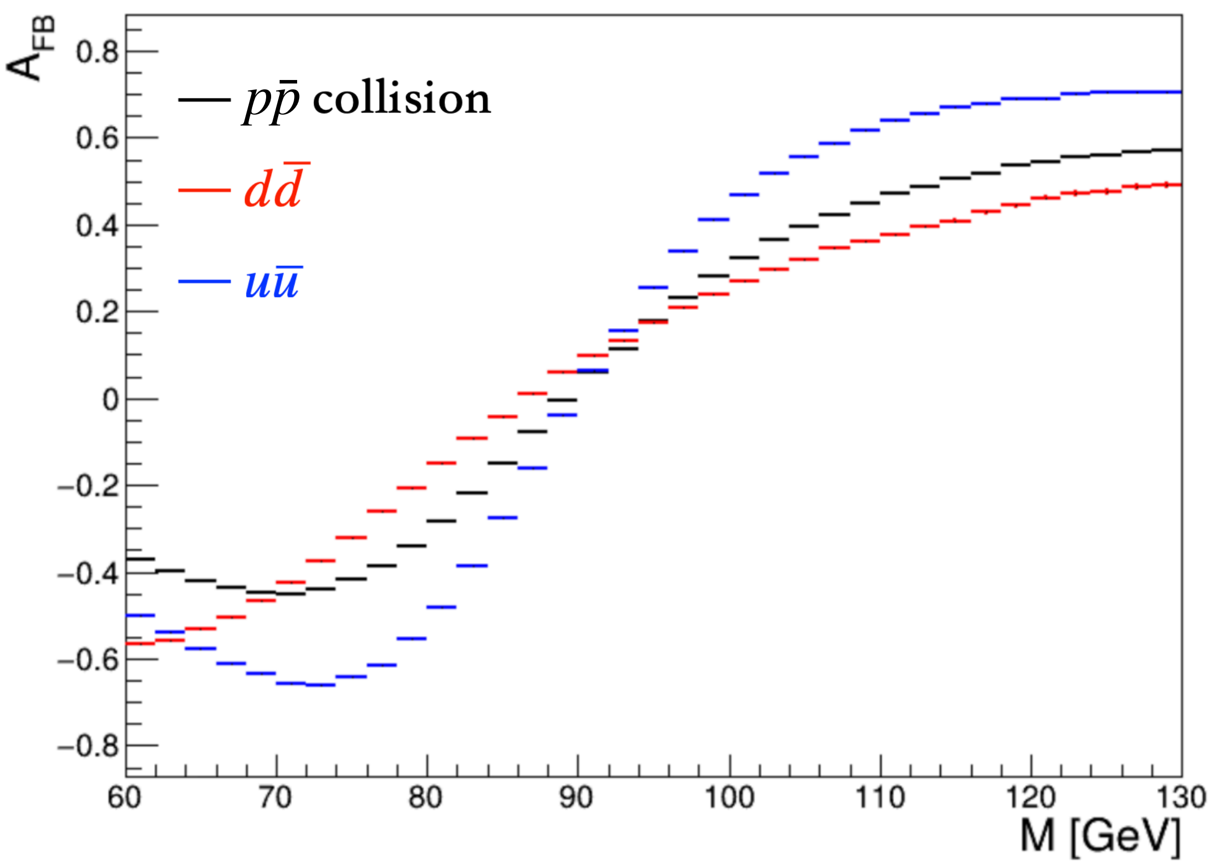
A_{FB} from different $q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+l^-$ hard process

Hard process A_{FB} and observed A_{FB}

- The observed A_{FB} is significantly affected by initial state quarks' PDF
  - At LHC, the observed A_{FB} is globally suppressed
  - At Tevatron, the observed A_{FB} is an average between $u\bar{u}$ and $d\bar{d}$ A_{FB}



LHC pp collision



Tevatron $p\bar{p}$ collision

ULB

A_{FB} factorization

CMS

- The observed A_{FB} at hadron collider can be factorized
  - A_{FB}^{u}: asymmetry of hard process $u\bar{u} \rightarrow Z/\gamma^* \rightarrow l^+l^-$
  - A_{FB}^{d}: asymmetry of hard process $d\bar{d} \rightarrow Z/\gamma^* \rightarrow l^+l^-$

  } Pure electroweak calculation, independent of proton structure and QCD calculation

  - C_u: structure parameter of u quark
  - C_d: structure parameter of d quark

  } Fully represent proton structure information

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

The factorization is valid to all orders.

Phys. Rev. D 106, 033001 (2022)

Eur. Phys. J. C 82:368 (2022)

Chin. Phys. C 45, 053001 (2021)

A_{FB} factorization and structure parameters

$$A^h_{FB}(Y, M, Q_T) = C_u(Y, M, Q_T) \times A^u_{FB}(Y, M, Q_T) + C_d(Y, M, Q_T) \times A^d_{FB}(Y, M, Q_T)$$

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

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

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

C_u and C_d for LHC pp collision

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

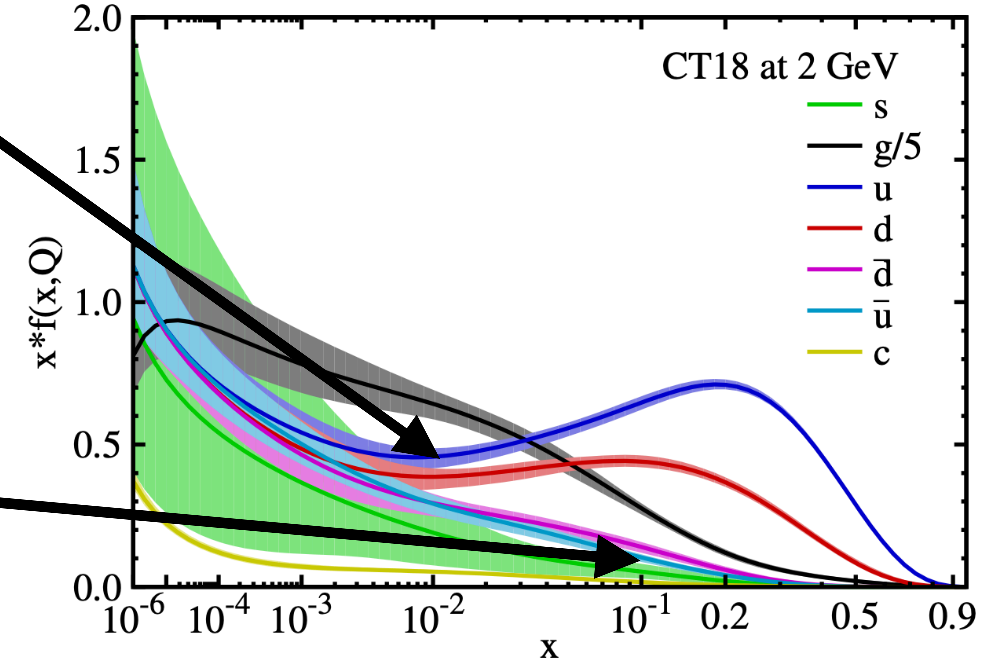
$$C_d(x_1, x_2) = \frac{[d(x_1)d(x_2) - \bar{d}(x_1)\bar{d}(x_2)]\sigma_u}{\sum_{q=u,d,s,c,b}[q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)]\sigma_q}$$

C_u and C_d for Tevatron $p\bar{p}$ collision

- Small x probes relative difference between quark and antiquark
  - At LHC, small Y region corresponds to $x \sim 0.01$

$$C_u \propto u(x_1)\bar{u}(x_2) - \bar{u}(x_1)u(x_2)$$

$$C_d \propto d(x_1)\bar{d}(x_2) - \bar{d}(x_1)d(x_2)$$



- Large x probes relative difference between u and d
  - At Tevatron and high Y region at LHC, $x \sim 0.1$

$$R_{\text{LHC}} = \frac{C_u}{C_d} \approx \frac{u}{d}$$

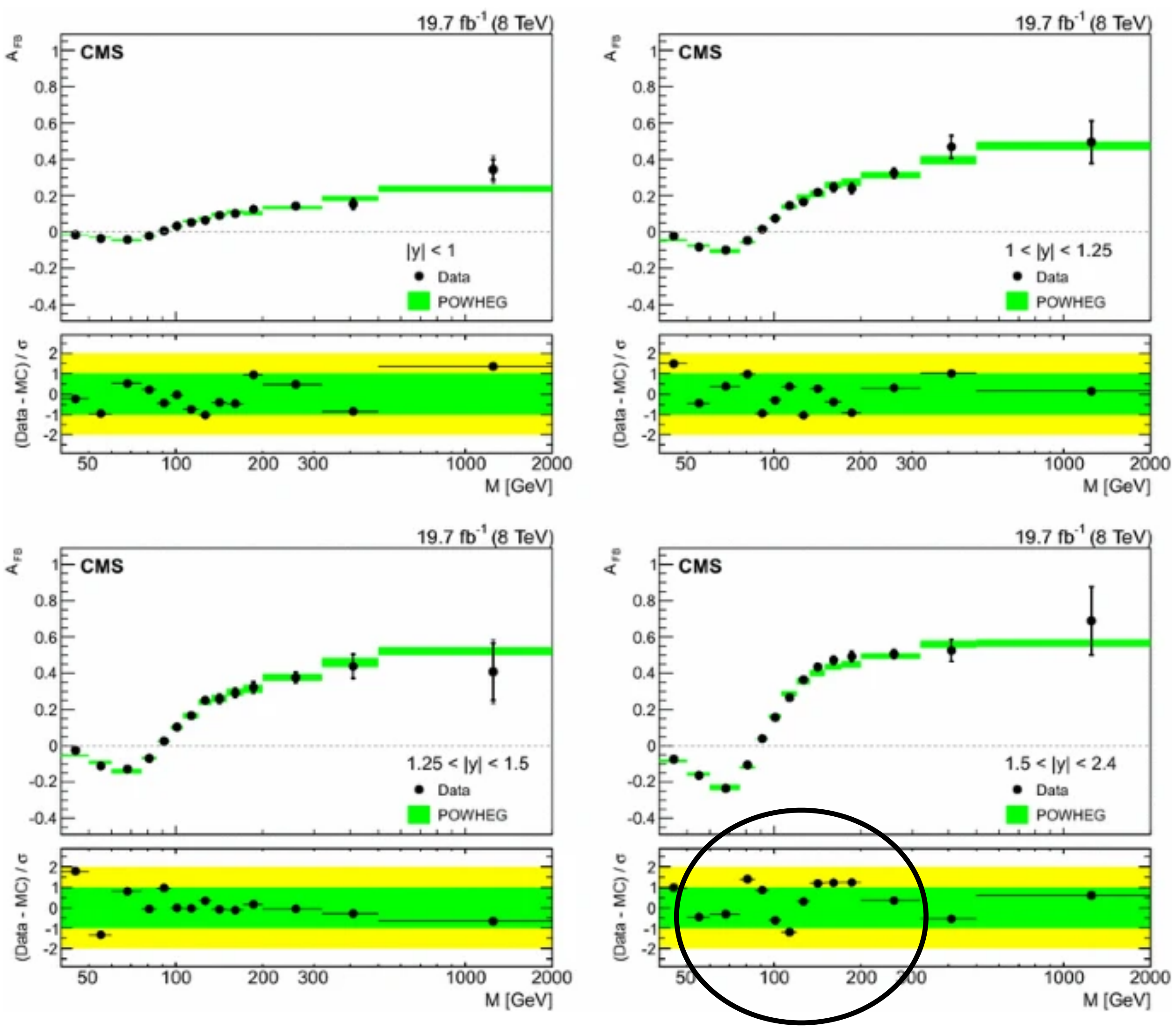
$$R_{\text{Tevatron}} = \frac{C_u}{C_d} \approx \frac{u^2}{d^2}$$

What have we done?

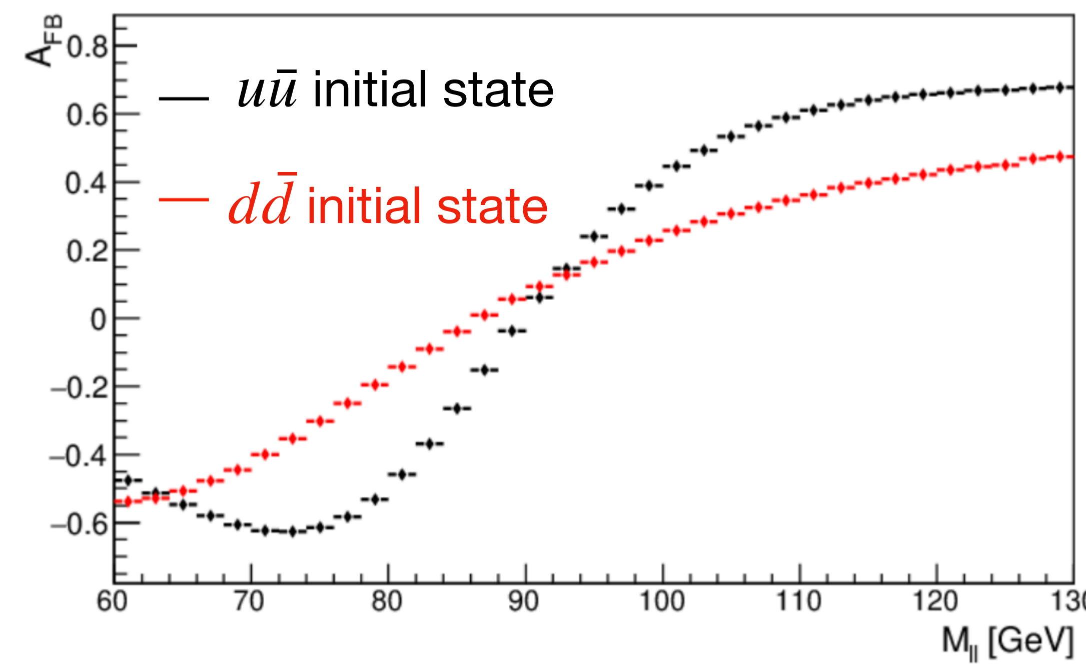
- Extract structure parameters from multiple experiments:
  - At LHC, from the published CMS 8 TeV and 13 TeV unfolded A_{FB}
  - At LHC, directly from ATLAS 13 TeV 2015+2016 data
  - At Tevatron, directly from D0 1.96 TeV RunII data

C_u and C_d measured from CMS 8 TeV

- CMS 8 TeV 19.6 fb^{-1}, both electron and muon channels used, 4 |Y| bins



Theory prediction: Powheg+CT10



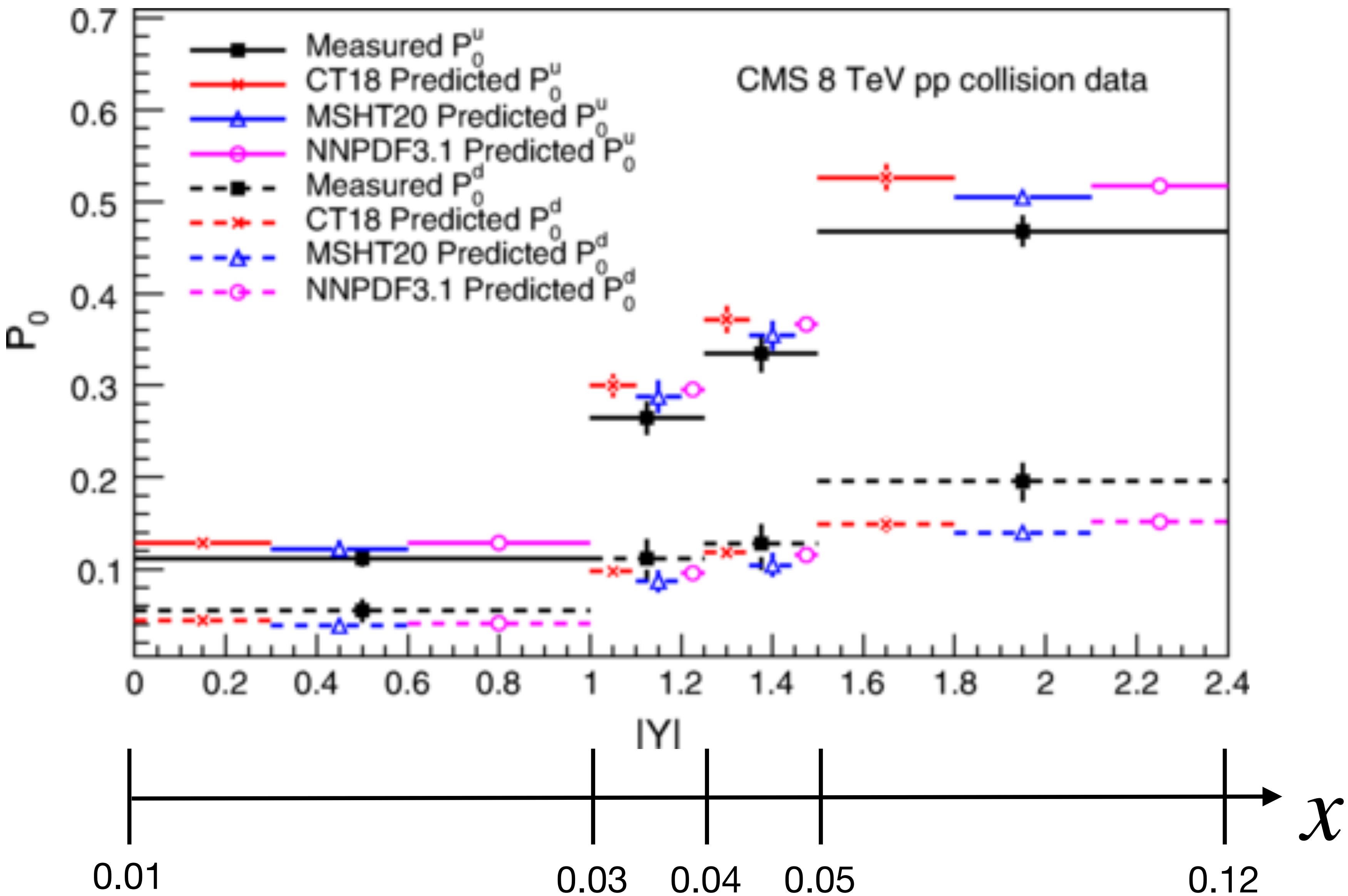
$$A^h_{FB}(Y, M, Q_T) = C_u(Y, M, Q_T) \times A^u_{FB}(Y, M, Q_T) + C_d(Y, M, Q_T) \times A^d_{FB}(Y, M, Q_T)$$

A_{FB} in data is smaller than theory prediction, suggesting more d quark contributions.

C_u and C_d measured from CMS 8 TeV

- The measured C_u is obviously lower than prediction, and measured C_d is higher
  - First evidence: more d quark contribution and less u quark contribution

Phys. Rev. D 107, 054008(2023)



C_u and C_d measured from D0 1.96 TeV

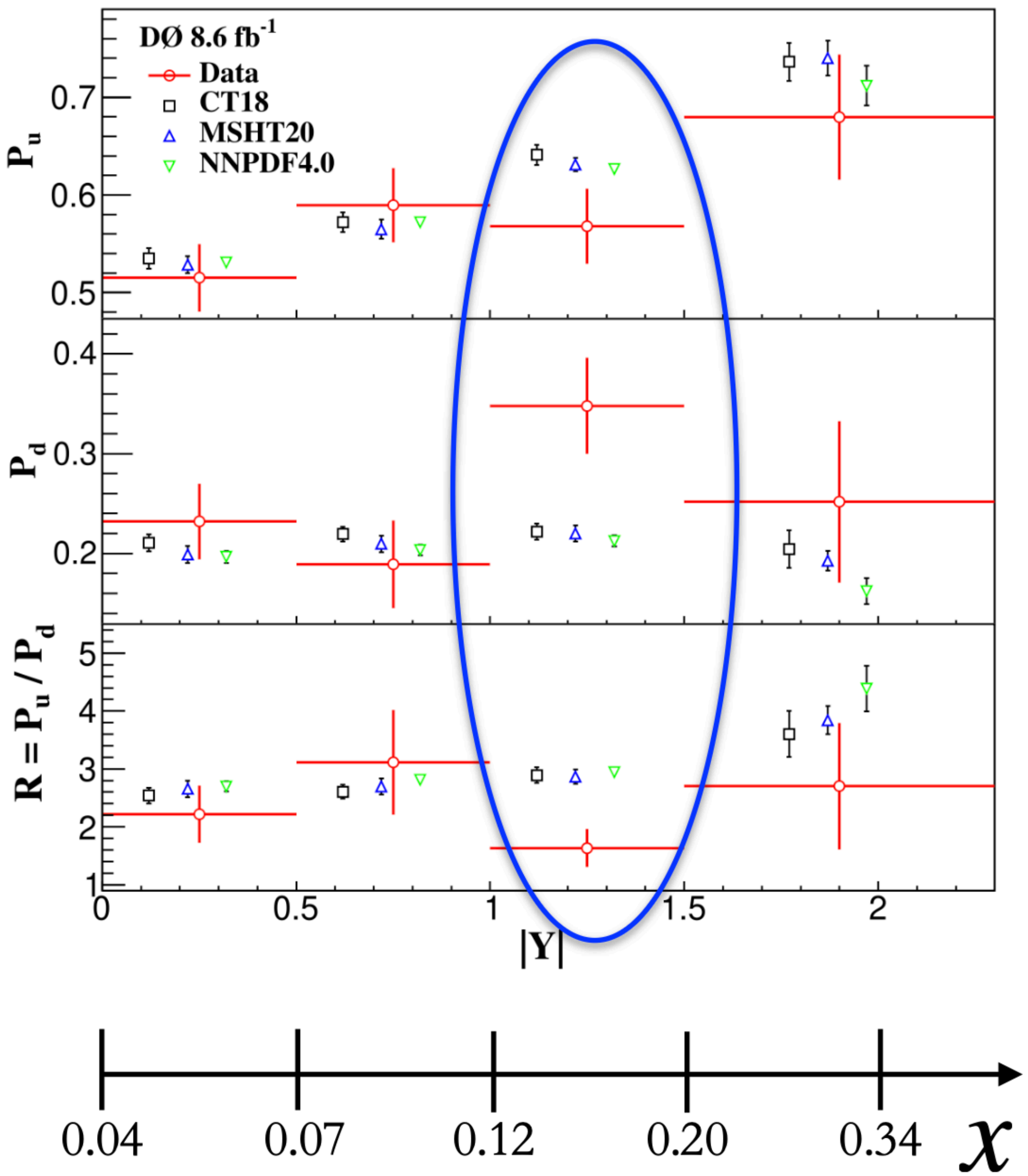
- 3.5σ deviation on u/d found in $x \sim [0.1,0.2]$ (peak region of valence quark distribution)

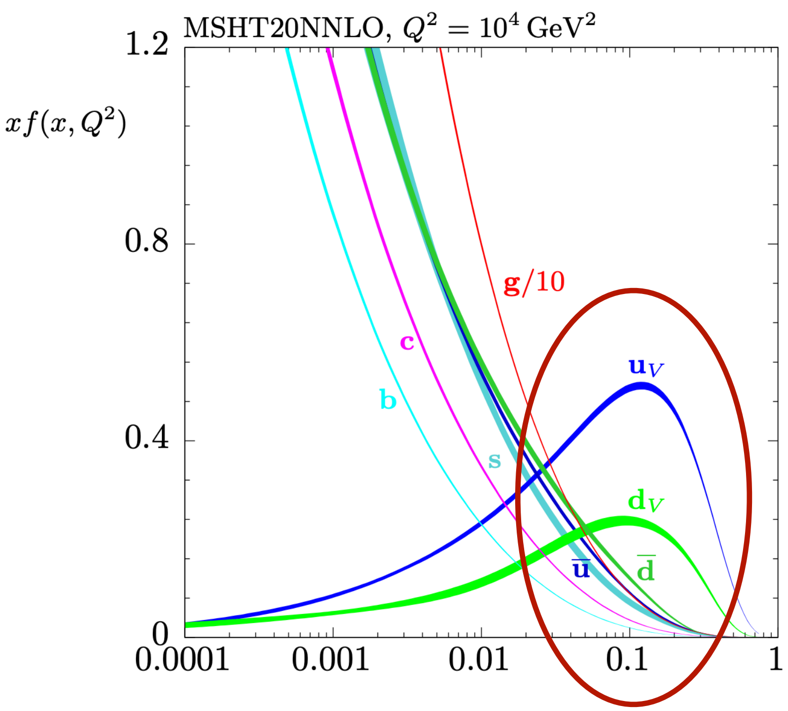
$$C_u(x_1,x_2) \propto u(x_1)u(x_2) - \bar{u}(x_1)\bar{u}(x_2)$$

$$C_d(x_1,x_2) \propto d(x_1)d(x_2) - \bar{d}(x_1)\bar{d}(x_2)$$

$$R_{\text{Tevatron}} = \frac{C_u}{C_d} \approx \frac{u^2}{d^2}$$

Phys. Rev. D 110, L091101(2024)



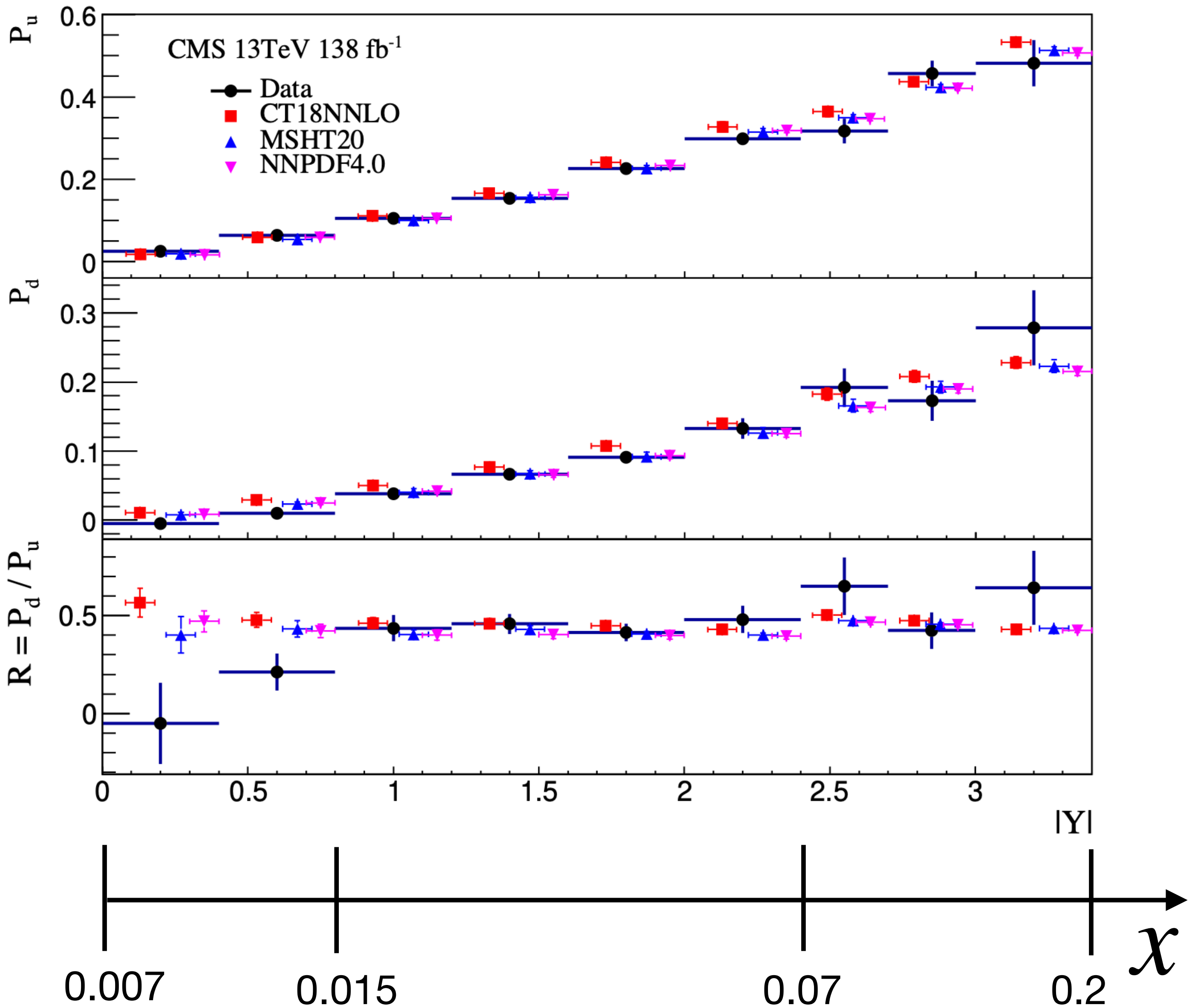


Further evidence that more d quark contribution and less u quark contribution

C_u and C_d measured from CMS 13 TeV

- Using 13 TeV unfolded A_{FB}, |Y| to 3.4, corresponding x range [0.01, 0.2]
  - Provide a clear trend for the evolution of the u, d quark ratio with x

arXiv:2505.17608



Extension

Same region covered by CMS 8TeV

Overlapping region with CMS 8TeV and D0

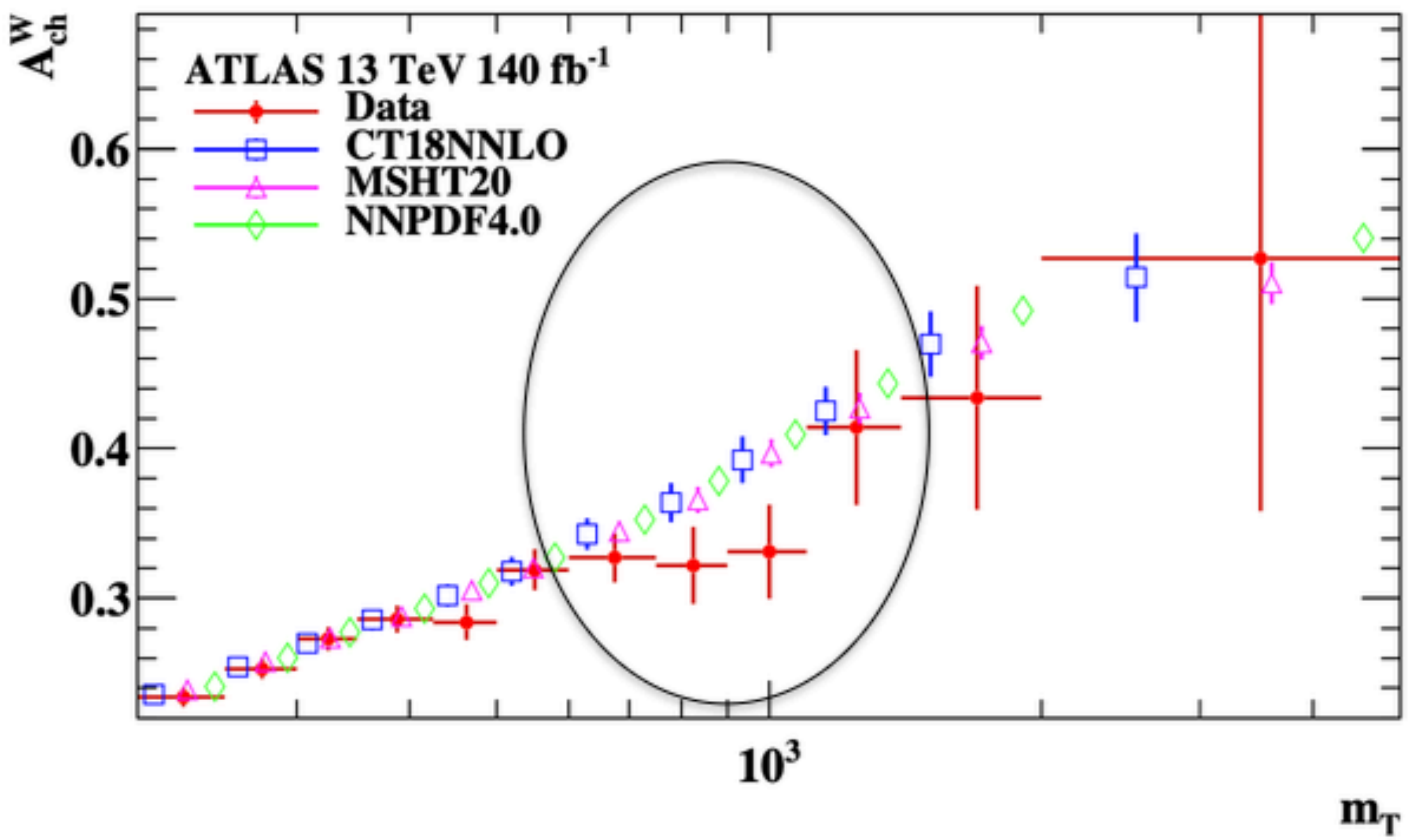
- high |Y| region: R is higher, but limited by statistics
- Middle |Y|: data and prediction agree well
- Low |Y|:
  - R is lower in data
  - C_d is closer to zero, means $d(x) \approx \bar{d}(x)$, perturbative QCD is more significant.

Evidence from other data

- High m_T measurement of the W charge asymmetry
  - With high m_T requirement, the high energy hadron collider data can reach a rather large x region around 0.1

$$A_W \sim \frac{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)} = \frac{u(x_1) + \bar{d}(x_1)}{d(x_1) + \bar{u}(x_1)}$$

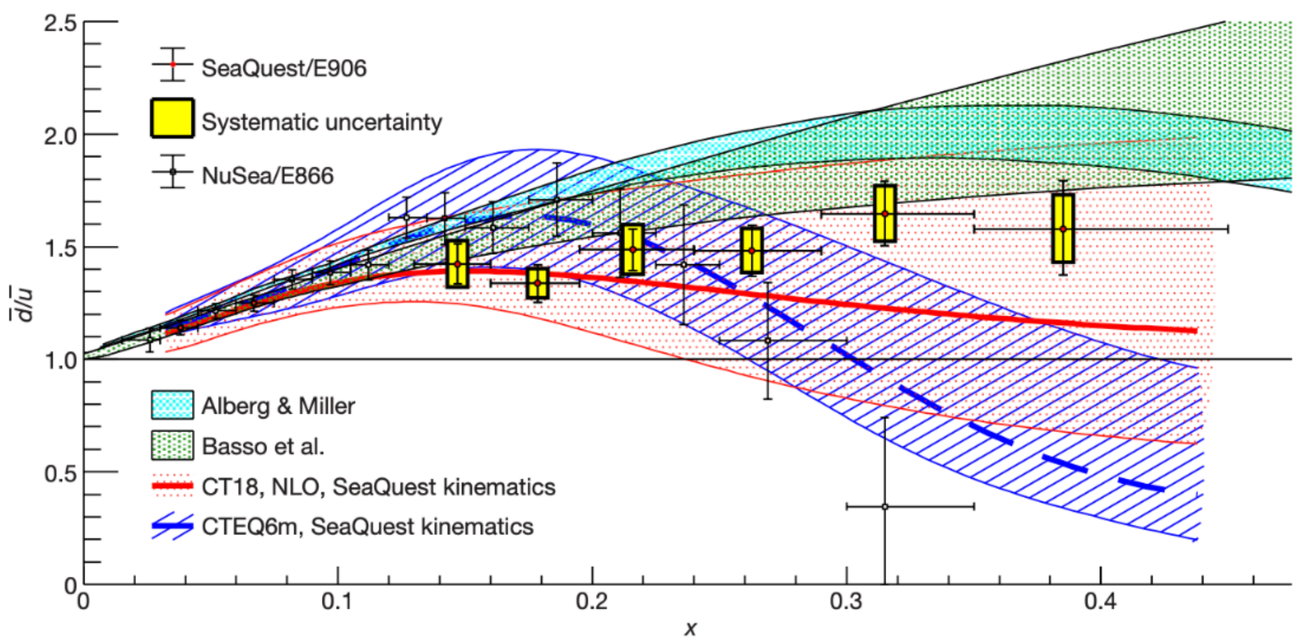
JHEP 07 (2025) 026

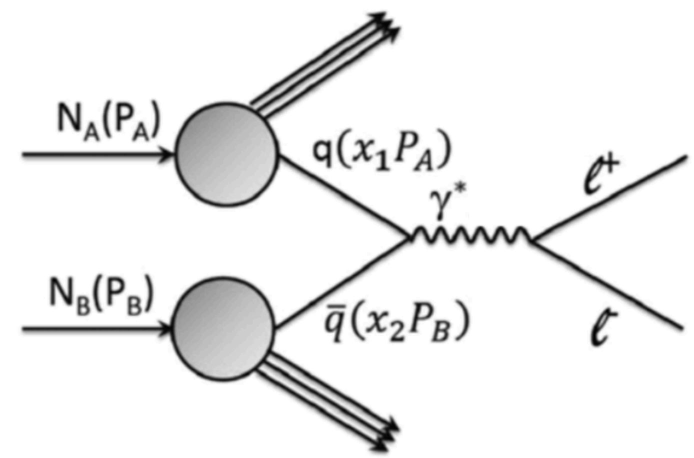


SU(2) flavor asymmetry

- The only evidence comes from the comparison between proton and deuteron interactions

NuSea: Phys. Rev. D 64, 052002 (2001)
SeaQuest: Nature Vol 590, 561-565, 2021





$$\frac{\sigma_{pD}}{\sigma_{pH}} = \frac{\sigma_{pp}+\sigma_{pn}}{\sigma_{pp}} = 1 + \frac{\sigma_{pn}}{\sigma_{pp}}$$

$$\frac{\sigma_{pn}}{\sigma_{pp}} = \frac{u(x_1)\bar{d}(x_2) + \frac{1}{4}d(x_1)\bar{u}(x_2)}{u(x_1)\bar{u}(x_2) + \frac{1}{4}d(x_1)\bar{d}(x_2)}$$

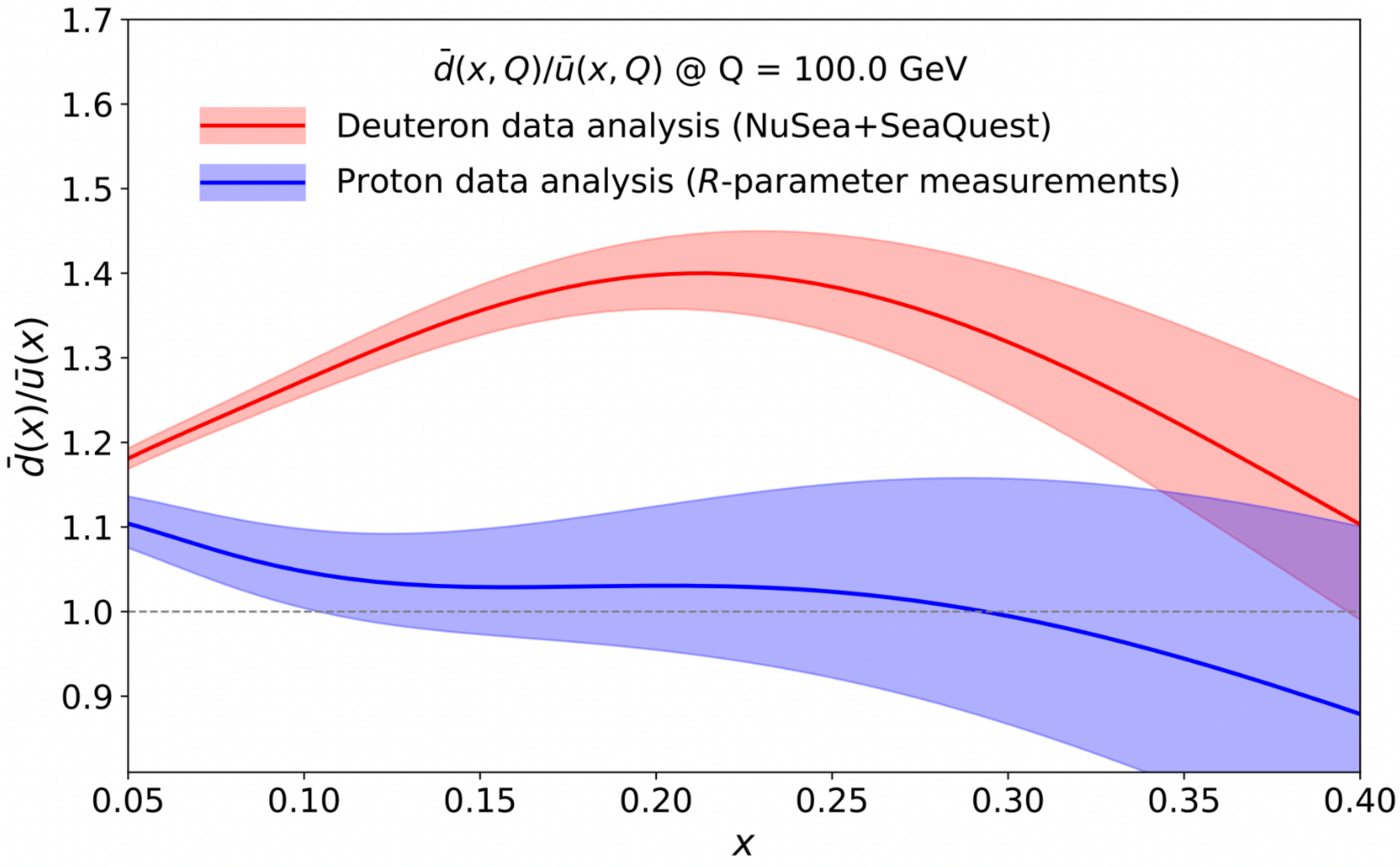
$$= \frac{\frac{\bar{d}(x_2)}{\bar{u}(x_2)} + \frac{1}{4}\frac{d(x_1)}{u(x_1)}}{1 + \frac{1}{4}\frac{d(x_1)}{u(x_1)}\frac{\bar{d}(x_2)}{\bar{u}(x_2)}} \approx \frac{\bar{d}(x_2)}{\bar{u}(x_2)}$$

- Assumption 1: nuclear effect is small: D = p+n
- Assumption 2: isospin symmetry

$$\frac{\sigma_{pD}}{\sigma_{pp}} \approx 1 + \frac{\bar{d}}{\bar{u}}$$

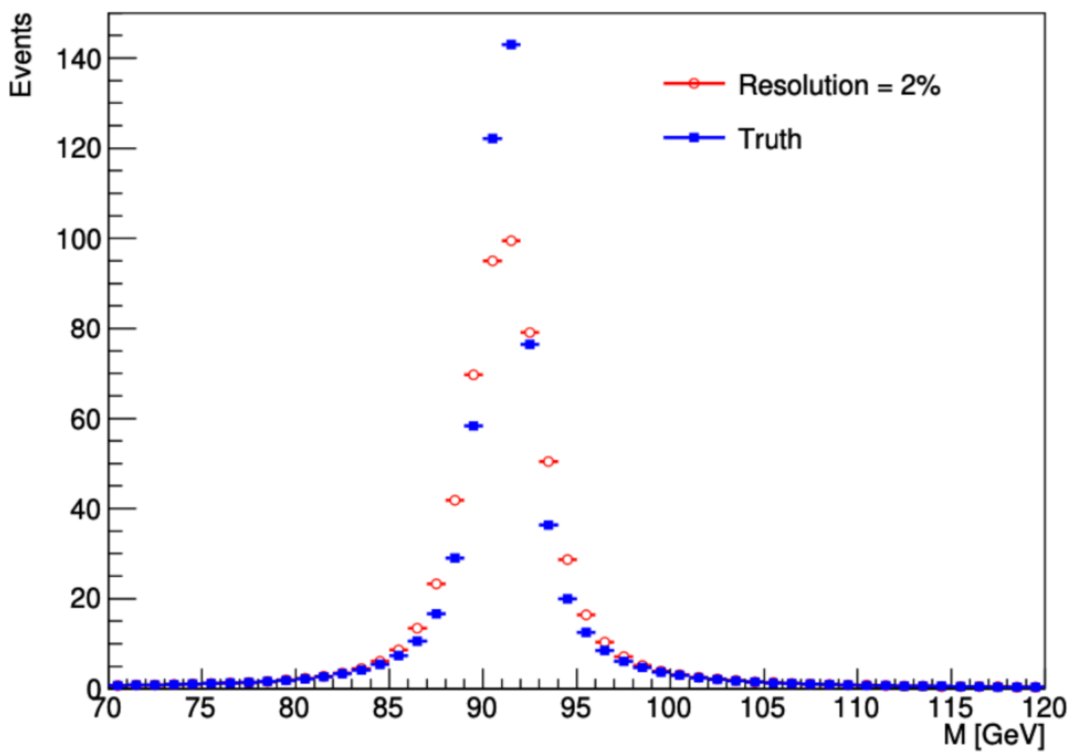
Global fit with newly measured C_u and C_d

- PDF global fit with hadron collider data + specific data   arXiv:2510.08941
  - Why do we see discrepancies between the pure proton data and deuteron data?
  - What impact it would have on our knowledge of proton structure?



Unfolding or not

- Unfolding method introduce potential theoretical model uncertainties
- The purity is lower, the model uncertainties are larger
- Unfortunately, A_{FB} unfolding has low purity due to Z peak shape
- Unfortunately, the major model uncertainty in A_{FB} unfolding is PDF



- It's not reasonable to use a PDF-dependent result to measure PDF!

Summary

- Newly defined structure parameters from A_{FB}
- Measurement of structure parameters show deviation on u, d quark ratio
- Discrepancy observed from pure proton data and deuteron data
- Lack of direct measurement on CMS