Up and Down Quark Structure of the Proton

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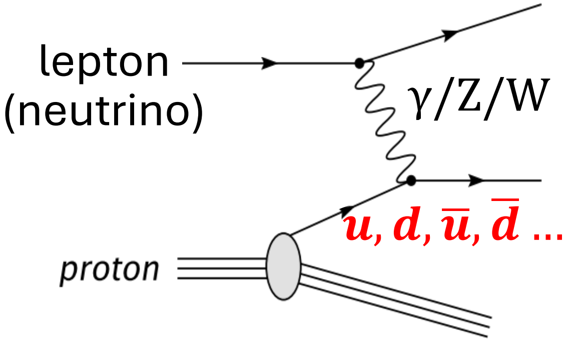
arXiv:2403.09331

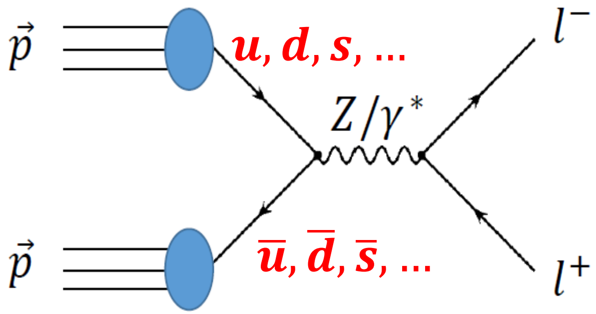
Review of the motivation

- Proton structure is determined by global analysis of all experimental observables due to mixed quark information



DIS

$x \sim O(0.01) - O(0.1)$



Drell-Yan process

$x \sim O(10^{-4}) - O(10^{-3}), O(0.01) - O(0.1)$

few observables vs mixture of various parton information

parton density strong depends on non-perturbative parameterization form, pQCD calculation and sum rules.

- Find new experimental observable to constraint proton structure information

Up and down quark structure

- More specifically, the experimental constraints for u and d quarks are limited despite all observables are relative to them.

- Few observables dominated by single quark
  - γ-exchange DIS, dominated by u, **mainly at large x**
  - W-exchange at HERA, separate u and d by W boson charge, **but statistics very limited!**

- Most observables are a mixture of u and d
  - $F_2^Z, F_3^Z, F_3^{W^+}(N), F_3^{W^-}(N), \sigma(W^+), \sigma(W^-), \sigma(Z)$
  - Also involve sea quark, heavy quark
  - Unable to give strong constraints

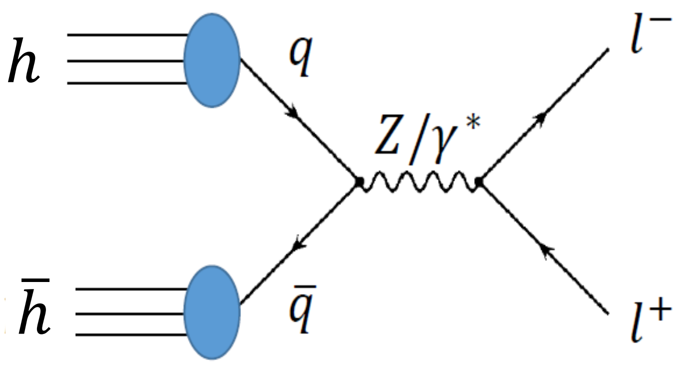
$F_3^W(N)$ from $l(\nu) - N$ scattering is indistinguishable for u and d because N is a combination of proton and neutron.

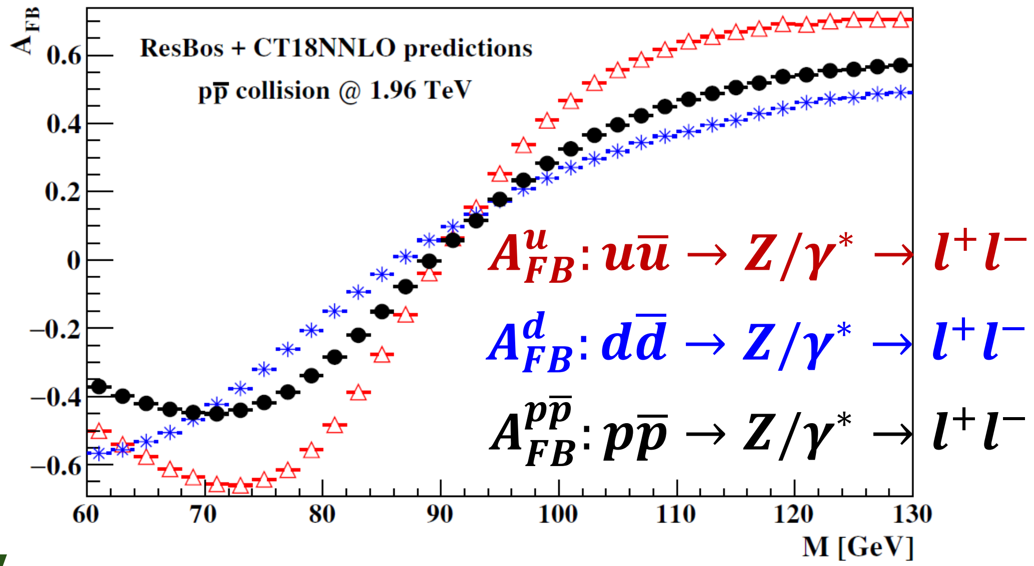
- It's important to have more direct measurement of u and d.

A new measurement of up and down quark structure of proton

arXiv:2403.09331

- $A_{FB}^{u}(u\bar{u}, c\bar{c}$ initial states) differs from $A_{FB}^{d}(d\bar{d}, s\bar{s}, b\bar{b}$ initial states)
- The observed $A_{FB}^{p\bar{p}}$ is a combination of A_{FB}^{u} and A_{FB}^{d}, where their weights reflect the up and down quark information separately





For the Tevatron, the $p\bar{p}$ initial state allows the Drell-Yan process to occur from mainly valence quarks.

Factorization of A_{FB}

- Up and down quark information can be factorized into proton structure parameters in A_{FB}, up to all orders.

Details in Phys.Rev.D 106,033001 (2022)

$$A_{FB}(M,Y,Q_T) = [\Delta_u(M,Y,Q_T) + P_u(Y,Q_T)] \cdot A_{FB}^u(M,Y,Q_T;\sin^2\theta_{eff}^l) + [\Delta_d(M,Y,Q_T) + P_d(Y,Q_T)] \cdot A_{FB}^d(M,Y,Q_T;\sin^2\theta_{eff}^l)$$

Proton structure parameters $\Delta_u, \Delta_d, P_u, P_d$: Separately represent the u and d quark information.

Electroweak asymmetry of the hard process $u\bar{u} \to Z/\gamma^* \to l^+l^-$ and $d\bar{d} \to Z/\gamma^* \to l^+l^-$, can be precisely predicted. **PDF-independent.**

P_u and P_d can be individually determined from the observed $A_{FB}^{p\bar{p}}$.

Proton structure parameters

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

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

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

- P_u (P_d) has no down (up) quark densities (except for a normalized total cross section)
- The numerators vanished for s, c and b, since there is no difference from their antiquarks.
- Predominant by u_v and d_v.
- Denominator cancelled in the ratio.

$$P_u \approx \frac{u_v^2}{\sigma_{total}} \qquad P_d \approx \frac{d_v^2}{\sigma_{total}}$$

$$R \equiv \frac{P_u}{P_d} \approx \frac{u_v^2}{d_v^2}$$

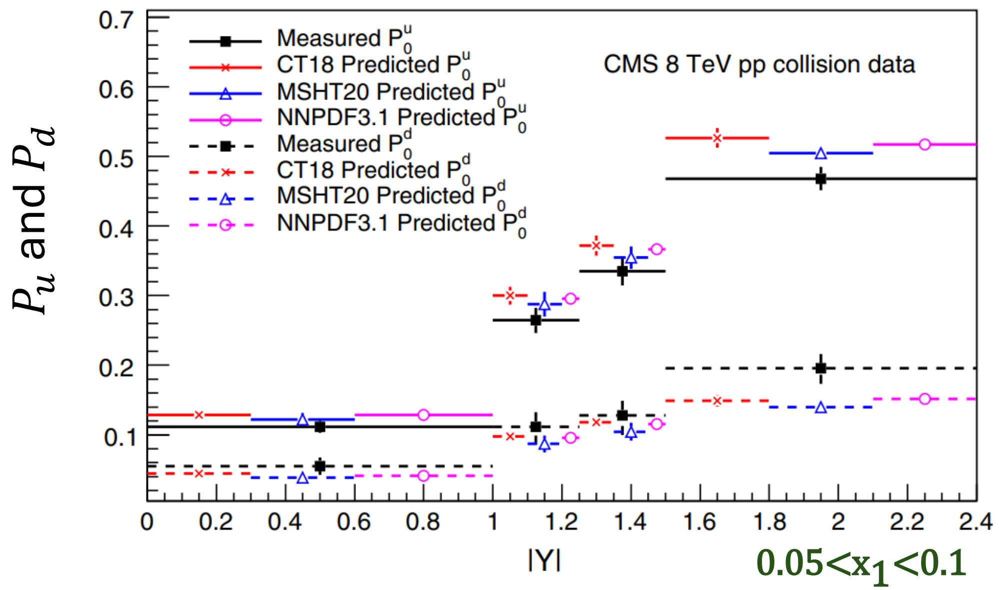
(Just an approximation to show the predominant information. Not used in real calculation)

Previous measurements

- Extracted from the unfolded $A_{FB}(M)$ spectrum

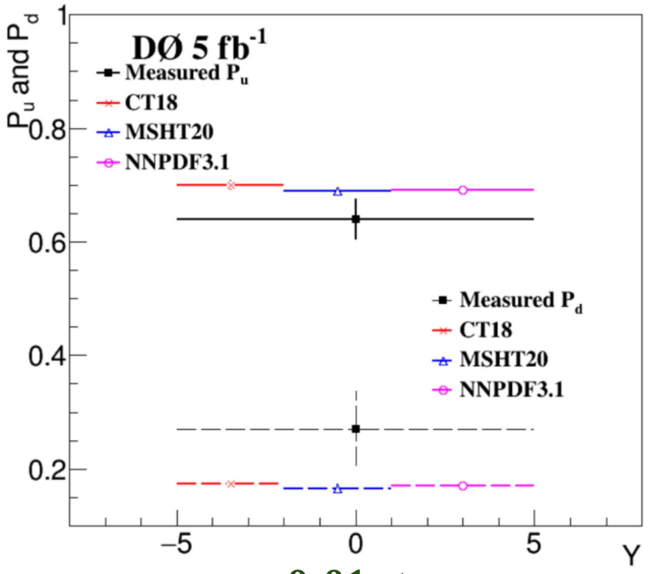
CMS 8 TeV ee+$\mu\mu$ A_{FB} 20 fb^{-1}
Eur. Phys. J. C 76. 325 (2016)

D0 1.96 TeV ee A_{FB} 5 fb^{-1}
Phys. Rev. D 84, 012007 (2011)



0.05<x_1<0.1
0.001<x_2<0.002

CMS results



$0.01 < x$

D0 results

Structure parameter extraction from both CMS and D0 A_{FB}

Phys. Rev. D 107. 054008(2023)

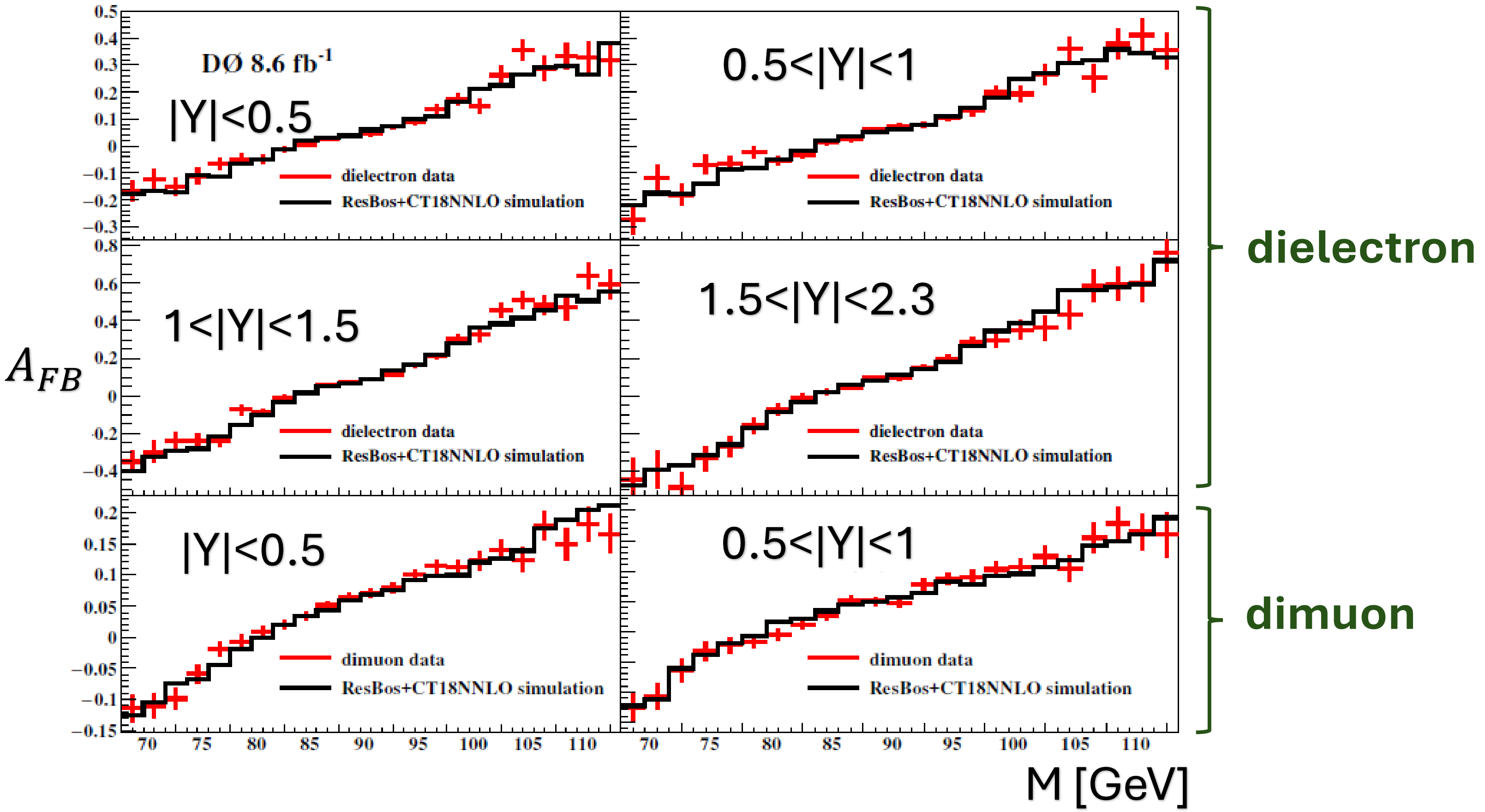
A tendency for P_u to be lower and P_d to be higher than prediction

LHC pp data is a mixture of valence and sea quarks, different from the Tevatron $p\bar{p}$ data

Details of this work

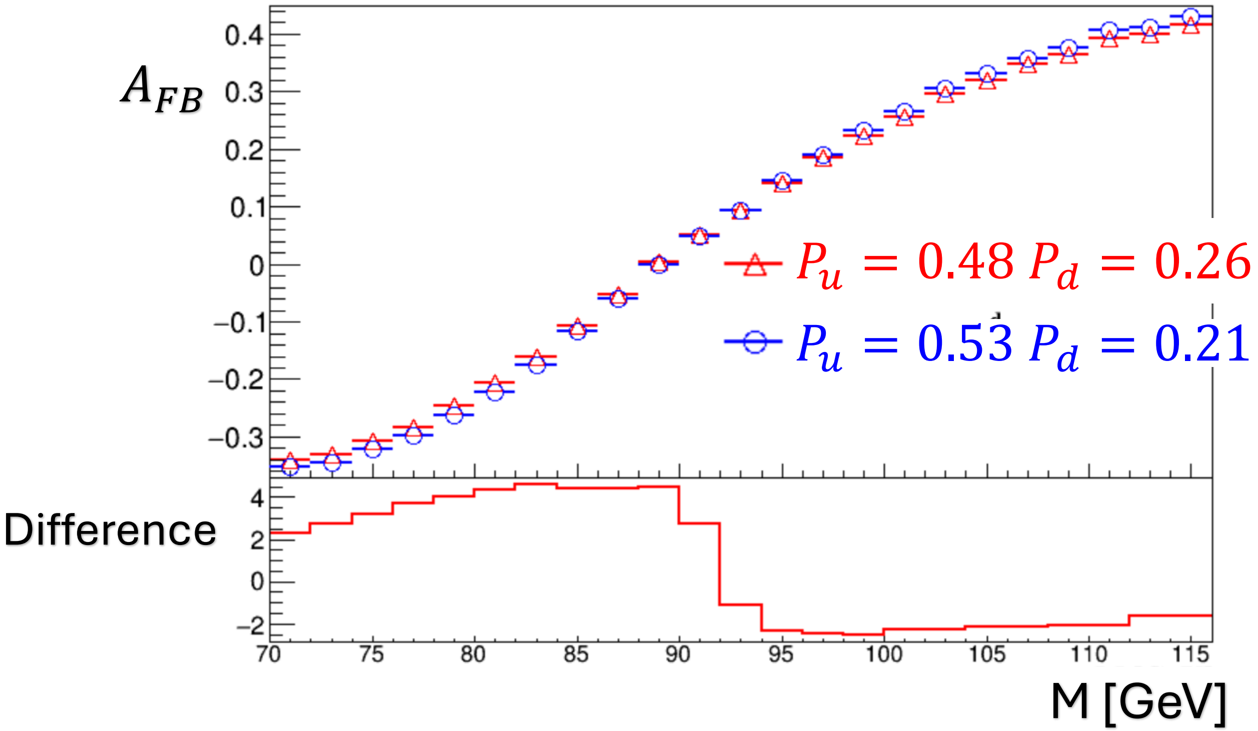
arXiv:2403.09331

- D0 8.6 fb^{-1}, both dielectron and dimuon final states
- Electron $|\eta| < 1.1$ (central), $1.5 < |\eta| < 3.5$ (endcap), $p_T > 25$ GeV
- Muon $|\eta| < 1.8$, $p_T > 15$ GeV
- Mass window $70 < M < 116$ GeV



Simultaneous fit of P_u and P_d

Varying P_u and P_d : A_{FB} templates of simulated MC samples



P_u and P_d are determined by requiring the best agreement between data and MC.

$$\chi^2 = \sum_i \frac{\left[A_{FB}^{data}(i) - A_{FB}^{MC}(i)\right]^2}{\sigma_i^2}$$

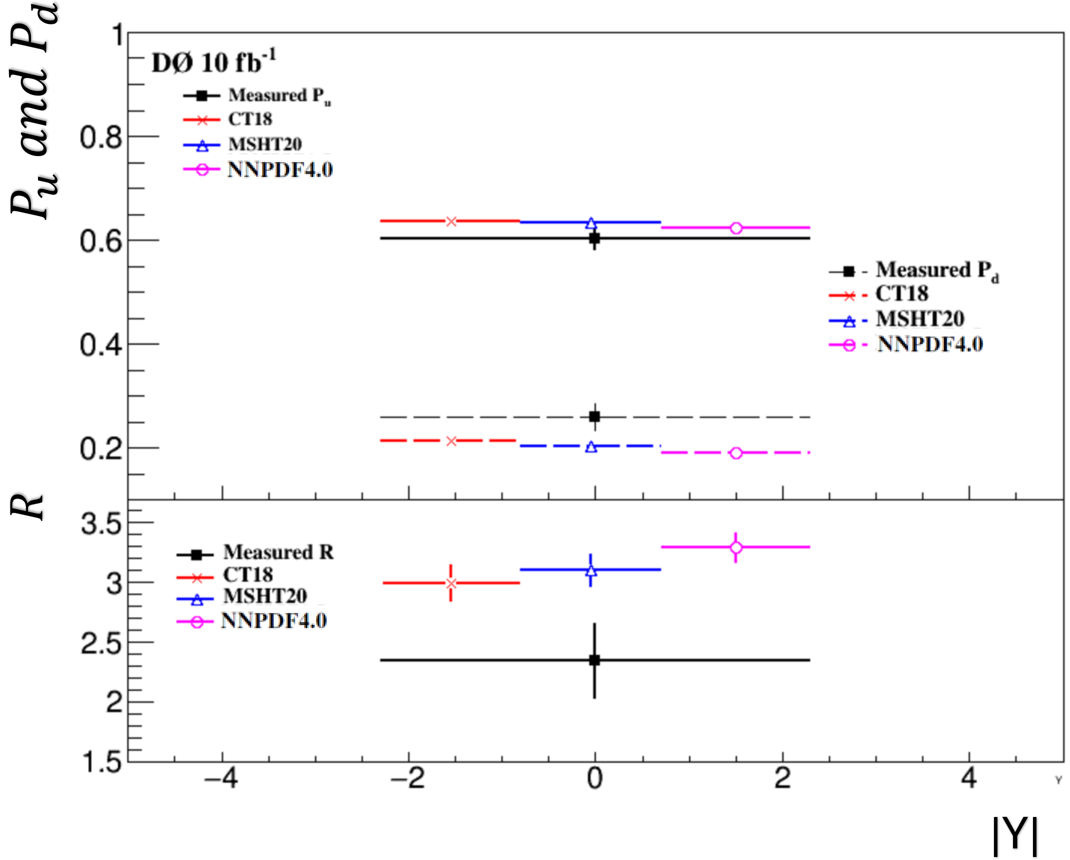
Uncertainties

- Experimental systematics
  - Calibration of electron energy and muon momentum
  - Efficiency determination
  - Estimation of $Z/\gamma^* \rightarrow \tau\tau$, W+jets, diboson (WW, WZ), $\gamma\gamma$, top quarks, multijets backgrounds. Total backgrounds less than 1%.
- Theoretical uncertainties
  - $\sin^2\theta^l_{eff}$: fixed at 0.23153 ± 0.00016 (LEP/SLC combination)
  - Δ-induced uncertainty: fix the mass shape of structure parameters at CT18NNLO prediction, uncertainty estimated using the PDF error sets.
  - QCD: The observed A_{FB} is an average over Y and Q_T. The difference between Pythia (LO) and Resbos (NLO) is taken as unc.

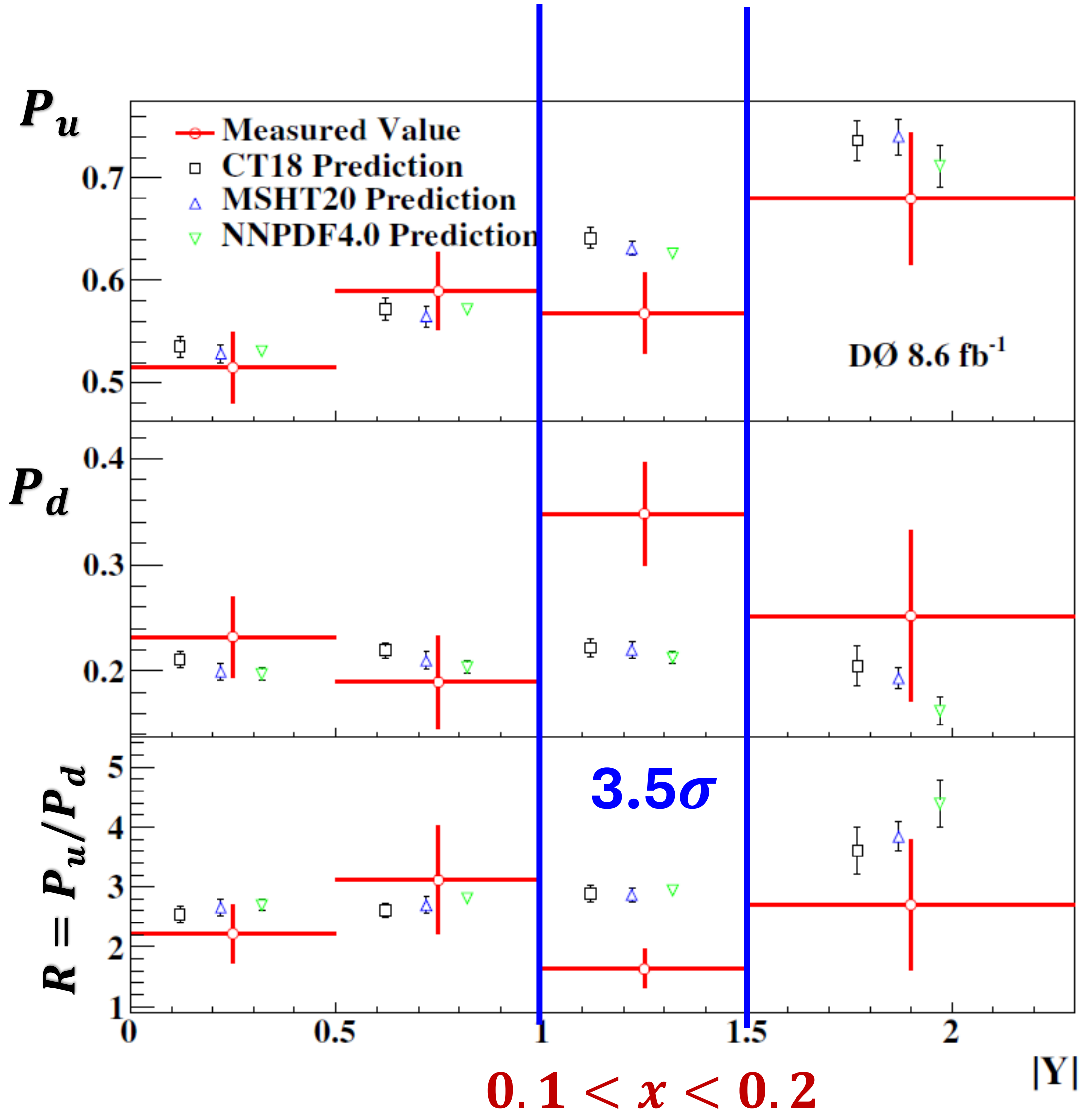
Measurement in |Y|=[0,2.3]

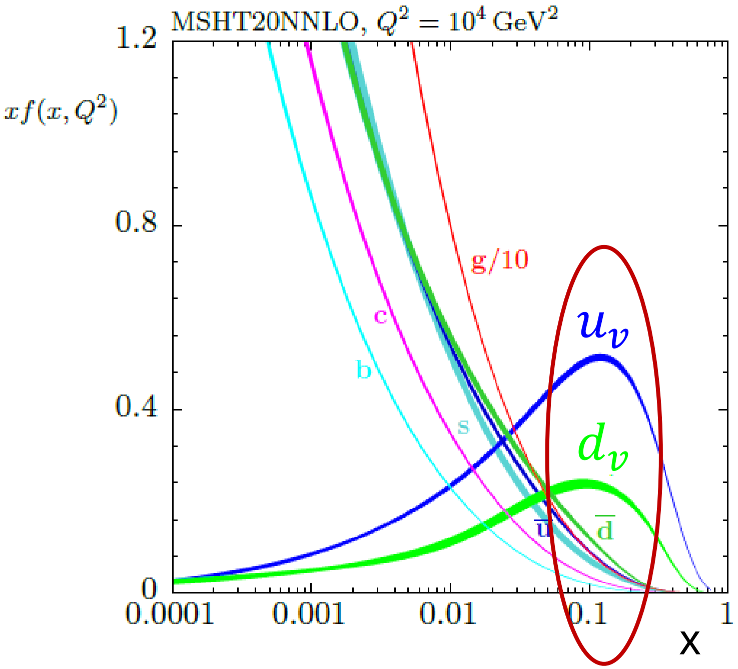
$$P_u = 0.602 \pm 0.019(stat.) \pm 0.010(theory) \pm 0.006(syst.)$$
$$P_d = 0.258 \pm 0.023(stat.) \pm 0.012(theory) \pm 0.005(syst.)$$
$$R = 2.34 \pm 0.32$$

Higher d quark contribution and lower u quark contribution



Measurement as a function of |Y|





The largest deviation locates in |Y|=[1,1.5], which is the peak region of u_v and d_v quark parton density distributions.

Summary and Outlook

- This measurement provide a new proton structure information

$$\boldsymbol{P_u \approx \frac{u_v^2}{\sum_{q=u,d,s,c,b} \sigma_q}} \qquad \boldsymbol{P_d \approx \frac{d_v^2}{\sum_{q=u,d,s,c,b} \sigma_q}} \qquad \boldsymbol{R \approx \frac{u_v^2}{d_v^2}}$$

P_u and P_d separately represent the valence u and d quark contribution, which are indistinguishable for other experimental observables, e.g. structure function, inclusive cross section of W,Z.

- We can also measure P_u and P_d at LHC pp collision

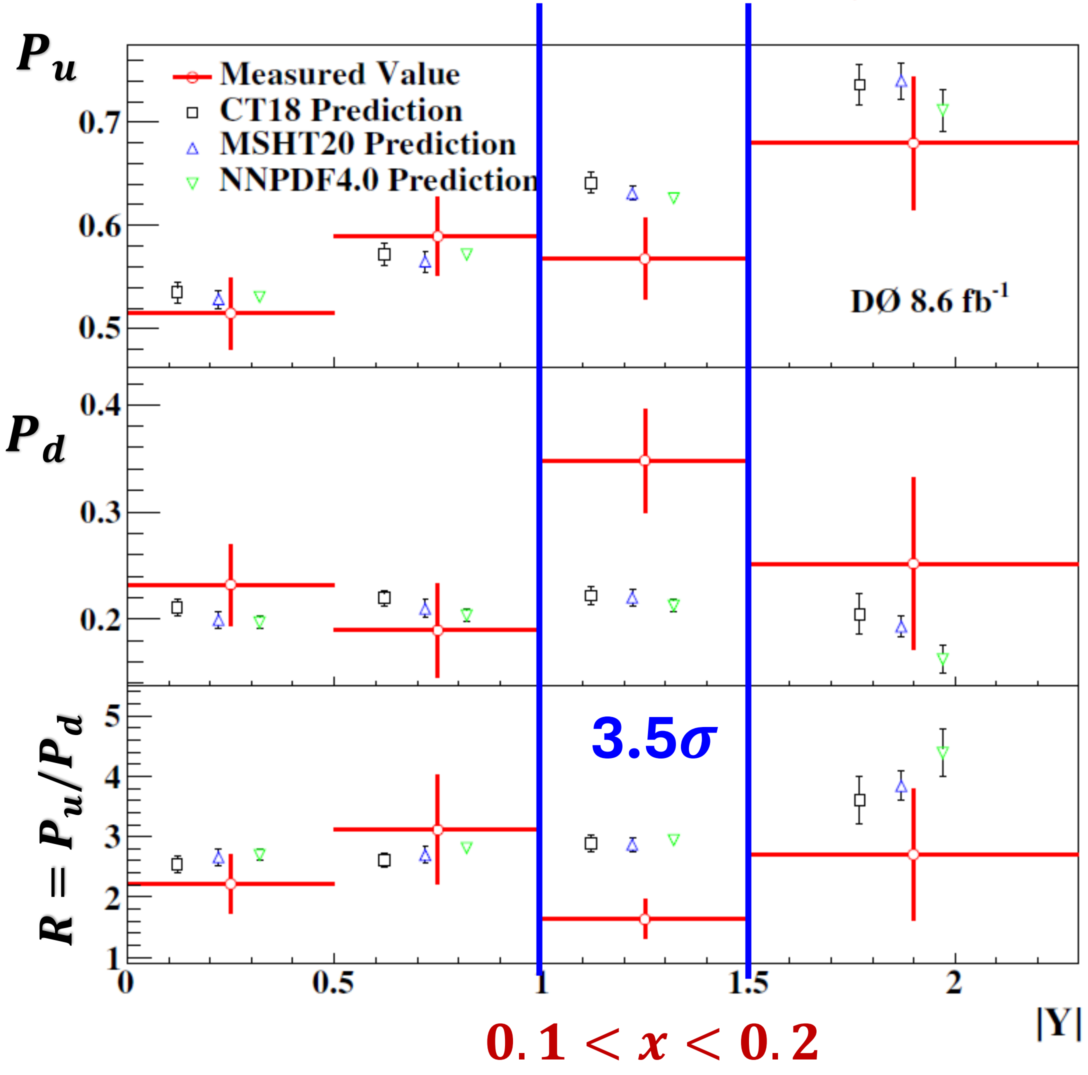
$$\boldsymbol{P_u \propto u(x_1)\bar{u}(x_2) - \bar{u}(x_1)u\,(x_2)}$$
$$\boldsymbol{P_d \propto d(x_1)\bar{d}(x_2) - \bar{d}(x_1)d(x_2)} \qquad x_1 > x_2$$

LHC measurements mix sea quark contributions comparable to the valence quarks, as well as larger range of x value

So measurement at Tevatron provide unique and novel information on the u and d valence quark distributions

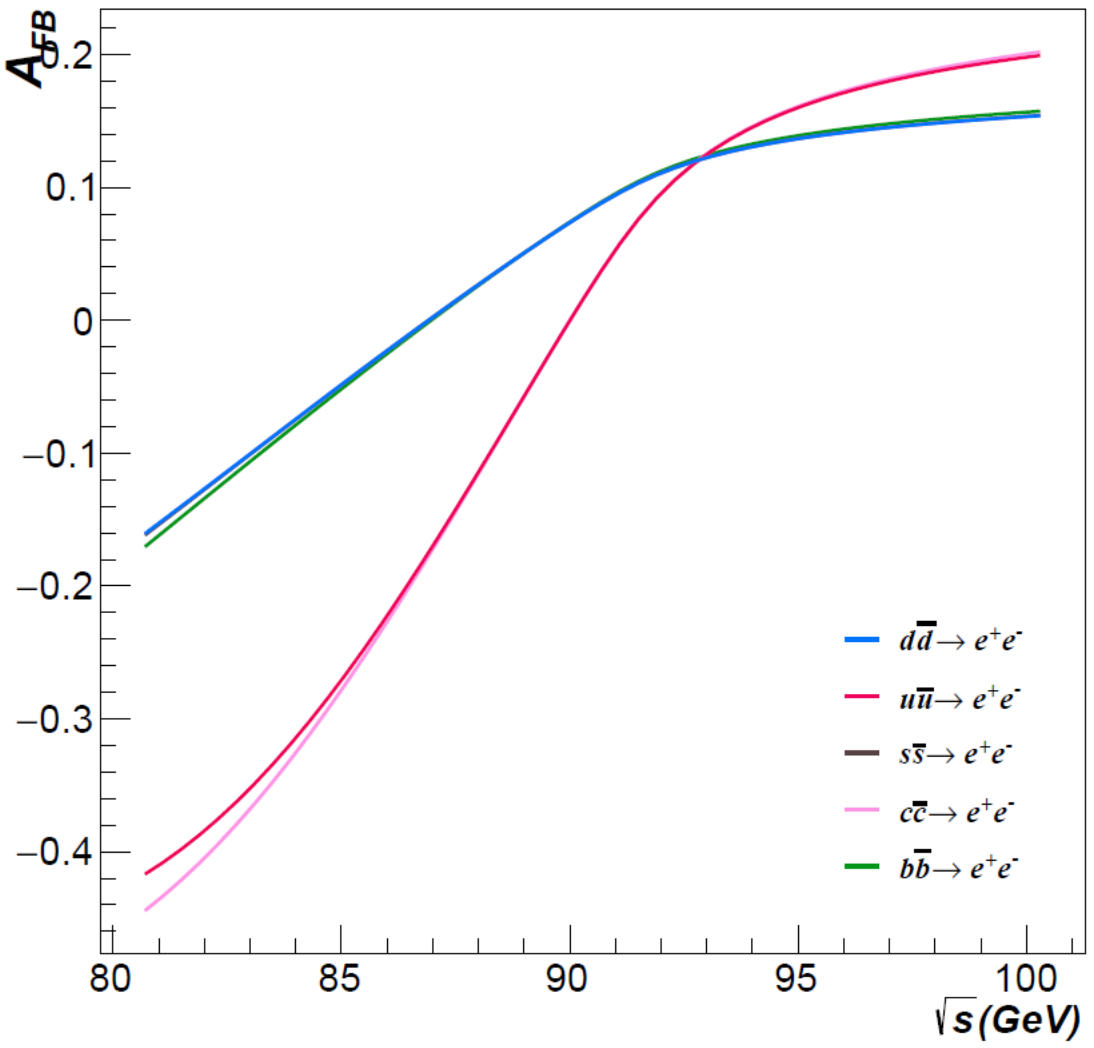
Summary and Outlook

- d valence contribution is higher than PDF prediction while u valence contribution is lower, their ratio differ from PDF prediction by 3.5 σ
- Impact not only on valence PDFs, but also constraining sea quarks through sum rules in the global analysis



Back up

A_{FB} for different quark flavor initial states



Average on M dependence

- We only measure an average information (P_u, P_d) in a specific mass region.

$$C_u(M, Y, Q_T) \equiv [\Delta_u(M, Y, Q_T) + P_u(Y, Q_T)]$$

$$C_d(M, Y, Q_T) \equiv [\Delta_d(M, Y, Q_T) + P_d(Y, Q_T)]$$

Average over mass measured in this work

$$P_u(Y, Q_T) \equiv \int C_u(M, Y, Q_T) dM / \int dM$$

$$P_d(Y, Q_T) \equiv \int C_d(M, Y, Q_T) dM / \int dM$$

Shape of mass fixed in this work

$$\Delta_u(M, Y, Q_T) = C_u(M, Y, Q_T) - P_u(Y, Q_T)$$

$$\Delta_d(M, Y, Q_T) = C_d(M, Y, Q_T) - P_d(Y, Q_T)$$

Measurement in the full |Y| range

Correlation between P_u and P_d is -0.859

	P_u	P_d	R
Measured	0.602±0.022	0.258±0.026	2.34±0.32
CT18NNLO	0.636±0.011	0.213±0.009	2.99±0.16
MSHT20	0.633±0.009	0.204±0.008	3.10±0.14
NNPDF4.0	0.624±0.008	0.190±0.007	3.29±0.13

Uncertainty breakdown

Uncertainties	P_u	P_d
Statistics	0.019	0.023
Experimental	0.006	0.005
$\sin^2 \theta^l_{eff}$	0.004	0.009
Δ-induced	0.009	0.009
QCD	0.002	<0.001

Measurement in Y-dependence

$\|Y\|$ range	P_u	δP_u
$[0, 0.5]$	$0.515 \pm 0.031 \pm 0.011 \pm 0.009 \pm 0.004 \pm 0.005$	0.034
$[0.5, 1.0]$	$0.589 \pm 0.035 \pm 0.010 \pm 0.008 \pm 0.004 \pm 0.005$	0.038
$[1.0, 1.5]$	$0.568 \pm 0.036 \pm 0.007 \pm 0.010 \pm 0.005 \pm 0.003$	0.038
$[1.5, 2.3]$	$0.680 \pm 0.060 \pm 0.009 \pm 0.020 \pm 0.005 \pm 0.003$	0.064

$\|Y\|$ range	P_d	δP_d
$[0, 0.5]$	$0.232 \pm 0.036 \pm 0.007 \pm 0.007 \pm 0.008 \pm 0.001$	0.038
$[0.5, 1.0]$	$0.189 \pm 0.042 \pm 0.008 \pm 0.007 \pm 0.008 \pm 0.004$	0.044
$[1.0, 1.5]$	$0.348 \pm 0.046 \pm 0.005 \pm 0.008 \pm 0.010 \pm 0.002$	0.048
$[1.5, 2.3]$	$0.252 \pm 0.076 \pm 0.014 \pm 0.020 \pm 0.009 \pm 0.002$	0.081

$\|Y\|$ range	R	δR
$[0, 0.5]$	2.22	0.50
$[0.5, 1.0]$	3.11	0.90
$[1.0, 1.5]$	1.63	0.33
$[1.5, 2.3]$	2.70	1.09

Correlation between P_u and P_d is −0.855, −0.862, −0.866 and −0.871 in 4 |Y| bins

Extraction of structure parameters P_u and P_d

Differential cross section of Drell-Yan process can be factorized as a function of P_u and P_d

$$
\begin{aligned}
\frac{d\sigma}{d\cos\theta_h dY dM dQ_T} &= \frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)\times \\
&\left\{(1+\cos^2\theta_h)+\frac{1}{2}A_0^f(Y,M,Q_T)(1-3\cos^2\theta_h)+[1-2D_f(Y,M,Q_T)]A_4^f(Y,M,Q_T)\cos\theta_h\right\} \\
&= \frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)\times\left\{(1+\cos^2\theta_h)+\frac{1}{2}A_0^f(Y,M,Q_T)(1-3\cos^2\theta_h)\right\} \\
&+\frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)[1-2D_f(Y,M,Q_T)]A_4^f(Y,M,Q_T)\cos\theta_h \\
&= \frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)\times\left\{(1+\cos^2\theta_h)+\frac{1}{2}A_0^f(Y,M,Q_T)(1-3\cos^2\theta_h)\right\} \\
&+\frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)\left\{\frac{\sum_{f=u,c}[1-2D_f(Y,M,Q_T)]\alpha_f(Y,M,Q_T)A_4^f(Y,M,Q_T)}{\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)}\cos\theta_h\right. \\
&\left.+\frac{\sum_{f=d,s,b}[1-2D_f(Y,M,Q_T)]\alpha_f(Y,M,Q_T)A_4^f(Y,M,Q_T)}{\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)}\cos\theta_h\right\} \\
&= \frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T)\times\{(1+\cos^2\theta_h) \\
&+\frac{1}{2}A_0^f(Y,M,Q_T)(1-3\cos^2\theta_h)+[\Delta_u(Y,M,Q_T)+P^u(Y,Q_T)]\,A_4^u(Y,M,Q_T)\cos\theta_h \\
&+[\Delta_d(Y,M,Q_T)+P^d(Y,Q_T)]A_4^d(Y,M,Q_T)\cos\theta_h\} \qquad (3.2)
\end{aligned}
$$

By changing the input value of P_u and P_d , we can get a different cross section and A_{FB}.

Extraction of structure parameters P_u and P_d

- Event-by-event reweighting

$$\frac{d\sigma}{d\cos\theta_h dY dM dQ_T}\Big|_{|Y|<2.3, Q_T>0} = \frac{3}{8}\sum_{f=u,d,s,c,b}\alpha_f(Y,M,Q_T) \times\Big\{(1+\cos^2\theta_h)+\frac{1}{2}A_0^f(Y,M,Q_T)(1-3\cos^2\theta_h) + [\Delta_u(Y,M,Q_T)+P^u]\,A_4^u(Y,M,Q_T)\cos\theta_h + [\Delta_d(Y,M,Q_T)+P^d]A_4^d(Y,M,Q_T)\cos\theta_h\Big\}$$

Reweighting factor defined as:

$$R(Y,M,Q_T,\cos\theta_h) = \frac{d\sigma(P^u,P^d)}{dY\,dM\,dQ_T d\cos\theta_h}\Big/\frac{d\sigma(P^u=\text{default},P^d=\text{default})}{dY\,dM\,dQ_T d\cos\theta_h}$$

- Closure-test

	P^u	P^d
Predictions in pseudo-data sample	0.5844	0.2256
Measured values using CC-CC events ($p_T > 25$ GeV)	0.5831±0.0039	0.2255±0.0058
Measured values using CC-EC events($p_T > 25$ GeV)	0.5843±0.0019	0.2260 ±0.0029
Measured values using di-muon events($p_T > 15$ GeV)	0.5849±0.0020	0.2270±0.0030
Measured values using CC-CC events ($p_T > 15$ GeV)	0.5844±0.0038	0.2273±0.0057
Measured values using CC-EC events($p_T > 15$ GeV)	0.5843±0.0018	0.2270 ±0.0028
Measured values using di-muon events($p_T > 25$ GeV)	0.5847±0.0021	0.2263±0.0031
Measured values using CC-CC + CC-EC + di-muon events ($p_T > 25$GeV for CC-CC and CC-EC, $p_T > 15$GeV for di-muon)	0.5847±0.0013	0.2266±0.0019

Method is closure regardless of the kinematic cut

D0 detector

- Central tracking system
- Silicon Microstrip Tracker (SMT)
- Scintillating Central Fiber Tracker (CFT)
- 1.9T Solenoid

- Calorimeter
- Liquid argon and uranium $|\eta| < 4.2$
- Electron energy measurement

- Muon system
- Scintillator
- Drift Tubes
- 1.8T iron toroids