Measurement of the proton structure parameters using the Drell-Yan forward-backward asymmetry (A_{FB}) at hadron colliders

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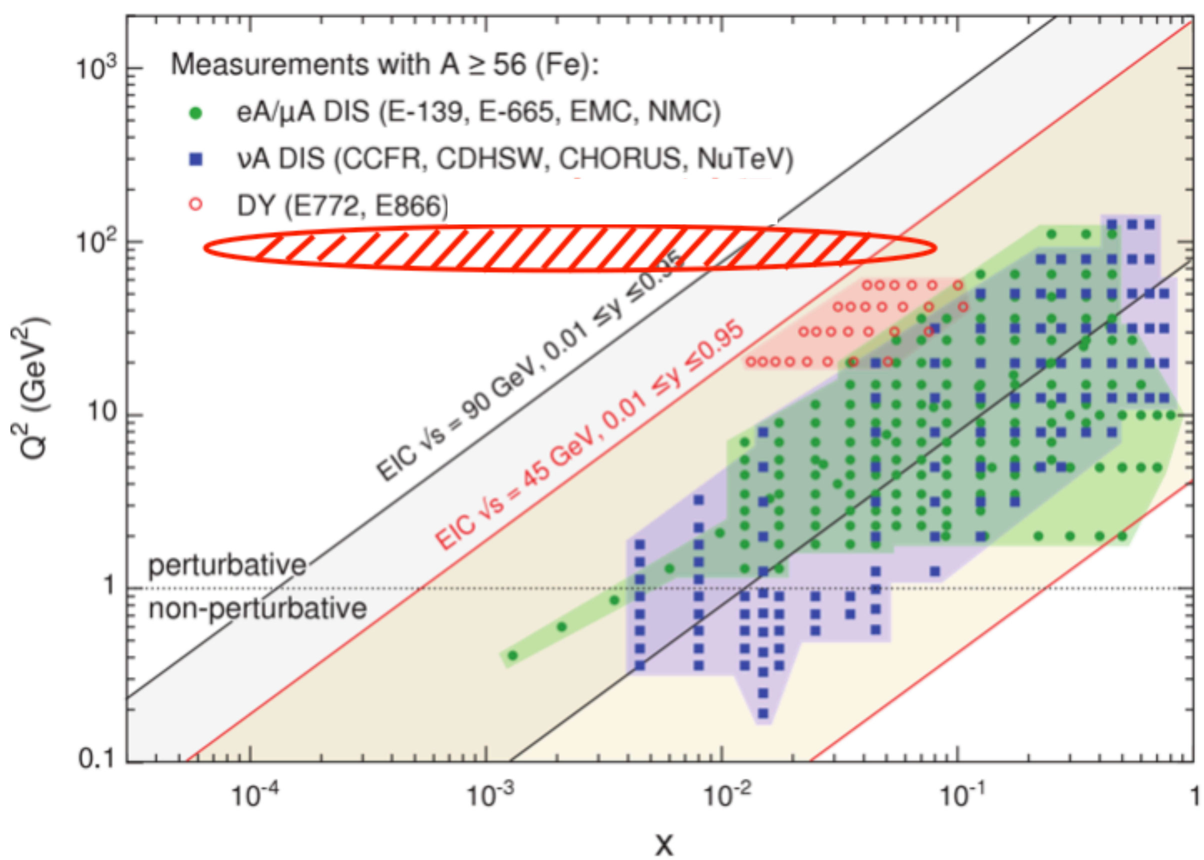
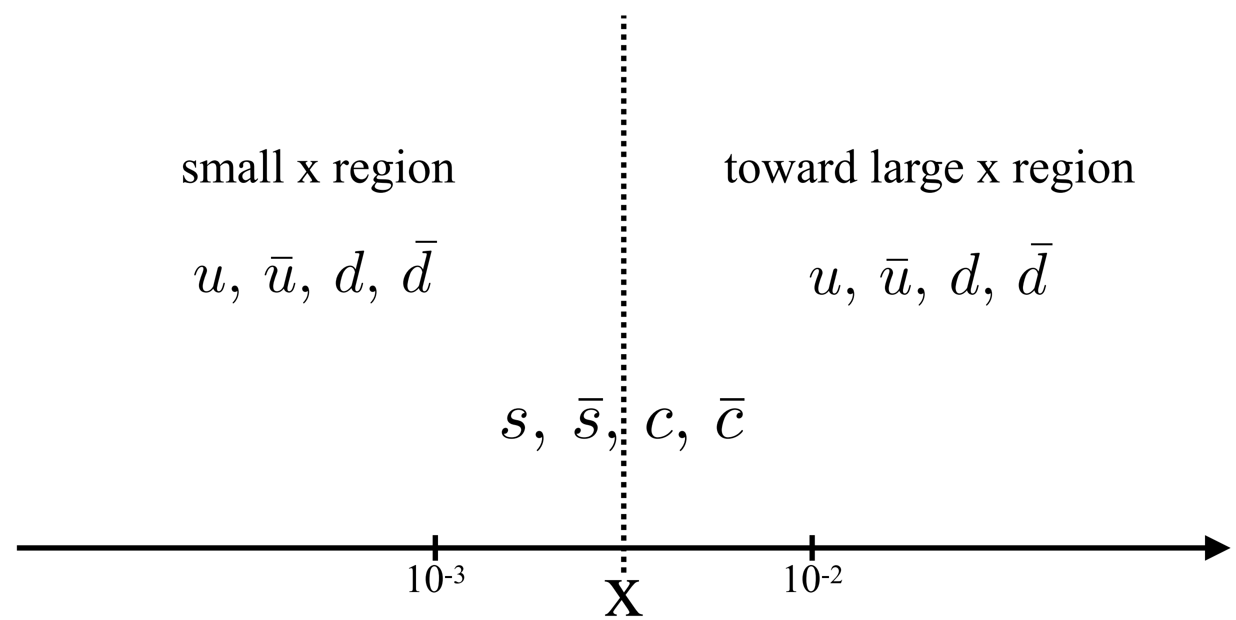
Proton structure study at the LHC

Expectations and difficulties

- advantages: high collision energy/large data sample, significant contribution from sea quarks / heavy quarks / large range of x region
- difficulties: few observables vs mixture of various parton information





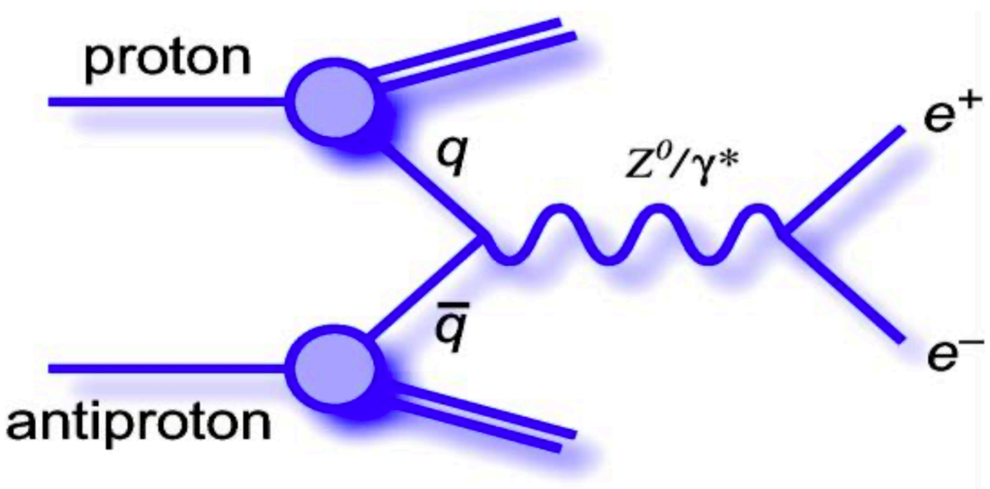
Currently, we only have the Z/W+/W- boson cross section measurement@LHC which are widely used in PDF global fitting

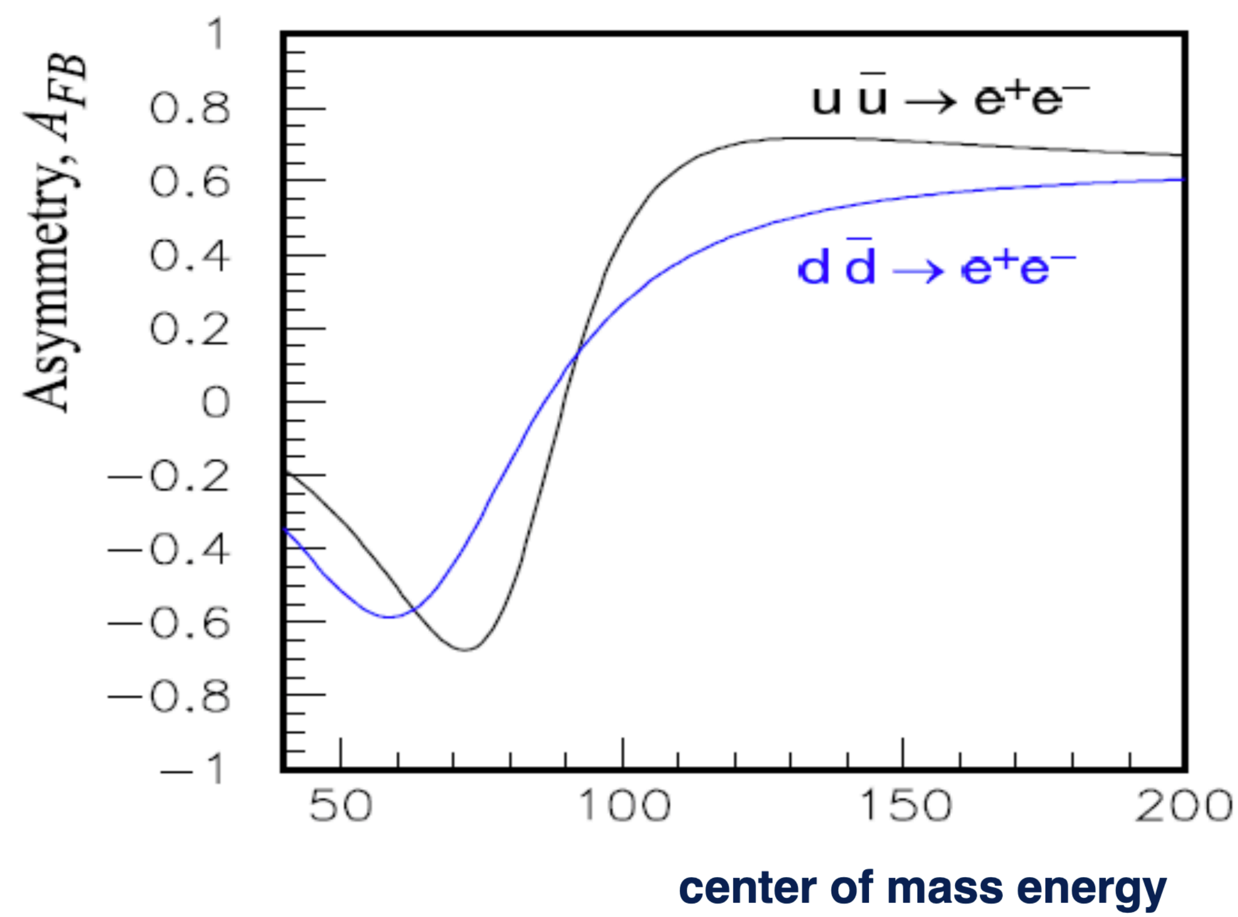
- Find new experimental observables to constrain proton structure information

Drell-Yan process and A_{FB}

A_{FB} from original EW symmetry breaking

- **Spatial asymmetry as function of dilepton mass**
- **Different in u-type and d-type contributions, due to different Z-quark couplings**

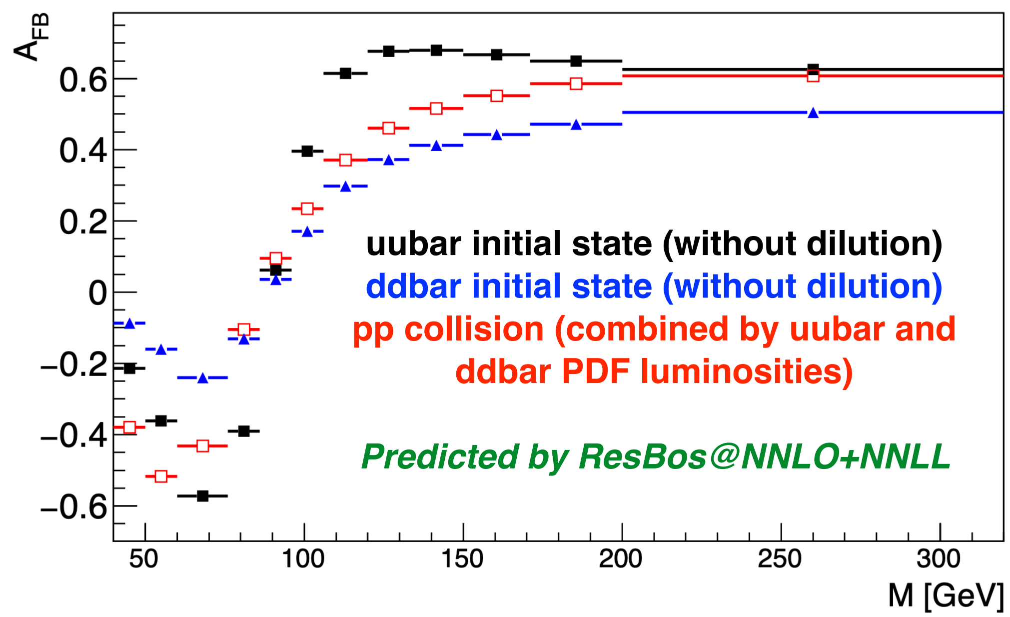




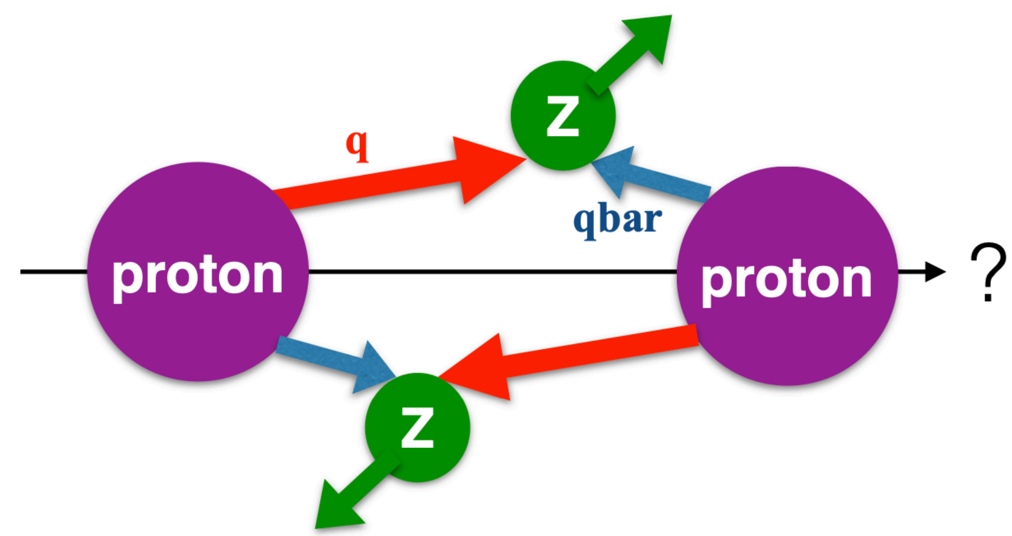
Drell-Yan process and A_{FB}

A_{FB} affected by the proton structure information

- PDF luminosities of uubar and ddbar govern the combination of the two contributions in the A_{FB} observation: cross sections
- Unknown quark direction which dilute the spatial asymmetry: dilution effect



Xsections: the observed Z production is the combined results of the uubar and ddbar initial states



Dilution: the quark directions are unknown. One needs to assume that quarks carry higher energy than antiquarks, so that the quark direction is along the dilepton system.

- No matter how PDF affects A_{FB}, it is possible that the u and d quark contribution can be separately observed, based on the fact that their original asymmetries are different

Factorization on A_{FB} and relavent proton structure information

Factorization

- To measure the proton structure information, we need to factorize the PDF contribution in A_{FB} into well-defined structure parameters.

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

$$
\begin{aligned}
A_{FB}(M) &= \frac{\sum_{q=u,c}[1-2D_q(M)]\alpha_q(M)}{\alpha_{\text{total}}(M)} \cdot A^u_{FB}(M;\sin^2\theta^\ell_{\text{eff}}) \\
&+ \frac{\sum_{q=d,s,b}[1-2D_q(M)]\alpha_q(M)}{\alpha_{\text{total}}(M)} \cdot A^d_{FB}(M;\sin^2\theta^\ell_{\text{eff}}) \\
&\equiv \boxed{[\Delta_u(M)+P^u_0]} \cdot A^u_{FB}(M;\sin^2\theta^\ell_{\text{eff}}) \\
&+ \boxed{[\Delta_d(M)+P^d_0]} \cdot A^d_{FB}(M;\sin^2\theta^\ell_{\text{eff}}), \qquad (1)
\end{aligned}
$$

- The observed A_{FB} is naturally factorized into a 2-term formality, which is the combination of the uubar and ddbar asymmetries
- The original EW asymmetries are governed by the effective weak mixing angle
- The coefficients of the two EW asymmetries, namely the weights in the combination, represent the proton structure information

Some discussions

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

Parameters at the Tevatron and LHC

- For LHC's pp collision: separating u and d contributions. However with both q and qbar; both small x and relatively large x

$$P_0^u \propto u(x_1)\bar{u}(x_2) - u(x_2)\bar{u}(x_1)$$

$$P_0^d \propto d(x_1)\bar{d}(x_2) - d(x_2)\bar{d}(x_1) \qquad x_1 > x_2$$

- For Tevatron's ppbar collision: qbar and small x contributions significantly suppressed

$$P_0^u \propto u(x_1)u(x_2) - \bar{u}(x_1)\bar{u}(x_2) \approx u(x)^2$$

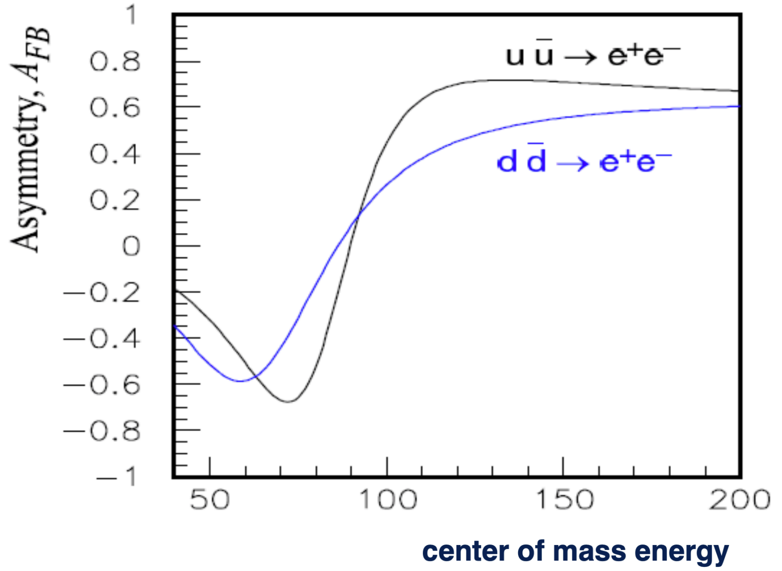
$$P_0^d \propto d(x_1)d(x_2) - \bar{d}(x_1)\bar{d}(x_2) \approx d(x)^2$$

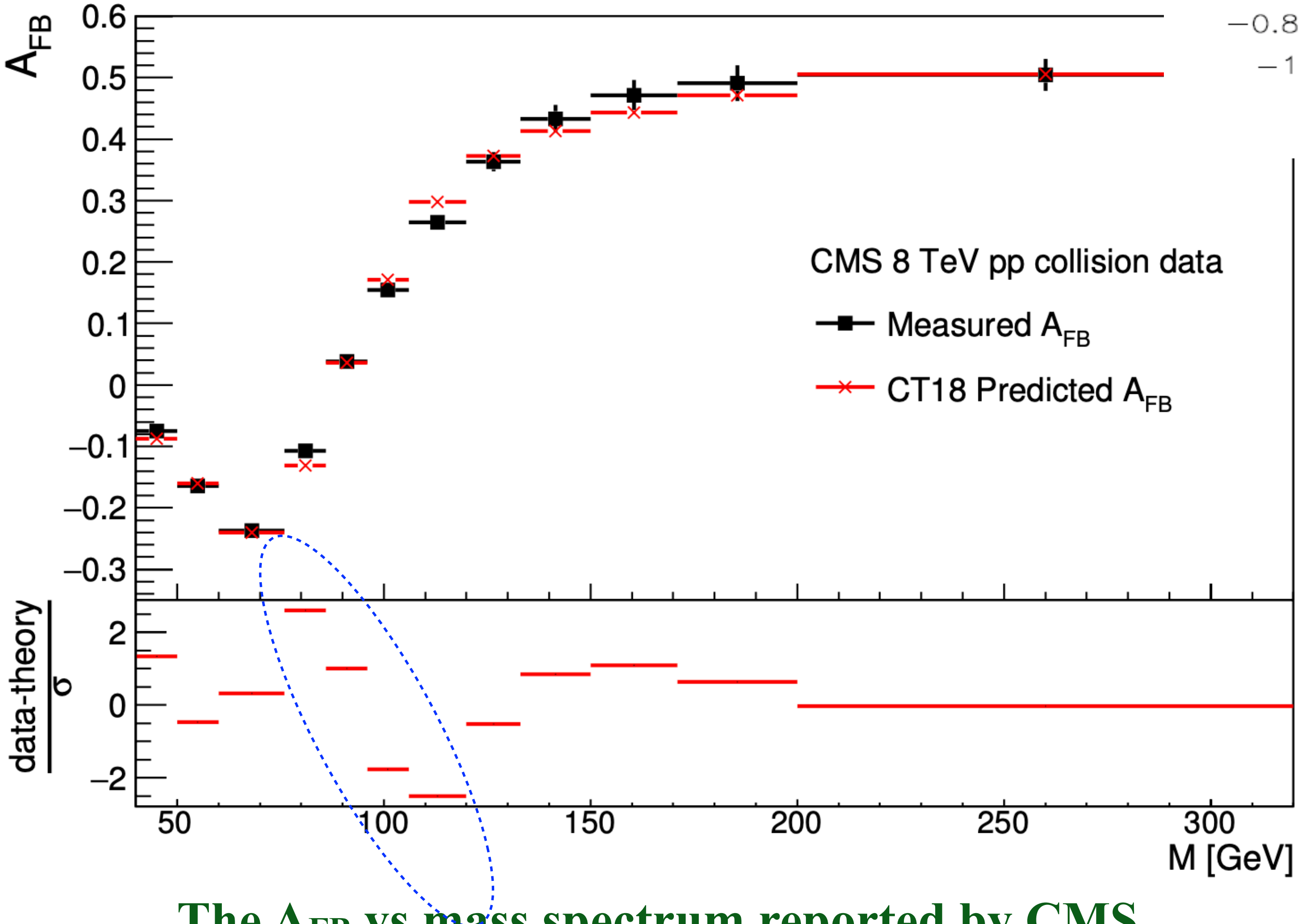
- Measurements using LHC and Tevatron data provide complimentary constraints on proton structure parameters

Measurement using the CMS data

A_{FB} measured using CMS data

- LHC 8 TeV data in Run 1
- A_{FB} vs mass measured in 4 ZY bins, up to 2.4





The A_{FB} vs mass spectrum reported by CMS, compared to the theoretical predictions from the PDF of CT18. This plot gives an example of the AFB in the ZY bin of [1.5, 2.4]

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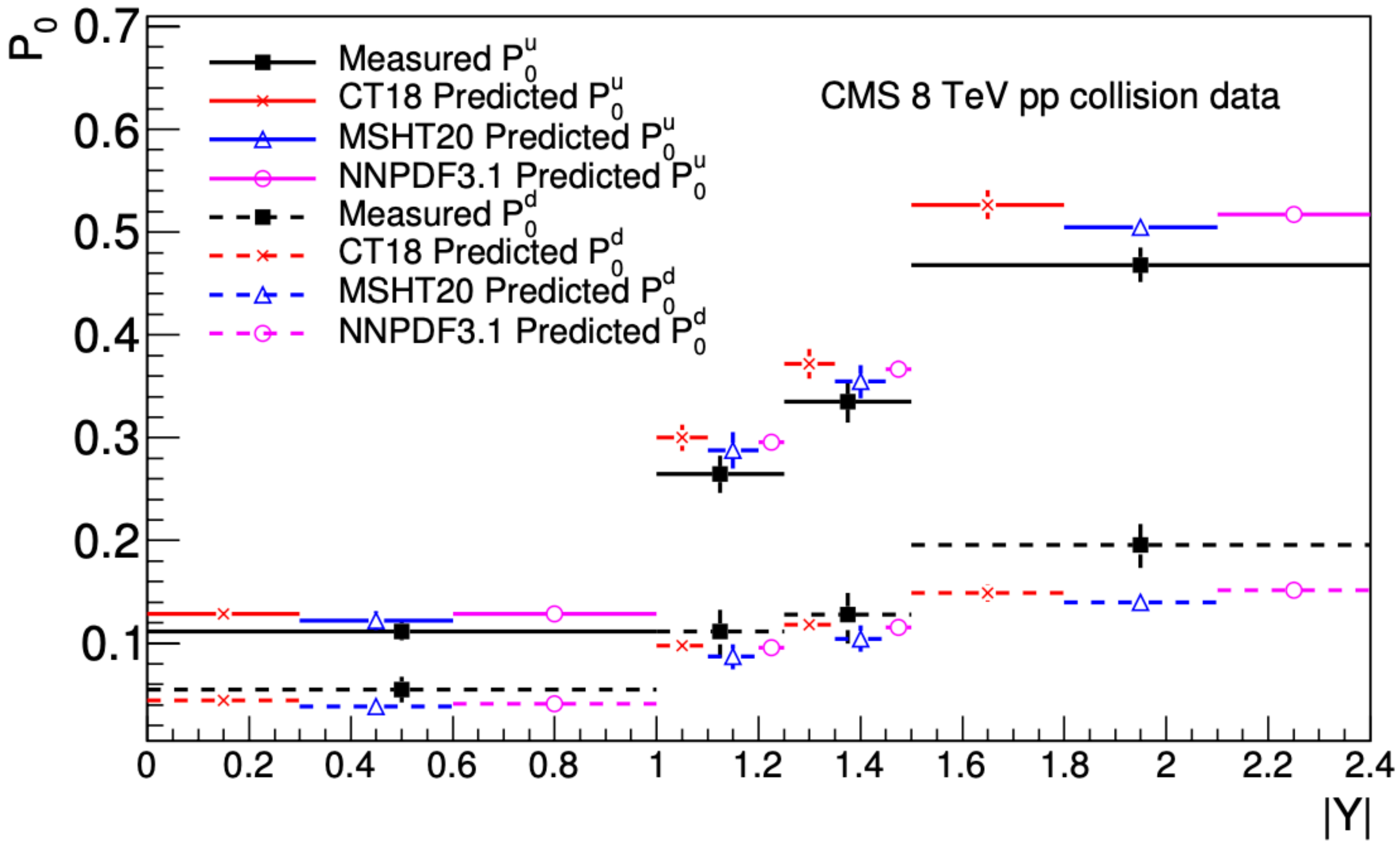
Measurement using the CMS data

Structure parameters measured in all ZY bins

- P0u consistently lower than predictions, while P0d higher than predictions
- In another word, the data indicates a stronger d-quark contribution

arXiv:2209.13143



$$P_0^u \propto u(x_1)\bar{u}(x_2) - u(x_2)\bar{u}(x_1)$$

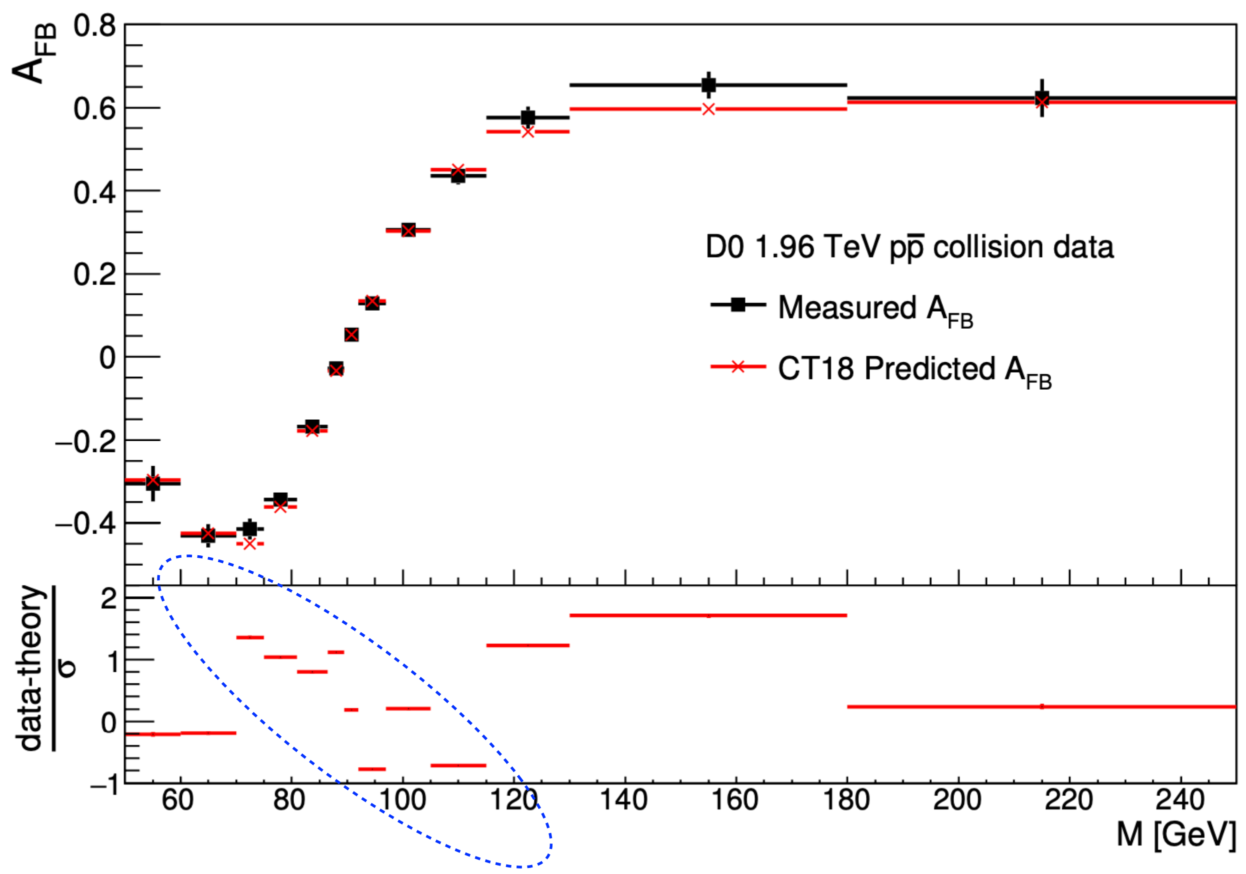
$$P_0^d \propto d(x_1)\bar{d}(x_2) - d(x_2)\bar{d}(x_1)$$

Measured structure parameters from all the 4 ZY bins using the CMS 8 TeV data

Measurement using the DØ data

A_{FB} measured using DØ data

- **Tevatron 1.96 TeV data in Run 2 (half DØ data set)**
- **A_{FB} vs mass in an integrated ZY phase space**



The AFB vs mass spectrum reported by DØ compared to the theoretical predictions from the PDF of CT18.

Measurement using the DØ data

Structure parameters

- P0u lower than predictions, while P0d higher than predictions
- Consistent with the CMS data

arXiv:2209.13143

	P_0^u	P_0^d
D0 data	0.6395 ± 0.0361	0.2706 ± 0.0665
CT18	0.6994 ± 0.0089	0.1733 ± 0.0062
MSHT20	0.6887 ± 0.0066	0.1658 ± 0.0075
NNPDF3.1	0.6919 ± 0.0054	0.1703 ± 0.0055

$$P_0^u \propto u(x_1)u(x_2) - \bar{u}(x_1)\bar{u}(x_2) \approx u(x)^2$$

$$P_0^d \propto d(x_1)d(x_2) - \bar{d}(x_1)\bar{d}(x_2) \approx d(x)^2$$

Some discussions

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arXiv:2209.13143

Correlations between P0u and P0d

- **Since P0u and P0d are simultaneously measured from one A_{FB} spectrum, they certainly have correlations, roughly at 90%.**

The effective weak mixing angle $\sin^2\theta_W$

- **$\sin^2\theta_W$ is treated as a free parameter in the measurement. In another word, it is also measured simultaneously.**
- **However, this is not our purpose. We treat it as free parameter simply to properly deal with the correlation between PDF and EW.**
- **The fitted $\sin^2\theta_W$ is consistent with the direct measurement on weak mixing angle reported by CMS and DØ using the same data sample.**

Average magnitude and mass-evolution

- **The structure parameters have P0 part and Δ part.**
- **P0 represents the average magnitude of the proton structure information in the mass window under investigation. Dominant part**
- **Δ represents the dependence with mass. Not dominant because A_{FB} is not measured in large mass range.**

Summary

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

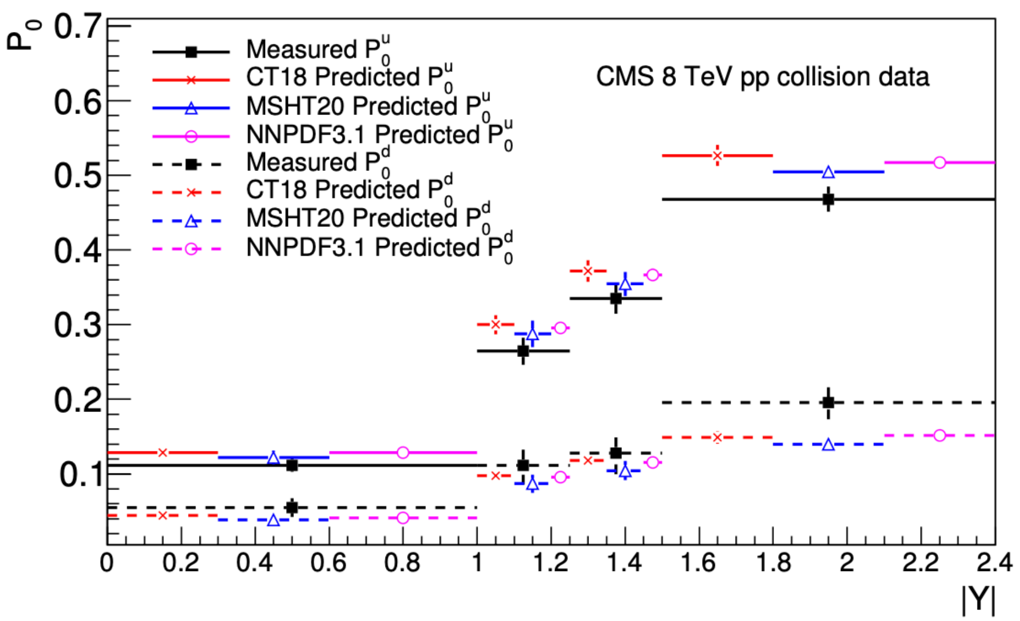
arXiv:2209.13143

A_{FB} factorization

- Define structure parameters, so that the u and d contributions can be separately measured

Measurement from the CMS and DØ data

- Both data show stronger contribution of d quark



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Backup

Some discussions

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Average magnitude and mass-evolution

- P_0 parameters: dominant part, representing the magnitude of the proton structure information averaged in the mass window under investigation

- Δ parameters: secondary effect, describing the dependence with mass. Not dominant because A_{FB} is usually measured in a narrow mass window around Z pole

$$
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