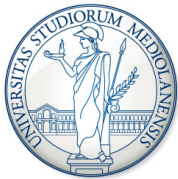


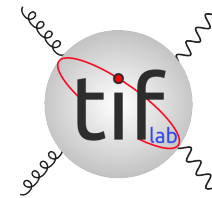


# PDF UNCERTAINTIES & BSM SEARCHES

STEFANO FORTE  
UNIVERSITÀ DI MILANO & INFN



UNIVERSITÀ DEGLI STUDI DI MILANO  
DIPARTIMENTO DI FISICA



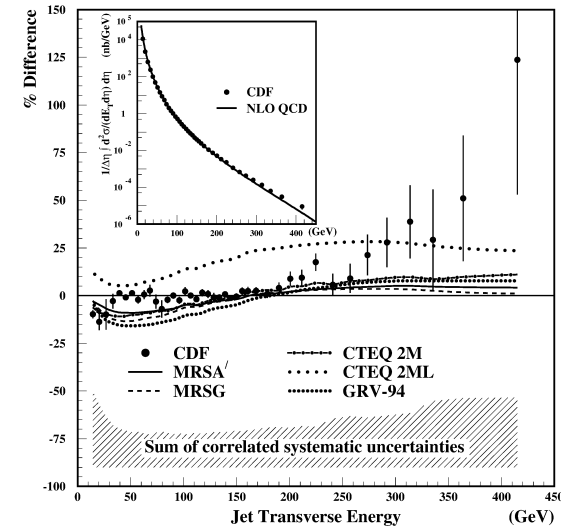
IRN TERASCALE MEETING

NANTES, OCTOBER 18, 2022

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740006

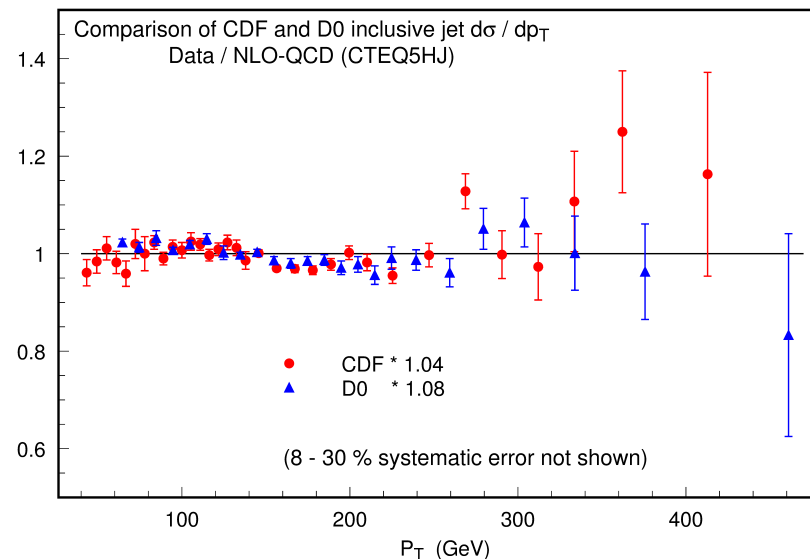
# PDF UNCERTAINTIES AND NEW PHYSICS: TEVATRON

- **DISCREPANCY** BETWEEN QCD CALCULATION AND CDF JET DATA (1995)
- EVIDENCE FOR **QUARK COMPOSITENESS?**
- RESULT **STRONGLY DEPENDS** ON GLUON AT  $x \gtrsim 0.1$
- PDF MUST VANISH AT  $x = 0$ , BUT (THEN) NO DATA FOR  $x \gtrsim 0.05!$



DISCREPANCY REMOVED IF JET DATA USED FOR GLUON DETERMINATION

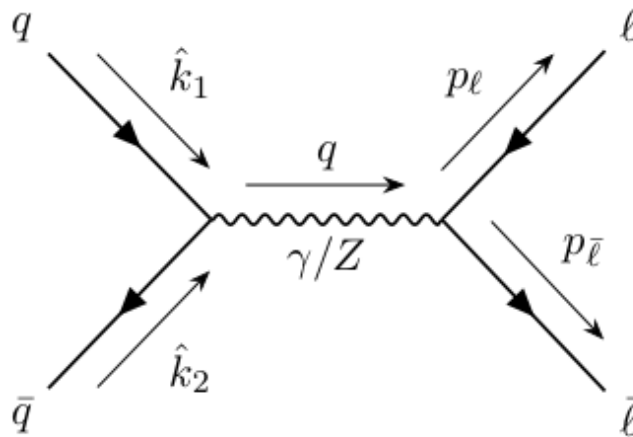
## NEW CTEQ GLUON (1998)



**NOW: NO DATA** FOR  $x \gtrsim 0.5 \Rightarrow$  **DISCOVERY** (THRESHOLD) REGION!

# NEW PHYSICS SEARCHES AT THE LHC

## THE DRELL-YAN FORWARD-BACKWARD ASYMMETRY

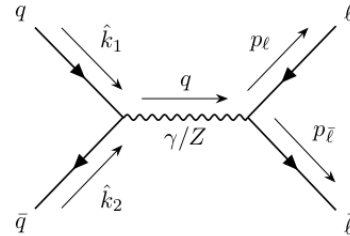


$$A_{\text{fb}}(\cos \theta) \equiv \frac{\frac{d\sigma}{d \cos \theta}(\cos \theta) - \frac{d\sigma}{d \cos \theta}(-\cos \theta)}{\frac{d\sigma}{d \cos \theta}(\cos \theta) + \frac{d\sigma}{d \cos \theta}(-\cos \theta)}$$

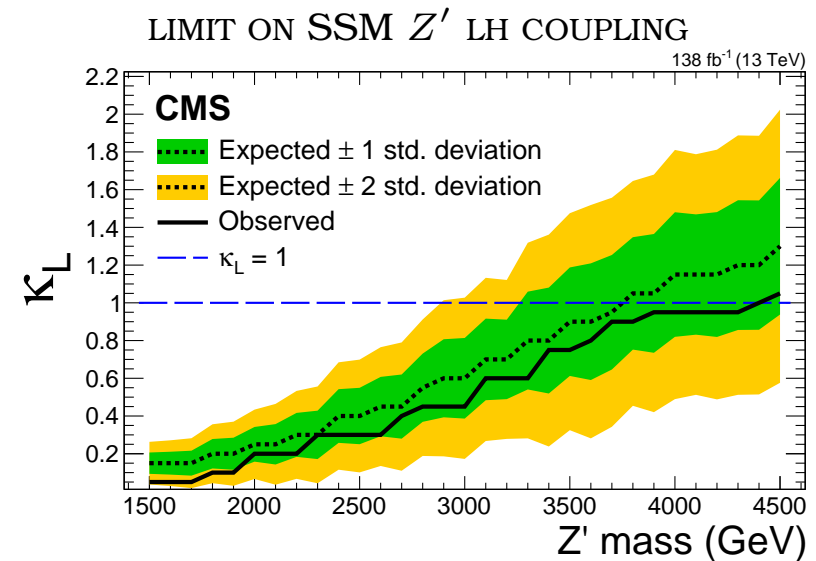
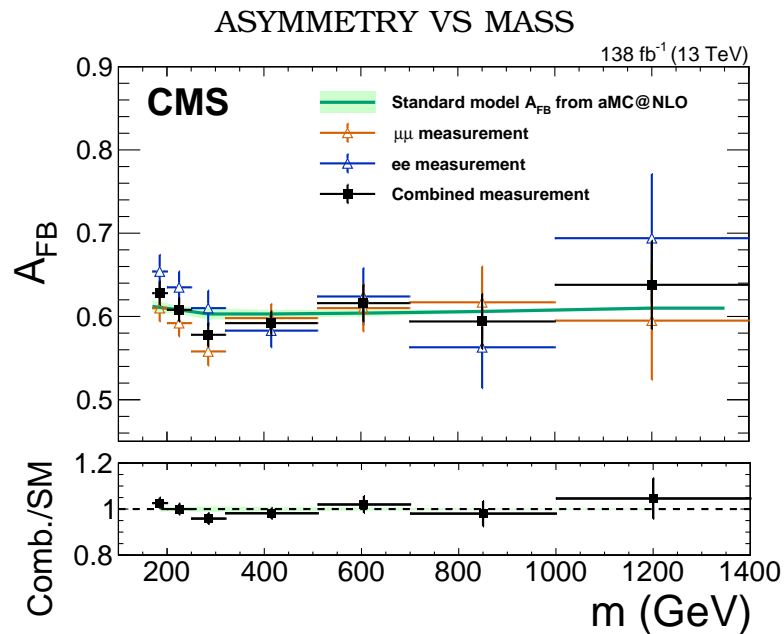
- **TH:** ASYMMMETRY SENSITIVE TO CHIRAL BSM COUPLINGS
- **EXP:** SEVERAL SYSTEMATICS CANCEL IN RATIO

# THE DRELL-YAN FORWARD-BACKWARD ASYMMETRY CMS BSM SEARCH

CMS, 2201.12327



$$A_{\text{fb}} \equiv \int_0^1 d \cos \theta \frac{\frac{d\sigma}{d \cos \theta}(\cos \theta) - \frac{d\sigma}{d \cos \theta}(-\cos \theta)}{\frac{d\sigma}{d \cos \theta}(\cos \theta) + \frac{d\sigma}{d \cos \theta}(-\cos \theta)}$$



## ANATOMY OF THE ASYMMETRY

- **SCATTERING ANGLE** IN THE PARTONIC CM FRAME  $\Leftrightarrow$  **LEPTON KINEMATICS**

(Collins-Soper frame):  $\cos \theta \equiv \frac{p_\ell^+ p_{\bar{\ell}}^- - p_\ell^- p_{\bar{\ell}}^+}{m_{\ell\bar{\ell}} \sqrt{m_{\ell\bar{\ell}}^2 + p_{T,\ell\bar{\ell}}^2}}, p^\pm = p^0 \pm p^3$

- MEASURE  $\cos \theta^* = \text{sign}(y_{\ell\bar{\ell}}) \cos \theta$ : W.R. DIRECTION OF  $Z$
- AT LO  $\Rightarrow$  DIRECTION OF PARTON WITH **LARGEST**  $x$

### LO CROSS-SECTION

$$\frac{d^3 \sigma}{dm_{\ell\bar{\ell}} dy_{\ell\bar{\ell}} d \cos \theta^*} = \frac{\pi \alpha^2}{3m_{\ell\bar{\ell}} s} \left( (1 + \cos^2(\theta^*)) \sum_q S_q \mathcal{L}_{S,q}(m_{\ell\bar{\ell}}, y_{\ell\bar{\ell}}) + \cos \theta^* \sum_q A_q \mathcal{L}_{A,q}(m_{\ell\bar{\ell}}, y_{\ell\bar{\ell}}) \right)$$

### PARTON LUMINOSITIES

$$x_1 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}} \exp(y_{\ell\bar{\ell}}), \quad x_2 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}} \exp(-y_{\ell\bar{\ell}}); \quad x_1 x_2 = \frac{m_{\ell\bar{\ell}}^2}{s}$$

#### SYMMETRIC

$$\mathcal{L}_{S,q}(m_{\ell\bar{\ell}}, y_{\ell\bar{\ell}}) \equiv f_q(x_1, m_{\ell\bar{\ell}}^2) f_{\bar{q}}(x_2, m_{\ell\bar{\ell}}^2) + f_q(x_2, m_{\ell\bar{\ell}}^2) f_{\bar{q}}(x_1, m_{\ell\bar{\ell}}^2)$$

#### ANTISYMMETRIC

$$\mathcal{L}_{A,q}(m_{\ell\bar{\ell}}, y_{\ell\bar{\ell}}) \equiv \text{sign}(y_{\ell\bar{\ell}}) \left[ f_q(x_1, m_{\ell\bar{\ell}}^2) f_{\bar{q}}(x_2, m_{\ell\bar{\ell}}^2) - f_q(x_2, m_{\ell\bar{\ell}}^2) f_{\bar{q}}(x_1, m_{\ell\bar{\ell}}^2) \right]$$

- **AXIAL** COUPLING  $\Rightarrow$  **LINEAR**  $\cos \theta$  DEPENDENCE
- $A_{\text{fb}} \Leftrightarrow$  **ASYMMETRIC** PARTON LUMINOSITY

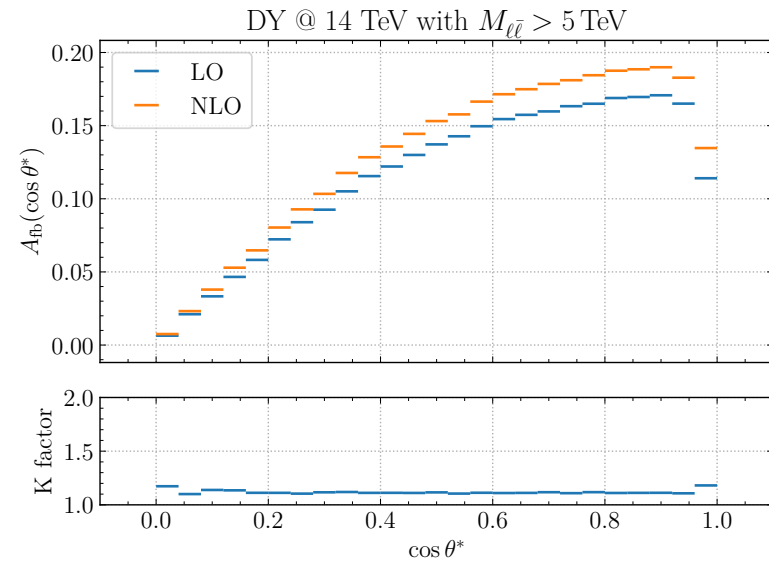
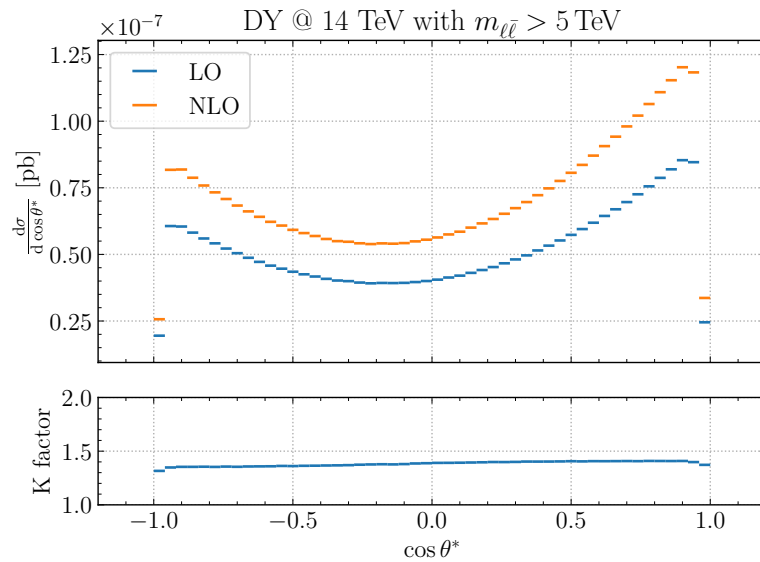
## QUALITATIVE BEHAVIOR: NLO vs. LO LO INTEGRATED RESULT (HIGH MASS)

$$A_{\text{fb}}(\cos \theta^*) = \frac{\cos \theta^*}{(1 + \cos^2(\theta^*))} \frac{g_A}{g_{S,q'}}; \quad g_{A,S} \propto \int \frac{dm_{\ell\bar{\ell}}}{m_{\ell\bar{\ell}}} \frac{dx_1}{x_1} \mathcal{L}_{A,S}(m_{\ell\bar{\ell}}, x_1)$$

LO vs. NLO FOR  $M_{z'} = 5\text{TeV}$

CROSS-SECTION

FORWARD-BACKWARD ASYMMETRY



- AT LO,  $A_{\text{fb}} \propto \cos \theta$ , **EFFECTIVE COUPLING** DETERMINED BY PDF **LUMINOSITY**
- NLO **K-FACTOR ALMOST  $\theta$ -INDEPENDENT**

## QUALITATIVE BEHAVIOR:

$$A_{\text{fb}} \propto \mathcal{L}_{A,q} = f_q(x_1)f_{\bar{q}}(x_2) - f_q(x_2)f_{\bar{q}}(x_1) = \frac{1}{2} \left( f_q^-(x_1)f_q^+(x_2) - f_q^-(x_2)f_q^+(x_1) \right)$$

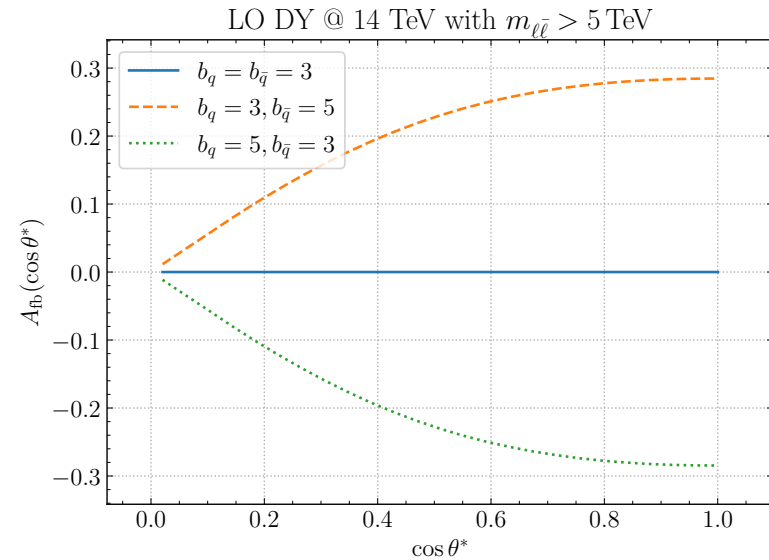
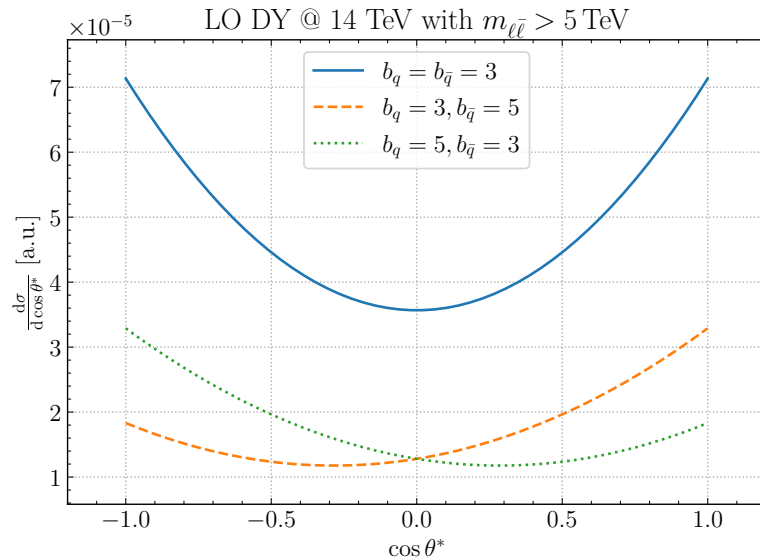
$$f_q^\pm = f_q \pm f_{\bar{q}}; f^- \rightarrow \text{VALENCE}; f^+ \rightarrow \text{SEA}$$

### TOY PDFS

$$x f_q^\pm = x^{-1} \left[ (1-x)^{b_q} \pm (1-x)^{b_{\bar{q}}} \right]$$

CROSS-SECTION

FORWARD-BACKWARD ASYMMETRY



- TOY: SIGN OF ASYM  $\Leftrightarrow$  SIGN OF VALENCE

- GENERAL: SIGN OF ASYM  $\Leftrightarrow$  DROP OF VALENCE VS. SEA

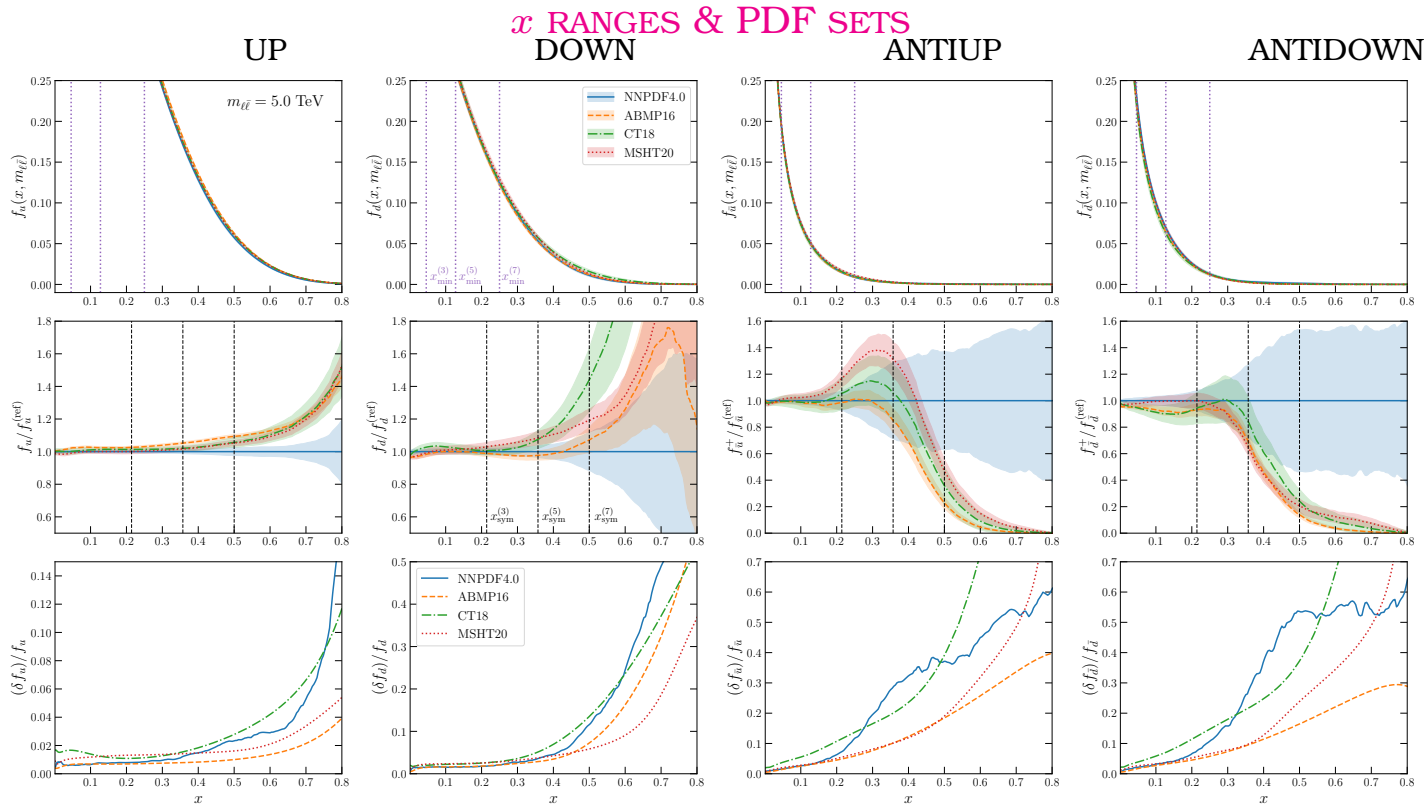
$$\text{sign} [\mathcal{L}_{A,q}] = \text{sign} \left[ \frac{f_q^+(x_2)}{f_q^+(x_1)} - \frac{f_q^-(x_2)}{f_q^-(x_1)} \right] = \text{sign} \left[ \frac{f_q(x_2)}{f_q(x_1)} - \frac{f_{\bar{q}}(x_2)}{f_{\bar{q}}(x_1)} \right], x_1 > x_2$$

- VALENCE DROPS FASTER  $\Rightarrow$  NEGATIVE ASYM

CANNOT HAVE NEGATIVE VALENCE, BUT FAST-DROPPING VALENCE ALLOWED

# QUALITATIVE BEHAVIOR: EXISTING PDF SETS

- DOMINANT CONTRIBUTION  $\Rightarrow$  up AND down QUARKS, ANTIQUARKS
- AS  $Z'$  MASS CHANGES,  $x$  RANGE CHANGES:  $x_1 x_2 = \frac{m_{\ell\bar{\ell}}}{\sqrt{s}}$   
BUT PDFS (LARGE  $x$ ) CHANGE VERY LITTLE



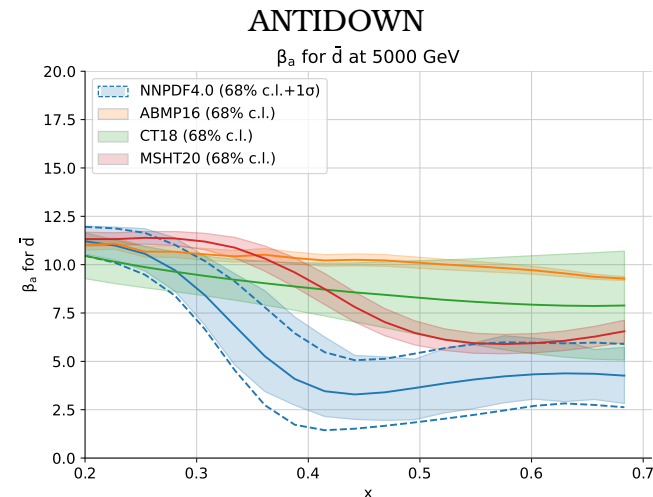
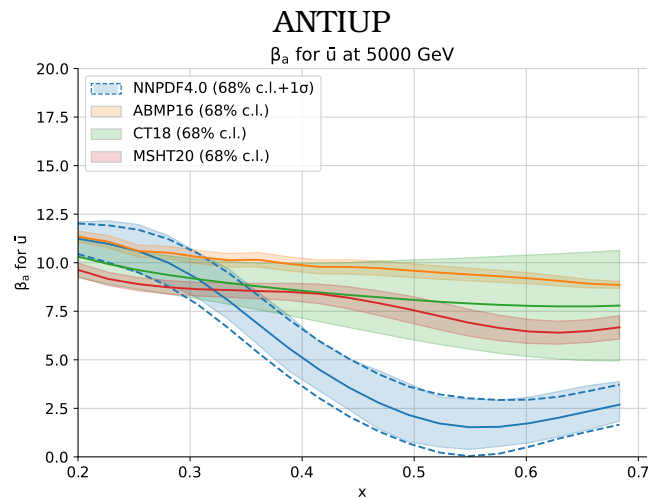
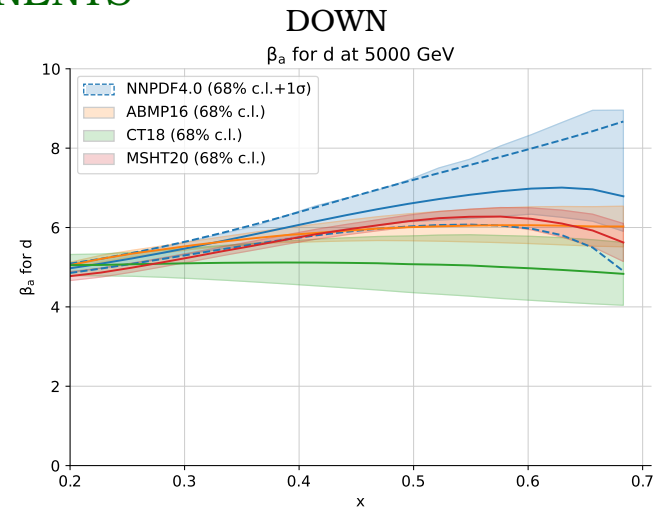
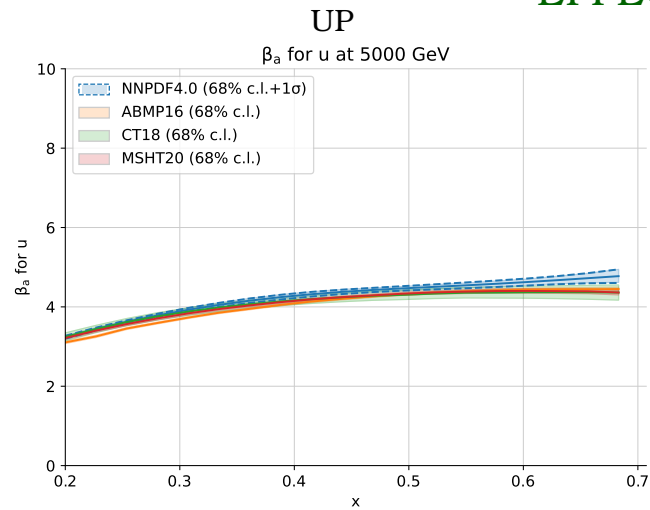
- $M \lesssim 3$  TEV  $\Rightarrow$  DATA REGION, ALL PDF SETS AGREE
- $M \gtrsim 5$  TEV  $\Rightarrow$  EXTRAPOLATION, NNPDF DISAGREES
  - DIFFERENT CENTRAL VALUE
  - LARGER UNCERTAINTY



# PDF BEHAVIOR: WHAT'S GOING ON?

- CT, MSHT, ABMP PARAMETRIZATION:  $f(x) = x^\alpha (1-x)^\beta g(x)$ ; NNPDF NEURAL NETWORK
- DEFINE **EFFECTIVE EXPONENT**  $\beta(x) \equiv \frac{\partial \ln |x f(x)|}{\partial \ln(1-x)}$

## EFFECTIVE EXPONENTS



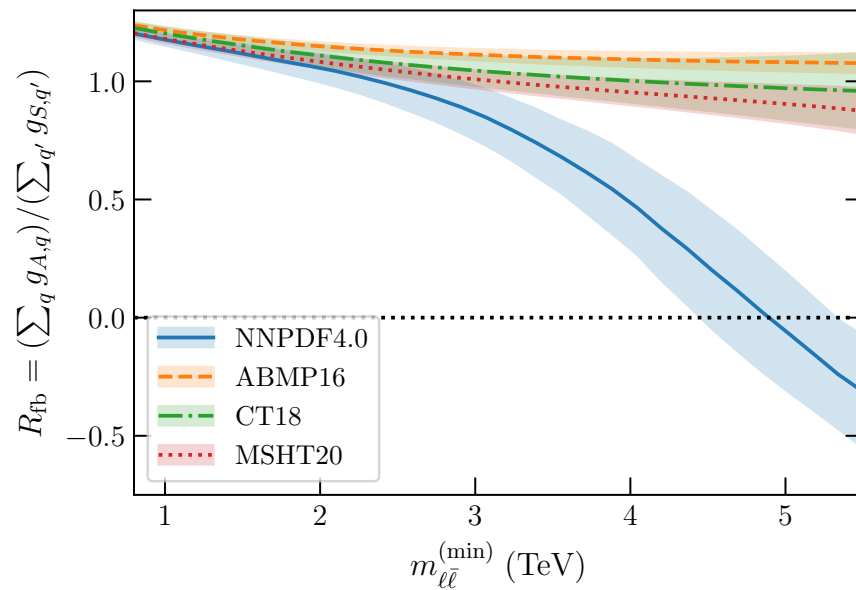
- **CT, MSHT, ABMP: LARGE  $x$   $\beta$  APPROX. CONSTANT**
- **NNPDF:  $\beta$  NOT FIXED BY PARAMETRIZATION**

## WHAT'S GOING ON?

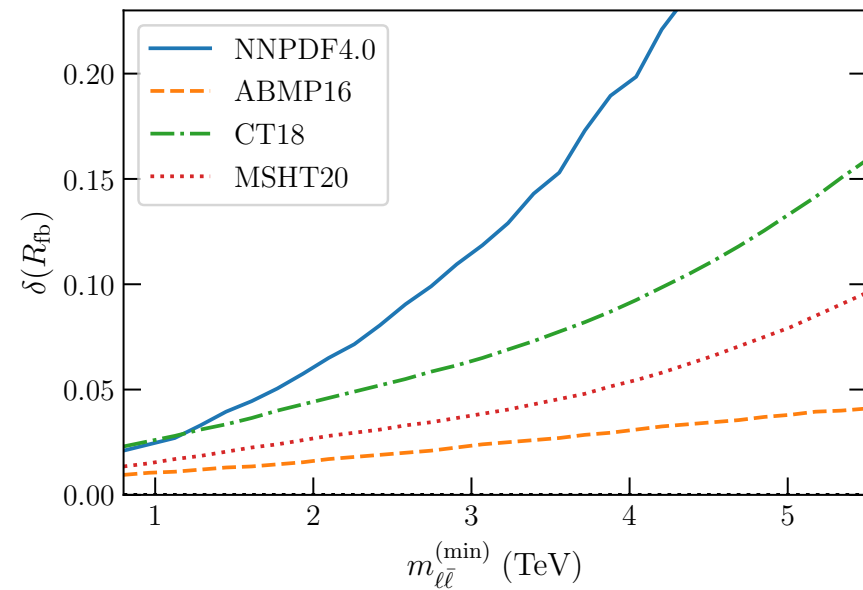
**THE EFFECTIVE COUPLING** RECALL  $A_{\text{fb}}(\cos \theta^*) = \frac{\cos \theta^*}{(1 + \cos^2(\theta^*))} \frac{g_A}{g_{S,q'}}$ ;

$$g_{A,S} \propto \int \frac{dm_{\ell\bar{\ell}}}{m_{\ell\bar{\ell}}} \frac{dx_1}{x_1} \mathcal{L}_{A,S}(m_{\ell\bar{\ell}}, x_1)$$

COUPLING



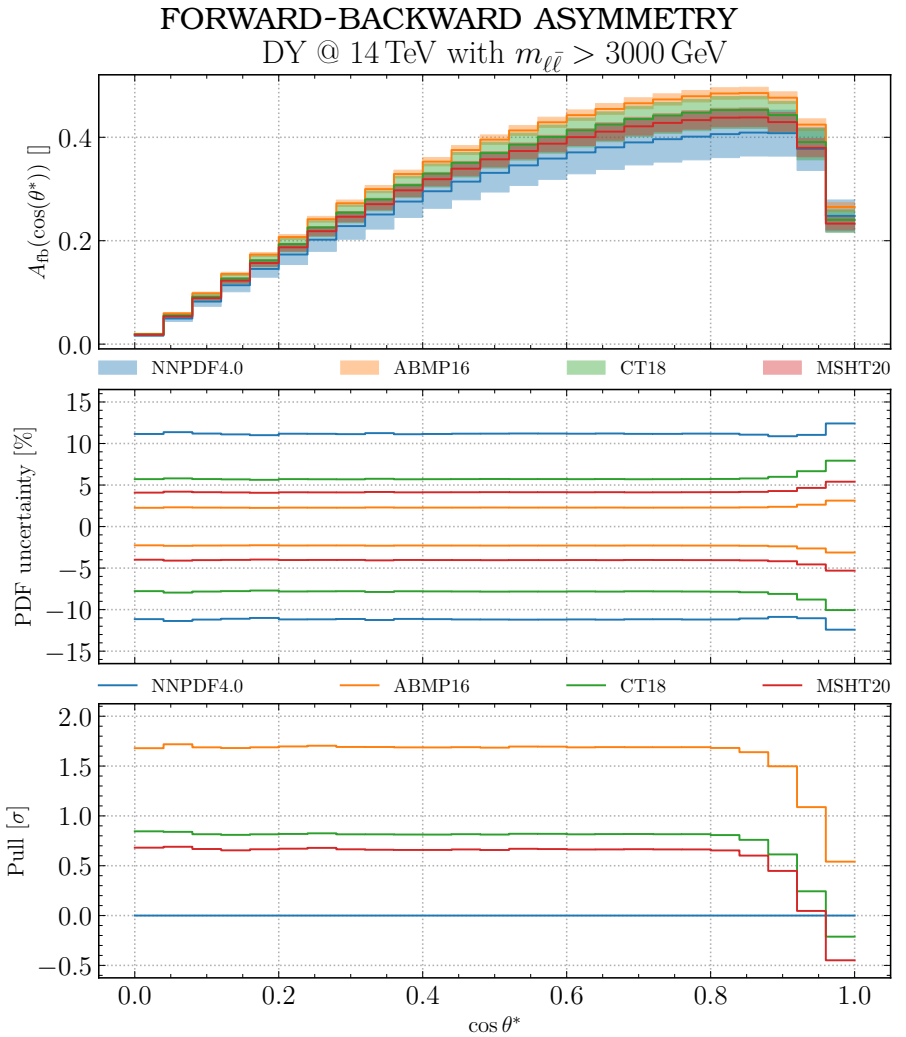
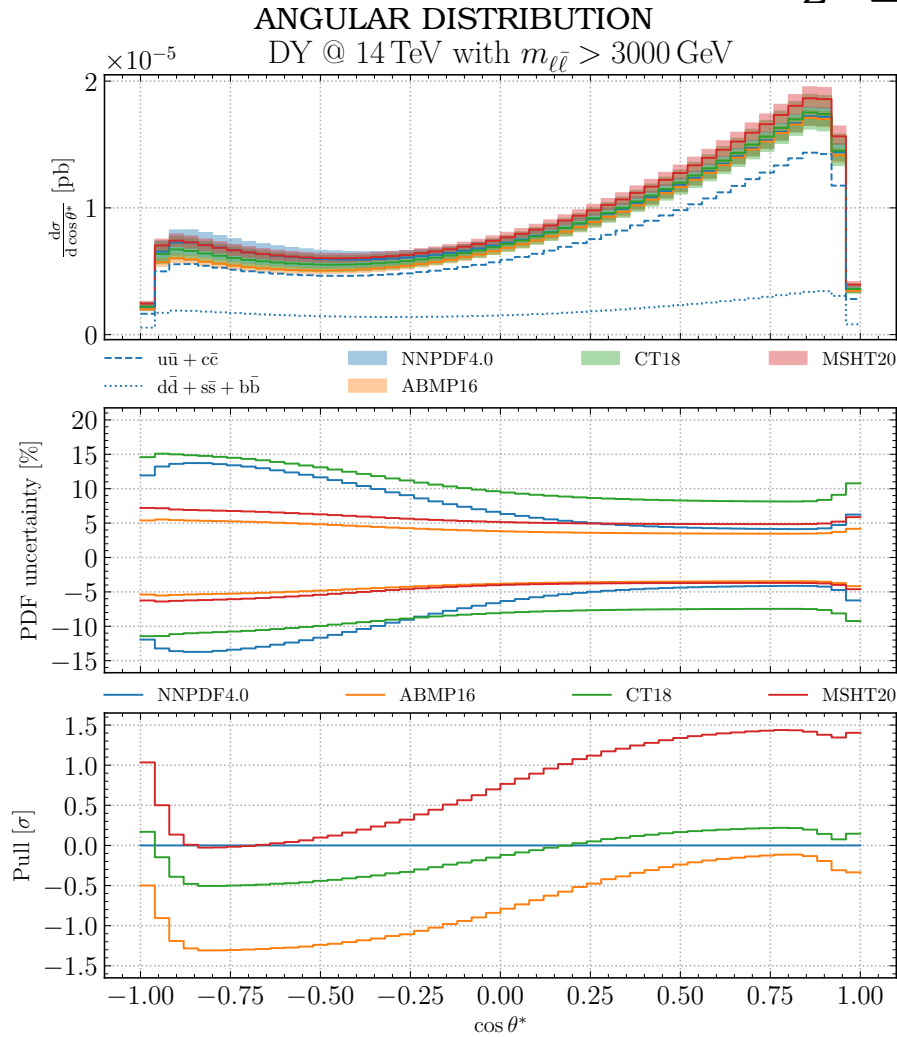
ABSOLUTE UNCERTAINTY



- AS SCALE INCREASES, LARGER  $x$  PROBED
- CT, MSHT, ABMP: COUPLING APPROX. SCALE INDEP.
- NNPDF: COUPLING DEPENDS ON SCALE, LARGER UNCERTAINTY

# THE FORWARD-BACKWARD ASYMMETRY

$$M_{Z'} \geq 3 \text{ TeV}$$

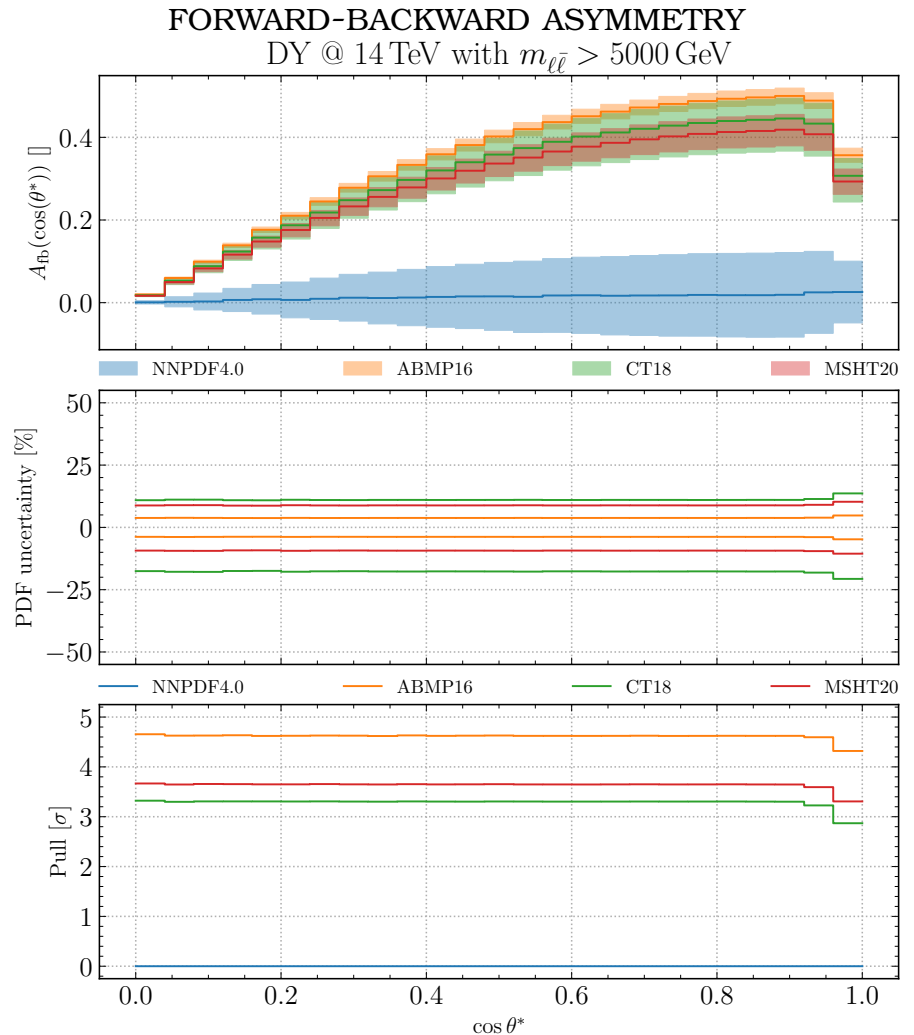
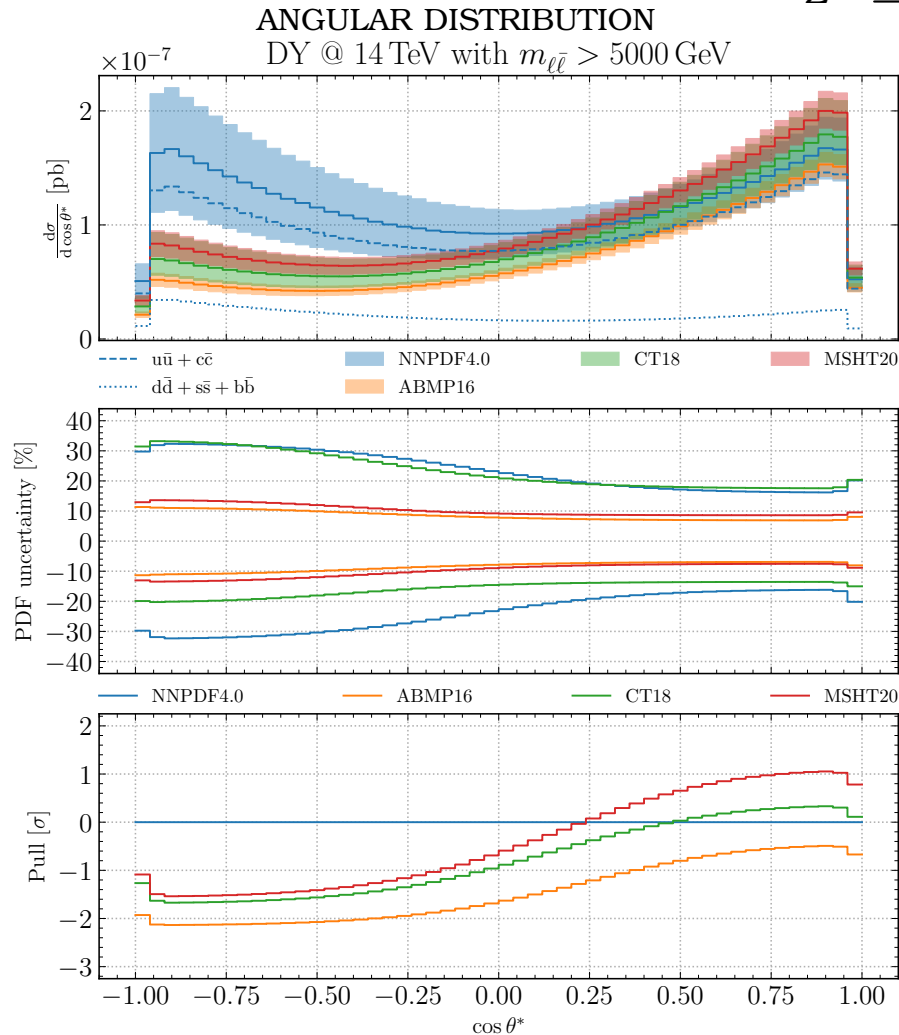


- $M_{Z'} \geq 3 \text{ TeV}$ : DATA REGION, ALL PDF SETS AGREE

- .

# THE FORWARD-BACKWARD ASYMMETRY

## $M_{Z'} \geq 5 \text{ TeV}$



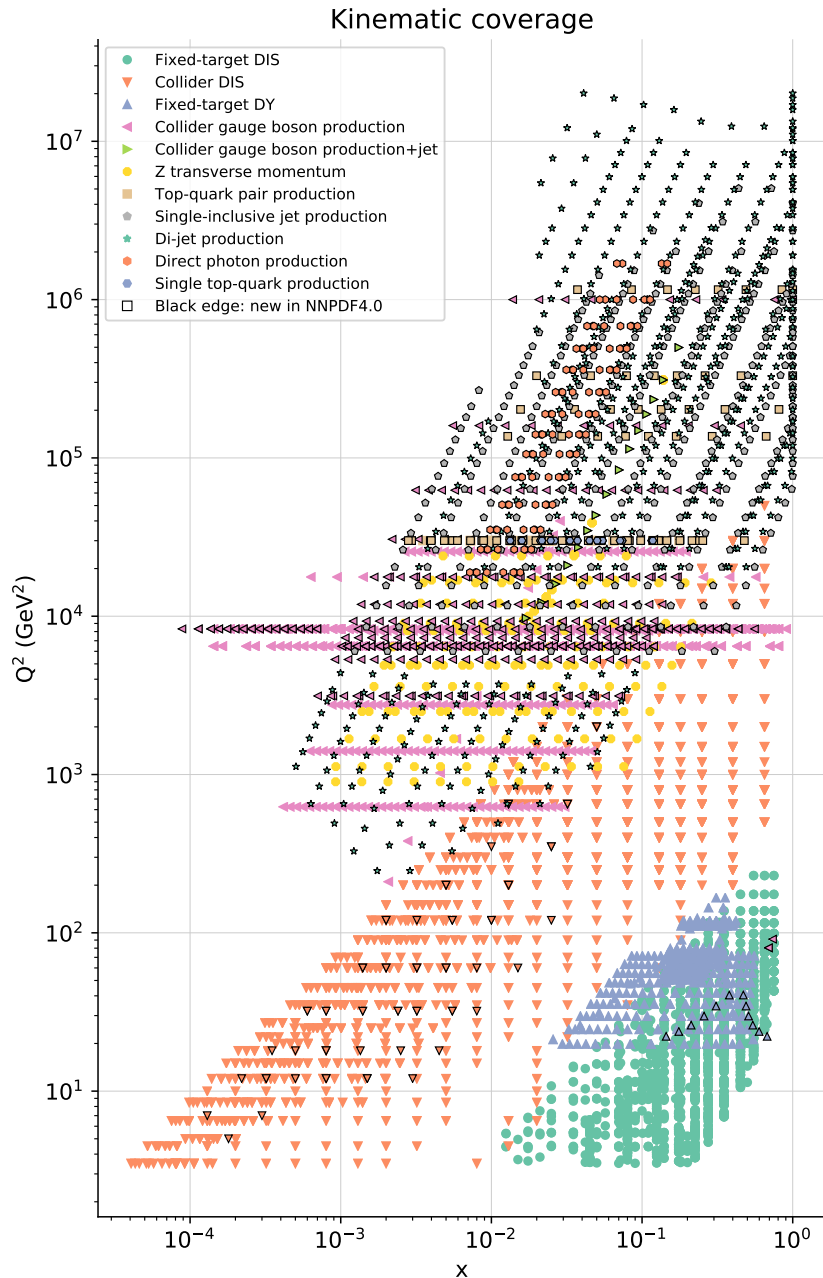
- $M_{Z'} \geq 3 \text{ TeV}$ : DATA REGION, ALL PDF SETS AGREE
- $M_{Z'} \geq 5 \text{ TeV}$ 
  - CT, MSHT, ABMP  $\Rightarrow$  ASYMMETRY UNCHANGED WITH INCREASING SCALE
  - NNPDF  $\Rightarrow$  ASYMMETRY DISAPPEARS AS SCALE INCREASES

# SUMMARY

- PDFs **LARGELY UNCONSTRAINED** IN THE **HIGH-MASS DISCOVERY** REGION
- FIXED-PARAMETRIZATION PDFs **OVERLY RESTRICTIVE**:
  - OVER-CONSTRAINED EXTRAPOLATION
  - UNDER-ESTIMATED UNCERTAINTIES
- **FLEXIBLE PARAMETRIZATION REQUIRED** FOR RELIABLE RESULTS
- **FUTURE DRELL-YAN** MEASUREMENTS IMPORTANT IN ORDER TO **CONSTRAIN**  
PDFs

**EXTRAS**

# NNPDF4.0 DATASET



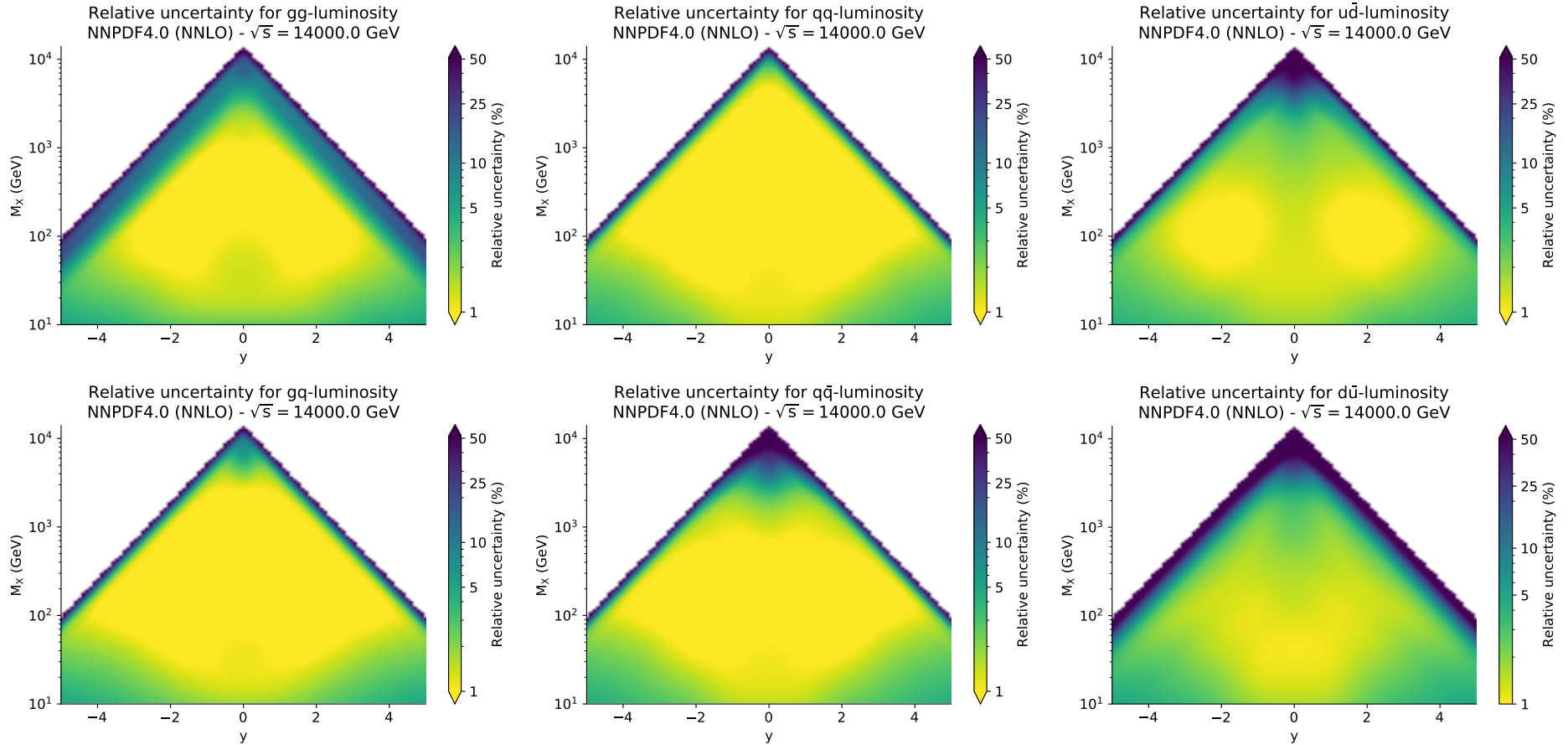
- ABOUT **50 NEW DATASETS** & **400 EXTRA DATAPOINTS**
- FULL DIS AND FT DY DATASET
  - AS IN NNPDF3.1: FINAL HERA, NMC, BCDMS, CHORUS, NuTeV
  - NOW ALSO **NOMAD NEUTRINO**
  - **SEAQUEST DY**
- FULL 7 TEV AND 8 TEV DATASET & EXTENSIVE USE OF **13 TEV** DATA:
  - *W*, *Z* PRODUCTION: RAPIDITY DISTRIBUTIONS, ASYMMETRIES, *Z*  $p_T$  DISTRIBUTIONS
  - TOP PAIR PRODUCTION: ALL AVAILABLE DISTRIBUTIONS
  - SINGLE-INCLUSIVE JETS
- SEVERAL **NEW PROCESSES**:
  - PROMPT PHOTON
  - SINGLE TOP
  - DIJETS
  - HERA JETS

# UNCERTAINTIES: NNPDF4.0

GLUON

SINGLET

FLAVORS

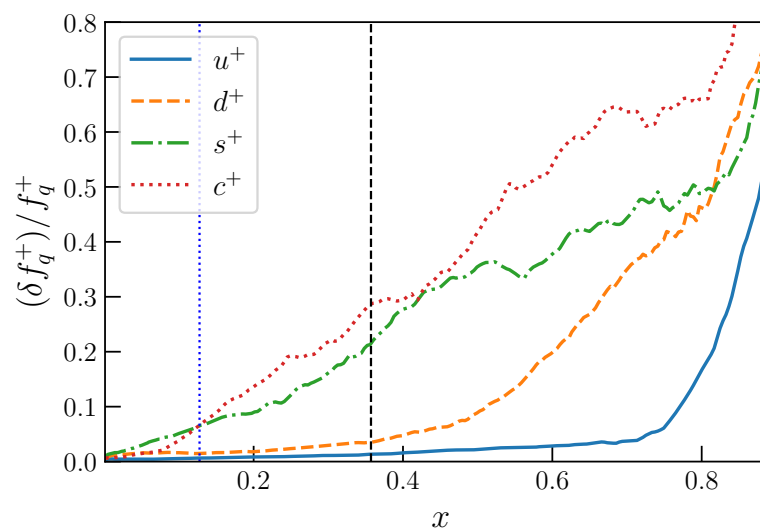
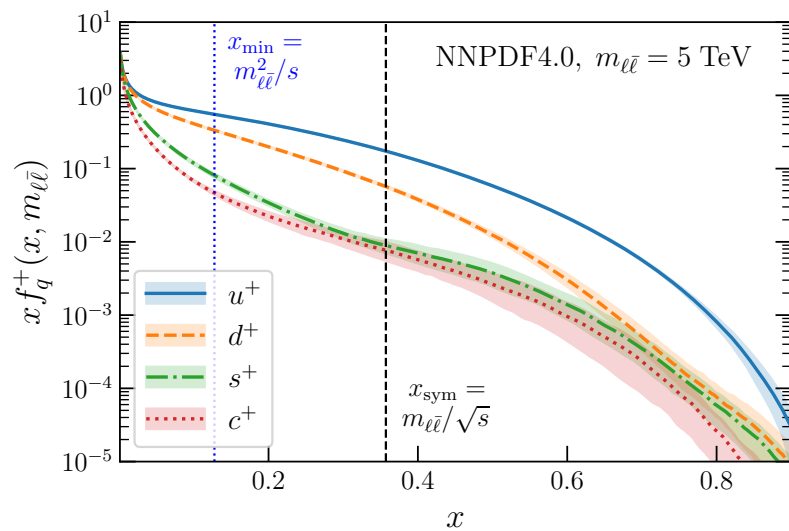


- TYPICAL UNCERTAINTIES IN DATA REGION: SINGLET  $\sim 1\%$ , NONSINGLET  $\sim 2 - 3\%$
- DATA REGION:  $10 \lesssim M_X \lesssim 3 \cdot 10^3$  TEV,  $-4 \lesssim y \lesssim 4$

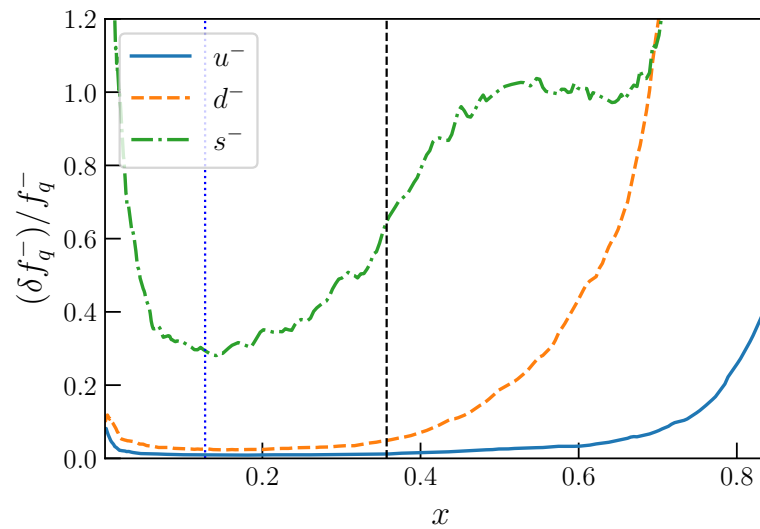
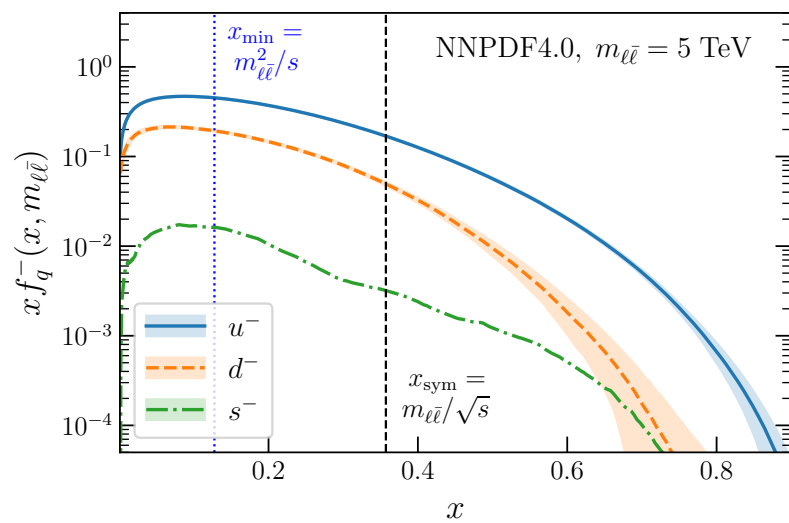


# PDF BEHAVIOR: INDIVIDUAL FLAVORS

## SEA



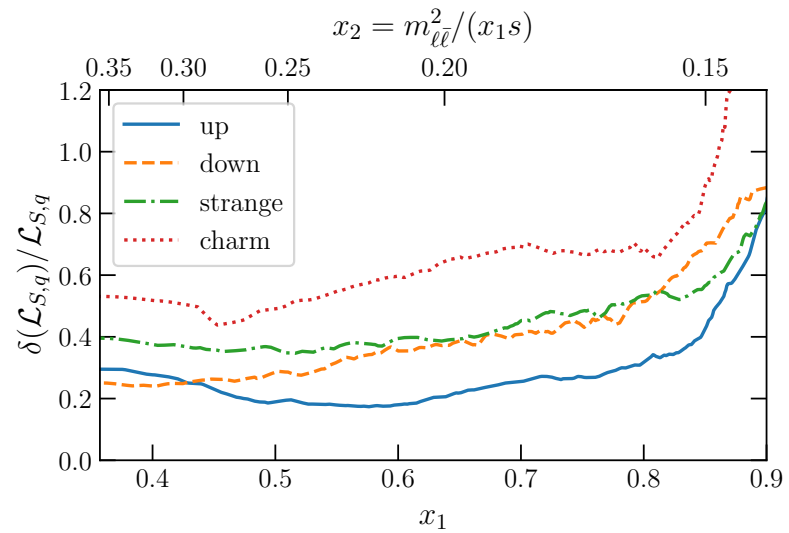
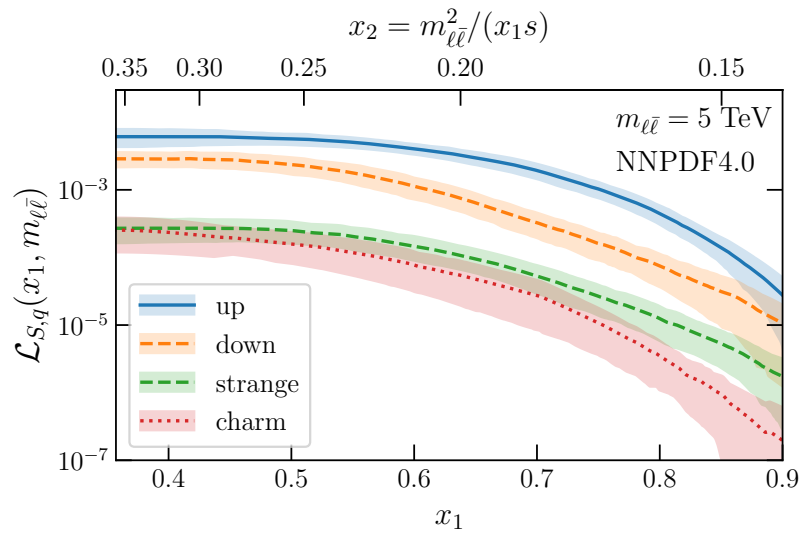
## VALENCE



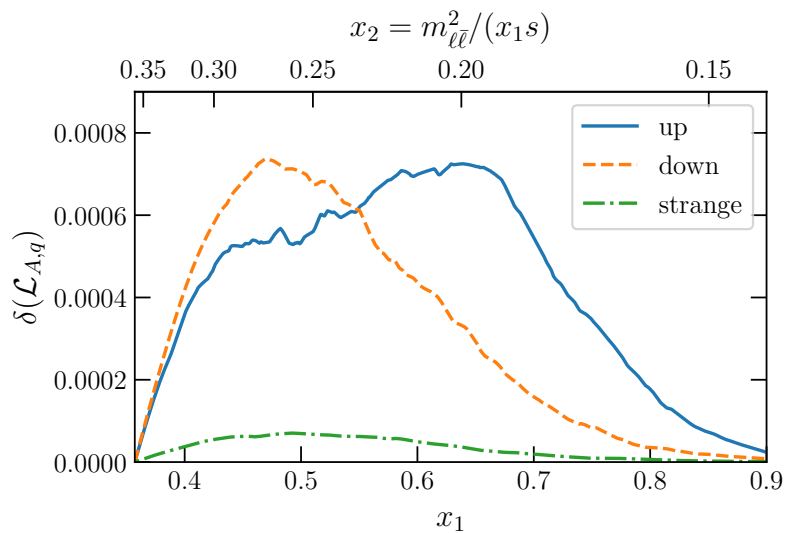
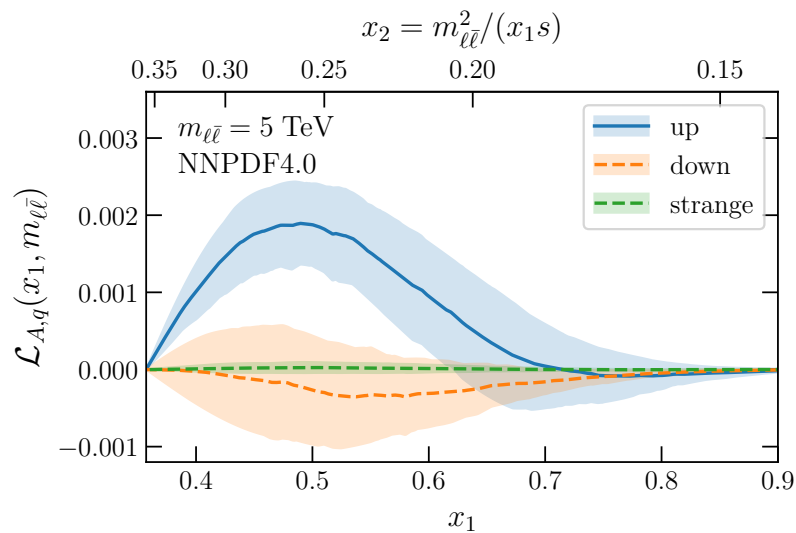
# PDF LUMIS

## INDIVIDUAL FLAVORS ( $M_{Z'} = 5 \text{ TeV}$ )

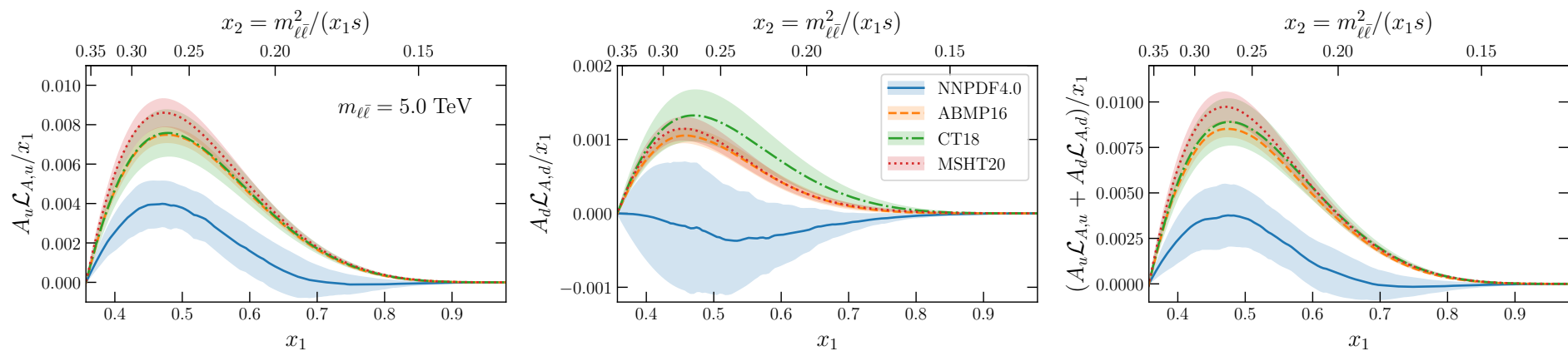
### SYMMETRIC



### ANTISYMMETRIC



# ANTISYMMETRIC PDF LUMIS COMPARING PDF SETS ( $M_{Z'} = 5$ TEV) PDFs



## ABSOLUTE UNCERTAINTIES

