PDF UNCERTAINTIES & BSM SEARCHES

STEFANO FORTE

UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO

DIPARTIMENTO DI FISICA

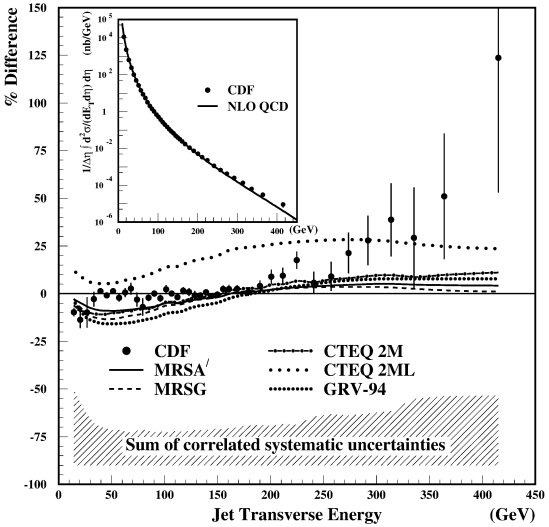
IRN TERASCALE MEETING

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

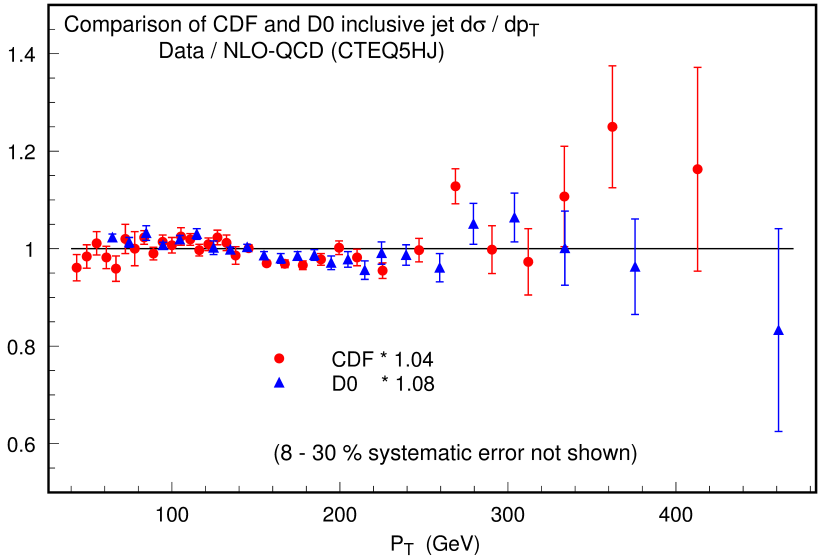
PDF UNCERTAINTIES AND NEW PHYSICS: TEVATRON

- 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

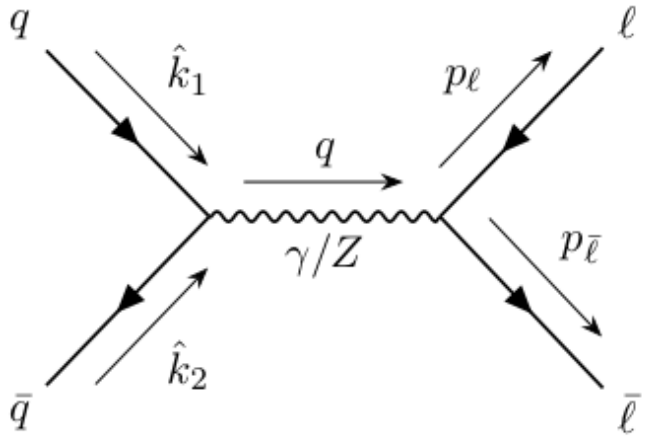
NEW CTEQ GLUON (1998)



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

NEW PHYSICS SEARCHES AT THE LHC

THE DRELL-YAN FORWARD-BACKWARD ASYMMETRY

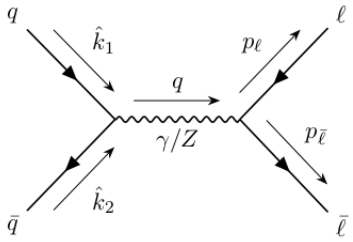


$$A_{\rm fb}(\cos\theta) \equiv \frac{\frac{d\sigma}{d\cos\theta}(\cos\theta) - \frac{d\sigma}{d\cos\theta}(-\cos\theta)}{\frac{d\sigma}{d\cos\theta}(\cos\theta) + \frac{d\sigma}{d\cos\theta}(-\cos\theta)}$$

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

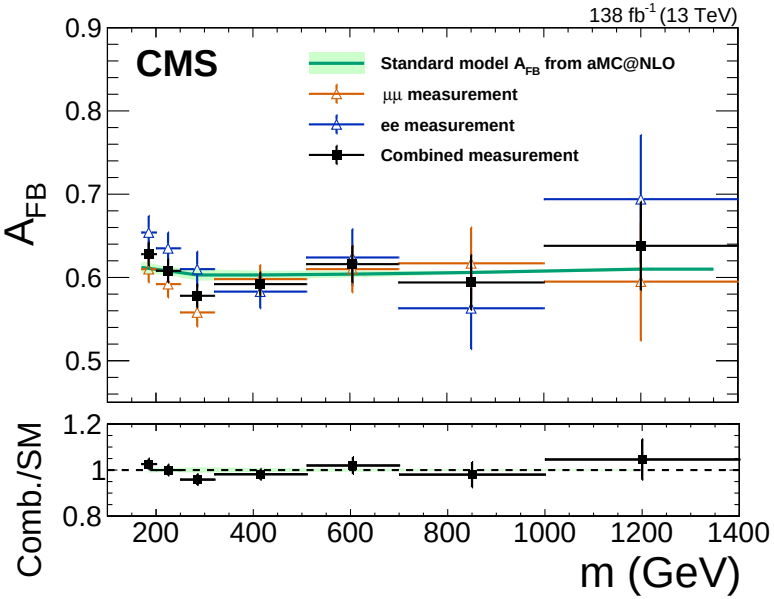
THE DRELL-YAN FORWARD-BACKWARD ASYMMETRY
CMS BSM SEARCH

CMS, 2201.12327

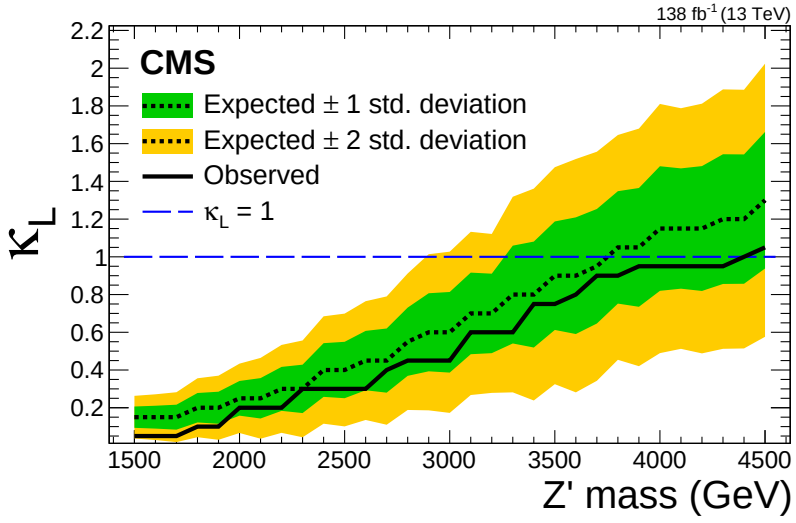


$$A_{\mathrm{fb}} \equiv \int_0^1 d\cos\theta \, \frac{\frac{d\sigma}{d\cos\theta}(\cos\theta) - \frac{d\sigma}{d\cos\theta}(-\cos\theta)}{\frac{d\sigma}{d\cos\theta}(\cos\theta) + \frac{d\sigma}{d\cos\theta}(-\cos\theta)}$$

ASYMMETRY VS MASS



LIMIT ON SSM Z' LH COUPLING



ANATOMY OF THE ASYMMETRY

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

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

- MEASURE $\cos\theta^* = \mathrm{sign}(y_{\ell\bar\ell})\cos\theta$: 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

$$x_1 = \frac{m_{\ell\bar\ell}}{\sqrt{s}}\exp(y_{\ell\bar\ell})\,, \quad x_2 = \frac{m_{\ell\bar\ell}}{\sqrt{s}}\exp(-y_{\ell\bar\ell});\; x_1x_2 = \frac{m_{\ell\bar\ell}}{\sqrt{s}}$$

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

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

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

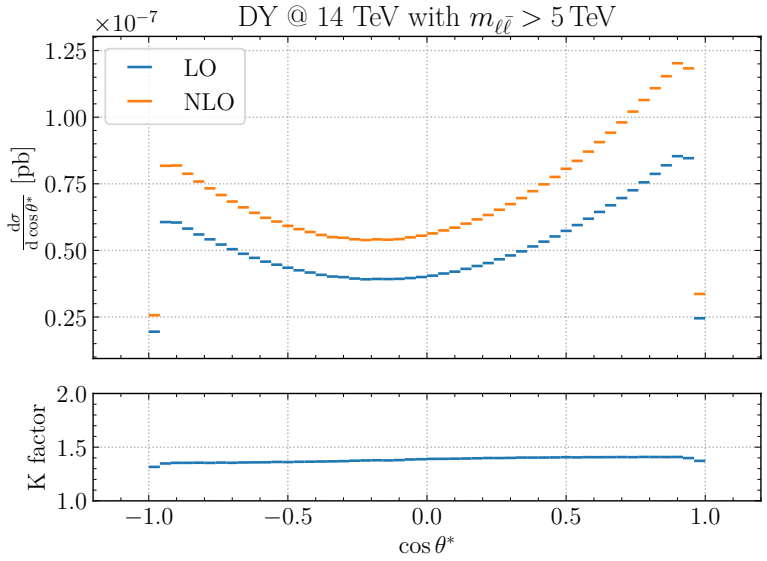
QUALITATIVE BEHAVIOR: NLO VS. LO

LO INTEGRATED RESULT (HIGH MASS)

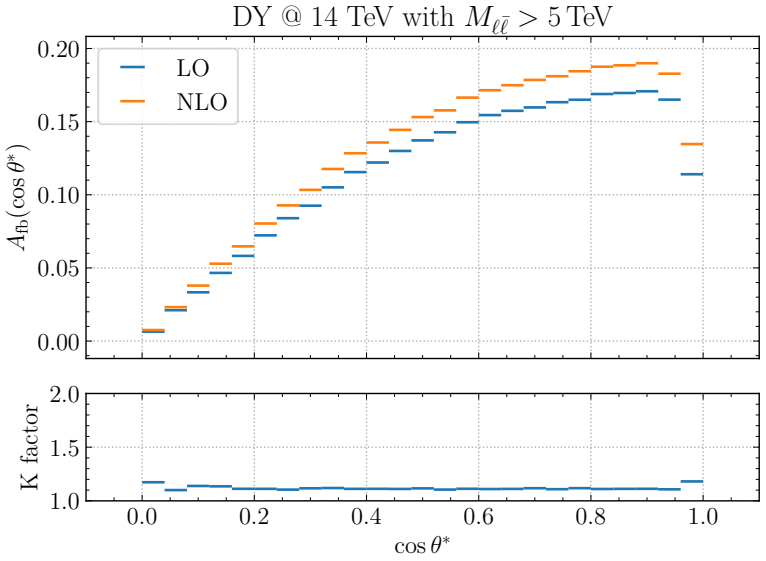
$$A_{\rm fb}(\cos\theta^*) = \frac{\cos\theta^*}{(1+\cos^2(\theta^*))}\,\frac{g_A}{g_{S,q'}}; \quad g_{A,S} \propto \int \frac{dm_{\ell\bar{\ell}}}{m_{\ell\bar{\ell}}}\,\frac{dx_1}{x_1}\,\mathcal{L}_{A,S}(m_{\ell\bar{\ell}}, x_1)$$

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

CROSS-SECTION



FORWARD-BACKWARD ASYMMETRY



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

QUALITATIVE BEHAVIOR:

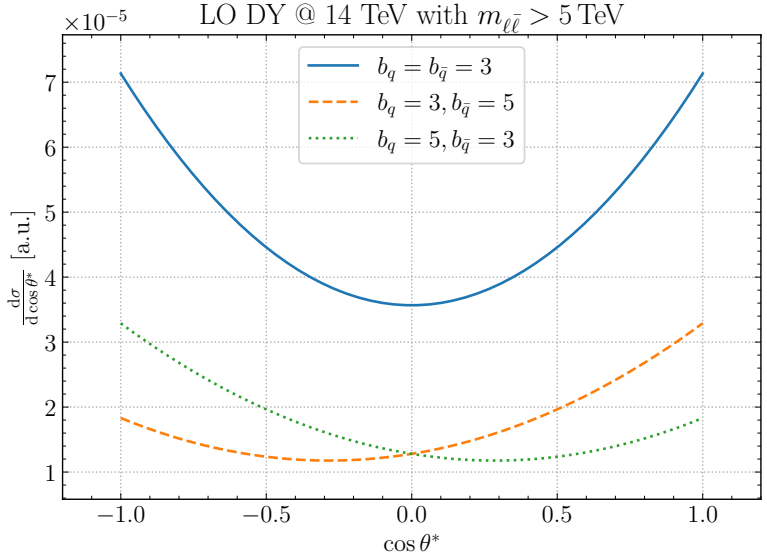
$$A_{\rm fb} \propto \mathcal{L}_{A,q} = f_q(x_1) f_{\bar{q}}(x_2,) - f_q(x_2) f_{\bar{q}}(x_1) = \tfrac{1}{2}\left(f_q^-(x_1) f_q^+(x_2) - f_q^-(x_2) f_q^+(x_1,) \right)$$

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

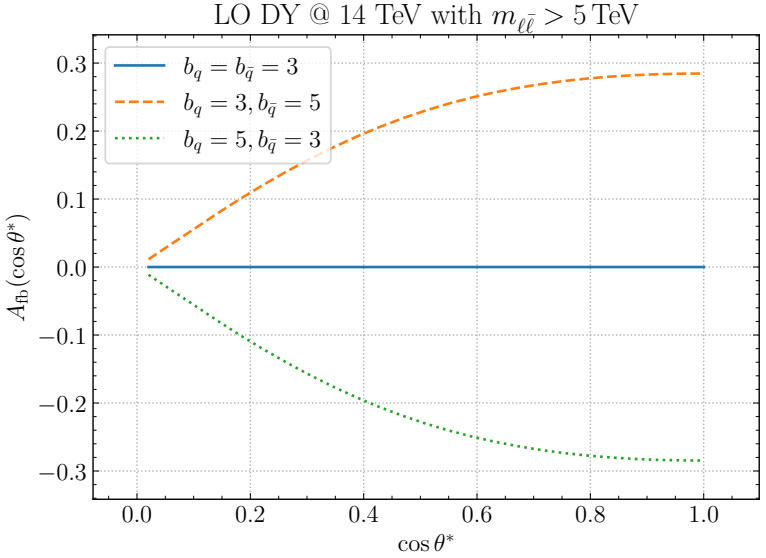
TOY PDFS

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

CROSS-SECTION



FORWARD-BACKWARD ASYMMETRY



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

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

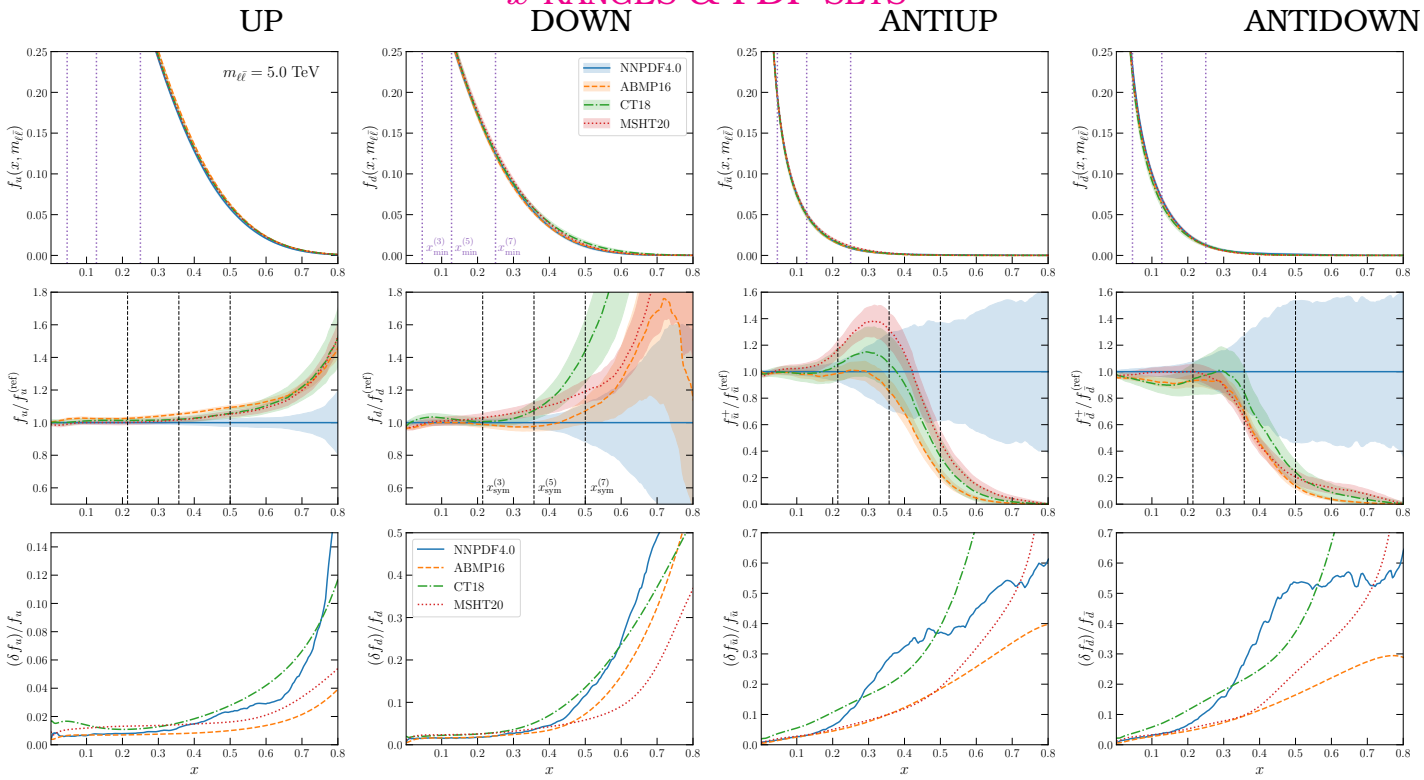
- VALENCE DROPS FASTER $\Rightarrow$ NEGATIVE ASYM

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

x RANGES & PDF SETS



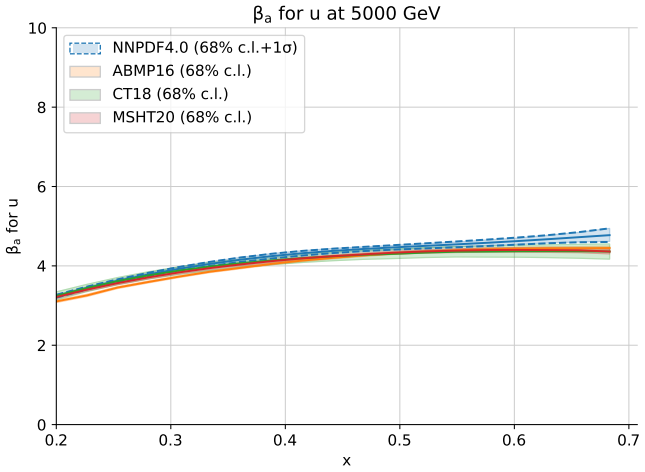
- $M \lesssim 3$ TEV $\Rightarrow$ DATA REGION, ALL PDF SETS AGREE
- $M \gtrsim 5$ TEV $\Rightarrow$ EXTRAPOLATION, NNPDF DISAGREES
  - DIFFERENT CENTRAL VALUE
  - LARGER UNCERTAINTY

PDF BEHAVIOR: WHAT'S GOING ON?

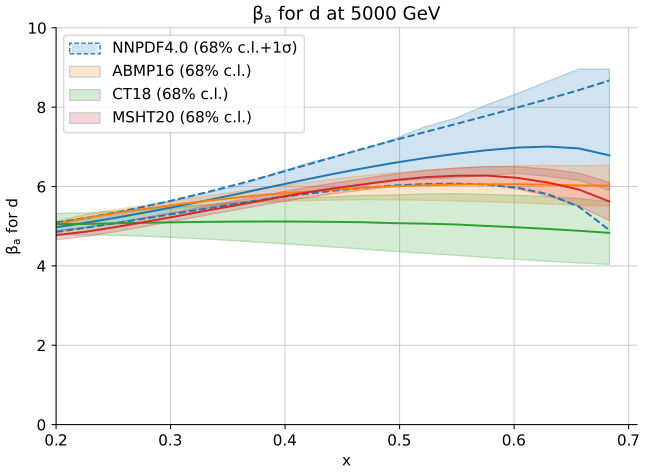
- CT, MSHT, ABMP PARAMETRIZATION: $f(x) = x^{\alpha}(1-x)^{\beta}g(x)$; NNPDF NEURAL NETWORK
- DEFINE EFFECTIVE EXPONENT $\beta(x) \equiv \frac{\partial \ln |xf(x)|}{\partial \ln(1-x)}$

EFFECTIVE EXPONENTS

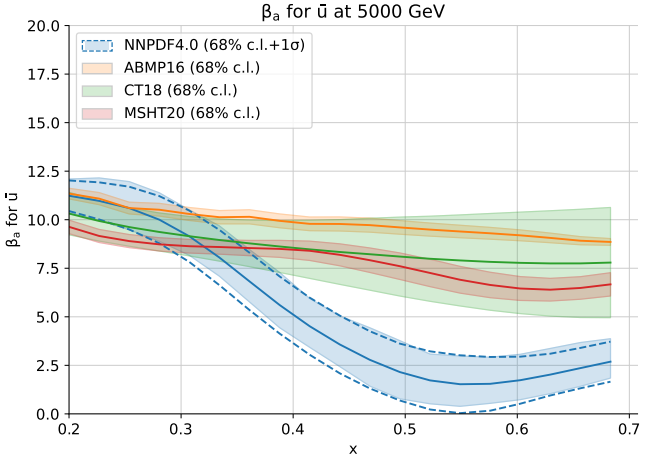
UP



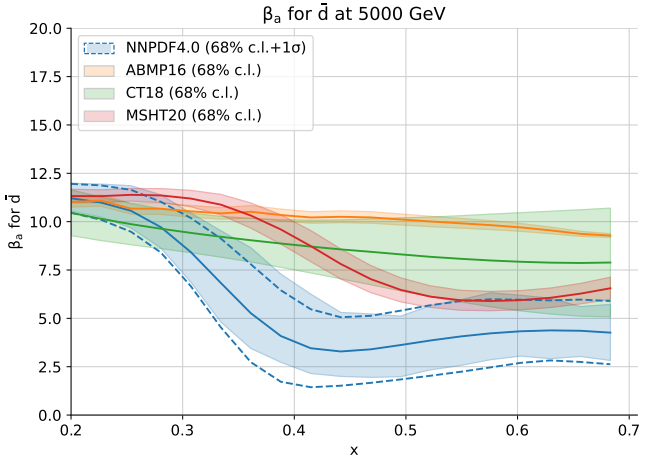
DOWN



ANTIUP



ANTIDOWN

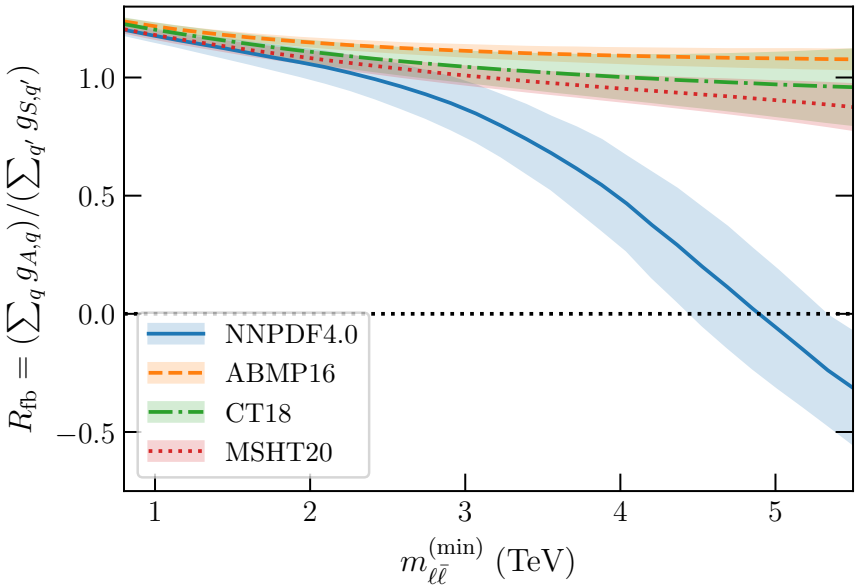


- CT, MSHT, ABMP: LARGE x β APPROX. CONSTANT
- NNPDF: β NOT FIXED BY PARAMETRIZATION

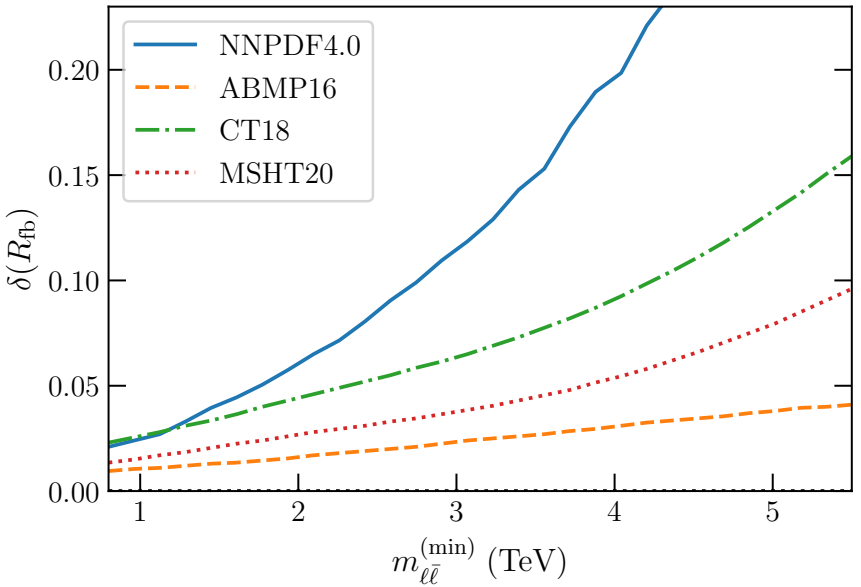
WHAT'S GOING ON?
THE EFFECTIVE COUPLING

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

COUPLING



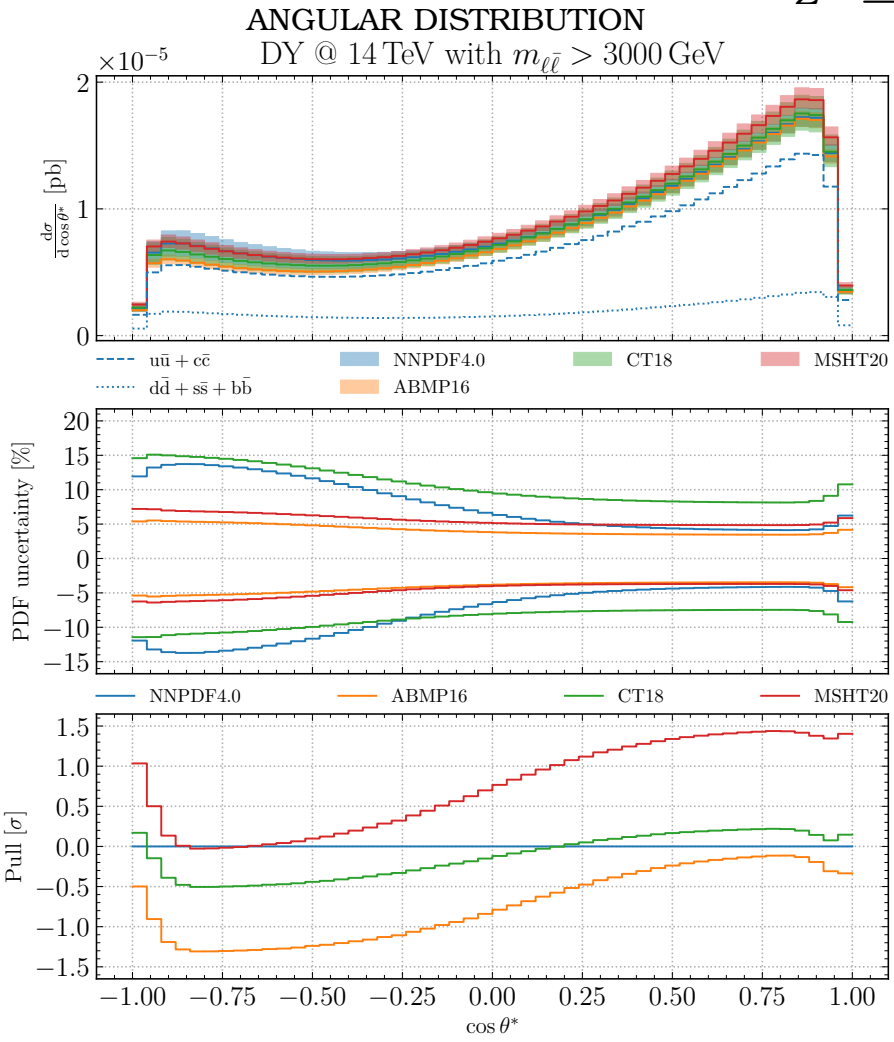
ABSOLUTE UNCERTAINTY

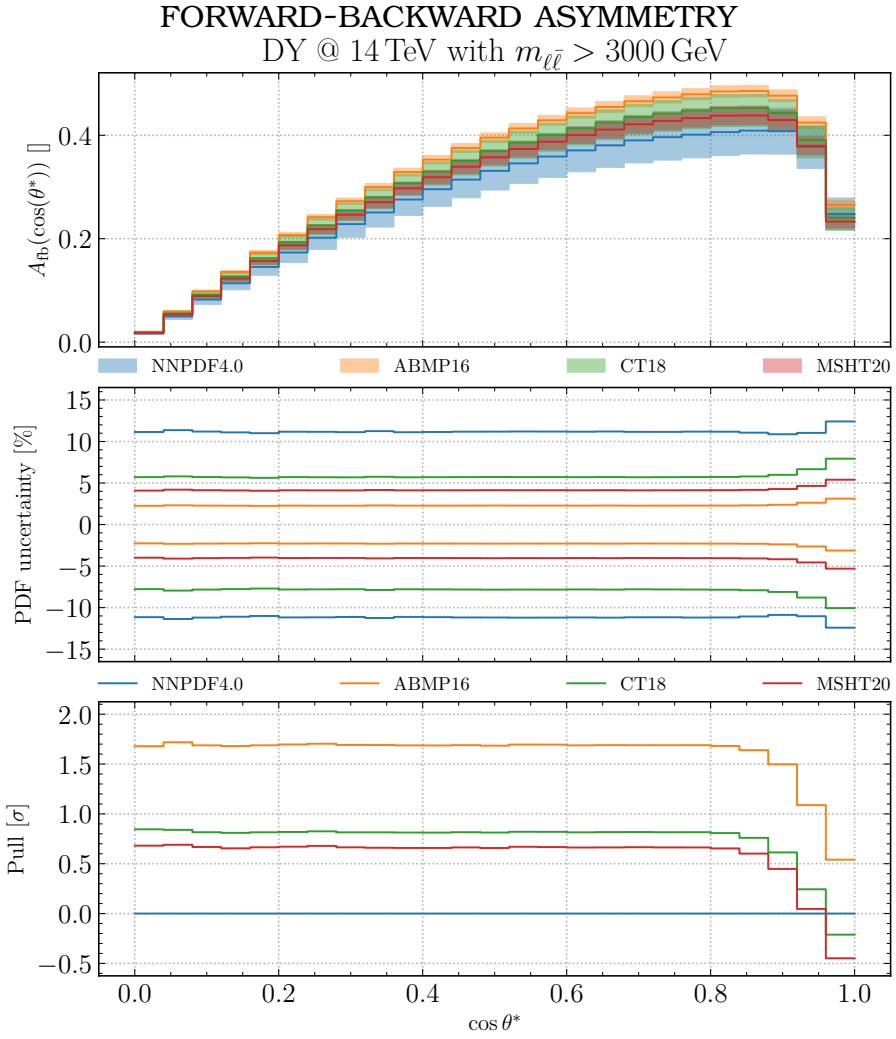


- AS SCALE INCREASES, LARGER x PROBED
- CT, MSHT, ABMP: COUPLING APPROX. SCALE INDEP.
- NNPDF: COUPLING DEPENDS ON SCALE, LARGER UNCERTAINTY

THE FORWARD-BACKWARD ASYMMETRY

$M_{Z'} \geq 3$ TeV

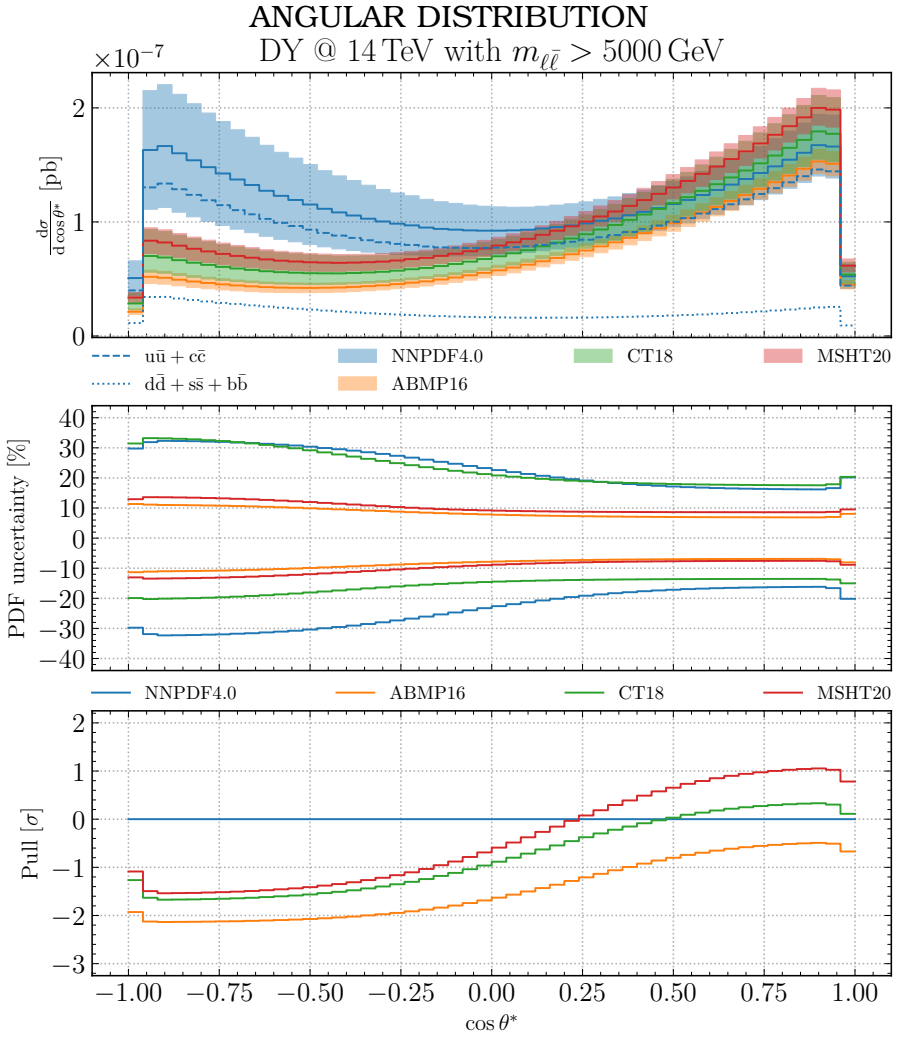


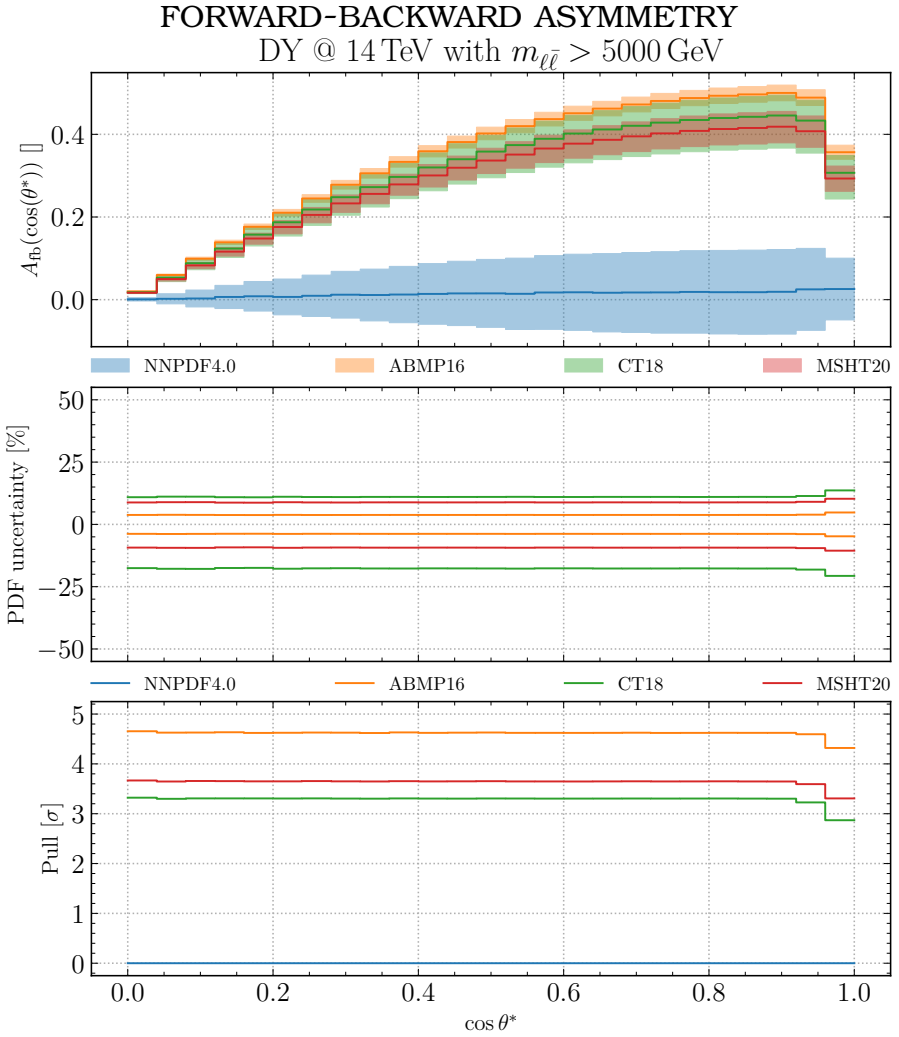


- $M_{Z'} \geq 3$ TeV: DATA REGION, ALL PDF SETS AGREE
- .

THE FORWARD-BACKWARD ASYMMETRY

$M_{Z'} \geq 5$ TeV





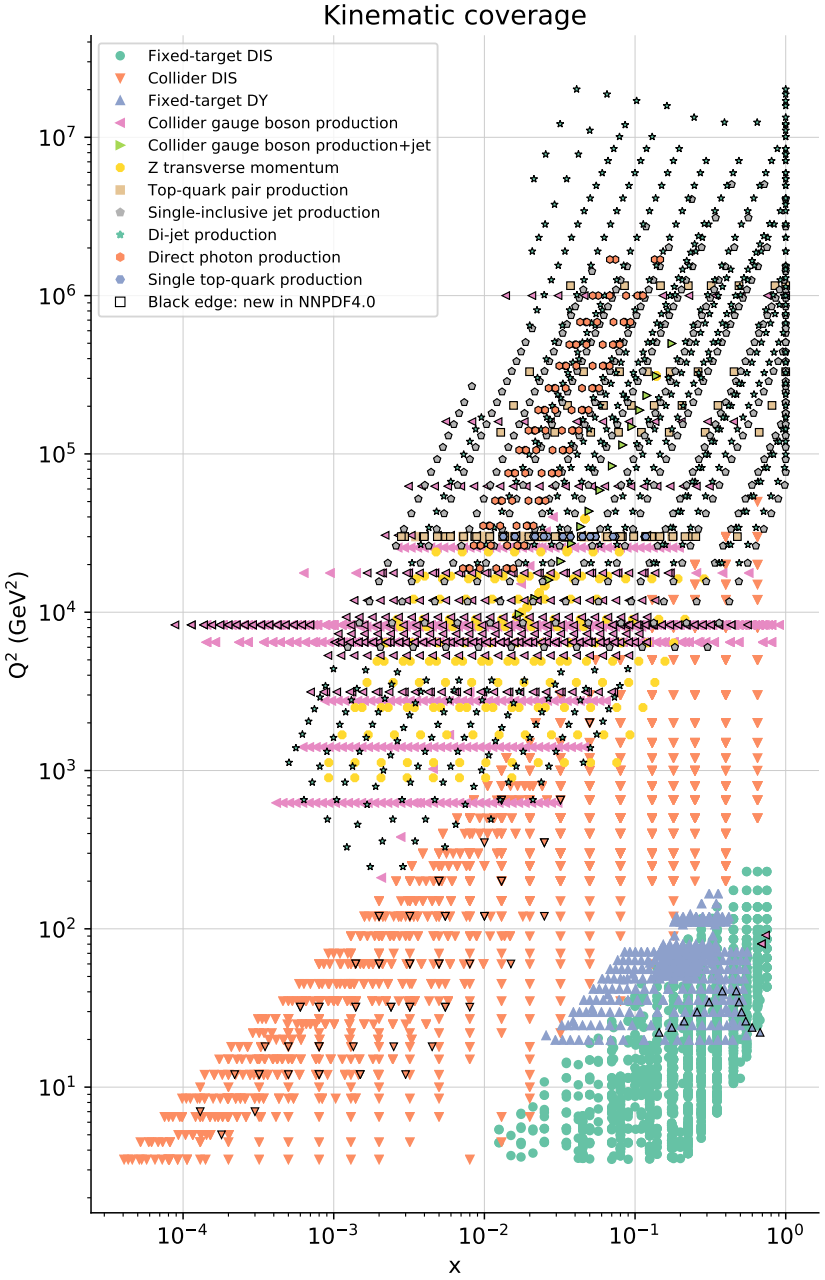
- $M_{Z'} \geq 3$ TeV: DATA REGION, ALL PDF SETS AGREE
- $M_{Z'} \geq 5$ TeV
  - CT, MSHT, ABMP $\Rightarrow$ ASYMMETRY UNCHANGED WITH INCREASING SCALE
  - NNPDF $\Rightarrow$ ASYMMETRY DISAPPEARS AS SCALE INCREASES

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

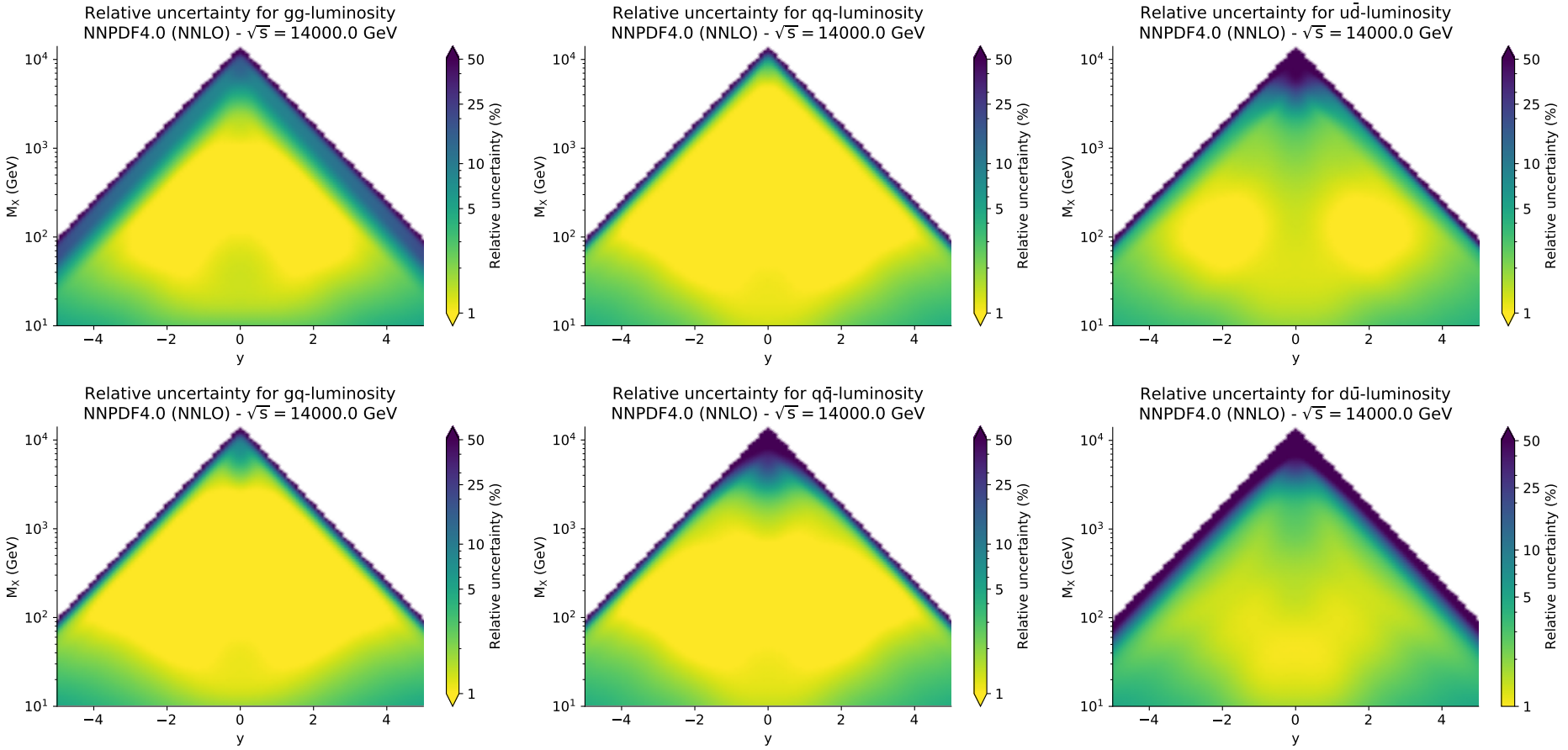
NNPDF4.0 DATASET



- 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

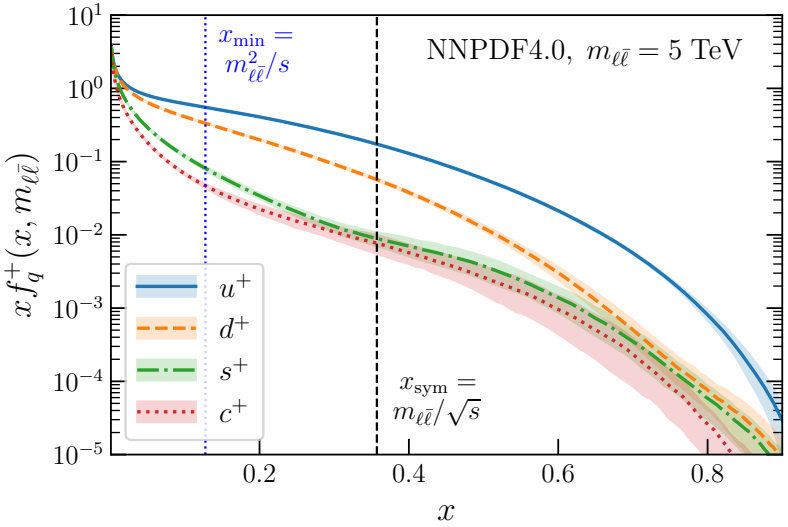
GLUON SINGLET FLAVORS

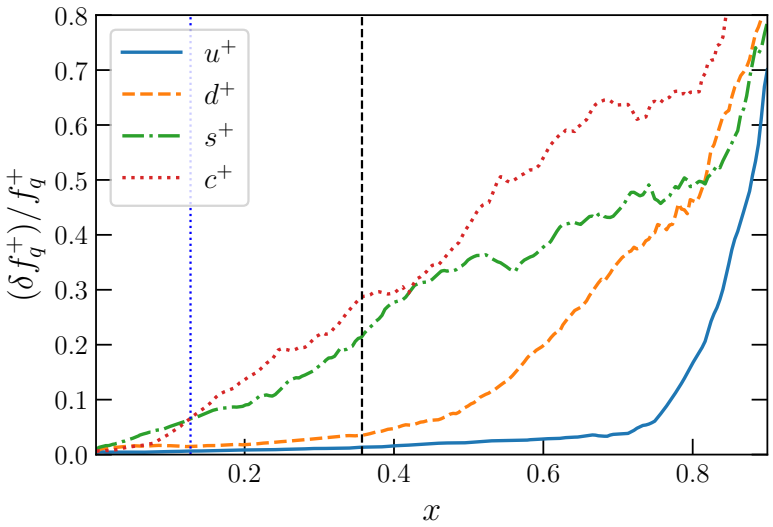


- TYPICAL UNCERTAINTIES IN DATA REGION: SINGLET $\sim 1\%$, NONSINGLET $\sim 2-3\%$
- DATA REGION: $10 \lesssim M_X \lesssim 3 \cdot 10^3$ TeV, $-4 \lesssim y \lesssim 4$

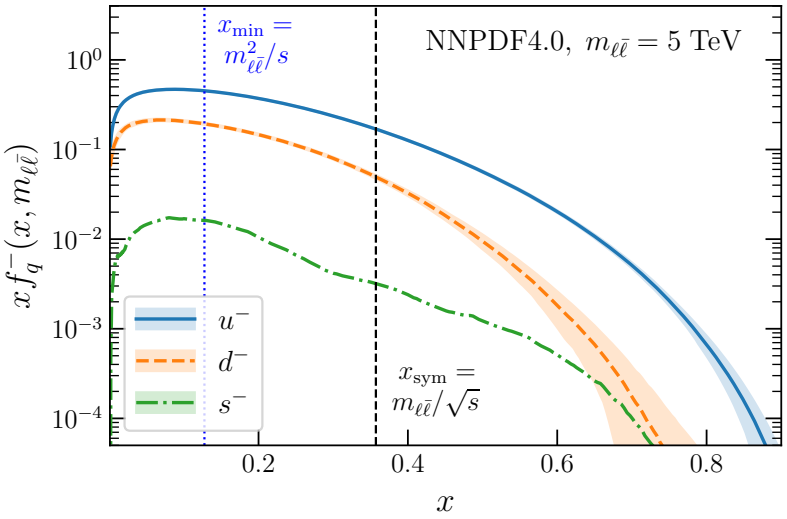
PDF BEHAVIOR: INDIVIDUAL FLAVORS

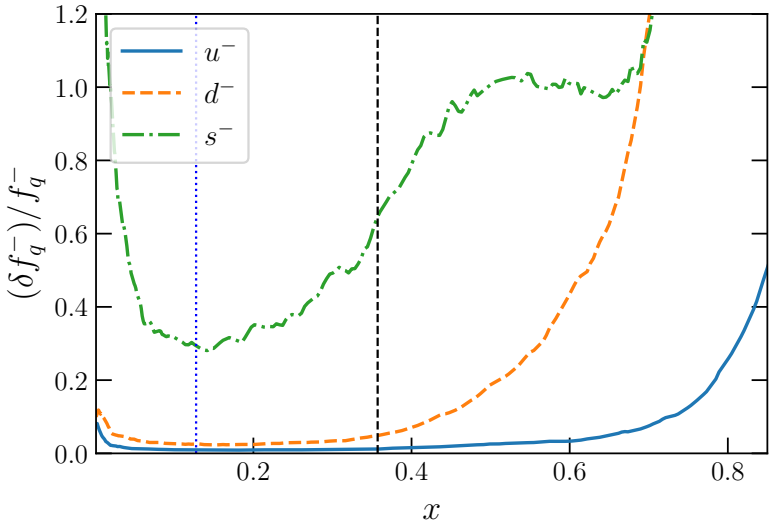
SEA





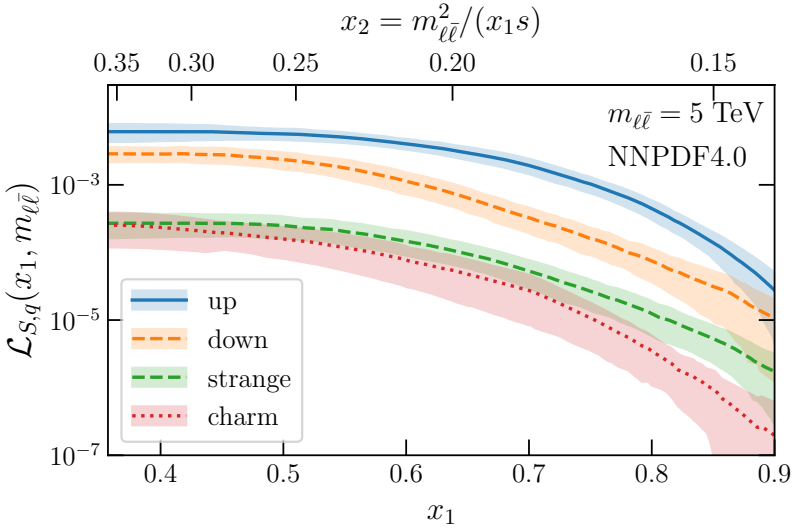
VALENCE

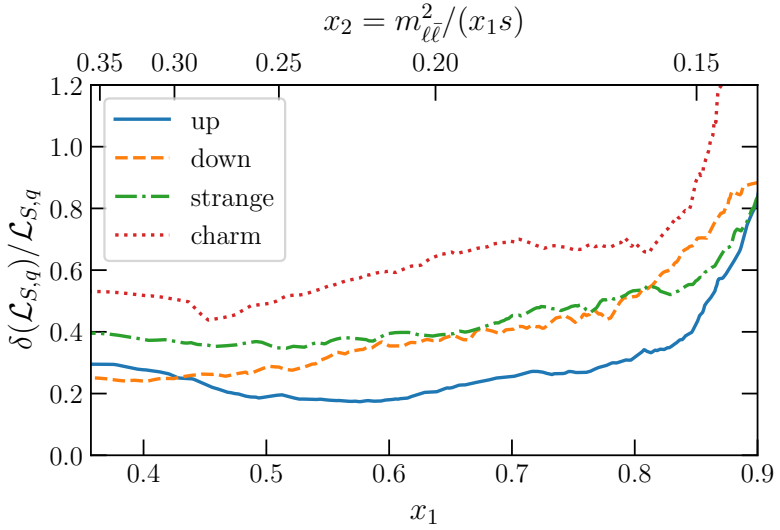




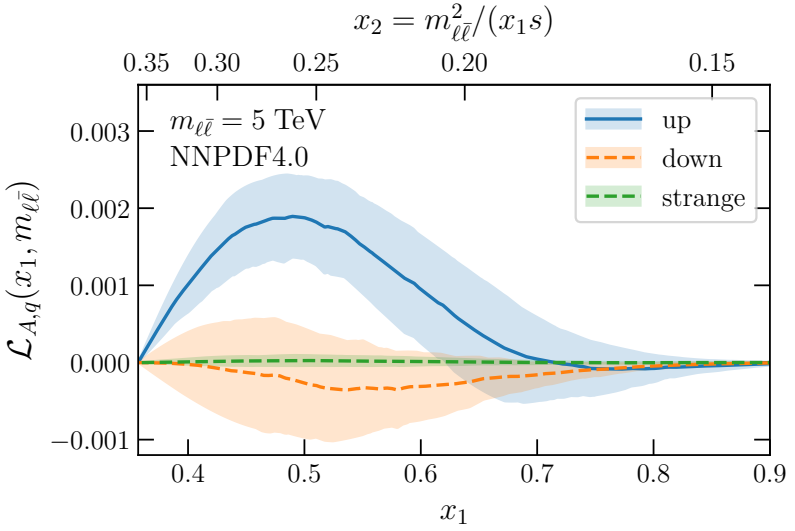
PDF LUMIS
INDIVIDUAL FLAVORS ($M_{Z'}$ =5 TEV)

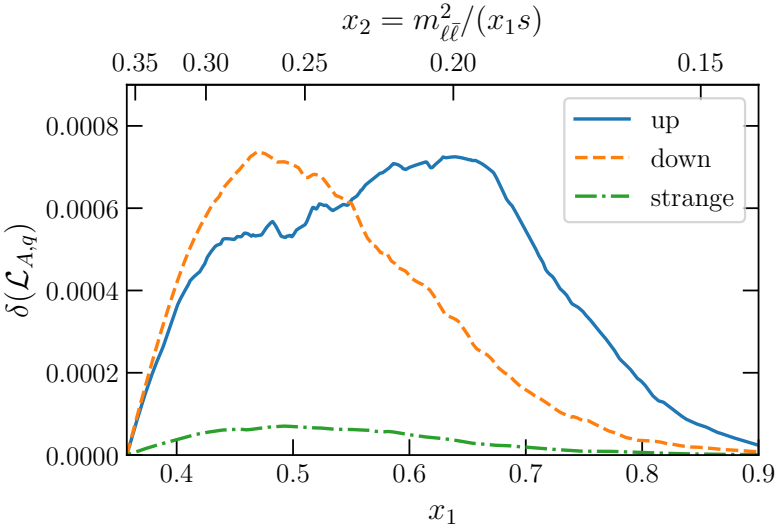
SYMMETRIC



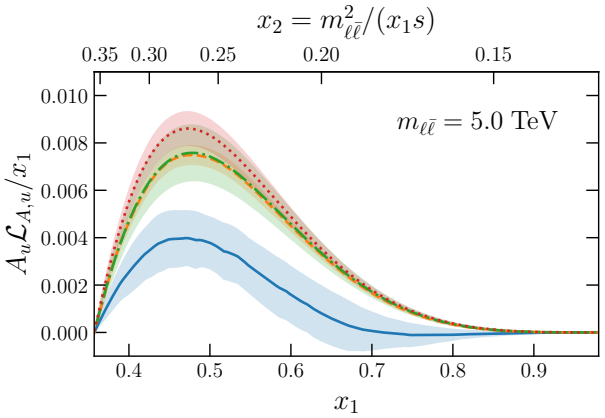


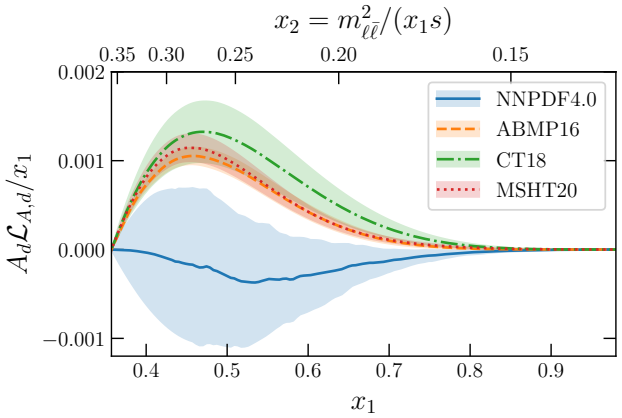
ANTISYMMETRIC

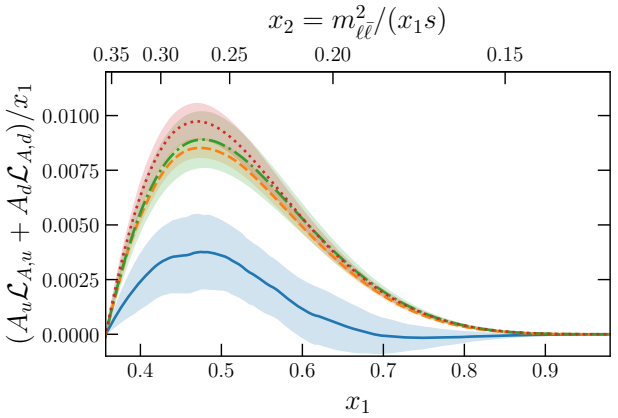




ANTISYMMETRIC PDF LUMIS
COMPARING PDF SETS ($M_{Z'}$ =5 TEV)
PDFs







ABSOLUTE UNCERTAINTIES