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# PDF UNCERTAINTIES

## CURRENT UNDERSTANDING & ISSUES


STEFANO FORTE

UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO

DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare


EWWG MEETING

CERN, NOVEMBER 13, 2018

# QUESTIONS

## DATA+METHODOLOGY ISSUES

- WHICH UNCERTAINTIES DO PDF UNCERTAINTIES INCLUDE AND HOW DO WE KNOW THAT THEY ARE FAITHFUL?
- ARE UNCERTAINTIES FROM DIFFERENT GROUPS CORRELATED AND HOW CAN WE COMBINE THEM?
- CAN WE DETERMINE THE BEST DATASET AND HOW?
- ARE THERE ADVANTAGES/DISADVANTAGES IN USING EIGENVECTORS VS. MONTECARLO AND CAN WE TELL?

## THEORY ISSUES

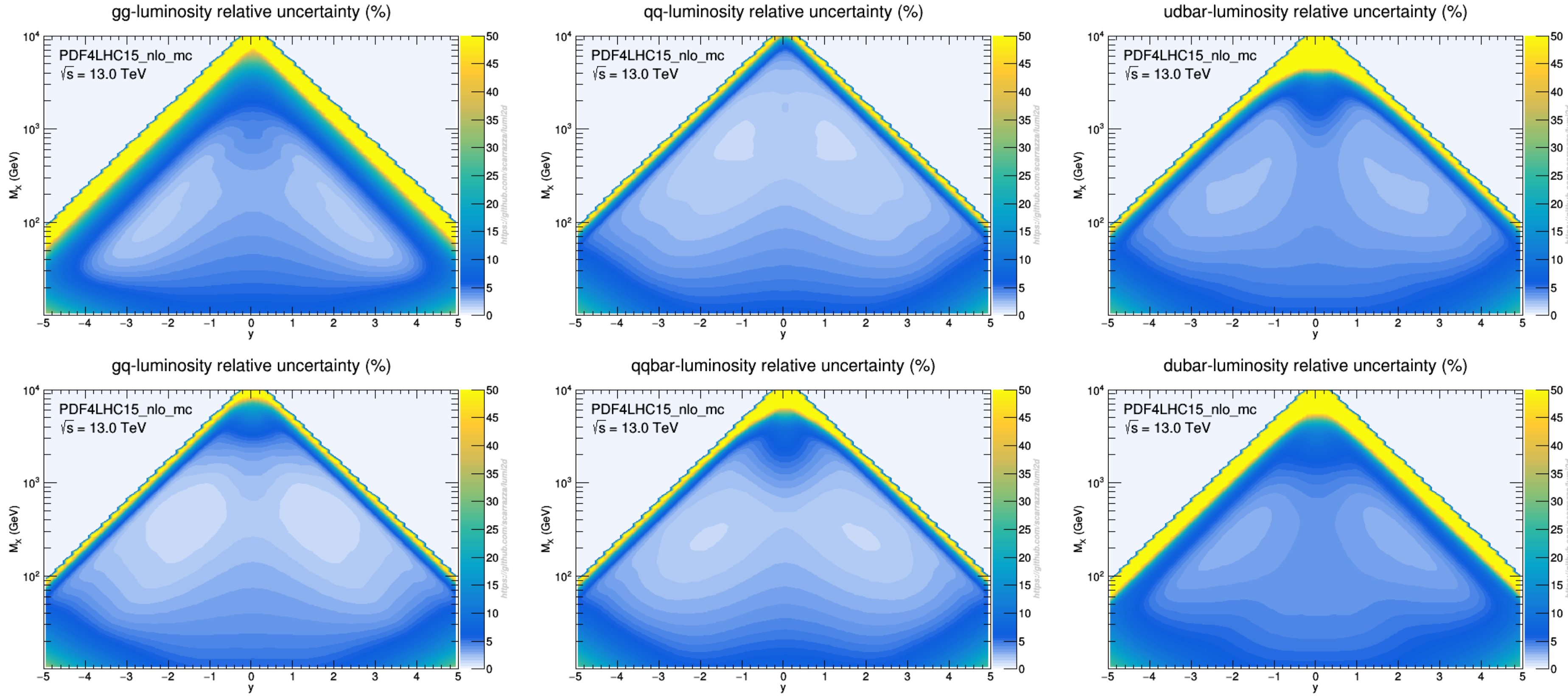
- HOW SHOULD ONE TREAT THE CHARM PDF?
- HOW SHOULD ONE TREAT THE PHOTON PDF?
- ARE THEORY (MHO) UNCERTAINTIES INCLUDED AND SHOULD WE WORRY ABOUT THEM?

# PDF UNCERTAINTIES

## THE KARLSRUHE PLOTS

# CURRENT PDF UNCERTAINTIES (PDF4LHC15: NLO)

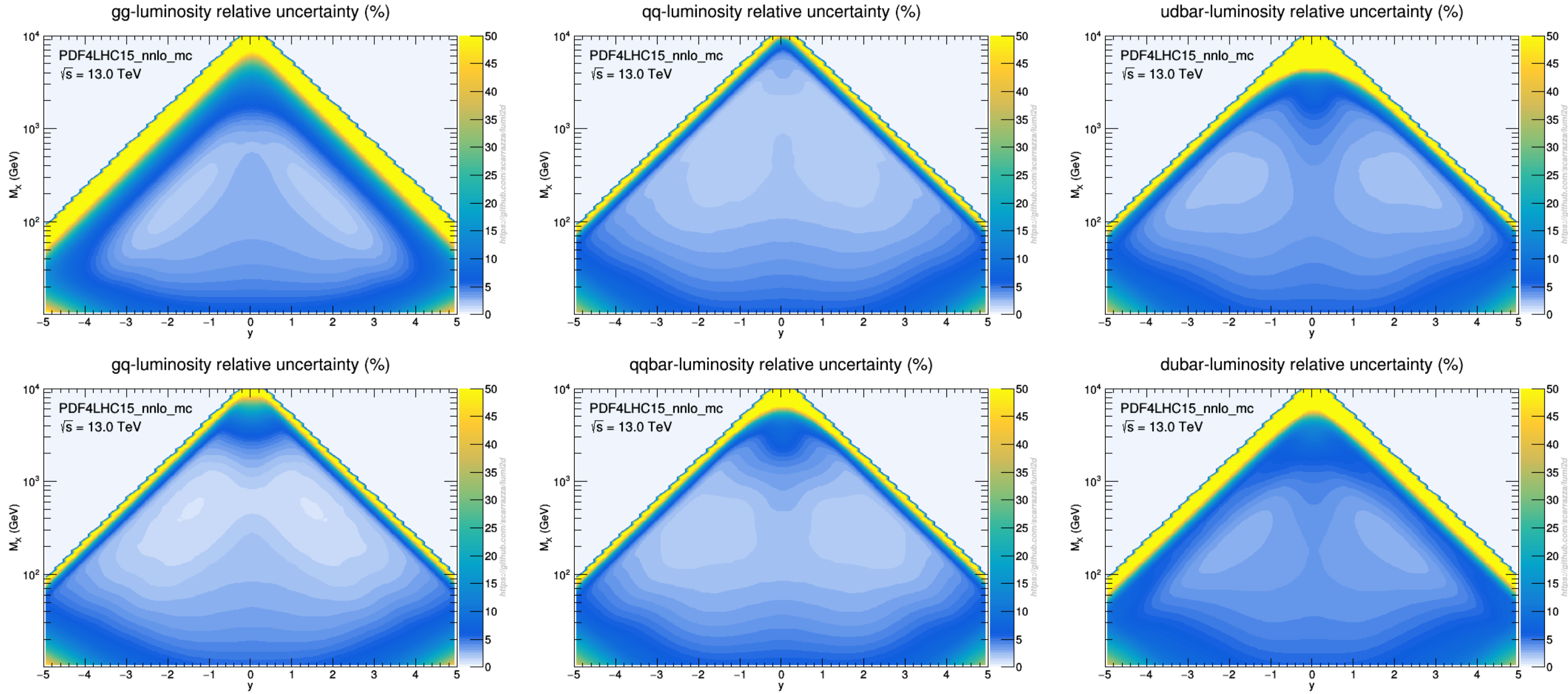
GLUON SINGLET FLAVORS




- GLUON BETTER KNOWN AT SMALL $x$, VALENCE QUARKS AT LARGE $x$, SEA QUARKS IN BETWEEN
- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 3-5\%$
- SWEET SPOT: VALENCE Q - G; DOWN TO $1\%$
- UP BETTER KNOWN THAN DOWN; FLAVOR SINGLET BETTER THAN INDIVIDUAL FLAVORS
- .

# CURRENT PDF UNCERTAINTIES (PDF4LHC15 NNLO)

GLUON SINGLET FLAVORS




- GLUON BETTER KNOWN AT SMALL $x$, VALENCE QUARKS AT LARGE $x$, SEA QUARKS IN BETWEEN
- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 3-5\%$
- SWEET SPOT: VALENCE Q - G; DOWN TO 1%
- UP BETTER KNOWN THAN DOWN; FLAVOR SINGLET BETTER THAN INDIVIDUAL FLAVORS
- NO QUALITATIVE DIFFERENCE BETWEEN NLO AND NNLO

# PDF UNCERTAINTIES

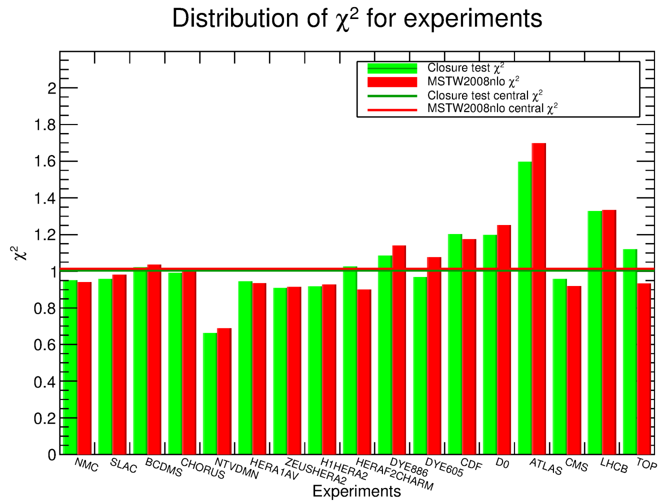
- INCLUDE UNCERTAINTY FROM DATA & METHODOLOGY (AND NOTHING ELSE!)
- HOW DO WE KNOW THAT THEY ARE FAITHFUL?

## CLOSURE TESTS (NNPDF)

### BASIC IDEA

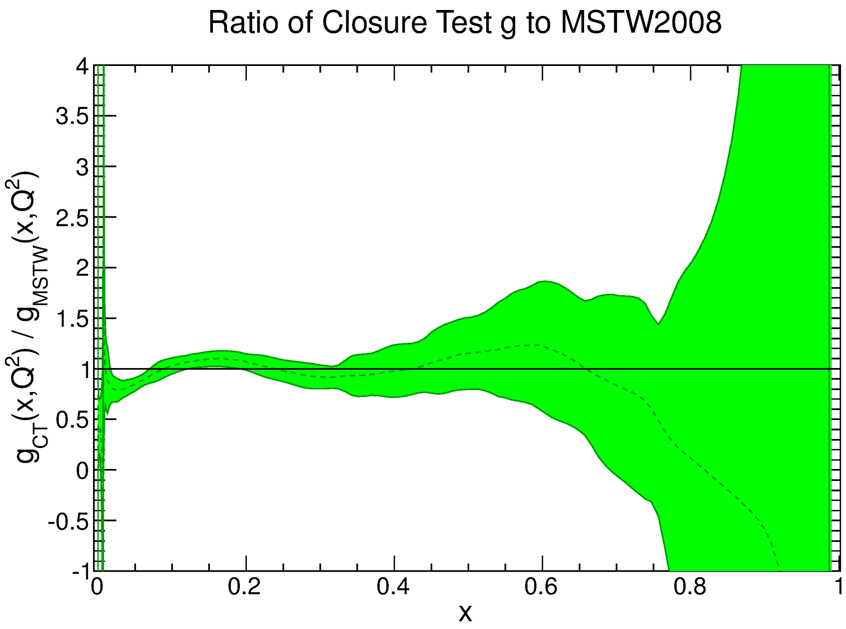
- ASSUME PDFs KNOWN: GENERATE FAKE EXPERIMENTAL DATA
- CAN DECIDE DATA UNCERTAINTY (ZERO, OR AS IN REAL DATA, OR . . . )
- FIT PDFs TO FAKE DATA
- CHECK WHETHER FIT REPRODUCES UNDERLYING “TRUTH”:
  - CHECK WHETHER TRUE VALUE GAUSSIANLY DISTRIBUTED ABOUT FIT
  - CHECK WHETHER UNCERTAINTIES FAITHFUL
  - CHECK STABILITY
    (INDEP. OF METHODOLOGICAL DETAILS)

# CLOSURE TEST RESULTS (NNPDF3.0)
## CENTRAL VALUES AND UNCERTAINTIES

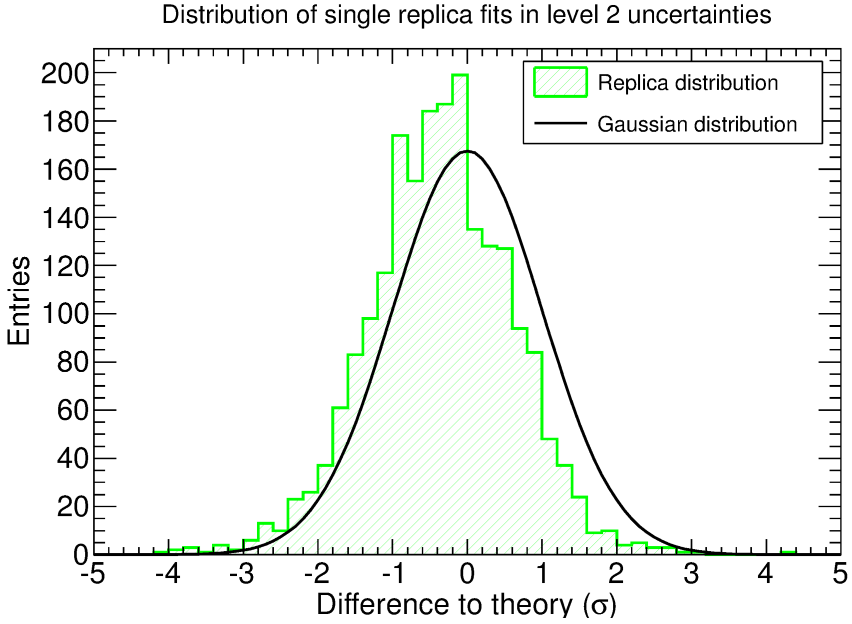



- CENTRAL VALUES:
  COMPARE FITTED VS. "TRUE" $\chi^2$
  BOTH FOR INDIVIDUAL EXPERIMENTS
  & TOTAL DATASET
  FOR TOTAL $\Delta\chi^2 = 0.001 \pm 0.003$
- UNCERTAINTIES: DISTRIBUTION OF DEVIATIONS BETWEEN FITTED AND "TRUE" PDFs
  SAMPLED AT $20$ POINTS BETWEEN $10^{-5}$ AND $1$
  FIND $0.699\%$ FOR ONE-SIGMA,
  $0.948\%$ FOR TWO-SIGMA C.L.

THE GLUON: FITTED/"TRUE"




NORM. DISTRIBUTION OF DEVIATIONS



# CLOSURE TEST RESULTS (NNPDF3.0)

## STABILITY TESTS

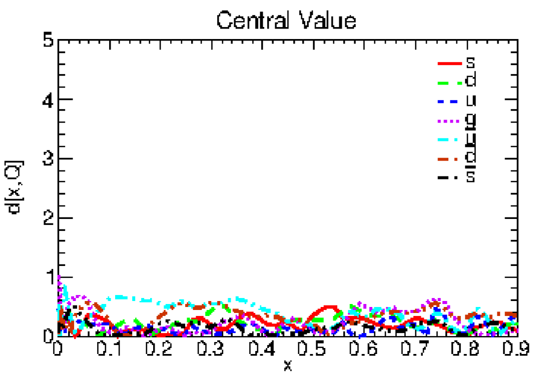
- CHANGE UNDERLYING PDF SET (CT10, NNPDF2.3)
- INCREASE MAXIMUM GA TRAINING LENGTH TO 80K
  TESTS EFFICIENCY OF CROSS-VALIDATION
- INCREASE NN ARCHITECTURE TO 2-20-15-1
  NUMBER OF FREE PARAMETRES INCREASE BY MORE THAT $10\times$
- CHANGE PDF PARAMETRIZATION BASIS
  OLD: ISOTRIPLET, $\bar{u}-\bar{d}$, $s+\bar{s}$, $s-\bar{s}$;
  NEW: ISOTRIPLET, SU(3)-OCTET, BOTH TOTAL $(q+\bar{q})$ & VALENCE $(q-\bar{q})$

## STATISTICAL EQUIVALENCE!

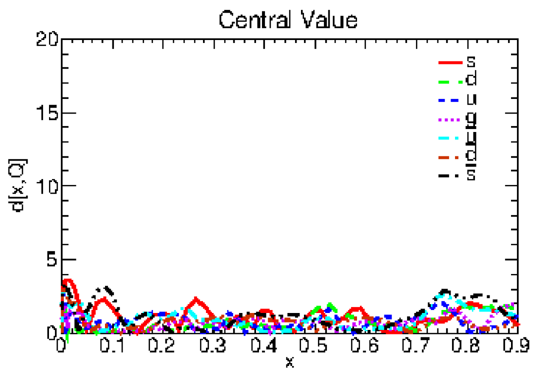
DISTANCES BETWEEN REF. AND NEW FIT:

difference in unites of standard deviation of the mean

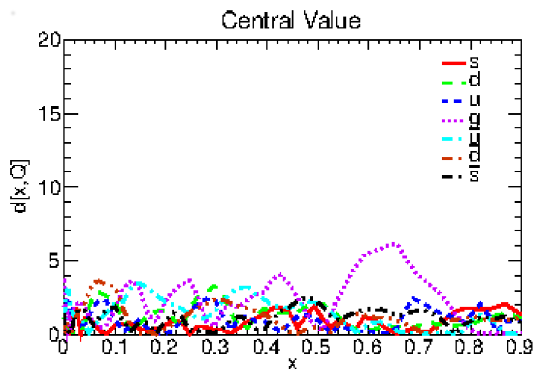
30K GENS VS 80K GENS




2.3 BASIS VS 3.0 BASIS




300 VS 37 PARMS



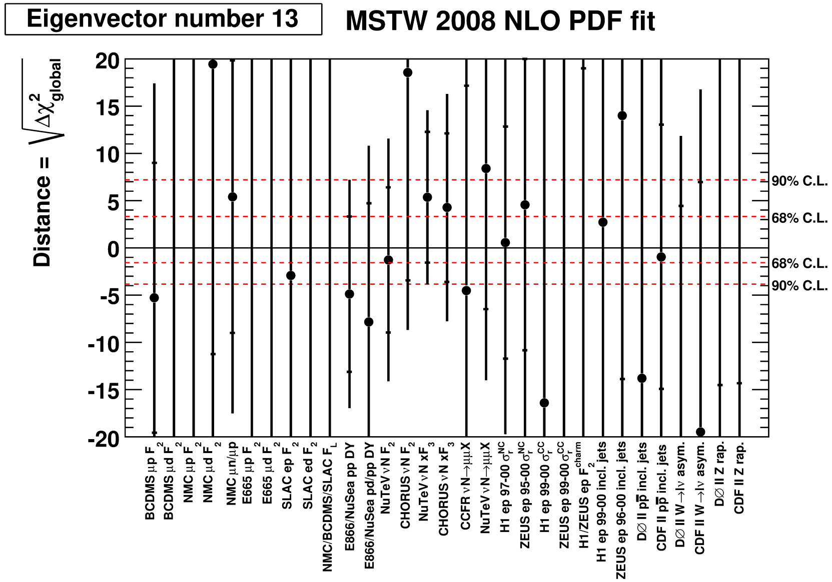
# PDF UNCERTAINTIES

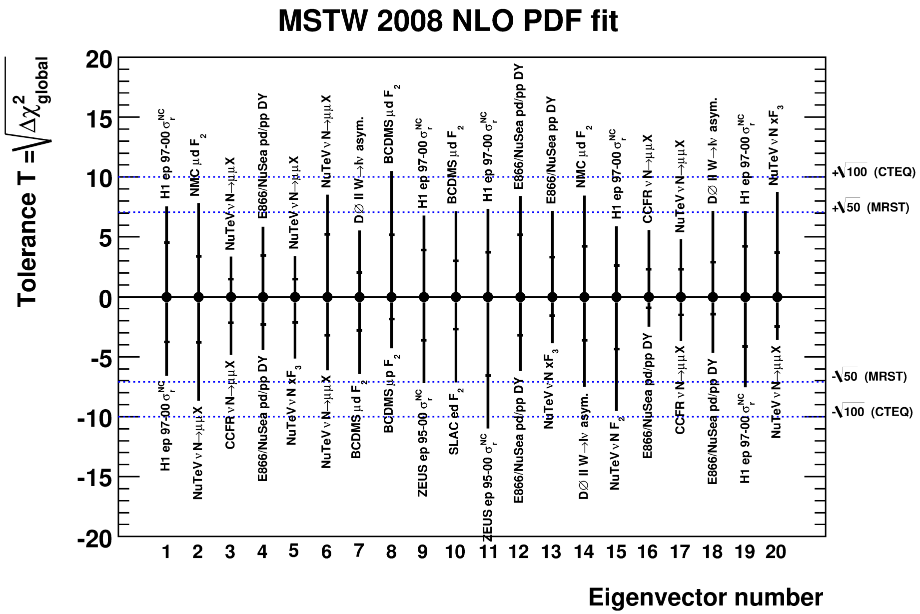
- PDF UNCERTAINTIES ON OTHER GLOBAL FITS HAVE SIMILAR SIZE
  – SIMILAR DATASETS
  – BUT DIFFERENT PROCEDURES
- BECAUSE OF UNCERTAINTY TUNING

## TOLERANCE (MMHT-CT)

GLOBAL MSTW TOLERANCE

MSTW TOLERANCE PLOT FOR 13TH EIGENVEC.




- (MSTW/MMHT) FOR EACH EIGENVECTOR IN PARAMETER SPACE DETERMINE CONFIDENCE LIMIT FOR THE DISTRIBUTION OF BEST-FITS OF EACH EXPERIMENT
- RESCALE $\Delta\chi^2 = T$ INTERVAL SUCH THAT CORRECT CONFIDENCE INTERVALS ARE REPRODUCED
- SIMILAR PROCEDURE ADOPTED BY CTEQ

# METHODOLOGY

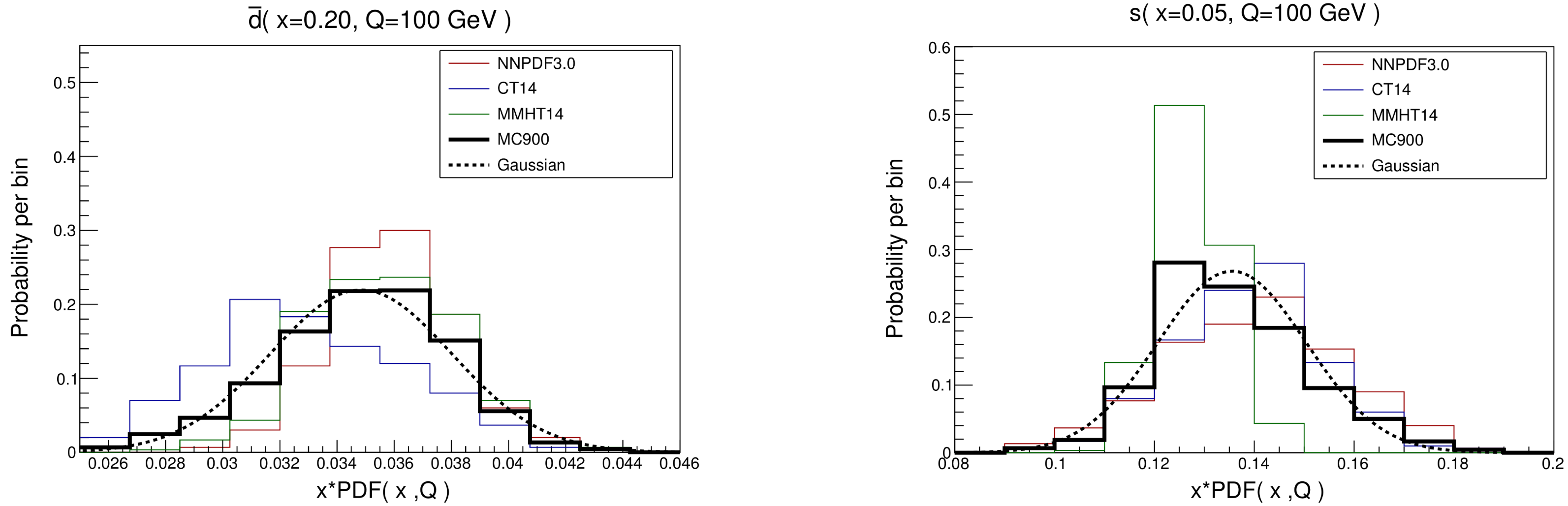
- SIMILAR DATASETS
- BUT DIFFERENT PROCEDURES

| | NNPDF3.0 | MMHT14 | CT14 |
|---|---|---|---|
| No. of fitted PDFs | 7 | 7 | 6 |
| Parametrization | neural nets | $x^a(1-x)^b\times$ Chebyschev | $x^a(1-x)^b\times$Bernstein |
| Free parameters | 259 | 37 | 30-35 |
| Uncertainties | Replicas | Hessian | Hessian |
| Tuning | Closure test | Dynamical tolerance | Dynamical tolerance |

# STATISTICAL COMBINATION

- MAY COMBINE DIFFERENT PDF SETS, AFTER MC CONVERSION OF HESSIAN SETS
- COMBINE MONTE CARLO REPLICAS INTO SINGLE SET

COMBINED PDF4LHC SETS FOR ANTIDOWN & STRANGE

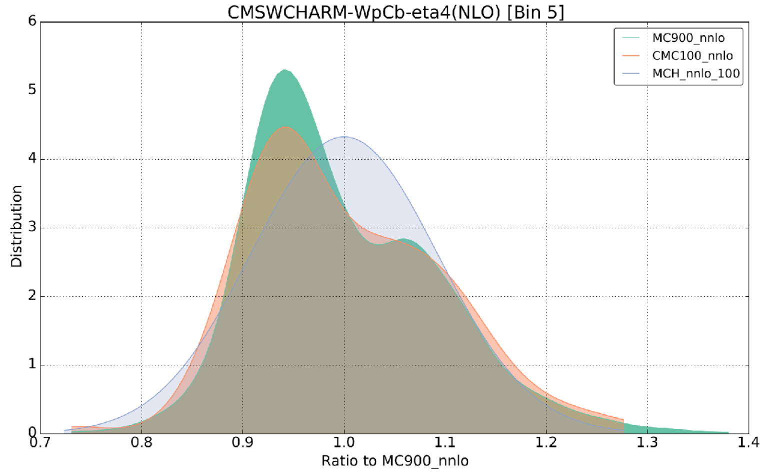



- NO UNCERTAINTY REDUCTION!
- COMBINED SET GAUSSIAN TO GOOD APPROXIMATION

# MONTECARLO OR HESSIAN
# NONGAUSSIAN BEHAVIOUR

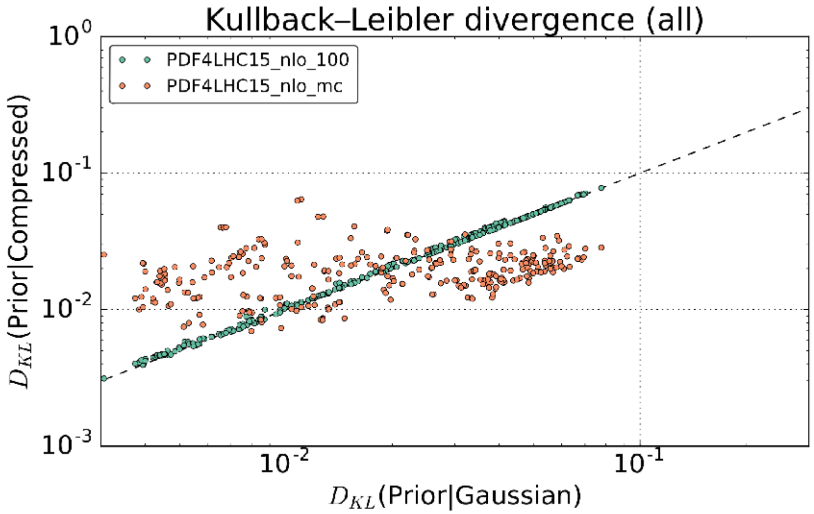
## MONTE CARLO COMPARED TO HESSIAN

CMS $W + c$ production




- DEVIATION FROM GAUSSIANITY E.G. AT LARGE $x$ DUE TO LARGE UNCERTAINTY + POSITIVITY BOUNDS
  $\Rightarrow$ RELEVANT FOR SEARCHES
- CANNOT BE REPRODUCED IN HESSIAN FRAMEWORK
- WELL REPRODUCED BY COMPRESSED MC

- DEFINE KULLBACK-LEIBLER DIVERGENCE $D_{\rm KL} = \int_{-\infty}^{\infty} P(x) \frac{\ln P(x)}{\ln Q(x)}\, dx$ BETWEEN A PRIOR $P$ AND ITS REPRESENTATION $Q$
- $D_{\rm KL}$ BETWEEN PRIOR AND HESSIAN DEPENDS ON DEGREE OF GAUSSIANITY
- $D_{\rm KL}$ BETWEEN PRIOR AND COMPRESSED MC DOES NOT

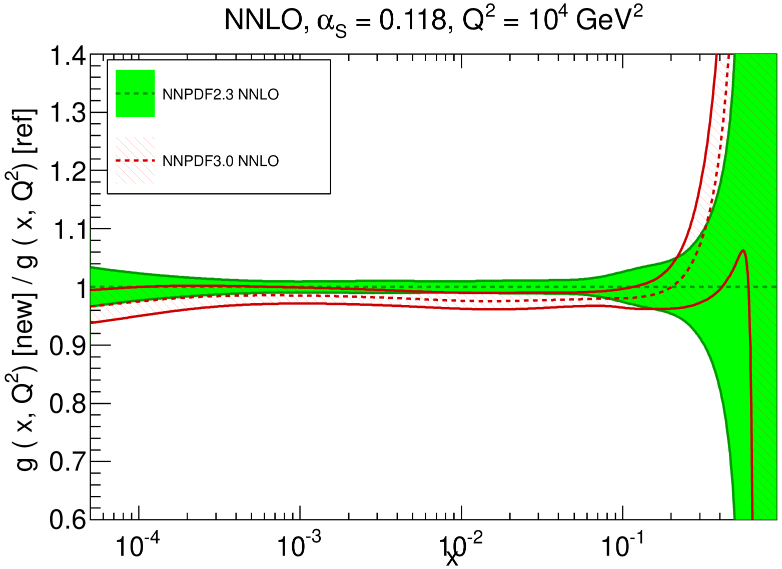


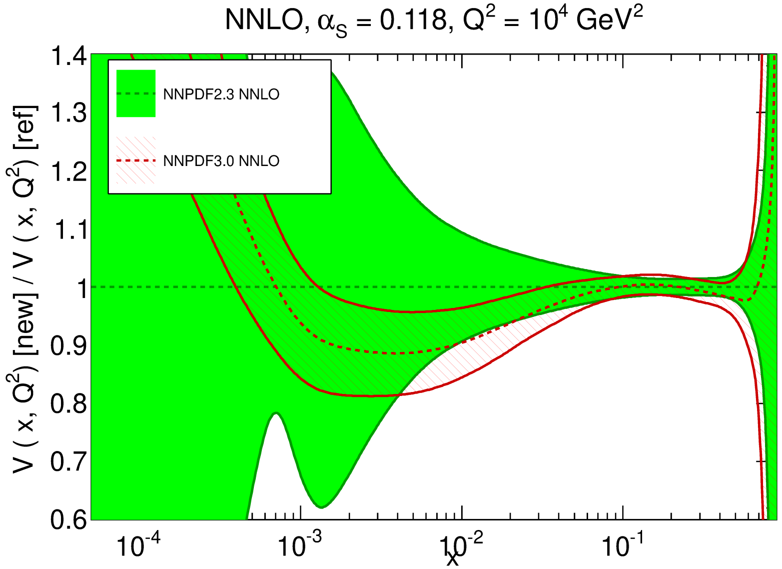

CAN (A) GAUGE WHEN MC IS MORE ADVANTAGEOUS THAN HESSIAN; (B) ASSESS THE ACCURACY OF COMPRESSION

# CONSISTENCY VS INFORMATION LOSS

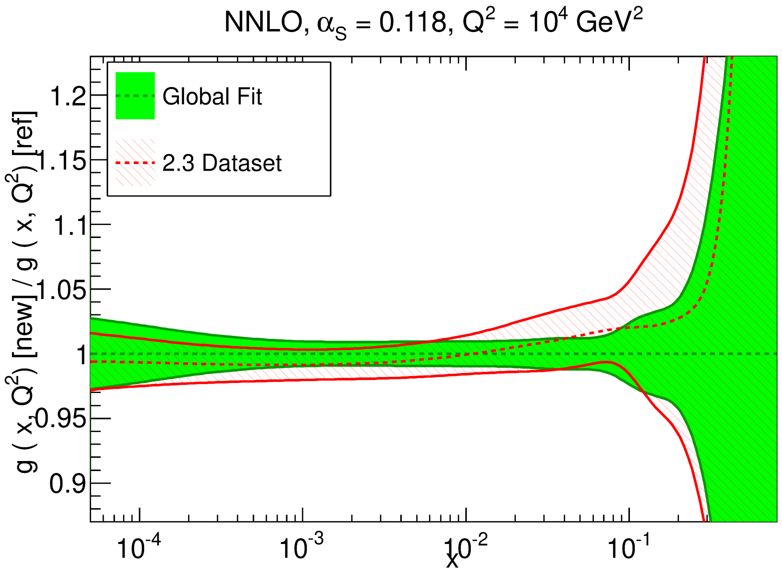
- PDF SETS MUST BE BACKWARD CONSISTENT (THEY ARE)
- PDF UNCERTAINTY MIGHT IMPROVE EVEN WITH UNCHANGED DATASET (THEY DO)

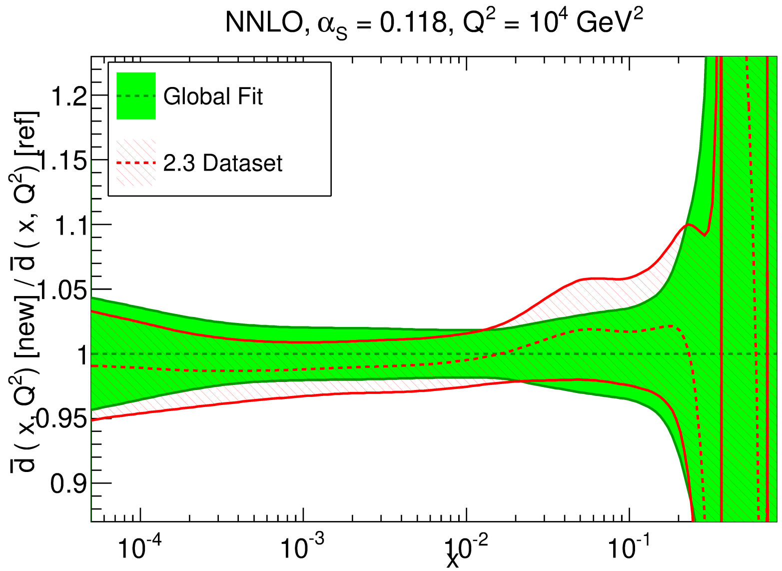
## NNPDF 2.3 VS 3.0: GLUON & VALENCE




## NNPDF 3.0 DEFAULT VS 2.3-LIKE DATASET: GLUON & ANTIDOWN

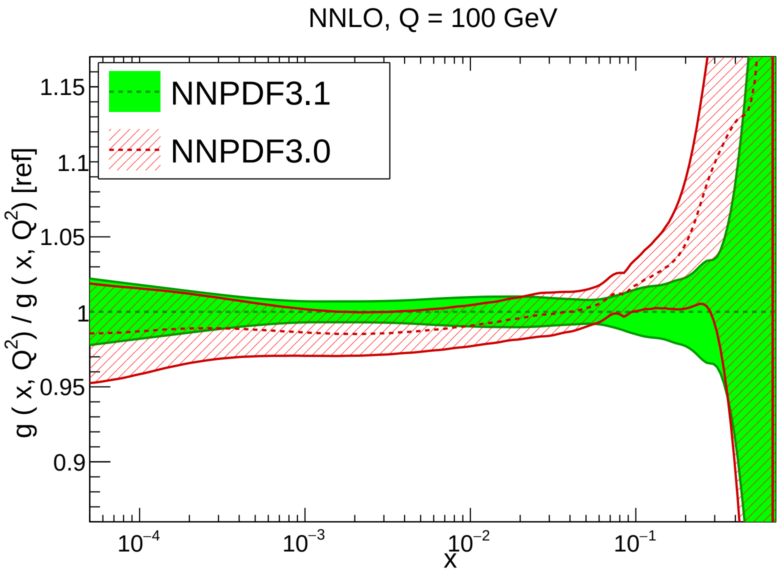


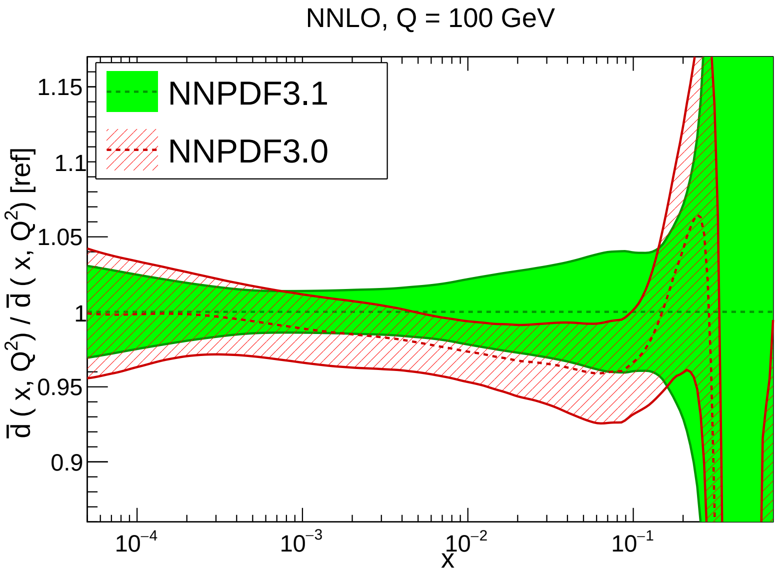



# CONSISTENCY VS INFORMATION LOSS

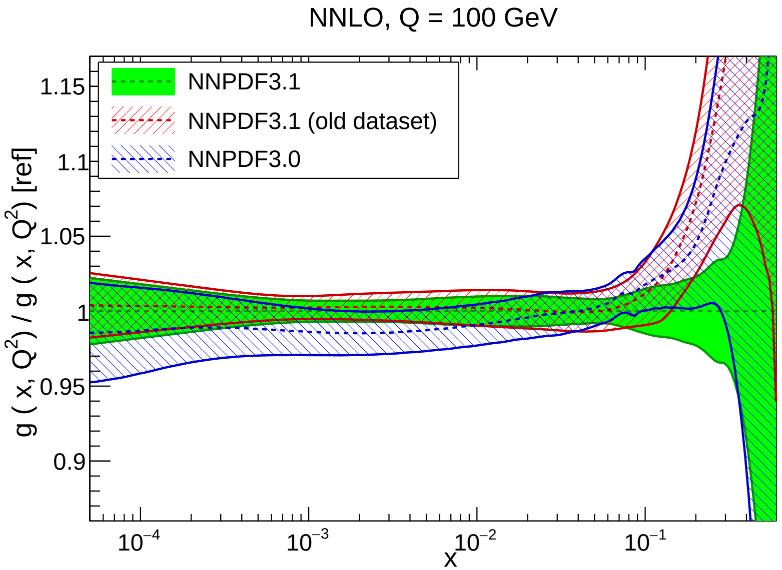
- PDF sets must be backward consistent (they are)
- PDF uncertainty might improve even with unchanged dataset (they do)

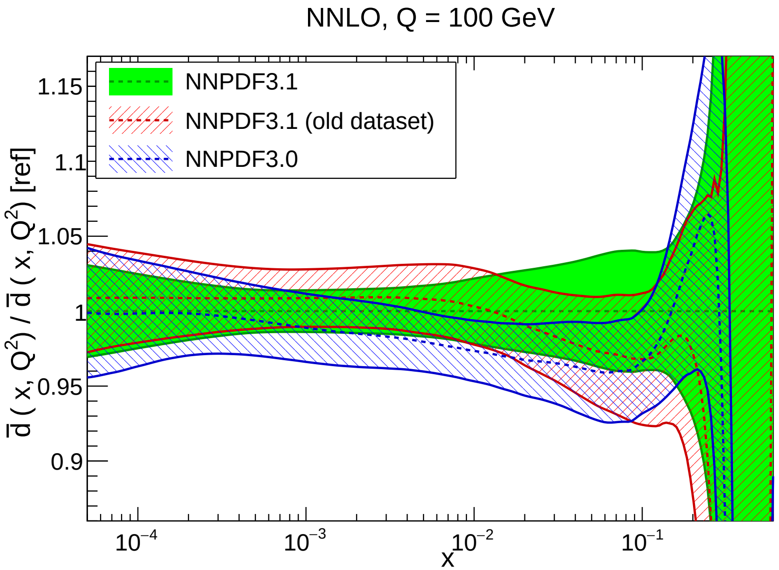
## NNPDF 3.1 vs 3.0: gluon & antidown




## NNPDF 3.1 default vs 30.3-like dataset

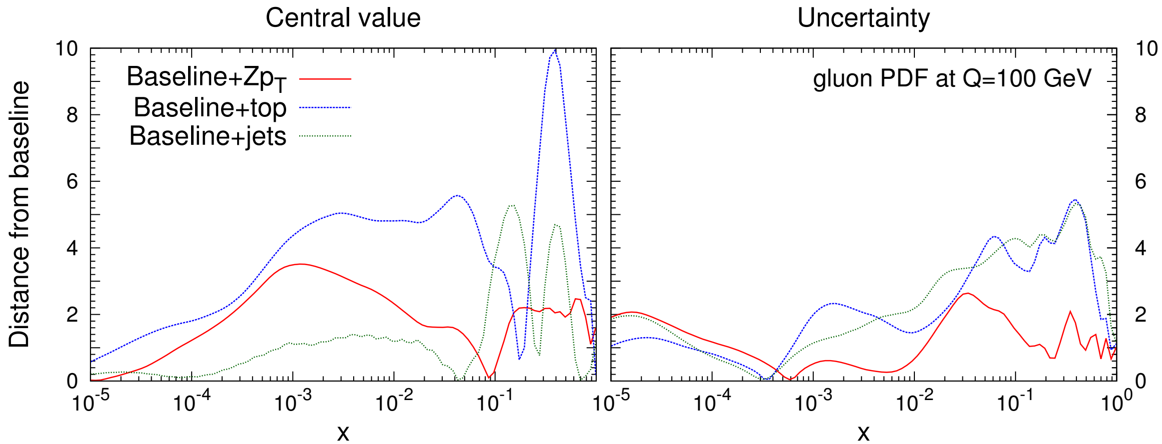


# DATA IMPACT: COMPATIBILITY
# THE GLUON

- BEFORE LHC ⇒ DIS SCALING VIOLATIONS, TEV JETS AT LARGE X
- AFTER LHC ⇒ JETS; $Z\ p_t$ , TOP

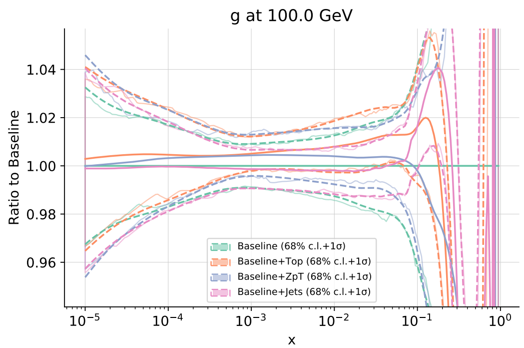
DISTANCES (difference in units of st. dev.)



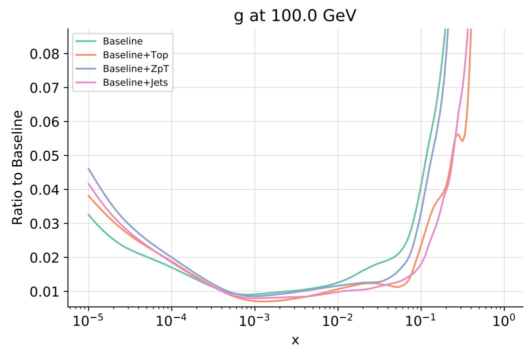

(Nocera, Ubiali, 2017)

## PDF COMPARISON

CENTRAL VALUE



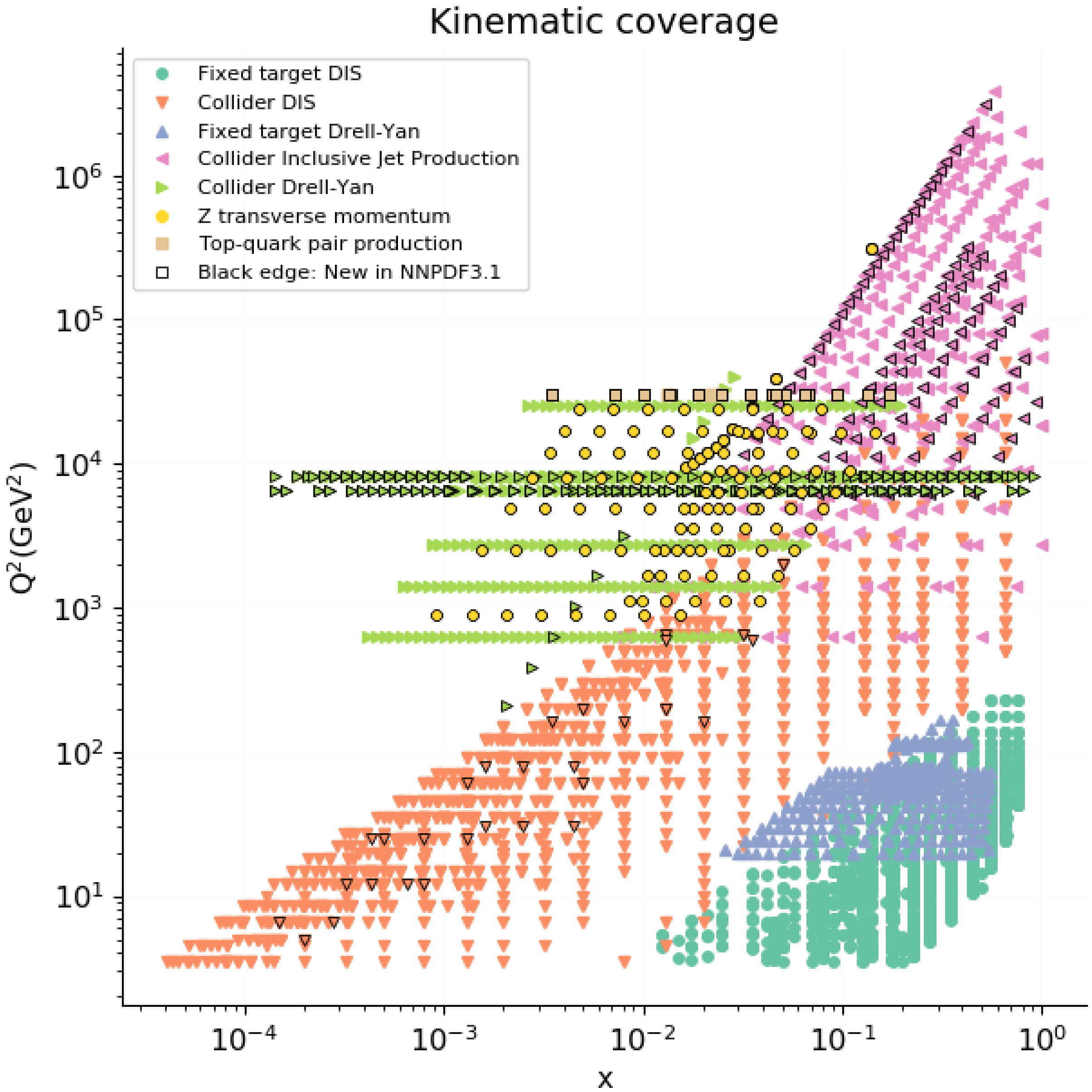

UNCERTAINTY




- TOP HAS LARGEST IMPACT, FOLLOWED BY JETS
- ALL LHC DATA PULL CENTRAL VALUE IN SAME DIRECTION!

# DATA IMPACT

## DATASET WIDENING: NNPDF3.0 VS NNPDF3.1

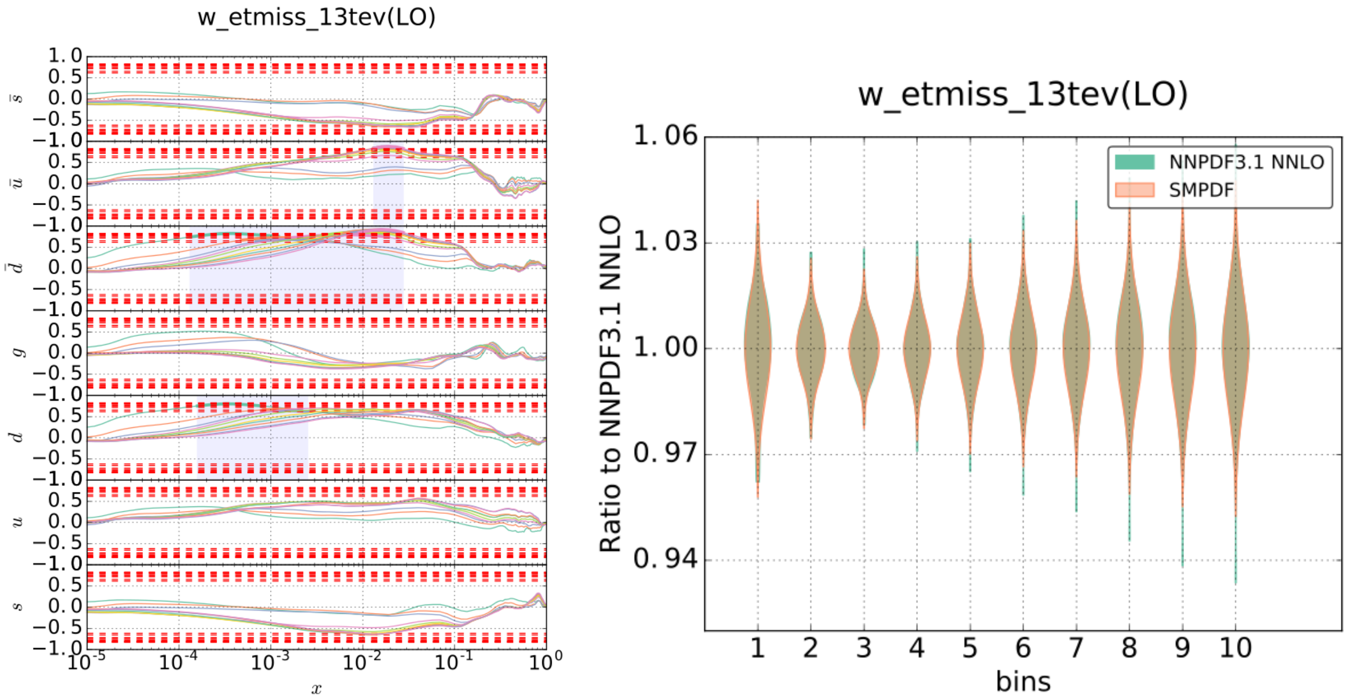



NEW DATA: (BLACK EDGE)
ALL NNLO THEORY

- HERA COMBINED $F_2^b$
- D0 $W$ LEPTON ASYMMETRY
- ATLAS $W, Z$ 2011, HIGH & LOW MASS DY 2011; CMS $W^{\pm}$ RAPIDITY 8TEV LHCB $W, Z$ 7TEV & 8TEV
- ATLAS 7TEV JETS 2011, CMS 2.76TEV JETS
- ATLAS & CMS TOP DIFFERENTIAL RAPIDITY
- ATLAS $Z$ $p_T$ DIFFERENTIAL RAPIDITY & INVARIANT MASS 8TEV, CMS $Z$ $p_T$ DIFFERENTIAL RAPIDITY 8TEV

# DATA IMPACT: OPTIMIZED PDFs
# SMPDF

- OLD ASPIRATION: PDFs OPTIMIZED TO PROCESSES (Pumplin 2009)
- SELECT SUBSET OF THE COVARIANCE MATRIX CORRELATED TO A GIVEN SET OF PROCESSES
- PERFORM SVD ON THE REDUCED COVARIANCE MATRIX, SELECT DOMINANT EIGENVECTOR, PROJECT OUT ORTHOGONAL SUBSPACE
- ITERATE UNTIL DESIRED ACCURACY REACHED
- CAN ADD PROCESSES TO GIVEN SET; CAN COMBINE DIFFERENT OPTIMIZED SETS
- WEB INTERFACE AVAILABLE




(Carrazza, SF, Kassabov, Rojo, 2016)

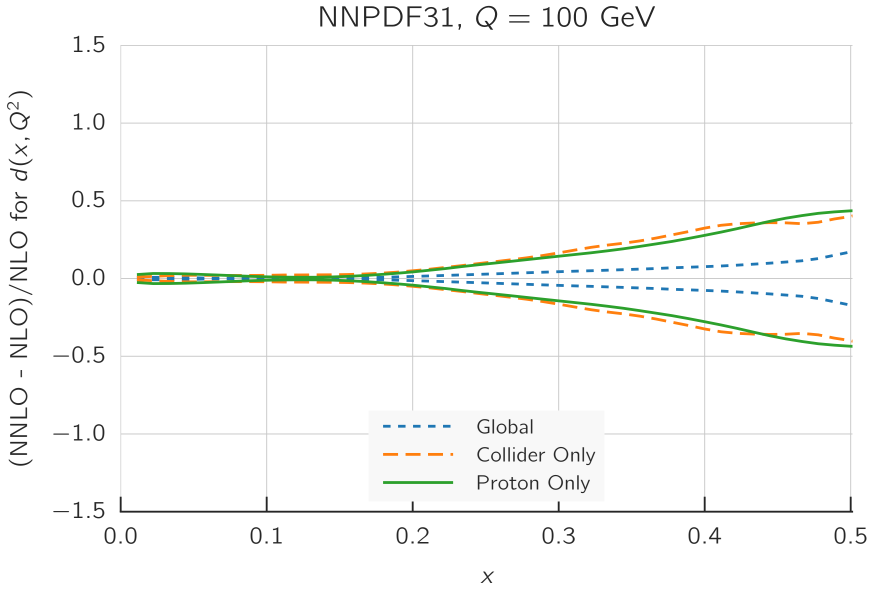
- EG $ggH$, $Hb\bar{b}$, $W\ E_T^{\rm miss}$ $\Rightarrow$ 11 EIGENVECTORS
- STUDY CORRELATIONS OF PDFs TO DATA AND AMONG THEMSELVES!

# DATA IMPACT

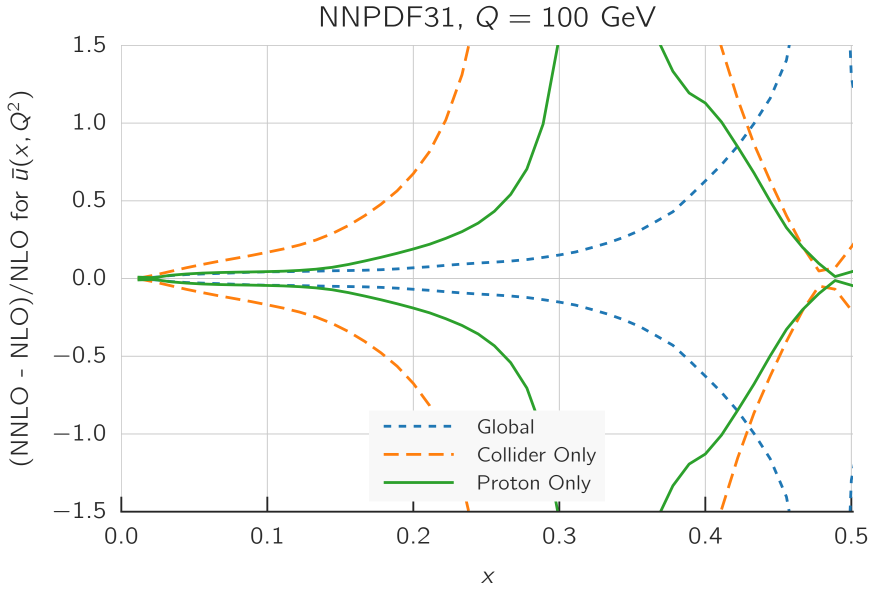
## PERTURBATIVE STABILITY

### GLOBAL VS RESTRICTED DATASETS

DOWN




ANTIUP

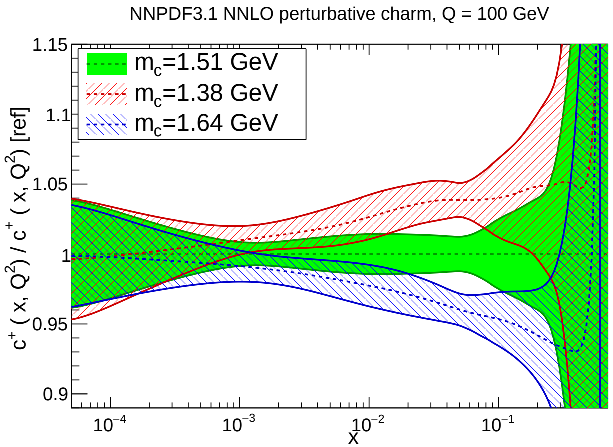



- NLO-NNLO SHIFTS SMALLER WITH LARGER DATASET
- GREATER STABILITY OF $\alpha_s$ ALSO OBSERVED

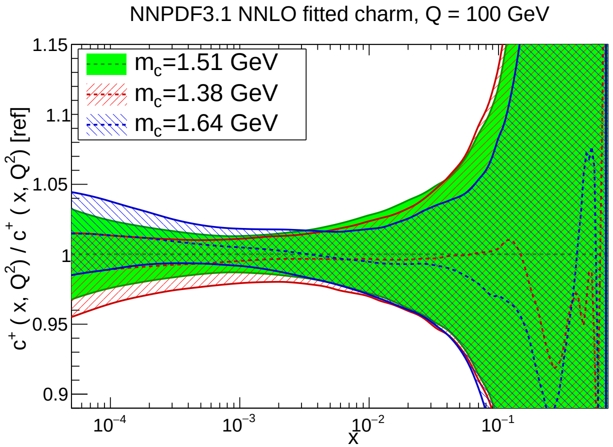
# HEAVY QUARK PDFs
## CHARM FROM DATA

- CHARM SHOULD NOT DEPEND STRONGLY ON CHARM MASS

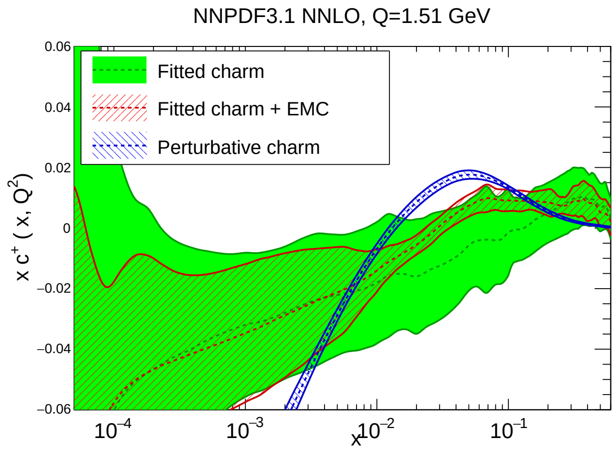
PERTURBATIVE CHARM VS $m_c$




FITTED CHARM VS $m_c$




FITTED VS. PERTURBATIVE CHARM



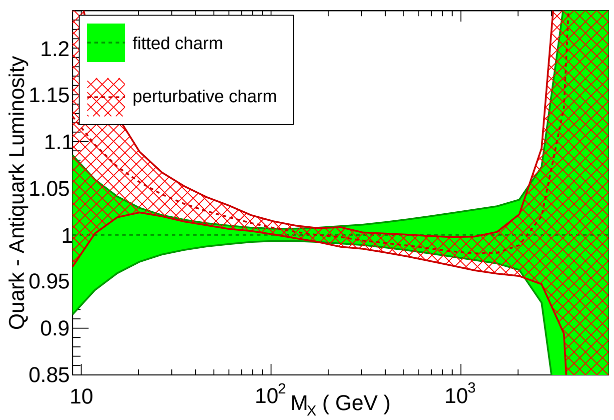

- ITS SHAPE SHOULD NOT BE DETERMINED BY FIRST-ORDER MATCHING (NO HIGHER NONTRIVIAL ORDERS KNOWN)
- MIGHT EVEN HAVE A NONPERTURBATIVE COMPONENT

FITTED VS. LO PERTURBATIVE:
SUPPRESSED AT MEDIUM-SMALL $x$, ENHANCED AT VERY SMALL, VERY LARGE $x$

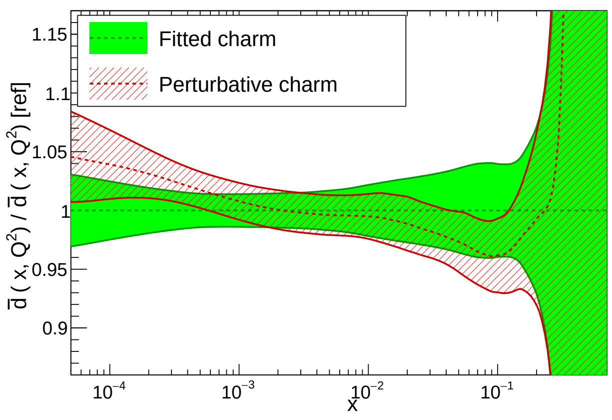
# THE CHARM PDF FROM DATA
# IMPACT ON LIGHT QUARK PDFS

## FITTED VS. PERTURBATIVE CHARM

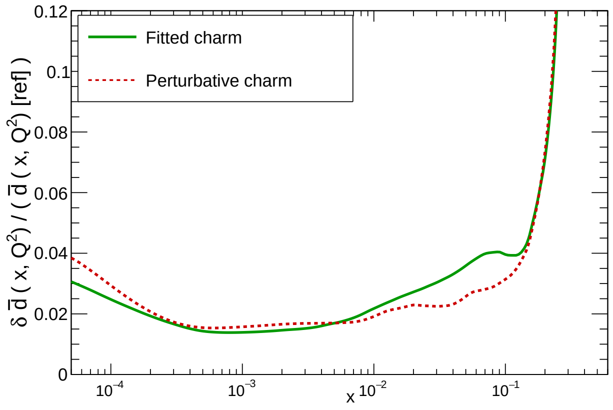
QQBAR LUMI




ANTIDOWN PDF



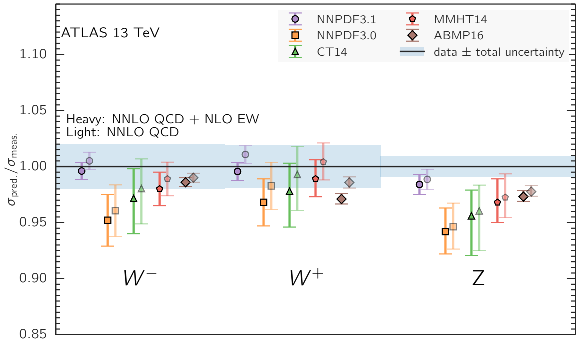

ANTIDOWN PDF UNCERTAINTY

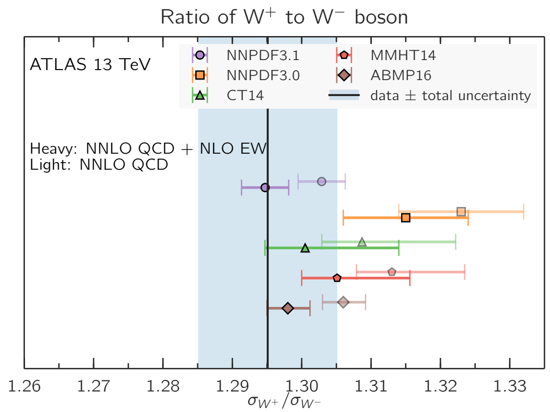


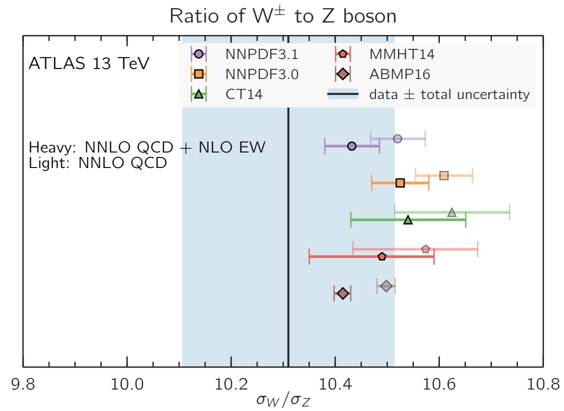

- QUARK (ESPECIALLY QUARK-ANTIQUARK) LUMI AFFECTED BECAUSE OF CHARM SUPPRESSION AT MEDIUM-$x$
- FLAVOR DECOMPOSITION ALTERED
- UNCERTAINTIES ON LIGHT QUARKS NOT SIGNIFICANTLY INCREASED
- AGREEMENT OF 13TeV W,Z PREDICTED CROSS-SECTIONS IMPROVES!

# CHARM FROM DATA
## IMPACT ON PHENOMENOLOGY

| Drell-Yan xsects | $W^+/W^-$ xsect ratio | $W/Z$ xsect ratio |
| --- | --- | --- |




- $W$, $Z$ cross-sections at 13 TeV in perfect agreement with data thanks to fitted charm!
- electroweak corrections important

# THE PHOTON PDF

- LUX QED (Manohar, Nason, Salam, Zanderighi, 2016): PHOTON PDF COMPUTABLE IN TERMS OF THE PROTON STRUCTURE FUNCTION INTEGRATED OVER ALL SCALES
- UNCERTAINTY ON RESULT (E.G. FROM ELASTIC FORM FACTORS) NEGIGIBLE
- EXTRA CONSTRAINT IN PDF FITS: IMPLEMENTED IN NNPDF3.1LUXQED

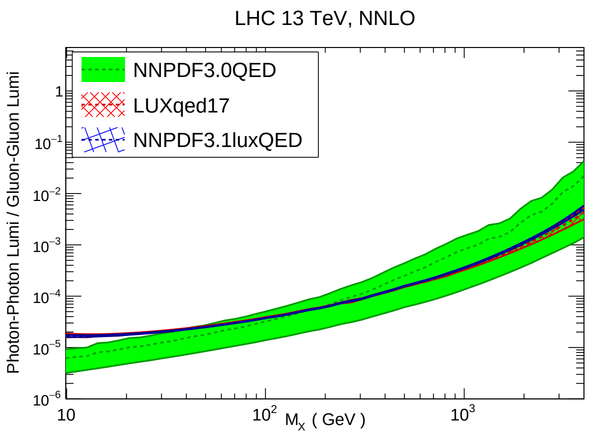
# THE LUXQED PHOTON PDF

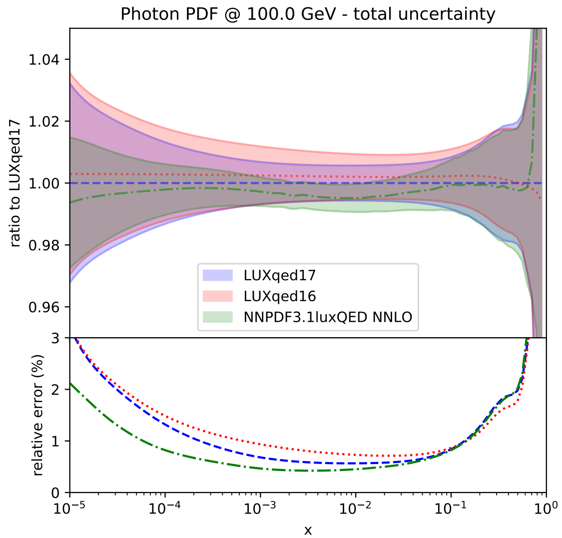
(Carrazza et al., 2017)

- FIRST PDF SET BASED ON CONSISTENT FIT WITH LUX CONSTRAINT: NNPDF3.1LUXQED
- NNPDF3.1LUXQED VS LUX17: GOOD AGREEMENT BUT SMALLER UNCERTAINTIES
- SIZABLE IMPACT ON PRECISION PHYSICS: EG ASSOCIATE HIGGS PROD. WITH $W$

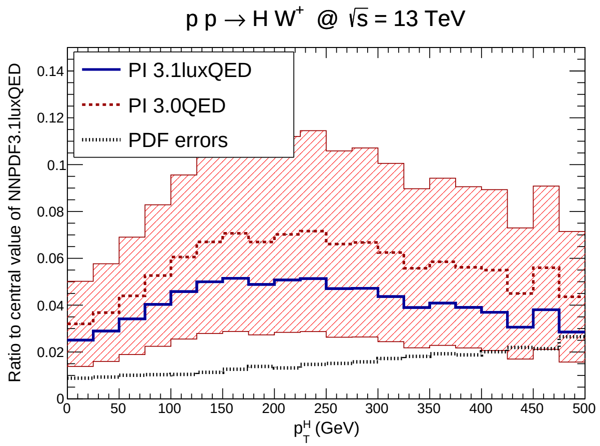
$\gamma$ PDF COMPARISON

$\gamma\gamma$ LUMI COMPARISON




$\gamma$-INDUCED VS QCD: HW

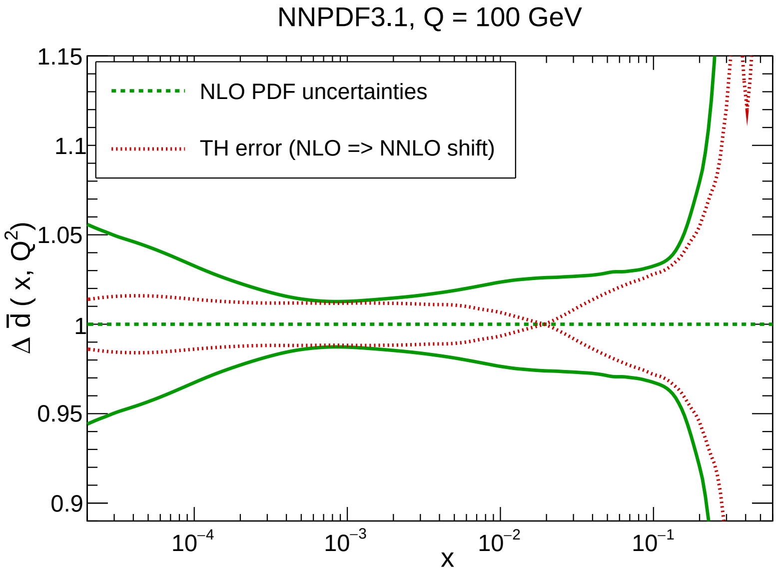


# THEORY UNCERTAINTIES
## THE MISSING HIGHER ORDER UNCERTAINTY

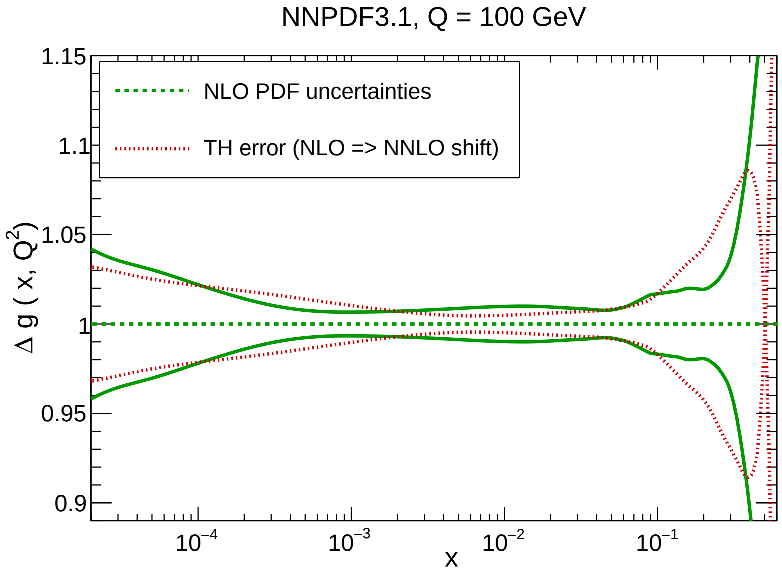
- DOMINANT THEORY UNCERTAINTY ON QCD PREDICTIONS $\Rightarrow$ MHOU (SCALE)
- NOT INCLUDED IN PDF UNCERTAINTY
- HOW LARGE IS IT?
  $\Rightarrow$ AT NLO, CAN CHECK NLO-NNLO PDF SHIFT

NLO-NNLO SHIFT VS. NLO PDF UNCERTAINTY (NNPDF3.1)

ANTIDOWN




GLUON




- TODAY: NLO PDF & MHOU UNCERTAINTIES COMPARABLE
- NEAR FUTURE: WORRY ABOUT NNLO MHOU!
- STAY TUNED!

# ANSWERS

## DATA+METHODOLOGY ISSUES

- which uncertainties do PDF uncertainties include and how do we know that they are faithful?
  PDF UNCERTAINTIES INCLUDE DATA & METHODOLOGY UNCERTAINTIES, WE KNOW THAT THEY ARE FAITHFUL BECAUSE THEY ARE CLOSURE TESTED

- are uncertainties from different groups correlated and how can we combine them?
  THE DATA UNCERTAINTIES ARE CORRELATED TO THE EXTENT THAT DIFFERENT GROUPS USE THE SAME DATASET;
  FURTHER METHODOLOGICAL UNCERTAINTIES COME FROM INFORMATION LOSS, UNCORRELATED BECAUSE DIFFERENT GROUPS USE DIFFERENT METHODOLOGY

- can we determine the best dataset and how?
  ALL EVIDENCE SUGGESTS THAT THE BEST DATASET IS THE WIDEST
  FOR SPECIFIC EXPERIMENTS, ONE CAN USE RESTRICTED EIGENVECTOR SETS, BUT THIS IS BETTER DONE A POSTERIORI, STARTING WITH A GLOBAL SET

- are there advantages/disadvantages in using eigenvectors vs. montecarlo and can we tell?
  MONTECARLOS ARE ADVATAGEOUS IN THE PRESENCE OF NONGAUSSIAN BEHAVIOR, WHICH CAN BE QUANTITATIVELY TESTED

## THEORY ISSUES

- how should one treat the charm PDF?
  THE CHARM PDF SHOULD BE FITTED IN ORDER TO AVOID A LARGE MHOU

- how should one treat the photon PDF?
  THE PHOTON PDF SHOULD BE INCLUDED AS AN EXTRA CONSTRAINT IN THE FIT VIA THE LUX PROCEDURE

- are theory (MHO) uncertainties included and should we worry about them?
  MHOU ARE NOT INCLUDED, THIS IS LIKELY NOT A PROBLEM NOW AT NNLO BUT IT WILL BE AS DATA UNCERTAINTIES GO DOWN