PARTON DISTRIBUTIONS

FOR PRECISION PHYSICS

STEFANO FORTE

UNIVERSITÀ DI MILANO & INFN

LHCP19

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SUMMARY

THE CHALLENGES OF PRECISION PHYSICS

- W MASS DETERMINATION AND PDFs
- "TENSION" VS. UNCERTAINTIES: TOP PRODUCTION
- DATA VS. METHODOLOGY

α_s: THE PITFALLS OF USING PDFs IN PRECISION ANALYSIS

- PARAMETER SPACE AND PDF SPACE
- CORRELATED REPLICAS

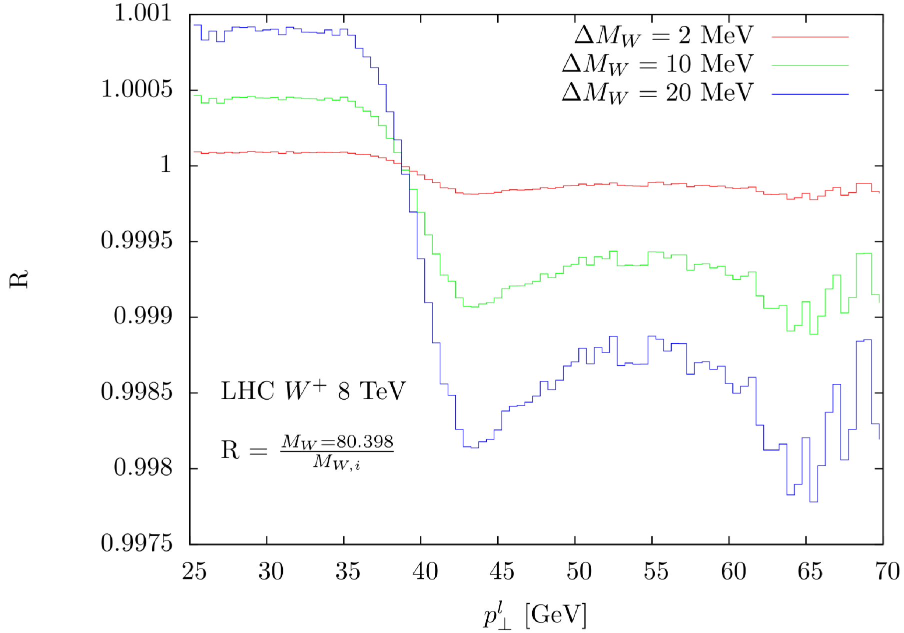
TOLERANCE: HOW ARE PDF UNCERTAINTIES DEFINED?

- $\Delta\chi^2$ AND FINITE-SIZE EFFECTS
- GAN REPLICA GENERATION

BETTER PDFs FOR PRECISION PHYSICS

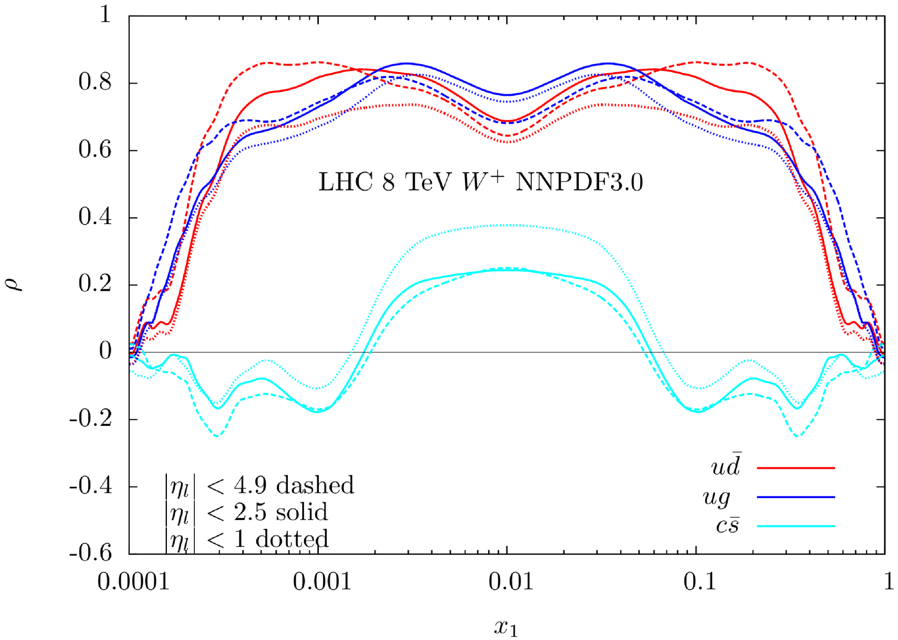
DETERMINING THE W MASS
THE TEMPLATE METHOD

p_T SHAPE VS. M_W



CORRELATION OF XSECT TO LUMI

($p_t^l = 40.5$ GEV, $p_T^W < 15$ GEV)

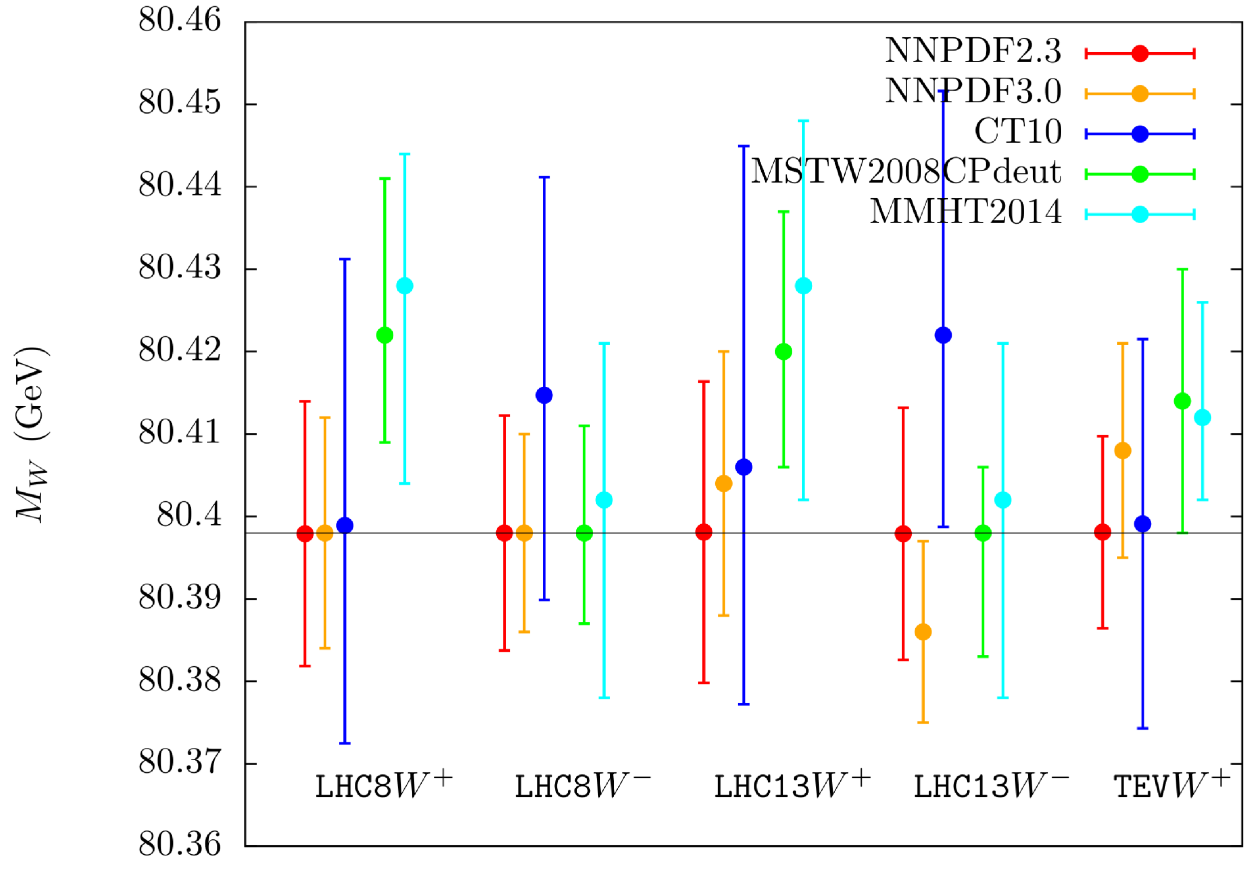


(Bozzi, Citelli, Vicini, 2015)

- TEMPLATE METHOD: W MASS EXTRACTED BY COMPARING OBSERVED SPECTRA TO THEORY: LEPTON PAIR TRANSVERSE MASS, LEPTON p_T^l
- SHAPE DEPENDS ON p_T^l: LARGER M_W, FASTER DROP AT HIGH p_T^l, LARGER XSECT AT SMALL p_T^l
- STRONG CORRELATION TO LEADING PARTON LUMIS ($u\bar{d}$ & $c\bar{s}$ FOR W^+) BUT ALSO TO NL LUMI (GLUON-INDUCED: ug)

DETERMINING THE W MASS

USING PDF4LHC15 GLOBAL SETS



(Bozzi, Citelli, Vicini, 2015), for CT confirmed by (Hussein, Isaacson, Huston, 2019)

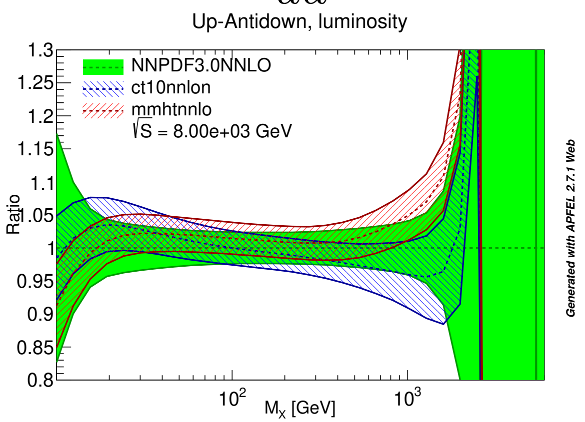
- STRONG DEPENDENCE ON PDF SET OF BOTH CENTRAL VALUE & UNCERTAINTY
- PECULIAR ASYMMETRY BETWEEN W^+ & W^-
- DIFFERENCE LARGE IN COMPARISON TO PDF UNCERTAINTY

WHAT'S GOING ON?

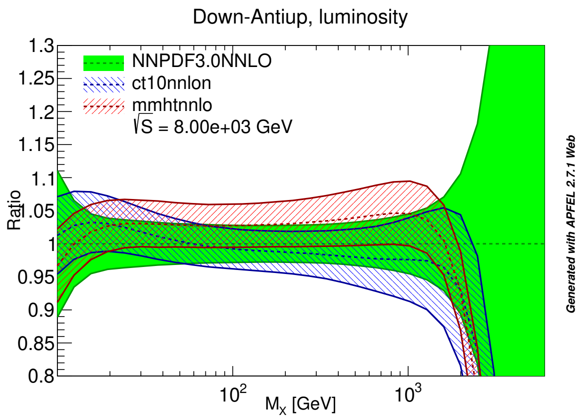
THE W MASS AND PDFs

LUMINOSITIES

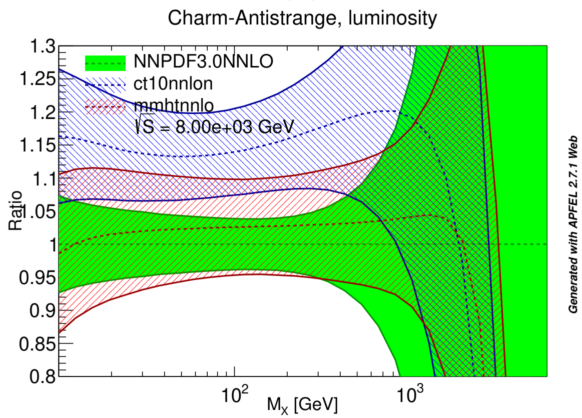
$u\bar{d}$



$d\bar{u}$



$c\bar{s}$



- FOR THE W p_T DISTRIBUTION THE HARD SCALE IS $M_X = \left(\sqrt{{p_T^W}^2 + m_W^2} + p_T\right)$
- DIFFERENT SETS HAVE SIGNIFICANTLY DIFFERENT M_X SLOPES $\Rightarrow$ DIFFERENT M_W
- UNCERTAINTIES IN $c\bar{s}$ LUMI SIGNIFICANTLY DIFFERENT

SMALL DIFFERENCES IN PDF AMPLIFIED TO LARGER DIFFERENCES IN SLOPE

- FLAVOR SEPARATION AFFECTED BY METHODOLOGY $\Rightarrow$ see plenary talk
- LHC DATA HELP $\Rightarrow$ see plenary talk

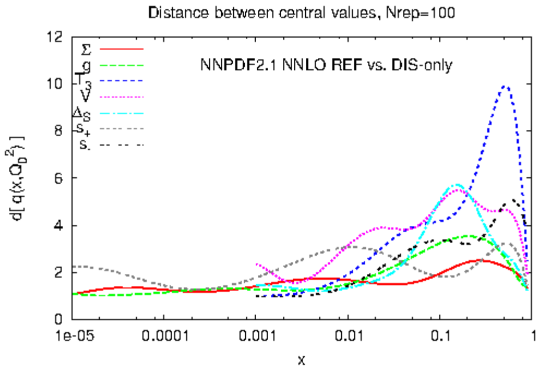
NEED BETTER PDFs!

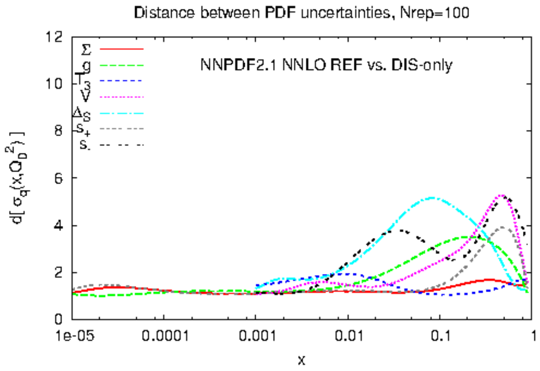
THE IMPACT OF LHC DATA

BEFORE LHC: PDFs MOSTLY DETERMINED BY DIS

NNPDF2.1 VS NNPDF2.1 DIS ONLY

DISTANCES (difference in units of st. dev.)

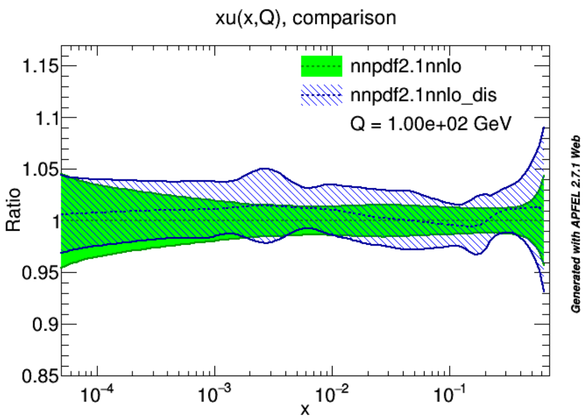




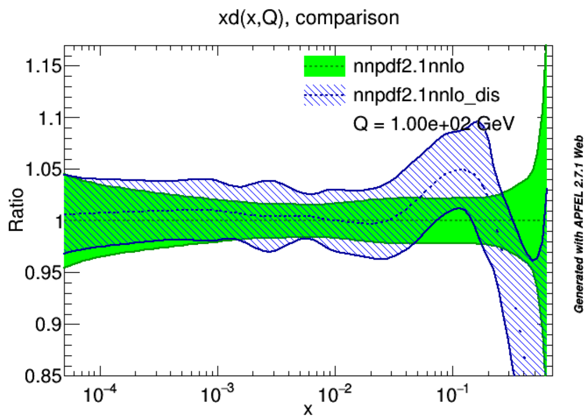
$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON

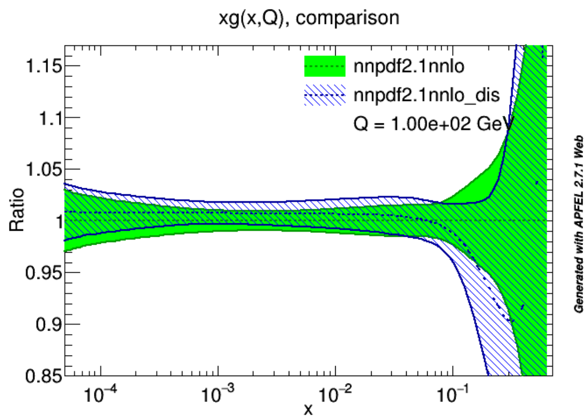
UP



DOWN



GLUON



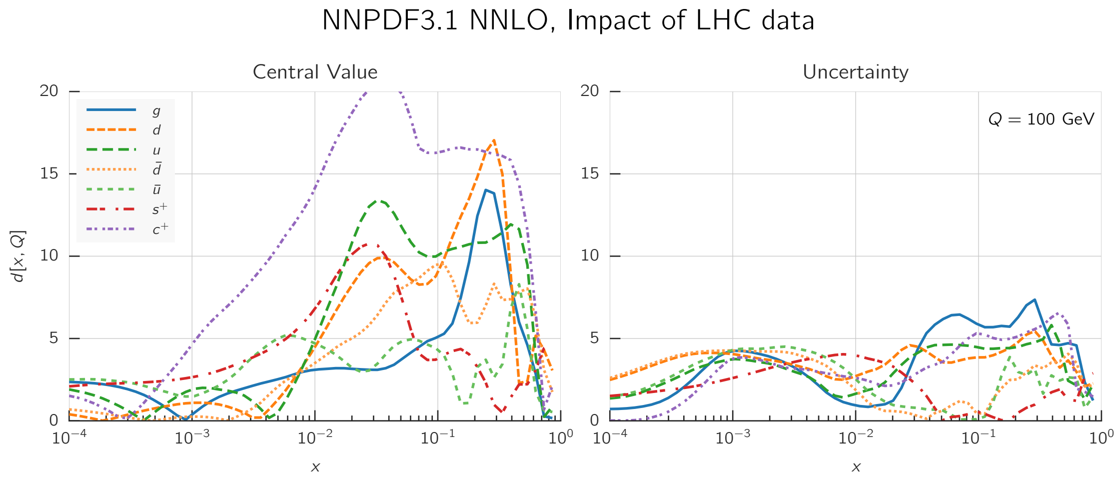
- ALL DIFFERENCES BELOW ONE SIGMA
- ONLY UP-DOWN SEPARATION SIGNIFICANTLY AFFECTED

THE IMPACT OF LHC DATA

NOW: PDFs LARGELY DETERMINED BY LHC DATA

NNPDF3.1 VS NNPDF3.1 NO LHC

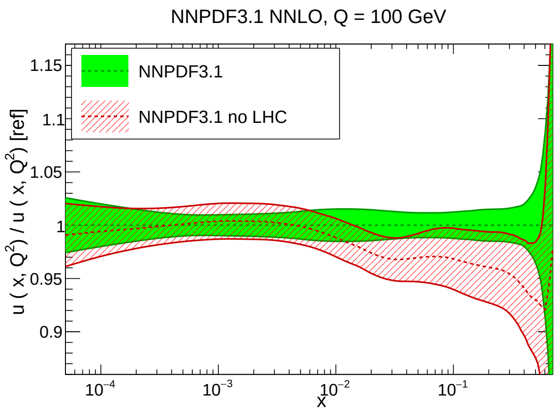
DISTANCES (difference in units of st. dev.)



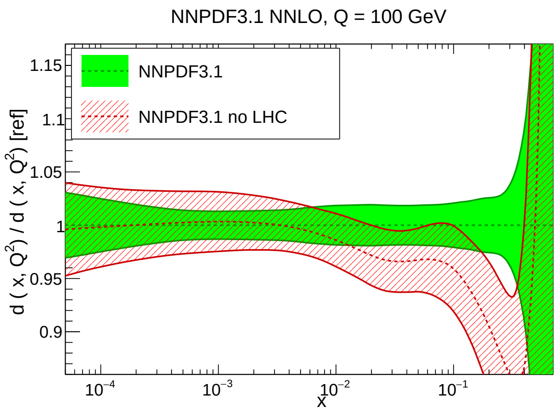
$d = 10 \Leftrightarrow$ one sigma difference

PDF COMPARISON

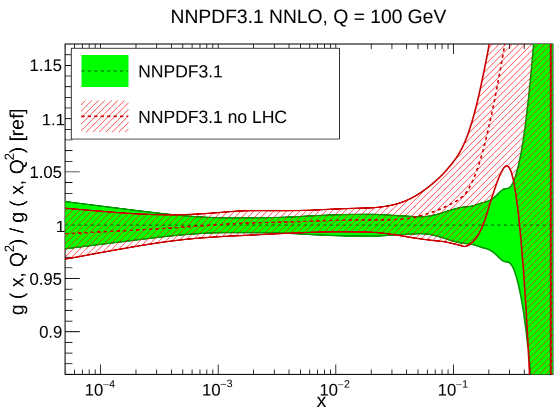
UP



DOWN



GLUON

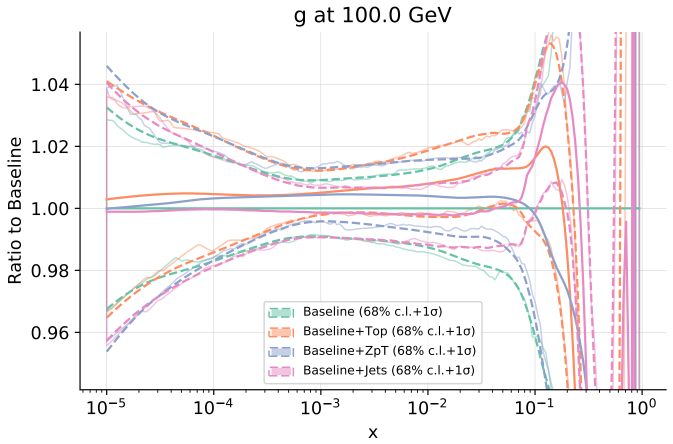


- MANY PDFs CHANGE BY MORE THAN ONE SIGMA
- BOTH FLAVOR SEPARATION & GLUON SIGNIFICANTLY AFFECTED

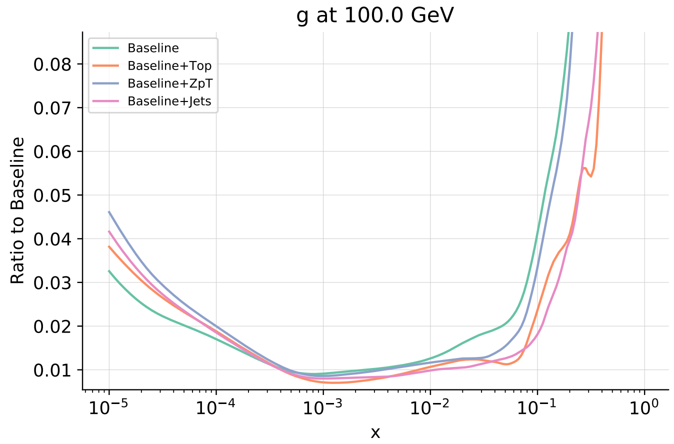
THE IMPACT OF LHC DATA
CONSISTENCY OF DIFFERENT OBSERVABLES
THE GLUON

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

CENTRAL VALUE



UNCERTAINTY



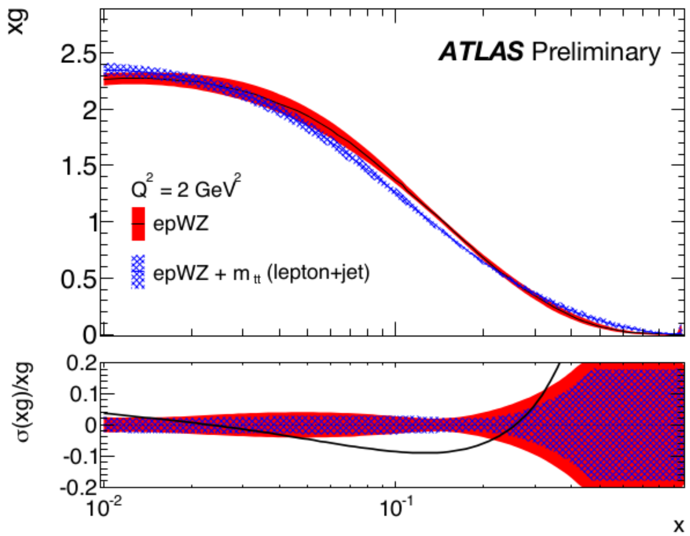
- TOP HAS LARGEST IMPACT, FOLLOWED BY JETS
- ALL LHC DATA PULL CENTRAL VALUE IN SAME DIRECTION!

CONSISTENCY OF DIFFERENT OBSERVABLES

TOP PRODUCTION AND THE GLUON

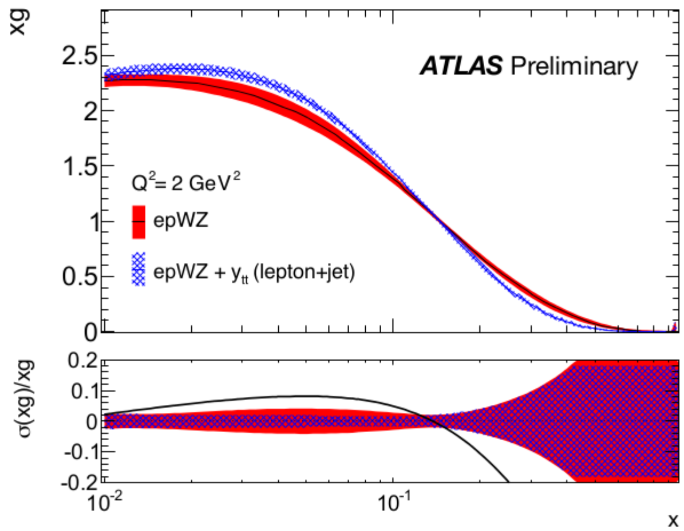
INCLUSION OF ATLAS TOP DATA IN HERA+TOP FIT (XFITTER)

HQ PAIR RAPIDITY DISTN



(a)

INVARIANT MASS DISTN.



(a)

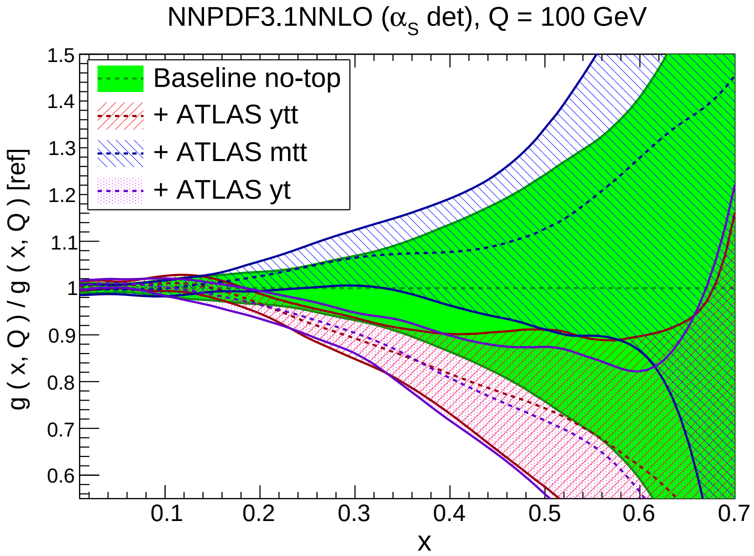
INCONSISTENCY?

CONSISTENCY OF DIFFERENT OBSERVABLES

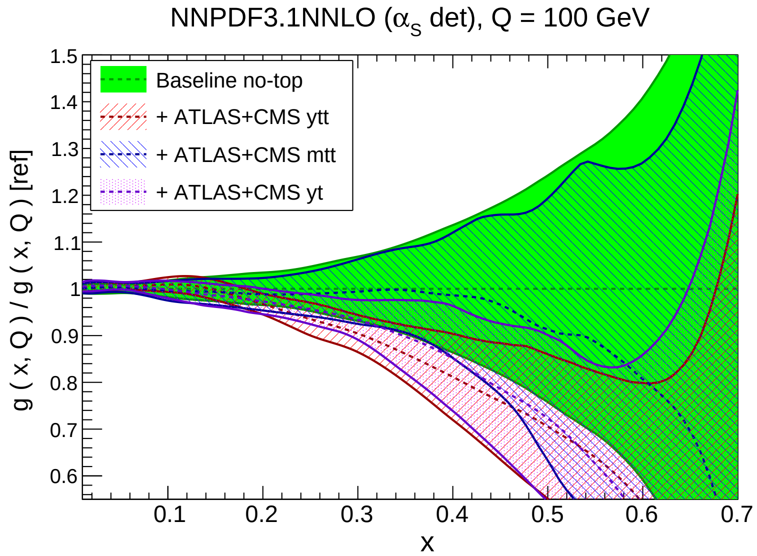
TOP PRODUCTION AND THE GLUON

INCLUSION OF ATLAS TOP DATA IN NNPDF3.1-LIKE FIT

ATLAS ONLY



ATLAS+CMS



- FOR ATLAS m_{tt} & y DISTRIBUTIONS PULL IN OPPOSITE DIRECTION
  $\Rightarrow$ COMPATIBLE WITHIN UNCERTAINTIES
- m_{tt} HAS MUCH LESS PULL
- FOR CMS, BOTH m_{tt} & y PULL IN THE SAME DIRECTION

CONSISTENCY!

LESSONS:

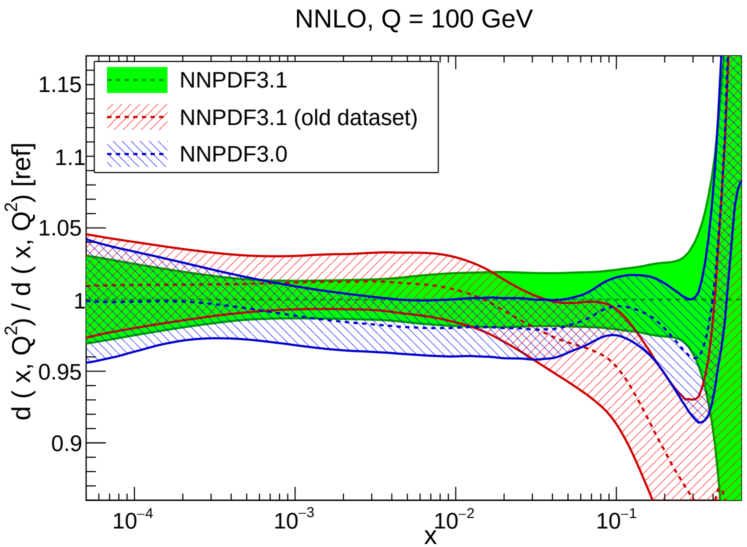
- BEWARE OF XFITTER HERA+X FITS
- IN A GLOBAL FIT, DIFFERENT DATA ALWAYS PULL IN DIFFERENT DIRECTIONS!

DATA VS. METHODOLOGY

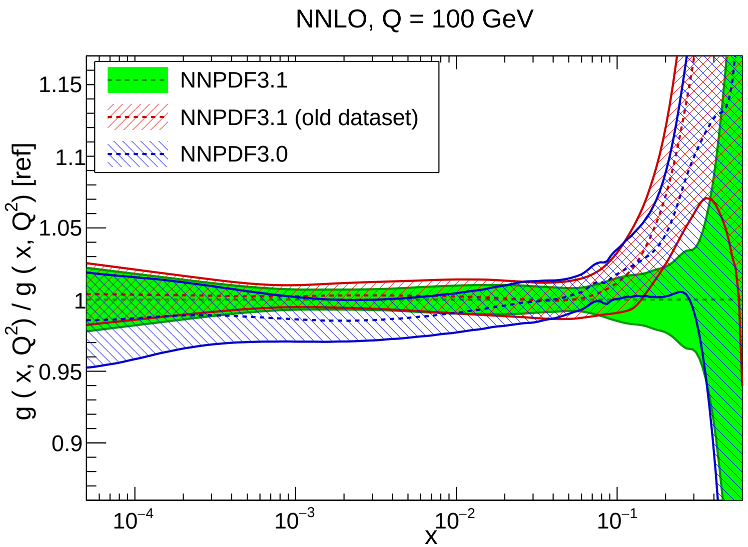
- EVEN WITH LHC DATA MAJOR METHODOLOGICAL CHOICES ⇒ SIGNIFICANT IMPACT
- EXAMPLE: HEAVY QUARKS INDEP. PARAMETRIZED ⇒ see plenary talk
- NNPDF3.1 VS NNPDF3.0: DATA AND METHODOLOGY HAVE SIMILAR IMPACT

NNPDF3.0 VS. NNPDF3.1 VS. NNPDF3.1 W/ NNPDF3.0 DATASET

DOWN



GLUON

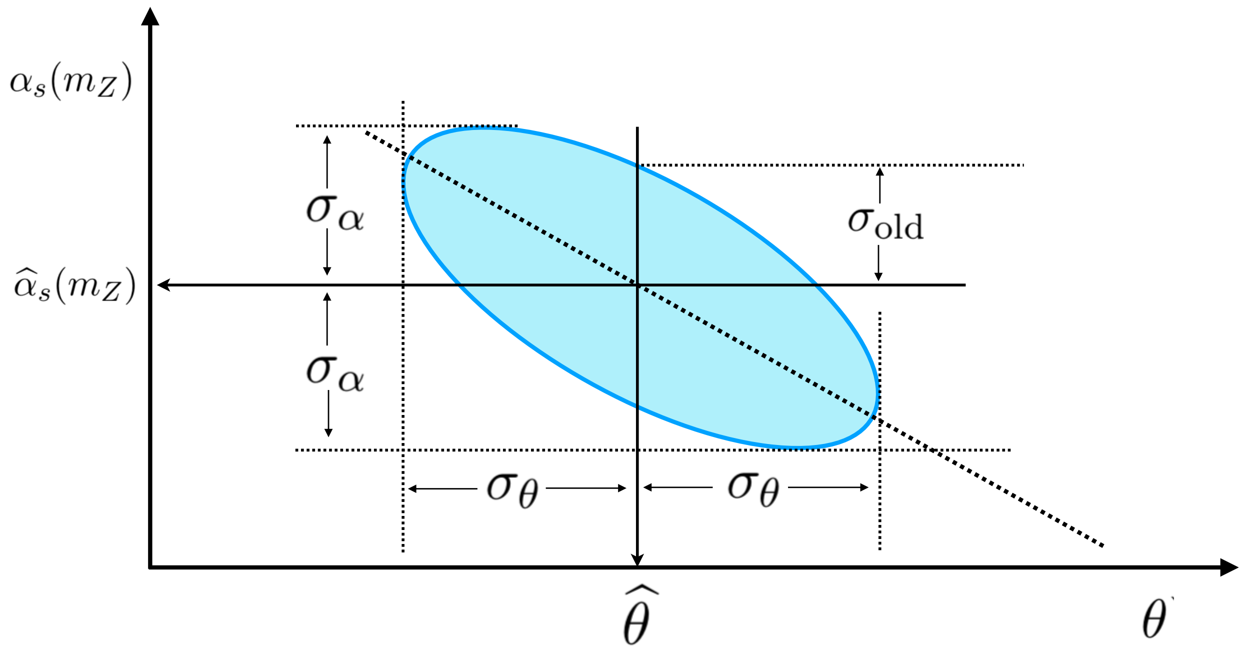


LHC DATA+ METHODOLOGICAL IMPROVEMENTS ⇒ BETTER PDFS

SM parameters from PDF-dependent observables

α_s DETERMINATION

WHAT'S THE PROBLEM?

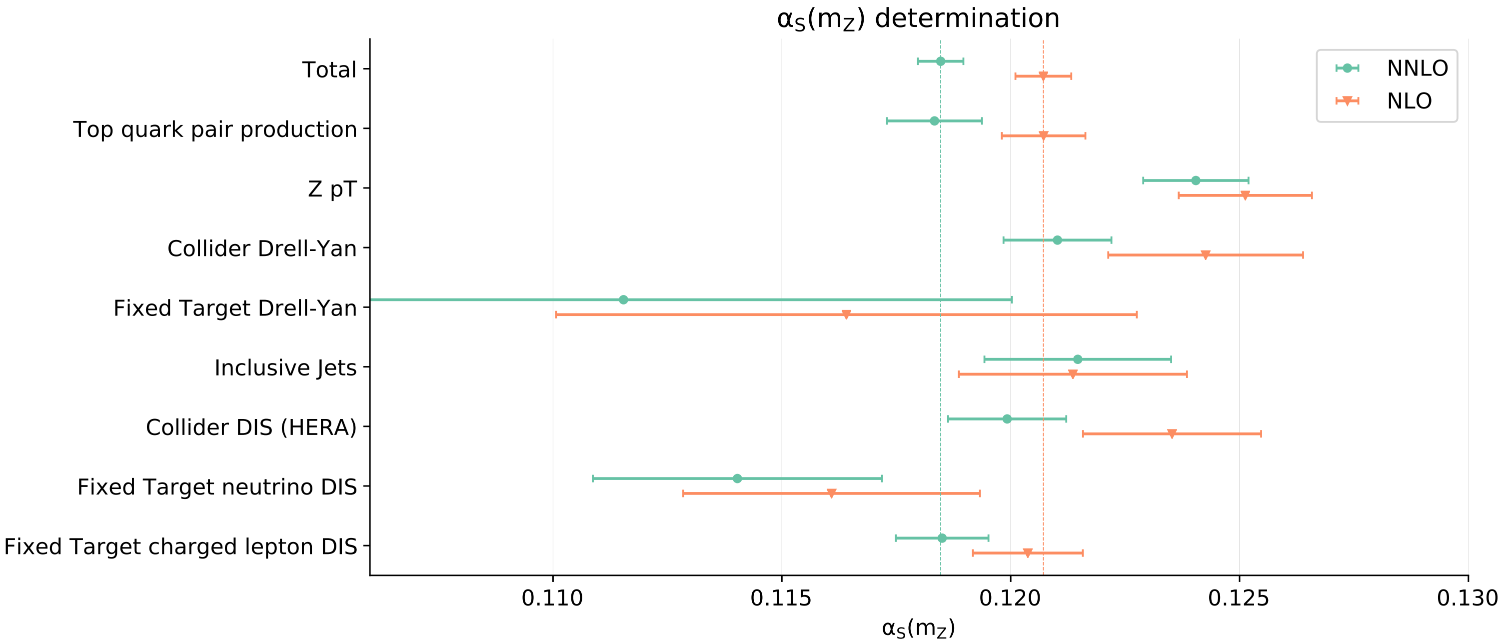


- MINIMUM DETERMINED ALONG THE "BEST PDF" LINE $\Rightarrow \sigma_{\rm old}$ FOR HIGHLY CORRELATED VARIABLES & UNEQUAL SEMIAXES, MAY UNDERESTIMATE ONE-σ ERROR $\Rightarrow \sigma_\alpha$

NEED SIMULTANEOUS MINIMIZATION IN (PDF, α_s) SPACE!

α_s FROM A GLOBAL FIT

PULLS FROM DATA SUBSETS



PULLS DON'T ADD TO ZERO?!

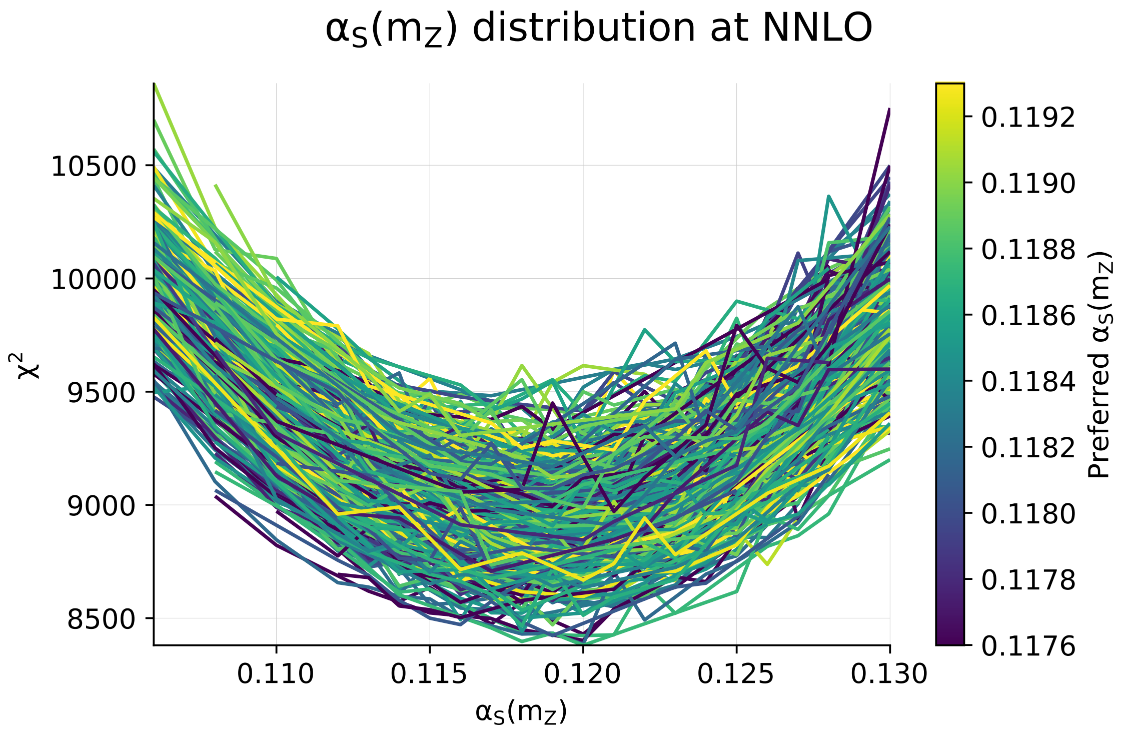
- PARTIAL VALUES ARE NOT PARTIAL BEST-FITS
- PDF SPACE HUGE $\Rightarrow$ MINIMUM AT DIFFERENT α_s VALUE WHEN INCLUDING NEW DATA, AGREEMENT WITH OTHER DATA ESSENTIALLY UNAFFECTED

$\Rightarrow$ CANNOT DETERMINE α_s WITHOUT ALSO DETERMINING THE PDF

THE CORRELATED REPLICA METHOD
NNPDF3.1 (2018)

- NNPDF METHOD $\Rightarrow$ EACH PDF REPLICA FITTED BY GA TO DATA REPLICA
- IDEALLY PERFORM GENETIC MINIMIZATION IN (PDF, α_s) SPACE
- PROBLEM THEORY PREDICTION $\Leftrightarrow$ PRECOMPUTED GRIDS DEPEND ON α_s $\Rightarrow$ DIFFICULT TO TREAT AS CONTINUOUS PARAMETER
- SOLUTION DETERMINE BEST-FIT PDF REPLICA TO EACH DATA REPLICA FOR SEVERAL (DISCRETE) α_s VALUES: C-REPLICA
  - EACH C-REPLICA $\Rightarrow$ χ^2 PROFILE $\Rightarrow$ α_s VALUE
  -

ENSEMBLE OF PARABOLAS



THE CORRELATED REPLICA METHOD
NNPDF3.1 (2018)

- NNPDF METHOD $\Rightarrow$ EACH PDF REPLICA FITTED BY GA TO DATA REPLICA
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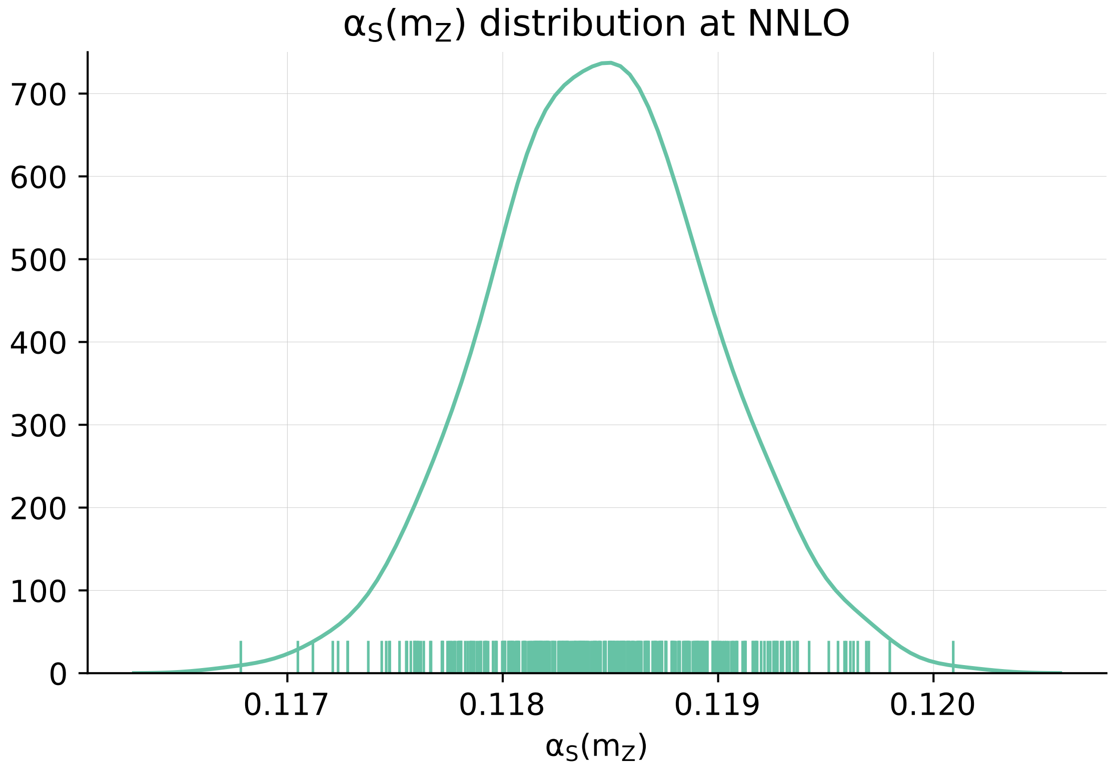
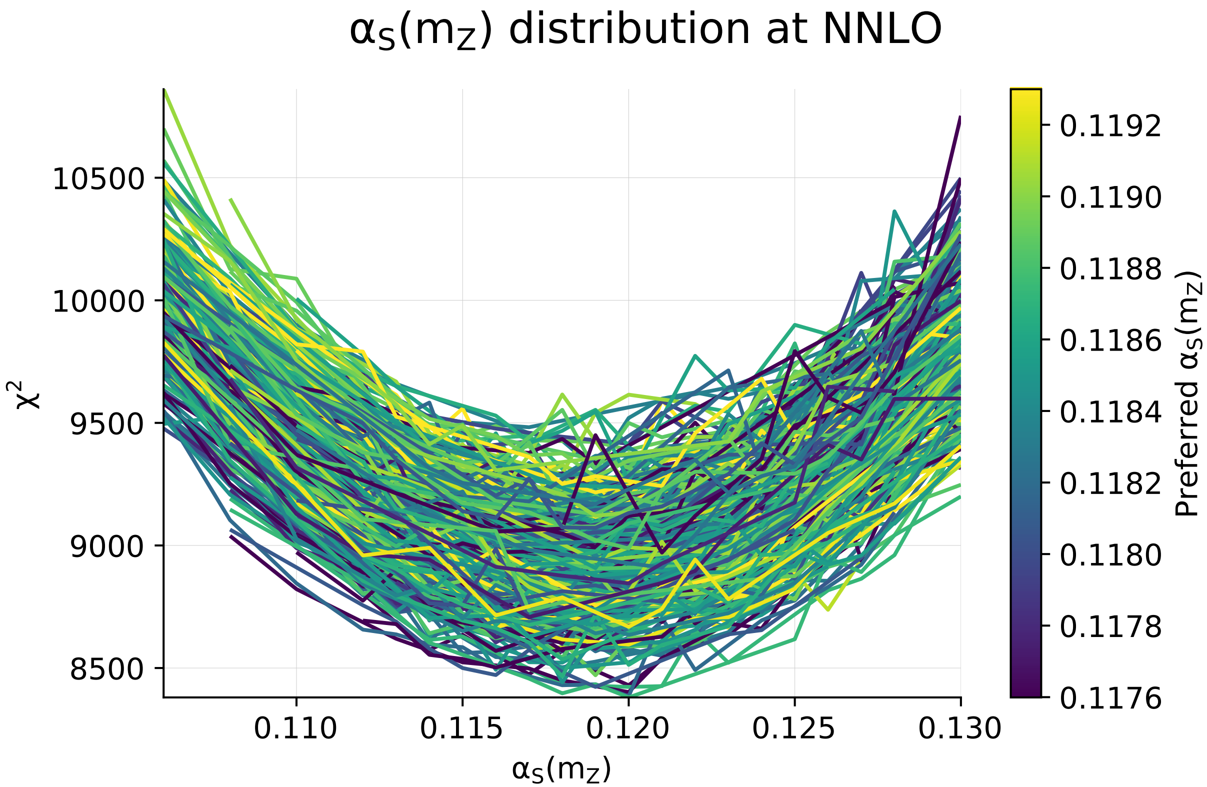
  - EACH C-REPLICA $\Rightarrow$ χ^2 PROFILE $\Rightarrow$ α_s VALUE
  - EACH C-REPLICA $\Rightarrow$ BEST-FIT α_sREPLICA

ENSEMBLE OF α_s VALUES



α_s FROM CORRELATED REPLICAS



- NNPDF3.1 DATASET (ONLY NNLO JET DATA) $\Rightarrow$ 3979 DATAPOINTS
- 400 C-REPLICAS FOR 21 α_s VALUES: $\alpha_s(M_z) = 0.106, 0.108, 0.102, 0.112, 0.113, 0.114, 0.115, 0.116, 0.117, 0.118, 0.119, 0.120, 0.121, 0.122, 0.123, 0.124, 0.125, 0.126, 0.127, 0.128, 0.130$
- EXPERIMENTAL UNCERTAINTY $\Leftrightarrow$ STANDARD DEVIATION OVER REPLICA SAMPLE

THE RESULT

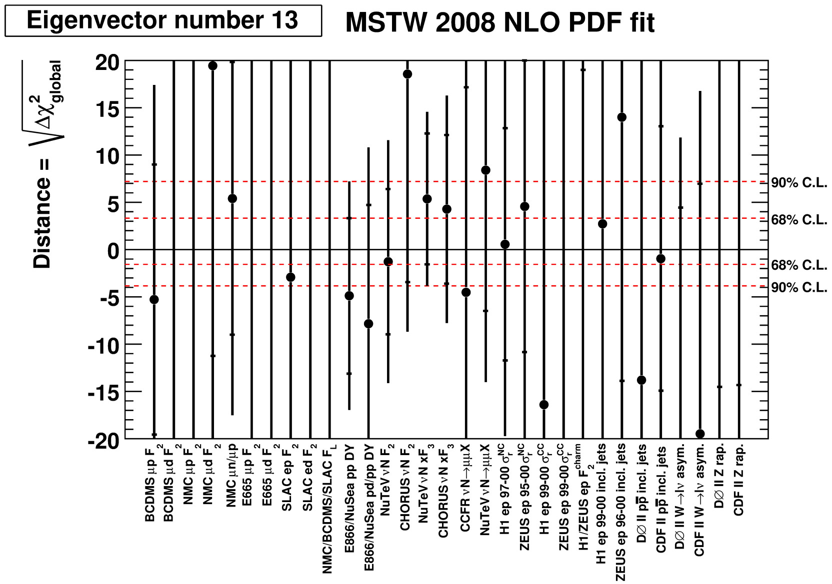
$$\alpha_s^{\mathrm{NNLO}}(M_Z) = 0.11845 \pm 0.00052^{\mathrm{exp}} \ (0.4\%)$$

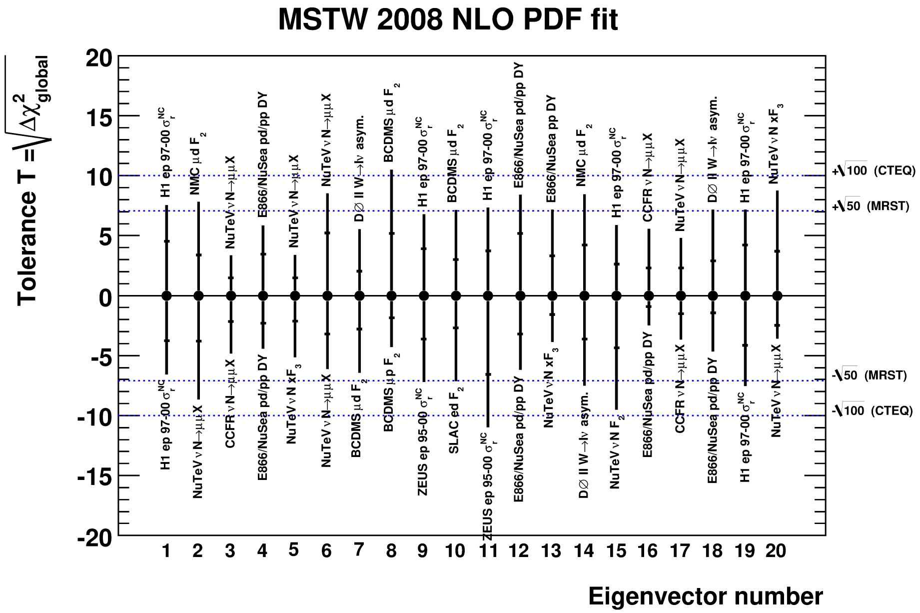
THE MEANING OF PDF UNCERTAINTIES

PDF UNCERTAINTIES: TOLERANCE (MMHT-CT)

GLOBAL MSTW TOLERANCE

MSTW TOLERANCE PLOT FOR 13TH EIGENVEC.





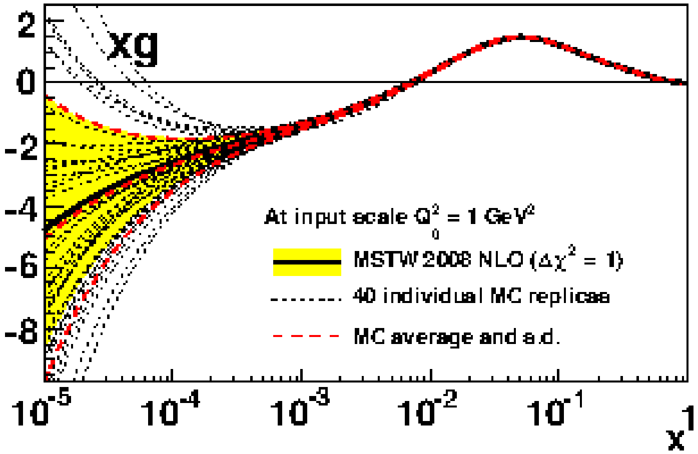
- (MSTW/MMHT) FOR EACH EIGENVECTOR IN PARAMETER SPACE DETERMINE CONFIDENCE LIMIT FOR THE DISTRIBUTION OF BEST-FITS OF EACH EXPERIMENT
- RESCALE $\Delta\chi^2 = T$ INTERVAL SUCH THAT CORRECT CONFIDENCE INTERVALS ARE REPRODUCED
- SIMILAR PROCEDURE ADOPTED BY CTEQ

WHAT ABOUT NNPDF?

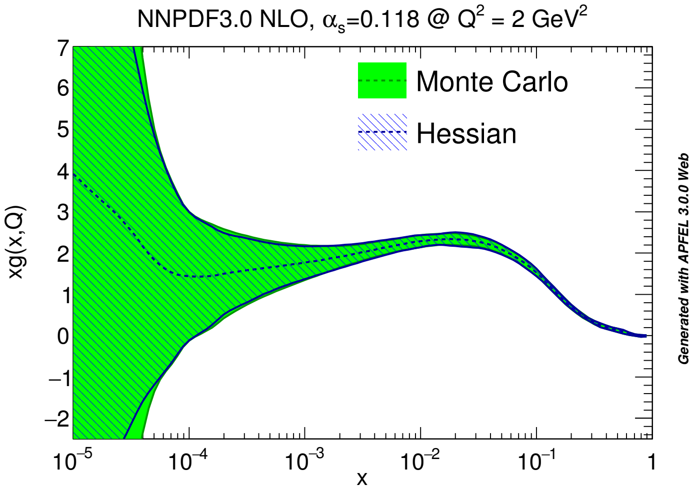
MC ⇔ HESSIAN

TWO DIFFERENT REPRESENTATIONS OF PDF UNCERTAINTIES

- TO CONVERT HESSIAN INTO MONTECARLO GENERATE MULTIGAUSSIAN REPLICAS IN PARAMETER SPACE
- ACCURATE WHEN NUMBER OF REPLICAS SIMILAR TO THAT WHICH REPRODUCES DATA



(Thorne, Watt, 2012)



(Carrazza, SF, Kassabov, Rojo, 2015)

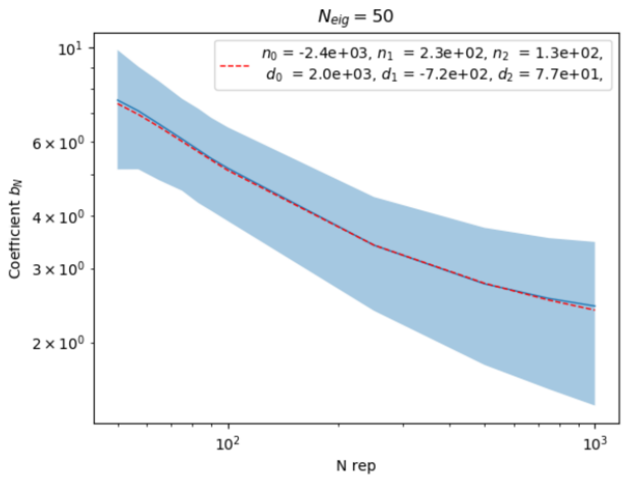
- TO CONVERT MONTE CARLO INTO HESSIAN, SAMPLE THE REPLICAS $f_i(x)$ AT A DISCRETE SET OF POINTS & CONSTRUCT THE ENSUING COVARIANCE MATRIX
- EIGENVECTORS OF THE COVARIANCE MATRIX AS A BASIS IN THE VECTOR SPACE SPANNED BY THE REPLICAS BY SINGULAR-VALUE DECOMPOSITION
- NUMBER OF DOMINANT EIGENVECTORS SIMILAR TO NUMBER OF REPLICAS ⇒ ACCURATE REPRESENTATION

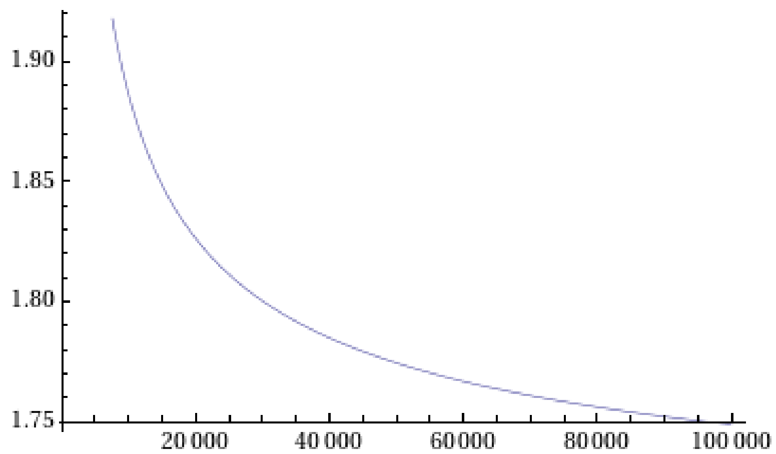
WHAT IS THE NNPDF "TOLERANCE"?

- PERFORM HESSIAN CONVERSION OF NNLO NNPDF3.1 PDFS
  50 OR 100 EIGENVECTORS
- DETERMINE χ^2 ALONG EACH EIGENVECTOR DIRECTION
- FIT A QUARTIC POLYNOMIAL
- STUDY DEPENDENCE ON
  NONGAUSSIANITY, NUMBER OF REPLICAS, NUMBER OF EIGENVECTORS,...

FINITE-SIZE EFFECTS

$\Delta\chi^2 = T^2$ VS NUMBER OF REPLICAS



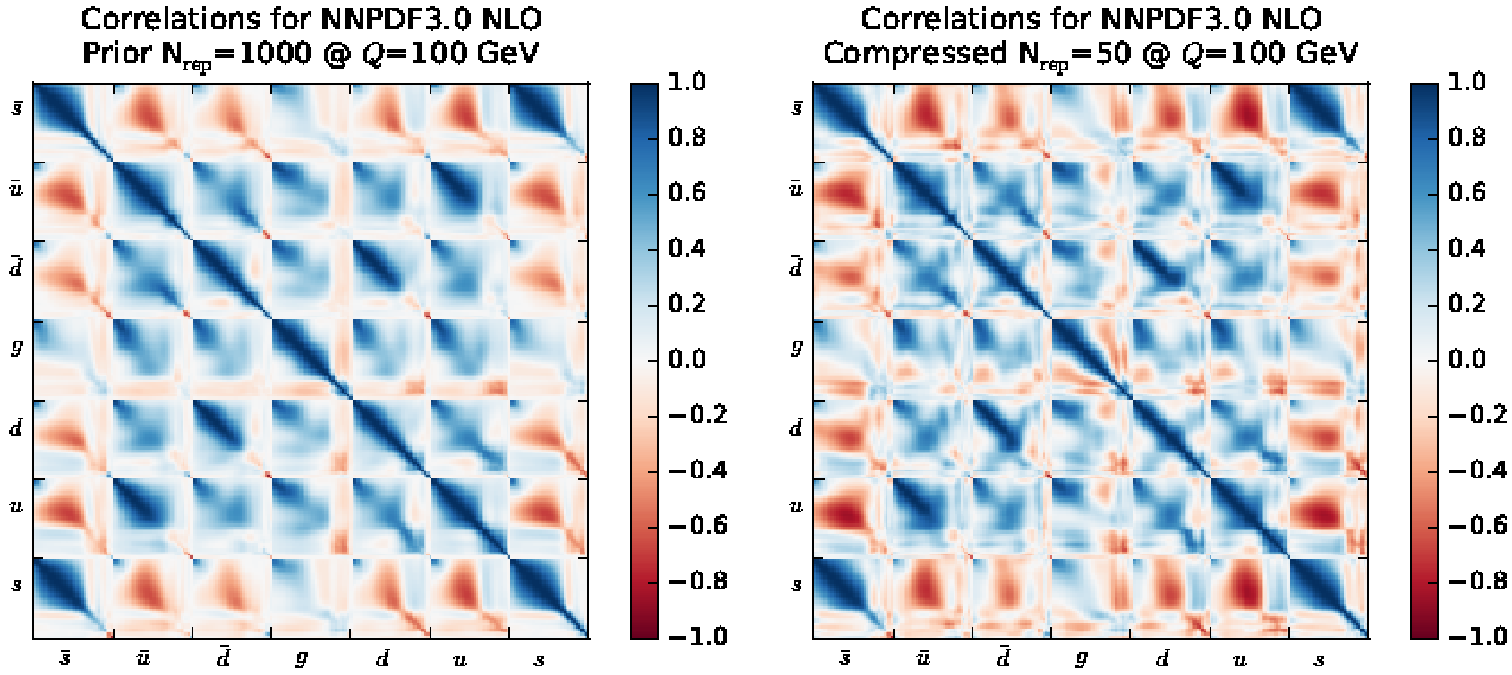


(Talon, MS thesis, 2019)

- NO SIGNIFICANT NONGAUSSIANITIY, DEVIATION FROM PARABOLIC,...
- SIGNIFICANT DEPENDENCE ON NUMBER OF REPLICAS
- ASYMPTOTIC TOLERANCE $T = 1.3 \pm 0.3$; $\Delta\chi^2 = 1.7 \pm 0.7$
- FOR $N_{\rm rep} = 100$, $T = 2.3$, EVEN FOR $N_{\rm rep} = 1000$, $T = 1.6$

DO WE HAVE TO FIT 10000 REPLICAS? DO WE HAVE TO USE 10000 REPLICAS?

SOLVING THE PROBLEM....
MONTECARLO COMPRESSION



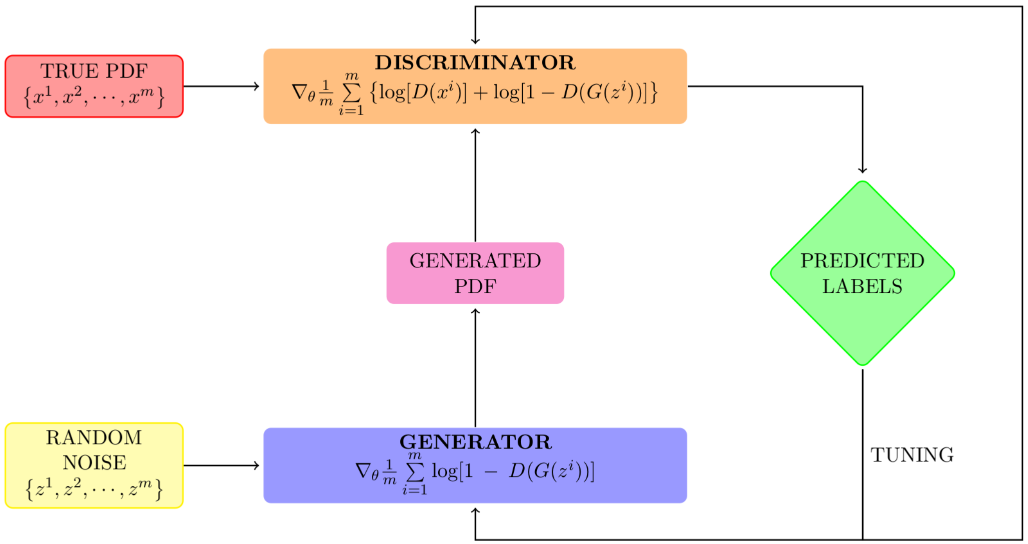
(Carrazza, Latorre, Kassabov, Rojo, 2015)

- START WITH LARGE REPLICA SAMPLE
- SELECT (BY GENETIC ALGORITHM) SUBSET OF REPLICAS $\Rightarrow$ STATISTICAL FEATURES OPTIMIZED TO PRIOR
- FOR ALL PDFs ON A GRID OF POINTS
  MINIMIZE DIFFERENCE OF FIRST FOUR MOMENTS, CORRELATIONS; OUTPUT OF KOLMOGOROV-SMIRNOV TEST (NUMBER OF REPLICAS BETWEEN MEAN AND σ, 2σ, INFINITY)
- 50 COMPRESSED REPLICA REPRODUCE 1000 REPLICA SET TO PRECENT ACCURACY

SOLVING THE PROBLEM....
GAN REPLICA GENERATION

- CAN WE REDUCE THE NUMBER OF COMPRESSED REPLICAS WITHOUT LOSS OF INFORMATION? SOLUTION FOR USER
- CAN WE INCREASE THE NUMBER OF REPLICAS WITHOUT REFITTING? SOLUTION FOR PDF FITTER

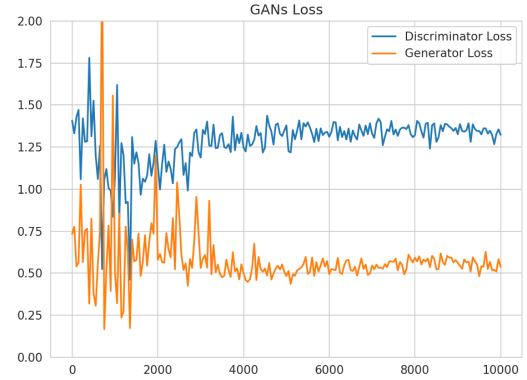
GENERATIVE ADVERSARIAL NETWORKS



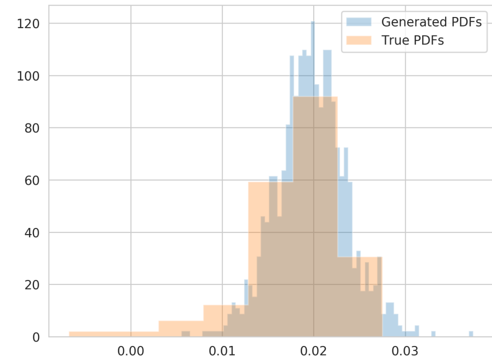
- TRAIN A NETWORK TO SIMULATE THE TRUE DISTRIBUTION (GENERATOR)
- TRAIN A NETWORK TO DISCRIMINATE TRUTH FROM SIMULATION (DISCRIMINATOR)
- TRAIN THE GENERATOR TO TRICK THE DISCRIMINATOR

SOLVING THE PROBLEM....
GAN REPLICA GENERATION

GAN TRAINING



UP VALENCE AT FIXED x

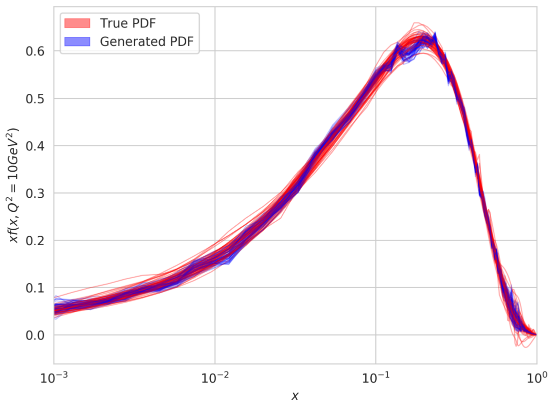


(Carrazza, Rabemananjara, preliminary)

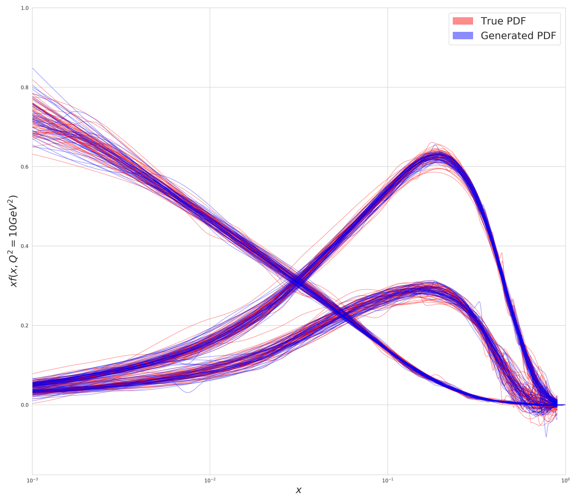
- 1D GAN: REPRODUCE THE INFORMATION IN THE UNDERLYING REPLICA SET, BUT NO GAIN (WIGGLY REPLICAS)
  $\Rightarrow$ REDUCE THE NUMBER OF COMPRESSED REPLICA WITH FIXED NUMBER OF FITTED REPLICAS W/O INFORMATION LOSS
- 2D GAN: COMBINE CORRELATED INFORMATION FROM UNDERLYING REPLICA SET INFERRING THE TRUE UNDERLYING DISTTRIBUTION
  $\Rightarrow$ REDUCE THE NUMBER OF INPUT REPLICAS W/O INFORMATION LOSS

N3PDF
Machine Learning • PDFs • QCD

ONE-DIMENSIONAL



TWO-DIMENSIONAL



OUTLOOK

SUMMARY

USE OF PDFs FOR PRECISION PHYSICS

DOES NOT ALLOW SHORTCUTS

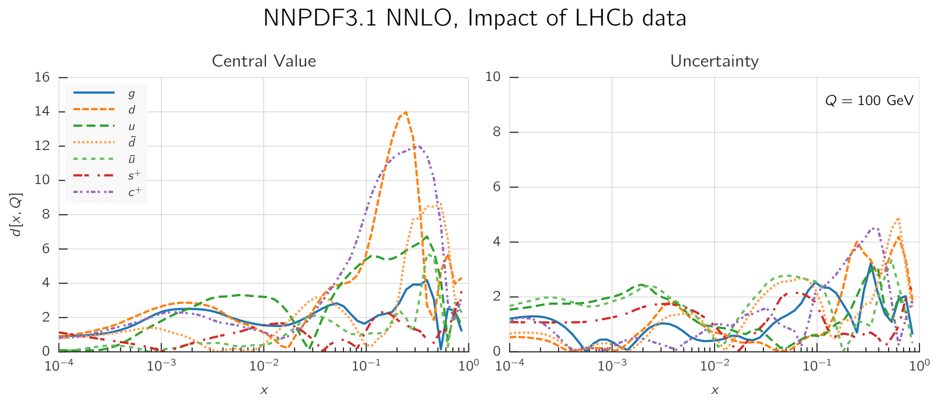
- CANNOT PICK THE DATASET
- MUST OPTIMIZE STATISTICS
- REMEMBER PDFS LIVE IN A SPACE OF FUNCTIONS

EXTRAS

THE IMPACT OF LHC DATA
FLAVOR SEPARATION

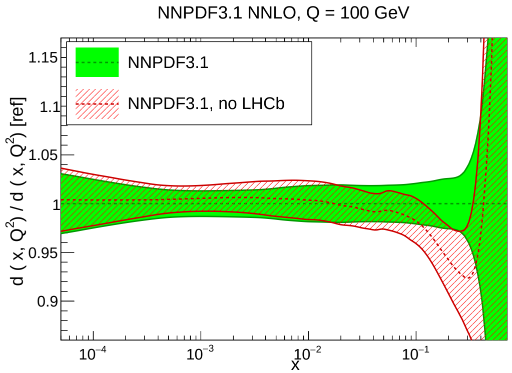
- BEFORE LHC $\Rightarrow$ CC DIS, TEV FIXED-TARGET DY, W ASYM.
- AFTER LHC $\Rightarrow$ WIDE RANGE OF W, Z PRODUCTION DATA

IMPACT OF LHCB
DISTANCES (difference in units of st. dev.)

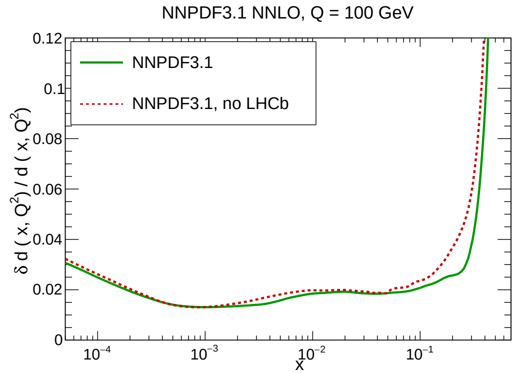


PDF COMPARISON: DOWN

CENTRAL VALUE



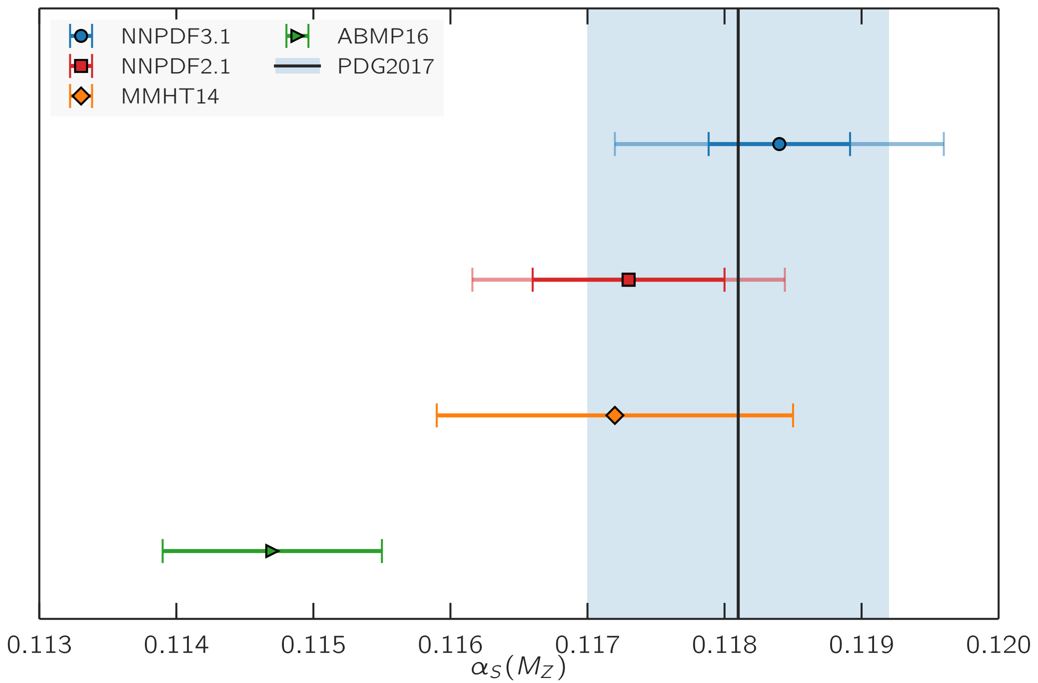
UNCERTAINTY



- SIZABLE SHIFT OF CENTRAL VALUE BY ALMOST ONE SIGMA
- LARGE x UNCERTAINTY DOWN BY LARGE FACTOR!

α_s FINAL RESULT & COMPARISON

$$\alpha_s^{\mathrm{NNLO}}(M_Z) = 0.1185 \pm 0.0005^{\mathrm{exp}} \pm 0.0001^{\mathrm{meth}} \pm 0.0011^{\mathrm{th}} = 0.1185 \pm 0.0012\ (1\%)$$

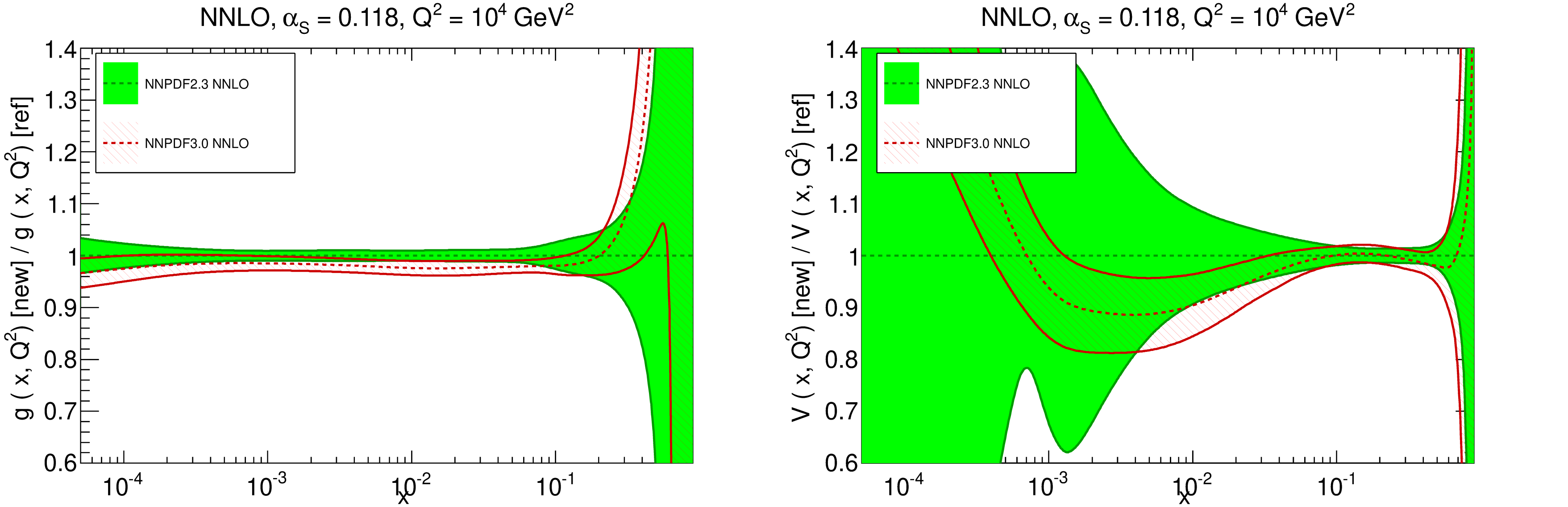


- SIGNIFICANTLY SMALLER EXP. UNCERTAINTY IN COMPARISON TO PREVIOUS NNPDF2.1 DETERMINATION (DESPITE MORE CONSERVATIVE ESTIMATE)
- SOMEWHAT LARGER CENTRAL VALUE THAN MMHT

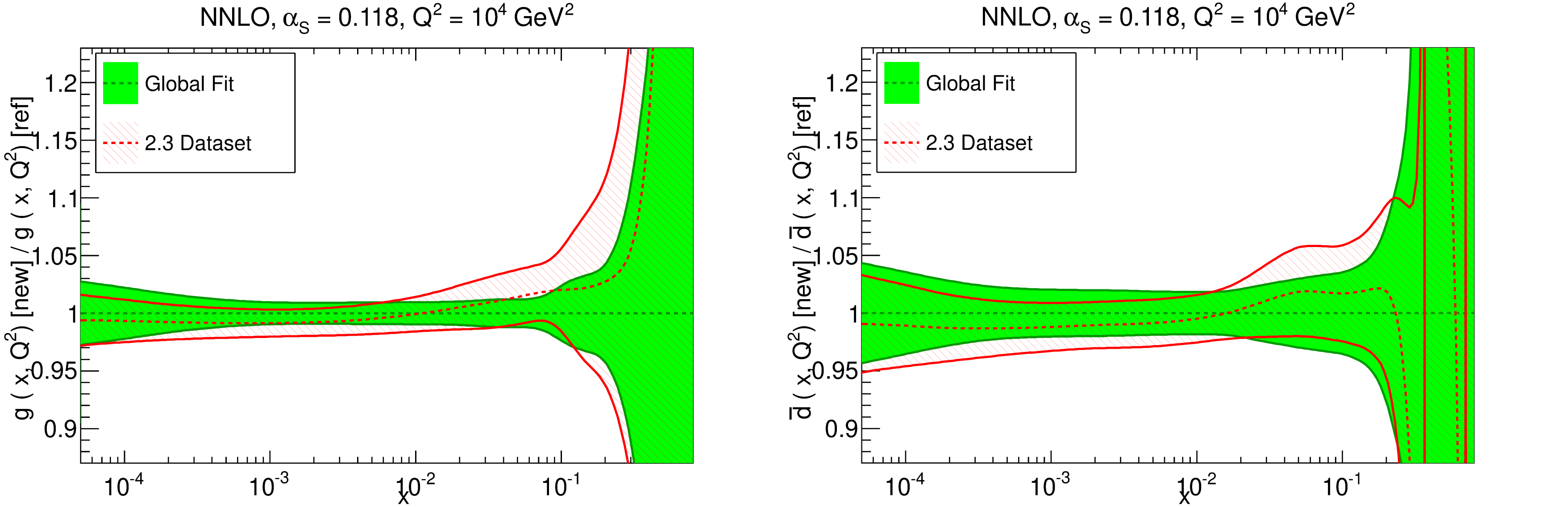
CONSISTENCY VS INFORMATION LOSS

- 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



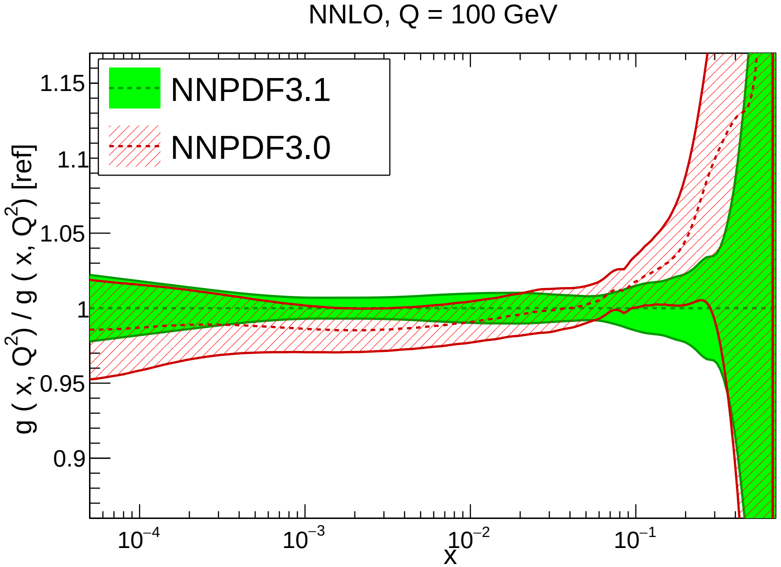
NNPDF 3.0 DEFAULT VS 2.3-LIKE DATASET: GLUON & ANTIDOWN

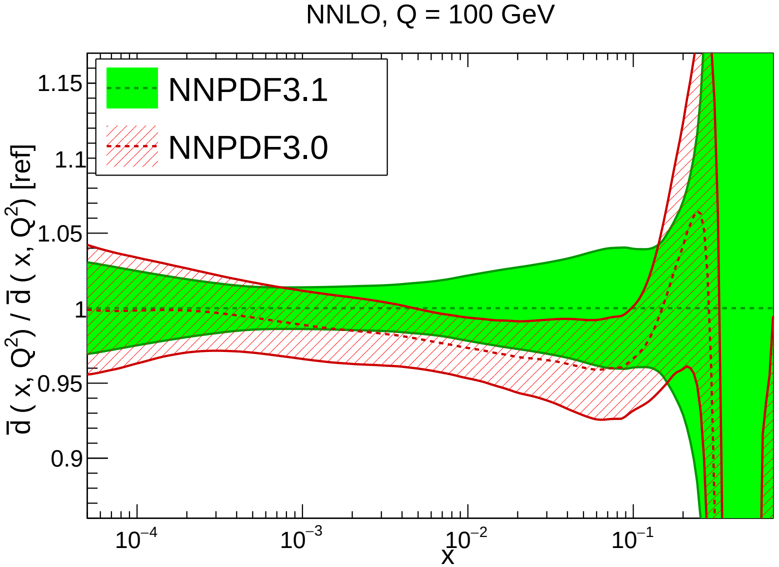


CONSISTENCY VS INFORMATION LOSS

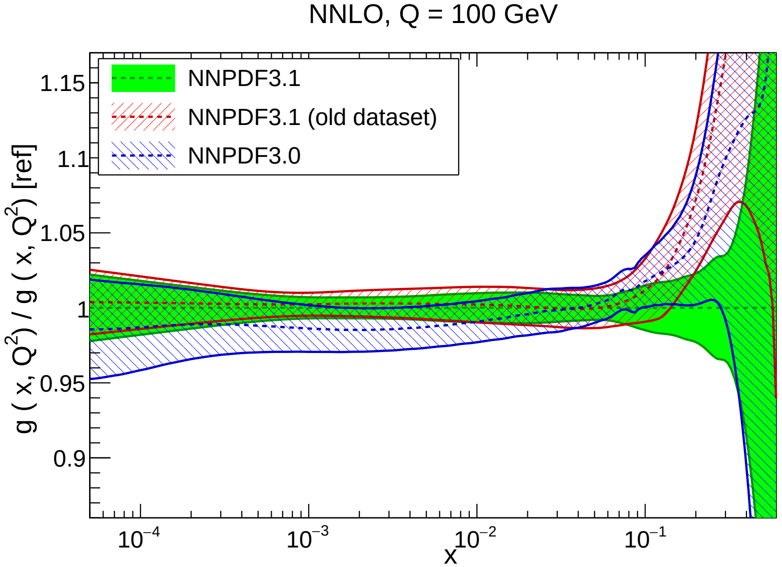
- PDF SETS MUST BE BACKWARD CONSISTENT (THEY ARE)
- PDF UNCERTAINTY MIGHT IMPROVE EVEN WITH UNCHANGED DATASET (THEY DO)

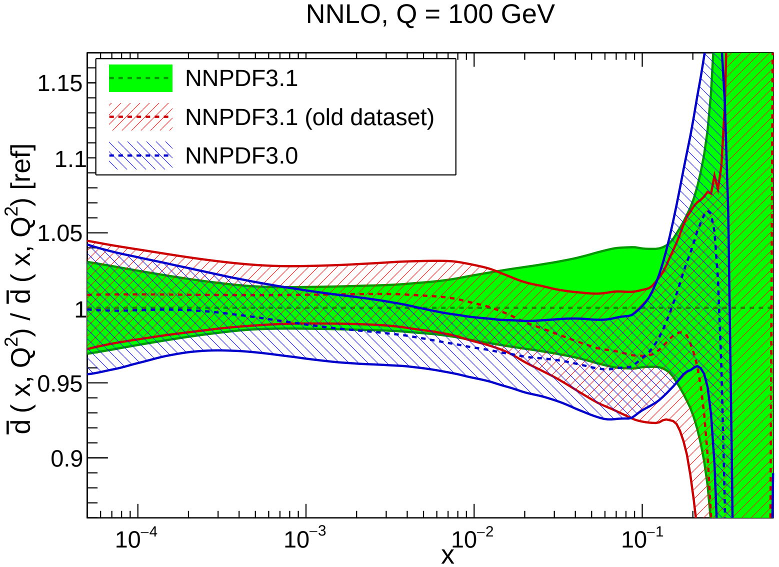
NNPDF 3.1 VS 3.0: GLUON & ANTIDOWN





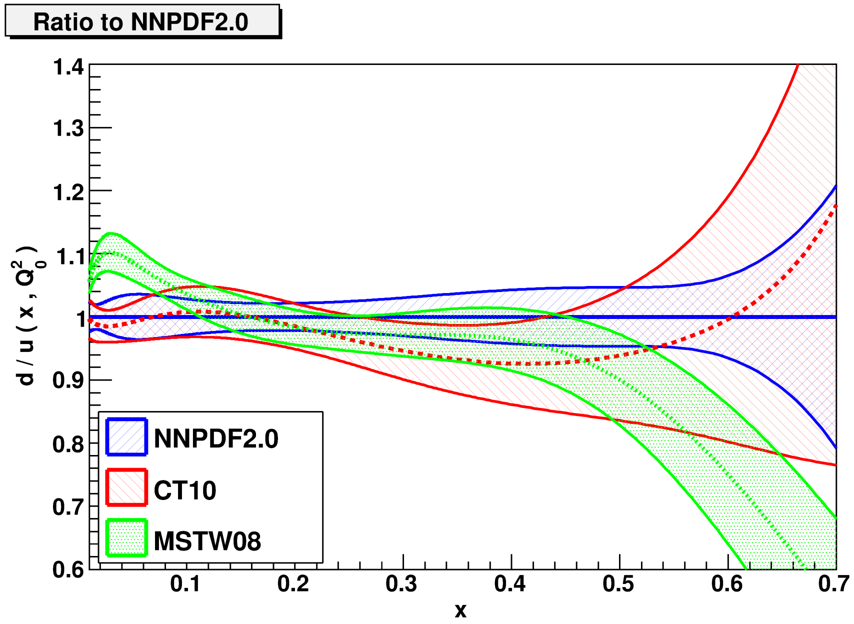
NNPDF 3.1 DEFAULT VS 3.0-LIKE DATASET



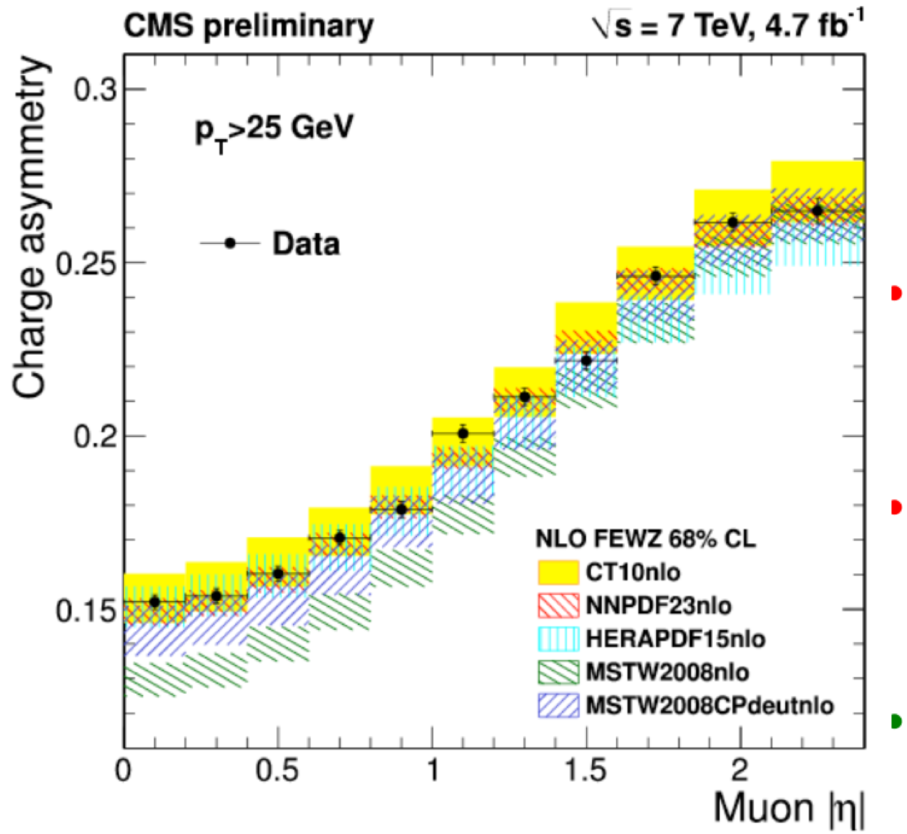


EXAMPLE OF DATA-DRIVEN PROGRESS
MSTW/MMHT: THE d/u RATIO

THE d/u RATIO



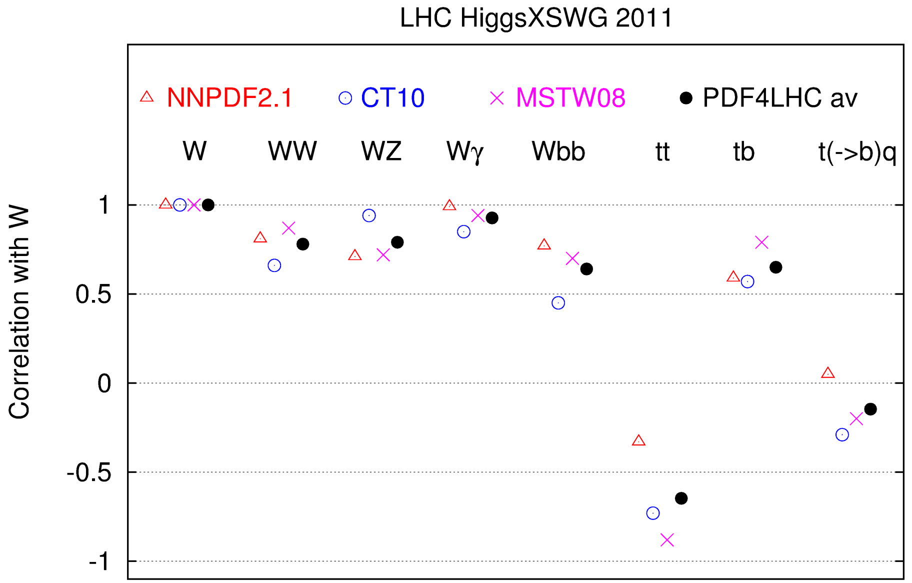
THE CMS W ASYMMETRY



- LONG-STANDING DISCREPANCY IN THE d/u RATIO BETWEEN MSTW AND OTHER GLOBAL FITS
- RESOLVED BY W ASYMMETRY DATA
- EXPLAINED BY INSUFFICIENTLY FLEXIBLE PDF PARAMETRIZATION $\Rightarrow$ FIXED IN MSTW08DEUT/MMHT

CORRELATING PDFS

CORRELATION BETWEEN HIGGS SIGNAL AND BACKGROUND (HXSWG, YR2)



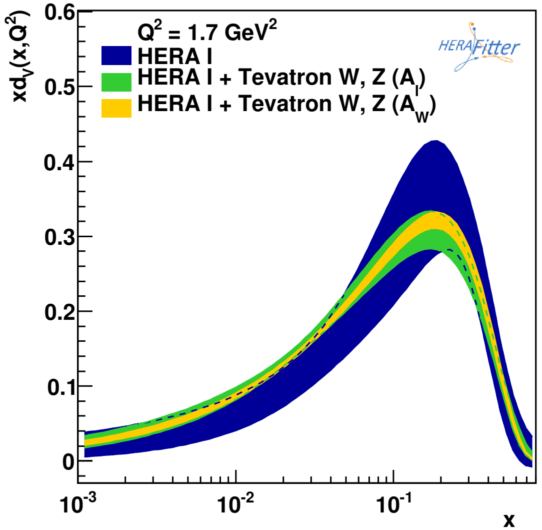
- CORRELATION BETWEEN PROCESSES AND PDFS, PROCESSES AND PROCESSES, PDF AND PDFS TRIVIAL TO COMPUTE $\Rightarrow$ NO NEED TO RUN DEDICATED FITS
- PREVIOUS EXERCISES SUGGEST VERY LARGE CORRELATION (SHOULD BE 100% FOR SAME DATA)
- IN PDF4LHC15 CORRELATION ASSUMED TO BE 100%: SIMPLE AVERAGE WEIGHTED AVERAGE DUBIOUS AND DANGEROUS
  - PDFS W/ SMALLER UNCERTANITY GET LARGER WEIGHT UNCERTAINTY DOMINATED BY METHODOLOGY $\Rightarrow$ SMALLER UNCERTAINTY COULD JUST BE BIAS!
  - UNCERTAINTY REDUCED IF CORRELATION LESS THAN 100% CAN WE BELIEVE IT IN THE ABSENCE OF NEW INFORMATION?

WHAT ABOUT XFITTER?

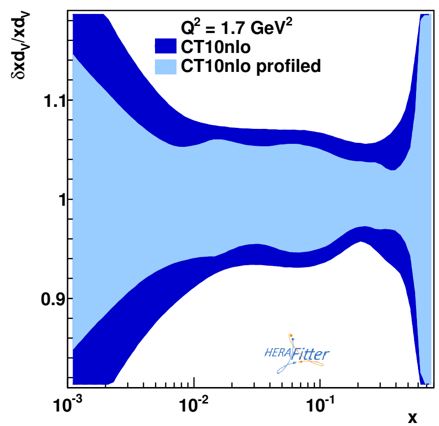
- OFTEN USED TO ASSESS IMPACT OF X IN "HERA+X" FITS

IMPACT OF THE TEVATRON W ASYMMETRY

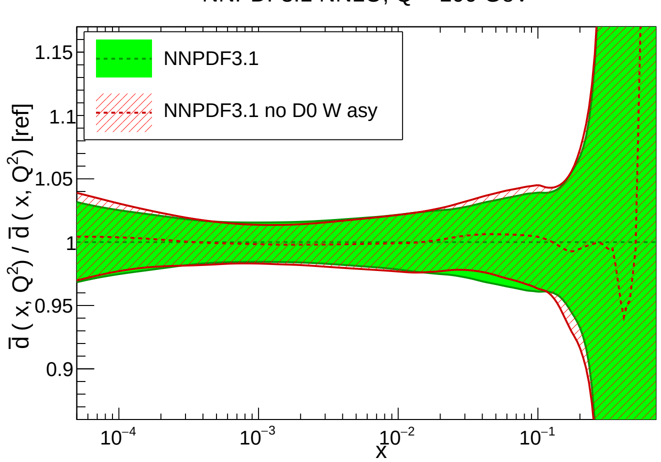
XFITTER: IMPACT ON HERA



XFITTER: IMPACT ON CT10



NNPDF3.1: IMPACT ON GLOBAL FIT



- IMPACT EXAGGERATED BY
  - COMPARISON TO SMALL DATASET
  - SOMEWHAT RESTRICTIVE PARAMETRIZATION