



PDF CHALLENGES HL-LHC AND BEYOND

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PUSHING THE BOUNDARIES

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PDFs TO 1% (OR BETTER)

PDFs NOW

- CURRENTLY PDF4LHC15 SET RECOMMENDED FOR PRECISION PHENO
- STATISTICAL COMBINATION OF CT14, NNPDF3.0, NNPDF3.0 \Rightarrow 2014 data, mostly pre-LHC
- NNPDF3.1 AVAILABLE (2017) \Rightarrow SIZABLE IMPACT OF RUN I LHC DATA \Rightarrow METHODOLOGICAL IMPROVEMENTS



WHY THE IMPROVEMENT? LHC DATA!: NNPDF3.0 vs NNPDF3.1

Kinematic coverage



NEW DATA: (BLACK EDGE)

- HERA COMBINED F_2^b
- D0 W LEPTON ASYMMETRY
- ATLAS *W*, *Z* 2011, HIGH & LOW MASS DY 2011; CMS *W*[±] 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

THE IMPACT OF LHC DATA NNPDF3.0 (2014) PDF UNCERTAINTIES (NNLO)



• TYPICAL UNCERTAINTIES IN DATA REGION $\sim 3-5\%$

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THE IMPACT OF LHC DATA NNPDF3.1 (2017) PDF UNCERTAINTIES (NNLO)



- TYPICAL UNCERTAINTIES IN DATA REGION $\sim 1-3\%$
- NEW LHC DATA \Rightarrow SIZABLE REDUCTION IN UNCERTAINTIES

"PDF" UNCERTAINTIES

CAN WE TRUST PDF UNCERTAINTIES?

- "PDF" UNCERTAINTIES REFLECT UNCERTAINTY FROM THE DATA & METHODOLOGY (NOT THEORY)
- UNCERTAINTIES ON GLOBAL FITS \Rightarrow SIMILAR SIZE DESPITE DIFFERENT PROCEDURES
- DUE TO UNCERTAINTY TUNING



- (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
- WHY DO WE NEED TOLERANCE?
- DO WE UNDERSTAND PDF UNCERTAINTIES?

PDF UNCERTAINTIES: HOW MUCH DO THEY VARY?

- COMPUTE PERCENTAGE PDF UNCERTAINTY ON ALL DATA INCLUDED IN GLOBAL FIT
- COMPARE GLOBAL FITS



- MEDIAN SIMILAR
- DISTRIBUTION VERY DIFFERENT!
- NNPDF: SMALLER MODE, BUT FAT TAIL \Leftrightarrow GREATER FLEXIBILITY

ARE PDF UNCERTAINTIES FAITHFUL? CLOSURE TESTING 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:
- TEST WHETHER PDF UNCERTAINTY FAITHFULLY REFLECTS DATA UNCERTAINTY: E.G. TRUE VALUE WITHIN ONE-SIGMA 68% OF TIMES

ARE PDF UNCERTAINTIES OPTIMAL? THE $\Delta \chi^2$ PROBLEM

- TOLERANCE MIGHT COMPENSATE FOR MISSING FUNCTIONAL UNCERTAINTY
- BUT WHAT IS $\Delta\chi^2$ for an NNPDF Fit?
- CAN ANSWER USING HESSIAN CONVERSION! $\Delta \chi^2 = 16 \pm 15$
 - NON-PARABOLIC BEHAVIOUR NEAR MINIMUM ON SCALE OF UNCERTAINTIES?
 - **INEFFICIENCY** OF THE MINIMIZATION PROCEDURE?

CLOSURE-TESTING THE PDF UNCERTAINTIES RESULTS

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.

- PDF UNCERTAINTIES ARE FAITHFUL
- BUT ARE THEY THE SMALLEST FROM GIVEN DATA?

CLOSURE TESTING THE SOURCES OF UNCERTAINTY

- LEVEL 0: ZERO UNCERTAINTY
 - CHECK WHETHER MINIMZATION EFFICIENT
 - CHECK FOR INTERPOLATION UNCERTAINTY
- LEVEL 1: DATA UNCERTAINTY, BUT NO REPLICAS
 - CHECK FOR UNIQUENESS OF BEST FIT \Rightarrow "FUNCTIONAL" UNCERTAINTY
- LEVEL 2: AS IN STANDARD PROCEDURE
 - CHECK WHETHER TRUE VALUE GAUSSIANLY DISTRIBUTED ABOUT FIT
 - CHECK WHETHER UNCERTAINTIES FAITHFUL

CLOSURE-TESTING: THE PARAMETRIZATION DEPENDENCE



(C. Mascaretti, 2016)

- CLOSURE TEST PERFORMED WITH DATA GENERATED BASED ON MST08 FUNCTIONAL FORM
- **REFITTED** EITHER WITH **NNPDF** OR MSTW-CT FUNCTIONAL FORM
- LEVEL 0: VANISHING DATA UNCER-TAINTY
 - MSTW-CT: FIT HAS ZERO UN-CERTAINTY
 - NNPDF: ABOUT HALF OF TOTAL UNCERTAINTY
- LEVEL 1: NOMINAL DATA UNCER-TAINTY, BUT REPLICAS FITTED W/O PSEUDODATA
 - MSTW-CT: FIT HAS SMALL UN-CERTAINTY
 - NNPDF: ABOUT 2/3 OF FINAL UNCERTAINTY
- LEVEL 2
 - NNPDF UNCERTAINTY LARGER THAN MSTW-CT
 - NNPDF UNCERTAINTY SIMILAR TO MSTW WITH TOLERANCE

"STANDARD" PARAMETRIZATION MISSES INTERPOLATION & FUNCTIONAL UNCERTAINTY?

MORE EFFICIENT MINIMIZATION?

- LOOK AT α_s DEPENDENCE (CORRELATED REPLICAS)
- SIGNIFICANT FLUCTUATIONS ABOUT PARABOLIC SHAPE NOT DUE TO FINITE-SIZE MONTE CARLO SAMPLE



- MINIMIZE EACH REPLICA MORE THEN ONCE & KEEP BEST RESULTS
- SIGNIFICANT STABILIZATION



- FROM 2011 TO 2012, UNCORRELATED UNCERTAINTIES DOWN TO SUB-PERMILLE
- 2011: $\chi^2/dof \sim 1$; 2012: IMPOSSIBLE TO FIT BETTER THAN $\chi^2/dof \sim 3$
- PATHOLOGICAL BEHAVIOUR OF COVARIANCE MATRIX \Rightarrow WHAT IS THE UNCERTAINTY ON IT?

CORRELATIONS & THE COVARIANCE MATRIX THE ATLAS 7TEV JETS

- Each rapidity bin can be fitted with $\chi^2/dof\sim 1$
- EACH LEADS TO INDISTIGUISHABLE BEST-FIT PDFS
- IF all bins fitted simultaneously, $\chi^2/dof\sim 3$



(Harland-Lang, Martin, Thorne, 1016)

- MISESTIMATED CORRELATIONS?
- CAN SINGLE OUT WHICH CORRELATION OUGHT TO BE REMOVED

THEORY UNCERTAINTIES

CAN WE TRUST NNLO CALCULATIONS? NUMERICAL INSTABILITIES



(Boughezal, Liu, Petriello, 2016)

- UNCORRELATED STATISTICAL UNCERTAINTIES AT PERMILLE LEVEL
- Large NNLO corrections $\sim 10\%$
- NOMINAL K-FACTOR UNCERTAINTIES VERY SMALL: UNDERESTIMATED?
- FIT ONLY POSSIBLE WITH RELIABLE ESTIMATE OF UNCERTAINTY ON THEORY PREDICTION
- NNPDF3.1: EXTRA 1% THEORY UNCERTAINTY ESTIMATED BASED ON FLUCTUATIONS W.R. TO INTERPOLATION (SHADED IN PLOT)

CAN WE TRUST NNLO CALCULATIONS? NUMERICAL INSTABILITIES

AN EXAMPLE: ATLAS 7 TEV p_T DISTRIBUTION THE NNLO/NLO K-FACTOR



(Boughezal, Liu, Petriello, 2017)

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CAN WE TRUST HEAVY QUARK PDFs?

- HEAVY QUARK PDFS DETERMINED BY (LOW-ORDER) MATCHING CONDITIONS + PERTURBATIVE EVOLUTION
- STRONG DEPENDENCE ON HQ (POLE) MASS



- MASS DEPENDENCE GREATLY REDUCED
- SHAPE DIFFERS FROM NNLO MATCHING



- FLAVOR DECOMPOSITION ALTERED
- UNCERTAINTIES ON LIGHT QUARKS NOT SIGNIFICANTLY INCREASED



- W, Z CROSS-SECTIONS AT 13 TEV IN PERFECT AGREEMENT WITH DATA THANKS TO FITTED CHARM!
- ELECTROWEAK CORRECTIONS IMPORTANT

WHAT ABOUT THE B PDF?

WHAT ABOUT MISSING HIGHER ORDERS?

- 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



- TODAY: NLO PDF & MHOU UNCERTAINTIES COMPARABLE
- NEAR FUTURE: SHOULD WE WORRY ABOUT NNLO MHOU?

WHAT IS THE IMPACT OF SCALE VARIATION ON PDFs?

SIMPLEST IDEA FOR PDF MHOU ESTIMATE

- PERFORM FIT WITH VARIOUS SCALE CHOICES
- TAKE ENVELOPE OF RESULTS
- COMPARE TO NLO-NNLO SHIFT IN ORDER TO TUNE RANGE OF VARIATION & CORRELATION PATTERN: VARIATION FULLY CORRRELATED ACROSS PROCESSES?



HOW CAN WE INCLUDE MHOU IN PDF ERRORS?

BETTER IDEA FOR PDF MHOU ESTIMATE

- PERFORM CALCULATION WITH VARIOUS SCALE CHOICES
- USE DISTRIBUTION OF RESULTS TO COMPUTE THEORY COVARIANCE MATRIX
- PERFORM FIT WITH EXTRA CONTRIBUTION TO COVARIANCE MATRIX







IF NO CHANGE IN α_s UNCERTAINTY,

WHERE DOES THE PDF AVERAGE COME FROM? PDG PRE-AVERAGES



- PDG average: χ^2 -averaging of six pre-averages, chosen to be maximally uncorrelated
- χ^2 AVERAGING \Rightarrow UNCERTAINTIES INFLATED OR CORRELATED UNTIL $\chi^2/dof = 1$
- EACH PRE-AVERAGE IS THE SIMPLE (UNWEIGHTED) AVERAGE OF ITS COMPONENTS, UNCERTAINTY ↔ AVERAGE OF UNCERTAINTIES (OR STANDARD DEVIATION OF VALUES IF LARGER)

WHAT'S THE PROBLEM?

- GLOBAL EW FIT THEORETICALLY SAFE, BUT NOT VERY PRECISE
- τ QUITE PRECISE, BUT LOW SCALE \Rightarrow PERTURBATIVE ACCURACY?
- LATTICE: VERY PRECISE, BUT WHAT IS THE ACCURACY OF THE TRUNCATION?
- ANY PROCESS WITH HADRONS IN THE FINAL STATE: DEPENDENCE ON THE PDF



DATASET PULLS ON GLOBAL α_s DETERMINATION

(NNPDF, 2018)

PULLS DO NOT ADD TO ZERO \Leftrightarrow BEST FIT PDF FOR DATASET IS NOT GLOBAL BEST FIT α_s USING EXTERNAL PDF SET POTENTIALLY BIASED DUE TO α_s -PDF CORRELATION

OUTLOOK

WHAT I TALKED ABOUT AND WHEN

- "PDF" UNCERTAINTIES
 - RELIABLE EXPERIMENTAL COVARIANCE MATRICES \Rightarrow LHC RUN II
 - OPTIMIZED MINIMIZATION \Rightarrow LHC RUN II
- THEORY UNCERTAINTIES
 - THEORY PREDICTIONS WITH SUB-PERCENT NUMERICAL ACCURACY \Rightarrow NOW LHC Run II
 - FITTED HEAVY QUARK PDFS \Rightarrow NNPDF3.1 (2018), PDF4LHC20
 - PDFs with theory uncertainty \Rightarrow NNPDF4.0 (2019)
- CONSENSUS α_s WITH SUB-PERCENT ACCURACY \Rightarrow HL-LHC

WHAT I DID NOT TALK ABOUT AND WHY

- HIGHER TWISTS, NUCLEAR CORRECTIONS \Rightarrow HISTORY!
 - FIXED-TARGET DATA OBSOLETE
 - COLLIDER-ONLY PDFS
- RESUMMED PDFS, N³LO PDFS, EW CORRECTIONS \Rightarrow LABORIOUS BUT TRIVIAL
 - AUTOMATIZATION OF HO CORRECTIONS
 - PUBLIC CODES
- PS-PDFs, MC-PDFs \Rightarrow Some way to go